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PROCEEDINGS OF THE LHC DAYS 2003

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Editor: Felix RODRIGUEZ-MATEOS

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FOREWORD

The overwhelming success of the *LHC days 2001*, held in Villars-sur-Ollon, convinced us all of the interest and necessity of making it a periodic annual event, following the development of the LHC project and the corresponding evolution of our activities. It also comforted us in the practical choices made for the organization, in particular concentrating the event over three days, thus permitting to maximize the number of participants attending the whole sequence of presentations and discussions, and giving preference to "transverse" topics to foster interactions between equipment specialists usually too busy in their own domain to look around and learn about other aspects of the LHC project. The stage was therefore set for organizing a 2002 venue. Unfortunately, the financial situation of CERN and the subsequent economy measures taken in 2002, as well as the ongoing reorganization of the Accelerator Sector, forced us to postpone the next venue to 2003.

The *LHC days 2003*, held in Les Diablerets from 2nd to 4th June 2003 and attended by more than 130 participants from 6 divisions of CERN, bear witness of the broad involvement of CERN in the LHC, and of the development of the project in its construction and installation phases. Of course the core responsibilities of the Accelerator Technology division, such as superconducting magnets, cryogenics and vacuum, took a large share of the program, but the related topics of machine installation, commissioning, testing and operation, as well as the interface with the experimental areas and their physics detectors provided the occasion of dynamic exchanges and intense discussions, as they constitute the forthcoming phases of our work on the project.

This report summarizes the presentations and discussions which took place during these three days. It represents the tangible result of the work of many colleagues in the organizing committee – in particular the scientific secretary and editor of the proceedings Felix Rodriguez-Mateos –, as well as speakers and session chairs, who all contributed to make this event a success. A special mention is due of Evelyne Delucinge who took care of perfect logistics. Let all of them be warmly thanked.

Philippe Lebrun

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Wednesday, 5 June 2003

Session 5: Interfaces to experiments and other systems

Chair: *R. Veness*
Scientific Secretary: *J. Bremer*

SUMMARY OF SESSION 1: INSTALLATION AND ASSEMBLY

C. Hauviller, J. Ph. Tock, CERN, Geneva, Switzerland

Abstract

This first session was dedicated to installation and assembly issues and included seven talks:

- Installation Scheduling (K. Foraz)
- It is not so easy to install (B. Nicquevert)
- Surveying LHC (J.P. Quesnel)
- Cryogenic distribution systems (G. Riddone)
- Preparation for and installation of SSSs (P. Rohmig)
- Preparation for and installation of main cryodipoles (D. Tommasini)
- Organisation of interconnections of cryomagnets in the tunnel (J.Ph. Tock)

This paper is divided into two main parts: first, a brief summary of each talk is given and then main issues from are presented after grouping them around common subjects.

SUMMARY OF THE TALKS

Installation Scheduling (K. Foraz)

The consolidated schedule was presented, explaining how the various constraints (key dates, contractual delays, transport restrictions, civil engineering, allocation of human resources, integration, …) were taken into account and have lead to a re-ordering for the sector installations. The importance of communicating changes as soon as possible was underlined.

It is not so easy to install (B. Nicquevert)

The installation of a component (putting it at the right place and at the right time) is not always an easy task. The rule for equipment handling is that each system provider has to design its component but also the handling tools and procedures. The criticality of PMI2 (the only pit available for lowering of cryodipoles) was highlighted. Typical examples of difficult integration areas were given. Overcoming these problems will only be possible thanks to everybody's understanding and help.

Surveying LHC (J.P. Quesnel)

For surveyors, the installation phase began in November 2001 and even before for the geodetic network. The main alignment activities (geodetic reference network, marking on the floor, check of the position of the QRL, positioning of the jacks, alignment of cryomagnets, maintenance) were listed, identifying the reference documents. Peculiarities of insertion regions (motorized jacks, permanent measuring devices) were presented. The data management and the related quality assurance were presented.

Cryogenic distribution systems (G. Riddone)

The architecture of the LHC cryogenics was presented, focusing on the main underground components: cryogenic interconnection box (QUI), 1.8 K refrigeration units, cryogenic distribution line (QRL). The installation of cryogenic equipments has already been performed but the main part has still to be done. The planning is very tight with almost no margin.

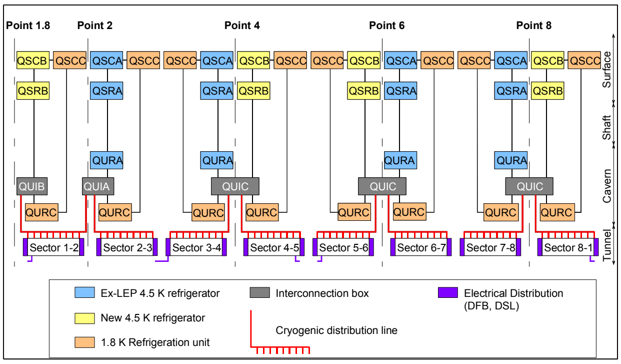

Figure 1: Architecture of LHC cryogenics.

Preparation for and installation of SSSs (P. Rohmig)

A SSS is composed of a twin aperture high-field superconducting quadrupole, corrector magnets and diverse specific equipment all housed in a common helium enclosure. The SSS cryostat also contains a vacuum barrier (25%), a technical service module (QQS), beam position monitors… and is also interconnecting the SSS with the cryogenic distribution line (QRL). The LHC contains 474 SSS of about 111 different types, reducing dramatically the sorting possibility. The sequence of activities from the reception of the cold mass to the start of the interconnection work is detailed, referring to the Quality Assurance documents.

Figure 2: Transport simulation of SSS5 at PX46.

Preparation for and installation of main cryodipoles (D. Tommasini)

Because of various types of magnets, of connection to the diode and of variants of extremities for interconnections, 27 types of cryodipoles will have to be installed in the LHC tunnel. The sequence of activities from the reception of the cold mass to the start of the interconnection work is detailed and the related quality assurance aspects are presented.

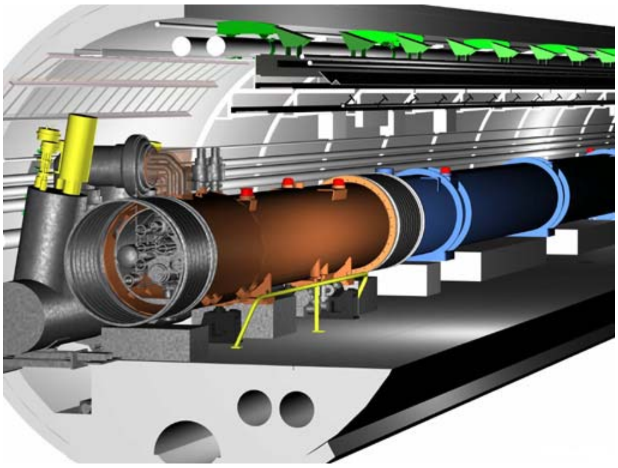

Figure 3: 3D view of the LHC tunnel.

Organisation of interconnections of cryomagnets in the tunnel (J.Ph. Tock)

After giving some key figures [1700 interconnections including about 123 000 joints, involving several millions of operations] the sequence of interconnection works, divided in various Interconnection Work Packages (IWP), has been presented: preparation works, interconnections between cryomagnets and with the Cryogenic line. Some open issues were listed. The Quality Assurance status was given. A Contract will be signed with an external firm for the assembly of the LHC interconnections.

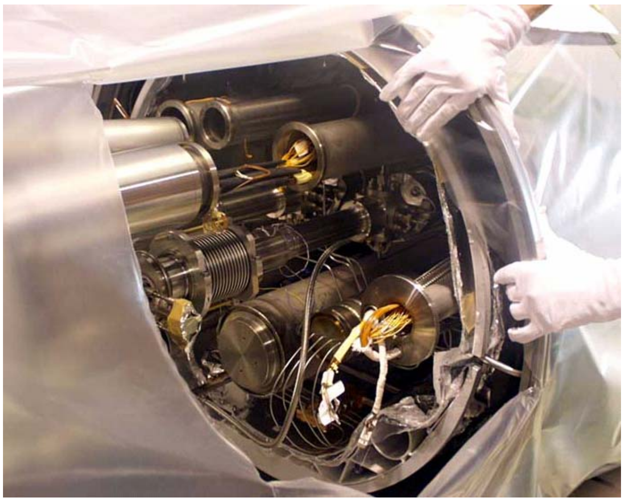

Figure 4: Interconnection of STRING2.

MAIN ISSUES

The seven presentations have shown common points out of which some main issues have been extracted.

The Schedule/ Coordination of interfaces

The scheduling has to be considered as the most important point which has been mentioned in all the presentations. Contrary to the situation for the services and the QRL (no margin for the latter), the planning for the machine elements is not consolidated at all. For example, for these machine elements, one can read terms like "Navigation a vue", one finds a planning of installation of SSS reorganized by the author and information from the survey that some missing magnets are acceptable for the initial alignment. This consolidation is deemed to be of prime importance. Improvement of the communication channels have also been stressed in relation with the coordination of the interfaces.

Space constraints / Integration/Handling

The rule established by the project management has been recalled: each system provider has to design not only its components, but also dedicated handling tools and procedures. This rule is applied for most of the Arc elements but not necessarily for the special ones.

The limited dimensions of the tunnel have led to the definition of a maximum transport volume which has always been respected by the designers of the elements.

Performing the interconnections in the tunnel already crowded is subject also to major space constraints.

Documentation

The work packages are defined for the activities presented. The documentation exists and the Manufacturing and Test Folder (MTF) is operational. Relevant parameters are introduced for the elements presented.

However, the volume of data stored was questioned, sometimes too much, sometimes too few. The floor has questioned the limited efficiency of the search tool. The situation has to be improved.

Quality assurance

This aspect has been treated in most of the presentations. Awareness exists and is being concretized. Treatment of non-conformities has been put or will be in place soon.

Sorting

Sorting should be used to optimise the localisation in the machine of the magnets in relation to their magnetic performances. However, in the case of the SSS, the sorting is very limited due to the high number of variants.

The situation for the cryodipoles is better; it is announced as possible, to a certain extent, for the first octant but thereafter no longer possible due to installation planning and storage capacities.

INSTALLATION SCHEDULING

K. Foraz, CERN, Geneva, Switzerland

Abstract

Since January 2003, the installation and coordination group takes care of the installation of the LHC. In March 2003 new target milestones have been issued. This paper aims to give an overview of what and how the new group interacts with project leader's office and CERN's groups and divisions to consolidate the target milestones.

TARGET MILESTONES

Since November 2002, the consolidation schedule has been analysed using:

- the main key dates defined by L. Evans in February 2001,
- the advancement and delays of civil engineering works along the ring,
- the cost of electricity during the winter season, and thus for QRL commissioning
- The empty periods between phases, in order to smooth resource allocation and therefore the associated costs.

In March 2003, the new installation scheduled was approved by CERN management and all the Project Leaders. The major changes were the re-ordering for the sector installations and the extension of the windows dedicated to services. As already shown, sectors 6-7 and 4-5 have been shifted, as well as sectors 1-2 and 3-4.

Table : Installation target milestones

Sector 1-2	
Services installation	-> 06/05/05
QRL installation	13/06/05 -> 21/10/05
QRL commissioning	19/06/05 -> 12/05/06
Magnet installation	19/06/05 -> 23/12/05
Hardware commissioning	08/01/06 -> 24/03/06
Sector 2-3	
Services installation	-> 07/11/03
QRL installation	10/11/03 -> 16/04/04
QRL commissioning	28/06/04 -> 20/08/04
Magnet installation	13/09/04 -> 27/05/05
Magnet commissioning	30/05/05 -> 09/09/05
Sector 3-4	
Services installation	-> 10/09/04
QRL installation	20/09/04 -> 11/02/05
QRL commissioning	23/05/05 -> 15/07/05
Magnet installation	08/08/05 -> 21/04/06
Magnet commissioning	24/04/06 -> 04/08/06
Sector 4-5	
Services installation	-> 18/06/04
QRL installation	28/06/04 -> 05/11/04
QRL commissioning	21/03/05 -> 13/05/05
Magnet installation	06/06/05 -> 17/02/06
Magnet commissioning	20/02/06 -> 02/06/06
Sector 5-6	
Services installation	-> 10/12/04
QRL installation	13/12/04 -> 06/05/05
QRL commissioning	27/07/05 -> 16/09/05
Magnet installation	21/11/05 -> 04/08/06
Magnet commissioning	07/08/06 -> 17/11/06
Sector 6-7	
Services installation	-> 18/03/05
QRL installation	21/03/05 -> 29/07/05
QRL commissioning	27/09/05 -> 21/11/05
Magnet installation	06/02/06 -> 06/10/06
Magnet commissioning	09/10/06 -> 21/12/06
Sector 7-8	
Services installation	-> 13/06/03
QRL installation	21/07/03 -> 12/12/03
QRL commissioning	19/05/04 -> 30/05/04
Magnet installation	03/05/04 -> 22/04/05
Magnet commissioning	25/04/05 -> 14/10/05
Sector 8-1	
Services installation	-> 02/04/04
QRL installation	05/04/04 –> 13/08/04
QRL commissioning	06/09/04 -> 21/10/04
Magnet installation	31/01/05 -> 07/10/05
Magnet commissioning	10/10/05 -> 20/01/06

INTEGRATION BEFORE IT IS TOO LATE

80% of the tunnel's circumference is more or less periodic and the integration is done using the automatic generation program DMU. The other 20%representing the non-standard zones (mainly the long straight sections) has to be integrated on time for the installation of the different equipment.

The "on time" notion has been materialized in the consolidation planning, taking into account the different constraints:

- Contractual delays between when CERN gives integration design to an outside company, and when the outside company actually starts the works.
- Human resources allocation in each design office concerned.

The schedule issued (and edited on the WEB) is reviewed monthly in integration meetings, with all the groups concerned.

STRATEGIC PLANNING CONSOLIDATION

Schedule development

The strategic planning established, we have to look deeper into each phase, division and group to ensure timely completion of the project.

First we take a closer look at each Project Leader in order to understand the activity he/she is in charge of, and determine with them the activity duration estimates, the dependencies, the constraints, the resource capabilities.

Then we analyse internally all the information for one phase, sequence the activities and then draw up a draft planning. We organise meetings with all the Project Leaders who have activities in this phase, and present the draft planning. When the consensual solution meets the respective strategic key dates, the consolidation planning is implemented and edited on the WEB, and the Project Leaders are notified.

Constraints

Constraints limit the options that are open whilst developing the schedule.

We consider four main categories of constraints:

- Strategic: Key dates fixed by the Project Leader.
- Contractual: Dates or duration might be contractually fixed in the contracts, and thus hardly moved.
- External: relationship between activities.
- Geographical : transport restrictions

Transport restrictions

Each Project Leader should be aware that it has been agreed to transport magnets during night shifts, and therefore the transport area should be free of all material at night. But they must also be aware that all other transport of material should be done during day shifts, and therefore might cross their worksite. If it were not the case, transport costs would increase by 25%. In order to avoid problems with transport restrictions, ST/HM and Project Leaders must write transport procedures at least 6 months before the start of the works. Then ST/HM and our section analyse these transport requests with the installation planning and see whether or not this could be achieved.

Planning follow-up and Alternative plans

Thanks to the consolidation planning, the reports coming from the work sites' team, the different group meetings and our own meetings, we are closely following the state of each task in work.

This planning follow-up and control aims to:

- Determine that the planning has changed, and hopefully that the work has speeded up. We report the % completed, what remains to be done and analyse the possible leads or jacks in the planning.
- Influence the factors that create change, and hopefully influence them in a positive way.
- Manage the changes when and as they occur: Changes can come from site reports or from Project Leaders and may arrive in any form: oral or written, direct or indirect, official or optional, but as soon as possible.

So when we have all the necessary information, we analyse all the inputs, document the changes and produce an updated version of the consolidation planning, and notify the appropriate stakeholders. At this point, we have two options:

- either the changes have not modified the strategic key dates and the baseline stays unchanged,
- or the strategic key dates cannot be respected. Then the Project Leader's office has to inform us, and we'll find a joint solution, and might change the baseline.

Status of the consolidation planning

- Service installation phase is consolidated
- Cryogenic phase is underway
- Machine phase has to be consolidated

STATUS OF THE WORK

Since August 2002, the installation works have started in 4 sectors: 7-8, 2-3, 8-1, 4-5. The services installation phase Sector 7-8 is 98% complete, by June 13.

The experience gained in this first sector will be very useful for the future.

This appetizer shows:

- Durations: durations announced by Project Leaders are more or less (but more rather than less) realistic.
- Contracts: all the contracts dedicated to this phase, despite some hiccups at the beginning, are now operational. We have to stay strong and factual in front of outside companies.
- Material: Project Leaders have to check at each phase that materials will be delivered on time.
- Transport: transport problems are not easy, we must also take into consideration that people who are transporting our own materials are not so motivated leading to some destructions; and that to have the transport area free every night requires everybody's cooperation.
- Hazards: there are always some additional works which consume a couple of weeks in each area, and therefore we have to keep some gaps in the schedule if we want to keep strategic key dates.
- Small works: To keep the planning, a lot of orphan, safety or unfinished jobs have to be performed at short notice. The introduction in IC group of a small team performing this type of activity eases considerably the situation.

REFERENCES

[1] G. Bachy, P. Bonnal, "A planning & scheduling system for the LHC project", CERN MT/95-09.

IT IS NOT ALWAYS SO EASY TO INSTALL

B. Nicquevert, CERN, Geneva, Switzerland

Abstract

Installation is not always a straightforward job; this paper focuses on adversities popping up during the preparation and first stages of installation so far: identified obstacles to installation, zones where integration is hardly possible, dealing with non-conformities during and after installation, missing tools are reviewed through a couple of examples picked up amongst a variety of many others, most of time hidden to the community of designers and future users of LHC.

RIGHT ITEM AT RIGHT LOCATION?

After delivery by project teams, it is more or less implicitly expected from installation team to transport the components in the tunnel, put them at the right functional position, all this at the right time, with sufficient precision, so that it is ready for assembly and commissioning. This is not always so easy!

A component delivered by a project team has to be dealt with through a number of operations: Stored (sometimes), transported on surface to a pit, lowered down in the pit, transported along the tunnel(s) to its functional position. Before installation can proceed, it must be clear where actually stands the so-called « right position »; that this functional position is free, and accessible; and how to proceed to handle the component

TRANSPORTS

On surface

When a component is ready, it does not mean that it can be immediately installed. It depends on schedule; it depends as well on the decision taken of the « right functional position ». For example, for the cryo-dipoles, The right functional position is defined only after MEB evaluation, decision and report (see D. Tommasini's paper). Meanwhile, cryo-dipoles need to be stored. A dedicated zone was prepared and is currently being progressively put in use at Prévessin.

Still with cryo-dipoles: it is not so easy to transport 16 m long, 35 tons items. This takes time, this takes space, and this requires dedicated handling tools. For those cryo-dipoles, three spreaders are requested at various locations to handle them, 2 are now under procurement.

There is a rule about handling: each system provider has to design not only its components, but also dedicated handling tools and procedures. It is not within scope of supply of the EST/IC group to take care of each of the systems, even if we require to be involved in the design, in order to homogenize the various equipments.

For cryo-magnets, they have to be transported mainly from point 18 to point I2. Here is an example of the small problems that have to be dealt with: during test ran end of April with the final 100 tons trolley, after going out of the SDI2 building, the lorry went to a place with missing asphalt (Fig. 1).

Figure 1

This zone will be completed, as soon as the barracks installed meanwhile are moved elsewhere.

Lowering down

Among others, two criteria of an easy installation in the accelerator ring can be used [1]: the Distance Between Accesses (in other words, the number of pits); and the Section of the ring tunnel. Compared with LEP era, the number of pits: seems to be increased, and the section kept the same. From the civil engineering point of view, this is correct, of course. Seen from the installation, this is no longer really the case.

First, as far as experimental pits are concerned, only a restricted use can be made of PXs. PX46 and PX64 require a platform; PX15 and PX55 can only be used by Atlas and CMS; PX24 is mainly reserved for Alice, and PX84 must be shared with LHC-b (already for QRL installation in sector 7-8). Then, PMs are usable only for small material; and PM18 (to be used for a cryogenic plant) was isolated from the main ring by a wall.

Remains PMI2, planned for lowering down the LHC magnets. This is the only place of all LHC. Its main drawback is that it is not over the main ring, but over the injection tunnel TI2. In addition, there is no lift or alimac: consequently, in case of problem, you need to walk, ride or drive to point 2 (3 km…) before being able to move from surface to underground area or vice-versa. It is the least to say that this is not convenient.

Though PMI2 is the only vertical access for cryo-dipoles, even there, the clearance is marginal in case of wish to lower down the magnets directly to the transport area underground. A conflict (hopefully minor) between power rail and electrical distribution in the TI2, requesting a bit of 3D integration, must be solved quickly, as installation has started in TI2, and will be at the level of PMI2 mid-June 2003. This is typical of the time response requested from the integration team nowadays.

In the sections of injection tunnel and main ring

Fig. 2 shows the very limited space in the section of the injection tunnel TI2. It is obvious that the occupation is much higher than in LEP tunnel, and that this area is quite crowdy.

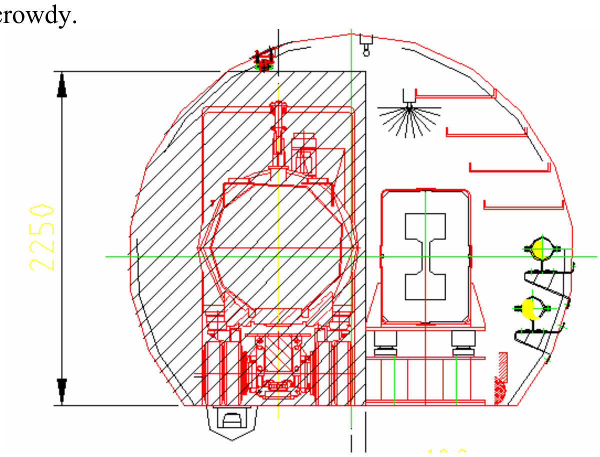

Figure 2

It is therefore of highest importance to respect the transport volume, as defined in the TWG in November 2000: 16.3 m long, 1.8 m high, 1.1 m wide, with restricted area of only 0.6 m over the last 0.25 m on top.

Let's now focus on some items which do not respect this available space: first, some SSS (to be placed in LSS) have an extended jumper up to 1060 mm high. Their total height exceeds 2.3 m! So far, 25 SSS of this type cannot be installed. At least they are not built so far, and there is some hope that an appropriate design can cope with this transportation problem (see V. Parma's talk).

Unfortunately, some other items do protrude out of this volume, but are already at CERN. These are the D2 to D4 separation dipoles. They are too high, due to their jumper, to be lowered down by PMI2; and too long to be lowered down in most of other pits. A dedicated solution must be found.

HARD INTEGRATION AREAS

Let's go down along TI2 (for those items which fit), and arrive in UJ22. This is typical of those areas hardly possible to integrate, as it includes LHC ring, with all associated general services, injection line with all kickers and special magnets, QRL in normal and upper position, the handling tool to move cryo-dipoles after installation, not forgetting transport volumes for both installation and exploitation eras. It appeared, after integration studies, that services out of TI2 could not reach UJ22. An ad-hoc solution is under study, with two additional bores to be drilled between TI2 and R22, in order to deviate general services and control cables, and let more room for warm services to injection magnets, leaving space for the transport volume while respecting the survey zone. Figure 3 shows this very crowdy zone (transport volumes are not represented).

In addition, the assembly sequence must be carefully visited, since due to the particular position of the QRL pillar, the usual sequence might have to revised.

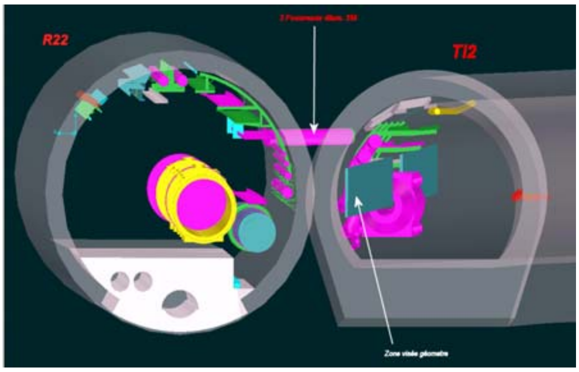

Figure 3: UJ22.

Region UJ76 is another example where services take quite some space. Point 3, without RR area, is quite congested (R36, TZ33) too. It is however not the purpose to mention all pending areas under integration here. Visit the ICL site, managed by EST/IC-IN [2].

A last example is the DBFL to be installed in UP33, and deals with items which can statically be integrated in their final position, but whose dynamical installation (handling tools, procedure and path) is not yet studied (see A. Perin's talk). Can this item reach its position?

DEALING WITH NON CONFORMITIES

Once the area is integrated by EST/IC-IN, once the item has reached its « right functional position » defined in EST/IC-DC database, you still can have bad surprises: what is supposed to be there is missing; or what is there is too large, or non conforming. A known example are supports for electrical trays in TI, which are larger than expected (by ca. 5 cm).. Elsewhere in R82, some pipes are protruding in the space reserved for QRL.

This must be reported as soon as possible to EST/IC-CI (coordination de l'installation) and EST/IC-LC (logistics coordination), in order to plan early action and intervention. The sooner the better! (see K. Foraz' talk)

SUMMARY AND CONCLUSION

Restricted access to pits, restricted paths in sections of TI2 or main ring, missing handling tools and procedures, restricted time (transports only during nights, means extra delays and extra cost)… all these points make installation a « not so easy task » to perform and to coordinate. By chance, thanks to everybody's understanding and help, this will become easier and easier with days and years. Rendez-vous is given in 2007 for another talk, entitled « It Was Actually Not So Difficult To Install LHC ».

ACKNOWLEDGEMENTS & REFERENCES

I would like to thank all those who contribute by providing ideas, examples and pictures: O. Capatina, S. Chemli, O. Choisnet, D. Galhaut, C. Hauviller, K. Foraz, M. Gielen, C. Magnier, Y. Muttoni, T. Renaglia.

[1] G. Bachy, "Design, Installation Problems and Criteria in Large Accelerators", CERN-LEP-IM/87-18, 1987.

[2] http://lhc-div-miwg.web.cern.ch/lhc-div-miwg/Main_Pages/miwg_site_overview.htm

SURVEYING LHC

J.-P. Quesnel, CERN, Geneva, Switzerland

INTRODUCTION

The installation phase of LHC began already in November 2001 for surveyors, and even before as far as the geodetic reference network is concerned. For defining the works under the responsibility of the EST-SU group, a series of documents has been published, approved and is part of the LHC baseline.

A review of each phase of the alignment work is presented, as well as the maintenance aspects for the alignment. After a presentation of the quality aspects of these activities, some question marks concerning these works are raised.

The metrological works made on the magnets themselves during their preparation are not presented here, as far as they do not concern directly the installation.

ALIGNMENT ACTIVITIES

The geodetic reference network

In the LHC ring, one point per half-cell is sealed in the floor, and the determination has been referred with respect to the LEP quadrupoles before their removal. In the TIs, one point is sealed in the floor each 30 m. Their determination has been performed during the winter shutdown 2002-2003, with a geometrical link to the SPS and the LHC ring.

Maintenance of this geometry is foreseen periodically up to end of the installation of the magnets.

See documents LHC-G-ES-0005, LHC-G-IP-0002 and LHC-G-IP-0003.

Marking on the floor

This work consists in marking on the floor the mean beam line and the position of the elements in the LSSs, the interconnection points and the vertical projection of the head of the jacks in the arcs. In the TIs, the beam line is drawn in the straight parts of the lines, as well as the position of all the elements defined by BEATCH file and their supports.

The accuracy of the marks is ± 2 mm.

See documents LHC-G-ES-0006 and LHC-G-IP-0004.

Actually about 80% of this work is already performed.

Control of the position of the QRL

The baseline is that the position of the jumpers will be controlled by EST-SU, and the group foresees no adjustment as this work is under the responsibility of AT-ACR. For this work, a jig with fiducial targets will be provided by AT-ACR. SU will provide to ACR the co-ordinates in CERN system of the interconnection point of the jumpers and of its geodetic reference network to allow the positioning by Air Liquid. As the points measured on the jumper for the positioning and the control will be different, a check that the two methods are in accordance will be performed at the beginning of the installation of the QRL. The jumpers have to be located within ± 2 mm when the bellows are in neutral position. In addition, SU recommends that the installation of the QRL take into account the ground motion of the tunnel, in particular in the sector 7-8, where a vertical movement down of about 2 mm per year of the tunnel is expected.

See documents LHC-G-ES-0015 and LHC-G-IP-0005.

Positioning of the jacks

Due to the very limited range of adjustment of the jacks, it is important to position the head of the jacks within ± 2 mm before the installation of the cryo-magnets, when the adjustment screws are in their mid position. Only in vertical, 5 mm of the range of the vertical screw can be used to compensate the errors of the floor. For larger deviations of the floor, shimming or grinding is needed.

This shimming or grinding, as well as the installation of the jacks and the fixation screws will have to be made prior to the positioning. After the positioning done by EST-SU, the jacks are sealed and fixed on the floor. SU recommends a global control to be performed after the completion of their installation and before the installation of the magnets.

See documents LHC-G-ES-008 and LHC-G-IP-0006.

First alignment of the cryo-magnets

See documents LHC-G-ES-0007, LHC-G-ES-0009, LHC-G-IP-0007 and LHC-G-IP-0008.

The work is done well in advance with respect to the connection work of the cryomagnets, and the methodology used allows some missing magnets.

Each magnet is aligned for itself from the reference geodetic network, and a small local smoothing is done to obtain a relative precision of the alignment of ± 0.25 mm in radial and vertical for each magnet, 0.5 mm axially, and 0.15 mrds in tilt.

For that work, the theoretical position of the fiducials is needed in advance.

Only after this alignment the connection work can start.

The smoothing

See documents LHC-G-ES-0010, LHC-G-IP-0010.

This phase is in fact the final alignment of the magnets. It can start when the magnets are connected, under vacuum and are cooled down, so that all the mechanical forces are taken into account.

The objective is to obtain a relative accuracy of 0.15 mm in radial and vertical.

The measurements in LEP show a deterioration of the alignment to 0.2 mm after one year. It's why a vertical smoothing is planed to be done each year, followed by a realignment of approximately 350 units.

For this operation, the access to the tunnel with ventilations as low as possible (5000/8000 m^3h) is requested.

Another aspect of the maintenance is the installation of sensors for giving a warning when large motion of magnets in interconnects occurs. Due to limited budgets, only half of the interconnects will be equipped in a first stage.

The insertion regions

Around the experiments, the inner triplets will be equipped with permanent measuring devices linked to motorized jacks.

These equipments will allow the connection Left to Right of the reference geometry through the experiments and the UPS galleries at point1 and 5 with an accuracy of about 0.2 mm r.m.s..

They will allow the relative positioning of the three quadrupole magnets Q1, Q2 and Q3.

They will allow also the permanent link of the geometry used for the alignment of the detectors ATLAS and CMS, and the TAS, to the geometry of the tunnel.

Due to the high level of radiation which is expected, all the electronics have to be transferred to less radioactive areas, and this increases a lot the cost of the equipment.

Quality Assurance

The following theoretical data are needed:

- definition of the LHC beam orbits in CERN co-ordinates XYZ (MAD);
- definition of the beam trajectories of the TI lines in CERN co-ordinates XYZ (BEATCH);
- position of the fiducials on each magnet, with respect to the ideal trajectory inside the magnet;
- position of the auxiliary equipments (BPM, correctors, etc.).

All these data are stored in databases. Some in SURVEY database, some somewhere else but should be accessible via SQL.

All the alignment measurements are stored in SURVEY database.

This database will contain also the real position of the elements after the alignment is done.

In fact this database contains already all these data for the existing machines.

As Built Measurements

Due to the quantity of equipments to be installed in the tunnel, as built measurements can be very useful in the most crowded areas, to be sure that at each step, the installation of the next equipment can be performed. UJ22 and LSS3 are examples of the concerned areas.

Laser scanner measurements analysed with software compatible with CAO tools existing at CERN can allow a comparison with the integration studies.

STRATEGY

The EST-SU Group has signed a contract with a firm for the duration of the construction of the project and its first maintenance. This contract is based on the specifications and procedures mentioned above. All the works in the arcs and the transfer lines are result oriented. The works in the LSSs, auxiliary galleries and the links with the existing machines will be managed on request. It is planed that one or two teams will be permanently able to work on request in these areas.

SOME DARK POINTS

Up to now, only few problems are still pending concerning our activities. Among them, the following ones can be mentioned:

- the auxiliary jacks needed for the vertical adjustment of the Indian jacks have to be built. SU and ME have developed a prototype which seems to work properly. It is now time to build additional ones;
- the stability of the cold mass of the cryomagnets in the tunnel is not yet well known;
- the redundant information and sometimes not very clear responsibilities do not help for finding theoretical data. A lot of work is done by IC and SU groups for collecting the good information (many thanks to Sami Chemli). Due to the "parcours du combattant" to find the information, EST-SU has decided to communicate to the responsible of each service the theoretical data he uses, for validation;
- the financial impact of some changes in the installation of the magnets in the transfer lines due to transport problems has to be studied;
- the ventilation conditions of the tunnels during the smoothing works are still not clear. In particular it is necessary to clarify if the low air flow rate of 9000 m^3h or less in a sector is compatible with the powered equipments needed in the tunnel for maintaining the cryomagnets cooled.

CONCLUSION

The aspects of the metrological works are defined. The conditions of work, the specifications and the procedures, participate to the logic of the positioning process of the magnets and their maintenance, and the inevitable modifications due to the installation would have to preserve this logic.

It seems that only few points still have to be clarified. The main problem today for us is to obtain the good information, only the needed information, but all the needed information.

CRYOGENIC DISTRIBUTION SYSTEM

G. Riddone, CERN, Geneva, Switzerland

Abstract

This paper, after giving a short introduction on the architecture of the LHC cryogenic, summarises the main aspects on transport, installation [1, 2, 3] and testing for the main new cryogenic equipment which are located in underground: cryogenic interconnection box, 1.8 K refrigeration units and cryogenic distribution line. In the last part of the paper the main critical points for the installation in underground are listed and the conclusions drawn up.

ARCHITECTURE OF THE LHC CRYOGENICS

The LHC cryogenic system is based on a 5-feed point scheme (see Fig. 1). Two cryoplants are located at each of the even points 4, 6 and 8 to serve the adjacent sectors. For space constraint reason, the second cryoplant at point 2 has been moved to point 1.8. Each cryoplant comprises a 4.5 K refrigerator (18 kW equivalent @ 4.5 K) and one 1.8 K refrigeration unit (2.4 kW @ 1.8 K). At each of the five points, an interconnection box installed in the underground caverns allows for the connection between the different cryogenic sub-systems. A cryogenic distribution line, starting from the interconnection box and running all along the tunnel, will feed with helium, at different temperatures and pressures, the cryomagnets, as well as the electrical feed boxes and superconducting accelerator cavities.

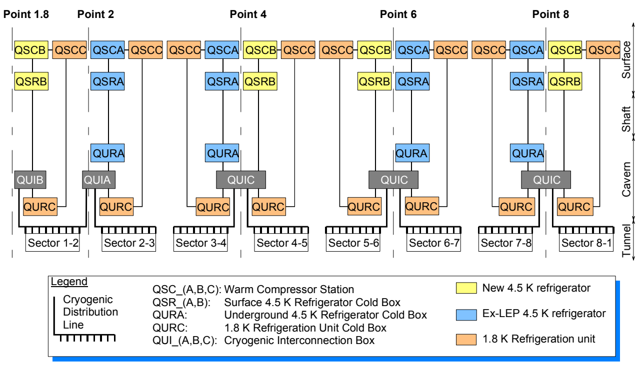

Figure 1: Architecture of LHC cryogenics.

MAIN UNDERGROUND COMPONENTS

Cryogenic interconnection box

The cryogenic interconnection box (QUI) is the central node of the LHC cryogenic system. The contract for the supply of the five QUI has been adjudicated to Air Liquide (FR). The QUI main components are: the vacuum insulated cold box, the warm instrumentation and valve manifold and the electrical cabinets. The cold box allows performing several functions, such as sector interconnection in case of failure of one refrigerator, quench release towards surface, cooldown and warm up via 600 kW heaters. The cold boxes at points 4, 6 and 8 [4], about 20 tonnes, 10-m long and with a diameter of 1.95 m, will be lowered down to the related underground caverns from the PX shafts. The cold boxes at points 2 and 1.8, are of smaller dimensions and weight (about 12 and 10 tonnes, 8.5 and 7-m long respectively with a diameter of 1.95 m) will be lowered via the shaft PX24 and PM18 respectively. The allocated time for installation, including warm commissioning, is about 3.5-4 months, and 5 weeks for reception testing. At present the QUI at point 8 is at its final position (see Fig. 2) and the installation activity will soon start. The second QUI (Point 2) will also be installed this year, whereas the other three cold boxes at points 4, 6 and 1.8 will be installed next year during the first, second and last quarter respectively.

Reception testing, depending also on the availability of other cryogenic equipment (e.g. vertical transfer line), will be performed only after 2-3 months from the end of the installation. It will include cooldown, electrical and instrumentation tests, and monitoring of steady state operation, including full capacity test of the 600 kW heaters.

Figure 2: Cold box of the QUI at point 8.

1.8 K refrigeration units

The 1.8 K refrigeration units are used to pump on the 1.8 K saturated helium flowing in the bayonet heat exchanger of the magnet cold mass for maintaining the saturation pressure. The contracts for the supply of the two pre-series units have been adjudicated to Air Liquide (FR) and IHI/Linde (JP/CH). After successful reception testing of its pre-series, three series units have been assigned to IHI/Linde. The Air Liquide pre-series unit is still under testing. The main underground components of the 1.8 K refrigeration units are the vacuum insulated cold box housing the centrifugal cold compressors (see IHI-Linde cold box in Fig. 3 and Air Liquide cold box in Fig. 4), the warm instrumentation and valve manifold, the electrical cabinets and the process control system. The four IHI/Linde units to be installed at point 8 (at the end of this year and the beginning of next year) and at point 4 (during the first two quarters of the next year) will be lowered down via the PX shafts [4] (about 20 tonnes, 7.2-m long and 5.4-m high). The other four units will be installed at point 2 (autumn 2004), point 1.8 (beginning of 2005) and point 6 (end of 2004), and lowered down via the PM25, PM18 and PX64 shafts respectively. The IHI/Linde cold boxes will be delivered to CERN as one piece, whereas the ones manufactured by Air Liquide as two pieces. The commissioning and reception tests to be performed at CERN comprise the pressure test and helium leak tests, electrical & instrumentation tests, steady-state operation modes showing at least nominal capacity and transients showing turn down ratio of 3.

Figure 3: IHI/Linde 1.8 K cold bo**x.**

Figure 4: Air Liquide 1.8 K cold box.

Cryogenic distribution line

The eight independent sectors of the cryogenic distribution (QRL), supplied by Air Liquide (FR), represent each a 3.2 km continuous cryostat which feeds the different LHC clients every 107 m via the so-called jumper connections. Depending on the LHC sector section, the QRL vacuum jacket (6100 mm or 650 mm) houses four or five headers (from DN80 to 250) at various temperatures (4 to 75 K) and pressures (1.6 kPa to 1.9 MPa). A QRL sector comprises about 240 straight pipe elements, 40 fixed point/ vacuum barrier elements, 37 service modules, 1 test module (used for reception test only), 1 return module, 2 to 3 steps, 2 elbows and 320 interconnections (including about 400 bellows).

A QRL standard cell (22 per sector, see Fig. 5) comprises one service module (about 6-m long and 2 tonnes) with its jumper connection, 8 standard pipe elements (each about 12-m long and 2 tonnes) and one fixed-point element (about 7-m long and 1.2 tonne). At every 4 cells, this last element is replaced by a vacuum-barrier element to guarantee the required insulating vacuum sectorisation. The QRL vacuum insulation is separated from that of the machine via a vacuum barrier inside each jumper connection.

The allocated time for the installation of one QRL sector is 21 weeks for the first two sectors and 19 weeks for the others. Eight weeks before the start of installation access will be given to the QRL supplier to mount the external supports. The installation will be carried out in two shifts with two teams each. The installation will then be followed by the commissioning tests (3 weeks) and the reception tests (12 weeks for the first sector and 8 weeks for the others). The transport of the QRL elements [5] from the central storage zone (SX4) to the corresponding access point will be carried out by CERN under the Air Liquide supervision, without interfering with the installation activities. Air Liquide will supply dedicated handling and transport tooling as well as corresponding procedures. The minimum number of transported elements to guarantee the good advancement of the installation sequence varies from 5 to 30 per week [6]. After the installation of each of the nine vacuum sectors, leak tests will be performed. Welding in situ will be carried out by four orbital welding machines[6]: two for the inner headers and two for the vacuum jacket. Five hours is the mean time required to weld a complete interconnection (2.5 h for 4 headers, and 2.5 h for the two welds of the vacuum jacket). The tooling for positioning the headers will also be used for the injection of the gas protection before the weld and for the weld leak test. Two video cameras will follow the welding operation, and the main data will be recorded. In parallel to the installation of the QRL elements, CERN activities will be carried out, such as verification of the service module positioning, pulling of the electrical cables, and checks of instrumentation (about 250 sensors per sector), valves (about 250 per sector) and process control system. Reception tests will not be performed during the winter period due to the high cost of the electricity. They will include cooldown, tests of instrumentations at cold conditions, two heat inleak measurements and warmup. After the reception tests, the test module will be demounted and replaced by a straight pipe element. The QRL will then be disconnected from the QUI and conditioned with dry air.

The installation of the supports for the sector 7-8 is at present under way, and the installation of the QRL elements will start on 21 July 2003. Parallel installation will start only from the third sector, whereas reception tests will always be done in series. The installation of the last sector will be completed by the end of 2005.

Figure 5: Air Liquide pre-series test cell.

CRITICAL POINTS FOR INSTALLATION IN UNDERGROUND

The date for availability of transport, integration and assembly sequence studies, considering a contractual period for the manufacturing, may affect the start of installation.

Installations of equipments have to follow a predefined sequence and delays on one equipment may affect the installation of others.

For the cryogenic equipments, which have to be installed in US and/or PM and/or UX, interferences with other services already in place give extra-work and effort for integration.

For the QRL, the installation of the pipe elements and service modules can only start once the general services are available. Furthermore possible interferences between the tunnel wall and the contractual position of the QRL according to the Technical Specification have to be treated with the supplier early in advance. The QRL contract is quite “rigid” with risk of consequent extra-costs and delays if CERN non-conformities with respect to the Technical Specification stop or slow-down the installation schedule.

All cryogenic equipments have to be transported and handled by CERN under supplier supervision, implying thus responsibility transfer between CERN and the suppliers. The transport of the cryomagnets shall not interfere with nor delay the QRL installation.

Loss of utilities during installation (electrical cuts, lifts, cranes…) may delay the installation with risk of extra-costs.

The closing of the Air Liquide Assago (IT) workshop has serious consequences on the industrial organisation of the QUI project. The new manufacturing site of the Italian firm Simind requires a closer follow-up from Air Liquide (FR) and CERN.

If the testing of the Air Liquide 1.8 K pre-series units will be successful, the cold box fabrication of the three series units, originally foreseen at Air Liquide Assago, has to be re-allocated.

For the manufacturing of the QRL standard service modules at FCM, a delay of two months has been identified at present, due to lack of workshop organisation and cleanliness issues. Corrective measures have been soon undertaken by Air Liquide, which proposed a full time presence of an Air Liquide representative at FCM with regular weekly meetings for at least all the period of the manufacturing of the first service module. In parallel, consultations for another fabrication site are being launched. For all the fabrication sites of the QRL elements, the foreseen manufacturing rate strongly depends on the procurement of the different components by Air Liquide, which for the future has to be further anticipated.

CONCLUSIONS

Some installations of cryogenic equipments have already been done, but the main part has still to be made. The planning imposed for all the concerned projects is very tight and with almost no margin to face, without extra delays and cost, potential problems, which may occur. The successful installation requires a deep involvement of the project team to clarify the input data, the reliability of the utilities, as well as an efficient technical coordination (and associated budget) of the different activities, Contacts between the project team and the different service responsible have to be initialized early in advance to clarify possible “grey” zones.

ACKNOWLEDGEMENTS

I thank S. Claudet for his precious contribution on the 1.8 K refrigeration units.

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PREPARATION FOR AND INSTALLATION OF SSS'S

P. Rohmig, CERN, Geneva, Switzerland

Abstract

In this paper, the different work activities of the LHC Short Straight Sections (SSS) from cold mass reception to the installation in the tunnel are presented. After an overview of the different groups and types of SSS, the work packages leading to the final LHC units are explained. The documentation for Quality Assurance and their present status are highlighted. The two levels of project co-ordination and project follow-up are explained. A chapter is dedicated to the on-line planning from the general LHC Construction and Installation schedule to the work planning for contracts and assembly. Open issues are listed. The conclusions list the achievements and the actions to be fulfilled to reach a smooth production of the 474 SSS of the Arc, Dispersion Suppressor and Matching Sections of the LHC.

The presentation is available in EDMS under no. 386621.

INTRODUCTION

A LHC Short Straight Section is composed of a twin aperture high-field superconducting quadrupole, two combined function corrector magnets and quench protection diodes, all housed with their bus bars in a common helium enclosure, the so called cold mass (CM).

Every second SSS contains a technical service module (QQS) housing beam diagnostics (BPM), current feedthroughs, instrumentation capillaries and cryogenic elements (He phase separator), and is interconnected with the cryogenic distribution line (QRL). 25% of the SSS also contain a barrier for sectoring the insulation vacuum.

