Collimators and Cleaning, Could this Limit the LHC Performance?

R. Assmann, CERN-AB/ABP

Chamonix XII
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Answer is easy:

You bet, collimation and cleaning can limit us!

The question we are considering:

How can we build a collimation system that will not limit LHC performance?
Work done in

**Beam Cleaning Study Group / Collimation WG**

**LHC Collimation Project**
(since 10/2002. Mandate: finalize design, build prototype, produce full system, supervise installation, commissioning)


Meetings:

**Collimator Project Meetings and LHC Collimation Working Group**

http://www.cern.ch/lhc-collimation
http://www.cern.ch/lhc-collimation-project
The Collimation Team:

- Project Management
- Engineering/Technical Support
- Material Simulations for Collimator Jaws
- Material Tests
- Theoretical Studies/System Design/System Simulations
- Operational Scenarios/Instrumentation/MD’s
- Additional Link Persons


+ colleagues in Collimation WG and Machine Protection WG

Link persons:


Many team members contribute only a small fraction of their time – expertise anyway crucial!
Outline

1. The LHC Collimation System

2. Limitations for machine availability (collimation hardware)

3. Limitations on machine parameters (cleaning efficiency)

4. Outlook
The Collimation System

Design and build a collimation system …

… that absorbs the beam halo

… of the high power LHC beam

… such that the quenches are avoided

… and the equipment is protected

… in the tight LHC cold aperture

… ensuring collimator survival

… respecting AP, vacuum, radiation boundary conditions

… and compatibility with operation
The LHC Cleaning Insertions

Two warm LHC insertions dedicated to cleaning:

IR3  Momentum cleaning
     1 primary
     6 secondary

IR7  Betatron cleaning
     4 primary
     16 secondary

Two-stage collimation system.

54 movable collimators for high efficiency cleaning, two jaws each + other absorbers for high amplitude protection

Significant system: ~ 200 degrees of freedom!
## Collimators & absorbers at 7 TeV:

<table>
<thead>
<tr>
<th>Region</th>
<th>Type</th>
<th>Orientation</th>
<th>Material</th>
<th>Number</th>
<th>Length</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR1</td>
<td>TCL (Q5)</td>
<td>X</td>
<td>Cu</td>
<td>2</td>
<td>1.0 m</td>
<td>10.0 σ</td>
</tr>
<tr>
<td>TAS</td>
<td>Round</td>
<td>Cu?</td>
<td>2</td>
<td>1.8 m</td>
<td>12.0 σ</td>
<td></td>
</tr>
<tr>
<td>TCL (D2)</td>
<td>X</td>
<td>Cu</td>
<td>2</td>
<td>1.0 m</td>
<td>10.0 σ</td>
<td></td>
</tr>
<tr>
<td>IR3</td>
<td>TCP</td>
<td>X</td>
<td>Al</td>
<td>1</td>
<td>0.2 m</td>
<td>8.0 σ</td>
</tr>
<tr>
<td>TCS</td>
<td>X, Y, XY</td>
<td>Cu</td>
<td>6</td>
<td>0.5 m</td>
<td>9.3 σ</td>
<td></td>
</tr>
<tr>
<td>IR5</td>
<td>TCL (Q5)</td>
<td>X</td>
<td>Cu</td>
<td>2</td>
<td>1.0 m</td>
<td>10.0 σ</td>
</tr>
<tr>
<td>TAS</td>
<td>Round</td>
<td>Cu?</td>
<td>2</td>
<td>1.8 m</td>
<td>12.0 σ</td>
<td></td>
</tr>
<tr>
<td>TCL (D2)</td>
<td>X</td>
<td>Cu</td>
<td>2</td>
<td>1.0 m</td>
<td>10.0 σ</td>
<td></td>
</tr>
<tr>
<td>IR6</td>
<td>TCDQ</td>
<td>X (1 side)</td>
<td>C</td>
<td>1</td>
<td>9.5 m</td>
<td>10.0 σ</td>
</tr>
<tr>
<td>IR7</td>
<td>TCP</td>
<td>X, Y, XY</td>
<td>Al</td>
<td>4</td>
<td>0.2 m</td>
<td>6.0 σ</td>
</tr>
<tr>
<td>TCS</td>
<td>X, Y, XY</td>
<td>Cu</td>
<td>16</td>
<td>0.5 m</td>
<td>3.0 σ</td>
<td></td>
</tr>
</tbody>
</table>

- Numbers are for Al, Cu system. Length is given per collimator.
- All collimators two-sided except noted.
- Number is per beam.
- TCL (D2) is an upgrade for LHC ultimate performance.
- Table is for 7 TeV.
- Settings are for nominal luminosity and nominal β* (n₁ = 7 in the triplet).
- For injection add TDI, TCL (inj), and TCDS. All around 10 σ. IR1 and IR5 settings could be open for injection, others remain at similar settings.
**Basic concept of collimation**

“Conventional” jaws (blocks of appropriate solid materials).

