LHC: Machine and Accelerator Physics

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- 26 658.883 m
- 6.5 TeV x 2
Themes and Topics

• “Level 0” Issues: Make it run
  – T1: LHC machine overview… consequences of SC magnets:
  – T2: Clean beampipes
  – T3: UFOs
  – T4: Halo collimation

• “Level 1” Issues: Performance (luminosity)
  – T5: Turnaround time, availability
  – T6: Collisions, pileups, proton lifetime
  – T7: Upgrades
T1: Types of Accelerators

- **Cyclotrons - 1930-40's**
  - E.O. Lawrence (UCB)

- **Betatrons - 1940-50's**
  - D. Kerst (UI)

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**LHC** is a synchrotron

\[
E[\text{GeV}]=0.3 \times B[\text{T}] \times R[\text{m}]
\]

R is fixed [4.24km]
State of the Art SC Magnets

1232 bending magnets 15m
NbTi cables, 13 kA@1.9 K 10 GJ

4.5T
4.5 K He, NbTi + warm iron
small He-plant

5.3T
NbTi cable
cold iron
Al collar

3.5T
NbTi cable
simple &
cheap

8.3T
LHC,
15 m, 56 mm
1276 dipoles

Tevatron,
6 m, 76 mm
774 dipoles

HERA,
9 m, 75 mm
416 dipoles

RHIC,
9 m, 80 mm
264 dipoles

NbTi cable
two bores

15  
1232
m
GJ
10

Shiltsev | LHC Machine
Focusing Beams with Quadrupole Magnets

Luckily...

...pairs give net focusing in both planes! -> “FODO cell”
As particles go around a ring, they will undergo a number of betatron oscillations $\nu$ (sometimes $Q$) given by

$$\nu = \frac{1}{2\pi} \int \frac{ds}{\beta(s)}$$

This is referred to as the “tune”. We can generally think of the tune in two parts:

- **Integer**: magnet/aperture optimization
- **Fraction**: Beam Stability

64.31
Emittance

\[ x' \pm \sqrt{\frac{\varepsilon \beta}{\pi}} \]

As a particle returns to the same point on subsequent revolutions, it will map out an ellipse in phase space, defined by

\[ \gamma_T x'^2 + 2 \alpha_T x x' + \beta_T x'^2 = \frac{\varepsilon}{\pi} \]

\[ \gamma_T \beta - \alpha^2 = 1 \]

Twiss Parameters

- Product size x angle \( X_{\text{rms}} x X'_{\text{rms}} \) is called emittance
- Emittance x gamma is adiabatic invariant
- In LHC: at IP 16 um x 30 urad x 7000\( \equiv \)3 mm mrad, in arcs 300 um x 1.6 urad x 7000 \( \equiv \) 3 mm mrad
- Luminosity \( \sim \frac{1}{\varepsilon} \)
Numerical Example: LHC ($\gamma \gg 1$, $\beta = v/c \approx 1$)

\[
\varepsilon_n(x,y) = \gamma \cdot \sigma_{x,y} \sigma'_{x,y}
\]

\[
\sigma_{x,y} = \sqrt{\frac{\varepsilon_n \cdot \beta_{x,y}}{\gamma}}
\]

\[
\sigma'_{x,y} = \sqrt{\frac{\varepsilon_n}{\gamma \cdot \beta_{x,y}}} = \frac{\sigma_{x,y}}{\beta_{x,y}}
\]

Squeeze in ATLAS/CMS

$\varepsilon_n = 2.9 \text{ mm} \cdot \text{mrad}$

$\gamma = 6930$

<table>
<thead>
<tr>
<th>$\beta^*$</th>
<th>$\Sigma^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 cm</td>
<td>13 um</td>
</tr>
</tbody>
</table>

$\beta_{\text{triplet}}$ | $\Sigma_{\text{triplet}}$
|----------------|----------------|
| $\sim 4.5 \text{ km}$ | 1.5 mm

$\sigma' = 0.3 \mu\text{rad}$

in the arcs:

$\beta \sim 200 \text{ m, } \sigma \approx 0.3 \text{ mm}$
Particles are typically accelerated by radiofrequency ("RF") structures. Stability depends on particle arrival time relative to RF phase. Note: the speed = fixed = speed of light, so time of arrival depends only on the energy (in the bunch – energy deviation wrt “reference central particle”)

Particles with lower E arrive earlier and see greater V.

Nominal Energy
Example: LHC

**RF Frequency 400 MHz**
(35640 times revolution frequency)

- RF Voltage = 8 cavities x 2 MV = 16 MV / turn (max)

In collisions \( \frac{dE}{dn} = 0 \text{ V/turn} \) (synchronouse phase ~0)

Slow energy-position oscillations (23 Hz or ~500 turns)

rms energy spread \( 1.3 \times 10^{-4} \) (1GeV)  
rms bunch length ~ 8cm
T2: Electron Cloud & Need of Scrubbing

- Primary sources of electrons in the LHC
  - At Injection (450 GeV) gas ionization
  - At 7 TeV Synchrotron Radiation

**Consequences:**
- instabilities, emittance growth, desorption \( \leftrightarrow \) bad vacuum, beam loss
- excessive energy deposition in the cold sectors

\[ E_{\text{max}} = 239.5 \text{ eV} \]
\[ \varepsilon_T = 2.5 \mu\text{m} \]

The critical energy of the photons at 7 TeV \(~ 44 \text{ eV}\)
What e-cloud can do to the Beam?

