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PhD Thesis

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SEARCH FOR NEW PHENOMENA IN HIGH ENERGY INTERACTIONS

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<sup>18</sup> **Chapter 1**

<sup>19</sup> **The LHC and CMS  
Machine**

<sup>21</sup> In this chapter, the working and the design parameters of **Large Hadron  
22 Collider (LHC)** and its one of main purpose detector, Compact Muon  
23 Solenoid (CMS), is briefly described.

<sup>24</sup> **1.1 The Large Hadron Collider**

<sup>25</sup> The famous quote “history repeats itself” applies well to the **High Energy  
26 Physics (HEP)** experiments. The starting point of experimental particle  
27 physics is the Rutherford  $\alpha$ -particle scattering, and even now we are doing  
28 the same thing just the method changed from “natural accelerator”  
29 to the “man-made” accelerator that can accelerate particles with the velocity  
30 close to the speed of light. The design and working of accelerator  
31 changed a lot over a period of time in going from MeV to GeV and in  
32 the TeV range. Now, these machines are not only used in **HEP** experiments,  
33 but extends its arena to treat human beings like cancer therapy,  
34 radioisotope production, 3-D x-ray, also to the industry for uses like material  
35 processing, sterilization, security scan, water treatment, and many more.

<sup>37</sup> The **LHC** is a hadron collider which can accelerate the two proton  
38 beams in opposite direction with maximum of 14 TeV energy in a 26.6  
39 km long tunnel which is about 100 m underground. The **LHC** is the latest  
40 and most-powerful accelerator everbuilt. It is a proton-proton collider  
41 built to improve our understanding of fundamental physics. It started on  
42 21<sup>st</sup> October 2008. It is built in the same tunnel where there was Large  
43 Electron Positron (LEP) collider, that collides electrons and positrons.

<sup>44</sup> LEP collaboration decided to switch to hadron collider because of following advantages:

- <sup>46</sup> • Hadron collider can reach a higher Center Of Mass (COM) energy,  
<sup>47</sup> because of much lower synchrotron radiation <sup>1</sup> emitted by hadrons  
<sup>48</sup> as compared to electrons. Synchrotron radiation loss is directly proportional to  $(Energy/mass)^4$ .  
<sup>49</sup>
- <sup>50</sup> • As hadrons are composite particles so it allows us to scan over wide range of energy.  
<sup>51</sup>

<sup>52</sup> For any particle accelerator there are mainly three components so for  
<sup>53</sup> the LHC. They are:

- <sup>54</sup> • Beam pipes  
<sup>55</sup> • Accelerating structure  
<sup>56</sup> • Magnet system

### <sup>57</sup> 1.1.1 Beam Pipes

<sup>58</sup> At LHC there are two beam pipes each with diameter  $\approx 6.3$  cm in which  
<sup>59</sup> proton beam travels in opposite direction. We should keep the beam  
<sup>60</sup> pipes with ultra-high vacuum<sup>2</sup> to minimize the number of collision with  
<sup>61</sup> the gas molecules which result in beam instability and loss of beam particles.  
<sup>62</sup> At LHC the beam pipes are kept at  $1.013 \times 10^{-13}$  bar pressure.

### <sup>63</sup> 1.1.2 Accelerating Structure

<sup>64</sup> Another main part of any particle accelerator is its accelerating structure.  
<sup>65</sup> 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.  
<sup>66</sup> At LHC the journey of proton starts from grabbing the proton from  
<sup>67</sup> Hydrogen gas and subsequently go into 5 different stages. The stages  
<sup>68</sup> can be decreased but could not be just one stage. Here, at LHC there  
<sup>69</sup> are five different stages before reaching to LHC as in between it serves

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<sup>1</sup>The radiation emitted by charged particle during acceleration in a circular path is known as synchrotron radiation. As the particle will loose energy with this so we must provide the additional energy to keep the beam at constant energy.

