INDUSTRIAL TECHNOLOGY FOR UNPRECENTED ENERGY AND LUMINOSITY: THE LARGE HADRON COLLIDER

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Abstract

With over 3 billion Swiss francs procurement contracts under execution in industry and the installation of major technical systems in its first 3.3 km sector, the Large Hadron Collider (LHC) construction is now in full swing at CERN, the European Organization for Nuclear Research. The LHC is not only the most challenging particle accelerator, it is also the largest global project ever for a scientific instrument based on advanced technology. Starting from accelerator performance requirements, we recall how these can be met by an appropriate combination of technologies, such as high-field superconducting magnets, superfluid helium cryogenics, power electronics, with particular emphasis on developments required to meet demanding specifications, and industrialization issues which had to be solved for achieving series production of precision components under tight quality assurance and within limited resources. This provides the opportunity for reviewing the production status of the main systems and the progress of the project.

INTRODUCTION

The Large Hadron Collider (LHC) now in construction at CERN will be the most advanced research instrument of the world's high-energy physics community for the next twenty years. It will allow exploration of the energy frontier above 1 TeV per elementary constituent, by providing proton-proton collisions at the unprecedented center-of-mass energy of 14 TeV and luminosity of 10^{34} cm^{-2}.s^{-1} to two large, multi-purpose detectors, ATLAS and CMS, and three more specialized experiments ALICE, LHCb and TOTEM. The LHC will also operate as heavy-ion (Pb) collider with luminosity of 10^{27} cm^{-2}.s^{-1}. For the sake of overall economy, the LHC reuses the 26.7 km circumference underground tunnel and technical infrastructure of the former LEP collider. It is served by the CERN injector complex, suitably upgraded to meet the demanding requirements of the new machine. These technical constraints set the general layout of the accelerator, consisting in eight 3.3 km sectors. Each sector connects two interaction points (IP) *via* a 2.5 km arc, two adjacent dispersion suppressors (DS) and two half insertion regions (IR). Of the eight insertion regions, four contain beam crossing points dedicated to physics experiments and the remaining four are used for beam acceleration (RF), beam instrumentation, beam cleaning and beam disposal. The layout and lattice configurations of the LHC were described in previous status reports at particle accelerator conferences [1, 2]. Detailed technical information on the project is available in the recently updated design report [3].

PARAMETERS AND PERFORMANCE

A look at the high-energy and high-luminosity colliders in operation or in construction around the world clearly reveals the outstanding performance challenges of the LHC, with a beam energy 7 times, and a luminosity 100 times higher than the previous state-of-the-art. To meet these ambitious goals, the LHC has required substantial developments in accelerator physics and technology [4], illustrated by the parameters in Table 1. The beam optics combines robustness against lattice perturbations in a large machine with flexibility to cope with future layout modifications. The high collision energy is achieved by guiding and focusing the two rigid, counter-rotating beams around the circumference of the collider through a system of twin-aperture, high-field superconducting magnets operating at 8.3 T in superfluid helium below 2 K, and bringing them into collision at small crossing angle in the four locations equipped with detectors. The high luminosity is obtained by colliding many bunches at high rate, each of them densely populated and having small transverse dimensions. This results in several challenging beam physics issues [5] – single-particle and collective effects [6], resonant acceleration of electrons by the bunch potential (electron cloud) [7], limitation of dynamic aperture by the non-linear field errors in the superconducting magnets.

Table 1: Main parameters of the LHC with protons

Circumference	26.7	km
Beam energy at collision	7	TeV
Beam energy at injection	0.45	TeV
Dipole field at 7 TeV	8.33	T
Luminosity	10^{34}	cm^{-2}.s^{-1}
Beam current	0.56	A
Protons per bunch	$1.1x10^{11}$	
Number of bunches	2808	
Nominal bunch spacing	24.95	ns
Normalized emittance	3.75	µm
Total crossing angle	300	µrad
Energy loss per turn	6.7	keV
Critical synchrotron energy	44.1	eV
Radiated power per beam	3.8	kW
Stored energy per beam	350	MJ
Stored energy in magnets	11	GJ
Operating temperature	1.9	K