- Fill: 2249 (2011)
- 25 ns Bunch Spacing
- Energy = 450 GeV
- Time between Injection to End ~10 min
- Dumped by BPM
- 1020 Bunches

Measured Emittance Growth
- ~33% Horizontal
- ~110% Vertical

Associated beam loss
Scrubbing @ 25 ns bunch spacing

So far it is the only cure in the LHC….Takes time to clean the surface and reduce SEY (secondary electron yield) from ~2.2 to ~1.5

Scrubbing “memory” kept while running with 25 ns beams - deconditioning was observed after few weeks of low e-cloud operation
T3: UFOs  ‘Unidentified Falling Objects’
**UFOs:** there are many of them, they are frequent!

UFO events observed quite often during operation at 6.5 TeV

Conditioning is observed on the UFO rate in spite of the increasing number of bunches

BLM thresholds being optimize to find a good compromise between availability and quench protection

- arc UFOs (cell >11): rates similar to end of 2015
  - did not lose conditioning over the Xmas stop
The LHC beam energy is 350 MJ. Already at injection the beam can damage a magnet.
Superconducting coil: \(T = 1.9\,\text{K},\) quench limit \(\sim 15\text{mJ/cm}^3\)

Proton beam: \(145\,\text{MJ}\) (design: \(362\,\text{MJ}\))

Factor \(9.7 \times 10^9\)

Aperture: \(r = 17/22\,\text{mm}\)

LHC “Run 1” 2010-2013: No quench with circulating beam, with stored energies up to 70 times of previous state-of-the-art!
LHC has **complex** and **distributed collimation** system of >100 collimators → several stages to protects LHC components as well as detectors

Collimation is designed to provide cleaning efficiencies > 99.99%
→ *need good statistical accuracy* at limiting loss locations;
→ *simulate only halo particles that interact with collimators, not the core.*
The LHC collimator
Two warm cleaning insertions, 3 collimation planes
  IR3: Momentum cleaning
    1 primary (H)
    4 secondary (H)
    4 shower abs. (H,V)
  IR7: Betatron cleaning
    3 primary (H,V,S)
    11 secondary (H,V,S)
    5 shower abs. (H,V)

Local cleaning at triplets
  8 tertiary (2 per IP)

Passive absorbers for warm magnets
Physics debris absorbers
Transfer lines (13 collimators)
Injection and dump protection (10)

Total of 108 collimators (100 movable).
Two jaws (4 motors) per collimator!
Super-Effective Halo Cleaning in LHC

2015

Betatron Beam 1 VER 6500GeV 2015-09-06 02:07:11

Local Cleaning Inefficiency

LHC ring position (m)
T5: LHC Machine availability -2015

Statistics for 25 ns run from September 7 to November 3

- LHC Downtime [h]
- System Downtime [h]

- Stable Beams, 450 h, 32 %
- Downtime, 427 h, 31 %

- Turnaround Time, 515 h, 37 %
2016 Availability: 11th June – 23rd July

From 32% to 67%
In one year!

Stable Beams 67%

Tevatron (2011):
Avg. 120 hrs / wk = 72%
Best 144 hrs / wk = 86%
The fastest turnaround in 2012 was 2 hours 8 minutes. This was close to the theoretical minimum for 4 TeV operation. The average for the year was around 5 hours 30 minutes.
Additional delays:

- Transfer and injection optimization and general wrestling with the injection process (respecting tight demands on beam quality etc.).
- Controls and data acquisition problems; kicker overheating; problems in the injectors; etc.
- Access recovery, precycle faults
- Fills lost in the ramp and squeeze to beam induced problems (instabilities) or, feedback system faults

Table 1: Breakdown of turnaround with estimated minimum times shown

<table>
<thead>
<tr>
<th>Phase</th>
<th>Time [minutes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp down/pre-cycle</td>
<td>60</td>
</tr>
<tr>
<td>Pre-injection checks and preparation</td>
<td>15</td>
</tr>
<tr>
<td>Checks with set-up beam</td>
<td>15</td>
</tr>
<tr>
<td>Nominal injection sequence</td>
<td>20</td>
</tr>
<tr>
<td>Ramp preparation</td>
<td>5</td>
</tr>
<tr>
<td>Ramp</td>
<td>25</td>
</tr>
<tr>
<td>Squeeze</td>
<td>30</td>
</tr>
<tr>
<td>Adjust/collisions</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>180</td>
</tr>
</tbody>
</table>
T6: Colliding Beams Luminosity

Circulating beams typically “bunched”

