Materials for Phase II Collimators

6th Collimation Upgrade Specification Meeting
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• Phase II Activities in EN-MME
• Phase II Collimator design principles
• R&D for Phase II Advanced Materials
• HiRadMat Materials Test
PHASE II ACTIVITIES IN MME

Prototype Design & Manufacturing

Novel Materials R&D

Task 8.2

Advanced Numerical Simulations

Material Testing
PHASE II COLLIMATOR DESIGN PRINCIPLES

- Ferrites
- BPM housing
- Fine Positioning system
- Jaw Active Material

CERN
Engineering Department
Assembled Jaw of Phase II 1st Prototype; active jaw in Glidcop

RF Ferrite Casing

RF Screen
Assembled Jaw of Phase II 1\textsuperscript{st} Prototype; active jaw in Glidcop

RF Ferrite Casing

RF Screen
Material Requirements for LHC Phase II Collimators

• Reduce RF impedance
  Maximize Electrical Conductivity

• Maintain/improve jaw geometrical stability in nominal conditions
  Maximize the stability indicator Steady-state Stability Normalized Index (SSNI)

• Maintain Phase I robustness in accidental scenarios
  Maximize the robustness indicator Transient Thermal Shock Normalized Index (TSNI)

• Improve cleaning efficiency (absorption rate)
  Increase Radiation and nuclear Interaction Lengths, i.e., Increase $Z$

• Improve maximum operational temperature
  Increase Melting Temperature, $T_m$

Additional “standard” requirements include ...
• Radiation Hardness, UHV Compatibility, Industrial producibility of large components,
  Possibility to machine, braze, join, coat ..., Toughness, Cost ...
Metal Matrix Composites

- Relevant **Metal Matrix Composites (MMC)** are advanced thermal management materials combining properties of Diamond or Graphite (high $k$, low $\rho$ and low $CTE$) with those of Metals ($\text{strength, } \gamma$, etc.).

- Sintering techniques include **Rapid Hot Pressing (RHP)**, **Spark Plasma Sintering (SPS)**, and **Liquid Infiltration**.

- Candidate materials include **Copper-diamond (Cu-CD)**, **Molybdenum-diamond (Mo-CD)**, **Silver-diamond (Ag-CD)**, **Molybdenum Graphite (Mo-Gr)**
### PHASE II MATERIALS RANKING

<table>
<thead>
<tr>
<th>Material</th>
<th>C-C</th>
<th>Mo</th>
<th>Glidcop®</th>
<th>Cu-CD</th>
<th>Mo-CD</th>
<th>Ag-CD</th>
<th>Mo-Gr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg/m³]</td>
<td>1650</td>
<td>10220</td>
<td>8900</td>
<td>~5400</td>
<td>~6900</td>
<td>~6100</td>
<td>~5600</td>
</tr>
<tr>
<td>Atomic Number (Z)</td>
<td>6</td>
<td>42</td>
<td>29</td>
<td>~11.4</td>
<td>~17.3</td>
<td>~13.9</td>
<td>~13.1</td>
</tr>
<tr>
<td>Tₘ [°C]</td>
<td>3650</td>
<td>2623</td>
<td>1083</td>
<td>~1083</td>
<td>~2623</td>
<td>~840</td>
<td>~2520</td>
</tr>
<tr>
<td>SSNI [kWm²/kg]</td>
<td>24</td>
<td>2.6</td>
<td>2.5</td>
<td>13.1 ± 15.3</td>
<td>6.9 ± 10.9</td>
<td>11.4 ± 15.4</td>
<td>7.4 *</td>
</tr>
<tr>
<td>TSNI [kJ/kg]</td>
<td>793</td>
<td>55</td>
<td>35</td>
<td>44 ± 51</td>
<td>72 ± 96</td>
<td>60 ± 92</td>
<td>115 *</td>
</tr>
<tr>
<td>Electrical Conductivity [MS/m]</td>
<td>0.14</td>
<td>19.2</td>
<td>53.8</td>
<td>~12.6</td>
<td>~9.9</td>
<td>~11.8</td>
<td>1 ± 18 **</td>
</tr>
</tbody>
</table>

- **C-C** stands out as to thermo-mechanical performances. Adversely outweighed by poor electrical conductivity, low Z, expected degradation under irradiation.

