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Large Hadron Collider Project

LHC Project Report 374

THE LARGE HADRON COLLIDER, A MEGASCIENCE PROJECT

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Abstract

The Large Hadron Collider (LHC) will be the next particle accelerator built to serve the world's high-energy physics community at CERN, the European Organisation for Nuclear Research. Reusing the 26.7-km circumference tunnel and infrastructure of the existing LEP collider, the LHC will make use of advanced technology - high-field superconducting magnets operated in superfluid helium - to push the energy frontier up by an order of magnitude, while remaining economically feasible. The LHC demonstrates on a grand scale several typical features of megascience projects, such as the need for international funding, world-wide co-operation and integration in the local environment, which we review in the following.

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1 Introduction

Megascience is a concept – and a neologism - coined by the OECD [1] to account for large scientific projects or programmes which, in view of their unique size, importance, complexity or duration, deserve special attention of the public and require long-term governmental commitment, often through international co-operation. Typical examples of megascience projects in physics are large experimental facilities such as astronomical telescopes and high-energy particle accelerators.

The Large Hadron Collider (LHC), a 26.7-km circumference particle accelerator presently under construction at CERN, the European Organisation for Nuclear Research near Geneva, Switzerland, will be the next large-scale world facility in high-energy physics [2]. Based on the extensive use of high-field superconducting magnets operated in superfluid helium below 2 K, the LHC will – upon its completion in 2005 - bring into collision intense beams of protons and ions at centre-of-mass energies in the TeV-per-constituent range, thus allowing to study the elementary structure of matter and its basic interactions on an unprecedentedly fine scale. In this respect, the LHC features many of the specific aspects of megascience projects, both technical and non-technical, which we shall review in the following. The basic layout of the machine, showing the location of the four large physics detectors located at the collision points, is shown in Figure 1, while its main technical parameters as a proton collider are listed in Table 1.

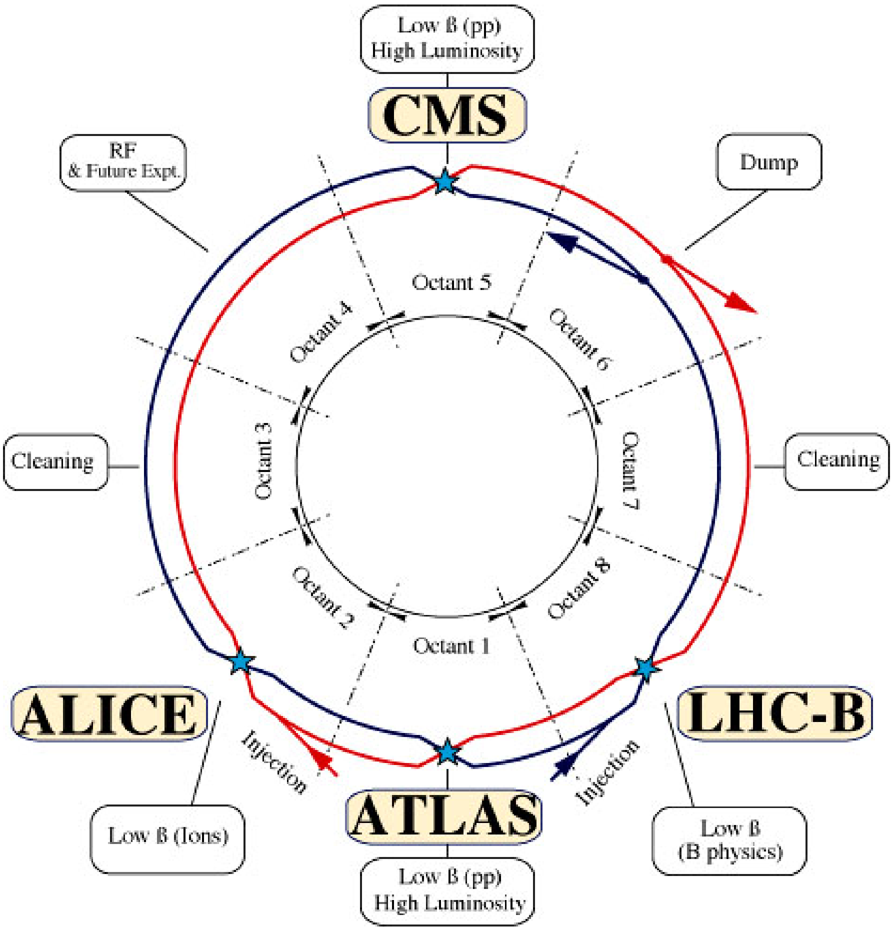

Figure 1. General layout of the LHC.

