Accelerator Physics and Technological Challenges of the LHC

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The LHC at CERN has completed its construction in summer 2008. It is just entering into its commissioning phase in preparation for collider operation for science in 2009. The first beams were already observed in an inaugural commissioning run on September 10, 2008. An inaugural ceremony for the collider organised on October 21, 2008 celebrated the achievement of bringing the LHC to reality by an international team of scientists with support from governments of nations around the globe contributing to the programme. As we anticipate the non-trivial task of a careful, detailed and prolonged commissioning of the collider, it is time to take stock of the achievements to date and the future potential of the LHC, highlighting contributions of our colleagues from India in particular and the sociology of global collaboration.

1. Introduction

The key objective for the Large Hadron Collider (LHC) is to explore the validity of the standard model at unprecedented collision energies, with sufficiently high collision rates and statistics that allow the discovery of new particles, such as the Higgs boson and supersymmetric particles. The LHC performance is measured by its centre of mass (CM) collision energy and the number of events it can deliver to its experiments. A successful operation of the LHC collider requires particle collisions with CM energies above 1 TeV (almost an order of magnitude higher than the current collider energy frontier in the Tevatron collider) and an event rate of more than 1 hadronic event per collision and roughly 30 million collisions per second spaced by intervals of 25 ns.

Since E.O. Lawrence's invention of the cyclotron, the particle accelerator technology has advanced by leaps and bounds, in enabling us to envision and construct the LHC, seven orders of magnitude higher in energy and five orders of magnitude larger in size than the original cyclotron (Fig. 1).

A collider can, in principle, be designed for a range of different particle species. Existing collider machines deploy beams of electrons, positrons, protons, antiprotons or ions. For example, the Tevatron collider, which currently defines the energy frontier for particle colliders, operates with proton and anti-proton beams and the last collider project at CERN, the Large Electron Positron (LEP) collider generated beam collisions between electron and positron beams. Each particle species has its own advantage and disadvantage and the choice of particles must be carefully tailored to the key objective of the collider project and plays a central role in the collider design. For example, Lepton collider machines, such as LEP, generate collisions between elementary particles with precisely defined CM collision energies. They are therefore well suited for high precision experiments. The beams of hadron colliders such as the Tevatron at Fermilab and the LHC project at CERN, on the other hand, consist not of elementary particles but are rather composites of smaller constituents. In its key operation mode the LHC deploys two beams of protons, which are not fundamental particles, but consist of quarks and gluons. The collisions in the LHC therefore occur between pairs of quarks and gluons each carrying only a fraction of the total proton energy and the CM energy of these collisions can vary significantly between different collisions. Hadron beam collisions therefore are not well suited for high precision experiments but offer a tremendous discovery potential which is well suited for the key objective of the LHC: the discovery of new particles whose properties (and mass) are not yet known. Another advantage for using proton beams is that protons are relatively heavy particles that loose only a small fraction of their energy during acceleration in form of synchrotron light. This feature allows the utilisation of superconducting magnet technology and thus, the construction of a reasonable size efficient circular machine where the particle beams have a chance to collide with each other at each turn.

The main drawbacks for using proton beams in a circular collider are the need for higher beam energies (only a fraction of the beam energy contributes to the CM collision energy). Using two counter rotating proton beams in a collider requires two separate vacuum chambers with magnetic fields of opposite polarity for

Figure 1. *Top:* First Cyclotyron: 1930 E.O. Lawrence, 11 cm diameter, 1.1 MeV protons. *Bottom:* The LHC, 2008 9 km diameter, 7 TeV protons, after 80 years, 10^7 times more energy and 10^5 times larger

the two counter rotating beams (a common magnetic field would deflect the two counter rotating beams in opposite directions). The only option for avoiding the construction of 2 separate vacuum systems would be the use of protons and anti-protons, a solution that has been adopted for the Tevatron collider at Fermilab. However, the currently achievable production rates for anti-protons are too low for the design performance of the LHC.

2. The LHC performance goals and constraints

The key design parameters for the LHC are the generation of CM collision energies above 1 TeV and an event rate of more than 1 hadronic event per beam crossing. Recognising that each proton consists of three quarks plus gluons the proton beam energies should be significantly higher than the target CM collision energy. The minimum required beam energies for the LHC are thus 5 TeV. However, the number of collisions with CM energies above 1 TeV increases with higher beam energies. The design beam energy for the LHC was therefore set slightly higher at 7 TeV.

The number of events that can be delivered to the experiments is given by the product of the event cross-section and the machine luminosity L which is entirely determined by the proton beam parameters

$$L = \frac{f_{rev} \cdot n_b \cdot N^2}{\sigma_x \cdot \sigma_y} \cdot F(\phi, \sigma_{x,y}, \sigma_s) \ , \tag{1}$$

where σ_x and σ_y are the transverse RMS beam sizes at the Interaction Points (IPs), f_{rev} the revolution frequency, n_b the number of particle bunches, N the number of particles within each bunch and F a geometric reduction factor for collisions at a crossing angle that depends on the crossing angle ϕ, the transverse RMS beam size and the RMS bunch length σ_s. In order to provide more than one hadronic event per beam crossing the design luminosity has been set to L = 10^{34} cm^{-2}s^{-1} leading to a design bunch intensity of 1.15×10^{11} protons per particle package (ppb), 2800 particle packages (called bunches), a transverse RMS beam size of 16 μm, an RMS bunch length of 7.5 cm and a total crossing angle of 320 μrad at the IPs. The LHC features six experiments: two high luminosity experiments, ATLAS [1] and CMS [2], requesting CM collision energies above 1 TeV, two supplementary low scattering angle experiments near ATLAS and CMS, LHCf [3] and TOTEM [4] respectively, one B-meson experiment, LHCb [5] and one dedicated ion physics experiment, ALICE [6,7]. Figure 2 shows a schematic layout of the LHC collider.

3. The LHC within the existing CERN infrastructure

In order to make best use of the existing infrastructure at CERN the LHC machine is being built in the existing 27 km long LEP [8] tunnel. Approximately 22 km of the LEP tunnel consist of curved sections that allow the installation of bending dipole magnets. The remaining 5 km of the LEP tunnel consist of 8 straight sections that provide space for the installation of the experiments, injection and extraction elements for the proton beams, acceleration devices and dedicated 'cleaning' insertions that protect the superconducting magnets from stray particles.

