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Review

The large hadron collider

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ABSTRACT

The Large Hadron Collider (LHC) is the world's largest and most energetic particle collider. It took many years to plan and build this large complex machine which promises exciting, new physics results for many years to come. We describe and review the machine design and parameters, with emphasis on subjects like luminosity and beam conditions which are relevant for the large community of physicists involved in the experiments at the LHC. First collisions in the LHC were achieved at the end of 2009 and followed by a period of a rapid performance increase. We discuss what has been learned so far and what can be expected for the future.

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1. Introduction

The LHC is the world's largest and highest-energy particle accelerator. As illustrated in Fig. 1, it is installed in an underground tunnel of 27.6 km circumference on the Franco-Swiss border near Geneva, Switzerland. The tunnel was initially built for and previously used by the large e^+e^- collider LEP.

The LHC is built with two beam-pipes which cross at four interaction regions, see Fig. 2 [1]. This allows particles of the same charge – proton–proton or heavy ions – to be accelerated and collided.

The most important design parameters for an accelerator for particle physics are the maximum energy and luminosity that can be reached. High energy is required to allow the production of new, heavy particles, like the yet undiscovered Higgs particle predicted by the Standard Model of particle physics. High rate of event production is about equally important, to allow for a high flux of particles resulting in a sufficiently high number of collisions.

The collision rate $\dot{n}$ for a process of cross section σ is the product of the luminosity L and the cross section

$$\dot{n} = L\,\sigma. \tag{1}$$

Cross sections are usually given in units of barn (symbol b), where $1\ \text{b} = 10^{-24}\ \text{cm}^2 = 10^{-28}\ \text{m}^2$.

The luminosity of a collider is determined by the particle flux and geometry [2]. For head-on collisions as illustrated in Fig. 3, the luminosity is

$$L = \frac{N_1\, N_2\, n_b\, f_{\text{rev}}}{A}, \tag{2}$$

where N_1, N_2 are the number of particles per bunch in beam 1 and 2, n_b is the number of bunches, f_{rev} the revolution frequency and A the effective beam overlap cross section at the interaction point. For beams with Gaussian shape of horizontal and vertical r.m.s. beams sizes σ_x, σ_y colliding head on, we have $A = 4\pi\, \sigma_x \sigma_y$.

The main path to very high luminosities in the LHC is to use many bunches, nearly 3000, and to reduce the transverse beam size at the Interaction Points (IPs) by manipulations of the magnetic focusing system at top energy, the so called squeezing of the beams before the beams are brought into collisions. The r.m.s. beam size at the position s in the machine is

$$\sigma(s) = \sqrt{\epsilon\, \beta(s)} \tag{3}$$

where ϵ is an average beam quantity called emittance, which represents the beam size in transverse phase space. For simplicity, we have assumed here, that the "dispersion" (change of optics with momentum) is small, which is generally the case in the interaction regions. See Eq. (6) for the more general expression with dispersion. Strong quadrupole magnets are used around the interaction regions to focus the beams. They allow to obtain small values of the β-function at the interaction point (called β^*) resulting in small beam-sizes and high luminosity.

Synchrotron radiation from protons at LHC energies becomes noticeable but is not a limitation.

The maximum beam energy in the LHC, or more precisely the beam momentum p is given by the maximum bending field strength B, according to $p = B\,\rho$, where the bending radius $\rho = 2804$ m is essentially given by the tunnel geometry. Numerically, $p\,[\text{GeV/c}] = B\,[\text{T}]\,\rho\,[\text{m}]/3.336$.

The LHC is built with superconducting NbTi magnets. The cross section of the main dipole magnets is shown in Fig. 4. They are operated at superfluid Helium temperature of 1.9 K, and allow fields up to $B = 8.33$ T and $p = 7$ TeV/c.

The main LHC parameters are listed in Table 1 and compared to its predecessor LEP [3] in its final running phase and the Tevatron [4]. The design LHC parameters for the magnetic field and beam intensity are particularly ambitious. The aim is to get the maximum energy and luminosity reachable with current technology.

2. Basic design considerations

2.1. Project goals

The idea of a proton–proton collider within the LEP tunnel was already considered at the very beginning of the LEP project. Discussions of the Large Hadron Collider (LHC) started as early as 1983 [5], long before the first electron–positron collisions took place in LEP in 1989. The LHC design parameters evolved significantly over the following 10 years in a continuous comparison and competition with the SSC project in the United States [6] leading to a tenfold increase of the LHC performance from the first design projections [7] to the nominal LHC performance specification [1].

The key objective of the LHC is the exploration of the Standard Model in the TeV energy range, the search for the Higgs Boson and potential new physics signatures. The LHC can be considered as a discovery machine, which uses collisions of hadrons. Collider storage rings can in principle be designed for a variety of particle species. Leptons are truly pointlike elementary particles and lepton colliders allow for a well defined collision energy and are well suited for precision measurements (e.g. LEP), but more limited in luminosity and maximum beam energy at comparable size and cost.

The energy limitation of electron rings from synchrotron radiation could in principle be overcome by using (short lived) muons rather than electrons. Muon colliders are being studied [8], but are at present very far from a technical realization.