The jumps in energy and luminosity with respect to previous accelerators also translate into a factor 100 on beam stored energy. The 350 MJ in each beam of the LHC are sufficient to melt some 420 kg of copper. This requires careful and reliable handling, for safe extraction and dump of the complete beam as well as for controlling beam losses in the superconducting magnets during operation [8, 9]. An adiabatic localized loss of less than 10^7 protons at 7 TeV, corresponding to some 10^{-8} of the circulating beam, is in fact sufficient to provoke a “quench”, i.e. a transition of a superconducting magnet to the resistive state. This demonstrates the importance of limiting beam losses by design, of confining most of them to cleaning insertions housing an elaborate collimation system [10, 11] and devoid of superconducting components, and of carefully monitoring the unavoidable ones in the sensitive arcs of the accelerator [12]. Even higher than the energy of the circulating beams, are the 11 GJ inductively stored in the superconducting magnets, though in eight independent sectors around the machine. Specific equipment has been designed and measures taken in order to discharge such huge energy in a controlled fashion without damage to the electrical circuits [13].

A GLOBAL ENGINEERING PROJECT

With a cost at completion of 3.2 billion Swiss francs, dominated by superconducting magnets and cryogenics, the LHC represents a large industrial project in advanced technologies (Fig. 1), several of which had to be developed expressly and validated on prototypes, a process which spread over a decade before one could proceed to industrialization and launching of series production through competitive tendering and adjudication of commercial contracts. Today some 90 main contracts are under execution, most of them in the industry of CERN member states, and a few in Canada, India, Japan, Russia and the USA through special contributions channeled via national laboratories and amounting to 13 % of the project’s value (Fig. 2). This implies a diversity of technical know-how and regional standards for components designed and constructed over

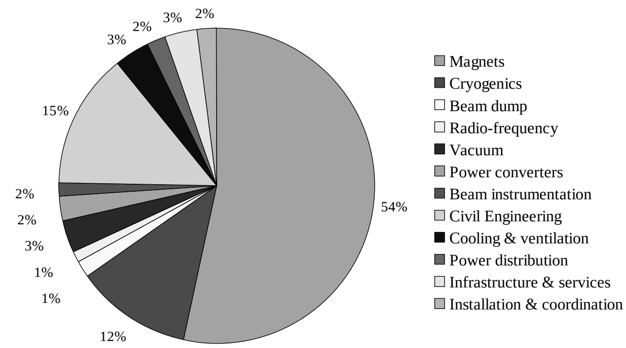

Figure 1. Cost structure of the LHC

the years by several generations of scientists and engineers, which eventually have to fit and operate together for the twenty-year lifespan of the machine. An essential tool to bridge this extended span in technological complexity, cultural diversity, geography and time is the Engineering Data Management System, which acts as a single repository of the technical memory of the project, accessible through the Web from a variety of informatics platforms. It provides world-wide availability to up-to-date design, construction and test information for components [14], and enables to construct and maintain a reference database for installation, commissioning and operation of the accelerator [15].

An idea of the quantity and diversity of LHC components is given in Fig. 3, together with the applicable domain of manufacturing organization. In most cases, the series exhibit moderate numbers and high variability, thus favoring flexible workshops, involving significant manual work and allowing individual reception testing. Only the large series of elementary components, such as magnet collars and laminations, fall