Not all of the space in the arcs of the LEP tunnel can be used for the installation of dipole magnets. In addition to bending fields a storage ring requires a focusing mechanism that keeps the particles centred on the design orbit. Most modern storage rings use the concept of strong focusing [9,10] where dedicated quadrupole magnets provide magnetic field components that are proportional to the particles deviation of the design orbit. The field pattern is designed such that the resulting

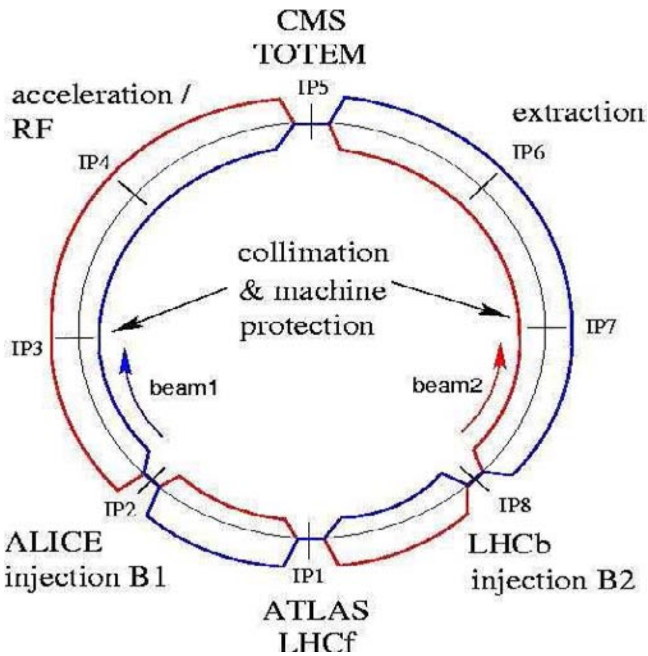

Figure 2. The schematic layout of the LHC collider

Lorentz force deflects stray particles back towards the design orbit and prevents their trajectories from diverging from the design orbit. Rather, it forces the particles to oscillate around the design orbit as they circulate in the storage ring. The number of transverse oscillations per revolution is referred to as the machine tune or 'Q' and presents a key parameter in the design and operation of a storage ring. The stronger the transverse focusing the smaller are the oscillation amplitudes (and thus the transverse RMS beam sizes) and the larger are the machine tunes.

The accelerator magnet design becomes easier and less expensive for small apertures of the magnets. In order to facilitate the magnet design one is therefore inclined to increase the number of focusing elements in the machine in order to minimise the transverse beam sizes. The price to pay with this approach is that not all the space in the tunnel can be used for the installation of dipole magnets and design of a storage ring requires a careful trade off between maximising the space for dipole installation (maximum beam energy reach) and providing sufficient space for the transverse focusing (smaller transverse beam sizes and more efficient magnet designs).

The LHC adopted a design where approximately 80% of the length of the arcs is actually filled with dipole magnets and where the maximum transverse RMS beam size in the arcs can be kept below 1.3 mm. Keeping 7 TeV proton beams on a closed orbit inside the LHC machine implies in this case the use of magnetic bending fields of 8.4 T which requires the use of superconducting magnets at the limit of the existing magnet technology (previous superconducting storage rings use maximum bending fields of ca 5 T). Confining two counter rotating proton beams into the existing LEP tunnel requires separate magnet apertures with opposite dipole field orientations for the two beams. In order to fit these two magnet systems into the existing LEP tunnel (internal tunnel diameter of only 3.76 m) and to minimise the cost and infrastructure requirements for the two storage rings the LHC adopted a novel 2-in-1 magnet design where the two magnetic coils share a common infrastructure and cryostat [11].

4. Challenges for the LHC magnet design

Figure 3 shows the schematic cross section of the novel 2-in-1 magnet design for the main LHC magnets.

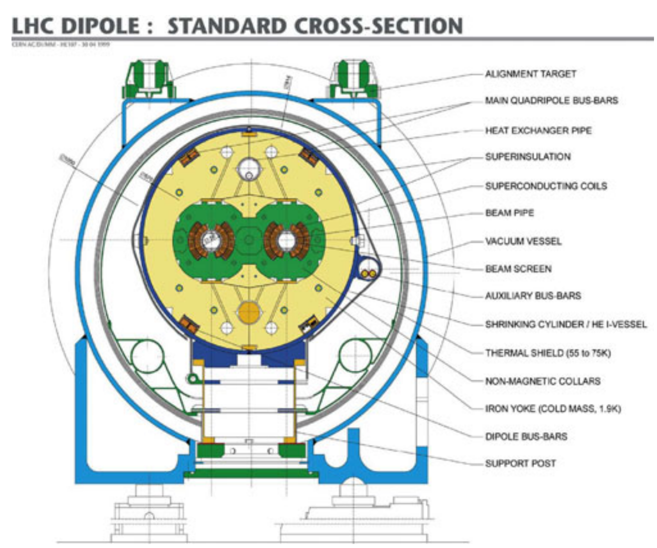

Figure 3. The schematic cross section of the 2-in-1 magnet design for the main LHC magnets

While the 2-in-1 magnet design provides a compact structure (cryostat diameter of 0.914 m) that allows the installation of 2 separate beam apertures into the existing LEP tunnel, it also couples the construction constraints of the 2 magnetic units imposing new challenges and tighter tolerances for the magnet production. The

LHC is the first particle collider that uses this magnet design and the magnet construction could therefore not build on existing experience from previous projects.

In order to minimise the number of magnet interconnections and thus, the lost space for dipole field installations, the LHC adopted a design option of 15 m long dipole magnets. The main LHC dipole magnets are more than a factor 2 longer than dipole magnets in previous accelerator projects (approximately 6 m for the Tevatron [12] and HERAp rings [13]) and weigh approximately 35 tons. The large dimensions of the LHC magnets impose tighter geometric constraints for the magnet construction and new limitations and challenges for the magnet transportation and installation as compared to previous magnet productions. Figure 4 shows the schematic layout of the periodic magnet structure inside the LHC arcs. Each half-cell consists of 3 bending dipole magnets (Main Bends) and one quadrupole magnet (Main Quadrupole). Each arc consists of 46 such half-cells.

