Novel Materials for Collimators at LHC and its Upgrades

Alessandro Bertarelli, CERN (EN/MME)
on behalf of F. Carra, A. Dallocchio, M. Garlaschè, L. Gentini, P. Gradassi, M. Guinchard, E. Quaranta, S. Redaelli, A. Rossi, O. Sacristan and many more ...

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East Lansing, MI, USA – November 13, 2014
Introduction and Motivations

High Energy Particle Accelerator Challenges

LHC Collimation System

LHC Collimators Requirements

Novel Materials for Collimators

HL-LHC Collimator Design and Testing

Summary
• Beams circulating in last-generation accelerators have reached **unprecedented energy** and **energy density**. This trend is set to continue for future upgrades (e.g. HL-LHC).

• **Beam-induced accidents**, **beam losses** and **beam stability** represent one of the **most relevant issues** for high power particle accelerators!

• **Collimators** are one of the **most critical systems** when these issues are of concern.
• **Several types of collimators** for multi-stage cleaning (primary, secondary, tertiary units) at multiple LHC locations (*100+ Collimators*).

• Active part of **jaws** made of various **materials** (*C/C, Graphite, Copper, Tungsten Heavy Alloy...*)
LHC Collimator Requirements

- Collimators are required to **survive** the **beam-induced accidents** to which they are inherently exposed given their vicinity to the beam.
- They must possess extremely **accurate jaw flatness** to maintain their beam cleaning efficiency.
- The collimation system is, by far, the highest contributor to **accelerator impedance**, which may significantly limit machine performances: they must have **lowest possible electrical resistivity**.
- Their lifetime and efficiency should be conserved under long-term particle irradiation.
- **No existing material** can simultaneously meet all requirements for LHC Future Upgrades!

**Development of Novel advanced materials, along with state-of-the-art simulations, are instrumental in facing these challenges!**
Introduction and Motivations

Novel Materials for Collimators
  - Materials R&D Program
  - Copper – Diamond (CuCD)
  - Molybdenum Carbide – Graphite (MoGr)
  - Figures of Merit and Material Ranking

HL-LHC Collimators Design and Testing

Conclusions
Material Requirements

Key properties must be optimized to meet requirements for Collimators in High Energy Particle Accelerators ...

- **Electrical Conductivity** ($\gamma$) Maximize to limit Resistive-wall Impedance
- **Thermal Conductivity** ($\lambda$) Maximize to maintain geometrical stability under steady-state losses
- **Coefficient of Thermal Expansion** ($\alpha$) Minimize to increase resistance to thermal shock induced by accidental beam impact.
- **Melting/Degradation Temperature** ($T_M$) Maximize to withstand high temperatures reached in case of accidents.
- **Specific Heat** ($c_p$) Maximize to improve thermal shock resistance (lowers temperature increase)
- **Ultimate Strength** ($R_M$) Maximize for improved thermal shock resistance (particularly strain to rupture)
- **Density** ($\rho$) Balance to limit peak energy deposition while maintaining adequate cleaning efficiency
- **Radiation-induced Damage.** Minimize to improve component lifetime under long term particle irradiation.

Most requirements shared with a broad range of applications requiring highly efficient Thermal Management!

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Extensive materials R&D program in collaboration with EU institutes and industries (EuCARD, EuCARD2, HiLumi)

Aim: explore composites combining the properties of graphite or diamond (low $\rho$, high $\lambda$, low $\alpha$) with those of metals and transition metal-based ceramics (high $R_M$, good $\gamma$)

Materials investigated are Copper-Diamond (CuCD), Silver-Diamond (AgCD), Molybdenum-Copper-Diamond (MoCuCD), Molybdenum Carbide-Graphite (MoGr)

Production techniques include Rapid Hot Pressing, Liquid Phase Sintering and Liquid Infiltration

Most promising are CuCD and (mostly) MoGr
- Developed by **RHP-Technology** (Austria)