<sup>2</sup>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 just acts as a thermal insulator as the cryogenic parts are kept at 1.9 K ( $-271.3^{\circ}C$ )

71 several other experiments at each stage, which are shown pictorially in  
72 Figure 1.1. The stages for proton acceleration are:

- 73     • Grab proton source: The source of proton is Duoplasmatron<sup>3</sup>[1].  
74         This feed protons to LINAC2.
- 75     • LINAC2 (Linear accelerator-2): It is the starting point of proton's  
76         journey in the LHC accelerator complex. Here, protons reaches  
77         to an energy of 50 MeV using the radio-frequency (RF) cavities<sup>4</sup>  
78         where it also gains 5% in mass. It feeds to the Proton Synchrotron  
79         Booster (PSB).
- 80     • PSB: It takes 50 MeV protons beams from LINAC2 and accelerates  
81         it to 1.4 GeV for the injection into Proton Synchrotron (PS).
- 82     • PS: It is one of key component in the LHC accelerator complex. It  
83         increases the energy of protons up-to 25 GeV and feeds to super  
84         proton synchrotron.
- 85     • Super Proton Synchrotron (SPS): It has a circumference of 7 km  
86         where protons are accelerated to an energy of 450 GeV. Then via  
87         two transmission line protons are then injected into LHC ring.
- 88     • LHC: It grabs two proton beams from SPS which is injected into  
89         opposite direction in parallel pipes. In LHC proton beams can be  
90         accelerated up-to 7 TeV.

91 The CERN accelerator complex is shown in Figure 1.2.

### 92 1.1.3 Magnet System

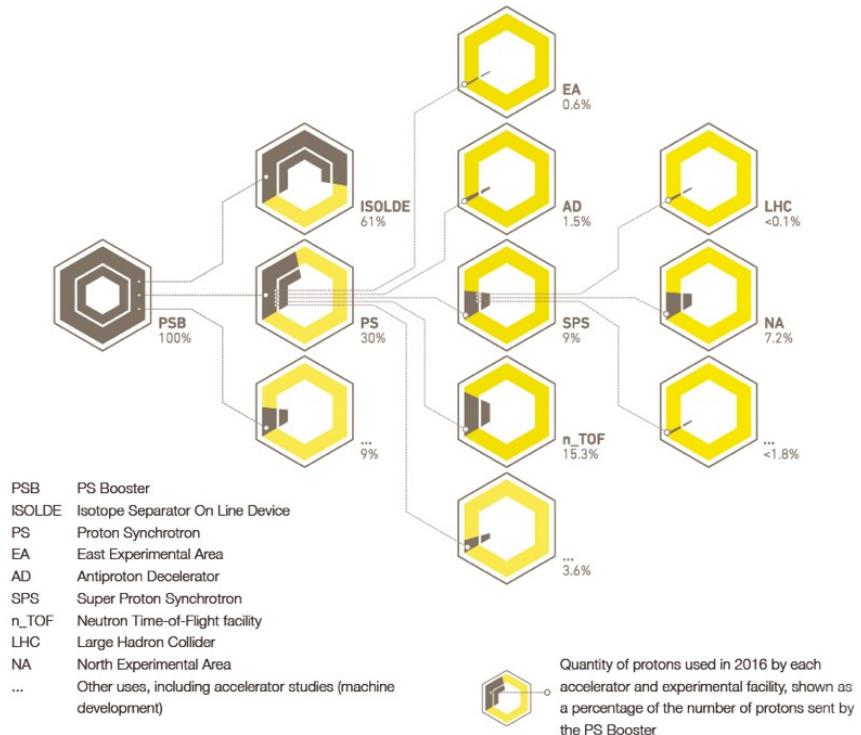
93 As the LHC is a circular collider so magnet system is its one of core part  
94 which give them a circular trajectory in the LHC beam pipes.

95 To be economical LHC is made in eight arcs and eight straight sections  
96 instead of a perfect circle. Along with the bending of beam it is also  
97 necessary to focus the beam as the same charge protons try to diverge.  
98 To focus the beam a pair of quadrupole magnets are used one focuses  
99 the beam width while other focus the beam height. Quadrupole magnet  
100 geometry is shown in Figure 1.3. There are total of 858 quadrupole

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<sup>3</sup>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

<sup>4</sup>A RF cavity is an metallic cavity that accelerates the charged particles using the electromagnetic field.



