Collimators and Beam Cleaning: First Results and Future Plans

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with Ralph Assmann, Stefano Redaelli, Adriana Rossi, Daniel Wollmann

Acknowledgements to:
B. Goddard and team for collaborative studies on injection & dump protection devices
B. Dehning and BLM team for beam loss studies
A. Masi and CO team, O. Aberle and HW commissioning team
Outlines

- Principle of operation with collimators (settings, thresholds…)
- Hardware commissioning tests
- Beam based alignment procedure, beam experience and first results
- Interlock threshold setup
- Analysis of collimation induced interlocks
- Beam loss studies
- Lessons and future plans
Logic of the LHC Collimation System Operation

- LHC collimators are needed during the full cycle of machine operations.
- Collimators must be set up implementing a well defined hierarchy.
- Alignment requirements and positioning tolerances become more demanding when increasing beam intensity and energy.
- A new beam based alignment must be performed any time beam and machine optics change, orbit drift, …
- LHC collimation is a dynamic system!
Nominal Cycle

Injection

Flat bottom

Energy ramp up

Flat top

Squeeze

Physics

Dump

Energy ramp down

Parking

Collimator Gap

Energy

Time

Intermediate settings.
Nominal Cycle

Nominal settings.
Defined collimator settings and limits must be associated to each beam process.
Thresholds and Interlocks

- **Position time dependent interlocks.**

- **Energy dependent interlocks.**

- **Temperature dependent interlocks.**
Thresholds and Interlocks

• **Position time dependent interlocks.**

  E-dep. gap interlock not opened for parking position ➔ jaws can move but beam is inhibited.

  Without squeeze or with nominal gaps: E-dep. gap interlock does not need to be changed! SAFE!

  Position interlock opened for parking position.

• **Energy dependent interlocks.**

• **Temperature dependent interlocks.**
Hardware commissioning

All 100 collimators have been tested in preparation for operations with beam:

- Hardware tests: minimum and maximum gap, maximum tilt, switches, mechanical play. These tests included also TDI and TCDQ (E. Carlier, C. Boucly).
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  https://winservices.web.cern.ch/winservices/Projects/CollimationHardware/2009/MP_tests/MPtests_summary_EDMS.xlsx
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For detailed information, refer to the following link:

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- **Automatic sequences to drive collimators through nominal OP cycles.**
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- Machine protection tests: check interlocks when exceeding position and energy dependent limits.
- Automatic sequences to drive collimators through nominal OP cycles.

Reproducibility better than 10 μm
Ramp Tests: Errors w.r.t. Settings

Corner position:
Errors < 50 μm

Collimator gaps:
Errors up to 200 μm

Impact on settings?

Courtesy of S. Redaelli LCSG 12/10/2009
Ramp Tests: Synchronization

Ramp up to 5 TeV (1300 s):
Collimators in different locations start together within 6 µs.
End times of profiles within 10 µs.

Courtesy of S. Redaelli LCSG 12/10/2009
The LHC collimation system has been used for beam cleaning and passive machine protection this year for the first time.

Beam based alignment:

Collimator jaw

Beam loss when jaw touches the beam
The LHC collimation system has been used for beam cleaning and passive machine protection this year for the first time.

Beam based alignment:

Gap => Beam centre
Beam size => Nominal settings
Setup Procedure

Schematic view of IR7

- **Horizontal**
- **Vertical**
- **Skew**

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schematic diagram of primary, secondary, and absorber sections
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Setup Procedure

- Start aligning last horizontal collimator by setting it at 5.7σ (nominal injection) => reference “beam edge”
• Start aligning last horizontal collimator by setting it at $5.7\sigma$ (nominal injection) => reference “beam edge”

• Close each remaining horizontal collimator going backwards w.r.t the beam (clean BLM signal) until touching the beam ($5.7\sigma$) and then retract to nominal position (i.e. IR7: TCSG at $6.7\sigma$, TCLA at $10\sigma$).
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- Close each remaining horizontal collimator going backwards w.r.t the beam (clean BLM signal) until touching the beam (5.7σ) and then retract to nominal position (i.e. IR7: TCSG at 6.7σ, TCLA at 10σ).
- Repeat for vertical and skew planes => Collimator hierarchy established!
Collimators set up in parallel for the two beams. No disturbing crosstalk in losses between beams.