“Exotic” schemes (e.g. crystal collimation) not foreseen in baseline solution. Unusual mechanical solutions can be envisaged (“consumable” jaws, connected jaws).

**Two stage cleaning systems:**

1) Primary collimators: Intercept primary halo
   - **Impact parameter:** ~ 1 µm
   - Scatter protons of primary halo
   - Convert primary halo to secondary off-momentum halo

2) Secondary collimators: Intercept secondary halo
   - **Impact parameter:** ~ 200 µm
   - Absorb most protons
   - Leak a small tertiary halo
Protection of aperture against halo and beam

Expected physical aperture limits (freely available, a is half aperture)

<table>
<thead>
<tr>
<th>Energy</th>
<th>Location</th>
<th>a [m]</th>
<th>$\beta$ [m]</th>
<th>$a_{\text{norm}} [m^{1/2}]$</th>
<th>$a_{\text{norm}}/\varepsilon^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV</td>
<td>Arc</td>
<td>0.012</td>
<td>180</td>
<td>$8.8 \times 10^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td>7 TeV</td>
<td>Triplet</td>
<td>0.015</td>
<td>4669</td>
<td>$2.2 \times 10^{-4}$</td>
<td>10</td>
</tr>
</tbody>
</table>

Collimator setting (prim) required for triplet protection from 7 TeV secondary halo:

$\sim 0.15$

Collimator gap must be 10 times smaller than available triplet aperture!

Collimator settings usually defined in sigma with nominal emittance!

Aperture allowances: 3-4 mm for closed orbit, 4 mm for momentum offset, 1-2 mm for mechanical tolerances.
Secondary and Tertiary Beam Halo (zero dispersion)

Strategy:

- Primary collimators are closest.
- Secondary collimators are next.
- Absorbers for protection just outside secondary halo before cold aperture.
- Relies on good knowledge and control of orbit around the ring!
Collimator settings:

- 5 - 6 σ (primary)
- 6 - 9 σ (secondary)

σ ~ 1 mm (injection)
σ ~ 0.2 mm (top)

Number of protons reaching 10σ:

10^{-4} of p at 6 σ
Outline

1. The LHC Collimation System

2. Limitations for machine availability
   (collimation hardware)

3. Limitations on machine parameters
   (cleaning efficiency)

4. Outlook
Limitations for Machine Availability

Physics Potential = Energy and Luminosity

High LHC luminosity translates into high transverse energy density:

\[ L = \rho_e \frac{f_{rev} N_p}{4 E_b} \sqrt{d_x d_y} \]

Parameter for material damage: \( \rho_e \)

LHC advancement: Factor 7 in beam energy
Factor 1000 in \( \rho_e \)

\( d = \text{demagnification (} \beta_{\text{coll}}/\beta^* \text{)} \)
\( N_p = \text{protons per bunch} \)
\( f_{\text{rev}} = \text{revolution freq.} \)
\( E_b = \text{beam energy} \)

Increase luminosity via transverse energy density.
LHC nominal Parameters:

- Number of bunches: 2808
- Bunch population: $1.1 \times 10^{11}$
- Bunch spacing: 25 ns
- Top energy:
  - Proton energy: 7 TeV
  - Transv. beam size: 0.2 mm
  - Bunch length: 8.4 cm
  - Stored beam energy: 350 MJ
- Injection:
  - Proton energy: 450 GeV
  - Transv. Beam size: 1 mm
  - Bunch length: 18.6 cm

At less than 1% of nominal intensity LHC enters new territory.

Collimators must survive expected beam loss…

Collimators will be highly activated!
**Beam loss at the $10^{-5}$ level can damage components:**

(for Cu)

Failures that we consider for collimator design:

<table>
<thead>
<tr>
<th>Fast cases (&lt; 1 turn)</th>
<th>Pre-fire of one dump kicker module (2.2 MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Asynchronous beam dump (miss dump gap) (0.5 MJ)</td>
</tr>
<tr>
<td></td>
<td>Impact from one full batch at injection (2.3 MJ)</td>
</tr>
<tr>
<td>Slow case:</td>
<td>Impact during low beam lifetime (0.2 h to 1 h) (4.4 MJ in 10s)</td>
</tr>
<tr>
<td>Beam types:</td>
<td>Protons and ions</td>
</tr>
<tr>
<td>Full stored beam power:</td>
<td>331 MJ (7 TeV)</td>
</tr>
<tr>
<td></td>
<td>Energy to melt 1 kg Cu: 0.7 MJ</td>
</tr>
</tbody>
</table>

**Observations:**

- Losses on the 1% level expected.
- Sufficient to melt several kg Cu.
- Al/Cu system (V6.4) would withstand on the < 0.01% level. **Factor 400 improvement** needed.