The conception and production of the SSS calls for a multi-disciplinary effort of magnet and electrical, cryogenic, vacuum and mechanical technologies.

The installation is managed under the responsibility of the EST and ST divisions.

SSS FAMILIES AND TYPES

The SSS of the LHC are divided in 3 families:

- SSS-Arc: Q12 left to Q12 right;
- SSS-Dispersion Suppressor (DS): Q11 to Q8 left and right;
- SSS-Matching Sections (MS): Q7 to Q4 left and right depending of the machine layout.

The SSSs of the Arc have all the same mechanical length and weight, whereas the SSSs of the DS and MS differ, apart of difference on magnets, also in their mechanical conception (2 or 3 support posts design, stand-alone units). Table 1 shows the number, types and the main mechanical parameters.

Table 1: LHC SSS families, types and their key parameter for installation

Description	SSS-Arc	SSS-DS	SSS-MS
Total number	360	64	50
Number of different types	60	30	21
Length (m)	6.5	7.8 to 9.6	6.5 to 12.9
Weights (tons)	8.7	10. to 12.6	8.7 to 19.2

WORK ACTIVITIES

The work activities, or Work Packages (WP), can be divided in five main groups, depending on their site of activity. *The interconnection work is subject of another paper (EDMS no.387462).*

Cold mass manufacture at industry and at CERN

The cold mass manufacture contains mainly the integration of the magnetic elements, bus bars and electric protection elements (diodes), cold bores and helium exchanger in a common helium enclosure. The ends of the cold mass have the interconnection elements and BPM support integrated.

All cold masses of the Arc arrive, as fully tested units, from industry. DS and MS cold masses are assembled at CERN and undergo the same qualification tests, as in industry.

Cryostat assembly and preparation before and after cold measurements WP11 to 13 and WP18

All SSS cold masses of the LHC will be assembled in their cryostat at CERN in a dedicated assembly facility in Bldg 904 at CERN. The preparation for the cold tests, including the assembly of the anti-cryostat tubes and MRB box, and the stripping (re-conditioning of the SSS for the LHC) are done at the same building.

Cold measurements and associated activities WP14 to 17

These Work Packages contain the installation on and, after cold measurements, the disconnection from the measuring bench in building SM18 of CERN.

Installation of BPM / beam screen assemblies WP19 and installation of cryogenic instrumentation

The assembly of the BPM with its beam screen, the integration of the cryogenic instrumentation and the final verification of LHC conformity are executed in building SMI2 of CERN. This building houses also the pit for the lowering of all machine cryomagnets.

The WP19 is carried out in-line with the tunnel installation, therefore any eventual storage has to be done before (between WP 18 and 19).

Transport on the surface and in the tunnel

The different work sites require a certain number of road transports of the SSS.

Once lowered in the tunnel, the SSS are moved with special vehicles to their final position, which may be up to 13 km away from the lowering pit.

QUALITY ASSURANCE

The Quality Assurance for the SSS follows closely the LHC QA requirements.

A number of Engineering Specifications (ES) have been edited to identify the specific parameters and technical requirements of each SSS. Three ESs define, for each SSS family, the equipment code for the cold mass, the cryostat and the final SSS type (EDMS no.103939, 383921)

The so-called Manufacturing and Test File MTF collects and stores all information of the components and the assemblies required for the French INB code (Installation Nuclear de Base) and the machine operation.

Included in the MTF are also the Non Conformity and Traveller files.

The so-called ID-card of each SSS contains the magnetic values (multipole-fields and quench behaviour), some main geometrical parameters and the NC history. Based on this ID-card, the Magnet Evaluation Board approves the SSS for its use in the LHC and may impose particular positions in the machine, i.e. *sorting*.

The high number of SSS types restricts the sorting to some areas of the Arc.

PROJECT CO-ORDINATION AND FOLLOW-UP

The SSS project co-ordination is managed on two platforms interlinked by common meetings. The co-ordination of the different work activities, production order (types) and planning, Non-conformities and edition of the ID-cards is the responsibility of the SSS-project co-ordinator. All technical issues of the SSS and its integrated systems are handled by the SSS Working Group.

The follow-up of the Work Packages is the responsibility of the Activity manager of each site (904, SM18 and SMI2).

The transport and installation is managed by the EST-IC Installation and Coordination group.

SCHEDULE AND STATUS

The LHC Construction and Installation is defined by the General Co-ordination schedule (EDMS no.102509). Respecting the order of installation, a Cold Mass & SSS supply dates document (EDMS no. 329512) is derived, which serves as reference for the components manufacture and assembly contracts in industry and at CERN. In parallel a common production schedule (*best guess*) for the cryostat assembly contract F422, covering cryodipoles and SSS, has been issued by AT-MAS and AT-CRI groups (EDMS no. 365639).

Imposed by delays in the conception (CM pressure restrictions) and procurement of components (MSCB corrector magnets essentially), this SSS master document has been adapted for the first 30 units. Finally, a monthly updated list of cold masse types is issued by the Arc CM contract responsible.

As consequence no valid planning can be actually prepared or followed.

It is expected, that after having overcome the present conception and production problems, and before the LHC installation starts in 2004, a real planning can be merged with the LHC master schedule.

OPEN ISSUES

In order to obtain a complete and reproducible production and installation, some open issues have to be settled in 2003.

Conception, handling and storage:

- Cold mass: pressure restrictions in the bus bar tubes (final design, leak performance and industrialisation) [AT-MAS, CEA-Saclay],
- He pressure gauges and He guards (domes) (product selection and integration design) [AT-ACR],
- Special interconnects between SSS-DS/MS and QRL (design and assembly/ handling and installation work breakdown) [AT-CRI, EST-IC].
- Transport girders for all SSS types and protection covers (design and procurement).[AT-CRI, EST-IC],

Planning:

- Reliable planning for all SSS activities [AT-CRI, AT-MAS, EST-IC],

CONCLUSIONS

Today SSS prototypes have been built and integrated in the LHC Test Strings 1 and 2. Their conception, assembly and integration techniques and magnetic performance have been validated. A prototype SSS5 has successfully undergone road and tunnel transport simulations.

The series production of SSS-Arc, cold masses and cryostat assembly has started and the cold measurement of the 1st series unit is expected for July 2003.

Know-how transfer has to be achieved for the in-house cryostating by an external firm, following the in-sourcing of this activity. Still more effort is required to assure a continuous high industrial quality for components manufacture, assembly and integration work, including QA matters (MTF etc.).

ACKNOWLEDGEMENTS

The SSS of the LHC is a machine unit requiring a common effort of different systems and teams at CERN and outside. I would like to thank the teams of AB-BDI, AT-ACR, AT-CRI and CNRS-Orsay, AT-MAS and CEA-Saclay, AT-MEL, AT-VAC, EST-IC, EST-ME, EST-MF, EST-SU for their contribution to this paper.

PREPARATION OF MAIN LHC CRYODIPOLES FOR INSTALLATION

D. Tommasini, CERN, Geneva, Switzerland

Abstract

The 1232 main dipoles for the LHC are delivered to CERN from three different magnet manufacturers as cold masses to be thereafter mounted inside a cryostat and prepared for installation in the LHC tunnel. The main steps between cold masses arrival at CERN and installation, the organization of activities, management of documentation and non-conformities, and means for progress reporting are presented and discussed. Finally a list of remaining critical issues is reviewed.

MAGNET TYPES

Four different types of cold masses are delivered by magnet makers to CERN.

The magnets differ by the polarity of the installed protection diode and by the presence or not of octapole/decapole corrector mounted on the upstream side of the dipole.

Diode polarity can be either R (anode on the Right) or L (anode on the Left). Polarity of protection diode is associated to a specific LHC octant : four octants are composed by magnets with polarity R and four by magnets with polarity L.

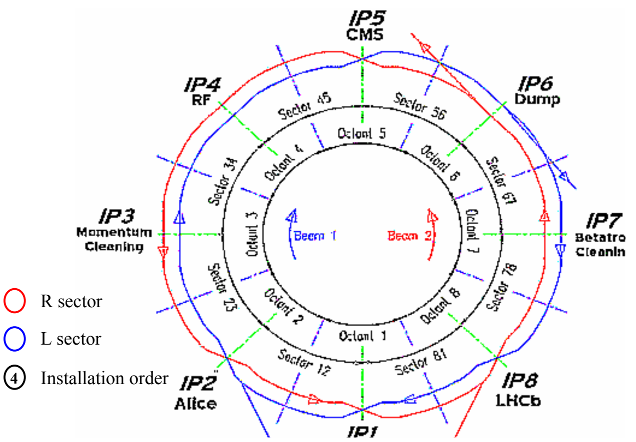

Figure 1: Diode polarity and installation sequence

The presence of octupole/decapole correctors on upstream side, in addition to sextupole on downstream side, identifies a cold mass type A with respect to a cold mass type B which has only the sextupole corrector on downstream side.

In each octant there are 138 cryodipoles installed in the arc and 16 in the dispersion suppressors. In total 1232 have to be installed in the eight octants of the LHC.

When a cold mass arrives at CERN it is then adapted for the installation following a sequence of operations which will be described later. One of the last steps is the insertion of the beam screen in the beam tube and the adaptation of magnet extremities to the specific position of the magnet in the tunnel. For example if a dipole is installed next to a quadrupole its interconnections are different from that of a cryodipole installed next to another dipole. In certain cases the interconnection depends even on the tunnel slope (going down or up). In the arcs the number of cryodipole variants is then 10 and in the dispersion suppressors 24. The total number of cryodipole variants to be installed in the LHC is 27 (see LHC-LBA-ES-0011).

MAIN STEPS BEFORE INSTALLATION

Activities on dipole cold masses and on cryodipoles are carried out at four different places in the CERN domain according to the flow in Table 1.

Table 1: main steps

Step	Description	Place
Cold mass reception	Unloading from the lorry, visual inspection, mechanical and electrical checks	SMA18
Cryostating	Mounting of thermal insulation and insertion inside the cryostat	SMA18
Power (cold) tests	Electrical and magnetic measurements, quench training	SM18
Stripping	First preparation of cold mass extremities	SMA18
Fiducialization	Referring cold mass position to referencials on the cryostat.	SMA18
Magnetic axis	Measurement, at warm, of the position of magnetic axis of dipole and of correctors	SMA18
Storage	Buffer storage waiting for final preparation for installation	Prevessin
Final preparation	Consists in cleaning the beam tubes, inserting the beam screen, trimming the cold mass connections for its specific position in the LHC tunnel	SMI2
Final checks	Cartography of extremities, electrical checks	SMI2
Installation	Transportation to the tunnel, positioning of the cryodipole on the jacks, first alignment, interconnections, cool-down, final alignment.	LHC tunnel

Figure 2: Cold mass reception and cryostating.

Transportation between the different sites is done on special trailers, at maximum speed of 20 km/h. During transportation the cold mass extremities are fixed to the cryostat by transport restraints (Fig. 3).

Displacement of cold masses and of cryodipoles inside SMA18 and SM18 buildings is done by a special vehicle which does not require installation of transport restraints on the cold mass because of its smooth operation (Fig. 4).

Figure 3: Cryodipole transportation and restraints.

Figure 4: The Cryodipole transport vehicle.

DOCUMENTATION AND CRYODIPOLE EVALUATION FOR INSTALLATION

Each of the activities described above is associated with a specific step in the MTF (Manufacturing and Test Folder) database for the LHC. In case of cryodipoles the MTF not only contains a description of the components, but also the test report about operations and measurements done on these components.

In case of non-conformities found during one of these operations specific procedures have been established and are operational on the field. In particular, in case the non-conformity may potentially affect other systems the non-conformity is submitted to an approval process.

In addition to the information found in MTF, an overview updated daily of cryodipole status is reported in the Web site of the Cryodipole Coordination (http://lhc-dipcoor.web.cern.ch/lhc-dipcoor/status.asp).

A summary of all main characteristics of a cryodipole relevant for the LHC machine installation and operation has been established as a single A4 sheet (Identity Card).

On the basis of this document the Magnet Evaluation Board assigns the cryodipole to a specific class setting the possible constraints for installation in the LHC. For example, a typical decision can be to impose installation of a cryodipole with geometrical shape outside tolerance in the middle of a half cell.

Due to the installation schedule, with the exception of the first octant, for which all cryodipoles will be available before the beginning of the installation, sorting has to be limited to very specific cases.

It is foreseen to keep the possibility of keeping apart up to 25 cryodipoles per octant, waiting for the good spot.

TWO YEARS START-UP

During the first two years of cryodipole activities on pre-series magnets, 55 magnets have been treated.

Forty-five of these were treated during the last year, allowing to define all aspects related to activity follow-up and documentation: at present a solid Quality Assurance Plan is operational, documentation for all cryodipoles is available in MTF, reporting of activities is implemented and operational.

Out of these 55 magnets, only 27 were tested, of which 18 during the last year.

More than 200 interventions have been organized to fix non-conformities. During the last period the number of non-conformities per magnet decreased, however this was compensated by a bigger magnet production rate making not foreseen works on non-conformities on the cold masses one of the major issues of last year works.

NEXT ACTIONS & PENDING ISSUES

- Define MTF flow for SMI2 activities
- Test transportation of a cryodipole to the tunnel
- Organize final electrical checks before installation
- Links between the CC Web page and MTF

Power tests still do not fully (but actions are under way) :

- Follow cold mass rate arrival (24 magnets out of 58 waiting)
- Provide documentation in MTF
- Notify provisional acceptance at the end of cold tests

➔ Specific tools have been designed and are implemented

and finally

NCs and non standard activities shall decrease.

ACKNOWLEDGEMENTS

Thanks are due to all teams involved in cryodipole works : almost all groups of the AT division. A particular mention to the EST/ISS team, who did an intensive and efficient work in adapting database resources to ground.

ORGANISATION OF THE INTERCONNECTIONS OF THE CRYOMAGNETS IN THE LHC TUNNEL

J. Ph. Tock, CERN, Geneva, Switzerland

Abstract

In this paper, the interconnections of the cryomagnets in the LHC tunnel are presented within the overall frame of the installation activities. First, the preparation works are described: extremities of the cryomagnets, extremities of the Cryogenic Distribution Line (QRL) and preparation of the Interconnection Installation Kits. After this, the interconnection work is presented, divided into various Interconnection Work Packages (IWP): Interconnection of the inner lines, Insertion and connection of the line N cable, Closure of the interconnections, and Realisation of the jumper interconnections. The interfaces with other teams (Survey, Electrical Quality Assurance, Leak and pressure test,....) are highlighted. Open issues are listed. The applied programme for Quality Assurance is described.

The replacement of a faulty cryomagnet is briefly mentioned. Finally, the strategy and the schedule for the interconnection activities are given.

This presentation is available in EDMS under No. 387462.

INTRODUCTION

The LHC interconnections comprise both the interconnections between cryomagnets and with the Cryogenic Distribution Line (QRL). The main part of the work has to be carried out in a specific environment: the LHC tunnel, a very constraining place.

The validation of the technologies was achieved by the successful assembly of STRING2. Interconnections have to ensure continuity of several functions (vacuum enclosures, beam screen, electrical powering, cryogenic circuits, thermal insulation,… ; main key figures are given in Table 1.

Table 1: LHC interconnections key figures

Description	Quantity
Interconnections between cryomagnets	1700
Interconnections with QRL	300
Inductively soldered splices (13 kA)	≈ 10 000
Ultrasonic weld (600 A)	≈ 50 000
TIG welds	≈ 40 000
MultiLayer Insulation (MLI)	≈ 200 000 m^2
Electrical current through one IC	≈ 100 000 A
Joining operations	> 100 000
Operations	Several 10^6

PREPARATION WORKS

Preparation of Cryomagnets extremities

Depending on the position of the cryomagnets within the LHC ring, their extremities have to be specifically prepared. The types of cryodipoles are defined in LHC-LBA-ES-0011: Cryodipole types in arcs and dispersion suppressors [Q8 to Q34]. These adaptations are carried out in SMI2 building, before lowering in the tunnel and are part of WP08B[LHC-LBA-ES-0004]. Protection devices have also to be installed.

Preparation of Interconnection Installation Kits

For each interconnection, some components are installed and transported with the cryomagnets (e.g. some bellows) but others have to be assembled in the tunnel. They are gathered and packed in standard containers (IWP0: LHC-LI-ES-0013). The transport from the preparation building to the interconnection work front is organised by EST-IC.

Preparation of QRL extremities

The QRL is equipped with test boxes. These boxes are used during commissioning of the QRL and are ensuring the flow of Helium and the tightness of the various enclosures (bypasses, caps). They have to be removed before the installation of the neighbouring Short Straight Section (SSS). These activities are described in IWP4: LHC-LI-ES-0012 and in presentation by C. Parente (AT-ACR) EDMS 384433.

INTERCONNECTION WORKS

The interconnection works have been divided intos several Interconnection Work Packages (IWP). Their organisation and their inter-relations are described in document LHC-LI-ES-0014.

Interconnection of the inner lines (IWP1)

IWP1 consists in the interconnection of the inner lines: beam lines (V1/V2), beam screen cooling lines (K1/K2), main and spool-pieces busbars lines (M1/M2/M3), heat exchanger lines (X/Y), beam screens and support posts cooling line (C'), thermal shield cooling line (E). It is fully described in LHC-LI-ES-0009 and includes mainly:

- Installation of the plug-in modules (AT-VAC),
- Induction soldering and electrical insulation of the six main busbars (13kA),
- Ultrasonic welding and electrical insulation of the spool pieces bus bars (600 A),
- Soldering of the inner line of the heat exchanger (copper tube),
- Closure by TIG welding of the cryogenic lines (about 14 welds per interconnection)

Electrical tests are carried out by an electrical test team under the responsibility of AT-MEL. Leak test on the beam vacuum interconnections is performed every vacuum sector, corresponding typically to 214 m. (two cells) before the start of IWP2. Helium lines will be leak tested after the completion of the whole arc (2800 m.)

Insertion and connection of line N cable (IWP2)

The superconducting cable containing the auxiliary bus bars is split in segments of about 54 m., each corresponding to the length of one LHC half-cell. Each segment incorporates a plug and connection boards (AT-MEL). The ultrasonic welding and electrical insulation of the splices (up to 46 per interconnection) are performed, interleaved with relevant electrical tests carried out by an electrical test team under the responsibility of AT-MEL. The line N is closed by TIG welding and the outside sleeve is installed to allow leak and pressure testing on the whole sector. These tests are performed by CERN or its representatives (AT-VAC). Insulation vacuum vessel will be leak-tested after IWP2, in every vacuum sector, corresponding typically to 214 m. The IWP2 is fully described in LHC-LI-ES-0010.

Closure of the interconnections (IWP3)

After completion of IWP2 and successful leak and pressure test, the closure of the interconnections can be performed. It is fully described in LHC-LI-ES-0011:

- Opening of the outside sleeve (closed for the leak and pressure test performed beforehand)
- Installation of the radiative insulation (stainless steel half-shell and one 10-layer MLI blanket),
- Installation of the thermal shield (Two aluminium half-shells to be welded and two 15-layer MLI blankets)
- Closure of the outside sleeve.

After IWP3, the interconnection between cryomagnets is completed. Insulation vacuum vessel is again leak tested every vacuum sector. (AT-VAC)

Realisation of jumper interconnections (IWP5)

After completion of IWP4 and installation of the corresponding SSS, the cryogenic lines passing through the jumper are connected. Up to 10 stainless steel TIG welds have to be performed for each jumper. Then the thermal shield and MLI blankets are assembled. Finally the outside sleeve is TIG welded to ensure the leak-tightness of the insulation vacuum. It is fully described in LHC-LI-ES-0016.

OPEN ISSUES

- Position monitoring devices for interconnections between cryomagnets and with QRL. (What? Who? How? How many?) [EST-SU/AT-ACR].
- Cryogenic instrumentation: installation procedure to be defined [AT-ACR].
- Pressure test to be organised.
- Preparation of beam screen cooling metal hoses. [AT-VAC].
- Connection of auxiliary bus bars (line N) [AT-MEL].
- Long Straight Sections (What? How? Who?).
- Schedule to be detailed.

QUALITY ASSURANCE

QA is required to assemble the LHC Interconnections and get a real machine which will attain the required performance, be safe, reliable, maintainable, and be completed in the agreed timescale

The equipment, process and operators will be qualified by CERN after realisation of samples. In parallel with the assembly of the interconnection and the on-line recording of the critical process parameters, a comprehensive off-line testing of samples will be carried out. Simultaneously, inspection teams will be set-up to minimise the mistakes and ensure the quality of the work.

REPLACEMENT OF A FAULTY MAGNET

Procedures are defined to disassemble interconnections to allow the replacement or upgrade of a cryomagnet. The timescale is described in LHC-PM-ES-0002 and a time of roughly 40 days has to be foreseen.

STRATEGY AND SCHEDULE

The AT-CRI-CI Section will sign a Contract with a firm for the assembly of the LHC interconnections. All the works in the arcs and DS zones are result oriented. The specific works in the LSS and unforeseen tasks will be managed as additional work (hourly rates) under direct CERN supervision.

As limited space has to be shared by several intervening teams like surveyors, inspector teams [LHC interconnections, electrical quality assurance, leak and pressure test], an effective coordination is mandatory.

The following schedule is foreseen:

April 2003:	Invitation to Tender
May 2003:	Bidders Conference
June 2003:	Opening of Bids
September 2003:	Finance Committee
Mid November 2003:	Organisation File
Mid January 2004:	Tooling Design Review
April 2004:	Start Interconnections (10 Pre-series)
February 2005:	First sector (7R/8L) completed
End of 2006:	Interconnections completed
Till? :	Maintenance and upgrades

Training and know-how transfer from CERN to the Contractor are of vital importance to ensure a reliable assembly of the interconnections. Therefore, models will be available for training and the assembly of the pre-series interconnection will serve as a validation sequence.

ACKNOWLEDGEMENTS

The interconnection works are involving a lot of intervening teams and require a wide collaboration. I would like to thank all the persons that have contributed to this paper, especially members of the AT-CRI-CI section (A. Jacquemod, F. Laurent, L. Perrollaz, B. Skoczen) but also the following groups: AT-ACR, AT-MEL, AT-VAC, EST-IC, EST-ME, EST-MF, EST-SU…

SUMMARY OF SESSION 2: HARDWARE COMMISSIONING AND BEAM TESTS

R.Bailey, K.Dahlerup-Petersen, CERN, Geneva, Switzerland

INTRODUCTION

The aim of the session was to summarise plans for commissioning the LHC without beam between now and 2007, to discuss tests with beam proposed over this period, and to identify associated controls activities. The six presentations made are summarised, and outstanding points arising in each presentation are highlighted.

FROM STRING2 TO THE FIRST SECTOR

Operation of the String in recent years has brought many benefits in several areas, for example installation and interconnections, validation of technical systems and investigation of collective behaviour of the different systems [1]. However, many things could not be done in a way that was representative of behaviour in the ring.

For all systems, the following could not be studied:

- Space restrictions of the tunnel
- Time loss due to tunnel
- Problem solving at several locations
- Problem solving for systematic errors
- Communication in a much bigger team
- Remote operations from a distant control room
- Features related to stored magnetic energy

Furthermore specific challenges remain in numerous systems:

- Assembly and interconnects
- Vacuum systems
- Electrical Quality Assurance
- Cryogenics
- Power converters
  - Scale and power
  - Tracking
  - Interlock system
- QPS

It is clear that during (parts of) the hardware commissioning, such as pressure tests or powering, access will be restricted. Controls will be needed, and time will be needed to commission this before it is needed for the first sector.

COOL DOWN OF A SECTOR

The cryogenic system for the LHC is large and complex, consisting of surface and underground installations distributed around the machine. Furthermore, these installations depend critically on the reliable functioning of a number of underlying services, such as electrical power, cooling, ventilation, vacuum, cryogen availability and controls. If any of these utilities 'fails', the performance of the cryogenic system will be adversely affected. The time taken to recover from a utility stop is estimated to be much quicker than it was for LEP. If the energy for operation is lower than 7TeV for the initial running, recovery times will be correspondingly quicker.

The commissioning strategy is to divide the overall plant into sub-systems and their components. Some of these will undergo preliminary tests as early as possible. After delivery and installation in the machine, each sub-system is individually qualified for operation. The qualified sub-systems are then used in a cascade way to commission dependent sub-systems. The collective behaviour of the system is progressively tested as installation proceeds. Considerable experience now exists in the validity of this strategy, notably from LEP and the String tests. However the overall process and collective behaviour needs to be assessed and optimized during the commissioning of the first sector. There is a strong suggestion from the cryogenics team to make a full-sector quench during the first sector commissioning.

The complexity of the system and the lack of resources do not allow sectors to be commissioned in parallel. Furthermore, the helium inventory does not allow having more than half of the machine cold until 2007. The present electrical contracts impose a 4-month shutdown in the winter.

OPERATING AND REGENERATING THE BEAM SCREEN AND THE NEG

The LHC vacuum system is composed of cryogenic and room temperature systems in close proximity. Procedures have been established for the cool down of the cold mass / beam screen, and for the conditioning of the room temperature components and NEG activation. Testing of these procedures is ongoing and includes experience from the string. The time needed for initial preparation and for reconditioning after an incident has been estimated. With the intensities expected in year 1 of LHC, reconditioning should not be necessary (except in case of incident).

For the room temperature systems it is proposed that the standard conditioning would be to perform the bake out of the non-coated surfaces separately from the activation of the coated surfaces. However, if the two could be made in parallel, a gain of around 50% in the overall time is possible.

For the cryogenic systems it is proposed to make the beam screen cool down with a 90K plateau followed by active cooling, in order to minimise condensation on the beam screen. The String has provided limited information on this issue, with more data expected from the COLDEX experiment installed in the SPS for machine studies during the 2003 run.

HARDWARE COMMISSIONING 2005-2007

After the installation and qualification for operation of the individual systems, equipment will be treated on a sub-sector basis. Finally, each sector will be commissioned as a whole up to the powering of all circuits to nominal current. As we pass through these various phases, the responsibility will be shared between different bodies, such as EST-IC, the Hardware Commissioning Working Group HCWG and the LHC Operation Project LHCOP. Validation of the procedures, as well as certain specific studies, will be carried out during the commissioning of the first sector.

The activities will proceed in parallel with and are closely linked to other ongoing activities, notably installation. The hardware commissioning appears on the official co-ordination schedule, but will need revision. In particular, the commissioning of the second sector (2-3) is scheduled to take place during the commissioning of the first (7-8), which should be avoided if at all possible. In order to optimize better the planning and scheduling, input is needed on a number of matters (inventories of individual system tests, proposal for sub-sector and sector commissioning), which will be pursued through the HCWG.

It is understood that AB/OP personnel will be involved in the hardware commissioning from the beginning. For 2005 this should pose no problems since the PS and SPS machines are not running, but AB/OP will hit serious resource problems in 2006 unless adequate recruitment is granted. Also, AB/OP effort should be through operation from a remote control room. While this may not be entirely possible for the first sector, it should certainly be the case for the remaining sectors. Hopefully by 2006 all operations at CERN will be from a single control room.

BEAM ACTIVITIES 2003-2007

Several activities with beam are foreseen in the coming years. Extraction into the beginning of TT40 is scheduled for 2 or 3 days in September and October 2003, and is well in hand. Transporting beam down to the second TED in TI8 is tentatively scheduled for a few days in September 2004, and while this poses a few more problems, they are manageable.

The injection test proposed for early 2006 [2] has potentially more impact and is under study, with a view to making a decision very soon on whether or not to do it. The proposal is to take beam down TI8, inject into the LHC, go through LHCb and sector 8-7, to a temporary beam stopper located after the Q6 to the right of point 7. The tests to be performed have been enumerated, and lead to a time estimate of 2 weeks, probably in May 2006. Numerous consequences have been examined, and there seems to be no technical reason for not making the test.

However, before a decision can be taken (by the project management), an estimation of the cost is needed. This is not only for installation and removal of equipment needed only for the test (such as the beam stopper), but also for resources needed from other areas of the project (such as to cool down the sector again).

Beyond the beam tests, commissioning with beam is foreseen for 2007. With the expected beam conditions for year 1 [3], there are possible implications for various sets of equipment. These need to be studied in more detail to see if there are any possible benefits to be gained through running with reduced intensity.

CONTROLS REQUIREMENTS 2003-2005

Controls are needed for all the activities described in the previous sections, and this provides clear milestones for tested software deliverables:

1.	TT40	Q3-2003
2.	QRL	Q1-2004
3.	TI8	Q3-2004
4.	First sector	Q2-2005
5.	Injection test	Q2-2006
6.	Full machine	Q2-2007

Not surprisingly, current controls activities concentrate on the earlier milestones, with the level of present activity falling sharply for the later milestones, reaching zero by point 5. In order to address controls issues arising in points 4,5,6, input is needed from the relevant bodies, namely HCWG and LHCOP.

In any case it is expected that new software will be based on forthcoming experience in TT40 and the QRL controls. New development methods are being established in these projects, and utilities are being developed that should be available thereafter for more generalised use, such as the logging system.

It is expected by AB/CO management that AB/OP personnel are involved in applications development. Again, while this is a valid activity for such personnel, care has to be taken that OP resources are sufficiently strong to honour all commitments.

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FROM STRING 2 TO THE HARDWARE COMMISSIONING OF THE FIRST SECTOR: A CHALLENGE?

F. Rodriguez-Mateos, CERN, Geneva, Switzerland

Abstract

The String Programme has mobilized a large multidisciplinary effort. This was deployed in view of the validation (assembly, commissioning) of systems, specific full-scale tests (experimental programme) as well as first hands-on experience towards the assembly (techniques, procedures, quality assurance) of the collider and its associated services. Both String 1 and, to a larger extent, String 2 provided conditions very close to what can be expected in the tunnel and underground areas.

This experience is a stepping stone towards the hardware commissioning of the sectors; however, a number of other aspects related to size of the circuits (e.g. electrical, cryogenic), to operation underground, etc could not be investigated. These are essentially all the aspects that could not be scaled up to the real case.

This contribution summarizes the major aspects which could not be tested nor learnt, and addresses the technical challenges we expect for the commissioning of the first sector.

THE OBJECTIVES

The String 1 and more specifically String 2 [1] facilities were built with the aim of validating the technical systems necessary to make LHC work. An intensive experimental programme focused on the studies pertaining to the operational characterisation of each system. Furthermore, the investigation of the collective behaviour when systems are operated together was a fundamental aspect, especially during the commissioning phases. Essentially, the key idea was to run the systems as they will run during their lifetime in a cell of the regular LHC arc.

THE LESSONS

The interested reader will find in [2] a detailed description of the principal lessons learnt and experiences gained along the installation, commissioning and experimental programme of the LHC full-cell prototype.

WHAT COULD NOT BE TESTED?

Besides the fact that there was no possibility to have beam “around “, every system’s responsible has in mind a list of tests and/or verifications that could not be made nor scaled up to the real size. The reasons for these are aspects that can be mainly attributed to either the different magnitudes in play (size, length, volume, energy, etc), or to the different environment and working conditions (String 2 was housed in the SM-18 hall, where differences with respect to the LHC tunnel are substantial, see below).

Common aspects across systems

Conditions in the SM-18 hall are very different when compared to the tunnel ones. One can list the following aspects, which will -no doubt- become more severe in the real case:

- In the tunnel the teams will be confronted to space restrictions, both for persons and mobile equipment.
- The time losses will increase due to the tunnel environment (displacement to the pit head, follow-up of controlled access routines, etc).
- The teams will need to work on different places simultaneously.
- Systematic errors due to the larger number of equipment to install, connect or commission may appear.
- Communication will need to proceed and prove efficient throughout a team of a much larger size.
- Last but not least: The control room (even for ad-hoc, local control areas) will be more distant.

All these are constraints that we all will be confronted in the near future.

Unfeasible to test: some particular cases

In the case of cryogenics, a limited “machine” length like the one in String 2 cannot give answers to questions related to the distribution of the cool down flow over a sector, how the cells will cross-talk in terms of temperature control, how the quench will propagate across cells or how a full-sector quench recovery will proceed.

For the Quench Protection System, there have been points related to the “size” of the circuits where an assessment was impossible: it will be for the first time in the tunnel that the energy extraction resistors will absorb the 1.1 GJ energy stored in each of the arc dipole circuits. Also, it will be there that the higher voltage rating VAB-49 breakers (dipole version) will be tested on a high-current/high-inductance load, since String 2 incorporated only the low-voltage version. The dimension of String 2 did not allow testing the arc-distributed, main bus bar quench detectors. Neither did it allow to check the quench loop (also distributed over a sector) nor the field-bus segments of the controls layer in the real size.

In terms of circuit types, the complex inner triplet configuration will remain untested for powering, quench detection and interlocks until the commissioning of the inner triplet in 8L of the machine. The low-threshold protection of the current leads was assessed, but this was not done in a very noisy environment.

SECTOR 7-8: A CHALLENGE

In the light of this large technical expertise acquired, considering also what was not possible to test, we list below the most tangible of the expected, technical challenges.

Vacuum

Leak and pressure testing of helium circuits requires the complete installation of a machine sector, or otherwise several tests as installation progresses. The sequencing of Q7 to Q6 zones requires detailed studies due to the presence of shuffling modules, DFBAs and room temperature vacuum equipment.

Installation of late equipment (e.g. behind the DFBAs) implies both access difficulty and delaying the NEG activation of the vacuum sector.

Electrical Quality Assurance

The complexity of the LHC electrical circuits system to be assembled, tested and commissioned has important implications to the hardware and software to be used in order to assure the full integrity of the circuits. Certainly one of the key points will be the reliable and correct connection of the auxiliary bus bar wires and associated SSS corrector magnets.

The practical integration of the accepted non-conformities, which will have an impact to the routing of circuits, polarity of magnets, position of diagnostic instrumentation, will be another key issue.

Cryogenics

The assessment on the performance of the cryogenic processes at large-scale and the operational mode is here the main issue.

The coupling between cells may cause instabilities on temperature regulation. The remote access and the parameterisation of the valve positions needs to be tested.

The management of the large instrumentation and signals databases will require specific support (maintenance, updates, etc).

Heat loads of a full sector will be assessed.

Power Converters and tracking

Problems with electro-magnetic compatibility are in general difficult to anticipate at 100%. This is one of the principal candidates to troublemaker.

A few aspects where the PC team finds potential unknowns are:

- The protection of the resistive current leads, where voltage signals are routed to the power converter for processing.
- The powering of the inner triplets within their nested configuration: only decoupling between converters allows obtaining the required precision.
- Cross talk between the two “sides” of 3-leads circuits (MQM, MQY)
- The large energy of a dipole sector (1.1 GJ) will be handled for the first time. The long natural time constant of the circuit (23’000 s, 16 H) could have an impact on the current regulation.
- Tunnel conditions in terms of heat loads, contact resistances etc will need to be confronted.
- The absolute calibration of B2 and B1 may pose problems at start-up. It is of concern the setting of the initial working point.
- The B2 field ripple seems to be larger by one or two orders of magnitude than what would be expected from the measured current ripple.

Quench Protection System

The first point to be solved before powering is the validation of the circuits: how to detect weaknesses of the circuits if they only manifest during a quench, for instance?

A second point where a common effort is needed is the management of the instrumentation of the cold, active parts (magnets, leads, etc) and of the corresponding list of signals. A rational database is required and the work has just started with the EST/IC group.

Finally, the reliability of the overall Quench Protection System over years of operation has to be monitored (e.g. monthly tests) and well kept within the acceptable level.

Common ground

A point to be stressed is that control systems and network must be operational for the individual system tests and commissioning of their equipment.

The efficient use of working hours (distances to get to the working areas, access restrictions imposed by safety, etc) or the availability of the infrastructure when many teams need to work together are points of concern to many of us and will influence the advancement of activities by the equipment groups.

The times allocated during Hardware Commissioning phases need to be carefully distributed.

CONCLUSIONS

The ratio between lessons and open challenges after running String 2 is, after all, high. Some hidden challenges might be waiting for us …

To overcome the future problems and obstacles, the first ingredient is team spirit. And String-2 has manifestly shown it!

ACKNOWLEDGEMENT

This contribution could not have been prepared without the help of Freddy, Luca, Davide, Paul, Paulo, Bruno, Roberto, Luigi, Blazej and Jean-Philippe.

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COOLING DOWN OF A LHC SECTOR

L. Serio, CERN, Geneva, Switzerland

Abstract

The LHC cryogenic system will be progressively commissioned at nominal operating temperatures in the coming years.

An introductory presentation of the cryogenics layout and main subsystems, and a description of the commissioning and cooldown sequences to obtain cryogenics powering conditions will be presented. Limiting factors for each operating mode and the organization of the cryogenics operation team (crew, responsibilities, control rooms and availability for intervention) will also be revised in view of the machine operation. Steady state and transient operation (i.e. magnet powering, quench recovery and partial sector warm-up for intervention) will be analyzed and the influence on the overall machine operation investigated.

INTRODUCTION

The layout of the cryogenic system is detailed in other specialised papers [1, 2].

In Fig. 1 the cryogenic system layout in one of the 5 points is presented.

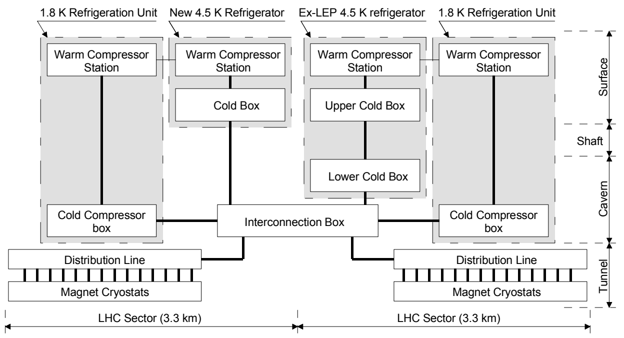

Figure 1: The cryogenic system architecture per point.

From surface down to the tunnel, the 4.5 K and the 1.9 K refrigeration units, the transfer lines, the interconnection boxes and the cryogenic distributions lines, will be individually cooled down, commissioned and their contractual performances evaluated. Each subsystem will go into operation just after acceptance to provide refrigeration power for cold acceptance of depending subsystems. Sub-systems are individually controlled and exchange main parameters for start-up and interlock as well as connection and disconnection with slave and master sub-systems.

The sector test will therefore be the final verification of the collective behavior and operation modes as well as to provide a valuable tool to define control strategies, procedures and operators training for the full machine operation.

SUB-SYSTEMS COMMISSIONING

Commissioning of cryogenic sub-systems is performed with dedicated test cryostats and/or other operational sub-systems. The commissioning consists in: pressure and helium leak tests, electrical, instrumentation and monitoring equipment tests, steady-states performances to verify nominal capacity as per specifications and transients to verify automatic adaptations and dynamics compliance. At the end the mass-flow, pressures and temperatures are verified to be as expected for the machine operation.

4.5 K refrigerators

New 4.5 K refrigerators are being commissioned. Two have already been accepted (one is already in operation since March 2002).

Ex-LEP refrigerators will be upgraded between 2004 and 2005 and commissioned after consolidation works and major overhauling on compressor stations.

1.8 K refrigeration units

The first pre-series has been accepted and demonstrated the required pumping capacity to maintain the magnets below 1.9 K as well as the necessary dynamics to follow the typical LHC machine cycle.

Cryogenic interconnection boxes (QUI)

The first QUI has been delivered in point 8 and will be connected via a vertical transfer line to the commissioned refrigerator for acceptance tests and commissioning. The other QUI’s will follow on other points and would be progressively commissioned.

Cryogenic distribution line (QRL)

Each QRL will be independently commissioned. Dedicated test cryostat will allow heat inleak measurements. After acceptance, the QRL will be conditioned and prepared for magnets interconnections.

POSSIBLE IMPACTS ON OTHERS DURING COMMISSIONING

The major hazards associated with cryogenics are (IS47): asphyxia, cold burns, expansion ratio and material brittleness. Asphyxia would be the only possible concern for others during cryogenic commissioning. A monitoring and alarm system would be installed in surface (galleries) and tunnel but the implementation in caverns still need to be finalised.

Radiation, which is not induced by any cryogenic test or activity could nevertheless be accumulated, via particles dust and impurities from magnets, on filters and subsequently be expelled in case of safety valve releases.

REQUIREMENTS FOR THE SUB-SYSTEMS COMMISSIONING

Electrical power

The cryogenic system would require 4 MW and about 1 GWh total power consumption during cool-down. Around 25 GWh would be consumed during one year operation at 1.9 K.

Fluids

12 tonnes of helium will be necessary to fill a sector. 60 % of which would be stored in the cryomagnets. Until 2007 the quantity of helium on-site would be limited due to lack of storage capabilities and would allow only 1 sector cold and filled at the time.

During cool-down about 1300 tonnes of liquid nitrogen will be vaporised. This is equivalent to 3 trucks per day during the first 10 days.

Operators

Due to the complexity (5 points, 8 18 kW refrigerators, 16 compressors and 9000 I/O channels per point) and geographical distribution (24 km at 1.9 K) of the cryogenic system, a minimum number of 6 operators and 1 CERN staff per point (allowing 2 operators on-call) would allow testing of one sector at the time plus parallel commissioning of cryogenic sub-systems.

EXPECTED PERFORMANCES AND LIMITATIONS

A sector cooldown to 1.9 K will take about 11 days. In case of an accelerated cooldown for emergency interventions on one sector (two cryoplants on the same sector), this time can be reduced down to 5.5 days.

Limitations have been found, during string tests, on the cooldown speed from 4.5 K to 1.9 K due to liquid helium entrainment which reduces the available cooling capacity of the bayonet heat exchanger. Re-cooling after 1 cell quench would require 4.5 hours.

String tests have shown that magnets and HTS current leads temperature control are within requirements during steady-state operation as well as transients.

In case of loss of utilities the recovery time for CRYO OK conditions has been estimated to be of the order of 6 hours plus 3 times the stop duration time.

TECHNICAL CHALLENGES STILL TO BE ADDRESSED

The following technical challenges, which were not addressed or partially addressed during String tests and sub-systems commissioning, would require further investigation during sector tests and commissioning.

Overall collective behavior of systems: cool down time and cooling flow distribution optimization, superfluid helium loop commissioning and optimization with adjacent cells cooling, cooling power distribution and transient disturbance between individual cooling loops and quench propagation and recovery for the sector.

Establish and validate interlocks and process for sub-systems collective behavior.

Furthermore, the commissioning of the magnets string and DFB's instrumentation, the superconducting cavities commissioning, the QRL at working temperatures and with full instrumentation (almost double of QRL without magnets) and the logistics for fluids (liquid nitrogen and helium) for a full sector can only be performed during the sectors tests.

CONCLUSIONS

Cryogenic system overall performances and reliability have been validated during dedicated individual sub-systems and String tests.

Performance and reliability of each cryogenic sub-system after in-situ installation is ongoing.

Sub-systems commissioning will improve: the sector commissioning time *(equipments ready for operation)* and the reliability of the cryogenic system *(training for operation and maintenance crews).*

Overall process and collective behavior needs to be assessed and optimized during first sector test.

The system complexity and lack of resources (CERN staff and operators) do not allow parallel sectors commissioning and machine-like performances till 2007.

Electrical power consumption limitations give 4 months shut-down per year.

The helium inventory storage system does not allow having more than half of the machine cold with liquid helium until 2007. Then, the options would be a virtual storage (selling back extra helium, renting helium) or additional storage systems.

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OPERATING/REGENERATING THE BEAM SCREEN AND THE NEG

A. Rossi, CERN, Geneva, Switzerland

Abstract

The LHC beam vacuum system is characterized by the proximity of cryogenic and ambient temperature chambers, the latter coated with TiZrV Non Evaporable Getter (NEG). A preliminary study on cold mass/beam screen cool-down sequence, beam screen warm-up, as well as NEG activation procedure to achieve low background pressure, is presented. Emphasis is given to the impact on the operation of the LHC, including some accident scenarios.

INTRODUCTION

The LHC beam vacuum system is composed of chambers at cryogenic temperature running through the superconducting magnets (about 20 of the 27 km of the machine circumference), and ambient temperature chambers coated with TiZrV sputtered NEG [1]. The reconditioning procedures of the entire vacuum system must be determined to achieve vacuum stability [2], beam lifetime of ~ 100h [3] and low background pressure to the experiments. In this paper, a preliminary study of these procedures is presented.

LHC CRYOGENIC SYSTEM

The LHC cryogenic system is constituted by the Arc cryostats (about 20 km), the Long Straight Section (LSS) Stand Alone Magnets, the LSS Inner Triplets, and, for the Interaction Regions 2 and 8, the beam separation-recombination dipoles D1 and D2. Each of the magnets is equipped with an unbaked beam screen (BS) tube (made out of stainless steel with copper co-lamination), perforated to provide gas pumping onto the cold bore surfaces. The BS is actively cooled and intercepts the synchrotron radiation thereby reducing the heat load on the cold bore [4].

The presence of the BS can also avoid ion induced pressure instability and guarantee a low background pressure since part of the residual gas molecules, and in particular H_2, are condensed on surfaces shadowed from the beam [5]. In the magnets working at 4.5K, H_2 will be cryosorbed on dedicated materials placed on the rear of the BS.