Table 1. Parameters of the LHC as proton collider.

Energy at collision	7	TeV
Energy at injection	450	GeV
Dipole field at 7 TeV	8.33	T
Coil inner diameter	56	mm
Distance between aperture axes (1.9 K)	194	mm
Luminosity	1	E34 $cm^{-2}s^{-1}$
Beam-beam parameter	3.6	E-3
Beam current	0.56	A
Bunch spacing	7.48	m
Bunch separation	24.95	ns
Number of particles per bunch	1.1	E11
Normalized transverse emittance (r.m.s.)	3.75	μm
Total crossing angle	300	μrad
Luminosity lifetime	10	h
Energy loss per turn	6.7	keV
Critical photon energy	44.1	eV
Total radiated power per beam	3.8	kW
Stored energy per beam	350	MJ

2 Economy through technology

The history of high-energy accelerators can be illustrated by the Livingston diagram [3], showing the evolution over time of the beam energy that they can deliver. This diagram shows a sustained exponential growth since the 1930s, over many orders of magnitude, thanks to the gradual implementation of emerging technologies, each superseding in due time the competing established technical solution as it began to show saturation. Thus the invention of the cyclotron and the synchrotron, the discovery of strong focusing, the construction of the first colliding beam accelerators are such essential milestones illustrating this mechanism. The most recent part of the diagram (Figure 2), plotting the available centre-of-mass energy – a parameter which allows to show on the same graph accelerators and colliders handling both leptons and hadrons – clearly establishes that the race to high energies could only be technically and economically sustained, over the last twenty years, by the emergence, diffusion and implementation of superconducting technology, in the form of high-gradient RF cavities for acceleration, and high-field magnets for bending and focusing of the particle beams. In this respect, the LHC can be seen as the latest generation of a long series of machines that have successfully developed and applied this technology. Its ambitions and challenges are however incommensurate with those of previous projects, both qualitatively – the field level in the magnets – and quantitatively – the sheer size and number of components of the ring - thus requiring novel technical developments, construction methods and managerial approaches.

2.1 High-field Nb-Ti superconducting magnets

The basic technological key to the LHC is the development and industrial production of high-field superconducting accelerator dipole and quadrupole magnets, producing magnetic induction in the 8 to 9 T range [4]. This is achieved by the winding of high-current Rutherford-type multi-strand cables of trapezoidal cross-section, in a two-layer cos θ geometry. The very large electromagnetic forces acting on the conductors are taken by non-magnetic collars resting against a stiff iron yoke, contained in an all-welded shrinking cylinder which also acts as helium enclosure and pressure vessel. The decreasing critical current density of Nb-Ti alloys with increasing induction (Figure 3) makes it impossible to use this material in normal helium at 4.5 K for building high-field magnets. After having explored the alternative of A15 compounds, e.g. Nb_3Sn, which are however plagued with their brittleness, long and costly processing at high temperature (wind-and-react process), and limited industrial availability – the LHC requires some 1200 tonnes of superconductor – CERN has decided to base the project on the use of Nb-Ti operating in superfluid helium at the temperature of 1.9 K, where it retains sufficient current-carrying capacity for building magnets up to about 10 T. This technique, which was pioneered a decade ago in the Tore Supra superconducting tokamak and other high-field magnets [5], is applied for the first time in a large accelerator. The increased current density in the superconductor when operated at lower temperature also brings economic benefits, as it allows reducing the amount of material, a major cost driver for the magnets [6]. The large dynamic range of the LHC – from 0.45 TeV at injection to 7 TeV at nominal energy for physics, also sets tight requirements on the linearity of the magnetic field, particularly at low level where persistent currents tend to produce remanence. The use of multi-filamentary Nb-Ti strands with filament diameter of 7 μm allows to maintain the remanent field effects at an acceptable level.