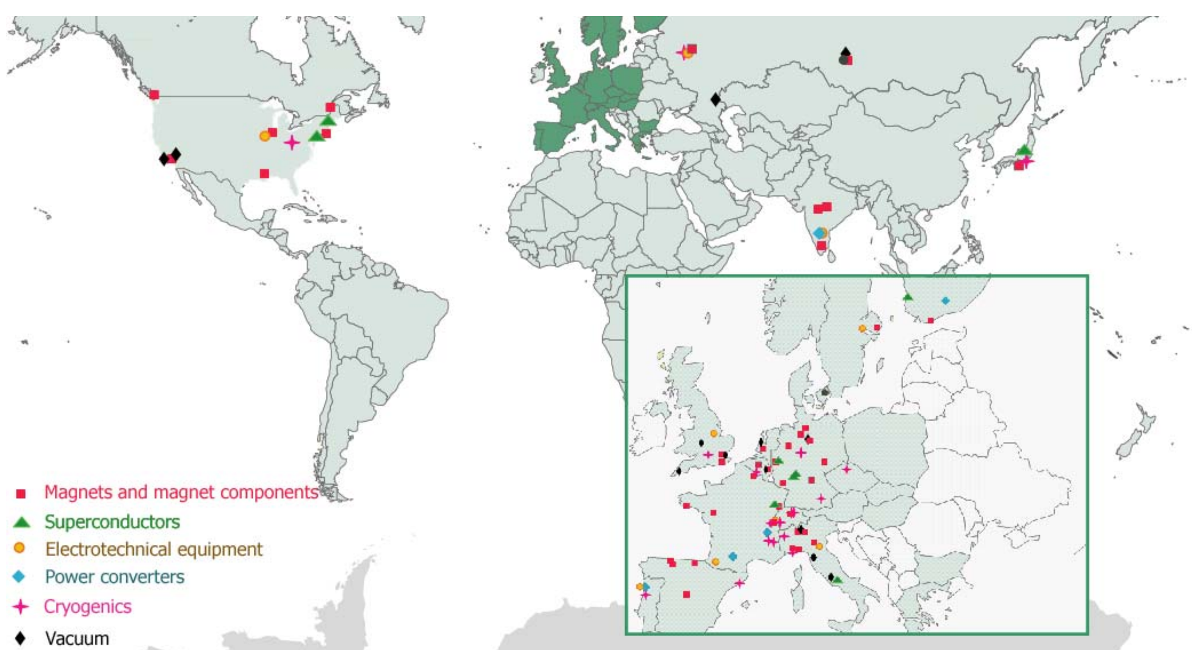

Figure 2. Geographical origin of LHC main series components.

within the domain of automatic production chains and require statistical process control. All components, whether produced by industry or assembled in the laboratory, must fulfil the demanding requirements of the project's Quality Assurance Plan, particularly as concerns management of technical documentation, approval of engineering changes, traceability of construction and test results.

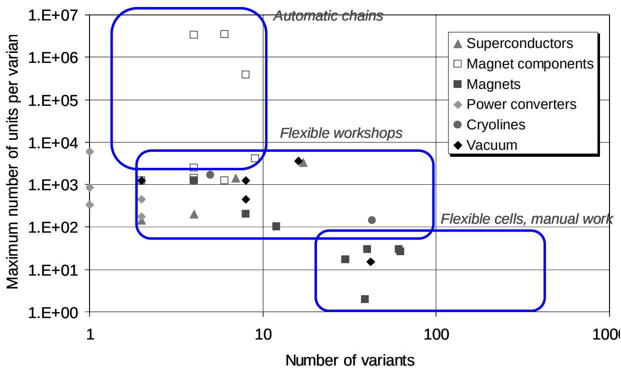

Figure 3. Variability and quantity of LHC components.

ADVANCED TECHNOLOGY ON AN INDUSTRIAL SCALE

Superconductors

The LHC requires 7000 km high-quality superconducting cable, made from 1200 tons multi-filament Nb-Ti in a copper matrix. This amounts to about 80 % of the world's yearly production, and clearly competes with the demand from MRI magnets. Five companies in Europe, Japan and the USA have produced by now about 2/3 of the total quantity, meeting the demanding specifications of filament size, cable geometry, critical current and for the first time in such a production, remanent magnetization and inter-strand resistance, two control parameters necessary to contain the low-field non-linearities, dynamic errors and ramping losses of the magnets. This was achieved through precise steering of the production, based on detailed measurements of superconductor characteristics both in industry and in the laboratories, application of homogeneization techniques to reduce natural dispersion, and thorough inspection of the cable lengths produced [16, 17].

