Performance of the LHC collimation system

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Acknowledgments

- Collimation team:
  F. Burkart, M. Cauchi, G. Valentino.
- R. Losito and A. Masi: collimator controls team.
- Engineering design team.
- Beam Loss Monitor team.
- LSA (LHC Software Architecture) team.
- LHC-OP crew.
- Injection and dump teams.
Outline

☑ Introduction
☑ Layout and challenges
☑ Collimator settings
☑ Operation and performance
☑ Conclusions
Layout of LHC collimation system

Two warm cleaning insertions
   IR3: Momentum cleaning
      1 primary (H)
      4 secondary (H,S)
      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!
The cold aperture must be in the shade of several layers of collimators.

**Leakage** to cold aperture must be below quench limit!

- LHC aperture sets the scale:
  - Injection: \( \geq 12.5 \sigma \)
  - \( 3.5 \text{ TeV}, \beta^*=3.5\text{m} \): \( \geq 15.0 \sigma \)

- Primary and secondary collimators are **robust** (Carbon).
  Absorbers and tertiary collimators (Tungsten) are not and must be protected.

- **Beam-based setup** → local beam position and beam size at each collimator.
Example of collimator gaps (i)

Collimator gaps (betatron cleaning):
- 450 GeV: \( \pm 4.3 \) mm
- 3.5 TeV: \( \pm 1.5 \) mm

Collimator settings depend critically on orbit and beta functions!
Intrinsic safety and redundancy: two-sided collimators!

MADX online: aperture model with measured collimator gaps (G. Müller)

S. Redaelli, HB2010, 28-09-2010
In the interaction regions (IRs), tertiary collimators protect the superconducting triplets. We have a change of beta during the squeeze, a change of centres from separation and crossing schemes: re-qualification needed if machine configuration changes.
Minimum gap with 3.5 TeV beams

3.5 TeV beam circulating in a gap as wide as the Italy on the 2 euro coin!!
Operational aspects and set-up strategy

- **Main operational challenges:**
  - High stored energy: Collimators needed in all phases (inj., ramp, squeeze, physics); Function-driven controls of jaw positions mandatory;
  - Small gaps: Mechanical precision, reproducibility (< 20 microns);
  - Beam cleaning: Big and distributed system (~ 100 collimators);
  - Machine Protection: Redundant interlock of collimator jaw positions and gaps.

- Collimator settings are given in terms of **local beam size** and **beam position**.

- Once settings are established, the system performance depends **critically** on:
  - the **mechanical precision** of collimator positions;
  - some machine parameters such as **orbit** and **optics**.

- Contrary to other machines, the collimator **alignment** is done **infrequently** and we rely on the reproducibility of settings.

  *Dedicated collimator alignment campaigns are done for each machine configuration (injection, flat top, squeeze, stable beams) and then we rely on the reproducibility of machine.*

- **Consequences** of this infrequent setup:
  - **constraints** on machine **reproducibility** (orbit stab. fill to fill < 150 μm, Δβ/β< 20%)!
  - require regular **monitoring** of cleaning performance.
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- Operation and performance
- Conclusions
(1) Reference halo generated with primary collimators (TCPs) close to 3-5 sigmas.
(2) “Touch” the halo with the other collimators around the ring (both sides) → local beam position.
(3) Re-iterate on the reference collimator to determine the relative aperture → local beam size.
(4) Retract the collimator to the correct settings.

