Figures of Merit for Collimator Materials

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Outline

- Introduction
- Figures of merit (FOMs) for collimator materials
- Required FOMs under different scenarios
- Radiation-induced material degradation
- Summary
Introduction

- The **choice** of a particular material for a BID, such as a collimator, is driven by the material **performance under different points of view**

- Such aspects may be **general** for all applications or **component-driven**

Some component-driven requirements include ...

Radiation Hardness, Robustness, UHV Compatibility, Industrial feasibility of large components, Possibility to machine, braze, join, coat ..., Cost ...

- All aspects can be **turned into** a set of arbitrary **Figures of Merit** (FOMs), in order to **assess** relevant materials for a given condition. **The higher the FOM, the better the material**

**IMPORTANT!** Figures of Merit rely on simplified, **constant material properties** at an arbitrary reference temperature. They should be used as **indicative**, **comparative tools in the design phase**; quantitative assessments done during this talk contain non-negligible approximations
Figures of Merit for collimators

**Thermomechanical Robustness Index (TRI)**

\[ TRI = \frac{\varepsilon_{Adm}}{\varepsilon_{Real}} \cdot \left( \frac{T_m}{\Delta T_q} - 1 \right)^m \]

- **TRI** is related to the ability of a material to withstand the impact of a rapid particle pulse.
- In thermal shock problems, **admissible strain** is the most meaningful quantity as the phenomenon is governed by thermal deformation.
- On the other hand, effective **strength** values \( R_M \) are much easier to obtain in literature.
- The term in \( T_m \) (**melting temperature**) provides an indication of the loss of strength at increasing temperature.
- \( \Delta T_q \) is a temperature increment related to the energy deposited \( q_d \) in the material by a given particle pulse.
- Deposited energy is (somehow) related to the **Geometric Radiation length** \( X_g \) and material **density** \( \rho \).
- \( C_R, n, m \) are **arbitrary** coefficients defining the influence of various parameters.

\[ \varepsilon_{Adm} = \frac{R_M}{E \cdot (1 - \nu)} \]

\[ \varepsilon_{Real} = \overline{\alpha} \cdot \Delta T_q \]

\[ \Delta T_q = \frac{C_R \rho^n}{c_p X_g} \propto \frac{q_d}{c_p} \]

\[ TRI = \frac{R_M c_p X_g}{E(1 - \nu)\overline{\alpha}C_R \rho^n} \cdot \left( \frac{T_m c_p X_g}{C_R \rho^n} - 1 \right)^m \]
Thermal Stability Index (TSI)

- Under steady-state or slowly transient heat deposition, TSI provides an index of the ability of the material to maintain geometrical stability of the component.

- It is related to the inverse of the curvature of a long structure induced by a non uniform temperature distribution (for given steady-state particle losses).

- TSI is proportional to thermal conductivity $\lambda$ and radiation length $X_g$: inversely proportional to CTE $\alpha$ and density $\rho$...

- For anisotropic materials (e.g. Carbon-Carbon, MoGr) weighted average properties are assumed.

$$TSI = \frac{\lambda X_g}{\bar{\alpha} C_S \rho^n}$$
RF Impedance Index (RFI)

- Components located in accelerator rings (collimators, absorbers, spoilers ...) are required to minimize their contributions to **RF impedance** to limit adverse electromagnetic effects on beam stability.

- In “classical” regime, **RF-impedance** drastically increases when beam approaches the “resistive wall” ($\propto 1/b^3$) ⇒ contributions to impedance are much larger from components sitting close to the circulating beam as BIDs.

- RF-impedance is inversely proportional to electrical conductivity ⇒ highest electrical conductivity is sought for materials sitting closest to circulating beams!

**RFI = $\gamma$**

![Graph showing collimators impedance/LHC impedance compared to different materials at various frequencies.](image)
Figures of Merit for collimators

Thermomechanical Robustness Index (TRI)

\[
TRI = \frac{R_M c_p X_g}{E(1-\nu)\alpha C_R \rho^n} \cdot \left(\frac{T_m c_p X_g}{C_R \rho^n} - 1\right)^m
\]

Thermal Stability Index (TSI)

\[
TSI = \frac{\lambda X_g}{\alpha C_s \rho^n}
\]

RF Impedance Index (RFI)

\[
RFI = \gamma
\]

- Several material properties contributing to the evaluation of the FOMs: which one to prioritize?
- Some of the properties appear in more than one FOM (\(\alpha, \rho\))
- RFI is entirely defined by one parameter (\(\gamma\))
### Required FOMs under different scenarios

**Which values would we like for LHC collimator materials? First estimation:**

<table>
<thead>
<tr>
<th></th>
<th>Design case</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TRI [-]</strong></td>
<td>Secondary Collimator</td>
<td>~500?</td>
</tr>
<tr>
<td></td>
<td>Tertiary Collimator</td>
<td><strong>tbd</strong></td>
</tr>
<tr>
<td><strong>TSI [-]</strong></td>
<td>Secondary Collimator</td>
<td>~20?</td>
</tr>
<tr>
<td></td>
<td>Tertiary Collimator</td>
<td>~0.05?</td>
</tr>
<tr>
<td><strong>RFI [MSm⁻¹]</strong></td>
<td>tbd</td>
<td>tbd</td>
</tr>
</tbody>
</table>

- **Where do these numbers come from?**
  - TRI (secondary collimator): estimated to have material failure in case of beam injection error (secondary collimators) or asynchronous beam dump (tertiary collimators).
  - TSI (tertiary collimator): required to respect the specification on jaw deformation (100 mm) under slow losses. *The value proposed for HL-LHC is linearly scaled with the intensity, no slow-losses simulations available!*
  - RFI (RF team): to be proposed by the RF team.
  - Estimations come from analyses of the simulations available and experimental tests performed (e.g. TT40 2004-2006, HRMT09, HRMT14).

