Contents

Chapter 1

The LHC and CMS Machine

In this chapter, the working and the design parameters of Large Hadron Collider (LHC) and its one of main purpose detector, Compact Muon Solenoid (CMS), is briefly described.

1.1 The Large Hadron Collider

The famous quote "history repeats itself" applies well to the High Energy Physics (HEP) experiments. The starting point of experimental particle physics is the Rutherford α-particle scattering, and even now we are doing the same thing just the method changed from "natural accelerator" to the "man-made" accelerator that can accelerate particles with the velocity close to the speed of light. The design and working of accelerator changed a lot over a period of time in going from MeV to GeV and in the TeV range. Now, these machines are not only used in HEP experiments, but extends its arena to treat human beings like cancer therapy, radioisotope production, 3-D x-ray, also to the industry for uses like material processing, sterilization, security scan, water treatment, and many more.

The LHC is a hadron collider which can accelerate the two proton beams in opposite direction with maximum of 14 TeV energy in a 26.6 km long tunnel which is about 100 m underground. The LHC is the latest and most-powerful accelerator everbuilt. It is a proton-proton collider built to improve our understanding of fundamental physics. It started on 21^{st} October 2008. It is built in the same tunnel where there was Large Electron Positron (LEP) collider, that collides electrons and positrons.

LEP collaboration decided to switch to hadron collider because of following advantages:

- Hadron collider can reach a higher center of mass (COM) energy, because of much lower synchrotron radiation emitted by hadrons as compared to electrons. Synchrotron radiation loss is directory proportional to $(Energy/mass)^4$.

- As hadrons are composite particles so it allows us to scan over wide range of energy.

For any particle accelerator there are mainly three components so for the LHC. They are:

- Beam pipes

- Accelerating structure

- Magnet system

1.1.1 Beam Pipes

At LHC there are two beam pipes each with diameter ≈6.3 cm in which proton beam travels in opposite direction. We should keep the beam pipes with ultra-high vacuum[1] to minimize the number of collision with the gas molecules which result in beam instability and loss of beam particles. At LHC the beam pipes are kept at 1.013×10^{-13} bar pressure.

1.1.2 Accelerating Structure

Another main part of any particle accelerator is its accelerating structure. A accelerator in TeV range can not start from rest and go to the TeV range in one go it should go into several stages depending on the energy. At LHC the journey of proton starts from grabbing the proton from Hydrogen gas and subsequently go into 5 different stages. The stages can be decreased but could not be just one stage. Here, at LHC there are five different stages before reaching to LHC as in between it serves several other experiments at each stage, which are shown pictorially in Figure 1.1. The stages for proton acceleration are:

[1] At LHC there are three different vacuum systems used. First one is used for beam pipe another is used for insulating the cryogenically cooled magnets and third one is used for insulating the helium distribution. In the later two it it just acts as a thermal insulator as the cryogenic parts are kept at 1.9 K ($-271.3°C$)

- Grab proton source: The source of proton is Duoplasmatron[2][1]. This feed protons to LINAC2.

- LINAC2 (Linear accelerator-2): It is the starting point of proton's journey in the LHC accelerator complex. Here, protons reaches to an energy of 50 MeV using the radio-frequency (RF) cavities[3] where it also gains 5% in mass. It feeds to the Proton Synchrotron Booster (PSB).

- PSB: It takes 50 MeV protons beams from LINAC2 and accelerates it to 1.4 GeV for the injection into Proton Synchrotron (PS).

- PS: It is one of key component in the LHC accelerator complex. It increases the energy of protons up-to 25 GeV and feeds to super proton synchrotron.

- Super Proton Synchrotron (SPS): It has a circumference of 7 km where protons are accelerated to an energy of 450 GeV. Then via two transmission line protons are then injected into LHC ring.

- LHC: It grabs two proton beams from SPS which is injected into opposite direction in parallel pipes. In LHC proton beams can be accelerated up-to 7 TeV.

The CERN accelerator complex is shown in Figure 1.2.

1.1.3 Magnet System

As the LHC is a circular collider so magnet system is its one of core part which give them a circular trajectory in the LHC beam pipes.

