Low Impedance Collimators for the HL-LHC


9th International Particle Accelerator Conference, Vancouver, Canada, 2nd May 2018
Outline

• Introduction to the HL-LHC project
• The HL-LHC impedance and stability model
• Experience with LHC
• Low impedance collimators for HL-LHC
• Tests with TCSPM prototype
  – Impedance measurements with beam
  – Impedance measurements with wire
  – Jaw material resistivity studies
• TMCI threshold in LHC/HL-LHC
• Conclusion and outlook
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The HL-LHC project

HL-LHC is an approved CERN project:

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of \( L_{\text{peak}} = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ with levelling} \), allowing:

An integrated luminosity of \( 250 \text{ fb}^{-1} \text{ per year} \), enabling the goal of \( L_{\text{int}} = 3000 \text{ fb}^{-1} \) twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of engineering margins:

\( L_{\text{peak ult}} \approx 7.5 \ 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) and Ultimate Integrated \( L_{\text{int ult}} \sim 4000 \text{ fb}^{-1} \)

LHC should not be the limit, would Physics require more...

From L.Rossi, “HL-LHC baseline and operational scenario”, LHC Performance workshop – Chamonix 2018
Main parameters

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC nominal</th>
<th>HL-LHC ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{peak}} \ [10^{34} \text{cm}^{-2}\text{s}^{-1}]$</td>
<td>5</td>
<td>7.5</td>
</tr>
<tr>
<td>$L_{\text{tot}} \ [\text{fb}^{-1}]$</td>
<td>3000</td>
<td>4000</td>
</tr>
<tr>
<td>$\beta^* \ \text{before collision} \ [\text{cm}]$</td>
<td>64</td>
<td>41</td>
</tr>
<tr>
<td>$\beta^* \ \text{stable beams} \ [\text{cm}]$</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Enhanced effect of long ranges

- Beam parameters:

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC standard</th>
<th>HL-LHC BCMS</th>
<th>LHC 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy \ [\text{TeV}]</td>
<td>7</td>
<td>7</td>
<td>6.5</td>
</tr>
<tr>
<td># of bunches</td>
<td>2760</td>
<td>2748</td>
<td>2544</td>
</tr>
<tr>
<td>$N_b \ [10^{11} \text{ppb}]$</td>
<td>2.3</td>
<td>2.3</td>
<td>1.2</td>
</tr>
<tr>
<td>$\varepsilon_{x,y}^{\text{rms}} \ [\mu\text{m}]$</td>
<td>2.1*</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>$\sigma_z^{\text{rms}} \ [\text{cm}]$</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

Ultimate scenario + BCMS → challenging for beam stability!
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The HL-LHC impedance model

- As the LHC, the HL-LHC impedance would be dominated by collimators’ impedance:
  - Large number (54/beam)
  - Tight gaps (<2 mm in IP7 betatron cleaning)
  - Highly resistive jaw material: majority made of Carbon Fiber Composite (CFC)
  - Not negligible impact of geometrical transitions

- Lowering the collimators impedance -> gain on stability and operation margins.
The HL-LHC stability model

- HL-LHC with LHC collimators: tight margins for BCMS beam

- Impedance: 480 A out of 570 A for Ultimate scenario at $\beta^* = 41cm$. 
The HL-LHC stability model

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- Impedance: 480 A out of 570 A for Ultimate scenario at $\beta^* = 41\,cm$.
- Considering long ranges effect:
The HL-LHC stability model

- HL-LHC with LHC collimators: tight margins for BCMS beam
- Impedance: $480 \text{ A}$ out of $570 \text{ A}$ for Ultimate scenario at $\beta^* = 41 \text{ cm}$.
- Considering long ranges effect: no margin for Ultimate scenario.
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Experience with LHC

- 2017 LHC operational evidence: **needed x2 higher octupole** current than expected.

- Destabilizing mechanisms under investigation (damper noise, coupling, optics errors, long range beam-beam, tail distributions, ...)