**Note:**

- Only one primary per plane.
- Disturbed beam can bypass primary and hit secondary (1 turn).
- **Any collimator can be hit** (don’t constrain LHC tune).
Consequences of damage for LHC (non-catastrophic):

**HERA experience:**

1. Observe quenches (lower cleaning efficiency).
2. Try to identify damaged jaw(s) (damage can be on ~ 100 µm level).
   Many jaws close-by in phase advance.
3. Confirm hypothesis by hardware inspection.
4. Remove highly radioactive jaw/collimator tank.
5. Install new jaw/collimator tank.

Can be a **lengthy procedure** (even if only a few times per year). Build **robust collimators** (no damage) or have **fully remote** procedure (revolver of jaws).

Further worry: 158 moving jaws (all coll/abs, 2 beams) with up to **316 motors** in a **highly radioactive environment**!
Basic strategy

Two possibilities:

1) A solution can be found that has sufficient robustness such that frequent damage is avoided (low Z jaws).

2) The jaws will be damaged regularly and we must foresee easy diagnostics and remote repair/exchange possibilities of the highly radioactive jaws (revolver of jaws).

Solution 1 is preferable and all effort concentrates on it for the moment!

Talk by P. Sievers!

Advance the most simple solution that promises to be adequate. Keep more complicated/less convenient concepts in mind as backup solutions. Carbon! (Beryllium, Diamond, multi-layer structures, crystal collimation, renewable high-Z collimators, repairable high-Z collimators, tertiary collimators at the triplets, primary collimators covering the phase space, anti-kicker at dump …)
Abnormal dump actions

Kicker MKD

Kick [$\mu$rad]

Downstream offset [$\sigma$]

All kicker modules

One kicker module prefire with retriggering after 1.3 $\mu$s

One module pre-fire
Abnormal dump actions as input for FLUKA

Beam abort asynchronous with abort gap:
Total: 6 bunches over 5 $\sigma$
Peak: 1.5 bunches in 1 $\sigma$

1 module pre-fire with re-triggering of 14 after 1.3$\mu$s:
Total: 20 bunches over 5 $\sigma$
Peak: 6 bunches in 1 $\sigma$

Talk by P. Sievers!

R. Assmann, B. Goddard, E. Weisse, G. Vossenberg

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Further cases under preparation: Slow losses and ions

Slow loss:

Uniform “emittance” blow-up

Beam lifetime: 0.2 h

Loss rate: 4.1e11 p/s

Loss in 10 s: 4.1e12 p (1.4 %)

Assume drift: 0.3 sig/s

5.3 nm/turn (sigma = 200 micron)

Transverse impact parameter

Almost all particles impact with $y \leq 0.2 \, \mu m$

Surface phenomenon!

Mode | $T$ [s] | $\tau$ [h] | $R_{\text{loss}}$ [p/s] | $P_{\text{loss}}$ [kW]
--- | --- | --- | --- | ---
Injection | cont 10 | 0.1 | $8.2 \times 10^{11}$ | 60
Top energy | cont 10 | 0.2 | $4.1 \times 10^{11}$ | 465
Outline

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A) Intensity at the quench limit

Allowed intensity
Quench threshold
(7.6 ×10^6 p/m/s @ 7 TeV)

\[ N_p^{\text{max}} \approx \tau \cdot R_q \cdot L_{\text{dil}} / \eta_c \]

Beam lifetime (e.g. 0.2 h minimum)
Dilution length (50 m)

Cleaning inefficiency
\[
\frac{\text{Number of escaping } p (>10\sigma)}{\text{Number of impacting } p (6\sigma)}
\]

Collimation performance can limit the intensity and therefore LHC luminosity.
Allowed Intensity Versus Cleaning Efficiency

Trade-off for given quench limit between:

- Inefficiency
- Allowed intensity
- Minimum allowable lifetime

For a 0.2 h minimum beam lifetime during the cycle.
B) Acceptable $\beta^*$

Tolerance for loosing less than 50% of efficiency:

$$n_{\text{prim}} \cdot \sqrt{\frac{\Delta \beta}{\beta_0}} \cdot \sigma_x + \Delta x_{\text{orbit}} \leq 0.6 \cdot \Delta x_{\text{retract}}$$

We find in simulations:

Beta beat: $\leq 8\%$
Orbit: $\leq 0.6 \sigma$

(less if we combine both)

If tolerances are violated during squeeze, for example:

risk of quench!

