EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN - ACCELERATORS AND TECHNOLOGY SECTOR

CERN/ATS 2010-178

COMMISSIONING AND FIRST OPERATION OF THE LARGE HADRON COLLIDER (LHC)

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Abstract

After some fifteen years of construction, the Large Hadron Collider (LHC) was commissioned at CERN, the European Organization for Nuclear Research in 2008. This high-energy particle accelerator of 26.7 km circumference – the largest scientific instrument ever built – brings into collision intense beams of protons and ions to probe the structure of matter and study the forces acting on its elementary components at the TeV scale, an order of magnitude higher than the previous stateof-the-art. To guide and focus its particle beams, the LHC uses several thousands high-field superconducting magnets operating in superfluid helium at 1.9 K. The project therefore constitutes a technological feat: all its components were developed, industrialized and series produced by industrial companies according to demanding specifications. Started as a CERN undertaking – by decision of the CERN Council and its twenty European member states – the project soon became global with special contributions from Canada, India, Japan, Russia and the United States of America. After recalling the technical stakes of the project, we present the main results from the construction and commissioning phases and from the first beam operation. We also summarize the detailed investigations conducted after the incident of 19 September 2008, to analyze its causes and draw conclusions for repair and consolidation. We finally report on the restart of the machine in 2009 and on its first operation for physics.

Invited plenary lecture at the 23rd International Cryogenic Engineering Conference (ICEC 23)
Wroclaw, Poland, 19-23 July 2010

Geneva, Switzerland

August 2010

Commissioning and First Operation of the Large Hadron Collider (LHC)

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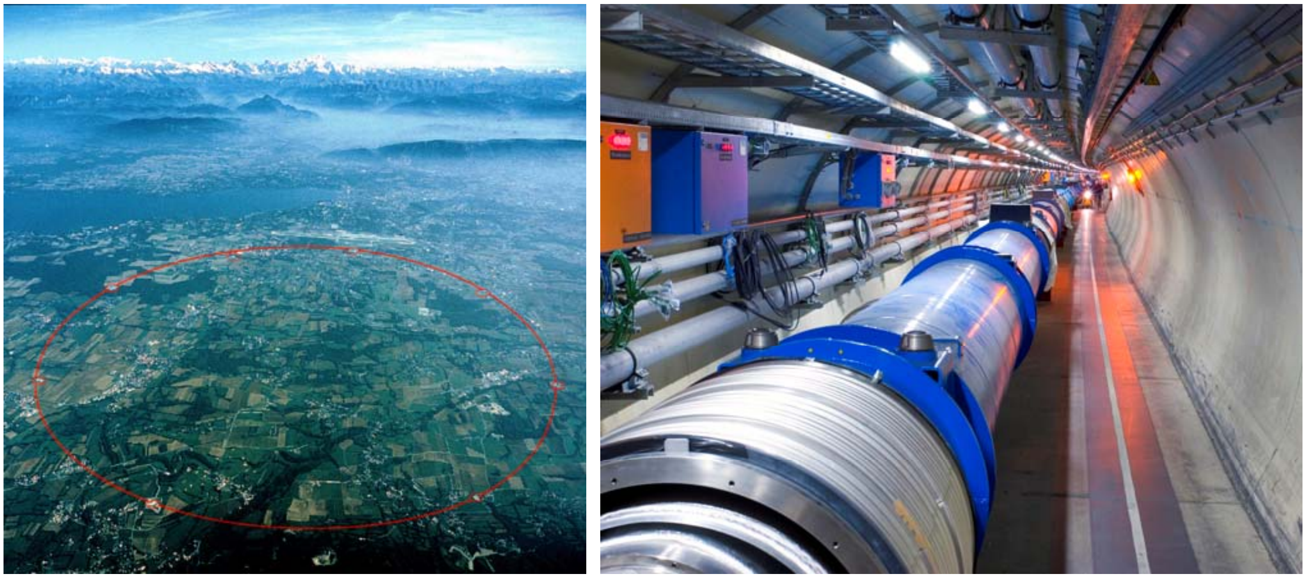
After some fifteen years of construction, the Large Hadron Collider (LHC) was commissioned at CERN, the European Organization for Nuclear Research in 2008. This high-energy particle accelerator of 26.7 km circumference – the largest scientific instrument ever built – brings into collision intense beams of protons and ions to probe the structure of matter and study the forces acting on its elementary components at the TeV scale, an order of magnitude higher than the previous state-of-the-art. To guide and focus its particle beams, the LHC uses several thousands high-field superconducting magnets operating in superfluid helium at 1.9 K. The project therefore constitutes a technological feat: all its components were developed, industrialized and series produced by industrial companies according to demanding specifications. Started as a CERN undertaking – by decision of the CERN Council and its twenty European member states – the project soon became global with special contributions from Canada, India, Japan, Russia and the United States of America. After recalling the technical stakes of the project, we present the main results from the construction and commissioning phases and from the first beam operation. We also summarize the detailed investigations conducted after the incident of 19 September 2008, to analyze its causes and draw conclusions for repair and consolidation. We finally report on the restart of the machine in 2009 and on its first operation for physics.

