PhD Thesis

THE MANAGEMENT OF A LARGE SCALE PROJECT IN PARTICLE ACCELERATORS: THE COMMISSIONING OF THE TECHNICAL SYSTEMS IN THE LHC

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A mis padres...

Abbreviations and acronyms

AC	Alternate Curren
ACN	Accelerating Normal-conducting Cavities
ACS	Accelerating Superconducting Cavities
ALICE	A Large Ion Collider Experiment
ATLAS	A Toroidal LHC ApparatuS
AUG	General Emergency Stop
BI	Beam Instrumentation
BIC	Beam Interlock Controller
BIS	Beam Interlock System
CERN	Conseil Européenne pour la Recherche Nucléaire
CLIC	Compact Linear Collider
CMS	Compact Muon Solenoid
DC	Direct Current
DFB	Distribution Feed Box
Di	Dipole magnet or circuit placed in the i-half cell of LHC
DSL	Distribution Superconducting Link
EE	Energy Extraction
ElQA	Electrical Quality Assurance
HC	Hardware Commissioning
HCA	Hardware Commissioning Activities
ILC	International Linear Collider
IP	Interaction Point
IR	Intersection Region
IST	Individual System Tests
ITER	International Thermonuclear Experimental Reactor
LACS	LHC Access Control System
LASS	LHC Access Safety System
LDB	Layout Database
LEIR	Low Energy Ion Ring
LEP	Large Electron Positron Collider
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty experiment
LINAC	LINear ACcelerator
LSS	Long Straight Section
MB	Main Bending Magnet

MFT	Manufacturing Test Folder
MKI	Kicker Magnets
MP	Post-mortem
MQ	Main Quadrupole Magnet
NCR	Conconformities
ODH	Oxygen Deficiency Hazard
PC	Power Converter
PIC	Powering Interlock Controller
PLC	Programmable Logic Controller
PS	Proton Syncrotron
PSB	Proton Synchrotron Booster
PT	Powering Tests
Qi	Quadrupole magnet or circuit placed in the i-half cell of LHC
QRL	Cryogenic Distribution Line
QSP	Quench Protection System
RAMSES	Radiation Monitoring System for the Environment and Safety
RB	Main Bending Circuit
RF	Radio Frequency
RQF-RQD	Main Focusing-Defocusing Quadrupole Circuit
SC	Superconducting Circuit
SCT	Short Circuit Test
SPS	Super Proton Syncrotron
TI	Transfer lines from SPS ring to LHC ring
UPS	Uninterruptible Power Supplies
WBS	Work Breakdown Structure

Contents

Introduction

The Large Hadron Collider (LHC) is the circular accelerator constructed at CERN that will provide head-on collisions of protons at a center of mass energy of 14 TeV for high energy physics (HEP) research. One of the technical challenges is the big complexity and size of the LHC machine. More than fifteen systems (not including the beam systems nor the experiments) are involved in the commissioning phase, also called Hardware Commissioning (HC). In some cases the complexity is huge due to the amount of components forming each system. A good example of this are the superconducting and normal conducting circuits with about 1600 circuits and its entire infrastructure to be commissioned together. The HC goal is to check that all the systems achieve the performance needed to match the machine design parameters. This commissioning phase is placed after the installation and before the beam test. The HC consists in the parallel commissioning of the groups of systems which work together (i.e. equipment groups). Before this, each system needs to complete their own tests, the so called Individual System Tests (IST), during which their individual performance (i.e. without the need of other systems) is verified . During the commissioning, some of the systems act in parallel, some work together and some need the result of others to start. This complex situation requires a thorough analysis to define the sequence and the procedures for an optimized start-up as well as a plan to guarantee quality assurance.

Motivation and scope

The scope of this thesis is to design and implement the tools for the HC Project needed for the development and maintenance of the project plan, which formalizes the execution and the control of the project. The key issues of the project have been identified as the visualization of the time to complete, the budget and cost and the final quality of deliverable. Key points as target dates, schedules to complete and resource limitations are applied to control the project schedule variances at completion. The tools give project tracking capabilities and answer the project management question of *"where are we in the project?"*. In addition, they assure project control to take decisions and reorient the baseline. The ad-hoc commissioning tools providing this added value to the project management designed in this thesis are: the HC schedule, the HC resources model and the HC planning. The HC Project has some specific characteristics that have been taken into account in the moment of the creation of these tools. It had both strong budget and time limitations. Due to historical reasons, consecutive budget increases and delays in the LHC Project, the HC Project has been limited by these two important restrictions.

Thesis main subjects

The main subjects of the thesis are the management and the coordination of the HC as a global approach and its technical preparation.

The coordination of the LHC Hardware Commissioning in a global approach needed the ad-hoc design of tools and the creation of an entire management infrastructure. "Global approach" means, for instance to have a common database, a common quality assurance tool and a common document plan. The term HC will always refer to an overall project which includes the commissioning of all the equipment groups as sub-projects of the same mission. The work carried out has been to: organize and make available the logic of the position of machine components respecting their geographical distribution around the machine, their functional distribution and prepare use cases in order to identify the user requirements.

Once the identification had been done and all the users agreed, a document plan and an architecture were designed to include all the blocks. This structure allows following up the project and evaluating the timing of the commissioning phases. It is a key tool in order to take decisions during the commissioning phase, to prepare the archiving structure for the technical documents (schedules, procedures, sequences, safety rules, etc.) and to guarantee that the LHC Quality Assurance Plan is respected [1].

The technical preparation of the project consists in the production of the test procedures for each equipment and each equipment group. These documents contain a detailed description of the steps to follow. They list the conditions required to start, a detailed description of the tests and the status of the system once these are successfully completed. The definition of the planning, including a resource study, has been done to illustrate the timing of the tasks and the interferences and dependencies between systems. The definition of the tests, their corresponding data collection, their analysis and the test results complete the technical preparation of the HC Project.

Chapters structure

The LHC motivation, characteristics, layout and main challenges are presented in Chapter 1. The introduction to project management in accelerators together with the antecedents study is introduced in Chapter 2. This chapter explains the lifetime of a project and the utility of the management tools developed by this thesis in its different phases. Afterwards, it is specified for large scale projects in accelerators and finishes with the particular case of the LHC Hardware Commissioning project.

Chapter 3 details the different systems concerned during this phase of the project with respect to the hardware commissioning. It gives a description of the systems, the individual system tests they follow, the hardware commissioning tests and their sectorization within the machine.

The technics followed for the definition of the HC schedule are given in Chapter 4. The chapter regards the definition of the time estimations and the network diagram that lead to the project schedule. In Chapter 5 the technique proposed for the resources study is explained. This study together with the HC schedule results in the HC planning and the outcome as a control tool and its integration in the LHC Project planning is given.

Chapter 6 is devoted to explain the methodology that the author proposes to create and implement the tools for the technical coordination of the project by designing a document plan, a quality plan and an arborescence architecture that homogenize the sectorization and the visualization of the project.

The design of a quality assurance tool specially costumized for the Hardware Commissioning project is explained in Chapter 7. This tool takes care, as well, of the requirements during the lifetime of the project (i.e. green light for tests execution) and future needs (i.e. as-built database).

Finally, in Chapter 8 the global impact of these tools in the project are presented by analyzing the implications of their application to the commissioning of the superconducting circuits system.

This is the equipment group to which major time and efforts are devoted during the LHC hardware commissioning phase due to its complexity and quantity.

Chapter 1

The Large Hadron Collider (LHC)

The motivation to construct the Large Hadron Collider (LHC) at CERN comes from fundamental questions in particle physics. The first problem of particle physics today is the one of the mass: is there an elementary Higgs boson? The primary task of the LHC is to make an initial exploration in the 1 TeV energy range. The major LHC experiments, ATLAS and CMS [2], should be able to accomplish this for any Higgs mass within the expected range. To get into the 1 TeV scale, a 7 TeV proton collider has been constructed, making use of the existing 27 km long tunnel. For the deflection of 7 TeV protons, a magnetic field of 8.33 Tesla is required that can only be generated with superconducting magnets. The machine is also designed for collision of heavy ions (for example lead) at very high center of mass energy. A dedicated heavy ion detector, ALICE, is being built to exploit the unique physics potential of nucleus-nucleus interactions at LHC energies. The fourth detector, LHC-B, will be devoted to precision measurements of CP-Violation and rare decays of B Meson [3].

The LHC accelerator has been prepared since the beginning of the eighties, with a research and development program for superconducting dipole magnets and the first design of the machine parameters and lattice. The CERN Council approved the LHC in 1994. At that time it was proposed to build the machine in two energy stages due to limited funding. Strong support for the LHC from outside the CERN Member States (Canada, India, Japan, USA and Russia contribute with manpower and money) made the CERN Council decide in 1996 to approve the LHC to be built in only one stage with 7 TeV beam energy. The LHC accelerator has been constructed in collaboration with laboratories from both Member and Non-Member States and regular beam operation shall start in 2008.

Particle physics requires for the LHC, a luminosity [1] in the order of $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, a significant challenge for the collider.

1.1 CERN and the LHC

CERN is the leading European Institute for Particle Physics. It is located close to Geneva across the French Swiss border. In 2008 there are 20 European Member States, 5 Observer States, and many other States participating in the research at CERN.

CERN has a unique expertise in the construction of hadron accelerators. The CERN Proton Synchrotron (PS) was built in the 50ies and is still in use. The first proton-proton collider, the Intersecting Storage Ring (ISR), was built in the 60ies. Two continuous proton beams were

[1] The luminosity is the number of interacting particles per unit area and unit time; it is expressed in $\mathrm{cm}^{-2}\mathrm{s}^{-1}$

colliding at a momentum of about 30 GeV/c. Later bunched proton and antiproton beams were accelerated from 26 GeV/c to 315 GeV/c and brought into collision at the SPS (Super Proton Synchrotron) [4], where the Z_0 and W bosons were discovered. Most of this infrastructure has been re-used for the LHC Project.

The LHC has been installed in the tunnel with a circumference of 27 km that has been previously used for the Large Electron Positron Collider (LEP). LEP reached its maximum momentum of 104 GeV/c (centre-of-mass energy about 208 GeV) after an upgrade of the Radio Frequency (RF) by installing a large number of superconducting cavities. In 2002, the LEP equipment was removed and the tunnel prepared for the new collider. Installation of the LHC equipment in the former LEP tunnel started in 2003 [5]. Major CERN milestones relevant to the LHC Project are given in Table 1.1.

1982	First studies for the LHC Project
1983	Z_0 discovered at SPS proton antiproton collider
1985	Nobel Price for S. van der Meer and C. Rubbia
1989	Start of LEP operation (Z-factory)
1994	Approval of the LHC by the CERN Council
1996	Final decision to start the LHC construction
1996	LEP operation at 100 GeV (W-factory)
2000	End of LEP operation
2002	LEP equipment removed
2003	Start of the LHC installation
2005	Start of hardware commissioning
2008	Commissioning with beam

Table 1.1: History of CERN related to the LHC Project.

The beams for the LHC machine will be prepared and accelerated by existing particle sources and pre-accelerators [6]. The injector complex includes many accelerators at CERN (see Figure 1.1): Linacs, Booster, LEIR (Low Energy Ion Ring) as an ion accumulator, PS and the SPS. The beams will be injected from the SPS into the LHC at 450 GeV/c and accelerated to 7 TeV/c in about 30 minutes, and then collide for about 10 hours.

The LHC beam parameters, sizes and intensities are basically determined by the performance of the injector complex. The pre-accelerators are already operational and the modifications required to achieve the LHC beam parameters are essentially finished. The main part of the civil engineering for the LHC consisted on the construction of two large underground caverns for ATLAS and CMS, two transfer tunnels each of 2.5 km length from SPS to the LHC and two tunnels to dump the beam.

1.2 The LHC as a High Energy Accelerator

A fundamental question for the LHC is the choice of the accelerated particles. Why will be protons (and not electrons) accelerated in the LHC and why is the LEP tunnel being re-used for the construction of the LHC? Why does one need to deploy superconducting magnets instead of classical resistive magnets, used for previous existing accelerators?

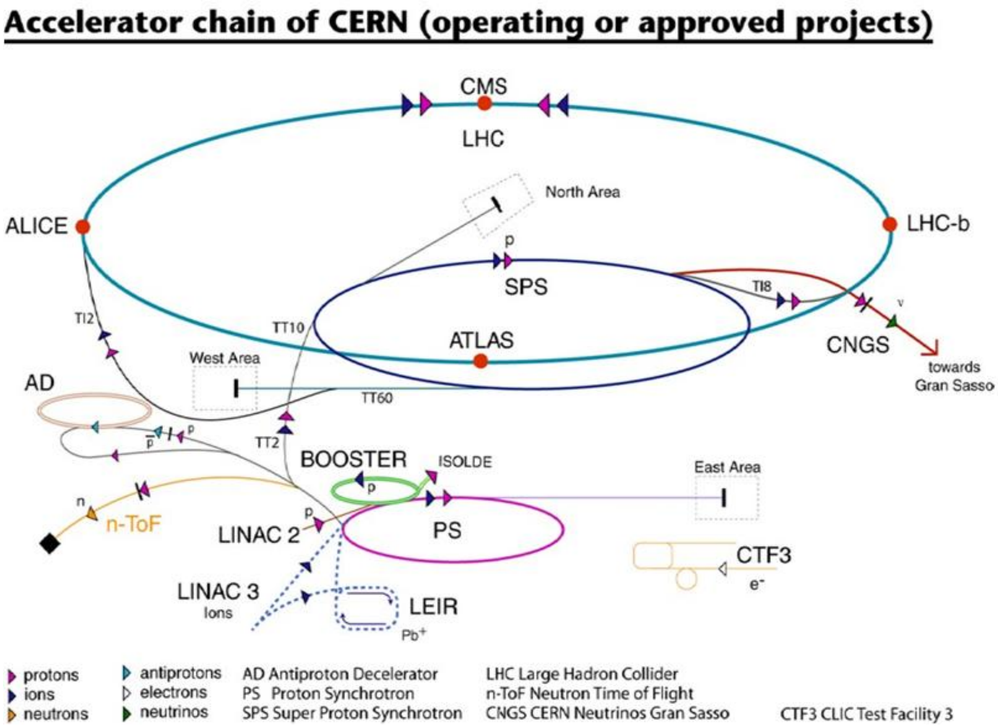


Figure 1.1: Schematic view of the LHC injector complex. The beam is injected from the SPS into the LHC at a momentum of 450 GeV/c. Booster and PS are used to prepare the bunches and to accelerate to the injection momentum of the SPS (26 GeV/c). LEIR is being used for accumulating and cooling of ions

1.2.1 Acceleration and Deflection of Charged Particles

The force on a particle with the charge q is given by the Lorentz equation with the electrical field $\mathbf{E}$, the magnetic field $\mathbf{B}$ and the particle velocity $\mathbf{v}$:

$$\mathbf{F} = \mathrm{q} \cdot (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{1.1}$$

An increase of energy of a charged particle is only possible by electrical fields, and not by magnetic fields. The energy gain is proportional to the force along the path:

$$\Delta E = \int \mathbf{F} \cdot \mathrm{ds} \tag{1.2}$$

The energy gain in an electrical field is:

$$\Delta E = \int_{s_1}^{s_2} \mathbf{F} \cdot \mathrm{ds} = \int_{s_1}^{s_2} \mathrm{q} \cdot \mathbf{E} \cdot \mathrm{ds} = \mathrm{q} \cdot \mathrm{U} \tag{1.3}$$

For an acceleration to 7 TeV (10^{12}) a voltage U of 7 TV is required. Since it is not possible to accelerate particles to an energy above, say, 1 MeV in a constant potential, RF acceleration is used for all high energy accelerators. In a RF cavity a time-varying electrical field accelerates charged particles that must enter in the cavity at the correct phase. A second particle coming later at the wrong phase would be decelerated. The consequence of acceleration with RF are bunched beams, it is not possible to accelerate, with RF, a continuous beam. The maximum electrical field in such cavities is in the order of 20-30 MV/m for continuous operation with superconducting RF cavities. Using pulsed cavities, gradients of about 60 MV/m have been achieved.

In circular accelerators (e.g. in a synchrotron) the particles pass many times through the cavity and are accelerated at each passage. Dipole magnets keep the particles during the acceleration on an (approximately) circular path. The typical frequency of an RF cavity is in the order of 10 MHz to some 100 MHz. The LHC RF equipment group operates at 400 MHz [7]. For comparison, accelerating protons to 7 TeV with a linear accelerator would require a length of about 350 km (!) (assuming 20 MV/m) for each beam.

Deflection of charged particles in an electromagnetic field is also determined by the Lorenz force:

$$\mathbf{F} = \mathrm{m} \cdot \mathbf{a} = \mathrm{q} \cdot (\mathbf{v} \times \mathbf{B}) \tag{1.4}$$

Assuming that a particle moves on a circle with radius ρ in a homogenous magnetic field perpendicular to the velocity, the Lorenz force is equal to the centrifugal force:

$$\mathrm{q} \cdot \mathbf{v} \cdot \mathbf{B} = \mathrm{m} \cdot \frac{\mathrm{v}^2}{\rho} \tag{1.5}$$

The radius of the accelerator is:

$$\rho = \frac{\mathrm{E}}{\mathrm{c} \cdot \mathrm{q} \cdot \mathrm{B}} \tag{1.6}$$

The bending radius of the magnets is determined by the LHC previously existing tunnel. For injection at 450 GeV/c the magnetic field is about 0.54 T. During acceleration, the field in the dipole magnets is increased up to 8.33 T for the maximum momentum of 7 TeV/c. Such high field can only be achieved with superconducting magnets.

Compared to a magnetic field in the LHC dipoles of 8.33 T, a typical electrical field that can be applied for the deflection of charged particles in an accelerator is limited to about 10^7 V/m. For these numbers, the force of the magnetic field is about 300 times stronger compared to the force of the electrical field. In high energy accelerators only magnetic fields are used for particle deflection (apart from some few exceptions for beam separation). The gravitational force is about 20 orders of magnitude smaller than the electromagnetic force and can be neglected.

1.3 The LHC Layout

The LHC layout has to be explained from two different points of view namely geographically and technically. Both views have been essential for the development of the tools designed in this thesis.

1.3.1 Geographical Machine Layout

For the geographical description the accelerator can be divided into the main ring and the adjacent installations and insertions (see Figure 1.2).

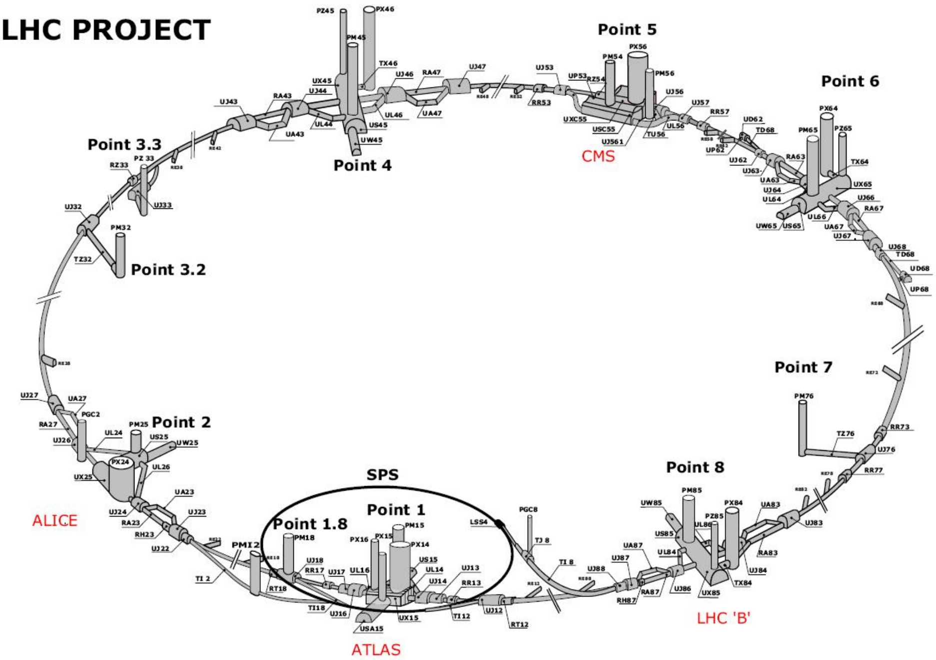


Figure 1.2: Diagram showing the geographical distribution of the main ring, the adjacent installations and insertions

The main ring

The LHC has an eight-fold symmetry with eight arc sections, and eight straight sections with experiments and systems for machine operation (see Figure 1.3). Each of the eight arcs is terminated with a dispersion suppressor (DS) region at each end, guiding the beams into the following straight section (LSS). In case of an interaction point (IP) with an experiment, the straight sections are followed by an inner triplet section for the final beam focusing. Two counter-rotating proton beams will circulate in separate beam pipes installed in twin-aperture magnets. The beams will collide in the center of the experimental detectors (ATLAS, ALICE, CMS and LHC-B), which are installed in four of the eight straight sections. A part from the main ring there are other insertion lines. In the insertions for ALICE and LHC-B the injection elements (from the SPS to the LHC) are installed. The other insertions are dedicated to machine operation, two for beam cleaning, one for the beam dumping, and one for RF and beam instrumentation.

The particle transport through the arcs requires dipole magnets for deflection and quadrupole magnets for focusing of the beams. Without quadrupole magnets, two particles with slightly different angle would move apart within a very short time. Quadrupole magnets focus in a way the particles similar to lenses used in light optics. A quadrupole magnet is focusing in one plane, and defocusing in the other plane. It can be demonstrated that for focusing the beams in both planes, a succession of focusing and defocusing quadrupole magnets with drift spaces in between is required, the so-called FODO structure.

Each of the eight LHC arcs consist of 23 regular cells, each with six dipole magnets to deflect the particles and two quadrupole magnets with a special arrangement to focus the beams in both planes (see Figure 1.4). Due to magnetic field errors, the movement of particles becomes nonlinear. In order to avoid these instabilities several thousand smaller correctors magnets (e.g. sextupole magnets) have been installed [8].

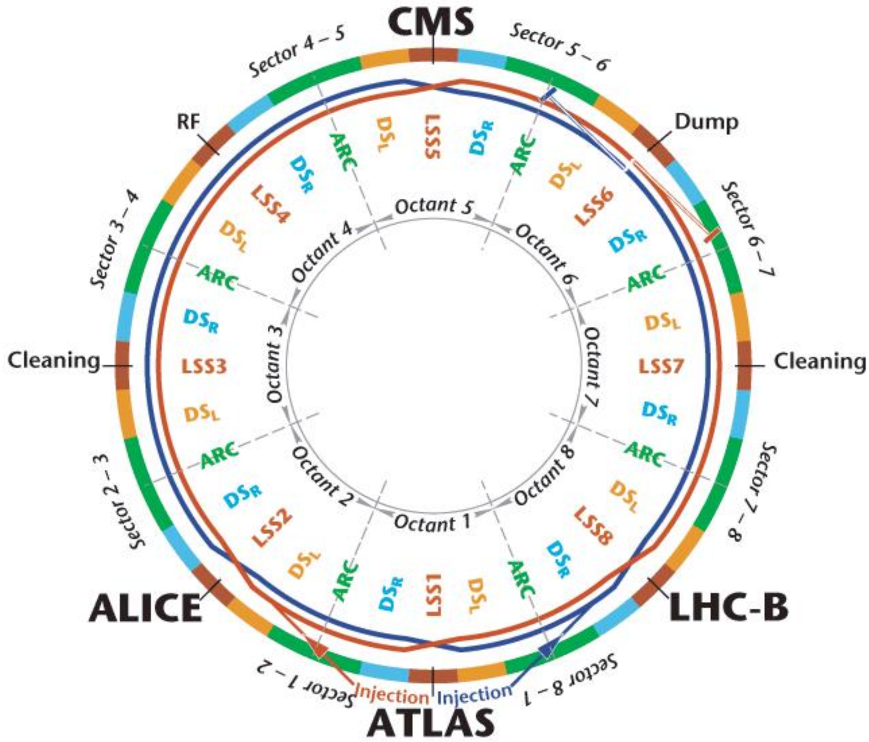


Figure 1.3: Schematic layout of the LHC machine

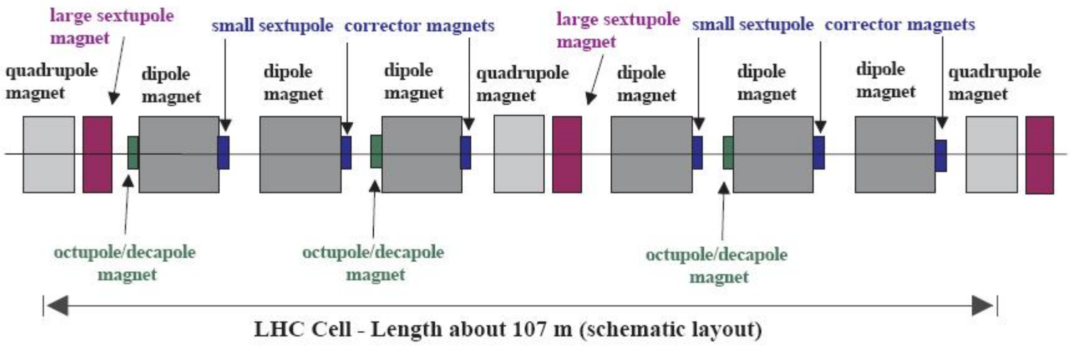


Figure 1.4: Schematic layout of one LHC cell with dipole, quadrupole and corrector magnets (not to scale)

Insertions and adjacent installations

Insertion lines for injection and dump, run parallel to the main ring and join it in some points depending on the line purpose (e.g. injection lines join the LSS2L and the LSS8R) (see Figure 1.3). In parallel with the main tunnel, where the machine components are installed, there is a net of underground areas used for access to the machine and to place infrastructure and non-radiation tolerant components as close as possible to the main ring. The main areas concerning the context of this thesis are:

RR caverns. Service caverns are apertures of the main tunnel on each side of points 1, 5 and 7, housing power converters and other electrical equipment for the LHC machine. Figure 1.5 shows the schematic layout of an RR and, as an example, the distribution of the different power converter types.

UA areas. Service and access tunnels parallel to the main tunnel on each side of the even points used for RF klystrons for the LEP machine. Now re-used to house the heavy current power converters of the LHC and other electrical equipment. Figure 1.6 shows the schematic layout of an UA and the distribution of the different power converter types.

TD tunnels. (Point 6) Tunnels at each side of point 6 housing the insertion lines for extraction of beams towards UD cavern.

TI tunnels. (points 2 and 8) Tunnels used to transfer beams from the SPS to the LHC machine clockwise and anticlockwise.

UJ junction chambers. Service caverns housing electrical equipment for LHC machine in points 1, 2, 5, 6, and 8 and connecting the TI2 and TI8 tunnels to LHC tunnel (UJ22 and UJ88). Also used as enlargements for transport purposes.

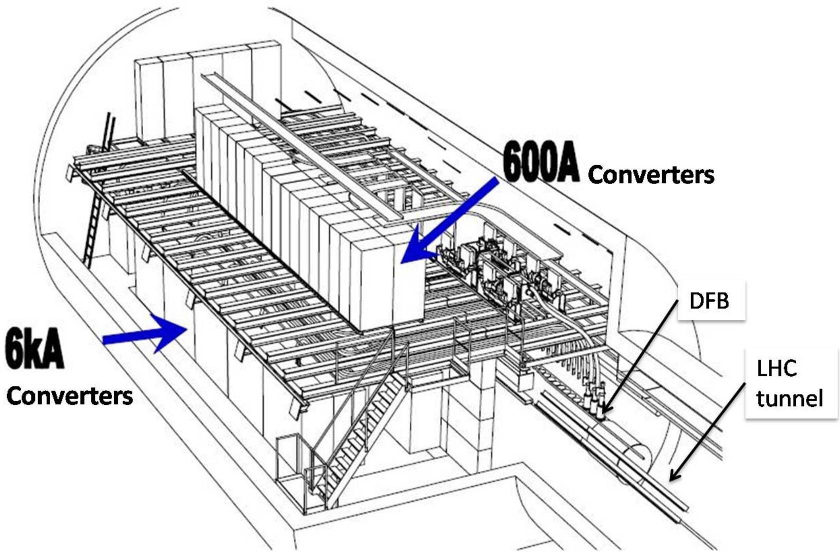


Figure 1.5: RR layout example with the position of the 600 A and 6KA power converters

From the eight points of the LHC there is yet a functional division in odd and even points. The even points represent the position for all "cryogenic islands" where all the refrigeration and ancillary equipment are concentrated (with the exception of point 1). It is as well the case for the demineralized water cooling plants with cooling stations on the even points. Another example is the ventilation, the air is supplied via air handling units located in the even points and air is extracted at the odd points.

1.3.2 Technical Machine Layout

The technical systems of the machine can be divided in four main groups namely, magnetic systems, cryogenic and vacuum systems, "beam-related" systems and general services and safety

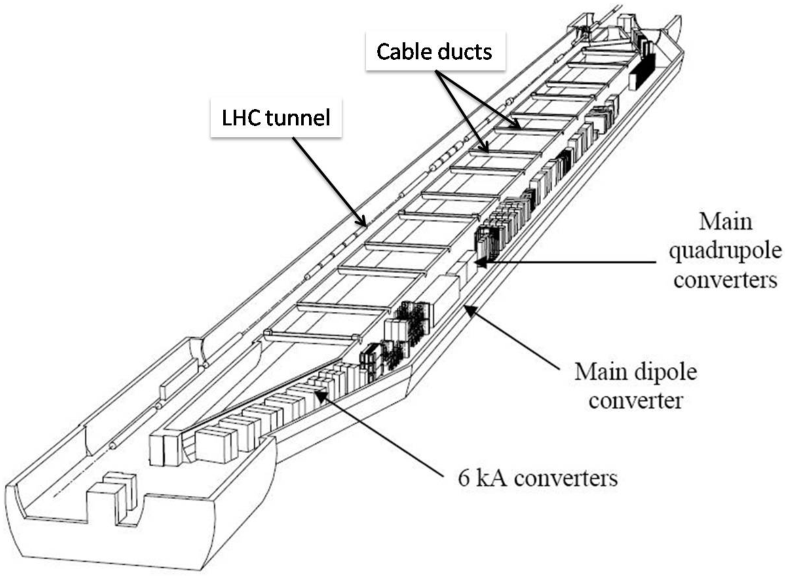


Figure 1.6: UA layout example and the emplacement of the power converters

systems. In Chapter 3 a wider description of each system relevant for the thesis is given. The specific understanding of this concept is very significant in the route of reaching the final objective of the thesis.

- **Magnetic systems**

  The proton beams are accelerated in the SPS from 26 GeV to 450 GeV, and then transferred to the LHC. To bend the particles at such energy a magnetic field of the LHC dipoles of about 0.54 T is required [9]. During the injection phase, 12 batches per beam (one batch has either 216 or 288 bunches) from the SPS are injected into the LHC. Injection of the two beams takes about 10 min. Then the field of the LHC dipole magnets is ramped within 25 min to 8.33 T corresponding to the beam momentum of 7 TeV/c. Normally, the beams will collide for several hours (physics run). At the end of the run, the beams will be dumped and the magnets will ramp down to prepare for the next injection. Before a new injection, the field is slightly lowered, and then ramped to injection level.

  To achieve these conditions several elements intervene. For the machine, 1232 Niobium-Titanium (Nb-Ti) superconducting main dipole and 392 main quadrupoles are required [10](see Figure 1.7). About 150 additional main superconducting dipoles and quadrupoles are installed in the long straight sections. Further, several thousand smaller superconducting magnets are required for correction of magnetic field errors [11]. In addition to the superconducting magnets, 140 normal conducting magnets are installed in the LHC ring, mainly in the cleaning insertions, and more than 600 additional ones in the SPS-LHC transfer lines.

  The magnets are electrically interconnected creating circuits of different kinds and 3286 power leads are needed to connect the superconducting wires or cables to the power supply cables, which are at room temperature. The design of these leads aims at high reliability and low heat load. A total of 1070 leads, operating between 600 A and 13 kA, incorporate a

Figure 1.7: Magnets already interconnected in the arc. The blue cryostats (vacuum vessels) are housing the dipole magnets

section with high temperature superconducting (HTS) material [12]. The HTS current leads are mounted in cryogenic electrical distribution feedboxes (DFBs). The limited space in the LHC tunnel requires the use of two different classes of feedboxes (see Figure 1.8). If the space is sufficient, the current is transferred to the arc magnets or to stand-alone magnets through locally installed DFBs. When the integration of a DFB close to the superconducting magnets is not possible, the magnets are powered through superconducting links (DSL) that connect the DFBs and the superconducting magnets at distances between 70 m and 500 m.

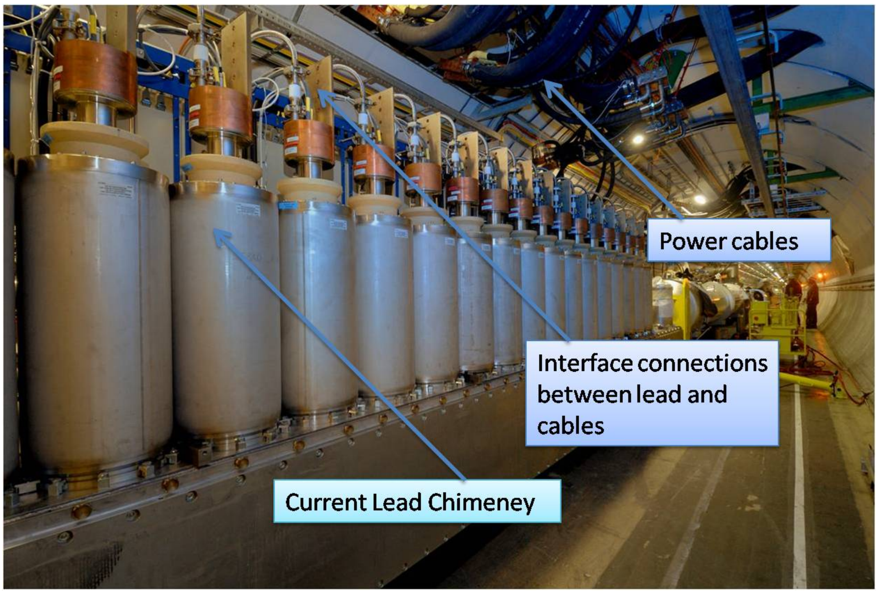


Figure 1.8: DFBAO from sector 78 with the cables not yet connected

The power cables connect the current leads to the power converters, and go from the tunnel to the respective underground areas where the power converters which feed each circuit are placed.

Finally, quench protection system and a powering interlock system related to each circuit protect the magnets. Without these systems, after a quench (the resistive transition in a superconducting magnet) [13], the temperature in the resistive zone would increase within less than one second to 1000 K, and the magnet would be destroyed.

- **Cryogenics and vacuum systems**

  To maintain the superconducting state of the niobium-titanium wires, the LHC magnets operate in a static bath of pressurized superfluid helium at 1.9 K, cooled by continuous heat exchange with flowing saturated superfluid helium. One cryogenic loop extends along a lattice cell of 107 m, supplying the magnets in one cell. In each sector, many loops are connected to the 3.3 km cryogenic distribution line (QRL) that is fed from one of the eight cryogenic plants (see Figure 1.9). In addition to the four existing cryogenic plants from LEP (each with a cooling power of 18 kW at 4.5 K), four new plants with the same cooling power have been installed. For the production of saturated superfluid helium, the compression of high flow-rates of helium vapor over a pressure ratio of 80 is achieved by means of multi-stage cold hydrodynamic compressors that were developed for this purpose. Below a temperature of 2.17 K helium undergoes a second phase transition and becomes superfluid (helium II). The viscosity of superfluid helium enables it to penetrate the magnet windings and make use of its very large specific heat [14].

  The LHC has the particularity of having four vacuum systems: namely, the insulation vacuum for cryomagnets, insulation vacuum for the QRL and two beam vacuums. The vacuum levels are of course very different. Driven by the requirements for the cryogenic system, the room temperature pressure of the insulation vacuum before cool-down of a sector does not have to be better than 10 Pa (10-1 mbar). At cryogenic temperatures, in the absence of any significant leak, the pressure stabilizes around 10^{-4} Pa (10^{-6} mbar). The requirements for the beam vacuum are much more stringent, driven by the requested beam lifetime and background to the experiments. Rather than quoting equivalent pressures at room temperature, the requirements at cryogenic temperature are expressed as gas densities and normalized to hydrogen taking into account the ionization cross sections for each gas species. Equivalent hydrogen gas densities should remain below $10^{15}\ H^2\ m^{-3}$ to ensure the required 100 hours beam lifetime [15]. In the interaction regions around the experiments the densities are below $10^{13}\ H^2\ m^{-3}$ to minimize the perturbation to the experiments results [16]. All vacuum systems are subdivided into manageable sectors by vacuum barriers for the insulation vacuum and sector valves for the beam vacuum. Sector lengths are 428 m in the QRL and 214 m for the magnet insulation vacuum. The beam vacuum is divided into sectors of various lengths, in most cases the distance between two stand-alone cryomagnets. However, there are no sector valves in the cold arc, leading to a length for this single sector of approximately 2900 m.

Beam-related systems

- **Injection system, dumping system and cleaning system**

Figure 1.9: The cold boxes are major components of the LHC cryogenic system. This photo shows the top of the first cold boxes delivered to CERN

Injection of beams into the LHC is performed in the combined experimental and injection insertions (IR) 2 and 8. The transfer line (TI) 2 (see Figure 1.10) brings the beam to a point 150 m left of IP2 for injection into Ring 1 and TI8 delivers the beam 160 m right of IP8 for injection into Ring 2. In both insertions the beam approaches the LHC from outside and below the machine plane. The beam is directed by a last series of dipoles, already located in the LHC tunnel, towards a series of five septum magnets which deflect the beam horizontally. A series of four kicker magnets deflects the beam vertically onto the LHC orbit. In order to allow a proper injection setup with pilot bunches and to protect the LHC in case of malfunctioning of the injection kickers, an injection beam stopper is placed 15 m upstream of the superconducting recombination dipole D1, supplemented by an additional shielding element 3 m upstream of D1. The protection against injection errors is further complemented by two collimators near the superconducting quadrupole Q6 on the other side of the insertion.

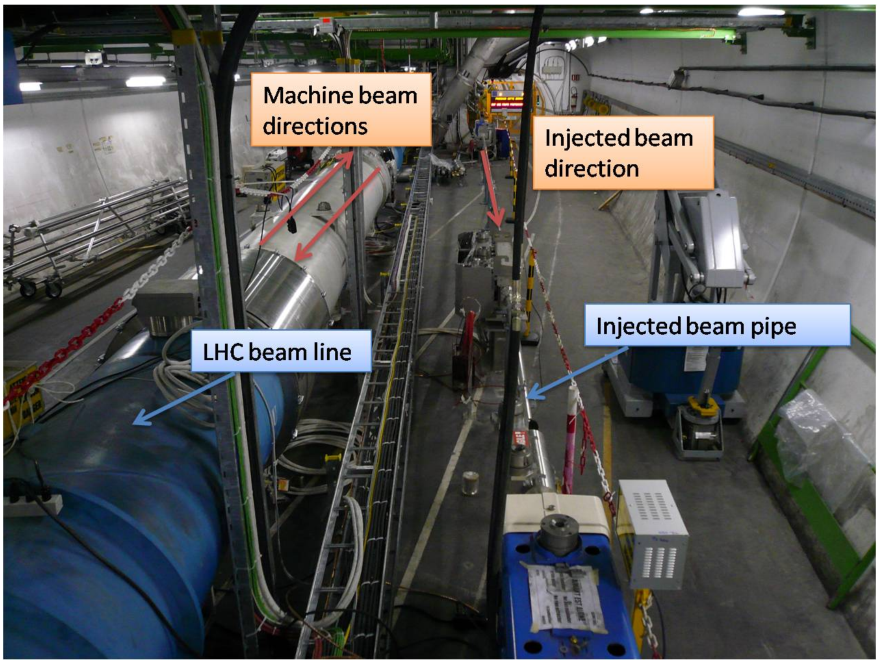


Figure 1.10: View of the UJ22 during the installation phase. The two beam lines can be appreciated: on the right side the TI2 (insertion line) and on the left side the LHC main ring

Beam impact in material produces particle cascades. The temperature increases with the energy deposition that depends mainly on the material and on the number and energy of the particles. The only element in the LHC that can absorb the full energy of the 7 TeV beam without being damaged is the beam dump block. The beam dump block has a graphite core and a concrete shielding. At the end of a physics run or in case of failure, the beams are extracted: 15 fast kicker magnets deflect the beam by an angle of 260 μrad. The extracted beam is further deflected by septum magnets into the beam dump tunnel.

Collimators in the beam cleaning system are absorbers that should capture all particles with large amplitude that could be lost around the accelerator, in particular into the superconducting magnets. The LHC is the first accelerator requiring collimators to define the mechanical aperture through the entire cycle [17].

- **Radio frequency system (RF)**

  The particles are injected into the LHC from the last pre-accelerator, the SPS, and are accelerated by the RF system. The RF frequency of the LHC (400.8 MHz) is then the highest multiple of the SPS RF frequency (200.4 MHz) compatible with the length of the SPS bunches at transfer. Eight single cavities per beam are needed. The maximum operating voltage per superconducting cavity is 2 MV, which corresponds to a very conservative average accelerating gradient of 5.5 MV/m. The cavities are made of copper with a thin film of niobium sputtered on the inside surface, identical to those used in the second phase of the LEP accelerator.

- **Beam interlock system (BIS)**

The BIS is the backbone equipment group of the beam related protection. A BIS controller takes inputs from user systems distributed around the machine and inhibits beam operation if a user system indicates that there is a problem, or that it is not ready for beam operation. The BIS links around 180 user systems, which are distributed around the circumference of the machine, to the beam dumping system. Each system is individually able to dump the beam [18].

- **Beam instrumentation (BI)**

  The system provide diagnostics instruments that allow the observation of the particle beams and collision parameters with the precision required to diagnose, tune, operate and improve the LHC. There are more that 20 different groups of instruments placed all around the ring and underground areas.

General services and safety systems

- **AC distribution, cooling and ventilation, controls and access**

  A vast infrastructure network provides to all the systems the needed AC distribution, cooling power and ventilation power to reach the nominal design conditions.

  A extremely complex controls system has been created for the systems in particular for the superconducting circuits.

  The LHC is considered by the French Authorities as a "Centre nucleaire de base", therefore the access systems must follow severs audits before start working. The LHC access systems are two complementary sub-systems dedicated to personnel protection inside the interlocked areas, which are all located within the underground installations. These two systems are the LHC Access Safety System (LASS) equipment [19] and the LHC Access Control System (LACS) equipment [20].

  When the accelerator is not operating with beam and is in access mode, the LACS controls the equipment in charge of positively identifying the person requesting access and checking that the required qualifications (safety training) and authorizations (access rights) of this person are valid. Access is then granted through the release of some access barrier. The system is also designed to limit, for operational or safety reasons, the number of users simultaneously present in the interlocked areas.

- **LASS, ODH, fire detection and radiation protection.**

  The LHC access systems do not protect against fire, explosive gas, oxygen deficiency hazards, beam losses, high radiation levels or malicious intents to defeat or circumvent the access systems. Therefore, other systems have been designed to this purpose.

  During machine operation, the LASS ensures the protection of personnel from the hazards arising from the operation of the accelerator and from the injection and circulation of the beams. It acts on specific equipment identified as important safety elements (ISE). By interlocking these elements, it is possible to establish the accelerator and equipment conditions in order to allow access to authorized personnel in the underground installations and vice versa, to allow the restart of the equipment and the accelerator when the access conditions are set to forbidden.

The LHC oxygen deficiency hazard (ODH) detection system is composed of numerous detectors located in selected areas, which trigger the indication to evacuate the concerned areas in case of, for instance, a major cryogenic gas leak [21].

The automatic fire detection system equipment is composed of detectors located in strategic areas and uses detectors of various kinds chosen for the most efficient fire detection. These detectors are connected to control systems which are located in service areas where their status can be monitored.

The RAdiation Monitoring System for the Environment and Safety (RAMSES) equipment is designed to comply with regulatory requirements for both the radiation protection and the environmental protection. RAMSES monitors ambient dose equivalent rate at work places in and around the LHC installations and controls releases of air and water into the environment. Although originally conceived for radiation protection, it integrates some conventional environmental measurements. The system is one of CERN's main tools for avoiding unjustified doses to people or pollution of the environment and to verify that legal limits are not exceeded. RAMSES triggers audible and visible radiation alarms for evacuation of personnel from areas with elevated radiation levels and generates operational interlocks where required. RAMSES transmits remote alarms on other monitored variables to control rooms, which shall trigger corrective actions by operators. It provides remote supervision, long-term database storage and off-line analysis of the acquired data. The system does not provide protection of material and equipment against radiation damage. With its interlocking functions, RAMSES could also be part of a beam injection authorization scheme, but without affecting the circulating beam [22].

1.4 LHC Challenges

1.4.1 LHC Parameters and Magnet Technology

The main LHC parameters are summarized in Table 1.2. Two proton beams will be brought into collision. Contrary to electron-positron or proton-antiproton colliders, the LHC beams need opposite deflecting magnetic field in the arcs. The consequence is to build either two separate superconducting dipole magnets or twin aperture magnets. Due to space constraints in the tunnel and economical reasons, the LHC uses superconducting twin aperture magnets for the first time in the accelerator technology.