**Composition:**
- 60\%\textsubscript{v} diamonds (90\% 100 µm, 10\% 45 µm)
- 39\%\textsubscript{v} Cu powder (45 µm)
- 1\%\textsubscript{v} B powder (5 µm)

- No diamond degradation
- Thermal (~490 Wm\textsuperscript{-1}K\textsuperscript{-1}) and electrical conductivity (~12.6 MSm\textsuperscript{-1})
- No direct interface between Cu and CD (lack of affinity). Partial bonding bridging assured by Boron Carbides limits mechanical strength (~120 MPa).
- Cu low melting point (1083 °C)
- CTE increases significantly with T due to high Cu content (from ~6 ppmK\textsuperscript{-1} at RT up to ~12 ppmK\textsuperscript{-1} at 900 °C)

BC “bridge” stuck on CD surface. No CD graphitization
Molybdenum Carbide - Graphite

- Co-developed by CERN and Brevetti Bizz (Italy)
- Broad range of processes and compositions investigated (Molybdenum, Natural Graphite, Mesophase Pitch-based Carbon Fibers).

Materials for Beam Interacting Devices

Why Natural Graphite?
- Low CTE (along basal plane)
- High Thermal Conductivity (along basal plane)
- Low Density
- Very High Service Temperatures
- High Shockwave Damping
- Low cost

Why Mesophase Pitch-based Carbon Fibers?
- Increase mechanical strength
- Contribute to Thermal Conductivity (highly ordered structure)

Why Molybdenum?
- Refractory metal
- Density lower than Tungsten

During sintering all Molybdenum reacts with Carbon Fibres creating Ceramic Matrix Composite with Molybdenum Carbides (MoC.)
Molybdenum Carbide – Graphite

- Homogeneous distribution of graphite, fibers and fine MoC_{1-x} grains
- Excellent crystalline structure of graphite and Carbon Fibres with highly Oriented Graphene planes
- Strong fiber-matrix bonding

High degree of graphitization obtained by the catalyzing effect of molten carbides! (They favor atom transport through liquid phase and graphite crystallite ordering!)
MoGr can be Mo-coated to increase surface conductivity

Core: 1.1 MS/m
Carbide layer: 1.5 MS/m
Mo Coating: 18 MS/m
Several Figures of Merit were defined to compare and rank materials against most relevant requirements.

- **Thermomechanical Robustness Index (TRI)** is related to the ability of a material to withstand the impact of a short particle pulse.
  - In thermal shock problems, admissible strain is the most meaningful quantity.
  - The term in $T_m$ (melting temperature) provides an indication of the loss of strength at increasing temperature.

- **Thermal Stability Index** provides an indication of the ability of the material to maintain the geometrical stability of the component (e.g. Collimator jaw).
  - $TSI$ 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).

- **Electrical conductivity**. Resistive impedance is inversely proportional to electrical conductivity $\Rightarrow$ highest electrical conductivity is sought for materials sitting closest to circulating beams!
• The higher the FOM, the better the material ... No one-fits-it-all material!

• **Carbon-based materials** feature excellent TRI and TSI thanks to low-Z, low CTE, low density, high degradation temperature, high conductivity ….

• **Beryllium** is outstanding under practically all points of view … unfortunately its use is severely limited by its **toxicity**.

• **Low electrical conductivity** penalizes **C-C** and **graphite** if RF-impedance is an issue. In such a case, **MoGr** is the most promising compromise, particularly if coated with higher conductivity thin films.

• **Note poor performance of Tungsten Alloy**, also due to the low melting temperature of the Ni-Cu matrix required to reduce material brittleness … **it is not pure W**!