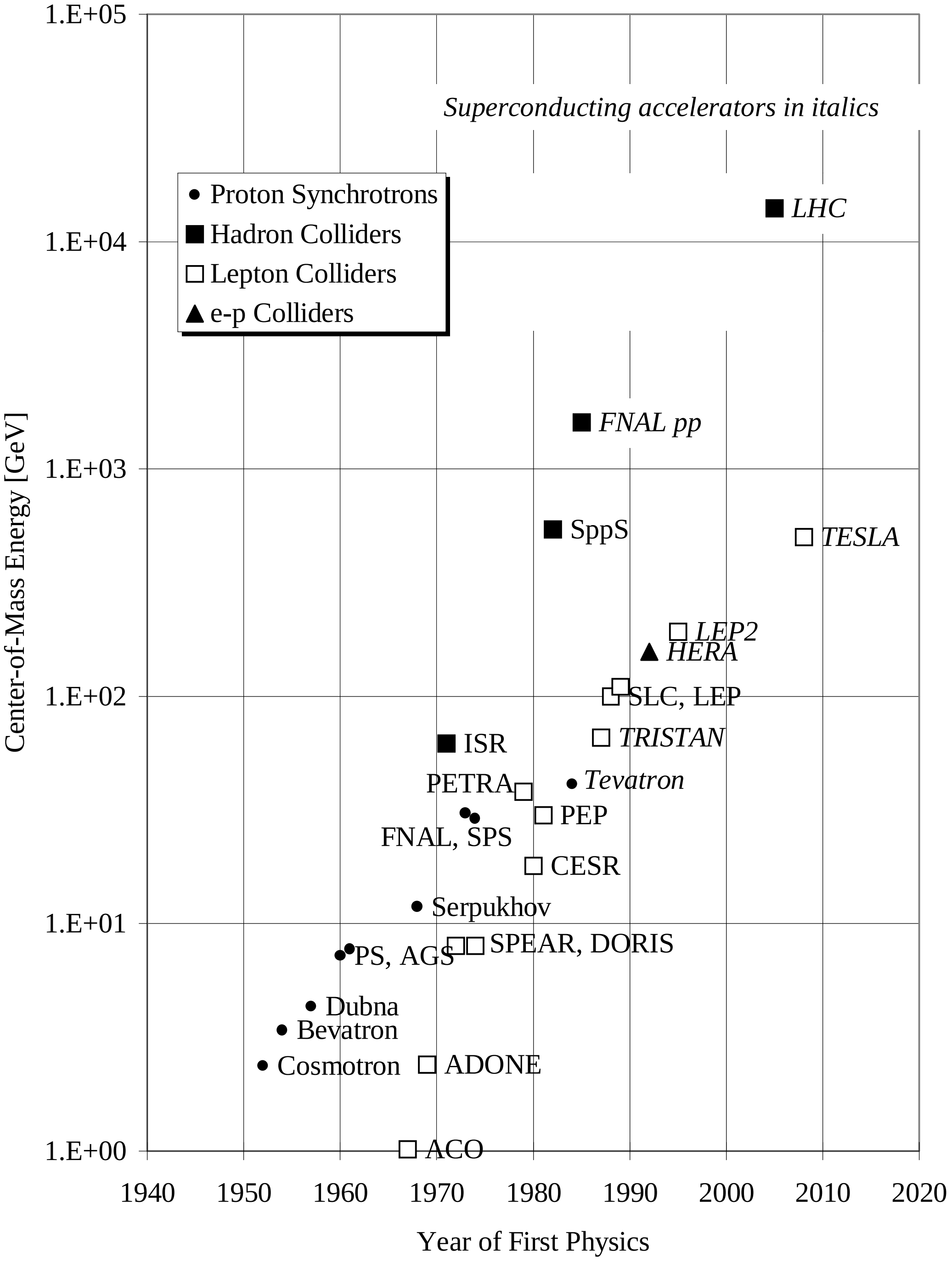

Figure 2. Superconductivity and the energy frontier in accelerators.