Beam lifetime requirements

The maximum average gas density around the accelerator ring to guarantee a beam lifetime of 100h [3] is of about 10^{15} molecules/m^3 hydrogen equivalent (corresponding to less than 10^{-8} Torr at ambient temperature). The density for different gas species scales with the nuclear scattering cross section:

$$n(H_2\ eq.) = n(H_2) + 5.4\ n(CH_4) + 7.8\ n(CO) + 12 n(CO_2).$$

The residual gas molecules are originated from desorption induced by ions, electrons and photons incident on the walls (dynamic desorption), and pumped on the BS cold surface or through the pumping slots. If the amount of gas condensed onto the BS exceeds few atomic MonoLayers (1ML ~ 10^{15} molecules·cm^{-2}) the residual gas pressure may go above the lifetime threshold, depending on the BS temperature. This is shown for hydrogen in Fig. 1, taken from COLDEX measurements [6]. Here one can see that if a large amount of H_2 is condensed on BS (at 5 to 10 K) prior irradiation with synchrotron radiation, the residual gas pressure will exceed the lifetime limit for a certain amount of time. In the case of other gas species, in particular CO, this time can be of the order of days, due to its very low recycling [6].

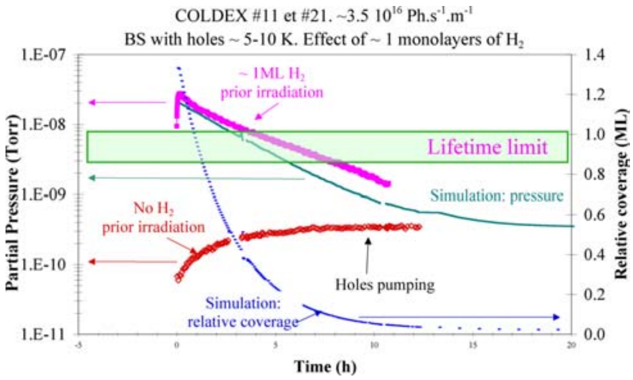

Figure 1: Time evolution of H_2 pressure (Torr at 300K) under synchrotron light irradiation in the COLDEX experiment.
Courtesy of V. Baglin, CERN AT-VAC.

For the above reasons, surface condensation on the BS must be minimised. The BS temperature should therefore be higher than the cold bore (CB) temperature. To limit thermal radiation to the cold bore and optimise the cryogenic thermal cycle, the maximum operating temperature of the BS is set around 20 K. At this temperature very low vapour pressure of all gas species, except hydrogen, will be maintained. For higher values (around 30 K) any temperature oscillation would cause large gas density variations, as it was observed in [6]. Note that the CO vapour pressure at 25 K with surface coverage ≥ 2 ML is about 10^{-9}Torr, close to the beam lifetime limit for CO [7]. In Table 1, the temperatures of the cryostats cold bores and beam screens in the LHC machine are listed.

Table 1: Cryogenic system temperatures

Machine element	Cold bore	Beam Screen
Arc dipoles and quadrupoles	1.9 K	5-20 K ± 5 K
Inner Triplets & Q7	1.9 K	5-20 K ± 2 K
Standalone/ Doublets	4.5 K	5-20K ± 2 K

In the following sections, the cooling and regenerating procedures recommended to achieve a low residual gas pressure are described.

Standard cool down procedure

At machine start up or after any machine opening, the beam line in the superconducting magnets will be pumped down with mobile turbo-molecular pump stations, with the aim of reducing the amount of condensable gas. The cool down of the cryostat can start when the line pressure is between 10^{-4} and 10^{-5} mbar (corresponding, in the considered geometry, to less than 1/100 of ML of condensed gas). The time estimated to reach such pressure is several hours, due to the chambers poor conductance and the high outgassing of the unbaked surfaces. Figure 2 [8] shows the pressure evolution in an LHC arc type geometry, with beam screen, and a distance between pumps of 108 m. In this case the pumping time is about one day.

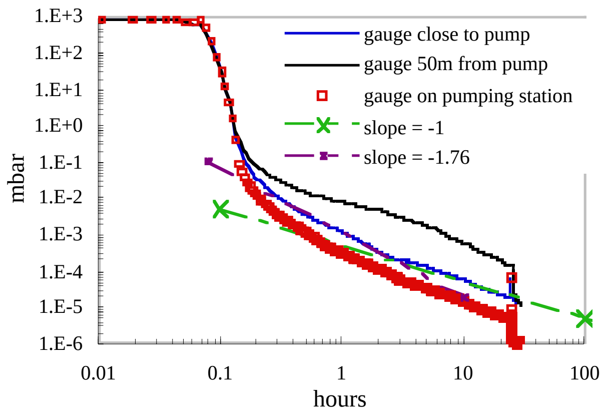

Figure 2: LHC-arc half-cell with beam screen. Time evolution of pressure during pump down. *Courtesy of J-M. Laurent, CERN AT-VAC.*

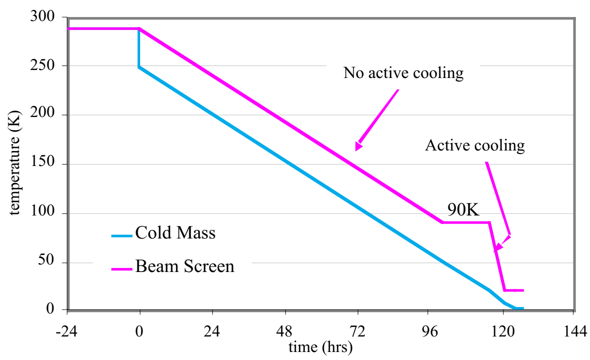

Figure 3: Cold mass and beam screen cool down procedure (above) and fast cool down procedure (below).

A schematic of the cool down sequence, as proposed, is shown in Fig. 3. The time for the cold mass to cool from ambient temperature to either 1.9 or 4.5 K is about 11 to 12 days (fast cooling in about half the time) as experienced in String 2 [9]. The procedure adopted so far was to let the BS be naturally cooled by radiation (with a temperature difference between cold bore and BS measured around 40 K) and finally actively cooled to reach the 20 K. In this paper it is proposed to retard the BS cool down, keeping it at ~90 K until the cold bore reaches about 20 K, after which it can be actively cooled. In this way, most gas species, including CO_2, are expected to condense on the cold bore with a very low vapour pressure, and not to easily move to the BS even when it reaches its lowest temperature. The proposed procedure does not require any additional time with respect to a procedure without plateau at 90 K.

The procedure was successfully tested in the String 2, in May 2003, details are reported in [10]

Beam Screen regeneration procedure

Due to dynamic desorption [11], gas coverage will accumulate onto the cold BS during beam operations. It is estimated that at machine start up and after machine conditioning ("beam scrubbing" campaign [12]), the time duration for the condensed layer to exceed few ML should be longer than the span between long shut downs (i.e. longer than one year operations).

For the "beam scrubbing" campaign, due to the additional gas source from electron multipacting, it may take few weeks, which corresponds to the time dedicated to the scrubbing. In this case it is recommended to regenerate the BS by raising its temperature while keeping the cold bore at its operating temperature. The gas condensed on the BS can evaporate and be pumped via the pumping slots to the CB. The BS regeneration consists of warming up to either 50 K to remove CO, or 90 K to remove also CO_2, for one hour, with an estimated time of several hours for the complete regeneration cycle. These temperature values are chosen to shorten the regeneration cycle to the minimum. At 50 K, the vapour pressure of CO_2 is too low to pump the gas behind the BS, while at 90 K the pressure would reach about 10^{-5} Torr (at 300 K equivalent), which would allow to pump >>1ML in less than 1h. Tests to verify the feasibility of the procedure have been carried out and are discussed in [10]. It should be noted that during long shutdowns, the BS temperature should reach 80 to 90 K without additional heating.

LHC AMBIENT TEMPERATURE SYSTEM

The majority of ambient temperature chambers between cryostats are TiZrV sputtered NEG [1] coated copper chambers 7 m long (standard LSS chamber), alternated to stainless steel bellows and pumping ports for Sputter Ion Pumps (SIP). Bellows and pumping ports are provided with RF copper screens [13] to reduce the longitudinal impedance seen by the beam. A typical LSS sector between cryostats is shown in Fig. 4.

In the experimental regions (about ± 20m from the Interaction Point) the vacuum chambers are made out of beryllium (in the central detector regions), stainless steel or BeAl alloys, deposited with few microns of electrolytic copper (except for the Be sections), for impedance constraints, and NEG coated.

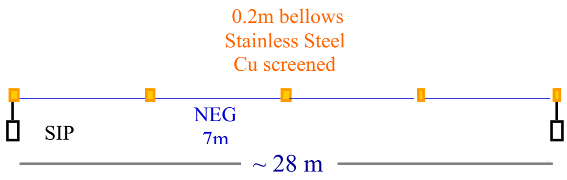

Figure 4: Schematic of a standard LSS sector.

TiZrV NEG coating has been chosen for its multiple properties suitable for accelerator vacuum systems, upon low temperature activation:

- Low static and dynamic gas desorption for all gas species combined with high pumping speed for "getterable" gas species such as H_2, CO and CO_2 can ensure minimum background pressure [1];
- Low secondary electron emission [14] reduces or cures electron cloud multipacting, and limits the detrimental effects on beam stability [15] and vacuum itself [16].

NEG coatings have a composition of 30-30-40 TiZrV [atomic %] and an activation temperature of about 200°C (24h) [1]. After several exposures to air at atmospheric pressure, the activation temperature can be increased to 250°C to recover the full NEG properties [1]. The full activation procedures are described in the following.

Ambient temperature systems NEG activation after exposure to atmospheric air

After any opening to atmospheric air, the ambient temperature vacuum system will be pumped down to at least 10^{-7}Torr and leak tested before NEG activation. The NEG activation consists of baking the uncoated surfaces and activating the NEG coated surfaces. Baking is carried out prior to the NEG activation, to reduce gas load on the NEG. During this phase, the NEG surfaces are kept to 80 to 100°C, so that the molecules released from the baked surfaces as well as from SIP conditioning, will not stick to it. The baking temperature varies from 250°C for bellow and pumping ports to 300°C for vacuum instrumentation such as pressure gauges and gas analyser. Activation of NEG is performed at 200°C for 24h, or shorter for higher temperatures (Fig. 5). Gas analysers will be used to monitor the vacuum and check for air leaks. Since the NEG is a very powerful oxygen and nitrogen pump, while it does not pump noble gases, air leak is monitored using the Ar peak.

The procedure requires the installation of mobile pumping stations (equipped with turbo-molecular pumps and gas analysers) to first pump down the line from atmospheric pressure, as mentioned before, and to evacuate the gas throughout the activation. In these pressure ranges, SIP cannot be used. The mobile stations will be disconnected and removed before operations start.

It should be noted that, since Kr gas is used as sputtering medium during NEG deposition, traces of Kr remain trapped in the film. For the first one or two activation cycles, Kr molecules will be released and must be evacuated from the system via the turbo-molecular pumps. The procedure must foresee to start the SIP pumps when the system is almost back to ambient temperature, to avoid pumping Kr with them.

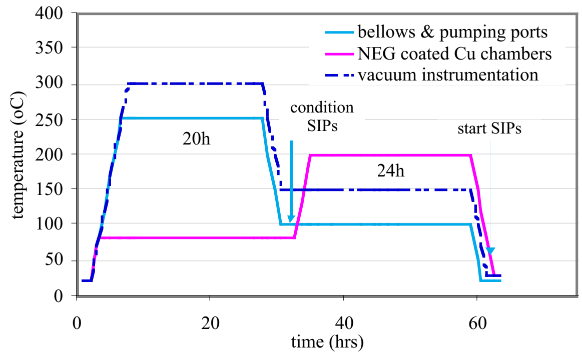

Figure 5: Standard NEG activation procedure after opening to air.

If the uncoated surface area < 1/10 coated area, the procedure pictured in Fig. 6 can be used. Baking of uncoated surfaces may be carried out almost simultaneously with the NEG activation, and at the same temperature. This procedure will be implemented only in the case of major time constraints, while the procedure in Fig. 5 has to be considered as the standard NEG activation procedure.

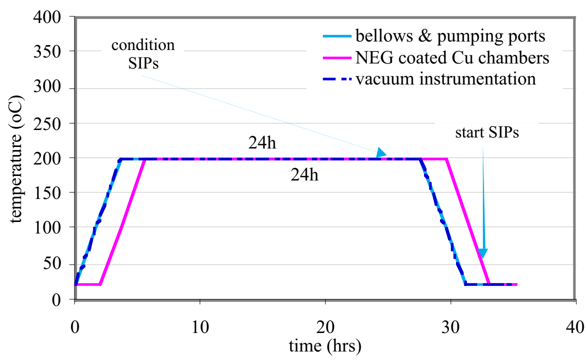

Figure 6: Accelerated NEG activation procedure applicable only if NEG coated/uncoated surface area < 1/10, and in the case of major time constraints.

NEG reactivation

NEG surfaces have a capacity of about 1ML of gas [1], and the pumping speed reduces as the saturation coverage is reached. If during machine operation, NEG performance has noticeably deteriorated, NEG surfaces can be reactivated by raising their temperature to 200°C for 24 h or 250°C for 2h (as plotted in Fig. 7). In this case, baking of uncoated surfaces and conditioning of SIPs are not necessary, since they have not been exposed to atmospheric air. This procedure can be employed also after the repair of a small leak. The possibility of not using mobile pumping stations is under investigation, since this would have the advantage of both saving time and reducing exposure for the personnel to radioactive environment.

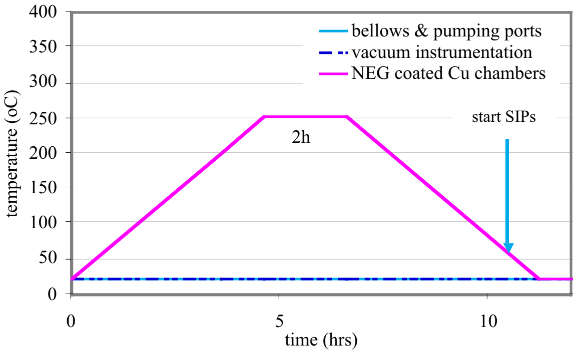

Figure 7: NEG reconditioning procedure.

EXPERIMENTAL REGIONS SPECIAL REQUIREMENTS

Experimental regions refer to the beam vacuum chambers extending ±20m from the beam collision point in IR1 (ATLAS), IR2 (ALICE) IR5 (CMS) and IR8 (LHCb) of the LHC machine. These regions are included between sector valves, which make their maintenance independent of machine activities during a shut down.

Due to particle transparencies requirements, the experimental beam pipe thickness is minimised to withstand atmospheric pressure, and for most of its length is not equipped with baking jackets. To minimise the risk of mechanical damage when working around the beam pipe, gas injection to atmospheric pressure is recommended. If left under vacuum any small concentrated force applied to the pipe could endanger its integrity. In order to activate pumping surfaces, it is foreseen to fill the pipe at atmospheric pressure, move parts of detectors into a "rest position" (this takes few weeks), and install the baking equipment. After NEG activation, the pipe will be again brought to atmospheric pressure using "ultra-pure" neon gas (not pumped by NEG) to allow removal of the baking equipment and installation of the detectors in their final position. The "ultra-pure" gas impurity content is below 100 ppb, to minimise NEG surfaces contamination: at 1atm, the contaminants correspond to <1/100 of the full NEG capacity. The gas is subsequently pumped down with auxiliary (mobile) pumping station before SIPs are again put into operation.

PUMPING SURFACE REGENERATION AFTER ACCIDENTS

In this section, a preliminary analysis of accident scenarios is presented, with consequences on beam down time due to surface regeneration.

Cryogenic systems

If the BS temperature rises above ~30K, condensed CO may move from one region to another of the BS, causing local accumulation of few ML. In this case BS regeneration or few hours beam conditioning may be required. Two accident scenarios are studied: magnet quench and loss of cooling in the superconductive magnet circuits.

Magnet quench:

In the case of a magnet quench, the cold bore temperature was measured [17] to rise from 1.9 to 20-30 K in about 1 minute with undetermined temperature excursions. It is estimated that the CB temperature may go up to 100 to 150 K [18]. Two case scenarios are to be considered:

1 Due to the short duration, the BS temperature does not exceed 30 K. In this case no particular action is required since the gas pumped on the CB is mainly hydrogen which even if released will be pumped back when the CB is cooled down. Any other gas species are expected to stick to the external surface of the BS.

2 The BS temperature goes above 30 K (as expected for example in the case of a full sector quench [17]). Gas molecules may move to colder parts of the BS and accumulate to several ML. In this case, BS regeneration or beam conditioning[i] is recommended.

Loss of cooling:

When cooling loss was simulated, the cold bore temperature increased from 1.9 to 5 K in about 24 hours [14], while no variation of the BS temperature (a small cool down because of thermal equilibration) was observed. At about 4.84 K, the hydrogen vapour pressure reaches about 10^{-5} Torr, and a non-negligible amount may go from the CB to the BS. This is not considered to be a problem since it is expected that when the cooling is recovered, the temperature of the whole BS will go to above 10 K, and H_2 will go back to the CB.

Ambient temperature systems

Air leak during NEG activation or re-activation:

As previously mentioned, air leaks are monitored during warm sections activation and re-activation. If an air leak is detected, NEG activation is stopped. Due to the tube heat capacity and the good thermal insulation, however, the temperature may take some time to lower. The air pumped by the NEG surface at high temperature can diffuse to the bulk. In the worst case, the NEG could saturate completely, and the change of the sector pipes has to be envisaged. If possible, taking into consideration the chambers radioactivity level, the NEG will be stripped and new coating deposited. If the activation is stopped in time, the leak will be repaired, and the activation procedure restarted. It is foreseen to make tests and check NEG properties after such an event. Tests to quantify the worse case scenario are ongoing in the CERN/EST division.

Air leak in LSS:

If an air leak opens during beam operation, the NEG will progressively saturate and a deterioration of vacuum shall be observed. Depending on the extent of the leak either full activation or re-activation are required. In the case of a small leak, the recovery after the leak is cured will take of the order of 12h (see Fig. 7).

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[i] Beam induced phenomena, such as photon stimulated desorption, as explained in previous sections.

Air leak in experimental regions:

This makes a special case because of the inaccessibility of the beam pipe in these regions. The detectors will have to be moved in rest position, the leak cured and the NEG reconditioned. The minimum recovery time declared by experiments is of about 4 weeks (which may not allow the ALICE detector to be operational).

An accident in the LHCb VELO tank causes a 2 weeks' down time, after which the LHCb detector will not be operational [19].

CONCLUSIONS

In this paper the procedures for operating/regenerating the pumping surfaces of the LHC beam pipe, both for the cryogenic and ambient temperature systems, that should allow meeting vacuum requirements of stability, beam lifetime and low background pressure have been presented. While for the ambient temperature systems a broad experience has been gained in previous machines, and in laboratories with TiZrV sputtered NEG coating, operations with large cryogenic systems such the LHC are less known. Further work should be invested to verify and validate the proposed procedures, if possible with dedicated tests.

Due to the complexity, duration and diversity of the work involved, a separation of the cryogenic and ambient temperature systems is desirable to ease the work for the personnel involved and allow for more flexibility. Valve interlocking should be foreseen to avoid cross contamination between the two systems, and limit regeneration time.

The analysis of recovery from accidents is still very preliminary and efforts in this direction should continue.

ACKNOWLEDGEMENTS

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LHC HARDWARE COMMISSIONING 2005-2007

R. Saban, CERN, Geneva, Switzerland

THE CONTEXT

The General Construction and Installation Schedule is presently undergoing a revision which alters the order of the installation of the sectors and therefore their commissioning. In all cases, the hardware commissioning activity is taking place more than once simultaneously in two sectors. Furthermore, during the commissioning of all but the last sector, one or more of: the machine installation, the QRL installation or commissioning, is ongoing in the neighbouring sectors. This will undoubtedly have an impact on the logistics, on the scheduling and the availability of the resources to be deployed for the activity. In all cases, resources will have to be distributed/shared between hardware commissioning and the installation and/or individual system tests.

The SPS stop (October 2004 to April 2006) takes place partly during the hardware commissioning (March 2005 to December 2006). It is agreed that control room operators will be deployed for hardware commissioning with the double objective of training the future operators of the LHC and helping the hardware commissioning team.

THE PHASES

The hardware commissioning will be prepared by a group of people from the equipment groups (project engineers, system owners) who have been either involved in operating the machine or the String. Initially during the analysis and design work, they will be organized as a *Working Group* and will turn into a *Team* when the work in the field has started.

Individual System Tests

Before the hardware commissioning starts all the systems required for it must be qualified. The definition of these tests is the responsibility of the owner groups (essentially in the AB, AT and ST Divisions). The conditions required to start the qualification tests, those needed during and those signalling the end of the qualification will also have to be defined.

It is the duty of the Hardware Commissioning Working Group to gather those requirements and to ensure they are satisfied for the tests. The Hardware Commissioning Team will coordinate the tests and beforehand, follow-up the preparation work of the assemblers and the specialised teams.

Hardware Commissioning

This term refers to the commissioning of the sectors or parts of the sectors as a single system.

It is in the mandate of the Hardware Commissioning Working Group to define the commissioning programme to be applied to the sector as a whole after the individual system tests. This task includes the definition of the procedures, their sequencing, the refinement of the time required for the commissioning, as well as the identification of the conditions required to start, those required during the commissioning and the conditions which determine the end of the commissioning. After this design/study phase, the Hardware Commissioning Team will run the hardware commissioning programme in the time frame allocated by the General Construction and Installation Schedule. For the first commissioned sector only, it will also carry-out validation and specific studies. By involving staff from the accelerator control room in the study and the execution of the hardware commissioning, a first bridge to commissioning with beam will be launched. In addition, a close level of collaboration with the LHC OP project will be maintained for this purpose.

THE LAYOUT

The sectors are composed of several cold and warm sections. These are mechanically separated, electrically and cryogenically independent; for insulation vacuum the subsectors are independent but coupled by the beam vacuum tubes. During the two commissioning phases, all this will impact on the order, the procedures and the usage of the resources.

As an example, consider Sector 7-8: it contains 125 independent electrical circuits, 77 of which traverse the whole of the main arc sub sector; another 94 circuits for the orbit correctors are individually powered locally, two per short straight section. The complexity of these circuits both in terms of number of components and powering scheme greatly varies: the biggest circuits in terms of components is the main dipole circuits (approximately 600 components: power converter, water cooled tubes and cables, current leads, cold bus bars, magnets, energy extraction switch and resistor, etc.) while the most tricky to commission will be the inner triplet circuit with its three nested power converters.

Most of the magnets will have been individually tested, however one of the most complex components, the electrical feed boxes (arc, matching sections, and inner triplet subsectors), which vary from sector to sector, might be cooled and operated for the first time during the hardware commissioning.

The hardware commissioning of a sector is considered finished when all the circuits have been powered to nominal current independently and in unison in a pattern representative for operation. The hardware commissioning of a sector as a whole, includes the injection, extraction, collimation and RF systems.

THE SEQUENCE AND THE PROCEDURES

Following a thorough analysis of the requirement for each type of system, the procedures to be applied for the commissioning of each system will be designed by the hardware commissioning working group and their sequence will be defined.

As an example consider the tests preceding the powering of the circuits. As for the String, they will probably involve two phases: during the first phase the magnets and the power converters will not be electrically connected and will be tested separately. The magnets will be tested for electrical insulation at different temperature levels during the cool down. Before the two sides are electrically connected, they will be linked by the machine protection system; the power converters will be turned on and tested on a short circuit as if they were delivering current to the magnets. The quench detection system will be fired on cold and unexcited magnets to verify the sequence of events.

Similar methods will have to be designed for every system (RF, extraction, injection, warm magnets, etc.), with the contradictory objectives of a safe, clean and quick commissioning.

THE ROLES

This section summarises the roles of the actors installing, assembling and commissioning equipment in LHC during the two phases mentioned above, namely individual system tests and hardware commissioning but also reminds the responsibilities in the phases preceding commissioning.

Installation and Assembly

The equipment owners are responsible for the installation and assembly of their equipment; they are coordinated during these phases by the Installation Coordination Group of the EST Division. During the preparation of the installation, a document describing the Work Units involved is prepared by the EST-IC Group together with representatives from the groups involved in the installation: there exists one such document for each particular zone and each LHC installation phase. The follow-up of the installation and its schedule is done in a series of meetings organized also in the field by the EST-IC Group.

Individual System Tests

The equipment owners are responsible for the individual system tests of their equipment; they are coordinated during this phase by the Hardware Commissioning Team. Like for the installation and the assembly phases, during the preparation of the tests, a document describing the tests is prepared by the Hardware Commissioning Group together with the equipment owners: this document will describe the tests with respect to the interfaces namely, the conditions required to start the tests, those needed during and those signalling the end of the tests. The follow-up of the tests is done in a series of meetings organized by the Hardware Commissioning Team.

Hardware Commissioning

The hardware commissioning is the responsibility of all those commissioning the sector as a whole, namely, the members of the Hardware Commissioning Working Team, the Groups owning the equipment and the operators from the Accelerator Control Room. Like for the preceding commissioning phase, documents describing the Hardware Commissioning procedures, sequences and conditions will be prepared by the Hardware Commissioning Working Group and its progress will be followed up in a series of meetings organized by the Hardware Commissioning Team.

THE HARDWARE COMMISSIONING WORKING GROUP

The working group has started operating in April 2003. After the setting of the scene two topics were addressed: the commissioning of the cryogenic system and the assembly and tests of the first inner triplet (left of point 8). While the first meeting revealed a very good level of organisation of the ACR group, the second highlighted many grey zones for the assembly of the inner triplet as well as for the timing and the procedures of the leak and pressure testing of the sector as a whole.

The identification of the systems which need to be included in the individual system test program and of their contribution to the hardware commissioning effort is ongoing.

An estimate of the electrical power requirements is being prepared in order to determine the powering profile during the years preceding LHC start up.

SUMMARY OF BEAM TESTS 2003 - 2007

M. Lamont, CERN, Geneva, Switzerland

Abstract

As equipment is installed in the SPS-LHC transfer lines and the LHC machine itself, a number of tests with beam are foreseen. The extraction test from SPS into TT40 in 2003 and the transport of beam down the TI8 line in 2004 will both be briefly covered. The justification for, and consequences of, injecting beam through sector 7-8 will then be addressed. Finally the expected beam parameters during year 1 will be summarized, and possible consequences of running with less than nominal beams are discussed.

INTRODUCTION

Tests with beam are foreseen: extraction into the first part of TI8 (2003), of the completed TI8 (2004), a possible sector test with beam of the sector 7-8 (2006), commissioning of TI2 (2007), culminating in the commissioning of the LHC itself (2007). It is clearly important that these tests be carefully planned to maximise their effectiveness and minimise their cost and impact.

TT40

The TT40 extraction test is planned for two 24 hour periods in September and October 2003. Objectives include the verifications of equipment functionality (kickers, septa, beam instrumentation, magnetic elements, power converters) as well as supporting systems such as interlocks and controls. It is planned for the most part to extract low intensity beam, to verify the extraction channel and trajectory in the line, measure the acceptance of the extraction channel and the reproducibility of trajectory in the line. It is also planned to look at double batch extraction required for CNGS and the effect of the extraction kicker ripple. Although relatively small in extent the test already poses an interesting integration exercise with issues such as radiation protection and access requiring careful attention. Planning for tests is already well advanced [1].

TI8

The TI8 tests with beam are planned for September/October 2004 with about 4 full days foreseen. Limited cooling capacity in the lines will prevent continuous pulsing during this period. The aims, again, are to verify equipment functionality and the proper integration of interlocks, surveillance, access and other systems. The line is around 2.7 km long and so this will be a non-trivial task. LHC pilot intensities (5×10^9) are foreseen for the most but up to 2.5×10^{11} proton per pulse (ppp) are allowed for. The tests will include trajectory acquisition & correction, reproducibility, commissioning of the beam instrumentation, measurements of the optics in the line, and matching between the line and the SPS.

The Radiation Protection Group (RPG) has produced estimated dose rates [2]. These show that with intensities of 2.5×10^{11} ppp over 24 hours at 50% efficiency, with a day's cool down, remnant dose rates along side the TED area would be around 120 μSv/h and around 3 mSv/h on the downstream face of the TED. These figures imply the need for extra shielding (iron/concrete) after the TED, and the area around the TED to be declared a Simple Controlled Radiation Area after the tests.

An access zone from the TED extending through UJ88 to UJ86 towards UX85 and US85, with a gate in the LHC tunnel towards point 1 will be required to prevent access down stream of the TED for the duration of the test. Appropriate radiation monitoring will be required.

INJECTION TEST IN 2006

The latest LHC installation schedule (LHC-PM-MS-0005 rev 1.7) includes a "possible injection test" in April 2006. This would involve the injection of beam down TI8, into the LHC at the injection point right of IP8, traversal of IR8 and LHCb, through sector 7-8 to a temporary dump located near the position of Q6 right of point 7. The motivations for performing this test were outlined at Chamonix 2003 [3] where it was strongly endorsed. However, there are many consequences and some potential problems were also identified [4].

Motivation

The beam provides a powerful diagnostic tool and will allow checks of the physical aperture, and give a means of checking the field quality in situ. It will be the first exposure to beam of much of the hardware and will, potentially, allow verification of assumed quench limits and spatial resolution of beam losses. It will also permit polarity checks of the corrector elements and the beam position monitors: key concerns in the installation procedure. First tests of important beam diagnostic system would also be possible.

Besides this it will provide an extremely high profile milestone forcing large-scale integration of all components. These would include controls, timing, transfer from the injectors, instrumentation etc. The test would potentially highlight over sights, misconceptions and shortcomings. Operationally the exercise would be extremely valuable and it can be argued that the time and effort spent on the test will be more than compensated by a more efficient start-up of the completed machine.

Any problems high-lighted would have a full year for resolution before the commissioning of the full machine.

A successful test would also validate the machine to the wider world.

Impact

There are many potential consequences:

- The test will necessitate the closing of sector 7-8 and at least part of 6-7 and 8-1. Installation is planned to be ongoing in sectors 3-4, 5-6 and 6-7 at the time of test. Thus transport of magnets through the sector 7-8, and interconnect work in the closed part of 6-7 will not be possible for the duration of the test.
- Hardware commissioning is planned for sector 4-5, and the test will inevitably pull in resources, firstly for the re-commissioning of sector 7-8 in preparation for the test and during the test itself.
- The test will force the commissioning schedule of certain systems e.g. access and interlock systems.
- Remnant radiation could potentially force parts of 7-8 and 8-1 to be declared a Simple Controlled Radiation Area with knock-on effects for magnet transport and subsequent installation.
- The test will clearly use resources: both manpower in the preparation, execution and recovery, material costs for items, which are not part of the final LHC configuration, plus exploitation expenses.

It is clear that a large number of issues need to be addressed to evaluate and cost the full impact of the test: radiation and INB approval, access and interlock systems, impact on LHCb, impact on injectors, re-commissioning of the transfer line, impact on hardware commissioning and installation, the need to install, monitor and remove the beam dump, for example.

Timing of the test

At present the test is scheduled to start week 2 April 2006. However, for start-up 2006 both the SPS and PS will be recovering from the 2005 shutdown and it is estimated that 4 weeks will be required for cold checkout and re-commissioning. Further the SPS is usually subject to energy consumption restrictions and should not normally pulse before April. Thus the test would be pushed until end April 2006 unless provision is made to start the SPS earlier.

For LHCb, April is the most convenient time and as such is taken into account in their planning. A delay of more than 10 weeks beyond April 2006 would jeopardise the LHCb overall commissioning.

Radiation

It planned to use LHC pilot intensities (5×10^9) for the most part with strict proviso not to irradiate LHCb: their zone must remain a so-called surveyed area after the test. The clear aim will be to minimise losses and use beam sparingly throughout the test. A maximum around 3000 shots is foreseen corresponding to a total intensity of 2×10^{13} protons over a two-week period [5]. This will be coupled with preparation time and high operational inefficiencies.

Simulations by the RPG [2] show that activation will be low. However, we must anticipate that parts of the zone that sees beam will be declared a “Simple Controlled Area” with potential warm spots neat the injection dump (TDI) and the around the position of the beam dump. The dump itself can be removed after the test. Passage through these controlled areas will be possible after the test. Radiation monitoring will be required during the test. The RPG will survey after the event to check levels of activation.

The INB will need to be informed and estimated intensities, estimates of likely activation and estimates of personnel doses provided. Appropriate restrictions could then be discussed. A report would be provided to them in 2004.

Access

Gates in tunnel sectors 6-7 and 8-1 would be needed, along with interlocked restricted access at PM76, PM85 and PZ85. Much of this infrastructure will be necessary in the final LHC configuration and can be made available for the test without too much extra cost [6].

LHC – FIRST YEAR OF OPERATION

Briefly, it is foreseen that the first four months or so of LHC operation will be dedicated to commissioning the machine with a single beam, establishing colliding beams, with the goal of a low intensity pilot physics run with 25 ns. bunch spacing. This will be followed by a 3-month shutdown, and then a physics run with the goal of establishing luminosities of up to 10^{33} cm^{-2}s^{-1} [7]. Bunch intensity will be restricted to around 4×10^{10} protons.

Restrictions during the first year include: the need to keep the event rate below or around 2 events per bunch crossing (10^{33} cm^{-2}s^{-1} at 25 ns.), total maximum intensity at 50% of nominal because only 8 out 20 of the beam dump dilution modules will be installed, bunch intensity to around 1/3 nominal with 25 ns bunch spacing to avoid electron cloud effects [8].

In addition machine protection and collimation systems will favour initial operation with low beam power and low transverse beam density as we learn how to deal with multipole effects, establish a reproducible operational cycle etc.

For the vacuum system, 3 phases are foreseen [9]. Firstly a start-up phase below the electron cloud threshold of $N_b \approx 3$ to 4×10^{10}, followed by a conditioning of the cryo-elements with scrubbing runs, and finally a post-conditioning phase. We might well not move beyond phase 1 during the first year of operation.

From a radiation standpoint the lower intensities will clearly favourably reduce the potential impact on equipment, electronics etc. and allow a gentle first look at reliability under what will become very harsh conditions.

For the cryogenics the lower intensity will mean lower heat load: from beam loss (given efficient collimation), from lower synchrotron radiation and lower image currents. The very difficult challenges for the LHC collimation system can be relaxed during commissioning by reducing the lower total beam intensity as foreseen, by keeping the β^* at reasonable values and by not reducing the emittances below nominal. Lower intensity means the lower cleaning efficiencies can be accepted for a given beam lifetime while still respecting the quench limits.

Lower energy

It is not possible to reduce the heat load on the cryogenics system significantly by reducing the beam energy [10]. Reducing the energy can increase the quench level margin, but in order to gain an order of magnitude, in the case of transient losses, one has to drop a long way. There is only a small gain with respect to continuous losses and lower synchrotron radiation.

The experiments are prepared to accept a 10% energy reduction for a limited period. This would buy something like a factor of two in the quench margin.

CONCLUSIONS

Beam tests provide important validation of ongoing installation, are important integration exercises and provide valuable milestones for many of the systems involved.

Planning for the TT40 test is well advanced and it will go ahead as foreseen later in 2003. Tests of TI8 are foreseen in Q3 of 2004, planning is underway, and careful consideration of radiation protection and access issues is already in progress.

There is strong motivation for an injection test into sector 7-8. However, the potential impact on ongoing installation on the rest of the ring is non-negligible and these consequences, and the cost of the exercise, need to be carefully evaluated before a final decision on whether or not to perform the test is made. The intensities that would be used are low, and acceptable radiation restrictions should be possible. The required access restrictions can be in place.

The first year's operation of the LHC will see reduced bunch intensity with a luminosity goal of 10^{33} $cm^{-2}s^{-1}$. At 25 ns. bunch spacing, the intensity should be below the electron cloud threshold easing life for the vacuum system. Lower intensities will also mean less radiation, less heat load on the cryogenics system and relaxed tolerances for the collimation system. This leeway will be vital as we attempt to climb the inevitably steep learning curve that commissioning the LHC will provide.

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CONTROLS REQUIREMENTS 2003 – 2007 AND BEYOND

R.J. Lauckner, CERN, Geneva, Switzerland

Abstract

Control of new equipment will be needed progressively from 2003, when the first LHC beam is extracted from the SPS. As the transfer lines and LHC machine itself are installed, a long testing and commissioning phase will require a variety of controls, including slow controls for underlying systems, specialized equipment diagnostics running both locally and remotely, generalized equipment control facilities for use by specialists and operations from the control room, and finally a suite of application software for operations with beam. These requirements will be discussed, as will the plans for meeting them.

INTRODUCTION

The major milestones for the development and commissioning of the Control System associated with the LHC Construction and Installation are shown in Table 1. The preparation of the SPS to extract the LHC Beam is now well advanced. It is the first extension to the CERN accelerators outside of the PS complex since LEP construction and since the creation of the single CERN accelerator control group.

Table 1: Major Controls Milestones

Event	Date
TT40 SPS Extraction	September 03
Sector 7-8 QRL reception tests	February 04
TI8 Transfer line test with beam	September 04
Sector 7-8 hardware commissioning	April 05
Possible injection test	April 06
LHC first beam	April 07

Later milestones will continue to build on the systems and controls services progressively requiring more of the final LHC controls system.

The following sections will concentrate on the QRL and hardware commissioning milestones, ending with some comments on global issues going beyond individual system control.

QRL 7-8 RECEPTION TESTS

The installation and pre-commissioning of the QRL, lasting 21 weeks, will be followed by 3 weeks of commissioning. The pre-commissioning phase ends with the delivery of the operational control system.

Cryogenics Control

The surface cryogenic plant and the equipment in the pits and caverns will be controlled by the UNICOS control system. For the QRL work central supervision is not yet foreseen. Servers for the local control room: SCADA, engineering support and supervision stations are installed in building SH8 as well as PLCs for control of the cryo-refrigerator. Another family of PLCs connects the warm compressors and cold boxes locally in SHM8 and SDH8 and remotely the cryogenic interconnection box in US85. All of the control for the surface cryoplant has been developed and the interconnection box control will be completed in September 2003.

Cryogenics Instrumentation

The UNICOS infrastructure described above will extend by Ethernet to the alcoves. PLCs or Ethernet to WorldFIP gateways will connect instrumentation crates alongside the tunnel cold masses. This radiation hard electronics for local signal acquisition is now entering the production phase. For the sector 7-8 QRL instrumentation a set of commissioning crates based on Profibus and Siemens equipment will be prepared.

The UNICOS database for instrumentation input and output is in preparation and the specification for Control Software is scheduled for end June. Thermometer calibration data is managed in collaboration with AB Controls data management team. Resource issues remain concerning parallel activities - commissioning of QRL sectors and full sector commissioning.

Vacuum Control

The vacuum group have developed an industrial control solution. This is operational in the SPS ring and is being deployed for TT40, TI 8 and the QRL vacuum systems. Central SCADA supervision is connected via Ethernet to master PLCs. For sector 7-8 these are located in UJ76, RE78, RE82 and UA83. Control crates either off-the-shelf or CERN developed are hardwired to pumps, gauges and valves in the tunnel radiation environment. A Profibus link runs parallel to these cables but is only used for mobile equipment which will be removed during beam periods. Current activities include hardware manufacture, software development and definition of interfaces to LHC Alarm and Logging facilities.

Control Services

In order to gather data during the QRL reception tests an LHC Logging Service is being prepared. In this first phase the service is designed to satisfy the cryogenic and vacuum users but already preparations are being made to integrate with technical services and beam operation requirements. The service will be available in September 2003 for TT40 data.

The CERN Alarm system which concentrates alarm information from across the CERN site is being modernised and extended for LHC operation. A commercial 3 tier JAVA software architecture will be introduced. The system will collate all alarm information pertinent to LHC operation. A smooth transition is in progress which will not perturb the current users - several control rooms at CERN.

More general controls services required are system administration and support for database, SCADA and fileservers. Communications at the TCP/IP and the fieldbus layers also require support. Commissioning requires TCP/IP access in the tunnel. A current dilemma is the technical unsuitability of the tunnel mobile networking that has been foreseen.

HARDWARE COMMISSIONING

The new hardware commissioning working group is still refining the definition of this activity. In this section the preparation for control of the individual systems is considered as well as the new controls services required.

Quench Protection

This system is charged with monitoring and supervising the protection systems for the superconducting magnets and busbars. It is a complex system with over 2000 chassis distributed around the machine, often in radiation areas. The chassis will be connected by WorldFIP to some 35 VME Gateway front ends. These front ends will have interfaces to the logging, alarm and post mortem control services as well as transmitting supervision information to specialists and LHC operators. A prototype gateway will be installed in the String 2 in June 2003. A surface test front end is foreseen in early 2004 which will be used to validate the software in the remote chassis and communication through the WorldFIP. Studies are currently in progress to compare the suitability of using commercial SCADA or JAVA components as the architecture of the supervision layer.

Machine Interlocks

The future machine interlock control system will comprise 16 VME based Beam Interlock Controllers and 36 PLC based Power Interlock Controllers. Only the Power Interlock is required for hardware commissioning.

Hardware choices, layout and cabling studies have been done for the Power Interlocks and a preliminary version of the firmware is running to check performance. It is not yet decided which technology to use at the supervision layer; however an operational system will be needed. Less essential but desirable will be the interfaces to and availability of the LHC Alarm and Post Mortem services.

Power Converters

The final machine will require over 1700 digital controllers; a controller will be embedded in each power converter. Up to 30 controllers will be connected by WorldFIP to around 80 Gateway front ends. These will require a deterministic communication service to a central server in order to handle the real time feedback as well as asynchronous traffic. Considerable experience of fulfilling requirements has been derived from String 2, including procedures for interoperating with cryogenics, quench protection and power interlocks systems.

This large system requires attention to reliability and availability issues. To support this, consideration is being given to diagnostic acquisition. Each converter will be equipped with up to 128 analogue channels, 768 digital channels and first fault detection with 8 μs resolution.

Controls Services

Accelerator timing, post mortem and high level applications will be required for hardware commissioning. After the merging of accelerator timing responsibilities at CERN, into the single AB-CO group, a vigorous development of timing hardware has started. The initial goal is to provide a common infrastructure for multicycling the injector complex by the end of 2003 and to develop technical solutions for the beam diagnostics synchronisation requirements.

An overall architecture for LHC Post Mortem has been proposed and some initial development is underway for diagnostics of the LHC Beams and equipment during TT40 extraction tests.

A modern software environment for control room software has been developed and is being used for the control software for TT40. This will be a crucial test for the teams and techniques ahead of LHC specific projects.

AND BEYOND

30 years experience controlling and operating large accelerators at CERN has shown that requirements greatly exceed the sum of the needs to run individual systems. This will be more than ever true for the LHC. One novel feature of this machine is the strong sectorisation and sub-sectorisation dictated by powering issues. During commissioning and beyond the machine will be operated as a set of decoupled powering sub-sectors adding software complexity. This and other novel features are being studied in working groups addressing hardware commissioning and beam operation issues.

CONCLUSIONS

The preparation of hardware controls and controls services for QRL testing and hardware commissioning is progressing. Despite building on previous phases hardware commissioning is a very challenging step for controls. Some conceptual work has been done concerning global operation of machine systems but the productivity of the Hardware Commissioning and Operations Working Groups is crucial. Their work should be captured in the future LHC Design Report.

It is important that these working groups become deeply involved with implementing the controls facilities needed to satisfy the requirements.

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SUMMARY OF SESSION 3: MAIN MAGNETS AND CORRECTORS

L. Bottura, G. de Rijk

Abstract

This paper summarises the main issues presented and discussed during Session 3, on the main ring magnets. As the intention is to provide a concise sumary of the conclusions, we must make inevitably extensive reference to the single contributions for the details that are not discussed here.

STATUS OF THE CABLE PRODUCTION CLOSE TO ONE THIRD OF THE TOTAL QUANTITY

The cable production is up and running close to flat top level. The results in terms of performance and homogeneity are excellent. It is now mandatory to keep a vigilant attitude, especially for the cables for the insertion quadrupole, and stick to the specification and plan in order to minimise variations in the produced cable properties.

At present cable sets are matched by producer for each magnet. This is done to insure symmetry in the cables and reduce random multipoles. A question that remained open during the discussion is whether the cables could be mixed further. This point will be addressed based on the implications for high-order harmonics (b5, b7), verifying whether there is enough budget in the field errors for further mixing. Note finally that differences in the electrical properties and especially RRR values may lead to additional constraints for cable mixing, although presently this does not seem to.

DIPOLES FOREVER (OR FOR 2006?)

Dipole cold masses are produced and delivered at an increasing pace. At present, however, the production rate is still a factor 3 from the level that is projected for series. The scale-up needs to be demonstrated, and shall take place in the coming 6 to 12 months thanks to the increase of the number of production lines and optimization of the manufacturing process (reduction of dead times).

It is however important to realise that an increase in production rate could reduce the quality of the magnets. The challenge is hence to maintain a sufficient quality control at a factor 3 higher production rate. This will surely require an additional effort from CERN, in order to monitor and react timely.

A common issue to dipoles, quadrupoles and correctors productions is that the downstream activities (i.e. storage and installation at CERN as an example) depend closely on the schedules of the firms. An uncertain or slipping schedule may pose major problems, not only because of slippage of the completion date, but also on cost associated with a mismatch between running contracts (e.g. production contracts with firms or contracts for the installation labour). For this reason the schedule should be maintained as realistic as possible, without releasing the pressure towards the final goal. Discussion on this point led to stressing the importance of a continuous, common follow up and consolidation of the planning.

FOCUSING ON QUADRUPOLES: PRODUCTION STATUS AND PLAN

Although very successful in the prototyping phase, the present organization of the collaboration of CEA and CERN for the series production of the Short Straight Sections may eventually lead to conflicts because of the split technical and contractual responsibilities. This point requires an improvement in the working mode or, possibly, a better definition of responsibilities in front of the producer.

Although the performance of the first main quadrupoles gives confidence that the technical objectives are achievable, there is at present a lack of feed-back towards the production. Production data, documentation, warm magnetic field measurements were mentioned as items that are clearly lagging behind the fabrication of the MQ cold masses. Similarly, cold tests that are important for the overall validation can be performed only very late.