Main superconducting magnets

The 1232 main dipoles and 392 arc quadrupoles of the LHC are high-field magnets, with peak value on the conductor respectively of 8.6 T and 6.9 T at nominal excitation. They are also precision elements of the machine optics, and in view of their series powering, must produce identical field integrals, free from multipole errors, to within a few 10^{-4}. This requires geometrical precision of typically 0.1 mm on the coil sizes, and 1 mm on the finished cold masses, multi-ton objects of length up to 15 m [18]. In order to ensure technical homogeneity of a production performed on several sites, to guarantee security of supply, and to benefit from economy of scale, CERN directly procures not only the superconductor, but most of the magnet components and provides them to the magnet assemblers. This approach, which also permits to achieve a better balance of industrial returns to the member states, however renders CERN responsible for managing an integrated supply chain, in which it appears both as intermediate supplier and end customer [19].

The main dipoles and arc quadrupoles, now produced in large numbers as build-to-print objects with limited guarantee of performance by five companies in Europe, are the result of a long development and validation process, which started in the late 1980s [20]. Although the development was essentially made in the laboratory, industry was associated very early to the process in view of the high technical challenges and economical stakes. For the dipoles, prototyping work alone proved not sufficient to complete the development, and the final industrialization was performed concurrent with pre-series production, thus leading to a slower than expected ramp-up [21].

Cryostats

In operation, the 36'800 ton cold mass of the LHC superconducting magnets exhibit a surface area of nearly 50'000 m^2 at 1.9 K. The cryostats which house the magnets must therefore achieve their demanding thermal, mechanical and geometrical performance in a robust and reliable fashion, compatible with their being produced, assembled and later interconnected by industrial methods. In view of the large capital costs incurred, the design of the cryostats is made as simple as possible, favoring standard production methods and concentrating the technical functions on specific components [22]. Support posts made of stiff glass-fiber/epoxy composite precisely position the cold mass from the outer vessel at room temperature, while limiting the heat in-leak to the 1.9 K level. A quasi-isothermal thermal shield, made of extruded aluminum profiles including a helium cooling channel, surrounds the cold mass. Multi-layer insulation is applied in the form of pre-fabricated blankets with controlled packing density. The outer vacuum vessels are essentially made of carbon steel, with stainless steel flanges. Precision beyond that of sheet-metal work, such as required for aligning the cold mass, is concentrated on the supporting areas which also feature the alignment fiducials. CERN acts as general contractor by procuring all components from industry and having the assembly of the cryostats around the magnets performed on its premises through a result-oriented industrial contract. After a learning phase, this operation is now performed at a rate matching that of the magnet deliveries.

Magnet tests and measurements

In view of the long production time and high cost of the superconducting magnets, it is essential to ascertain quality and intercept construction errors as early as possible in the production chain. This is done through an elaborate quality control, involving in particular magnetic measurements at room temperature, with the magnet windings - in the resistive state – excited by a small current. These measurements, performed on collared coils and on assembled cold masses at the industrial production sites [23], have permitted to detect, locate and correct errors which had escaped other tests and checks. The final validation of magnet performance, however, is provided by cryogenic tests following reception at CERN. Each magnet is connected in turn to a cryogenic test station, equipped with 12 benches, and fed from one of the eight large helium refrigerators of the LHC [24]. The station runs 24 hours, 7 days, thus permitting to check mechanical integrity, leak-tightness, electrical insulation and quench performance at 1.9 K in real operating conditions on all magnets, at the maximum rate of 14 per week [25]. Cold magnetic measurements, demanding in bench occupancy, equipment and manpower, are only performed on a statistical sample of the total production, typically one third. They are primarily focused on the understanding of non-linear and transient effects which cannot be observed at room temperature, and on the establishment and maintenance of so-called cold/warm correlations of field strength and quality [26, 27]. Besides quality control and production steering, these tests provide information for optimal grouping and allocation of the magnets in the tunnel, through complex though practically manageable algorithms [28], as well as for the future operation of the accelerator.

Powering

The LHC magnet circuits will be powered by 1720 power converters, with currents ranging from 60 A to 12 kA, requiring precision of few ppm over a large dynamic range and high reliability (MTBF ~ 10^5 h). Their underground implantation imposes compactness, efficiency above 80 % and for those installed in the machine tunnel, radiation tolerance. These demanding requirements are best met by the switched-mode technology, based on the use of solid-state power electronic components such as IGBTs, and implemented in the form of modular units which can be assembled, as real current sources, in a variety of configurations meeting the needs of the project [29, 30].