During acceleration from 450 GeV/c to 7 TeV/c beam size decreases proportionally to the energy. The beam size is largest at injection and determines important parameters such as the required size of the vacuum chamber. The cold bore of the superconducting magnets has a diameter of 56 mm. At injection, the beam fills a significant fraction of this vacuum chamber.

Top Energy	TeV	7
Injection energy	TeV	0.45
Dipole field at top energy	Tesla	8.33
Number of dipole magnets		1232
Number of quadrupole magnets		430
Number of corrector magnets		about 8000
Luminosity	$cm^{-2}s^{-1}$	10^{34}
Coil aperture	mm	56
Distance between apertures	mm	194
Particles per bunch		$1.1 \cdot 10^{11}$
Number of bunches		2808
Bunch spacing	ns	25

Table 1.2: Some machine parameters.

1.4.2 Challenges for LHC Technology

Figure 1.11 shows a view of a typical tunnel cross-section in the arcs, with some of the major systems. During the design of the LHC big innovations have been faced. In this section are summarized the more relevant.

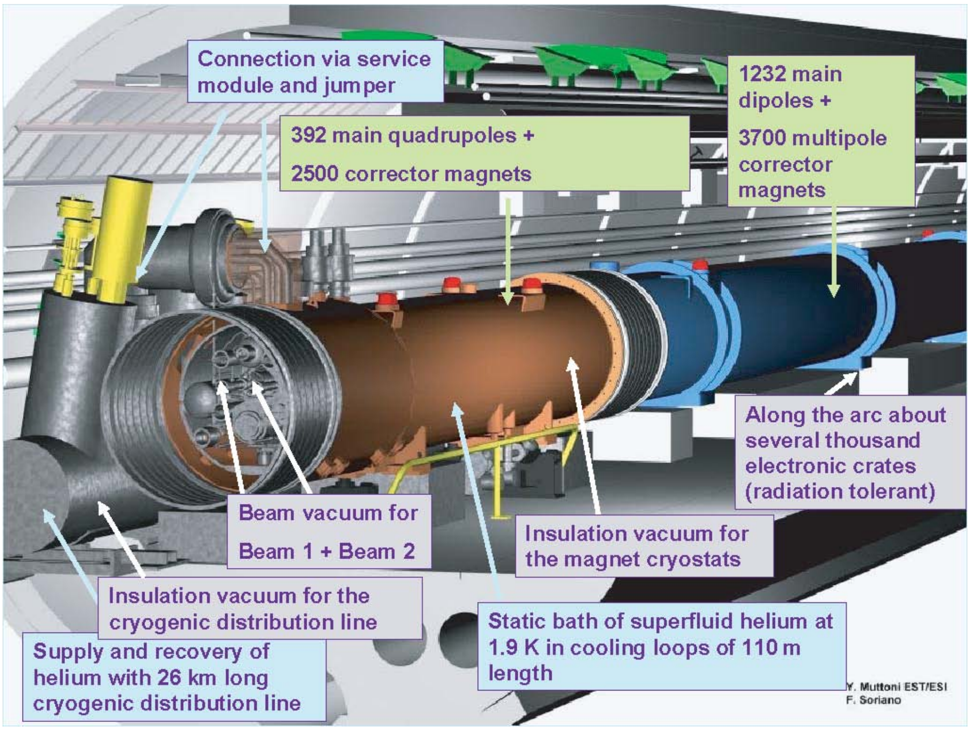


Figure 1.11: View of the LHC tunnel with superconducting magnets and cryogenic distribution line.

There have been the design of the high field superconducting magnets operating at 1.9K and the large cryogenic system distributed around the entire accelerator supplying and recovering the He with a 26 km long cryogenic.

It has been developed, as novel technology, the industrial use of High Temperature Superconducting material [23] to assure performance in the region of the temperature transition of the electrical circuits components (current feedthroughs installed in feed-boxes) feeding the current from ambient temperature into the magnets operating at 1.9 K.

With respect to the vacuum technology, four vacuum systems have been designed in the machine: one for each beam, one insulation vacuum for the magnets and one for the cryogenic distribution line.

The necessity of radiation tolerant technology, mainly electronics, has been confronted [24]. As a result there are installed along the arc several thousand of crates for quench protection, power converters, instrumentation for the beam vacuum diagnostic and cryogenics system.

1.4.3 Challenges when Operating with High Beam Current

To achieve the required luminosity at 7 TeV, high intensity beams with about 0.5 A of beam current per beam are accelerated (10^{11}) proton per bunch within 2808 bunches. The energy stored in each beam is about 350 MJ (Figure 1.12), two orders of magnitude more than for any other accelerator [17]. Since the LHC beams are very small, the transverse energy density is even a factor of 1000 above the transverse energy density in machines such as CERN-SPS, TEVATRON at Fermilab and HERA at DESY. Due to these large stored energies, three of the eight LHC insertions are reserved for beam cleaning and machine protection systems.

After a physics run or in case of failure, the safe deposition of the beams is very challenging. When operating at 7 TeV with nominal beam intensity, a very small fraction of the beam in the order of 10^{-7} lost in a superconducting dipole magnet would cause a quench. Particle losses are only acceptable in the cleaning insertion with normal conducting magnets. The efficiency of beam cleaning must be in the order of 99.98%, only a very small fraction of the particles should be lost in the arcs and other insertions.

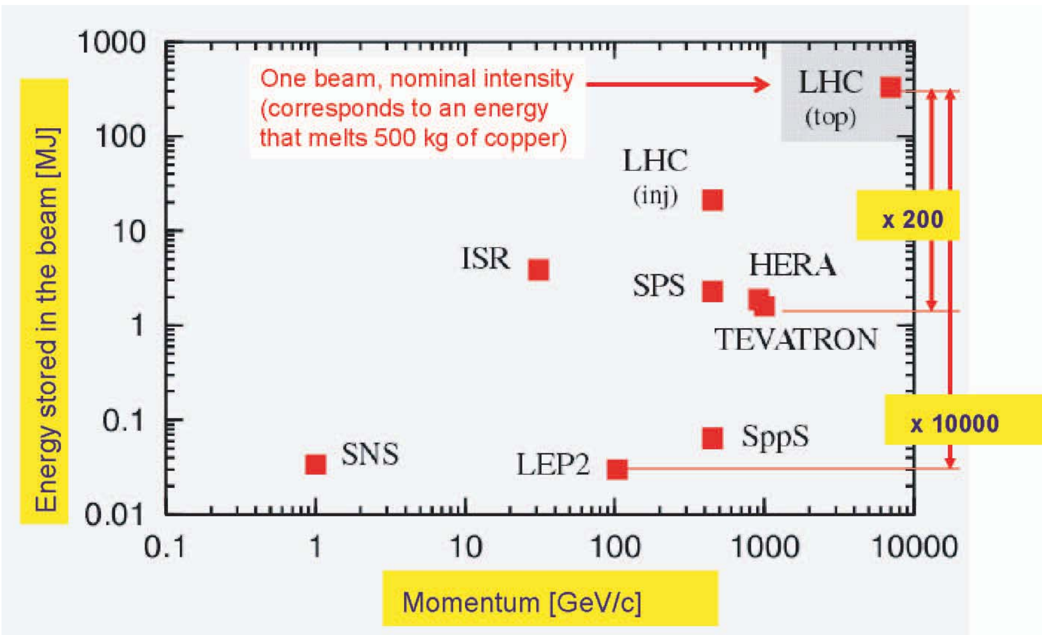


Figure 1.12: Livingston Plot. Energy stored in the beams for different accelerators

Vacuum stability has to be ensured in the beam vacuum of the arcs with a cold bore at a temperature of 1.9 K and in the insertions with sections at 1.9 K, 4.5 K and 300 K. A beam screen operating between 5 K and 20 K is inserted in the cold bore around most of the accelerator's circumference to intercept the heat load from synchrotron radiation and other effects.

Chapter 2

Project Management of a Very Large Scale HEP Accelerator

2.1 Experience from other Machines

Technical and managerial are the two perspectives which can be used in order to study the historical background of the Hardware Commissioning Project (HC).

Technical antecedents

There are three large superconducting accelerators built and in operation so far, namely Tevatron, HERA (Electron Proton Beam Facility) and RHIC (Relativistic Heavy Ion Collider). The experience gathered in all of them has been considered as the start up of this thesis.

- TEVATRON started operation in 1983 at the Fermi National Accelerator Laboratory (Fermilab) in Chicago. It is a proton-antiproton 1 TeV machine, and data collected during the recent re-commissioning on some topics are very relevant for the LHC HC [25], [26]. The ring is of 1 km radius with a total of 1014 superconducting circuits, 774 main dipoles (4.4 T) and 216 main quadrupoles with a total of 1/3 GJ of stored energy. The maximum magnet current during routine operation is 4300A [27].

  The physics goals of the Tevatron experiments are tests of the standard theory of particle physics, the so-called Standard Model. Due to the high center of mass energy, a broad spectrum of physics studies and measurements are possible: measurement of the Top quark properties, determination of the W-Boson properties with high precision, search for the Higgs particle, search for new particles, e.g. supersymmetric particles, studies of the strong interaction (QCD), physics of the Bottom quark, including an improved understanding of the Standard Model and the origin of CP violation.

- HERA was put in operation in 1990 at the Deutsches Elektronen-Syncrotron (DESY) Institute. HERA accelerates and stores electrons or positrons and protons and provides the opportunity of studying lepton-quark interactions. The two storage rings are 6 and 3 km long and are roughly 20 m below the surface. The electrons and protons are pre-accelerated with various linear accelerators (LINAC) and two former storage rings (DESY, PETRA) and then fed to the large HERA rings where the particles reach their final energies of 30 GeV for the electron ring and 820 GeV for the superconducting proton ring.

For the proton ring, superconducting magnets have to be used to bend the proton beam to a stable trajectory. The ring is made of a chain of 424 main dipole and 224 main quadrupole magnets connected in series and powered by one common power supply. The maximum magnet current during routine operation is 5025 A [28]. There is a factor of 20 for some of the systems in complexity between the LHC and this accelerator (e.g. in the case of the power converters). Along the storage rings of HERA there are four large experimental halls which are H1, HERMES, ZEUS, and HERA-B.

The main goals have been to measure the structure of the protons to study the fundamental interactions between particles, and to reach for physics beyond the Standard Model of the elementary particles.

- RHIC started operation in 2000 in Brookhaven National Laboratory (BNL) in New York. RHIC is a 3.8 km circumference collider consisting of two superconducting rings that intersect at six interaction regions. RHIC started its Physics operation in 2000, and it is capable of accelerating a variety of species from protons to fully stripped gold or copper ions.

  The maximum beam energy is 100 GeV/u for gold and 250 GeV for protons. RHIC serves five experiments, STAR, PHENIX, BRAHMS, PHOBOS, and PP2PP. The Solenoidal Tracker at RHIC (STAR) is one of the two large detectors at RHIC and is located in the Interaction Point IP6. It is specialized in tracking the thousands of particles produced by each ion collision, and its goal is to obtain a fundamental understanding of the structure of interactions between hadrons. The Pioneering High Energy Nuclear Interaction experiment (PHENIX) detector is the other large detector, located in IP8. It is designed specifically to measure direct probes of the collisions such as leptons and photons. The PHOBOS experiment is one of two small detectors and is located in the IP10 position of RHIC. It is designed to examine and analyze a very large number of unselected collisions with the premise that rare events are readily identified. The Broad Range HAdron Magnetic Spectrometer (BRAHMS) is the other small detector at RHIC located at IP2. It provides precise measurements of charged hadrons over a large range of rapidity in transverse momentum. The PP2PP experiment shares the IP2 interaction region with BRAHMS. Its goal is to study proton-proton elastic scattering and therefore participates only in proton runs [29].

Crucial milestones in the way to the final design of LHC were achieved through experimental set-ups consisting of full-size models of a half-cell and an entire cell of the collider, so-called String-I and String-II respectively.

String-I, the first LHC Prototype Half-Cell [30], entered into operation in December 1994 and run intensively until December 1998. It consisted of one quadrupole and three 10-m twin aperture dipole magnets which operated at 1.9 K in superfluid helium. One electrical circuit powered all the magnets in series. This set-up was used to observe and study for the first time the phenomena which appear when the different magnet systems are assembled in one unit and therefore influence one another.

As a continuation of the experimental program carried-out with String-I, the LHC project management decided towards the end of 1995 to construct an LHC prototype Full-Cell, the String-II facility [31].

String-II was a mock-up of an LHC cell of the regular part of the arc. It was composed of six dipole magnets with their correctors, two short straight sections with their orbit and lattice corrector magnets, and a cryogenic distribution line running alongside the magnets. The commissioning of String-II started in April 2001. The facility allowed for the individually validation of the final versions of the LHC systems and the investigation of their collective behavior during normal operation (pump-down, cool-down and powering) as well as during exceptional conditions such as quenches. String-II was a stepping stone towards the commissioning of the first sector of LHC and yielded precious information on the infrastructures, the installation, the tooling and the procedures for the assembly, the testing and the commissioning of the individual systems, as well as the global commissioning of the technical systems. Resulting from about two years of experiments, a fundamental piece of information was the first estimation of time durations for the commissioning activities.

Most useful information has been extracted from these five projects and extensively applied during the planning phase of the HC. String-I and String-II have been extremely valuable for the project in general, not only for the preparation of the technical documents but also for obtaining a unique hands-on experience on how to commission the magnet systems and how much time was required to do it.

Project management antecedents

The main part of the existing scientific articles about commissioning of accelerators is focused on the results of tests and the performance of the systems mainly during beam commissioning, and there has not been a global approach to the projects in terms of information management, databases design and commissioning coordination (i.e. detailed schedule, planning, resources study, quality assurance, project control, etc.).

Even if project management techniques are widely applied nowadays, it is also true that their application to the commissioning of accelerator technical systems has been rather limited up to now. For instance for RICH, each system owner involved in the HC phase were individually managing their commissioning and regular meetings were done to follow the advancement and consolidate the schedule, but there was not a centralized management of the commissioning project as a whole [32] [33]. There is without any doubt, room for advances in this particular domain. In the case of the LHC, there has been from early stages of the studies an evident need to work in depth on the management and technical coordination areas. From the previous above can be appreciated that the increase in complexity with respect to the previous machines shows this need. This is the leitmotif of this thesis, the creation of reference project management tools for future accelerators.

2.2 Management of a Large Scale Project

The project life cycle is used to define the beginning and the end of a project. There are three phases in the life cycle of a project, which are part of a general logic sequence: study, project execution and results.

First phase, consist on the identification of an opportunity, in the frame of the organization, and the conclusion to respond to the opportunity. The next phase is the study of the solutions followed by the solution selection. Once the solution is chosen, it has to be defined and the deliverable detailed [34]. At this point of time the planning studies can start. The second phase contains the execution of the project. At the end of this phase comes the transfer to the owners, which represents the final result of the project.

This thesis develops tools for the successful execution of these phases in large scale projects in the domain of particle accelerators. In particular, they have been applied and the results analyzed for the Hardware Commissioning (HC) Project.

For the study phase, the tools developed in this thesis have been: the definition of all the technical systems of the LHC from the HC point of view (explained in Chapter 3), the design of a document plan which includes all the technical and managerial specifications (explained in Chapter 6) and finally the schedule baseline definition and planning (explained in Chapters 4 and 5).

For the phase of project execution, the tools developed have been designed to assure project control and are the HC schedule, the HC planning and the HC MTF (explained in Chapter 7).

For the phase of transfer to the owners, the main objective of the tools is the quality assurance of the deliverable and has been achieved thanks to the design of the HC MTF.

Figure 2.1 shows the phases of the lifetime of a project and the position of the tools explained above.

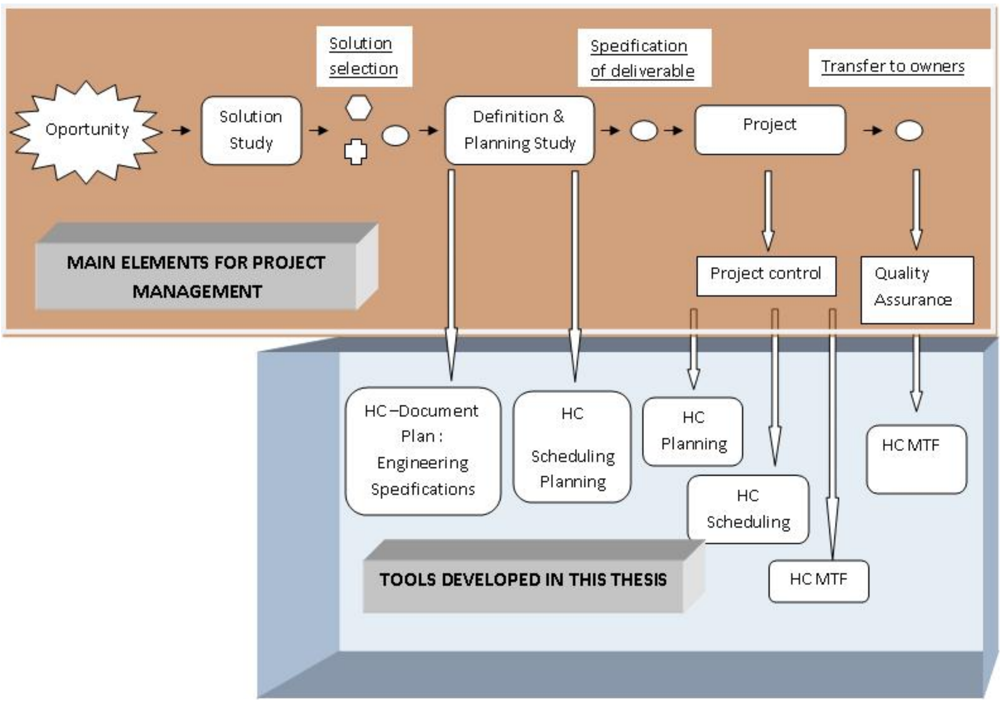


Figure 2.1: Project management tools developed by this thesis

Characterization of the deliverable

The characterization of the deliverable is the first step to succeed in the management of a project. Since every project is undertaken for a result, a project can only start when the deliverable is defined and known. The major cause of a project failure is when the work starts although the deliverables are not defined yet.

For the characterization of the deliverable some parameters have to be clear (see Figure 2.2 and 2.3).

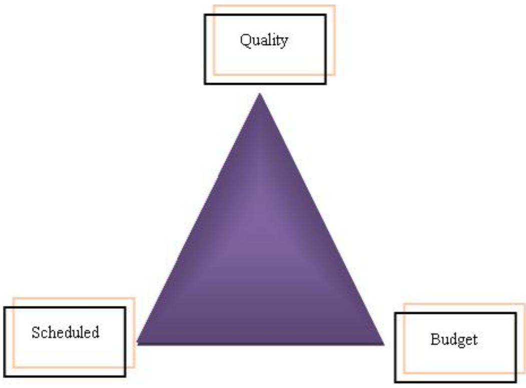


Figure 2.2: Parameters to do the project right

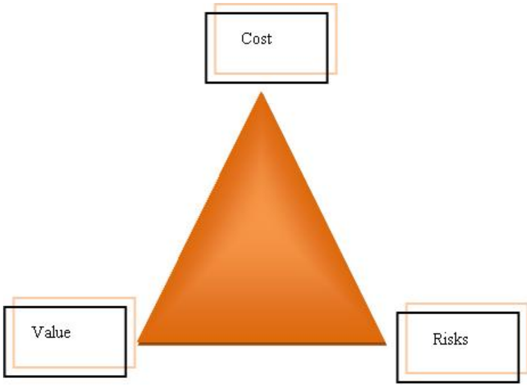


Figure 2.3: Parameters to do the right project

- Parameters to do the project right are quality, schedule and budget. The level of quality needed to assure the results has to be defined. To execute the project and apply control, the schedule representing the sequence of activities taking into account needs and incompatibilities has to be consolidated. The budget definition will allow the study of resource availability and limitations before hand.

- Parameters to do the right project are cost, value and risks. The cost of the project has to be calculated and confronted with the value to be able to apply anticipating solutions and risks analysis.

2.3 Management of a Large Scale Project: HEP Accelerator

Although a significant history of accelerators has been accumulated since the first applications, around half a century ago, there is a project management deficiency during the commissioning phase of the accelerator projects. Past and existing research accelerators were designed and operated towards two main goals:

- Collision energy: the aim of reaching deeper knowledge about atom and nucleus structure is limited by the center of mass energy in collision. During the first decades of accelerator applications, energy was the only research limitation.

- Luminosity: once nuclear physics moved to particle physics, the interesting events became rare even at enough energy. Luminosity is related to the collision rate, hence to the beam intensity and focusing.

The figure of merit of current accelerators is based on these two characteristics. These accelerators were conceived as prototypes whose main objective was not the efficiency but to push the performance to the limit. As a consequence, there is no developed methodology for a project management oriented design, since management of the project was not considered as major topic of interest [35]. Project sizes were still manageable, resource limits were not a problem, neither was budget. The first project with a bigger scale and complexity, the Superconducting Super Collider (SSC) [36] failed as a project, due to a lack of project management from the start, and the lack of political will to support an ever increasing budget.

More and more the new accelerator projects reach complexities and sizes that no one has reached before, the LHC complexity is something like 3 orders of magnitude more than any other already built. A new era of accelerator projects has arrived with the need for project management tools that deal with:

- Management of huge budget and budget restrictions.
- Limited resources.
- Limited time.
- Technical complexity.
- Vast amount of information.

In conclusion, project management design as a systematic tool for the whole lifetime of accelerators projects is just giving its first steps and studies for large scale scientific facilities. Private companies for project management consultancies are starting to study the accelerator market in order to exploit it.

2.4 Management of a Large Scale Project in a HEP Accelerator: The LHC Hardware Commissioning

There has already been an effort in introducing project management in the LHC Project by applying Earn Value Management (EVM) for projects and budget, Engineering Documents Management Support (EDMS) for all documents (i.e. design specifications, engineering specifications,etc.), Manufacturing Test Folder (MTF) for the relation with the industry quality control production and a unified installation planning (long and short term). However, all this elements refers to the LHC Project and not to the different sub-projects that are found inside.

For the LHC HC Project, a global approach has been applied in this thesis for the project management tools. Meaning by a global approach that all the tools are linked between them and represent the global project.

Superconducting accelerators, like Tevatron at FNAL and HERA at DESY, have already been successfully working for a long time . The RHIC at BNL finished their commissioning seven years ago and is currently operating without major problems. The reason why project management shows up as an essential tool for CERN's new collider is that, although it is based on very well known superconducting and cryogenic technologies and it can use the experience provided by its predecessors, its complexity makes it a totally different machine. The same reasons apply to the experience coming from other project as nuclear power plants or space projects. Some of the operational and design challenges regarding the LHC complexity are listed below.

And they are different from other big projects because of the reasons specified below:

- **Energy Stored in the Beam**

  The large luminosity required together with the huge collision energy leads to beams with large stored energy. The two beams of 7 TeV circulating inside the LHC will carry a total energy of 0.7 GJ. If this energy or a part of it is locally deposited, it can be enough to damage the magnetic components. If the energy is not instantaneously deposited but the losses are distributed along the machine, the accelerator hardware will keep its integrity but some quenches could be generated on the superconducting elements due to particle deposition. The LHC beam will be monitored and actions will be taken to avoid hardware damage and quenches or the magnet energy extraction system.

- **Energy Stored in the Magnets**

  The eight LHC main dipole circuits store a total energy of about 10 GJ. This energy is enough to heat up from cryogenic temperature and melt 15t of copper. The most usual way of this energy to be released is via a quench.

- **Number of components**

  The extension of the accelerator (27 km tunnel) together with the required flexible optics makes the number of critical components required for operation of the LHC much larger that any existing accelerator. The very high quality of components is not enough to achieve the expected availability and redundant systems are essential. Therefore, the number of components to be tested increases a lot.

- **Repair times**

  Maintenance in the LHC will not be like in similar accelerators. This is mainly due to the low operation temperature. As it has been explained, the cryogenic equipment group sectorization is designed to enable maintainability with the minimum length of machine warmed up. Still repair times of 15 days have been experimented for interventions that do not require the breaking of the beam vacuum or the venting of the heat exchanger tube (short intervention), and up to 12 weeks for interventions when the entire continuous arc cryostat has to be warmed up, repaired and re-cooled (long intervention as the change of a dipole magnet).

- **Data uncertainty**

  Systems data sources have to be used taking into account the special conditions under which LHC equipment works. Although the historical data referring to previous experience can be used as starting point, methods like planning sensitivity analysis or resources studies have to be used in order to include their uncertainty.

- **Budget**

  The LHC Project was approved in 1996 with a budget for materials of 2.6 billion Swiss francs for the completion of the accelerator and the experimental areas. In addition, the CERN contribution to the LHC experiments was budgeted at 210 million Swiss francs. In 2003 a cost increase was presented corresponding to a 19% overrun, which represented a total budget of 3340 millions Swiss francs (for example, the prototyping research and development for the superconducting magnets costed 150 million). The scale of costs and the increase, made the budget to be an important limitation in the LHC Project and all the sub-projects linked to it.

- **Resources**

  The condition of limited resources due to the limitation of budget (explained above) and a limitation of experts existing in the world for the different systems involved in the commissioning.

- **Space availability**

  The LHC uses the LEP tunnel and alcoves in order to reduce infrastructure costs, and although some new caverns have been made functional, there is a very important constraint due to the limited space availability. This together with the limitation in time available for the commissioning, increases the co-activity between system tests.

2.5 Main Challenges for the Hardware Commissioning Project Management

As a result of all the aspects explained above, the project management of the HC Project has as main challenges:

- Long time of execution of tests due to the amount of systems and their dimensions, and due to the danger related to the energy conditions of the machine.
- Overlap between the phases of the project installation and commissioning in parallel due to the limitation in the budget which develops in a strong limitation for the deadline of the project. Consequently, engineering specifications with a very high level of detail are needed to be able to study parallelism between activities.
- Big amount of changes through the project since its the first time that a lot of the technology used has been tested. Therefore, a flexible and a systematic control for the identified links are essential.
- No space for failures due to the big time of reparations needed if problems arose.
- Due to the characteristics of the HC Project, the design of management tools is needed to successfully achieve the objectives of the project.

Chapter 3

The Commissioning of the LHC Technical Systems

This chapter treats two key points for the design of management tools for the Hardware Commissioning (HC) project or future large scale projects, which are:

- Description of the technical systems involved in the project and the recognition of the system components with the level of granularity needed for the project. This has been essential to identify the main points of each system and to identify all the dependencies between them. Once this has been done the next step is an exhaustive identification of the different tests to be applied in order to guarantee the desired performance.
- Since each system has been designed as an individual item, it is needed to identify the different nomenclature used by each one. After they have been all identified and well understood an unified HC "language" has been created that covers all the systems and optimizes the communication between systems, during and after the life of the project. In the case of the project that is being studied, the HC Project, the sectorization of the different systems around the machine has showed to be a delicate point due to the diversification among systems.

Once these two points have been completed, the results have been used as the main inputs for the definition of different project management tools that this thesis develops including scheduling, planning and quality assurance.

3.1 The Concept of the Individual System Tests and Hardware Commissioning

There is a big amount of systems are involved in the commissioning phase. In some cases the complexity is huge due to the amount of components which form the systems. Taking as an example the superconducting and normal conducting circuits: there are around 1600 circuits and their entire infrastructure to be commissioned together and more than 1700 power converters feeding them. The HC tests that all the systems are able to achieve the performance needed to reach the machine design parameters. This phase is placed after the installation and before the beam test. A classification of the tests in two groups has been created the individual system tests (IST) and the hardware commissioning (HC) tests.

Individual System Tests

The IST are the firsts verifications that an equipment responsible has to carry out without the need of any other system support. The single units that follow this individual system tests are called in this thesis "equipment".

Hardware Commissioning

The HC tests consist in the parallel commissioning of the groups of equipment which work together. These groups will be referred along this work as "equipment groups". There is a clear functional link (dependency) between the systems within an "equipment group". Before this, each equipment needs to complete their own IST. During the commissioning phase, some of the systems act individually, some work together with others and some need the result of others to start. The last two cases show examples of "dependencies".

3.2 Technical Systems Descriptions and Commissioning

This section gives an explanation of the commissioning technical characteristics of the systems involved in the HC Project. These systems can be classified on equipment or equipment groups depending on their features.

3.2.1 Beam Instrumentation

This equipment group is composed of diagnostic instruments that allow the observation of the particle beams and collision parameters of LHC with the precision required to diagnose, tune, operate and improve the installations. During the commissioning the attention is focused in a part of these equipment as specified below [37] [38].

- The DC beam current transformers: provide intensity measurements, the equipment group is based on the principle of magnetic amplifiers which measure the mean value of the intensity or the current of the circulating beams.
- Fast beam intensity measurement transformers: provide intensity measurements and are capable of integrating the charge of each LHC bunch.
- Beam loss monitor: the loss of a very small fraction of the circulating beam may induce a quench of the superconducting magnets or even physical damage to machine components. The detection of the lost beam protons allows protection of the equipment against quenches and damage by generating a beam dump trigger when the losses exceed pre-defined thresholds.
- Beam position monitor: the equipment consists of distributed monitors per LHC ring, all measuring positions in both horizontal and vertical planes.
- Synchrotron light telescope: transverse profile measurements are performed with this device.
- Beam Profile TV screen Monitors: measure the beam profile.
- Control crates are included in electronic racks for the control of all the above-mentioned instruments.

Individual System Tests

Each of the equipment has to follow different kind of tests due to its diversity, all the individual system tests are done on the surface before the installation [39]actually some of the final IST's are done in the tunnel.

Hardware Commissioning

After the IST the equipment is ready to be installed. Once the installation is completed, including all the interfaces with other systems (e.g. vacuum), the HC tests can start. These tests assure the proper functioning of the electronics, the mechanical parts, the control equipment and the data acquisition [40].

Sectorization

For the entire list presented above, some of the elements are part of the beam line (e.g. beam position monitors) or they are attached to main ring components (e.g. beam loss monitors), other run parallel to the main ring in the injection lines or dump lines and part of them are placed in the underground areas (e.g. control crates). This equipment group can be found practically everywhere in the machine.

3.2.2 Beam Dumping System and Beam Injection System

The function of the beam dumping system equipment group, is to fast-extract the beam in a loss-free way from each ring of the collider and to transport it to an external absorber. The equipment group comprises for each ring [41]:

- Extraction kicker magnets (MKD) located between the superconducting quadrupoles Q4 and Q5 (i.e. fourth and fifth quadrupole magnets after the interaction point).
- Steel septum magnets (MSD) (see Figure 3.1) located around IP6.
- Two types of dilution kicker magnets between the MSD and Q4.
- The beam dump proper situated in a beam dump cavern located 750 m from the center of the septum magnets.
- The collimator absorber blocks for protection.
- The secondary collimator for cleaning.
- The vacuum system.
- The beam instrumentation.
- The beam interlock equipment and its controllers (BIS and BIC).
- The beam energy monitoring equipment (BEM).

The beam injection system equipment group, assures the correct transfer of the beam from the injector accelerator SPS to the LHC. The equipment making it up are [42]:

Figure 3.1: View of the MSD Magnets installed in the LHC tunnel

- Four magnets which deflect the injected beam on the nominal orbit (MKI), the capacitor banks, discharged via thyratron switches into the magnets and two resonant charging systems.
- The absorbers which include the injection beam stoppers and the collimators.
- The beam instrumentation.
- The beam interlock equipment and their controllers (BIC).

Individual System Tests

Both the beam dumping and injection equipment group are composed of the different equipment of the list. The equipment go through a list of tests [43] [44] which individually validate them before any interaction with other systems. Some of the equipment from this equipment group, as for instance the beam instrumentation and the magnets follow the IST which are explained in the other sections of this chapter.

Hardware Commissioning

Once the IST, described in the previous sections, have been successfully completed the integral system should be tested [42] [43], from the CERN Control Center, simulating as close as possible the future operation with beam.

Sectorization

For the beam dumping equipment group, the equipment are located in the LHC main ring between Q5 on the left and right of point 6, in the two beam dump lines TD62 and TD68 and the beam dump caverns UD62 and UD68. So, the equipment are not placed exclusively in the main ring but also in the two dump lines which run parallel with and angle and die into the caverns where the beam is completely stopped.

The beam injection system equipment group, follows the same philosophy as the dumping system, there are two injection lines one in point 2 and one in point 8 which come from the SPS and once in the LHC tunnel run parallel to the main ring and join it.

3.2.3 Radio Frequency System

This equipment group assures the acceleration needed to achieve the nominal energy of the particles. This equipment group is composed of:

- the ACN system equipment, which contains the 200MHz copper cavities. There are four cavities on each side of point 4, to reduce injection loss and ease operation [45]
- the ACS system equipment, which contains the 400MHz superconducting cavities. It is composed of 16 superconducting cavities, the power converters, the klystron modulators with their power supplies, the high voltage switches and the high power lines. The injected beam is captured, accelerated and stored using this equipment. Each cryomodule has a single inlet for liquid helium and a single outlet for the helium evaporated by static and dynamic losses [46]
- the transverse damping systems
- the control system

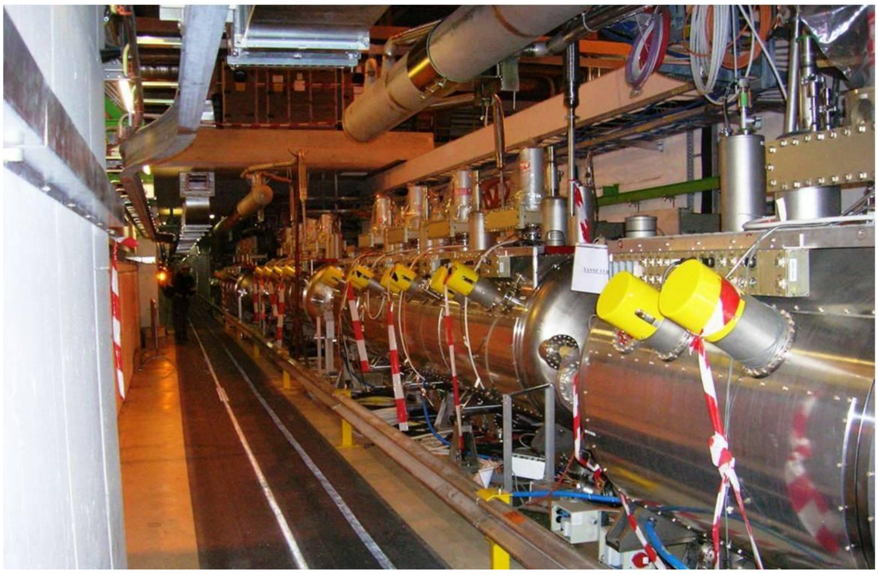


Figure 3.2: ACS modules of the RF cavities installed in the long straight section on the right of point 4

Individual System Tests

Each of the equipment specified above undergo their specific IST [47] once the installation is finished. All the components are powered at low RF level and the control system is validated.

Hardware Commissioning

The superconducting cavities equipment have to be tested and tuned at 4.5 K in order to be able to reach the designed power levels. After the IST of all equipment and once the cavities have been cooled down to the nominal temperature, the equipment group is tested as a whole [47].

Sectorization

This equipment group is placed in point 4, the cavities are part of the main ring in the long straight sections left and right of the point, from Q6 left of point 4 to Q5 right of point 4. Some of the equipment as the power converters and klystrons are all placed in the underground areas situated around the point. The cavern, the building at the surface contain equipment, so two different sectorization have to be taken into account.

3.2.4 Collimation System

There is a robust and reliable collimation system equipment group, which prevents the quenching of the magnets during regular operation and accelerator components from damage in the event of beam loss.

There are two types of collimators, namely primary and secondary collimators. To efficiently clean the beam halo, which is continuously filled by beam dynamics processes, a multi-stage collimation equipment group is needed, since the secondary beam halo generated by the primary collimator is still above the quench level of the superconducting magnets. The momentum and betatron cleaning of the beam is done in separate locations, momentum cleaning in intersection region 3 (IR3) and betatron cleaning in intersection region 7 (IR7).

Individual System Tests

Once the collimators arrive at CERN and before being installed they go through the individual system tests. Each collimator is visually inspected and vacuum tested. After these, there are the tests of the motorization equipment and its functionality under vacuum. The collimators are then ready to be transported to the LHC [48].

Hardware Commissioning

Once they are installed, aligned and connected to the cooling equipment, another set of tests are done [48] to achieve their performance for operation.

Sectorization

As it can be observed in Figure 3.3 the collimators are spread along the accelerator forming part of the main ring.

3.2.5 Controls: Beam Interlock, Powering Interlock and WorldFip

The CERN Controls group have developed many new applications for the HC phase. For classic operations, like power converters controls, they have reused the software developed for the injection lines. For the supervision of several important systems, such as the quench protection system

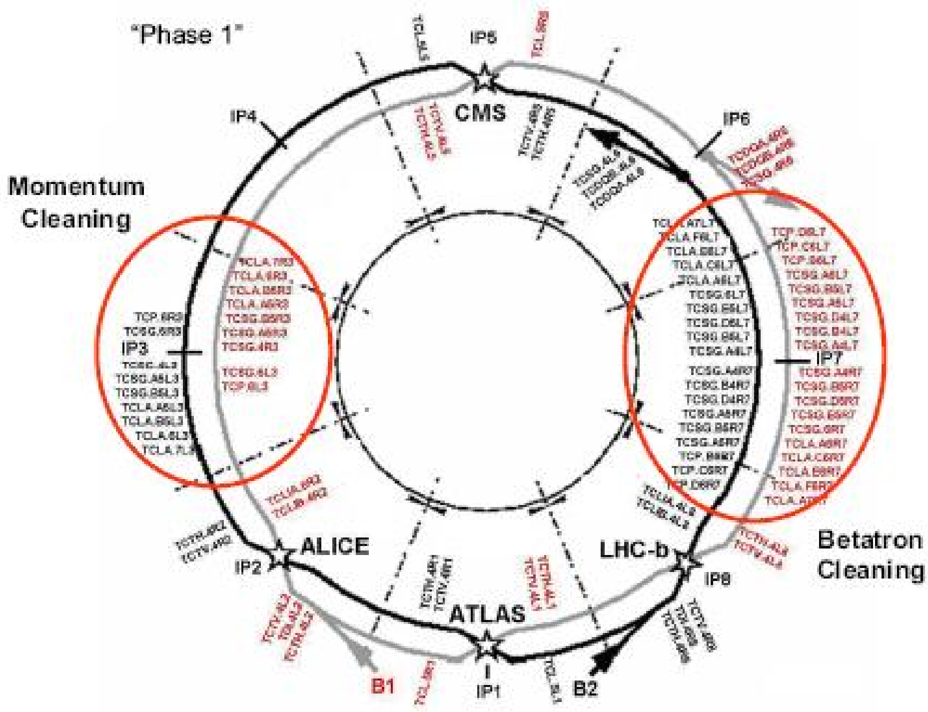


Figure 3.3: Collimators distribution around the ring

and powering interlock controller, new industrial controls have been introduced. General control services include: handling and displaying alarms, post-mortem recordings and analysis, measurements and logging, fixed displays and consoles to manage, monitor and secure the connectivity inside the domain. Last but not least, an extensive group of tools for automated procedures which provide means for repetitive tasks have been designed and prepared. Figure 3.4 shows the three-tier architecture of this equipment.

Individual System Tests

Since almost all the other systems in the machine use this equipment group to perform their HC tests, the IST are needed to be performed as soon as possible. For each of the hardware, there is an individual system tests through which its readiness is reached [49].

Hardware Commissioning

The equipment could be divided mainly in hardware components, timing distribution network and WorldFIP infrastructure. Its HC tests are always part of the equipment group to which they assist.

Sectorization

For the sectorization, each component assumes the same sectorization used for the equipment group they assist.

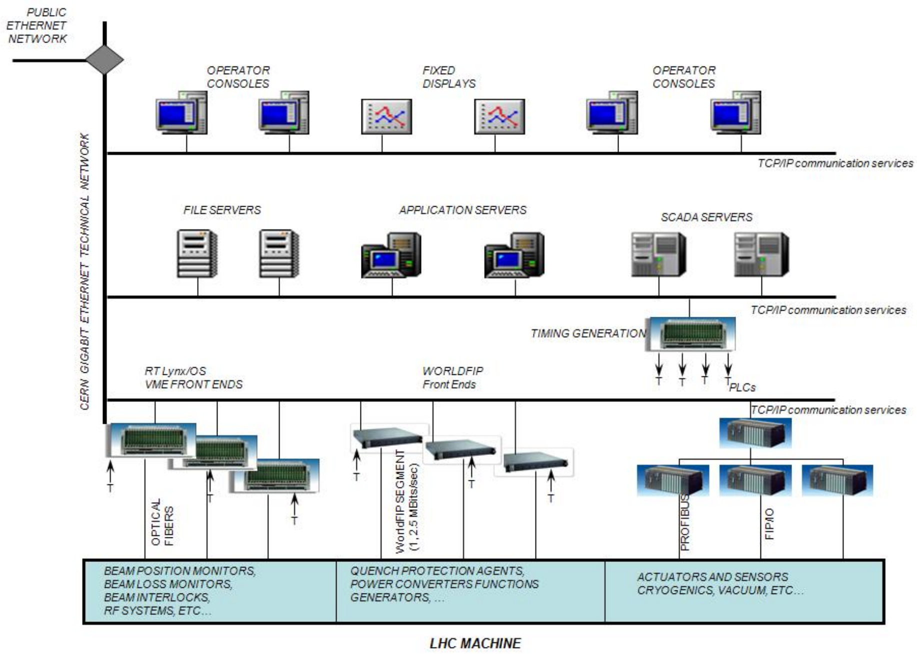


Figure 3.4: LHC Control Hardware Infrastructure

3.2.6 Cryogenics

The superconducting magnet windings in arcs, dispersion suppressors, inner triplets and RF superconducting cavities are immersed in a pressurized bath of superfluid helium at about 0.13 MPa (1.3 bar) and a maximum temperature of 1.9 K [2]. As the specific heat of the superconducting alloy and its copper matrix fall rapidly with decreasing temperature, the full benefit in terms of stability margin of operation at 1.9 K instead of at the conventional 4.5 K may only be reaped by making effective use of the transport properties of superfluid helium, for which the temperature of 1.9 K also corresponds to a maximum in the effective thermal conductivity [50] [51]. The cooling requirement applies during both ramping and stored-beam operation. In the case of fast current discharge, the temperature excursion may be larger but must still remain below the helium II/helium I phase transition [14].

In the long straight sections, with the exception of the inner triplets and the superconducting dipoles D1, the field strength and heat extraction requirements are such that operation at 1.9 K is not necessary. These magnets have their superconducting windings immersed in a bath of saturated helium at a temperature of 4.5 K .

The cryogenic designed has been conceived to cope with quenches of the superconducting magnets, which occasionally occur in the machine. It must limit the thermal front propagation to the neighboring magnets and recover in a time that does not seriously detract from the operational availability of the LHC. A resistive transition extending over one lattice cell should not result in a down time of more than a few hours. In addition to these basic operational duties, the LHC cryogenic equipment group allows for rapid cool-down and warm-up of limited lengths of cryo-magnet strings, e.g. for repairing or exchanging a defective unit. It deals with the resistive transition of a full sector, this defining the maximum credible incident, without impairing personnel or equipment safety. Finally, to ensure reliable operation, it provides some redundancy among its components and sub-systems.

Individual System Tests

Like other technical systems in the machine, each cryogenic equipment with its own process and logic has been commissioned and validated before any interaction with other systems.

One of the equipment composing the cryogenic equipment group is the cryogenic instrumentation. Due to the complexity and to the quantity of elements it has been decided to include its individual system tests in the project in a much detailed way than any other IST. A wider description is given later in the this section.

Hardware Commissioning

The main HC test [52] of the cryogenic equipment group is the "cool-down". During the cool-down the objective is to get to the conditions needed for the powering of the magnets, the temperature is reduced from 300K to the 1.9K needed for operation.

There are three sub-phases to be considered during the cool-down:

- From 300K to 4.5K. This phase automatically requires the cool-down of the 4.5 K refrigerator. The other LHC systems are mainly passive components flushed and cooled down by helium at progressively colder temperatures. Because of pressure design reasons the cool-down of the RF cavities and the electrical distribution feedboxes (DFBs) begin only when the pressure is below 2 bar. This phase is terminated when all the systems have reached 5 K.

- Liquid helium filling at 4.5 K. This phase can only start once the refrigerator is in nominal operating conditions and the LHC components have been cooled below 5 K. At this point, liquid helium is distributed via Joule-Thomson expansion valves to the DFB, the RF cavities and the magnets to fill the cryostat to the required level. At the same time the beam screen circuit is cooled and the superfluid helium circuits can be pre-cooled by passing a small flow of liquid helium and maintaining the pressure above 1 bar.

