Why do we need coated collimators?


HL-LHC WP2 MEETING, 28.08.18
What is the motivation for collimator impedance reduction?
Impedance of LHC collimators has to be reduced for the Hi-Lumi upgrade

Octupole current close to threshold

- Linear coupling
- Magnet imperfections
- Feedback noise
- Optics errors
- Uncertainty of beam distribution

Current study:
- Ultimate OP scenario
- Right before collision
- No beam-beam
- No help from ATS

Present operational experience:
- Need a factor 2 margin at least
- Compared to pure impedance
Impedance of LHC collimators has to be reduced for the Hi-Lumi upgrade

Octupole current close to threshold

Dominant component is the collimator impedance

11 secondaries in IR-7 - 200 A
  • To be upgraded
  • 4 to be replaced during LS 2

4 primaries - 100 A
  • To be upgraded*
  • 2 to be replaced during LS 2

All other collimators - 70 A

Everything else - < 10 A

* 2 approved at the moment
Study of the low impedance collimator in LHC

Currently, both primary and secondary collimators have CFC jaws ($\rho_c = 5 \mu\Omega m$)

Primary collimators:
- MoGr to replace CFC

Secondary collimators:
- MoGr jaw
- Low-resistivity coating
The largest reduction of the resistive wall tune shift measured for Mo coating.

\[ \Delta Q_{RW} \propto A \frac{1}{n^3} \]

[Graph showing model vs measurement data with ±1σ fit errors for CFC, MoC, TiN, and Mo coatings.]
IR-7 Secondary collimators are the right target for impedance reduction

Collimator tune shift goes down

Significant reduction in impedance was measured in the TMCI MD

That’s a huge tune shift!

Measured tune shift of 1 collimator: TCSG.D4, TCSPM
Low impedance collimators
How does the gain scale with coating resistivity?
One collimator, closer to the beam: Coating is very efficient

Vertical collimator, Halfgap: 1.4 mm
One collimator, closer to the beam: Coating is very efficient

Vertical collimator, Halfgap: 1.4 mm
Coating is less efficient when other sources of impedance take part

Horizontal collimator, Halfgap: 3.1 mm
Coating is less efficient when other sources of impedance take part.

Horizontal collimator, Halfgap: 3.1 mm
Broadband components of impedance limit how much the total can be reduced
Stability diagram: Full machine
Further reducing the resistivity gets less effective as one goes to better conductors.

\[
\begin{align*}
\text{Resistivity (nΩ-m)} & \quad \text{Octupole threshold reduction} \\
\text{Cu (TDIS)} & \quad \text{Standard beam} \\
\text{Mo (TCSPM)} & \\
\text{MoGr} & \\
\text{CFC} & \end{align*}
\]
What could be different (go wrong)?

Need tighter collimator settings for machine protection

Mo coating does not perform as expected

Have to settle for uncoated secondary collimators

Something left unaccounted for in the model
  ◦ Refining the model of geometric impedance
  ◦ Noise leading to instabilities with large latency times
  ◦ Beam-beam interaction reducing the Stability Diagram
LHC keeps tightening the collimator gaps during its operation

Originally, there were three collimator scenarios for HL-LHC:

- 1.0 $\sigma$: TCP – 6, TCS – 7 (for 3.5 $\mu$m ref. emittance, “Nominal” design report)
- 1.5 $\sigma$: TCP – 5, TCS – 6.5
- 2.0 $\sigma$: TCP – 5.7, TCS – 7.7

Ultimately became the baseline

Are we sure the settings are not going to change in the future?
Little or no safety margin for tighter settings if the full impedance reduction is not done

Nominal settings

Tight (non-baseline) settings
Not coating the secondary collimators: Octupole current threshold – similar to post-LS2
The actual resistivity of Mo coating might be higher than the model value.