- **High-Z metals (Cu, Mo)** possess very good electrical properties. High density adversely affects their thermal stability and accident robustness.

- **Metal-diamond composites** exhibit a balanced compromise between TSNI, SSNI, electrical conductivity, density, atomic number.

- **Molybdenum-graphite**, currently under development and characterization, shows very promising figures of merit.

*Estimated values
  **γ=18 MS/m with Mo surface coating
No diamond degradation (in reducing atmosphere graphitisation starts at ~ **1300 °C**)

Good thermal (~**490 W/mK**) and electrical conductivity (~**12.6 MS/m**).

No direct interface between Cu and CD (lack of affinity). Limited bonding surface assured by Boron Carbides hampers mechanical strength (~**120 MPa**).

BC brittleness adversely affects material toughness.

Cu low melting point (**1083 °C**) limits Cu-CD applications for highly energetic accidents.

CTE increases significantly with T due to high Cu content (from ~**6 ppmK⁻¹** at RT up to ~**12 ppmK⁻¹** at **900 °C**)

Cu-CD fracture surface. Note absence of CD graphitization

BC “bridge” stuck on CD surface
- **Irradiation studies** on Cu-CD at Kurchatov Inst.
- 30 MeV protons, $\Phi = 1\times10^{17}$ p/cm$^2$.
- Properties measured before and after irradiation.
- Results obtained for $k$, $\gamma$, CTE, $E$.
- Yield stress and elongation still to come.

<table>
<thead>
<tr>
<th>Property at $T_a$</th>
<th>Before Irradiation</th>
<th>After Irradiation</th>
<th>Variation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTE [ppm/m/K]</td>
<td>7.8</td>
<td>8.3</td>
<td>-6%</td>
</tr>
<tr>
<td>$k$ [W/m/K]</td>
<td>580</td>
<td>330</td>
<td>-43%</td>
</tr>
<tr>
<td>$\gamma$ [MS/m]</td>
<td>$10 \pm 0.2$</td>
<td>$9.8 \pm 0.2$</td>
<td>-</td>
</tr>
<tr>
<td>$E$ [GPa]</td>
<td>$240 \pm 50$</td>
<td>$330 \pm 30$</td>
<td>+40%</td>
</tr>
</tbody>
</table>

**Irradiated Cu-CD sample**

**Thermal Diffusivity**

Before irradiation

After irradiation
**Liquid Phase Sintering (LPS)**
- Addition of low-melting phase (Cu or Cu-Ag) to fill in the pores between Mo and CD
- Good mechanical strength (400+ MPa) and Thermal Conductivity (185 W/mK)
- Max \( T_{\text{Service}} \) limited by low-melting phase (Cu)

**Assisted Solid-state Sintering (ASS)**
- Addition of small amounts of activating elements (Ni, Pd) enhances Mo sintering at low \( T \) (~1300 °C)
- Absence of low-melting phase increases service \( T \) up to ~2600 °C
- Large diamond particles interfere with Mo compacted.

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**Irradiation tests to start at Kurchatov**

- CD slightly graphitized
- Synthetic Diamond (Fracture Surface)
- Developed by **EPFL**, Switzerland.
- Characterized at EPFL and CERN (**EuCARD**).
- Manufactured by Liquid Infiltration of cylindrical samples (Ø100 mm, H 100 mm)
- ~60% Diamond, ~40% Ag-Si alloy

- Excellent bonding between Ag and CD assured by Silicon Carbides formation on diamond.
- High Flexural Strength (~500 MPa) and toughness.
- High Electrical Conductivity.
- Max $T_{\text{Service}}$ limited by low-melting eutectic phase Ag-Si (840 °C).
- Hard to manufacture large components (>100 mm)
- Material non homogeneities due to liquid metal infiltration intrinsic limitations.
Why Graphite?