- Cool-down from 4.5 to 1.9 K. This phase only concerns the magnet cold masses of the arc, the inner triplet and the D1 magnet. It can be started only when the magnet cold masses are filled with liquid helium and the 1.9 K refrigeration unit has been started. During this cool-down phase to about 2.2 K the density increase requires opening the filling valve of the cold mass to maintain the pressure at 1 bar and therefore achieve the full volume of pressurized superfluid helium instead of a partial filling of saturated superfluid helium together with its vapor. This phase is terminated once the magnet string is filled with liquid helium at 1.9 K.

  The first cool-down has been carried out in the LHC in the Sector 78 in April 2007 [53]. Figure 3.5 shows the curve that the temperature of the magnets have followed, the upper graph shows the magnet temperature profile along the sector 78 and the one on the bottom shows the evolution of the magnet temperature in the sector, for a period of a week.

Sectorization

As for the other systems of the machine, the sectorization used is specific to the equipment group and has been studied in detail. The granularity with respect to the other systems of the machine have been defined [52]. Due to the fact that the LEP infrastructure has been re-used, there are site constraints, which make the cryogenic layout of the machine to have five cryogenic "islands" at

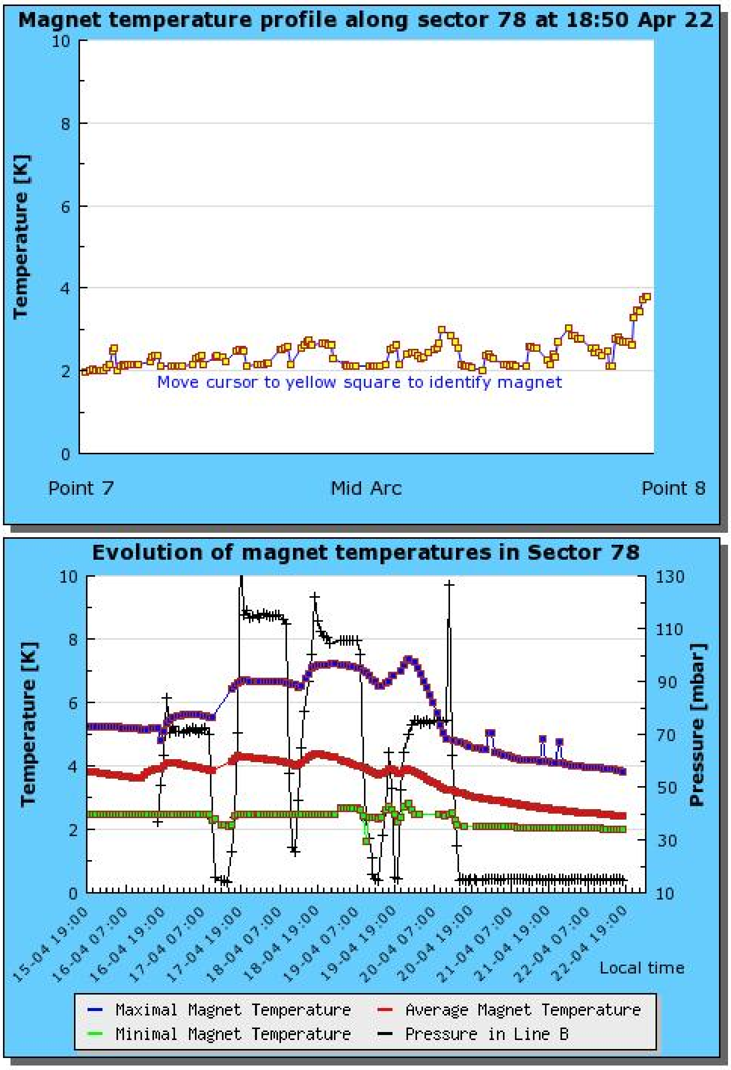


Figure 3.5: Magnet temperature evolution at 1.9 K for the first sector cool-down. Evolution with time (bottom) and along position in the sector (up)

access points 1.8, 2, 4, 6 and 8, where all refrigeration and ancillary equipment is concentrated (see Figure 3.6). Figure 3.7 shows the general architecture of the cryogenic system. Equipment at ground level includes electrical substations, warm compressor stations, cryogenic storages (helium and liquid nitrogen), cooling towers, cold-boxes and at underground level cold-boxes, 1.8 K refrigeration unit boxes, interconnecting lines, and interconnection boxes. Each cryogenic island houses one or two refrigeration plants that feed one or two adjacent tunnel sectors. A refrigeration plant comprises one 4.5 K refrigerator and one 1.8 K refrigeration unit. The 4.5 K refrigerator is either one of the four refrigerators recovered from LEP or one of the four new integrated-cold box refrigerators. At each cryogenic island, an interconnection box couples the various refrigeration equipment and the cryogenic distribution line. They also permit redundancy among the refrigeration plants.

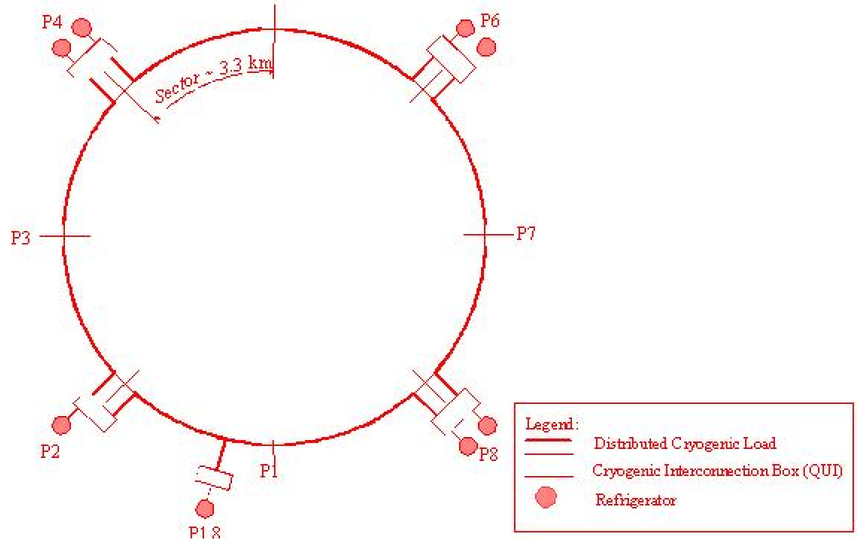


Figure 3.6: Distribution of the cryogenic stations around the machine

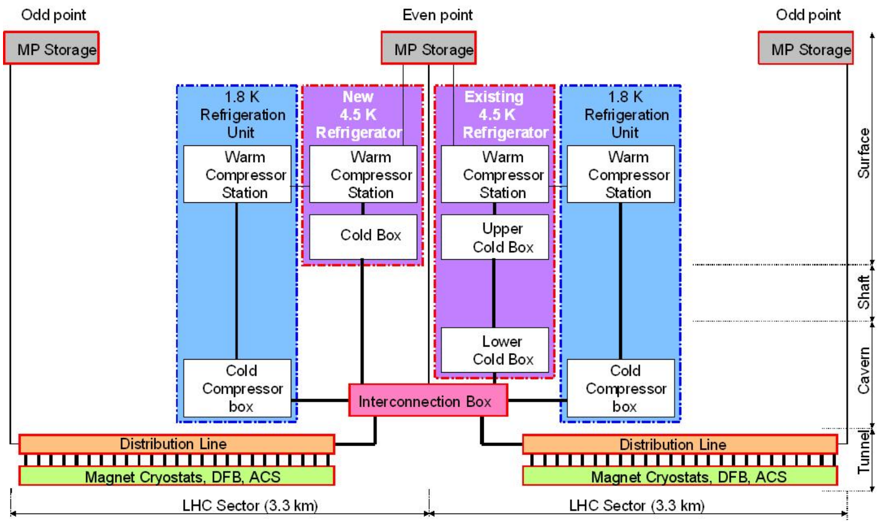


Figure 3.7: Cryogenic system layout for two sector from odd point to odd point

Cryogenics instrumentation

The cryogenic operation of the LHC requires a large number of sensors, electronic conditioning units and actuators, most of which are located inside the machine tunnel and must therefore withstand the radioactive environment. The tight temperature margins allowed along the cryo-magnet strings require the implementation of precision cryogenic thermometry. During final helium filling and normal operation it is very important to know when the cryo-magnet cold mass is completely filled with pressurized superfluid helium. This information is obtained from warm pressure transducers hydraulically connected to the cold-mass [54].

The process control equipment follows an industrial approach and is composed of Programmable Logic Controllers (PLCs) and a Supervisory Control and Data Acquisition (SCADA) systems. The control hardware architecture follows a scheme to save cabling costs and keep subsystems within a certain degree of autonomy. Local cryogenic equipment (e.g. refrigerators, interconnection boxes, storage, etc) have always been interfaced with industrial controllers and the solutions adopted are based in the previous experience with the LEP cryogenics. The tunnel hardware is composed of standard industrial equipment and of distributed, radiation tolerant [55], Input/Output (I/O) units.

Sectorization

The industrial equipment is installed in protected areas (16 alcoves and 8 IPs) and it is composed of PLCs, Ethernet gateways, fieldbus gateways, "intelligent" valves and ancillary equipment. The distributed I/O units are custom designed to withstand the radiation in the arcs and the dispersion suppressor regions. Data exchange between PLCs and distributed I/O elements is performed via an industrial fieldbus. The elements are in the tunnel and in the underground areas, this is taken into account for the definition of the HC sectorization, which is explained later.

3.2.7 Power Converters of the Electrical Circuits

There are 1720 power converters having a total steady state input power of 63 MW and a peak power of 86 MW. They supply a total current of about 1850 kA and are, in general, characterized by their high current and low voltage [56].

The strategy for the design, production and test of the power converters divides the power converters in three independent parts as is showed in Figure 3.8:

- A power part acting as a voltage source.
- Two independent current transducers.
- A digital electronics control module, which performs the current regulation and makes the link with the slow control network. A special effort has been made towards standardization, using the same electronic control modules for all types of converter.

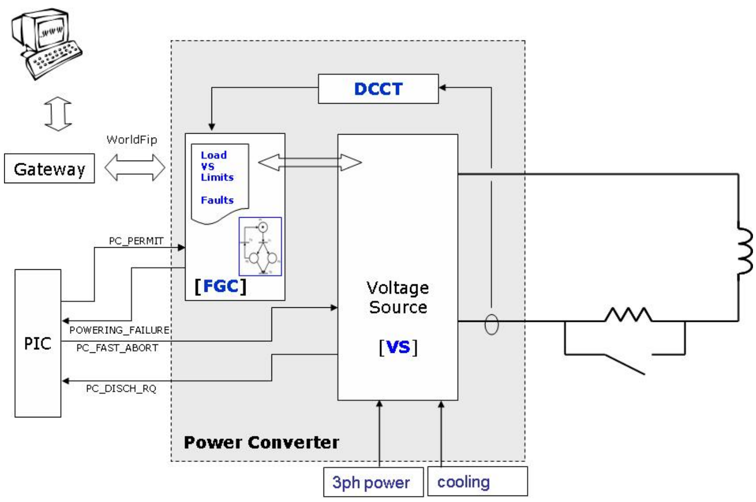


Figure 3.8: Power Converters Structure

There are five main types of converters which are the result of an effort to minimize the complexity of the equipment group.

- The first type of converter corresponds to the main dipole magnet converter. There is a dipole circuit per sector, each powered by a separate power converter. The steady state specification for physics is 13 kA, 10V.

- The second type of converter corresponds to the converters for the main quadrupoles, the insertion quadrupoles and the separation dipoles. The output rating specifications are [13 kA, 18V], [8kA, 8V], [6kA, 8V] and [4kA, 8V].

- True bipolar power converters [±600 A, ±10V], [±600 A, ±40V] and unipolar converter [600 A, 10V], [600 A, 40V] are required to power the sextupoles, the sextupole and decapole spool piece circuits, the octupoles and some warm quadrupoles in the cleaning regions.

- Each quadrupole and each aperture of the LHC machine has a small dipole orbit corrector associated with it. The best solution has been to locate the 60 A converters in the LHC tunnel close to the quadrupole magnets, thus reducing the cabling costs and of the converter power.

- For all warm and septa magnets with voltages above 40 V, conventional thyristor converters are used, the main dipole magnet converter is also line-commutated.

Individual System Tests

The re-use of the LEP infrastructure and the underground installation are the driving forces for reduced volume and high efficiency of the power converters. To minimize the ventilation installation, low air losses has been an important requirement for the design of the power converters. All the power converters are water cooled, except the orbit correctors 60A and 120 A converters. Due to the compact installation and the close vicinity to all the other equipment (magnet protection, beam injection and beam extraction systems, experiments, etc.), the electro magnetic compatibility has been a severe design constraint and needs to be studied and tested when all other equipment has been installed.

The individual system tests of these equipment are done on the surface, once the reception of the element have been done. The tests consist in a software fine calibration with the introduction of the transfer function for each converter.

Hardware Commissioning: Short Circuit Tests (SCT)

There are two phases where the power converters are tested with other equipment, which correspond to the HC period.

- The first phase are the so called Short Circuit Tests. At the beginning of the project these were seen as an individual system tests but due to the level of involvement of other systems they were finally considered as a HC activity.

- The second phase corresponds to the powering tests where the converters are seen as any other equipment from the equipment group of the superconducting circuits. The powering tests deserve a special treatment because they are by far the largest HC activity and their completion marks the end of the commissioning of a sector.

The SCT [57] are performed with the warm part of the SC circuits short-circuited at the level of the extremities of the power cables (just before the connection to the DFB). The tests are meant to validate the normal conducting part of the electrical circuits powering superconducting magnets, extending from the 18 kV and 400 V feed and including the water-cooled cables before their connection to the superconducting part of the circuit. Once this is done for all the circuits of an underground area, the validation of the water and air cooling infrastructure is carried-out by means of 24-hour heat runs with all the circuits powered at ultimate current.

The tests also yield the verification of the individual and global thermal aspects, and the calibration of the power converters for the main dipole, the main quadrupole and the inner triplet circuits. Figure 3.9 shows the configuration for these tests.

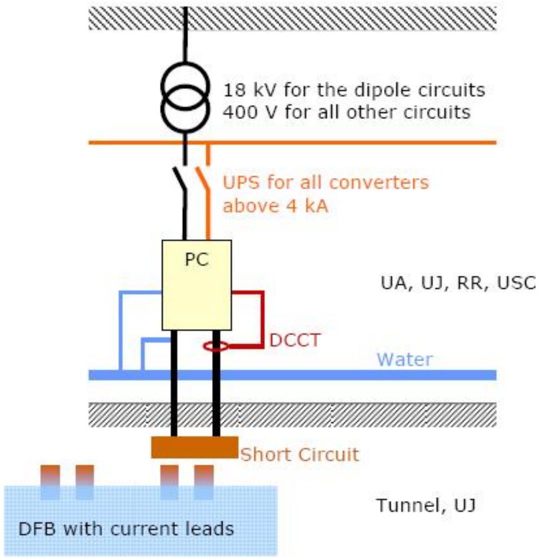


Figure 3.9: Diagram showing the configuration of cables and PC during the SCT

Sectorization

The large galleries, parallel to the tunnel (the UAs, see Figure 1.6), host the high current power converters very close to the current feedthroughs. In the odd points, special enlargements of the tunnel (the RRs, see Figure 1.5) have been required to install auxiliary power converters (for dispersion suppressors, insertion quadrupoles, insertion orbit correction) with a current range from 6kA to 120A converters. In the cleaning insertions of points 3 and 7, the insertion quadrupoles and dipole separators use warm magnets which can be powered from the surface using the existing surface buildings and cabling of LEP.

Each of the underground areas, surface buildings or service tunnels is univocally linked to a so-called powering subsector, as explained in more detail in Section 3.2.11.

3.2.8 Powering Interlock Controller

A total of thirty-six powering interlock controllers (PIC) are installed in the underground areas forming the powering interlock equipment. Together with their associated equipment (namely the power converters and the quench protection equipment) they have to assure the protection of superconducting equipment, powered in more than 1600 different electrical circuits.

To do that, the controllers guarantee the following aspects:

- Protection on a circuit by circuit basis.
- Additional protection mechanisms on a powering subsector basis.
- Link between magnet powering to technical services and safety systems (e. g. uninterruptible power supplies (UPS), emergency stop (AUG) and cryogenics).
- Link between magnet powering to beam interlock system.
- Communication of powering failures to the operator.

The components of the equipment are: the powering interlock controllers, a PLC and a hardware matrix. The electrical DC network powering the superconducting magnets is subdivided into 28 independent powering subsectors [58], supervised by one or (in the case of an arc) two powering interlock controllers [59]. The number and types of electrical circuits to be controlled are different for almost every powering interlock controller and they are defined in the LHC Layout Database [60].

The exchange of protection signals is based on the use of hardwired current loops in between all involved systems [61]. The PLC give green light for powering if all necessary conditions for safe powering are met. In case of failure, it initiates power aborts, energy extraction and possibly a beam dump if the faulty electrical circuit is essential for continuous beam operation. To guarantee fast system reaction times but also to increase reliability for the transmission of safety critical signals, a parallel signal path for the generation of the beam dumping signal through a hardwired matrix is implemented.

Individual System Tests

Upon installation of a powering interlock controller in an underground area, a series of tests start to qualify the correct functionality of the interlock system before its connection to other systems. The equipment has been previously tested on the surface using the same procedures and is re-tested during this commissioning phase after its installation in the tunnel. To simulate the protection signals due to the absence of the related systems (power converters, quench protection system, AUG and UPS), a dedicated test system is used during this commissioning phase (see Figure 3.10). Depending on the individual configuration of the powering interlock controller under test, the according number and types of interfaces are connected to the test system and automatically tested using sequences defined in detail (see [62])

Hardware Commissioning

Once the individual system tests have been completed the commissioning of the equipment has to be carried out in interaction with the other equipment related to it. There are two different parts: before and after connection of the power converters to the magnet string, the so-called PIC1 and PIC2 tests [63]. The two parts together are used to qualify all the powering interlock systems for superconducting magnets and their connected systems in the underground areas. Figure 3.11 shows the main signals that every PIC manages for a circuit to protect the systems.

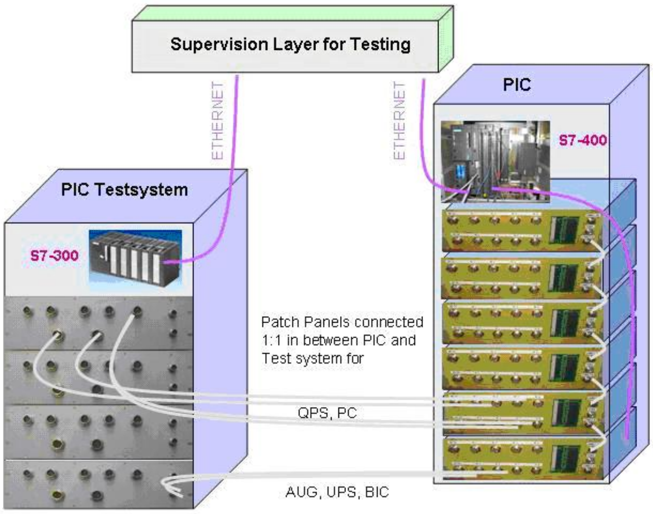


Figure 3.10: Connection of PIC during the individual system tests

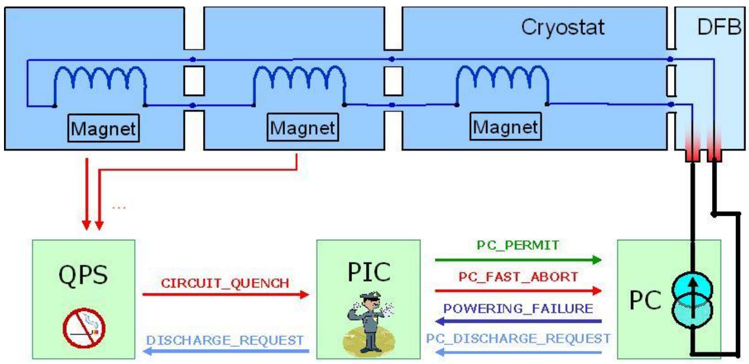


Figure 3.11: Flux of signals managed by PIC to protect a circuit

Sectorization

This equipment can be sectorized in terms of the attached powering interlock controller (see Figure 3.12) and also, in an equivalent manner, in terms of the powering subsectors.

3.2.9 Energy Extraction and Quench Protection System

The energy extraction system (EE) is an equipment that can be divided in two main groups according to the current level and the energy for which they have been designed. All the units belong to either the 13 kA family or 600 A family. In each LHC sector, the three circuits, operating at a ultimate current of 13 kA power the main bending magnets, the main focusing and the main defocusing quadrupole magnets. In order to extract the energy of the circuits (mainly in case of a quench), the current is deviated into external dump resistors by the opening of a set of DC

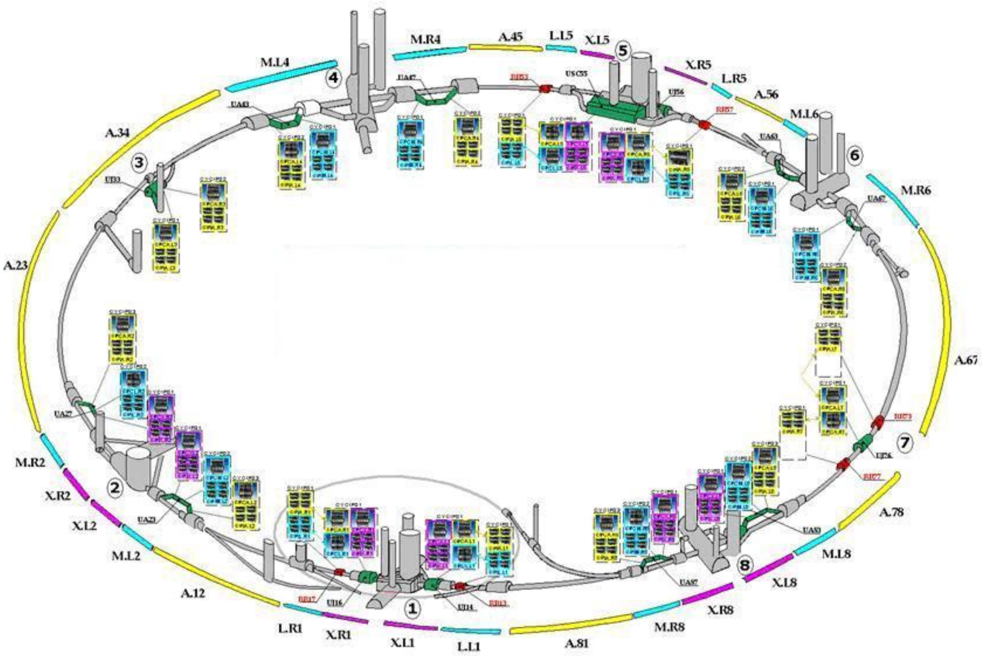


Figure 3.12: Powering interlock controllers and warm interlock controllers tunnel distribution

breakers, which normally carry the magnet excitation current. The EE equipment not only protects the magnets but also the superconducting bus bars connecting the magnets and the superconducting current leads. For the 600 A circuits with large stored energy and medium-level extraction voltage, separate extraction facilities are installed.

If, due to some disturbance, part of a magnet coil is heated beyond the critical temperature the cable becomes normal-conducting in this region. Depending on the size of the zone, the cooling equipment may be sufficient to recover superconductivity or else the heating provoked by Joule dissipation is so violent that the transition is irreversible and then the magnet quenches. It is a delicate situation because superconductors are able to operate at such high levels of current density. In almost all superconducting elements (e.g. magnets, connections, current leads), an active protection equipment is needed in order to avoid overheating of the coil and inadmissible voltages across the circuits. This equipment is the quench protection system (QPS) equipment [13].

Individual System Tests

For the EE equipment all the components have been already tested to ultimate current before arriving to CERN. Once they have been installed the IST check that the basic electrical, mechanical and hydraulic parameters, perform as expected. Functional tests of the complete facility follow and the last step is the commissioning of the supervision system [64].

The QPS individual system tests start with the final testing and configuration of all equipment on the test benches before installation. A second group of tests are done after or during the installation of the racks and components. All the tests must be completed before the powering cables of the superconducting circuits protected by the QPS modules are connected to the current leads, hence before the electrical circuits powering tests. The individual system tests, which also include the verification of the QPS controls, can be divided in various phases including tests with the superconducting elements at warm and at cold [65].

Hardware Commissioning

After the individual system tests, these equipment are commissioned together with other equipment forming up the superconducting circuits equipment group. In this way, when the full superconducting circuit are completed (magnets, power converters, cables, energy extraction, DFBs, powering interlock, controls and cryogenics) the HC phase (powering tests) can start.

Sectorization

Since this equipment is applied on a circuit by circuit bases, the sectorization used for the electrical circuits equipment group will be applied in these two cases.

3.2.10 Electrical Quality Assurance

The electrical quality assurance system is defined as a series of measurements that shall ensure the proper functioning of the electrical circuits of the LHC machine. The aim has been to define a electrical quality assurance to be applied to the machine during installation and commissioning. It provides the procedures, tools and resources to perform the necessary checks and tests during assembly and commissioning that grant the traceability of the work and tests performed at the different stages.

Individual System Tests

The IST of this equipment are performed during the assembly and interconnection works in the tunnel. It consists in the verification of the correct wiring for the 1712 circuits with about 70000 splices for the powering of all-together 10094 magnet units in the LHC accelerator.

Hardware Commissioning

The HC tests [66] lead to qualify each individual electrical circuit for powering, to gather all the necessary electrical parameters for operation, and to trace all the data acquired and to manage the related non conformities. The procedures are composed of seven qualification stages that comprise the tests to be performed during the HC before and during cool-down, at 80K, and at cryogenic conditions. The parameters and related measurement for each circuit are:

- Ohmic resistance. A constant DC current of maximum 6 A is supplied to the circuit and the voltage drop is measured. It allows checking that the circuit is closed and allows determining the resistance values at warm and at cold for each circuit.
- High voltage qualification. Each circuit is individually set to a pre-defined potential with respect to ground by means of a DC voltage source. This allows detecting excessive current leakages or short circuits between the tested circuit and any of the other circuits grounded.

- Transfer function of the impedance. This measurement determines the complex impedance of the magnet chains as a function of frequency. The transfer function is measured at room-temperature and at cryogenic conditions and is compared to reference data. The results of these measurements are used to adjust the converters regulation.

- Continuity tests. There are two objectives of this measurement: the first is to verify that the instrumentation for the current lead protection and the global circuit protection are placed at the right position and are routed to the right connectors, and the second is to certify the absence of broken or disconnected instrumentation wires after the cool-down.

- Diode Polarity Test. The goal of this test is to prove that none of the protection diodes, in parallel to the magnets of the three main circuits, is reversely connected. With DC current this test can be done only at warm, when the circuits are resistive.

  After these tests in the different temperature phases of the cool-down the equipment can be consider completely commissioned.

Sectorization

Since this system is applied by circuit, the sectorization used by this equipment is the same as the one for the electrical circuits which is explained in the next section.

3.2.11 Electrical Circuits

A very large number of both superconducting and resistive conductor magnets are installed in the LHC [67]. Besides the main magnets for bending and focusing, the demanding requirements on the quality of the magnetic fields involve a large number of distributed corrector magnets around the circumference. Most magnets of the same type in each of the eight symmetric sectors are combined in families and powered in series. This minimizes the number of power converters but at the same time the increased stored magnetic energy can become a major concern. Magnet families do not extend over more than one sector, hence limit stored magnetic energies and voltages during energy extraction. Although protection of the magnets is of vital importance, reduced availability of the accelerator due to the large number of protection equipment is a concern [68].

- Main Circuits

  Each one of the eight LHC sectors contain one electrical circuit of the type RB, connecting all the main bending magnets in series. In addition the focusing and defocusing quadrupoles form in all sectors the circuits named RQF and RQD, powering the main quadrupoles in two electrical circuits dedicated to focusing of the two beams in the long arc cryostats. Currents enter the cryostat through a close-by distribution feedbox, equipped with high temperature superconductor current leads for the transition to the cryogenic environment. The circuits are connected throughout the cryostats using stabilized superconducting busbars placed in dedicated slots of the magnet yokes. The stored energy in these circuits requiring the installation of special EE. For the main dipole circuit an EE, consisting of a high current switch in parallel with the extraction resistor, is placed on either side of the arc cryostat, while only one system is connected for each quadrupole circuit.

- Dipole Field Correctors

Due to inevitable production tolerances and nonlinearities in the dipole field, a number of higher order correctors are installed together with every dipole assembly in the long arc cryostat. Two different types of dipole assemblies are installed alternatively in the LHC arcs. One type contains in addition to the main dipole coil on each of the two beam pipes a combined decapole-octupole corrector at the connection side of the cryo-assembly and a sextupole corrector at the far end of the cryo-assembly. The other type contains only a sextupole corrector at one end beside the main dipole coil. All correctors of a family are connected in series for each beam (forming the circuit families RCS, RCO and RCD)[1].

- Short Straight Sections

  Beside the two independent main quadruple magnet coils, each short straight section (SSS) in the arcs contain four higher order corrector magnets at the upstream connection side and two orbit corrector dipoles at the downstream connection side. The orbit corrector magnets are powered with currents of 60 A (120A for a SSS in the dispersion suppressor regions).

- Dispersion Suppressor Extension (Q12-Q13[2])

  The eight arc cryostats are continued with a dispersion suppressor region before being terminated by the DFBA or the Q6 respectively. The dispersion suppressor extension regions consist of Q12 and Q13, containing main quadrupole magnets, fitted with individually powered trim quadrupoles type corrector magnets on each beam.

- Dispersion Suppressor (Q8 - Q11)

  At both ends of the long arc cryostats magnets for the dispersion suppressors are installed. The final elements are two DFBAs, one at each end of the arc cryostat. In all sectors, except in the insertions dedicated to betatron and momentum cleaning (IR3 and IR7), most of the dispersion suppressor short straight sections are built around individually powered quadrupoles. No additional quadrupole correctors are required when individually powered quadrupoles are used. However, the Q11 (and for IR3 and 7 even Q7 to Q11) are in all sectors of the same type as the main quadrupoles and are powered in series together with the arc quadrupoles.

- Matching Sections (Q4 - Q7)

  Except left and right of IR3 and IR7, the matching sections are built with individually powered quadrupoles. No additional correctors are required when these types of magnets are used. The configuration of the matching section depends on the special features of the insertion. From Q4 to Q6, the magnets are fitted in individual cryostats whereas Q7 is located at the end of the long continuous arc cryostat beside the electrical feed box DFBA. Left and right of IR3 and IR7 (cleaning insertions), several normal conducting magnets replace the superconducting magnets used in other insertions because of higher radiation levels of these regions. The Q6 quadrupoles of IR3 and IR7 are built as 6 superconducting low current (600 A) magnets connected in series and housed in one individual cryostat on each side of the IP.

- Separation Dipoles and Final Focus

[1] R refers to the rectifier converter which gives name to the circuit in general; C referees to corrector; S, O, D refers to sextu, octu, deca-pole

[2] Qi, i represents the half-cell where the magnet is installed

While the sectors differ already in the matching sections, the differences are even more pronounced in the separation regions and close to the interaction points. Special insertion triplets are installed in the 1, 2, 5 and 8 insertion regions. They consist on 2 8kA magnets from the High Energy Accelerator Research Organization (KEK) and 2 13 kA magnets from the Fermi National Accelerator Laboratory FNAL, forming the quadrupoles Q1 to Q3. The four magnets are powered in series via an 8 kA power converter, while an embedded power converter of 4 kA superimposes additional current in a nested configuration. A third but yet smaller power converter of 600 A is used as a trim converter over the Q1 magnet. Hence only 4 current leads for the high current connections of the 4 quadrupole magnets have to be installed in the DFBX feed box close to the inner triplet. Separation and combination for the interaction of the two beams is done via two bending magnets (D1 and D2) installed in the long straight section in between the inner triplet and the beginning of the matching section. In the insertion regions for ALICE and LHCb (IP2 and IP8) superconducting D1 magnets (from BNL) are installed to separate the beams. In such a case, two more 8 kA current leads are present on the DFBX of this insertion region. For insertions with high luminosity experiments (ATLAS and CMS in IP1 and IP5) 6 normal conducting magnets are installed, powered in series on both sides of the IP with one single power converter located in the surface building of these insertions.

The electrical circuits can be then divided in two mains groups superconducting circuits equipment group and normal-conducting circuits equipment group. They will be treated during the HC phase as two well differentiate groups since the equipment composing them are different and the operation conditions as well. Chapter 8 gives a more detailed analysis of the superconducting circuits equipment group.

Individual System Tests

All the equipment have to undergo IST testing prior to their installation in the machine. The magnets have been cooled down, electrically tested and for the superconducting magnets quench trained in the benches on the surface [69].

Hardware Commissioning

Once all the electrical components forming the circuit (magnets, the electrical feed boxes, the power converters, the EE and the protection systems)and the general services linked to them have been individually tested and connected, each circuit is tested with current (powering tests).

Sectorization: Powering subsectors

The magnets distributed around the circumference of the LHC are powered in 8 independent and symmetric sectors (see Figure 3.13) [70]. Within these sectors, more than 40 different cryostats house the superconducting magnets, the normal conducting magnets are located in the long straight sections (LSS) close to the interaction points (except for IP4 where no normal conducting magnets are installed). Especially in the cleaning insertions (IP3 and IP7) and around experiments with high luminosity (IP1 and IP5), high radiation levels could lead to systematic quenches of superconducting magnets and require the installation of normal conducting magnets. The eight long arc cryostats span the major part of the circumference and contain the main bending and focusing magnets. Smaller cryostats located around the interaction points house magnets that are specifically required for this insertion. In total there are 131 different types of electrical circuits, connecting main bending magnets, magnets for beam focusing, dipole field correctors, orbit correction or higher order correctors. Some circuit types appear in each of the eight sectors (e.g. the main dipole circuit) while others are only present in dedicated insertions (as e.g. warm compensators for the ALICE experiment). Due to the complexity of the equipment group, a detailed description of this electrical powering scheme has been described within the LHC Layout Database [60] and is reflecting the connection information of all 1614 electrical circuits, formerly only described in a set of 40 circuit drawings [71].

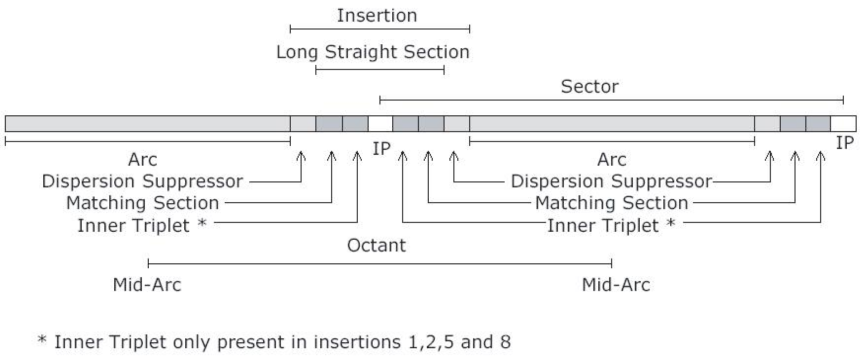


Figure 3.13: Sectors and octants in the LHC

Segmentation of the powering of such an extended electrical systems reduces the stored energies in the circuits, limits build-up voltages during extraction and improves grounding. It also allows easier installation, testing, commissioning and operation. On the other hand, it requires a larger inventory of components for the powering of the electrical circuits (power converters, current leads, normal conducting cabling...). The eight LHC sectors have been subdivided into 28 powering subsectors as shown in Figure 3.14. Four different types of subsectors can be distinguished:

- 8 arc powering subsectors containing all powering equipment related to magnets in the long arc cryostat
- 8 powering subsectors for powering of the inner triplet cryostat, housing the quadrupole magnets Q1 to Q3 for final focusing in the insertions with physics experiments and additionally the separation/recombination dipole D1 in the insertions 2 and 8
- 12 powering subsectors to power magnets in smaller cryostat in the matching sections, containing individually powered quadrupoles and separation and combination dipoles
- 7 powering subsectors for powering of normal conducting magnets installed in the LSS left and right of an IP

3.2.12 General Services: Cooling and Ventilation

The cooling and ventilation equipment for the LHC machine and experimental areas [72] [73] [74], provide the users with the water and air cooling capacity needed. All cooling and ventilation systems are controlled by PLC-systems and a local (SCADA) supervision equipment. Alarms are

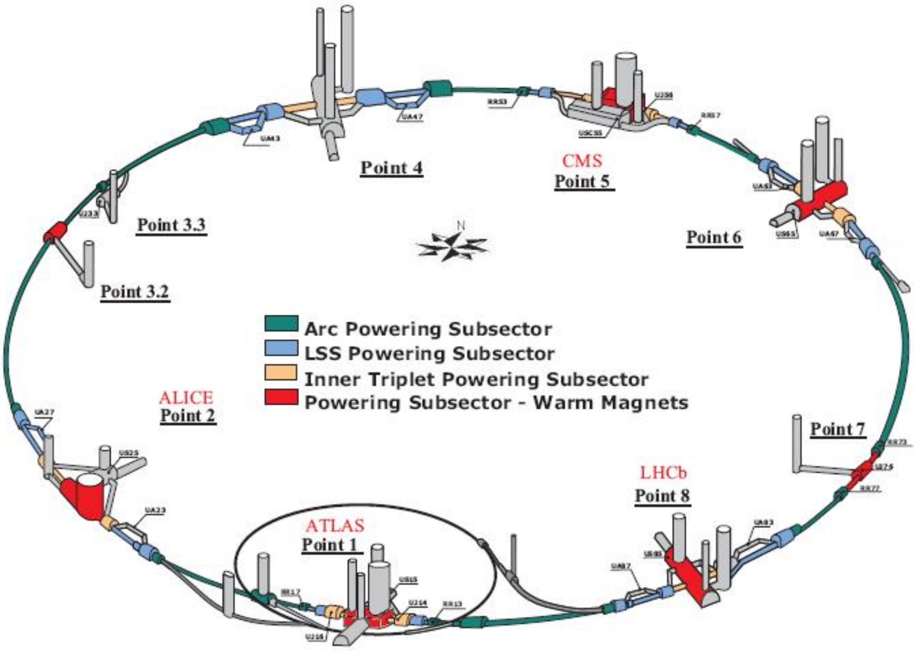


Figure 3.14: Powering subsectors of the LHC

transmitted via an Ethernet communication network to central servers. Different cooling circuits compose this equipment, namely primary water circuit, demineralized water, chilled and mixed water circuit, fire fighting water systems, compressed air systems and clean and waste water systems. Just the circuits/systems related to the machine components are tracked by the HC Project and are the ones treated in this section.

The primary circuit is supplied from the cooling towers and principally provides a heat sink for cryogenic components, such as compressors, cold boxes etc. The demineralized water circuits serve the underground areas and the condensers of chillers located in the surface buildings.

The demineralized water is used in underground areas to cool power converters, cables, warm magnets and auxiliary equipment in the LHC tunnel, the experiments, the radio frequency system at point 4 and magnets installed in TI 2 and TI 8 injection tunnels.

The ventilation equipment [75] provides the air flow needs calculated based on the different cooling necessities from the equipment installed. Two air handling units supply air at each even point of a sector, while two extraction units remove air at the odd points of the corresponding sector. The air is supplied via air handling units located in the surface buildings. The treated air is transported by air ducts, via shafts down to the junction chambers. The air is pulsed into the tunnel on the machine side of these junction chambers. The exhaust air is extracted from the odd points via the junction chambers. Partitions separate the airflows coming from points 2 and 4, points 4 and 6, and points 6 and 8.

Individual System Tests

Both systems undergo through their individual system tests before being ready for the HC phase.

Hardware Commissioning

During the HC of the cooling equipment [76] a sequence of steps lead to the validation of the flexible connections of the water cooled cables, warm magnets, energy extraction systems and power converters. Mainly three actions are taken: the first one related to the installation of the flexible or rigid connection to the main collector, the second one related to the regulation and balancing of the circuit and the third one linked to check of the water quality and filters. For the ventilation equipment the Short Circuit Tests are their commissioning phase. During these heat loads are generated mainly by the converters at ultimate current and by the DC cables.

Sectorization

The cooling equipment is directly linked to the cooled equipment, consequently the sectorization is done by the user equipment.

The ventilation equipment of the LHC tunnel itself with associated technical underground areas is formed by the RR caverns, the beam-dump region and the RE alcoves, the UA caverns and the cavern which house the machine radio frequency equipment. The main tunnel is divided into eight independent volumes, which correspond to the sectors which are treated separately.

3.2.13 General Services: Access and Safety

The access and safety equipment group is composed of the LHC access safety system (operation with beam) and the LHC access control equipment (operation without beam), which have been introduced in Chapter 1. The components of these systems can be found on the surface in each of the eight access points of the machine (sites) as a first access door, and in the tunnel as sector doors which separate the interlocked parts of the machine form the safe ones.

Another safety equipment is the RAdiation Monitor System (RAMSES) which monitors the radiation levels in different places of the machine, including underground and surface areas. The equipment is composed of the detectors, the electronic associated to it and a control equipment which communicates with the alarm equipment [22].

Individual System Tests

The individual system tests for the access system consist of local validation tests for signals and connections of the system interfaces with the different machine components on the access points on surface. The tests are performed by detector so unity tests [77].

Hardware Commissioning

In the access equipment, once the IST have been finished, the elements are integrated and the interfaces are ready for the commissioning. Two tests are performed the functional tests of each site and global LHC test, which includes all the elements of the machine together.

For the RAMSES equipment the tests validate the operation all the components of the LHC Radiation monitoring System. The tests cover the measurement, the alarms, the interlocks and the remote supervision [77] and all sensors are tested with a reference radiation source.

Sectorization

For access and safety equipment groups, the equipment and tests are sorted by point (or so called in this context "site"). Both on the surface and in the tunnel the communication and control loops are verified by point.

3.2.14 General Services: AC and DC Distribution

The power distribution at CERN, and in particular for the LHC can be briefly summarized as follows: the main 400 kV power supply line comes from the Electricite de France (EDF) Bois-Tollot substation. The installed total power is 490 MVA. The estimation for the future power consumption at CERN when the LHC will be in full operation is in the order of 1000 GWh per year. The main LHC transformers are the two 110 MVA, 400/66 kV units. The energy transport system to the main load centers is conducted by 66 kV cable links, which cover the five substations (SE1, SE2, SE8, SE4, SE6 were the number represents machine points where the substation is placed). The design of the power distribution network is to a large extent determined by the load to supply all the machine services. Other voltage levels existing at CERN are:

- 18 kV Power distribution system, CERN wide,
- 3.3 kV Power distribution system, dedicated to large motor-compressor sets for cryogenics,
- 0.4 kV Power distribution, general and dedicated services.

The high current DC cables equipment is used between power converters and DFBs or between power converters and warm magnets. The power cables are either conventional, or water cooled depending on the current level requirements.

The water cooled cables equipment is composed of the cables and tubes and is used for high current DC interconnections between power converters and superconducting current leads, located in various parts of the LHC tunnel (mainly UA, RR and UJ). Figure 3.15 shows an example of a lay-out in a UA gallery. An electrical feed box may receive between 2 and more than 40 current leads.

The cross-sections of the copper cables are 240, 500, 800, 1000, 1300 and 2000 mm2 and the cross-section of the tube is approximately 2550 mm2. The main dipole and main quadrupole circuits are composed of water cooled cables and water cooled tubes and are installed between the power converters, the EE and the current leads to the cryostat. Tubes are only used in the straight parts of the circuits. The auxiliary quadrupole circuits are composed of 500, 800, 1000 or 1300 mm2 water cooled cables installed between the power converters and the current leads.

Individual System Tests

For the AC distribution system the tests performed prior to the user's arrival were mainly visual inspection, verification of the earth system, isolation tests, protection tests, verification of phase sequence and alarms [78]. For the DC cables equipment the IST are carried out prior to the tests on site containing prototype tests, mechanical tests and electrical tests.

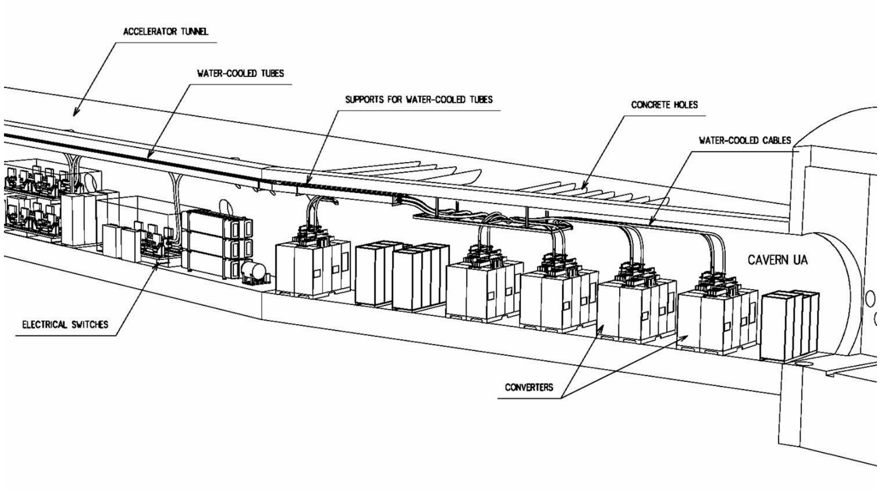


Figure 3.15: Example of a lay-out for the installation of DC cable systems

Hardware Commissioning

Once the user systems are installed and have undergone their own IST the phase of HC starts. For the AC distribution each equipment has added in their procedures a fist verification that AC powering is working fine. With respect to the DC cables equipment two phases can be differentiated. One first phase [79] where the water cooled cables have been connected to the water circuit and both types of cables connected to the power converter. In this phase the cables go through the water tightness tests, electrical tests, and connection verifications. And a second phase in which the systems (power converters) are switch on. This phase is part of the Short Circuit Tests (see Section 3.2.7).