<table>
<thead>
<tr>
<th>Material</th>
<th>Model</th>
<th>Beam</th>
<th>Lab: DC</th>
<th>Lab: RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC</td>
<td>5000</td>
<td>4030 ± 380</td>
<td>5000 – 6000</td>
<td>-</td>
</tr>
<tr>
<td>MoGr</td>
<td>1000</td>
<td>760 ± 60</td>
<td>900 ± 100</td>
<td>-</td>
</tr>
<tr>
<td>TiN</td>
<td>400</td>
<td>340 ± 40</td>
<td></td>
<td>~400</td>
</tr>
<tr>
<td>Mo</td>
<td>53.5</td>
<td>250 ± 50</td>
<td>100 – 300</td>
<td>~300</td>
</tr>
</tbody>
</table>

S. Antipov, et al., IPAC’18
Surface studies

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

• Surface impurities could also increase effective resistivity

N. Biancacci, et al., IPAC’18
Bench RF measurements suggest the importance of the microstructure

- Change in Q-factor $\rightarrow$ Real part of longitudinal impedance
- Agreement within error bars on TiN stripe
- Lower impedance reduction measured on Mo stripe $\rightarrow$ $\sim 300\,\Omega\cdot m$ Mo resistivity (expected $53\,\Omega\cdot m$)

N. Biancacci, et al., IPAC’18
Impact of higher than expected Mo resistivity

Assuming measured Mo resistivity (250 vs 54 nΩ-m): 25 (20) A reduction in margin for BCMS (Standard) beam
Latest Mo-coated samples show good electrical conductivity

Eddy current measurement is required to qualify the coating
- DC not enough – not ‘beam’ frequency, does not account for surface roughness

N. Biancacci, Update on Mo coating resistivity, 18.05.18

Newer coatings show 60-70 nΩ-m

Some (older ones) feature up to 300 nΩ-m
The increase in Mo resistivity is likely to be governed by its microstructure.

J. Guardia, Impedance Meeting, 24.08.18
The increase in Mo resistivity is likely to be governed by its microstructure.

J. Guardia, Impedance Meeting, 24.08.18
Propose to set the limit for production such that a degradation of the octupole current is < 10%
Changes in geometric impedance: New taper geometries

<table>
<thead>
<tr>
<th></th>
<th>TCS</th>
<th>TCSP</th>
<th>TCSPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle</td>
<td>11,6°</td>
<td>16°, 16,5°</td>
<td>16,5°, 5°</td>
</tr>
<tr>
<td>Length</td>
<td>97 mm</td>
<td>37 mm, 27 mm</td>
<td>36 mm, 80 mm</td>
</tr>
</tbody>
</table>

This is the only geometry in the model at the moment. Simulated as a broadband flat taper impedance.

Optimized for Imp.

E. CarIDEO
Noise triggers an instability with high latency time at Flat-Top
Stability diagram collapses as the beams are brought into collision

Minimum at a certain beam separation

Predicted theoretically and observed in a dedicated MD

X. Buffat et al., CERN-ACC-NOTE-2018-0036, 2018
Conclusions

IR-7 primary and secondary collimators are the right target for impedance reduction
- From the past operational experience, a x2 margin in octupole threshold is required
- Mo coating on MoGr offers the largest reduction of impedance and octupole current in HL-LHC
- For the ultimate scenario one gains up to 150 A (BCMS beam) by coating all the secondaries in IR-7
- Additional 30 A (BCMS) can be gained by replacing the 2 primary collimators with MoGr
- 1/2 the gain with LS2 upgrade (2 primary + 4 secondary) or with uncoated MoGr secondaries

A collimator resistive wall component of the octupole threshold scales as $\rho^{1/2}$
- Coating provides a large gain $(\rho_{Mo}/\rho_{CFC})^{1/2} \approx 10$
- Only for the collimators that are close to the beam; further away – the taper geometry plays a role

