The LHC Collimation System

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for the people who are working / have worked on LHC Collimation:

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…and related activities (beam dump).
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I. Overview on LHC collimation

II. Defining and building the final system

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I. Overview on LHC Collimation

Number of bunches: 2808
Bunch population: 1.1e11
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

Factor 1000 in transverse energy density!

Physics Potential = Energy and Luminosity:

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

\[ d = \text{demagnification} \]
\[ N_p = \text{protons per bunch} \]
\[ f_{rev} = \text{revolution freq.} \]
\[ E_b = \text{beam energy} \]

Increase transverse energy density
Handling of High-Intensity Beams: LHC Collimation System

1) Protect sensitive cold aperture against beam loss…

i. … from beam losses during regular operation
   (99.9 % of protons lost, e.g. with 1 h beam lifetime at 7 TeV, are captured in the collimators)

ii. … from beam losses during failures (without being destroyed)
    (Less than 0.002 % of the stored beam intensity can be lost at any place in the ring other than the collimators, because otherwise magnets could be damaged)

2) Detect any abnormal beam loss at collimators and initiate beam abort
   (basic machine protection philosophy)

   Beam Loss Detectors monitor beam loss rate at collimators.
   Compare signals with a threshold.
   Trigger the beam dump to protect the machine

3) Important: Background minimization is only a side aspect
   Beam much above pilot bunch cannot be put without working collimation system.
Concept of LHC 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
Requirements for Collimator Settings

Reminder: Normalized available LHC aperture specified to be about $10\sigma$ at injection (arcs) and top energy (triplets).

+ 3-4 mm for closed orbit, 4 mm for momentum offset, 1-2 mm for mechanical tolerances

Collimator settings:

- 5 - 6 $\sigma$ (primary)
- 6 - 9 $\sigma$ (secondary)

$\sigma \sim 1$ mm (injection)
$\sigma \sim 0.2$ mm (top)

Number of protons reaching $10\sigma$:

$10^{-4}$ of $p$ at 6 $\sigma$
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

Big system: 108-200 degrees of freedom!
Present layout half IR3:

Special optics requirements (phase advance, dispersion)

Importance of LHC collimation reflected by the fact that two insertions are dedicated to it!

Concept and basic layout developed and verified over last 10 years.
II. Defining and building the final system

1. Understand the driving requirements and define detailed specifications. (AP, operation, machine protection, radiation protection, vacuum)

2. Design, build prototype collimator jaws with the required properties, as robustness against beam loss, scattering properties, absorption quality. (material science, mechanical engineering, AP)

3. Put together a functional collimation system (~70 movable jaws/beam) that delivers high robustness and excellent cleaning efficiency. (AP, operation, instrumentation, controls)
Who is doing the work?

(resource allocation is ongoing)

Optics design
D. Kaltchev
T. Risselada

Collimation efficiency
R. Assmann
J.B. Jeanneret
D. Kaltchev

Operational aspects
R. Assmann
M. Lamont
R. Schmidt
J. Wenninger

Other issues
Dump kicker
Injection collimation
TCDQ
Vacuum
Impedance
Local electron cloud
Diffusion model

Machine Protection
V. Kain
R. Schmidt
J. Wenninger

LHC Beam Cleaning Study Group
Chair: R. Assmann

BLM’s/Instrumentation
B. Dehning
G. Ferioli
E. Gschwendtner

Radiation Protection
I. Baishev
M. Brugger

Scattering Studies
A. Ferrari
V. Vlachoudis

Collimation Unit
E. Chiaveri

Mechanical design
O. Aberle
L. Bruno
E. Chiaveri
S. Marque

Collimator controls
Collimator handling

MPWG
RA LHC MAC 13/9/02
Contents

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III. Status of work

Much work in LHC Beam Cleaning Study Group (since Sep 2001): (Chairman R. Assmann)

Mandate: Study beam dynamics and operational issues for the LHC collimation system. Identify open questions, assign priorities, and show the overall feasibility of the LHC cleaning system.