Finally, the production of SSS magnets is presently suffering from insufficient supply of critical component such as corrector magnets or cryogenic plugs. This causes logistics problems for CERN and ACCEL.

RESTORING PERFORMANCE: CORRECTORS STATUS AND PLAN

The production of the numerous and different superconducting corrector magnets for the LHC has been affected lately by significant technical problems that were related mostly to specific production process and technology limits at the producer. The most critical magnets are at present the MSCB (for the SSS), and the MCBX (for the Inner Triplet).

The impact of the technical problems mentioned above has been surely exacerbated by a lack of experienced manpower at CERN able to react and provide feed-back, leading in some cases to late delivery.

Although the high priority matters are now covered, and most of the corrector species are being produced as planned, the lack of resources was stressed by the fact that the follow-up cannot be comfortably guaranteed. Examples are the evaluation of warm magnetic measurements and cold testing at CERN.

A solution needed urgently is to make more experienced manpower available, or possibly, to access other sources for corrector production. These resources could be provided from the teams affected by the production and delivery delays of the corrector magnets.

STANDARDIZED BANANAS: THE MAIN DIPOLE GEOMETRY

A great deal of activity is being undertaken to understand, monitor and control the geometry of the cryodipoles from the production, through the cold test and eventually the installation in the ring. At present, and although much progress has been made since the initial symptoms were declared, we cannot state that we understand all the reasons for the instability of the shape. This situation is not comfortable, as it could bear the risk that dipole magnets may move more than observed so far (e.g. reshaped dipoles that did not deform back into the original shape after welding of the shrinking cylinder). It is clear that the on-going activities on this matter need further support to reach better control of the production. In fact, a question that remains open and will be hopefully resolved during the next months is the shape of the cold mass in cold conditions, subjected to cool-down and EM forces.

A practical matter that needs an urgent response is to find a remedy for existing magnets whose shape is out of tolerance. Two possibilities were mentioned: blocking the central foot in aligned position after cryostating, or corrective welding seams after cold-mass assembly (as based on the BNL experience on RHIC and US-LHC magnets). The first possibility is being tested at present, but may need qualification for the long-term operation in the LHC.

An alternative to undertaking correcting actions is to install the magnets as they are, in optimised position, and accept a trade-off between shape and emittance, to be studied further at the accelerator physics level.

TO BURN OR NOT TO BURN

One of the most worrying findings during this initial phase of the production of the cryodipoles are the several minor to major non-conformities and faults caused by insulation problems. The percentage of magnets affected so far is relatively high (15 to 20 %). Many of these problems are related to the quench heaters. Clearly, a 20% fault rate is much too high, although it is not yet clear whether the faults found could be related to early production or whether there is a more fundamental issue. This uncertainty calls for continued extensive testing and study, which is an on-going activity, and for strict quality control as well as integral cold testing.

In spite of this, warm and cold testing will not detect every problem: surprises will still be possible in the ring. This is because the effect of cool-down and Lorentz forces over long-term life in the LHC cannot be simulated on a test bench. Furthermore, warm (dry air) and cold (helium) test conditions are essentially different. Breakdown voltage in air is six times larger than in helium, and magnets cold tested (i.e. polluted with helium) may no longer be re-checked at “equivalent cold voltages” in warm conditions. It is finally important to realise that failure of a single magnet could also induce further faults, which increases the importance of electrical insulation.

DO YOU REALLY WANT TO TEST THEM ALL (COLD)?

The discussion on cold testing was mainly motivated by the fact that the present test capacity is below the production rate. In addition, when comparing projections of the test capacity vs. the production rate for the series phase, the best estimates are that by December 2006 approximately 300 magnets will be waiting for cold tests. This observation is now motivating studies on partial testing, sampling scenarios and on their consequences. It was not possible at the session to be more specific, in particular on what are the conditions for sampling, on which class of cryomagnets, and on which basis. More elements, necessary to arrive to a motivated choice, will be available in short, in any case before September 2003.

It was however clear that taking into account the performances of the present production, and especially because of the necessity to verify systematically the electrical integrity of the cryodipoles, it is mandatory to test the dipoles in operating conditions to qualify them for installation.

The present issue is then to decrease the cold test time. Today a cold test takes on average about 20 days vs. the projected 4.5 days in series mode. The reduction in the test time will require a decrease in the number of tests, a simplification of testing procedures and an increase in the overall testing efficiency. All these elements are pursued, but pose a clear challenge, to be demonstrated in the next months as more test stations come on-line.

Finally, most test plans are based solely on cryodipoles and arc SSS’s. Additional testing activities on Dispersion Suppressor and Matching Section magnets was stressed as a source of interference that could decrease the overall efficiency.

STATUS OF THE LHC CABLE PRODUCTION AT ONE THIRD OF THE TOTAL QUANTITY

L. Oberli, CERN, Geneva, Switzerland

INTRODUCTION

The construction of the LHC machine requires the production of 1200 tons of the superconducting cables needed for the main dipoles and quadrupoles. The contracts for the production of the superconducting cables have been split among six suppliers. The status of the LHC cable production is presented in this paper. The paper reviews also the most important properties of the cables.

STATUS OF THE LHC CABLE PRODUCTION

The procurement of the LHC superconducting cables has recently reached a level close to the full production rate. All the strand manufacturers have almost reached (within 10%) the plateau of production for the strands. The performances required by the LHC cable specification are obtained by all the manufacturers. The problems with strand breakages encountered during the beginning of the production by few manufacturers have been solved, but two manufacturers have still from time to time a recrudescence of the breakages.

The exact status of the production is summarized in the Table 1. The cables 02 are for dipoles and the cables 03 having the same specification as the cables 02 are for quadrupoles. All the manufacturers have produced more than 30% of the total quantity of strands foreseen to achieve their contract, with the exception of one manufacturer having received a contract 2 years later than the others manufacturers. One manufacturer has finished the strand production and nearly all the cables have been delivered to CERN. Cabling for two manufacturers is not yet optimal and slows down the cabling rate. In total 32% of the 01 cables has been delivered, about 36% of the 02/03 cables and about 7% for the insertion quadrupole cables. The production of cables for the insertion quadrupoles has been delayed by strand breakages and low critical current densities at the beginning of the fabrication. These problems have been overcome by the manufacturer and CERN. The production will increase to recover partly the delays of the insertion quadrupole cables.

STRAND AND CABLE PROPERTIES

In order to ensure the homogeneity of the production and to obtain a high degree of confidence in the quality of the LHC cable, a strong Quality Assurance System has been put in place. The main properties of the strands and cables are measured and displayed during the manufacturing to verify that the production is under control. Each strand manufacturer has to perform systematic quality control on the strands and cables while CERN is measuring the strands and cables characteristics by sampling. The strand magnetization and the cable inter-strand cross contact resistance Rc are only measured by CERN. Measured results of the most important characteristics of the cables such as cable critical current, strand and cable magnetization, cable dimensions and cable Rc are presented in the next paragraphs.

Table 1: Status of the strand and cable production

Manufacturer	Quantity in octant	Strand	Cable
01B	5	43 %	40 %
01E	3	30 %	19 %
02B-03B	3	38 %	33 %
02C-03C	2	40 %	10 %
02D-03D	1	18 %	7 %
02G-03G	1	78 %	58 %
02K-03K	1	100 %	99 %

CABLE CRITICAL CURRENT AT 4.2 K AND AT 1.9 K

The critical current of the cables is measured at BNL only at 4.2 K on cable samples cut before the heat treatment applied on the cable to control the inter-strand cross contact resistance by oxidation of the SnAg layer. This measurement is mandatory to give the final acceptance of the cable. CERN performs as well critical current measurements at 4.2 K and at 1.9 K on cable samples not measured by BNL and on extracted strands after cable heat treatment. The average critical current of the cables given in Table 2 for each manufacturer are above the specified values by about 8%. For all the manufacturers the standard deviation does not exceed 2% indicating a small variability in all the processes that influence the critical current. It is also interesting to point out that the shift in field at the same current level between 4.2 K and 1.9 K varies between 2.9 T and 3.1 T depending on the manufacturer and the cable type. Based on the average critical current reached by each manufacturer, the temperature margin of the dipoles at 1.9 K and 8.4 T operation field is around 1.6 K for the inner layer cable and 1.7 K for the outer layer cable.

Table 2: Average cable critical current at 4.2 K and temperature margin of the dipoles

Supplier	Average Ic [A]	σ(Ic) in %	Shift in field [T]	T margin at 1.9 K
Cable 01	**@ 7T**			
B	15097	2.0	3.11	1.60
E	15342	1.4	3.05	1.62
Cable 02	**@ 6T**			
B	15064	2.0	3.07	1.77
C	14818	2.1	3.02	1.69
D	14851	1.5	3.07	1.72
G	15613	1.4	3.02	1.87
K	15125	1.3	2.93	1.73

STRAND MAGNETIZATION

A specific requirement of the LHC cable specification concerns the magnetization (M) in order to reduce the effects of the persistent currents at injection. In the dipoles, the largest negative contribution to the b3 error component comes from the outer layer coil wound with cable 02. Fig. 1 shows for strand 02 the measured values of the width of the magnetization loop at 1.9 K and 0.5 T normalised to the average magnetization of each strand manufacturer. The strand magnetization is measured on a sample of every billet. The figure shows that a significant number of billets produced by two manufacturers have a high value of the magnetization. To accommodate billets with high magnetization, CERN has requested to limit the use of these billets in a cable strand map to a limited number of strand positions. By a proper mixing of strands in cable, the variations of the magnetization from cable to cable are controlled for each manufacturer within control limits of ± 4.5 % and with a standard deviation less than 2.4%.

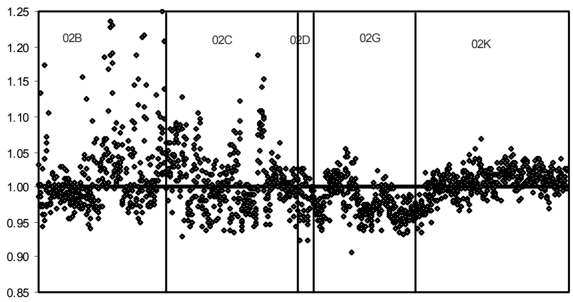

Figure 1: Width of the magnetization loop at 1.9 K and 0.5 T for strand 02 measured on one sample of each billet produced by the manufacturers.

CABLE DIMENSIONS

The cable dimensions are measured using a so called CMM (Cable Measuring Machine) on a control line equipped with an image inspection system to detect the presence of cross-overs. The cable unit lengths controlled at CERN are selected by sampling taking at least one unit length by cabling run and taking into account the information on cable quality transmitted by the manufacturer. 2500 unit lengths have already been controlled at CERN. The cable dimensions are well within the specified limits.

CABLE INTER-STRAND CROSS CONTACT RESISTANCE (RC)

The Rc values measured at CERN on finished heat treated cables are summarized in Table 3. The measurements show that the Rc values are under control even though the standard deviations are quite large. In the dipoles, the harmonic errors generated by the inter-strand eddy currents during the ramping-up of the machine are inversely proportional to Rc and are mainly originated in the inner layer coil wound with cable 01. With the projected exponential type of current ramp at injection, the induced errors are much smaller that the expected values given in the FQWG-9901 table [1].

Table 3: Cable inter-strand contact resistance

Type	Average Rc [μΩ]	σRc [%]
01B	38	61
01E	26	61
02B	122	39
02C	117	46
02G	41	43
02K	67	35

CABLE SUPPLY TO MAGNET COLD MASSES

CERN has presently supplied to the cold mass assemblers cables for 221 dipoles and 51 quadrupoles and is supplying now a quantity equivalent to 30 dipoles per month. For the first three octants, only cable 01 delivered by the same cable manufacturer will be supplied. For cable 02, the cables are supplied from different cable manufacturers as the mixing of cable 02 in an octant is acceptable. The use of the same cable 01 manufacturer per octant gives the smallest random field errors for the normal error components b5 and b7. Even for a complete mixing assuming dipoles randomly distributed in the machine, the random field errors for the normal error components b3, b5 and b7 are less than 30% of the error budget [2]. In a dipole, the cables for each layer will be selected from the same manufacturer and if possible produced during the same cabling run in order to avoid skew error components.

STOCK OF CABLES AT CERN

The actual stock of cables at CERN has reached a level equivalent to five months contingency for the dipoles and the quadrupoles with the supply of cables foreseen for the full series production rates of the cold masses. The number of cables in stock corresponds to the quantity needed to cover the risks of delay during cable production. The stock of cables shall not only cover the risks of production delay with the strand manufacturers but also the risk of a major accident which could stop for a while the production of a manufacturer.

CONCLUSION

The LHC cable production has nearly reached the full production rate. The performances required by the LHC cable specification are obtained by all the manufacturers. Actual cable Rc and cable magnetization are well under control and cause errors smaller than the expected values. All the measurements performed at CERN are essential to follow the production and to ensure its homogeneity.

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DIPOLES FOR EVER OR FOR 2006?

P. Fessia, on behalf of the MAS-MD section, CERN, Geneva, Switzerland

INTRODUCTION

The aim of the talk is to provide realistic view of the present LHC dipoles production ongoing in the 3 CMAs and the actual problems highlighting, where feasible, the solutions that have been or that will be put in place.

DATA CONCERNING THE PRESENT PRODUCTION RATE: COLLARED COIL PRODUCTION

1) Coils: the 3 CMAs have increased production of coils significantly starting from the month of October 2002. In May 2003 the rate of production is about 16 inner and 16 outer layers per month equivalent to one collared coil per week. To cope with the foreseen delivery schedule it is necessary to multiply the present production by a factor 3 or 4 depending on the CMAs.
2) Collaring: the production rate of collared coil follows the coils production with a shift of at least 30 days.
3) Total production time for collared coil: the time necessary to produce one collared coil from the moment when the 1st coil is being wound to the moment when the collared coil is completed has significantly been reduced in the 3 CMAs. At BNN and Ansaldo the time needed to produce 4 layers has been reduced by generally a factor 3 (exception for Ansaldo inner layers that were produced in short time already at the beginning) respect to the time needed to produce the same layers at the beginning of the pre-series production
4) Tooling: winding and curing tooling are almost fully operational apart from Ansaldo, where new winding machines have still to be commissioned. The bottlenecks could be: at BNN in the curing rate, having only 2 curing presses serving 4 winding machines, and at Jeumont in winding, having only 2 winding machines for a foreseen production of 2.5-3 collared coils/week.
5) Further gain on production time: reduction of production time will have to be obtained acting on 4 "knobs":
   A. reduction of controls granted by CERN changing from pre-series to series mode;
   B. improvement of production organization by the CMAs;
   C. hiring and training of new staff by the 3 CMAs;
   D. optimization of the use of tooling (increase of efficiency of the usage of tooling);
6) Possible problem to be kept under control: the coils show jumps in dimensions that could oblige to use not nominal shims affecting field quality. Further studies are necessary to identify the origin of variations and to master them (if possible).

DATA CONCERNING THE PRESENT PRODUCTION RATE: COLD MASS PRODUCTION

1) Cold mass production time by phases: dividing the production of cold masses in production phases it is possible to observe that:
   A. The time from starting of the cold mass assembly till the end of welding has decreased quite significantly after few extra CERN training and few cold masses assembled.
   B. The time between end of welding and X-ray is not negligible. No productive operations are performed in this time frame. It is the result of the internal work organization of the CMAs. Reduction of time means better process flow organization
   C. The time from X-ray till warm magnetic measurement: this lapse of time includes welding repair, alignment, cold mass finishing. The improvement in welding and the enlargement of assembly tolerances should allow decreasing significantly the time taken by this production phase, which for the moment is too long.
2) Actions to improve the results of the longitudinal welding: 3 problems were isolated and addressed. These are operational problems of the welding press, problem related to poor welding quality, commitment of the CMAs. The actions taken were the following:
   A. CERN organized and provided extensive training on the following subjects: welding posts technology and use (Lincoln), welding press operation (CTE Sistemi and ORSI), laser tracker operation in standard and emergency mode (ServoRobot).
   B. System upgrade: upgrade of ServoRobot software, installation of new software to control the welding parameters effectively transmitted to the torch (Lincoln).
   C. Optimization and training by welding experts: Lincoln, CERN, Institut de Soudure.
   D. Re-evaluation of the requirements on the weld seam quality: change of welding class for defects: from class B to Class E: Extensive study of the weld seam according to Linear Fracture Mechanics.
3) Actions to reduce cold mass finishing time: enlargement of assembly tolerances (see Marta Bajko's talk), optimization of the welding

press geometry (effect on the curvature quality to be evaluated after a significant sample), installation of the new warm magnetic systems, improvement of the pressure leak tests where necessary.

QUALITY CONTROL RELATED PROBLEMS

The introduction of new tooling in the production lines, the increase of the staff in the 3 CMAs and the increase of production rates have created problems to keep the quality levels high. The problem related to quality control can be described as belonging to 3 different categories:

A. Appearing discrepancies between practice and agreed and foreseen procedures
B. Occasional accidents (shocked coil during transport, …)
C. Serious repetitive accidents where the divergence of one or more parameters bring to the production many non conforming objects without any reaction by the CMAs quality control.

CERN has reacted:

A. Obliging companies to produce written procedures to be installed in the workshops
B. Pushing companies to have more accurate production inspection
C. Improving CERN-ISQ resident inspector training (check lists …)
D. Continuous monitoring of production via direct intervention of the field and quality documentation control

In addition CERN has 3 levels of check on the production:

A. Via the holding points (shim approval, Collared Coil warm magnetic measurements approval, Cold Mass warm magnetic measurements approval)
B. Technical control on E-modulus measurements and electrical checks
C. Verification of the quality documentation (MTF+CMA's traveler), CERN reception acceptance test

FIELD QUALITY CONTROL

MA section of MD group carefully studies the results of the warm magnetic measurements in order to detect problems and unexpected non conformities. Up to now measurements of 105 collared coils and of 64 cold masses have been processed. Only 29 have been tested at cold. The shortest time between warm magnetic measurements of a collared coil and cold test has been, up to now, 7 months. 2 collared coils have been dismantled for assembly errors, a third is under study. 2 cold masses have been dismantled for NCR in the main field variation angle.

PROBLEM RELATED TO COMPONENTS

3 possible problems related to components have been isolated:

1) Poor shell geometry: this affects cold mass assembly time (longer) and it makes more difficult the welding operation. In addition mismatches between upper and lower shells, poor chamfer quality, not correct welding gap dimensions have affected cold mass assembly. In order to try to cope with these problems, actions have been taken in order to push the supplier to change more often the milling tools for the chamfer while for the overall geometry problems the elimination of the corrections applied locally should allow getting smoother shells. Despite of the large average errors these more regular shells could be tracked more accurately by the tools that guide the welding torch. Tests will be performed very soon. The first results are encouraging.
2) Packing of laminations: some problem have been encountered in one CMA to obtain prescribed packing factor. The possible relationship with tooling or supplied lamination is under verification.
3) Collars: one CMA has experienced problem in collaring with collars of one collar supplier. The problem is under investigation.

Generally speaking no problems related to components shortage have to be signalled. Components provided in smallest quantity, up to now, are corrector magnets.

SHORT TERM PLANNING

The 3 CMAs have planned to increase significantly production in the following 6 months.

1) Company number 1: 1 cold mass per week from May to August, 2 cold mass per week from August to December. Feasible planning if the company will concentrate pro-actively to solve residual welding problems.
2) Company number 2: one cold mass per week from now till the end of the year. The company is gaining efficiency but the planning for May and June looks slightly optimistic.
3) Company number 3: one cold mass per week up to the month of August, 3 cold masses per week from September to December. The abrupt increase in production at September looks optimistic. An increase up to 2-2.5 cold masses per week for the end of the year looks more realistic.

The increase of production that will be detected and possible in the next 2-3 months will allow us to evaluate better the long term aspect of the production planning.

ACKNOWLEDGMENTS

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FOCUSING ON QUADRUPOLES: PRODUCTION STATUS AND PLAN OF MQ COLD MASS FABRICATION

K.M. Schirm, CERN, Geneva, Switzerland

Abstract

The MQ main quadrupole magnet production and its integration into cold mass assemblies for the LHC arcs are discussed. Three years after placing a contract with one company following a competitive tendering, the technology and tooling transfer from CEA Saclay to industry is close to conclusion. The experience with the transfer, the status of production and the logistics chain, some performance aspects and first results of measurements are described.

INTRODUCTION

The MQ short straight sections (SSS) of the LHC machine consist of one main quadrupole magnet MQ each together with 2-3 corrector magnets of different types. All magnets are designed to operate at 1.9 K. They are integrated, with superconducting bus bars and instrumentation, into a closed stiffening structure, the He vessel, to form a cold mass, that will finally be inserted into a cryostat at CERN. 400 MQ magnets (incl. 8 spares) are needed for 360 arc-SSS and 32 DS-SSS for the dispersion suppressor regions. The combinations of different magnets for the cold mass assemblies are outlined in tables 1 and 2.

Table 1: Magnet combinations for the arcs

#	Quantity	Corrector MO, MQT or MQS	Main Quadrupole	Corrector MSCB type
1	46	MO	MQ, D-F	MSCBB
2	24	MQS	MQ, D-F	MSCBB
3	80	MQT	MQ, D-F	MSCBB
4	32	MO	MQ, D-F	MSCBD
5	58	MO	MQ, F-D	MSCBA
6	8	MQS	MQ, F-D	MSCBA
7	80	MQT	MQ, F-D	MSCBA
8	32	MO	MQ, F-D	MSCBC
Total	360			
	168	MO	146	MSCBA
	160	MQT	150	MSCBB
	32	MQS	32	MSCBC
	360		32	MSCBD
			360	
		182	MQ, D-F	
		178	MQ, F-D	
		360		

Table 2: Magnets for the dispersion suppressor regions

Magnet type				Quantity	I.T. Length
MQ	MQTL	MSCB		16	6.63 m
MQ	MQTL	MCBC		12	6.63 m
MQ	MQTL	MQTL	MCBC	4	8.03 m
				32	

Based on a competitive tender, a contract for the production of the MQ main magnets and the assembly of the arc-SSS has been placed with ACCEL Instr. GmbH, as single source, in July 2000. A contract for the assembly of the 32 DS cold masses will be placed at a later stage. Having done the development and the prototyping of the SSS cold mass in collaboration with CERN, CEA Saclay [1] has kept the technical responsibility for the technology transfer to industry and the series production, the commercial part being under CERN responsibility governed by CERN purchasing rules.

Three years have passed after placement of the contract but the full production rate is not yet reached at the supplier. Due to the delays in the programme and major CERN supplies, the technology transfer is still proceeding and the contractual schedule and the logistics had to be adapted in amendments to the contract. CERN agreed to accept bare MQ magnets together with delivered components from ACCEL's subcontractors for the cold mass assembly as so called "spare cold mass", ahead of the final product. Every tenth bare MQ magnet shall successfully undergo cold testing in a vertical cryostat at CERN before a transfer of property for batches of "spare cold masses" is processed and the guarantee period for these units is started. The completion of the cold mass is then, formally, only a minor additional assembly work. These modifications implicitly have a strong impact on the logistic and follow-up where additional storage capacity, transports incl. packaging, additional protection devices, that where meant to be recycled after cryostating, etc. are needed. The non-availability of specific supplies is at the moment limiting as well the types of cold mass that can be assembled, thereby jeopardizing a planning based on the official LHC installation schedule. The supply of cold mass components is described in Table 3.

Table 3: CERN supplies for MQ magnet and cold mass

Components common to dipoles	Components specific to quadrupoles
Superconducting cable	Collar steel (MAS, F382/LHC/LHC)
Insulation cable - ground	Quench heaters (MAS, F401/LHC/LHC)
Yoke steel	Diode packs (MEL Group)
Main Bus-bars	BPM supports (VAC Group)
Interconnection Bellows	Corrector magnets (MEL Group)
Instrumentation	All aux. bus bars incl. spools (MEL Group)
Cold bore tubes	Cryogenic pressure plugs (CEA Saclay)
Heat exchanger tubes	Transport and protection structures (MAS)

MQ MAGNET FABRICATION

The MQ main quadrupole is a twin aperture superconducting magnet designed for a nominal gradient of 223 T/m at 11870 A. It has been developed in a close collaboration between CERN and CEA Saclay (F) [2]. The first two series produced MQ magnets have been delivered to CERN in July 2002 as bare magnets for studying the quench performance and field quality in a vertical test cryostat. Both magnets have performed better than the prototypes [2,3], reaching ultimate current 12860 A without any training quench inside the coils. Details on the results including field quality at cold (1.9 K) can be found elsewhere [4].

ACCEL has initially worked using the tooling provided by Saclay for the production of the coils. In parallel they have qualified additional production lines with ACCEL tooling that should provide for reaching the contractual production rates of bare magnets MQ. Nevertheless, excessive coil thickness variations, recently observed, needing coil recuring, and repeated equipment breakdown of the e-modulus and of the warm field measurement systems have up to now prevented ACCEL from reaching a stable production rate of MQ magnets. The coil dimension and e-modulus variations are actually under investigation at ACCEL. One team exclusively on one production line is producing coils right now for reducing the number of parameters in the production. The production status as by June 30th, 2003 is summarized in Table 4.

Table 4: Production status at ACCEL on 30/06/2003

From Components to finished Cold Mass	Numbers
Coils, used - accepted (total) - produced	104 - 261 - 296
Apertures on stock	4
Bare magnets on stock	6
Bare magnets delivered to CERN	5
Dummy cold mass delivered	1
Cold mass in fabrication & tests	2 + 3 + 1 + 2
Finished cold mass delivered to CERN	3

MQ ARC COLD MASS ASSEMBLY

When the production of MQ magnets had accumulated delays in the setting up of tooling and debugging, it has been decided to firstly built a so-called “dummy cold mass”, meaning a helium vessel including end flanges and tubing, but without any magnets or bus bars inside. Such an assembly aimed at qualification of toolings, weldings and procedures and to set-up the assembly line. In addition the dummy was urgently required for launching the production at the company chosen for the cryostating of the MQ cold masses according to the contractual planning. Unfortunately, just three days after reception of the dummy at the cryostating site, the insolvency of the Babcock Borsig Holding led to a production stop and finally to the insourcing of the activity including dummy cold mass to CERN, where no test assembly was required due to the existing experience [5].

The first completed cold mass of type LQMOE was delivered to CERN in February 2003, followed by CM002 in March and CM004 in May 2003. Eight more cold mass assemblies are in a more or less well advanced stage close to delivery. Deliveries from ACCEL subcontractors are ahead of the actual production and they are causing storage shortage at ACCEL. At CERN, reception tests of the geometry at room temperature and electrical tests have confirmed the data obtained from ACCEL, and the cryostating of CM001 was started with the well known delays caused by the insourcing of the contract [5]. The first cold mass testing at 1.9 K is now scheduled for end of July 2003. By that time ACCEL will have produced, at least, another 11 cold masses and eventual non-conformities could concern a total of 12 assemblies without having the possibility to correct whatsoever inside the structure.

CONCLUSION

The production of MQ quadrupole magnets and their integration into completed cold mass assemblies is well underway at ACCEL Instr. GmbH. The technology transfer by CEA Saclay has been successful, in general, as concerns the bare magnet fabrication, whereas delays in cryostating and cold tests of the first cold mass assemblies prevent from concluding the second part of the transfer. A continuous production rate is not yet reached at the main contractor due to frequent shortage in main CERN supplies as well as being caused by repeated break-down of essential tooling, initially designed for R&D work, in the coil production. The production planning, the logistics as well as the contractual delivery figures had to be adapted to make up for cash flow shortage of the supplier caused by the delays. The production will now probably extend into year 2006 and the delays might have an impact on the actual LHC installation schedule. The quench behaviour of the bare MQ magnets, tested so far, is excellent, and the field quality at 1.9 K in the straight parts correlates well with the warm field measurements at the supplier. It is now urgent to perform the first warm/cold measurements of the completed cold mass, in particular regarding magnetic axis, insulation properties and the performance of the many connections.

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CORRECTORS: PRODUCTION STATUS AND PLAN

M. Allitt, CERN, Geneva, Switzerland

Abstract

There will be over 4,600 superconducting corrector magnets of approximately 20 different types used in the Large Hadron Collider (LHC). This presentation gives an overview of the different corrector types and their design principles, describes the organisation of the contracts placed with European and Indian industry for the fabrication and testing of correctors, and summarizes the current status of the production of the different types of corrector.

THE CORRECTOR SECTION (AT-MEL-MC)

The Correctors Section is small, with 4 CERN staff members, 2 external quality inspectors and 5 industrial support staff. The section leader is Rob Wolf, recently taken over from Albert Ijspeert who retires in two weeks, with corrector production activities in industry and at CERN being followed by project engineers Mike Allitt and Mikko Karppinen, supported by technician Jacky Mazet. The industrial support staff are engaged in production of a small series of MCSTX correctors, performing reception tests on incoming magnets delivered to CERN, and electronic traveller processing and database development. The two quality inspectors share their time between 4 European corrector companies, monitoring quality assurance and process control.

CORRECTOR TYPES

These corrector magnets will be used for correcting field errors in the main dipole and main quadrupole magnets, for making fine adjustments to the particle beams and for controlling beam instabilities. The correctors range from dipole to dodecapole, with the smallest corrector having a length of approximately 15 cm and weighing about 4 kg while the largest is about 1.5 m long and weighs close to 2 tonnes. They operate at nominal currents ranging from 50 A to 550 A, main fields vary between 0.03 T and 3.3 T. The correctors are superconducting, using NbTi conductor, and although a few will operate in normal liquid helium at 4.3 K most will operate in superfluid helium at 1.9 K. With the exception of the MCSTX sextupole/dodecapole which is made at CERN, all the correctors are manufactured by European or Indian companies, with whom a total of 10 contracts have been placed worth ~50 MCHF. The different corrector types are summarized in Table 1.

CORRECTOR DESIGN

All the correctors have been designed at CERN to meet the LHC baseline requirements. The focus was on developing low-cost designs suitable for production in industry in series quantities [1, 2]. To this end, unnecessarily tight manufacturing tolerances have been avoided (±0.1 mm tolerances are typical) which is the principle factor determining the field quality of the correctors. The correctors feature epoxy impregnated coils, with return yokes as close to the coils as feasible in order to maximise the field strength. Pre-stress is applied by shrink fitting aluminium cylinders machined to have an interference fit to the yoke outer diameter. The amount of interference is chosen to give the correct pre-stress when the magnet is energised at operating temperature. The magnets have been designed to have a considerable safety margin, with a nominal operating current typically 60% of the critical current at operating temperature (40% for spool pieces). The spool pieces, MCBX and MQSXA are single aperture magnets, the other correctors are twin-aperture magnets constructed by assembling two single-aperture magnet modules together in a twin-aperture support structure. Construction techniques have been tested by the construction of prototype correctors in-house and other prototypes have also been built in industry, to test the designs and to transfer technology to companies who would later be bidding for series contracts.

CONTRACT ORGANISATION

For each magnet type CERN supplies drawings sufficient to define the magnetic and mechanical design of the magnets (including end-spacer machining files for dipole correctors) and specifies the materials and construction methods. CERN supplies the superconducting wire and in some cases also yoke laminations and steel for magnet support structures. CERN also supplies equipment to each company for measurement of magnetic field at room temperature and for data acquisition during cryogenic magnet training tests.

The manufacturers are responsible for the creation of all fabrication drawings, design and procurement of tooling, procurement of all components not supplied by CERN, fabrication and testing of the magnets, and quality assurance (including supplying test results to CERN in the form of electronic travellers).

Testing

For each magnet the manufacturers are required to make various mechanical measurements at different stages of construction in order to verify the dimensions of components and assemblies and to check that the magnet has the correct pre-stress at room temperature. In addition they must train the magnets at 4.3 K, measure the magnetic field at room temperature and also make various electrical checks both at 4.3 K and room temperature to verify the integrity of internal connections and to look for

Table 1 **:** Corrector types

	Magnet Type	Magnet Description	Number of variations	Number ordered	Manufacturer
Main Dipoles	MCS	Sextupole spool piece	1	1232 + 1232	Antec (Bilbao, Spain) KECL (Bangalore, India)
	MCDO	Combined decapole/octupole spool piece	1	616 + 616	Tesla Engineering (Lancing, UK) Crompton Greaves (Bhopal, India) MCO inserts CAT (Indore, India)
Short Straight Sections	MO	Landau damping octupole	1	368	Antec (Bilbao, Spain)
	MQT	Tuning quadrupole	1	160	Ansaldo (Genoa, Italy)
	MQS	Skew quadrupole	1	40	Ansaldo (Genoa, Italy)
	MSCB	Combined chromaticity sextupole/orbit dipole	4	376	Tesla Engineering (Lancing, UK)
Insertion Regions / Dispersion Suppressor	MQTL	Long trim quadrupole	2	56	Ansaldo (Genoa, Italy)
	MCBC	Short dipole	4	78	Tesla Engineering (Lancing, UK)
	MCBY	Wide aperture dipole	2	44	Tesla Engineering (Lancing, UK)
Inner triplets	MCBX	Combined horizontal/vertical dipoles	2	27	Sigmaphi (Vannes, France)
	MQSXA	Combined skew quadrupole/nested skew sextupole,skew octupole	1	9	Ansaldo (Genoa, Italy)
	MCSTX	Sextupole/dodecapole insert for MCBX	1	9	CERN

short circuits, both internal and to ground. The magnetic field measurements serve to verify the strength of the main harmonic and the position of the magnetic axis of the corrector. Should the field harmonics contain unexpectedly high components this indicates that the manufacturing tolerances have not been respected and inverse-field calculations can be made to find the source of the error.

For each contract a number of magnets at the beginning of the production are defined as pre-series magnets. These magnets are re-trained at 4.3 K by the manufacturer after initial training and thermal cycling to room temperature. At CERN, the pre-series magnets undergo visual inspection, re-training tests at 4.3 K and 1.9 K and magnetic field measurements at room temperature (to verify correct operation of the measurement equipment used by the manufacturer) and 1.9 K (to measure hysteresis and saturation). For each contract, it is also planned to select a certain percentage of magnets at random to undergo the same tests at CERN as the pre-series. However, this is proving difficult due to the high load already placed on the resources of Bloc 4.

STATUS OF CORRECTOR CONTRACTS

Main dipole correctors (spool pieces)

Both the MCS and the MCDO production have been split, with contracts for equal numbers of magnets placed in Europe and India in each case. The contracts placed in India are followed by the Centre for Advanced Technology in Indore, who are responsible for quality assurance and testing of the magnets. These contracts are all in the series production phase with magnet deliveries on average at the required rate (although deliveries from India are erratic) with the exception of the European MCDO, which has been delayed largely due to the concentration of effort by both the manufacturer and CERN into other contracts placed with the same manufacturer. Small problems are frequently found in the magnets delivered to CERN for all these contracts, minor in the sense that they are repairable but they do need to be repaired before they can be used in the LHC. Consequently every magnet produced needs to be inspected by qualified CERN personnel before it is delivered to a cold mass assembler.

Short Straight Section (SSS) correctors

These correctors are single-sourced, with a single European manufacturer for each type. The MO is in full production with regular deliveries of 8 magnets/month, this rate is expected to reach the required 10 magnets/month by the end of 2003. MQT and MQS are combined into a single contract, pre-series testing should be complete by the end of July 2003. Two pre-series units have already been tested successfully at CERN, as a result of which approval has been given for series production to begin without waiting for the test results of the remaining two pre-series units. This contract has been delayed by problems with the manufacturers' cold testing equipment (now apparently solved) and cold testing will be the bottleneck to be overcome in order to reach the required 10 magnet/month production rate: the planned rate of two tests/month will be sufficient only to supply 8 magnets/month, a way will therefore need to be found to increase the testing rate. Delays in the MSCB contract have meant that magnets have been delivered directly to the cold mass assembler without undergoing testing at CERN (only one magnet has been tested at CERN).

Various process problems need to be overcome before the supply becomes stable. Currently MSCB production is stopped while the source of a problem with dipole re-training is traced.

Insertion region/Dispersion suppressor/Inner triplet correctors

The first MQTL magnets are expected to arrive at CERN at the end of 2003. They are part of the same contract as MQT/MQS and the same manufacturer also has the contract for MQSXA, which means there is a competition for resources between these magnet types. The manufacturer has so far concentrated on MQT since it is easier to make than the MQTL, which is 4 times longer. In order to cut the tooling development time for MQTL, CERN is in the process of fabricating winding and impregnation tooling for MQTL coils which will be loaned to the manufacturer for this contract.

The MCBC/MCBY contract has been placed with the same company who make MSCB, and has been delayed since most attention has been placed on MSCB. The pre-series magnets are expected at CERN July 2003.

The first MCBX magnet was destroyed in testing at CERN, leading to a design change. The first magnets of the new design are now being tested at CERN, the results look promising. All MCBX magnets will be tested at CERN.

The first MQSXA has been delivered to CERN, there is now a delay due to a request by the beam physicists' to change the design to separate the quadrupole and nested multipole parts of the magnet. Production of this small series should be complete by the end of the year.

Production of MCSTX insert coils is well underway at CERN, none have yet been tested since a working MCBX is needed to test them.

CONCLUSIONS

A number of contracts are still in the start-up phase, meaning that the manufacturers' require a great deal of technical support from CERN. At the same time, those contracts that are in production require close attention in order to ensure that the required quality levels are maintained. The Quality Inspectors are useful in this work but do not have sufficient experience to detect every problem or solve technical difficulties. Also, as more and more magnets begin to be produced, the administrative workload (travellers, data analysis, EVM …) is increasing rapidly. We see also that the warm magnetic measurement benches used by the manufacturers need close follow-up in order to ensure that there are no problems with the benches and that the manufacturers' are using them correctly. The rate of testing of corrector magnets is slow, as is the rate of inspecting magnets delivered to CERN. This means that the length of time required to provide feedback to manufacturers about any problems found is too long, so that many magnets need to undergo corrective action once a problem is detected. The level of experienced manpower available to tackle these issues is currently insufficient.

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STANDARDIZED BANANAS: THE MAIN DIPOLE GEOMETRY

M. Bajko, CERN, Geneva, Switzerland

Abstract

Through this paper the author will report on the status of the geometry of the dipole cold masses of the pre-series production. An answer will be given to the questions: what differences are between the nominal geometry and the geometry of the as-built dipoles? What checks are done in industry and at CERN? Is the geometry stable? What are the causes and remedies? The effects of the deformations on feed-down and mechanical aperture will be shortly summarized.

THE GEOMETRY OF THE AS-BUILT DIPOLES

The production of the dipole cold masses has started in all 3 magnet manufacturers for approximately 1.5 years. In one of the companies the series production has already started. The first statistics and conclusions regarding industrial feasibility are made. The companies respect the requirements on the dipole CM geometry arising from optical needs of the LHC machine and of the mechanical boundary conditions of the interconnection zone. However in many cases this is not obtained by the standard procedures or in the foreseen allocated time for the operations linked to the final assembly.

Shaping the dipole cold mass

The dipole cold mass curvature in the transversal plane is obtained by placing the magnet on a curved press table and, under press load, welding the two half-cylinders to form a skin around the active part. When the load is released after welding, the magnet loses a non-negligible fraction of the curvature due to elastic spring back. To compensate the spring back, the press table is shaped to a slightly higher curvature (smaller radius) than that of the CM nominal shape.

The half-cylinders are made by stainless steal of grade 316LN and they are pre-bent with an initial sagitta of 9 mm in some cases following the baseline specification of these components and up to 20 mm in some other cases. There is a concave and a convex half cylinder for each dipole cold mass.

In some cases, after application of the above-described procedure, the elastic spring back of the dipole cold mass is such that the shape of the dipole is not within the required tolerance. In these cases, in order to correct the shape, a special procedure was introduced. Each cold mass, to be corrected, was placed on a so-called "re-shaping bench" and after the longitudinal welding of the half cylinders, the cold masses were deformed plastically in several steps until reached the nominal shape within the specified tolerance of ± 1mm.

Measurement-assisted assembly steps

During the assembly of the cryo-dipole at several stages is necessary to perform geometrical measurements.

The first measurements are done, when the cold mass is under the welding press before performing the longitudinal welding of the half cylinders. This measurement is foreseen only for a reduced number of cold masses and is used to confirm the correct shape of the pre-aligned cradles of the welding press. Once the active part is welded the final assembly steps are started. Those steps are all assisted by the measurements. From these measurements are recorded: the shape of the cold mass, the twist of the two cold bore tubes, the position of the corrector magnets, the cold feet pads, the end covers, and the end flanges. For a reduced number of cold masses, for analysis, measurements are performed also after the pressure and leak test. The analysis intends to verify the stability of the cold mass.

After delivery at CERN, on 10% of the cold masses a complete reception test is performed. Measurements are then performed during cryostating and after cold test to determine the correct position of the fiducials and to position them on the top of the cryostat.

Shape of the as-built dipoles

The shape of the as-built dipole is within the required tolerances before the delivery to CERN. However not all magnets were produced with the standard shaping procedure.

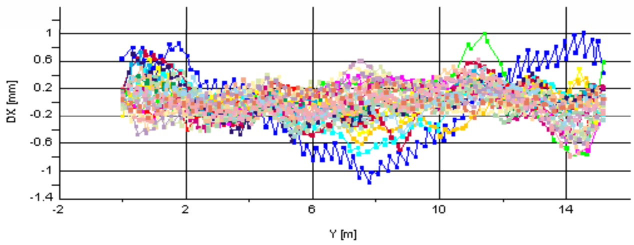

Figure 1: The shape of the as-built cold masses in the horizontal plane. Firm No. 1.

The shape in the vertical and horizontal plane of the magnets produced in firm No. 1 is shown as an example in Fig. 1.

The good results of the final assembly operation are confirmed by the position of the cold bore tube ends and the end covers (See Figs 2 and 3). However the statistical analysis on the first magnets has shown the difficulties to achieve the required tolerances in an industrial process. Therefore a review of those tolerances was made and new-relaxed values were defined and their compatibility checked with the requirements of the interconnections and the mechanical aperture.

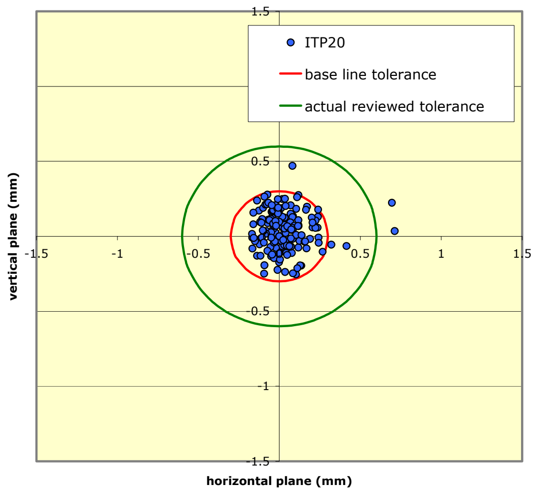

Figure 2: Position of the cold bore tube flanges of the as-built cold masses.

The relaxed tolerances assure a gain of time in the assembly, which after an initial learning period became comparable to the time foreseen for those operations.

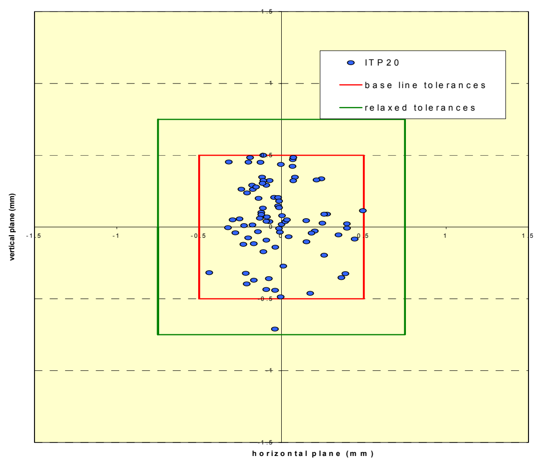

Figure 3: Position of the end covers on the as-built cold masses.

SHAPE OF THE CRYO-DIPOLES AFTER COLD TEST

Is the geometry stable?

After the cold test of the cryo-dipoles a change of the horizontal plane of some the cold masses was observed and related later on with the non standard assembly procedures of the cold masses.

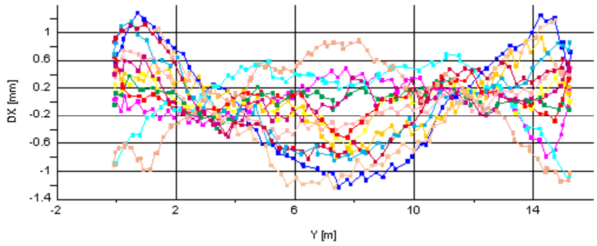

Figure 4: The shape of the cryo-dipole in the horizontal plane after cold test.

Causes and Remedies

The cold masses which after the longitudinal welding needed corrective action to achieve the nominal shape, tend to re-gain their initial form after cold test. The relative movement of those cold masses, in their horizontal plane, in some cases was up to 1.5 mm, while in cases of cold masses assembled with standard procedure was 0.3 mm maximum. The non-standard assembly procedures were stopped at the industry. However even after improvement made on the geometry of the cradles of the welding press in some cases the shape of the cold masses is out of the tolerance within some tens of mm.

The geometrical behaviour of the cold mass is non-linear because of the friction between the components of the cold mass. Therefore the disassembly of a cold mass, which after longitudinal welding is out of tolerance, is not only a very expensive corrective action, but is not a guarantee for a good result after a new assembly. As the cold mass is supported on 3 positions, the structure is hyper-static and therefore the position of the central foot could be the reason of a shape variation as it could be the remedies also. In this case, the working conditions of the central foot would be changed. A third solution would be to check if magnets with radial errors higher than 1 mm with respect to the nominal, theoretical geometry could be accepted.