- Need at least factor 2 margin also in HL-LHC → Collimator impedance reduction
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**Low impedance collimators**

- Investigated new jaw absorber materials for HL-LHC to:
  - Cope with larger power deposition
  - Reduce beam impedance
- Main options:

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity [$\mu\Omega$ m]</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
<td>5000</td>
<td>Present in LHC</td>
</tr>
<tr>
<td>MoGr</td>
<td>1000</td>
<td>Baseline bulk</td>
</tr>
<tr>
<td>Mo</td>
<td>53</td>
<td>Baseline coating</td>
</tr>
<tr>
<td>TiN</td>
<td>400</td>
<td>Alternative coating</td>
</tr>
<tr>
<td>Cu</td>
<td>19</td>
<td>Alternative coating</td>
</tr>
</tbody>
</table>
Low impedance collimators
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- Coating all secondaries in IP7 will reduce the octupole threshold by ~150 A.
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- With 2 primaries in MoGr (HL-LHC baseline): x2 margin for operation (- 30 A).
Low impedance collimators

- Coating all secondaries in IP7 will reduce the octupole threshold by \(~150\) A.
- With 2 primaries in MoGr (HL-LHC baseline): x2 margin for operation (- 30 A).
- Staged implementation foreseen (4/11 secondaries/beam) during next LHC Long Shutdown (LS2)
Staged installation of low impedance collimators

- Selection constraints:
  1. Gain in impedance reduction.
  2. Rate of injection/extraction failures or asynchronous dumps.
  3. Amount of exposure to steady beam losses.

- Selected set:
  - 1 Vertical: D4L/R7
  - 1 Horizontal: B4L/R7
  - 2 Skews: E5L/R7 and 6L/R7
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The TCSPM is a three stripe vertical collimator prototype installed during the 2016-2017 LHC winter shutdown (thanks to all the team involved!) with aim to quantify experimentally the gains in terms of coating impedance reduction.

Materials exposed to the beam:
1. Mo coating on MoGr bulk
2. MoGr uncoated bulk
3. TiN coating on MoGr bulk
Probing HL-LHC collimator impedance

- Studied **tune** change Vs **gap** movement for TCSPM and adjacent CFC collimator.
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- Sequence of fast collimator gap cycling + kick $\rightarrow 10^{-5}$ **accuracy reached thanks to ADT team!**
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Probing HL-LHC collimator impedance

- Clear gain with respect to CFC collimators.
- Factor x2 higher tune shift on Mo stripe \( \rightarrow 250n\Omega m \) resistivity (expected \( \sim 53n\Omega m \)).
Bench RF measurements

- Resonant wire measurements performed:
  - Wire capacitive coupled → the collimator is made resonant
  - Change in Q-factor → Real part of longitudinal impedance.

- Agreement within errorbars on TiN stripe.

- Lower impedance reduction measured on Mo stripe → Compatible with \( \sim 300n\Omega m \) Mo resistivity (expected 53\( n\Omega m \)).
Surface studies

• Higher Mo resistivity could be related to:
  1. Coating grain size and number of boundaries.
  2. Coating surface roughness.
  3. Presence of large ( < 10μm ) bumps on the surface.

• Surface impurities could also increase effective resistivity.

• Investigations ongoing on specific coating procedures:
  o Ultra-sound,
  o Surface polishing,
  o CO2 blasting,
  o ...
Impact of Mo resistivity on stability

- What is the impact of the measured Mo resistivity (250 nΩm instead of 53 nΩm) on the HL-LHC baseline?
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  - -25 (20) A reduction in margin for BCMS (Standard) beam

- Still close to operation margin for HL-LHC Standard and BCMS beams.
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Probing HL-LHC TMCI threshold

Measurement of **tune shift versus intensity** gives information on:
- Transverse impedance of the machine
- Maximum reachable intensity before TMCI (coupling of $Q_x$ with $Q_x - Q_s$)
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- Performed in LHC: threshold close to expected $3.5 \cdot 10^{11}$ ppb
Probing HL-LHC TMCI threshold

- Measurement of tune shift versus intensity gives information on:
  - Transverse impedance of the machine
  - Maximum reachable intensity before TMCI (coupling of $Q_x$ with $Q_x - Q_s$)

-Performed in **LHC**: threshold close to expected $3.5 \cdot 10^{11}$ ppb

- HL-LHC low impedance collimators were *imitated* by opening the LHC collimator gaps.

- **HL-LHC TMCI threshold** close to expected $6 \cdot 10^{11}$ ppb (factor x2 higher than LHC)
Conclusions and outlook

• Beams brightness will more than double in the HL-LHC → challenge for beam stability.

• New materials have been studied for collimation upgrade and impedance reduction.

• Dedicated machine tests confirmed:
  o Reduction of collimators’ impedance with Mo coating.
  o Increase of TMCI threshold by a factor of 2.

• Discrepancies remain between measured Mo resistivity and the expected value.
  o Surface observations on going to identify the cause.
  o Different coating procedures and materials being tested.

• Even accounting for worse Mo resistivity, HL-LHC stabilizing octupole current is close to the operational margin to account effects other than impedance.

See also poster of S.Antipov THPAF035
Thanks for your attention!