Activities:

- 16 meetings
- LHC collimation web site
- 7 LHC project notes and reports
- Organization CERN Meeting on Collimation (180 p minutes)
- Presentations/discussions at BI-Review, LCC, EPAC, …

First priority: Consensus about collimation requirements and design criteria.
CERN-LHC-PROJECT-REPORT-599: REQUIREMENTS FOR THE LHC COLLIMATION SYSTEM.
Fischer, B. Goddard, E. Gschwendtner, M. Hayes, J.B. Jeanneret, R. Jung, V. Kain, D.
Kaltchev, M. Lamont, R. Schmidt, E. Vossenberg, E. Weisse, J. Wenninger (CERN &
Serpukhov, IHEP & TRIUMF).

CERN-LHC-PROJECT-REPORT-598: EFFICIENCY FOR THE IMPERFECT LHC COLLIMATION
SYSTEM.

CERN-LHC-PROJECT-REPORT-592: EQUILIBRIUM BEAM DISTRIBUTION AND HALO IN THE

CERN-LHC-PROJECT-REPORT-589: TIME DEPENDENT SUPERCONDUCTING MAGNETIC
ERRORS AND THEIR EFFECT ON THE BEAM DYNAMICS AT THE LHC. By R. Assmann, S.
Fartoukh, M. Hayes, J. Wenninger (CERN).

LHC-PROJECT-NOTE-293: The consequences of abnormal beam dump actions on the LHC
collimation system
by: Assmann, R ; Goddard, B ; Vossemberg, E ; Weisse, E ; (2002)

LHC-PROJECT-NOTE-282: Summary of the CERN Meeting on Absorbers and Collimators for the
LHC
by: Assmann, R ; Fischer, C ; Jeanneret, J B ; Schmidt, R ; (2002)

LHC-PROJECT-NOTE-277: Preliminary Beam-based specifications for the LHC collimators
by:
Assmann, R ; (2002)
Scenario for worst case shock beam impact

Danger of damage to accelerator components.
In particular: Collimators close to beam!

Equipment failures
Equipment errors
Operational errors

Beam dump: Designed to extract beam within 2 turns.
Pulse rise time of 3 µs (dump gap).

Failure modes:
- Total failure of dump or dump trigger (> 100 years)
- Dump action non-synchronous with dump gap
- Dump action from 1 of 15 modules, others retriggers after 1.3 µs.

Difficult to predict
Assume at least once per year!
Abnormal dump actions

Kicker MKD

Kick [$\mu$rad]

Downstream offset [$\sigma$]

One module pre-fire

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Abnormal dump actions

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 $\sigma$
Ease requirements from dump system?

One module pre-fire depends on details of dump kicker design (pulse form, number of magnets, re-trigger design)!

Possible remedies are being studied (require modifications to dump system).

Collimators should **withstand this impact** without damage!

Consequences for choice of *material, jaw length, operation, exchange facilities, setting of TCDQ (10\(\sigma\)), distribution of radioactivity, …*
Important consequences

Detailed calculation with measured kicker waveform yields *higher beam impact* on collimators than assumed.

*Frequency of abnormal beam dumps* (several times per year) much higher than previously assumed (1/20y).

**LEP technical solution (Cu, Al) cannot be used:**

Damage threshold 0.05 bunches. We look for 20 bunches or we might need to replace collimators a few times per year!

*New technical solutions are being pursued* (low Z material, CERN meeting on collimators and absorbers).
Energy deposition map in a jaw

Half a nominal LHC bunch

Cu secondary coll.