The corrector magnets are fixed to the end plate of the dipole cold masses, before the end cover closes the cold mass. The change of the shape is directly influencing the position of the corrector magnets. On 16 magnets the position of the correctors after cold test was estimated: all of them were within a radial error of 1.5 mm with a more important spread in the horizontal plane than vertical plane. [1]

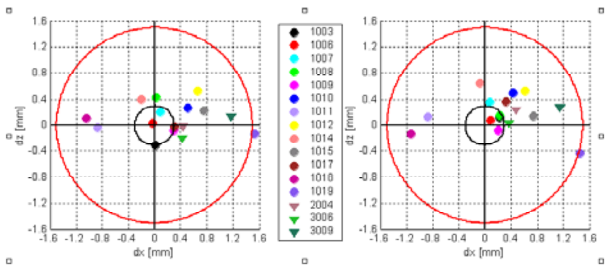

Figure 5: Position of the correctors after cold test.

[1] Estimation made by the AT/MAS-MA.

TO BURN OR NOT TO BURN

K. H. Meβ, CERN, Geneva, Switzerland

Abstract

For the first dipoles the electrical integrity turned out to present a problem. The electrical tests at the various stages are discussed as well as the general limitations of tests.

INTRODUCTION

Despite the strict procedures for manufacturing the dipoles a number of electrical problems have shown up. In one case such a fault went undetected until the magnet was burned during the quench test. This event inspired the title, as it was given to me. I take the liberty to paraphrase the title, in order to set the scene:

To burn, or not to burn: that is the question:
Whether 'tis better in the ring to suffer
The slings and arrows of outrageous fortune,
Or to take arms against a sea of troubles,
And by opposing end them? To think: to test;
No more; and by a try to say we end
The head-ache and the thousand natural shocks
That magnets feel too, 'tis a consummation
Devoutly to be wish'd….

In fact, the paraphrased monologue of Hamlet summarizes already the situation quite well. At this stage of the production some magnets suffer severe electrical problems. Space limitations forbid to paraphrase the original talk, given in Les Diablerets, in a useful way. I will instead list the electrical tests the dipoles undergo, before and while they are tested at low temperature at full current and force. Next, I will discuss why some faults are obviously not detected and I will try to draw a conclusion from that. This article mentions only dipoles. In reality the problems may occur in all other superconducting magnets as well.

ELECTRICAL TESTS

The electrical test during manufacturing are described in LHC-MMS/98-198 Rev 1.1 (IT-2708) and the voltage withstand levels are defined in LHC-PM-ES-0001-0010 (EDMS 90327) which was explained in details in the EEWG meeting of March 25, 1998. The tests to be done during reception have been streamlined since by an ad hoc working subgroup, headed by A. Siemko. The results were presented to MARIC in 2003 [1]. As it is not published elsewhere yet, I take the liberty to list the screening tests done at CERN. The idea is that tests are repeated only if in the meantime degradation could have occurred.

- Basic electrical reception tests of dipole cold mass,
- Basic electrical checks during cryostating,
- Full electrical integrity tests at room temperature on test benches before and during cool-down,
- Electrical integrity and performance in liquid helium before powering the magnet, under power and after powering,
- Electrical integrity tests at room temperature on test benches during and after warm-up,
- Final electrical integrity tests before lowering down,
- Electrical integrity tests during installation after soldering, after welding and tests of whole circuits,
- Commissioning of electrical circuits in liquid helium.

The tests at room temperature repeat basically the tests at the manufacturers' premises. The tests at cold are summarized below. Here, g/ng indicates an essential (go/ no go) test.

Table 1: Tests at low temperature before power test

Item	Aim	Criteria	?
T sensor	Resistance	$R=R_{nom}$	
	Insulation (ground)	R>10MΩ, 20V	
Heater, cryo	Resistance	R=100Ω	
	Insulation (ground)	R>10MΩ, U=700V	
Heater, quench	Resistance	$R=R_{nom}$, I=0.1A	g/ng
	Integrity	Nom. discharge	g/ng
	Insulation (coil)	U=2.7kV, I<20μA, 120s	g/ng
	Insulation (ground)	U=3.1kV, as above	g/ng
V taps, Dipole	Continuity	1A<I<10A	g/ng
	Insulation (ground)	U=3.1kV, as above	g/ng
Bus bars	Insulation (ground)	U=3.1KV, as above	g/ng
Coils	Interturn	Z(ϖ)	g/ng
V taps, Spool	Continuity	0.1<I<1A	
	Insulation (ground)	U=1.3kV, 30 s (MCS,MCD) U=1.5kV (MCDO)	g/ng

RESULTS

On May 21st 2003 P. Pugnat summarized the results of these tests for the first 33 dipoles during a meeting, dedicated to this issue [2]. The results are given in an abbreviated form in Table 3.

Table 2: Electrical tests under power

Item	**Aim**	**Criteria**	**?**
Heaters, Quench	Test protection	Quench delay	g/ng *)
	Efficiency	Coil Temperature	g/ng *)
	Integrity	Continuity	g/ng
	Insulation (coil)	U=2.7kV, as above	g/ng
	Insulation (ground)	U=3.1kV, as above	g/ng
Dipole taps	Quench detection	1A<I<10A	g/ng
	Insulation (ground)	U=3.1kV, as above	g/ng
Coils	Insulation (ground)	U=3.1kV, as above	g/ng
	Interturn	Z(ϖ)	g/ng
Splices	Resistance	R<1.2nΩ intern R<0.6nΩ extern R<7nΩ total	g/ng *)
Spool taps	Integrity	0.1A<I<1A	
	Insulation (ground)	U=1.3kV/1.5kV As above	g/ng

**) under certain circumstances.*

Table 3: Insulation faults

Magnet	**Description**	**Test Phase**
1001	Q-heater, continuity	Before quench
3002	Q-heater to ground	Before quench
2002	Q-heater insulation	Before quench
3004	Winding short	During quench
1019	Heater to ground	Before quench
3003	Heater to coil and ground	Before quench
2006	Heater to ground, disappeared while warming up	Before quench in 2^{nd} cool down

Clearly all these faults show up under special conditions: Either under very high forces or during the first (or second) cool down. I.e. the faults seem to be related to relative movements between coil, heaters and Helium vessel. Moreover it seems to be particularly common for the first magnets.

WHAT CAN BE DONE, WHAT IS DONE?

Why are so many magnets affected and why are the faults not detected in time? As said, it may be just the start-up phase of production with not optimised and dirty conditions. MAS has taken action to mend these problems. It is striking that most failures show up at low temperature. Clearly relative movements may displace insulating material and shorten the distance between not insulated parts considerably. To simulate this effect at room temperature is not possible, because the movement is related to the cool down. Moreover Helium is a relatively bad insulator. Using the rules of Ref. [3] one estimates test voltages in air exceeding the withstand voltages at the bus bar terminals. Attempts to apply the high voltage locally, using high voltage pulses or discharge pulses are of limited use only. The pulse must be shorter than the propagation through a dipole (order of ms). On the other hand it must be long enough to “see” the coil as a distributed inductance. However impedance measurements show that the eddy currents turn the phase of the impedance already at frequencies as low as 100Hz. Hence the two conditions can not be met simultaneously.

SUMMARY AND CONCLUSIONS

In summary, too many dipoles show serious electrical defects while their quench performance seems quite adequate. The main line of attack must of course be to find and fight the reasons for the faults. MAS is already doing this. However, some faults will always happen. Clearly, a test can not prevent the fault, but it can help to avoid additional problems. To sort out dangerous magnets, as a last line of defense, tests have to be performed. Faulty magnets like 3004 can cause too high voltages in its neighbours and thus spread the disease

So do we need to test at cold? For quench properties probably not. But until the quality is not completely insured there will always be questions.

HORATIO:
O day and night, but this is wondrous strange!

HAMLET:
And therefore as a stranger give it welcome.
There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy. But come;
Here, as before, ever, do test the magnets.

ACKNOWLEDGEMENTS

I would like to thank all my colleagues, that helped me to prepare the talk and this, quite different, paper. In particular I learned a lot from A. Siemko, P. Pugnat and F. Rodriguez Mateos, who let me use their transparencies and photos. D. Tommasini was never tired to explain and put in perspective the various faults. I thank Maria Llorente Herraiz and Merethe Olafsen for their help in preparing the talk.

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DO YOU REALLY WANT TO TEST THEM ALL AT COLD?

S. Sanfilippo, CERN, Geneva, Switzerland

Abstract

The main ring magnets for the LHC must satisfy strict performance requirements that are checked by extensive testing at cold condition, prior to their installation in the machine. An amount of 1650 magnets (bending dipoles + short straight sections i.e. SSS) is expected to be tested before the end of 2006. We start with the evaluation of the present situation of the cold tests for the pre-series magnets and with the comparison of the series magnets test requirements with the cold test capacity. The prospective shows a missing capacity of about 300 cold tests. Based on the results obtained for the 30 first pre-series magnets (powering and field quality aspects) we discuss the possibility of a sampling of the magnets tested.

INTRODUCTION

In the next three years a total of about 1650 main ring magnets (SSS+ bending dipoles) is planned to be tested at cold at CERN, before their installation in the tunnel. Following the actual baseline [1], the first 24 magnets from each of the manufacturing companies are treated as pre-series and are supposed to undergo an extended test program. The main goal of this phase is to give feedback to the magnet builders and designers to allow a fine-tuning of the MQ and MB structures. The tests at cold of the series phase are expected to start at the end of 2003. Initially 100% of the series magnets are foreseen to be cold tested with an optimised test program. The scenario includes a maximum of 20 % of magnets (i.e.10 % of problematic magnets and 10 % of magnets taken as spot-checks) that will follow an analogous extended cold test program as for the pre-series with a thermal cycle. In this paper we make an overview of the present situation regarding the tests of the pre-series magnets and we recall the main phases of the cold test program forecast for the series. The comparison of the expected test rate to the magnet delivery reveals a missing capacity of about 300 cold tests at the end of 2006. The aim of the second part is to consider if, based on the results obtained for the 30 pre-series magnets, a remedy would be a sampling of the magnets to be tested.

TEST CAPACITY VS PRODUCTION

Aims of the cold tests

The aims of the cold tests are threefold:

- To guarantee that the cryo-magnets meet the specifications. They are related to the cryogenic, vacuum and electrical integrity, to the capacity to reach nominal (8.33 T) and ultimate field (9 T) levels after a maximum specified number of quenches, to the efficiency of the magnet protection and to the quality of the field [2].
- To provide information and data for installation of the cryo-magnet in the ring.
- To provide information and data for the operation of the machine.

The test programs presented in sections 2.3 and 2.4 are based on these requirements.

Test capacity of the SM18 test plant.

The cold tests are performed at the CERN Superconducting Magnet Test Plant (SMTP) in the SM18 Test hall. At present, two prototype test benches are operational and the first two, series-type benches are at the end of the commissioning. As from spring 2004, the SMTP is supposed to provide twelve test benches, grouped in six clusters ready to accept bending dipoles or arc SSS. The control of the cool down and of the warm up of a cryo-magnet is provided by cryogenic feeder boxes, CFB (one per bench). Each CFB can maintain the magnet in saturated liquid helium at 4.5 K or in pressurized superfluid helium at 1.9 K for magnetic measurements and power tests. The projected global capacity of pumping on magnets heat exchangers is 18 g/s @ 16 mbar. This allows a first 4.5 K-1.9 K sub-cooling and 4 quenches at 1.9 K, recovered down to 1.9K [3]. Considering a training duration of two quenches per magnet, the maximum sub-cooling capacity corresponds to maximum of 3 magnets/day cold tested. On the other hand, the helium circulation capacity i.e. the cooling down and the warming up capacity will be 300 g/s in mid 2004. This limits the rate of the cold testing to a maximum of 2.5 magnets per day. The sequencing of all these cryogenic operations between the benches (cool down, warm up, sub-cooling) allows, at the end, to test at cold two magnets per day [3]. This constitutes the first main limitation of cold test rate. The second one is the human resources. The presently planned number of operators (28) and technicians (7) up to the end of 2006 corresponds to a capacity of two day cold tested magnets/day. The powering capacity (up to 4 magnets per day) and the measurement equipment, provided if it is correctly maintained, may not be a limitation.

Present Situation (pre-series phase).

The pre-series magnets (72 bending dipoles and 10 SSS) are undergoing a denser test program according to [4]. In addition to the tests dedicated to electrical integrity, quench performance and field quality study, it foresees an extended investigation of the magnet protection efficiency, additional magnetic measurements around the injection field (2 additional cycles in average) and an extensive quench study around 4.3 K (cable conductor limit, sensitivity to ramp rate). For the first 8 magnets from the three manufacturing companies, the test campaign is divided into two runs separated by a thermal cycle to validate the memory of the quench training. The average duration of the cold tests for the two runs is about two weeks and the average occupation of a cryo-magnet in the test bench between installation and dismantling is for the moment not better than 20 days (cool down, warm up, pumping included). For pre-series magnets without a thermal cycle, a maximum of one week at cold is forecast, duration that has to decrease progressively to reach the projected 4.5 days in series mode.

2.4 Series phases.

The main phases of the standard test cycle for the main LHC dipoles are described in Fig.1 [4].

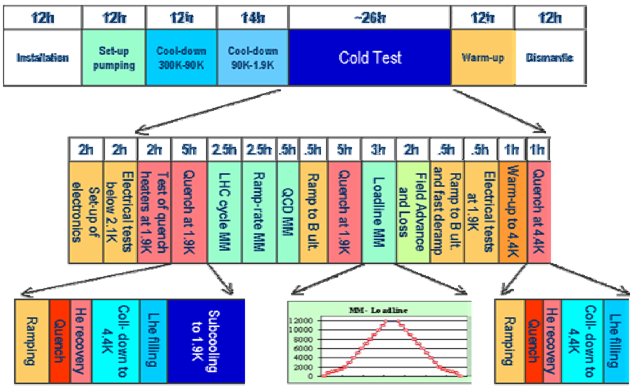

Figure 1: Phases of the standard program for series dipoles.

The total duration between magnet installation and dismantling is estimated at 100 h (4.5 days). The duration of the cold tests is fixed roughly at 26 h with 16 h dedicated to power tests and 10 h for field quality measurements. The projected test scenario for the arc SSS implies an average of 50 h of cold tests (see Fig. 2) divided into 16 hours for power tests and 34 h for field quality measurements.

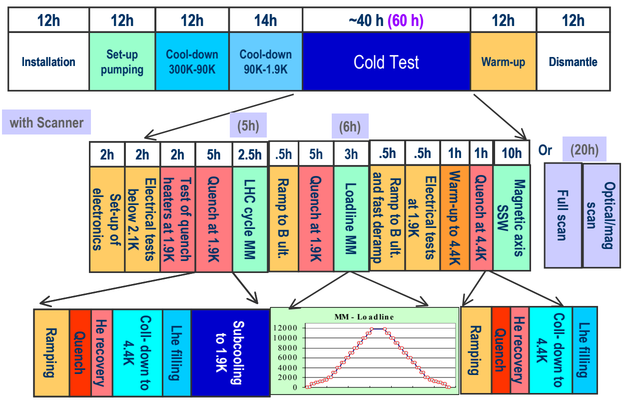

Figure 2: Phases of the standard program for arc SSS.

In these scenarios, a typical number of two quenches at 1.9 K is predicted. Based on these tests programs and on the CFB delivery and installation schedule, a prospective up to the end of 2006 has been made [4] and leads in the best case to an average testing rate of 45 magnets per month as from March 2004. This includes contingency for problem cases and extended testing (see base-line described in the introduction). As depicted in Fig. 3, a corresponding accumulated test output of 1400 magnets is projected at the end of 2006 [4]. In the best estimate, a missing capacity of about 250-300 cold tests is therefore to be expected.

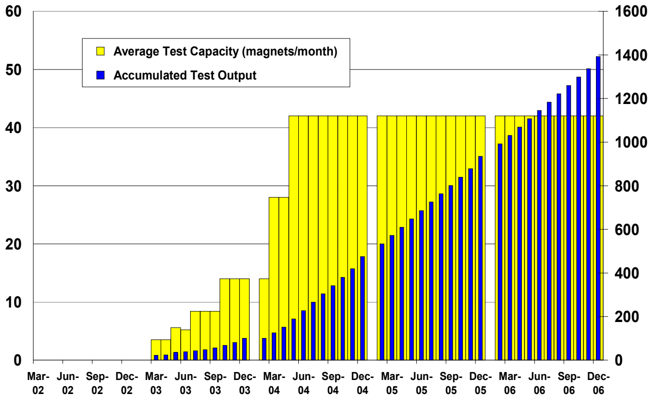

Figure 3: Test capacity and accumulated test output forecast till the end of 2006 [4].

IS TEST SAMPLING POSSIBLE?

The purpose of this section is to consider the impact of cold test sampling on the control of the production and on the start up of the machine. The conclusions are based on the results and on the experience gained during the cold tests of about 30 pre-series dipoles. We divided the discussion in three parts. The first part concerns all the powering aspects (electrical tests, quench performance), the second is dedicated to field quality and the third one to open questions related to cold mass geometry and alignment.

Powering aspects

The details of the quench and electrical performance of the first 30 pre-series cryodipoles were already presented in [4] and [5]. Only the striking items related to magnet acceptance criteria are recalled:

- 5 magnets showed an electrical insulation fault. These magnets passed all the tests at warm and, in one case, the loss of electrical integrity developed during a quench at nominal field as a result of a short circuit between turns. The main lesson learned is that the check of the electrical integrity at cold is necessary but may be not sufficient to detect all possible electrical faults. For this aspect, the cold tests must be completed by a minimum of two quenches performed at nominal field to reach a safe guarantee that the magnets can operate in the machine. Installing these dipoles without having detected these faults may damage not only the magnet itself but also its neighbours in the cell trough a propagation of the electrical faults [6].

- 14 magnets reached the nominal field after one or more quenches. Training in the tunnel would be required if these magnets would not undergo the cold tests.
- 1 magnet did not reach the nominal field. It would have to be replaced in the tunnel.

Field quality aspects

For field quality the question of the sampling attempts to answer two major issues:
- Are warm data sufficient for the control of the production and for the operation of the machine?
- Can we predict the field quality at operating conditions including dynamic effects like the decay and the snap-back of the magnetisation?

Warm cold correlation for multipoles and main field

The study of the correlation between multipoles measured at 300 K in the assembled cold mass [7] and in operational conditions (injection and flat top) was carried out for the 30 pre-series dipoles measured at cold. The relevant quantity of the analysis for the control of the production is the spread of the data around the ideal correlation line compared to the allowed ranges for systematic errors imposed by the beam dynamics [8]. For most of the multipoles, the spread induced by correlations is small with respect to the allowed range. The situation remains delicate for a2, a4 and b5. Concerning the main field, the transfer function (TF) presents a large uncertainty corresponding to 5 units r.m.s of b1. This is large and not far from the specification of 8 units r.m.s imposed by the beam dynamics.

Table 1: Spread of the correlations between assembled cold mass [7] and injection and high field compared to the allowed range of beam dynamics [8]

	$\sigma_{w/c}$ (Injection field)	$\sigma_{w/c}$ (High field)	Half allowed range
b_2	0.37	0.43	1
a_2	0.39	0.17	0.87
b_3	0.4	0.33	2.91
a_3	0.12	0.12	1.41
b_4	0.04	0.03	0.3
a_4	0.12	0.04	0.12
b_5	0.14	0.07	0.29
TF	4.91	5.23	8

Decay and snap-back effects

The field contribution of persistent currents decays during injection, resulting in systematic effects in the allowed multipoles and random effects in the non-allowed multipoles. This "decay" is followed by a so-called "snap-back" to the initial field value as soon as the current is ramped. Decay and snap/back effects are large for the low order allowed multipoles (few units for b_3), potentially not reproducible because they strongly depend on the powering history of the magnet and difficult to predict in particular when a large spread in decay exists among the magnets. These phenomena will affect the key beam parameters like the orbit, the tune and the chromaticity that should fall into restricted bounds. One of the most difficult parameter to control is the chromaticy, which exhibits large changes due to the systematic b_3 errors. The chromaticity bounds are about 2 units whereas it is expected to change by 100-150 units over 70 s during the snap-back [9]. This yields for a control of the sextupole at a percent level, which appears to be two orders of magnitude larger than the persistent current decay shown in Fig.4.

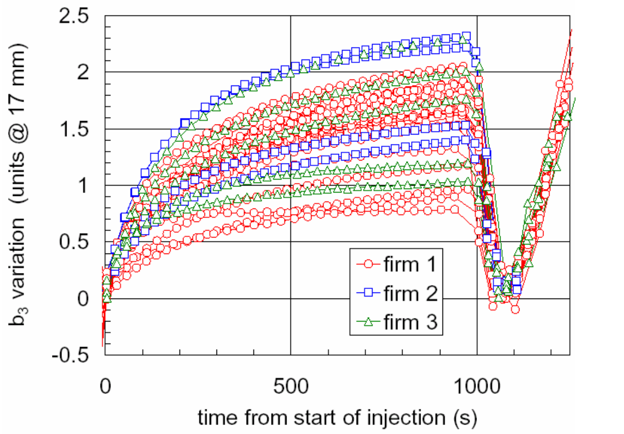

Figure 4: Normal sextupole decay during an injection plateau of 1000s and snap-back measured in the same pre-cycle conditions.

Figure 4 displays the measured sextupole decay during a simulated injection plateau of 1000s followed by the 'snap-back' corresponding to the field ramp at the end of the injection. All magnets were quenched and pre-cycled to a flat-top current of 11850 A (8.34 T) for 1800 s before ramping to a minimum current of 350 A (0.25 T) and finally to the injection current of 760 A (0.54 T). Despite identical powering history the magnets behave quantitatively different. The sextupole decay, quantified by taking the difference between the value at the beginning (0 s) and at the end (1000 s) of injection is within the allocated contingency (nominal systematic of 3.3 units expected), but exhibits a substantial standard deviation of about 0.4 units. This spread is comparable to the ones observed for the persistent current errors and the geometric errors with the b_3 and b_5 corrected cross-section. In contrast to these field error sources, however, there is no direct way to control decay and snap-back in magnets through production parameters. In order to cope with these dynamic effects, one of the foreseen feed-forward systems is the multipole factory that will take care at least of 80% of the effect [10]. Its goal is to predict the actual errors in the machine for different operation cycles using measured multipole errors implemented into a database and with the help of reference magnets It will therefore provide online information on the multipoles errors in the magnets. As an open loop system, its success will depend on the accuracy of the prediction of the field errors and will be very sensitive to model errors. As we can see in Table 2, the present knowledge of the multipoles based mainly on the multipole warm/cold correlation appears not be sufficient for the beam stability [11].

Table 2: Spread of the correlations between assembled cold mass and at the end of injection plateau (after a decay of 1000s) compared to the tolerances on multipoles required to control the beam (data are from [11])

multipoles	$\sigma_{w/c}$ (end of Injection)	Tolerances for the beam
b_2	**0.4**	**0.55**
a_2	**0.39**	**0.8 (r)**
b_3	**0.66**	**0.02**
a_3	**0.13**	**0.17**
b_4	**0.05**	**0.07**
a_4	**0.15**	**0.15**
b_5	**0.18**	**0.18**

Alignment and geometry: open points

The main concern for cryodipoles is the position of the corrector spool pieces, which must be centred w.r.t. the theoretical beam orbit within 0.3±1.5 mm (systematic and random). The warm magnetic axis is now being measured on all pre-series magnets at the end of the cold test run, and results so far are within the tolerance; however, crosschecks are being made with different measurement systems and reliable statistics will be available only at the end of the pre-series. Also, cold axis measurements are planned on 5% of the dipoles and 100% of quadrupoles and will be essential to verify the stability of the geometry.

CONCLUSIONS

In the best case, a missing of 300 cold tests with respect to the magnet delivery plan is anticipated at the end of 2006. The present bottlenecks are identified:
- the helium circulation and the sub-cooling capacities for a sequencing of the cold tests across the benches,
- the human resources,
- the complexity of the tests. This is related to the superconducting nature of the magnets and the tight specifications required (power performance and field quality).

When considering the possibility of a sampling of the magnets tested at cold, it is worth to recall that the maximum beam energy of the LHC will be restricted by the quench performance of the weakest main ring magnet and that the beam quality will depend on the efficiency of the feedback loops. At the present state, a sampling scenario for magnet testing at cold is therefore difficult to consider since:
- A significant part of the pre-series dipoles displays clear insulation faults that could not be detected at cold.
- The knowledge of multipoles on the basis of warm measurements, essential for a timely reaction at early stage for the field quality control, may not be sufficient for the control of the beam.

A shortening of the test duration appears to be the most reasonable direction to increase the testing rate. In this way, the situation has to be reviewed at the end of the pre-series phase.

ACKNOWLEDGEMENTS

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Thanks are due to the AT/MTM operation, TF and analysis teams who performed the tests and the analysis of the results.

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SUMMARY OF SESSION 4: INSERTIONS

R. Ostojic, CERN, Geneva, Switzerland

The session on the LHC insertions comprised seven talks. The first group of three talks covered the status of the superconducting quadrupoles for the dispersion suppressors and matching sections, the status of their cryostating and finally the plans for cold testing and acceptance of these cryomagnets. The topic of insertion magnets was concluded with a presentation of the status of the resistive separation dipoles. The last three talks covered some of the more specific issues: tunnel integration and installation of the low-beta triplets, design and testing of the DFBA feed boxes and superconducting links, and finally the design of the beam vacuum system in the warm sections of the insertions.

In the first talk, Julio Lucas presented the production status of the two families of insertion quadrupoles, MQM and MQY. He presented the situation with the magnet production tooling in companies, and with the tooling and procedures for assembly of the special quadrupole cold masses in CERN. He then commented on the delivery profile of the critical components and the expected build-up in the production with reference to the LHC "just-in-time". He also presented the very encouraging test results of the first two pre-series MQM quadrupoles.

As a general comment, Julio mentioned the fact that because no prototype was built of an insertion quadrupole cold mass, some aspects of its electrical and cryogenic design still need to be validated. As one example, he mentioned the issue of the efficiency of coil cooling when the magnet is equipped with an OD 53 mm cold bore and cooled in a helium bath at 4.5 K. The other issue could be the transverse temperature gradient, which may occur during cool-down due to asymmetric cooling (the baseline assumes that the filler, normally installed in the main dipoles in the dispersion suppressors, is removed from the lower part of the MQM magnets).

Vittorio Parma reported on the plans for cryostating of the insertion quadrupoles. He pointed out a large number of variants and small number of units that have to be integrated, which generate problems in design and procurement. In view of the recent re-organization of the arc SSS procurements and assembly contracts, Vittorio presented the current baseline for the purchase of special SSS cryostat components and assembly work proper. In conclusion, he pointed out that the problem of transport of those special SSS which are equipped with non-standard QQS modules still remains to be resolved. In addition, handling of vacuum forces on the short magnet strings (e.g. D2-Q4) also needs attention. He reported that the start of the assembly activities on the cryostating of special SSS is foreseen for October 2003.

Andrzej Siemko had a provocative question to answer: are special SSS orphans when it comes to cold testing. He first summarized the main reasons why cold testing of the special SSS is required, which are: check of the vacuum, electrical and cryogenic integrity, and validation of the quench and magnetic field performance. In many ways the test plan for the special SSS is similar to the main arc magnets, except for the level of precision in measuring field quality of the Q4 and Q5 magnets, which should be comparable to the low-beta quadrupoles. Some of the tests on the pre-series magnets can be performed in the vertical cryostat in Block 4, but most tests must be done on completed units in SM18. Andrzej explained that most of the equipment exists, but that some modifications need to be made on the test benches to accommodate the large number of variants. The design work has started, and he foresees that the first tests of insertion quadrupoles in SM18 would be possible beginning 2004. The discussion brought out that additional effort and time will be required for connecting and testing the special SSS, and that in general there will be competition for test slots in the available test stations.

Délphine Gerard and Suitebert Ramberger presented the status of the resistive magnets, in particular the separation dipoles MBW and MBXW. The pre-series units of these magnets were recently delivered from BINP and re-mesured in CERN with a rotating probe to cross-check the Hall probe array used in Novosibirsk. The data presented for the first time showed that the field quality of both magnets is well within specification. They also remarked that the present plan foresees that the cross-checks will be made only on three magnets, at the beginning, middle and end of the series production. This approach was questioned, and Stephane Fartoukh suggested that the measurement plan be modified so as to increase the frequency of measurements in CERN.

Sonia Bartolome Jimenez presented the tunnel integration and installation of the low-beta triplets, with emphasis of IR8, which is the first triplet to be installed. Sonia pointed out that placing the Q1 cryomagnets in their final positions is difficult due to their placement close to the experiments, so that there is no lateral access to Q1, and the standard transfer tables cannot be used. Several solutions are presently considered, with the aim of standardization and minimizing the costs. She also pointed out that the interface with the experimental shielding is a concern not only in the high luminosity insertions but also in IR2 and 8. Finally, Sonia shortly discussed the possible transport routes for the equipment to be installed close to the IRs, and remarked that for the time being no technically viable solution was found for the transport of D2/D4 separations magnets, equipped with a "high" jumper.

Antonio Perin presented the current design of the DFBA feed-boxes. He described the modular approach of the design, and presented some details of the high and low current modules, and of the shuffling module. He commented on the status of the integration studies, and presented the current plans for procurement and production of the feed-boxes, and for their testing in SM18. The planning raised some concern related to the short time for the delivery of the first feed box, foreseen for July 2004. Antonio finally informed of the design status of the superconducting links.

Christian Rathjen presented the beam vacuum system in the warm sections of the machine, taking IR8 as an example. He recalled that the baseline is a system based on NEG coated copper chambers, separate for the two beams, and sectorised at each cold-warm transition. He then presented the design of the standard drift tube and of its supporting elements. He went to the recombination chambers in IR8, which is identical to that in IR1 and 5 (TAN recombination chamber), and IR2, which is quite specific due to the constraints of the ALICE zero-degree calorimeter. Christian also reported on the test results for the elliptical chambers, to be used as replacement of the cruciform design in MQW, which achieved a bakeout temperature of 250 C with 50% of heater power. Note was taken of the fact that certain equipment in the insertions is still in the initial design stage, and that local radiation doses are not well known everywhere, both of which slow down the detailed design work. Finally, some questions remain as to the responsibilities for the alignment of critical vacuum chambers (e.g. ALICE-ZDC).

In summary, the session was very informative and lively, and raised a certain number of less known issues which should not be forgotten. A common point of all presentations was the large number of different equipment to be built, in spite of the previous efforts to standardize the insertions. In this respect, the team working on the DFBA feed-boxes is in a particularly difficult position, as a slightly different design is needed for each of the 16 systems installed in the LHC!

DESIGN AND PRODUCTION OF THE MQM AND MQY COLD MASSES .

J. Lucas, CERN, Geneva, Switzerland

Abstract

This report presents the status of the design and the production of the LHC insertion cold masses containing MQY and MQM-type magnets. After a short description of the design of the magnets, the status and planning of their production contracts is given. The results of the cold tests of the first two pre-series MQM-type magnets is presented. The status of the preparation of the cold masses is presented.

DESIGN OF THE MAGNETS

The MQM magnets that are the core for the LHC insertion cold masses that will be used from Q5 to Q10 in most of the points, are based in a cable of 8.8 mm. The objective is to individually power these cold masses with currents under 6 kA, so that a lighter power supply infrastructure is required in the tunnel. The MQY magnets have a coil inner diameter of 70 mm and are used wherever a larger geometrical aperture is required, mainly in Q4 in the experimental insertions. Cross sections of both magnets are shown in Fig. 1.

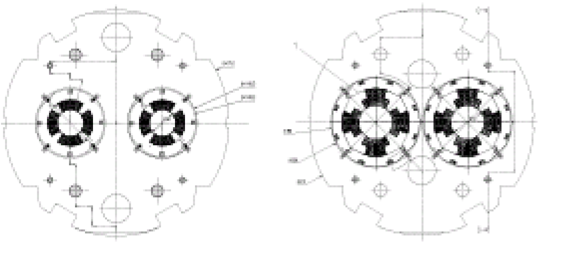

Figure 1: Cross section of the MQM and MQY magnets.

MQM magnets are made of two layers of cable 4 wound without an intermediate curing. MQY magnets are made out of two double pancake windings. The innermost pancake uses two different types of cable with one internal splice. Table 1 presents the main characteristics of the magnets.

DESCRIPTION OF THE CONTRACTS FOR THE MAGNETS

The contracts for the magnets have been placed at Tesla Engineering (MQM) and ACCEL Instruments (MQY). Both contracts are similar, CERN supplies:

1. The superconducting cable which is in the critical path for both magnets. The present agreement on magnet delivery is in the limit of the cable available at CERN. Therefore, **no further shift in cable procurement may happen without affecting magnet fabrication.**
2. Stainless steel for collars and low carbon steel for the yoke laminations.
3. Quench heaters.

Table 1: Characteristics of the MQM and MQY magnets

	MQM	MQY	
Cable type	4	5	6
Cable width (mm)	8.80	8.30	8.60
Mid-thickness (mm)	0.85	0.85	1.28
No of strands	36	34	26
Strand dia. (mm)	0.48	0.48	0.74
Cu/SC Ratio	1.75	1.75	1.25
Filament dia. (μm)	6	6	6
Operating temp.(K)	1.9/4.5	4.5	
Nominal gradient(T/m)	200/160	160	
Nominal current (A)	5370/4300	3550	
Inductance(mH/m)	4.40	21.7	
Length(m)	2.5/3.5/5.0	3.5	
Number of units	15/43/38	26	

No cold test is made at the contractor premises. The contractor is responsible of the manufacturing quality, but only of reaching 50% of the nominal current before the first quench.

MQM PRESERIES RESULTS

Two magnets of the 2.5-m long type have been cold tested at CERN. Both reached LHC ultimate gradient of 217 T/m without quenching. Only the first one was trained having a first quench at 218 T/m and reaching 235 T/m in the third one. The magnets went through a thermal cycle and were powered again to ultimate current without quenching. MQMC1 reached 234 T/m after the thermal cycle without quenching, showing a 100% memory effect. Both magnets reached the conductor limit at 4.5 K with no quench. The field quality is shown in Table 2.

MQY CONTRACT STATUS

The tooling is now complete. Four coils of layers 1 and 2, and 11 of layers 3 and 4 have been wound. A 1-m long collared coil has been produced and assembled with series components. The first full length collared coil is expected by the end of June and the first magnet by the end of July.

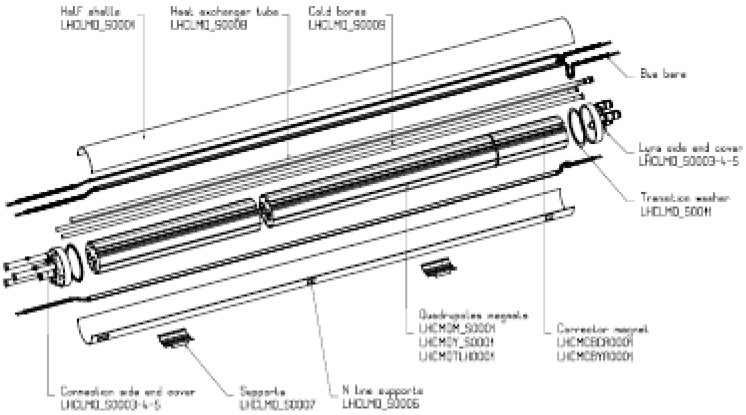

Figure 2: View of a Q9-type cold mass made out of two series connected quadrupoles and a dipole corrector.

Table 2: Harmonics table of the first two MQMC magnets, measured at nominal current

N	Aperture 2		Aperture 1	
MQMC2	Normal	Skew	Normal	Skew
3	-0.46	2.18	0.79	-0.18
4	0.27	1.66	0.48	-0.04
5	-0.71	-0.41	-0.17	0.19
6	**0.77**	-0.58	**0.60**	-0.35
10	**0.10**	-0.09	**0.24**	-0.10
MQMC1	Normal	Skew	Normal	Skew
3	1.22	1.79	-2.97	1.34
4	0.07	0.58	-0.57	0.96
5	0.65	0.02	0.94	0.30
6	**1.22**	0.06	**1.58**	0.03
10	**0.15**	0.00	**0.35**	-0.08

STATUS OF THE COLD MASSES

The MQM-type and MQY magnets are assembled in cold masses similar to the one represented in Fig. 2. One or two quadrupoles are assembled together with 1 or 3 dipole orbit correctors inside two half-cylinders which are longitudinally weld. Two end covers are welded in the extremities. A set of 13 kA bus-bar goes through the cold mass to interconnect the DFBA with the arc magnets. In the last 2 years an extensive program has been carried out to complete the design of the cold masses and to set up building 181 as the insertion cold mass factory.

Mechanical design of the enclosure: The cold mass is considered as a pressure vessel. To comply with the French norm, CODAP, an extensive study has been performed.

Development of the welding process: The components have been designed to optimize the welding and the parameters defined on samples. A complete qualification has been carried out including the DMOS (Description de Mode Opératoire de Soudure), QMOS (Qualification de Mode Opératoire de Soudure) and the appropriate qualification of the welders. This program has been made in a collaboration with ST/MF since summer 2001.

Component procurement: Most of the components required are already available. The main concerns are about the **13 kA bus-bars** and the **dipole correctors.**

Prototypes: Two mock-ups have been made to test most of the features that will be encountered in the fabrication of the cold masses.

OPEN ISSUES IN THE DESIGN

A few issues are considered as open. The 6 kA powering to the cold mass is made through a *leak tight plug*. This plug has been designed with a technology developed by ACR for the DFBMs. The transient cool down of the plug has to be studied.

In order to improve the hydraulic section of the cold mass the filler piece symmetric to the heat exchanger in the continuous cryostat cold masses cannot be installed. The transient has to be carefully studied to avoid the development of *thermal stresses due to the cooling asymmetry*.

Finally, a decision has to be taken about the *cold bore for the cold masses at 4.5 K*. A 50 mm ID tube is preferred for geometrical aperture, nevertheless, it must be proved that the cooling of the coil is not degraded.

CONCLUSIONS

- The preseries of MQM magnets is advancing well and should finished by end of July. The results of the first 2 MQM magnets are encouraging.
- The first MQY magnets will arrive at the end of July.
- The design of the 1.9 K cold masses is completed and the set-up of building 181 and validation of assembly technology have been finished. The cold masses may be assembled as soon as the magnets arrive.
- Nevertheless, these cold masses have never been tested and some surprises may be found. It is important to perform these tests as soon as possible.

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CRYOSTATING OF MS AND DS QUADRUPOLES

V. Parma, CERN, Geneva, Switzerland

Abstract

The optical lattice of the LHC requires 115 specific superconducting quadrupoles in the Dispersion Suppressors and Matching Section regions, housed in cryostats to form the DS and MS Short Straight Sections (DS SSS and MS SSS).

This paper presents the status of the design of the DS and MS SSS and of the related assembly tooling, and the status of the supply of the cryostat component. The major pending issue in the design and integration of the SSS are also highlighted.

LHC INSERTIONS AND QUADRUPOLES

The optics scheme in the 8 LHC insertions is mainly imposed by their specific function: 4 dedicated to the experiments, 2 for beam cleaning, 1 for RF cavities, and 1 for the beam dumps. 4 main types of magnet layouts appear therefore around the insertion points. The standardisation of magnet design and of the integration of the quadrupoles and corrector magnets in common cold masses yield 4 different combinations of magnets in the DS SSS and 8 in the MS SSS, as shown in tables 1 and 2.

Table 1: DS SSS Cold masses

Cold mass/position	Magnets	T°	Cold mass Length (mm)	Cold mass weight (kN)	No. Units
Q11 IR 1-8	MQ + MQTL+MSCB	1.9	6620	74.16	16
Q10, Q8 except IR3,7	MQML + MCB	1.9	6620	74.16	24
Q10, Q8 IR3,7	MQ + MQTL+MSCB	1.9	6620	74.16	8
Q9 except IR3,7	MQMC+MQM+MCB	1.9	8020	93.1	12
Q9 IR3,7	MQ+2 MQTL+MCB	1.9	8020	93.1	4

Table 2: MS SSS Cold masses

Q7 IR4	MQM + MCBC	1.9	5345	~58.2	2
Q5, Q6 IR4 Q4, Q5 IR6	MQY + MCBY	4.5	5345	~58.2	8
Q7 IR3, 7	MQ + MQTL + MCBC	1.9	6620	74.16	4
Q5, Q6 IR1, 5	MQML + MCBC	4.5	6620	82.4	8
Q4 IR1, 5	MQY + 3 MCBY	4.5	8020	93.1	4
Q7 IR 1, 2, 5, 8	2 MQM + MCBC	1.9	8995	110.9	8
Q6 IR2, 8	MCBC+MQML+MQM	4.5	10400	123	4
Q6 IR3, 7	6 MQTL + MCBC			~123	4
Q4, Q5 IR2, 8	2 MQY + 3 MCBY	4.5	11355	140.7	8

DS AND MS SSS CRYOSTATS

Main Cryostat Parameters

The SSS cryostats have been designed to house the variety of cold masses listed above by extending the solutions adopted in the arc cryostats as far as possible, for obvious reasons of standardisation and consequent cost effectiveness. In particular, the cross-section features could be kept the same as those in the arc cryostats: diameter and thickness of the vacuum vessels, cross-section of the thermal shields, MLI blankets and composite material support posts.

However, to cover the full range of length and weight of the family of cold masses, their cryostats have been adapted in length on the main dimensions marked in Fig. 1.

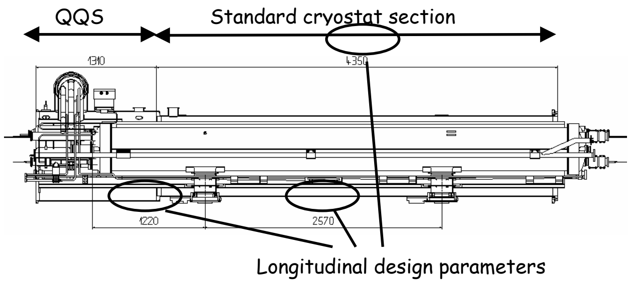

Figure 1: Main cryostat design parameters for an SSS.

Fortunately enough, in all cases both weight and length of the cold masses are within those of an arc SSS and a main cryo-dipole.

The design principles of the arc SSS cryostat have been preferred to those of the dipole cryostat, considering the isostatic two-point supporting of the cold mass as a simpler and somewhat "healthier" solution. Moreover, considering that all DS and MS SSS are equipped with a technical service module (QQS) and a jumper connection to the QRL, it was preferred to adopt the SSS solution in which the cold mass is fixed longitudinal to the vacuum vessel at the support post closest to the QQS, which limits the thermal contractions of all cryogenic piping in the QQS and jumper.

For the longest and heaviest cold masses however, due to the need for a third intermediate supporting point to reduce the self-weight sagitta, dipole-type vacuum vessels had to be adopted.

In total, a family of 6 types of cryostats are needed to cover the full range of DS and MS SSS. Fig. 2 shows the variety of DS and MS SSS, including the additional variants introduced by the cryostat end-caps for the stand-alone SSS.

Specific Features

In addition to the variety of cold masses, the DS and MS SSS have to cope with very specific features required by the topology of the machine, the cryogenic layout and the powering schemes. For instance, the MS SSS from Q6 to Q4 are stand-alone cryogenic and superconducting units, i.e. they are not in the continuous arc cryostat and therefore need dedicated cryogenic and electrical feeding.

Their cryogenic operation in saturated helium baths at 4.5 K, requires that the filling of the magnets with helium be done from the highest point in the sloping tunnel to avoid the accumulation of vapour, thus requiring that the SSS and jumper to the QRL are conveniently oriented. The SSS therefore need to be assembled accordingly, which introduces an additional variant in the types of SSS. Furthermore, end-caps to close the vacuum vessels at each end are required, equipped with cold-to-warm transitions (CWT) to provide low heat in-leak onto the beam tubes.

As a further example, the DS SSS in Q10, Q9 and Q8 and the MS SSS in Q7 require local electrical feeding of the 6 kA MQM magnets (except in points 3 and 7). These are powered from the DFBA via line N and fed to the magnets through a dedicated feedbox in the QQS, which requires a specific design and integration.

Summing up all the specificities introduced by either the cold masses or the specific features of the SSS, the number of variants reaches 30 for a total of 64 units for the DS SSS and 20 for a total of 50 units for the MS SSS.

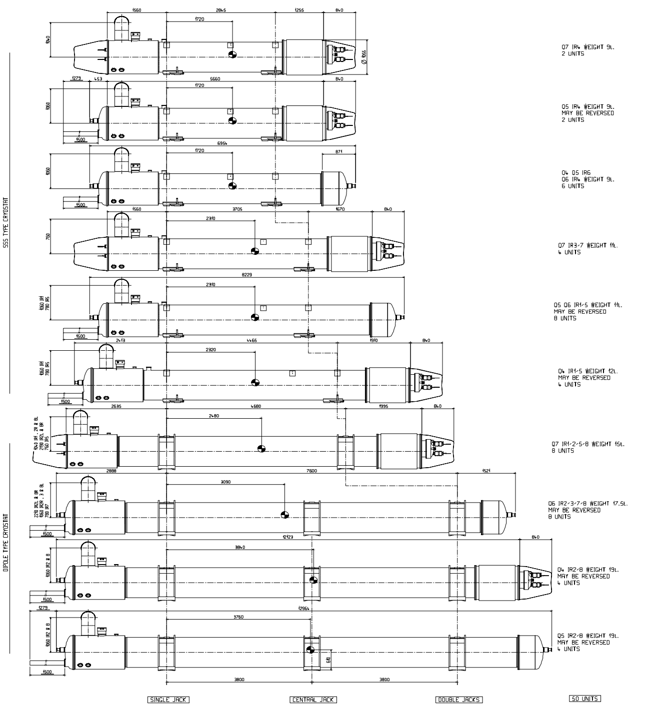

Figure 2: Variety of DS and MS SSS.

