Introduction to dispersion suppressor collimation

Stefano Redaelli for the collimation team
Inputs from: G. Arduini, R. Bruce, O. Brüning, F. Cerutti, J. Jowett, B. Salvachua, A. Verweij, and many other people.
Outline

☑ Introduction
☑ Present LHC collimation
☑ DS collimation concept
☑ Scope of this review
☑ Ongoing LS1 upgrades
☑ Conclusions
Introduction

Superconducting coil: $T = 1.9 \, \text{K}$, quench limit $\sim 15 \text{mJ/cm}^3$

Proton beam: $145 \, \text{MJ}$
(LHC design: $362 \, \text{MJ}$)
(HL-LHC: $500 \, \text{MJ}$)

Factor $9.7 \times 10^9$
Aperture: $r = 17/22 \, \text{mm}$

LHC “Run 1” 2010-2013: No quench with circulating beam, with stored energies up to 70 times of previous state-of-the-art!
The LHC collimator
Requirements to handle 360 MJ

Main collimation challenges:

- **High stored energy:**
  Collimators needed in all phases (inj., ramp, squeeze, physics);
  Function-driven controls of jaw positions mandatory;
  **Robustness** and **cleaning efficiency**;
  Big and **distributed** system (100 collimators).

- **Small gaps:**
  Mechanical **precision**, **reproducibility** (< 20 microns);
  Constraints on orbit/optics **reproducibility**;
  Machine **impedance** and beam instabilities.

- **Collimator hierarchy:**
  Collimators determine the LHC $\beta^*$ reach.

- **Machine protection:**
  Redundant **interlocks** of collimator jaw positions and gaps.

- **High-radiation environ.:**
  **Radiation**-hard components (HW + SW);
  Challenging remote **handling**, design for quick installation.

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R. Assmann et al. (2003)
Based on “bulk” amorphous jaws. Different materials: CFC, W, Cu, graphite.

The **multi-stage collimation** keeps leakage to sensitive equipment at safe levels.

Define of local collimation **cleaning inefficiency**: \( \eta_c = \Delta N_{\text{lost}} / N_{\text{abs}} \times \frac{1}{\Delta s} \)

Approximated in measurements by ratio of BLM signals to losses at primaries.

Cold magnets: must stay below their quench limit.

Cold losses, \( \eta_c \times N_{\text{tot}} / \tau_b \), in case of bad beam lifetime (\( \tau_b \)) must be below quench limit \( R_q \)

Other important role of the collimation system: minimize radiation doses to equipment.

Minimize radiation doses on warm magnets in IR3/7 [not discusses in this review].

Robust system providing excellent passive protection in case of failures.
Present LHC collimation layout

Two warm cleaning insertions, 3 collimation planes

- IR3: Momentum cleaning
  1 primary (H)
  4 secondary (H)
  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!

Full system commissioned in 2010!
Collimation cleaning at 4 TeV ($\beta^* = 60\text{cm}$)

2012-13: “tight” collimator settings (TCP gaps as at 7 TeV) for higher beta$^*$!
60 cm for protons, 80 cm for ions.

Highest COLD loss location: inefficiency < 1e-4. For most of the cold aperture it is actually < 1e-5!
**Loss maps in IR7**

Critical location (both beams): losses in the dispersion suppressor (highest at the Q8) from single diffractive interactions with the primary collimators. No other significant limitation have been observed so far from collimation cleaning.

Do the critical cleaning locations also limit the LHC and HL-LHC performance?
Experience at 4 TeV with Pb-p beams confirmed the results at 3.5 TeV: IR7 cleaning in the order of \textbf{a few percents} for ion beams! Present collimation not optimized for ions!
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Dispersion suppressor losses

Particles that change rigidity (e.g. lose energy) in a straight insertion are lost in the dispersion suppressor (DS): this is the first location with high dispersion.

Cleaning insertions (IR3/7): proton mainly lose energy due to single-diffractive interactions with the primaries†.

Experimental regions (IR1/2/5/8): protons lose energy in the collision process.

Different physics for ions: similar qualitative behaviour due to rigidity change.

Collimators are in the straight section: first dipoles in the DS act as spectrometers.

No local protection available in the DS.

The present LHC collimation system cannot protect efficiently the DS!

This limitation predicted by simulations is confirmed by the operational experience (DS’s are the highest cold loss locations).

† IR3: dispersion not zero but optimized to have TCP’s as bottleneck -> same problem.
7 TeV extrapolations are scaled from measurements of achieved losses in dedicated quench tests and measured and simulated collimation cleaning. Important: uncertainty on beam lifetime at higher energies.