A. Ferrari, V. Vlachoudis

Cu cannot take 20 bunches!
Radiation levels

Goal: Benchmark codes against measured activation for various materials

Measurements at CERF and NA60: M. Brugger, Y. Donjoux, A. Mitaroff, S. Roesler, M. Silari

CERF:
120 GeV mix-beam (p, K, mesons)
2cm size
1.4e8

Materials:
Al, Cu, Fe, stainless steel, BnNi, C composite

NA60:
400 GeV mix-beam (p)
1mm size
1e7-1e9

Materials:
Be, In, Pb

Benchmark FLUKA. Once material is decided radiation levels will be predicted within factor 2 or better.
Beam scenarios

Continuous beam impact

Worst case shock beam impact

- Energy deposition map in a jaw
- Damage/fatigue analysis

Material, length

Cleaning efficiency of total system

- Vacuum
- Impedance
- Optics IR3/7

Radiation levels

Handling

- Mechanical design of jaws (dimensions, cooling, …)

Performance of instrumentation

Tank

Prototype jaw

Tolerances

- Collimator controls
- Motors Electronics Software
- Beam loss prediction

Layout of instrumentation

Tests

Tests

Production

Installation

Operation
Scenario continuous beam impact

Proton losses observed in routine operation (include operational variation of beam lifetime)!

Studies for system with Al/Cu jaws.

Desirable:

1) Possibility to run at quench limit ($\tau = 0.2$ h for top energy)

2) Accept low lifetimes during cycle

<table>
<thead>
<tr>
<th>Mode</th>
<th>$T$ [s]</th>
<th>$\tau$ [h]</th>
<th>$R_{loss}$ [p/s]</th>
<th>$P_{loss}$ [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection</td>
<td>cont 10</td>
<td>1.0</td>
<td>$0.8 \times 10^{11}$</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.1</td>
<td>$8.2 \times 10^{11}$</td>
<td>60</td>
</tr>
<tr>
<td>Top energy</td>
<td>cont</td>
<td>1.0</td>
<td>$0.8 \times 10^{11}$</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.2</td>
<td>$4.1 \times 10^{11}$</td>
<td>465</td>
</tr>
</tbody>
</table>

Additional requirements for collimator hardware!

Material, length, cooling, ...
Running at the quench limit for $\tau = 0.2$ h

Trade-off for given quench limit between:

**Inefficiency** – **Allowed intensity** – **Minimum allowable lifetime**
Beam scenarios

Continuous beam impact

Worst case shock beam impact

Energy deposition map in a jaw

Damage/fatigue analysis

Vacuum

Impedance

Optics IR3/7

Cleaning efficiency of total system

Radiation levels

Material, length

Mechanical design of jaws (dimensions, cooling, ...)

Handling

Tolerances

Prototype jaw

Tests

Prototype jaw Tests

Tank Tests

Performance of instrumentation

Layout of instrumentation

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Prototype jaw Tests

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Production

Installation

Operation
System evaluation: Tolerances

Value of imperfections for 50% increase (each) in inefficiency:

<table>
<thead>
<tr>
<th>Error</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>0.6 $\sigma$</td>
</tr>
<tr>
<td>Beta beat</td>
<td>8%</td>
</tr>
<tr>
<td>Longitudinal angle</td>
<td>50 $\mu$rad</td>
</tr>
<tr>
<td>$\Delta L/L$ (prim)</td>
<td>75%</td>
</tr>
<tr>
<td>Surface flatness (prim)</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>$\Delta L/L$ (sec)</td>
<td>20%</td>
</tr>
<tr>
<td>Surface flatness (sec)</td>
<td>25 $\mu$m</td>
</tr>
<tr>
<td>Setting accuracy (prim)</td>
<td>-1.0/+0.5 $\sigma$</td>
</tr>
<tr>
<td>Setting accuracy (sec)</td>
<td>$\geq$ ± 0.5 $\sigma$</td>
</tr>
</tbody>
</table>

Collimators need not only be robust, but also precise!

HERA experience:

Beam

$5 \sigma$

(1mm)
Set-up of tools, thinking about operation started

Tools: SIXTRACK with collimators
      Comparison of scattering physics
      Interface of halo prediction to BLM studies

Operation: Operational strategies
           Orbit feedback
           Machine protection
           Required accuracy for beam diagnostics
           Allowed deterioration of beam parameters

All ongoing… (fast results when mechanical properties decided)
Inefficiency versus settings

Aperture limited at 8 $\sigma$

Aperture limited at 10 $\sigma$

$n_1 = \text{setting of primary collimator}$

$n_2 = \text{setting of secondary collimator}$
IV. Outlook

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

Now engineering design starting: appropriate materials (low Z), lengths, mechanics, cooling, damage and fatigue analysis, tolerances, …

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

Two cleaning insertions, each two-stage, defined since years for high efficiency cleaning.