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Inefficiency versus imperfections

**Beta beat**

- Graph showing inefficiency versus $\delta\beta/\beta$ [%].

**Non collinearity**

- Graph showing inefficiency versus Rms tilt of sec coll [urad].

**Orbit**

- Graph showing inefficiency versus $y$ orbit error [$\sigma_y$].

**Jaw length**

- Graph showing inefficiency versus Active jaw length [m].

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If retraction is adjusted such to allow some maximum transient beta beat and orbit error, then constraint of $\beta^*$:

$$\beta^* \geq \frac{C}{a_{\text{triplet}}^2 \cdot \beta_{\text{coll}}} \left( n_{\text{prim}} + \Delta A_{\text{max}} + 1.7 \cdot \left[ n_{\text{prim}} \cdot \sqrt{\frac{\Delta \beta_{\text{max}}}{\beta_0}} + \frac{\Delta x_{\text{orbit}}^{\text{max}}}{\sigma_x} \right] \right)^2$$

- Increase triplet aperture
- Increase primary
- Minimize any transient beta beat
- Close primary
- Sufficient number of secondaries at specific phases
- Minimize transient orbit changes

Larger $\beta^*$ - A way to relax operational collimator tolerances!

*(However, loose passive protection)*

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Inefficiency for different collimator settings:

\[ n_1 = \text{setting of primary collimator} \]

\[ n_2 = \text{setting of secondary collimator} \]

Aperture limited at 8 \( \sigma \)

Aperture limited at 10 \( \sigma \)
C) Impedance limit:

Third look at impedance in Feb 03 revealed a problem:

\[
\frac{Z_{\text{coll}}}{Z_{\text{arc}}} \sim \frac{(L_{\text{coll}}/L_{\text{arc}}) \times \sqrt{\rho_{\text{coll}}/\rho_{\text{arc}}}}{(\alpha_{\text{coll}}/\alpha_{\text{arc}})^3} \\
\sim \frac{(20 \text{ m}/20 \text{ km}) \times \sqrt{RRR \sim 30}}{(1.8 \text{ mm}/18 \text{ mm})^3} \\
\sim \frac{10^{-3} \times 5}{10^{-3}} \sim 5!
\]

F. Ruggiero

1 INJECTION
D. Angal, L. Vos, Coupled Bunch Instabilities in the LHC, EPAC 2002:
Budget transverse impedance resistive, \(H,V\)

- 45 57 MΩ/m
- Includes contribution single graphite collimator (estimated aperture and \(\beta\)):
  - 0.3 1.1 MΩ/m
- Impedance of all graphite collimators with correct aperture and \(\beta\) (2003):
  - 13.3 16.8 MΩ/m
- New total:
  - 58 73 MΩ/m

Can be handled by transverse feedback

2 HIGH ENERGY
D. Angal, L. Vos, Coupled Bunch Instabilities in the LHC, EPAC 2002:
Budget transverse impedance resistive, \(H,V\)

- 84 118 MΩ/m
- Includes contribution single graphite collimator (estimated aperture and \(\beta\)):
  - 2.2 7.9 MΩ/m
- Impedance of all graphite collimators with correct aperture and \(\beta\) (2003):
  - 841 1017 MΩ/m
- New total:
  - 923 1127 MΩ/m

L. Vos

Main problem at 7 TeV: Al/Cu system doubles impedance budget!
C system increases impedance tenfold!

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Impedance for different materials as a function of collimator half gap:

**F. Ruggiero, L. Vos**

**Half gap b [m]**

**LHC impedance without collimators**

**Typical collimator half gap**

**Transverse impedance M2/m**

**Total collimation length of 20 m**

- Coated boron nitride
- Carbon
- Copper

**How to counteract?**

- Factor 10 higher gain of transverse feedback (factor 3-4.5 margin) before collision.
- Check thresholds for beam instabilities, stabilizing effect of long-range beam-beam.
- Metallic plate or low-Z metal (Be?).
- Copper doped graphite to reduce impedance?
- Open collimators (hardly possible w/o additional collimators at triplets or increase of $\beta^*$).
- Increase beta function at collimators (not possible and gain only with sqrt).
- Increase triplet aperture (not possible, triplets have been built).