<table>
<thead>
<tr>
<th>Material</th>
<th>Beryllium</th>
<th>Carbon-Carbon</th>
<th>Graphite</th>
<th>Molybdenum Graphite</th>
<th>Copper-Diamond</th>
<th>Glidcop ®</th>
<th>Molybdenum</th>
<th>Tungsten Alloy (IT180)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ [g/cm³]</td>
<td>1.84</td>
<td>1.65</td>
<td>1.9</td>
<td>2.50</td>
<td>5.4</td>
<td>8.90</td>
<td>10.22</td>
<td>18</td>
</tr>
<tr>
<td>Z</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>~6.5</td>
<td>~11.4</td>
<td>~29</td>
<td>42</td>
<td>~70.8</td>
</tr>
<tr>
<td>$T_m$ [°C]</td>
<td>1273</td>
<td>3650</td>
<td>3650</td>
<td>2589</td>
<td>~1083</td>
<td>1083</td>
<td>2623</td>
<td>~1400</td>
</tr>
<tr>
<td>TRI [-]</td>
<td>790</td>
<td>1237</td>
<td>1101</td>
<td>634</td>
<td>6.8</td>
<td>5.3</td>
<td>6.4</td>
<td>0.5</td>
</tr>
<tr>
<td>TSI [-]</td>
<td>17.1</td>
<td>44.6</td>
<td>10.1</td>
<td>69.4</td>
<td>9.9</td>
<td>0.8</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>$\gamma$ [MSm⁻¹]</td>
<td>23.3</td>
<td>~0.14</td>
<td>~0.07</td>
<td>~1+18</td>
<td>~12.6</td>
<td>53.8</td>
<td>19.2</td>
<td>8.6</td>
</tr>
</tbody>
</table>
A new modular design for HL-LHC Secondary Collimators is at an advanced stage of design.

The concept allows to install 10 jaw inserts made of either CuCD or MoGr.

The BPM pickup end seat is lengthened to reduce RF perturbations.

A full-scale prototype should be installed in the LHC for MD as of end of 2015 / early 2016.
Why Experimental Tests?

Why Beam Impact Tests at CERN HiRadMat Facility?

• With accidental beam impacts, one enters a relatively **unknown territory**, that of **high power explosions and ballistics**

• The **state-of-the-art wave propagation codes (Hydrocodes)** required to deal with **large density changes, phase transitions, fragmentations** can be very reliable, provided the **complex material models** required are available and precise

• Existing material constitutive models at **extreme conditions** are limited and mostly drawn from military research (**classified**). They are often **unavailable** for specific alloys and composites

• **Additional consequences** on UHV, electronics, bellows, etc. **cannot be easily anticipated** by numerical simulations

• Only **ad-hoc material tests** can provide the correct inputs for numerical analyses and validate/benchmark simulation results on **simple specimens** as well as on **complex structures**.

• A **dedicated facility** has been designed and commissioned at CERN to test materials and systems under high intensity pulsed particle beams: **HiRadMat** (High Radiation to Materials)

• Every new component to be installed in the **LHC** exposed to beam accidental impacts must be first qualified in HiRadMat
HRMT14 (2012) Experiment Goals

- **Benchmark** advanced numerical simulations and material constitutive models through extensive acquisition system
- Characterize six existing and novel materials currently under development for future Collimators: **Inermet180, Molybdenum, Glidcop, MoCuCD, CuCD, MoGr**
- Collect, mostly in real time, experimental data from different acquisition systems (Strain Gauges, Laser Doppler Vibrometer, High Speed video Camera, Temperature and Vacuum probes)

### Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>440 GeV</td>
</tr>
<tr>
<td>Number of protons per bunch</td>
<td>1.1e11</td>
</tr>
<tr>
<td>Bunch Spacing</td>
<td>25 ns</td>
</tr>
</tbody>
</table>

**Medium Intensity Tests:**
- Sample: Ø 40 mm, L30 mm

**High Intensity Tests:**
- Sample: half-moon; Beam Offset 2 mm
Inermet180 (Tungsten Alloy) samples as seen from viewport and camera
### High Intensity Tests: Comparison between numerical simulation (SPH) and experiment