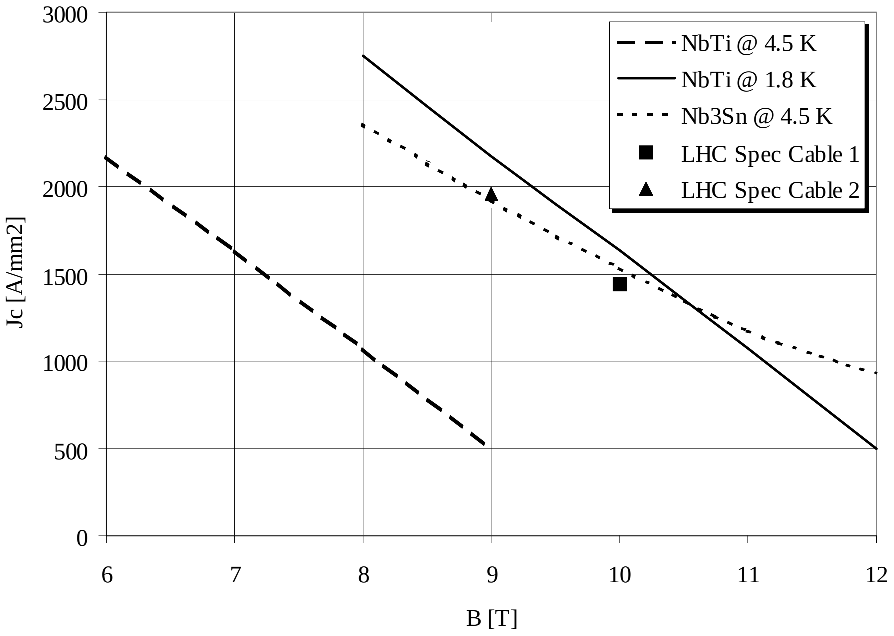

Figure 3: Critical current density of technical superconductors.

Another specific feature of the LHC main magnets is their twin-aperture design. To produce the anti-parallel fields required to guide the counter-rotating particle beams along the quasi-circular tunnel, the collider needs two separate magnetic channels, conventionally produced in separate strings of magnets, installed side by side. By combining two sets of windings in a common mechanical and magnetic structure, the LHC magnets can be made more compact and more efficient, as the stray flux of one aperture contributes to increasing the field in the neighbouring one. The resulting cross talk between the twin apertures is not a drawback, as the LHC magnets will be operated with the same field level in both apertures.

Besides the 1232 main dipoles and 392 main quadrupoles, the LHC also makes use of many types of auxiliary magnets for correcting multipoles and orbit errors, adjusting beam optics, and increasing luminosity at the collision points, amounting to a total of some 8000 superconducting magnets [7].

2.2 Superfluid helium cryogenics

The use of superfluid helium as magnet coolant brings other advantages than lower operating temperature alone [6]. Its high specific heat – 2000 times that of the conductor per unit volume – and low viscosity make it a prime component for stabilising the windings against thermal disturbances, while its large thermal conductivity permits to operate them in a quasi-isothermal environment, thus minimising the temperature differences associated with the extraction and transport of heat over long distances [8]. The thermodynamic penalty of producing refrigeration at lower temperature can be limited by appropriate staging of heat loads, through intermediately cooled thermal shields and heat intercepts, as well as by designing high-COP refrigeration cycles based on efficient machinery. In view of the low saturation pressure of helium at 1.8 K, the vapour compression at high volumetric flow-rate can only be performed economically using cold hydrodynamic compressors, novel machinery derived from aeronautical technology. As a result of several decades of development (Figure 4), effective solutions for large-capacity helium refrigeration at 4.5 K and 1.8 K are commercially available today from European industry [9].

