# R&D on Novel Advanced Collimator Materials: Results and Perspectives

## Highlights in EuCARD


Alessandro Bertarelli, CERN



EuCARD 4th Annual Meeting
CERN, Geneva – *10-14 June, 2013*


EN Engineering Department

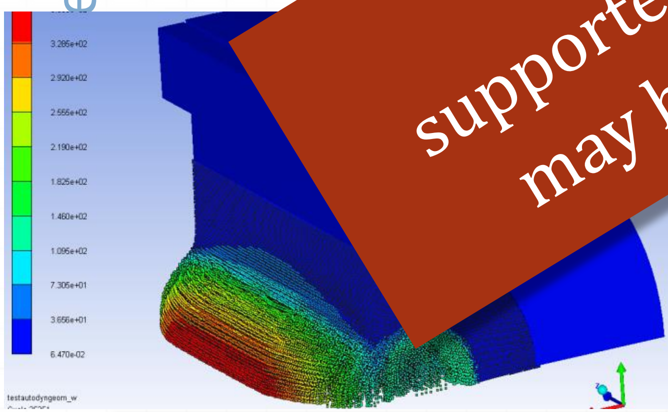
# Outline

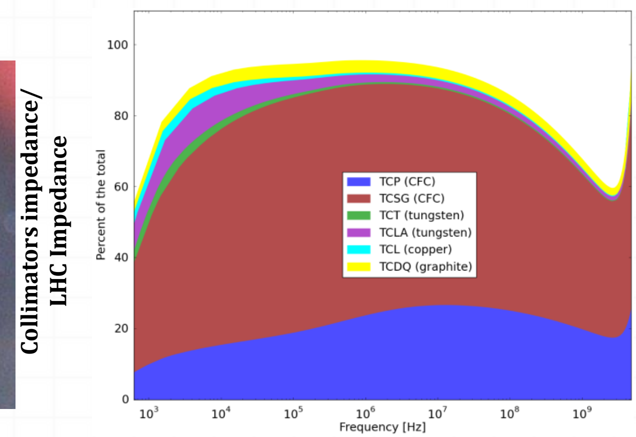
- **Context**
- Status of the Collimator Materials R&D Program
- Material Tests
  - High Intensity Beam Simulations and Tests (HiRadMat)
  - Dynamic Fracture Tests (Polito)
  - Long-term Irradiation Tests (NRC-KI, BNL, GSI)
- Summary and Perspectives

# Context

- **LHC** is reaching unprecedented **energy** and **energy density** (2-3 orders of magnitude above other machines).
- **Beam-induced accidents** are among the m… dangerous and still less explored event… accelerators.
- **Collimators** (and all **Beam I**… inherently exposed to s…
- Collimators are … machine **im**… …serious **instab**…


**Novel advanced materials,**
**supported by state-of-the-art simulations,**
**may help in meeting these challenges!**





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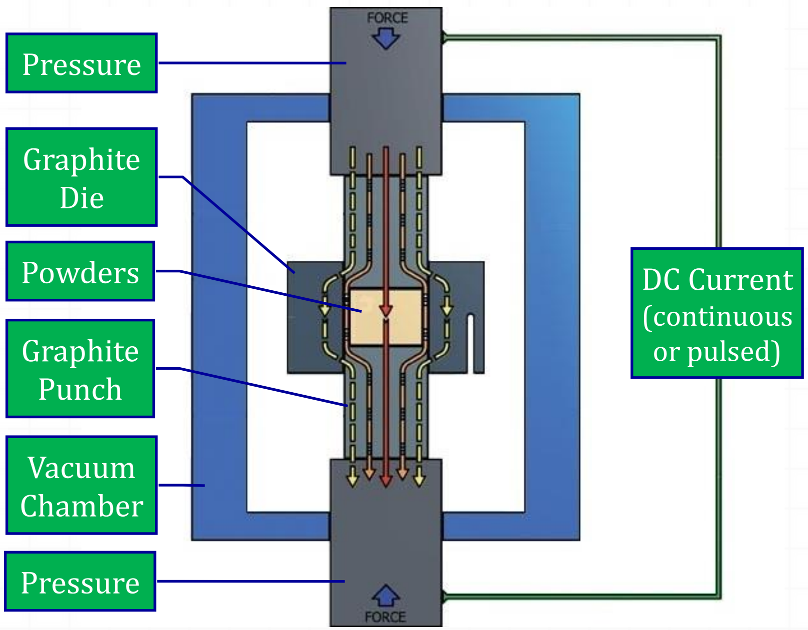
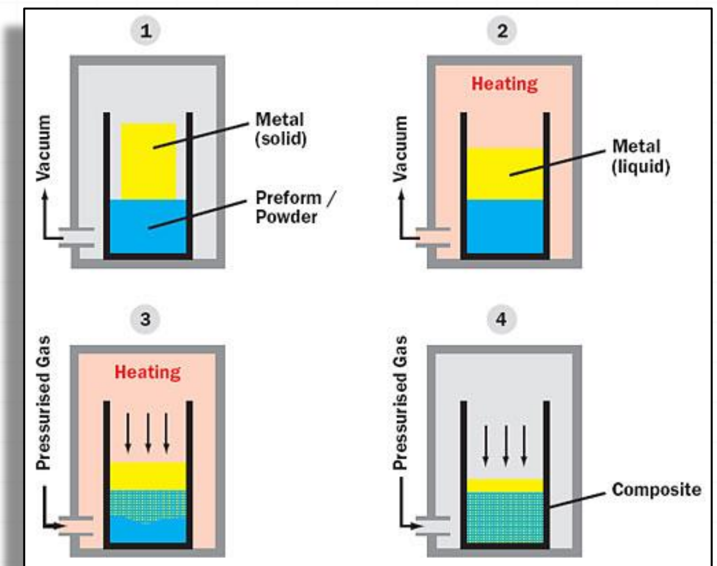
# Metal Matrix Composites

- Material development program carried out pursuing **two complementary paths**:
  - **EuCARD- WP8** (**Task 8.2**) by **CERN**, **RHP-Technology**, **EPFL**, **Polito**, **GSI**, **NRC-KI**.
  - **Partnership Agreement** between **CERN** and Italian SME (**Brevetti Bizz**).
- R&D focused on **Metal Matrix Composites** (**MMC**) with **Diamond** or **Graphite** reinforcements as they have the potential to combine the properties of Diamond and Graphite (**high** $k$, **low** $\rho$ and **low CTE**) with those of Metals (**strength**, $\gamma$, …).
- Production techniques include **Rapid Hot Pressing** (**RHP**), **Spark Plasma Sintering** (**SPS**) and **Liquid Infiltration**.



# Metal Matrix Composites





- Materials investigated are **Copper-Diamond** (**Cu-CD**), **Molybdenum-Diamond** (**Mo-CD**), **Silver-Diamond** (**Ag-CD**), **Molybdenum-Graphite** (**Mo-Gr**)
- Most **promising materials** are **Cu-CD** and **Mo-Gr**.
- Ag-CD and Mo-CD are, by now, sidelined as they are limited by (relatively) low melting temperature (Ag-CD) and insufficient toughness (Mo-CD).
- **Mo-Gr** is particularly appealing as it can be **coated with** a **Mo layer** dramatically **increasing electrical conductivity** ...