To be economical LHC is made in eight arcs and eight straight sections instead of a perfect circle. Along with the bending of beam it is also necessary to focus the beam as the same charge protons try to diverge. To focus the beam a pair of quadrapole magnets are used one focuses the beam width while other focus the beam height. Quadrapole magnet geometry is shown in Figure 1.3. There are total of 858 quadrupole magnets are installed in LHC to keep the beam focused. Along with this every protons in the beam are not exactly with the same energy and

[2] It strips electron from hydrogen gas and creates a plasma of protons, electrons and molecular ions. This plasma expands towards the extraction electrodes and a proton beam is formed

[3] A RF cavity is an metallic cavity that accelerates the charged particles using the electromagnetic field.

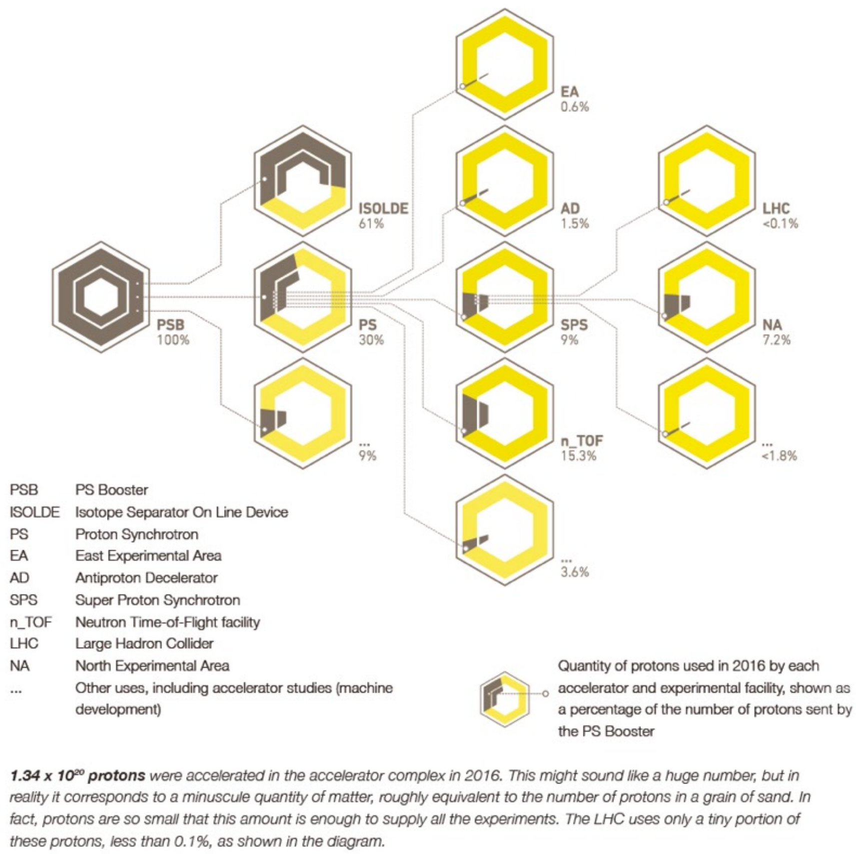

Figure 1.1: Other experiments at the LHC accelerating chain [2]

