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The LHC project: The accelerator and the experiments

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ABSTRACT

The LHC project comprising the accelerator and the experiments is described. The project was conceived to address fundamental questions in particle physics. Some of the challenges faced in the design and construction of the accelerator and experiments are outlined. The experiments are ready for LHC beam foreseen at the end of 2009.

1. Introduction

Over the last 100 years the marriage of Quantum Mechanics and Special Relativity and the discovery of hundreds of particles has led to the Standard Model of Particle Physics (SM). LEP, SLC and the Tevatron have established that the SM works wonderfully well and that we do really understand physics at constituent energies up to $\sqrt{s}\sim 100$ GeV. Any new particles will have masses in the range of hundreds of GeV up to a few TeV in some cases. Although the SM is a beautiful theory, and arguably one that is most precisely tested, we know it is only a low-energy effective theory. Amongst the issues still to be addressed are the following:

i) *the SM contains too many apparently arbitrary features*—presumably these should become clearer as we make progress towards a unified theory.
ii) *the SM has an unproven element*—the generation of mass. The Higgs mechanism is a favoured one, but Nature could have chosen another path. The issue is why is the mass of the photon zero whilst that of its close relatives, the W and Z bosons, 100 times the mass of the proton? The answer will be found at LHC energies.
iii) *the SM gives nonsense at LHC energies.* The probability of some processes, such as W_LW_L scattering becomes greater than 1 at the higher end of the energies probed by the LHC! This is Nature's slap on the wrist! The Higgs mechanism can also provide a solution to this problem.
iv) *supersymmetry?* Even if the Higgs exists, and found, all is not 100% well with the SM alone. The next question that arises is "why is (Higgs) mass so low"? If a new symmetry (supersymmetry) is the answer, it must show up at $O(1\ \text{TeV})$ i.e. at the LHC energies.
v) *SM is logically incomplete* as it does not incorporate gravity. Is Superstring theory the way forward? If it is, dramatic concepts would be introduced such as supersymmetry, extra space–time dimensions, etc.

Hence the aim of the experimentalist at the LHC is to find new particles, new forces and new symmetries amongst which could be the Higgs boson(s), supersymmetric particles, Z' bosons, extra space–time dimensions. There could easily be surprises.

The LHC will also allow in-depth studies of CP violation in the B sector and that of quark-gluon plasma.

2. The LHC accelerator

The installation of a hadron collider in the LEP tunnel was first foreseen by CERN in the early 1980s. A Long-Range Planning Committee, set up in 1985, under the chairmanship of Carlo Rubbia, recommended that a high energy large hadron collider, with a sufficiently large interaction rate, was the right choice for CERN's future.

To be competitive with the proposed Superconducting Super Collider in the U.S., the Committee proposed running at a centre-of-mass energy of 7 TeV with a design luminosity of the CERN accelerator increased by an order of magnitude to $10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$ (leading to about one billion pairs of protons interacting per second at the heart of the ATLAS and CMS detectors). Not only was the development of advanced high-field superconducting dipole magnets required on a time-scale of a decade or so, but so was the development of detectors that could handle

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such high luminosities. For the latter, CERN established an extensive detector research and development program that triggered a wide range of studies, from properties of new materials to prototype readout systems.

The LHC [1,2] is situated 100 m underground on the outskirts of the city of Geneva, predominantly in the French countryside. The LHC uses much existing infrastructure of CERN in order to reduce costs. This imposed a number of strong constraints on the technical choices to be made:

i) The 27 km circumference of the LEP tunnel. The maximum energy attainable depends on radius of this tunnel and the field strength in the dipole magnets. Given that the tunnel existed, and the design energy was set at ~7 TeV, the dipole field strength had to be > 8 T—the design value is 8.3 T.
ii) The small (3.8 m) tunnel diameter. The LHC is (just like the ISR) not one but two machines. A superconducting magnet occupies a considerable amount of space. To keep it cold, it must be inserted into a cryostat and well insulated from external sources of heat. Due to the small transverse size of the tunnel, it would have been impossible to fit two independent rings. Instead, a novel and elegant two-in-one magnet design, with the two rings separated by only 19 cm inside a common yoke and cryostat, was developed. This was not only necessary on technical grounds, but also saved a considerable amount of money, some 20% of the total project cost.