# Cu-CD Composite

- Developed by **RHP-Technology** (Austria)

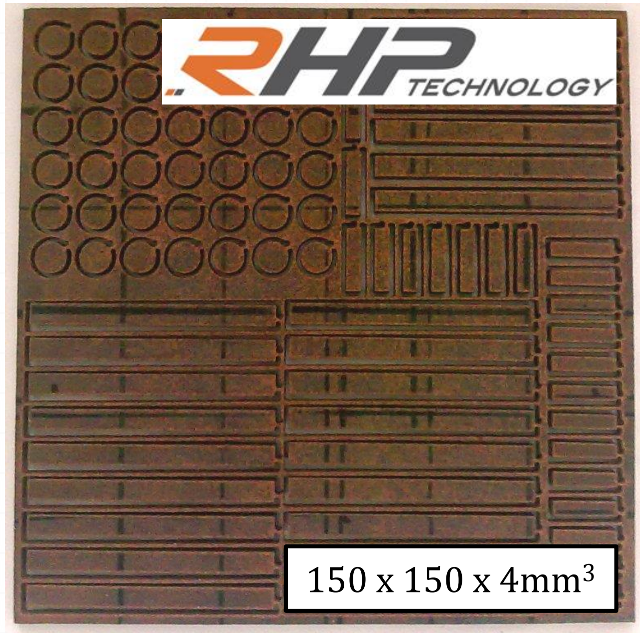
No diamond degradation (in reducing atmosphere graphitisation starts at **~ 1300 °C**)

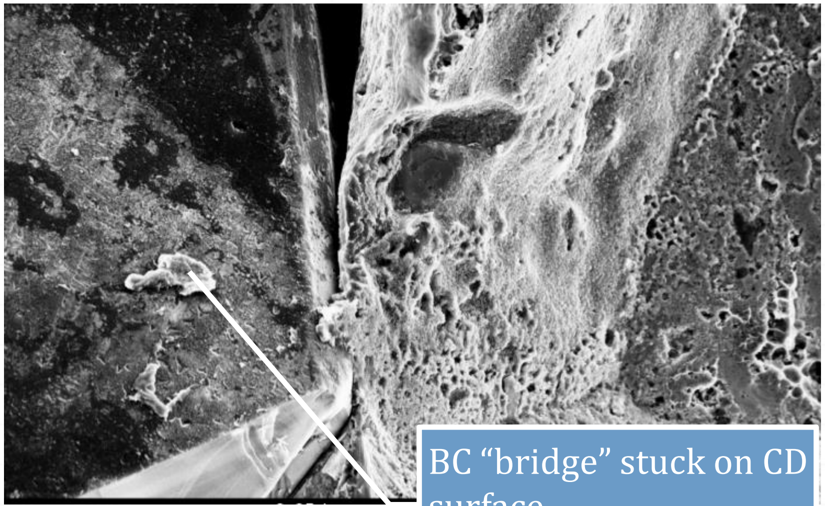
Good thermal (**~490 W/mK**) and electrical conductivity (**~12.6 MS/m**).

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

Cu low melting point (**1083 °C**) may limit 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**)



BC "bridge" stuck on CD surface.
No CD graphitization

# Mo-Gr Composites

- Co-developed by **CERN** and **Brevetti Bizz**.

**Why Graphite?**

- Low CTE
- Low Density
- High Thermal Conductivity (grade-dependent)
- Very High Service Temperatures
- High Shockwave Damping

↑ Very high melting point (**2500+°C**)

↑ Low Density

↑ **Outstanding Thermal Conductivity** (**700+ W/mK**). ***180% Cu, 170% Ag*** *!!!* ☺☺☺

↑ No reinforcement degradation

↑ Possibility to reach excellent electrical conductivity by Mo coating.

↓ Mechanical strength to be improved …


- R&D program still going on to **further improve** physical properties, particularly **mechanical strength**

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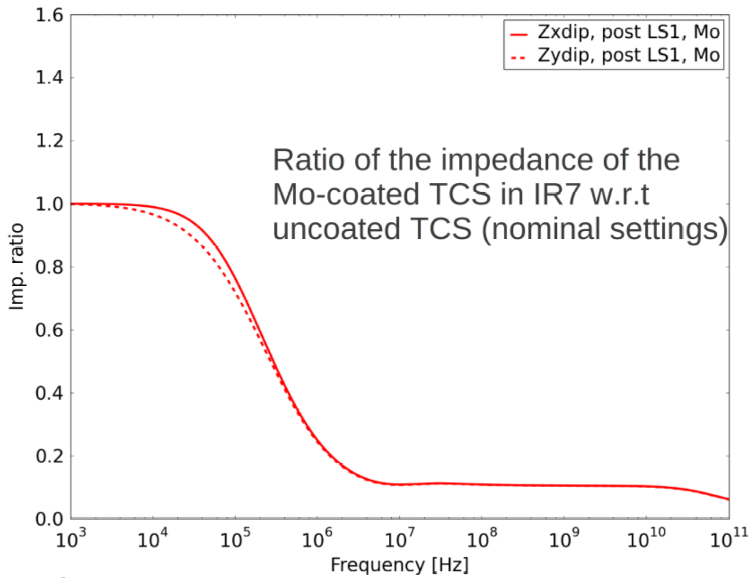
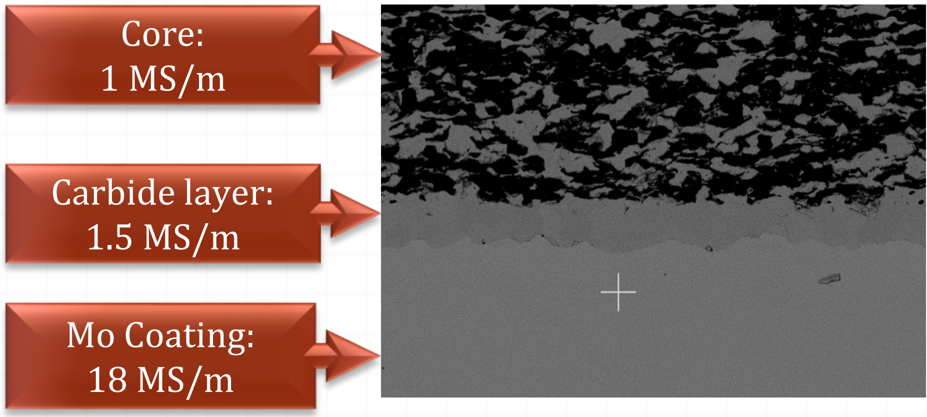
# Mo-coated Mo-Gr

- 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.


**N. Mounet et al.**, *Impedance @ 2013 Collimation Review*, May 2013

⇒ Impedance of these collimators decreased by a factor 10.




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

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# Material Tests in HiRadMat