INTRODUCTION

The Large Hadron Collider (LHC) [1] is now currently delivering colliding beams of protons at the unprecedented center-of-mass energy of 7 TeV, to the six particle physics experiments located in four underground caverns around its 26.7 km circumference (Figure 1). This is both the end of a long story of engineering design, targeted R&D in the key technologies of superconducting magnets and cryogenics, industrialization, construction, installation and commissioning, and the beginning of a twenty-year operation phase for physics at the energy frontier (Table 1). In the following, we recall the essential features of the project [2] and describe the cryogenic aspects of its commissioning and first operation.



(a) (b)

Figure 1 The Large Hadron Collider: (a) footprint in the Geneva basin; (b) inside the machine tunnel

Table 1 Time line of LHC project

Preliminary conceptual studies	1984
Start of structured R&D program	1990
Project approval by the CERN Council	1994
Industrialization of series component production	1996-1999
“Déclaration d’Utilité Publique” and start of civil works	1998
Adjudication of main procurement contracts	1998-2001
Start of installation of services in tunnel	2003
Cryomagnet installation in tunnel	2005-2007
Cooldown and functional tests of first sector	2007
First commissioning with beam	2008
Repair, consolidation and re-commissioning	2009
Operation for physics	2010-2030

In order to bend, focus and bring into collision intense beams of protons and ions at center-of-mass energy of up to 14 TeV, the LHC uses several thousand high-field superconducting magnets, using Nb-Ti superconductors operating at 1.9 K in superfluid helium [3]. The 1232 dipoles (nominal field 8.33 T) and 392 main quadrupoles (nominal gradient 223 T/m), occupy most of the circumference of the machine and constitute the largest fraction of its 37’000 ton cold mass. In view of the size of the project, all such components had to be produced by industry according to CERN specifications [4]. Following quality assurance procedures applied at room temperature on the manufacturers’ premises, the superconducting magnets were assembled into their cryostats by industry on the CERN site. A major challenge was to design, series manufacture and assemble helium II cryostats with demanding thermal budget (heat inleak on the cold mass of 0.2 W/m at 1.9 K [5]) using industrial methods applied by non-specialized personnel, so as to contain costs while achieving reliable and robust performance [6]. To this end, the cryostats feature *inter alia*, an all-welded helium enclosure made of austenitic stainless steel, a gaseous-helium cooled thermal shield of extruded aluminium with built-in cooling channel, pre-fabricated blankets of multi-layer insulation around the magnet cold mass and the thermal shield, and low heat in-leak, high-strength support posts made of non-metallic composite material with heat intercepts [7]. Following assembly, each cryo-magnet was connected to a cryogenic test bench, where it underwent its first cool-down to operating temperature, leak-tightness and electrical insulation tests, instrumentation checks, powering up to resistive transition, training to 9 T and, for a sample of the total number, detailed magnetic measurements [8]. Performing these tests required considerable resources in terms of cryogenic infrastructure [9], and sustained round-the-clock operation for several years. They however proved essential to clear the cryo-magnets for installation in the tunnel, as they permitted to detect a few defects which had not been intercepted by the quality assurance checks performed at room temperature.

The cryo-magnets were then transported underground and pre-aligned to their final positions in the tunnel. Electrical and cryogenic interconnections then proceeded [10], from cryo-magnet to cryo-magnet as well as to the cryogenic distribution line previously installed in the tunnel [11], to constitute 3 km long sectors electrically powered in series from current feed boxes located at either end, through current leads using high-temperature superconductors [12]. Global leak and pressure tests finally validated the completed sectors for cryogenic operation.