Assembly tooling

The assembly of the various types of DS and MS SSS required the development of two specific cold mass integration benches, one allowing the assembly of all the SSS-type cryostats, and a second one dedicated to the assembly of the dipole-type cryostats featuring the three-point supporting of the cold mass. The assembly of the QQS can be carried out using most of the tooling developed for the arc SSS, but also needs additional mechanical tooling to cope with all specific cases. This tooling is still to be designed.

PROCUREMENT OF COMPONENTS

All cryostat components of the DS SSS are being procured together with the arc SSS ones. The first sets of components will be available in October 2003.

The manufacture of the main cryostat components for the MS SSS, which were not yet designed at the time of tendering for the arc SSS, is under negotiation as an extension of the running contracts with the companies producing the arc cryostats. Considering that the manufacturing experience on all critical components (castings, forged flanges, etc.) has been included in the design of the MS SSS, no major production inconvenience is expected, and the first components could be available at the beginning of 2004.

PENDING ISSUES

The jumpers of the SSS have to match the vertical position defined by the QRL interfaces. As a consequence, 6 different jumper heights are to be provided, ranging from the standard height of the arc SSS jumpers (760 mm) up to some 2000 mm for the highest ones. Considering the limited tunnel height in TI2, through which all cryo-magnets are supposed to be transported, some 45 SSS with non-standard jumper cannot be transported using the standard cryo-magnet transport vehicle, due to interference with the ceiling and service infrastructure. This issue is still presently unsolved and needs to be tackled by providing a specific and more compact vehicle, by assembling the jumpers in the tunnel after transport or by finding another transport route. A second open issue is the interference between the vacuum vessels of 6 MS SSS and the injection beam lines in point IR2L and IR8R, and the beam dumps in IR6. For these cases, a specific design of the vacuum vessels is presently under study, which would require minor modifications to the standard components.

SUMMARY

Some 50 types of SSS are required for the 115 units in the DS and MS regions. The design of these units is mostly completed and the procurement of the components is foreseen through the existing contracts for the arc cryostats. However a few major technical problems are still outstanding and are presently being addressed. The main assembly tooling has been defined and is mostly available although a considerable effort for specific tooling is still needed.

The assembly of the first DS SSS and MS SSS will start at the end of 2003 and at the beginning of 2004 respectively.

COLD TESTING OF SPECIAL SHORT STRAIGHT SECTIONS

K. Naoui, A. Siemko, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider magnets must satisfy strict performance requirements. Their quality will be checked throughout extensive testing at cold conditions, prior to installation in the machine. An overview of cold test aspects of the insertion region magnets, regarding cryogenics, powering, mechanics and magnetic measurements will be presented.

INTRODUCTION

The LHC ring is composed of eight octants. Each octant comprises two half arcs and an insertion region. Four insertion regions are dedicated to experiments while the other four are used for collider systems like for example, RF, beam cleaning and beam dump. Most of the magnets in the insertion regions are superconducting, based on NbTi technology. The general layout of two LHC octants is shown in Fig. 1.

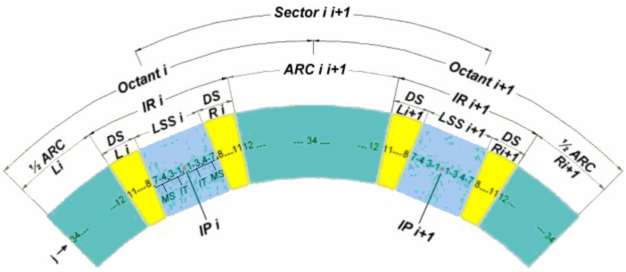

Figure 1: Schematic layout of two LHC octants [1].

On both sides of the collision point the short straight sections housing the quadrupole magnets are numbered from Q1 to Q34. The insertion regions contain units from Q1 to Q11 while the arcs from Q12 to Q34. Q1 to Q3 form the Inner Triplet (IT), Q4 to Q7 the Matching Section (MS) and Q8 to Q11 the Dispersion Suppressor (DS). All together 114 DS and MS Short Straight Sections will be installed in the LHC [2, 3]. Their main composition [cf. 3, 4] is listed in Table 1.

This report describes the status of the preparation to the cold tests [5, 6] for 114 Special Short Straight Sections in terms of mechanics, powering, cryogenics and magnetic measurements.

IMPORTANCE OF COLD TESTS OF SPECIAL SHORT STRAIGHT SECTION MAGNETS

Assessment of the performance of the superconducting cryo-magnets can only be carried out at cryogenic temperatures and operating conditions. The importance of the cold tests is not only related to the magnet quench training, but also to their cryogenic, vacuum and electrical integrity and as well the magnetic field quality. The main objective of the cold tests of the special SSS units is the quality check-up and acceptance prior to installation in the machine.

Table 1: Main categories of magnets in the MS and DS Short Straight Sections

Type/Position Q.../IR...	Number of units	Magnets composition in sp. SSS assembly	Cryostated lengths mm
Q5,Q6 IR 1,5	8	MQML+MCBC	6935
Q6 IR 3,7	4	6xMQTL+MCBC	10715
Q6 L IR 2	1	MQM+MQML+MCBC	10715
Q6 R IR2, Q6 IR8	3	MQM+MQML+MCBC	10715
Q7 IR4	2	MQM+MCBC	5660
Q7 IR 1,2,5,8	8	MQM+MQM+MCBC	9310
Q5IR2R,IR8L	2	MQM+MQM+3xMCBY	11670
Q4/Q5 IR6	4	MQY+MCBY	5660
Q5/Q6 IR4	4	MQY+MCBY	5660
Q4 IR 1,5	4	MQY+3xMCBY	8335
Q4 IR 2,8	4	MQY+MQY+3xMCBY	11670
Q5IR2L,IR8R	2	MQY+MQY+3xMCBY	11670
Q7 IR3,7	4	MQ+MQTL+MCBC	6935
Q8, Q10 IR3,7	8	MQ+MQTL+MCBC	6935
Q9 IR 3,7	4	MQ+2xMQTL+MCBC	8335
Q11 IR1-8	16	MQ+MQTL+MSCB	6935
Q8/Q10 IR1,2,4,5,6,8	24	MQML+MCBC	6935
Q9 IR1,2,4,5,6,8	12	MQMC+MQM+MCBC	8335

The initial assumptions to perform the cold tests of these magnets in SM18 test facility are the following:

- to use existing infrastructures in SM18;
- to use existing hardware and measuring systems;
- to avoid major research and development;
- to minimize the total cost of the tests.

BEAM OPTICS REQUIREMENTS FOR THE FIELD QUALITY OF SPECIAL SSS

Dedicated tracking studies were performed in order to assess the importance of the field quality in the special

SSS magnets [7]. The main results of these studies can be summarized as follows:

- the tolerances on alignment and transfer functions associated with the insertion quadrupoles are of the same order as those associated with the arc quadrupoles;
- the tolerances on multipole components at injection energy for Q4 and Q5 in Points 4 and 6 must fulfill the specifications listed in the so-called 9901 table [8];
- at collision energy, Q4 magnets should follow the specification applied for MQX in Points 1 and 5.

MECHANICS

Three magnet families for testing

Although 114 DS and MS magnets are of 51 different types, from the point of view of their cold tests and taking into account magnet lengths, cold feet positions, jack positions, powering and availability of magnetic measurement systems, special SSS units can be grouped in 3 main families.

- Family 1: 11670 mm, 10715 mm;
- Family 2: 9310 mm, 8335 mm;
- Family 3: 6935 mm, 5660 mm.

Anti-cryostats

As the magnetic measurement shafts must work at room temperature, anti-cryostats are required in order to create a thermal barrier between the cold bore and the measurement shafts.

Anti-cryostats with lengths different from those of the arc SSS type are required to perform the cold testing of the special short straight sections. Each anti-cryostat type will be used for several magnet lengths of the same family.

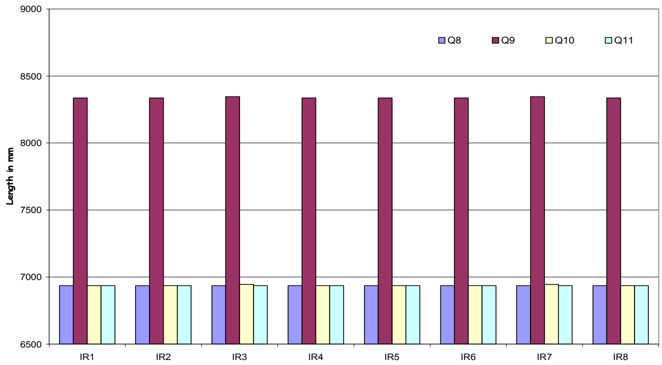

Figure 2: Dispersion suppressor lengths in the LHC.

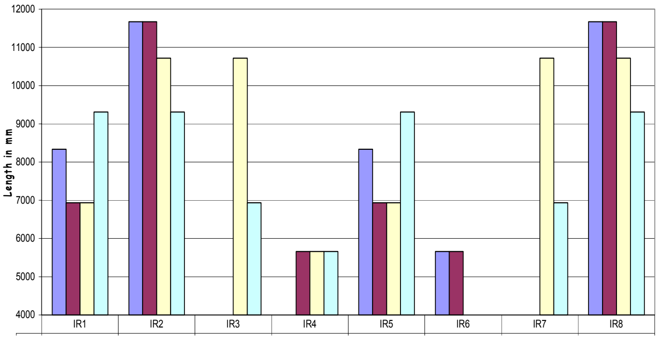

Figure 3: Matching section lengths in the LHC.

Extension modules

For adapting one type of the anti-cryostat to several magnet lengths of the same family, an extension module is needed. This extension module which is an expansion of the cryostat will be located between the magnet and the Magnet Return Box (MRB). There will be two types of extension modules. Each of them will be composed of a rigid extension of the vacuum vessel, an active thermal screen and flanges for fixing them on the cryostat and on the MRB.

Wide aperture magnets (ø=70 mm)

For Q4 in IR1,2,5,6,8; Q5 in IR2,4,6,8; Q6 in IR4, the adaptation pieces have to be developed in order to fix actual anti-cryostats in wider apertures.

CRYOGENICS

Dispersion suppressor magnets are cooled at 1.9 K in superfluid helium whereas most of the matching section tand-alone units operate at 4.5 K. In the SM18 test facility the cryogenic and electric feeding are carried out through the Cryogenic Feed Boxes (CFB's) connected to one end of the magnet. A magnet return box closes the opposite end of the cryo-magnet under test. The functions of the CFB are to control the cooldown and the warm-up of a cryo-magnet, to maintain a magnet cold mass in saturated liquid helium at 4.5 K or in pressurized superfluid helium at 1.9 K for magnetic measurements, power tests and quench training.

The superconducting magnet test plant in SM18 which is configured for the arc cryo-magnet cold tests will remain unchanged to test most of the special short straight sections. In terms of cryogenics, all special short straight sections, which operate at 1.9 K (Q7 to Q11) are equipped with the same cryogenic lines as arc dipoles and arc SSS, namely the heat exchanger line (X), the thermal shield cooling line (E), the cold feet cooling down line (C') and the special cryogenic line (N). On the other hand, for the 36 stand-alone units which operate at 4.5 K that is to say Q4, Q5, Q6 in each region, the cooling process has to be adapted for testing them.

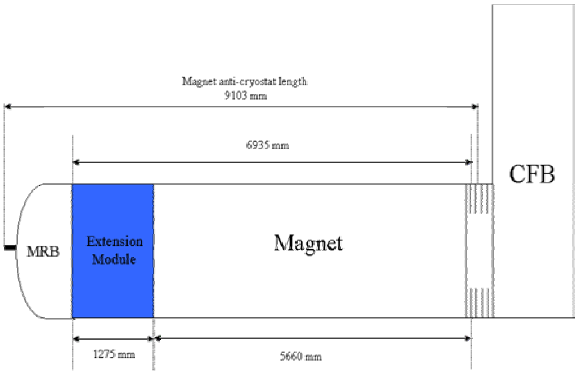

Figure 4: Schematic view of the test bench with the extension module used for the 3rd family.

For the matching section (stand-alone units) from Q4 to Q6 which operate at 4.5 K, no N line exists in the present design. N lines already designed for the arc cryo-magnets have to be added on all these cold masses in order to keep the standard cooling process of the existing test benches.

Figures 5 and 6 show the synoptic diagrams of the planned cryogenic operation of special SSS's on the test benches in the SM18 test facility.

POWERING

The beam optics flexibility of the LHC insertion magnets is provided by the individually powered quadrupoles in the dispersion suppressors and the matching sections.

In terms of powering, the SM18 test benches are sufficiently equipped to carry out all the tests required, except the one in which the magnetic field is unbalanced between two apertures. This feature cannot be tested because the SM18 test benches are equipped with only one principal power converter circuit.

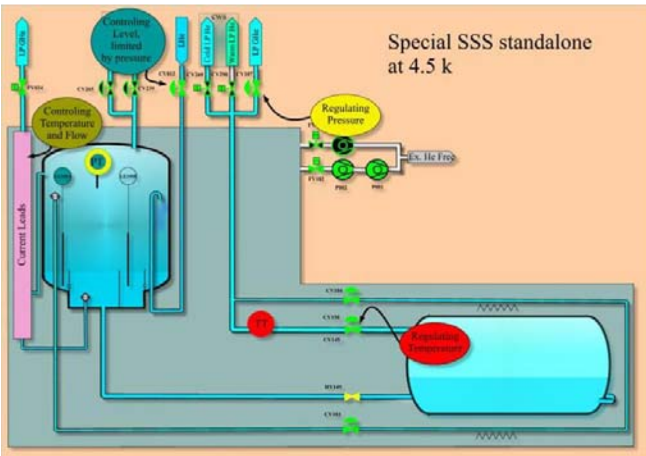

Figure 5: CFB synoptic for the operation at 4.5 K (Courtesy of A. Tovar-Gonzalez).

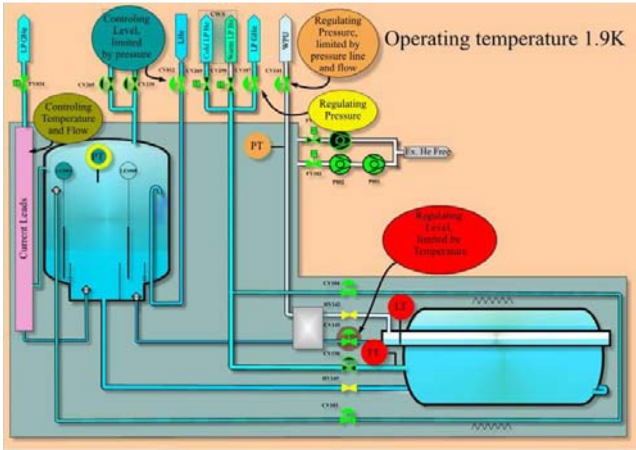

Figure 6: CFB synoptic for the operation at 1.9 K (Courtesy of A. Tovar-Gonzalez).

The principal circuit will be used to feed the 6 kA quadrupole cables which have to be routed to the CFB by the N line to the CFB M3 line.

The corrector circuit which is fed by the 100 A power supply will be used when units have a single corrector. In this case, the power supply will be directly plugged on the DCF (warm flange connection) which is located on the cryostat.

The SM18 test benches are also equipped with two auxiliary corrector circuits fed by two 600 A power converters which will be used to test units composed of three correctors (Q4 in IR1, 2, 5, 8, Q5 in IR2, 8). Indeed for these units, the 12 corrector cables coming out at the MRB side have to be interconnected and routed to the CFB for connection to the power supplies.

MAGNETIC MEASUREMENTS

In terms of magnetic measurements as per AB/ABP recommendations, precise magnetic axis and harmonic measurements are required for Q4, 5 in IR4, 6 at injection energy (L = 11670 mm) and Q4 in IR1, 5 at collision energy (L = 8335 mm).

It is planned to use the Chaconsa Scanner whenever possible to perform both magnetic axis and harmonic measurements. Unfortunately, the measurement span of this measuring system is limited to 9538 mm, excluding reference magnet lengths and their supports.

As a secondary measuring system SSW (Single Stretched Wire) can be used to measure magnetic axis and integrated field.

Table 1 shows that in several cases, special SSS units are longer than the Chaconsa measurement span. This implies that both systems have to be used for testing these units, namely the Chaconsa for the harmonic measurements and the stretched wire for the magnetic axis measurements. Time to allocate to magnetic measurements can be estimated at 72 hours.

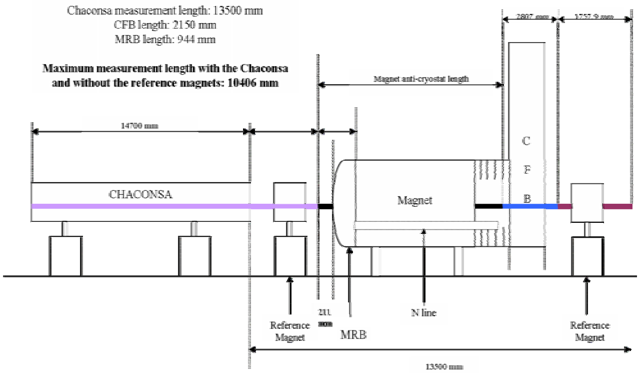

Figure 7: Test bench schematic layout with the Chaconsa.

The actual Chaconsa Scanner configuration enables to test 70 units (all units which are shorter than 7 m).

In order to measure magnets of the family 2, some modifications concerning the Chaconsa Scanner position and reference magnet lengths are required. The Chaconsa Scanner has to be installed closer to the magnet and the reference magnets have to be more compact. It is clear that the family 3 units have to be tested with both systems (Q4 in IR1,5 belong to these units).

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WARM SEPARATION DIPOLES: STATUS AND PRODUCTION PLAN

D. Gerard, S. Ramberger, CERN, Geneva, Switzerland

Abstract

20 MBW, 16 MCBW, and 25 MBXW dipole magnets as well as 48 MQW twin aperture quadrupole magnets will be installed in the insertion regions of the LHC. While the manufacturing of the quadrupole magnets is nearing completion in Canada, the series production of the dipole magnets made in collaboration with BINP in Russia, is ready to start. The MBW and MCBW magnets will be installed in the cleaning insertions IR3 and IR7. The MBW magnets will increase the separation of the 2 beams from 194 mm to 224 mm, the MCBW magnets are needed to adjust the vertical and the horizontal beam orbit. MBXW magnets will be installed in the experimental insertion regions IR1 and IR5 to further reduce the beam separation for collision in the experiments.

LAYOUT

The layout of IR1, IR3, IR5, and IR7 is symmetric on both sides with regard to the insertion point (IP). Starting from the IP in IR3, the warm magnets are placed in 3 separate groups. The first group consists of 2 MCBW and 6 MQW magnets, and the second has 2 MCBW, 6 MQW, and 3 MBW magnets. The last group employs 3 MBW magnets. In IR 7, the warm magnets are distributed in 4 separate groups. The first and second group are formed by 2 MCBW and 6 MQW magnets, whereas the third and the last group have 2 MBW magnets. Both, IR1 and IR5 employ a group of 6 MBXW magnets on either side. One MBXW magnet will be installed next to the LHCb experiment on one side of IR8 only.

MQW MAGNETS

The MQW magnets are built by ALSTOM Canada in collaboration with TRIUMF. In total 48 MQW magnets will be installed in the LHC. Until September 2003, all the 48 magnets and 4 spares will be ready at CERN.

MBW MAGNETS

Characteristics (Table 1)

In contrast to the other warm separation dipoles, the MBW yoke shape features two distinct apertures for a larger beam separation.

Magnetic measurements at BINP

BINP uses a hall probe array for the magnetic measurements. The technical specification of the magnets requires an integral field error on 2 orbits separated by 209 mm of better than:

- $\pm 5.10^{-4}$ at 0.09 T in a region of ±25 mm
- $\pm 5.10^{-4}$ at 1.42 T (720 A) in a region of ±12 mm

Table 1: MBW magnet characteristics

	Unit	Value
l_{core}	mm	3400
l_{magnet}	mm	3796
w_{core}	mm	1080
w_{magnet}	mm	1080
h_{core}	mm	730
h_{magnet}	mm	810
pole gap	mm	52
coils		2 coils of 42 turns
Cu cross-section	mm^2	18 X 15
Cu hole diam.	mm	8
B	T	0.09 to 1.42
$B_{ult.}$	T	1.53
$I_{nom.}$	A	~710
$I_{ult.}$	A	810
Weight	t	18

Fig. 1 shows that the magnetic field error of the pre-series magnet is well within the specifications.

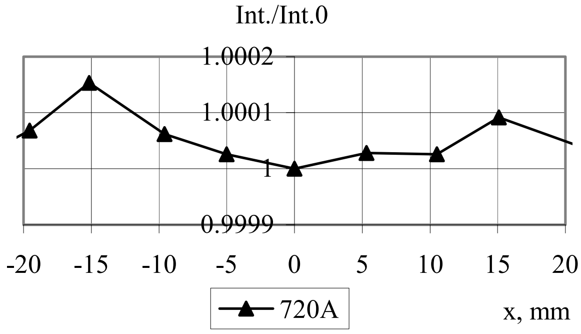

Figure 1: Integral field error of the pre-series magnet MBW01 at nominal field after shimming; aperture 1, y=0.

Status

The pre-series magnet arrived at CERN in December 2002. The series production delivery schedule foresees that all dipole magnets will be at CERN at least 3 months before their installation (rev.1.7) in order to do acceptance tests, and to furnish them with alignment target holders and the vacuum chamber.

MCBW MAGNETS

Characteristics (Table 2)

Magnetic measurements at BINP

The technical specification requires an integral field error in a region of ±23 mm of better than:

- $\pm 5.10^{-4}$ at 0.1 T
- $\pm 3.10^{-4}$ at 1.1 T (550 A)

Table 2: MCBW magnet characteristics

	Unit	Value
MCBWH		
l_{core}	mm	1700
l_{magnet}	mm	2056
w_{core}	mm	746
w_{magnet}	mm	746
h_{core}	mm	494
h_{magnet}	mm	649
MCBWV		
l_{core}	mm	1700
l_{magnet}	mm	2008
w_{core}	mm	494
w_{magnet}	mm	720
h_{core}	mm	746
h_{magnet}	mm	854
MCBW		
pole gap	mm	52
coils		2 coils of 42 turns
Cu cross-section	mm^2	16 X 10
Cu hole diam.	mm	5
B	T	0.0 to 1.1
I	A	0 to 500
weight	t	4

Fig. 2 shows that the magnetic field error of the pre-series magnet is well within the specifications.

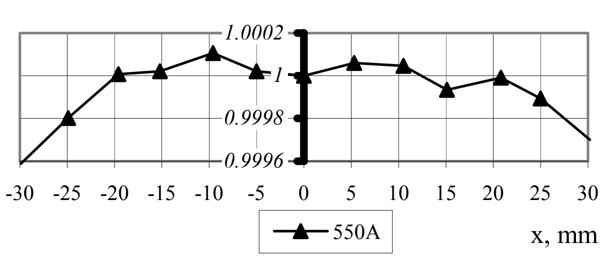

Figure 2: Integral field error of the pre-series magnet MCBWH01 at nominal field after shimming; y=0.

Status

The pre-series magnet arrived at CERN in April 2003.

MBXW MAGNETS

Characteristics (Table 3)

Magnetic measurements at BINP

The technical specification requires an integral field error in a region of ±41 mm of better than:

- $\pm 5.10^{-4}$ at 0.08 T
- $\pm 2.10^{-4}$ at 1.38 T (750 A)

Figure 3 shows that the magnetic field error of the pre-series magnet is well within the specifications.

Table 3: MBXW magnet characteristics

	Unit	Value
l_{core}	mm	3400
l_{magnet}	mm	3814
w_{core}	mm	870
w_{magnet}	mm	870
h_{core}	mm	598
h_{magnet}	mm	678
pole gap	mm	63
Coils	mm	2 coils of 48 turns
Cu cross-section	mm^2	18 X 15
Cu hole diam.	mm	8
B	T	0.08 to 1.38
B_{ult}	T	1.48
$I_{nom.}$	A	~750
I_{ult}	A	830
weight	t	11.5

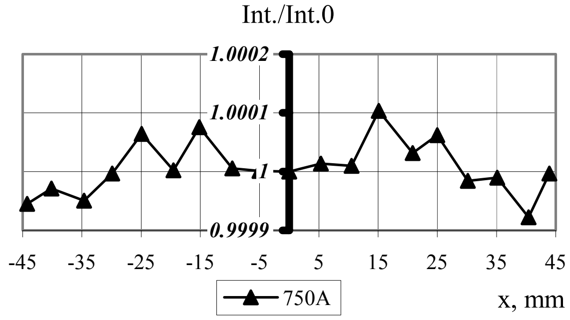

Figure 3: Integral field error of the pre-series magnet MBXW01 at nominal field with corrected shims; y=0.

Status

The pre-series magnet arrived at CERN in January. 2003.

ACCEPTANCE TESTS AT CERN

For acceptance at CERN, the water-cooling circuit and its interlock system, the resistance, the inductance, and the insulation of the coils are tested for all MBW, MBXW, and MCBW separation dipole magnets. Additionally the multipole components of 3 magnets of each type (the pre-series one, one during, and one at the end of production) are measured by the AT/MTM group with rotating coils.

MBW multipole measurements

The Hall-probe measurements on the MBW pre-series magnet at BINP have been verified to be in very good agreement with multipole measurements at CERN with the advantage of a higher precision of the rotating coil system. Table 4 shows multipoles of aperture 1 at injection at two extreme beam positions A and B.

Table 4: Multipoles of aperture 1 at injection at two extreme beam positions A and B

normal	ap. 1A	ap. 1B	skew	ap. 1A	ap. 1B
b_2	-1.39	1.06	a_2	-0.11	-0.29
b_3	0.85	1.45	a_3	0.05	0.05
b_4	0.44	-0.09	a_4	-0.05	0.00
b_5	-0.16	-0.38	a_5	0.00	-0.04

CONCLUSIONS

While the delivery of the MQW magnets will be finished in September 2003, the series production of the MBW, MBXW, and MCBW dipole magnets is ready to start. All the pre-series magnets passed the basic acceptance tests. Hall-probe measurements of the pre-series magnets at BINP are within specification and compare well with rotating coil measurements at CERN. The delivery schedule foresees that the magnets are available at CERN at least 3 months in advance of their installation.

TUNNEL INTEGRATION AND INSTALLATION OF LOW-BETA TRIPLETS: EXAMPLE OF IR8

S. Bartolomé Jiménez, CERN, Geneva, Switzerland

Abstract

Installation of the Inner Triplets (Q1-Q2-Q3), DFBX and Separation Magnets (D1, D2) needs to be dealt with specifically for each of the four Insertion Regions. This paper focuses on the main aspects and difficulties for the integration [1], the installation and the transport of these components in IR8 and gives an overview of the problem in the remaining insertion regions.

EXAMPLE OF IR8

The underground structures where the Inner Triplets, DFBX and D1, D2 will be installed are RB84, UJ84 and RA83 for the left side of IR8, and RB86, UJ86 and RA87 for the right side.

Difficulties for the installation of these items in IR8 have arisen from the specific geometry of this region, i.e., distance between IP8 (interaction point) and MP8 (centre of the experimental cavern) is 11,220m (see Fig. 1).

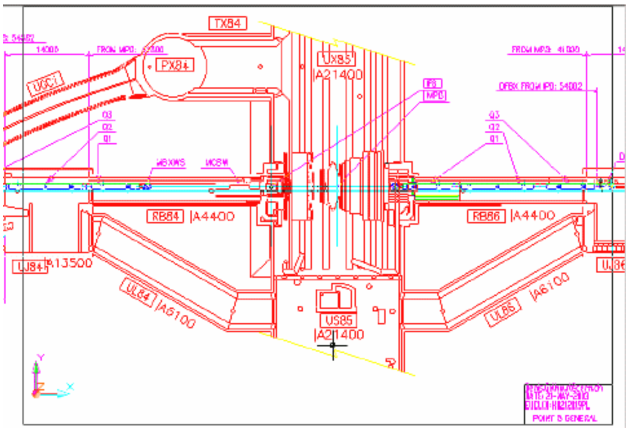

Figure 1: Location of Q1-Q2-Q3 in IR1.

Moreover, LHCb spectrometer magnet is a dipole so it requires the presence of warm magnets (MBXW and MBXWS) and the fact that the injection occurs in IR8 explains the presence of a TDI (similar configuration shall be found in IR2, due to ALICE experiment).

The alignment system in the vertical plane shall be achieved by the Hydrostatic Levelling System (HLS) that shall be installed from Q3 left to Q3 right through the main tunnel and the UX85 cavern. Its mechanical integration is currently under study.

Integration and installation of IR8 left

The integration studies of this zone have been completed and, in principle, no specific problems are expected for the installation and/or disassembly of the items concerned. LHCb experiment [2] requires the installation of a 1000mm thick shielding plug in RB84, by the end of 2005, whose position, as it has been defined so far, shall not interfere with MBXW magnet.

The installation of IR8 left [3] shall start in August 2004.

Integration and installation of IR8 right

Due to the 11,220m distance between IP8 and MP8, the items functional position is closer to LHCb than in IR8 left; more precisely, MBXWS and Q1-Q2-Q3 are located in RB86.

Integration of these items is already completed. However, feasibility studies of the logistics involved have shown that the standard tools and vehicles can not be used for transporting Q1 and Q2 to this zone, and consequently, studies are being carried out in order to provide a solution to this problem.

An option under consideration proposes to use 24m long rails, fitted in the RB86 floor, to transport Q1 and Q2 to their right position and then, to transfer them on the jacks by means of the transfer equipment sets. This option involves non-negligible civil engineering works and a high cost investment, and should be compatible with the installation schedule. Since the solution adopted for IR8 shall be also applied for IR1, IR2 and IR5, further alternatives should be evaluated before any decision is taken, such us the use of the monorail line, commercial standard handling equipment designed for short distance and heavy loads transport, etc.

LHCb requires a 2000mm thick shielding plug in RB86, by the end of 2006, whose position shall interfere with Q1. This shielding should permit access to MBXWS magnet for installation and/or dismount (see Fig. 2). The design of this shielding is presently under consideration.

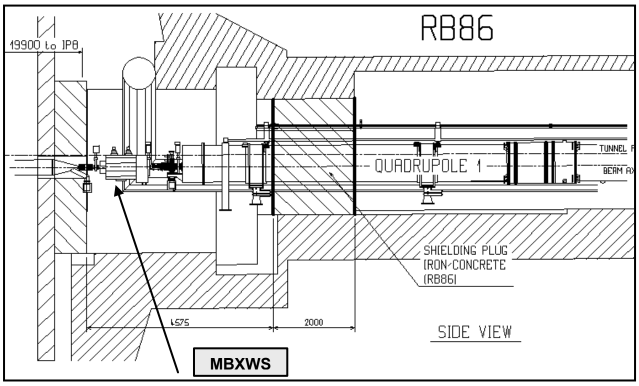

Figure 2: MBXWS, Q1 and shielding plug in RB86 [2].

The installation start date of these components is scheduled in January 2005 [3].

OTHER INSERTION REGIONS

IR2

The layout of this insertion region follows a similar configuration to IR8. Hence, the transport method to be adopted for RB86 should be also implemented for the transport of Q1-Q2 in IR2 left.

ALICE requires shielding plugs in both sides of the experiment. The precise composition of the shielding, design and right location have to be determined.

The mechanical integration of the HLS network, interconnecting both Q3 magnets through the UX25 cavern, is underway.

IR1

The items of this insertion region are located symmetrically with respect to the IP1. Q1 magnets shall be installed partially in the ATLAS shielding plugs situated after RB14 and RB16. Transport and installation in these zones are a main concern and are not defined yet.

The HLS network and the Offset Reference line (ORL) to achieve the horizontal alignment shall be installed in the UPS galleries excavated for this purpose. Currently, the mechanical integration is under study.

IR5

This insertion region's items are positioned symmetrically with respect to the IP5. Part of the Q1 magnets shall be installed in the approximately 4x2x2(m) CMS shielding in UXC55. For the installation of the DFBX, 150mm deep holes have been dug in UJ56 and RZ54 caverns. As already mentioned for the other three insertions, the transport and handling tools and the installation procedure have to be determined. The mechanical integration solutions for the HLS and ORL networks in the UPS galleries shall be applicable for both IR1 and IR5.

TRANSPORT ISSUES

The vehicles and handling tools for the transport of the Inner Triplets, DFBX and D1, D2 as well as the trajectories from the surface into the tunnel have to be thought about in order to find the optimum solution to each specific case. Thus, DFBX's are compact elements (see Table 1 for dimensions) which could be lowered down the PM's pits; however, should not pass through the injection tunnel TI2 due to its limited section space.

Other items to be focused on are the D2 magnets, delivered with a high jumper installed, that makes the total height be 1780mm (see Table 1). Therefore, they are too high to be lowered down the PMI2 and then transported through TI2, and they are too long to be lowered down most of the other pits (born in mind that PX's pits can be used with restrictions and are mainly reserved for the experiments).

The rest of the items here concerned could be lowered down PMI2 and transported along TI2.

Table 1: Overall dimensions and weights

Type	Qty	Length in transport configuration L (mm)	Transport weight W (tons)	Outer ring diameter R (mm)	Total height with jumper J (mm)	Maximum tilt	
						X axis	Y axis
Q1 – IR1, 2, 5, 8	8	8492	15	1055	-------	+/- 1.4%	+/- 1.4%
Q2 – IR1, 2, 5, 8	8	13213	18				
Q3 – IR1, 2, 5, 8	8	9029	15				
DFBX – IR1, 2, 5, 8	8	2587	6		2071		
D1 – IR2, 8	4	11263	4.73	750	-------	+/- 1.4%	+/- 1.4%
D2 - IR5	2	11361	22.7	1055	1500		
D2 – IR1, 2, 8	6				1780		

CONCLUSIONS

The Insertion Regions, as they constitute the interface between the experiments and the LHC machine, are composed of a great variety of items delivered from different suppliers, some requiring permanent alignment and positioning (Q1-Q2-Q3) and, often, located in zones of limited space and accessibility for their installation. Moreover, the logistics requires dedicated solutions to cope with the difficulties arising from the fact that the overall dimensions are not always within the limits.

The installation planning of these regions has to be consolidated on the basis of the delivery of all the components and accessories.

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THE CRYOGENIC ELECTRICAL DISTRIBUTION FEEDBOXES AND THE SUPERCONDUCTING LINKS OF LHC

A. Perin, V. Benda, R. van Weelderen, CERN, Geneva, Switzerland

Abstract

The superconducting magnets of LHC, operating at 1.9K and at 4.5K, are powered via more than 1000 electrical terminals supplying currents ranging 60A to 13kA. This article briefly describes the CERN supplied cryogenic electrical distribution feedboxes and the superconducting links that are required to transfer the electrical currents from the power supplies cables operating at room temperature to the superconducting bus bars at liquid helium temperature.

INTRODUCTION

Where the space in the LHC tunnel is sufficient, the current is transferred to the arc magnets or to standalone magnets through locally installed cryogenic electrical distribution feedboxes (DFB). When the integration of a DFB is not possible close to the superconducting magnets, the magnets are powered through superconducting links (DSL) that connect the DFBs and the superconducting magnets on distances varying from 70m to 500m.

ELECTRICAL DISTRIBUTION FEEDBOXES

There are 3 types of electrical distribution feedboxes:

- The DFBAs, connected to each end of the LHC octants, ensuring also the functions of arc termination. There are 16 DFBAs in the LHC.
- The DFBMs, powering standalone magnets in the long straight sections. There are 23 DFBMs in the LHC.
- The DFBLs, powering the superconducting links. They also supply a cryogenic interface for the DSLs. There are 5 DFBLs in the LHC.

Except for the DFBAs, that also ensure the termination of the LHC arcs, the main function of the DFBs is to transfer high currents from room temperature cables to superconducting bus bars via current leads. The current leads are gas cooled devices designed to transfer high currents with limited transmission of heat to the 4.5K liquid helium in which the bus bars are immersed. The variants of DFBs, the types of current leads and their respective number for each type of DFB are summarized in Table 1.

Table 1: List of DFB and their current leads

DFB type	Number	Type of leads (nb/DFB)
DFBA	16	13kA (2-6), 6kA (12-15), 600A (44-62), 120A(0-4)
DFBM	23	6kA (3-5), 600A(4-12)
DFBL	5	6kA (0-5), 600A(0-44), 120A(0-12)

Design of the DFBs

The DFBs are of modular design. They consist of two types of current leads modules, assembled together with interfaces and other specific equipment that depend on the requested configuration. The high current module integrates 13kA and 6kA leads while the low current module integrates 6kA, 600A and 120A leads. The number of leads and their arrangement is different for each DFB.

A summary of the basic configurations for the 3 types of DFBs is shown in Fig. 1.

A view of the DFBA located at the left side of IR8, therefore powering sector 7-8, is shown in Fig. 2. This DFBA, a typical example of the above cited modular design essentially consists of:

- The shuffling module: this equipment ensures the arc termination functions and also allows the rerouting of the bus bars to the current modules. It withstands all forces related to its position at the end of the arc, while ensuring a very precise positioning of the beam pipes.
- A high current module connected to the shuffling module and integrating a jumper connection to the QRL.
- A low current module.

All DFBs are built by combining the two types of current lead modules and equipment specific to each DFB.

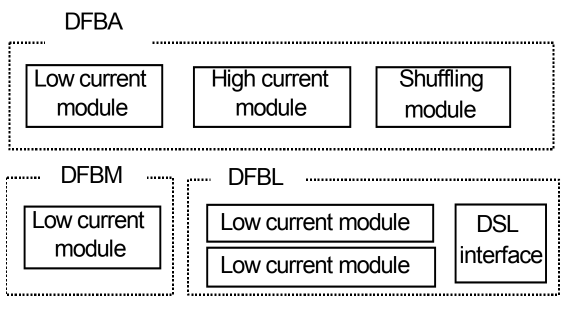

Figure 1: Schematic representation of the DFB configurations.

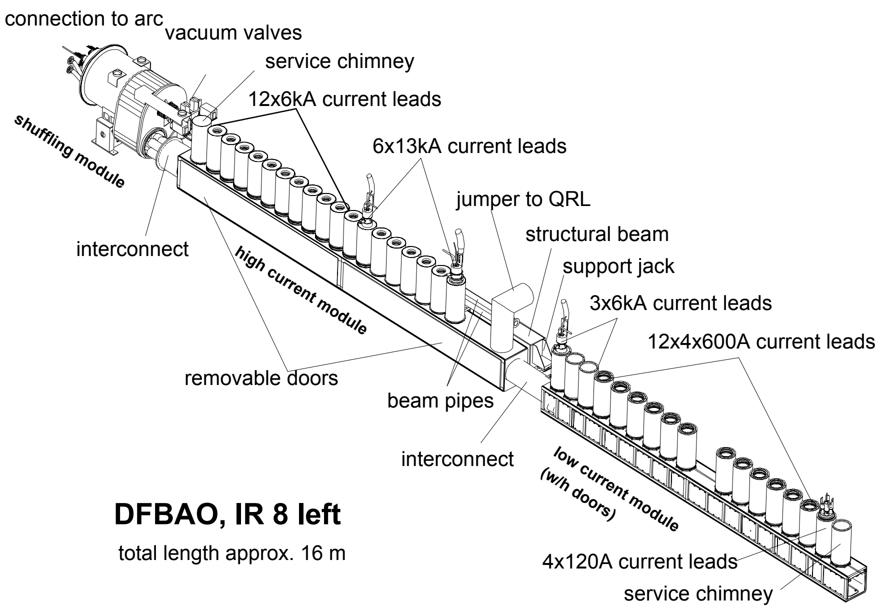

Figure 2: DFBA of IR 8 left, powering sector 7-8 of the LHC.

SUPERCONDUCTING LINKS

When the integration of a DFB close to the magnets is not possible, the electrical current is transferred from the DFBs to the LHC magnets through superconducting links (DSL).

Five DSLs will be needed. One of them will be exceptionally long, about 500 m in length without any intermediate branches. It will link the 3 km long continuous cryostat of accelerator magnets of Arc 3-4 of the LHC to a current feed box located in UJ33 some 500m away. Besides its power transmission function, the link will also need to provide the cryogens for this current feed box. Additional four, significantly shorter, links will be used at points 1 and 5 of the LHC machine to bring power from current feed boxes to individual magnet cryostats (Q6, Q5 and Q4D2). Each of those four links will be about 70 m in length with two intermediate branches, roughly 3 m in length, to individual magnet cryostats. A summary of the characteristics of the superconducting links of LHC is shown in Table 2.

Table 2: List of the DSLs

DSL type	length	Connected to
DSLA, DSLB DSLD, DSLE	70m	DFBL & Q4D2, Q5, Q6
DSLC	500m	DFBL & DFBA

Design

The DSL consist essentially of cryogenic, vacuum insulated, transfer lines housing one or more superconducting cables. Superconducting links are used for several circuits with current ranging from 120 A to 6kA. Nominal operation temperatures will be from 4.5 K to 6 K for the part which houses the cable, and about 70 K for the heat shielding. Cross sections of the two types of DSLs are shown on Fig. 3.

CONCLUSION

The complex task of powering the LHC superconducting magnets in the very limited underground available space will be performed with a combination of locally installed cryogenic electrical distribution feedboxes and the use of superconducting links for the locations where the space limitations do not allow the installation of DFBs.

ACKNOWLEDGEMENTS

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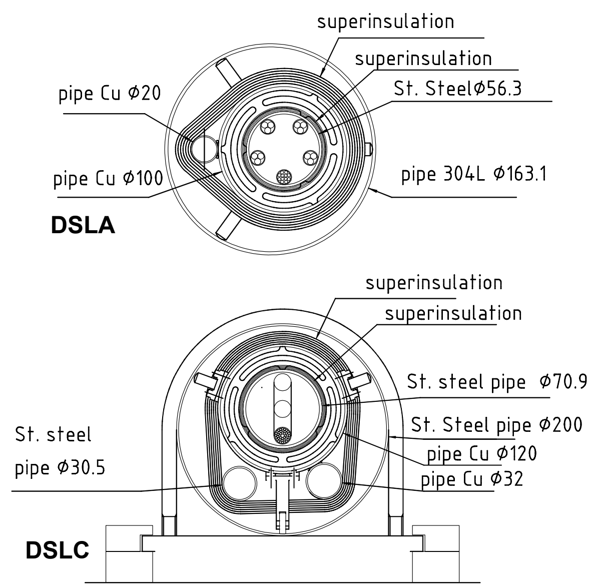

Figure 3: cross sections of the two types of DSL.

BEAM VACUUM SYSTEM IN THE LONG STRAIGHT SECTIONS

C. Rathjen, CERN, Geneva, Switzerland

Abstract

An overview of the status of the vacuum system in the long straight sections (LSS) of the LHC is given. The overview concentrates on the warm part of the LSS. The base line and standards are presented. Special solutions are required in several areas, in particular for warm magnets and recombination zones.

INTRODUCTION

Work for the LSS initially focussed on the cold parts, which are now well advanced. Following a conceptual design review for the warm part of the LSS in November 2001, many components have been standardised. Due to a high modularity, the total number of components could be reduced. These components are now going into production phase. Special solutions are required in particular for the warm magnet vacuum system and for the recombination zones. Most of them are challenging and still under development. For many components the design can only be done in combination with mechanical integration studies, which have to run in parallel. Mechanical integration is therefore essential to finalise designs. Besides the special solutions, installation and commissioning of the LSS will be a future challenge.

COLD PART OF THE LSS

Status: Beam screen dimensions and positions are fixed. Manufacture contracts for 50, 53, 63, 69 and 74 mm cold bores are placed. Due to the late decision on the beam screens, their delivery will be 6 month late compared with the general LHC coordination schedule. New cooling tubes exits for the rotated beam screens are still under development. The new cold warm transitions have been integrated in the cryo-magnet and the DFBA designs. Cryosorbers for 900 m of cold vacuum in D2 and Q4-6 at 4.5 Kelvin have to be provided.

WARM PART OF THE LSS

Status: Instrumentation layout and cabling is finished for the interaction regions (IR) 2R, 3L, 7R, and 8L; 1L is currently under work. The mechanical integration was carried out for these zones but has to be repeated because of a new layout/optic version. The design for several standard components – in particular standard drift tubes, bellows modules, supports and pumping stations – is well advanced; the production phase is starting now. For the standard bakeout equipment, tests are currently performed and specifications are compiled. Special, non standard solutions are under development. In particular these are vacuum systems for warm magnets, recombination zones in IR 1, 2, 5, 8, including the experimental vacuum chamber for the X2ZDC calorimeter, special bellows modules for the warm magnets and big drift spaces, special chamber supports and the chamber alignment.

Baseline for the warm vacuum system of the LSS

Wherever possible, NEG (non evaporable getter) coated, 80 mm copper chambers (2 mm wall thickness) will be installed. The standard length is 7 m. Shorter chambers are foreseen for length adaptation between fixed components (e.g. cryostats or collimators). The maximum foreseen temperature for NEG activation and reconditioning is 250 °C. 300 °C is the design temperature for baked components in order to provide a safety margin. Wherever possible, separate vacuum systems should be foreseen for each beam line. At each cold-warm transition, sector valves are foreseen. Additionally, integration rules exist for: directions of expansion (towards IP), cross-sectional transitions (if possible inside bellows modules), and interfaces to components (flexible side of modules towards fixed component).

