LHC Collimation and Loss Locations

BLM Audit

Th. Weiler, R. Assmann, C. Bracco, V. Previtali, S Redaelli

Accelerator and Beam Department, CERN
Outline

- Introduction / Motivation
  - LHC Layout
  - The LHC Challenge
  - Collimation Principle / Multi Stage Cleaning
- Loss Rates
- Intensity and Cleaning Inefficiency
- Simulations: SixTrack and Beam Loss Pattern
- Loss location around the ring (injection and top energy)
- Summary
Layout of the LHC Ring

- 7 TeV protons for collision
- super-conduction magnets to bend and focus beam
- four experimental insertions
- two dedicated cleaning insertions in region with normal conducting magnets
- dump protection (in case of kicker failure)
The LHC Challenge

- Stored beam energy $360 \text{ MJ}$, $\approx 200$ times larger than any other existing proton machine, enough energy to melt $500 \text{ kg}$ of copper.
- For quenching a superconducting magnet one needs $\approx 10 \text{ mJ cm}^{-3}$
Multi-Stage Cleaning

- Core
- Primary halo (p)
- Secondary halo
- Shower
- Tertiary halo
- Triplets and Experiments

Beam propagation

Unavoidable losses

Impact parameter ≤ 1 μm

CFC

CFC

CFC

Cu / W

tertiary collimator: W

Th. Weiler, AB/ABP-LCU, CERN
Multi-Stage Cleaning

- Core
- Primary halo (p)
- Secondary halo
- Shower
- Absorber
- Tertiary halo

Beam propagation
Unavoidable losses

Impact parameter ≤ 1 μm

Normalized amplitude [σ_radial]

Normalized population

Th. Weiler, AB/ABP-LCU, CERN
**Loss Rates (slow)**

The following table summarises the specified maximum loss rates for a safe operation of the LHC machine and its collimation system.

<table>
<thead>
<tr>
<th>Mode</th>
<th>T</th>
<th>τ</th>
<th>R&lt;sub&gt;loss&lt;/sub&gt;</th>
<th>P&lt;sub&gt;loss&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[s]</td>
<td>[h]</td>
<td>[p/ s]</td>
<td>[kW]</td>
</tr>
<tr>
<td>Injection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cont.</td>
<td>1</td>
<td>0.1</td>
<td>0.8 × 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>0.1</td>
<td></td>
<td>8.6 × 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>63</td>
</tr>
<tr>
<td>Ramp</td>
<td>1</td>
<td>0.006</td>
<td>1.5 × 10&lt;sup&gt;13&lt;/sup&gt;</td>
<td>1098</td>
</tr>
<tr>
<td>Collision</td>
<td>cont.</td>
<td>1.0</td>
<td>0.8 × 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>97</td>
</tr>
<tr>
<td>10</td>
<td>0.2</td>
<td></td>
<td>4.3 × 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>487</td>
</tr>
</tbody>
</table>

Keep in mind that for nominal LHC operation at 7 TeV the beam lifetime is 20 h.
Loss Rates (fast)

For an asynchronous dump (dump kicker pre-fire) it is assumed that 6 bunches can be lost into the collimation system. Similar scenario as for injection kicker failure.

- Collimators (prim. and sec. type) can sustain shock beam impacts of $6.4 \text{ MJ mm}^{-2}$ in 200 ns (7 TeV)

- TCT collimator may be hit by one bunch in case of misalignment of the dump protection by about $2\sigma$, otherwise the TCT is in the shadow of the dump protection and primary/secondary collimators. The intensity of one bunch is sufficient to damage the collimator (tertiary are made of tungsten).
Intensity and Cleaning Inefficiency

\[ N_{\text{max}}^{p} \approx \frac{\tau \cdot R_{q} \cdot L_{\text{dil}}}{\eta_{c}} \]

quench threshold
\begin{align*}
7.8 \times 10^{6} \text{ p/m/s at 7 TeV} \\
7.0 \times 10^{8} \text{ p/m/s at 450 GeV}
\end{align*}

dilution length
50 m (simplified)

allowed intensity
beams lifetime e.g. 0.22h

\begin{align*}
\text{cleaning inefficiency} \\
(\text{for } L_{\text{dil}} = 1 \text{ m}) \quad \eta_{c} &= 2 \times 10^{-5} \text{ m}^{-1} \text{ at 7 TeV} \\
\eta_{c} &= 1 \times 10^{-3} \text{ m}^{-1} \text{ at 450 GeV}
\end{align*}
Simulation Tools: SixTrack

For the collimation studies we use an extended version of SixTrack (full 6d treatment) including a scattering routine for simulating the interaction of the primary protons in the collimator (Colltrack routines). The field maps are generated using MADX (using official LHC optics).