Beam 1:
- IR7: Set up horizontal and vertical primary collimators plus all absorbers. Secondary collimators left at coarse position (around $10\sigma$, not enough time for detailed setup).
- IR3: Set up primary collimator ($8\sigma$) and 1 TCLA ($10\sigma$). Other tungsten collimators (TCLA) and secondary collimators left at coarse position (nominal + $3\sigma$).

Beam 2:
- IR3: All collimators set up at nominal settings (TCP at $8\sigma$, TCSG at $9.3\sigma$, TCLA at $10\sigma$).

20 Collimators set up in about 3 hours, $\sim 200$ $\mu$m accuracy. Accuracy from step size used.
Highest losses in the collimation insertions at the primary collimators!

99.9% cleaning efficiency.

All tertiary collimators: half gap = 15mm (~15-20 σ)

Offset without beam (background) subtracted.
November 29th: Second LHC Collimator Setup

New alignment after defining a reference “golden orbit”: Santa Klaus.
- IR3, IR6 and IR7: all collimators set up at nominal settings.
- IR1: horizontal and vertical tertiary collimator positions crosschecked and set at 15mm. Remaining TCT not touched and kept at 15mm.

Beam 2:
- IR3, IR6 and IR7: All collimators set up at nominal settings.
- All TCT untouched and kept at 15mm.

First full multi-stage collimation set up! We implemented directly 4 stage cleaning: primary ➔ secondary ➔ tertiary ➔ active absorbers

62 Collimators set up in about 7 hours, ~50-100 μm accuracy. Accuracy given by step size used during collimator setup (larger steps to speed up process).
Difference Theoretical – Measured Collimation Gaps

Theoretical gaps calculated for:
Emittance = 3.5 \mu m rad

Beam 1 differences:
IR6 – TCDQ set-up accuracy
IR7 – Large initial difference

Average difference [mm]

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>V</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1</td>
<td>+2.77</td>
<td>+0.45</td>
<td>+1.35</td>
</tr>
<tr>
<td>Beam 2</td>
<td>-1.30</td>
<td>+1.12</td>
<td>-0.70</td>
</tr>
</tbody>
</table>

H: horizontal collimators  
V: vertical collimators  
S: skew collimators

β-beat problem beam1 in IR7?
Comparison β-Beat From Collimation and Measurement.

**β-beat: \( \Delta \beta / \beta_0 \)**

*Data for β-beat courtesy of Glenn Vanbavinckhove*
Cross check of beam size and beam centre at the collimators used as a reference for beam based alignment (IR7, TCLA).

- TCLA.C6L7.B2 (vertical)
  - Beam centre ~ 4.0 mm
  - Beam size ~ 793 μm
### Comparison of the Results

**Full beam scraping:**

<table>
<thead>
<tr>
<th></th>
<th>Beam 1</th>
<th></th>
<th>Beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCLA</td>
<td>Beam Centre [mm]</td>
<td>Beam Size [μm]</td>
<td>Beam Centre [mm]</td>
</tr>
<tr>
<td>Hor.</td>
<td>0.4</td>
<td>736</td>
<td>N.A.</td>
</tr>
<tr>
<td>Vert.</td>
<td>2.2</td>
<td>920</td>
<td>4.0</td>
</tr>
</tbody>
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**Beam based alignment:**

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</tr>
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<td>0.2</td>
<td>683</td>
<td>0.2</td>
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<tr>
<td>Vert.</td>
<td>1.2</td>
<td>1051</td>
<td>1.4</td>
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- Reasonable agreement, except beam2 vertical: how to explain 0.25mm difference in beam size?
- Indication of inaccurate collimator beam-based alignment (see also shift in centre) or drift?
Loss Map Beam 1 Injection for Full Setup

Same loss pattern as previous alignment. Factor of 30 lower losses in IR3.