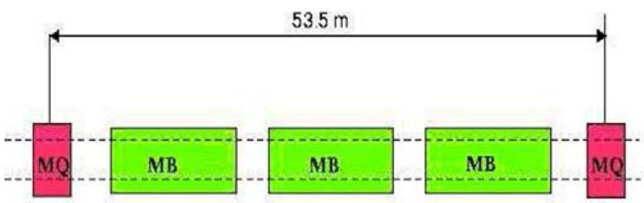

Figure 4. Periodic structure of the magnet installation in the LHC arcs. Each dipole magnet (MB) has a length of 15 m. The quadrupole magnets have a length of 3.4 m yielding a total length of 53.5 m for the basic periodic structure

Figure 5 shows an LHC dipole on the CERN site ready for installation on the back of a truck and Fig. 6 shows the tight manoeuvring in the LHC tunnel during installation.

The superconducting material used for the LHC magnets is NbTi. Like all superconducting materials NbTi is only in a superconducting state provided the key operational parameters, temperature, current density and ambient magnetic field are below the critical values required for sustaining a superconducting state. The critical values define a critical surface in the three-dimensional parameter space of temperature, current density and ambient magnetic field. Figure 7 shows the critical surface for NbTi. An operating magnet field of 8.4 T requires very low operating temperatures and relatively small current densities in the superconducting cables. The operating temperature for the LHC was chosen at 1.9 K allowing a current density between 1.5 kA and 2 kA inside the superconducting cables. The magnets are cooled using liquid He and the choice of an operating temperature below 2 K offers the additional benefit of a high thermal conductivity of He that facilitates the cooling of the magnet coils. However, operating the magnets at a temperature of 1.9 K and an ambient magnetic field of 8.4 T implies only very small margins during the operation of the magnets and even small particle losses inside the magnets, or any other sources for fluctuations in the magnet temperature, can lead to the loss of the superconductive state of NbTi.

Figure 5. An LHC dipole on the CERN site ready for installation on the back of a truck

If such a transition occurs during the magnet operation NbTi becomes normal conducting and the Ohmic losses lead to a further increase in the operating temperate and an unstable set of operating parameters. This process is called a magnet quench. All magnets in the LHC are designed to withstand a magnet quench and quenching the magnets prior to their installation presents a central acceptance test for all magnets. However, in order to minimise the likelihood for this process during operation, the LHC has two dedicated 'cleaning' sections where dedicated absorbers remove stray particles from the beams before they can reach the superconducting magnets in the tunnel.

Figure 6. Example for the tight manoeuvring in the LHC tunnel during installation. The picture shows the installation of the low-B triplet magnets near the experimental detectors

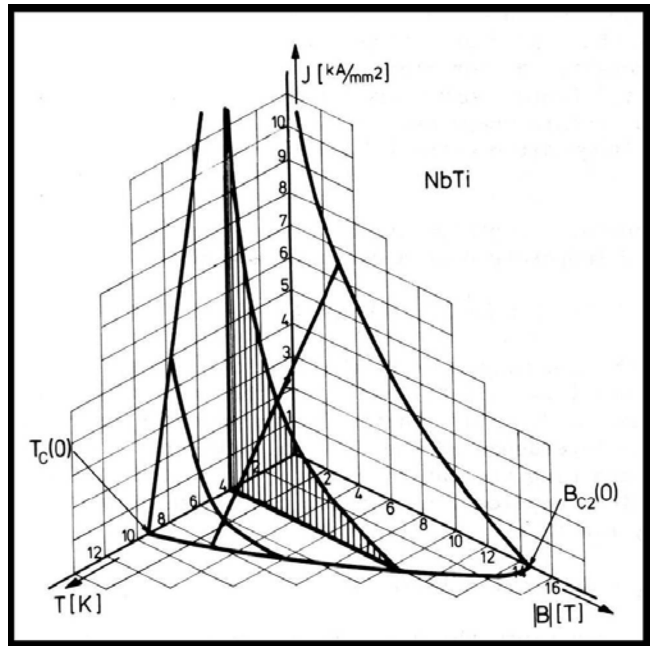

Figure 7. Critical surface for NbTi. The shaded area indicates the preferred operating temperature for most existing superconducting accelerators. The LHC will operate the magnets at a temperature of 1.9 K

5. Challenges to get the LHC ready: Cryomagnet tests at CERN

The LHC magnets constitute roughly 50% of the LHC machine costs; together with cryogenics, this figure comes to $\sim$ 66% of the total material costs of around 3300 MCHF. From the first pre-series production cryomagnet arrival in $\sim$ 2001 to the recent installation of the last dipole in the tunnel in April 2007, the testing of all the cryomagnets of the LHC was a $\sim$ 5 year long major task prior to connection, cool-down and hardware commissioning of the LHC systems in the tunnel. The LHC essentially consists of two interleaved synchrotron rings of 26.7 km circumference. The main elements of these rings are the two-in-one superconducting dipoles and quadrupoles operating in superfluid helium at a temperature of 1.9 K. Cryomagnet assemblies include 1232 dipoles (with correctors), 360 Short Straight Sections (SSS) integrated with quadrupoles and higher order poles which are needed for the different accelerator lattice functions and 114 matching and Dispersion Suppressor region magnets integrated in Special SSS (IR-SSS).

Testing, training and qualification of these magnets under cryogenic conditions was a prerequisite to their installation in the tunnel; these tests were not feasible at the manufacturers' premises.

The testing and qualification activities of a magnet was intended to verify its cryogenic, mechanical and electrical insulation integrity, qualify the performance of magnet protection systems, train the magnet up to the nominal field or higher so as to minimise training of magnets in the tunnel, characterise the intended magnetic field, accept the magnet based on its quench and training performance and generally, ensure that the magnet met its design criteria. These may be categorised broadly within the five phases namely, to connect, cool down, cold test, warm-up and to disconnect respectively.

The SM18 magnet test facility was assembled at CERN to accomplish the goal of testing the 1706 cold masses produced in Europe since 2001 for the LHC [11].