Feeding large currents, for a total of 1.7 MA, into the cryogenic environment requires efficient current leads to minimize the impact on cryogenics. After a product development phase making use of industrially available materials, CERN designed and validated current leads based on high-temperature superconductors, bringing a reduction of the entropic refrigeration load by a factor 3 with respect to the normal conducting technology. Following procurement of 31 km BSCCO2223 tape meeting specifications, the series leads are now in production [31].

Cryogenics

The base refrigeration load for the LHC is produced by eight large 4.5 K helium refrigerators, four of which recovered from LEP and adequately upgraded, and four new ones [32]. For reason of economy and partial redundancy, all machines are located on five sites serving adjacent sectors. They provide isothermal and non-isothermal refrigeration down to 4.5 K by supplying and recovering helium flows at different pressures and temperatures, corresponding to an equivalent entropic capacity per plant of 18 kW@4.5 K. The refrigerators were procured from industry through functional specification with an incentive in power efficiency. Adjudication was based on the sum of the quoted capital price and ten years integrated power costs, including externalities. During reception tests, the effective power consumption was measured and compared to the quoted values, thus leading to apply a bonus/malus clause. All machines produce the specified refrigeration, with efficiency around 30 % of the Carnot limit, which represents a measurable progress.

The final stage of refrigeration at 1.8 K is produced by cold hydrodynamic compressors maintaining low saturation pressure on liquid helium. These non-lubricated machines feature low heat in-leak, axial-centrifugal wheels operating at high revolution frequency on active magnetic bearings, a combination of aerospace and cryogenic technologies developed at CERN’s request by industry through a prototyping phase. The cold compressors are integrated in multi-stage configurations in eight 2.4 kW@1.8 K refrigeration units, fed from the main helium refrigerators. Extended tests on pre-series have demonstrated good performance, and the series units are now under production and installation [33].

Distribution of cryogenic refrigeration to the magnets around the ring is devoted to a compound cryogenic line, running along the tunnel wall and feeding the magnet string at every cell. Following a prequalification phase on the basis a full-scale 107 m test length, a single turn-key contract was attributed to a well-established company. Execution of the contract has been plagued with many technical and organizational problems, delaying the start of subsequent operations such as the installation and interconnection of the magnets in the ring.

CONCLUSIONS

The LHC experience confirms that large scientific projects also constitute major industrial ventures, and as such are exposed to the constraints, strengths and weaknesses of the industrial world. This is particularly true of the challenges presented by the transition from prototyping to series production, or by the step increases in production capacity achieved through the opening of new manufacturing lines and the recruitment and training of new staff, which should not impact on the quality of the products. Conversely, the necessary rigidity of running production lines against technical changes must be preserved if throughput is to be maintained and deadlines are to be met. In terms of market weight, the one-off construction of a large scientific instrument cannot compete with the recurrent demand and promise of future markets for consumer goods, thus leading to unfavorable prioritization in domains of clear overlap.

Procurement contracts which spread over many years are also subject to business instabilities, usually characterized by much shorter time scales, and the projects must be ready to cope with, and recover from mergers, buy-outs, insolvencies and bankruptcies which unfortunately are the lot of industry today.

A decade after first approval of the project, the LHC has successfully negotiated many of these challenges, as series production of most components in industry is meeting quality and delivery rate. Industrial contracts are under execution for more than 3 billion Swiss francs, of which 65 % value have been earned. Technical and organizational difficulties in the execution of a single major contract for the cryogenic distribution line in the tunnel have delayed the start of magnet installation and interconnection, as well as the reception tests of the first 3.3 km sector of the machine. Work is however proceeding with the completion of the first 2.6 km long injection line for the LHC, due to undergo beam tests in the autumn of 2004 [34]. CERN is fully committed to recover installation delays and strive for producing first collisions at the LHC in the summer of 2007.

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