Sectorization

The AC distribution equipment sectorization is by geographical position: underground areas, RR caverns, RE alcoves, arcs and straight parts of the tunnel. The tests that these systems follow are different depending on the areas. For the high current DC cable equipment since each cable is connected to a power converter terminal and each power converter is part of a circuit, the sectorization is done by circuit.

3.3 Highlights on the LHC Technical Systems

As a result of this part, all the systems have been completely analyzed and dissected with a new perspective for the hardware commissioning phase, something non-existent prior to the start of this study. The main objectives reached have been:

- Identification of the systems that take part in the HC Project.
- Definition of the concepts individual system tests and hardware commissioning. Classification of the different tests to be done in each equipment or equipment group with respect to these two concepts.

- For all the systems involved in the HC Project, there has been a definition of the tests including the components, the conditions required to start, during and after the tests. All are documented and validated through an approval process.
- It has been concluded that, the systems directly linked to the superconducting circuits (e.g. power converters, quench protection system, cryogenics, etc.) needed more attention in this project than the beam-related ones.
- One of the important results of this chapter is the identification of the sectorization used by the different systems, something that was not clear before the start of this study, and which solved already some important issues, like the mismatch between the sectorization of the cryogenics system and the powering subsectors.

Chapter 4

Scheduling the Hardware Commissioning

This chapter and the next one explain the design and the implementation of the Hardware Commissioning (HC) Schedule and the HC Planning, which is used for the execution and control of the project.

Scheduling has been identified as the first step to specify the project and to define its boundaries. It is the first level to get the objective of the creation of a general quality assurance plan for the HC Project. It is required to create a general awareness of the existence of dependencies and to follow a well pre-defined sequence during the project. In such large projects it can be observed that the responsible systems have been preparing their own commissioning with a project knowledge of their needs but without control of what is coming after them, nor about the single readiness of the requisites and conditions they ask for. The schedule provides all this information of the project at large scale.

The first schedule for HC has been developed using standard blocks for all the sectors which were afterwards positioned with respect to the general installation schedule. Each sector of the machine has been planned to be commissioned between the end of the installation and before the commissioning with beam. All the activities within the tasks have been described in detail in technical procedures documents and discussed for each one of the equipment groups involved. It was expected that the HC schedule would be dominated by the commissioning of the very complex powering system for superconducting magnets and its associated infrastructure.

This chapter presents the different steps that have been followed to produce the schedule of the HC Project together with the result of the implementation.

The schedule definition process (see Figure 4.1) starts with the identification of the mission of the project and its implementation. With this information the workflow, which corresponds to the definition of the project structure, can be defined and represented within a flowchart. Afterwards, the definition of the summary levels of activities to be done and the definition of the minimum duration work package lead to the work breakdown structure (WBS). The identification of the tasks forming the activities of the WBS ends in the final format of the schedule for the project.

4.1 Hardware Commissioning Workflow

The workflow [80] is a project planning technique to support identification of the activities of a project through the integration of the knowledge from the future contributors. The objectives for the definition of a flowchart in a large scale project, as the one concerned by this thesis, are to:

- ensure that all the contributions share a common view,

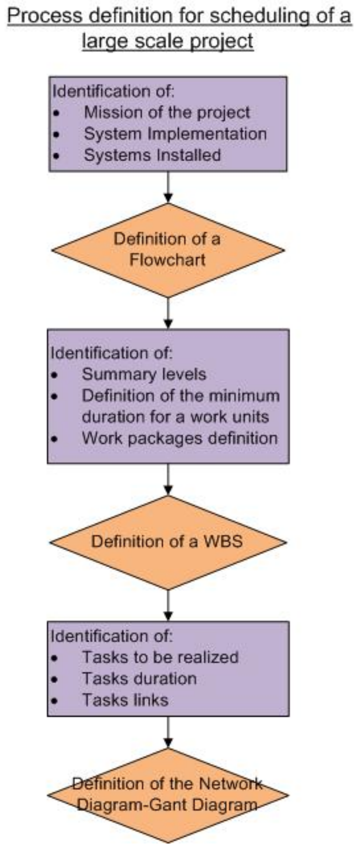


Figure 4.1: Process designed for the schedule definition of a large scale project

- reflect the project plan decisions and options,
- found the project roadmap to completion,
- identify missing activities,
- highlight paths which do not reach final deliverable of the project,
- and ensure that the final deliverable is specified, and that activities and intermediate deliverables are not out of scope.

The main actors of a project in the workflow are: the signed mission order, the system implementation and the results. In the case of this thesis:

Signed mission order: assures that all the systems (equipment groups) of the LHC collider (excluding the experiments) are ready for combined operation at nominal conditions.

Implementation: represents the execution of the tests that leads to the completion of the project.

- Individual systems tests (IST) at warm
- Individual system tests during cool-down and at cold
- Hardware commissioning activities
  - Cool-down of the sector

– Powering of the superconducting circuits

Result: all equipment groups tested.

Figure 4.2 shows the flowchart for the HC Project[1] workflow.

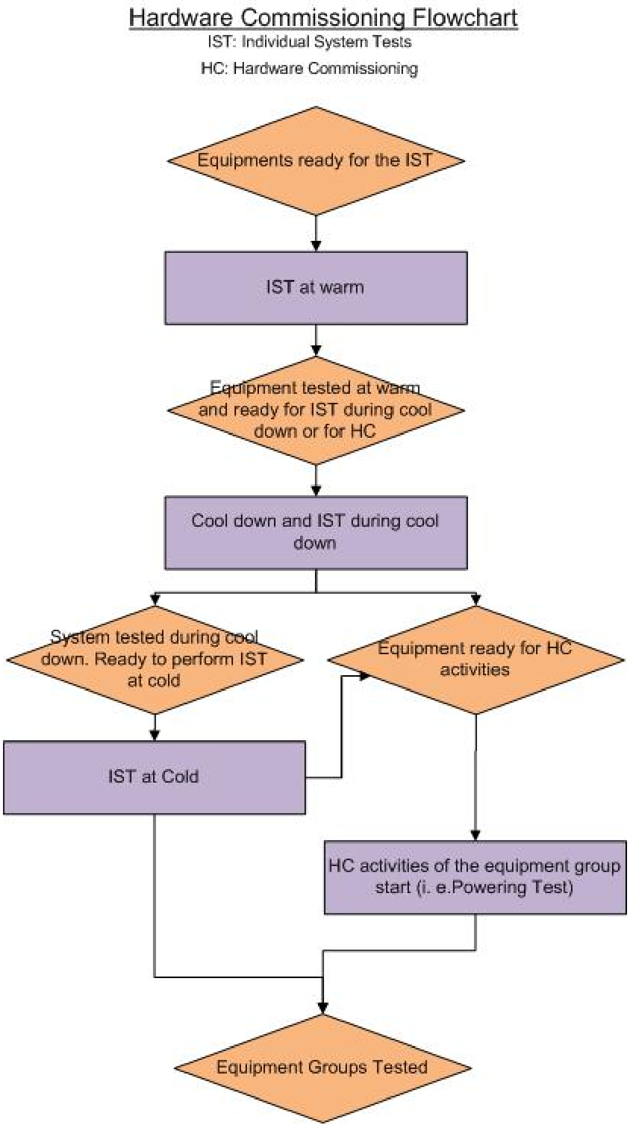


Figure 4.2: Flowchart for the Hardware Commissioning Project workflow from the IST to the HC activities

4.2 Work Breakdown Structure and Gant Diagram

A Work Breakdown Structure (WBS) [80] is a technique used for defining and organizing the whole scope of a project by means of a hierarchical arborescence structure. The first two levels of the WBS (i.e. the root node and Level 2) define a set of planned outcomes that collectively

[1] A standard code exists for the representation of a project flowchart: squares shape represent activities and oval or rhomboid shapes represent status or project deliverables

and exclusively represent 100% of the project scope. At each subsequent level, the children of a parent node collectively and exclusively represent 100% of the scope of their parent node. A well-designed WBS describes planned outcomes instead of planned actions. Outcomes are the desired ends of the project, and can be predicted accurately; actions comprise the project plan and may be difficult to predict accurately. A well-designed WBS makes it easy to assign any project activity to one and only one terminal element of the WBS.

The WBS has been designed to structure summary levels for the project time and cost management. It contains all the activities (work units) of the project. The tasks (activity steps) are not part of the WBS but of the network diagram explained in the next section. The definition of the different work packages (group of activities) is done up to the project level. If possible, the optimum is to be able to create a standard unit that behaves as a block in case of date changes. This is the case for HC since its position between the end of the installation and the commissioning with beam makes it an excellent candidate for changes in the start date and therefore in the available duration.

Following the workflow, explained in the previous section, the definition of the HC levels or activities for each workflow element has been done. The granularity of the work packages (activities) has been created and each responsible has defined the boundaries of his/her action. For the HC Project the minimum duration of a work package has been set to 1 day, so all the activities below this duration are not detailed. For tasks, network units, the same rule has been decided. The HC WBS shows a pattern which is repeated in all the sectors and generally consists of:

1. Installation phase and IST
   - (a) Cryogenic instrumentation installation
   - (b) Cryogenic instrumentation tests
   - (c) Powering interlock controller (PIC) installation
   - (d) PIC IST at warm
   - (e) PIC IST at cold
   - (f) Power converters (PC) IST
   - (g) Quench protection system (QPS) & Energy extraction system installation (EE)
   - (h) QPS & EE tests at warm
   - (i) QPS & EE tests at cold
2. Magnet interconnections, final closure and all cryostats closed
3. Hardware Commissioning tests
   - (a) Electrical quality assurance (ElQA) tests
     - i. ElQA at warm
     - ii. ElQA during cool-down
     - iii. ElQA at cold
   - (b) Cool-down and fine tunning
   - (c) Electrical circuits powering tests

Some of the activities represented on the workflow are not from the HC project but are activities coming from the previous phase (e.g. the installation phase). Its integration into the LHC Installation Planning has been necessary in order to be able to control the boundaries needed to start the HC activities. On the other hand, not all the commissioning tests have been integrated in this planning in a first stage. Only those related to the superconducting circuits which may lead to conflicts, due to its complexity and because they represent mainly the critical path [2] of the project have been included. The rest have been studied and analyzed but they are placed in the shadow of the critical path.

A significant result of this design has been the identification of some "gray zones" where responsibilities were not clear. There has been some other activities that they were not being considered since no one had identified them like his own responsibility. These activities have been, typically, interface activities.

4.3 Network Definition and Gant Diagram

For the definition of the network, two new aspects have been introduced: the list of tasks for each activity and the dependencies between activities. The study has been done through all the activities involved in the HC but the representation, showed below, takes into account just the critical path and activities that could affect to it.

1. Installation and IST
   (a) Cryogenic instrumentation
   (b) Powering interlock controller
      i. Installation
      ii. PIC IST
      iii. "Post-mortem" recordings and analysis
   (c) Power converters short circuit test
   (d) Quench protection system & energy extraction System
      i. QPS installation
      ii. Installation deployment and commissioning of QPS/EE control at warm
      iii. QPS control at cold
      iv. Final validation of QPS/EE control
      v. QPS IST warm
      vi. QPS IST at cold
2. Magnet Interconnections
   (a) Interconnection and temporary closure
   (b) Leak and pressure tests
   (c) Final closure of the vacuum vessel

[2] The critical path is the sequence of project network activities which add up to the longest overall duration. This determines the shortest time possible to complete the project. Any delay of an activity on the critical path directly impacts the planned project completion date

   (d) All cryostats closed

3. Electrical quality assurance (ElQA)
   (a) Pumpdown of last vacuum sector and ElQA at warm
   (b) ElQA during cool-down
   (c) ElQA at cold

4. Cool-down and fine tuning
   (a) Cool-down from 300K to 80K
   (b) Cool-down from 80K to 4.5K
   (c) Cool-down from 4.5K to 1.9K and fine tuning

5. Electrical circuits powering tests

Once all the activities have been defined and the levels identified, the next step is to identify individual logical relationships between activities, locate and suppress loops. The result is showed in Figure 4.3.

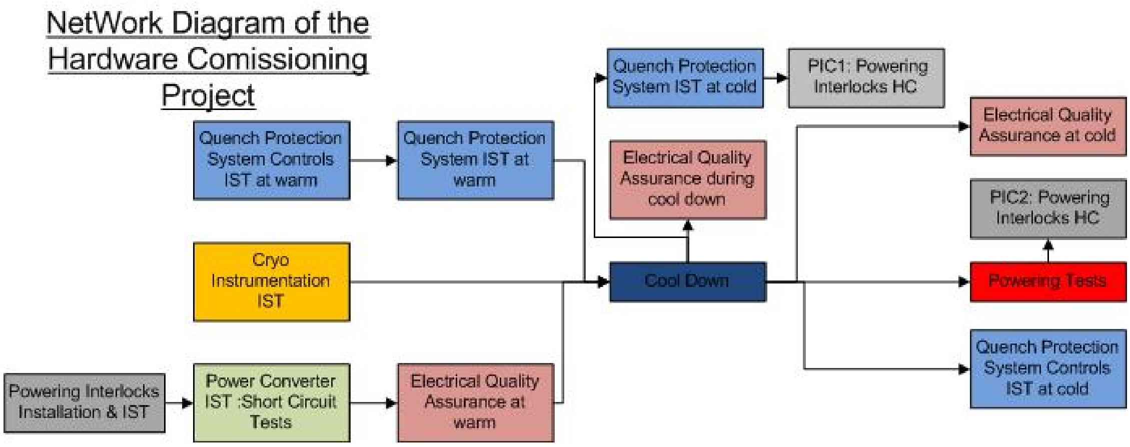


Figure 4.3: Network Diagram for the Hardware Commissioning project from the IST to the HC activities

4.4 Time Estimations by Work Package & Tasks

The estimation of the times and the resources (see Chapter 5) has been done following the experience from the String-I and String-II facilities, as well as from the commissioning of the HERA collider. Some main activities time estimations are explained below.

Cryogenic instrumentation

This activity represents the installation and tests introduced in Section 3.2.6. The time estimation has been 20 weeks to perform two sectors in parallel. Appendix A shows the detailed planning were the study for the calculation of the activity duration is detailed.

Powering interlock controller

For the installation and the individual system tests of the powering interlock controller the estimation has been 2 weeks for an underground area UA and 1 week for an RR.

For PIC1 which are the same interlock tests that are done during the powering tests without the power cables connected to the current leads, a detailed list of steps has been prepared and time durations have been assigned to each one, depending on whether the tests were done by circuit or by powering interlock controller module (for a powering subsector). For the Post-mortem tests [81] 1 day has been estimated. Appendix A shows the tables detailing the calculation of these time estimations.

Quench protection system and energy extraction

The installation time per sector has been estimated by the experts of around 12 weeks for both systems. For the tests at warm a total of 15 weeks are assigned, and 18 weeks for the tests at cold, which is the time that the circuits are cold. This does not mean that experts need all that time. This time just represents the window available for them. There has been, as for the rest of the systems, a detailed calculation of the time usage for both EE and QPS.

Electrical quality assurance

For the quality assurance of the superconducting electrical circuits the time estimation for a sector has been of 2 weeks at warm. During cool-down the ElQA covers all the cool-down period, and at cold it represents 3 weeks, from which 1.5 weeks are done during the end of the cool down and the other 1.5 weeks in the period of powering tests.

Cool-down

The cool-down period can be divided in 3 phases (represented in the network diagram above), as a first estimation the total time given by the experts with the experience from the String-I and String-II has been of 10 weeks of cool-down for a sector.

- Cool-down from 300K to 80K: 3 weeks
- Cool-down from 80K to 4.5K: 5 weeks
- Cool-down from 4.5K to 1.9K and fine tuning: 2 weeks

Electrical circuits powering tests

The time calculations corresponding to the powering tests are widely explained in the last Chapter of this thesis.

4.5 Highlights on Scheduling

As a result of all the steps explained in the previous sections, the schedule for one sector is showed in Figure 4.4.

In order to integrate it in the LHC General Planning, the schedule has been firstly studied by each sector considering unlimited resources. The network, identified in Section 4.3 by tasks and dependencies, represents the baseline for the schedule per repetition unit sector. The critical path has been identified using the baseline target as the start of the operation with beam.

The schedule shows the requirements in terms of time and interaction between systems during the entire commissioning period. The first iteration in order to integrate all activities in one common schedule showed some problems that needed to be solved:

- Missing activities during the interface between the installation and the commissioning.
- Difficult integration in the general installation schedule in terms of co-activities. It came out that the co-activity between installation and commission activities had some points of conflict or some lack of preparation. Some examples are: safety conditions to allow co-activities, level of readiness to declare one installation activity finished or to allow one commissioning activity to start, definition of responsibilities in the interface time between phases and clear interferences that they had not been seen before. Thanks to this tool these problems were discovered and solved.
- Incompatibilities between systems concerning the conditions required to start the tests. The need of a more detailed description of tests procedures and conditions came out.
- Excessive duration of the tests in some cases, which has prevented the integration of the activities in the time frame available.

All these have shown the necessity of a more detailed description of tests procedures and boundary conditions.

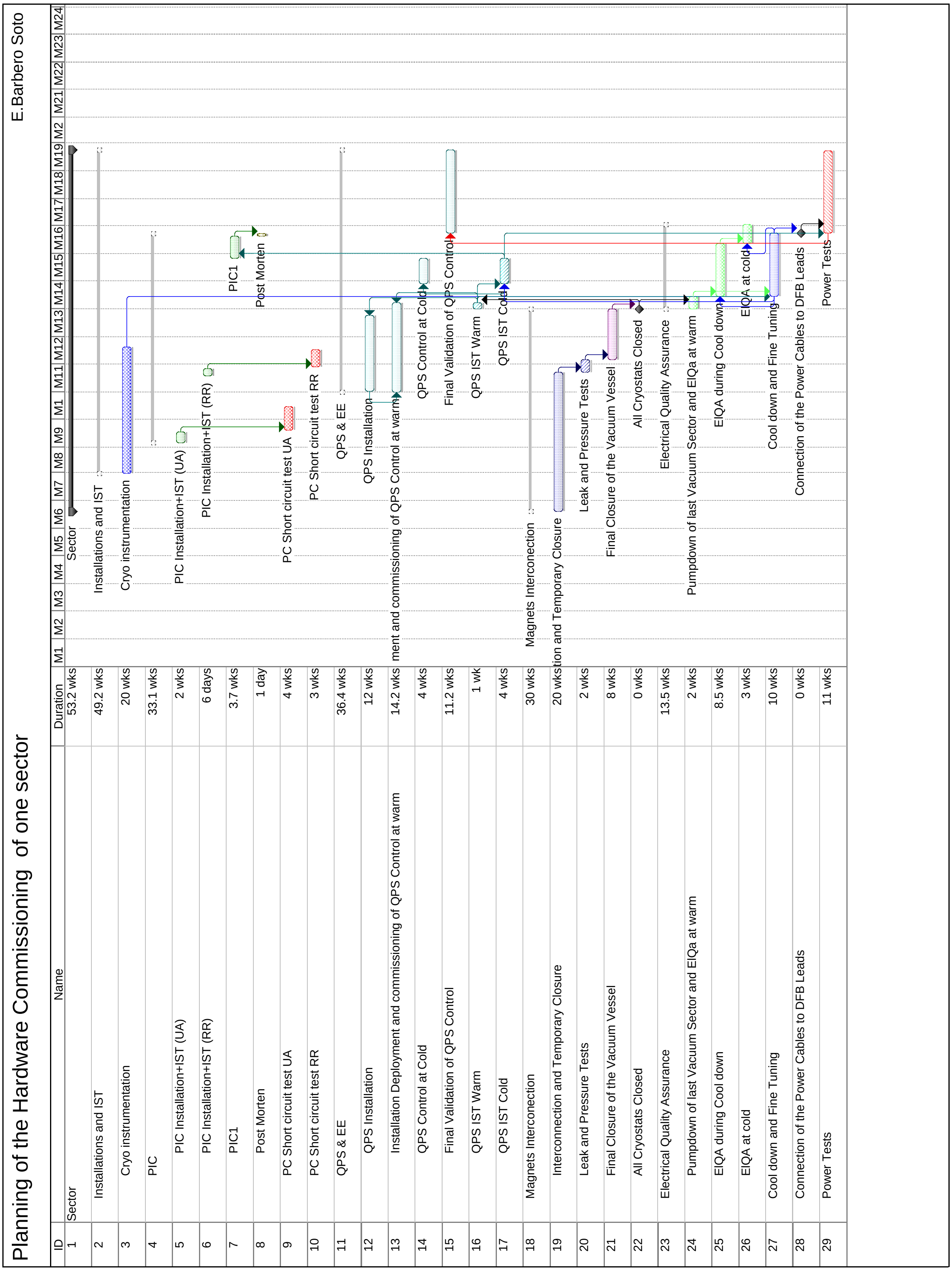


Figure 4.4: Schedule result for a sector to be repeated in all the sectors

Chapter 5

Planning the Hardware Commissioning (HC)

Once the schedule is defined, its feasibility with respect to the budget (i.e. resources) has to be assured. A resource study together with the schedule, determines the planning and has become a strong tool to define and anticipate risks and to react fast in front of delays or technical challenges. This chapter describes the procedure followed to determine the resource study that has provided the capability to adapt and to predict new necessities while changes come up. The creation of this tool for the HC Project was necessary for the start up of the project and has proved to be an efficient arm for changes management.

5.1 Resources Model

The total quantity of work packages or activities that take place during the HC are almost 176. According to these tasks, resources have been allocated to the teams that will perform the work. These resources can be used in another task at the same time. This can happen due to the fact that there is no rule to avoid that two tasks are done in parallel. Frequently the resources are used in different tasks means that the work units needed for each team have to be re-calculated in order to cover all the activities.

A wide study of the resources (personnel and budget) has been done to obtain the real needs during the tests and compare them with the ones actually available. Following the basic assumptions listed below, a study was conducted to derive the resources needed for different scenarios when some of the restrictions are lifted or relaxed. To deduce easily the new necessities in case of schedule changes, some actions have been undertaken:

- The resources have been grouped in teams. Each team has been defined with a number of persons and with the work capacity they have.
- Each task has one or several teams for the different tests. The relation between teams and tasks has been defined.
- The human resources have been classified in different categories depending on the type of contract (e.g. CERN staff, collaborations with National Institutes, industrial contracts, etc.).
- The presence has been defined in two main categories: present in the field and on-call.

With this structure and basic assumptions (see next section) any change can be easily analyzed. This is the objective of this tool when applied to a large scale project, when changes appear, fast reactions are needed.

5.1.1 Original Basic Assumptions

To develop the resource model basic assumptions (inputs) were defined to well determine the conditions. It was always kept in mind that assumptions may change, because of the users or because of management reasons, and the model should support these likely changes.

Later on in this chapter it is presented how they changed due to management guidelines and how the designed model reacted and recalculated the new needs.

The original basic assumptions have been:

1. Parallel commissioning of the two sectors (not more, not less) around an even point. Resources for the same type of activity have been planned only for two sectors as is showed in Figure 5.1. This does not exclude the possibility of a staggered commissioning of another set of two sectors as long as the same activity is not taking place in more than two sectors. This implies that the teams involved in the individual system tests (IST) at warm should not be redeployed on activities taking place during the powering tests.

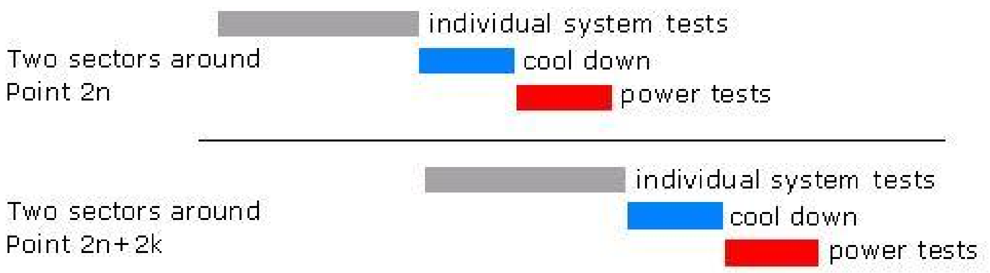


Figure 5.1: Block diagram for parallel commissioning of two sectors following the original basic assumptions

2. Five-day working weeks

3. Two shifts during the powering tests

4. Two commissioning fronts on each sector during the powering tests: one front attacks the arc and the matching section on the even side and the other the arc, the matching section on the odd side and the inner triplet(s)

5. An operation team is present in the field during the two shifts of powering tests: it is composed of one operation crew member and one member of the Hardware Commissioning Coordination sector.

6. The RF equipment group is commissioned during the six months preceding the commissioning with beam in the machine. Only in this case all the resources required for cryogenics (operation crews and instrumentation commissioning) can be are available.

5.1.2 The Different Categories of Personnel

Four categories of personnel are involved in the individual systems tests and the commissioning activities. [1]

	Category	Abbreviation
1	CERN staff	S
2	Collaborations with National Institutes	NI
3	Industrial Support either Work Package with responsibility or task oriented	IS
4	Field Support Units	FSU

5.1.3 Presence

The personnel can be deployed in field or on-call. The on-call service can take the following three different forms which are summarized in Table 5.1.

On-call	during the period specified
On-call for 8 hours per 24 hours	this refers to staff available during an 8 hour working day in support of a team deployed in the field during two shifts; continued presence of staff in the field will be guaranteed in case of emergency through flexible hours; this however can not be extended without limit.
On-call for 24 hours	this refers to a 24 hour piquet service which can either support a team present in the field for two shifts or complement it when needed during the 8 hour unmanned operation of the equipment

Table 5.1: The on-call service can take the following three different forms

5.2 HC Resources Definition

The sections below describe the personnel involved in the different activities, the time allocated per activity and the parallelism when applicable [82]. Owing to the fact that the commissioning is dominated by the powering of the superconducting magnets equipment and their associated infrastructure, it was decided that time and investment for additional personal has been mainly spent for this activity. Some of the activities below take place during the IST of a system, others during the powering tests. In these two phases the working hours and the staff deployed are different, while for the IST the presence in the field concerns the team owning the equipment,

[1] IS and FSU are two modes of contract labor used at CERN to respect the Host Members legal environment

during the powering tests all the parties involved are present in the field or provide an on-call service during two shifts per day. During this phase personnel involved in the commissioning of the electrical circuits is deployed on two fronts for each sector.

After the description of each activity the definition of resource groups is presented. As example, for some of them a table gives the details of each team involved including team name, range of reaction, presence and composition.

Operation of cryogenics during the leak and pressure tests (COLPT)

After the temporary closure of the interconnects the leak and pressure test of the helium vessel and leak test of the vacuum vessel of the cryogenic subsectors of each sector take place. This activity involves mainly the vacuum group, however they have been assisted by the operators of the cryogenic equipment group in order to pressurize and evacuate the lines for the needs of the tests. The test is programmed for two weeks per sector and involves one technician (S) and two operators (IS)(see Table 5.2).

Team Name	COLPT - Cryogenic operation during leak and pressure tests	
Range of Action	One sector	
Presence	One shift, five days a week	
Composition		
1 Technician	Field	Staff
2 Operators	Field	IS

Table 5.2: Description of the resource group COLPT

Cryogenic instrumentation individual system tests at warm

After the positioning and connection of the electronic crates to the local cabling, the commissioning of the cryogenic instrumentation and process control equipment takes place in three phases which are staggered. This activity takes 30 weeks for the first two sectors and 20 weeks for the subsequent sectors. The durations given below are 50% higher for the first pair of sectors. The phases and group of resources are:

- Crate connection (CIWCC): this consists in the installation and connection of all crates. This phase requires 10 weeks and 2 technicians per sector.
- Crate stand-alone start-up (CIWSU): this activity consists in the validation of the instrumentation connected to the crates. This phase requires 10 weeks (12 for the first sectors), 4 technical engineers and 4 technicians.
- Connection of the custom electronics to the fieldbus (CIWCE): the activity includes setting the WFIP network and verification that all the instruments and process data are available at the gateways. This phase requires 8 weeks (12 for the first sectors), 2 engineers, 1 technician and controls support on-call.

- Control system commissioning (CIWCS): check of channel coherence, programs, process logic, alarms, interlocks, etc; During this last phase the Profibus network, which has already been checked during the QRL cold tests, is restarted. This phase requires 16 weeks (21 for the first sectors), 4 engineers, 1 IS engineer and 4 technicians. During the cryogenic instrumentation IST at warm, the cryogenic operation team supports the cryogenic instrumentation team.

Table 5.3 shows the description of these groups of resources.

Operation of cryogenics and optimization of the cryogenic equipment during powering tests (COCD)

The cryogenic operation team maintains nominal operating conditions and recovery during the powering tests. These take place in two shifts five days a week. During each shift one technician (S) and two operators (IS) are deployed. They are supervised by an engineer (S) who is on-call during normal working hours. This team is composed by the members of the team involved in the cool-down (COCD) with the addition of the manpower required for supporting the powering tests in two shifts. During the powering tests, the cryogenic instrumentation team supports the operation team with one engineer (S) and one technician (S); it is active on the two sectors, for the optimization of the control system (e.g. quench recovery). The team members except the FSU, are already counted in the team for cryogenic instrumentation IST during cool-down. The activity takes between 11 and 13 weeks depending on the number electrical of circuits on the sector. The costs for the missing IS and FSU are given for the commissioning of 2 sectors (11-13 weeks). See the description of the resources in Table 5.4.

Cool-down and fine tuning of the cryogenic equipment (CICCT)

The cool-down of the magnets of the two sectors around an even point is carried-out by a cryogenic operation team composed of one engineer (S), two technicians (S) and four operators (IS) during normal working hours. The cryogenic instrumentation IST at cold is performed in parallel with cool-down and also at nominal operation conditions. It consists in the follow-up of instrumentation behavior during cool-down, validation of instrumentation at nominal conditions and check and tuning of the control logic during each phase of operation. This activity takes 10 weeks for the first two sectors and 8 weeks for the subsequent sectors. The cryogenic instrumentation team is composed of two engineers (S), two technical engineers (S), two technicians (S) and one engineer (IS). The team assists the operation team for the validation and tuning of the cryogenic instrumentation and controls. See the description of the resources in Table 5.4.

Electrical quality assurance (ELQA)

There is one team present in the field working one shift per day. It is composed of one expert and one technician. After the installation of the equipment is finished, the electrical quality assurance at warm takes two weeks. During the cool-down equipment are installed to monitor the electrical quality during the cool-down. The electrical quality assurance at cold takes 3 weeks. For both the warm and cold tests the same team carries-out the tests provided they do not fall at the same time. A time lag of three weeks between the commissioning of the two sectors is introduced to ensure that this team can be deployed on both sectors.

Team Name	CIWCC Crate connection		
Range of Action	Two adjacent sectors around an even point		
Presence	One shift, five days a week		
Composition			
4	Technicians	Field	NI

Team Name	CIWSU - Crate stand-alone start-up		
Range of Action	Two adjacent sectors around an even point		
Presence	One shift, five days a week		
Composition			
4	Technical Engineer	Field	Staff
4	Technician	Field	NI

Team Name	CIWCS - Cryo control system commissioning		
Range of Action	Two adjacent sectors around an even point		
Presence	One shift, five days a week		
Composition			
4	Technical Engineer	Field	Staff
4	Technician	Field	NI
1	Engineer	Control room	IS

Team Name	CIWSP - Support team		
Range of Action	Two adjacent sectors around an even point		
Presence	One shift, five days a week		
Composition			
1	Engineer	On-call	Staff
1	Database Engineer	On-call	Staff
2	Technician Engineer	field	Staff, FSU
2	Technician	field	Staff

Team Name	CIWCE - Connection of the custom electronics to the fieldbus		
Range of Action	Two adjacent sectors around an even point		
Presence	One shift, five days a week		
Composition			
2	Engineer	Field	Staff
2	Technician	Field	NI,FSU

Table 5.3: Resource group definition for the cryogenic instrumentation individual system tests

Quench protection individual system tests (QPIST)

There is one team present in the field working one shift/day. It is composed of one expert, one engineer and one technician. The QPS IST at warm include the fieldbus and detector tests and the dry tests of the extraction systems. The connection of the magnets and heaters also take place during this phase. It is expected to take 2 days per sector. This is followed by a final check of the equipment group. After the cool-down the QPS IST is carried-out and they last for 4 weeks. A time lag of three weeks between the commissioning of the two sectors is introduced in the schedule to ensure that this team can be deployed on both sectors. One sector is treated after the other.

Quench protection during powering tests (QPPT)

There are two teams present in the field working two shifts per day. Each team is composed of half an expert, one engineer and one technician. The two teams carry-out the heater tests, energy extraction tests with current and support the powering teams in parallel in two sectors. As these teams need all the time available, one back up team is needed for holidays, illness etc. One backup team is also sufficient when the commissioning of 4 sectors at a time will eventually be necessary.

Machine interlock system individual system tests (MIIST)

During the individual system tests of the powering interlock equipment there is one shift per day with one expert (S) and one senior technician. On the average, the tests take about 40 days for two sectors and include the installation and interface tests of the powering interlock controller in the LHC underground areas. Sectors are treated in sequence.

Team Name		COCD - Cryogenic Operation during initial cool-down	
Range of Action		Two adjacent sectors around an even point	
Presence		One shift, five days a week On-call 24h/day and 7days/week	
Composition			
1	Engineer	On-call	Staff
2	Technician	Field	Staff
2	Operator	Field	IS
1	Operator	On-call	IS

Team Name		CICCT - Cryogenic Instrumentation IST during cool-down	
Range of Action		Two adjacent sectors around an even point	
Presence		One shift, five days a week	
Composition			
2	Engineer	Field	Staff
2	Technical Engineer	Field	Staff
2	Technician	Field	FSU
1	Engineer	Control room	IS

Table 5.4: Resource group definition for cryogenic activities during cool-down

Machine interlock system support for PC on short circuit (MI-PCSCT)

The machine interlock team contributes to the commissioning of some of the electrical circuits with superconducting magnets (main bending and quadrupole circuits), since the 13 kA energy extraction equipment must be operational. The signal from the energy extraction is transmitted via the powering interlocks to the power converters. During these tests there is one shift per day with one expert (CERN staff) and one senior technician. On average, the tests take about 4 days for the two sectors.

Machine interlock system during powering tests (MIPT)

During this phase, the machine interlock team tests the powering interlocks for the superconducting magnets and provide support during the commissioning of the electrical circuits up to nominal current. During the powering tests there are two shifts per day. During each shift, there are two interlock teams. Each team consists of two people: one expert (S) and one senior technician. In addition, there is one expert and one senior technician on-call to support the powering procedures up to nominal current once the interlock equipment is fully commissioned.

Power converter short circuit tests (PCSCT)

After the installation of the equipment in the UAs, RRs and the tunnel, a 3 week campaign is carried out by two teams to connect the AC and DC and water cables. This is followed by the short circuit test. There is one team present in the field working one shift per day and five days a week. It is composed of half of one engineer (S), one senior technician (S), two engineers (FSU) and three technicians (FSU) for two adjacent sectors. Support from specialists (S) having performed the reception tests is available.

Power converters during powering tests (PCPT)

Two senior engineers (one engineer in charge per week) supervise and organize these tests in close collaboration with the coordination of hardware commissioning team. There is one team present in the field working two shifts per day (6h-22h) and five days a week. The team is in charge of the powering tests of both sectors around an even point. The team is composed of two technicians (FSU) present in the field during each shift: they are supported by two engineers (S+FSU) and one technician (S) who are available on request but not necessarily present in the field all the time. They are in charge for one week and their presence in the field is 8h per day. Support from specialists (S) are available: 7 engineers and 9 technicians.

Coordination of hardware commissioning (HCCF, HCCM)

A hardware commissioning team (HCCF)is present in the field control rooms, intervene in case of events of any nature impairing on the smooth progress of the commissioning and is involved in administrative work related to the handling and the management of test data and its interpretation.

A team is composed of one engineer and one technician who are in charge of the two commissioning fronts of the sector. Their functions include the support to operation but also the information recording and presentation as well as the reporting of the advancement of the programme. The engineer directly reports to the project leader. Two such teams are required: one per sector around an even point.

The parallelism of individual system tests where the hardware commissioning coordination team is involved (e.g. leak and pressure test, cool-down, short circuit tests, RF, injection system, etc.) and the hardware commissioning of the electrical circuits imposes the presence of a third team.

The coordination of hardware commissioning is managed by a project management team (HCCM) which consists of the Project Leader, his deputy, an informatics expert for Web/Database/MTF related issues and an administrative assistant in charge of data entry, communication, publications, organization and recording of meetings.

Control system support (COSS)

A team provides field support, with additional on-call support, for the entire infrastructure that the control group supplies. Because of the wide range of systems being considered, different expertise is required to provide these services for both the industrial control systems and the accelerator control systems. The field support is a technician present at the even point being commissioned with on-call backup. This level of service is similar to the one provided to accelerator operations. In order to ensure this, it is necessary to decouple the services given to the control room and to the field. Therefore additional personnel is required during the hardware commissioning periods.

Considering the range of expertise required, the parallel developments for beam commissioning and comparing with the LEP experience 2 engineers are needed to answer to the demand for evolution and improvement of the control software.

Operation

A team supports the HC activities by manning the field control room or the console devoted to them in the control room with one operator during two shifts throughout the commissioning of the LHC without beam. The duty of the operator and the technician associated to him/her from the hardware commissioning coordination team is to give assistance in terms of status information, liaison with other teams, taking over the monitoring of automatic procedures, etc.

5.3 HC Planning

The resources model created for the HC and for the IST, presented in the previous section, was designed to be flexible and easily adaptable to schedule changes. These changes are mainly for the sequence of activities and for the total project duration (available time).

The result of this resource model together with the schedule defines the HC planning. These tools have helped to define and cope with the changes in budget and durations. The result of the schedule with resources can be found in Figure 5.2 where all the activities with their resources associated are represented for one sector.

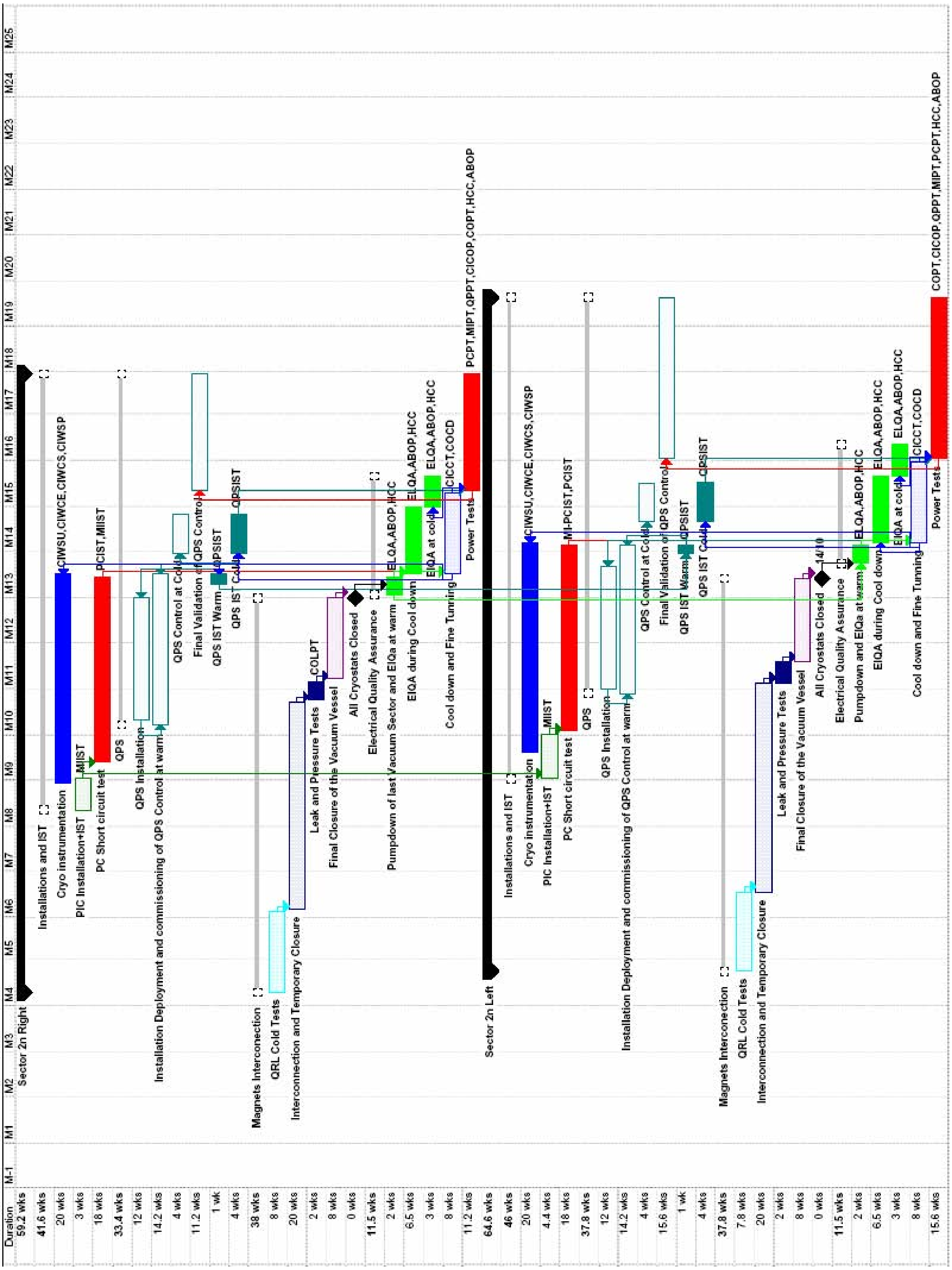


Figure 5.2: Planning parallel commissioning of two sectors

5.4 HC Planning Results

Because of delays during installation, there was a drastic reduction on the available time for commissioning. Three different results using the HC planning are presented in this chapter: first study for a HC in 28 months, HC in 20 months and the last one in 13 months.

Two strategies where undertaken to reach the objectives imposed:

- Decrease of the test durations: once the critical path passed to be the constraint, it was necessary to decrease the test durations in order to get closer to the management baseline.
- Increase of parallelism between tasks: this is a limited resource. A change on strategy is needed once you are on the critical path.

The efficiency of the solutions and the repercussion in terms of budget and resources were analyzed thanks to the HC Schedule and HC Resources Model.

5.4.1 Decrease of the Tests Durations

The critical path study showed that in order to accomplish the new goal it was necessary to reduce the time for the tasks in the critical path the ElQA, cool-down and powering tests.

ElQA: it has not been possible to reduce the time because it is an activity associated to the quality assurance plan and to the equipment safety.

Cool-down: 2 weeks reduction could be obtained in 6 of the 8 sectors.

Powering tests: the powering of the superconducting systems is the task that has more weight in the critical path of each sector. Due to its complexity, different strategies for powering were studied and designed to get the specification for the powering of the superconducting circuits and the management baseline match in terms of time.

- Classification of the circuit by types (see Section 8.2).
- Creation of different fronts that are specialized in a type of circuit and do the powering in parallel, following a strategy for powering (see Figure 5.3), which takes into account the technical constrains (i.e. there are types of circuits that cannot be powered in parallel due to hardware constrains).
- Battery tests for circuits of the same type and powering subsector.

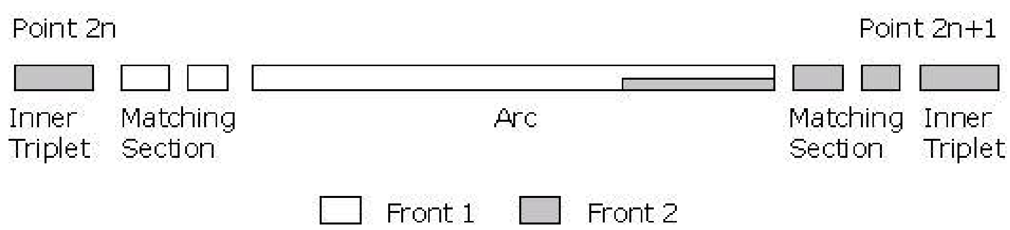


Figure 5.3: Distribution and specialization of fronts in a sector

These actions could be the same for any of the studied durations (28-20-13 months commissioning) since, being actions on the critical path, the result was in all cases the same.

5.4.2 Increase of the Parallelism between Tasks

The change in the resources needs, after applying the time reductions, gives different results for each of the durations studied. This happens because much more flexibility exists if the actions are taken out of the critical path.

- 28 months duration for the HC

  For the **28 months** constraint, the original basic assumptions are respected. The result showed a need of about 100 persons deployed in the field with the assumption of a five-day-week and two shift parallel commissioning of two sectors situated around an even point.