7 TeV intensity reach: \(9.9 \times 10^{14} \text{p}\) for minimum lifetime of 0.2h
- This is about 3 times nominal (1.15e11/bunch); 1.5 times HL-LHC (2.2e11/b)
- Assumes tight settings and “pessimistic” lifetime from observations in 2012
- More realistic lifetime assumptions: 0.5-1.0 h (best beam) give more margin!
- Next talks: quench limits, lifetime, interplay stability/beta* /number of dumps

No new inputs for ion operation: a quench tests could not be performed!
- See talk by J. Jowett.

With the given uncertainties, it is important to keep the option to assess these assumptions with operational experience at energies close to 7 TeV.

Need feedback from the review: Safety factors appropriate? Correct assumptions on lifetime?
DS limitation (2): physics debris

Losses seen in the whole experimental insertion and DS from collision products.

IR1/5 (high luminosity): concerns for matching quadrupoles, Q5 in particular.

Possible concerns: peak DS losses when establishing collisions as well as total doses due to long physics runs.

Different pattern for proton and ions - details in talks by A. Marsili and J. Jowett.
Comment on losses during the cycle

Our present understanding:
- Quenches in the cleaning insertions (e.g., IR7 DS) depends on total beam intensity;
- Quenches in the experimental regions’ DSs depend on peak luminosity;
- Radiation doses in all IRs depend on integrated luminosity.

See losses in a typical cycle (F3202, L=7e^{33} cm^{-2}s^{-1}, I~2.2e^{14}p):
loss spikes during setup (injection, ramp, squeeze, collision setup).
Loss at a TCP and at two limiting cold locations in IR7 and IR1.
Comparison to peak losses during 4 TeV quench tests (without quench)

**Losses in a typical cycle**

**Achieved losses in Q8-L7 during quench test!**
Summary of DS collimation needs

**Scope of this review!**

<table>
<thead>
<tr>
<th></th>
<th>Until HL-LHC (before LS3) [L=2.5x10^{34}\text{cm}^{-2}\text{s}^{-1}, I_{\text{tot}}=3.2x10^{14}\text{p}]</th>
<th>HL-LHC era (after LS3) (L=5x10^{34}\text{cm}^{-2}\text{s}^{-1}, I_{\text{tot}}=6.2x10^{14}\text{p})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Protons</td>
<td>Ions</td>
</tr>
<tr>
<td>IR7</td>
<td>Betatron cleaning</td>
<td>Needed?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Needed? with or w/out ATS</td>
</tr>
<tr>
<td>IR3</td>
<td>Momentum cleaning</td>
<td>Not needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not needed</td>
</tr>
<tr>
<td>IR1/5</td>
<td>ATLAS/CMS</td>
<td>Not needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Needed</td>
</tr>
<tr>
<td>IR2</td>
<td>ALICE</td>
<td>Not needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Needed</td>
</tr>
<tr>
<td>IR8</td>
<td>LHCb</td>
<td>Not needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not operating</td>
</tr>
</tbody>
</table>

“Dynamic” table that might evolve during this review...

Complex parameter space that will be presented in the next talks.

**Goal for the collimation project at this stage**: we want to have solution available to address possible issues revealed by the operational experience at ~7 TeV. Decide then on which IR the priority should be put on.

**Larger uncertainties for HL-LHC era, but more time to freeze layouts.**
Do we have alternatives?

DS collimation solution poses important **technological challenges** but otherwise is a robust solution that provides the required cleaning (several talks on that). Local cleaning in DS works both for cleaning and experimental insertions! Other possibilities exist on paper. Can they be ready for implementation in LS2? Note that the **option to move magnets** (see later) remains on the table!

<table>
<thead>
<tr>
<th>IR</th>
<th>Beam scraping / halo control</th>
<th>Crystal collimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR7</td>
<td>Betatron cleaning</td>
<td>Potentially yes.</td>
</tr>
<tr>
<td>IR3</td>
<td>Momentum cleaning</td>
<td>Potentially yes.</td>
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<tr>
<td>IR8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*These alternatives require **conceptual studies** and **beam tests** before being considered as a valuable alternative for LS2. In additional, there is **no obvious cure** for the experimental regions. These ongoing studies are therefore not part on the review mandate. Studies/beam test program ongoing for HL-LHC.*
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Baseline for DS collimation until 2011

- Concept of IR3 “combined cleaning”:
  - 2 DS collimators in IR3
  - Add vertical secondaries to achieve betatron and momentum cleaning
- Cleaning not ideal but sufficient until LS2, IR7 upgrade would come later.
- Involved moving magnets between Q7 and Q11 at either side of IR3.
- Motivation: IR3 more radiation tolerant and DS easier to modify.
Baseline for DS collimation until 2011

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In 2011, following also the recommendation of the review, it was decided to postpone the important works for the IR3 combined system:

- Acceptably small risk of seeing performance limited between LS1 and LS2 compared to risk taken in changing layout
- Significant manpower involved for moving magnets

- Encouraged to prepare for implementation in LS2+, profiting of 11T dipole research
- Why another review now?
What has changed?
(only aspects relevant for DS collimation)

- More operational **experience**: could handle **140MJ** beams!
- Confirmed the collimation performance with “tight” settings, understand better the **hierarchy setting limits**.
  - More insight on the **interplay** between $\beta^*$ **reach** and **impedance limits**
- **New quench tests**: we raised the lower quench limit estimate
  - Still no quench with losses 3-10 times larger than 2011!
- **BUT**: we experienced a **worsening of beam lifetime** for smaller $\beta^*$ operation with tight collimator settings.
  - Lost more than a factor 20 compared to 2011;
  - Now losses during whole cycle and not only when bringing beam in collision
- The option of the temporary IR3 combined cleaning is dismissed. We consider instead one single solution for HL-LHC.
  - 11T dipoles would ease the implementation in IR7, if needed.
  - IR7 will be more radiation tolerant thanks to electronic relocation - No talk scheduled on that unless requested by review panel!
- **Important experience on IR debris cleaning** for protons
  - New TCL collimator layout proposed!
- **Decision on warm vs cold DS collimator made** for LS2 timeline
- **Planned ALICE upgrade** for $6 \times 10^{27} \text{cm}^{-2}\text{s}^{-1}$
Scope and mandate

☑ I think that major decisions on the DS modification for high intensity proton operation should be taken after some **experience at 6.5-7 TeV**

☑ Can we decide now about implementation for **ion operation**?

☑ **What do we need to do in the next ~2 years in order to make sure that in 2015 we will have all the technical background to decide on the DS collimation, if needed?**

☑ Are there viable alternatives to the scheme based on the 11T dipoles?
A look at the program

Three main sessions:

S1. Introduction and review scope
- The HL-LHC timeline - L. Rossi
- Introduction to DS collimation - S. Redaelli
- Present LHC collimator - R. Losito

S2. Estimated performance reach at > 6.5 TeV
- Cleaning performance - B. Salvachua
- Setting limits and beta* reach - R. Bruce
- Impedance - N. Mounet
- Collimation cleaning with ATS optics for HL-LHC - A. Marsili
- DS collimation for heavy-ion operation - J. Jowett
- Energy deposition simulations for quench tests - E. Skordis
- Quench limits: extrapolation of quench tests to 7 TeV - A. Verweij
- Overview of quench limits for faster time ranges - M. Sapinski

S4. Status of DS collimation implementation
- What do we need to decide now to have Nb3Sn dipoles?
- Status of 11T dipole program - M. Karppinen
- Cryogenics design choices and integration issues - V. Parma
- Status of the TCLD collimator design - A. Bertarelli
- Heat load scenarios and protection levels for ions - G.

☑️ Outlook of HL-LHC collimation studies in one single talk in S4
☑️ “Social” program:
- Visit of collimation workshops on Wed.
- Review dinner on Thu.

Many thanks to Julia D. for the help in the organization! Feel free to contact her, Lucio or myself in case of any issue!

Many thanks to all speakers!
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**Collimation operational experience**

- **Very good performance** of the collimation system so far (up to 140MJ):
  - Validated *all* critical design choices (HW, SW, interlocking, ...);
  - Cleaning close to simulations and ok for operation after LS1;
  - We learned that we can rely on the machine stability!
  - Established and improved semi-automatic alignment tools;
  - Performance estimates based on 2011 quench tests - to be reviewed at the end of 2012.

- The present LHC collimation **cannot protect** the cold dispersion suppressors.
  - Critical locations with present layout: IR7, IR1/5, IR2 (ions).
  - Investigations ongoing on limitations from quench and magnet lifetime.

- The collimators determine the **LHC impedance**
  - Rich program on “dream” materials and new collimator concepts.

- Collimation alignments and validation of new setting are **time-consuming**.

- The **operation flexibility** in the experimental regions (VdM scans, spectrometer polarity changes, $\beta^*$ leveling, ...) is affected by collimation constraints.

- The $\beta^*$ **reach** is determined by collimation constraints: retraction between beam dump and horizontal TCTs which are not robust.

- Collimator handling in **radiation environment** will be challenging.
LHC collimation after LS1

The 16 Tungsten TCTs (industrial production) in all IRs and the 2 Carbon TCSGs in IR6 (in-house production) will be replaced by new collimators with integrated BPMs.

Tests in the SPS with mock-up collimator very successful

Gain: can re-align dynamically during standard fills. No need for special low-intensity fills

→ Drastically reduced setup time (gain of a factor ~100) => more flexibility in IR configurations

→ Improved monitoring of TCT centres in the IRs (reduce validation time)!