**$1.34 \times 10^{20}$  protons** were accelerated in the accelerator complex in 2016. This might sound like a huge number, but in reality it corresponds to a minuscule quantity of matter, roughly equivalent to the number of protons in a grain of sand. In fact, protons are so small that this amount is enough to supply all the experiments. The LHC uses only a tiny portion of these protons, less than 0.1%, as shown in the diagram.

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

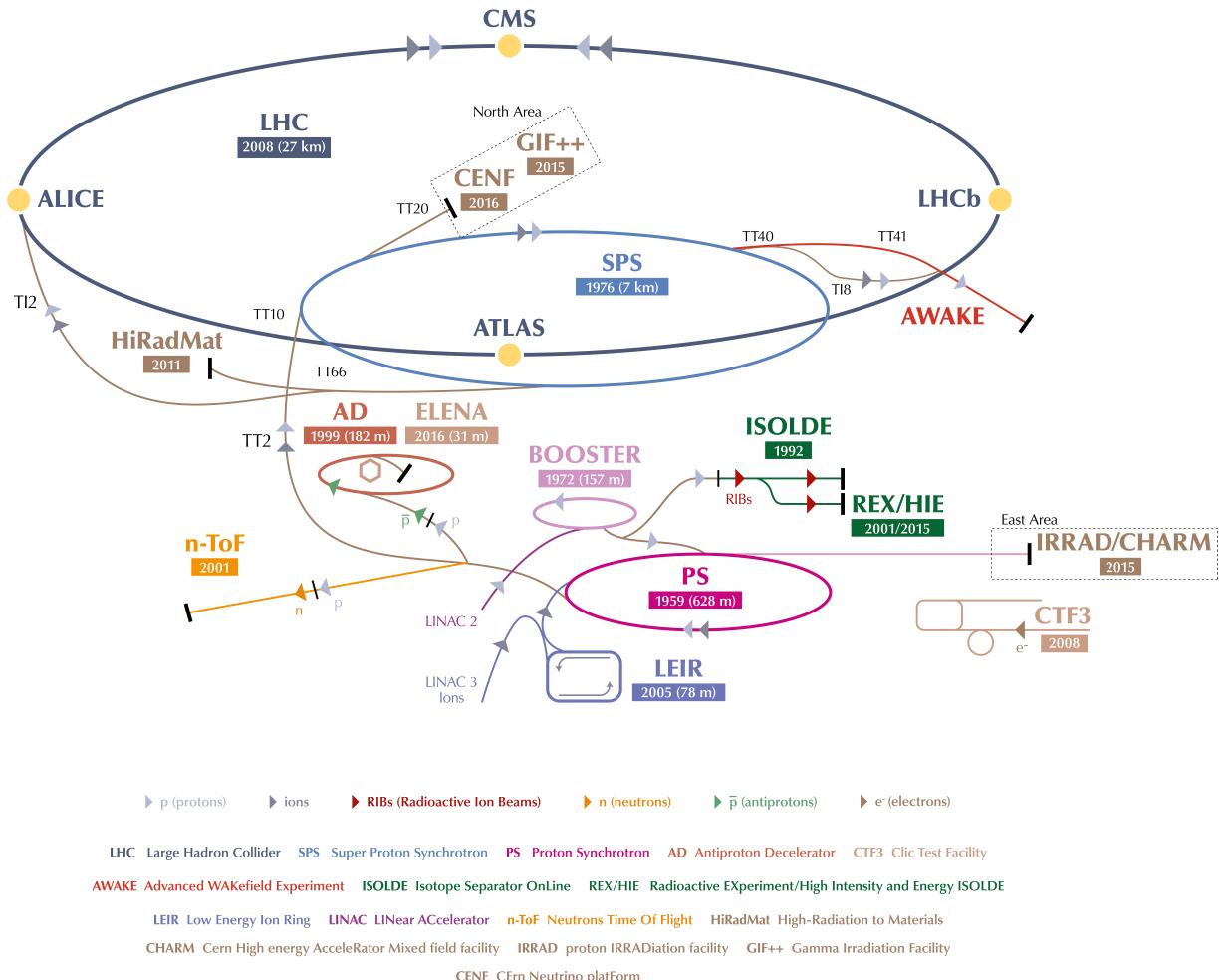


Figure 1.2: LHC accelerator chain along with all its other experiments which uses proton beam from other part of accelerator either from PSB, PS or SPS[3]