Tedious procedure that is repeated for each machine configuration.
Collimator setting generation

Collimator settings: parameters space

- Momentum
  - $\theta_{\text{coll}}$
  - $L_{\text{coll}}$
  - $\epsilon_{\text{beam}}$
  - $\beta_{\text{coll}}$
  - $\alpha_{\text{coll}}$

Settings
- $N_\sigma$
- Apert [mm]
- Angle [mrad]
- J1Pos
- J1Angle
- J2Pos
- J2Angle
- M1 [mm]
- M2 [mm]
- M3 [mm]
- M4 [mm]

Beam-based

Nominal settings:

\[ \text{jaw} = x_{\text{beam}} \pm n_0 \times \sigma_x \]
\[ \sigma_x = \sqrt{\frac{\epsilon_n}{\gamma_1}} \beta_x \quad \text{: Beam size along collimation axis "x"} \]
\[ n_{tcps} = 6 \]
\[ n_{tcsg} = 7 \quad \text{: Normalized settings} \]
\[ \ldots \]

(More complex if angles are taken into account)

Scaling for ramp settings:

\[ n_0 = n_0(\gamma) \quad \sigma_x = \sigma_x(\gamma) \quad h(\gamma) = n_0(\gamma) \times \sigma_x(\gamma) \]

\[ h(\gamma) = \left[ n_0 + \frac{n_1 - n_0}{\gamma_1 - \gamma_0} (\gamma - \gamma_0) \right] \times \frac{1}{\sqrt{\gamma}} \left[ \frac{\sqrt{\epsilon_1 \beta_1} - \sqrt{\epsilon_0 \beta_0}}{\gamma_1 - \gamma_0} \right] (\gamma - \gamma_0) \]

\[ \text{jaw}(\gamma) = \left[ x_0 + \frac{x_1 - x_0}{\gamma_1 - \gamma_0} (\gamma - \gamma_0) \right] \pm h(\gamma) \]
Ramp settings

Collimator jaw positions [mm]

- TCLAs
- TCSGs
- TCP

Settings from beam-based sizes and collimator centres

Now: beam-based (BB) beam positions for all cases + BB sigmas at injection only (nominal optics at 3.5 TeV)

Functions generated for all collimators (R. Bruce) and imported in the control system:
- 396 functions for motor settings
- 2376 functions for interlock thresholds
- 194 gap limits as a function of energy
Squeeze settings

Beam size change at the tertiary collimators in the experimental regions during the betatron squeeze at constant energy. No changes in the betatron and momentum cleaning.

TCTs closed to 15 sigmas below $\beta^*=7m$
Squeeze settings

TCTs closed to 15 sigmas below $\beta^* = 7\text{m}$

Crossing angle change during the squeeze

Beam size change at the tertiary collimators in the experimental region during the betatron squeeze at constant energy. No changes in the betatron and momentum cleaning.
Measured jaw positions

“Dry” execution without beam.

This ensures that the collimators sit all the time at the optimum settings!
Don’t forget interlock limits!

Dump thresholds of 400-500 microns around each axis and gap (24 functions per collimator) to detect early on unsafe situations!
Don’t forget interlock limits!

Dump thresholds of 400-500 microns around each axis and gap (24 functions per collimator) to detect early on unsafe situations!
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## Run configurations and settings

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<th>Unit</th>
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<td>9.3-10.6</td>
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</table>

Smooth transition between one configuration and the other with functions.
Handling of collimator settings is managed by the LHC sequencer.

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Collimator settings in physics
Operation during inj, ramp & squeeze

Current of Q5-L1 [A]

450 GeV

3.5 TeV

Ramp

Squeeze

β*=7m

β*=3.5m

Stable beams

TCP-IP7

TCSG-IP6

TCSGs-IP7

TCTs

Collimator gaps [mm]
Reproducibility of settings

Collimator settings are reproducible within a few micrometers over periods of several days!
Beam losses in collision

Luminosity debris (0.35 x 10^{32} cm^{-2}s^{-1})

Total Losses: 5.448E-03 [Gray / s]

ATLAS ALICE CMS LHCb
Beam losses in collision

Luminosity debris (0.35 x 10^{32} cm^{-2}s^{-1})
Higher loss rates: beam across the 3rd order resonance.
Repeated for ALL run configs.