- Low CTE
- Low Density
- High Thermal Conductivity
- High Melting (degradation) point
- High Shock wave dumping

Compared to Mo-CD:

- No low melting phase (Cu in LPS Mo-CD)
- Lower Density
- Similar Thermal Conductivity
- No reinforcement degradation
- Lower Costs
- Mechanical strength not yet satisfactory

- Mo-GR under intense development program.
- Material properties can still be improved by optimizing base materials, composition and processes.
- Solution to increase electrical conductivity of the composite up to 18 MS/m: sandwich structure;
- Molybdenum – Graphite core with two surface layers of high electric conductive pure Mo;
- Sandwich with 1 mm thick Mo layers;
- Coating thickness can be decreased to < 0.1 mm: optimal thickness to be defined with RF team!

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Electrical Conductivity (MS/m)</th>
<th>Thermal Conductivity (W/mK)</th>
<th>Flexural Strength (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.68</td>
<td>18</td>
<td>-</td>
<td>260</td>
</tr>
</tbody>
</table>
Explicit calculations performed on Inermet180, Copper OFE and Molybdenum samples

Calculation on Inermet180 shown below: representative case (σ = 2.5 mm, bunch intensity = 1.5E11 particles)
SPH calculations on different beam scenarios to determine spray behaviour, thus:

- window covering (due to vaporized material)
- material density change
- load on Be window
- Acquisition feasibility
In the HiRadMat facility, novel materials under development for Phase II can be tested under the extreme conditions they may encounter in case of accidental beam impacts.

Objectives:

- Gather, mostly in real time, experimental data on these materials properties (EOS, Strength models, Failure Models).
- Benchmark advanced numerical simulations.
- To the best of our knowledge, such an extensive test has never been done before.
- Characterize **six different materials** (Inermet180, Glidcop, Molybdenum, Copper-Diamond, Molybdenum-Diamond, Molybdenum-Graphite)

- **Medium intensity** and **high intensity** tests, with different material samples for each material (Type 1, Type 2)

- Each sample holder tier can host up to **10 specimens**

- Extensive **real time data acquisition**

- **Post mortem** analysis
- Beam energy: 440 GeV
- Bunch spacing: 25 ns
- Protons/bunch: 1.5E11
- Beam size: 2.5x2.5 mm$^2$ (medium intensity) or 0.25x0.25 mm$^2$ (high intensity)
- Up to 72 bunches (~4 LHC bunches), limited by Be window.
- Total expected number or protons ~ 1.3E14

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### Irradiation History for Inermet180 (Tungsten)

<table>
<thead>
<tr>
<th>Target</th>
<th>Protons per bunch</th>
<th>Bunches per pulse</th>
<th>Beam size ($\sigma_x \times \sigma_y$) [mm x mm]</th>
<th>Number of pulses</th>
<th>Time before next pulse [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1 sample Tungsten</td>
<td>5e10</td>
<td>1</td>
<td>2.5 x 2.5</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.5e11</td>
<td>1</td>
<td>&quot;</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.5e11</td>
<td>2</td>
<td>&quot;</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.5e11</td>
<td>4</td>
<td>&quot;</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.5e11</td>
<td>6</td>
<td>&quot;</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>&quot;</td>
<td>1.5e11</td>
<td>20</td>
<td>&quot;</td>
<td>1</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Target</th>
<th>Protons per bunch</th>
<th>Bunches per pulse</th>
<th>Beam size ($\sigma_x \times \sigma_y$) [mm x mm]</th>
<th>Number of pulses</th>
<th>Time before next pulse [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 2 sample Tungsten</td>
<td>5e10</td>
<td>1</td>
<td>0.25 x 0.25</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Type 2 sample Tungsten</td>
<td>1.5e11</td>
<td>60</td>
<td>0.25 x 0.25</td>
<td>1</td>
<td>30</td>
</tr>
</tbody>
</table>
- **LDV** (remote): measures radial velocity of outer cylindrical surface (type 1 samples). Sampling rate > 2.5 MHz

- **High Speed Camera** (remote): acquires live images of impacted type 2 samples. Capture rate up to 30kfps. Critical issue is sufficiently powerful lighting.

- **Strain gauges** (in situ): measures circumferential and axial strains generated on outer surface (type 1 and 2). Acquisition rate > 2.5 MHz.