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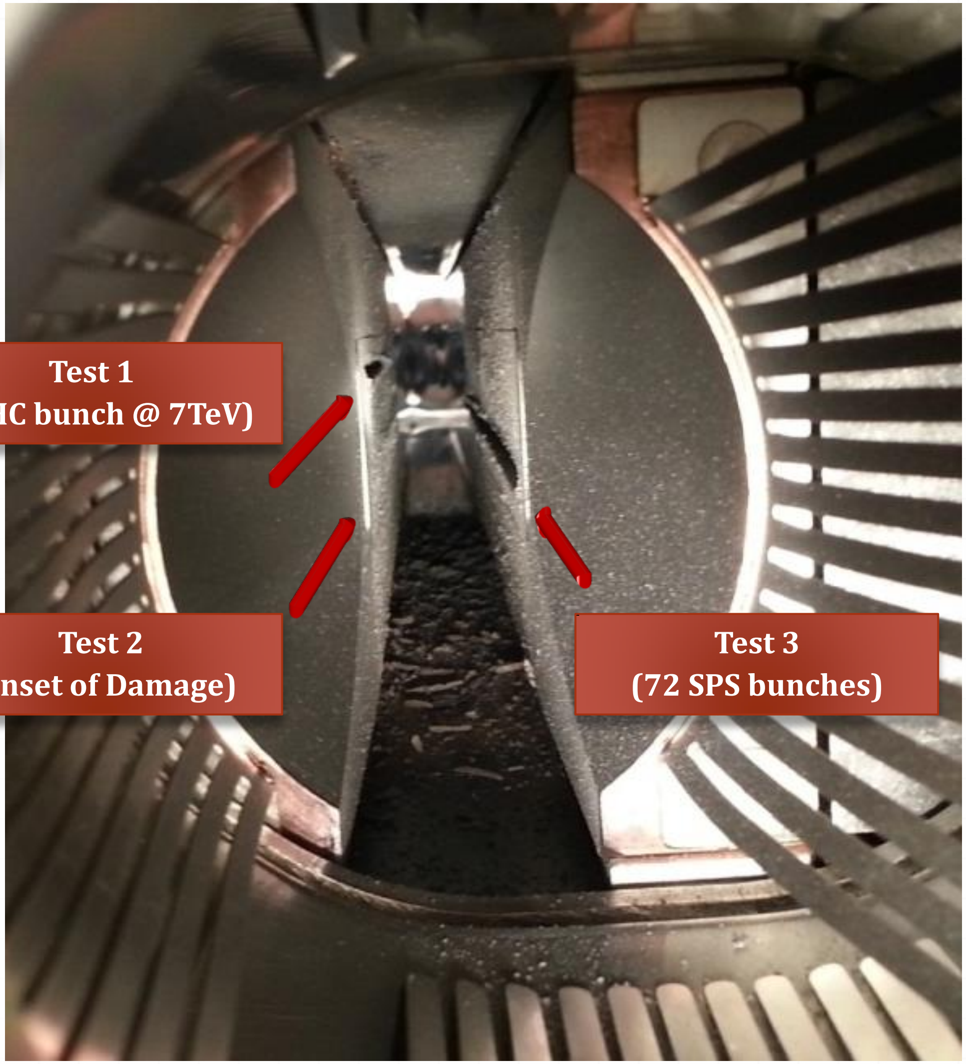
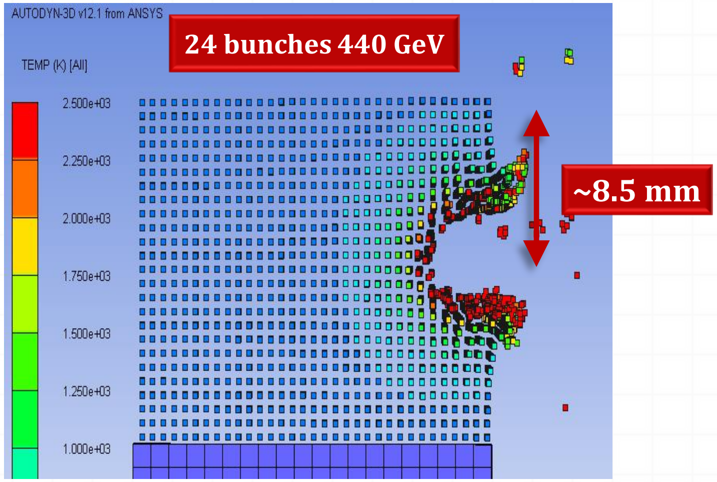
## Why HiRadMat Experiments?

- With accidental beam impacts, one enters a relatively **unknown territory**, that of high power explosions and ballistics.
- Existing material **Constitutive Models** at extreme conditions are limited and mostly drawn from military research (classified).
- Simulations are **sophisticated**, but unavoidably affected by **uncertainties and approximations**.
- Consequences on UHV, electronics, bellows cannot be easily anticipated by numerical simulations.
- **Only dedicated material tests can provide the correct inputs for numerical analyses and validate/benchmark simulation results**.
- Based on this, **two complementary experiments** at CERN **HiRadMat** facility were approved:
  - Destructive Test of a **complete tertiary collimator** for a thorough, integral assessment of beam accident consequences (**HRMT09 – A. Rossi, O. Aberle, S. Redaelli, M. Cauchi** et al.).
  - Controlled test on a **multi-material test bench** hosting a variety of specimens conveniently instrumented for online and offline measurements (**HRMT14** ).

# HRMT09: Post-irradiation observation

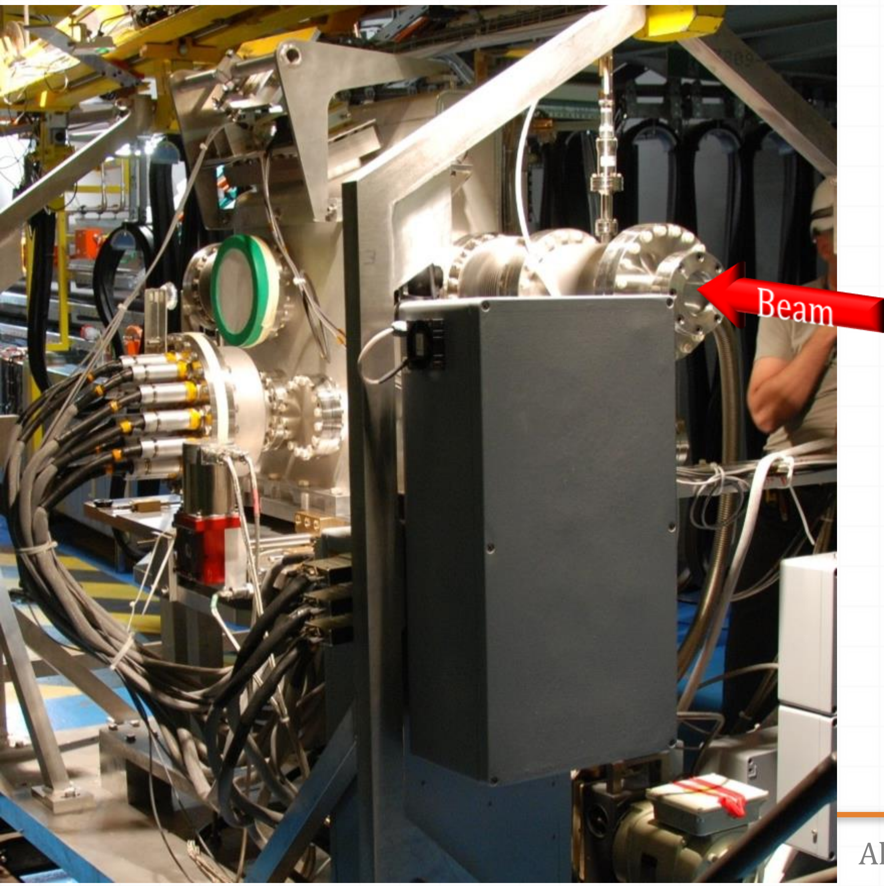



- Good matching between tests and simulations (e.g. groove height)
- Impressive **quantity of tungsten ejected** (partly bonded to the opposite jaw, partly fallen on tank bottom or towards entrance and exit flanges)
- **Vacuum degraded**
- **Tank contaminated**

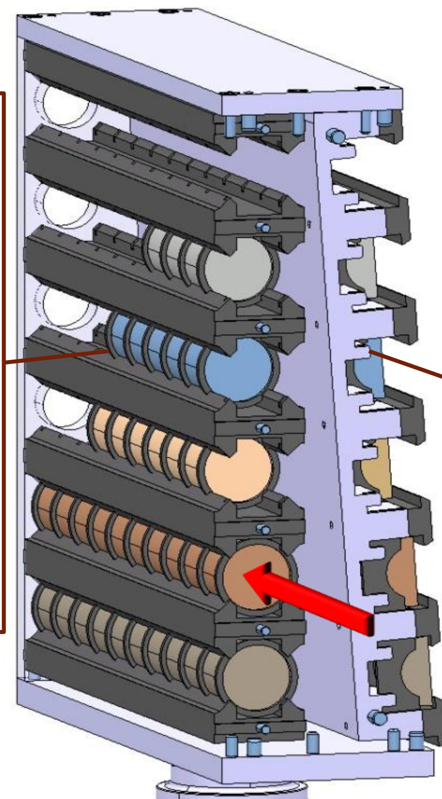
# HRMT14 Experiment

- **Benchmark** advanced numerical simulations and **material constitutive models** through extensive acquisition system.
- Characterize in one go **six existing** and **novel materials** under development: Inermet180, Molybdenum, Glidcop, Mo-CD, Cu-CD, Mo-Gr. **2 sample types, 12 target stations, 88 samples**.
- **Collect**, mostly in real time, **experimental data** from different acquisition devices (Strain Gauges, Laser Doppler Vibrometer, High Speed video Camera, Temperature and Vacuum probes).




**Medium Intensity Samples (Type 1)**

- Strain measurements on sample outer surface;
- Radial velocity measurements (LDV);
- Temperature measurements;
- Sound measurements.



