Operational Experience with the LHC Collimation System

R. Assmann, CERN
5/5/2009
for the Collimation Project Team
PAC09, May 3-8 2009, Vancouver
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First Experience with the LHC Collimation System

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The LHC Challenge

- LHC extrapolates stored energy by 2-3 orders of magnitude beyond state of the art, while beam momentum is extrapolated by factor 7!

High stored energy and stored energy density!

80 kg TNT

Small collimation gaps!

Injection

Jaw opening

~ 12 mm

~ 3 mm

Top energy

Low emittance at 7 TeV!

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Luminosity and Stored Energy

- Luminosity can be expressed as a function of transverse energy $E_{\text{stored}}$ that is stored in each beam (for round beams at IP):

$$L = \frac{1}{4\pi \cdot m_0 c^2} \cdot \frac{f_{\text{rev}} \cdot N_p \cdot F}{\beta^* \cdot \varepsilon_n} \cdot E_{\text{stored}}$$

- To reach $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ the LHC needs to store 360 MJ per beam, more than 100 times the present world record in super-conducting colliders.

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\( \beta^* = \text{IP beta function} (\beta_x = \beta_y) \)

\( \varepsilon_n = \text{norm. transv. emittance} \)

\( N_p = \text{protons per bunch} \)

\( f_{\text{rev}} = \text{revolution frequency} \)

\( F = \text{geometrical correction} \)

\( m_0 = \text{rest mass, e.g. of proton} \)

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- IR optics limits

- tunnel length

- beam-beam limits

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LHC luminosity is increased via stored energy!

- To reach $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ the LHC needs to store 360 MJ per beam, more than 100 times the present world record in super-conducting colliders.
SC Magnets: Preventing Quenches

- Shock beam impact: \(2 \text{ MJ/mm}^2\) in 200 ns \((0.5 \text{ kg TNT})\)

- Maximum beam loss at 7 TeV: 0.1\% of beam (360 MJ) per second
  \(\text{assumed lower than Tevatron/HERA}\)

- Quench limit of SC LHC magnet:
  \(~5 \text{ mW/cm}^3\)

- 360 kW \(\rightarrow\) proportional to stored energy

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LHC Collimators: Dilute and Stop

Quench limit: $\sim 5 \, \text{mJ/mm}^2$ (any SC magnet)

Required “filter” factor:

$$1 \times 10^{-10} = \text{Leakage / Dilution}$$

Leakage factor (inefficiency): $10^{-4}$

Dilution factor: $10^6$

Cannot be achieved with single collimator $\Rightarrow$ therefore multi-stage collimation for betatron cleaning ($x$, $y$, skew) and momentum cleaning.

Incoming: up to $\sim 50 \, \text{MJ/mm}^2$ (primary collimator)
Multi-Stage Cleaning & Protection
3-4 Stages

Beam propagation

Unavoidable losses

Impact parameter ≤ 1 μm

Primary halo (p)

Secondary halo

Tertiary halo

CFC collimator

CFC

W/Cu

W/Cu

Superconducting magnets

SC magnets and particle physics exp.

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Multi-Stage Cleaning & Protection
3-4 Stages

Beam propagation

Unavoidable losses

Impact parameter ≤ 1 μm

Core

Primary halo (p)

Secondary halo

Shower

Tertiary halo

CFC collimator

Primary collimator

CFC

Vacuum shields

High Z coll.

Superconducting magnets

W/Cu

SC magnets and particle physics exp.

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Multi-Stage Cleaning & Protection
3-4 Stages

Beam propagation

Core

Primary halo (p)

Unavoidable losses

Impact parameter
\( \leq 1 \, \mu m \)

Secondary halo

\( \pi \)

\( p \)

Shower

CFC
collimator

Tertiary halo

\( p \)

\( \pi \)

\( e \)

\( e \)

High Z coll

Superconducting magnets

CFC
collimator

W/Cu
collimator

W/Cu
collimator

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“Phase I”

108 collimators and absorbers in phase I (only movable shown in sketch)