→ Reduced orbit margins in cleaning hierarchy => more room to squeeze $\beta^*$ (see R. Bruce’s talk)

BPM buttons

Courtesy O. Aberle, A. Bertarelli, F. Carra, A. Dallocchio, L. Gentini et al.
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    → Improved monitoring of TCT centres in the IRs (reduce validation time)!
    → Reduced orbit margins in cleaning hierarchy => more room to squeeze $\beta^*$ (see R. Bruce’s talk)

- Other **system improvements** ongoing:
  → Improved layout in IR8 (better impedance);
  → Additional passive absorbers in IR3 to increase the warm magnet lifetime;
  → Improved **TCL layouts in IR1/5** for better absorption of physics debris.

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Figure 8: Correlation between measured beam centres (BPMs - red, BLM based method - blue) and the bump settings for the orbit offset at the collimator. The error in the bump settings was estimated to about 10% of the movement increment.
Solution of limitations in IR1/5

Losses in the IR5 DS for L=10^{34}\text{cm}^{-2}\text{s}^{-1}

- Baseline layout to improve debris losses with “TCL” collimators proposed for implementation in LS1 already
  - S. Redaelli, LMC Nov. 7th, 2012.
- Present layout: 1 TCL in cell 5 (TCL-5)
- New layout: add TCL-4 and TCL-6
- With TCL-4, losses below 1 mW/cm^3, i.e. more than a factor 10 below quench limit!
- Sufficient margin for the operation until LS3 with peak luminosity below 3\times10^{34}!
- Further gain by factor > 50 with TCL-6 expected in DS.

Caveats:
- Ongoing comparison with 4 TeV measurements to improve understanding
- Loss distributions with new TCLs need assessment against R2E requirements
- Operationally, need to synchronize with need of forward physics community
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Conclusions

- The present collimation system was introduced.
- The achieved collimation performance was reviewed and the concerns on dispersion suppressor (DS) losses introduced.
  - The LHC and the collimation system worked very well (140MJ; ~30fb⁻¹)!
  - The present LHC collimation cannot protect efficiently the DS’s
  - Is this going to induce a performance limitation for the LHC and HL-LHC?
- We ask advice to an external review panel on whether we are on good track to address potential performance limitations revealed by the LHC operation in 2015 at energies close to 7 TeV.
  - The overall performance is very encouraging, but we want to be sure that future performance limitations are excluded with appropriate margins
  - Our goal is to be ready for actions in LS2 if needed.
- If available in time, the 11 T dipoles would provide an elegant and “transparent” solution, “easily” applicable to several IR’s
  - Can we have a solution bases on this technology for possible actions in LS2?
- Other upgrade studies will be presented at the end of this review!
Reserve slides
Losses from luminosity debris

Ongoing program (beam measurements + tracking and energy deposition simulations) followed up by the CoIUSM to understand the present losses from luminosity debris ➔ feedback on layout of experimental regions.
Measurements of TCL scans in IR1/5

Gap scans with the physics debris collimators (TCLs) in IR1/5: direct measurements of loads in matching section and DS; simulation benchmark. Immediate interest: update of IR1/5 layout during LS1!

Proposal to perform cryogenics measurements in standard physics fills in different conditions.

See also talk by F. Cerutti at the CWG, Aug. 2012.
The local cleaning in the IR7 DS’s was improved by a factor $\sim5$ compared to 2011. Improvements from 2011 driven by the deployment of collimator “tight” settings. (TCP settings equivalent to 7 TeV nominal gaps), studies in MDs in 2011. Drawbacks: we are now dealing with larger losses in standard operation: tail removal during ramp and beam instabilities from larger impedance!
Comparison: 2011 vs 2012

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- even by the deployment of collimator “tight” settings. TeV nominal gaps), studies in MDs in 2011.
- ing with larger losses in standard operation: tail am instabilities from larger impedance!
Collimator alignment

2012 commissioning: alignment campaigns

<table>
<thead>
<tr>
<th>Setup Type</th>
<th>Injection</th>
<th>Flat Top</th>
<th>Squeezed</th>
<th>Colliding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>21/03</td>
<td>29/03</td>
<td>31/03</td>
<td>30/03</td>
</tr>
<tr>
<td>N. of coll.</td>
<td>86</td>
<td>80</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>

Number of dump triggered during collimator align.

<table>
<thead>
<tr>
<th></th>
<th>2010 (Manual)</th>
<th>2011 (1 Hz)</th>
<th>2012 (8 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. of dumps</td>
<td>1 (inj) + 4 (3.5TeV)</td>
<td>2 + 0</td>
<td>0 + 0</td>
</tr>
</tbody>
</table>

Ph.D. work of G. Valentino
See a recent ICAP + HB2012 papers