MAIN FEATURES OF LHC CRYOGENICS

In parallel with the production and reception testing of cryo-magnets, the components of the LHC cryogenic system [13] were procured, installed and commissioned. The basic layout is shown in Figure 2: five of the eight access points to the tunnel are cryogenic “islands”, housing refrigeration and ancillary equipment serving the adjacent underground sectors. This configuration provides partial redundancy by allowing any of the two plants in one island to serve either adjacent sector, through an interconnection valve box. A standard island thus contains two 4.5 K cryogenic plants and two 1.8 K refrigeration units with their compressor stations, the interconnection box to the tunnel, six 250 m^3 and ten 75 m^3 gaseous helium storage vessels at 2 MPa [14], two 50’000 l liquid nitrogen vessels, piping and cryogenic lines interconnecting the different components, and a local control room.

The 4.5 K cryogenic plants, of 18 kW equivalent refrigeration capacity at 4.5 K, provide mixed refrigeration and liquefaction duties. Four of these plants were recovered from the previous LEP project and suitably upgraded [15], while the other four were procured from industry upon functional-and-interface specification [16]. All plants deliver the specified refrigeration duties with high thermodynamic efficiency, showing COP of 220 to 240 W/W at nominal capacity [17].

The 1.8 K refrigeration units provide 2.4 kW each [18] using three or four stages of hydrodynamic cold compressors, with the final compression performed at room temperature by sub-atmospheric screw compressors. The cold compressors feature axial-centrifugal impellers rotating at speeds up to 800 Hz on active magnetic bearings, thus achieving high efficiency over a dynamic range of 3:1 [19]. The combination in series of cold hydrodynamic and warm volumetric compressors, as well as the use of elaborate control strategies, yield good compliance to flow transients while ensuring COP of about 900 W/W for the 1.8 K refrigeration units at nominal capacity [20].

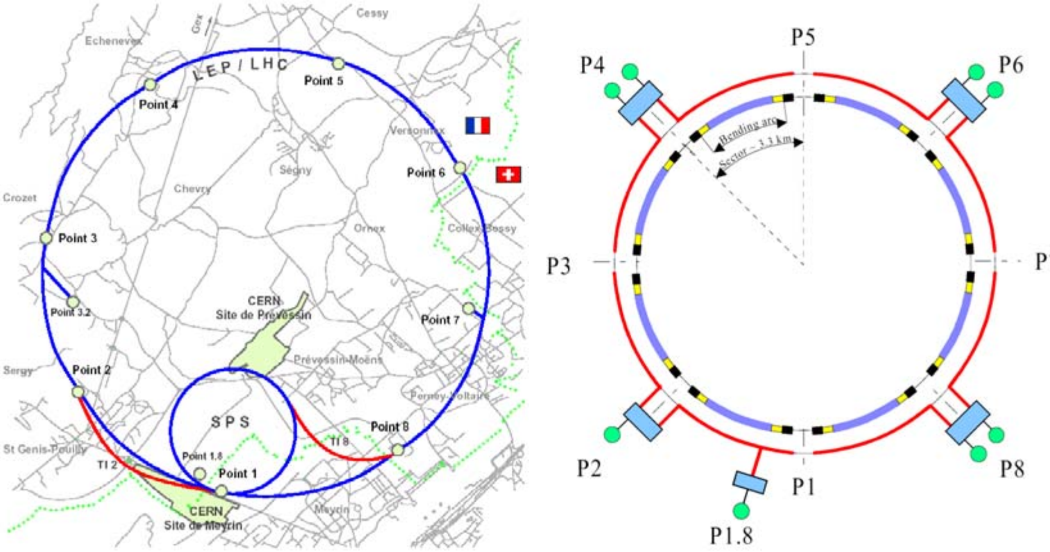


Figure 2 Simplified map of the LHC and architecture of the cryogenic system

Cryogenic instrumentation [2] matches the size and technical demands of the project, with *inter alia*, 4500 thermometers covering the range 1.6-300 K with precision up to 10 mK at the low-temperature end, and radiation-tolerant electronics. The control system is based on distributed PLC interfaced to equipment via field buses, and communicating via Ethernet to operator stations using a common SCADA protocol [21]: it simultaneously manages 4700 analog control loops.

FIRST COOLDOWN, FIRST POWERING, FIRST BEAMS

In November 2007, the first sector was cooled down to operating temperature [22, 23]. A prerequisite was to flush all cryogenic circuits with high flow of gaseous helium at room temperature from the refrigeration compressors used as circulators, with periodic removal of filters protecting the sensitive components. This procedure, systematically applied to each sector after any intervention, permitted to collect dust, debris of insulation material and metal filings from the magnets, as well as a few unexpected objects resulting from the installation field work. Controlled cooldown to about 100 K of a 4635 ton sector is achieved by forced circulation through the magnets of gaseous helium, pre-cooled at the rate of up to 600 kW by vaporization of liquid nitrogen at ground level. Thus a complete cooldown of the LHC uses some 10’000 ton liquid nitrogen, which have to be brought on site in a coordinated way by 500 semi-trailer trucks. The final cooldown and liquid helium fill of the sector is performed with the turbines of the 4.5 K cryogenic plant, after which the 1.8 K units are started to progressively subcool the helium in the magnets down to the operating temperature of 1.9 K. After tuning of the cryogenic controls for the steady operation of the sector, the heat loads were measured and the different magnet circuits powered [24]. Cooldown in turn of the seven remaining sectors was performed in the spring and early summer of 2008 (Figure 3).