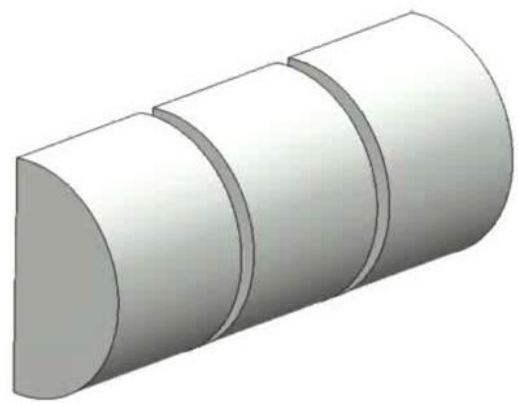
**High Intensity Samples (Type 2)**

- Strain measurements on sample outer surface;
- Fast speed camera to capture fragment front formation and propagation;
- Temperature measurements;
- Sound measurements.

# HRTM14: High Intensity Tests

## Inermet samples as seen from viewport and camera





# HRMT14: High Intensity Tests

## Inermet : comparison Autodyn (SPH) between simulation and experiment

Beam

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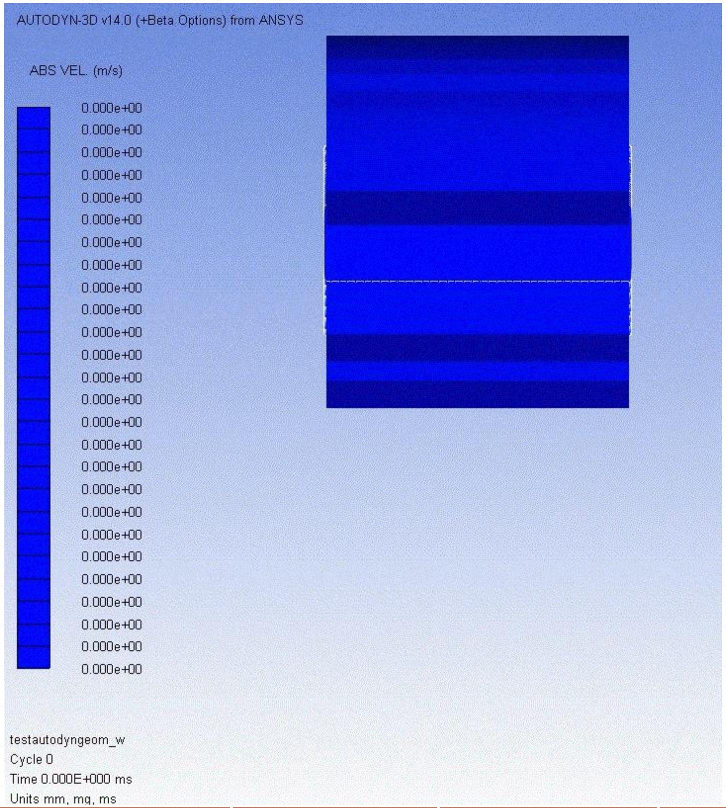
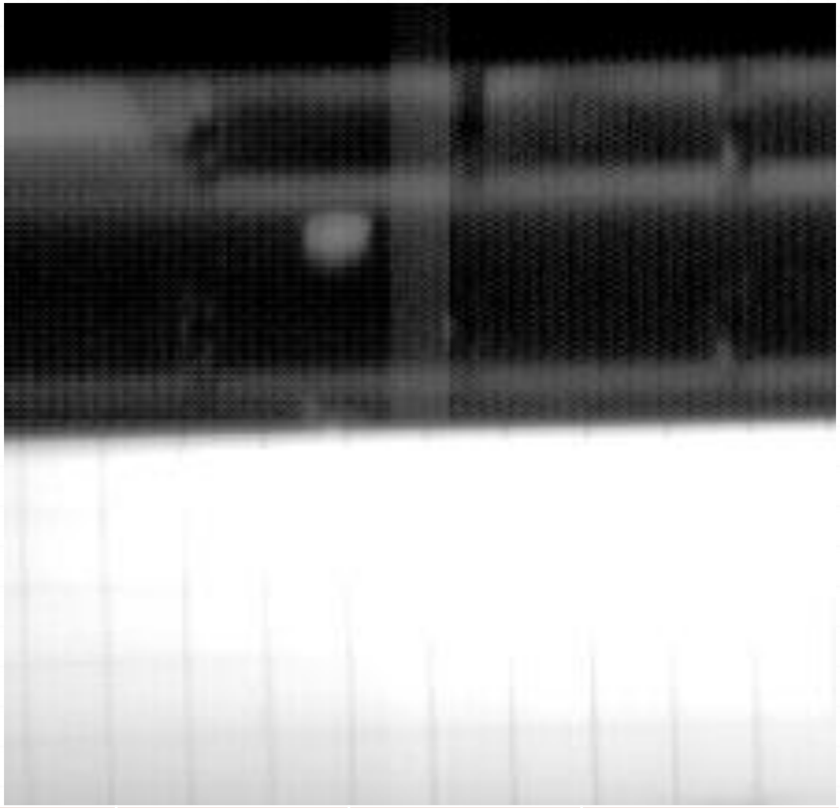
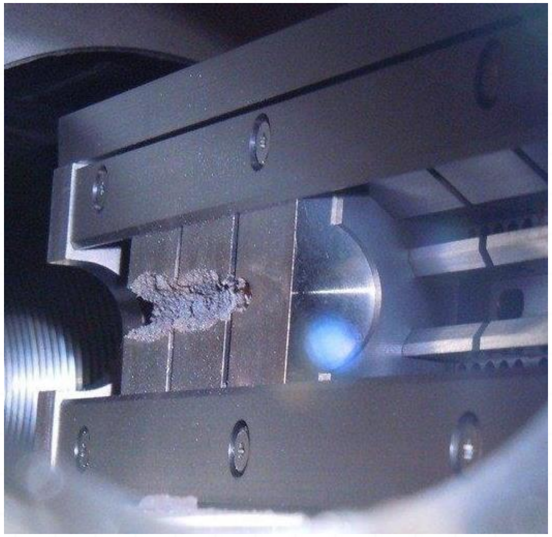


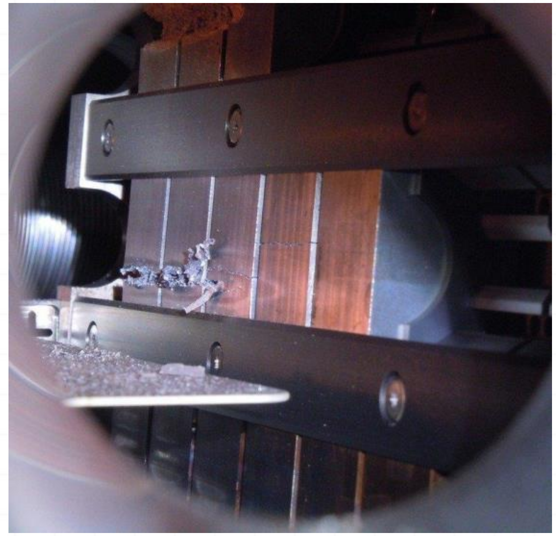



| Case | Bunches | p/bunch | Total Intensity | Beam Sigma | Specimen Slot | Velocity |
|---|---|---|---|---|---|---|
| Simulation | 60 | 1.5e11 | 9.0e12 p | 2.5 mm | 9 | **316 m/s** |
| Experiment | 72 | 1.26e11 | 9.0e12 p | 1.9 mm | 8 (partly 9) | **~275 m/s** |