The test facility is equipped with 12 test benches and the necessary cryogenic infrastructure to perform the power tests and magnetic measurements for qualifying these magnets. Testing of the first series production magnets commenced in ~2001. Since early 2003, the test facility was operated round the clock to meet the target to complete the testing of all the magnets required for the LHC by December 2006. The construction of all the 12 test benches was only completed around June 2004 and full usage started soon after. The cryomagnets were all successfully tested by February 2007, within budget and nearly in time.

For these tests, considerable challenges had to be faced and overcome since 2002; in particular, the majority of staff for tests and measurement purposes was provided by India on a rotating, one-year-stay basis, as part of the CERN-India Collaboration for the LHC. This was complemented by some CERN accelerator operation staff. While only 95 dipoles were tested till 2003, the efforts and innovative ideas coming from the Operation Team contributed significantly to the completion of tests of all 1706 cryomagnets. These included the improvements and management of the tests work flow as well as the test rates. Amongst these, certain pivotal ideas to stream-line the tests methodology as proposed and implemented successfully by the Indian Associates deserve a special mention. The following gives a broad insight into this as well an overall view of the tests operation, together with an indication of some of the operation-related results from the tests programme.

The workforce in the SM18 test facility consisted of three teams, with the tests and measurement Operation Team as the pivotal entity supported by the Cryogenics Team and the Magnet Connect/Disconnect Team (called ICS). The Operation Team consists mainly of associates from the Department of Atomic Energy (DAE), India, along with a number of regular CERN employees. The other two teams consist of contract employees from industrial consortia. A CERN team called Equipment Support looked after the improvements, exploitation and the troubleshooting of tests hardware and software on an on-call basis. A sub-team of ICS handles the movement of magnets within the test facility by means of a remotely controlled vehicle named ROCLA. All these teams worked in mutual collaboration to complete the magnet tests by February 2007.

6. Tests concerns and hurdles

Like any facility of unique, one-off requirements, SM18 had also its own characteristic issues, ranging from personnel logistics to infrastructure limitations. Following is a brief account of some of the major issues and challenges that had to be addressed in the routine operation of the facility.

Personnel logistics issues: In early 2002, for financial, technical and organisational reasons, the outsourcing of the tests operation was no more an option. Moreover, due to various factors, only 7 non-experienced CERN staff members from accelerator operation could be assigned to run the SM18 test facility. However, for an anticipated round the clock operation of the facility with 12 test benches, a minimum of 4 persons per shift was necessary, thereby demanding minimum staff strength of 24. It was at this time that DAE, India, offered technical human resources for SM18 operation. India already had a collaboration agreement with CERN since the nineties for the LHC, including a 10 man-year arrangement for tests and measurements during the magnet prototyping phase. Subsequently, over 90 qualified personnel from 4 different Indian establishments participated in the LHC magnet tests on a one-year rotational basis. The technical acumen and success of the early group of Indian Associates lent credence and confidence that the tests activity could be successfully carried out in this manner. The strict, one year rotation was a condition desired by India, leading to the necessity of a large number of persons participating in the programme. Figure 8 shows the President of India visiting the Indian Associates of the LHC cryomagnet tests team in SM18.

Figure 8. President of India with the Indian Magnet Tests Team in SM18 at CERN May 2005

The Indian technical engineers, being not directly related to operation or CERN type of activities, had to get familiar with the magnet tests work before being productive. This essentially necessitated a continuous mentoring programme, hence, limiting the number of 'trained staff' at any time. Preparing the work shift schedule with the limited experienced personnel and keep within the CERN rules and regulations was a major hurdle. Arranging proper facilities for the Indian associates to make them 'feel at home' in Europe was also an equally challenging task.

Novelty aspects: Considering that the LHC cryomagnets were unique, they were tested with a research and development mindset by magnet and equipment specialists during the initial phases of SM18 operation. Partially automated test systems (for one magnet at a time) which existed then were considered adequate for usage by the experts. When the Indian and accelerator operation staff took over the running of the facility, the system appeared to be more or less a 'black box' where, not many details of the test systems and test sequences were provided. Testing of the SSS magnets was a challenging task until the end of 2004 while all necessary information got collected and collated; similarly, testing of the special SSS magnets was a grey area even till beginning of 2006; the special SSS magnets have a large variety of structures, types, temperature regimes and their complexity made the collection of all the relevant information required for tests an extremely complex task. Even the role and responsibilities of the Operation Team had to be properly defined during the early phases.

Magnet qualifying criteria: During the early phases, each dipole was trained to reach its ultimate field (about 8% above the one required for the LHC), which was a major time consuming activity. Extensive magnetic, special measurements and thermal cycles were carried out in majority of the magnets. Qualification of 'poorly performing' magnets was another laborious task, whereby the magnet was removed from the test bench, fitted with anticryostats and quench location instruments and brought for re-testing at a later date.

Co-ordination of teams: Language was the biggest obstacle in proper co-ordination of activities of different teams involved in magnet testing. Indian associates, all non-French speaking, found it difficult to verbally communicate with other teams which were exclusively French speaking. For this major issue, an innovative solution had to be found and implemented

Nature of industrial contracts of other teams: The nature of consortium contracts was also a hurdle. It had been observed that many times, the work slowed down during the weekends because the contractual working hours of the ICS/ROCLA team got exhausted for the week; magnets were not moved, connected or disconnected. Likewise, lack of suitable technical support in case of malfunctioning of certain systems during outside normal hours was also a factor which affected the overall performance.

Infrastructure limitations: The test facility in SM18 is organised in 6 clusters of two test benches each, total 12 benches. However, for space and costs reasons, each cluster has a common power converter, one set of data acquisition system and one set of quench heater power supplies, shared by both benches. This meant that at any given time, these resources could only be utilised by one of the two benches in a cluster.

The cryogenic infrastructure had limited resources which could not feed to the simultaneous demand from all the 12 benches. This put forth a limit on the number of magnets at superconducting temperatures concurrently, the number of training quenches allowed within a specified time period as well as a precise number of magnets using the cryogenic cool-down or warm-up resources [14]. Water resources (to cool down the power converters and other auxiliary systems) are also limited. These constraints necessitate the operation team to optimise all the work by following a complex set of rules and by exercising judicious judgement.