In a realistic accelerator the scaling is worse than $\rho^{-1/2}$
- Other sources of impedance: beam screen, tapers, etc. Act on 50% of effective beam impedance
- At small resistivities, a further reduction is less effective
- Can set a limit of 100 nΩ-m for the production Mo coatings
Back-up
Stability diagram: 1 Collimator

![Stability Diagram](image)

- Small gap - RW
- Small gap - full
- Large gap - full

8/28/2018  S. ANTIPOV, 128TH HL-LHC WP2 MEETING
Geometric component of collimator tapers is comparable to resistive wall after the upgrade.
Staged installation of low impedance collimators in LS2: Maximizing reduction in the most critical, horizontal plane

- Impedance reduction
- Injection/extraction failure events or asynchronous dumps
- Steady exposure to beam losses
Fitting the taper impedance: \( Z[\text{Ohm/m}] = A \cdot g[\text{m}]^{-\alpha} \)

<table>
<thead>
<tr>
<th>Name</th>
<th>( A )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCS</td>
<td>2.07\times10^{-3}</td>
<td>1.9</td>
</tr>
<tr>
<td>TCSP</td>
<td>2.57\times10^{-3}</td>
<td>2.0</td>
</tr>
<tr>
<td>TCSPM</td>
<td>1.02\times10^{-3}</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The model can be used to refine the prediction for HL-LHC
- Work ongoing

E. Carideo
## TMCI Threshold for different coating scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TCPs</th>
<th>TCSGs</th>
<th>TMCI threshold (DELPHI) [$10^{11}$ p. p. b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC ft 2017</td>
<td>-</td>
<td>-</td>
<td>2.6</td>
</tr>
<tr>
<td>LHC ft 2017, TCSGs at 14$\sigma_{coll}$</td>
<td>-</td>
<td>-</td>
<td>5.0</td>
</tr>
<tr>
<td>HL-LHC LS2.2 uncoated TCSGs</td>
<td>2 in MoGr</td>
<td>4 in MoGr</td>
<td>5.7</td>
</tr>
<tr>
<td>HL-LHC LS2.2 coated TCSGs</td>
<td>2 in MoGr</td>
<td>4 in MoGr with Mo coating</td>
<td>6.3</td>
</tr>
<tr>
<td>HL-LHC full upgrade uncoated TCSGs</td>
<td>2 in MoGr</td>
<td>All in MoGr</td>
<td>6.7</td>
</tr>
<tr>
<td>HL-LHC full upgrade (baseline)</td>
<td>2 in MoGr</td>
<td>All in MoGr with Mo coating</td>
<td>8.7</td>
</tr>
</tbody>
</table>
Conclusions

- The resistivity of the coating is affected by the combination of grain size and defects (discontinuities). This seems to explain the resistivity results.

<table>
<thead>
<tr>
<th>Substrate roughness</th>
<th>Mo grain size (average)</th>
<th>Amount of coating discontinuities</th>
<th>Coating conductivity (MS/m)</th>
<th>Coating resistivity (nΩ.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>~0</td>
<td>+</td>
<td>no</td>
<td>4.3 [DC] 5.0 [RF]</td>
</tr>
<tr>
<td>Alumina</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>4.6 [DC] 4.1 [RF]</td>
</tr>
<tr>
<td>MoGr</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td>14.3-16.7 [RF]</td>
</tr>
<tr>
<td>CFC</td>
<td>+++++</td>
<td>++ (big voids)</td>
<td>n.d. (substrate)</td>
<td>n.d. (substrate)</td>
</tr>
</tbody>
</table>

- The discontinuities are created in the deep valleys (too rough substrate).
- Too flat substrate is not good either for low resistivity → smaller grains (<300nm) and low adherence.
- More comprehensive studies of grain size can be performed if needed (polishing + SEM or FIB), more in background slides.
- Thermal treatments to increase grain size could be investigated, above Mo recrystallization temperature (900-1300°C [1]). Problems: coating detachment, Mo+C→carbide, gas influence during treatment [2].