To reduce computing time only the beam halo, which hits the primary collimator (6σ half-gap), is considered in the simulations. A typical simulation tracks around 5 million particles over 200 turns. Reminder: aim is a cleaning inefficiency of $2 \times 10^{-5} \text{ m}^{-1}$

In general the simulation treats only the beam halo particle, beam gas interactions are not included. But it is possible load an external distribution for tracking studies (e.g. for kicker failure or for p-p interactions)
Simulation Tools: Beam Loss Pattern

The tracking information received by SixTrack is afterwards analysed using the beam loss pattern program. It compares the particle tracks with an detailed aperture model and returns the loss locations (particles touching the aperture before being absorbed in a collimator) with an 10 cm resolution.

Trajectory of a halo particle

Magnets locations (thin lenses): $\Delta s \leq 100m$

Interpolation: $\Delta s = 10 \text{ cm}$ (270'000 points!)

S. Redaelli
Th. Weiler, AB/ABP-LCU, CERN

System Performance at 7TeV (Phase1)

beam 1
- 7 TeV
- horizontal betatron halo
- standard settings
- ideal machine

beam 2
- 7 TeV
- horizontal betatron halo
- standard settings
- ideal machine

IR1 IR2 IR3 IR4 IR5 IR6 IR7 IR8

low optics, 7000GeV
interaction points
losses in warm section
losses in cold section
losses in collimator

s [m]
0 5000 10000 15000 20000 25000

local inefficiency $\eta_s$ [1/m]
Cleaning Insertion in IR7

[Graph showing local inefficiency vs. s [m] for different regions: optics, interaction points, losses in warm section, losses in cold section, losses in collimator.]

Th. Weiler, AB/ABP-LCU, CERN
System Performance at Injection

IR1  IR2  IR3  IR4  IR5  IR6  IR7  IR8

beam 1
- 450 GeV
- horizontal betatron halo
- standard settings
- ideal machine

beam 2
- 450 GeV
- horizontal betatron halo
- standard settings
- ideal machine

Th. Weiler, AB/ABP-LCU, CERN
System Performance at 7TeV (Phase1)
(with closed orbit, alignment error, jaw flatness error)

beam 1
- horizontal betatron halo
- collimator misalignment
- closed orbit

horizontal betatron halo
- collimator misalignment
- closed orbit
- aperture misalignment

C. Bracco
**p-p Interactions (DPE)**

Loss locations according to momentum loss for DPE

Expected loss rate for DPE and SD events at peak luminosity $10^{34} \text{ cm}^{-2} \text{s}^{-1}$
Losses for Ions

**IR7 @ collision energy**

**Beam1**

Losses confined to IR7 dispersion suppressor, cells 9 & 11
Two peaks downstream in the arc for Beam2

**Beam2**

G. Bellodi LHC CWG meeting Nov. 2006
Simulation Results available

Overview of available simulated cases.

- standard optics (injection, early collision, all IRs squeezed, IR1 and IR5 squeezed), ideal machine
- start-up configuration (early collision optics with reduced number of TCS collimators in IR7)
- commissioning scenarios
- energy ramp
- error scenarios
  - collimator misalignment (tilt, gap, offset)
  - closed orbit
  - aperture misalignment
- losses from p-p interactions in the IRs (only IR5 so far)
# Loss Locations

<table>
<thead>
<tr>
<th>injection energy</th>
<th>collision energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam 1</td>
<td>beam 2</td>
</tr>
</tbody>
</table>

(see thesis G. Robert-Demolaize)

<table>
<thead>
<tr>
<th>p-p interactions for beam 2 from IR5</th>
</tr>
</thead>
</table>
Summary

- Full set of simulation tool available to simulate the cleaning inefficiency of the collimation system and generate beam loss maps along the ring.

- Loss location for different optics, running scenarios and mechanical alignment errors available.

- Standard run considers around 5 million particles, due to the required low cleaning inefficiency only a few hundred particles are lost to the aperture.

- Main loss locations (see also previous slide):
  - dispersion suppressor after the cleaning insertions
  - dispersion suppressor in experimental insertion (for p-p interaction)
  - Q6 in IR3
Spare Slides
### Estimated Damage Interlock Limits