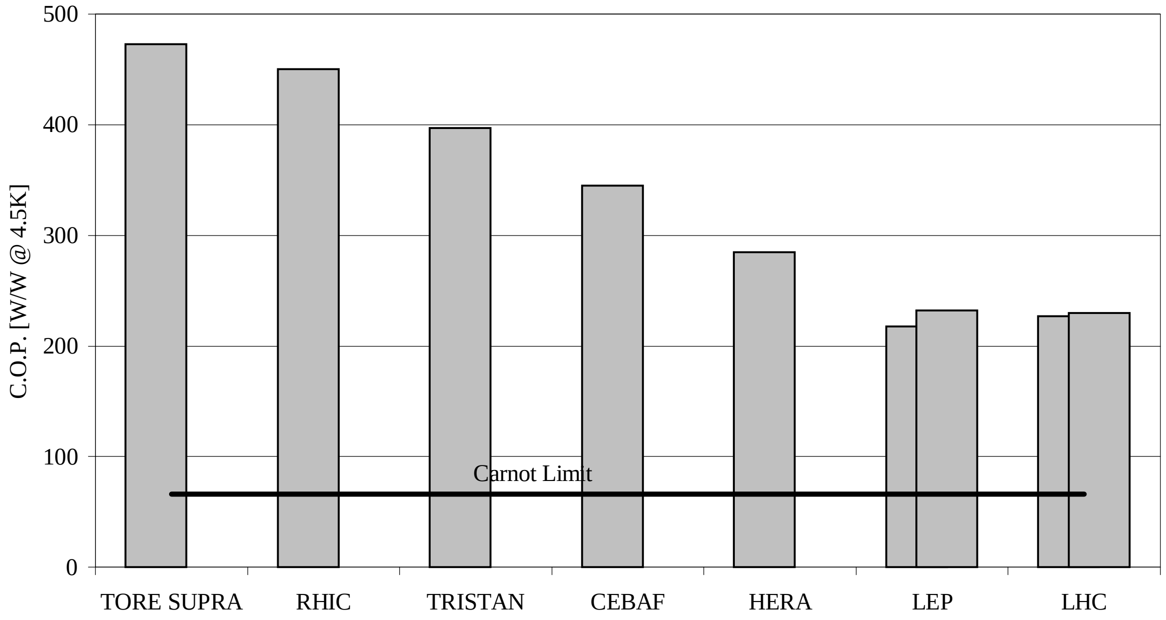

Figure 4: Progress in efficiency of cryogenic helium refrigerators.

2.3 High-temperature superconductor (HTS) based current leads

Powering all superconducting magnet circuits in the LHC requires feeding 3.6 MA into the cryogenic helium environment. The conventional solution of vapour-cooled resistive current leads would require installation of significant extra refrigeration capacity. With the advent of practical HTS materials, and using the favourable cooling conditions available in the LHC cryogenic system, HTS-based current leads have the potential of reducing the entropic load by a factor 3 with respect to their resistive counterparts. Prototypes of such current leads, manufactured by industry, are being tested and show promising results [10].

2.4 Cold ultra-high vacuum subject to high-intensity beams

Achieving adequate beam lifetime for physics in the LHC requires ultra-high vacuum. The beam pipe, operated at 1.9 K, would provide very efficient distributed cryopumping in absence of beam. Under the effect of the high-energy, high intensity beams, cryotrapped molecules may be desorbed from the cold surfaces, through several mechanisms – synchrotron radiation bombardment, photoelectrons resonantly accelerated by the beam potential, protons scattered by the residual gas – which have never shown on such a scale in previous accelerators. To cope with this, the LHC features beam screens in the magnet cold bores, which intercept beam-induced heat loads at higher temperature and shelter the 1.9 K surfaces from the beam-induced effects, thus permitting to operate at high luminosity [11].

3 International co-operation and funding

Although CERN is primarily financed by its twenty European member states, high-energy physics has a long tradition of even wider international co-operation, and the large experimental detectors of today are customarily built by world-wide collaborations involving hundreds of scientists from several tens of research institutions. The two large physics experiments in construction at the LHC show the latest development in this trend, each with some two thousand scientists from 150 institutes. As a result, CERN has *de facto* become a world laboratory, with about a quarter of its present users originating from non-member states. In view of its unique potential at the forefront of energy and luminosity, the LHC is a truly world project, a status reflected in its funding, some 20% of which come from outside the CERN budget in the form of special contributions. These contributions, which can take several forms - in kind, in cash or in qualified manpower - have been negotiated at governmental level and established on the basis of bilateral agreements with non-member states having communities of high-energy physicists eager to do research at the LHC, i.e. Canada, India, Japan, Russia and the USA. The special contributions from the non-member states, which eventually consist in industrial supplies, are usually channelled through their national laboratories, thus providing these laboratories with new challenges and enabling CERN to benefit from the competence and experience of their scientists and engineers. A main concern of the CERN management has been to acknowledge these special contributions within the framework of the organisation’s strict purchasing rules and policy, while preserving fair return to the member state industries. The host states – France and Switzerland – also bring in special contributions, in addition to their normal share of the CERN budget, as a recognition of the particular benefit which they expect to reap from the installation of a new large research facility on their territory.

