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

• What do protons do in “spare time” before collisions:
  – T1: Betatron oscillations
  – T2: Luminosity, beam lifetime
  – T3: Emittance growth
  – T4: Halo collimation

• What sets the LHC store duration
  – T5: Cryogenics trips
  – T6: UFOs
  – T7: Turnaround time, ramp

• What do LHC “machinists” do between/before collision runs
  – T8: Fix splices
  – T9: Clean beampipes
  – T10: Execute upgrades
T1: Betatron Oscillations

- 2800 bunches/beam x ~1.1e11/bunch = 3e14 /beam
- 11,000 revolutions/s x 10 hrs = 0.4 billion turns
  - Only ~ 1 billion protons die in collisions per second
- Transverse betatron oscillations ~60 times/revolution:
  - Also called *betatron oscillations*
  - Rms amplitude = beam size
  - 200-300 micron in arcs, 16 micron at IPs
  - Angular divergence: ~2 microrad in arcs, 30 microrads at IPs
- Longitudinal oscillations – slow – 7 Hz:
  - Also called *synchrotron oscillations*
  - Particles change positions in the bunch, rms bunch length ~8 cm
  - Particle’s energies vary, too – rms 1 GeV (dE/E_rms=1.1e-4)
Accelerator Nomenclature Reflects History

LHC is a synchrotron

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

- **Betatrons - 1940-50's**
  - D. Kerst (UI)
Focusing Beams with Quadrupole Magnets

Luckily...

...pairs give net focusing in both planes! -> “FODO cell”
Longitudinal Motion: Phase Stability

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”)

\[ V(t) \]

Particles with lower E arrive \textit{earlier} and see greater V.
T2: Luminosity

The relationship of the beam to the rate of observed physics processes is given by the “Luminosity”

\[ R = L \sigma \]

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

Example: total \( p-p \) inelastic+elastic cross section at 13 TeV cme is \( \sim 110 \) mbarn (60 inel+ 12 ssd+40 el not seen) \( \rightarrow \) \( \sim 40 \) interactions per crossing (NB: pile up is only \( \sim 20 \)! ) \times \( 40,000,000 \) collision/sec = 1.6B protons leave each beam every second

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

\[ 3 \times 10^{14} \text{protons}/(1.6 \times 10^9/\text{s}) = 46 \text{hours} \]
E.g., 2015 Luminosities

**Peak**

- $5 \times 10^{33} \text{ cm}^{-1} \text{ s}^{-1}$
- Design $10^{34} \text{ cm}^{-1} \text{ s}^{-1}$

**Integrated**

- ATLAS
  - ATLAS Online Luminosity
  - Peak Lumi: $5.22 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
  - Data included from 2015-05-03 08:41 to 2015-11-03 06:23 UTC
  - Preliminary Offline Luminosity

- CMS
  - CMS Peak Luminosity Per Day, pp. 2015, $\sqrt{s} = 13 \text{ TeV}$
  - Max. Inst. Lumi: 4900.86 $\text{ fb}^{-1}$
  - Preliminary Offline Luminosity

- CMS Integrated Luminosity, pp. 2015, $\sqrt{s} = 13 \text{ TeV}$
  - Data included from 2015-06-03 08:41 to 2015-11-03 06:23 UTC
  - Preliminary Offline Luminosity

**ATLAS**

**CMS**
Colliding Beams Luminosity

Circulating beams typically “bunched”

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

Total Luminosity:

\[
= \left( \frac{N_1}{A} \right) N_2 \sigma
\]

(number of interactions)

Cross-sectional area of beam

Circumference of machine

Number of bunches

Rate of collisions

Record Hadronic Luminosity (LHC): 0.8E34 cm\(^{-2}\)s\(^{-1}\)

(80% of the LHC design; x20 Tevatron lumi)

Record e+e- Luminosity (KEK-B): 2.1E34 cm\(^{-2}\)s\(^{-1}\)
As a particle returns to the same point on subsequent revolutions, it will map out an ellipse in phase space, defined by

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

\[ \gamma_T \beta_T - \alpha_T^2 = 1 \]

Twiss Parameters

- **Product size x angle** 
  \( X_{\text{rms}} \times X'_{\text{rms}} \) is called emittance

- **Emittance x gamma** 
  is adiabatic invariant

- In LHC: **at IP 16 um x 30 urad x 7000 = 3 mm mrad**, in arcs 300

- Luminosity \( \sim \frac{1}{\varepsilon} \)
**T3: Emittance growth**

\[ T_x = \varepsilon_x / (d\varepsilon_x / dt) \]

- **Intra-beam scattering:** 80 hrs (growth)
- **Synchrotron radiation:** 26 hours (cooling)
  - Each proton loses 67 keV/turn (many 44 eV photons... yes, LHC beams shine!)
  - 0.17 W/m/aperture (total cryo capacity \( O(1) \) W/m)
- **Scattering on residual gas** 1000 hrs (growth)
- **So the total is cooling** (26 < 80 < 1000) ??
T3: Emittance growth in reality

![Graph showing emittance growth over time][1]

[1]: Image of the graph showing emittance growth with different data points and lines indicating Lumi ATLAS, Lumi CMS, BSRT, and a model line.
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

BEAM

1.0m + 0.2m tapering

1/11/2016 V.Shiltsev | LHC Machine
LHC Collimation System Layout

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
T5: Cryogenics, Trips

- LHC: 8 cryoplants total 35 MW wall plug; 130 tons of LHe to keep 36,000 tons at 1.9K
- Efficiency ~250 W wall plug power per Watt at 4.5 K
  - CERN cryocapacity of 150 kW @4.5K and 20kW at 1.9K
- Three Temperatures:
  - 50-70 T-shield
  - 4.6 K Heat Intercept
  - 4.6-20 K Beam Screen
  - 1.9K cold mass
- Safety factor 1.6 (design)
- Reality: ~none (1.1?)