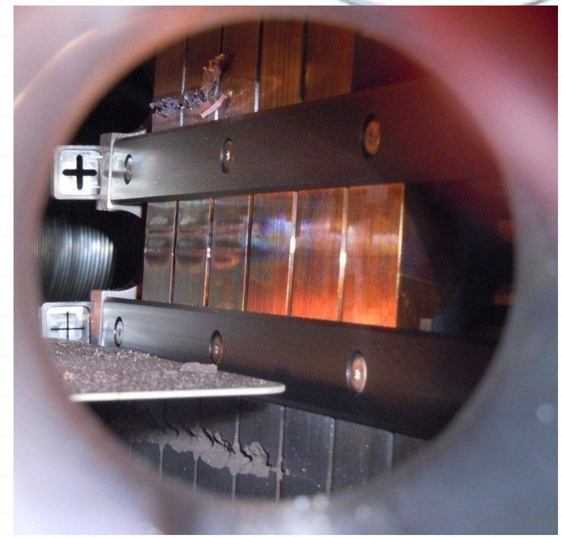
# HRMT14: High Intensity Tests



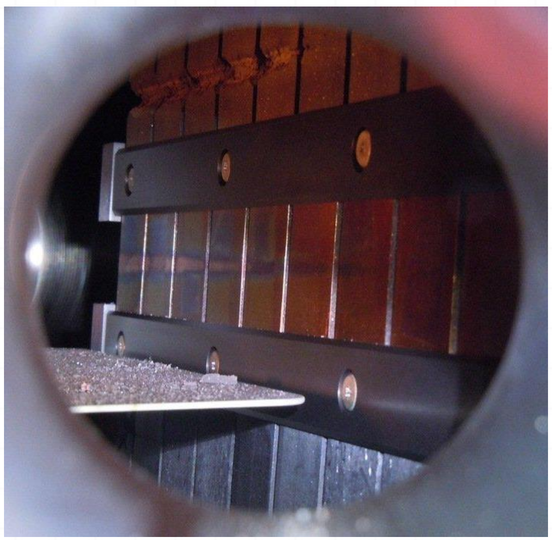
*Inermet 180, 72 bunches*



*Molybdenum, 72 & 144 bunches*



*Glidcop, 72 bunches (2 x)*



*Copper-Diamond*
*144 bunches*

*Molybdenum-Copper-Diamond*
*144 bunches*

*Molybdenum-Graphite (3 grades)*
*144 bunches*

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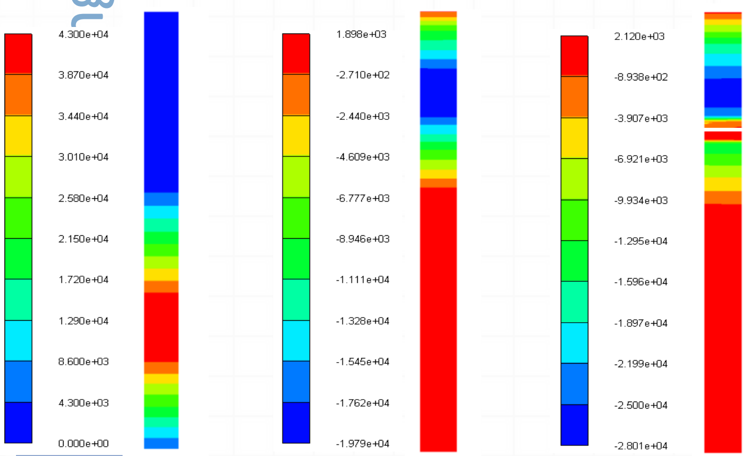
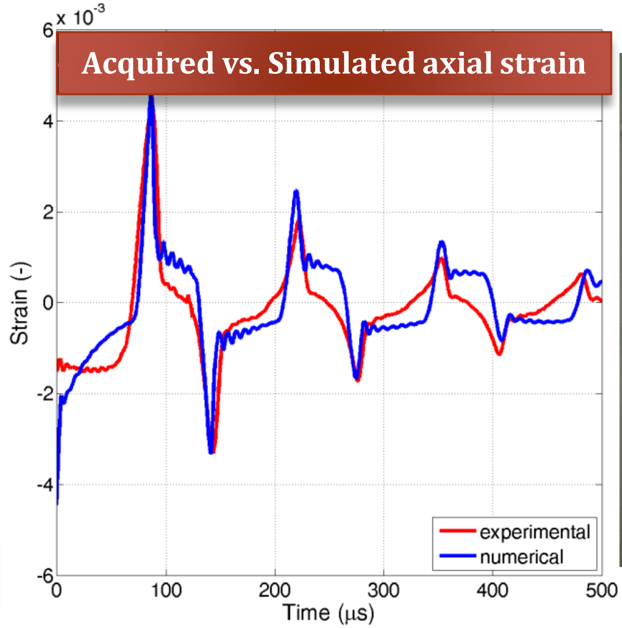
# Dynamic Fracture Test of Graphite

- Dynamic tests performed at Politecnico di Torino with **Split Hopkinson Pressure Bar (SHPB)** to evaluate the fracture behavior of **graphite at high strain rates**.
- Determination via reverse engineering of a **visco-elastic strength model** and a **failure model** for graphite to be used in **wave propagation code** (Autodyn).
- Simulated and acquired signals are in good agreement!

Split Hopkinson Pressure Bar




Pressure wave propagating through the sample




Acquired vs. Simulated axial strain

Tested graphite sample

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# Radiation Hardness Studies

- **Radiation Hardness** is a key requirement.
- Benefit from **complementary studies in two research centers** with different irradiation parameters, different materials and approaches. Results benchmarking
- Additional irradiation studies possible at GSI.

**Ongoing Characterization Program in RRC-Kurchatov Institute** (Moscow) to assess the radiation damage on:

- **CuCD**
- **MoCD**
- **SiC**

Features:

- Irradiation with protons and carbon ions at **35 MeV and 80 MeV** respectively
- Direct water cooling and T~100°C
- Thermo-physical and mechanical characterization at different fluencies ($10^{16}$, $10^{17}$, $10^{18}$ $p/cm^2$)
- Theoretical studies of damage formation

**Proposal for Characterization Program in Brookhaven National Laboratory** (New York) to assess the radiation damage on:

- **Molybdenum**
- **Glidcop**
- **CuCD**
- **MoGr**

Features:

- Irradiation with proton beam at **200 MeV**
- Indirect water cooling and T~100°C (samples encapsulated with **inert gas**)
- Thermo-physical and mechanical characterization for fluence **up to $10^{20}$ $p/cm^2$**
- Possibility to irradiate with **neutrons** (simulate shower on secondary coll.)

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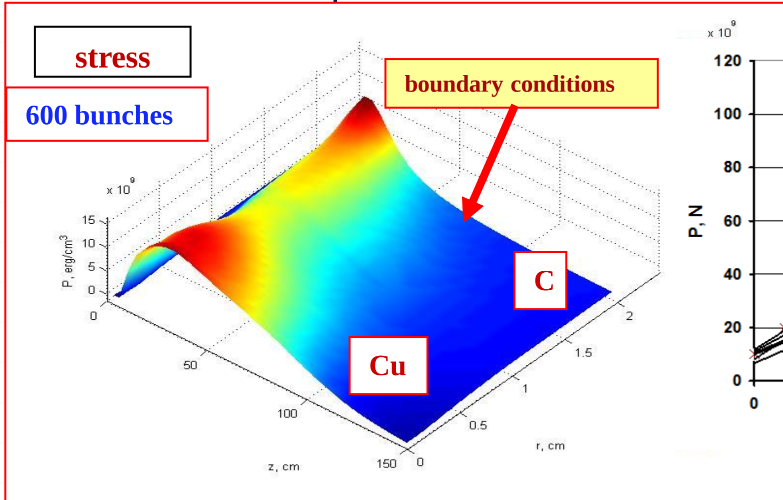
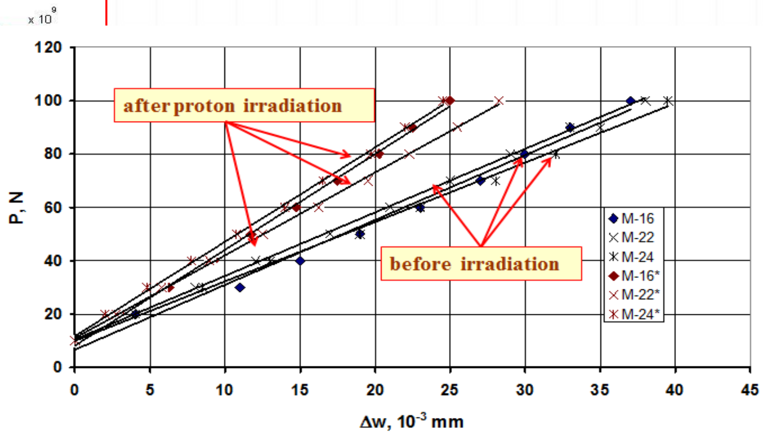
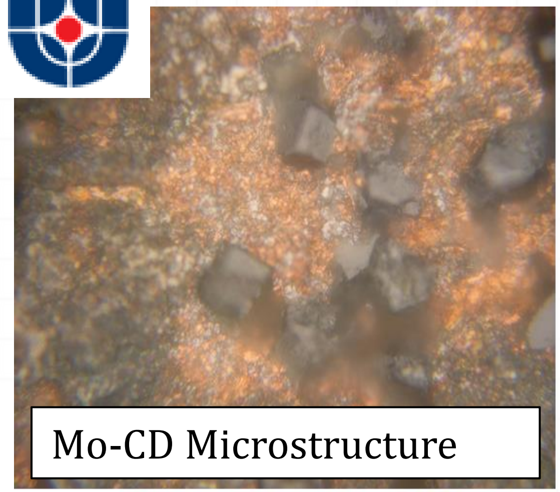
# Radiation Hardness Studies at NRC-KI