Sometimes due to some imposed factors, the shared resources were blocked. For example, when some special tests were conducted on a magnet, exceptional priority was assigned to this bench, which affected operation on many other benches due to the interlinking of various resources.

The synchronous, cog-wheeling approach foreseen initially [15] was never applied in routine operation because of varying performance of magnets; rather, the 'asynchronous' approach managed by the operation team yielded the desired magnet test rates, aided by the fine trimming of the magnetic and quench performance programmes [16].

7. Early tests performance

Magnet tests work began in $\sim$ 2001 with two benches and a limited cryogenic infrastructure. The work environment that existed till late 2002 was not favourable for a time limited and challenging activity like this. Tests were conducted mainly with laboratory type of systems and mobile racks which were not suitable for round the clock operation. The first sets of dipoles consisting of 30 samples from each of the three suppliers (called the pre-series magnets) were required to be tested elaborately with full magnetic measurements and many other extensive tests. In the early phases of testing till end-2003, due to the lack of readiness of all test benches and cryogenic feed boxes, adequate information, supporting tools and operational experience, only 95 dipoles (including pre-series ones) could be tested [17].

Figure 9 shows the time required for testing the dipoles during the early stages of 2001–2. With such a low testing rate it would have been impossible to meet the target. Hence, it was imperative to formulate proper throughput strategies and to develop supporting tools for enhancing the throughput; this necessitated

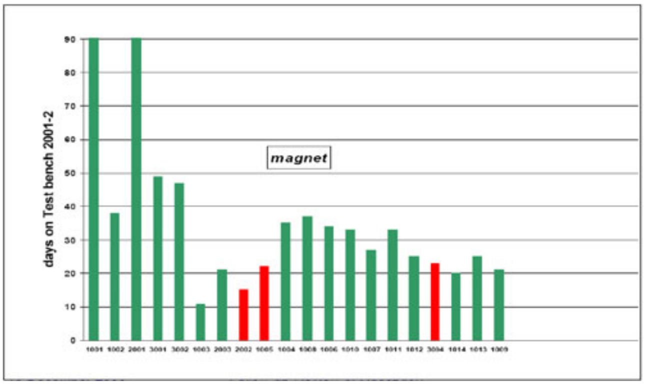

Figure 9. Bench occupancy during 2001–02

an ambitious figure of 16–18 magnet tests per week, higher than anticipated, in order to complete the tests of all magnets by December 2006. This also entailed an extensive study [18] resulting in the application of a selective and reduced magnetic measurement effort.

8. Tests operational strategies and tools

In the attempt to overcome the inherent hurdles and to attain maximum throughput, some effective management principles had to be addressed, necessary supporting tools developed and significant level of operator empowerment had to be efficiently implemented, based on several innovative ideas and techniques. Feedback based on operational experience was given due importance in framing the strategies. Furthermore, the web-based network backbone of CERN and computer facilities have been widely used for developing the supporting tools.

Most important innovations and strategies which essentially helped in achieving a high throughput included the introduction of a template based tests approach, web-based tools for tests management, magnet training rules and criteria for 24-hour operator decision taking and empowerment, general and cryogenic priorities handling by the shift crew, thermal cycle criteria and so forth.

For the final, smooth operation of the facility with 12 benches, it was necessary to ensure a minimum staff strength of 24 at any time, comprising at least 15 experienced staff; however, the staff strength had to be appropriately adjusted according to the expected departures, arrivals and experience as and when required. This aspect was even further exemplified by the projected work load while the full 12 benches were still under construction on a cluster by cluster basis in 2003–4. To ensure all this, the number of Indian associates inducted into the project at any given time had to be carefully defined and planned, considering the strict one year rotation as well as input of the additional CERN staff during 2005 due to the year-long accelerator shutdown. Figure 10 gives a histogram of the total staff strength during the peak period 2005–6, and depicts the intricacies of manpower management. The staff strength was projected to drop steadily after December 2006, the scheduled deadline for the completion of all tests. Mentoring of newly inducted associates was designed to be an 'on the job' and a continuous process, increasing the number of personnel per shift during the process to ensure that the throughput was not affected.

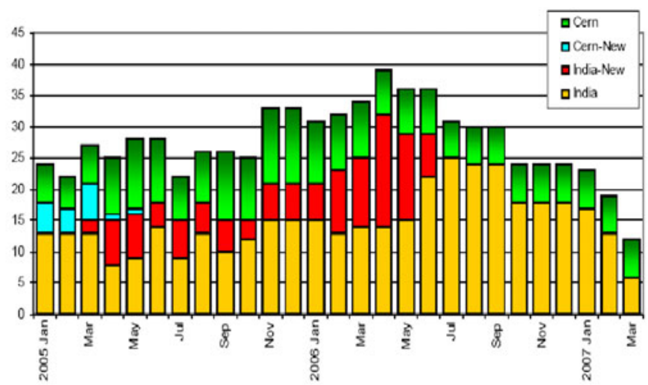

Figure 10. Variation of operation staff strength 2005–06

On the initiative of the Operation Team, a number of new features to aid the magnet tests had been brought in since mid-2003; the whole process of operation for magnet tests underwent a renaissance from crude manual data logging to a more efficient, sophisticated and highly automated tests management system.

A *To-Do-List* was created, which described the minimum set of tests to be performed on a magnet [19]. The tests were sequentially numbered and prefixed with the nature of tests i.e. *Preparatory test* (PREP) or *Power test* (PT). The *To-Do-List* approach weaned away the R&D culture in magnet tests and evaluation to a very stable and clear cut approach that could be handled by the Operation Team. Operation methods necessary for conducting each test in the *To-Do-List* were systematically prepared and reviewed to avoid the human errors in magnet testing to the maximum possible extent.

The Magnet Tests Report templates were designed in a manner for ease of use, with operational notes/checklists appended wherever necessary. The flow of tests in the template obeyed the *To-Do-List* to ensure that the tests were carried out systematically, efficiently and in a failsafe, sequential manner.

A new operation website was developed where all important documentation like operation methods, manuals, presentations, various template files, troubleshooting procedures, shift-plan and so forth could be obtained with minimum effort. This site immensely helped in easing the training of fresh staff as well as in managing the daily operation activities. The Indian Associates were the exclusive contributors to these very significant and essential documentation production and continual mentoring activities.