4 Efficient project management tools

The LHC shows much larger extent in time and space than previous CERN projects. A simplified list of project milestones (Table 2) shows that it took ten years of studies and technological R&D as prerequisite to get the project approved, followed by another decade of effective construction, before its commissioning, operation and later upgrades spreading over an expected lifetime of some twenty years. This overall time span exceeds that of a professional career, and several generations of scientists and engineers are already collaborating on the project. Technical components for the accelerator are designed and constructed world wide, often using diverse forms of industrial know-how and regional standards, before being receptioned and installed at CERN. The LHC also exhibits much higher complexity and intricacy among its different technical systems, some of which highly critical, that upon completion will be difficult to access and service inside the machine cryostats. Finally, funding and manpower resources are comparatively scarce for an endeavour of this size, and the pressure on the project engineers is consequently high.

Table 2: Some milestones of LHC history.

Preliminary conceptual design studies	1984
First high-field magnet models	1988
Structured R&D program engaged	1990
Construction approved by CERN Council	1994
"D.U.P." and civil engineering start	1998
Major procurement markets	1998-2000
Installation in tunnel start	2002
First beam injected (sector test)	2003
First colliding beams	2005

It is therefore essential to benefit from an integrated, efficient project management system, in the form of a project baseline implemented on an engineering data management system (EDMS), and a detailed quality assurance plan (QAP) [12]. These tools are accessible world wide on the Web, thus enabling real-time, unified access to updated technical documents – design notes, technical specifications and drawings, working schedules - in their latest approved version, from a variety of informatics platforms [13]. This system, which has already proved its value in the project definition and design phases, will further integrate constructional data and measured performance of the components, thus permitting to maintain a complete description of the LHC as it will effectively be built. It will then constitute a prime tool for early detection and swift correction of possible drifts in series production, optimal matching of components to reduce statistical scatter in their combined characteristics, and establishing a functional database for operation and control software.

5 Site integration and environment protection

The LHC will be installed in the vicinity of Geneva, straddling the border between France and Switzerland, in a suburban and rural area close to several protected sites such as Lake Léman and the Jura high range. Particular care has been taken to minimise the impacts of the project on its natural and human environment, throughout its life cycle. By virtue of its installation in a deep tunnel, some 100 m below ground, the machine will be little visible in the landscape. Only at eight points around the circumference can one find fenced, landscaped sites accommodating surface buildings and access shafts to the underground works. Special measures have been taken to reduce the nuisances at the fence produced by technical equipment, e.g. noisy compressors or cooling towers, through adequate siting, integration or corrective action. Moreover, high-energy accelerators are considered by French regulations as “Installations Nucléaires de Base” (INB), and as such, subject to strict authorisation procedures enforced by the central administration, from construction to commissioning, operation and dismantling. Before undertaking the construction of the LHC, CERN has submitted a detailed impact study of the project to public enquiry, in order to be granted the “Déclaration d’Utilité Publique” (DUP) by the French authorities, a prerequisite for groundbreaking. Similar procedures were also conducted on the Swiss side, at the federal and cantonal levels. Besides these regulatory obligations, CERN has fostered improvements in the local infrastructures (roads, drainage, land reclaiming) and deployed sustained activity in public information among the local communities. A dedicated Web site keeps track of these actions [14].

6 Conclusions

The key technologies of high-field superconducting magnets and helium cryogenics, developed on a scale without precedent over the last fifteen years, account for two thirds of the LHC investment costs alone. The whole project however involves many other important technical, organisational and sociological aspects, thus representing a new challenge for the high-energy physics and particle accelerator community. Construction of the project is now in full swing, as procurement contracts in force account for more than half of the total expenditure, mostly on schedule and within budget estimates. Extended international collaboration makes the LHC a truly world-wide enterprise, opening the way for future global projects in science and engineering.

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