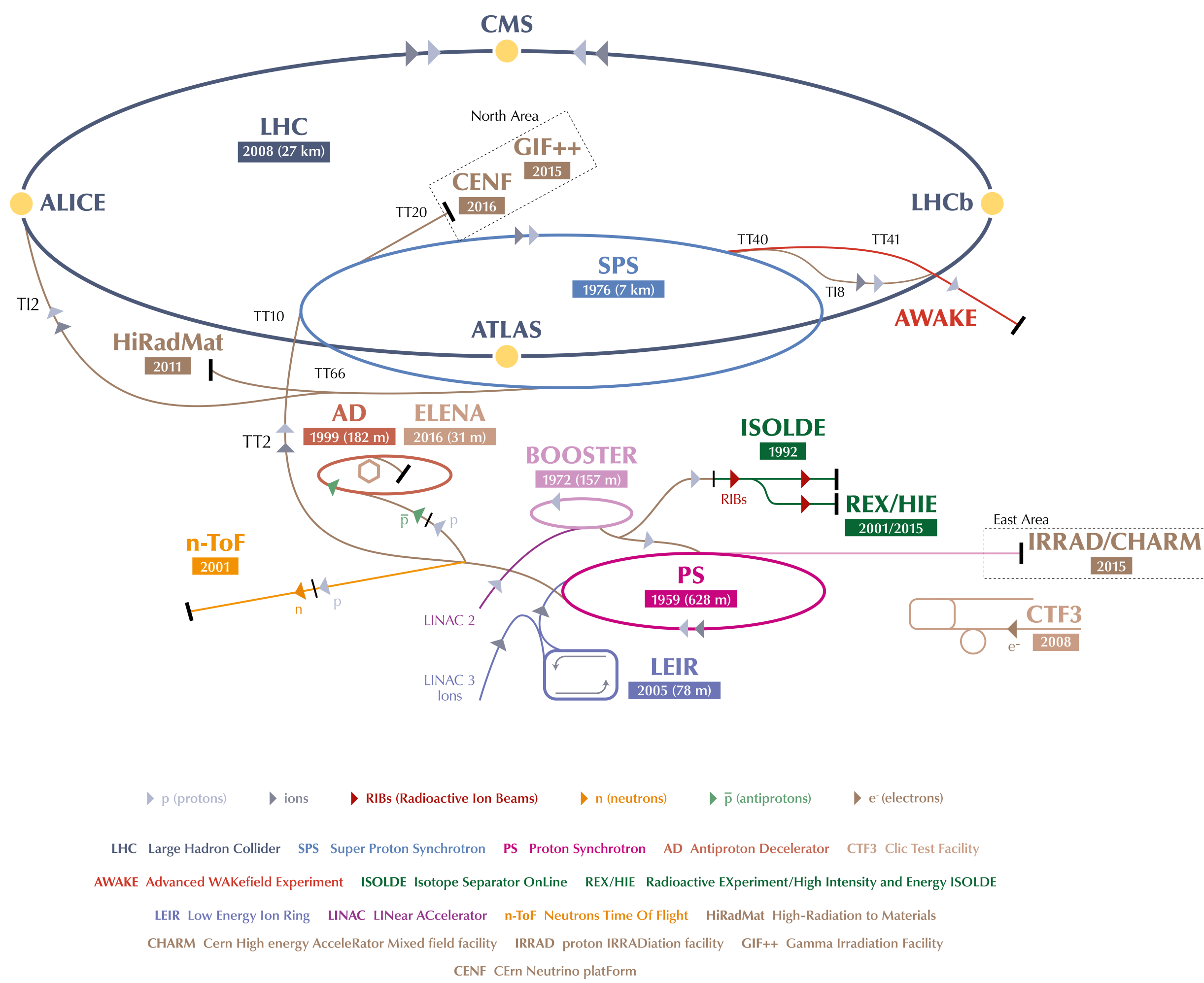

Figure 1.2: LHC accelerator chain along with all its other experiments which uses proton beam from other part of accelerator either from PSB, PS or SPS[3]

in same path. To correct this focusing with change in energy there are sextupoles magnets are used. There are several other magnetic multipoles are used that help us to keep beam focused if the beam suffers from gravitational interactions over protons, electromagnetic interactions among bunches, electron clouds from pipe wall, and so on. Different types of magnets used in LHC are listed here [4]. Along with this there are eight sets of “inner triplets” are used. These are used at the four interaction points to focus the beam while collide to increase the luminosity. Here the size of bunch goes from 0.2 mm to 17 μm at the interaction point of ATLAS or CMS. At the interaction point of ALICE or LHCb it is 71 μm. Summary of important parameters of LHC is given in Table 1.1.

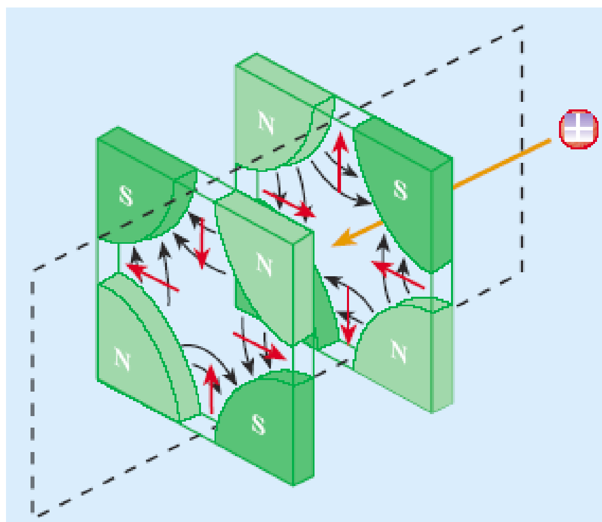

Figure 1.3: Pair of quadrupole magnets.