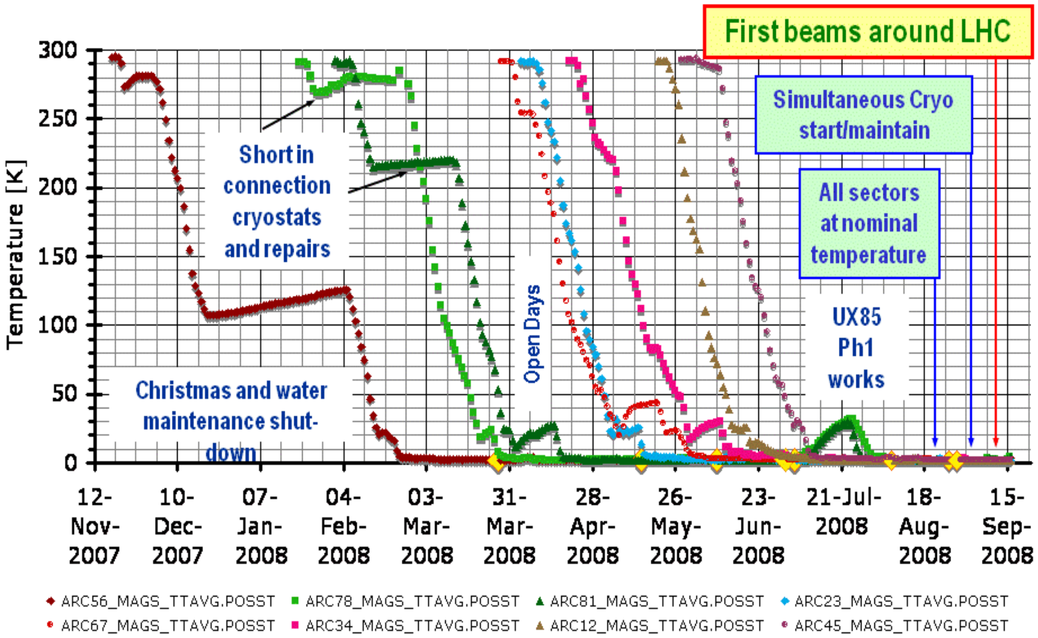


Figure 3 First cooldown of the LHC sectors and first beams in the machine

The combination of static pressurized and flowing saturated helium II in the magnet cooling scheme [13] confirmed its efficiency for extracting the heat loads under minute temperature differences, maintaining excellent temperature homogeneity along complete sectors (Figure 4), controlling temperature stability during current ramps and recovering from magnet resistive transitions. In spite of the long heat transport distances, the scheme achieves high exergetic efficiency thanks to the optimal use of the thermophysical properties of helium II and the absence of circulator pumps [25].