A web-based system using HTML and ASP codes called the SM18 Test Management System (SMTMS) was developed with all the data relevant to magnet tests stored in this system [20]. Based on the *To-Do-List*, the web-based retrieval from SMTMS permitted the automatic generation of the test sequences and reports such as the CDPT (CryoDipole Power Tests, which contains the training history), MAPS (Magnet Appraisal and Performance Sheet, which is a single page tabulation of the goodness of the magnet) and so forth. This enabled a fast, reliable and error-free generation of crucial data pertaining to the magnet tests. With SMTMS, it was also possible to keep track of times taken for the various phases in magnet tests; all persons directly concerned could keep track of the tests progress from varied geographical locations in CERN and outside [21].

An electronic log-book was implemented using the CERN network backbone in providing web-based applications. Apart from ensuring easy access and usage by all SM18 operation or support personnel, this helped in categorising and recording the different faults that occurred during the course of magnet testing.

To ensure smooth interaction between the various teams during the different stages of preparation before testing as well as at the end of the tests, a web based tool in the form of an Electronic-Workflow manifest called the e-traveller was created [20,22]. The interface of this tool with mobile phones alerted and informed relevant teams (via short message service in appropriate languages) about the need for their services on a particular magnet. This helped the Indian associates to overcome the difficulties in verbal communication with the other teams but maintained the work rhythm as well as keeping an automatic record of the tests phases.

9. Magnet training criteria for tests

In order to attain a high throughput, it was necessary to reduce the number of training quenches per magnet, both from the point of view of limited cryogenic resources as well as the time involved. During 2003, the Operation team had observed that the majority of the magnets cross their nominal field (8.33 T or 11850 A) in the second ramp (Fig. 11), whereas not much additional information on the 'goodness' of the magnet was available from the third and higher quenches [23]. Based on this, a new training rule named the 'Two-Quench Rule' was accepted by the magnet experts [16], under which it was recommended to do only two training quenches in each magnet provided it crossed the nominal field with a small margin. Later on, this rule was complemented by the so called 'Three-Quench Rule', under which a magnet was accepted if it crossed a field of 8.6 T (12250 A) in the third quench even if it had not passed the preceding rule. This strategy drastically reduced the overall cold tests time, thereby resulted in a high throughput. Likewise, the introduction of a Rapid On Bench Thermal Cycle (ROBTC) for magnets with poor performance in the first run was another major step towards reducing the overall magnet test time. These new rules, along with a 24-hour decision taking by the operator on the goodness of the magnet by analysing the results and using the MAPS, helped in achieving a higher throughput. ROBTC and MAPS are discussed in detail elsewhere [24,25]. The criteria for arriving at precise MAPS formulation were based on clear-cut rules and magnet specifications as well reviews, e.g. [26].

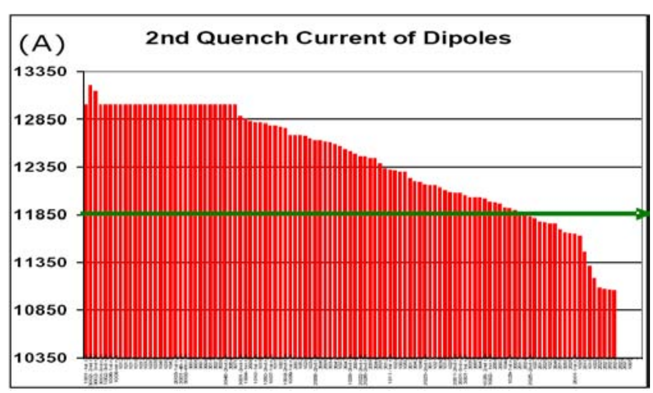

Figure 11. 2nd Quench current of dipoles till December 2003

Magnet	300–80 K (hours)	80–4.2 K (hours)	4.2–1.9 K (hours)	1.9–300 K (hours)
Dipole	16	10	4	15
Quadrupole	8	7	3	12
Special SSS	8	7	3	12

Figure 12. Average cooling and warm-up times (2005)

10. Overall and cryogenic priority handling in tests

Overall priority allocation becomes critical for maximising the throughput from a constrained system with limited resources. In this context, operation team empowerment for deciding and setting the overall and cryo priorities has played a crucial role in maximising the throughput through effective and clash-free resource management.

The limited cryogenics infrastructure [17] in SM18 could support only 6 magnets at a time out of the total 12 that could be in the cooling-down, warming-up or cold test phase. To effectively utilise even this 50% capacity, the operation team has to make careful priority decisions keeping in mind the average time requirement for cooling down/warming up of the particular type of magnet (Fig. 12) along with the constraints in the number of magnets that can co-exist simultaneously within each cryo regime, such as

- 3–5 magnets at 1.9 K
- Up to 2 magnets in 300 K to 80 K phase
- Up to 2 magnets in warm up phase
- 2 magnets in 80 K to 4 K phase
- Maximum 3 magnets simultaneously in cool down and warm up phases put together
- Minimum of 20 minutes delay between two quenches.

The operation team initiated a priority change based on the following broad guidelines [27]:

- A magnet under warm-up phase shall be assigned highest priority (1 or 2), allowing it to go out as fast as possible
- Due consideration shall be given to a cooling down magnet assessing the overall situation for the next 12 hours
- Magnets already at 1.9 K shall be given next higher priority (2–5) with maximum of 3 magnets getting the major share of cryo cool-down/warm-up resources (85 g/s for each magnet out of the total 300 g/s gaseous helium) and a fourth one with the remaining resources
- Priority numbers 6–8 could be assigned amongst the magnets cooling from 80 K down to 4.4 K
- The remaining priorities were allotted to the other magnets considering their exact status and the time that would elapse before they required the resources.