- 20 months duration for the HC

  Due to delays with installation and IST of some systems in November 2004 the necessity of doing the HC in a total of **20 months** became the only possibility. Applying this new constraint and keeping the basic assumptions, the HC resources model was applied. The result of the analysis showed an overload of resource for almost all the teams. The decision taken to solve this situation was to slightly relax the basic assumptions.

  Indeed, only one of the original basic assumptions was relaxed: it was foreseen to carry-out the staggered commissioning of two sets of two adjacent sectors where only the powering tests cannot overlap as showed in Figure 5.4 (to be compared with Figure 5.1). This flexibility is used just in some pair of sectors as showed in Figure 5.5 since it was not required in all of them.

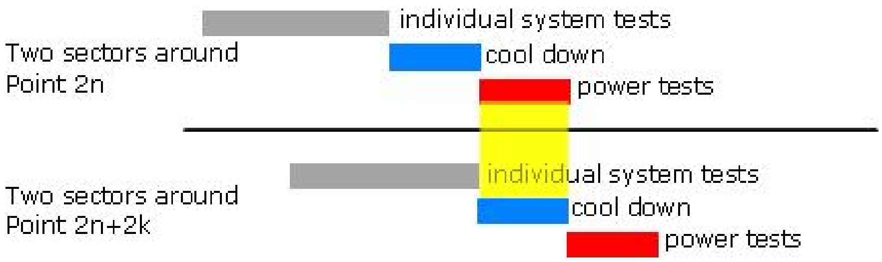


Figure 5.4: Block diagram for parallel commissioning of two sectors following the relaxed basic assumptions

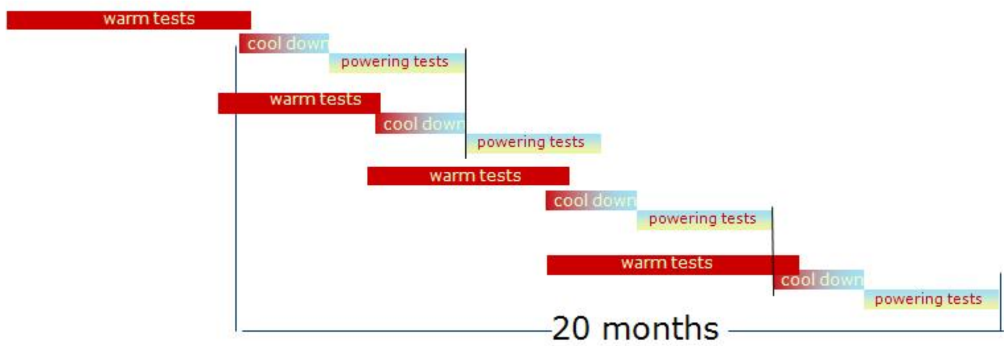


Figure 5.5: Diagram of the commissioning of the four pair of sectors with a duration of 20 months

One of the most affected activities by the reduction to 20 months was the IST of cryogenic instrumentation. It came out as a result of the study that since the maximum scenario was two teams working in the sectors around and even point, there was an overload of 100%. Then, half a team more is needed for the four types of activities (CIWSU, CIWCE, CIWCS, CIWSP) included in the cryogenic instrumentation. Figure5.6 and Figure 5.7 show this example.

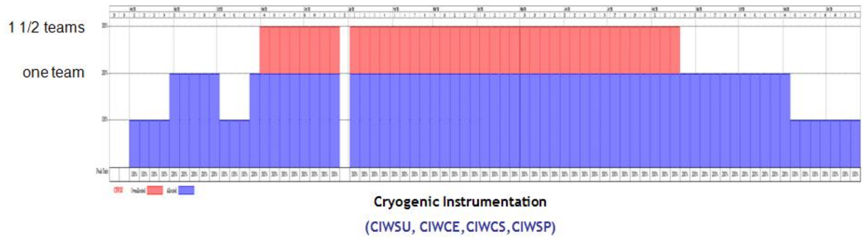


Figure 5.6: Resource study showing: in blue the available resources and in red the overloaded resources for the teams CIWSU, CIWCE, CIWCS, CIWSP

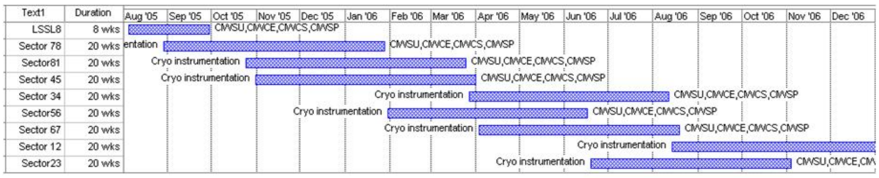


Figure 5.7: Planning showing the activities where the teams CIWSU, CIWCE, CIWCS, CIWSP are active during the life time of the project

Another conclusion is that the overload of resources is avoided in almost all the teams. Only the operation, the HC coordination and the cryogenic operation teams keep on showing overload. The resource study showed a total need of 154 people of which 56 were missing, which implied on the additional budget requirement for IS and FSU of 1.78 MCHF.

- 13 months duration for the HC.

  In April 2005 a new reduction on the available time for HC was identified as necessary creating a new scenario (**13 months** duration). A first analysis of the resource situation and the HC baseline with respect to the new constraints was done with the HC tools. The results showed that in order to further reduce time without overloading the resources it was needed a time reduction of the critical path. This time was something already optimized at maximum with respect to all the existing technical constraints. Therefore, the only solution was to increase the parallelism. The analysis confirmed an overload of the existing resources.

  In this case, the full flexibility of the relaxed basic assumptions was used to get to the 13 months, as it is showed in Figure 5.8. From this point on, any reduction of time would mean a relaxation of hardware constrains, which could include safety mechanisms increase of risk or general reviewing of technical specification procedures.

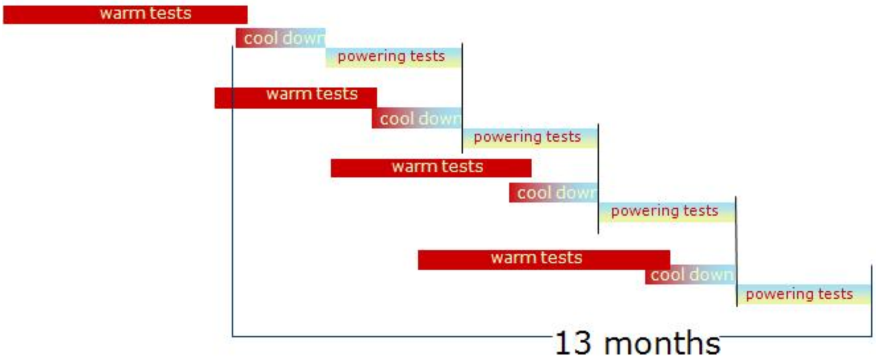


Figure 5.8: Diagram of the commissioning of four pairs of sectors with a duration of 13 months

> The resources study identified two missing resource lines: those for which industrial services (IS) or field supports units (FSU) can be identified and those resources coming from National Laboratories which have to be integrated in existing teams because of a particular competence. The first line totals 2.32 MCHF for IS and FSU while the second states 90 missing persons.

The 13 months is believed to be the "speed-of-light" scenario: an increase of the resources would not have as consequence a reduction of this commissioning time. The duration is driven by hardware constrains.

5.5 Highlights on Planning

20 and 13 months commissioning scenario

Several iterations have been done in order to respect all the requirements and the duration of the commissioning imposed by the LHC general schedule. Decisions based on these iterations were taken to solve these problems. Some relaxed basic assumptions [82] were considered and approved.

Table 5.5 sums up the composition of each team with the actual number of staff needed to carry-out its mission taking into account the deployment (space) and the presence (time) required. The last six columns give the number of people needed, those missing, and where applicable, the cost of IS or FSU. The first three refer to the 20 months schedule while the last three those for the 13 months schedule.

				20 months schedule			13 months schedule		
Team	Composition		Presence / Category[2]	Needed	Missing	FSU missing [kCHF]	Needed	Missing	FSU missing [kCHF]
COLPT	1	Technician	F/S	1	0		1	0	
	2	Operators	F/IS	2	0		2	0	
CIWCC	4	Technician	F/NI	4	2		6	4	
CIWSU	4	Technical Engineer	F/S	4	2		6	4	
	4	Technician	F/NI	4	2		6	4	
CIWCE	2	Technical Engineer	F/S	2	0		3	1	
	2	Technician	F/FS	2		200	3		300
CIWCS	4	Technical Engineer	F/S	4	2		6	4	
	4	Technician	F/FS,NI	4	2		6	4	
	1	Engineer	CR/IS	1		320	1.5		360
CIWSP	1	Engineer	O/S	1	0		1.5	0.5	
	1	Database Engineer	O/S	1	1		1	1	
	2	Technician	F/S,FS	2	1	200	3	2	200
	2	Technical Engineer	F/S	2	2		3	3	
COCD	1	Engineer	O/S	1	0		2	1	
	2	Technician	F/S	2	0		4	2	
	2	Operator	F/IS	2	0		4		160
	1	Operator	O/IS	2		80	4		160
CICCT	2	Engineer	F/S	2	1		2	1	
	2	Technical Engineer	F/S	2	2		2	2	
	2	Technician	F/FS	2	1	80	2	1	80
	1	Expert	F/IS	1		160	1		160
COPT	1	Engineer	O/S	1	0		1	0	
	2	Technician	F/S	4	0		4	0	
	2	Operators	F/IS	4		105	4		105
	1	Operators	O/IS	4		105	4		105
CICOP	1	Engineer	F/S	0	0		1	1	
	1	Technician	F/FS	0			1		160
ELQA	1	Expert	F/S	1	0		3	2	
	1	Technician	F/S	1	0		3	2	
QPIST	1	Expert	F/S	1	0		2	1	
	2	Technician	F/S	2	2		3	3	
	2	Operator/Technician	F/FS	2	0		3	1	
QPPT	0.5	Expert	F/S	3	0		3	0	
	1	Engineer	F/S,NI	5	5		5	5	
	1	Technician	F/S,NI	5	5		5	5	

				20 months schedule[1]			13 months schedule		
Team	Composition		Presence / Category[2]	Needed	Missing	FSU missing [kCHF]	Needed	Missing	FSU missing [kCHF]
MIIST	1	Expert	F/S	1	0		1	0	
	1	Senior technician	F/FS	1		50	1		50
MI-PCSCT	1	Expert	F/S	1	0		1	0	
	1	Senior Technician	F/S	1	0		1	0	
MIPT	1	Expert	F/S	4	0		4	0	
	1	Expert	O/S	0.6	0		0.6	0	
	1	Senior Technician	F/S,NI	4	4		4	4	
	1	Senior Technician	O/S,NI	1	1		1	1	
PCSCT	0.5	Engineer	F/S	0.5	0		0.5	0	
	2	Engineer	F/FS	2	0		2	0	
	1	Senior Technician	F/S	1	0		1	0	
	3	Technician	F/FS	3	0		3	0	
PCPT	1	Supervision engineer	8H/S	1	0		1	0	
	1	Engineer in charge	8H/S	1	0		1	0	
	1	Engineer	8H/FS	1	0		1	0	
	1	Technician	8H/FS	1	0		1	0	
	2	Technician	F/FS	5		400	5		400
	7	Specialist engineer	8H/S	7	1.5		7	1.5	
	9	Specialist technician	8H/S	9	2.5		9	2.5	
HCCF	1	Engineer	F/S,NI	6	6		9	9	
	1	Technician	F/S,FS	6	6		9	9	
HCCM	2	Engineer	F/OF,S	2			2		
	1	Engineer (Data Analysis)	F/OF,S/NI	1	1		1	1	
	1	Engineer (Informatics Sup)	F/OF,S/NI	1	1		1	1	
	1	Administrative Ass.	OF/FSU	1		80	1		80
COFL	1	Engineer	O/S	1	0		1	0	
	1	Technician	F/S	3	1		4	1.5	
COSS	1	Software Engineer (Industrial Control)	F/S,IS	1	1		1	1	
	1	Software Engineer (Accelerator Sys)	F/S,NI	1	1		1	1	
ABOP	1	Operator	F/S	4	0		6	2	
	0.5	Engineer	F/S	1	0		1.5	0.5	
			TOTALS	154.1	56	1780	194.6	89.5	2320

Table 5.5: This table represents the available and the missing resources needed to respect the management constrain of 20 months commissioning and 13 months commissioning. The study was done with the HC resources model

Chapter 6

Hardware Commissioning Quality Assurance and the Global Approach Solution

Table 6.1 shows the strategy adopted to fulfil the HC Project needs and the tools developed for the global approach solution. In this chapter and the following the HC Quality Assurance, Document Plan, Arborescence and MTF tools are explained. The previous chapters explained the scheduling and planning tools. In this chapter there will be, as well, an explanation of how all these tools are linked between them forming a self-consistence block, hence a unique information system.

Project Needs	Strategy and/or tools
Define the grouping of equipment into equipment groups via commissioning procedures	Equipment Owners and Hardware Commissioning Working Group (HCWG) [83]
A structure containing the machine equipment geographically distributed	The HC Arborescence
Structured documentation	HC Document Plan and the HC MTF
Quality assurance program per equipment (IST) and equipment group (HC)	HC MTF
Project execution and control	HC Schedule and HC Planning

Table 6.1: Tools Developed for the global approach solution

6.1 Quality Assurance

Covering both cases, the individual system tests (IST) and the hardware commissioning (HC), the information system has been designed to:

- Organize and make available the logical distribution of the machine components (e.g. by equipment, by equipment group, etc.) and their geographical distribution (e.g. the quench protection system has components, which are located in different places and are connected to the same electrical circuit).

- Archive the technical documents, prepared by the equipment groups or the HC team in collaboration with them. These documents are to be used during the commissioning phase (e.g. schedules, procedures, sequences, safety rules, etc).

- Provide process tracking capabilities, identify deviations, create proper reporting lines and update.

- Perform quality assurance surveillance with well defined references.

This information system allows to precisely evaluate the duration of the different commissioning phases and the situation with respect to the general planning as well as to prepare information for the future route. It has the adequate flexibility in case that unexpected events make changes necessary.

6.1.1 Conceptual Design and Architecture Implementation

Together with the Scheduling and Planning all the tools developed for the HC have to be linked between them to create a self-consistence group and a unique information system structure. The tools explained in this chapter and Chapter 7 are designed to facilitate this links. The information system structure must be accessible from several entry points. Access should be possible from equipment groups, equipment, geographical locations, tasks, documents and schedules. For example, if the input is a power converter of a magnet circuit, the information about the equipment group and the equipment to which it belongs could be obtained starting from the converter itself: where is it located?, when is it going to be commissioned?, which tests and documents are going to be applied or have already been applied?

The structure representing the equipment being commissioned must be self-consistent and static: all the parts of the architecture are fixed and defined once for all. The only data that may change are the schedule dates since it is considered that the schedule can be modified/updated throughout the life of the project. Figure 6.1 shows a diagram explaining how the different tools are linked.

- **Equipment group**

  An equipment group is defined as the collection of equipment concerned by a set of commissioning procedures (general services not included). The aim of this classification is to have a coherent association of the equipment in the machine with the services that they require. It also results in a more efficient management for both scheduling and tracking. In this way, equipment interdependencies are treated in a more refined manner.

- **Geographical distribution**

  The granularity of the geographical distribution depends on each equipment. A common project breakdown strategy around the whole machine has been needed in order to uniformly identify dependencies and interferences. For instance, cooling and ventilation equipment are subdivided into machine sectors, whereas for machine protection the division is by powering subsectors. Consequently, HC regions have been defined for the complete LHC.

- **List of equipment per equipment group**

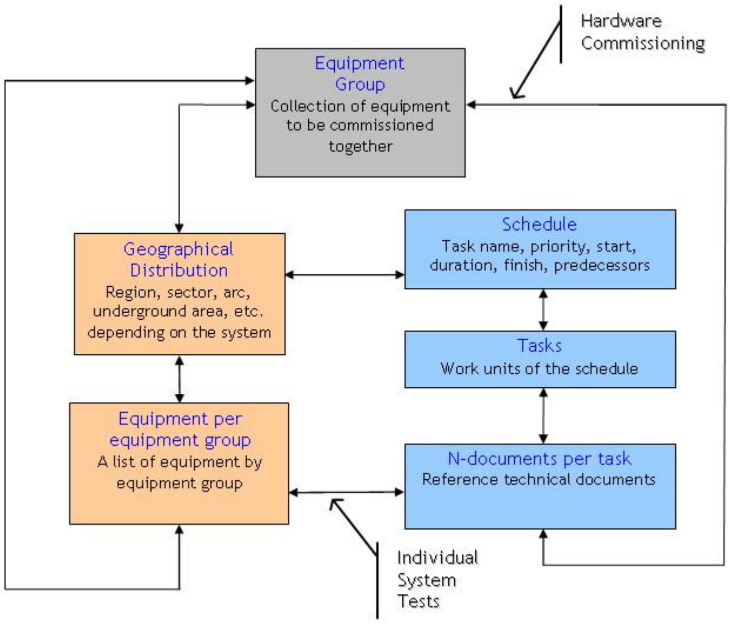


Figure 6.1: Block diagram of the information system

Each equipment group has a list of equipment belonging to it; these lists have been defined by the equipment owners within the frame of the hardware commissioning working group. For instance, the beam dumping equipment group is composed of the equipment collimators, masks, etc.

- **Schedule**

  The schedule is formed by tasks, structured by equipment group and geographical positions. The schedule contains the following elements: the task name, the priority, the start date, the expected duration, the finish date, its predecessors and the resource identifications. This is the only part potentially subject to changes since, obviously, dates and sequences may change before and/or during the commissioning process itself.

- **Document related to a task**

  There is a group of documents belonging to each task. These documents are of different types, namely reference technical documents (i.e. procedures, sequences, interfaces, dependencies), results files and safety-related documents. Equipment groups come with commissioning documents attached to them. Equipment, on the other hand, use IST documents as showed in 6.1.

6.1.2 Quality Assurance Plan

To define the quality assurance plan of the HC Project, the following directives have been used:

Quality policy. Definition of the quality assurance requirements, always in consistency with the quality plan of the LHC [1], the project to which HC is a sub-project.

Procedures. These include documents and parameters for process control and non-conformities policy.

Definitions. Definition of the conventions in use throughout the project. In order to standardize the terminology inside the project, it is a necessary basis to define a naming and code convention for all the systems involved in the HC.

Standards. Schedule and planning definition, including the resource studies and the WBS, seen already in Chapters 4 and 5.

Instructions. A full description of tests for all the systems has been conducted, checked and approved by the project and systems responsible.

Project control. The tests have been implemented in a control tool, which tracks and ensures the quality needed to achieve the objectives of the project.

6.2 Document Plan

The control of the activities to be carried out for each different system is done through dedicated and tailored documents. The document plan is composed of two main groups of specimens. All the documents are classified under a defined and coherent structure.

Technical specifications define the objects of the contract, i.e. the "as specified" configuration of the product, which for the HC Project are the system tests. These documents collect all the execution input data and specify completely and unambiguously the tests to execute and the objectives to achieve. They detail the quality requirements for the tests execution and define precisely the deliverables and their associated documentation. They globally give a full picture of the different steps to be carried out, documented with standard format and contents.

The standard format contains:

- An introduction to the system tests.
- The purpose of the document.
- The scope of the tests.
- The conditions required for the tests to start.
- The test procedures.
- The status of the system after the tests.
- The safety aspects during the tests.
- The tests assurance requirements references.
- All the applicable documents.

In Figure 6.2 an example of the index of one of the documents produced for the HC is showed. It can be seen the standard format described above.

LHC Project Document No.
LHC-R-HCP-0001 rev 1.4
Page 3 of 14

Table of Contents

Figure 6.2: Table of contents of the HC document "The Commissioning of the Hardware in the LHC Sectors: the Power Converters Connected to the DC Cables in Short Circuit "

Management specifications define all the quality assurance requirements for the process execution. The purpose is to ensure that all the systems involved use the same rules and allow the HC Project Leader to monitor properly the advancement.

The specifications include:

- An introduction.
- The subject of the document.
- The references and applicable documents.
- The management requirements.
  - The responsibility.
  - The work plan (WBS).
  - The resources.

– The non-conformity.
– The time schedule.
– The information and documentation. requirements (language to use, list of documents and records to be issued and controlled).
– The risk management (failure scenarios analysis).

6.3 Hardware Commissioning Arborescence Structure

Each system, before the start of this thesis had their own way of organization. A common architecture, for all the actors present in the HC Project, has been designed and the system owners have adapted their software and way of working to fit this structure. One of the major successes of this thesis is the organization of the HC Project, which has unified strategies and operation modes and in the end, the equipment owners themselves have asked to engage in this coordination policy.

The most efficient solution for the project has been to implement a mix between a product breakdown structure and an assembly breakdown structure [84] called HC Arborescence. It represents one simple structure for all the systems involved in the commissioning, which was not the case before, since all the systems were still focused on the installation phase.

The result arborescence has a total of 4 levels. The fist two levels follow a geographical logic, while the last two follow a functional one. This has been designed by studying carefully how all the systems are organized, the location of their equipment, the system software and hardware, identifying all the dependencies between systems (see Chapter 3) and analyzing the way in which the system tests have to be done.

Geographical distribution

Historically, based on the installation phase, all the systems were organized geographically. Therefore, in order to keep this knowledge the distribution of the machine layout is divided in points, sectors and regions. The different segments follow the next rules:

- they are understandable segments for all users,
- they cover of the entire machine and,
- they follow some global specification of the machine.

The first level of the arborescence contains the points and the sectors, while the second level contains the HC regions.

Functional distribution

In order to fit the commissioning requirements it has been necessary to create a functional distribution in the structure. The hardware is spread around all the machine and the commissioning requires a map of the functional links.

The third level of the arborescence is formed by the equipment groups. These contain all the equipment and systems concerned by a common commissioning procedure in each region. As two examples, consider the superconducting circuits of one region or all the electrical quality assurance activity to be carried-out in that region.

The fourth level is the equipment, which constitute the equipment groups and which is formed by the hardware.

6.3.1 First and Second Level: Geographical Distribution

The first and second level of the structure contain the geographical distribution of the machine and it is designed to homogenize the granularity of the machine. Each system used its own segmentation of the machine and this fact made it difficult to identify the geographical coactivity. With this new strategy all the systems are using the same "language", helping to identify each system location with respect to the others.

- *Point (First Structure Level)*

  The 8 points distributed along the LHC circumference are represented with nodes. They correspond to the four experimental points and the other four access points. They contain both surface and underground space. Points are considered in this HC structure because some systems will work and will be commissioned by points. Moreover, the location of some of the equipment is found in the surface points buildings.

- *Sector (First Structure Level)*

  Each LHC sector is determined by the space between two consecutive points. This is historically a common concept for all the systems in the LHC and previously in LEP. Therefore, has been also implemented in the HC arborescence.

- *Cold Regions and Warm Regions (Second Structure Level)*

  Each sector has been subdivided in HC regions. To decide on this partition two parameters have been taken into account: the systems distribution in the machine and the cryogenic characteristic of the LHC machine that defines the morphology of most of the systems.

  The regions are delimited by the beam vacuum pump groups. These groups are used to isolate the cold parts of the beam line, which are fed from the QRL with super-fluid helium, from the parts that are just refrigerated with water, air or independent cooling systems. This sectorization creates what in this thesis is defined as cold regions and warm regions. It has been found that, this division is consistent with the partition that can be done for most of the systems.

  These regions cover the whole machine as showed in Figure 6.3. The distribution of all the equipment groups and equipment to each region has followed the next rules:

  - The equipment physically placed in the main ring has been assigned to the pertinent regions. For instance, since the magnets are part of the hardware around the beam line and they are clearly delimitated by vacuum valves, they are easily assigned to a region.
  - On the contrary, for the equipment that is placed not in the main ring but in the adjacent areas, the allocation has been set through the application point. In other words, each equipment or equipment group that is not directly in the tunnel but has a final action on hardware located in the tunnel itself. As for instance the power converters, which are all placed in the underground areas but they are feeding the DFBs, which are part of the hardware main ring.

  Each LHC sector has a different number of regions and different region names since each one has to commit to both a global common objective and specific objectives for each sector (e.g. all the sectors have superconducting magnets but only sectors 34 and 45 host radio frequency facilities). In the Appendix B the definition for all the regions can be found. There is a total of 109 regions covering the LHC machine.

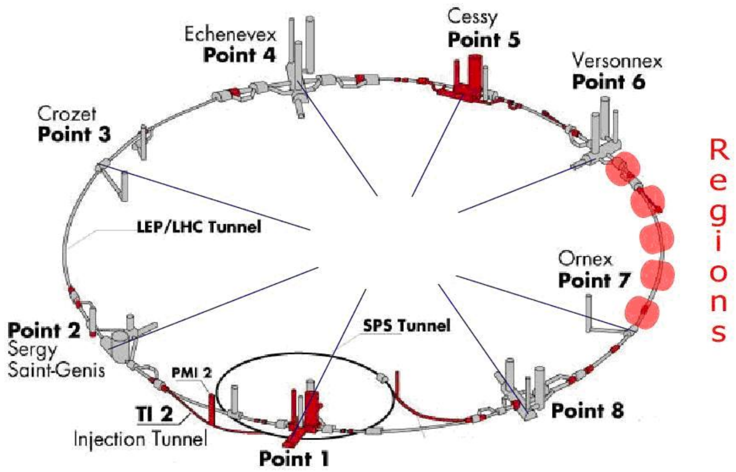


Figure 6.3: Regions distribution scheme for sector 67. For the rest of the sectors the pattern would be the same as sector 67

6.3.2 Third level: Equipment Groups Functional Distribution

Once the geographical levels (first and second) are defined, the third level has been used to reflect the functional distribution of the machine. The rule to distribute the equipment groups within the regions is such that the latter should include everything that needs to be fully and successfully commissioned to complete the commissioning of the region. There are equipment groups composed of equipment that are exclusively present in each region. General services are needed in all the regions. Hence, for all the equipment groups this level represents the HC phase but for the general services the IST. For both, warm and cold regions, a pattern of active equipment groups has been identified and defined. Figure 6.4 shows the HC arborescence with some of the regions of sector 23 and the equipment groups (green folders) that can be found in those regions.

Appendix C describes the composition of this third level.

6.3.3 Fourth Level: Equipment within Equipment group

Each equipment being part of an equipment group has to undergo the IST before being commissioned together with the group. In order to assure full quality assurance of the project all equipment are represented in the HC arborescent structure.

In Appendix C a detailed list of equipment by equipment group is given and explained.

6.3.4 HC Arborescence Structure Implementation

The HC arborescence architecture is implemented within the Engineering Data Management Service (EDMS) and the Manufacturing Tests Folder (MTF) [85]. The EDMS/MTF are CERN tools, which uses a commercial engineering data management system providing management services.

Summarizing what has been seen till now: each sector is made of different regions and each region contains different equipment groups and an equipment group is the collection of different equipment which are commissioned together. As identification attributes, the equipment groups have their type and a unique ID. The equipment groups contain a list of equipment with their ID

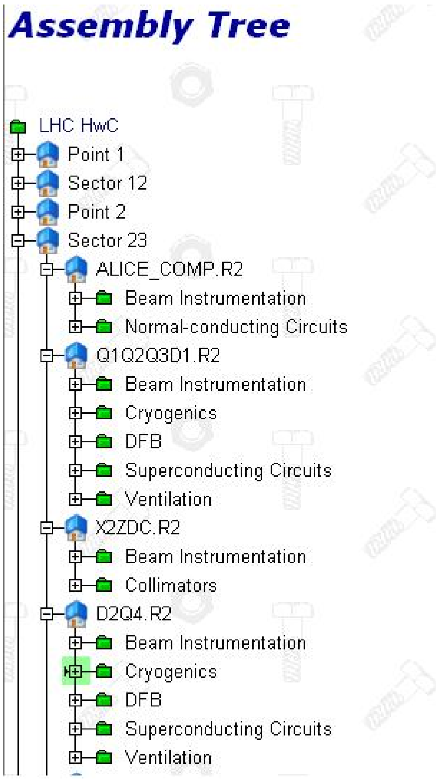


Figure 6.4: Beam Instrumentation, Normal-conducting Circuits, Cryogenics, DFB, Superconducting Circuits, Ventilation, Collimators equipment groups distributed by the different HC regions in sector 23

and type. These equipment can, in some cases, belong to several equipment groups. An example is cryogenics, that is an equipment group by itself but it is also an equipment forming part of the superconducting circuits equipment group. The objective of all this exercise is the full machine divided and structured in an arborescence that is implemented and supported by EDMS.

Identification names

The HC arborescence structure is part of the Quality Assurance Plan of the HC Project and at the same time matches the Quality Assurance Plan of the LHC Project. Therefore, a procedure to assign IDs had to be defined. The key aspects follow:

- Use the identification names of the LHC Layout Database.

  In order to guarantee unique naming for any equipment group, system, equipment or geographical location that already had an ID in the LHC Layout Database they have to keep this ID in the HC arborescence. It has been important to follow this rule for different reasons. Some of the equipment and equipment groups concept, as for instance power converters and circuits, existed already and were part of the layout database. So in order to assure consistence between databases, the IDs assignation for these type of nodes is done directly from the Layout Database. This brought in important advantages:

  - periodic checks will help to update any change in the names or any modification in the equipment layout and,

– being ready for future fusion between databases to obtain an "as built" Database.

For the equipment groups and equipment for which the HC concept did not exist (e.g. the quench protection system), an ID has been created and introduced into the reference database.

- Follow the LHC Naming Convention

  In order to respect the LHC Quality Assurance Plan, the creation of new IDs for the nodes that do not correspond to any concept used before, the LHC rules have been applied [86].

- Follow the HC Naming Convention

  The definition of a naming convention for commissioning purposes did not exist, hence one has been designed to fulfil the needs. See some examples in Table 6.2 and Table 6.3

Node (regions and equipment groups)	**ID origin**	**ID**
HC Region	Created for HC and Introduced in LDB	LDB ID Region name
Superconducting Circuits	Already existed in the LDB	LDB ID Circuit Name
Normal-conducting circuits	Already existed in the LDB	LDB ID Circuit Name
Access & Safety	Created for HC	Y.region name
AC Distribution	Created for HC	E.region name
Beam Instrumentation	Already existed in the LDB	LDB ID Instrumentation Name
Beam Interlock	Created for HC	BIP.Underground area.Position respect point
Cooling and Ventilation	Created for HC	U.Underground area
Collimators	Already existed in the LDB	LDB ID Collimator Name
Control	Created for HC	C.region name
Cryogenics	Created for HC	Q.region name
Radio Frequency	Already existed in the LDB	LDB ID Element Name
Vacuum	Created for HC	V.region name
Beam Dumping	Already existed in the LDB	LDB ID Element Name
Beam Injection	Already existed in the LDB	LDB ID Element Name

Table 6.2: IDs' rules for regions and equipment groups

Node (Equipment)	ID origin	ID
Cooling	Created for HC	UR. circuitID
Electrical Quality Assurance	Created for HC	DE.circuitID
Energy Extraction	Created for HC	DQEMC.circuitID
Power Cables	Created for HC	DW.circuitID
Power Converters	Already existed in the LDB	LDB ID Circuit Name
Magnets	Already existed in the LDB	LDB ID Magnet Name
Powering Interlock Controller	Created for HC	CIP.circuitID
Quench Protection	Created for HC	DQ. circuitID
Radiation Monitors	Already existed in the LDB	LDB ID Monitor name
Warm Magnet Interlock Controller	Created for HC	CIW.circuitID

Table 6.3: IDs' rules for equipment

Results from the HC architecture arborescent structure

As a result of the strategy described in this section, an arborescent structure for the full LHC machine has been implemented and is currently being used. An example of the result is showed in Figure 6.5, that shows a diagram of the structure implemented for Sector 45. The whole machine structure can be seen in www.edms.cern.ch/nav/CERN-0000068056.

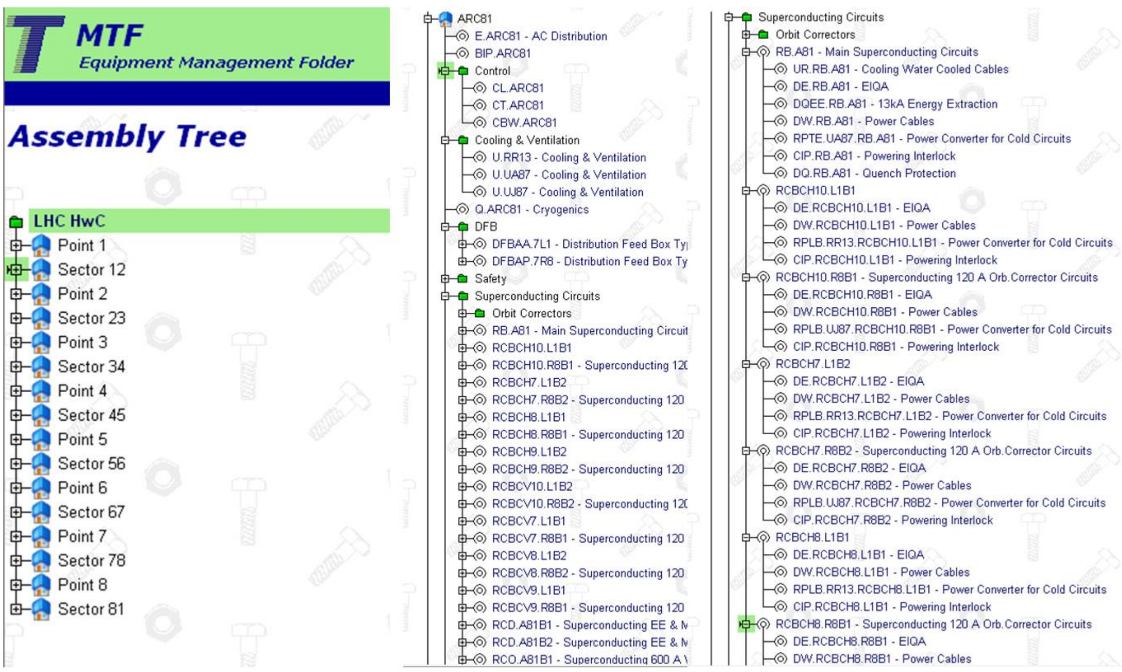


Figure 6.5: Arborescence structure for a superconducting circuit of a cold region in sector 45

6.4 Highlights on Document Plan and Arborescence Structure

The result of this study and its implementation is an arborescent structure for the LHC machine including all the equipment groups and equipment which are involved in the project.

With the standardization of the arborescent structure by hardware levels and by geographical and functional classification any system in the LHC can be integrated in the structure with high flexibility. Since its creation, more and more groups have been added and still today, there are plans for future implementations. The situation in January 2008 was:

- Number of points implementation: 8
- Number of regions implementation:109
- Number of equipment groups implementation:25
- Number of equipment nodes implementation: a total of 14.000 nodes representing all the systems and classified in both a functional and geographical ways. See the functional distribution of this number in Figure 6.6

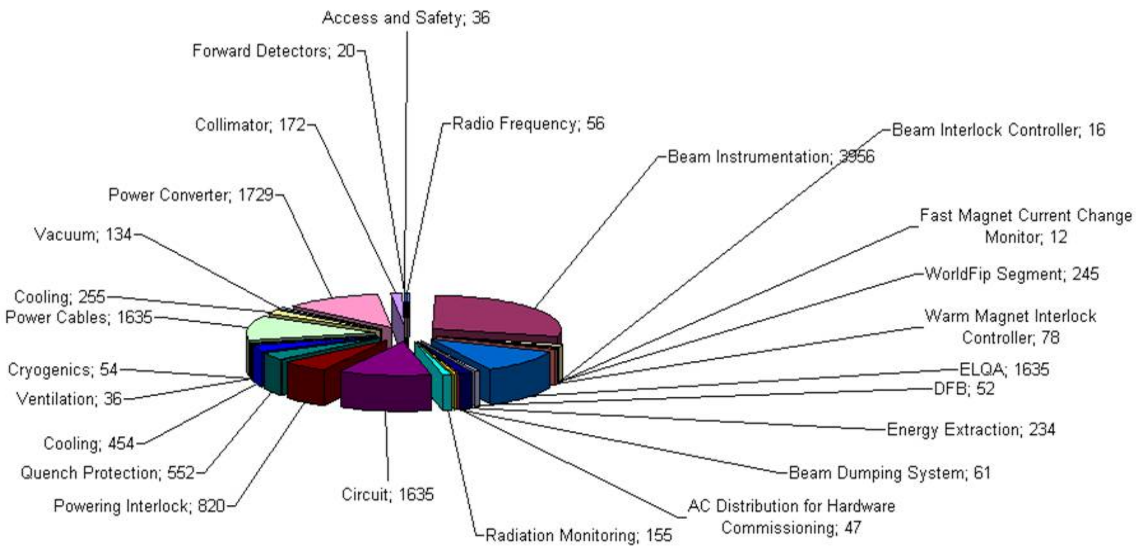


Figure 6.6: Statistics on the number of equipment nodes by functional characteristics

As it can be observed, one of the equipment groups which has the largest number of nodes is the beam instrumentation system. This system will make extended use of this tool during the operation of the machine with beam.

Another one that is very well populated are the electrical circuits and all the equipment linked to them. This results from the detailed tracking of the tests needed to advance in the evolution of the tests.

A unique sectorization for the HC Project has been created solving the Babel Tower situation. Figure 6.7 and 6.8 show, for few equipment groups and equipment, the distribution of the different sectorization used originally by the system owners and how they fit today with the commissioning sectorization, along the arc and the long straight section.

Figure 6.7: The top schema shows the machine layout for the arc of sector 45. Below there is the original sectorization for some examples of equipment groups and equipment and how they fit with the LHC machine layout and the HC sectorization

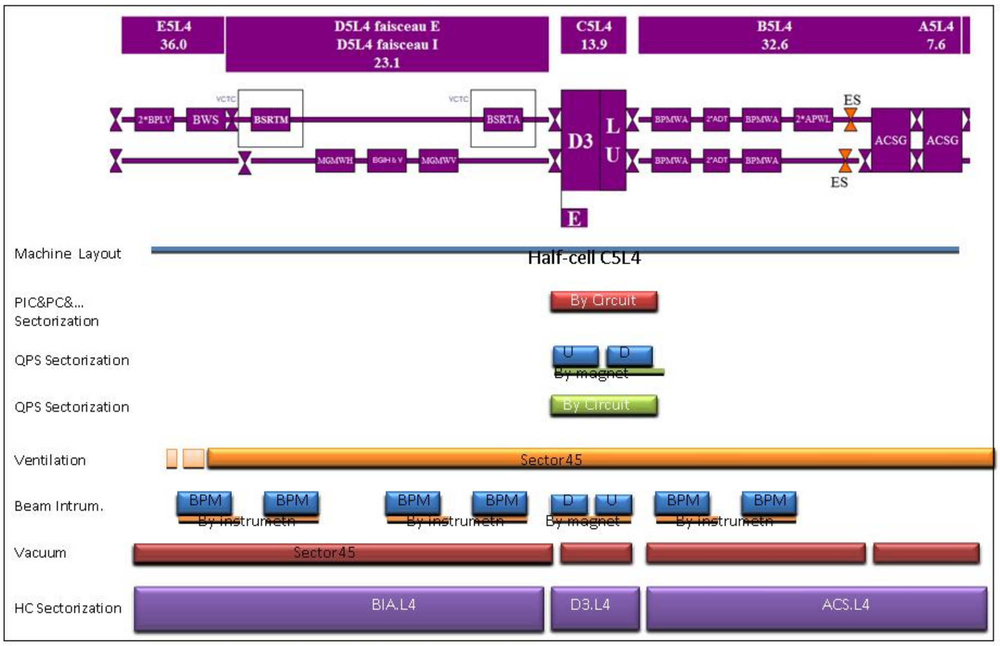


Figure 6.8: The top schema shows the machine layout for the long straight sections. Below there is the original sectorization for some examples of equipment groups and equipment and how they fit with the LHC machine layout and the HC sectorization

Chapter 7

Hardware Commissioning Manufacturing and Test Folders (HC MTF)

During the commissioning of the LHC technical systems [87] a large number of test sequences and procedures are applied to the different systems and components of the accelerator. All the information related to the coordination of the Hardware Commissioning (HC) is structured and managed towards the final objective of integrating all the data produced in the Hardware Commissioning Manufacturing and Test Folders (HC MTF) [88] at both equipment (i.e. individual system tests) and commissioning level (i.e. HC phase). The HC MTF is mainly used to archive the results of the tests (i.e. status, parameters and waveforms) which will be used later as reference during the operation with beam. It is a kind of "identity card". It is also an indispensable tool for monitoring the progress of the different tests and ensuring the proper follow-up of the procedures described in the engineering specifications; in this way, the quality assurance process will be completed. This section describes the specifications for the development of the MTF, their general structure, as well as the methodology used for their implementation in an optimal and reliable way.

7.1 HC MTF Design

The requirements

The required features in order to fulfil the objectives of the tool can be sub-divided into:

- Quality Assurance properties:
    1. Electronic implementation of all the specific steps to be followed during the tests, which strictly represents all the document plan described in Chapter 6.
    2. Data quality, for ensuring and maximizing the quality, utility and integrity of the data been stored.
- HC lifetime properties:
    1. Continuous monitoring of the advancement of the tests.
    2. Configuration database for parameters used during tests.
    3. Recording of the tests result parameters.
    4. Traceability to define the status of the HC Project.

- Future need properties:

  1. Repository of data that ensure perennity of the tests results.
  2. Creation of an "as built" database.
  3. Tools for analysis of results.
  4. Flexibility for the implementation of this tool in other projects.

After a deep study done "shoulder to shoulder" with the system owners in order to understand their needs (expectations and constrains), the result is a tool presently used by the systems during the commissioning. Moreover, the future use of this tool during operation is being considered (e.g. beam instrumentation).

We should start by defining some specific vocabulary used in this chapter:

Entities are the result of the classification for the HC arborescent nodes.

Slots are the specific arborescent structure nodes with an MTF attached.

Steps are the smallest units in a test composition.

Properties are the variables linked to the slots.

Profiles are the group of slots that follow the same specifications in terms of tests and properties.

Using as a case study one 60 A superconducting circuit, the name of the circuit will be an entity in the HC arborescence since it is represented by a node in the structure. The name of the circuit will be as well a slot since it has an MTF attached. In the MTF there will be a set of steps to follow and a list of properties both linked to the circuit name. And as a profile it will correspond to the 60 A circuits profile, meaning that it will have the same tests and properties as the rest of the 60 A circuits in the machine.

The architecture

Hanging from each node of the HC arborescence there is a MTF containing the data. The MTF application is an integral part of EDMS at CERN, and was developed to capture manufacturing and test information for the LHC Project to provide traceability of large quantities of complex parts manufactured in a world-wide geographically distributed environment.

A large development effort has been done to adapt the tool to the commissioning needs. There are two main HC MTF designs, one for the individual systems tests and one for the HC activities. They contain mainly parameters that come from the layout database and from measurements, tests (e.g. status, dates and results) and documents.

The general scheme of the combination of both the HC arborescence and HC MTF is showed in Figure 7.1. The rounded shapes represent the nodes classified by type and have been assigned with an unique ID. The squared shapes represent the MTFs containing all the information.

7.1.1 HC MTF Entities

The criterion that has been followed is based on the arborescence design. Let us recall now the two main needs geographic distribution and hardware functionality. Different MTFs patterns have been designed for the different entities:

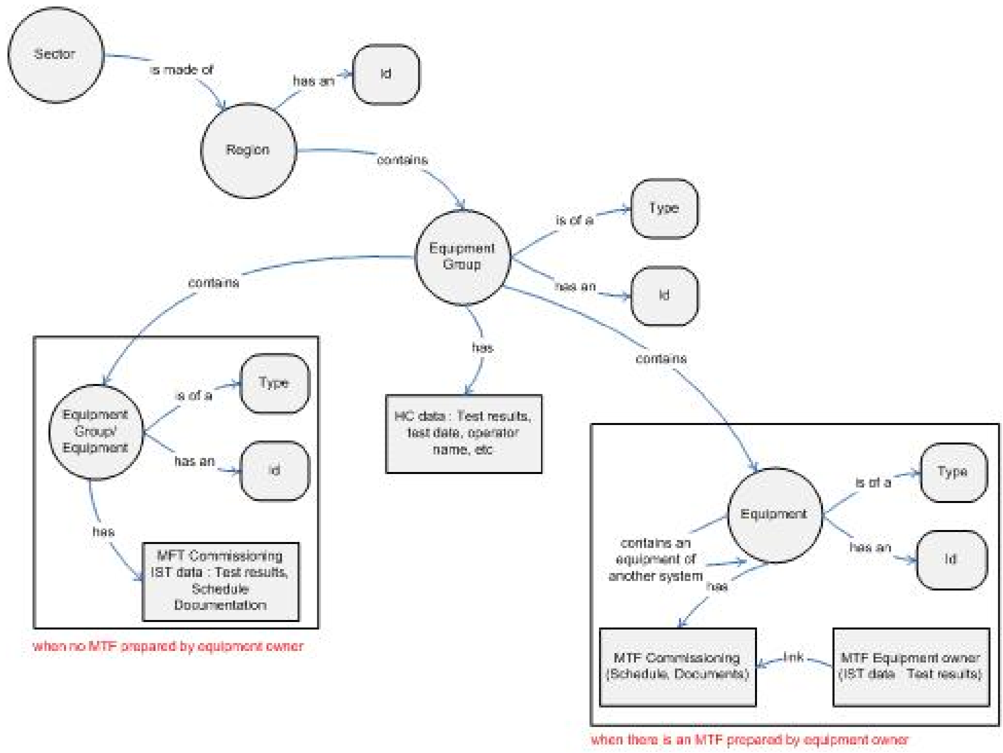


Figure 7.1: Breakdown of the machine into equipment and equipment groups, and associated documentation.