Accelerator physics and operational analysis is ongoing:

Overall tolerance specifications (flatness, required adjustments, orbit and optics requirements, …). Operational optimization. Realistic diffusion and aperture models (BLM signals). Chromatic effects. Cross-checks of different scattering and tracking tools.
The performance of the collimation system can limit…

… **peak luminosity** due to maximum allowed intensity.

… **integrated luminosity** due to beam aborts and repair time.

This we want to prevent!

Collimation is a performance-critical topic
from day 1 of LHC physics!

It pushes **accelerator physics understanding of beam halo** and **material science** to new frontiers!
Schedule

Sep 2001  LHC Beam Cleaning Study Group started
June 2002 Consensus on worst case beam impact
          Core team of competence established

Required schedule:
July 02 – Dec 02 Showering, damage studies
Dec 02     Propose material, length, basic design
Mar 03     Verify system performance, specify
tolerances, verify optics, iterate on length
Dec 03     First prototypes
2004/05    Production
2006       Installation

Resource allocation ongoing to assure that this schedule can be met.
Additional slides
Secondary and tertiary beam halos

Scattering in collimator jaws (at 6/7 \( \sigma \))

Transverse scattering angles + momentum loss

Halo at zero dispersion

Halo at max dispersion

Local inefficiency [1/m]:
Integrate halos above 10\( \sigma \)
Divide by dilution length (50 m)
Tertiary halo in phase space

Halo generated at specific phase space locations!

Input to studies of local loss distribution (dilution, expected signals of Beam Loss Monitors BLM).
Inefficiency versus imperfections

**Beta beat**

![Graph showing Beta beat inefficiency vs. δβ/β [%]](image)

**Non collinearity**

![Graph showing Non collinearity inefficiency vs. Rms tilt of sec coll [urad]](image)

**Orbit**

![Graph showing Orbit inefficiency vs. y orbit error [σ_y]](image)

**Jaw length**

![Graph showing Jaw length inefficiency vs. Active jaw length [m]](image)
Scattering physics
Multi-turn properties and impact parameter

**Primary impact parameter**

**Survival half time**

**Survival after impact**

**Proton number vs turn**

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**Material Damage**

**Destruction limits**

<table>
<thead>
<tr>
<th>Case</th>
<th>Destruction threshold [nominal intensity]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1.9e-3, 1.8e-5</td>
</tr>
<tr>
<td>Beam screen</td>
<td>1.6e-3, 7.0e-5</td>
</tr>
<tr>
<td>S.C. coil</td>
<td>4.2e-3, 14.0e-5</td>
</tr>
</tbody>
</table>

This made the reconsideration of present collimator jaw materials necessary!

5-12 nominal bunches at injection

0.05-0.4 nominal bunches at top energy

No safe operating point for LHC (top) without protection!
Super-Conducting Environment

Proton losses into cold aperture

Local heat deposition

Magnet can quench

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>Loss rate (10 h lifetime)</th>
<th>Quench limit [p/s/m] (steady losses)</th>
<th>Cleaning requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>8.4e9 p/s</td>
<td>7.0e8 p/s/m</td>
<td>92.6 %</td>
</tr>
<tr>
<td>7000</td>
<td>8.4e9 p/s</td>
<td>7.6e6 p/s/m</td>
<td>99.91 %</td>
</tr>
</tbody>
</table>

Control transient losses (10 turns) to ~1e-9 of nominal intensity (top)!

Capture (clean) lost protons before they reach cold aperture!
Required efficiency: \(~ 99.9 \%\) (assuming losses distribute over 50 m)
Two stage collimation system

Betatron cleaning: 4 primary and 16 secondary collimators
Optimize phase advance for minimal secondary halo

Adapted from J.B. Jeanneret