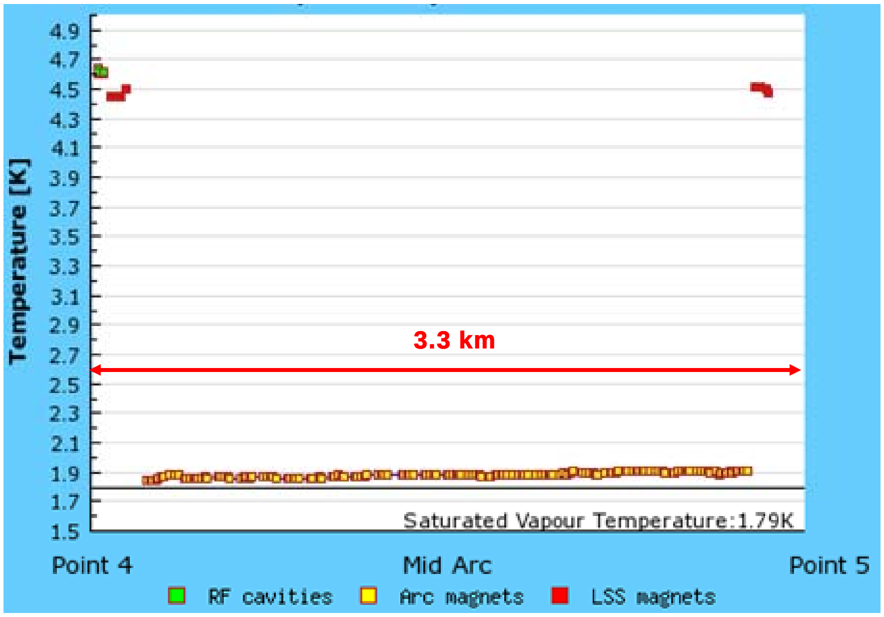


Figure 4 Measured temperature profile along a sector of the LHC; the sector is cooled from Point 4

Measurement of the steady-state heat in-leaks on different sectors show values well within the thermal budget [26] both for the magnet cryostats [27] and the cryogenic distribution lines, thus confirming *a posteriori* the methodology for sizing the cryogenic plants and the assessment of design margins [28]. All these measurements – some of them incredibly precise on such an industrial-size system – also provided a validation of the design choices and technical implementation of the LHC cryogenic instrumentation [29], in particular the calibration of thermometers [30].

In parallel with the main magnets discussed above, all other cryogenic sectors of the ring, including long straight sections at the end of the arcs [31] and low-beta insertions around the collision points [32] were also commissioned. With all accelerator systems operational – the main magnet circuits having been commissioned only up to 7 kA out of the nominal 11.85 kA – the first beams were successfully injected at 450 GeV and circulated around the LHC on 10 September 2008.

THE 19 SEPTEMBER 2008 INCIDENT

While completing commissioning of the dipole magnet circuit of sector 3-4, an electrical arc occurred at the interconnection between two magnets when the current ramp reached 8.7 kA. This was traced back to the presence of an abnormal, undetected resistance of 220 nΩ in the electrical interconnect, and of a bad contact between the superconducting cable and the copper stabilizer, the combination of which led to heat dissipation and fast thermal runaway. Although not substantiated by the quality assurance documents, it is likely that the occurrence of these two defects stemmed from a single flaw in the soldering of the interconnection. Electrical detection systems reacted as expected, triggering “fast” discharge of the 595 MJ energy inductively stored in the circuit, with an initial time constant of 100 s. Meanwhile, the resulting electrical arc, already dissipating several MW after only one second, punctured the helium and beam vacuum enclosures. The sudden discharge of helium from the magnet cold mass into the vacuum enclosure occurred at a peak rate of 20 kg/s, an order of magnitude above the sizing conditions of the relief devices on the cryostat vacuum vessel. As a consequence, the pressure in the vacuum enclosure rose to about 0.8 MPa, well above the design value of 0.15 MPa. The resulting axial pressure forces on the vacuum barriers went up to 560 kN, displacing the magnets from their supports and breaking the ground anchors. As a consequence, several other interconnections were damaged, creating secondary arcs. The inrush of helium into the beam vacuum also carried contamination by soot and chips of torn multilayer insulation to large distances into the beam pipes. About 2 t of helium were eventually released to the tunnel in the first two minutes, creating ODH conditions for several hours. A detailed analysis of the incident, including lessons drawn and recommendations, can be found in reference [33].

REPAIR, CONSOLIDATION AND RESTART

The incident damaged some 750 m of machine, requiring the removal of 53 cryo-magnets and their replacement by available spares between January and April 2009. *In situ* inspection and cleaning of the beam pipes were performed on the remaining length of the sector. The maximum credible incident for helium discharge from the cold mass was redefined [34] and 900 additional, larger pressure relief ports were fitted to the vacuum enclosure. Ground anchors were reinforced, and new longitudinal restraints were fitted to the cryostats housing the insulation vacuum barriers. A new magnet protection system monitoring the interconnections with a detection sensitivity increased by three orders of magnitude was implemented, requiring the pulling of some 250 km new cables connecting 6500 new electronic crates to the magnet terminals. High-current magnet interconnections in the other sectors of the machine were checked by calorimetric [26] and electrical methods, revealing potentially risky operation at nominal level. Following cooldown and re-commissioning of the sectors, it was therefore decided to restart the LHC at maximum center-of-mass energy of 7 TeV and operate it for physics in the period 2010-2011. A long shutdown in 2012 will then be devoted to the final consolidation to allow operation at full energy from 2013 onwards. In spite of some difficulties inherent to the first operation of such a complex system, the LHC is now running smoothly and producing collisions for physics, with an overall cryogenic availability of about 90 % [35].

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