- Points and sectors
- Region
- Equipment group
- Equipment

Each of these four entities has a common first design pattern that will be individualized for each type.

Profiles

With the pattern designed in the sections above, the assignation of MTF to the different nodes can be done by groups, the so called profiles. In addition, the profiles will solve the requirements for the assignation of steps. The equipment belonging to an equipment group can have different requirements in terms of information needed or tests to be applied. To avoid the creation of an individual MTF for each equipment, profiles matching the different equipment types have been created and correspondingly assigned.

A total of 78 types of equipment and equipment groups (slots) have been identified. Each entity can have more than one profile depending on their needs in the classification of their equipment. Number of slots per profile already implemented in the HC MTF are represented in Figure 7.2 A total of 14.000 slots are represented in the arborescence. The largest number of slots correspond to the following equipment groups and equipment: beam instrumentation, power converters, electrical circuits and equipment related to circuits as e.g. the electrical quality assurance.

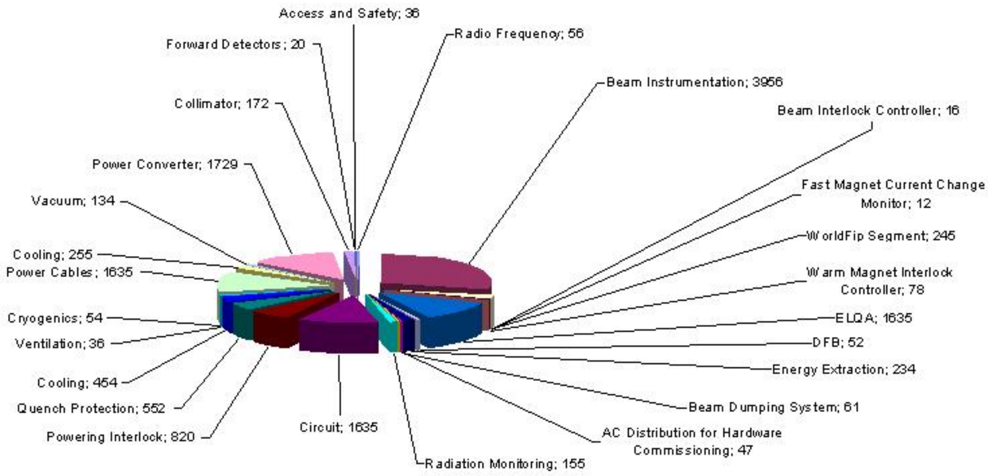


Figure 7.2: Distribution of slots by profile

The list of profile names and codes is detailed in Appendix D.

7.1.2 HC MTF Entries

A study has been done in order to define the type of information that may be useful and necessary to store to fulfill the HC needs.

After analysis of all these parameters, the amount of information by entity was so large that it was decided to create groups in order to homogenize the structure. This itemization has created a model to follow which helps to identify errors, missing data and to guarantee the understanding of the information that users from one specific equipment group could need from another.

For the HC Project this study ended in the following result: for each MTF entity, there are three types of information stored in the HC MTF. These three types correspond to three of the tabs that have been implemented in the MTF interface: Slot Data, Installation & Commissioning and Documents. Figure 7.3 shows an example.

The rest of tabs: Main, Operation and History are designed for the future use of the HC MTF during the operation of the machine.

The properties

Properties are applied to the slots and can also be linked to one or several steps. There are arborescent types of parameters that can be introduced:

- External Properties: these data come from other databases, as for instance the LHC Layout Database, or other systems databases. These values are used as references for the tests execution of the tests or as a key information source.

- Property Values: values used for tests or results from them.

- Parameters: values used to create a historical tracking.

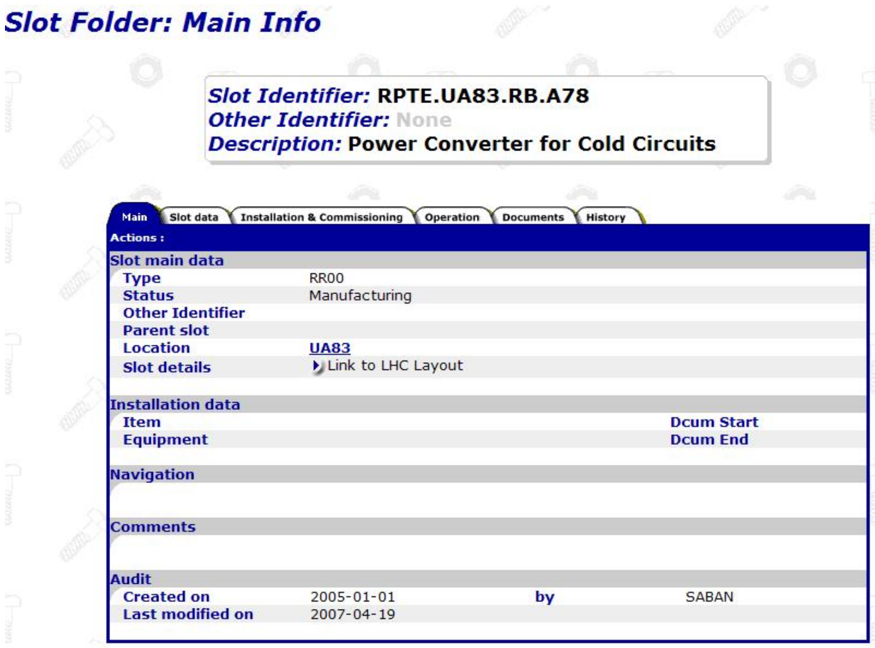


Figure 7.3: MTF interface corresponding to an slot of power converters in sector 78

The records come from the "as-design" Reference Database of the LHC and from test results that will be stored in the MTF database. In the future these data will be integrated in the "as-built" database as will be explained in Section 7.3.

Figure 7.4 shows an example of these properties already implemented in the HC MTF for a power converter.

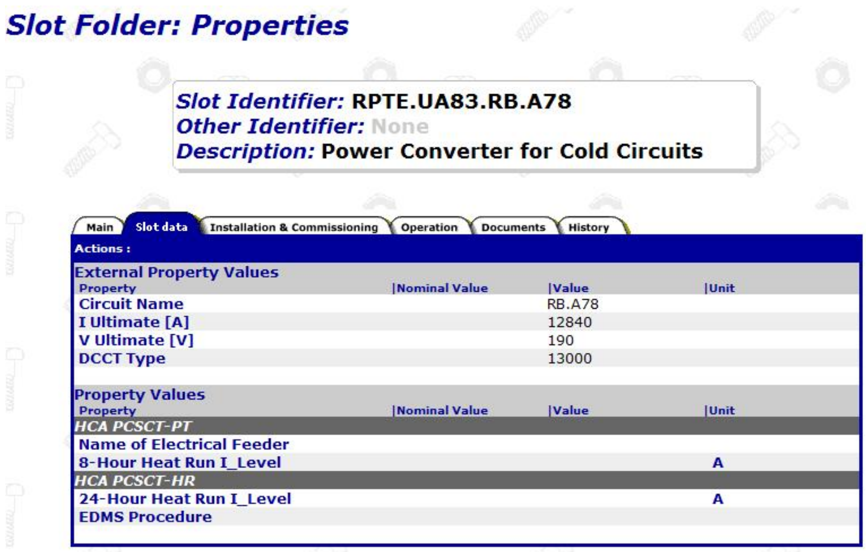


Figure 7.4: Properties tab from a power converter in sector 78

Hardware commissioning steps

This is the list of tests which will be carried out during the commissioning of the equipment and which are described in the approved procedures [82]. Every step in the HC MTF must have a corresponding step in the technical procedure applied.

Tracking has to be done through the history of the steps including repetitions, these are implemented with a label that identifies them as repeated steps. Figure 7.5 shows the list of steps in a slot with a repeated step.

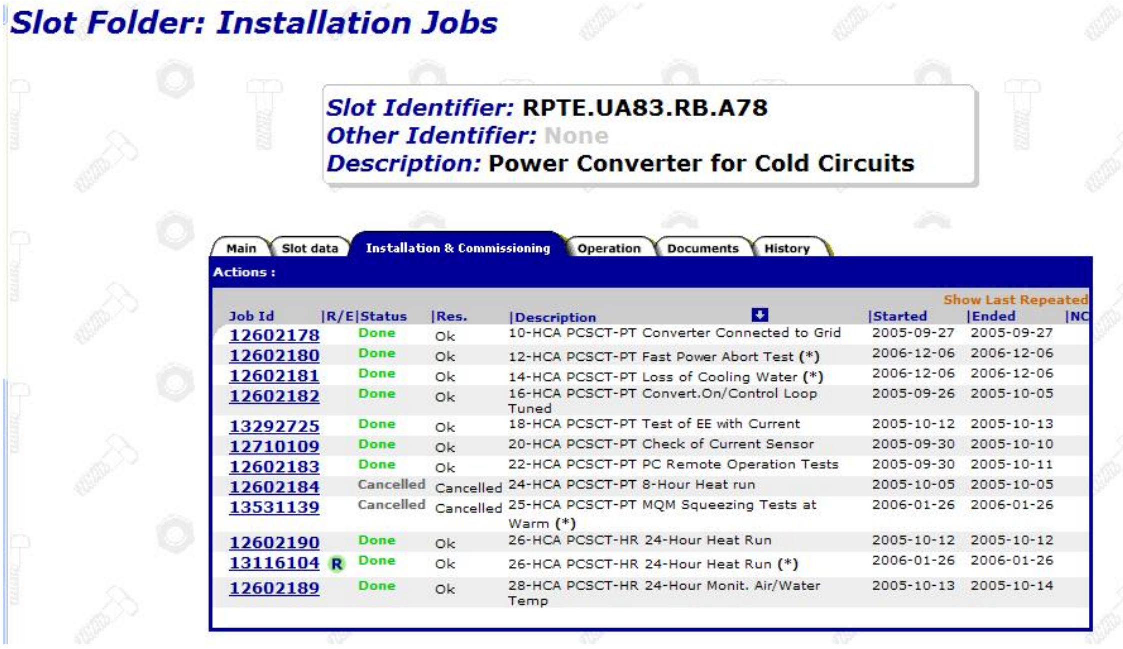


Figure 7.5: Step tab from a power converter of sector 78. Note that step 26 has been repeated

An example of the list of steps for a profile is given in Appendix D.

Documents & Non Conformities (NCRs)

This area covers the documents describing the equipment, the system, the individual system tests, the HC steps and the results. As a request from the users, in some cases a view from the MTF database is provided in order to open directly the documents from the web interface independently from the document format.

Everything meant to be stored in the HC MTF has to be properly documented and approved in order to assure quality. No exceptions have been done regarding this point. Every deviation from the specifications stored in the document plan (procedures, test conditions, tests results, etc.) has to be defined, stored, and if applies, resolved. HC MTF will be used, as well, to manage the non conformities. These will be attached to the entry they belongs to.

7.1.3 Types of HC MTF

The MTF has been adapted to the level of the structure to which it is linked.

MTF for a region

It contains a link to the approved schedule for the commissioning of the region showing the times allocated for each equipment group. It includes the status for each entry in the schedule containing the percentage completed, the person responsible and the documents and status of tests.

MTF for an equipment group

The MTF concerning an equipment group contains the information about the its HC activities. It includes reference parameters, results, the tests to be applied and their status with the date of execution and the person responsible, as well as the applicable reference documents.

MTF for an equipment

At the level of equipment we will find two different situations:

- In the first case, there are MTF data concerning the individual system tests introduced by the equipment owner. If so, the data will be automatically linked to the hardware commissioning MTF. It will have all the IST details (components, test parameters and test results).

- In the second case, there is no MTF defined by the equipment owners. The information about the IST will be just the status (i.e. ok, not ok, done, not done, who did it, when and the related non conformities) introduced directly in the commissioning MTF. This is the minimum information required in order to assure Quality Assurance in the project. This last option has been the most widely applied.

7.1.4 Implementation of the HC MTF: Grants

To assure the quality of the data stored in MTF, together with the correct use of this tool, a structure has been implemented to define access rights.

All the information that is stored in the HC database is actively accessed by all the implicated users. There are two types of owners, the equipment owner and the equipment group owners. The first group corresponds to the individual systems tests and the second to the HC activities. To assure security and reliability of the stored data different grants have been defined.

- Read rights: all the information is world public to facilitate its use during and after the HC.

- Write rights: each owner defines a list of people or users that are allowed to write information in the MTF belonging to them, always together with the HC coordination owner that will survey the correct use of the tool and guarantee its quality and availability.

The assignment can be done by profile or even increase the granularity inside the profile by changing rights inside depending on the field. For the correct functionality of the tool and analyzing the needs, managing of write and read access rights has to be done by entity: slots, profile, steps, properties and documents.

Slot level. A group (of persons) and a context (of rights) are defined at the slot level. Write access to slots is granted to all members of the group associated with the context of the slot.

Profile level. A default context is defined at the profile level. This profile context is used to restrict write access, the creation and closing of non conformities (NCRs) only to the users granted in the context.

Steps level. Due to the fact that some equipment owners wanted to differentiate access between steps, standard steps might have tasks associated to them. Tasks are used to restrict write access to step data and give authorization only to the users who are granted with the corresponding role in the context. In the absence of a task associated to the step, all users with write privileges in the context are authorized to edit the step.

Properties. For writing access to properties not belonging to any step, the user is required to have accordingly write access to the equipment. For writing access to properties associated to a step the step rules are applied. For writing access to the equipment in the absence of a role, the corresponding role in the equipment context is applied.

Documents level. Like for the properties, we can find documents related to a step or not. To attach documents or non-conformities not related to a step but to the slot, the user is required to have write access to the slot and read access to the document. When attaching documents or NCRs related to a step, the step rules are applied.

7.1.5 MTF Interfaces

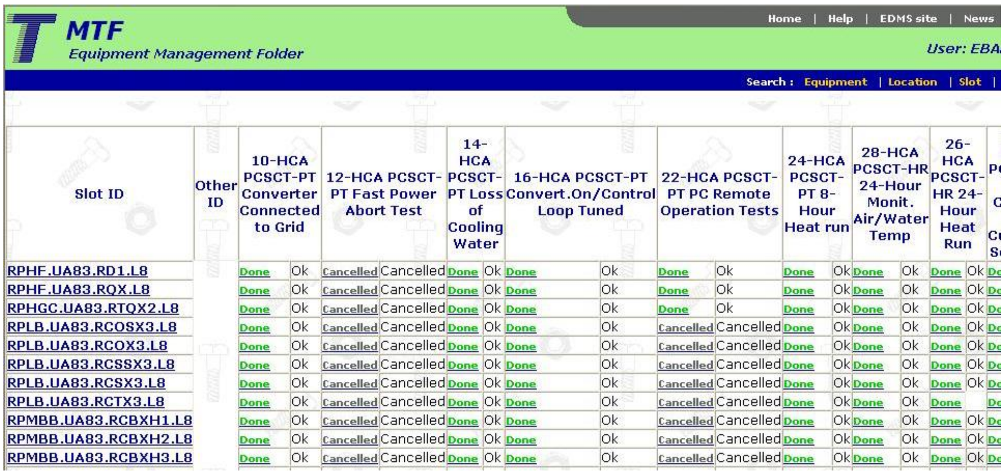
In order to improve the performance of the MTF from the user point of view, use cases have been carried out for identifying the different ways of interaction with MTF capabilities. Three different interfaces have been designed for the time being.

- Navigator (editable). The navigator consists in a clickable structure from which it is possible to access the MTF web page nodes directly.
- Parameter Reports (non editable). These are of two types by system or by sector. In order to have a view of the needed parameters defined by the users, an interface has been designed that reports on the chosen elements.
- Step report (non editable). These are also two types, that are by system or by sector. To fulfil the process tracking necessities, the step report shows the status of the tests and the non conformities of the chosen elements.

As the commissioning advances and new necessities appear, other interfaces can be created thanks to the flexibility of the system. Figure 7.6 shows one example of an interface already in used.

7.2 Filling up the Hardware Commissioning MTF

To cope with the users necessities, two kind of procedures have been designed to fill the HC MTF with all the required information [89]. These two procedures are explained below.



Slot ID	Other ID	10-HCA PCSCT-PT Converter Connected to Grid		12-HCA PCSCT-PT Fast Power Abort Test		14-HCA PCSCT-PT Loss of Cooling Water		16-HCA PCSCT-PT Convert.On/Control Loop Tuned		22-HCA PCSCT-PT PC Remote Operation Tests		24-HCA PCSCT-PT 8-Hour Heat run		28-HCA PCSCT-HR 24-Hour Monit. Air/Water Temp		26-HCA PCSCT-HR 24-Hour Heat Run	
RPHF.UA83.RD1.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok	Done	Ok	Done	Ok	Done	Ok
RPHF.UA83.RQX.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok	Done	Ok	Done	Ok	Done	Ok
RPHGC.UA83.RTQX2.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok	Done	Ok	Done	Ok	Done	Ok
RPLB.UA83.RCOSX3.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok
RPLB.UA83.RCOX3.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok
RPLB.UA83.RCSSX3.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok
RPLB.UA83.RCSX3.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok
RPLB.UA83.RCTX3.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	
RPMBB.UA83.RCBXH1.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok
RPMBB.UA83.RCBXH2.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok
RPMBB.UA83.RCBXH3.L8		Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Cancelled	Cancelled	Done	Ok	Done	Ok	Done	Ok

Figure 7.6: Step report for the short circuit tests of some power converter in sector 78 (Data from January 2008)

Online storing: Manual

All the information generated by the tests can be introduced through a webpage interface or by editing and updating the interfaces explained in Section 7.1.2. This method has been implemented to have readily available the information which is required as validation in order to continue the tests, online, at the same moment that it is obtained. This made reference to the steps dependencies and is needed not to slow down the advancement of the tests.

Quasi on-line, automatic storing of data

In order to upload big amounts of data coming from steps or parameters which are not needed in real time, a procedure has been created. All test results are homogenized in one kind of file that contains the result of the test (i.e. done, ok, not ok), the name of the operator performing the test, the date and the resulting files (i.e. diary file and an analysis file) as well as any other desirable information. This is an XML [90] file that will be the bridge between the system results formats and the input for the upload of information to MTF.

To improve this automatic system, different actions have been asked to the different actors, and are already implemented:

By the users. For some systems (the most complex ones) a script has been created and added at the end of the software application used to run the equipment under test. Depending on the test results, the script produces a XML file. This report is automatically sent by the software application for its update.

By the maintainer group of MTF. Maintainers have all the information, which is coded in an XML file and stored in a determined directory called "inboxes". A process has been developed allowing to browse through the inboxes and create import requests into the EDMS, through a document that will directly access MTF. If the content of the inbox is a file, it is simply uploaded into the EDMS document. If it is a directory, all the XML files that are in it are concatenated into one file which is uploaded into the EDMS document.

By the coordination team. To facilitate the production of the XML files (in principle the only compulsory condition imposed for the upload of results) a web page (see Figure 7.7) assists the coordinators in the production of the XML file.

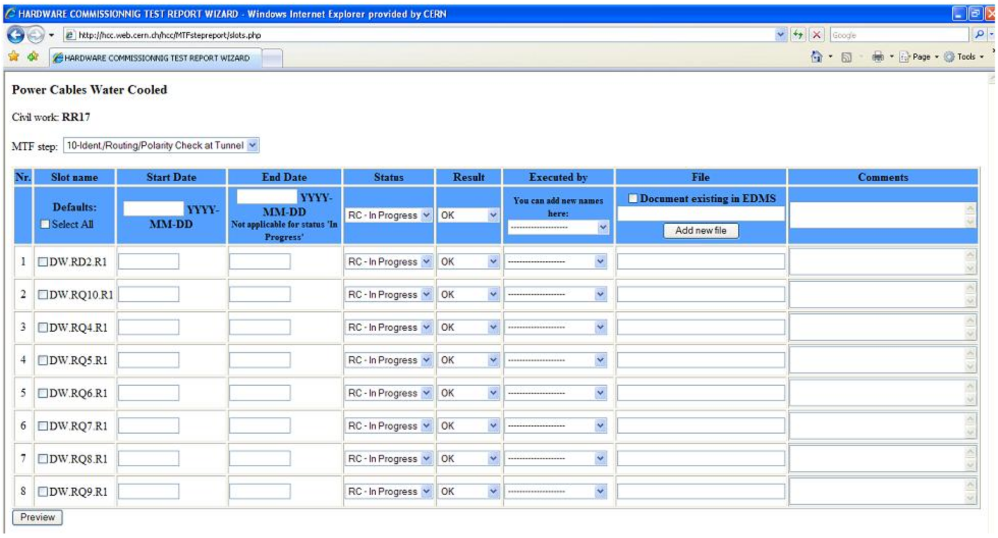


Figure 7.7: Web interface for the automatic creation of the xml file for the water cooled power cables placed in the underground area RR17

The result process is represented in Figure 7.8, where the "ad hoc" tools created to increase the automatization of the process are represented in red and the inputs and outputs in grey.

7.3 Databases

The project works with existing databases that in the future are going to change, evolve and increase. Perfect control of both states, before and after the project, is very important for its integration in the project portfolio where it belongs and in future projects.

7.3.1 As designed: LHC Layout Database

When the LHC Project entered its phase of integration and installation with thousands of diverse components, collecting and distributing reliable and coherent information of the equipment and their layout became a crucial must in the lifecycle of the project. Existing database tools had to evolve to a more generic model to cover not only the acceleration optical layout, but also mainly the mechanical and electrical aspects.

7.3.2 As built: Production Database

Once the design and installation phases are finished, a new database has to be created containing all the acquired knowledge. All the contract changes due to specification changes, design errors or technical problems will contribute to the creation of the new database. In the case of the LHC Project, the different sub-projects which have been executed will contribute to the creation of the as-built database. In this exercise, all the equipment group databases, the equipment production

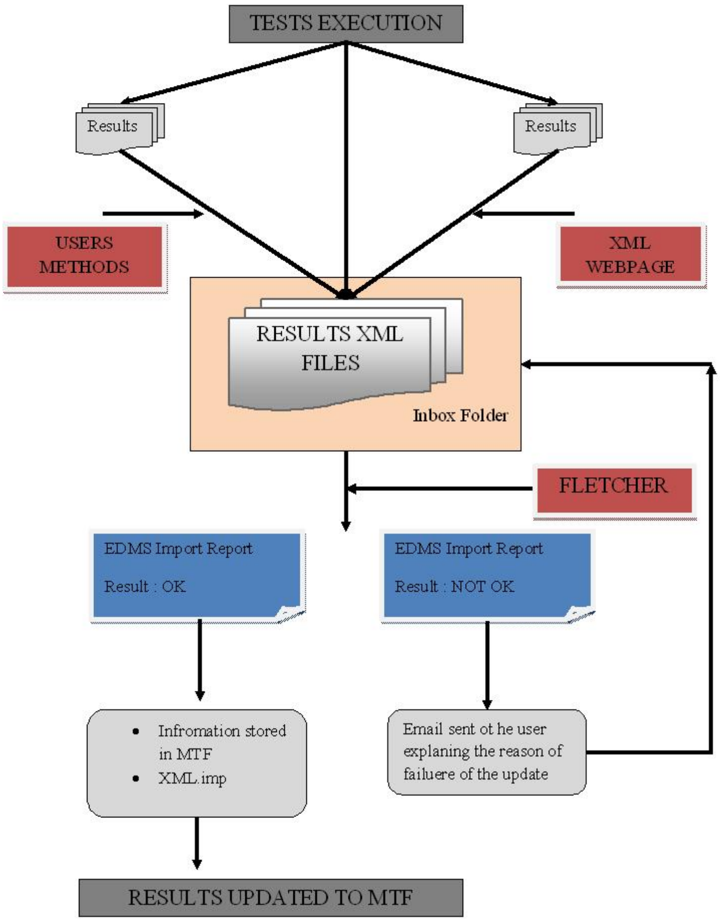


Figure 7.8: Workflow of the automatic data capture in MTF

MTF, the integration databases and the HC MTF will participate. The HC Project management assures the optimal coordination towards its final completion. The HC MTF has been of course designed taking this strategic objective into account.

7.4 Highlights on the HC MTF

Some statistics on the number of systems steps, stored information, etc. are presented in this Section. The results can be divided in two groups i.e. the HC period results and the long term period results. As short term result, there is a database that has been created for the HC in order to automatize tests. The HC database includes parameters (e.g. di/dt,R,L,load parameters) that are used for the tests. Some of these parameters are calculated (phase i) in the different phases of the project, re-measured (phase i+1) and used (phase i+2). A track of these parameters must be stored in MTF. One of the uses of the HC MTF is as a green light to execute the tests. For instance, for the superconducting circuits, the start of the powering in one circuit can only executed when the first step defined in MTF for this circuits has been set in a DONE and OK state (Chapter 8 gives a wider explanation of this).

At a long term vision, it has been planned that tools should to be fully operational and performing for the HC Project but as well for future stages of the project. Indeed, the idea of using it during the operation of the machine is already taking shape. Some systems have already started to store parameters that are prone to be used during the operation with beam.

HC MTF is as well the source of information for other tools used for operation and monitoring as for instance the LHC Software Aplications database which feeds the control software used for the execution of the tests [91].

Implementation results

The results of the implementation of the tool give a clear picture of the distribution of steps and properties. We will present the total number of steps introduced by the systems, the total number of parameters defined, and the related documents.

The steps. Figure 7.9 shows the number of steps per system (slot). Individual profiles can range from 1 to 100 steps. The systems that are traced in more detail are superconducting circuits, RF, beam dumping system and power converters.

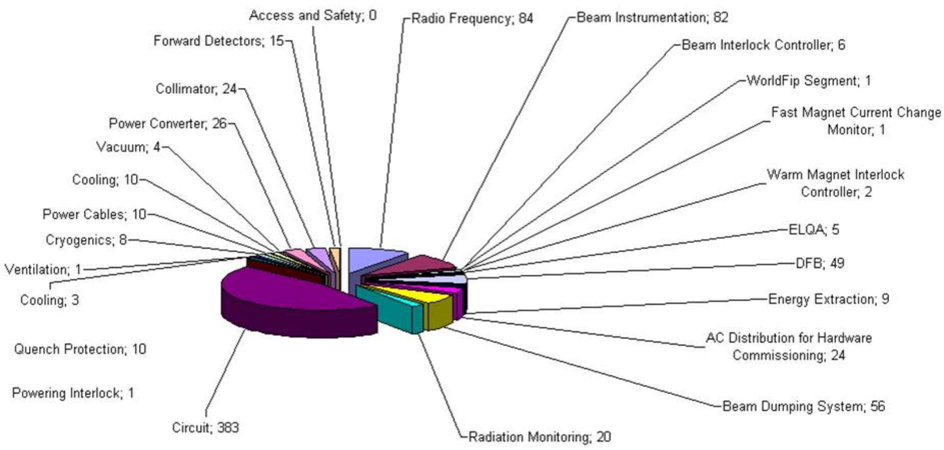


Figure 7.9: Statistics on the number of steps by equipment group (January 2008)

Figure 7.10 is showing the total number of steps (step per number of slots, see Section 6.4) amounting to a total of around of 116000 entries.

The properties. Individual profiles store between 1 (e.g. EDMS Procedure) and 60 parameters. The classes tracking the most parameters are circuits, energy extraction and beam instrumentation. Figure 7.11 shows the number of properties per system (slot).

Quality of data

Another objective of this tool was to assure the quality of the data to guarantee the performance needed to fulfill the project objectives. Different indicators show the result from the data quality tracking:

- The repeated steps show the search for of the good results (the systems are complex and need tunning so, iterations are needed to obtain good results). Some examples: 10-30% repeated entries SC circuits, 16-20 % repeated entries for PC, 5% repeated entries WorldFip, Cooling and 5% for other classes.

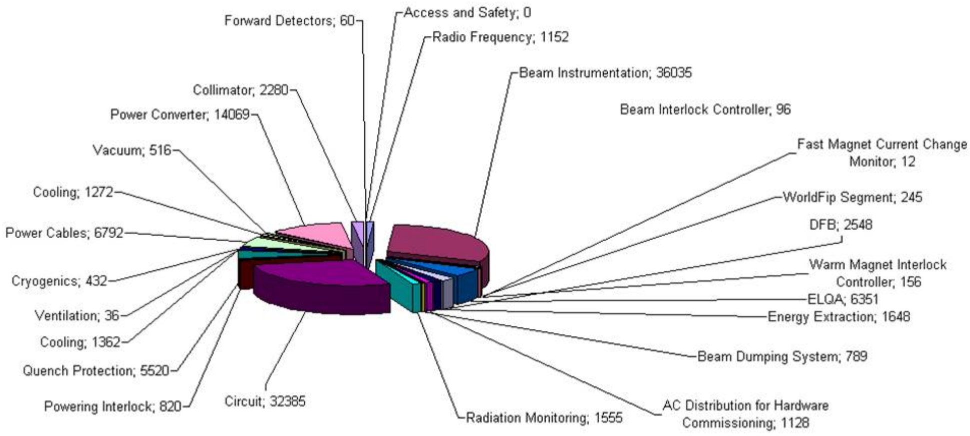


Figure 7.10: Statistics on the total number of steps by equipment group (January 2008)

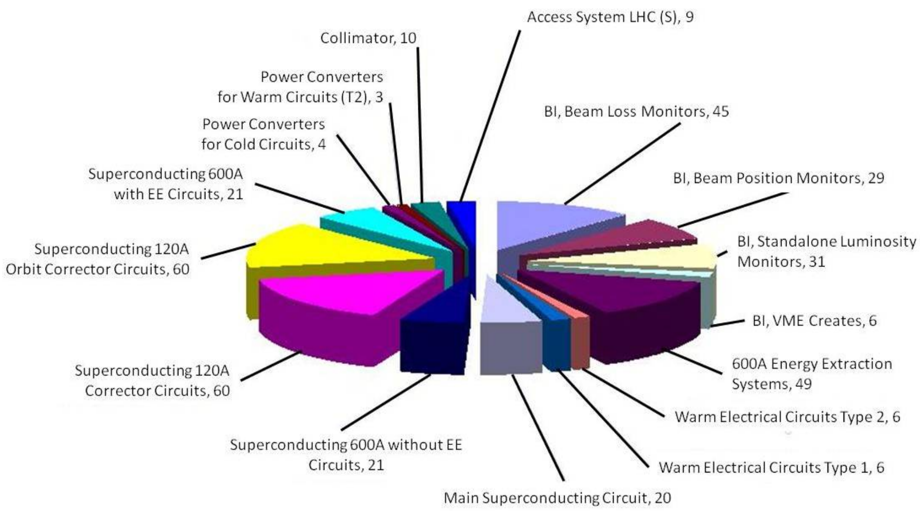


Figure 7.11: Statistics on the number of properties by equipment group (January 2008)

- Documents stored mainly include engineering specifications and tests results coming directly from the control software executing the tests. See Table 7.1

- Non-conformities (NCRs). Non-conformities are an easy and visible flag to point out to possible problems. This is particularly interesting during the HC to detect if systems have any limitation during its commissioning. this is a reliable piece of information to be passed on to the responsible of machine operation with beam

  In the January 2008, 249 non-conformities had been linked to the HC MTF slots or steps.

Profile Name	**Code**	**% entries**
Cryogenics	RC11	3
Quench Protection	RC08	3
System d' acces LHC	Y001	5
Powering Interlock	RC07	7
BI Synchrotron Radiation Telescope	BSRT	13
Radiation Monitoring - Standard RP	PM01	19
Radiation Monitoring Air, Water, Standalone	PM02	25
Power Converter for 60 A Orbit Correctors	RPLA	32
Power Converter for Warm Circuits (T2)	RW00	35
Power Converter for Cold Circuits	RR00	41
Warm Electrical Circuit Type 2	RC00	46
600 A Energy Extraction System	DQE1	48
Warm Electrical Circuit Type 1	RC01	50
Inner Triplets/Individually Powered Quadruples/Dipoles Circuit	RC18	69
Individually Powered Dipole Circuit	RC21	73
SC 600 A Without EE Circuit	RC03	74
Superconducting 600 A Without EE With Crowbar Circuit	RC17	76
Superconducting 120 A Correctors Circuit	RC04	79
13 kA Energy Extraction System	DQE2	86
Superconducting 600 A With EE Circuit	RC06	86
Main Superconducting Circuit	RC02	97
WorldFip Segment	CBW1	99
ELQA for Warm Circuits	DE01	100
Superconducting 60 A Orbit Correctors Circuit	RC05	100

Table 7.1: List of Percent of entries with documents by system (January 2008)

Most of these came from the 600 A energy extraction system and from the electrical quality assurance for cold circuits; some are related to the power converter for cold circuits, other to beam instrumentation.

The coherence between the LHC Layout Database (LDB) and the HC MTF is guaranteed via a direct link between them (See Figure 7.12) and is continuously checked and monitored through an interface.

Uploaded data

Up to the January 2008 nearly 30000 entries have been uploaded, which means that about 25% of the database volume is filled. The accumulated entries by class are showed in Figure 7.13. The average upload per month is about 1200 entries.

Tracking results

The HC MTF tool shows tracking of advancement of works as each action is recorded and quantified. A visual interface has been created by the hardware commissioning coordination team to have

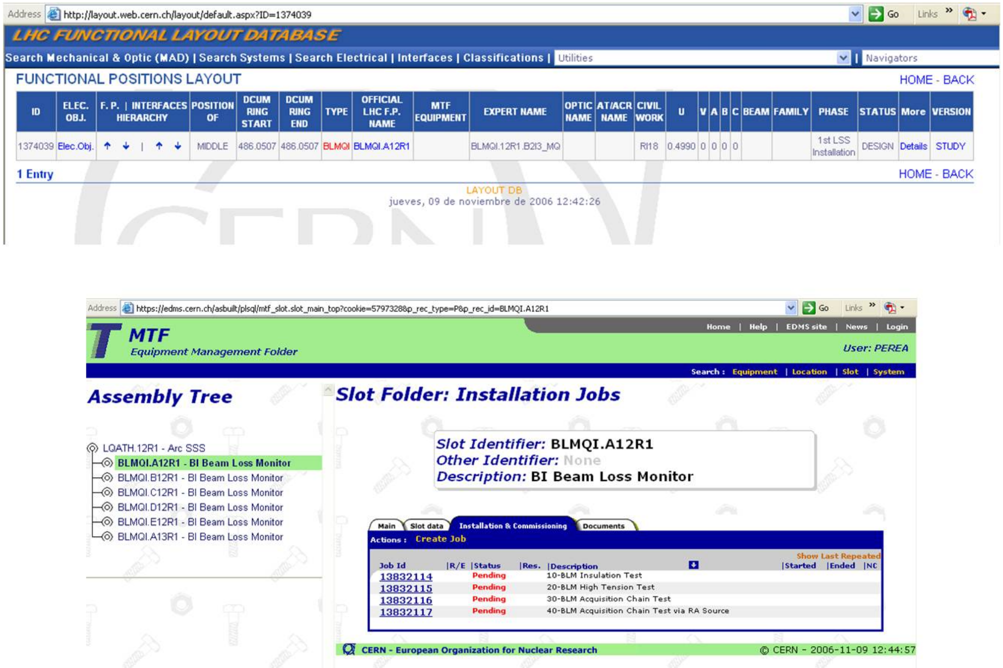


Figure 7.12: Interfaces from the LDB and the HC MTF, showing the same ID used in one element stored in both tools

an over view of the advancement of the project in the whole machine by extracting the information from the HC MTF.

Thanks to the defined structure, the tracking can be done geographically (see Figure 7.14) or by functional equipment groups and equipment (see Figure 7.15). In this way both, the project manager and the equipment groups owners, can track the evolution of the whole project and of a single equipment group. The HC MTF tool helps to better control the project or and provides the right information to the management to minimize undesired consequences when taking corrective actions.

Each system has expressed its preferences for the way data should be graphically displayed. Most of the systems that are distributed along the LHC ring have kept a geographical layout while systems like the radio frequency or the beam dumping systems have very specific and functionally-based views, as seen in Figure 7.16.

Tests Execution Tool

Last but not least, the HC MTF is being used as green light for the execution of tests following a sequence, where each test depends on the completion of the previous one. This utility is widely explained in Chapter 8.

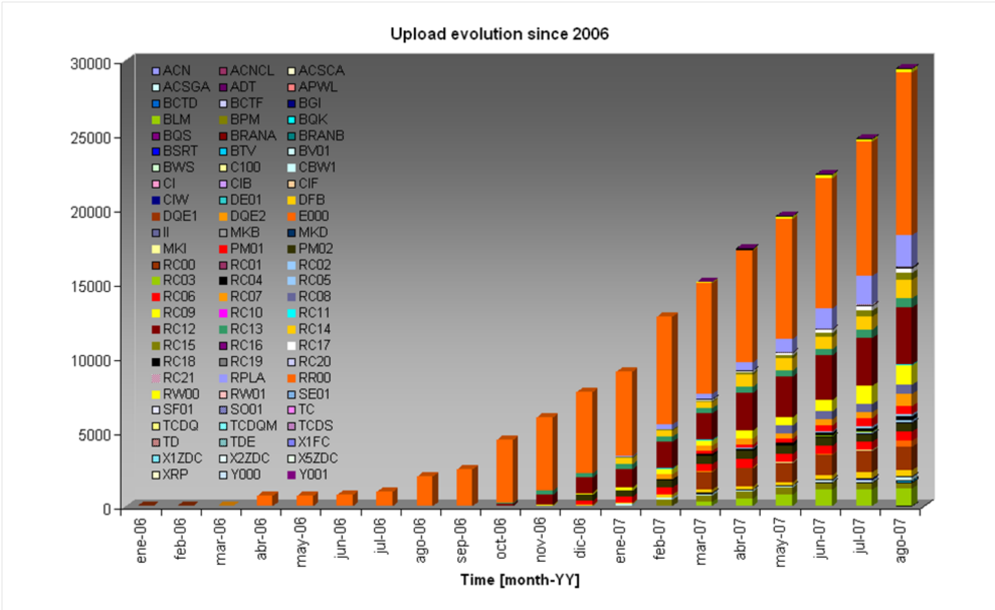


Figure 7.13: HC MTF accumulated entries upload evolution since 2006. In January 2008 about 25% of the database is filled.

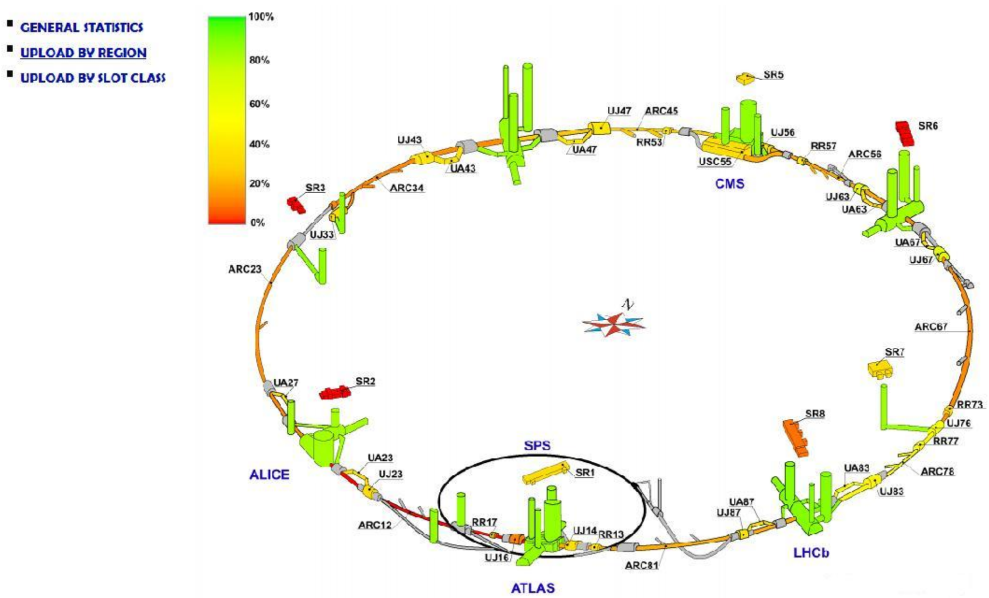


Figure 7.14: Tracking of the advancement of the project in a geographical view for a given date in this case January 2008

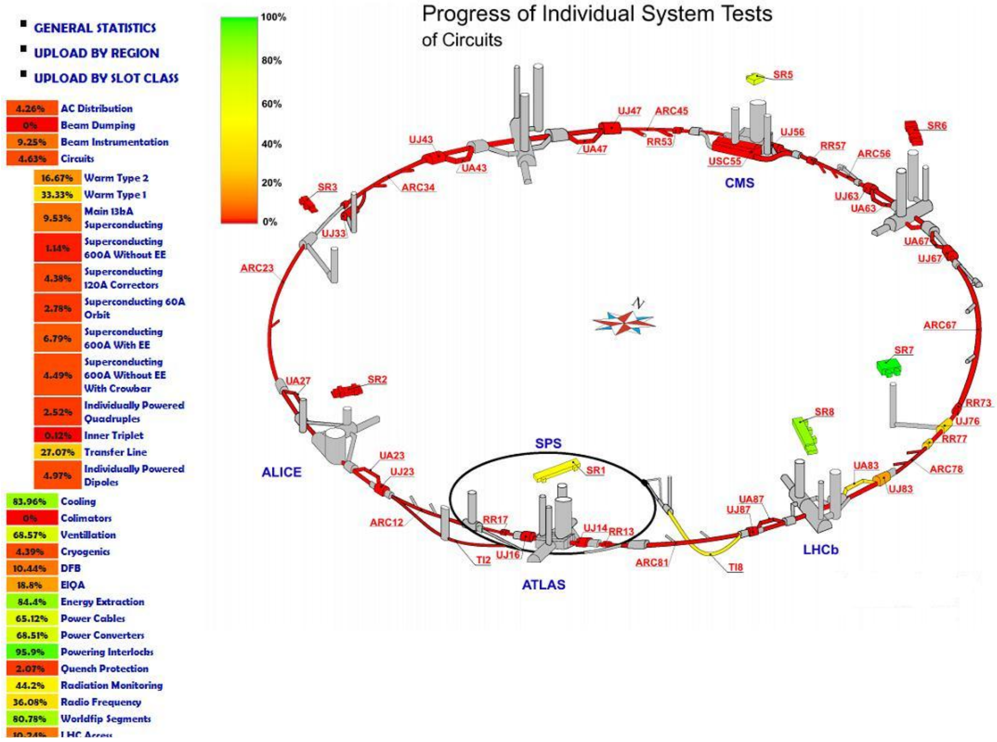


Figure 7.15: Tracking of the advancement of the project for one specific equipment group: circuits for a given date in this case January 2008

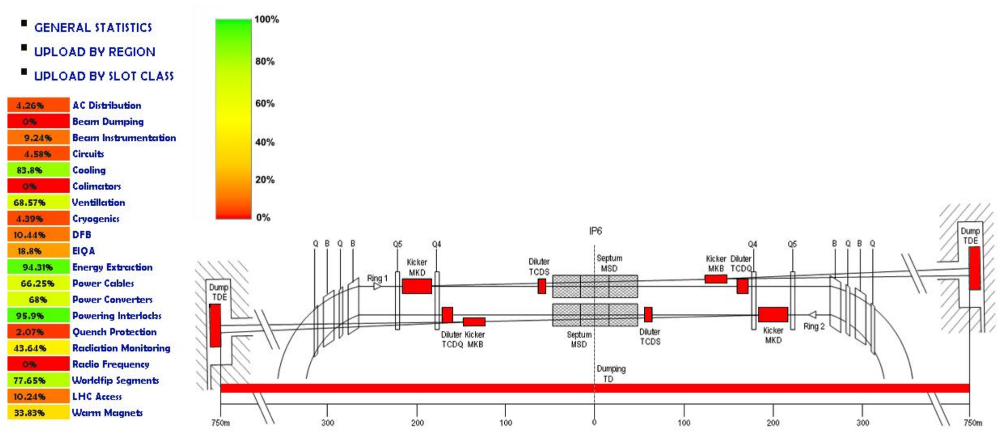


Figure 7.16: HC Interface for the Beam Dumping System, enhancing the functional link between the different components

Chapter 8

The Results for an Equipment Group: Superconducting Circuits and Their Commissioning

Due to its volume and complexity, the superconducting circuits (SC) form the equipment group to which most time and effort is devoted during the LHC hardware commissioning (HC) phase. Therefore, this is the system which has gone through the finest study and has had a major impact on the developed tools.

The main points taken into account for the design of the HC strategy for the superconducting circuits have been:

- Definition of all the equipment that has to be successfully commissioned in order to consider the superconducting circuits of the LHC commissioned (i.e. ready to fulfill operation requirements).