Too early to conclude! Studies are ongoing to address this problem!
Showering studies for BLM system (mock-up C collimation system)

Question:

What do the BLM signals measure?
Can the BLM signals be used to tune the collimator settings?

<table>
<thead>
<tr>
<th>Collimator (j)</th>
<th>Beam loss monitor (i)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>TCP1</td>
<td>0.0178</td>
</tr>
<tr>
<td>TCS1</td>
<td>0.0</td>
</tr>
<tr>
<td>TCS2</td>
<td>0.0</td>
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<tr>
<td>TCS3</td>
<td>0.0</td>
</tr>
<tr>
<td>TCS4</td>
<td>0.0</td>
</tr>
<tr>
<td>TCS5</td>
<td>0.0</td>
</tr>
<tr>
<td>TCS6</td>
<td>0.0</td>
</tr>
</tbody>
</table>

I. Kouroutchikov (IHEP), B. Dehning, J.B. Jeanneret

Non-diagonal response matrix of the BLM system for the collimation system in IR7.

Good decoupling for the two beams.

Non-trivial tuning of collimator settings with BLM’s.

Further studies ongoing (response to settings, operational conditions, …).
4. Outlook

Beam **impact requirements** analyzed (failure modes and operational requirements) for a robust and efficient LHC collimation system! Tolerances established.

The collimation and cleaning can strongly **limit** the LHC performance (diagnostics and repair time, intensity limits, limit on $\beta^*$, impedance, tuning time, radiation exposure of personnel, …)

Detailed **engineering design** has started to avoid any LHC performance limits from collimation: appropriate materials (low Z), lengths, mechanics, cooling, damage and fatigue analysis, tolerances, …

Additional concerns are studied: **Impedance, vacuum, local e-cloud, radiation impact**.

Concentrating for now on a **low-Z system based on Graphite** (simplest solution, see Peter Sievers).

**Operational considerations** have been started. However, first decide the basic design: collimator material, length, insertion optics, …

We plan to have an appropriate system ready for the LHC start-up. However, it will be a large and difficult system, central for integrated luminosity (avoiding quenches).

System commissioning with **relaxed requirements**: Lower intensity + larger emittance + larger $\beta^*$.

*When we push luminosity: Not unsimilar to the LEP2 RF system.*
The set-up and schedule

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep 2001</td>
<td>LHC Beam Cleaning Study Group</td>
</tr>
<tr>
<td>Jan 2002</td>
<td>Consensus to consider low Z material (impedance presented as non-critical)</td>
</tr>
<tr>
<td>Jun 2002</td>
<td>Consensus on detailed requirements</td>
</tr>
<tr>
<td></td>
<td>First tolerances</td>
</tr>
<tr>
<td>Oct 2002</td>
<td>Project LHC Collimation, new ATB group</td>
</tr>
<tr>
<td>Jan 2003</td>
<td>Full simulation chain: Beam – FLUKA – ANSYS</td>
</tr>
<tr>
<td></td>
<td>Cleaning efficiency and optics with low Z</td>
</tr>
<tr>
<td></td>
<td>Review of impedance, other constraints</td>
</tr>
<tr>
<td>Apr 2004</td>
<td>Prototype collimator</td>
</tr>
<tr>
<td>2004/2005</td>
<td>Production</td>
</tr>
<tr>
<td>2006</td>
<td>Installation</td>
</tr>
</tbody>
</table>
\[ \Delta x_{\text{retract}} \approx 1.7 \cdot \left[ n_{\text{prim}} \cdot \sqrt{\frac{\Delta \beta_{\text{max}}}{\beta_0}} \cdot \sigma_x + \Delta x_{\text{orbit}}^{\text{max}} \right] \]

Assuming that retraction is set to limits of beta and orbit errors

\[ A_{\text{secondary}}^{\text{max}} = n_{\text{prim}} + \frac{\Delta x_{\text{retract}}}{\sigma_x} + \Delta A_{\text{max}} \]

\[ A_{\text{secondary}}^{\text{max}} = n_{\text{prim}} + \Delta A_{\text{max}} + 1.7 \cdot \left[ n_{\text{prim}} \cdot \sqrt{\frac{\Delta \beta_{\text{max}}}{\beta_0}} + \frac{\Delta x_{\text{orbit}}^{\text{max}}}{\sigma_x} \right] \]

\[ a_{\text{coll}} \propto a_{\text{triplet}} \cdot \sqrt{\beta^* \cdot \beta_{\text{coll}}} \cdot \left( \frac{n_{\text{prim}}}{A_{\text{secondary}}^{\text{max}}} \right) \]