Offset without beam (background) subtracted.
December 5\textsuperscript{th} : Third Collimator Setup

Re-setup collimation after power cut.

- Golden orbit re-established
- Collimators set at the settings defined on November 29\textsuperscript{th}. No retuning was performed but we relied on machine and optics reproducibility.

Both beams injected with \(\sim 30\%\) intensity loss.

Collimator setup still valid after 6 days! Not as good as before but hierarchy OK! TDI too tight (see Wolfgang's talk)

Reference settings in the sequencer!

Offset without beam (background) subtracted.
Low beam intensity allowed to keep the collimators with static settings during all the phases of the machine cycle.

Position dependent thresholds set up ➔ interlocks if outside of limits:
  a) All IR3 and IR7 collimators: limits at ±0.5mm around defined position
  b) All tertiary collimators: limits at ±1mm around defined position

Also set position dependent thresholds for injection protection collimators (TDI) which have to be moved IN during injection and OUT for stable beam.

Energy dependent thresholds active but relaxed: maximum gap = 60 mm.
### All Interlocks Generated by collimators (during beam commissioning)

<table>
<thead>
<tr>
<th>Date &amp; Time</th>
<th>Beam</th>
<th>Activity</th>
<th>Collimator</th>
<th>Remarks</th>
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<tr>
<td></td>
<td></td>
<td>Interlocked</td>
<td></td>
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</tr>
<tr>
<td>01.12.09, 04:32</td>
<td>B1</td>
<td>Open TCTH in IR1 to ±15mm due to losses</td>
<td>TCTH.4L1.B1</td>
<td>Position out of limits, interlock active</td>
</tr>
<tr>
<td></td>
<td>dumped</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td>Interlocked</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.12.09, 00:53</td>
<td>B1</td>
<td>B1 collimators moved out of sequence to parking position</td>
<td>TCLIB.6R2.B1 TCLIA.4R2</td>
<td>Position out of limits, interlock active</td>
</tr>
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Courtesy of D Wollmann
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<tr>
<td>05.12.09, 14:11</td>
<td>B1</td>
<td>Start of collimator studies (no entry in logbook)</td>
<td>TCTVA.4L5.B1, TCTH.4L2.B1,</td>
<td>Position out of limits, interlock active</td>
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Only hardware problem caused interlock from the collimation system. All other cases generated by inappropriate user requests: violating interlock limits!

Courtesy of D Wollmann
Loss Map at Top Energy (Beam 1)

Measured loss map at 1.18TeV for Beam 1 (ramp of December 8th)

Simulated proton loss map at 1TeV for Beam 1

*note that shower development is not included, only primary proton losses.
Loss Map at Top Energy (Beam 1)

Measured loss map at 1.18 TeV for Beam 1 (ramp of December 8th)

Beam loss studies were performed in several loss regime (betatron losses by crossing the 1/3 integer resonance, momentum losses by changing the RF frequency) ➔ highest losses at primary collimators in the cleaning insertions.

Simulated proton loss map at 1 TeV for Beam 1

*note that shower development is not included, only primary proton losses.
Loss Map Ratio Beam 2 Crossing 1/3 Integer Resonance (Qy)

Graph showing the distribution of acquisition/reference values across different IP positions (IP1 to IP8) with labels for Collimators, Cold Magnets, and Warm Magnets.