101 magnets are installed in LHC to keep the beam focused. Along with  
 102 this every protons in the beam are not exactly with the same energy and  
 103 in same path. To correct this focusing with change in energy there are  
 104 sextupoles magnets are used. There are several other magnetic multi-  
 105 poles are used that help us to keep beam focused if the beam suffers  
 106 from gravitational interactions over protons, electromagnetic interactions  
 107 among bunches, electron clouds from pipe wall, and so on. Different types  
 108 of magnets used in LHC are listed here [4]. Along with this there are eight  
 109 sets of “inner triplets” are used. These are used at the four interaction  
 110 points to focus the beam while collide to increase the luminosity. Here  
 111 the size of bunch goes from 0.2 mm to 17  $\mu\text{m}$  at the interaction point  
 112 of ATLAS or CMS. At the interaction point of ALICE or LHCb it is 71  
 $\mu\text{m}$ . Summary of important parameters of LHC is given in Table 1.1.

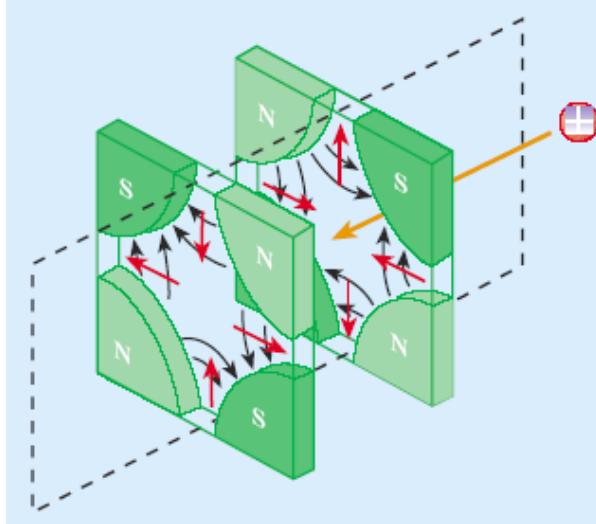


Figure 1.3: Pair of quadrupole magnets.

113

#### 114 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:

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

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)	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Maximum instantaneous luminosity (2012)	$7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
Maximum instantaneous luminosity (2016)	$1.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
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	$1.6 \times 10^{11}$
Protons/bunch (average at start of collision) (nominal)	$1.15 \times 10^{11}$
Protons/bunch (average at start of collision) (2012)	$1.5 \times 10^{11}$
Protons/bunch (average at start of collision) (2016)	$1.1 \times 10^{11}$
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)	$1.9 \times 10^{-3}$
Energy spread (at collision)	$0.45 \times 10^{-3}$
Half crossing angle (nominal)	$143 \mu\text{rad}$
Half crossing angle (2012)	$146 \mu\text{rad}$
Half crossing angle (2016)	$185 \mu\text{rad}$
$\beta^*$ (nominal)	0.55 m
$\beta^*$ (2012)	0.6 m
$\beta^*$ (2016)	0.4 m
RMS beam size at IP1 & IP5	$17 \mu\text{m}$
RMS beam size at IP2 & IP8	$71 \mu\text{m}$
$\epsilon_n$ (transverse emittance, rms, normalized) (at injection)	$3.5 \mu\text{m}$
$\epsilon_n$ (transverse emittance, rms, normalized) (at collision point)	$3.75 \mu\text{m}$
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)	9
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].

115 where,  
116  $k_b$  is the number of bunches per ring,  
117  $N_b$  is the number of protons per bunch,  
118  $f_{rev}$  the revolution frequency,  
119  $\epsilon_n$  is the normalized RMS transverse beam emittance (same in both )  
120  $\beta^*$  is the beta-function at the interaction point

121  
122 Based on the definition of luminosity, we can maximize it by following  
123 means:

- 124 • By decreasing beam emittance,  $\epsilon_n$ .  
125 • By improving the cryogenic system. As the factor  $k_b.N_b$  is limited  
126 by thermal energy produced by synchrotron radiation.  
127 • By decreasing beam-beam effect. As it scales with  $N_b/\epsilon_n$  which  
128 causes the spread in betatron tunes.  
129 • Also, the space charge scales with  $N_b/\epsilon_n$ .