- Physical and mechanical characterization to assess evolution of material properties after proton and Carbon ion beam irradiation.

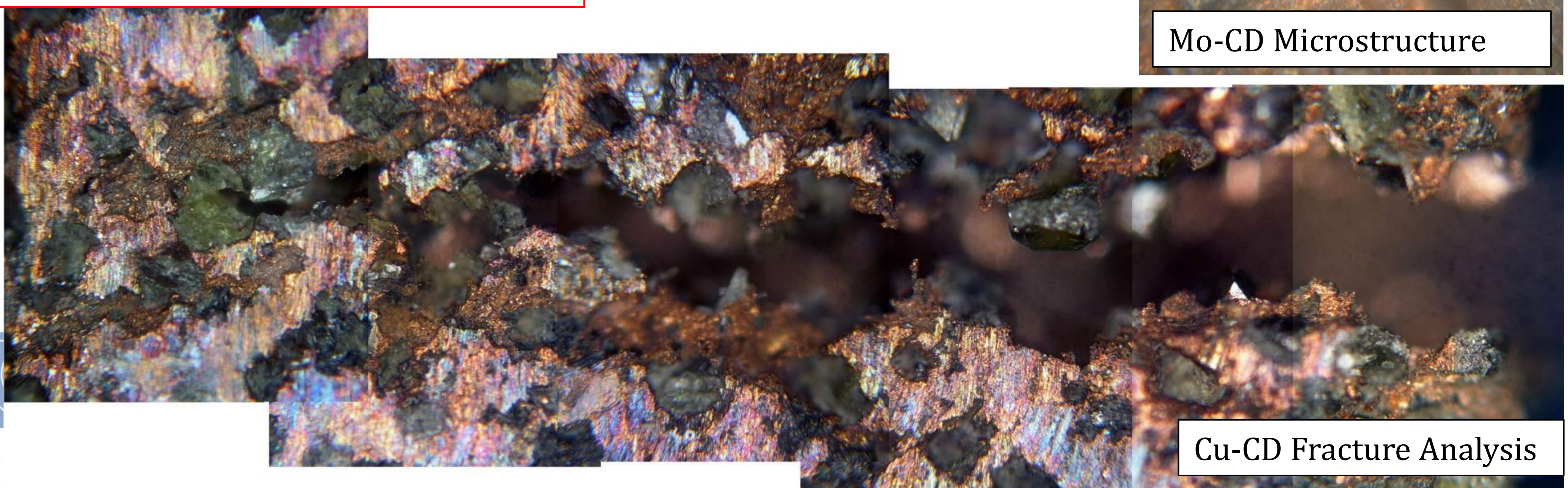



Cu-CD Flexural Strength



Mo-CD Microstructure

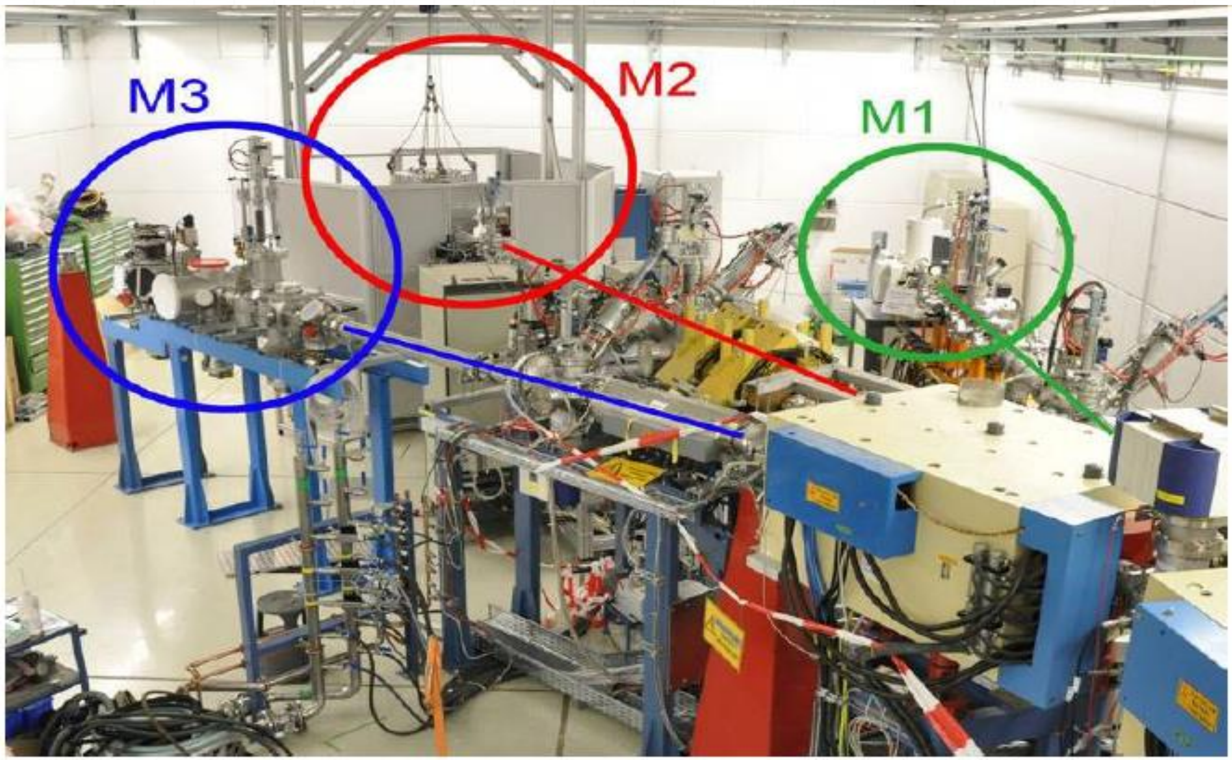


Cu-CD Fracture Analysis

# (Future) Irradiation Studies at GSI

**M-branch irradiation facility at GSI**

- energies close to Bragg peak to maximize energy deposition and damage and to avoid activation
- online and in-situ monitoring available: video camera, fast IR camera, SEM, XRD, IR spectroscopy

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# Summary and Perspectives

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- Bringing LHC beyond nominal performances will likely require a new generation of collimators embarking novel advanced materials.
- An ambitious R&D program is focusing on the development, simulation and test of such materials and in the production of prototypes to validate them.
- Two complementary paths are pursued: EuCARD WP8 (CERN, RHP-Tech, EPFL, RRC-KI, GSI) and Partnership Agreement CERN/Brevetti Bizz.
- Cu-CD, Ag-CD, Mo-CD and Mo-Gr studied and successfully produced.
- Experiments on a full collimator and a multi-material test bench under extreme conditions were successfully carried out at CERN's HiRadMat facility.
- Results, mostly collected in real time, very well match numerical simulations.
- Visual observations indicate that Mo-Gr and Cu-CD survived extreme impacts (144 SPS bunches).
- Molybdenum behaved much better than Tungsten (Inermet 180), which can be damaged by a fraction of a LHC bunch.

