Advanced Composite Materials for Thermal Management Applications

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Outline

- Context

- Objectives for Material R&D
  - Metal/Ceramic Matrix Composites (MMC & CMC)
    - MMC/CMC for High Energy Physics (BID)
    - MMC/CMC for Open Market Applications
    - Aluminum-Graphite
    - Molybdenum Carbide-Graphite

- Further Applications ...

- Summary and Perspectives
- LHC is reaching unprecedented **energy** and **energy density** (2-3 orders of magnitude above other machines).
- **Beam-induced accidents** are among the most dangerous and still less explored events for particle accelerators.
- **Collimators** (and all Beam Intersecting Devices) are inherently exposed to such extreme events.
- Collimators are by far the highest contributors to machine impedance, potentially leading to serious instabilities.

Development of Novel advanced materials, along with state-of-the-art simulations, are instrumental in facing these challenges!
Objectives for Material R&D

Set of Requirements defined to assess relevant materials:

- Maximize Electrical Conductivity
- Maximize Thermal Conductivity
- Minimize Coefficient of Thermal Expansion
- Maximize Strength and Robustness
- Maximize Operational Temperature
- Ensure Radiation Hardness
- Ensure industrial feasibility of large components
- Produced at affordable costs

Many requirements shared with a broad range of applications requiring efficient Thermal Management.
Metal/Ceramic Matrix Composites

Two parallel paths followed:

1. Materials for Beam Intercepting Devices (through EuCARD1/2 and Partnership Agreement with Italian SME Brevetti Bizz)
   - Materials investigated are Copper-Diamond, Molybdenum-Diamond, Silver-Diamond, Molybdenum Carbide-Graphite (MoGr)
   - Most promising materials is MoGr (easy to machine, is versatile and can be coated with a Mo layer dramatically increasing electrical conductivity ...)

2. Materials for Open Market Applications (KT-funded project)
   - Initially favored were low-temperature, low-cost materials, e.g. Aluminum-Graphite (AlGr)
   - High Temperature Thermal Management applications are also pushing for new materials ...
   - Excellent results obtained for BID/HEP applications are encouraging to “join efforts” with high-temperature materials.
Aluminum-Graphite Composites

- 8 different Al-Gr plates produced, 6 of them fully characterized
- Thermal Conductivity: up to 385 W/mK
- Flexural strength: up to 44 MPa
- Electrical Conductivity: up to 3.1 MS/m
- Coefficient of Thermal Expansion: ~9x10^-6 K^-1
Molybdnum-Graphite Composites

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

Why Molybdenum?
- Refractory metal
- Density lower than Tungsten

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
- Developed by CERN and Brevetti Bizz
- Broad range of processes and compositions investigated (Molybdenum, Natural Graphite, Mesophase pitch-based Carbon Fibers).

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

During sintering all Molybdenum reacts with Carbon creating Carbides (MoC_{1-x})

Ceramic Matrix Composite!
Molybdenum-Graphite Processing

- Best results obtained by **Liquid Phase Sintering** at ~2600°C (MoC$_{1-x}$ melt at 2580°C)
- **Composition (Grade MG-3110)**
  - 40% vol Natural Graphite (~45 μm)
  - 20% vol Molybdenum powder (5 mm)
  - 20% vol Short Carbon Fibres (300 μm)
  - 20% vol Long Carbon Fibres (3 mm)
- **Process**
  - Powders pre-cleaning under H$_2$-N$_2$ atmosphere
  - Field Assisted Sintering, dwell time 20 min at ~2600°C, 35 MPa
  - Reducing H$_2$-N$_2$ atmosphere at 10$^{-4}$ mbar.
  - Liquid carbide allowed to spill out of the molds to enhance compaction and reduce final density.
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!)
Molybdenum-Graphite Properties

- Outstanding RT Thermal Conductivity up to 2000°C
- Excellent dimensional stability up to 2000°C
- Material can be coated
- Possibility to tailor composition to adapt to specific needs
- International Patent Filed!
Potential range of applications can be further expanded thanks to the tailoring possibilities of Molybdenum-Graphite composites ...
New frontiers of High Energy Physics are giving impulse to the development of novel advanced materials.

An ambitious R&D program is focusing on their development relying on complementary paths: EuCARD/EuCARD2 and Partnership Agreement CERN/Brevetti Bizz.

Most of the requirements for HEP BID are shared by high-end thermal management applications.

AlGr was thoroughly investigated for low-temperature applications.

Outstanding properties were reached for Mo-Gr, particularly thermal conductivity ($750\,\text{Wm}^{-1}\text{K}^{-1}$) and low CTE (<2 ppm/K).

KT-funded and HEP R&D are moving closer … further appealing materials are in sight!

Newly developed materials are already attractive for a broad range of industrial applications and have the potential for a real impact on society … interest shown by several companies, development tests to start in one Electronic company soon …
Thank you for your attention!
Aluminum-Graphite Composites

Aluminium Carbon Fibres
Longitudinal direction

Aluminium Carbon Fibres
Transversal direction
Mo-coated Mo-Gr

- Co-developed by **CERN** and **Brevetti Bizz**.
- Molybdenum–Graphite core with pure Mo cladding.
- Sandwich structure drastically increases electrical conductivity.
- Excellent adhesion of Mo cladding thanks to carbide interface.

<table>
<thead>
<tr>
<th>Core</th>
<th>Cladding</th>
<th>Carbide layer</th>
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<tbody>
<tr>
<td>1 MS/m</td>
<td>18 MS/m</td>
<td>1.5 MS/m</td>
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N. Mounet et al., *Impedance @ 2013 Collimation Review*, May 2013

- Collimator **impedance reduced by a factor 10** through Mo-coated Mo-Gr.
- Wish to **install** soon a full collimator with Mo-coated jaw in LHC...
- New **challenge**: turn material R&D into a suitably industrialized product in a short time...
- ... and each new material should be **validated by accident simulations and tests (HiRadMat)**

We must cross the valley of death in a dreadfully short time!
HRMT14: High Intensity Tests

- **Inermet 180, 72 bunches**
- **Molybdenum, 72 & 144 bunches**
- **Glidcop, 72 bunches (2 x)**
- **Copper-Diamond 144 bunches**
- **Molybdenum-Copper-Diamond 144 bunches**
- **Molybdenum-Graphite (3 grades) 144 bunches**