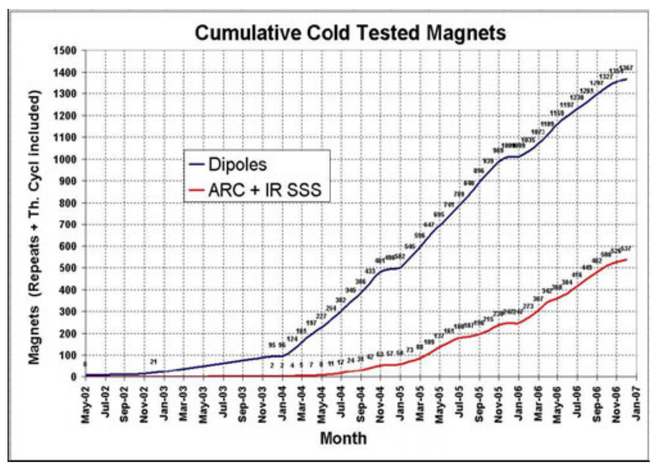

Figure 13. Cumulative cold tested magnets

11. Tests results and first tunnel commissioning

Figure 13 depicts the cumulative number of magnet tests, including repeats, since 2002. While the throughput was low till end-2003, it picked up sharply after the introduction of throughput strategies and tools. The plateau regions at the end of each year are due to the annual cryogenic infrastructure shutdown of typically seven weeks. Figure 14 gives further details of the magnets tested each year. It segregates the number of dipoles, arc SSS and IR-SSS tested each year, along with the cumulative number of magnets tested in that year. Starting with the meagre 21 magnets tested in 2001–2 and 76 in 2003, 456 magnets were tested in 2004. This count went up to an all time high of 703 magnet tests during 2005. During 2006, 648 magnet tests have been carried out; while this may appear low compared to 2005, it was a remarkable achievement taking into account the fact that the majority of the Special SSS magnets were also tested during 2006. Testing of the Special SSS magnets was a major time consuming activity in logistics and magnet training; each of the 114 magnets needed a special, dedicated to-do-list. Often, each special magnet was trained until it reached the ultimate field and elaborate magnetic measurements were also required [28]. Average repeat rates for the dipole, arc SSS and Special SSS magnets have been around 9%, 12.5% and 12.8% respectively, not counting the repaired and renamed magnets. In addition, ∼3% of the dipoles and ∼6% of the SSS had to be repaired or rejected after the cold tests due to unacceptable quench performance. The latter type of issues, observed early in the project, confirmed the need to systematically test all the LHC magnets under cryogenic conditions.

Period	Dipoles tested (Reqd. Number = 1232)			ARC-SSS + 500 tested (Reqd. Number = 392)			IR-SSS (Reqd.Number = 82)			Total magnets tested
	Fresh	Repeat	Total	Fresh	Repeat	Total	Fresh	Repeat	Total	
Year 2002	21	0	21	0	0	0	0	0	0	21
Year 2003	74	0	74	2	2	2	0	0	0	76
Year 2004	356	45	401	49	3	52	3	0	3	456
Year 2005	468	45	513	148	17	165	20	5	25	703
Year 2006	326	32	358	187	37	224	59	7	66	648
Total	1245	122	1367	386	57	443	82	12	94	1904

Figure 14. Magnets tested in each year

Magnetic measurements were performed on ∼18% of dipoles, ∼13% of arc SSSs and ∼31% of Special SSSs. Often, exceptional tests were performed by the magnet experts on the Special SSSs, needing a considerable amount of time and data analyses.

Overall, about 38% of the total number of tested dipoles reached nominal field without a training quench. About 9% of the dipoles were tested for a second time after a thermal cycle, mostly to further investigate weak quench performance.

In the LHC tunnel, during the hardware commissioning of one of the first sectors in February 2008, the first natural quenches occurred at around 9.8 kA (at an equivalent energy of ∼5 TeV). The other LHC sectors have yet to hardware commissioned at the time of writing this paper.

12. Tests concluding remarks

To complete in ∼5 years the tests of all the LHC cryomagnets well in time before the LHC installation and hardware commissioning in the tunnel, several innovative ideas, strategies, tools and techniques were introduced and implemented by the magnet tests operation team. The results and statistics of magnet tests underline the significance of them in the successful completion of the tests. While many challenges were met and overcome in operation, delays in magnet delivery issues particularly since mid-2006 remained beyond the control of the operation team. Nevertheless, all magnet tests for the LHC were completed by February 2007. The LHC magnet tests operation has also been a singular and very successful example of a large scale collaborative effort in terms of human resources; over 90 persons from India have spent one year each at CERN since 2001 and hence, it remains a unique example in international collaboration of that scale in the particle accelerator domain. Figure 15 shows the last group of Indian Associates who participated in this massive tests effort.

Figure 15. Indian Tests Team in October 2006, nearly at the end of the 5-year collaboration for the LHC magnet tests

13. Challenges in the LHC cryogenics

Ten years of multidisciplinary R&D for the LHC have resulted in significant advances in cryogenic engineering of large helium – particularly helium II – systems. The installed cryogenic system of the LHC is the largest in the world in terms of refrigeration capacity, with an equivalent to 144 kW at 4.5 K [29,30]; working under normal operation needs about 400,000 litres of superfluid helium for the 25 km of superconducting magnets below 2 K, implying a cryogen inventory of ∼100 tons of helium.

The LHC magnets are cooled with pressurised superfluid helium, which has some interesting properties that make it a unique engineering material. Best known is its very low bulk viscosity which allows it to permeate the smallest cracks. This is used to advantage in the magnet design by making the coil insulation porous and enabling the fluid to be in contact with the strands of the superconductor. It also has a very large specific heat, 100,000 times that of the superconductor per unit mass and 2000 times per unit volume. Hence, superfluid helium provides very high thermal conductivity. Just to illustrate the size and complexity of the systems, some examples are appropriate; during the cool-down of the first octant of the LHC in 2007, ∼1200 tons of liquid nitrogen were required (equivalent of 64 trucks of 20 tons each) for the pre-cooling of this octant from room temperature to 80 K. From 80 K to 4.5 K, cool-down was carried out with the refrigerator plant, needing about three weeks with about 4700 tons of material to be cooled. Lastly, from 4.2 K to 1.9 K, cold compressors at 15 mbar were employed, needing four days for achieving this cool-down.