Evian, 20/01/2010
LHC Beam Workshop
Reference: loss pattern before massive losses ➔ there should be a “constant” gain factor: the ratio of proton losses from steady state to increased loss rate when crossing resonance. Still in “learning period”!
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Loss Map Ratio Beam 2 Crossing 1/3 Integer Resonance (Qy)

Loss Ratios Downstream of IR6 (Beam 2)

![Graph showing loss ratios downstream of IR6 for Beam 2. The graph includes beta functions, dispersion, and acquisition reference plots for Collimators, Cold Magnets, and Warm Magnets.](image)
Loss Ratios Downstream of IR6 (Beam 2)

Red arrows: Maximum $\beta_y$
Loss Ratios Downstream of IR6 (Beam 2)

Red arrows: Maximum $\beta_y$

Black arrows: Maximum $\beta_x$  Maximum $D_x$
Loss Ratios Downstream of IR7 (Beam 2)
Loss Ratios Downstream of IR7 (Beam 2)

Red arrows: Maximum $\beta_y$
Loss Ratios Downstream of IR7 (Beam 2)

Red arrows:  
Maximum $\beta_y$

Red circle:  
Dispersion suppressor
Loss Map Beam 1 Changing RF frequency

Offset without beam (background) subtracted.
Loss Map Beam 1 Changing RF frequency

Offset without beam (background) subtracted.
Loss Map Beam 1 Changing RF frequency

Offset without beam (background) subtracted.
Loss Map Beam 2 Changing RF frequency

Offset without beam (background) subtracted.
Loss Map Beam 2 Changing RF frequency

Offset without beam (background) subtracted.

Collimators
Cold Magnets
Warm Magnets

Zoom in IR3….
Loss Map Beam 2 Changing RF frequency

Offset without beam (background) subtracted.

Losses $\sim 5 \times 10^{-4}$
Loss Map Beam 2 Changing RF frequency

Offset without beam (background) subtracted.

Losses $\sim 5 \times 10^{-4}$
Lessons learnt, including the unexpected…

- System works as designed. Nice start of beam commissioning for LHC collimation. Expected cleaning and leakage processes seen.
- Possible to verify passive protection: losses at primary collimators.
- Beam-based settings different from theoretical: why? Need to understand in more detail. More beam time.
- Drift LVDT: tracked to problem of backplane connection in one rack.
- Wrong sequence ➔ collimators parking ➔ interlocks. Safe but not nice. Follow logical & debugged sequence is essential. Cannot set up by hand.
- Power cut: all collimators could be reset by STI piquet quite fast (~2h). This is a feature, as controls is on UPS, not the high power drivers.
- Need faster analysis for loss maps, collimator movements, interlocks, …
Expected Intensity Reach (no reason to doubt our simulations, so far)

Peak beam loss rate: 0.2 %/s

Intensity Limit Collimation [p]

Energy [TeV]

Nominal LHC

Tight

Intermediate

3.5 TeV

1.5e+14

6.5e+13

Tevatron

1e+16

1e+15

1e+14

1e+13

1e+12

1 2 3 4 5 6 7

Courtesy of R. Assmann, LMC 19/03/2009
Expected Reach Stored Energy (no reason to doubt our simulations, so far)

Peak beam loss rate: 0.2 %/s

![Graph showing stored energy limit vs energy](image)

- Tight
- Intermediate
- Nominal LHC

3.5 TeV

Tevatron

x 18

Stored Energy Limit [MJ]

Energy [TeV]

Courtesy of R. Assmann, LMC 19/03/2009
Future Plans

- Further understanding of loss locations and collimation leakage (qualitatively looks as expected on first analysis).
- Assure BLM thresholds at factor of 3 below quench limit (together with BLM team).
- Commission variable collimator settings during ramp with beam (first with tolerance optimized settings then nominal settings).
- Change of collimator settings during squeeze to be commissioned with beam.
- Automatic procedure for MP temperature interlock verification (as exists for rest).
- Beam-based alignment at higher beam energy.
- Better accuracy alignment for higher intensity and energy.
- Performance commissioning with higher loss rates (up to 5 kW tested, goal is 500 kW to 1,000 kW).