# Summary and Perspectives





- Radiation hardness assessment is ongoing for a set of materials at RRC-KI and is starting at BNL. Dynamic fracture tests were carried out at Polito.
- Outstanding thermal conductivities were reached for Mo-Gr (700+ W/mK).
- RF impedance studies show that Mo-coated Mo-Gr reduces Collimator Impedance by a factor 10.
- A full LHC Collimator with this new material may be installed in the LHC …
- ... this calls for an additional effort to strengthen the R&D program while progressing toward industrialization.
- Any new material should be validated by high intensity tests (HiRadMat, GSI).
- Newly developed materials are appealing for a broad range of industrial applications and have the potential for a real impact on society …

LHC Collimation Project CERN

CERN

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

GSI

BREVETTI BIZZ

RHP TECHNOLOGY

EuCARD

ColMat

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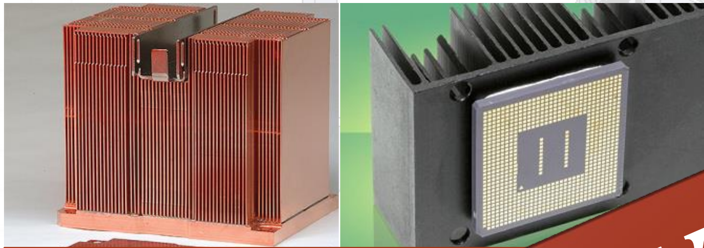


Thermal Management for …
Electr…

…ring

# Thank You For your attention

Advanced Br…

Solar Energy Applications

# Context

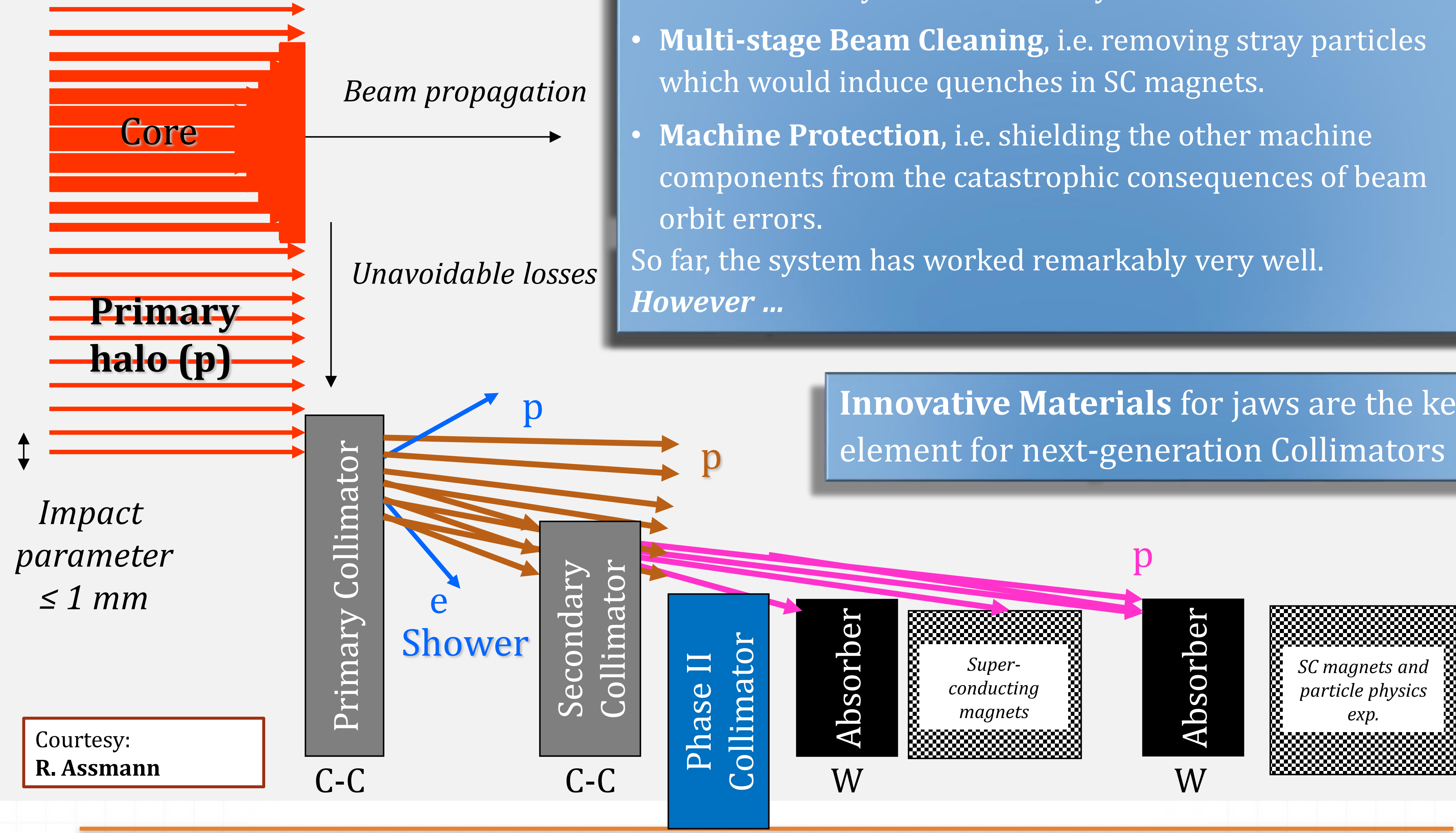
The collimation system must satisfy **2 main functions**:

- **Multi-stage Beam Cleaning**, i.e. removing stray particles which would induce quenches in SC magnets.
- **Machine Protection**, i.e. shielding the other machine components from the catastrophic consequences of beam orbit errors.

So far, the system has worked remarkably very well.

***However …***

**Innovative Materials** for jaws are the key element for next-generation Collimators




Courtesy:
**R. Assmann**

LHC Collimation Project

# Example of an Accidental Impact

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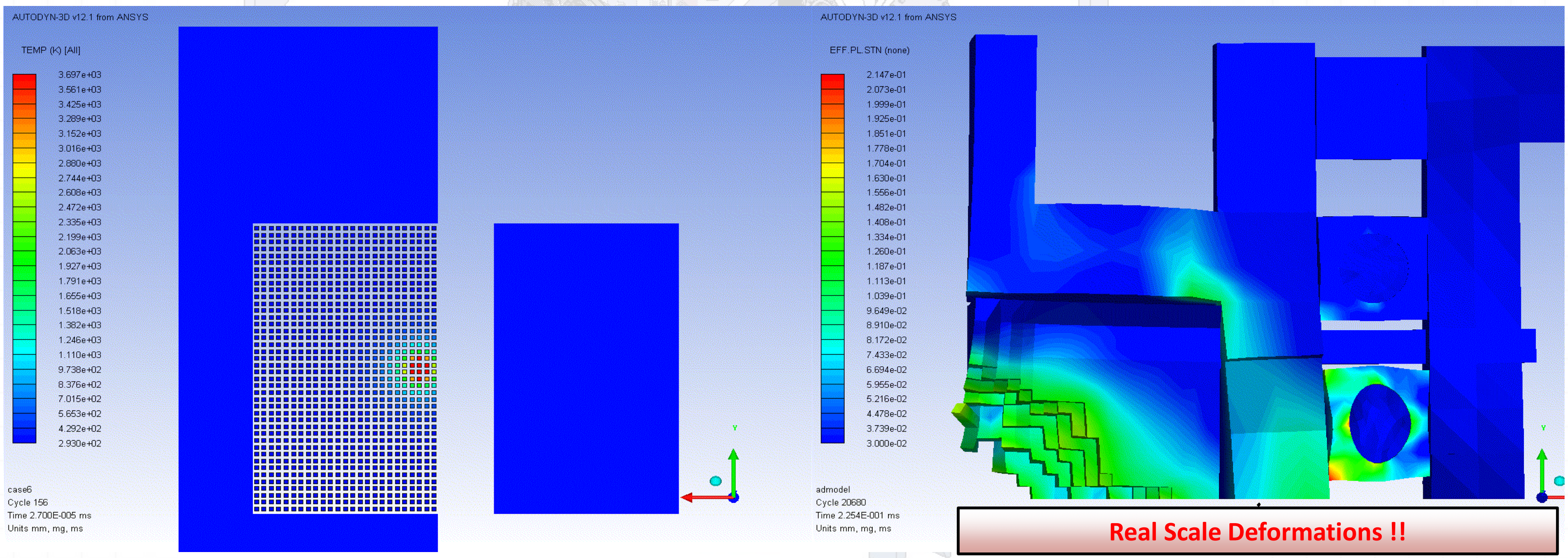
## Simulation of 8 LHC bunches at 5 TeV impacting a Tungsten Jaw (TCTA)

- Probability of **water leakage** due to very severe plastic deformations on pipes.
- Impressive **jaw damage**:
  - Extended eroded and deformed zones.
  - **Projections** of hot and fast solid tungsten bullets (**T≈2000K**, $V_{max}$ **≈ 1 km/s**) towards opposite jaw. Slower particles hit tank covers (at velocities just below ballistic limit).
  - Risk of “bonding” the two jaws due to the projected re-solidified material.