14. Total stored energy and machine protection issues

Generating the required dipole field of 8.33 T for the nominal LHC operation with 7 TeV proton beams requires a magnet current of 11.85 kA [11]. With 1232 magnets and an electrical inductance of L = 98.7 mH per magnet, this implies a total stored electromagnetic energy of 8.5 GJ for the dipole circuits alone (E = 0.5 * L * I2). 1 MJ is sufficient energy for melting 2 kg of Cu. The total stored electromagnetic energy inside the LHC dipole magnet chain exceeds the stored energy of previous superconducting storage rings by more than an order of magnitude (HERA: E = 0.7 GJ [13]) and presents a significant damage potential to the LHC equipment. In case of a magnet quench this electromagnetic energy needs to be extracted and dissipated in a controlled way before any of the magnet equipment is damaged. These protections is achieved by separating the main LHC magnet circuits into 8 independent powering sectors (stored electromagnetic energy comparable to that in previous superconducting storage rings) and by dissipating the energy during a quench into dedicated dump resistors and bypass quench diodes. One challenge for the LHC operation will be to synchronise the powering of the independent magnet sectors to the required accuracy. Existing storage rings avoid this synchronisation problem by powering all main magnets in series in a central circuit. The LHC will enter into new territory in this respect due to 8 independent powering sectors.

The stored beam energy provides another source for potential equipment damage during the LHC operation.

The LHC beam parameters translate to a total circulating beam current of approximately 0.5 A that corresponds to total stored beam energy of 370 MJ at 7 TeV. In case of problems during the machine operation the beams have to be quickly removed from the machine before the stored beam energy can damage any of the LHC hardware in the tunnel. An elaborate machine protection system, that constantly monitors all critical beam parameters and the beam losses along the storage ring, plays therefore a central role in the LHC machine design.

15. Other accelerator physics issues

The beam lifetime in the LHC is expected to be limited by beam-beam interaction, rest gas collisions, achievable vacuum levels (cryo pump), dynamical non-linear resonances and the resulting dynamic aperture of stability, the limitations of realistic number of corrector circuits and tolerances, dynamic effects and persistent currents. The challenge of adjusting the circuit settings and the need for non-destructive measurements and observables are higher than ever.

The resonances arising in single particle dynamics of a circulating particle in the collider, the various collective effects and instabilities (e.g. intra-beam coulomb scattering and beam-wall electromagnetic interaction), fluctuations in the power converter and ambient noise and vibrations will cause emittance growth of the proton beams leading to loss of luminosity.

The LHC needs a very effective collimation system as it needs to absorb stray particles. The cleaning inefficiency, specification of the required opening tolerances, hardware tolerances (e.g. surface flatness and temperature margins during operation) and operational tolerances all call for a very well designed LHC collimation system.

In order to protect the magnets, the LHC requires a dedicated and special Magnet Quench Protection System including voltage tabs, dedicated heater systems and beam loss monitors. The total number of input signals and reliability requirements compare close to safety related to flying a plane

The total event pile up rate and topology of hadronic showers in the experimental detectors are important concerns, needing detector commissioning with low luminosities.

The radiation inside the detector and central tracker lifetime are important issues requiring collider operation with lead for cool down before shut down.

16. Outlook and upgrade options

The LHC team is already considering various upgrade scenarios with collaboration from Europe (CARE) and US (LARP). The upgrades will comprise of: (a) IR and detector upgrades and (b) injector complex upgrade options of the original proton synchrotron PS2 and the linac systems. The radiation damage limit at an integrated luminosity of 700 fb^{-1} will require replacing the interaction region magnets any way by 2012, allowing us to design new tighter collision focus and incorporate novel techniques of crossing angle geometry and transversely deflecting "crab" cavities to reach the ultimate LHC luminosity going beyond 10^{34} to possibly 10^{35} cm^{-2}s^{-1}and beyond. The crab cavities allow us to compensate for the strong beam-beam interactions at the 4 primary IPs and 30 long range collisions per IP as shown in Fig. 16.

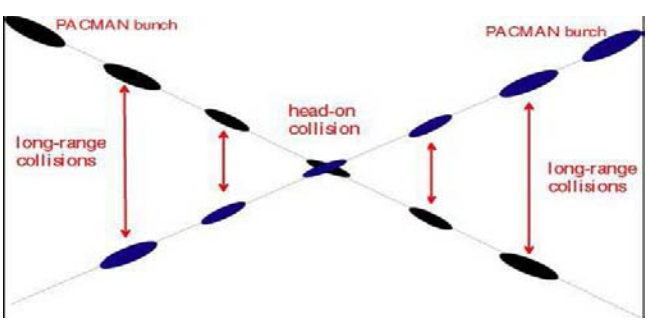

Figure 16. Beam crossing at a crossing angle

The ultimate luminosity of the LHC will possibly be determined by a process known as the Electron-Cloud Effect, depicted in Fig. 17, where photo-emission and secondary electron emission from the surrounding vacuum chamber in presence of beam leads to an amplification process ultimately shutting down proton beam sustenance in the collider. Such a phenomena might be expected at a luminosity of between 10^{35} to about 10^{36} cm$^{-2}s^{-1}$.

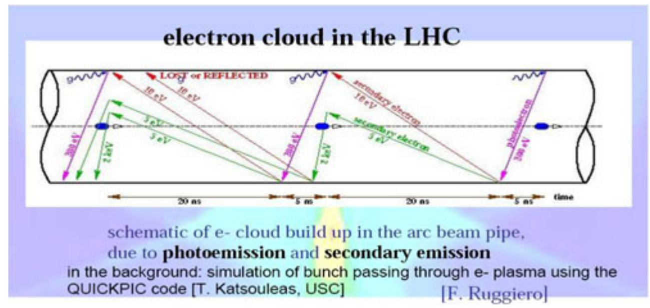

Figure 17. The electron cloud effect

17. Summary and outlook

We have given an impression of the currently configured LHC and its potential future upgrades. Most appropriately for this publication, we have highlighted at some length, at the risk of losing some technical readers, the sociological dimension of the international collaboration that defines the LHC. In particular, in the critical labour-intensive area of bench-testing and qualifying the pioneering superconducting magnet test programme, the contributions of Indian colleagues are inestimably immense. May the success of the LHC be a beacon for further successful international multinational scientific collaborations and herald the arrival of a large productive nation such as India on the international arena of large facilities.

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