- Definition of a HC circuit classification as the "minimum common multiple" for all the equipment composing the equipment group. These new circuit types have been defined towards a as simple homogenization as possible of the equipment. All the systems involved in the commissioning of the circuits use this definition to communicate between them and with the group of experts (i.e. MPP for Magnet Performance Panel created to help on the definition of the standard powering procedures).

- Identification of the tests and their sequence: once they were standardized and approved have been implemented in the HC MTF to assure the quality of the tests.

- Creation of groups of tests (profiles) by circuit type in order to homogenize the tests under a structure with a conformable flexibility for the changes and adaptations. Instead of having a group of tests for each circuit a group of tests by circuit type has been defined. There are 8 types of superconducting circuits for a total number of 1564 cold circuits [60].

8.1 Equipment Group Definitions and Modeling

The SC equipment group is composed by the following equipment (see Section 3.2.11):

- Power Converters (PC)

- Powering Interlock Controller (PIC)
- Quench Protection System (QPS)
- Energy Extraction (EE)
- Electrical Quality Assurance (ElQA)

All of these systems have been identified as a potential part of each circuit type. The different combinations of these equipment (as for instance with or without EE) and their characteristics is what explains the 8 circuit types. Figure 8.1 shows the scheme of the integration of these equipment in the arc. The quench heaters are distributed all along the arc, and the circuit cables pass through the continuous cryostat till the DFB. Once in the DFB, the conductor passes from cryogenic temperature to ambient temperature via the current leads. Once the cables are at normal temperature they go to the energy extraction system (if the type of circuit has one) or directly to the power converters that are feeding the circuit. The PIC is the master element controlling when and when not the string of magnets can be powered.

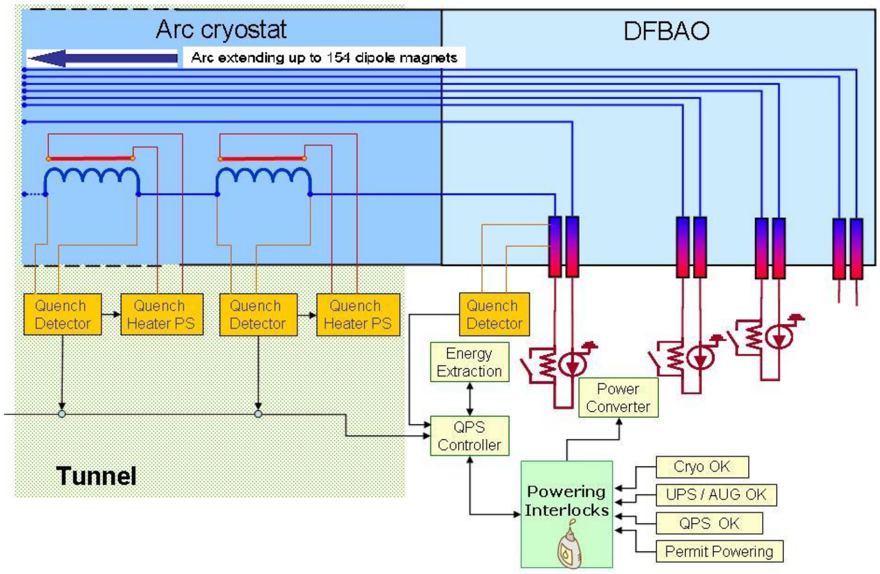


Figure 8.1: Scheme showing the equipment composing the superconducting circuits equipment group

8.2 Hardware Commissioning Circuit Types

In the beginning, every equipment which is part of the superconducting circuits equipment group had applied its own classification of the circuits. The power interlock system (PIC) has divided the circuits in type A, B1, B2, C, D, depending on the electronics interface to the controller; the power converter system used 5 different types based on the type of power converter and does not match the classification of PIC; the QPS had also define different types for the circuits. The necessity of a common classification is therefore obvious. The new groups are based on the type of global protection and the circuit current.

As a result the HC circuit types have been defined as follows:

- **13 kA Main Circuit**: main dipoles and main quadrupole circuits, with individual quench heaters and global bus detection energy extraction.
- **IP Dipoles**: individually powered dipoles with quench heaters and without energy extraction.
- **IP Quad**: individually powered quadrupoles with quench heaters and without energy extraction.
- **600 A EE**: 600 A corrector circuits with external energy extraction.
- **600 A EE Crowbar**: 600 A corrector circuits with energy extraction in the converter.
- **600 A no EE**: 600 A corrector circuits without energy extraction.
- **80-120 A**: 80-120 A corrector circuits.
- **60 A**: 60 A closed orbit corrector circuit.

The two tables below give the inventory of all the superconducting circuits of the LHC by circuit type. Table 8.1 contains all the circuits powered from the service areas situated at the extremities of the arcs, while Table 8.2 contains the orbit corrector circuits which are powered by converters situated below the central dipole of each cell and connected directly to the adjacent short straight sections. The majority of the circuits in Table 8.1 are powered via the DFBs; only the 80-120 A correctors are powered via the current leads in the short straight sections.

Circuit Type	Sector								LHC
	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-1	
13 kA Main	3	3	3	3	3	3	3	3	24
Individually Powered Dipoles	3	2	2	3	1	0	2	3	16
Individually Powered Quadrupoles	14	7	6	13	12	5	7	14	78
600 A with Energy Extraction	23	27	28	24	23	27	27	23	202
600 A Energy Extraction in Converter	14	20	20	14	14	20	20	14	136
600 A no Energy Extraction	16	9	2	9	9	2	9	16	72
80-120 A Correctors	50	37	22	33	33	22	37	50	284
TOTAL	123	105	83	99	95	79	105	123	812

Table 8.1: Circuits powered from the service areas in the arc extremities

Circuit Type	Sector								LHC
	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-1	
60 A Closed Orbit Correctors	94	94	94	94	94	94	94	94	752

Table 8.2: Circuits powered from the arc

8.3 Commissioning Procedures of Equipment and Equipment Groups

The purpose of the powering commissioning procedures [92] is to establish a baseline of the tests that lead to the commissioning of the electrical circuits of each sector. These tests have been defined and described in detail, each one has been divided in smaller parts called steps. A test is therefore formed by a group of steps.

The sequence and tests

The sequence is constituted by two sets of tests:

- those which are carried-out with the magnets not connected to the power converters,
- those which are carried-out with the magnets connected to the power converters.

During the first set of tests, a number of activities are carried out independently for every equipment type: the individual system tests (IST). Other activities, called Hardware Commissioning Activities (HCA), require the collaboration between system specialists (see Chapter 3). In general, the execution of the procedures in the second part requires the collaboration of all the system specialists. Figure 8.2 translates these principles into a graph indicating the different phases to be encountered during the commissioning of the superconducting circuits. The scheme only contains tests or activities pertaining to the electrical systems or their controls. Some others are not included like the connection of the power cables to the DFB leads, which nevertheless constitutes another HCA since several groups are involved, and defined sequences and procedures are to be respected.

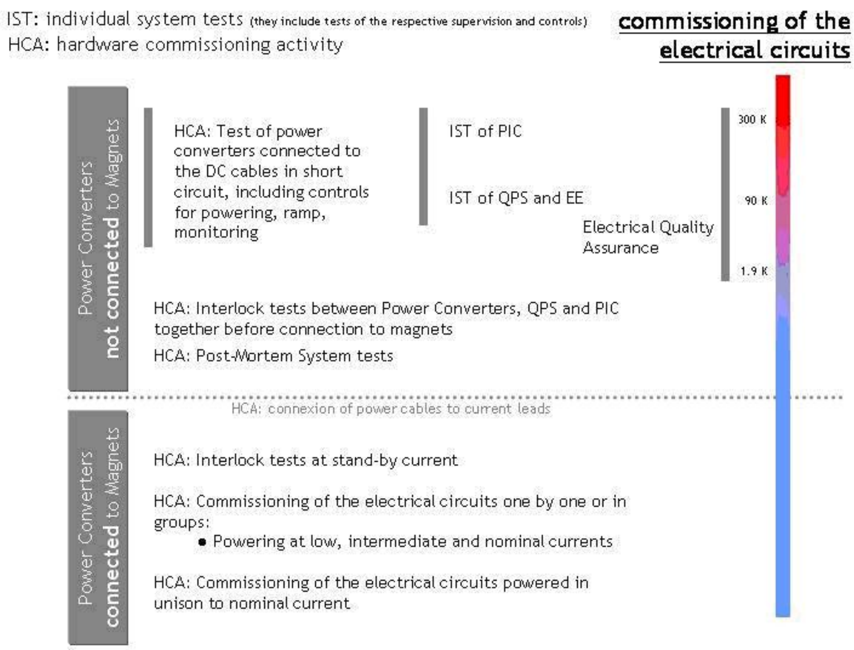


Figure 8.2: The phases during the commissioning of the electrical circuits

Tests with magnets not connected to the power converters

For this part, the following conditions must be present:

1. All the DC cables are connected to the power converters.

2. All the power converter outputs are short-circuited at the magnet end of the DC cables and the DC cables are not connected to the current leads thus isolating the power converters from the magnets.

3. For the individual tests of the power converters and the powering interlock system the magnets are not required to be at nominal temperature. However, the Electrical Quality Assurance of the magnets requires measurements at warm and during cool-down.

4. In case of the main bending and quadrupole circuits, the interlock system and part of the quench protection system (energy extraction) are connected to the power converters.

The main group of steps are:

IST:QPS - Individual system tests of the quench protection system

The objectives of theses tests, which have been already introduced in Section 3.2, are [65]:
- the verification of the correct installation of all quench protection equipment with respect to the corresponding implementation schemes;
- the commissioning of the QPS supervision system and all quench detectors;
- to test the QPS quench loops, which are internal to this system [61];
- to assure the adequate functionality level of the QPS equipment for the powering tests.

IST:EE - Individual system tests of the energy extraction system

Two types of circuits have to go through these tests: the 13 kA circuits and some of the 600 A circuits. The objectives of the tests [64] for the 32 extraction facilities of the 24, 13 kA circuits are:
- to check that the basic electrical, mechanical and hydraulic parameters of each system have not changed since global system tests were performed at IHEP (Russia) prior to delivery and installation in the LHC;
- to verify the local infrastructure, required for operating the EE facilities, once connections to the equipment are established;
- to perform functional tests of the complete facility;
- to commission the supervision system of each facility;
- to commission the DQR cooling stations (only for the sixteen dipole facilities);
- to verify the adequate activation of the internal fault signals.

The objectives of the tests for the two hundred and two extraction facilities of the 600 A circuits:
- to verify that the already fully tested systems are installed and connected correctly;
- to verify that the UPS, the controls infrastructure, the fast power abort loop and the local control loop to the power converter of the same circuit are connected correctly and operating correctly with the EE facility;
- to perform functional tests of the complete system. This includes also the commissioning of the link to the power converter;
- to commission the supervision system of each extraction facility and to verify the adequate activation of the internal fault signals.

IST:PIC - Individual system tests of the powering interlock system

The 36 powering interlock controllers which will be deployed for the protection of the electrical circuits powering the superconducting magnets will be tested in stand-alone mode before their connection to the quench protection system and to the power converters. All the hardware and software functionalities of the controllers will be tested on the surface. After their transport to the tunnel the controllers will be tested with a dedicated test system, emulating every cable which will be later connected to the interlock controller.

The objectives of these tests [93] are:

- the verification of the correct functioning of each powering interlock controller before its connection to the power converters and the QPS in the tunnel;

- the preparation and later commissioning of the interfaces for the short circuit tests of the main dipole and quadrupole circuits, including the energy extraction systems

- to commission the supervision system of each powering interlock controller.

IST:ELQA - Electrical quality assurance

The objectives of these tests [66] are:

- to electrically qualify each superconducting electrical circuit, including the current leads, at warm, during the cool-down and at nominal operating conditions;

- to measure electrical parameters of each superconducting electrical circuit for defining reference values for the machine operation

- to verify the integrity of instrumentation for the protection of the superconducting magnets, electrical circuits and current leads.

These IST are carried out in three phases of the commissioning: at warm, during the cool down and at nominal cryogenic conditions.

HCA:SC - Short Circuit Tests of Power Converters

These tests [57] have been widely explained in Section 3.2.7. The objectives are to verify:

- correct performance of all the power converters after their installation;

- the hardwired communication between the PICs and the power converters for the 13 kA circuits; commissioning of the local and remote control of the power converters;

- the reliable setting and monitoring of circuit currents by the control system; the cooling of the power converters and of the DC water cables when operating over representative durations (8 hours heat run tests);

- the global cooling of the warm powering part (power converter, DC cables and discharge system) when all circuits are at nominal current (24 hours heat run tests with all power converters at nominal current).

HCA:PIC1 - Interlock tests with the power converters in short circuit

Once the independent qualification and electrical quality assurance of both the resistive and superconducting parts of the electrical circuits are completed, the powering interlock system is commissioned together with the quench protection system and the power converters.

The magnet string has to be at its required nominal operating temperature for a correct functioning of the QPS. The functionality of the powering interlock system is independent from the current in the magnets, the tests will therefore be performed at zero or very low current. All the interfaces between the powering interlock controller, the quench protection systems and the power converters have to be in place and working. The actions which need to be undertaken (e.g. quench, internal faults of the different systems provoking abort, etc.) by these systems will be completely checked under the different abort scenarios.

The objectives of these tests [63] are: to commission the protection functionalities of the powering interlock controllers and all the connected systems; to verify the correctness of cable installations for the exchange of protection signals between the implied systems; to define the arming sequences in detail with respect to the intervening systems and to commission the additional protection interfaces with the AUG and UPS and the link with the beam interlock controllers.

HCA:PM - Post mortem tests

In the event of a fault occurring during the operation of the superconducting circuits it will be essential to collect and archive information from several accelerator systems. This responsibility is assigned to the post mortem system which will be tested before connecting the power converters to the magnets.

The objectives of these tests [94] are to verify: the correct triggering of the data collection; the reliable transmission of the data to the archive; the correct time stamping of the data.

The power converters, quench protection and energy extraction electronics and the powering interlock controllers will independently initiate the transfer of post mortem data to the archive (self-triggering). In addition, the power converters must respond to a post mortem data request from the timing system.

Tests with magnets connected to the power converters

After the circuits have undergone successfully all the tests enumerated in the previous section, the short circuit in the output of the converter is removed and the DC cables connected to the current leads.

For this phase, all the components of the circuit (e.g. magnets, bus-bars, current leads, etc) are required to be in the nominal operating configuration (e.g. connections, settings, etc.) and at nominal cryogenic conditions.

Each system can be commissioned at a different current level:

- The functionalities of the interlock system can be commissioned at zero current.
- The quench protection system can be commissioned at an intermediate current level at which the full functionality (mainly quench heater performance) is already assured.
- Both the power converters and the energy extraction system must reach nominal current before they can be considered as fully commissioned.
- Nominal current ramp rates will be applied to all circuits to verify the behavior of the magnets and the performance of the converters.
- For the insertion magnets squeeze rates representative of nominal operation are applied.

- For the energy extraction facilities can be considered as commissioned only when they have gone through circuit discharges at nominal stored energy.

HCA:PCC - Power converter and circuit calibration

This test is to be performed in all circuits. It is the first test carried out after the electrical connection of the power cables to the current leads. Therefore, it is the first time that current is injected into the superconducting circuits. The test consists mainly in the calibration of the power converter connected to the electrical circuit.

The objectives of theses tests are: the initialization of current loop parameters before the first powering; the verification of the power converter protection system (free-wheeling path and internal discharge system for the 600 A bipolar power converters).

HCA:PIC2 - Interlock tests at minimum current

Once the power cable is connected to the leads, the interlock tests which were done with the converters in short-circuit (PIC1) are repeated with the power converters running at the minimum stable (stand-by) current. These tests are performed on all the circuits except the 60 A closed orbit correctors).

The objectives of these tests are: to commission the protection functionalities of the powering interlock controllers and all its connected systems with current through the circuits; to verify the compatibility of the switching-on and switch-off process of the converters with the sensitivity of the protection systems and to validate automated circuit commissioning.

HCA:PCS - Verification of the superconducting splices

The HCA:PCS test is especially devoted to find faulty splices (i.e. link between superconducting busbars), which could lead to a dangerous non-detectable overheating. As mentioned above, it is performed on all the 600 A circuits with and without energy extraction [95].

The sequence of the tests is as follows: ramp the current to a safe current level (where an overheating would be detected) as fast as possible, stay there for 10 minutes, then reverse the current to a safe negative value as fast as possible, stay again 10 minutes and finally ramp the current down to zero by provoking a fast power abort or opening the energy extraction switches. The quench detector should reveal any faulty splice during the plateau periods.This test will be also used to tune the inductance tables used by the numerical global quench detectors.If during any of the ramps described above the quench detector trips, the detector is calibrated and the step repeated.The behavior of the splices when more than one circuit are powered together is studied during the PGC tests (see below).

HCA:PLI - Powering at low and intermediate currents

These tests are performed at different current levels. Depending on its type a circuit will go through all the intermediate levels or just some of them. The definition of these levels are explained in the next section.

The objectives of these tests are:

- to set up the power converter current loops;

- to validate the protection mechanisms under real powering conditions and with limited amount of energy in the circuits;

- to validate quench-related procedures (e.g. cryogenic recovery procedures);
- to validate the sensitivity and compatibility during ramps of the systems susceptible to noise pick-up, couplings, etc;
- to validate automated circuit commissioning;
- to validate analysis tools and fully understand the events (e.g. provoked quenches, energy extraction, etc.)
- to perform a last check of the polarities of the circuits by verifying voltages across the current leads.

HCA:PNO - Powering at nominal current

Finally the different systems have to be validated at the nominal operational current of the machine. The objectives of these tests are: to verify that the power converters work correctly during the nominal ramp of the current; to calibrate the main power converters; to verify that the calibration systems work correctly; to validate the protection mechanisms under real powering conditions and with nominal energy in the circuits and to assess on the adequate quench levels of all circuits.

HCA:PGC - Powering of groups of circuits

During these tests the circuits are not anymore powered individually but in groups: circuits from the same DFB, circuits from the same powering subsector, and as last test, all circuits from the same sector. The objectives of these tests are: to verify the tracking of the current; to verify thermal performance of the ventilation and water cooling systems in underground areas and to have a 24-h reliability run to detect premature failures due to wrong settings or possible assembly errors.

All these tests have been widely detailed in the document [94].

8.4 Powering Strategies by Circuit Type

The first time a superconducting circuit is powered, special attention must be devoted to the 'bad' splices slowly heating at low currents: this concerns the interconnections which were carried out during installation and have therefore never been tested before. This effect is difficult to detect because no dedicated instrumentation is available on each side of the splices. Reference [95] demonstrates that powering of the superconducting circuits can be conducted in most of the electrical circuits without endangering the integrity of the splices (even in the case they are resistive above the specification limits). However, the splices of the 600 A circuits have to be checked before injecting high currents and this is the test which is explained in the section above HCA:PCS.

To understand the general behavior of the circuits and its components (power converter, current leads, etc.) the powering of the circuits must stop at intermediate current levels where temperatures and voltage are measured and the decision to continue or abort the test is taken. Figure 8.3 shows the current profile for a 120 A circuits where plateaux of several minutes are applied before the next current step is applied. The amplitude of the latter also depends on the current level reached: smaller at the beginning and bigger after a certain level. The values for these stops are stored in the LSA database [96].

These stops allow the measurement of the resistive voltage component (i.e. the one eventually caused by 'bad' splices) stripped of the inductive contribution (L dI/dt); it will hence ease the detection of premature quenching.

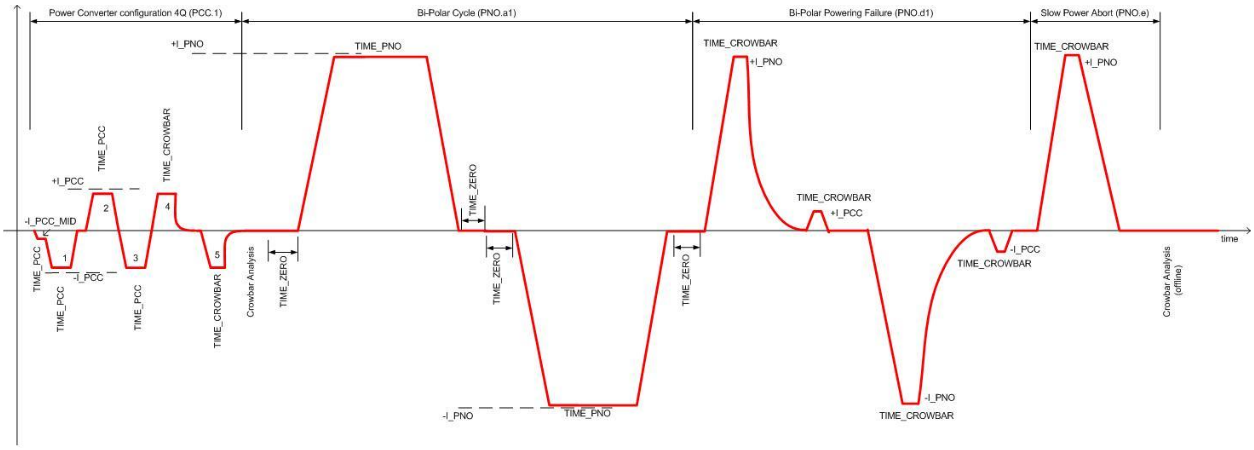


Figure 8.3: The current profile to be applied during first powering of a 120 A Superconducting Circuit. The axis represents I (out) and times for each circuit and can be found in the LHC LSA Database

Verified, automated procedures will be used to apply this current profile, to take the measurements and to make the decision in a fast and reliable manner. The maximum ramp rates are stored for each circuit in the layout database [60]. In the case of the corrector circuits, the first ramps to nominal current will be used to initialize the inductance tables used by the numerical quench detectors.

8.4.1 Powering to Nominal

In a powering subsector, once all equipment (e.g. QPS, PC, PIC, etc.) composing the superconducting circuits equipment group have successfully passed their IST and the interlock tests with current (PIC2), the circuits forming this powering subsector can go through the different powering-to-nominal steps. Each circuits is progressively powered and tested at different current levels (i.e. from PLI to PNO).

The current levels are:

1. Injection Current (PLI.1 test)
2. Intermediate Current 1 - 20% of nominal (PLI.2 test)
3. Intermediate Current 2 - 50% of nominal (PLI.3 test)
4. Intermediate Current 3 - 70% of nominal (PLI.4 test)
5. Nominal Current (PNO test)

The number of current levels applied for each circuit type is driven by the need of validating the energy extraction and the quench heater performance. Circuits with energy extraction facility and quench heaters will need to go through all the levels while those protected internally by the power converter will be tested directly at nominal current. At each current level the circuit will go through different test steps. Again, depending on its type, the circuit will go through more or less steps.

These steps are:

1. Current cycle up to the test current: this test is performed in all the superconducting circuits of the machine at each test current level. Its main objective is to validate the performance of the whole circuit by applying a certain current cycle with a specific current shape. The test is used for measuring the behavior of the power converter, calibrating the quench detectors and validating the proper performance of the current leads.

2. Forced energy extraction: before provoking any event in the circuit (e.g. quenches, slow power abort, powering failure, etc.), the energy extraction system (if present) has to be validated. This is done by powering the circuit up to the test current and either sending a fast power abort from the PIC or opening manually the energy extraction system from the QPS application (QPS Expert).

3. Provoked quench: the whole protection system is validated by sending an artificial input signal to one of the quench detectors of the circuit. This will fire the quench heaters in the selected magnet triggering the whole QPS protection protocol.

4. Simulation of a fast power abort from the powering interlock: this test evaluates the performance of the power converters, the QPS and the energy extraction system when a fast power abort is requested by the PIC. This will provoke the opening of the energy extraction switches and the disconnection of the power converter from the system. For the circuits without external energy extraction, the energy will be dissipated in the internal crowbar.

5. Simulation of a powering failure of the converter: this event has very different consequences depending on the circuit type. In the circuits with bipolar power converters, the current is controlled ramped down by applying an opposite voltage. For the circuits with unipolar converters, the current goes down naturally while the energy is dissipated in the warm cables of the circuit.

6. Simulation of a slow power abort from the powering interlock: only the power converter is affected by this event, the current is slowly ramped down to zero as in the powering failure mode.

7. Verification of the current leads performance: this test consist on a visual inspection of the status of the current leads during and after the test cycles. It is important that no water is condensed or ice formed around the leads or adjacent equipment.

A detailed list of tests has been defined by type of circuit. An example is presented in Appendix D.

8.4.2 Powering Times

Once each test has been defined, it has been broken down into steps and the sequence per step has been established. An execution time has therefore been given to each step.

Several iterations of this process have been done. The first one was an estimation defined by circuit type, as the result of the added time by system involved, using the times deployed during the String-I and II commissioning [31]. The last detailed study was done once the specifications for the tests were established. A time duration time has been defined per step/test and per circuit type at the different current levels.

The study done for the main bending dipole circuit (RB) is given in Table 8.3 for the sequence at nominal current. The powering times calculation have been done for all the circuit types. Two examples (inner triplet and 600 A with EE) are detailed in Appendix A. The time is expressed in working days considering two shifts (15 hour per day).

	Current Decay Time with EE [m]							
	9.12							
	Max Ramp Rate (A/min)	**I min op**	**Injection**	**Interm1**	**Interm2**	**Interm3**	**Nominal**	**Ultimate**
	600	*350*	760	2000	6000	9000	12000	12840.0
	RB Main Circuit							
	PNO (300-11850 A)							
	Tests Steps	Analysis	Preparation	Ramp	Test	De-ramp	Recovery	
HCA PNO.1ii	Current loop stability. Ramp from Imin_op to nominal current		10	19.4	320	19.4	0	
HCA PNO.1ii	PC failure and check current decay	120	10	19.4	10	19.4	0	
HCA PNO.2	Fast power abort by the PIC	120	10	19.4	10	9	0	
HCA PNO.3	Heater firing	0	10	19.4	10	9	270	
HCA PNO.4	DCCT calibration	0	10	19.4	960	19.4	0	
HCA PNO.6	Current Lead Temp Control	0	0	0	10	0	0	
	Result	240	50	97.0	1320	76.3	270	
	Total time [m] without analysis	1813.3						
	Total time [m] with analysis	2053.3						

Table 8.3: Times in minutes calculated for the RB circuit going to nominal current

The first column of the table "Test" are the steps executed at the actual current level, which in this case is a ramp from injection current to nominal current. The rest of columns represent time in minutes. Each time per step and per circuit is composed of:

- Analysis: represents the integrated time for analysis to be deployed during the step based on the String-I and II commissioning experience.

- Preparation: it is the time needed for the preparation to start the tests in terms of software, hardware and experts deployment in the field .

- Ramp time: it is calculated as
$$T = \frac{[(Ii) - (Io)]}{di/dt} \tag{8.1}$$
where I_i (A) represents the current to be reached during the test (in this case is nominal current), I_o the initial current from which the test has started and dI/dT represents the maximum ramp rate in A/s to be applied in a circuit type. dI/dT and Ii-Io are defined in the LHC Layout Database.

- Test: represents the integrated time of the step based on the software and hardware design.

- De-ramp: the de-ramp time can be calculated in two different ways depending on whether the de-ramp is done by the power converter or by the energy extraction system. This is driven by the type of test being performed. For the power converter case the time is calculated with Equation 8.1 and for the de-ramps via the energy extraction with Equation 8.2.

$$I(t) = Io \times e^{\frac{-t}{\tau}} \tag{8.2}$$

$$\tau = \frac{L}{R} \tag{8.3}$$

$$t_{currentdecaytime} = -Ln(\frac{I(t)}{Io}) \times \frac{L}{R}(finitelimitused5\tau) \tag{8.4}$$

circuit Type	PIC2	Powering	Total
RB	0.1	10.9	11
RQD, RQF	0.1	5.2	5.3
IP Q&D	0.1	1.7	1.8
IT	0.1	5.6	5.7
600 A with EE	0.1	0.9	1
600 no EE crowbar	0.1	0.8	0.9
600 A no EE	0.1	0.6	0.7
80-120 A	0.1	0.1	0.2
60 A	0.1	0.1	0.1

Table 8.4: Days required to commission each type of circuit

- Recovery (magnets and/or energy extraction): for some circuits types, every time that a quench is generated above a certain current level, cryogenics conditions are lost and some time is needed to recover them. Figure 8.4 shows the estimated time to recover the cryogenic conditions after a quench depending on the current in the circuit and the number of cells to which the quench has propagated. Even when there is no quench a fast current discharge can make the system loose the cryogenics conditions due to the heat load created by the eddy currents [97] following the dB/dt. The recovery time for such extraction at 12 kA can be up to two hours. Besides this cryogenic recovery, the energy extraction dump resistors also need to be cooled down to ambient temperature after an energy extraction request (e.g. following a quench, fast power abort, etc.).

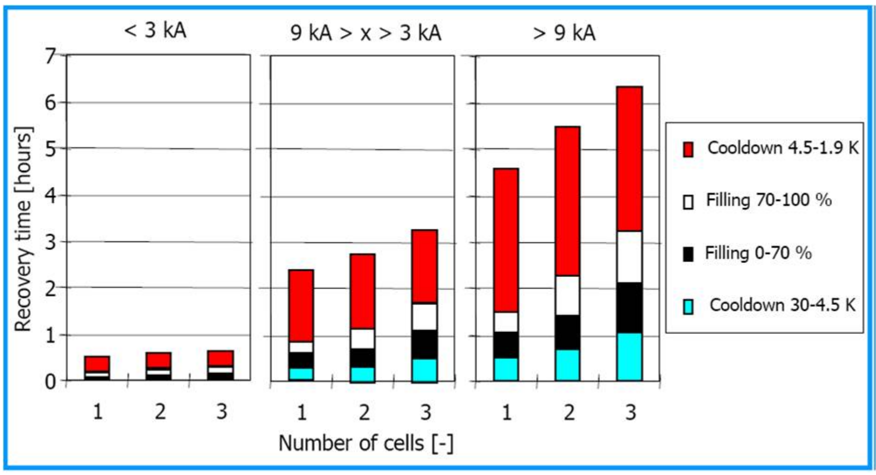


Figure 8.4: Recovery time after limited resistive transitions (Quenches)

Results

The summary of powering times by circuit type can be found in Table 8.4.

8.5 Scheduling the Powering Tests: Commissioning Strategies

Parallelism and resource constrains

It has been seen in Section 5.1 that there is a limit in the available resources to complete the project. This limit has to be taken into account to design the commissioning strategies. The resource limitations will affect to the parallelism between sectors and between fronts [98].

Parallelism and hardware constraints

The parallelism between circuits will be driven by hardware limitations and can be divided in two types parallelism between fronts and parallelism between circuits within a front (battery tests) [99].

- Parallelism between fronts
  - The tests carried out by one front should be transparent to other ones. This means that two different fronts can test simultaneously circuits in the same powering subsector only if these are corrector circuits. Most of the actions on main circuits (e.g. quenches, fast power aborts, etc.) will have an effect on all the other circuits of the subsector (e.g. cryogenic effect, interlocks, quench heater discharges, energy extraction switch openings, etc.), which will end up screening the tests carried out by the other fronts.
  - By definition, one front can commission only one circuit or one battery at a time.
- Parallelism between circuits, a battery of tests cannot
  - Include circuits above 600 A to avoid cross-talk between tests.
  - Imply more than two DFB chimneys to closely monitor the performance of the current leads implied during their first powering (e.g. temperature drift, ice formation).
  - Imply more than one DFB, which is a direct consequence from the previous.
  - Include circuits sharing the same QPS controller due to the architecture of the QPS.
  - Include circuits from different circuit type due to controls software constrains.
  - From the definition of front, one cannot test circuits from different powering subsectors simultaneously within the same front.

The result of these constrains together with the estimated powering times can be found in the schedule showed in Figure 8.5.

8.6 Data Storage

The HC MTF has been the main tool to gather the results of the powering tests of the LHC circuits. The data which are stored in this database includes the history of evolution of the tests; failed tests and repeated tests, including the reasons of failure; numerical results (e.g. number of quenches by circuit), variation from the designed parameter (e.g. circuit resistance, circuit impedance). The contents of all this information have been defined together with the experts in order to give continuity in the future during the operation of the machine with beam.

ID	Task Name	Duration	Number of Circuits
1	**Two sectors around an even point**	**61 days**	**0**
2	**Front 1 Left of even point**	**56 days**	**0**
3	MB	11 days	1
4	MQF	5.5 days	1
5	MQD	5.5 days	1
6	Separately Powered Quadrupoles and Dipoles	12 days	7
7	600 A circuits	21 days	26
8	**Front 2 Left of even point**	**54 days**	**0**
9	MQX	5.5 days	1
10	600 A circuits	26 days	32
11	80 & 120 A Orbit Correctors (arc and IT)	18 days	59
12	**Front 1 Right of even point**	**58 days**	**0**
13	MB	11 days	1
14	MQF	5.5 days	1
15	MQD	5.5 days	1
16	Separately Powered Quadrupoles and Dipoles	12 days	7
17	600 A circuits	21 days	26
18	**Front 2 Right of even point**	**57.5 days**	**0**
19	MQX	11 days	2
20	Separately Powered Quadrupoles and Dipoles	12 days	7
21	600 A circuits	24 days	30
22	80 & 120 A Orbit Correctors (arc and IT)	9 days	28

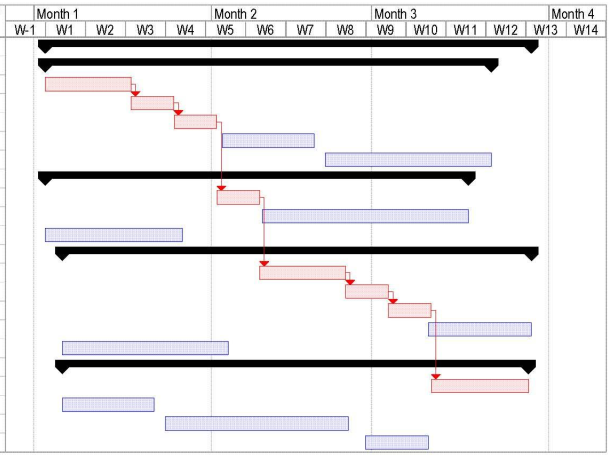


Figure 8.5: Commissioning plan by circuit types

There are other tools that are used for data collection and analysis, but not for quality assurance as is the case for the HC MTF. These are: the logging that is a tool to continuing keep the history of the most important values of the collider hardware systems, and the post-mortem that after a failure during the operation, records a coherent set of post-mortem information, which will be required from the various sub-systems to analyze the causes of the failure.

8.7 Highlights on the Superconducting Circuits Commissioning

In order to cope with the reduction of time available for tests and due to the learning curve after the first sectors, changes have been implemented using the tools presented in this thesis.

Evolution of test procedures

The first version of the test procedures for the superconducting circuits (also called powering procedures) were developed by defining a current cycle for each test at the different current levels. A standard current cycle includes:

- Switch on the power converter (or converters).
- Ramp of the converter to its minimum operational current (I_MIN_OP).
- Small plateau at I_MIN_OP to check that systems are OK.
- Ramp to test current.
- Plateau at test current.
- At this point the cycle may continue in two ways:
  - Continue the cycle to another current level.

  - Provoke an event (e.g. quench, converter fault, fast power abort, etc.)

- Switch power converter off.
- Creation and sending of post-mortem data.
- Analysis of the test by the different system experts.
- Final approval of the test.
- End of the test, update of MTF and LSA databases.

The very short powering tests carried out during summer 2007 in sector 7-8, showed that the considerable amount of current levels and tests type defined made the powering times longer than expected. The actions needed in order to go from one step to the other within and between cycles required in some cases more time than the tests themselves.

In order to reduce the commissioning time per circuit two decisions were taken. First, it was decided to eliminate as many steps as possible. After discussing with the experts it was seen that some of the tests done at a certain current level (e.g. slow power abort) did not need to be repeated at higher levels since the additional information provided by such repetitions were not worth the time spent for carrying out the test two and even three times. Secondly, a more detailed study of the cycles required by each system expert showed that some of the tests could actually be done using a single cycle. Of course by doing so some information was lost, but the added value to the commissioning of those data would not justify the time spent.

The global impact of this optimization on the commissioning time of each circuit was already seen during the so-called "dry runs" (i.e. simulation tests carried out without the power converters connected to the magnets, used for debugging the software tools and getting an estimation of the commissioning times). The latter showed a reduction of the time required by the 60 A and 80A-120A circuit types of about 30% with respect to the time needed in Sector 7-8 and up to 50% for the 600 A correctors and main magnets.

Evolution of the powering tests planning

Once the powering strategy per circuit was optimized, the next step was to increase as much as possible the parallelism between circuits types (fronts) and circuits of the same time sharing powering subsector (batteries). As it has been already seen, the powering constraints considered during the definition of the baseline were two the hardware constrains and the limited human resources.

Regarding the hardware, it was learned during the first days of the sector 7-8 powering that some operational mode settings which are not needed at all during the commissioning phase cause many troubles and are very time consuming during the tests. A clear example was some interlock features which prevent to power different circuits in parallel. In the scenario of powering with beam the goal of the powering interlock is double protect the machine and protect the beam (i.e. reduce as much as possible the time without beam). Of course, during the phase of hardware commissioning, this second aim is not needed. The main consequence was that the "Global Protection Mechanism" could be disabled. The "Global Protection Mechanism" is an extremely useful feature of the PIC during beam operation that sends a fast power abort to all the converters in the powering subsector when a magnet in a main circuit quenches. This reduces the number of magnets quenched after a quench event due to thermal and hydraulic propagation. For instance, it was seen in the String-II

circuit Type	PIC2	Powering	Total
RB	1	10	11
RQD, RQF	0.1	5	5.1
IP Q&D	0.1	1.9	2
IT	0.1	5.6	5.7
600 A with EE	0.1	0.15	0.25
600 no EE crowbar	0.1	0.15	0.25
600 A no EE	0.1	0.15	0.25
80-120 A	0.1	0.1	0.2
60 A	0.1	0.1	0.1

Table 8.5: Days required to commission each type of circuit

that after a quench in a dipole the quadrupoles quenched some seconds afterwards. This would not happen if the current in the quadrupoles had been reduced (e.g. by opening the energy extraction switches) during the propagation time. Except for the last commissioning steps, when several magnets are powered together in order to check couplings, the main circuits in a subsector are always commissioned one after the other, hence there is no need to have this mechanism activated.

Having this mechanism disabled during the commissioning will allow to carry out tests in main circuits and correctors in the same powering subsector as long as no quench shows up. This increase in the parallelism has allowed to reduce the expected time for the powering tests of a sector by about a 20%.

Another very important hardware constrain regarding the number of current leads that can be powered at the same time has been removed. The highly performing cryogenic supervision system allows the monitoring of each current lead temperature and helium flow from a single terminal in the control room. This implies that batteries (i.e. circuits of the same type within the same powering subsector powered in parallel by one front) are not limited anymore by this.

Not much could be done in terms of human resources optimization, the number of experts needed to perform a test in a circuit type remained unchanged. However, some improvement was envisaged by increasing the automatization of the tests. Although experts were always needed to monitor the performance of each sub-system (QPS, power converters, cryogenics, etc.) during the test, the use of automatic and semi-automatic computing tools considerably reduced the work load of the experts.

New estimations of the powering duration by circuit type

After the results coming from the first tests a new set of times have been applied to the planning. The summary of times by circuit type can be found in Table 8.5. The changes are explained by the improvements detailed above. These new times together with the increase in the parallelism results in a shorter planning for the powering tests.

HC MTF use for the execution of tests

During the first powering tests carried out in Sector 7-8, it was seen a large increase on the amount of information to be stored in the HC MTF, this was due to the characteristics of these first tests, which had to be repeated several times due mainly to interruptions during the test sequences (e,g, sequencer exceptions, training quenches, spurious quench detections, etc...). These new needs showed a necessity of an adaptation to this scenario. For instance, during the powering tests, mainly in the first weeks of operation, most of the tests were not completed and had to be repeated. This pointed out a new need in HC MTF: the versioning. Thanks to the rigorous structure followed by for the design and implementation of the HC MTF, the integration of the new features has been easily and cleanly done. The new release of the tool in January 2008 already faces the non-completed and repeated test issues.

Since MTF is the core of the quality assurance of the commissioning project, it has been improved to be used as the safe communication tool for exchanging information between the system owners and the commissioning responsible.

The first step of all the superconducting circuit test profiles is the "Release of the Circuit for Powering". Only the so-called MPP delegates (Magnet Performance Panel members) have the right to fill manually this step and change its status to "OK", which means that the circuit is ready to be powered. The commissioning team only puts current in a circuit once the MPP expert has released the circuit.

This very important step was implemented for preventing powering of circuits with non-conformities. MTF, as a quality assurance tool, is a very rigid database which does not allow easily changes from one state to another once the test (step) is set as DONE. Thus the OK for powering has to be given only when MPP is sure that the circuit can be powered.

The other MTF step that must be filled manually is the last step of each profile. In the same way as the first one represents the OK from MPP for powering the circuit, the last one is filled by the same expert to release the circuit for operation, this sets the circuit as fully commissioned. The person with rights for changing the status of this step is responsible of checking the output of all the previous steps in the profile and set the circuit as ready for beam operation or not. Of course, the Large Hadron Collider can be considered as fully commissioned once the 1564 circuits of the ring have status OK as status in their last MTF profile.

Conclusions and Outlook

One of the key issues to start up with this thesis was the analysis of *the state of the art* in project management for the commissioning of the technical systems in superconducting accelerators. We have seen that, although other superconducting accelerators have been commissioned in the past, no global approach on project management was applied to any of them.

It has been demonstrated here that in LHC, due to the change of scale with respect to previous projects together with its accentuated time and budget constrains, the project management tools are a powerful and useful means to assure quality and success.

The Hardware Commissioning management tools provide a systematic and fast response during the execution of the HC Project. They assure readiness before the start of the project, control and quality assurance during the project, as well as data and results perennity to be readily available in the future during the operation phase of the LHC with beams.

The results obtained before the start of the commissioning have contributed to the resources plan, required to execute the project within the envisaged milestones. As any big project, the HC has suffered changes from the beginning. There have been reductions in the available time to fulfill the project. Technical specifications and restrictions have been updated due to the learning process. Even the goals have changed! And the tools developed in this thesis have successfully achieved their objectives by giving specific solutions every time that a new scenario was needed or imposed.

Summary of the Results

All the systems involved in the HC Project have been completely analyzed and dissected with the new perspective of their start-up, something that had never been done in this or previous accelerators.

The main management challenges of the HC Project have been identified.

A methodology has been created for the definition of the schedule, the resources study and the planning in this kind of complex projects. In particular, the HC schedule has been integrated in the LHC General Schedule by identifying and solving all the co-activity conflicts. The HC resources study has been useful to redefine the needs every time that a different time constraint has appeared. 195 full time equivalent units have been identified, out of which 90 were missing. This represented an additional budget of around 2.3 MCHF. This budget was approved and allocated by CERN management.

A document plan has been created and is operational. It contains all the documentation needed to perform the tests. A HC arborescence architecture is implemented and has homogenized sectorization and visualization of the project. The interface problems between systems have been identified and solved out thanks to this tool. All the system specialists use now the new "HC language" to communicate across them. The approach used to define the arborescence makes changes and updates easy to implement.

The HC MTF is implemented and has already been used for the commissioning of two sectors. Progressively, it has been optimized and adapted to the changes, incorporating features and improvements from the continuous experience. It is presently being used as a "green light" for execution of tests, a storage database and a quality assurance tool, ensuring that the tests have been performed strictly following the procedures defined by the experts.

Outlook

More than half of the LHC machine still has to be commissioned. The tools have already proven to be serviceable and meeting the expected performance.

The HC arborescence will be used in the future also by beam-related systems. The HC MTF will continue running for the rest of the commissioning without beam and after with beam. The proven flexibility opens ample route for new implementations during beam operation. Maybe, one day, with improvements in delays for uploads, the HC MTF will become an on-line, realtime tracking tool.

The developed tools can be applied to other accelerator projects (e.g. CLIC, ILC) and also outside the high energy physics field (e.g. ITER). I hope this study demonstrates the feasibility and usefulness of project management tools during the entire lifetime of complex scientific installations, like a particle accelerator, from project to commissioning and further in operation.

Appendix A

Calculation of commissioning times for equipment and equipment group: some examples

Calculations have been computed for all the HC activities and used to define the HC schedule. In this appendix some examples are presented.

Cryogenics instrumentation times commissioning

The total time of 20 weeks needed for the IST at warm, can be dissociated in the different phases that can be seen in the planning in Figure A.1. This calculation is the same for all the sectors.