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FOMs related to the robustness/geometrical stability of the **single collimator** embarking a given material.

FOM that can be defined **ONLY** as a **global index for the whole LHC or HL-LHC**. The single collimator impedance will be then established looking at which collimator is gives the biggest contribution to impedance, receives the highest radiation dose or has the most sensitive material. Study to be performed.
Desired FOMs under different scenarios

Including the FOMs calculated for collimator materials:

<table>
<thead>
<tr>
<th></th>
<th>Design case</th>
<th>HL-LHC</th>
<th>CFC</th>
<th>MoGr</th>
<th>CuCD</th>
<th>Glidcop</th>
<th>Tungsten Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRI [-] Secondary</td>
<td>~500? tbd</td>
<td>~1000? tbd</td>
<td>1237</td>
<td>634</td>
<td>6.8</td>
<td>5.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Tertiary</td>
<td>tbd</td>
<td>tbd</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSI [-] Secondary</td>
<td>~20? ~0.05?</td>
<td>~40?* ~0.1?*</td>
<td>44.6</td>
<td>69.4</td>
<td>9.9</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Tertiary</td>
<td>tbd</td>
<td>tbd</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RFI [MSm⁻¹]</td>
<td>tbd</td>
<td>tbd</td>
<td>0.14</td>
<td>~1÷18</td>
<td>~12.6</td>
<td>53.8</td>
<td>8.6</td>
</tr>
</tbody>
</table>

- No one-fits-it-all material!
- Carbon-based materials feature the best TRI and TSI thanks to low-Z, low CTE, low density, high degradation temperature, high conductivity ....
- However low electrical conductivity penalizes C-C if RF-impedance is an issue. In such a case, MoGr seems a good compromise, particularly if coated with higher conductivity thin films.
Questions (& some answers)

1) Can we include in our FOMs an expression of the material resistance to radiation damage?

- Discussed during the 2nd Eucard2 ColMat-HDED Annual Meeting
- Proposal:

\[
F_{OM_{NM}} = F_{OM_{AB}} \cdot \left( \frac{DPA_{max}}{1 + \frac{\sigma_{H,He}(E)}{\sigma_0(E)}} \right)_{NM} \cdot K_{MT}
\]

Legend:
- \(F_{OM_{AB}}\) is any FOM previously mentioned
- \(DPA_{max}\) is the DPA threshold which usually indicates the integrated radiation load level (as measured in DPA) at which the certain property starts to show a significant change. Usually it uses a 30 to 50% change in the property of interest to define that threshold.
- \(\sigma_{H,He}\) is the gas production cross section
- \(\sigma_0\) is a normalization factor
- \(K_{MT}\) is a factor accounting that it is not always possible to reach \(DPA_{max}\), especially for ion irradiation

From the meeting minutes
Questions (& some answers)

2) Can we define the maximum acceptable degradation of the material properties, due to radiation?

- Since collimator performances are driven by a combination of material properties, it makes more sense to speak about acceptable degradation of the FOMs.
- The only exception is RFI, controlled only by the electrical conductivity; in this case, the maximum acceptable degradation of $\gamma$ can be directly estimated (once the reference value is known).

\[
TRI = \frac{R_M c_p X_g}{E(1-\nu)\bar{\alpha}C_R \rho^n} \cdot \left(\frac{T_m c_p X_g}{C_R \rho^n} - 1\right)^m
\]

\[
TSI = \frac{\bar{\lambda}X_g}{\bar{\alpha}C_S \rho^n}
\]

\[RFI = \gamma\]
What’s next? Proposals

- The calculated FOMs of collimator materials are usually based on measurements at **room temperature, in static conditions**: an extensive characterization is needed at higher temperatures and \( \dot{\varepsilon} \) to better define these indexes

- **TRI index** contains arbitrary constants that have been adjusted in order to match the material behaviour observed in a limited number **beam-impact tests and simulations**; this statistic must be increased through:
  - New HiRadMat tests (e.g. HRMT23, MultiMat)
  - Fluka+FEM beam impact simulations with different materials of a simple geometry (e.g. a cylinder, 2D), looking for the threshold of damage for each material

- Required TRI for **tertiary collimators has to be calculated against asynchronous beam dump**: simulations are currently ongoing

- **TSI index**: the acceptable values at HL-LHC have been extrapolated from the nominal LHC scenario. Simulations of slow-losses are needed to better estimate this parameter

- **RFI index**: to be defined with RF team

- **Rad-hardness FOM**: if we agree on the definition, a campaign of irradiation tests and simulations with different codes should be launched to calculate it for different materials
Summary

- **Figures of Merit (FOMs)** can be adopted during the choice of materials for collimators to provide a quick and useful tool for comparative rankings.

- With a considerable degree of approximation, FOMs can also express what is the influence of a **single material property on the collimator performance and its acceptable degradation due to radiation**.

- The acceptable values of FOMs have been proposed for two scenarios, nominal LHC and HL-LHC. Values have been extrapolated and are affected by large uncertainties.

- For RFI, the acceptable value should be defined keeping into account the **whole LHC impedance**; for TSI and TRI, the acceptable values are related to the **behavior of the single collimator**.

- The proposal of an index representing the **material behavior under irradiation** has been done during the 2\(^{nd}\) Eucard2 ColMat-HDED Annual Meeting; the values of this index for collimator materials has to be measured through experimental and simulation campaigns.
Thank you for your attention!