1.1.4 Few key requirements

The HEP collider is mainly characterized by the two parameters center of mass (COM) energy and the luminosity. The production rate of heavier particles like Higgs increases with COM energy. The luminosity is proportional to the number of events per second so it should be maximized. Luminosity is defined as:

$$L = \frac{k_b N_b^2 f_{rev} \gamma}{4\pi \epsilon_n \beta^*} \tag{1.1}$$

Parameters	**Value**
Circumference of LHC ring	26658.883 m
Maximum dipole magnetic field	8.33 T
Dipole operating temperature	1.9 K
Maximum stored energy per beam (nominal)	362 MJ
Maximum stored energy per beam (2012)	143 MJ
Maximum stored energy per beam (2016)	266 MJ
Beam energy at Injection	450 GeV
Beam energy at collision (nominal)	7 TeV
Beam energy at collision (2012)	4 TeV
Beam energy at collision (2016)	6.5 TeV
Maximum instantaneous luminosity (nominal)	10^{34} cm^{-}2 s^{-1}
Maximum instantaneous luminosity (2012)	7.7×10^{33} cm^{-}2 s^{-1}
Maximum instantaneous luminosity (2016)	1.4×10^{34} cm^{-}2 s^{-1}
Number of bunches per proton beam (nominal)	2808
Number of bunches per proton beam (2012)	1380
Number of bunches per proton beam (2016)	2076
Maximum number of protons per bunch	1.6×10^{11}
Protons/bunch (average at start of collision) (nominal)	1.15×10^{11}
Protons/bunch (average at start of collision) (2012)	1.5×10^{11}
Protons/bunch (average at start of collision) (2016)	1.1×10^{11}
Bunch collision frequency (nominal)	40 MHz
Bunch collision frequency (2012)	20 MHz
Bunch collision frequency (2016)	40 MHz
Bunch length (at injection)	1.7 ns
Bunch length (at collision)	1.05 ns
Energy spread (at injection)	1.9×10^{-3}
Energy spread (at collision)	0.45×10^{-3}
Half crossing angle (nominal)	143 μrad
Half crossing angle (2012)	146 μrad
Half crossing angle (2016)	185 μrad
$\beta*$ (nominal)	0.55 m
$\beta*$ (2012)	0.6 m
$\beta*$ (2016)	0.4 m
RMS beam size at IP1 & IP5	17 μm
RMS beam size at IP2 & IP8	71 μm
ϵ_n(transverse emittance, rms, normalized) (at injection)	3.5 μm
ϵ_n(transverse emittance, rms, normalized) (at collision point)	3.75 μm
total longitudinal emittance (at injection)	1.0 eVs
total longitudinal emittance (at collision)	2.5 eVs
Average mean pile-up (nominal)	
Average mean pile-up (2012)	??
Average mean pile-up (2016)	??
Energy loss per turn at 14 TeV	7 keV
Energy loss per turn for electrons	

Table 1.1: LHC technical parameters for proton-proton collisions: nominal, 2012 and 2016 values.[5, 6, 7, 8].

where,
k_b is the number of bunches per ring,
N_b is the number of protons per bunch,
f_{rev} the revolution frequency,
ϵ_n is the normalized RMS transverse beam emittance (same in both)
β^* is the beta-function at the interaction point

Based on the definition of luminosity, we can maximize it by following means:

- By decreasing beam emittance, ϵ_n.
- By improving the cryogenic system. As the factor $k_b.N_b$ is limited by thermal energy produced by synchrotron radiation.
- By decreasing beam-beam effect. As it scales with N_b/ϵ_n which causes the spread in betatron tunes.
- Also, the space charge scales with N_b/ϵ_n.

1.2 Experiments at the LHC

In LHC there are four interaction points (IPs) where the two proton beams are made to collide. At every IP one detector is placed. They are ATLAS, CMS, ALICE, and LHCb as shown in Figure 1.4. Also, there are two more small detectors LHCf and TOTEM installed close to the IP of the two main detectors ATLAS and CMS respectively.

ATLAS (A Toroidal LHC Apparatus) and **CMS** (Compact Muon Solenoid) are large general-purpose detectors having similar design and same physics goal. The main difference in the two is in their magnet systems. ATLAS has an eight toroidal magnets combined with a smaller inner solenoid while CMS has a powerful solenoid magnet only. CMS detector will be described in detail in Section 1.3.

ALICE (A Large Ion Collider Experiment) is a heavy-ion detector. It is specially designed for the study of strongly interacting matter at high densities in quark-gluon plasma phase.