Standards

Fig. 1 shows standard components in a vacuum sector. Besides the 80 mm copper drift tubes, bellows modules play a central role in the standardisation and the reduction of variants. Up to 80 mm inner diameter DN 100 modules are foreseen in two lengths. While the short modules (200 mm) only provide compensation for length and offsets, the longer modules (300 mm) optionally provide ports and supports. Inserts inside the modules adapt to chamber diameters and provide cross-sectional transitions. With the aid of the modules, sector valves can be integrated in compact, self-standing assemblies. A further standard component is the support for 80 mm drift tubes. The design decouples adjustment and fixation in the aligned position. Thanks to the demountable adjustment tooling, supports are in total cheaper than conventional designs.

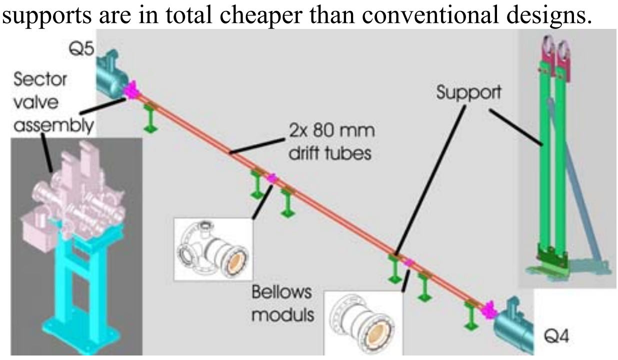

Figure 1: Simple drift space at IR 8L/Q4-Q5.

Special solutions

A further chamber type is the 212 mm stainless steel drift tube for the recombination zones in IR 1, 5 and 8.

For these chambers a special bellows module and support variants are developed. With these components, standards exist for the recombination zones as well. An exception is the recombination zones in IR2, where big vacuum vessels for the X2ZDC calorimeter require special engineering. One design study proposes a 30 m long tube on rollers to suppress expensive bellows (ID 797 mm). The RF transition, which should be transparent to the experiment, requires special attention (see Fig.2).

The warm magnets in the LSS (MQW, MBXW, MBW, MCBW, MSI, MSD) require dedicated vacuum systems. Beside MSD/MSI magnets, the MQW magnet poses the highest requirements in terms of aperture. A first chamber design did not provide sufficient aperture and could not be baked above 200 ºC. A special chamber geometry in combination with a thin bakeout system is under development to provide sufficient aperture and low impedance. The new polyimide/stainless steel bakeout system offers the potential of substantial cost savings. After successfully testing, the industrialisation of the bakeout system has to be solved. To further reduce heat losses, an additional reflective screen is under study. A technology transfer to other magnets is foreseen. Still to be solved is the in-situ welding of one flange to a copper chamber (magnets cannot be opened for installation). This is particularly difficult since the chambers are NEG coated and wrapped in polyimide foil.

Furthermore chamber supports and bellows modules have to be developed for the warm magnets.

Simple solutions to align vacuum components have to be provided especially for long drift spaces.

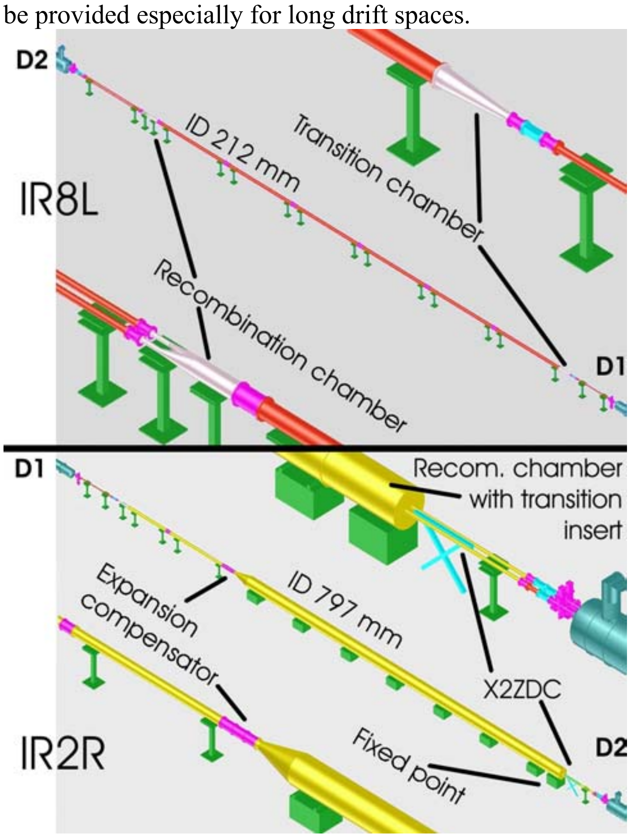

Figure 2: Recombination zones in IR 2 and 8.

COMPLICATIONS

In performing the mechanical integration for the vacuum system in the LSS, the following problems were encountered: Many components in the LSS, in particular the collimators are still poorly defined (number, positions, dimensions). Components on single beam lines require special supports. Gaps smaller than 200 mm cannot be closed due to non existing bellows modules. Non vacuum components interfere due to insufficient space (eg.: roman pots and collimators at IR5). New layout/optics versions and possible shielding prevent the completion of the mechanical integration, which hinders or blocks the design of components that rely on the input from the mechanical integration. Radiation doses are only partly known. Planning of interventions and necessary improvements of the design are not yet possible.

WARM PART OF LSS IN NUMBERS

About 1200 chambers have to be provided for the LSS. Among them are 600 long and 200 short standard 80 mm drift tubes, 330 warm magnet chambers, 40 big drift chambers (212 mm) and some transition chambers, where transition cannot be performed with bellows modules. There are 1800 bellows modules: mainly modules with DN100 bodies in 25 variants and about 70 special modules for bigger diameters in two variants. Furthermore 2400 supports, 240 sector valves, 600 gauges and 500 ion pumps have to be provided.

PLANNING

The preferred installation scenario for the LSS foresees an installation of special machine components (stand-alone cryostats, warm magnets, collimators, etc.) first since they are taken as a reference for the alignment of warm vacuum components. Installation of vacuum components first is not recommended since it requires additional reference points and realignment after missing machine components are installed. A vacuum sector should be installed and commissioned in a short period of time to avoid long exposure of UHV components to air.

At the moment the LHC construction and installation schedule (Rev. 1.7) does not allow a detailed production and installation planning for the LSS. Only a fraction of vacuum sectors is free of non vacuum components (see Fig.2); these sectors could be installed from mid 2004.

SUMMARY

Components for the warm part of the LSS have gained a high level of modularity and standardisation. Special zones in the LSS are still in the development phase. Work on the mechanical integration is hindered by unfinished layout/optic version. Finalisation of designs and inventories are therefore blocked. Production cannot start for many components.

The installation in many vacuum sectors depends on components which are late (e.g. collimators). The closure of the LHC in time will be a challenge in terms of logistics and resources for the vacuum group.

SUMMARY OF SESSION 5: INTERFACES TO EXPERIMENTS AND OTHER SYSTEMS

J. Bremer, R.Veness, CERN, Geneva, Switzerland

Abstract

The session on interfaces with experiments and other systems contained a diverse range of presentations covering both the experimental areas and the insertion regions (IRs) of the LHC. A number of general issues for the IR design and commissioning were revealed, as well as specific issues for the systems concerned.

This note summarises the issues that were raised, both in the presentations and in the following discussions.

INTRODUCTION

Session 5 of the 2003 LHC Days workshop covered 'Interfaces with Experiments and Other Systems'. The session can be broken down into three areas. It started with presentations on the interfaces with the ALICE, CMS and TOTEM experiments, made by representatives of the experiments. There followed two presentations on technology supplied to the experiments by the AT division, specifically the experimental vacuum systems and the detector cryogenic systems. Then the session closed with two presentations on key systems for the LHC from the AB division: the beam collimation and the injection and ejection systems.

Despite the broad range of subjects discussed, a number of common themes were apparent. These are presented in the following chapter. A number of issues specific to areas or presentations then follow. Summaries of the individual presentations are given in other notes in this publication.

COMMON THEMES

Machine Layouts

It became clear during the session that a number of systems plan changes to the layouts of the insertion regions (IRs) of the LHC, either before or after first beam. Two particular examples of 'pre-first beam' changes are the beam collimation system and the TOTEM experiment. Both of these systems are still in a design stage, and have a number of uncertainties in their specific requirements for space and position in the IRs. These may result in requests to change the machine layouts over the next year. In addition, since the LHC Days, the ATLAS experiment has announced that it intends to implement a similar system of Roman Pot detectors to TOTEM. These are not included in the actual machine layouts.

The discussions during the session revealed that due to the level of advancement of the design, in particular as the cabling of the tunnel is under way, and the vacuum chambers are being manufactured, any changes to the layouts will have a significant cost impact. It was agreed that all such changes would need to be agreed and documented as Engineering Change Requests.

System Upgrades

A number of the systems presented plans for upgrades after first beam. The CMS and TOTEM experiments had well developed plans for changes to machine systems for nominal luminosity operation. Specifically, the CMS experiment may wish to re-design part of the beam vacuum chamber in the experiment. TOTEM discussed a number of possible design changes, including detectors inside magnet cryostats. The collimation system is being designed for nominal luminosity. However it will require upgrading for ultimate conditions.

Commissioning

A number of presentations touched on the issue of both system and hardware commissioning. It became clear that these operations will be complex in the experimental insertions. There are a number of interlinked and order-sensitive operations for commissioning of the experimental vacuum systems and the roman pots. These will require coordination of machine and experiment schedules and resources.

Transport

The experiments are currently involved in a series of installation reviews requested by the LHCC. These have shown the experiments to be generally well advanced and coordinated with CERN transport services. The presentations in this session demonstrated the large volume of material to be transported by the experiments over the coming years. In the discussions, the issue of potential resource conflicts between machine and experiment installations was raised.

Both ALICE and CMS presented the current status of their manufacture and installation.

First Beams

Despite some problems with civil engineering and detector construction, both ALICE and CMS expressed confidence that they would be ready for first beam in April 2007. This will be achieved in part by staging the installation of certain sub-detectors. Specifically, parts of the ALICE TRD and PHOS detectors will not be installed for first beam due to funding limitation. Parts of the CMS end-caps will only be installed for high luminosity running and, more importantly, the Pixel detector will not be installed for machine commissioning and pilot runs. This has an impact on the machine schedule in the first year, as CMS are requesting a 3 month shutdown in the summer of 2007 to install this detector. Since ALICE does not request this shutdown, some discussion with all LHC experiments will be required to resolve the issue.

The experiments were also keen to stress the point that new and potentially exciting physics can be done with only a few fills (proton or ion) and at considerably less than nominal luminosity. They are keen to see colliding beam physics operation from the LHC at the earliest opportunity.

SPECIFIC ISSUES

ZDC and LHC Luminosity Measurement

The long straight sections in IR2 contain a Zero Degree Calorimeter (ZDC) detector belonging to the ALICE experiment at the point where the one vacuum chamber from the experimental sectors become the two vacuum chambers of the standard machine. There is also a plan to install a 'standard' luminosity measurement system in all experimental insertions. There appears to be some conflict of space requirements for the two systems in IR2 that should be addressed.

Activation of LAr

The possibility of activation of the liquid argon used in the ATLAS liquid argon calorimeter and subsequent problems of handling and disposal was raised during the discussion session. This question was referred to the ATLAS group responsible for the system. They confirmed that the issue had been considered in the design, but that there would be no significant activation of argon during the LHC lifetime.

Beam Collimation system

It was clear from the presentation on this subject that there a number of technical challenges to be overcome to reach the nominal LHC performance requirements. In particular, reaching an acceptable level of beam impedance will be difficult with the preferred choice of material.

A very active design and development programme is under way in order to meet the tight deadlines by the LHC schedule.

CONCLUSIONS

Manufacture and assembly of the LHC detectors is advancing rapidly and the experimental collaborations express confidence that they will be ready for startup of the machine. The experimental vacuum systems and cryogenics supplied to the experiments by the machine sector also seem to be advancing as required. The two other systems discussed: beam collimation and injection / ejection systems are clearly complex and critical for machine operation.

A number of machine / experiment interface issues were revealed during the session. It will be important to maintain close communication between the various hardware, installation and commissioning groups during the coming years to resolve these issues and ensure rapid startup of physics operations.

THE COMPACT MUON SOLENOID (CMS) EXPERIMENT: THE LHC FOR HIGH ENERGY AND LUMINOSITY

E. Tsesmelis, CERN, Geneva, Switzerland

Abstract

CMS is one of the two high luminosity and high energy experiments at the LHC. It will be largely assembled and tested on the surface before being lowered into a specially-constructed cavern at Point 5 of the LHC. A brief description of the experimental area and of the detector construction and assembly status will be given and some specific interface issues with the LHC machine will be elaborated.

INTRODUCTION

The CMS Collaboration is constructing a general-purpose proton-proton detector, which is designed to exploit the full discovery potential of the LHC machine. The experiment will be operational at the start-up of the LHC and will be able to investigate the physics accessible during the initial lower luminosity running as well as handling the highest luminosity that will be available later from the machine.

The primary aim of the experiment is to discover the Higgs boson and to search for other new particles predicted in theories beyond the Standard Model such as supersymmetry, or SUSY for short. In the framework of the Standard Model, particles acquire mass through their interaction with the Higgs field. This implies the existence of a new particle – the Higgs boson H^0. In extensions to the Standard Model such as the Minimal Supersymmetric Standard Model (MSSM) there are 5 Higgs bosons – h^0, H^0, A^0 and $H^{\pm}$. CMS has been optimised to discover the Higgs bosons in the complete expected mass range. SUSY also predicts that for every known particle there is a `sparticle' partner equal in charge but differing in spin. Production of `sparticles' will reveal itself through spectacular kinematical spectra even at low operating luminosities.

Moreover, the CMS experiment will be able to study the products from colliding beams of heavy nuclei such as lead. Collisions between these nuclei will produce `little bangs' at an equivalent temperature around 100,000 times that at the centre of the Sun, and a density up to 20 times that of normal matter. Under these extreme conditions, which mimic those in the period less than 1 second after the Big Bang, the constituent protons, neutrons and gluons `melt' to form a `Quark-Gluon Plasma' (QGP). CMS is well-suited to study some aspects of the formation of the QGP.

THE POINT 5 EXPERIMENTAL AREA

The CMS detector will be hosted at the LHC Point 5 experimental area located at Cessy in France. The surface area is dominated by the SX5 main assembly hall. Other buildings to be used for gas, primary cryogenics, cooling, ventilation and the CMS control room will also be provided. The underground areas include the experimental cavern UXC55, the auxiliary service cavern USC55, the access pits PX56, PM54 and PM56 and the LHC machine by-pass tunnel.

Civil engineering works at Point 5 have been advancing well. Most of the surface buildings have already been handed over to CMS and excavation of the two underground caverns has been completed. Concreting of the floors is well-advanced in both caverns.

However, although the cavern crowns have been strengthened, water leaks have now appeared in both the PX56 and PM54 access shafts. Repair work must be carried out, and the extra time required to do this is under evaluation. Delays must be mitigated, particularly for the USC55 cavern since outfitting this cavern is on the critical path for operation in April 2007. Outfitting the USC55 service cavern is critical due to the short time available to install and commission the Trigger and DAQ system.

An agreed management structure for the Point 5 experimental area has been put in place, whereby the newly-formed EST-IC group provides the general management of Point 5 and CMS, together with the EST-LEA group manage, well-defined zones within this experimental area.

Sharing of the experimental area between CMS and the LHC Machine has also been agreed. Space for power supplies and control racks for LHC machine components such as the DFBX and vacuum equipment has been reserved in the USC55 cavern and the detailed lay-out of this zone is being worked-out. The PM54 shaft is a shared access for CMS and the LHC Machine and the PM56 shaft is to be made available to CMS as an emergency exit for personnel. The by-pass tunnel is reserved for the passage of LHC machine components. The Point 5 underground experimental area is shown in Figure 1.

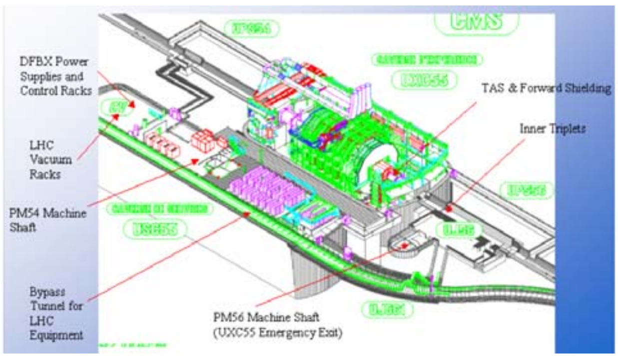

Figure 1: The Point 5 Underground Experimental Area.

THE CMS DETECTOR

Central to the design of CMS is the superconducting solenoid magnet. The solenoid will be 6 m. in diameter and 13 m. long. It will generate a field of 4 T, meaning that the stored energy will be 2.5 GJ.

A particle emerging from the collision point and travelling outwards will first encounter the Tracking system – consisting of the Pixel and Silicon Strip Tracker detectors. They will measure precisely the positions of passing particles allowing the particle track to be reconstructed. Charged particles will follow spiralling paths in the CMS magnetic field and the curvature of their paths will reveal their momenta. The energies of the particles will be measured in the calorimeters forming the next layers of the detector. The electromagnetic calorimeter (ECAL) is designed to measure the energies of electrons and photons. Hadrons deposit most of their energy in the next layer, the hadron calorimeter (HCAL). The only particles to penetrate beyond the HCAL are the muons and neutrinos. Muons will be tracked in dedicated muon chamber detectors – the drift tube (DT) and cathode-strip detector (CSC) - and their momenta will be measured from the bending of their paths in the CMS magnetic field. Dedicated muon chambers – resistive plate chambers (RPCs) – will provide the time and position of a muon hit with the accuracy required for trigger purposes. Since neutrinos are neutral and hardly interact with matter, their presence will be inferred by the `missing momentum' when adding up the momenta of the detected particles. Figure 2 shows the CMS detector.

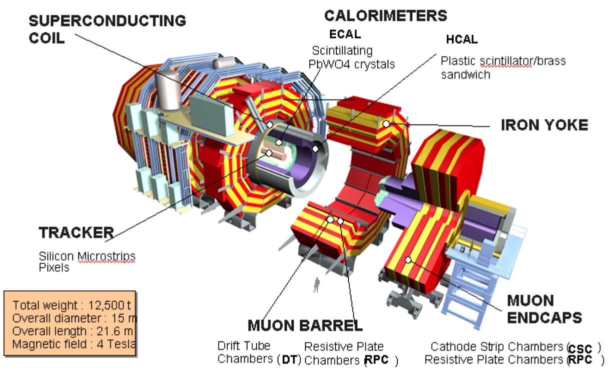

Figure 2: The CMS Detector.

CMS has been engineered from the beginning to ease installation, access and maintenance. Dividing the barrel yoke of the magnet in 5 ring-sections and the end-cap yoke in 3 disks allows all sub-detectors to be maintainable by opening CMS in large sections to provide a nominal maximum opening of 10 m. Movement of the sections is possible without de-cabling attached sub-detectors and without breaking the chain of services. Each major yoke section is supported on horizontal grease pads for movements of up to 300 mm. and can be moved on air pads up to 10 m. The added benefit of the grease pads is that CMS can be easily realigned around the beampipe to within ± 50 mm in all directions.

While waiting for the underground caverns to be completed, CMS is being assembled and tested in the SX5 surface hall. This provides the advantage of minimising the underground assembly operations while at the same time allowing CMS to rehearse the risky operations on the surface and to cope with the unplanned spread of the sub-detector delivery.

Once the underground hall will be available and following the surface magnet tests in mid-2005, all heavy elements of the detector will be slid over the SX5 building floor using high-pressure air pads to the top of the mobile radiation shielding plug above the PX56 shaft. This plug, which will be constructed starting at the end of 2003, will consist of a 2 m.-thick concrete structure and has been designed to support the 2000 t. weight of the central section of the magnet. A rented gantry crane will be installed over the SX5 building to lift and transfer the heavy pieces of the CMS detector to the underground area.

The requirements for transport, handling, access and temporary storage space, particularly for the installation phase, needs careful attention and together with the needs of the other experiments and the LHC machine is being followed in the LHC Experiment Installation Reviews.

The majority of the CMS detector sub-systems are well in the construction phase. All five barrel rings and the six end-cap disks of the magnet yoke have been assembled at SX5. Production of the conductor is progressing. All 21 lengths, each with a length of 2650 m., of the Rutherford cable and the insert have been produced and the four remaining lengths to be reinforced will be completed by July 2003. The winding operation has turned out to be faster than expected and the critical path now goes through the manufacture of the mandrels, which show a delay of 4 months with respect to the baseline CMS Master Schedule (Version 33). The estimated delay can be reduced by speeding up production of the coil and by limiting the underground test of the magnet to a functional testing of the cool-down, electrical and leak properties of the cold magnet. The proximity and external cryogenics should be available in time for the 4-month magnet tests on the surface starting in March 2005.

Construction of the Silicon Strip Tracker is underway. The first sensors from the series production have been received and all elements to start the module series production are in hand except for the front-end hybrid electronics, whose procurement has been delayed due to problems with the mechanical properties of the first prototypes. Good progress has been made on the Pixel electronics and sensors.

Production of supermodules for the ECAL is advancing. Although more than 15000 out of the 62000 of the Barrel ECAL crystals have been delivered, their continued delivery is now on the critical path due to earlier delays. In an effort to mitigate the delays, CMS is introducing a procedure to increase the production capacity by making four crystals per *boule* instead of the present two. The order for the end-cap ECAL crystals must be placed by the end of 2003 in order not to affect the schedule for completing the ECAL by April 2007. The ECAL electronics is undergoing a major revision primarily to contain costs. CMS expects to choose the final front-end electronics in the summer 2003 following a series of system tests.

The HCAL Barrel calorimeter has been assembled in the SX5 building and the onboard electronics will be installed by Q2 2004. Following actions to correct the perpendicularity of one of the HCAL End-cap calorimeters, the detector has now been remounted on its end-cap yoke disk in the SX5 building while the second HCAL End-cap calorimeter will be mounted in the summer of 2003.

Most of the CSC modules have been produced and their installation on to the end-cap disks is scheduled to commence in mid-June 2003. The DT chambers are being produced at the required rate and their installation is scheduled to commence in Q4 2003. Studies of Barrel RPC detectors are ongoing in beam and no sign of degradation has been observed while production of the gaps is continuing. An RPC End-cap gap factory has been set up and the first gaps are scheduled to be produced as of mid-2003.

CMS aims to complete the initial detector for first LHC operation in April 2007. The staged components, ME4 muon end-cap chamber, RE RPC end-cap system at $|\eta|>1.6$, and 50% of DAQ, will be installed for the high luminosity running. The proposed staging plan is aimed at minimising the adverse effect on the Higgs and SUSY sensitivity at luminosities of $\sim10^{33}$ cm^{-2} s^{-1}. The Pixel detector will be ready but will not be installed for the machine commissioning and pilot runs. Its installation, during a 3-month shutdown period in the summer of 2007, will be in time for the physics run starting in August 2007. The Silicon Strip Tracker schedule is considered to be tight but the aim is to keep any net delay within the shadow of the delay of the coil, and the ECAL schedule is challenging but it is realistic to have the complete ECAL installed by April 2007.

THE CMS – LHC MACHINE INTERFACE

An Engineering Design Review for the CMS (and TOTEM) experimental beampipe in April 2002 approved the configuration of the region ±11 m. around the interaction point (IP). The call for tender for the Be central section was launched thereafter leading to the signing of the contract for the procurement of this section. The stainless steel material for the large cones has been ordered and awaits delivery to CERN. Installation of the experimental beampipe in CMS (and TOTEM) is scheduled for the period August to November 2006.

The lay-out of forward region beyond ±11 m. from the IP has been agreed to within the CMS and TOTEM collaborations. The region has been designed to host potentially the newly-proposed CASTOR calorimeter, whose primary aim is to study heavy-ion collisions but which will also take data in proton-proton mode, and a shortened version of the TOTEM T2 telescope based on silicon technology. The physics requirements for this set-up point to a smaller-diameter beampipe of 55 mm. ∅ between 13 m. $< |z| <$ 18 m. and a significantly enhanced forward radiation shielding due to the possible presence of CASTOR. Such a set-up would allow CASTOR to return regularly for heavy-ion runs throughout the early years of LHC operation and to run up to a luminosity of $\sim2 \times 10^{33}$ cm^{-2} s^{-1} in proton-proton mode. Various aspects of the proposed lay-out of the experimental beampipe in this forward region, such as the vacuum stability, beam aperture, alignment and activation, are currently being evaluated. The present radiation shielding may still allow the baseline smaller-diameter beampipe to be used for the nominal LHC luminosity of 10^{34} cm^{-2} s^{-1} once CASTOR has completed its physics programme and been removed. Should this not be possible, then a beampipe with 400 mm. ∅ and a heavier forward radiation shielding may need to be installed.

The CMS maintenance procedure provides for a minimal interference between the opening of CMS and safeguarding the experimental beampipe. Normally, the beampipe remains in place under clean gas and is covered with a shell for mechanical protection. The beampipe must, however, be opened for the removal of the Tracker. Removal and installation of the Pixel detector requires a special study as it will most likely be an annual operation and it may be necessary to install local temporary shielding around activated components.

The contact doses and those at a typical 50 cm distance from the beampipe allow for about 100 h. of annual handling and access [1]. As the dose decreases by about a factor of 10 towards the end of an annual long shutdown period, the expected more time-consuming operation of re-installation is done in more favourable conditions.

Finally, CMS has requested that the average total pressure inside the vacuum system should be in the range 10^{-8} to 10^{-9} Torr in order to limit beam-gas interactions which give rise to backgrounds particularly in the Tracker.

The outgoing 14 TeV total energy from the collision region will be shared between components of the CMS detector and the LHC machine, with the latter receiving the bulk of the energy. The Forward Radiation Shielding is being built to a) provide effective shielding along the beamline, b) protect the experimental area against machine-induced background emerging from the LHC tunnel, c) reduce the rates in the CMS outer muon chambers by up to 3 orders of magnitude, d) protect the electronics in the cavern and e) form an integral part of the personnel shielding. The Forward Radiation Shielding, made up of the Cubical Steel Frames, the Fixed Iron Noses and the Rotating Shielding, consists of heavy components made primarily from steel and concrete and is being built at IHEP Protvino. The Cubical Steel Frames are complete while construction of the Fixed Iron Noses is well-underway and the Rotating Shielding is entering its production phase following a recent Engineering Design Review. As a result of the Forward Radiation

Shielding, the radiation level in the UXC55 cavern is about 1 Gy/yr and CMS will be rather insensitive to machine-induced backgrounds such as upstream beam losses [2]. Muons, which remain as the only particles that penetrate the shielding from the machine side, are estimated to arrive at CMS at a rate of < 10 μ cm^{-2} s^{-1} [2].

The inner triplet quadrupoles, being built at KEK and FNAL to provide the low-β needed for the high average luminosities requested by CMS, will extend into the UXC55 experimental hall and will be positioned on a solid concrete platform in order to guarantee a stable foundation. The platform serves as a radiation-shielded alcove for the HF forward hadronic calorimeters and as a support for the Cubical Steel Frames of the Forward Radiation Shielding. They will be installed from the machine tunnel in Q2-Q3 of 2005 and will be surveyed subsequently with respect to the LHC geometry and cavern reference network.

Beam screens in the inner triplets are required to ensure vacuum stability. The baseline lay-out is similar to that for the arcs and consists of the `racetrack' design. The orientation of the beam crossing plane is fixed once such `racetrack' beam screens are installed and the current baseline crossing plane is vertical at Point 1 and horizontal at Point 5. However, the uncertainty and reduced safety margin of the energy deposition in the inner triplet coils may result in a difference of luminosity between ATLAS and CMS as there may be a need to increase β* and/or decrease the crossing angle at the more problematic IP. At luminosities much below nominal, the safety margin is sufficiently large to allow for proper operation. However, for LHC operation at the nominal luminosity and above, CMS requests continued evaluation of alternative schemes, such as the `marguerite'-type racetrack design, as an upgrade option if needed.

CONCLUSION

CMS expects to be closed and ready for first LHC beam in April 2007 and, following a short shutdown in the summer of 2007, will be ready for the physics run starting in August 2007. Exciting physics is likely to be within reach soon after LHC start-up and a continued common effort between CMS and the LHC machine is needed to ensure the highest data quality for physics.

ACKNOWLDEGEMENTS

The author wishes to express his gratitude to the organisers of *LHC Days 2003* for the very enjoyable and interesting workshop and for the opportunity to present the CMS experiment.

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THE ALICE EXPERIMENT: A LARGE ION COLLIDER EXPERIMENT FOR LHC

L. Leistam, CERN, Geneva, Switzerland

INTRODUCTION

ALICE is a specialized detector designed to study the physics of strongly interacting matter and quark-gluon plasma in nucleus-nucleus collisions. It is being built around the magnet of the L3 experiment, which took data at CERN's previous accelerator; LEP.

Many small institutes have joined in the effort of building a general purpose heavy ion (HI) detector for the LHC. The collaboration includes about 1000 people from 28 countries and 80 Institutes. The CERN involvement in Alice is of fundamental importance.

DESCRIPTION OF THE ALICE DETECTOR

The ALICE experiment is being installed in the existing experimental area at Point 2. Only minor modifications to the civil engineering are necessary. Large shielding installations are necessary in order to comply with the LHC radiation environment. As much as possible of the existing infrastructure is adapted to the needs of the ALICE experiment. The ALICE experiment is re-using the L3 solenoid magnet and the "hanging" counting rooms.

Central to ALICE is the inner tracking system (ITS). It consists of six cylindrical layers of silicon tracking detectors. The innermost layers consist of silicon pixel detectors. Surrounding the pixels are silicon drift detectors and layers of silicon strip detectors complete the inner tracking system.

Tracking continues beyond the ITS in a time projection chamber (TPC), which is the main tracking devise for the ALICE detector. A TPC works by measuring the time it takes ionization caused by a passing particle to reach the detectors at the end of a large gas filled volume called the field cage.

Identification of many different particles is an important design feature of ALICE. Several sub-detector systems are dedicated to the task – a time-of flight (TOF) array, a smaller system dedicated to high-momentum particles (the HMPID), a transition radiation detector (TRD) for identifying high-momentum electrons, a small-acceptance, high precision photon spectrometer (PHOS), and a forward muon spectrometer.

In addition to the L3 magnet, ALICE will also have a large dipole on one side to analyze escaping muons.

Most of the sub-systems of the ALICE detector have entered the construction phase. The Alice detector has > 12 different sub-detector systems, which constitutes a real challenge. Size is not always difficult in regards to experimental installations; however, complexity is always a complication.

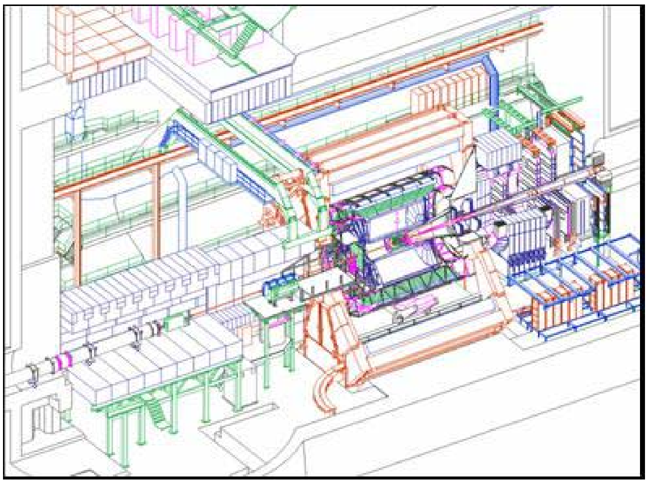

Figure 1: The ALICE detector.

PHYSICS OBJECTIVES

The Alice detector has two main Physics objectives:

- Measure most (2π * 1.8 units η) of the hadrons (dE/dx + ToF), leptons (dE/dx) and photons (EM calorimetry) produced in pp and HI collisions.
- Track and identify particles from very low (< 100 MeV/c) up to fairly high pT (~100 GeV/c).

The main difficulty comes from the very high charged-particles density ($dN/d\eta \leq 8,000$; i.e a total of 15'000 tracks in the central tracker), present in a heavy ion collision.

THE ZDC DETECTOR

ZDC stands for Zero Degree Calorimeter. It consists of two separate units ZP (protons) and ZN (neutrons), placed at 116 m from the IP2, just in front of the D2 magnet (Fig. 2).

The ZDC detector is fundamental to the triggering of the ALICE experiment. The number of protons and neutrons emerging from the collision is a measure of the type of impact; head on or peripheral (centrality measurements). The ZDC will also be used for luminosity monitoring.

ZN1 has been built and tested and performs according to expectations. The connection of the fiber bunches with the PMs is to be improved with the insertion of a light mixer.

The construction of ZN2 started and the absorber has been machined and quartz fibers cut and polished. Some delay is expected compared to the previous planning.

The definitive project of the vacuum chambers from D1 up to the ZDC location has started and official reservation of cables in the LHC tunnel has been made.

Design of supports and detailed integration will follow as soon as the final design of the vacuum system is available.

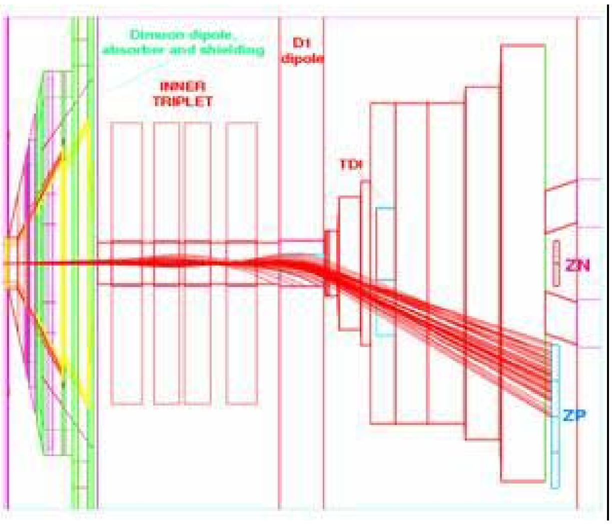

Figure 2: The ZDC detector.

Table 1: Characteristics of the ZDCs

	ZP	ZN	ZEM
Absorber	bras	W alloy	lead
Fibers angle (with respect to beam dir.)	0º	0º	45º
Fibers diameter (µm)	550	365	550
Fibers spacing (mm)	4	1.6	

SCHEDULE AND OPERATION

The Alice detector will be ready for 1st beam April 2007, apart from parts of the TRD and PHOS detectors, were the construction schedule is limited by the funding.

The planning for the initial operation of the Alice detector is:

- First few (1-3) months: running in the detector. Beam-gas, first pp collisions.
- Next few months: pp physics pilot run. Plan for physics data taking (MinBias event characteristics in pp). 10^{29} cm^{-2} s^{-1} < L < 3 x 10^{30} cm^{-2} s^{-1}. ALICE does not request an extended shutdown before physics pilot run.
- Before first long (>3 months) shutdown: HI pilot run. HI run at the end of first LHC proton run and > 1 week at > few % design L, i.e > few 10^{25} cm^{-2} s^{-1}.

It is expected that significant physics output comparable to first RHIC run, can be obtained even during a short run at very low luminosity.

The continuation of the Heavy Ion program for the Alice detector is divided into the following operation phases:

Year 1 (1 LHC year = 10^7 s of pp + 10^6 s of AA):

- pp: detector commissioning & physics data.
- PbPb physics pilot run: global event-properties, observables with large cross-section.

Year 2 (in addition to pp @ 14 TeV, L< 3.10^{30} cm^{-2}s^{-1}):

- PbPb @ L~ 10^{27} cm^{-2}s^{-1}: rare observables.

Year 3:

- p(d, a) Pb @ L ~ 10^{29} cm^{-2}s^{-1}: Nuclear modification of structure function.

Year 4 (as year 2).

Year 5:

- ArAr @ L ~ 10^{27}-10^{29} cm^{-2}s^{-1} : energy density dependencies.

Options for later:

- pp @ 5.5 TeV, pA (A scan to map A dependence), AA (A scan to map energy-density dependence), PbPb (energy-excitation function down towards RHIC energies).

CONCLUSIONS

The installation and construction of the Alice detector are progressing according to the planning. Re-using the L3 magnet and the Point 2 experimental area has allowed to significantly reduce the overall cost of the experiment.

The HI machine review end of March 2003 gave encouraging conclusions on technical issues, however, manpower, schedule and cost give raise to concerns.

THE TOTEM EXPERIMENT

K. Eggert, CERN, Geneva, Switzerland

Abstract

TOTEM will measure the total *pp* cross-section at LHC by using a luminosity independent method based on simultaneous evaluation of the total elastic and inelastic rates. For an extended coverage of the inelastic and diffractive events, two forward tracking telescope are employed. The elastically or diffractively scattered protons are measured by a set of special detectors, which can be moved close to the circulating protons beams.

INTRODUCTION

The TOTEM experiment was proposed to measure[1, 2]:

- the total cross-section with an absolute error of 1 mbarn by using the luminosity independent method, which requires simultaneous measurements of elastic *pp* scattering down to the four-momentum transfer squared of $-t \sim 10^{-3}\,\mathrm{GeV}^2$ and of the inelastic *pp* interaction rate with an adequate acceptance in the forward region. Present extrapolations of the world data to LHC energies together with the existing cosmic ray data have a typical uncertainty of $\pm 15\%$.
- the elastic *pp* scattering up to $-t \sim 10\,\mathrm{GeV}^2$
- the diffractive dissociation, including single, double and central diffraction.

Given the large cross-sections involved, the experiment does not require intense beams, but a special high-beta optics is needed for the measurement of low t elastic scattering. The experiment will be ready to take data at the beginning of the LHC operation and will also provide an absolute luminosity determination.

The TOTEM experiment uses precision detectors inserted in Roman Pots installed in the machine tunnel to measure the elastically and diffractively scattered protons close to the beam direction, and two separate forward telescopes to detect charged particles with rapidity coverage from $3 < \eta < 6.8$ (Fig. 1). With these additional detectors a fully inclusive trigger, also for single diffraction, can be provided with an expected loss on the inelastic rate of less than 2 %.

ELASTIC SCATTERING AND A SPECIAL LHC OPTICS

The precise luminosity independent measurement of the total cross-section requires that $d\sigma_{el}/dt$ is measured down to $-t \sim 10^{-3}\,\mathrm{GeV}^2$, which corresponds to a proton scattering angle of $5\,\mu\mathrm{rad}$.

In order to detect elastic protons with scattering angles of a few $\mu\mathrm{rad}$, the beam divergence at the interaction point (IP) has to be reduced. Beam divergences of less than $1\,\mu\mathrm{rad}$ can be achieved by reducing the transverse emittance of the beam and by increasing β at the IP to values between 1 and 3 km. As a consequence, the transversal beam size will increase to about 0.5 mm, a size at which it will be impossible to avoid multiple bunch interactions in the straight section. Hence the number of bunches should be reduced. With 36 bunches, the bunch spacing would be $2.5\,\mu$s, a number compatible with the LHC injection scheme. With the above running conditions, and the proton bunch density reduced by a factor of three, the LHC luminosity would be of the order of $10^{28}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The elastically or diffractively scattered protons are measured on both sides of the interaction point with silicon detectors located symmetrically with respect to the IP. The detectors, which are placed in Roman Pots – enclosures with a secondary vacuum – can be moved as close as 1 mm to the circulating LHC proton beams.

For an ideal optics the effective length L_{eff} should be as large as possible and the magnification $v \sim 0$ in order to reduce the dependence on the proton coordinates at the interaction point. This condition of parallel-to-point focussing is reached at the location along the machine where the phase advance $\Delta\mu$ is $\pi/2$.

The original TOTEM optics had a $\beta^* = 1100\,\mathrm{m}$ and parallel-to-point focussing conditions in the vertical plane at the distance of 147 m and in the horizontal plane at 220 m from the IP.

A recently conceived new LHC beam optics scheme provides significant improvements to the original one. By increasing the β^*-value from 1100 m to 1540 m, the effective length in the vertical plane, L^y_{eff}, is almost doubled and – more important – the parallel-to-point focussing conditions are achieved both in the horizontal and vertical planes at the distance of 220 m from the IP (Fig. 2). The new optics greatly improves the resolution of the polar and azimuthal angle measurements. The layout of the beam lattice and the proton measurement stations is shown in Fig. 1.

SILICON DETECTORS IN THE ROMAN POTS

The measurement of the elastic scattering to the smallest t values demands a big effort in designing and running a special optics for the machine, the construction of Roman Pots with sophisticated technology and *edgeless* detectors. Modern technologies for processing planar silicon detectors allow very fine segmentation. However, an insensitive border region extending several hundreds microns into the

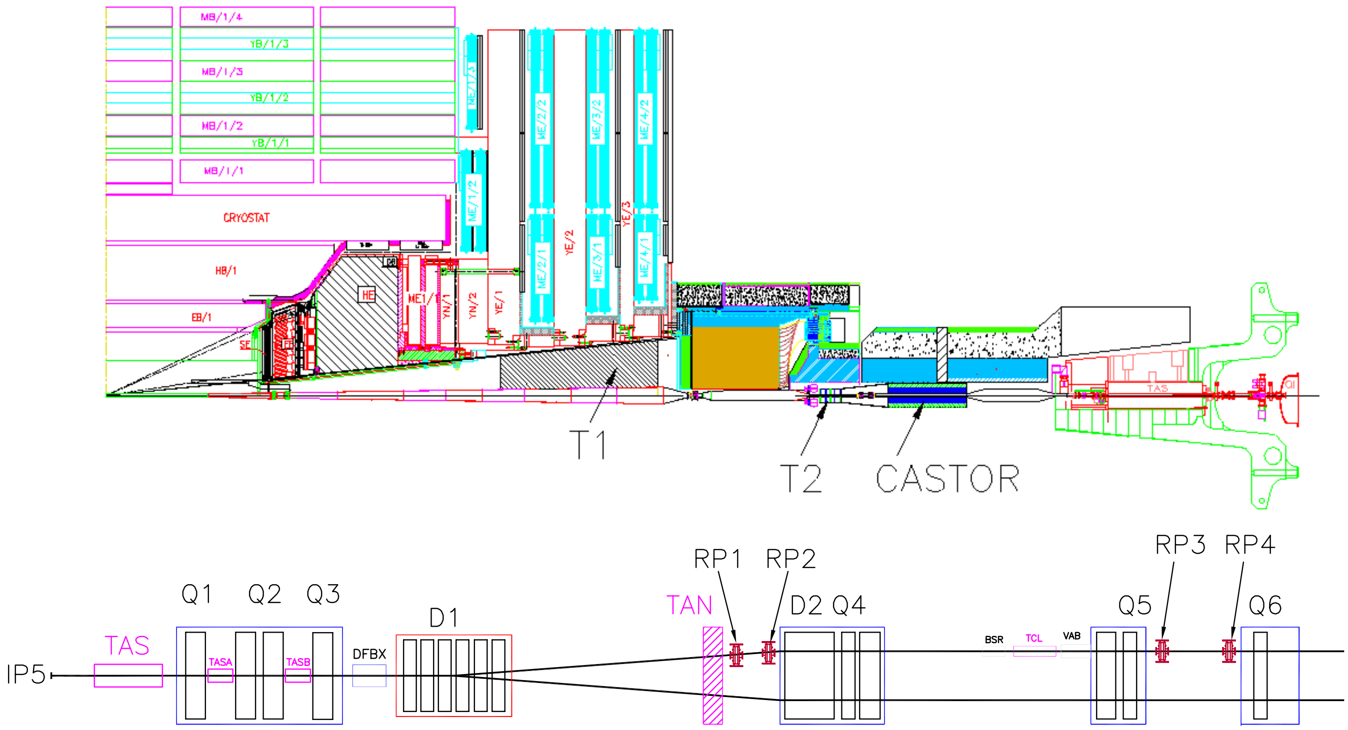

Figure 1: The TOTEM detectors installed in the CMS forward region (top). The LHC beam line and the Roman pots at 147 m and 220 m. (bottom).