Cleaning performance: 3.5 TeV, $\beta^*=3.5m$

Legend:
- Collimators
- Cold losses
- Warm losses

Longitudinal position [km]

Relative beam loss rate

0 5 10 15 20 25

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

IP2 IP3 IP4 IP5 IP6 IP7 IP8 IP1

Beam 1

Betatron

Off-momentum

Dump

TCTs

0.00001

0.000001

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Cleaning performance: 3.5 TeV, $\beta^* = 3.5\text{m}$

Limit location: $1.79 \times 10^{-4}$

**Legend:**
- **Collimators**
- **Cold losses**
- **Warm losses**

**Table:**

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<thead>
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<th>Leakage</th>
<th>Efficiency</th>
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<td>B1-H</td>
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<td>B1-V</td>
<td>$1.79 \times 10^{-4}$</td>
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<td>B2-H</td>
<td>$3.86 \times 10^{-4}$</td>
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<tr>
<td>B2-V</td>
<td>$1.72 \times 10^{-4}$</td>
<td>99.983</td>
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</table>
Stability of cleaning performance

**Set-up established in mid-June** remained valid until end of August.

Betatron cleaning setup at 3.5 TeV: still valid now after **3.5 months**!

We have just prepared the new settings in preparation for the ~30 MJ operation!
Conclusions

- LHC collimation system has seen an exciting commissioning!
  - Full system of ~100 collimators commissioned and operational.
  - Meticulous preparation without beam has ensured a smooth and safe startup!

- LHC collimation works essentially as specified:
  - Confirmed all basic design choices (layout, controls, mechanics, survey,...).
  - It is operated as foreseen in all machine phases, from injection to physics.

- Cleaning performance: leakage in cold magnets is a few 1e-4.
  - No single quench with circulating beams up to 6 MJ stored energy!!
  - Machine aperture is shielded by the collimators in all conditions.
  - Flexible and safe operation is ensured (could handle losses 200x design).

- Setting strategy: infrequent beam-based set-ups+reproducibility
  - Long alignment campaigns, but then ok for months (3.5 months in IR7).
  - Validation campaigns for machine protection + performance monitoring needed.

- The LHC collimation is ready for the operation in 30 MJ regime.
  Looking forward to achieving the luminosity goal of $10^{32}$ cm$^{-2}$s$^{-1}$!
Reserve slides
Momentum cleaning

Momentum losses ($dp/p$, $f=+500\text{Hz}$), B1 (01.05.2010, 17:25:20)
Collimator positioning system

Settings: 4 stepping motors for jaw corners - 1 motor for tank position.
Survey: 7 direct measurements: 4 corners + 2 gaps + tank
4 resolvers that count motor steps
10 switch statuses (full-in, full-out, anti-collision)

Redundancy: motors+resolvers+LVDT’s (Linear Variable Differential Transformer) = 14 position measurements per collimator

Two-jaw design: Beam cannot “drift away” if gap under control!
Position and gap interlocks

Dump threshold

Operational tolerance

Settings

Energy functions (gaps only)

- **Inner** and **outer thresholds** as a function of **time** for each motor **axis** and **gap** (24 per collimator). Triggered by timing event (e.g. start of ramp).
- **Internal clock**: check at 100 Hz!
- “Double protection” → BIC loop broken AND jaw stopped.
- **Redundancy**: **maximum allowed gap versus energy** (2 per collimator).
Limit functions (24 per collimator!!) are loaded for all ring collimators. Constant limits remain active also for collimators that do not move (TCTs). Function execution is triggered by the ramp timing event.
Gap energy limits

It would catch within 2-4 min after the ramp start (~ 500-600 GeV) if the collimator did not move.

TCP collimator gap

Energy limit = maximum allowed gap

Redundant interlock, independent on trigger: it uses the safe machine parameters. Beam dumped if a collimator does not start moving during the ramp (and sits happily within time-dependent limits).

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Accuracy of function execution

Requested/executed settings vs. time

- Motor step = 5 μm
- Operational motor speed = 2 mm/s
- “Slow” functions are interpolated with the appropriate rate of step execution

Low-level implementation in the PXI system by A. Masi
# List of acronyms

<table>
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<th>Acronym</th>
<th>Material</th>
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