- **Temperature** and **vacuum** sensors, **microphones** (in situ).
- Design very advanced, details finalization.
- Manufacturing has started.
- All main data acquisition choices made.
- New LDV purchased.
- Material samples ordered and partly delivered.

20.04.2012
Alessandro Bertarelli – EN-MME
<table>
<thead>
<tr>
<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Last proton in LHC</td>
<td>0 days</td>
<td>Wed 31/10/12</td>
<td>Wed 31/10/12</td>
</tr>
<tr>
<td>Installation &amp; run of equipment</td>
<td>2 days</td>
<td>Fri 24/08/12</td>
<td>Mon 27/08/12</td>
</tr>
<tr>
<td>Equipment ready to run</td>
<td>0 days</td>
<td>Fri 24/08/12</td>
<td>Fri 24/08/12</td>
</tr>
<tr>
<td>Validation &amp; test of equipment</td>
<td>40 days</td>
<td>Mon 02/07/12</td>
<td>Fri 24/08/12</td>
</tr>
<tr>
<td>Dimensional control and Equipment alignment</td>
<td>35 days</td>
<td>Mon 14/04/12</td>
<td>Fri 29/06/12</td>
</tr>
<tr>
<td>Manufacturing of mechanical sub-elements</td>
<td>75 days</td>
<td>Mon 30/01/12</td>
<td>Fri 11/05/12</td>
</tr>
<tr>
<td>Mechanical assembling</td>
<td>45 days</td>
<td>Tue 01/05/12</td>
<td>Mon 02/07/12</td>
</tr>
<tr>
<td>External sub-components received</td>
<td>0 days</td>
<td>Mon 30/04/12</td>
<td>Mon 30/04/12</td>
</tr>
<tr>
<td>Manufacturing of last sub elements</td>
<td>30 days</td>
<td>Mon 18/04/12</td>
<td>Fri 26/08/12</td>
</tr>
<tr>
<td>Last sub-elements design (mirrors, Be windows, vacuum pumping port)</td>
<td>30 days</td>
<td>Mon 05/04/12</td>
<td>Fri 13/04/12</td>
</tr>
<tr>
<td>Equipment drawings delivery</td>
<td>57 days</td>
<td>Thu 01/12/11</td>
<td>Fri 17/02/12</td>
</tr>
<tr>
<td>End of the 3D design</td>
<td>0 days</td>
<td>Mon 12/12/11</td>
<td>Mon 12/12/11</td>
</tr>
<tr>
<td>Start of the design</td>
<td>66 days</td>
<td>Mon 12/09/11</td>
<td>Mon 12/12/11</td>
</tr>
<tr>
<td>Study of instrumentation adapted</td>
<td>78 days</td>
<td>Mon 05/04/11</td>
<td>Wed 21/12/11</td>
</tr>
<tr>
<td>Instrumentation elements chosen</td>
<td>1 day</td>
<td>Wed 21/12/11</td>
<td>Wed 21/12/11</td>
</tr>
<tr>
<td>Test of equipping sample with gauges</td>
<td>1.5 mats</td>
<td>Thu 05/02/12</td>
<td>Wed 15/02/12</td>
</tr>
<tr>
<td>Equipping all samples with gauges</td>
<td>2 mats</td>
<td>Tue 06/03/12</td>
<td>Mon 05/04/12</td>
</tr>
</tbody>
</table>
EN-MME Phase II Collimator modular design permits the maximum flexibility on the choice of the active jaw material.

- A first prototype, with Glidcop jaws, is being built by MME.
- Several novel materials are under study and development for the Phase II jaw.
- MMC combining metal properties with those of graphite or diamond are particularly appealing.
- Figures of Merit were defined, allowing to pinpoint “best” candidates and to set ambitious goals.
- Cu-CD, Mo-CD and Ag-CD were studied and successfully produced. Size challenge has been met for Cu-CD and Mo-CD.
- Promising results have been achieved in the last months on Mo-Gr development; substantial room for improvement seem to exist.
- Radiation hardness assessment is almost completed for Cu-CD, still to come for the other selected materials.
- Beam tests under extreme conditions foreseen at CERN’s HiRadMat facility.
- Design of HiRadMat test bench finalized. Procurement and production ongoing.