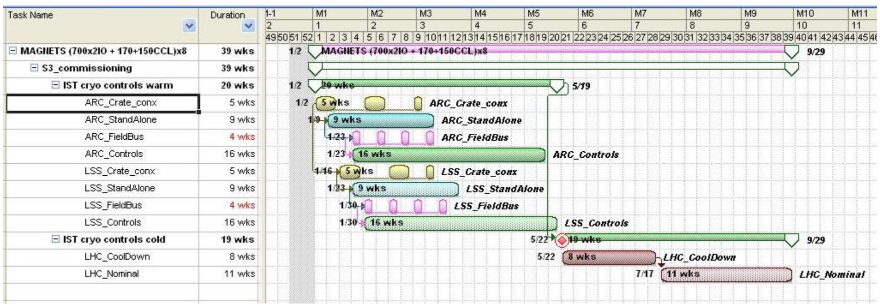


Figure A.1: Duration of the cryogenic instrumentation activities at warm and at cold

Test duration for the powering interlock system

In the Table A.1 can be found the definition of the tests duration for the powering interlock system tests. The steps of the two main tests, PIC1 and PIC2, are represented for one type of circuit. this calculations have been done for all kind of circuits in order to implement the schedule.

Main Circuits Step	**test**
10-HCA PIC1 Tests of Soft. Link (PIC & Cryo)	per PIC
12-HCA PIC1 Tests of Soft. Link (PIC & QPS)	0.04
14-HCA PIC1 PC Permit	0.04
16-HCA PIC1 Powering Failure	0.04
18-HCA PIC1 Circuit_Quench via QPS	0.04
20-HCA PIC1 Fast_Abort_Request via PIC	0.04
22-HCA PIC1 Discharge_Request via PC	0.04
24-HCA PIC1 Discharge_Request via PIC	0.04
26-HCA PIC1 Global Protection Mechanisms Test	per PIC
28-HCA PIC1 Hard. Test Links (PIC & AUG & UPS)	per PIC
-	
30-HCA PIC2 Tests of Soft. Link (PIC & Cryo)	per PIC
32-HCA PIC2 Tests of Soft. Link (PIC & QPS)	0.02
34-HCA PIC2 PC Permit	0.02
36-HCA PIC2 Powering Failure	0.02
38-HCA PIC2 Circuit_Quench via QPS	0.02
40-HCA PIC2 Fast_Abort_Request via PIC	0.02
42-HCA PIC2 Discharge_Request via PC	0.02
44-HCA PIC2 Discharge_Request via PIC	0.02
46-HCA PIC2 Global Protection Mechanisms Test	per PIC
48-HCA PIC2 Hard. Test Links (PIC & AUG & UPS)	per PIC
-	
50-HCA PM Post Mortem Tests	

Table A.1: Times calculation in hours for the powering interlock tests on a circuit from the type main circuits

Powering times

A very precise time calculation for the duration of the powering tests has been done. For every circuit type and for every step composing the tests a time estimation or calculation has been identified. The tables below [1] A.2, A.3, A.4, A.5 and A.6 show an example for each circuit for a different current levels type (except main circuits which are is in Chapter 8). All the de-ramp times (current decay time) which are not done through the PC are calculated always for Inom, being aware of the over estimation of time.

[1]The maximum ramp rate is determined by the power converter and has been taken from the LHC reference database. The current decay time after a switch opening and/or a quench heater firing has been calculated when possible (e.g. dipole and quadrupole main circuits) and estimated for very rapid processes such as the quench heater firing in the inner triplet magnets.

	Current Decay Time [m]							
	1							
	Max Ramp Rate (A/min)	**I min op**	**Injection**	**Interm1**	**Interm2**	**Interm3**	**Nominal**	**Ultimate**
	321.2	*200*	415	1000	3000	x	6450	7000.0
	MQXA Circuit from the inner triplet							
	PL1 (60-415 A)							
	Tests Steps	Analysis	preparation	ramp	test	De-ramp	Recovery	
HCA PLI1.1	Check of the current loop stability	0	10	0.7	1600	0.7	0	
HCA PLI1.2	Fast power abort	120	10	0.7	10	0.7	0	
HCA PLI1.3	PC Failure	120	10	0.7	10	1	0	
HCA PLI1.5	Heaters firing	90	10	0.7	10	1	30	
HCA PLI1.7	Current Lead Temp Control	0	0	0	10	0	0	
	Result	330	40	2.7	1640	3.3	30	
	Total time [m] without analysis	1716.1						
	Total time [m] with analysis	2046.1						

Table A.2: Times calculated for the powering of a circuit from the inner triplet in the phase of injection to the first intermediate current level

	Current Decay Time [m]							
	1							
	Max Ramp Rate (A/min)	**I min op**	**Injection**	**Interm1**	**Interm2**	**Interm3**	**Nominal**	**Ultimate**
	1088	*150*	350	1000	3000	x	550	6500.0
	IP Dipoles & Quadrupoles							
	PL2 (60-1000 A)							
	Tests Steps	Analysis	preparation	Ramp	Test	De-ramp	Recovery	
HCA PLI2.1	Current loop stability. Ramp from I_minop to interm. current	0	10	0.8	53	0.8	0	
HCA PLI2.3	Heaters Firing	90	10	0.8	10	1	30	
HCA PLI2.4	Slow power abort and current decay	60	10	0.8	10	0.8	0	
HCA PLI2.5	Loss of sub-converter	0	10	0.8	10	0.8	0	
HCA PLI2.6	Current Lead Temp Control	0	0	0	10	0	0	
	Result	150	40	3.1	93	3.3	30	
	Total time [m] without analysis	169.4						
	Total time [m] with analysis	319.5						

Table A.3: Times calculated for the powering of the IP Dipole circuit from injection to the second intermediate current level

	Current Decay Time [m]							
	0.1							
	Max Ramp Rate (A/min)	**I min op**	**Injection**	**Interm1**	**Interm2**	**Interm3**	**Nominal**	**Ultimate**
	300	*0*	50	100	300	x	550	600.0
	600 A Circuit with Energy Extraction System							
	PL3 (0-300 A)							
	Tests Steps	Analysis	preparation	Ramp	Test	De-ramp	Recovery	
HCA PLI3.1	Current loop stability. Ramp from I_minop to interm. current	0	10	1	0	1	0	
HCA PLI3.2	Energy extraction discharge	60	10	1	10	0.1	0	
HCA PLI3.4	Current Lead Temp Control	0	0	0	10	0	0	
	Result	60	20	2	20	1.1	0	
	Total time [m] without analysis	43.1						
	Total time [m] with analysis	103.1						

Table A.4: Times calculated for the powering of a 600 A circuit with energy extraction system circuit from injection to the second intermediate current level

	Current Decay Time [m]							
	10							
	Max Ramp Rate (A/min)	**I min op**	**Injection**	**Interm1**	**Interm2**	**Interm3**	**Nominal**	**Ultimate**
	60	*0*	x	x	x	x	100	110.0
	80-120 A							
	PNO (0-100 A)							
	Tests Steps	Analysis	preparation	Ramp	Test	De-ramp	Recovery	
HCA PNO.1i	Current loop stability. Ramp from I_minop to nominal current	0	10	1.7	0	1.7	0	
HCA PNO.1ii	PC Failure and check current decay	0	10	1.7	10	1.7	0	
HCA PNO.2	Fast power abort by the PIC	0	10	1.7	10	10	0	
HCA PNO.4	DCCT calibration	0	10	1.7	0	1.7	0	
HCA PNO.5	Check feed-through protection	0	0	0	10	0	0	
HCA PNO.6	Current Lead Temp Control	0	0	0	10	0	0	
	Result	0	40	6.7	40	15	0	
	Total time [m] without analysis	101.7						
	Total time [m] with analysis	101.7						

Table A.5: Times calculated for the powering of the 80-120 A circuit from injection to the nominal current level

	Current Decay Time [m]							
	10							
	Max Ramp Rate (A/min)	**I min op**	**Injection**	**Interm1**	**Interm2**	**Interm3**	**Nominal**	**Ultimate**
	40	*0*	x	x	x	x	50	60.0
	60 A							
	PNO (0-50 A)							
	Tests Steps	Analysis	preparation	Ramp	Test	De-ramp	Recovery	
HCA PNO.1i	Current loop stability. Ramp from I_minop to nominal current	0	10	1.4	0	1.4	0	
HCA PNO.1ii	PC Failure and check current decay	0	10	1.4	10	1.4	0	
HCA PNO.2	Fast power abort by the PIC	0	10	1.4	10	10	0	
HCA PNO.4	DCCT calibration	0	10	1.4	0	1.4	0	
HCA PNO.5	Check feed-through protection	0	0	0	0	0	0	
HCA PNO.6	Current Lead Temp Control	0	0	0	0	0	0	
	Result	0	40	5.5	20	14.1	0	
	Total time [m] without analysis	79.6						
	Total time [m] with analysis	79.6						

Table A.6: Times calculated for the powering of the 60 A circuit from injection to the nominal current level

Appendix B

Hardware commissioning regions sectorization

List of HC regions

One of the objectives of this thesis has been to create a Hardware Commissioning (HC) view of the machine with the different tools created and by homogenizing the sectorization of the machine. The table B.1 lists the hardware commissioning regions. The columns represent the name of the region and the start of the geographical position and the end in the LHC machine, from 0m to 27000m.

These data has been, as well, integrated in the LHC Layout Database formalizing the homogenization of the machine sectorization.

FULLNAME	START	END	FULLNAME	START	END	FULLNAME	START	END
TAS.R1	0	22.105	D3.R4	10041.14	10055.71	TCL.7L8	23069.4	23078.71
Q1Q2Q3.R1	21.915	59.102	BIA.R4	10055.05	10114.8	Q6.L8	23078.06	23091.37
D1.R1	58.457	151.93	D4Q5.R4	10114.14	10133.53	TCL.6L8	23090.72	23138.17
D2Q4.R1	151.275	173.343	BIB.R4	10132.88	10163.52	Q5.L8	23137.52	23151.79
TCL.R1	172.688	192.072	Q6.R4	10162.87	10171.13	DRIFT.L8	23151.14	23170.78
Q5.R1	191.417	200.956	BIC.R4	10170.48	10257.35	Q4D2.L8	23170.12	23195.52
DQWCS.R1	200.301	223.972	ARC45	10256.7	13073.49	TC.4L8	23194.87	23245.72
Q6.R1	223.317	232.856	XRP3.L5	13072.83	13097.24	D1Q3Q2Q1.L8	23245.07	23293.39
EE.R1	232.201	256.109	Q6.L5	13096.59	13106.12	LHC_COMP.R8	23315.3	23337.41
ARC12	255.454	3075.8954	EE.L5	13105.47	13129.14	Q1Q2Q3D1.R8	23337.22	23385.53
DRIFT.L2	3075.2404	3084.1854	Q5.L5	13128.49	13138.02	TDI.4R8	23384.89	23435.74
Q6.L2	3083.5304	3096.8494	TCL.5L5	13137.37	13156.75	D2Q4.R8	23435.08	23460.48
MSI.L2	3096.1944	3155.2224	Q4D2.L5	13156.1	13178.17	MKI.R8	23459.83	23479.48
Q5.L2	3154.5674	3168.8414	D1.L5	13177.51	13270.98	Q5.R8	23478.83	23493.1
MKI.L2	3168.1864	3187.8344	Q3Q2Q1.L5	13270.34	13307.53	MSI.R8	23492.45	23552.71
Q4D2.L2	3187.1794	3212.5824	TAS.R5	13329.44	13351.55	Q6.R8	23552.06	23565.38
TDI.L2	3211.9274	3262.7774	Q1Q2Q3.R5	13351.36	13388.54	DRIFT.7R8	23564.72	23583.14
D1Q3Q2Q1.L2	3262.1324	3310.4454	D1.R5	13387.9	13481.37	ARC81	23582.49	26402.93
ALICE_COMP.R2	3332.3604	3354.4654	D2Q4.R5	13480.72	13502.78	EE.L1	26402.27	26426.08
Q1Q2Q3D1.R2	3354.2754	3402.5884	TCL.4R5	13502.13	13522.12	Q6.L1	26425.42	26434.96
X2ZDC.R2	3401.9434	3452.7934	Q5.R5	13521.47	13531	DQWCS.L1	26434.3	26457.98
D2Q4.R2	3452.1384	3477.5414	TCL.5R5	13530.35	13554.02	Q5.L1	26457.32	26466.86
DRIFT.R2	3476.8864	3493.6614	Q6.R5	13553.37	13562.9	TCL.5L1	26466.2	26486.2
Q5.R2	3493.0064	3507.2804	EE.R5	13562.25	13585.55	Q4D2.L1	26485.54	26507.61
TCL.6R2	3506.6254	3567.9144	ARC56	13584.9	16405.57	D1.L1	26506.95	26600.43
Q6.R2	3567.2594	3580.5784	DRIFT.L6	16404.91	16450.43	Q3Q2Q1.L1	26599.78	26636.97
TCL.7R2	3579.9234	3588.9804	Q5.L6	16449.77	16458.03	TAS_ATLAS.L1	26636.78	26658.88
ARC23	3588.3254	6406.3918	MKD.L6	16457.38	16486.83			
EE.L3	6405.7368	6457.5858	Q4.L6	16486.17	16494.43			
Q6.L3	6456.9308	6470.2498	MSDMKB.R6	16661.8	16830.43			
Q4Q5D3D4.R3	6664.7208	6859.2098	Q4.R6	16829.77	16838.03			
Q6.R3	6858.5548	6871.8498	MKD.R6	16837.38	16866.83			
EE.R3	6871.1948	6923.2048	Q5.R6	16866.17	16874.43			
ARC34	6922.5498	9736.9662	DRIFT.R6	16873.78	16928.54			
BIB.L4	9736.3112	9824.2842	ARC67	16927.89	19735.83			
Q6.L4	9823.6292	9831.8932	EE.L7	19735.18	19759.88			
BIC.L4	9831.2382	9861.2842	Q6.L7	19759.23	19772.55			
Q5D4.L4	9860.6292	9880.0222	Q4Q5D3D4.R7	19994.16	20217.09			
BIA.L4	9879.3672	9939.1152	Q6.R7	20216.44	20229.76			
D3.L4	9938.4502	9953.0172	EE.R7	20229.1	20252.65			
ACS.R4	9997.0812	10041.7902	ARC78	20251.99	23070.06			

Table B.1: Sectorization of the machine in HC regions

Appendix C

Description of the different levels of the HC Arborescence

C.0.1 First and second level: geographical distribution

Explained in the main body of this thesis.

C.0.2 Third level: equipment groups functional distribution

Equipment groups for points

- *Access and Safety.* The commissioning of the access system is composed of two types of tests. The first type concerns the sector (i.e. all the regions), and the second type concerns the points [2] [100]. It will be therefore present in the 8 points of the structure and in all the regions of a sector. All these nodes will contain the same information.

- *Beam Instrumentation.* Some of the instrumentation crates are found in the surface buildings. They are therefore placed on the point geographical nodes.

- *Control: Beam Interlock Controller.* The machine protection system at the level of the region is represented just by the beam interlock system. There are around 250 critical links with users (PERMIT_USERS). Some equipment groups present in the regions are part of these users on the cold parts (e.g. access and safety, vacuum, PIC, etc.) and on the warm parts (e.g. collimators, beam instrumentation, radio frequency, vacuum, etc). Therefore, the equipment groups which are interfaced with the beam interlock have to be individually commissioned before enabling the HC tests to start.

- *Radiation Monitoring.* The commissioning of the radiation monitors is done at the level of points, even if part of their equipment is distributed inside the sectors as well. The visibility of the whole equipment is done through points representing better their commissioning philosophy [22].

- *WorldFip.* The commissioning of WorldFip (which is a commercial fieldbus used to control QPS and power converter devices) is as well defined by point due to their components installation. This system is used by many other equipment groups as for instance circuits, power converters, and beam instrumentation. All of them need this equipment group to be fully commissioned before proceeding with their individual system tests.

As already explained, together with the symmetry of many systems there is a characterization of each point of the machine with a different function. Point 4 devoted to radio frequency, point 6 to beam dumping, point 2 and 8 host the injection system, and point 3 and 7 beam cleaning systems. And this characterization is represented in the points of the HC arborescence.

- *Dumping System.*

  It has been introduced in the arborescence at the level of point. This equipment group is not placed on the main ring but in two adjacent lines (one on the right side of the point and the other on the left side) which run tangent to the main ring and join it in order to extract the beam. Therefore, the better solution has been to treat it as a point equipment group [43].

- *Injection System.*

  [101] This system is localized in points 2 and 8 were the injection lines are placed. The same philosophy as for the dumping system is applied, i.e. point equipment group.

- *Radio Frequency.* The equipment composing this equipment group are placed in the beam line around point 4 but distributed in the right and left side. So, it is considered inside a point node [102].

Equipment groups for sector

- *Ventilation*

  This system is considered in the project as a general service. The commissioning tests of the regions cannot start if the ventilation is not nominally operating. This starts with the units situated in the extremities of the arcs which impulse and expel the air.

- *Access & Safety System*

  This system is considered in the project as a general service. The commissioning tests of the region cannot start if the safety system is not nominally operating. All the different equipment composing this equipment group must be therefore commissioned. In this case, we find the same situation for AC distribution (see below) and the nodes are repeated throughout the arborescence.

  - *Fire Detection*
  - *Oxygen Deficiency Hazard*
  - *Evacuation*

  These three equipment have not been used yet in the arborescent structure. The commissioning tests of the region cannot start if the safety systems are not nominally operating. So all these equipment group must be commissioned before starting with the other systems in the region [103]. In this case we find the same situation as for AC distribution and the nodes are repeated throughout the arborescence.

Equipment groups for cold regions

At this level, the equipment groups that act in each region are represented enabling all the users to identify the co-activities and co-dependencies. These cold regions are systematically composed of the same equipment groups; this is due to the fact that the cryogenic components mainly contribute to the general functionality of the machine. The reason of the presence of each equipment group in the cold regions is explained below. Figure C.1 shows the equipment group corresponding to one of the cold regions of sector 23 through the HC arborescence.

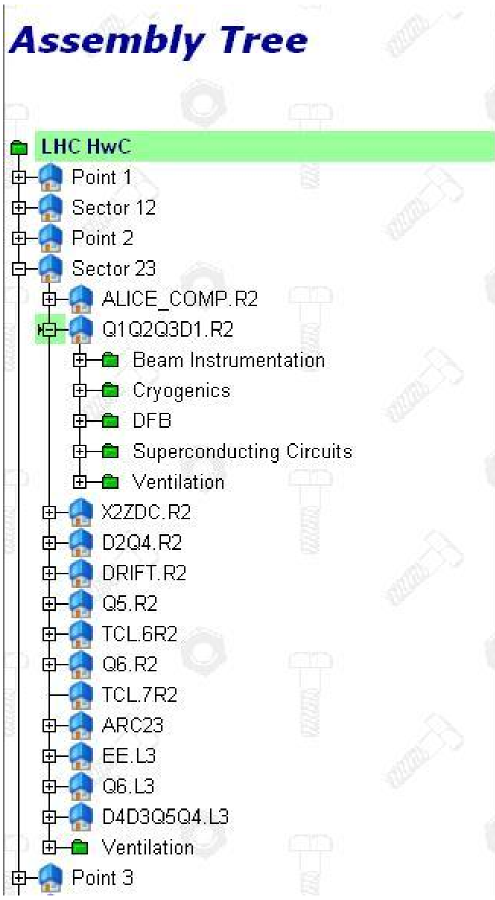


Figure C.1: Beam Instrumentation, Cryogenics, DFBs, Superconducting Circuits and Ventilation are the equipment groups that act in the cold region Q1Q2Q3D1.R2

- *AC Distribution*

  This system is considered in the project as a general service. These equipment groups do not differentiate between cold or warm regions and they are present in both.

  The power distribution system is composed of a series of underground structures. The areas concerned by the IST prior to the connection of user's hardware are: the tunnels, the underground galleries and the caverns.

  Fitting this general service into the arborescence is a bit more difficult than for the superconducting circuits. It may happen that the same structure covers more than one region or that one region is covered by more than one structure. The HC arborescence supports these special cases: the repetition of a node through the structure can be implemented and the information contained can be transferred to any other node. This is possible thanks to the ID assignments to each node, which will be explained later in section 6.3.4.

- *Beam Instrumentation*

  At the level of the cold regions, the beam instrumentation found in the sectors are beam position monitors and beam loss monitors which are mounted respectively inside the cold mass of the magnets or just around them. They can be divided by continuous cryostat (i.e. volumes between contiguous beam sectors valves) which matches the definition of regions.

- *Cryogenics*

  Cryogenics as an equipment group includes refrigerators and cryogenics distribution lines, controls, instrumentation, as well as the insulation vacuum.

  Instead of filling up the next levels of the arborescent structure with the different equipment enumerated above, in order to assure their readiness with the IST, this equipment group responsible has decided to include them in a sequence of tests. Thus, at this level the reported tests will be both hardware commissioning tests and individual system tests.

  In this case there is no specific information by region but by sector; this leads to an information impact through all the regions of a sector. Even if the information is the same in all the regions, it is important to show them in each one because other equipment groups, as for instance superconducting circuits, need to use this information to proceed with their own tests [52].

  One cryogenic node is present in each cold region what corresponds to a total of 58 nodes in the arborescent structure. In order to fit better the specifications of this equipment group each node of Cryogenic may be, in a near future composed of diverse nodes representing smaller fractions.

- *Distribution Feed-Box (DFB)*

  There is a total of 52 DFBs [104] in the machine and each one has a node in the structure. Since these elements are directly linked to the cryostat. There is at leat one DFB by cold region.

- *Superconducting Circuits*

  Each superconducting circuit is composed of magnets, power converters, DFBs and DC cables. The magnets that are part of the circuit are superconducting, which means that stable cryogenic conditions are needed for their operation. They are always placed in the cold regions. Each circuit is placed only in one region so there is no need to transfer information or nodes across regions.

  The HC arborescence for each region contains an exhaustive list of active circuits, which will be commissioned under the same HC test procedure [94], [105]. To agree with the commissioning strategy (see Section 8.5), the 60 A circuits the so called closed orbit correctors, are all separately grouped in one node. Unlike all the other circuits, the closed orbit correctors do not have any internal arborescent structure. There is a total of 58 describing nodes for circuits in the whole machine. Inside each of these nodes there is a list of circuits. The total number of circuits attached to the nodes is 1564.

- *Vacuum*

  The vacuum equipment group covers both warm and cold regions but different procedures are applied for each of them [106]. This characteristic and its implementation will be widely explained in the next chapter since it is transparent in the HC arborescence. In the arborescence we just see that the equipment group is there as a node, but it will be when storing information that it will be clear that the same information is in several nodes.

  For the cold regions, the insulation vacuum system uses a granularity that is represented by the HC regions. Between two vacuum pump groups there is, at least, one vacuum subsector (see Figure C.2).

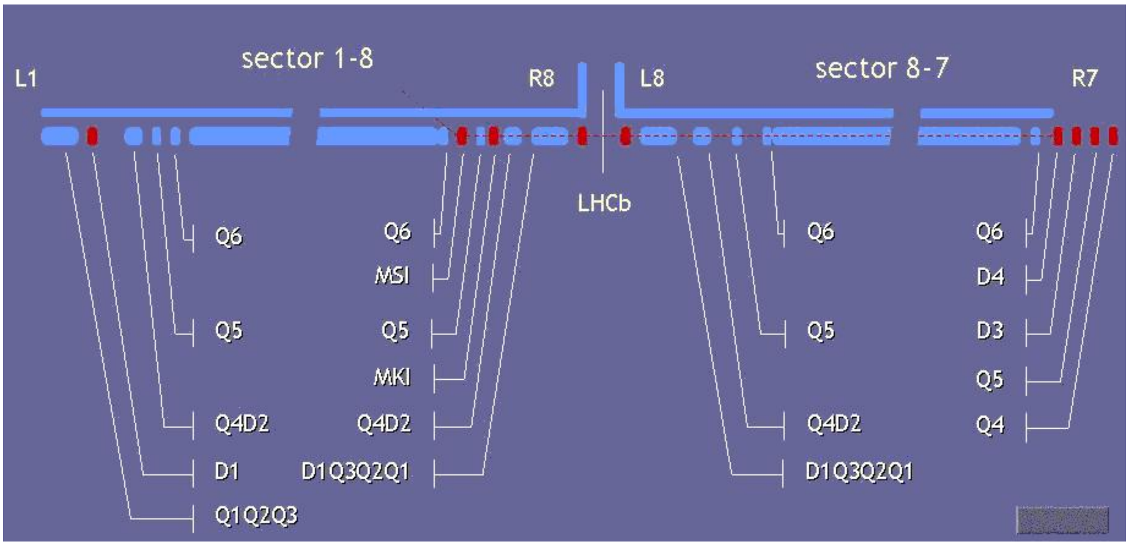


Figure C.2: Cold Vacuum divisions for sectors 1-8, and 7-8.

  One vacuum node is present in both cold and warm regions that correspond to a total of 109 nodes in the arborescent structure.

- *Ventilation*

  The commissioning tests of the region cannot start if the cooling and the ventilation are not nominally operating. In this case we find the same situation as for other general services where the nodes are repeated throughout the arborescence.

  This equipment is commissioned by underground areas, so each cooling and ventilation node placed in the regions contains the underground areas concerned by the region.

  There is one descriptive node per region and inside of each node there is an smaller sectorization of the equipment group.

Equipment groups for warm regions

- *AC Distribution*

  See AC distribution in the cold regions.

- *Beam Instrumentation*

The beam instrumentation system has part of its IST performed during its installation and is completely independent from any other system (excluding the general services). It is the case of some equipment like for instance the beam loss monitors and beam position monitors placed in the cold regions. Such IST tests are not considered as part of the hardware commissioning phase but part of the installation. On the other hand, the equipment that are placed in the warm regions need other systems to perform their tests so they are considered under the HC coordination.

Beam instrumentation elements are installed in almost all the warm regions and match perfectly the HC region division.

- *Collimators*

  The collimators equipment group has the equipment strategically distributed in the main ring as showed in Figure 3.3 It is always located in a HC warm region but is not present in all of them.

  The collimators node is a descriptive node and it is broken down in several equipment groups, the number depending on the region. There is a total of 172 collimators around the machine. IST and HC [107] will be applied by collimators, as explained in Chapter 3.

- *Forward Detectors of the LHC Experiments*

  This type of detectors are used to do physics with the particles that scape from the high luminosity detectors placed on points 1, 2, 5 and 8. They are placed in warm regions, are part of the beam line and are commissioned in co-activity with the rest of the LHC components.

- *Normal-Conducting Circuits*

  Each normal-conducting circuit is composed of classical magnets, power converters and cables. The magnets that are part of the circuit are resistive, which means that no cryogenic conditions are needed for their operation. The main difference with respect to the superconducting circuits is that there are some circuits that correspond to more than one region, so some nodes are repeated in two regions. This is due to the fact that the power converter is placed in the surface so it feeds both sides of the point.

  The HC arborescence for each warm region containing circuits presents an exhaustive list that will be commissioned under the same HC procedure [66], [108].

  There is a total of 13 warm regions containing normal-conducting circuits and a total of 46 circuits for all the machine.

- *Vacuum*

  The room temperature vacuum equipment group is present in all the warm regions as it provides a continuous characteristic needed in the whole beam pipe. Its granularity matches exactly the HC regions division [106]. The conclusion of part of its commissioning is needed for the start up of other systems commissioning.

- *Ventilation*

  Not all the warm regions have the need of ventilation for their tests. So, even if there is the presence of ventilation everywhere in the warm regions it will be specified only if any system (e.g.warm magnets) has this as a pre-requisite for their tests..

C.0.3 Fourth level: the equipment within equipment group

Beam Instrumentation

All the groups of elements specified below (equipment), are placed between two vacuum valves. All of them are normally placed in warm regions, with the exception of the BLM and the BPM that can be found in both, cold and warm regions. Around point 4 there is maximum amount of beam instrumentation placed. All these equipment are traced at the level of regions. The equipment forming this equipment group are the following.

For point 4:

- *BI DC Beam Current Transformers for the Rings*
- *BI Fast Beam Current Transformer*
- *BI Ion Profile Monitor*
- *BI Stripline Kicker for PLL Measurement*
- *BI Schottky Monitor*
- *BI Synchrotron Radiation Telescope*
- *BI Wire Scanner Profile Monitor*

For the rest:

- *BI Beam Loss Monitor(BLM)* all around the machine.
- *BI Beam Position Monitor(BPM)* all around the machine.
- *BI TAN Type Luminosity Monitor* can be found around point 1 and point 5 since the instrument is designed to monitoring the High Luminosity Experiments.
- *BI Standalone Luminosity Monitor* only found around point 8 and 2, which means the sectors around these points.
- *BI Beam Observation TV Monitor* only found around point 2,6,4.
- *BI VME Crate* all the points (this is the only one at the level of points).

Beam dumping system

As already explained, this equipment group is only found at the level of point 6. The commissioning will proceed in the different equipment specified below before in an independent way IST and only at the end there will be a common test for all of them in order to consider the equipment group commissioned. The different equipment are:

- *Collimator for Q4 Protection (IR6)*
- *Mask for Q4 Protection (IR6)*
- *Collimator for MSD Protection (IR6)*
- *LHC Beam Dumping System*
- *Dump for Ejected Beam, External*

Beam injection system

This equipment group follows the same rules as the previous one. The different equipment are:

- *Beam Injection System*
- *Diluter Dump Kicker*
- *Ejection Dump Kicker*
- *Injection Kicker*

Radio frequency

This equipment group follows the same rules as the previous one. The different equipment are:

- *RF Normal Conducting Cavity*
- *RF Coaxial Line for Normal Conducting Cavity Module*
- *RF Superconducting Bare Cavity*
- *RF Superconducting Cavity Module*
- *RF Transverse Damper*
- *RF Instrumentation*

Superconducting circuits

A very meticulous study of each equipment involved in this equipment group has been carried out. This has been documented with the collaboration of the system owners and the HCWG [83].

For the superconducting circuits the equipment that will be commissioned together are specified below and are always the same in every circuit node, excluding the energy extraction system which is present only in some kind of circuits (see Chapter 3.

- *Magnets*

  One node represents each circuit which contains a determinate number of magnets. this simplifies the tasks since the about 10.000 magnets can be treated in this way.

- *Power Converters (PC)*

  Most of the circuits are fed with just one power converter i.e. one unique node. There are few exceptions (the inner triplet circuits [109] and the matching quadrupoles) that are fed with two or three power converters and each of them are represented in the structure with a unique node.

  These equipment are the only ones that after the IST and before the global equipment group commissioning (powering tests) undergo some intermediate hardware commissioning tests called short circuit tests [57]. As explained in Chapter 3, QPS, EE, PIC and the PC are tested together and all the results are stored in a level that for the rest of the equipment corresponds to the IST.

  There are 1712 nodes in the structure representing all the power converters of the machine.

- *Quench Protection System*

  This equipment is part of each superconducting circuit (with the exception of the closed orbit correctors). The nodes placed in each circuit represent the group of elements from the quench protection system that are on the circuit.

  There is a total of 820 nodes representing these equipment in the whole machine.

- *Energy Extraction System*

  This equipment is part of the 13 kA and 600 A circuits, with energy extraction, and therefore a node is placed for each of these circuits [64]. Each node represents the EE group of active elements actives in the circuit (e.g. switches, resistors and control). The IST completion will be needed for the start of the power converters tests.

  In the whole machine there is a total of 226 nodes for these equipment.

- *Control: Powering Interlock System*

  This equipment is part of each superconducting circuit, with the exception of the closed orbit correctors. Figure 3.12 shows the distribution of its PLCs around the ring. The IST [93] are needed for the equipment group to be commissioned.

  There is a total of 820 nodes for the whole machine.

- *Power Cables*

  This equipment is part of each circuit and connects the power converters with the magnets. A node is placed in each circuit, excluding the closed orbit correctors. The exclusion of the cables in the closed orbit correctors does not mean that they do not exist; it means that the tests are part of the SCT of the converters.

  The power cables have been classified in different groups depending on the circuit types. This differentiation, as for the circuits, is not represented in the HC arborescence structure but in the MTF and will be explained in the following section. The IST have to be finished before the power converters tests can start.

  A total of 820 nodes have been implemented in the structure representing these equipment.

- *Cooling*

  This equipment is part of each circuit, excluding circuits with a nominal working intensity smaller than 120 A. It provides cooling conditions to some of the equipment (i.e. power converters racks, water cooled power cables and energy extraction switches) composing the equipment group. Trace of IST [110] at this level has been strongly requested.

  The cooling of the superconducting circuits has two different fields of action: the power converters and the power cables that are water cooled.

  There is a node by circuit so a total of 820 nodes for the whole machine.

- *Electrical Quality Assurance*

  The HC arborescence structure represents this equipment with a node in each circuit so a total of 820 nodes.

Normal-conducting circuits

The structure and equipment in a normal-conducting circuit equipment group follows the same ideas as for the superconducting one. All the IST of the equipment specified below need to be finished and documented before the commissioning of the equipment group.

- *Magnets*

  As for the superconducting circuits the magnets are intrinsically part of the circuit. In the arborescent structure they are represented by one node.

- *Power Converters*

  The power converters of the normal-conducting circuits have the same function as for the superconducting circuits but there are two notable differences: two types of power converters are used (see Chapter 3) and some nodes are repeated thought the regions [108].

- *Control: Warm Magnet Interlock Controller*

  This is a PLC based system for the protection of normal conducting magnets. Each normal-conducting circuit is protected so a node has been placed in each circuit. A total of 46 nodes are implemented.

- *Power Cables*

  The function of the power cables in the normal-conducting circuits is the same as for the superconducting circuits [110]; therefore the same pattern is followed one node per circuit. On the contrary, in this equipment group we will not find different types of power cables (in terms of commissioning tests procedure). A total of 46 nodes are implemented.

- *Cooling*

  This equipment is part of each circuit to provide cooling to the equipment forming the equipment group, mainly the power converter. A node is needed in each circuit and not repeated anywhere else. A total of 46 nodes are implemented.

Appendix D

Hardware commissioning MTF implementation

This appendix gives some examples of implementation in MTF of the arborescence for the Hardware Commissioning Project. The full implementation can be found in the web page http://hcc.web.cern.ch/hcc/mtf_links.html.

Profiles

The table D.1 gives the list of profile names and codes, for the equipment and equipment groups implemented in the HC MTF.

Power Converters Profile and Steps

There has been a definition of the profiles for each equipment and equipment group. Table D.2 shows how the equipment power converter from the equipment group superconducting circuits is divided in different profiles and the steps to be done for each profile. Equivalent lists exist for each one of the circuit types.

Steps

For each hardware commissioning profile there is an exhaustive list of steps implemented in the HC MTF that has to be executed. Table D.3 shows the steps implemented for the profile of the circuit type: main quadrupoles.

Profile Name	Code	Profile Name	Code
System d' acces LHC	Y001	Ejection Dump Kicker	MKD
AC Distribution	E000	Injection Kicker	MKI
BI Fast Beam Current Transformer	BCTF	LHC Beam Dumping System	TD
BI DC Beam Current Transformers for the Rings	BCTD	Dump for Ejected Beam, External	TDE
BI Beam Loss Monitor	BLM	Non Water Cooled Power Cables	RC12
BI DC Beam Current Transformers for the Rings	BCTD	Water Cooled Power Cables	RC13
BI Fast Beam Current Transformer	BCTF	Power Converter for 60 A Orbit Correctors	RPLA
BI Ion Profile Monitor	BGI	RF Power Converter	RPTK
BI Beam Loss Monitor	BLM	Power Converter for Cold Circuits	RR00
BI Beam Position Monitor	BPM	Power Converter for Warm Circuits (T2)	RW00
BI Stripline Kicker for PLL Measurement	BQK	Power Converter for Warm Circuits (T1)	RW01
BI Schottky Monitor	BQS	Powering Interlock	RC07
BI TAN Type Luminosity Monitor	BRANA	Quench Protection	RC08
BI Standalone Luminosity Monitor	BRANB	RF Normal Conducting Cavity	ACN
BI Synchrotron Radiation Telescope	BSRT	RF Superconducting Bare Cavity	ACSCA
BI Beam Observation TV Monitor	BTV	RF Transverse Damper	ADT
BI VME Crate	BV01	RF Instrumentation	APWL
BI Wire Scanner Profile Monitor	BWS	RF Instrumentation	APWL
WorldFip Segment	CBW1	Radiation Monitoring - Standard RP	PM01
Beam Interlock System	CIB	Radiation Monitoring Air, Water, Standalone	PM02
Fast Magnet Current Change Monitor	CIF	Evacuation	SE01
Warm Magnet Interlock Controller	CIW	Fire Detection	SF01
LHCf	X1FC	Oxygen Deficiency Hazard	SO01
LHCf	X1FC	Main Superconducting Circuit	RC02
ATLAS Zero Degree Calorimeter	X1ZDC	Main Quadrupole Circuit	RC22
TOTEM Roman Pot	XRP	Individually Powered Dipole Circuit	RC21
Collimator	TC	SC 600 A Without EE Circuit	RC03
Collimator for Q4 Protection (IR6)	TCDQ	Superconducting 60 A Orbit Correctors Circuit	RC05
Mask for Q4 Protection (IR6) Slot	TCDQM	Superconducting 120 A Correctors Circuit	RC04
Collimator for MSD Protection (IR6)	TCDS	Superconducting 600 A Without EE With Crowbar Circuit	RC17
Cooling	RC09	SC 600 A Without EE Circuit	RC03
Cooling and Elettas Calibration	RC15	Superconducting 600 A With EE Circuit	RC06
Cryogenics	RC11	Inner Triplets Plus Individually Powered Quadruples and Dipoles Circuit	RC18
DFB	DFB	Inner Triplet Circuit	RC19
600 A Energy Extraction System	DQE1	Ventilation	RC10
13 kA Energy Extraction System	DQE2	Transfer Line Electrical Circuit	RC20
ELQA for Warm Circuits	DE01	Warm Electrical Circuit Type 2	RC00
ELQA	RC14	Warm Electrical Circuit Type 1	RC01
Diluter Dump Kicker	MKB		

Table D.1: Profiles implemented in the HC MTF

Equipment Description	Profile	NoSteps	Steps Description
Power Converter for 60 A Orbit Correctors	RPLA	5	10-HCA PCSCT-PT Converter Connected to Grid
Power Converter for 60 A Orbit Correctors	RPLA	5	16-HCA PCSCT-PT Convert.On/Control Loop Tuned
Power Converter for 60 A Orbit Correctors	RPLA	5	24-HCA PCSCT-PT 4-Hour Heat Run
Power Converter for 60 A Orbit Correctors	RPLA	5	26-HCA PCSCT-HR 24-Hour Heat Run
Power Converter for 60 A Orbit Correctors	RPLA	5	30-HCA PCSCT CLW Lead Protection at warm
RF Power Converter	RPTK	8	10-PC Individual System Tests
RF Power Converter	RPTK	8	20-PC Connection to the Grid
RF Power Converter	RPTK	8	30-PC Interlock Tests
RF Power Converter	RPTK	8	40-PC Setting (Half Power Configuration)
RF Power Converter	RPTK	8	50-PC Performance Tests (Half Power Config.)
RF Power Converter	RPTK	8	60-PC Setting (Full Power Configuration)
RF Power Converter	RPTK	8	70-PC Performance Tests (Full Power Config.)
RF Power Converter	RPTK	8	80-PC Thyratron Protection Tests
Power Converter for Cold Circuits	RR00	11	10-HCA PCSCT-PT Converter Connected to Grid
Power Converter for Cold Circuits	RR00	11	12-HCA PCSCT-PT Fast Power Abort Test
Power Converter for Cold Circuits	RR00	11	14-HCA PCSCT-PT Loss of Cooling Water
Power Converter for Cold Circuits	RR00	11	16-HCA PCSCT-PT Convert.On/Control Loop Tuned
Power Converter for Cold Circuits	RR00	11	18-HCA PCSCT-PT Test of EE with Current
Power Converter for Cold Circuits	RR00	11	20-HCA PCSCT-PT Check of Current Sensor
Power Converter for Cold Circuits	RR00	11	22-HCA PCSCT-PT PC Remote Operation Tests
Power Converter for Cold Circuits	RR00	11	24-HCA PCSCT-PT 8-Hour Heat run
Power Converter for Cold Circuits	RR00	11	25-HCA PCSCT-PT MQM Squeezing Tests at Warm
Power Converter for Cold Circuits	RR00	11	26-HCA PCSCT-HR 24-Hour Heat Run
Power Converter for Cold Circuits	RR00	11	28-HCA PCSCT-HR 24-Hour Monit. Air/Water Temp
Power Converter for Warm Circuits (T2)	RW00	8	10-HCA PCSCT-PT Converter Connected to Grid
Power Converter for Warm Circuits (T2)	RW00	8	12-HCA PCSCT-PT Fast Power Abort Test
Power Converter for Warm Circuits (T2)	RW00	8	14-HCA PCSCT-PT Loss of Cooling Water
Power Converter for Warm Circuits (T2)	RW00	8	16-HCA PCSCT-PT Convert.On/Control Loop Tuned
Power Converter for Warm Circuits (T2)	RW00	8	22-HCA PCSCT-PT PC Remote Operation Tests
Power Converter for Warm Circuits (T2)	RW00	8	24-HCA PCSCT-PT 8-Hour Heat run
Power Converter for Warm Circuits (T2)	RW00	8	26-HCA PCSCT- HR 24 - Hour Heat Run
Power Converter for Warm Circuits (T2)	RW00	8	28-HCA PCSCT-HR 24-Hour Monit. Air/Water Temp
Power Converter for Warm Circuits (T1)	RW01	1	10-Power Converter IST

Table D.2: Profiles for the equipment group power converters

Equipment Description	Profile	NoSteps	Steps Description
Main Quadrupole Circuit	RC22	38	00-MPP OK to start powering
Main Quadrupole Circuit	RC22	38	01-HCA PIC1.1 Tests Software Link (PIC-Cryo)
Main Quadrupole Circuit	RC22	38	02-HCA PIC1.2 Tests Software Link (PIC-QPS)
Main Quadrupole Circuit	RC22	38	03-HCA PIC1.3 PC Permit
Main Quadrupole Circuit	RC22	38	04-HCA PIC1.4 Powering Failure
Main Quadrupole Circuit	RC22	38	05-HCA PIC1.5 Circuit Quench via QPS
Main Quadrupole Circuit	RC22	38	06-HCA PIC1.6 Fast Abort Request via PIC
Main Quadrupole Circuit	RC22	38	07-HCA PIC1.7 Discharge Request via PC
Main Quadrupole Circuit	RC22	38	08-HCA PIC1.8 Discharge Request via PIC
Main Quadrupole Circuit	RC22	38	091-HCA PCL Current Leads Verification
Main Quadrupole Circuit	RC22	38	097-HCA PCC.3 Converter Configuration 1Q
Main Quadrupole Circuit	RC22	38	09-HCA PIC1.9 Test Hardware Links
Main Quadrupole Circuit	RC22	38	10-HCA PIC2.1 Tests Software Link (PIC-Cryo)
Main Quadrupole Circuit	RC22	38	11-HCA PIC2.2 Tests Software Link (PIC-QPS)
Main Quadrupole Circuit	RC22	38	12-HCA PIC2.3 PC Permit
Main Quadrupole Circuit	RC22	38	13-HCA PIC2.4 Powering Failure
Main Quadrupole Circuit	RC22	38	14-HCA PIC2.5 Circuit Quench via QPS
Main Quadrupole Circuit	RC22	38	15-HCA PIC2.6 Fast Abort Request via PIC
Main Quadrupole Circuit	RC22	38	16-HCA PIC2.7 Discharge Request via PC
Main Quadrupole Circuit	RC22	38	17-HCA PIC2.8 Discharge Request via PIC
Main Quadrupole Circuit	RC22	38	18-HCA PIC2.9 Test Global Protection Mech.
Main Quadrupole Circuit	RC22	38	19-HCA PIC2.10 Test Hardware Links
Main Quadrupole Circuit	RC22	38	332-HCA PLI1.d2 Unipolar Powering Failure
Main Quadrupole Circuit	RC22	38	355-HCA PLI1.f5 Heater Provoked Quench 13 kA
Main Quadrupole Circuit	RC22	38	413-HCA PLI2.b3 Energy Extraction from QPS
Main Quadrupole Circuit	RC22	38	442-HCA PLI2.e2 Slow Power Abort 13 kA
Main Quadrupole Circuit	RC22	38	451-HCA PLI2.f1 Heater Provoked Quench 13 kA
Main Quadrupole Circuit	RC22	38	513-HCA PLI3.b3 Energy Extraction from QPS 13 kA
Main Quadrupole Circuit	RC22	38	532-HCA PLI3.d2 Unipolar Powering Failure
Main Quadrupole Circuit	RC22	38	551-HCA PLI3.f1 Heater Provoked Quench 13 kA
Main Quadrupole Circuit	RC22	38	613-HCA PLI4.b3 Energy Extraction from QPS 13 kA
Main Quadrupole Circuit	RC22	38	713-HCA PNO.b3 Energy Extraction from QPS 13 kA
Main Quadrupole Circuit	RC22	38	732-HCA PNO.d2 Unipolar Powering Failure
Main Quadrupole Circuit	RC22	38	751-HCA PNO.f1 Heater Provoked Quench 13 kA
Main Quadrupole Circuit	RC22	38	9985-HCA PCR Circuit Released by PO
Main Quadrupole Circuit	RC22	38	9986-HCA PCR Circuit Released by QPS/EE
Main Quadrupole Circuit	RC22	38	998-HCA PTT Circuit Type Test
Main Quadrupole Circuit	RC22	38	999-HCA PCR Circuit Released

Table D.3: List of steps for the type of circuits : main quadrupole circuits

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