In July 1908, in his laboratory in Leiden, Heike Kamerlingh Onnes became the first person in the world to liquefy helium. He succeeded in producing 60 ml of liquid, enough to fill a small teacup. Kamerlingh Onnes soon used liquid helium to cool-down other materials in order to measure their properties at very low temperature. In 1911, he discovered that the resistance of solid mercury abruptly disappeared at 4.2 K, a property that he dubbed “superconductivity”. He also observed another phenomenon—supefluidity. Almost exactly 100 years later, these two discoveries, superconductivity and superfluidity, have been brought together as the two pillars on which the design rests of the largest and most complex scientific instrument ever built. The LHC refrigeration today liquefies around 32,000 l of He liquefied per hour using eight big cryogenic plants making the ensemble the largest refrigerator in the world!

The LHC magnets are cooled with pressurized superfluid helium which has unique engineering properties. The low bulk viscosity of superfluid helium allows it to permeate the smallest of cracks. This is used to advantage in the magnet design by making the coil insulation porous enough to enable the fluid to be in intimate contact with the strands of the superconductor. The large specific heat, some 100,000 times that of copper per unit mass and 2000 times per unit volume.

The field strength of the dipole magnets is about 60% higher than that achieved in previous machines. This pushed the design of superconducting magnets and their associated cooling systems to a new frontier.

The design energy of 7 TeV and luminosity of 10^{34} cm^{-2} s^{-1} are, respectively, a factor of 7 and 30 higher than that for the Tevatron. The challenge is illustrated in Fig. 1. It can be seen that, on both axes, orders of magnitude increases had to be made.

2.1. The LHC startup

At 09:30 on the 10 September 2008, a bunch of 450 GeV protons, comprising a few times 10^9 protons, was injected into the LHC. A bright spot was registered on a thin fluorescent screen at

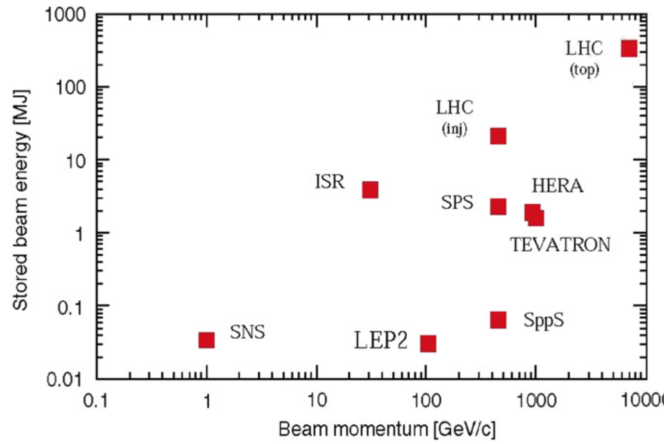

Fig. 1. The parameters of the LHC compared with previous accelerators.

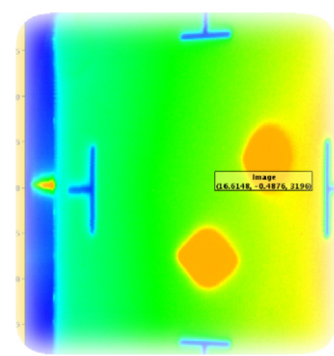

Fig. 2. The two small spots signalled the completion of the first turn of a proton beam.

the entrance to the machine as the beam passed through it. Over the next hour, absorber blocks at the end of each sector were removed as the beam progressed from one sector to the next one. The first full revolution of 27 km was observed as two small spots on the fluorescent screen (Fig. 2). During that day the beam was also circulated in the counter-clockwise direction. In the days that followed, rapid progress was made in getting the beam to circulate with good lifetime. The radio-frequency system was tuned to “capture” the beam, keeping it tightly bunched. The captured beam was well centred and “clean” i.e. with few halo particles. All of this bodes well for a fast and smooth commissioning of the accelerator.

On 19th September 2008, an incident occurred which has put the machine out of operation for more than a year. Before the 10th of September the magnets of seven out of the eight octants had been power-tested beyond the energy chosen for the run namely 5 TeV. For lack of time the eighth octant, Sectors 3–4, had only been tested to 4 TeV. A few days of downtime to replace a failed power converter were being used to complete the final powering tests in Sectors 3–4. This last main-bend circuit was being taken to just above 5 TeV when the incident occurred. The root cause was found to be a failure of one of the 50,000 soldered joints between two magnets. It resulted in the triggering of quench heaters of about 100 magnets. A large amount of liquid helium evaporated into the tunnel, provoking a shock-wave within two machine-cells (about 300 m). Just the warming-up of this sector for repair took about five weeks. Furthermore, it was found that there had been substantial collateral mechanical damage due to the pressure-wave. The high-pressure build-up damaged the magnet interconnects and the super-insulation. The beam-pipe was perforated resulting in the pollution of the vacuum system