<table>
<thead>
<tr>
<th>Temp. level</th>
<th>Heat load source</th>
<th>LHC nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>TS</td>
<td>Heat inleaks</td>
<td>[W/m]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total TS</td>
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<tr>
<td>HI</td>
<td>Heat inleaks</td>
<td>[W/m]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total HI</td>
</tr>
<tr>
<td>BS</td>
<td>Heat inleaks, Synchrotron radiation, Image current, Photo-electron cloud</td>
<td>[W/m]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total BS</td>
</tr>
<tr>
<td>CM</td>
<td>Heat inleaks, Resistive heating, Beam-gas scattering</td>
<td>[W/m]</td>
</tr>
</tbody>
</table>

V. Shiltsev | LHC Machine
Performance assessment of all sub-system (at least a type test) before being connected to the next one.
Cryo: Complex and Large Machinery

LHC Cryo Plant: Machines Status

<table>
<thead>
<tr>
<th>S12</th>
<th>S23</th>
<th>S34</th>
<th>S45</th>
<th>S56</th>
<th>S67</th>
<th>S78</th>
<th>S81</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 K</td>
<td>4.5 K</td>
<td>1.8 K</td>
<td>1.8 K</td>
<td>4.5 K</td>
<td>4.5 K</td>
<td>1.8 K</td>
<td>1.8 K</td>
</tr>
</tbody>
</table>

- **Compressors 4.5 K**
- **Cold Box 4.5 K**
- **Compressors 1.8 K**
- **Cold Box 1.8 K**

Machine status:
- Alarm: Red
- Off: White
- On: Green
- No data: Blue

Most recent data: 10 Jan 2016 04:38:26 UTC
2015 LHC Machine availability

Statistics for 25 ns run from September 7 to November 3
T6: 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
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
T8: State of the Art SC Magnets

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

4.5T

HERA,
9 m, 75 mm
416 dipoles

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

5.3T

RHIC,
9 m, 80 mm
264 dipoles

NbTi cable
cold iron
Al collar

5.3T

8.3T

LHC,
15 m, 56 mm
1276 dipoles

NbTi cable
two bores

3.5T

1/11/2016
• A splice with bad thermal and electrical contact between the superconductor and the copper produced sufficient resistive heating to lead to thermal runaway.
• This provoked the melting of the material surrounding the splice, and subsequently an electric arc developed between two exposed cable ends.
• This arc melted through the helium line in which the cable travels, releasing Helium into the insulation vacuum of the interconnect.
• The rapid and voluminous expansion of the Helium caused a pressure wave that propagated along the insulation vacuum causing extensive damage.
Quench: MRI magnet* (~1/30,000 of LHC)

*Pulled off the web. We recover our Helium.
Sample Joint X-Rays

Sample 3A left (26 $\mu\Omega$)
Sample 3A right (43 $\mu\Omega$)
Sample 3B (21 $\mu\Omega$)
Sample 2A right (43 $\mu\Omega$)
Sample 2B (42 $\mu\Omega$)

Pictures by J.-M. Dalin

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A 13kA splice has a resistance of about 300 pΩ, which can be measured with a precision ~20pΩ. The acceptance criteria is 10 nΩ. Any splice does not meet this criteria is replaced/repaired. The resistance acceptance criteria at the Cu - superconducting splice joints was 5 µΩ. Any joint does not meet this criteria is replaced or repaired.
T9: 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 \( \rightarrow \) bad vacuum, beam loss
- excessive energy deposition in the cold sectors

The critical energy of the photons at 7 TeV \( \sim 44 \text{ eV} \)

E\text{max} = 239.5 \text{ eV}
\( \varepsilon_T = 2.5 \mu\text{m} \)

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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
T10: 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**,
    • design for $\mu \sim 140 \ (\sim 200)$
    • (peak luminosity of $5 \ (7) \ 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)
  – Design equipment for ‘ultimate’ performance of **7.5 $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$** and **4000 fb-1** => Ten times the luminosity reach of first 10 years of LHC operation
LHC Luminosity Upgrade : Machine Goals

**Luminosity recipe**:

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

1) maximize bunch intensities

2) minimize the beam emittance

3) minimize beam size (constant beam power);

4) maximize number of bunches (beam power);

5) compensate for ‘F’;

6) Improve machine ‘Efficiency’

⇒ Injector complex

⇒ LIU ⇔ IBS

⇒ triplet aperture

⇒ 25ns

⇒ Crab Cavities

⇒ minimize number of unscheduled beam aborts
HL-LHC Scale: Hardware and Cost

The HL-LHC Project

976MCHF (-142 +208)

~2,500 man-years

- New IR-quads Nb$_3$Sn (inner triplets)
- New 11 T Nb$_3$Sn (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
Further Reading on Accelerator Physics

- **Accelerator Physics**, S.Y. Lee (World Scientific, 1999)
- **CAS CERN Accelerator Physics Courses** [http://cas.web.cern.ch/](http://cas.web.cern.ch/)
- **Accelerator Physics at the Tevatron Collider** - by V. Lebedev and V. Shiltsev, Springer (2014)
Thank you for your attention!

Questions !?