Total Luminosity:

\[ L = \left( \frac{N_1 N_2}{A} \right) r_b = \left( \frac{N_1 N_2}{A} \right) n \frac{c}{C} \]

Rate of collisions

Cross-sectional area of beam

Number of bunches

Circumference of machine

Record Hadronic Luminosity (LHC): 1.5E34 cm^{-2}s^{-1}
(50% over LHC design; x35 Tevatron lumi)

Record e+e- Luminosity (KEK-B): 2.1E34 cm^{-2}s^{-1}
E.g., 2016 Luminosities

ATLAS

Design $10^{34}$ cm$^{-1}$ s$^{-1}$

Peak

6 years since 1$^{st}$ collisions in April’2010

Integrated

- $\sim$40 fb$^{-1}$ delivered to ATLAS & CMS
- 3 fb$^{-1}$/very good week

CMS

10% diff?

$6\%$ diff
The relationship of the beam to the rate of observed physics processes is given by the “Luminosity”

\[ R = L \sigma \]

“Luminosity”

Standard unit for Luminosity is \( \text{cm}^{-2}\text{s}^{-1} \)

Example: total \( p-p \) inelastic+elastic cross section at 13 TeV cme is \( \sim 110 \) mbarn (58 inel+ 12 ssd+40 el not seen) \( \rightarrow \)

\( \sim 30 \) interactions per crossing (NB: pile up is only \( \sim 20! \) ) \( \times \)

40,000,000 collision/sec= 1.1B protons leave each beam every second

Beam lifetime due to such “Burn up” \( T=N/(dN/dt)= \)

2.5e14 protons/(1.1e9/s) =63 hours
Luminosity lifetime

Take into account two IPs (ATLAS, CMS and 3% LHCb) \(1/64 + 1/64\) hrs\(^{-1}\)
Take into account beam gas \(1/110\) hrs\(^{-1}\) and that \(Lumi \sim N^2 \rightarrow x2\)

ATLAS luminosity and fit – Fill 5102 Average tau: 24.

\[2 \times (1/64 + 1/64 + 1/110) \text{ hrs}^{-1}\]
\[= 8\% / \text{hr} \ (12.5 \text{ hrs lifetime})\]
T9: Upgrades

• The main objective of HiLumi-LHC Upgrade (2022-2024) is to install new hardware and guarantee beam parameters that will allow the LHC to reach the following targets:
  – Prepare machine for operation **beyond 2025 and up to 2035-37**
  – Devise beam parameters and operation scenarios for:
    • enabling a total integrated luminosity of **3000 fb-1**
    • implying an integrated luminosity of **250-300 fb-1 per year** now ~40
    • design for $\mu \sim 140 (\sim 200)$
    • (peak luminosity of $5 (7) \times 10^{34}$ cm$^{-2}$ s$^{-1}$) now ~1.4
  – Design equipment for ‘ultimate’ performance of $7.5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ and **4000 fb-1** => Ten times the luminosity reach of first 10 years of LHC operation
LHC Luminosity Upgrade: Machine Goals

Luminosity recipe:

\[ L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{\text{rev}}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s) \]

→ 1) maximize bunch intensities
→ 2) minimize the beam emittance
→ 3) minimize beam size (constant beam power); → triplet aperture
→ 4) maximize number of bunches (beam power); → 25ns
→ 5) compensate for ‘F’;
→ 6) Improve machine ‘Efficiency’

→ Injector complex 1.15 → 2.2e9
→ LIU ↔ IBS 3.75 → 2.5 μm

Avoid 0.3 w/o Crabs: 0.83 w. Crabs as now

With all these changes luminosity could peak at \( \sim 20e34 \rightarrow 20x \) design

and 20x pile up, ie \( \mu > 540 \rightarrow \) luminosity leveling will be done at \( \sim 5e34 \)
HL-LHC Scale: Hardware and Cost

The HL-LHC Project

976MCHF (-142 +208)
~2,500 man-years

- New IR-quads Nb₃Sn (inner triplets)
- New 11 T Nb₃Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

Major intervention on more than 1.2 km of the LHC
Quadrupoles of LARP

LQS01a: 202 T/m at 1.9 K
LQS01b: 222 T/m at 4.6 K
227 T/m at 1.9 K

LQS02: 198 T/m at 4.6 K 150 A/s
208 T/m at 1.9 K 150 A/s
limited by one coil

LQS03: 208 T/m at 4.6 K
210 T/m at 1.9 K
1st quench: 86% s.s. limit

3.3 m coils
90 mm aperture

Target:
200 T/m gradient at 1.9 K
Acknowledgements

Materials and slides used here come from many sources, including the USPAS lectures, Eric Prebys, Mike Lamont, various conferences, workshops, LHC and LARP reviews, etc

Questions !?
Further Reading on Accelerator Physics

- Accelerator Physics, S.Y. Lee (World Scientific, 1999)
- Accelerator Physics at the Tevatron Collider - by V.Lebedev and V.Shiltsev, Springer (2014)