LHCb (Large Hadron Collider beauty) is made asymmetrically with respect to the IP of the detector. It is made specially to study the slight differences between the matter-antimatter through the study of b-quarks.

LHCf (Large Hadron Collider forward) and **TOTEM** (TOTal cross-section, Elastic scattering and diffraction dissociation Measurement at

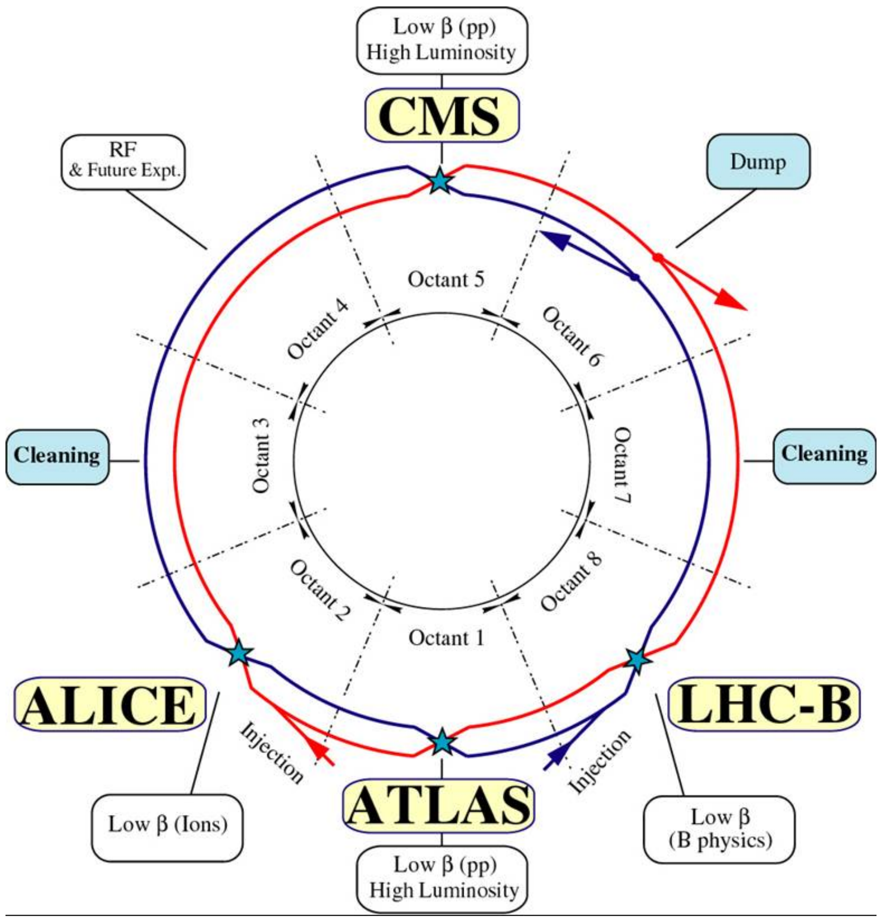

Figure 1.4: LHC geometry with arcs and straight sections.

the LHC) are located near ATLAS and CMS respectively, for the study of forward physics.

1.3 CMS Experiment

The CMS is a general-purpose detector at the LHC. It is built around a huge solenoid magnet. This takes the form of a cylindrical coil of superconducting cable that generates a field of 4 Tesla, about 100,000 times the magnetic field of the Earth. The field is confined by a steel "yoke" that forms the bulk of the detector's 12,500-tonne weight. The complete detector is 21 meters long, 15 meters wide and 15 meter high.

1.3.1 Detector Design

CMS[9] detector is a general purpose deetector which consist of layers of material that exploit the different properties of particles to catch and measure the energy and momentum of each particles passing through it. So, CMS needs:

- a high quality central tracking system to give accurate momentum measurements with good efficienccy of offline tagging of b-jets and τ's.

- a high resolution ($\approx 1\%$ at 100 GeV) method to detect and measure electrons and photons (an electromagnetic calorimeter) and isolate them.

- a "hermetic" hadron calorimeter, designed to entirely surround the collision and prevent particles from escaping along with fine lateral segmentation.

- a high performance system to detect and measure muons with good time and momentum resolution ($\approx 1\%$ at 100 GeV).

1.3.2 CMS sub-systems

Tracker

The Electromagnetic Calorimeter

The Hadronic Calorimeter

The Muon System

1.4 CMS Trigger and Data Acquisition system

1.5 CMS Offline Computing

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