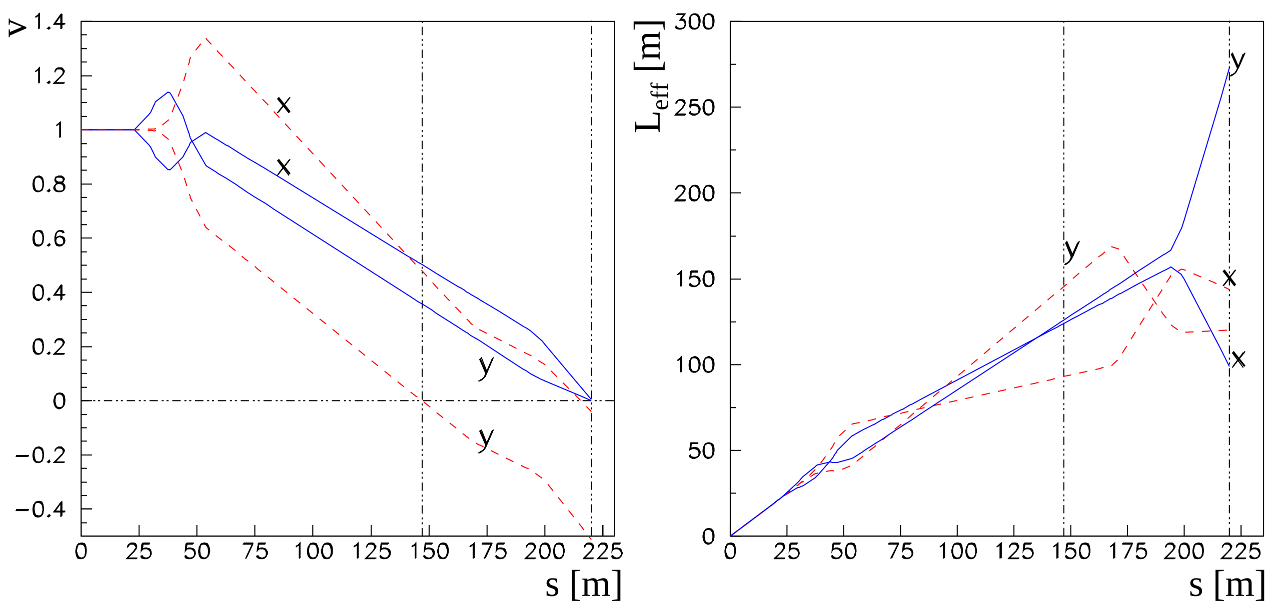

Figure 2: Plot of the magnification v and the effective length L_{eff} as a function of the distance from the IP (solid lines $\beta^* = 1540\,\mathrm{m}$, dashed lines $\beta^* = 1100\,\mathrm{m}$).

detector volume is needed for guard-rings which control the device's electric field and the surface leakage currents that may develop at the edge of the detector.

It was suggested that silicon planar detectors can be operated without guard rings if cooled down to $130K$[3], thus obtaining a drastic reduction of the inefficient material at the border of the detector. A successful measurement of the efficiency up to the edge of the silicon sensor has been performed with a microstrip detector cut through the sensitive area [4].

A novel technology, the edgeless 3D silicon detectors, has been proposed by S.Parker and collaborators [5][6] .

In this configuration, the p^+ and n^+ electrodes are processed inside the bulk of the silicon wafer, rather than being implanted on its surface as in planar devices.

The detector is built using deep reactive ion etching, developed for micro-electro-mechanical systems. By this technique micro-holes with a thickness-to-diameter ratio as large as 20:1 can be etched in silicon. In the 3D detectors presently processed holes are etched in wafers several hundred microns thick, at distances as short as $50\,\mu\mathrm{m}$ from one another.

The holes are then filled with polycrystalline silicon doped with either boron or phosphorus. Once the electrodes are filled, the polycrystalline silicon is removed from the surfaces, and the dopant is diffused into the surrounding single-crystal silicon to form the detector electrodes. Aluminum is then deposited to provide contact with the electrodes in a pattern that will depend on how the individual electrodes are to be read out. Detectors fabricated with these dimensions can reach a spatial resolution of $10 - 15\,\mu\mathrm{m}$.

THE INELASTIC MEASUREMENT

TOTEM only needs a few runs, each of one day duration, with the special running conditions of a high $\beta^* \sim 1500\,\mathrm{m}$, and a low luminosity of $\mathcal{L} \approx 10^{28}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This is sufficient to collect an integrated luminosity of typically $10^{33}\,\mathrm{cm}^{-2}$ which corresponds to $10^7 \div 10^8$ minimum bias events.

Almost half of the total cross–section at the LHC is predicted to be due to coherent elastic scattering, single, double and central diffractive processes.

At $\beta^* \sim 1500\,\mathrm{m}$, the TOTEM experiment efficiently detects protons with $t > 0.004\,\mathrm{GeV}^2$, i.e. 97 % of all the diffractively scattered protons, independent of their longitudinal momentum loss in the range of $10^{-8} < \Delta p/p < 0.2$. With the TOTEM acceptance extending up to the pseudorapidities of 6.8, and with the efficient proton detection capabilities close to the LHC beams, it is only the diffractively excited states with masses below $4\,\mathrm{GeV}/c^2$ that are missed by the experiment.

The telescopes (T1 and T2, Fig.1) for measuring inelastic events have a good trigger capability, provide tracking to identify beam-beam events and allow the measurement of the trigger efficiency. To discriminate beam-beam from beam-gas events the telescope will identify the primary interaction vertex with an accuracy at the level of a cm by reconstructing a few tracks from each side of the interaction point; the knowledge of the full event is not needed. Minimum bias events are easily detected using a double-arm trigger which requires the coincidence of a left and right arm. The task becomes more challenging in the case of single diffraction events. For these topologies tracks are in only one hemisphere and sometimes the multiplicity of the event is low. Moreover, a beam-gas event has a very similar topology. The detection of a proton in the Roman Pots in the opposite arm makes the single diffraction trigger cleaner.

THE LUMINOSITY MEASUREMENT

The measurement of the total cross-section in the $high\ \beta$ runs provides the absolute calibration of the machine luminosity. With the knowledge of the luminosity calibration any appropriate combination of TOTEM and CMS detectors can become a luminosity monitor, the only requirement being a negligible contamination from background events. Various combinations of triggers will be monitored regularly and their relative stability will give an indication on the background conditions of each run.

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BEAM VACUUM INSIDE THE EXPERIMENTS

J. Knaster, CERN, Geneva, Switzerland

Abstract

Beam pipes passing through the four LHC experiments are perhaps the most intimate interface between machine and experiments. All particles seen by the detectors must first pass though these machine vacuum chambers.

An overview of the project, outlining special requirement from machine and experiments will be given. From this, the special designs, including the use of beryllium and conical vacuum chambers, will be derived. Finally, particular risks for machine operation coming from these sectors will be outlined.

INTRODUCTION

The experimental beam pipe is the part of the LHC's beam vacuum system that passes through the core of the experiments housing the beam. Four big experiments will be installed in the LHC with its own peculiarities and objectives (Fig. 1).

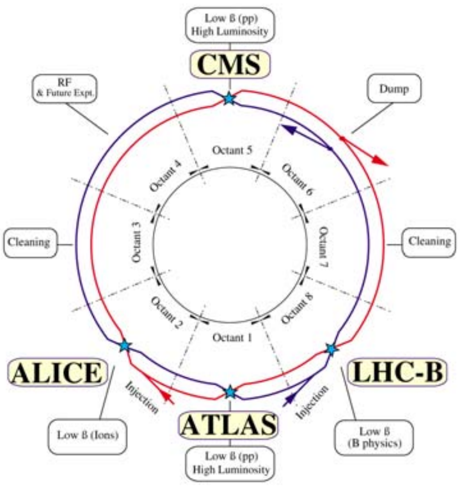

Figure 1: Overall layout of the LHC.

These experiments will have, as common issue, the beam pipe as its main interface between the beam and the detectors.

CONFLICTING REQUIREMENTS

The ideal beam pipe for an experimental physicist would consist of a completely transparent vacuum chamber, housing absolute vacuum and with a small diameter so that the pixel detectors could be placed close to the beam axis to track the secondary particles from its origin. On the other hand, beam physics require a "beam stay clear" that, together with alignment and mechanical tolerances considerations yield a common ID58 for ALICE, ATLAS and CMS in the area around IP [1]. LHCb has a roman pot-like Vertex detector that allows a Φ12 mm aperture once the beam is collimated thanks to its special features [2]. The electromagnetic interaction of the beam with the surrounding beam pipe requires smooth tapered transitions (typically < 15˚), shielding of cavity-like zones and resistive impedance optimization.

REALISTIC ACHIEVABLE BEAM PIPE

UHV conditions are required to minimize the interactions of protons with gas molecules. Vacuum static values are better than the ones can be achieved with the beam running. Protons interact electromagnetically with negative charged particles. The accelerated ions and electrons may desorb molecules when impinging on the beam pipe inner wall. Photons from synchrotron radiation, not completely negligible in the LHC, also will desorb molecules [3]. The combined effect of these phenomena together with the e^- multipacting may cause the beam loss. The coating of NEG's in the beam pipe inner wall reduces these effects in addition to allowing a distributed pumping [4]. NEG's gets saturated needing a periodical activation to refresh their properties. This activation is done ideally once per year in a temperature ranging from 180˚ C to 250˚ C. This implies the necessity of in-situ baking the experimental beam pipes and adds a special constraint to the design.

Wake fields and coupling impedances may cause losses and beam instabilities. In the LHC, the transverse impedance instability is the most critical issue [5]. It depends on the square root of the electrical resistance and the inverse cubic power or the beam pipe radius. To minimize its effect, stainless steel vacuum chambers need to be Cu coated with a thickness depending on the beam pipe radius. Bellows expansion joints need to be shielded wherever the implied increase of radius is possible.

The shape of the beam pipe influences the background intensity. A circular section allows an azimuthal symmetry of detectors around the beam axis. Cylinders present a bigger interface to secondary particles than cones.

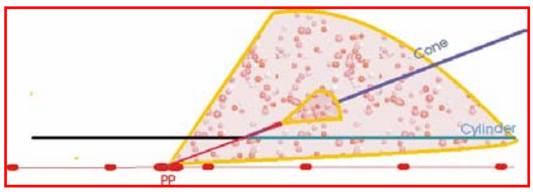

Figure 2: Influence of beampipe shape on collisions with secondary particles.

From the previous figure one could easily deduce that cones are more interesting than cylinders, however the indetermination of the collision point due to the bunch length and the mechanical and alignment tolerances triggers a discussion on the subject. In particular ALICE, CMS and LHCb have conical vacuum chambers whereas ATLAS has chosen a cylinder.

To minimize the background generated by the beam pipe, a careful choice of the material is also needed. Two nuclear parameters, the *radiation length* X_o and the *interaction length* λ_I [6] describe the interaction of particles with matter. Given an external pressure, the thickness is inversely proportional to the cubic root of the Young modulus; and obviously, it is also directly proportional to its mass. Beryllium is found to be the best compromise between material transparency and mechanical behaviour, where $X_oE^{1/3}$ is a figure of merit derived from the radial buckling classical formula for an infinite cylinder under external pressure [7].

Table 1: Comparison of several materials – Mechanical performance and transparency

Material	***Be***	***CFC***	***Al***	***Ti***	***Fe***
E (GPa)	290	~200	70	110	210
$X_oE^{1/3}$	2.34	~1.58	0.37	0.17	0.11

The installation and alignment of the beam pipe inside the experiment is a difficult issue. The integration needs to be done in parallel with the experiment. Lack of references for alignment will have to be overcome. A pre-installation and pre-commissioning will be tested in two assembly bench tests already existing in Prevessin (Fig. 3).

Figure 3: Installation bench test.

DEVELOPMENTS FOR THE LHC

The previous requirements have required several developments:

Beryllium: besides its high price and toxicity if inhaled, it has been traditionally used for military and Aerospatiale applications and hence its technology is not public. TIG and e-beam welding of Be-Be and Be-Al2219 have been qualified for UHV applications and in a similar way vacuum brazing of Be-316L (Fig. 4). Due to Be high price, a reduction has been sought with an AlBe alloy. This has been characterized at the NEG activation temperature of 250˚C, as well as e-beam welding of AlBe-AlBe and AlBe- Al2219.

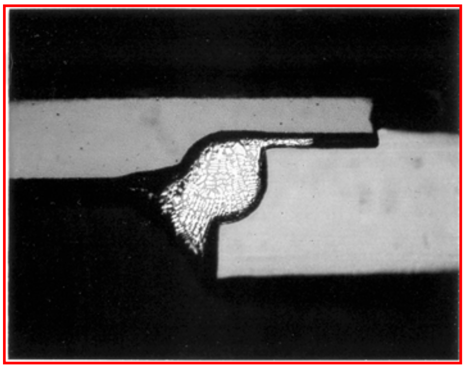

Figure 4: Be S200-316L vacuum brazing.

Machined aluminium bellows (Fig 5) have been qualified for UHV and will be installed in LHCb. They form an universal joint of 8 convolutions 0.4 mm thick that will compensate a stroke of ~1 cm during NEG activation process. They will work in the elastic regime so no fatigue issues are expected.

Figure 5: Aluminium universal joint of bellows.

An *Annular ion pump* (Fig. 6) to be installed in ATLAS and probably in ALICE in a position closed to the IP to enhance the dynamic vacuum performance. It presents a minimum background to the detectors with a stainless steel body 0.8 mm thick. It has a pumping speed around 25 l/s [8].

Figure 6: Annular ion pump.

Optimized flanges (Fig. 7) have been qualified for UHV applications in Aluminium and stainless steel [9]. The vacuum seal will be Helicoflex type. In the next figure can be seen the comparison between a standard DN63 CF flange and the optimized one. These optimized flanges will be installed in the four experiments.

Figure 7: Comparison of optimized flange with standard DN63CF.

Heaters for in-situ bakeout (Fig. 8) have been developed. Two different systems: alumina plasma sprayed with a stainless steel resistor and a polyimide heater with an inconel resistor. These will be thermally insulated by means of an aerogel insulator. These systems will be installed in ATLAS and ALICE.

Other developments are in progress: *clean gas injection system*, *fast valves*, *vertex detector window*,…

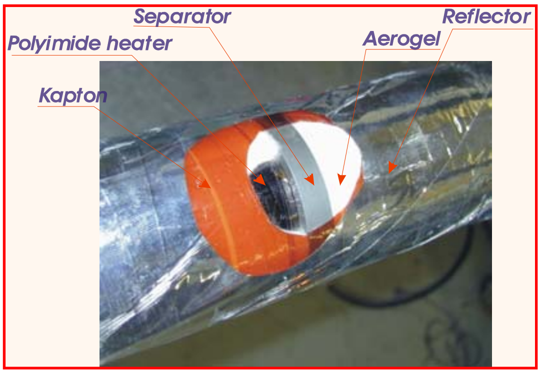

Figure 8: Polyimide heater and aerogel insulator.

IMPLEMENTATION IN THE EXPERIMENTS

All these previous considerations and developments have been implemented in the four experiments with certain differences between them. In particular, *LHCb* has a single arm spectrometer with 3 different half angles acceptance cones (390, 25 and 10 mrad) (Fig. 9). A machined Al6061 2 mm thick spherical window OD838 mm will seal the vertex detector. A machined Aluminium bellows universal joint will be placed to separate the 25 mrad and the 10 mrad Beryllium cones that will cover up to +13100 mm form IP. The installation of optimized flanges is also foreseen. Fast valves might be installed to protect from an accident in the Vertex detector area that might deposit debris in the inner triplets.

PRESENT STATUS

The contract for the supply of the beryllium vacuum chambers for ALICE, ATLAS and CMS central part has been signed and the fabrication is progressing. LHCb is considering the choice of material between an allegedly cheaper AlBe alloy or Beryllium; a decision will be taken before the end of 2003. CMS and ALICE are already fabricating their conical stainless steel vacuum chambers. The handling and installation tooling study has also begun following the experiments installation review held in March 2003. The first milestone concerning installation is linked to ALICE whose beam pipe integration will begin in 2004.

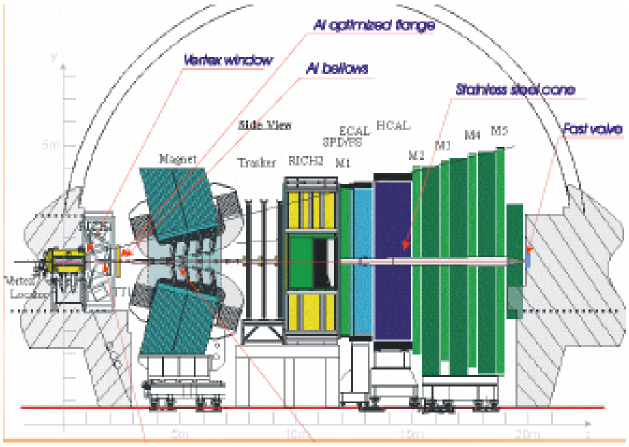

Figure 9: LHCb geometry.

ACKNOWLEDGEMENTS

This note shows the common work of the experimental vacuum chamber team: W. Cameron, G. Foffano, J. Knaster, H. Kos, P. Lepeule, A. Rossi, G. Schneider and R. Veness.

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CRYOGENICS FOR LHC EXPERIMENTS

J. Bremer, CERN, Geneva, Switzerland

Abstract

This paper gives a brief description of the cryogenic installations for the LHC experiments. The objects to be cooled are presented, as well as the cooling principles used and the cryogenic systems delivering the necessary cooling power.

INTRODUCTION

The ECR group of the AT division provides the cryogenic systems to the LHC experiments CMS and ATLAS. These systems include the production of the cooling capacity (external cryogenics) and the delivery of the coolant (proximity cryogenics) in the correct state (pressure, temperature and mass flow) to the objects to be cooled.

The CMS experiment will, before its lowering into the experimental cavern, be completely assembled and tested on the surface. Also the cool down of the central solenoid has been foreseen at the surface and its cryogenic installation has thus first to be installed at the surface, before being lowered for its final installation into the underground caverns. For the ATLAS experiment it is however impossible, seen its size and planning, to foresee a test of the complete experiment at the surface, and all cryogenic objects are individually tested at the surface in dedicated test areas.

CMS

The central solenoid of CMS has an inner diameter of 5.9 meter, a length of 12 meter and a cold mass of 225 tons. With its nominal field of 4 T, the magnet stores an energy of 2.6 GJ. The static heat load is estimated at 160 W @ 4.5 K, and the dynamic load at 365 W @ 4.5 K. The heat load on the thermal screens (60 to 80 K) is estimated at 3 kW, while the current leads need a liquid helium flow of 3 g/s. The CMS magnet is cooled via the thermal siphoning principle. The liquid helium needed to cool the magnet is taken from a phase separator placed on top of the experiment. This liquid is brought to the bottom of the solenoid, from where it is distributed over heat exchangers placed in contact with the cold mass. The thermal load will create helium gas in the heat exchangers which are always going into an upward direction. Because of the difference in density between the line full of liquid going down to the bottom of the solenoid and the heat exchanger lines going up, the hydrostatic pressure difference creates a driving force circulating the helium through the heat exchangers back to the phase separator.

A 1.5 kW @ 4.5 K equivalent helium refrigerator is re-liquefying the created gas into a 6000 liter intermediate storage dewar which has been placed nearby the experiment. The level in the phase separator is regulated with liquid helium coming from this dewar, its buffer volume guaranteeing a five hour cooling period, sufficient for the slow ramp down of the magnet, even in case of refrigerator failure.

The CMS experiment is first completely assembled on the surface. Its refrigerator system has been foreseen to function for the first time with a test cryostat by the end of September 2003, while the cool-down of the central solenoid at the surface has been foreseen for the beginning of 2005. The magnet will be cooled-down for the first time in the experimental underground area in 2006.

ATLAS MAGNET SYSTEM

The ATLAS experiment houses three different magnet systems:

- One Barrel Toroid, consisting of 8 coils housed in individual vacuum tanks;
- Two End Cap Toroids, each consisting of 8 coils housed in a common vacuum tank;
- One Central Solenoid.

A summary of the main parameters for each of the magnet systems is given in Table 1.

The central solenoid is cooled via the thermal siphoning method already discussed before. The three toroid systems are cooled by forced flow indirect cooling. The liquid

Table 1: Main parameters ATLAS magnets

	Inner diameter (meter)	Cold mass (tons)	Peak field (T)	Stored energy (MJ)	Static heat load (W @ 4.5 K)	Dynamic heat load (W @ 4.5 K)
Barrel Toroid	9.4	370	3.9	1080	660	350
End Cap Toroids	1.6	160	4.1	206	180	110
Solenoid	2.6	5.4	2	38	80	80

helium to be circulated is taken from the bottom of a phase separator dewar by a liquid helium pump, which pressurises 1.2 kg/s of helium by 400 mbar. This helium is then distributed over 10 parallel cooling circuits (8 for the barrel toroid magnets and one for each of the end cap toroids) and passed through heat exchangers which are placed in contact with the cold mass of the magnets. The helium gas / liquid mixture coming from the heat exchangers is returned to the phase separator dewar. The gas returned is brought to the refrigerator (6 kW @ 4.5 K equivalent) and returned as liquid to a 11000 liter buffer, which in turns regulates the liquid level in the phase separator. This intermediate dewar supplies a two hour cooling capacity for the magnets in case of refrigerator failure, guaranteeing cooling power during the time of a slow ramp down of the magnets. In contrary to the thermal siphoning method where no external pressurisation system is needed, the forced flow method depends completely on the functioning of the helium pump to circulate the helium. To guarantee the functioning of this system the pump has been backed-up by a second one, while the electrical power for the pumps and their control system has been backed up by a UPS system.

The thermal shields of the magnets are cooled by a 20 kW (40 -80K) helium refrigerator, which will also be used for the cool down of the cold masses delivering 60 kW of cooling power when boosted by liquid nitrogen.

The toroid magnets will first be tested individually in a especially build test area functioning on the cooling principle as described above. The first Barrel Toroid magnet will be cooled down in this test area by September 2003. The first End Cap Toroid will be tested by the end of 2004. After surface tests, the magnets will be lowered into the experimental cavern, where the first functional test of the complete ATLAS magnet system has been foreseen for 2006.

ATLAS CALORIMETER SYSTEM

The ATLAS liquid argon calorimeter is housed in three independent cryostats: one Barrel cryostat and two End Cap cryostats. The main parameters of these cryostats are given in Table 2.

Table 2: Main parameters ATLAS Calorimeter Cryostats

	Cold vessel volume (m^3)	Weight of full cryostat (tons)	Number of signal wires	Static Load (kW)
Barrel	58	203	130000	1.8
End Cap	43	269	50000	2.5

Each of the argon baths of the three calorimeter cryostats is connected to an expansion vessel which is placed away from the cryostat on a higher level. The temperature in this expansion vessel and in the cryostat itself is regulated at 87.3 K, creating an argon bath which is sub-cooled by 5 K to 8 K, depending on the localization in the cryostat. This sub-cooling is needed to avoid the formation of argon gas since bubbles would have fatal consequences for the high voltage system present in the cryostat.

The argon baths are cooled by forced flow liquid nitrogen passing through heat exchangers placed in the baths. The liquid nitrogen is taken from a phase separator by a nitrogen pump which circulates the nitrogen through the heat exchangers. The mass flow and pressure of the nitrogen can be regulated for each of the heat exchangers individually. The nitrogen mixture coming from the heat exchangers is returned to the phase separator from where the gaseous nitrogen is send to a nitrogen refrigerator (20 kW @ 84 K equivalent). The liquid nitrogen from the refrigerator is supplied to the phase separator.

The ATLAS Calorimeter cryogenic system has to function continuously over the complete lifetime of the ATLAS experiment. To guarantee this functioning:

- the nitrogen refrigerator has been backed-up by two 50000 liter nitrogen storage tanks which will supply the necessary cooling power in case of non availability of the nitrogen refrigerator;
- the nitrogen pump circulating the liquid nitrogen through the heat exchangers has been backed-up by two other pumps on stand-by;
- the End Cap cryostats can be transferred over a distance of twelve meters, while in normal cryogenic operation. The displacement of these cryostats allows for access to electronics placed close to these cryostats.

The three calorimeter cryostats will be tested individually before being lowered into the ATLAS experimental cavern. The cool down of the first calorimeter (the Barrel calorimeter) in its test area has been foreseen for January 2004. This cryostat will after this test directly be installed at its final position and will be cooled down for the first time here in January 2005. The complete ATLAS liquid argon calorimeter installation should be operational in the underground area by the end of 2005.

CONCLUSIONS

The magnets and calorimeters of the LHC experiments needing cryogenics are all tested at the surface before being lowered into their final position. These test areas are now being finished, all of them are foreseen to function before the beginning of 2004.

In the mean time installation work of the cryogenic systems is starting in the underground areas. All these installations should be operational in the first half of 2006.

THE COLLIMATION SYSTEM AND ITS IMPACT ON THE OTHER MACHINE SYSTEMS

R. Aßmann, CERN, Geneva
for the Collimation Team*

Abstract

The Large Hadron Collider (LHC) will collide proton beams at 14 TeV c.m. with nominal design luminosities of up to 10^{34}cm^{-2}s^{-1}. This luminosity can only be achieved by storing and colliding high transverse energy densities in the super-conducting ring, advancing the state of the art by 2-3 orders of magnitude beyond HERA and the TEVATRON. In particular, the population in the beam halo is much above the quench level of the superconducting magnets. The handling of high-intensity beams becomes a major obstacle for LHC operation and requires a powerful collimation system. An appropriate system is presently under study. Though it is too early to describe the proposed solution in this paper, the basic design is explained and requirements are given.

INTRODUCTION

The LHC will be the first particle physics collider that requires efficient collimation through its complete operational cycle with beam: injection, ramping, low beta squeeze, collision. During all these phases small fractions of the LHC beams can easily induce quenches of one or several of the super-conducting magnets. It is expected that the LHC will be 2-3 orders of magnitude more sensitive to beam-induced quenches than HERA or TEVATRON. An efficient collimation system must capture spurious beam loss such that quenches are avoided. Each magnet quench will disrupt the operation of the LHC and reduce the overall luminosity production.

The LHC collimation system must offer efficient cleaning of the beam halo to protect against beam-induced quenches, tuning of the beam-induced experimental backgrounds, and limited passive protection of the machine aperture. A passive protection of the machine aperture is desirable but can only be provided within a limited scope. The collimators will just survive impacts of less than 1% of the stored intensity within one or a few turns. The LHC machine is therefore mainly protected by the active beam dump system, relying on elaborate monitoring systems [1].

The design of the LHC collimation system is pursued since October 2002 by the LHC collimation project in the AB division [2]. It is complemented by the LHC Collimation Working Group [3]. A status report has been published in [4]. It is too early to publish a recently presented proposal in this paper but slides presented at the AB LHC Technical Committee are available on the web [5].

* O. Aberle, R. Assmann, M. Brugger, L. Bruno, H. Burkhardt, E. Chiaveri, B. Dehning, A. Ferrari, B. Goddard, J.B. Jeanneret, M. Jimenez, V. Kain, M. Lamont, F. Ruggiero, R. Schmidt, P. Sievers, J. Uythoven, V. Vlachoudis, L. Vos, J. Wenninger, CERN, Geneva, Switzerland, I. Baishev, IHEP, Protvino, Russia, D. Kaltchev, TRIUMF, Canada

SYSTEM DESIGN

The collimation system must fulfil a number of important design constraints, which are listed below for proton operation. Similar constraints must be respected for operation with ions.

Beam loss rates Regular LHC operation is assumed to include short periods of reduced beam lifetime. At 7 TeV the collimation system should accept losses of $4.1 \cdot 10^{11}$ p/s (0.2 h lifetime) for 10 s or $0.8 \cdot 10^{11}$ p/s (1 h lifetime) continuously. The proton losses during regular operation occur mainly in the first several 100 nm of the collimator surface and can induce a considerable heat load ($\approx$ kW), requiring active cooling.

Cleaning efficiency Assuming the above beam loss rates, the expected quench levels and nominal intensity, the required local cleaning inefficiency is calculated to be $2 \cdot 10^{-5}$ m^{-1} at 7 TeV [7]. The local inefficiency is defined as the inefficiency (number of halo protons reaching $\geq 10\sigma$ per impacting primary proton) divided by the length over which losses are spread (e.g. 50 m).

Number of collimators and phase advance requirements The above mentioned goal for cleaning inefficiency can only be achieved with a cleaning system that has at least two stages with collimators put at special phase advance locations [8, 9]. Momentum and betatron cleaning must be performed separately. Cleaning systems based on aluminium and copper jaws have been integrated into the LHC layout and optics. The jaw materials and lengths are being reviewed and the IR3 and IR7 insertions must be adapted to the final design choices, that rely on longer low-Z jaws. In the old design 7 collimators per beam (1 primary and 6 secondaries) provide momentum cleaning in IR3 and 20 collimators per beam (4 primaries and 16 secondaries) provide betatron cleaning in IR7. The goal inefficiency is achieved. Some additional absorbers are required to capture the proton induced showers in the cleaning insertions. An eventual opening of collimator gaps would require additional collimators in the experimental insertions.

Beta functions in cleaning insertions Ideally, beta functions should be large at the collimators in order to alleviate the consequences if some bunches impact on the jaw. However, the available space in the warm cleaning insertions limits the beta functions to values of 50 m to 350 m (IR7) [9]. Corresponding transverse beam sizes are small, from 160 μm to 420 μm at 7 TeV.

Collimator gaps The available LHC physical aperture is about 10 σ both at injection (limited in arcs) and at 7 TeV (limited at triplets). The primary and secondary collimators must then be closed to nominally 6 σ and 7 σ, respectively, for providing the required cleaning inefficiency at 10 σ. The corresponding collimator full gaps at 7 TeV are small (2.2 - 4.4 mm). It is noted that there is some flexibility in the collimator settings [10].

Operational and mechanical tolerances The relevant tolerances derive directly from the difference in settings between primary and secondary collimators ($1\sigma \approx 200\mu$m), as well as from the impact parameter at the secondary collimators (average impact parameter is 200 μm). Tolerances are a fraction of these values. For example, the tolerances for transient orbit movements and transient beta beat were determined to be 0.6 σ and 8%, respectively. Tolerances were estimated for jaw surface flatness ($\sim 25\mu$m), reproducibility of jaw settings ($< 20\mu$m), step size in jaw movements ($\sim 10\mu$m, $\sim 15\mu$rad) and knowledge in collimator gap $< 50\mu$m. Some trade-off between different tolerances is possible.

Impedance The collimators produce significant transverse resistive impedance due to the small gaps at 7 TeV (impedance scales inversely proportional to the third power of gap size). At nominal beam intensity, the LHC octupoles provide Landau damping of the rigid dipole modes for a total collimator impedance of up to 110 MΩ/m, to be compared with an impedance of 100 MΩ/m generated by the rest of the ring. The RF heating can be significant with several 100 W/m.

Shock beam impact In case of irregular beam dumps several bunches can be deflected on a collimator jaw. Any jaw can be hit, because the primary collimators only cover one phase space location and the overall LHC tune should be allowed to vary. The collimator hardware should withstand beam impact during irregular dumps. The expected maximum beam impact is calculated to be about 8 bunches out of 2808 bunches at 7 TeV. At 450 GeV a full injected SPS batch can hit a collimator.

Reliability and maintenance The lost protons will activate the installations in the cleaning insertions leading to maximal dose rates of up to several mSv/h at direct accessible hot-spots, e.g. shielding or downstream magnets. The collimator jaws may reach higher values. The expected dose rates depend strongly on the collimation layout, the materials chosen, the cooling time as well as the exact location in the insertion. However, human interventions such as maintenance nearby highly activated installations must be restricted to the absolute minimum, hence collimators and belonging equipment must be designed for maximum reliability. Detailed studies are ongoing.

Vacuum aspects The collimators must be bakeable and outgassing rates must remain acceptable. For example, for a graphite collimator this imposes special heat treatment at 1000°C (before assembly), careful in-situ outbaking at 250°C, and a maximum jaw temperature of 50°C, to be assured by collimator cooling. Graphite dust is believed to be uncritical. This is supported by the absence of any dust close to the SPS graphite dump. The magnitude of a local electron cloud and its possible effects are being studied and outgassing measurements are being performed.

Interface to other machine components The collimators interact directly with the other LHC equipment through space and access requirements, induced radioactivity close to the collimators, possible downstream damage due to particle cascades from collimators, and local vacuum issues. All these issues and possible solutions are being followed in the collimation project.

The design of the collimation hardware should address the listed constraints in a consistent way, even though some constraints support conflicting preferences.

CONCLUSIONS

Collimation is a crucial problem for the LHC, requiring efficient solutions for the new LHC regime of very intense high-energy proton beams. A possible collimation system is being worked out with high priority in the LHC collimation project. A proposal has been presented. This paper summarizes the basic system requirements. Details of the proposed scheme will be published in forthcoming reports. It is hoped that the machine design can be frozen by the end of 2003 for all collimator locations, including the dedicated cleaning insertions IR3 and IR7.

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THE LHC INJECTION AND BEAM DUMPING SYSTEMS

B. Goddard, CERN, Geneva, Switzerland

Abstract

The LHC injection systems located in points 2 and 8 are comprised of several elements common to the LHC ring and the downstream ends of the TI 2 and TI 8 transfer lines. The LHC beam dumping system is located in the LHC tunnel in point 6 and in the specially built TD tunnels and UD caverns. The injection and beam dumping system hardware are briefly reviewed. For both systems, the interfaces to the surrounding LHC equipment are described, together with specific outstanding system issues. The requirements and schedule for installation and hardware commissioning are presented.

INJECTION SYSTEMS

The injection systems [1] are located in points 2 and 8 of the LHC and comprise (per ring) 5 injection septa MSI [2], 4 injection kickers MKI [3], the protection devices TDI and TCDD [4], together with various beam instrumentation [5] and control electronics.

Injection subsystems

The main injection subsystems are:

- MSI septum (5 units – total 12 mrad deflection) – issues include injected beam vacuum chamber positioning, aperture for injected beam / septum protection (TCDI), vacuum interconnect details;
- MKI kicker (4 units – total deflection 0.85 mrad) – issues include flashover rates for failures dangerous to LHC collimation system;
- TDI absorber (1 unit – mobile ±10 σ_y setting) – issues include bakeout + beam screen, loading scenarios at injection, hBN properties after irradiation;
- TCDD absorber (1 unit - ±10 σ_y setting) – issues include fixed or movable jaws, definition of final requirements;
- Beam instrumentation (BPMs, BTVs, BLMs, BCT).

Interfaces to other systems

The injection system interfaces to several other LHC machine systems and services, as well as the obvious general services. The interfaces include:

- Circulating beam vacuum;
- Injection line vacuum (BI, MSI);
- Collimator system (TCDI, TDI settings);
- Machine Protection system (MKI);
- SPS machine (injection sequences, interlocks);
- Controls system (setting, alarms, timing, logging, …);
- RF system (synchronisation);
- PO (magnet powering);
- CV (MKI, MSI cooling);
- Safety (fire detection, access, emergency stops);

System level issues

In addition to the specific issues remaining for the individual hardware subsystems, there are several system level issues which are still being addressed:

- Injection collimation system to be finalized (machine protection, collimators, performance);
- Injection system (+ LTI) failure modes quantified;
- Overall injection oscillations (1.5 σ budget) to be quantified (including SPS and transfer lines);
- Detailed integration with ICL/MIWG;
- Detailed installation sequencing with EST/IC;
- HW commissioning aspects with EST/IC, HCWG;
- Beam commissioning aspects with AB/OP, LHC-OP.

Hardware commissioning requirements

In order to perform the Hardware Commissioning of the system a certain number of requirements must be met, including availability of services and other systems. These include:

- General services available (cooling water, ventilation, power, emergency stops, phones, …);
- All equipment installed and individually tested;
- Sufficient test time in schedule;
- Controlled access conditions (tunnel + galleries);
- Vacuum system operational;
- Machine Interlock system operational (beam permit);
- Controls available (Ethernet, pre-pulse, timing, control room s/w, trims, alarms, logging, post-mortem, sequencer, …);
- Connection to dump kickers (via BIC + direct).

Overall schedule

The required main deadlines are given, as a function of main LHC milestones (rev 1.7).

- Injection point 8 (UA87):
  - Installation completed Q4 – 2005
  - Commissioning complete Q1 – 2006 with sector 8.1
  - Sector test (?) Q2 – 2006
- Injection point 2 (UA23):
  - Installation complete Q3–2006
  - Commissioning complete Q1–2007 with sector 1.2

BEAM DUMPING SYSTEM

The beam dumping system [6] is located in point 6 of the LHC and comprises (per ring) 15 extraction kickers MKD [7], 15 extraction septa MSD [2], dedicated protection devices TCDS and TCDQ [8], 10 dilution kickers MKB [9], special vacuum chambers for the long drift section, beam instrumentation [10] and the final beam dump block [11], together with associated control electronics.

The system under construction comprises (per ring) 15 extraction kicker magnets MKD, 15 steel septum magnets MSD, the TCDS and TCDQ protection devices, and 10 modules of dilution kicker magnets MKB, together with various beam instrumentation. The beam dump proper, situated in a cavern 750 m from the centre of the septum magnets, comprises the TDE core and shielding.

Beam dumping subsystems

The main beam dumping subsystems are:

- MKD kickers (15 units – total 0.27 mrad deflection) – issues include failure rates (missing, pre-triggering) for loading of collimator systems;
- MSD septa (15 units, total 2.4 mrad deflection) – issues include aperture for circulating and extracted beam (investigating larger circulating chamber in MSDC, ±4 mm orbit interlock), reworking of connection boxes, vacuum interconnects;
- MKB kickers (10 units, ± 0.28 mrad X, ± 0.28 mrad Y deflection) – issues include staged installation (4/10 units) which limits LHC intensity to 50%;
- TCDS absorber (1 unit, fixed +14 σ_x setting) – issues include vacuum + impedance issues with Carbon;
- TCDQ absorber (1 unit, mobile +10 σ_x setting)- issues include interdependence with collimator settings;
- TDE beam dump (1 unit, 7m long, ~1000 t shielding) – issues include containment (N_2 overpressure, possible additional TD diluter), staged water-cooling limits initial power deposition;
- TD vacuum system (640 m long. 110-610 mm OD);
- Beam instrumentation (BPMs, BTVs, BLMs, BCT).

Interfaces to other systems

The beam dumping system interfaces to several other LHC machine systems and services, as well as the obvious general services. The interfaces include:

- Circulating beam vacuum;
- Extraction line vacuum;
- Collimator system (TCDQ settings);
- Machine Protection system (BIC, TCDQ);
- Controls system (setting, alarms, timing, logging, …);
- RF (abort gap synchronisation);
- PO (powering, DCCTs for Beam Energy Meter);
- CV (TCDS, TCDQ, TDE, MSD, ventilation)
- Safety (fire detection, access, emergency stops);

System level issues

In addition to the specific issues remaining for the individual hardware subsystems, there are several system level issues which are still being addressed:

- Overall reliability analysis;
- Energy tracking of MKD, MSD, MKB;
- MSD aperture;
- Machine protection (TCDQ settings, additional interlock BPM functionality);
- Loading of collimators (asynchronous dump);
- Detailed integration with ICL/MIWG;
- Detailed installation sequencing with EST/IC;
- HW commissioning aspects with EST/IC, HCWG;
- Beam commissioning aspects with AB/OP, LHC-OP.

Hardware commissioning requirements

In order to perform the Hardware Commissioning of the system a certain number of requirements must be met, including availability of services and other systems. These include:

- General services available (cooling water, ventilation, power, emergency stops, phones, …);
- All equipment installed and individually tested;
- Sufficient test time in schedule;
- Controlled access conditions (tunnel + galleries);
- Vacuum system operational;
- Machine Interlock system operational (beam permit);
- Beam Energy Meter operational;
- Controls available (Ethernet, pre-pulse, timing, control room s/w, trims, alarms, logging, post-mortem, sequencer, …);
- Connection to injection kickers (via BIC + direct).

Overall schedule

The required main deadlines are given, as a function of main LHC milestones (rev 1.7).

- Beam Dumping System UA63, TD62 tunnel, UD62:
  - Installation complete Q2–2006
  - Commissioning complete Q3–2006, with sector 5.6
- Beam Dumping System UA67, TD68 tunnel, UD68:
  - Installation complete Q3–2006
  - Commissioning complete Q4–2006, with sector 6.7

The beam dumping systems also need to have a reliability run (system validation, check of failure / availability predictions, debugging of system, INB, …). For this run the systems will have to be connected in their proper operational way: UA63 to TD68, UA67 to TD62. The estimated time required for a useful reliability run is 3 months, and the period foreseen is Q1–2007 (together with commissioning of sector 1.2.).

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AUTHOR INDEX

LIST OF PARTICIPANTS

ALLITT Michael - AT/ MEL
ASSMANN Ralf Wolf - AB/ ABP
BAGLIN Vincent - AT/ VAC
BAILEY Roger - AB/ OP
BAJKO Marta - AT/ MAS
BALLARINO Amalia - AT/ MEL
BALLE Christoph - AT/ ACR
BARTOLOME JIMENEZ Sonia - EST/ IC
BENDA Vladislav - AT/ ACR
BERRIG Olav Ejner - AT/ MTM
BOJON Jean-Paul - AT/ VAC
BOTTURA Luca - AT/ MTM
BOUTBOUL Thierry - AT/ MAS
BREMER Johan - AT/ ECR
CASAS-CUBILLOS Juan - AT/ ACR
CATALAN LASHERAS Nuria - AB/ BDI
CENNINI Enrico - ST/ MA
CHARIFOULLINE Zinour - AT/ MAS
CHEMLI Samy - EST/ IC
CHOHAN Vinod - AT/ MTM
CLAUDET Serge - AT/ ACR
COELINGH Gert-Jan - AT/ MEL
COLLIER Paul - AB/ OP
CORNELIS Marc - AT/ MAS
CRUIKSHANK Paul - AT/VAC
DENIAU Laurent - AT/ MTM
DENZ Reiner - AT/ MEL
DOS SANTOS DE CAMPOS Paulo - AT/ CRI
DURET Dorothee - AT/ ADM
EGGERT Karsten - EP/ TOT
EVANS Lyndon - DG/
FABRE Caroline - AT/ ECR
FARTOUKH Stephane - AB/ ABP
FASSNACHT Patrick - EP/ ATA
FAUGIER Andre - AC/ SY
FESSIA Paolo - AT/ MAS
FORAZ Katy - EST/ IC
FORKEL-WIRTH Doris - TIS/ RP
FRAMMERY Bertrand - AB/ CO
GARCIA PEREZ Juan Jose - AT/ MTM
GAVAGGIO Richard - AT/ VAC
GERARD Delphine - AT/ MEL
GIRARDOT Roger - AT/ ACR
GODDARD Brennan - AB/ BT
GOMES Paulo - AT/ ACR
GUILLAUME Jean-Claude - ST/ EL
HATZIANGELI Eugenia - AB/ CO
HAUVILLER Claude - EST/ IC
HILLERET Noel - AT/ VAC
HUHTINEN Mika - EP/ CMM
JACQUEMOD Andre - AT/ CRI
JIMENEZ Jose Miguel - AT/ VAC
KERSHAW Keith - EST/ IC
KIRBY Glyn - AT/ MEL
KNASTER REFOLIO Juan - AT/ VAC
LAMONT Mike - AB/ OP
LAUCKNER Robin - AB/ CO
LAUGIER Isabelle - AT/ VAC
LE NAOUR Sandrine - AT/ MAS
LEBRUN Philippe - AT/
LEISTAM Lars - EST/ LEA
LEPEULE Patrick - AT/ VAC
LUCAS Julio - AT/ MEL
MARQUE Sebastien - AT/ CRI
MERTENS Volker - AB/ BT
MESS Karl Hubert - AT/ MEL
MILES John - AT/ MAS
MISSIAEN Dominique - EST/ SU
MUTTONI Yvon - EST/IC
NICQUEVERT Bertrand - EST/ IC
OBERLI Luc - AT/ MAS
OSTOJIC Ranko - AT/ MEL
PARENTE Claudia - AT/ ACR
PARMA Vittorio - AT/ CRI
PASSARDI Giorgio - AT/ ECR
PENGO Ruggero - AT/ ECR
PERIN Antonio - AT/ ACR
PERRIOLLAT Fabien - AT/ ADM
PIROLLET Bernard - ST/ CV
PONCET Alain - AT/ CRI
POTTER Keith - EST/ LEA
PRIN Herve - AT/ MEL

PUGNAT Pierre - AT/ MTM
QUESNEL Jean-Pierre - EST/ SU
RAMBERGER Suitbert - AT/ MEL
RATHJEN Christian - AT/ VAC
RICHTER David - AT/ MAS
RIDDONE Germana - AT/ ACR
RODRIGUEZ-MATEOS Felix - AT/ MEL
ROHMIG Peter - AT/ CRI
ROSSI Adriana - AT/ VAC
RUEHL Ingo - ST/ HM
RUSSENSCHUCK Stephan - AT/ MEL
RUSSO Aniello - AT/ MAS
SABAN Roberto - EST/ IC
SANFILIPPO Stephane - AT/ MTM
SANMARTI Manel - AT/ ACR
SCHIRM Karl-Martin - AB/ BT
SCHMIDLKOFER Martin - AT/ CRI
SCHMIDT Frank - AB/ ABP
SCHMIDT Rudiger - AB/ CO
SCHNEIDER Gerhard - AT/ VAC
SERIO Luigi - AT/ ACR
SICARD Claude Henri - AB/ CO
SIEMKO Andrzej - AT/ MTM
SMIRNOV Nikolay - AT/ MTM
STRUBIN Pierre - AT/ VAC
TAVIAN Laurent Jean - AT/ ACR
THIESEN Hugues - AB/ PO
TOCK Jean-Philippe - AT/ CRI
TODESCO Ezio - AT/ MAS
TOMMASINI Davide - AT/ MAS
TORTSCHANOFF - Theodor - AT/ MAS
TRANT - Ralf - TIS/ GS
TSESMELIS - Emmanuel - EST/ LEA
UYTHOVEN - Jan - AB/ BT
VAN WEELDEREN - Rob - AT/ ACR
VANDONI - Giovanna - AT/ ECR
VANENKOV - Iouri - AT/ MAS
VENESS - Raymond - AT/ VAC
VENTURINI DELSOLARO - Walter - AT/ MTM
VERDIER - Andre - AB/ ABP
VERWEIJ - Arjan - AT/ MAS
VITASSE - Michel - AB/ ABP
VLOGAERT - Jos - AT/ MAS
VOLLINGER - Christine - AT/ MAS
VULLIERME - Bruno - AT/ ACR
WALCKIERS - Louis - AT/ MTM
WEISZ - Sylvain - EST/ IC
WETERINGS - Wim - AB/ BT
WILDNER - Elena - AT/ MAS
WILLIAMS - Lloyd Ralph - AT/ CRI
WOLF - Robert - AT/ MEL