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Precision Requirements

closest to beam: primary (TCP) and secondary (TCS) collimators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaw material</td>
<td></td>
<td>CFC</td>
</tr>
<tr>
<td>Jaw length TCS</td>
<td>cm</td>
<td>100</td>
</tr>
<tr>
<td>Jaw length TCP</td>
<td>cm</td>
<td>60</td>
</tr>
<tr>
<td>Jaw tapering</td>
<td>cm</td>
<td>10 + 10</td>
</tr>
<tr>
<td>Jaw cross section</td>
<td>mm²</td>
<td>65 x 25</td>
</tr>
<tr>
<td>Jaw resistivity</td>
<td>µΩm</td>
<td>≤ 10</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>µm</td>
<td>≤ 1.6</td>
</tr>
<tr>
<td><strong>Jaw flatness error</strong></td>
<td>µm</td>
<td>≤ 40</td>
</tr>
<tr>
<td>Heat load</td>
<td>kW</td>
<td>≤ 7</td>
</tr>
<tr>
<td>Jaw temperature</td>
<td>°C</td>
<td>≤ 50</td>
</tr>
<tr>
<td>Bake-out temp.</td>
<td>°C</td>
<td>250</td>
</tr>
<tr>
<td><strong>Minimal gap</strong></td>
<td>mm</td>
<td>≤ 0.5</td>
</tr>
<tr>
<td>Maximal gap</td>
<td>mm</td>
<td>≥ 58</td>
</tr>
<tr>
<td>Jaw position control</td>
<td>µm</td>
<td>≤ 10</td>
</tr>
<tr>
<td>Jaw angle control</td>
<td>µrad</td>
<td>≤ 15</td>
</tr>
<tr>
<td><strong>Reproducibility</strong></td>
<td>µm</td>
<td>≤ 20</td>
</tr>
</tbody>
</table>

Gaps: ± 6/7 σ

2-3 mm

LHC collimators must work as precision devices!

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The LHC Collimation System

- The **by far largest and most precise system of its kind** that has been built to this date:
  - 130 phase I collimators and absorbers produced with specifications and control at 10 μm level (including spares).
  - **Phase I:** In total **108 devices** installed (~210 m length occupied). 97 movable collimators with a total of 194 jaws and > 450 degrees of freedom for positioning. **All ready for LHC startup. Results shown here...**
  - **Phase II:** In total **158 devices** installed (~ 310 m length occupied). 147 movable collimators. Majority approved and infrastructure installed.
  - **Maximum possible:** In total **168 devices** installed (~ 330 m length occupied). Only space reservations at this time.

- Investment (cost & manpower) comparable to a small accelerator.
- Design, R&D, prototyping, series production, installation and commissioning has been managed since late 2002 through the CERN LHC collimation project.

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Production: Minimum Collimation Gap (Ring)

Sample: 32 TCSG, 30 TCT

High precision collimators produced adequate for LHC conditions!
Flatness better than many feared. Out of tolerance collimators were placed in locations with more relaxed tolerances, meaning larger beta (limited sorting). Enough collimators for tightest places (40 $\mu$m).
Mechanical play in movement system when reversing direction. Specification of 20 μm well achieved. Will be corrected for in operational use.
Tunnel: Cleaning Insertion IR7

- Radiation-hard cable path
- Water feeds
- Collimator
- Collimator cable trays
- Phase I/II water distribution
- Transport zone
- Beam pipes
Tunnel: 3 Primary Betatron Collimators
Tunnel: Passive Absorber TCAPA
Tertiary Collimator “Splash” Events

Events now, background later...

CMS view of beam hitting collimator

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Performance Highlights

- Collimators used very successfully as stoppers and fixed targets during September 10 first beam day (collimator events) and earlier injection tests. Unforeseen but entertaining use of tertiary collimators at experiments...

- Machine protection functionality completely checked (interlocks from temperature and position sensors activated by violating limits). Few residual sensor issues identified. System was fully safe (ready for higher intensities/energies).

- No opportunity to set up with beam as collimators.

- Collimators kept operational since August, except IR3 collimators which were switched off after incident in 3-4. All 18 collimators in IR3 fully OK.

- Used time after incident to perform reproducibility test over 10 days with all 28 collimators in IR7.
Nominal Collimator Cycle

Measured gap for 3 primary collimators beam1

- Park Position
- Injection Position
- Energy Ramp
- Collision

Real functions for 28 collimators generated in collimator control. Executed by operation crew on shift (thanks!).

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Test Procedure

- Each collimator has 6 position sensors: 4 jaw corners and 2 gaps measured independently.
- Redundancy for 6 sensors and 4 DOF.
- Stepping motors are driven through the collimator cycle without any feedback from measured positions.
- Position monitoring implemented completely independent (safety) and used for measuring the jaw position and the gaps.
- Jaw positions used for operational interlocks (time driven).
- Gap sensors used for independent MP interlock (energy driven).
- How well do we control collimators?
Reproducibility Run

TCP.B6L7.B1

Analyzing 19 cycles after T=0 (reset of collimator sensor calibrations).