<table>
<thead>
<tr>
<th>Case</th>
<th>Bunches</th>
<th>p/bunch</th>
<th>Total Intensity</th>
<th>Beam Sigma</th>
<th>Specimen Slot</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>60</td>
<td>1.5e11</td>
<td>9.0e12 p</td>
<td>2.5 mm</td>
<td>9</td>
<td>316 m/s</td>
</tr>
<tr>
<td>Experiment</td>
<td>72</td>
<td>1.26e11</td>
<td>9.0e12 p</td>
<td>1.9 mm</td>
<td>8 (partly 9)</td>
<td>~275 m/s</td>
</tr>
</tbody>
</table>

**Figure:**
- A sesquidodecahedron with a legend: ABS VEL (m/s) with values ranging from 0.000e+00 to 0.000e+00.
- An image showing a beam with a legend: testadyngeom_w Cycle 0.
- A caption: Time 0.0000000000 ms Units mm, mg, ms.
HRMT14 Experiment

Design and Testing for HL-LHC Collimators

Tungsten Alloy, 72 b
Molybdenum, 72 & 144 b
Glidcop, 72 b (2 x)
Copper-Diamond 144 b
Molybdenum-Copper-Diamond 144 b
Molybdenum-Graphite (3 grades) 144 b

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A new experiment (HRMT23) currently under manufacturing is planned for mid-2015 to simultaneously test 3 separate complete jaws extensively instrumented.

Main goal is to qualify (or disqualify) jaws to be used in a full-scale HL-LHC prototype under highest and brightest 450 GeV beam available (e.g. $288 \times \sim 1.5e11 \ p/b$) in view of LIU parameters.

- 2 HL-LHC jaws (inserts in CuCD and MoGr)
- 1 LHC secondary collimator jaw (TCSP) …

System equipped with comprehensive set of strain gauges, and sensors for online acquisition, viewports for optical acquisition, LDV, etc. and fast dismounting system for glove box post-irradiation observations.
Irradiation Tests at GSI

- M-branch irradiation facility at GSI UNILAC
- In-situ online and offline monitoring: camera, fast IR camera, SEM, XRD, LFA, nanoindentation and Raman spectroscopy
- 3 irradiation campaigns completed, more to come ..

February-March 2014:
- $^{238}\text{U}$ irradiation: 1.14 GeV, $4 \times 10^9$ ions cm$^{-2}$s$^{-1}$
- $^{208}\text{Bi}$ irradiation: 1 GeV, $1.2 \times 10^9$ ions cm$^{-2}$s$^{-1}$
- Materials tested: CuCD, C-C, MoGr (non-annealed),
- Fluence: up to $1 \times 10^{14}$ ions cm$^{-2}$

July 2014:
- $^{197}\text{Au}$ irradiation: 945 MeV, $\sim 1-2 \times 10^9$ ions cm$^{-2}$s$^{-1}$
- C irradiation: 11.4 MeV/u, $5 \times 10^9$ ions cm$^{-2}$s$^{-1}$
- CuCD, C-C (2x orient.), MoGr (low-temperature annealed), C fibres
- Fluence: up to $1 \times 10^{14}$ ions cm$^{-2}$s$^{-1}$

October 2014
- Sm irradiation: 360 MeV/u
- Fluences: $1e11$, $5e11$, $1e12$, $2e12$:

EuCARD$^2$
- Analysis of experimental data is just starting
- Preliminary results indicate a degradation of thermal diffusivity for both CuCD and MoGr (larger for MoGr)
- Deformation under irradiation was also observed on MoGr transversal samples: this is likely due to release of internal residual strains. Subsequent annealing was seen to have beneficial effects.
Irradiation Tests at BNL

Tandem van de Graaff:
Irradiation with **28 MeV protons** for very localized damage (MoGr, CuCD, Glidcop)

- Irradiation up to **200 MeV protons** (Glidcop, Mo, MoGr, CuCD)
- Spallation neutrons from **112 MeV protons** (CuCD, Graphite)
• Bringing LHC beyond nominal performances will require a **new generation of collimators** embarking **advanced materials**.