<table>
<thead>
<tr>
<th>Device</th>
<th>Location</th>
<th>Energy</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP</td>
<td>IR3</td>
<td>450 GeV</td>
<td>dN/dt &gt; 1.2e12 p/s for T &gt; 10 s (87 kW)</td>
<td>dN/dt &gt; 6e12 p/s for 1 s &lt; T &lt; 10 s (430 kW)</td>
<td>dN/dt &gt; 1.5e13 p/s for T &lt; 1 s (1.1 MW)</td>
</tr>
<tr>
<td>TCP</td>
<td>IR7</td>
<td>450 GeV</td>
<td>dN/dt &gt; 1.2e12 p/s for T &gt; 10 s (87 kW)</td>
<td>dN/dt &gt; 6e12 p/s for T &lt; 10 s (430 kW)</td>
<td></td>
</tr>
<tr>
<td>TCP</td>
<td>IR3, IR7</td>
<td>7 TeV</td>
<td>dN/dt &gt; 0.8e11 p/s for T &gt; 10 s (90 kW)</td>
<td>dN/dt &gt; 4e11 p/s for T &lt; 10 s (449 kW)</td>
<td></td>
</tr>
<tr>
<td>TCSG</td>
<td>IR3</td>
<td>450 GeV</td>
<td>dN/dt &gt; 1.2e11 p/s for T &gt; 10 s (9 kW)</td>
<td>dN/dt &gt; 6e11 p/s for 1 s &lt; T &lt; 10 s (43 kW)</td>
<td>dN/dt &gt; 1.5e12 p/s for T &lt; 1 s (110 kW)</td>
</tr>
<tr>
<td>TCSG</td>
<td>IR7</td>
<td>450 GeV</td>
<td>dN/dt &gt; 1.2e11 p/s for T &gt; 10 s (9 kW)</td>
<td>dN/dt &gt; 6e11 p/s for T &lt; 10 s (43 kW)</td>
<td></td>
</tr>
<tr>
<td>TCSG</td>
<td>IR3, IR7</td>
<td>7 TeV</td>
<td>dN/dt &gt; 0.8e10 p/s for T &gt; 10 s (9 kW)</td>
<td>dN/dt &gt; 4e10 p/s for T &lt; 10 s (43 kW)</td>
<td></td>
</tr>
<tr>
<td>TCLA</td>
<td>IR3</td>
<td>450 GeV</td>
<td>dN/dt &gt; 6e8 p/s for T &gt; 10 s (45 W)</td>
<td>dN/dt &gt; 3e9 p/s for 1 s &lt; T &lt; 10 s (215 W)</td>
<td>dN/dt &gt; 7.5e9 p/s for T &lt; 1 s (550 W)</td>
</tr>
<tr>
<td>TCLA</td>
<td>IR7</td>
<td>450 GeV</td>
<td>dN/dt &gt; 6e8 p/s for T &gt; 10 s (45 W)</td>
<td>dN/dt &gt; 3e9 p/s for T &lt; 10 s (215 W)</td>
<td></td>
</tr>
<tr>
<td>TCLA</td>
<td>IR3, IR7</td>
<td>7 TeV</td>
<td>dN/dt &gt; 4e7 p/s for T &gt; 10 s (45 W)</td>
<td>dN/dt &gt; 2e8 p/s for T &lt; 10 s (225 W)</td>
<td></td>
</tr>
</tbody>
</table>

R. Assmann: Damage Limits for LHC Collimators (note in preparation)
Estimated Damage Interlock Limits

<table>
<thead>
<tr>
<th>Device</th>
<th>Location</th>
<th>Energy</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCTTH, TCTVA, TCTVB</td>
<td>IR1, IR2, IR5, IR8</td>
<td>450 GeV</td>
<td>$dN/dt &gt; 6e8$ p/s for $T &gt; 10$ s (45 W)</td>
<td>$dN/dt &gt; 3e9$ p/s for $T &lt; 10$ s (215 W)</td>
<td></td>
</tr>
<tr>
<td>TCTTH, TCTVA, TCTVB</td>
<td>IR1, IR2, IR5, IR8</td>
<td>7 TeV</td>
<td>$dN/dt &gt; 4e7$ p/s for $T &gt; 10$ s (45 W)</td>
<td>$dN/dt &gt; 2e8$ p/s for $T &lt; 10$ s (225 W)</td>
<td></td>
</tr>
<tr>
<td>TCL, TCLP</td>
<td>IR1, IR5</td>
<td>450 GeV</td>
<td>$dN/dt &gt; 6e9$ p/s for $T &gt; 10$ s (450 W)</td>
<td>$dN/dt &gt; 3e10$ p/s for $T &lt; 10$ s (2.2 kW)</td>
<td></td>
</tr>
<tr>
<td>TCL, TCLP</td>
<td>IR1, IR5</td>
<td>7 TeV</td>
<td>$dN/dt &gt; 4e8$ p/s for $T &gt; 10$ s (450 W)</td>
<td>$dN/dt &gt; 2e9$ p/s for $T &lt; 10$ s (2.2 kW)</td>
<td></td>
</tr>
<tr>
<td>TCLIA, TCLIB, TCSG</td>
<td>IR2, IR6, IR8</td>
<td>450 GeV</td>
<td>$dN/dt &gt; 1.2e11$ p/s for $T &gt; 10$ s (9 kW)</td>
<td>$dN/dt &gt; 6e11$ p/s for $T &lt; 10$ s (43 kW)</td>
<td></td>
</tr>
<tr>
<td>TCLIA, TCLIB, TCSG</td>
<td>IR2, IR6, IR8</td>
<td>7 TeV</td>
<td>$dN/dt &gt; 0.8e10$ p/s for $T &gt; 10$ s (9 kW)</td>
<td>$dN/dt &gt; 4e10$ p/s for $T &lt; 10$ s (45 kW)</td>
<td></td>
</tr>
</tbody>
</table>

R. Assmann Damage Limits for LHC Collimators (note in preparation)