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Zoom into Collision Gaps

TCP.B6L7.B1

Note 1 μm sensor noise.

5.7 μm over 10 days
Reproducibility IR7 collimators in 10 days

168 position sensors for 28 collimators. Only 1 sensor above 30 μm!
Reproducibility IR7 collimators in 10 days

Includes mechanical, motor and sensor stability! Specification is surpassed: major success for all involved! Possible to control at better than 30 μm level!
Issues Learnt and Fixed

100 μm electro-magnetic interference from magnet powering ➔ Fixed.
Issues Learnt and Fixed

200 µm reading over-shoot after 70 mm movement with long cable capacitance. Recovery over minutes. ➔ Fixed.

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First Beam Loss Maps with LHC Beam

BLM system fully reacting to beam loss and showers from collimators.

Expected feature: Carbon much more transparent than tungsten!

Carbon used for diluting, tungsten for absorbing!

Exponential decay of loss signals

- Carbon (low Z) 17.4 m
- Tungsten (high Z) 1.7 m

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Finishing Phase I Work with Beam

- LHC collimators used for stopping beam reliably around the ring. As such important pre-requisite for injection tests and first turn of beam.

- Unfortunately, 2008 beam experience with collimators was quite limited. However, system worked as specified mechanically and electronically.

- Next run: Set up collimators with beam for establishing passive protection and beam cleaning. Measure cleaning efficiency!

- Completed when phase I system shows predicted cleaning efficiency.

- Prediction:
  - Phase I collimation good for something around 20 MJ, ~10 times beyond present world record.
  - Prediction depends on multiple parameters to be verified with LHC operation.

- Work on phase II collimation is ongoing with work plan until 2014.

- Phase II prepared in tunnel and will allow nominal and higher intensities.
Tunnel: Phase II Secondary Collimator Slots

PHASE I TCSG SLOT

EMPTY PHASE II TCSM SLOT (30 IN TOTAL)
Tunnel: Phase II Beam Scraper Slots

EMPTY PHASE II SCRAPER SLOTS (8 IN TOTAL)
Phase I Collimation Limit for Stored Energy vs Beam Energy

R. Assmann and W. Herr

Stored Energy [MJ]

Energy [TeV]

Tight
Intermediate
Nominal LHC

beam-beam limited
beam loss limited

Tevatron

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Phase I Collimation Intensity Limit versus Peak Loss Rate 5 TeV

![Graph showing the relationship between maximum intensity and peak fractional loss rate.](Image)

- **Tight**
- **Intermediate**

- **nominal**

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**Downstream of IR7 β-cleaning**

Losses of off-momentum protons from single-diffractive scattering in TCP

- Imperfect
- Perfect

**Upgrade Scenario**

NEW concept: 2008 Breakthrough

- cryo-collimators

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Phase II Collimation Work Plan

- R&D on advanced, low impedance materials for LHC collimators.
- Design, prototyping and testing of phase II secondary collimators, implementing in-jaw pick-ups (improved operation) and various jaw materials (lower impedance). Construct 30 plus spares.
- Install HiRadMat beam test facility for beam verification of advanced collimator designs.
- Start R&D, prototyping and testing on hollow e-beam lens for LHC scraping: FNAL and CERN.
- Support R&D on advanced new concepts (crystal collimation, …).
- Collaboration with 12 institutes in Europe, funded by EU (FP7). Collaboration with 3 institutes in U.S., funded by DOE (LARP).
Conclusion

- LHC collimation is designed to extend the intensity frontier by more than 2 orders of magnitude. It will not be easy: staged approach.
- Phase I is completed and already is the largest such system built to date. Worked as specified without beam: showed control and stability to better than 30 μm (width of human hair). Loss maps well behaved.
- Once LHC beam is back, phase I system will be set up and cleaning efficiency measured. Expect to reach around 20 MJ (10 times world record) with phase I collimation, but below nominal design.
- Phase II collimation has been worked out and will be implemented in steps until 2014 to upgrade performance. It will allow nominal and higher intensities (hopefully before 2014).
- Work is performed in international collaboration, supported by EU and DOE/LARP. Thanks to all who help us in this challenge!
- Please see many LHC collimation posters at PAC09 for more detail!
The Collimation Project Team & Close Collaborators

- Results on phase I collimation that I presented are outcome of lot of work performed over last 6 years by the following **CERN colleagues**:


- Crucial work also performed by **collaborators** at:

  TRIUMF (D. Kaltchev), IHEP (I. Baishev & team), SLAC (T. Markiewicz & team), FNAL (N. Mokhov & team), BNL (N. Simos, A. Drees & team).