• An ambitious **R&D program** at CERN is focusing on their development in the frame of EU-sponsored collaborations and Partnership agreement.

• A new generation of **metal- and ceramic- matrix composites** with **diamond** or **carbon** reinforcements is showing promising results, in particular **Copper – Diamond** (CuCD) and specially **Molybdenum Carbide – Graphite** (MoGr)

• **Outstanding properties** were reached for **MoGr** produced by High Temperature Liquid Phase Sintering (RT Thermal Conductivity 770+ Wm⁻¹K⁻¹, CTE ~1÷2x10⁻⁶ K⁻¹).

• A **full-scale prototype** of a newly designed **HL-LHC Collimator** should be installed in the LHC in the coming months.

• Qualification of the design and validation of advanced materials constitutive models calls for ad-hoc **comprehensive tests** to be carried out at CERN **HiRadMat facility**.

• An **extensive campaign** to study **materials behavior under irradiation** is underway at **GSI, BNL** and **Kurchatov Institute**. First results should become available soon.
Thank you for your attention!

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project EuCARD, Grant Agreement 227579 and EuCARD-2 Grant Agreement 312453

alessandro.bertarelli@cern.ch
• Irradiation campaign completed. Data analysis to start soon
• X-ray beam from NSLS at Brookhaven National Laboratory has been used for phase and strain mapping of cold and irradiated collimator material samples.
• 2 runs: April and September 2014 ("last light" before NSLS shutdown).
• The new beamlines in NSLS II will start the operations in mid-2015
### Accident Simulations on TCTA

<table>
<thead>
<tr>
<th>Material</th>
<th>EOS</th>
<th>Strength model</th>
<th>Failure model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>Tabular (SESAME)</td>
<td>Johnson-Cook</td>
<td>Plastic strain/ Hydro (Pmin)</td>
</tr>
<tr>
<td>Copper OFE</td>
<td>Polynomial</td>
<td>Johnson-Cook</td>
<td>Johnson-Cook</td>
</tr>
<tr>
<td>Stainless steel AISI 316</td>
<td>Shock</td>
<td>Johnson-Cook</td>
<td>Plastic strain</td>
</tr>
<tr>
<td>Water</td>
<td>Shock</td>
<td>-</td>
<td>Hydro (Pmin)</td>
</tr>
</tbody>
</table>

- **Jaw bloc (x5)** (W(95%)-Ni(3.5%)-Cu(1.5%) partly modelled as pure W)
- **Bloc Support** (OFE-Copper)
- **Stiffener** (Glidcop modelled as OFE-Cu)
- **Screw (x40)** (Stainless Steel)
- **Water**
- **Cooling Pipes** (Cu(89%)-Ni(10%)-Fe(1%) modelled as OFE-Cu)
HRMT14: Medium Intensity Tests

- Extensive numerical analysis *(Autodyn)*, based on FLUKA calculations to determine stress waves, strains and displacements.
- Comparison of simulated **Hoop and Longitudinal Strains and Radial velocity** very well match measured values on sample outer surface.

Inermet180 24 bunches
Total intensity: 2.7e12 p
σ ≅ 1.4 mm
MoGr, MoGrCF Post-irradiation

MoGR H1_CENTER:
144 bunches at 450 GeV,
(1.95E13 protons),
impact at 2 mm from the free surface.

Results:
- Extended damage on denser MoGr (last samples),
- No damage on MoGRCF samples,
- No color variation!
- LPS MoGRCF (2.7 g/cm³) can only be better!

MoGR (5.4 g/cm³)
MoGRCF SSS (3.7 g/cm³)
Inermet180 H6_CENTER: 72b, 1.9 mm $\sigma$, 9.05E12 Total Intensity
- Extended damage (~1 cm)
- No visible plastic deformation
- Granular aspect of damaged microstructure.

$\Omega \sim 10.5$ mm

$\Omega \sim 9.2$ mm