130 **1.2 Experiments at the LHC**

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

136 **ATLAS** (A Toroidal LHC Apparatus) and **CMS** (Compact Muon Solenoid)  
137 are large general-purpose detectors having similar design and same physics  
138 goal. CMS detector will be described in detail in Section ???. The main  
139 difference in the two is in their magnet systems. One additional choice  
140 that affects this is the momentum resoultion for muons. The momentum  
141 resolution for muons,  $\Delta p_T/p_T$ , are proportional to  $B^{-1}L^{-2}$ , where B is  
142 magnetic field and L is distance of momentum measurement from the  
143 IP of detector. So, To imporve the momentum resoltuion there are two  
144 possible choices.

- 145 1. Increase the magnetic field with compact design, or  
146 2. Work with low magnetic field with long lever arm, L

147 There is also a third possiblity to increase the lever arm as well as  
148 magnetic field but it will increase the cost of detector by several factor.

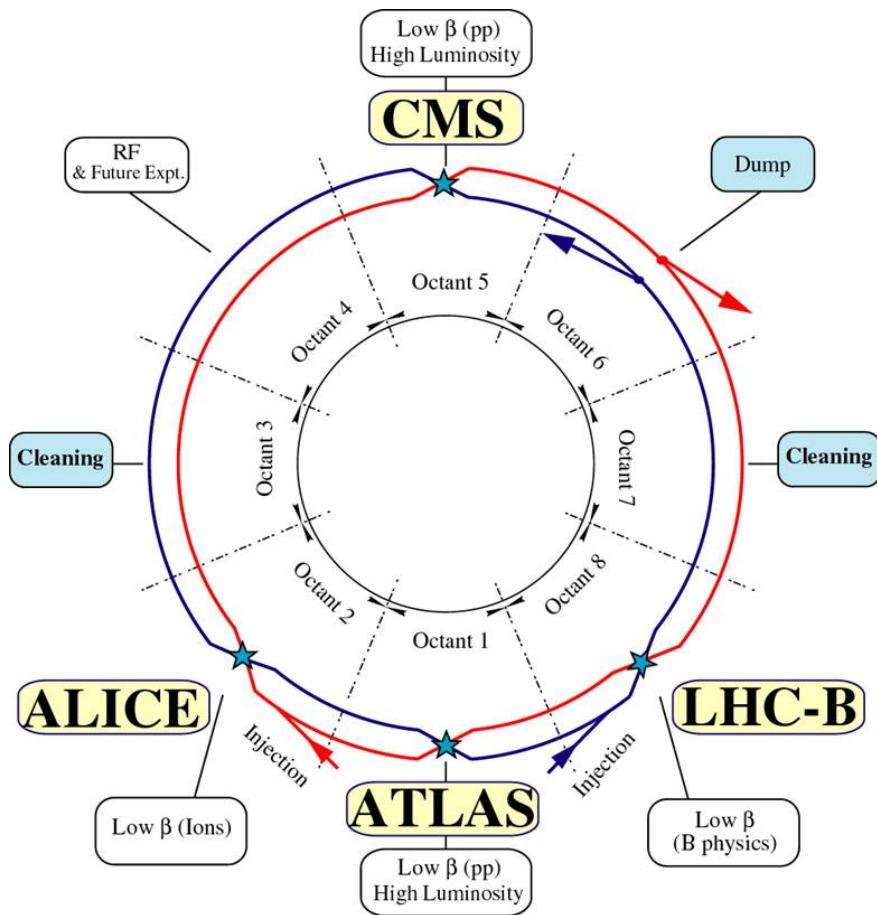


Figure 1.4: LHC geometry with arcs and straight sections.

149 So, CMS chooses the first point, i.e., to increase the magnetic field with  
150 compact design<sup>5</sup> while ATLAS chooses the design with low magnetic field  
151 with long lever arm.

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

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

158 **LHCf** (Large Hadron Collider forward) and **TOTEM** (TOTal cross-  
159 section, Elastic scattering and diffraction dissociation Measurement at  
160 the LHC) are located near ATLAS and CMS respectively, for the study  
161 of forward physics.

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<sup>5</sup>This is why there is word **compact** in the name of CMS.

<sup>162</sup>

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