# Objectives for Material R&D

**Objectives have been turned into a set of Figures of Merit to assess relevant materials**

- **Reduce RF impedance**
  Maximize **Electrical Conductivity** — $\gamma$
- **Maintain/improve jaw geometrical stability in nominal conditions**
  Maximize the stability indicator **Steady-state Stability Normalized Index (SSNI)** — $\frac{k}{\rho\alpha}$
- **Maintain Phase I robustness in accidental**
  Maximize the robustness indicator **Transient Thermal** **ex TSNI)** — $\frac{R(1-\nu)c_{pv}}{E\alpha\rho}$
- **Improve cleaning efficiency (absorption ra**
  Increase Radiation and nuclear Interaction Lengths, i.e — $Z$
- **Improve maximum operational temperature**
  Increase **Melting Temperature**. — $T_m$

Note Conflicting requirements as to Density

**Additional "standard" requirements include ...**

- Radiation Hardness, UHV Compatibility, Industrial producibility of large components, Possibility to machine, braze, join, coat ..., Toughness, Cost ...

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# Material Ranking

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| Material | C-C | Mo | Glidcop ® | Cu-CD | Ag-CD | Mo-Gr |
|---|---|---|---|---|---|---|
| Density [g/cm³] | 1.65 | 10.22 | 8.90 | ~5.4 | ~6.10 | 2.8 |
| Atomic Number (Z) | 6 | 42 | 29 | ~11.4 | ~13.9 | 8.3 |
| $T_m$ [°C] | 3650 | 2623 | 1083 | ~1083 | ~840 | ~2520 |
| SSNI [kWm2/kg] | 24 | 2.6 | 2.5 | 13.1 ÷ 15.3 | 11.4 ÷ 15.4 | 83* |
| TSNI [kJ/kg] | 793 | 55 | 35 | 44 ÷ 51 | 60 ÷ 92 | 195* |
| Electrical Conductivity [MS/m] | 0.14 | 19.2 | 53.8 | ~12.6 | ~11.8 | 1 ÷ 18 ** |

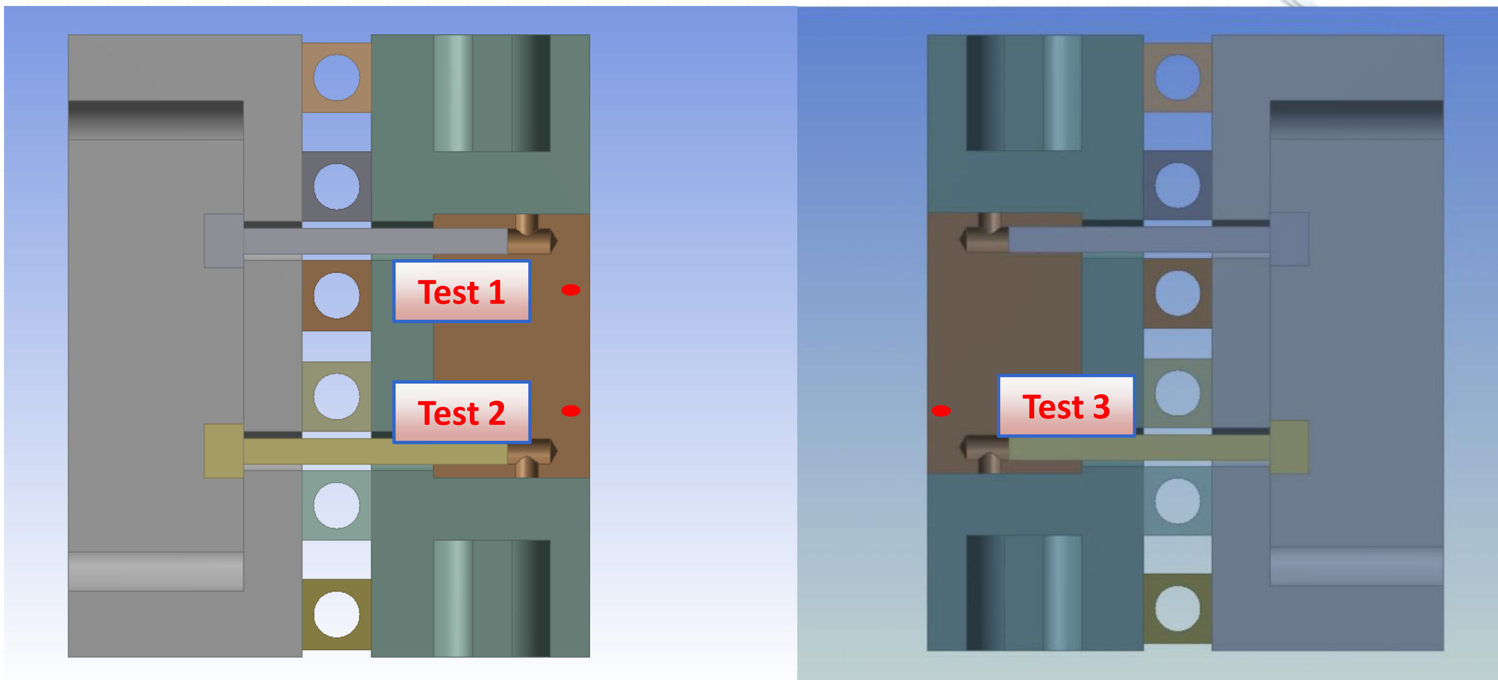
worse — better

** Estimated values*
*** with Mo coating*

- **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.
- **Cu-CD** exhibits a balanced compromise between TSNI, SSNI, electrical conductivity, density, atomic number. Its main limitation is the (relatively) low melting point.
- **Molybdenum-graphite** shows overall very promising figures of merit.

# HRMT09 Experiment

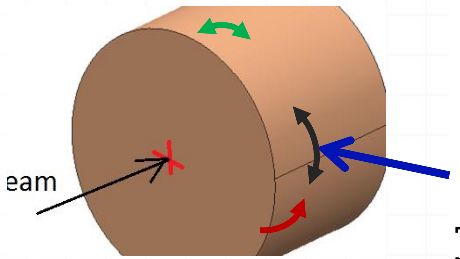
- Beam energy: **440 GeV**
- Impact depth: **2mm**
- Jaws half-gap: **14 mm**




| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| **Goal** | **Beam impact equivalent to 1 LHC bunch @ 7TeV** | **Identify onset of plastic damage** | **Induce severe damage on the collimator jaw** |
| **Impact location** | Left jaw, up (+10 mm) | Left jaw, down (-8.3 mm) | Right jaw, down (-8.3 mm) |
| **Pulse intensity [p]** | $3.36 \times 10^{12}$ | $1.04 \times 10^{12}$ | $9.34 \times 10^{12}$ |
| **Number of bunches** | 24 | 6 | 72 |
| **Bunch spacing [ns]** | 50 | 50 | 50 |
| **Beam size [$\sigma_x$ - $\sigma_y$ mm]** | 0.53 x 0.36 | 0.53 x 0.36 | 0.53 x 0.36 |

# 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