Advanced Composite Materials for Thermal Management Applications

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Advanced Materials and Surfaces
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Outline

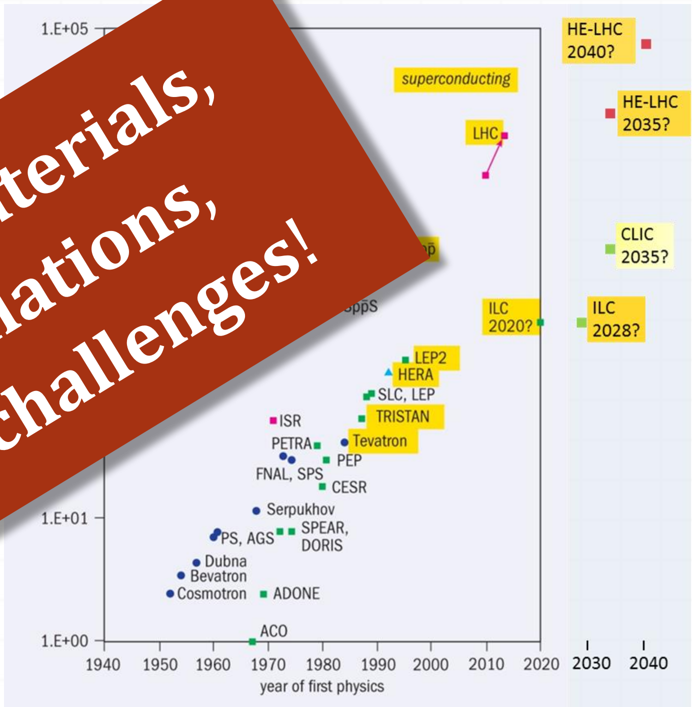
Engineering Department

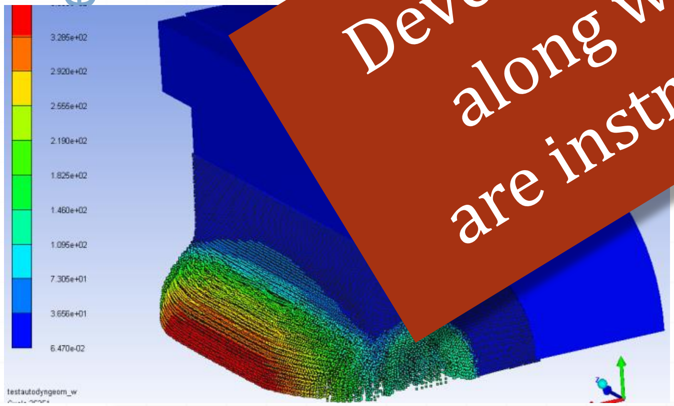
- Context
- What is a Collimator?
- Metal Matrix Composites
  - Copper-Diamond Composites
  - Molybdenum-Graphite Composites
- Material Tests in HiRadMat
- Further Applications …
- Summary and Perspectives

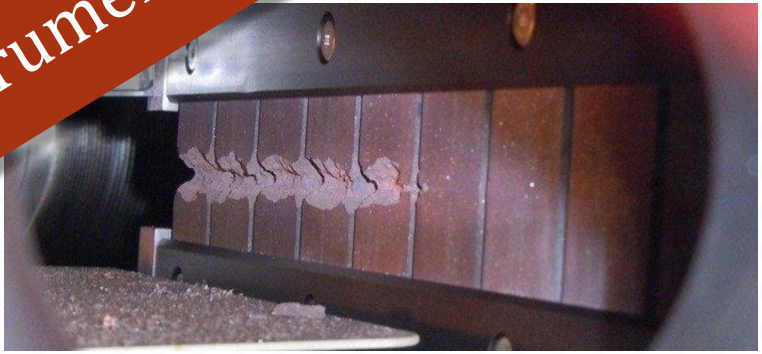
Context

- **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 events accelerators.
- **Collimators** (and all **Beam I** inherently exposed to s
- Collimators are machine **im** o serious **instabi**

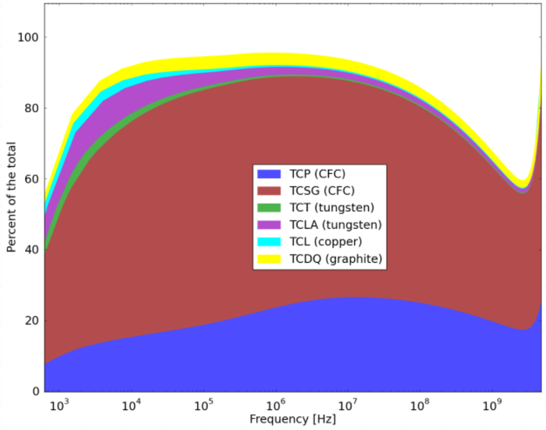
Development of **Novel advanced materials**, along with **state-of-the-art simulations**, are instrumental in **facing these challenges!**







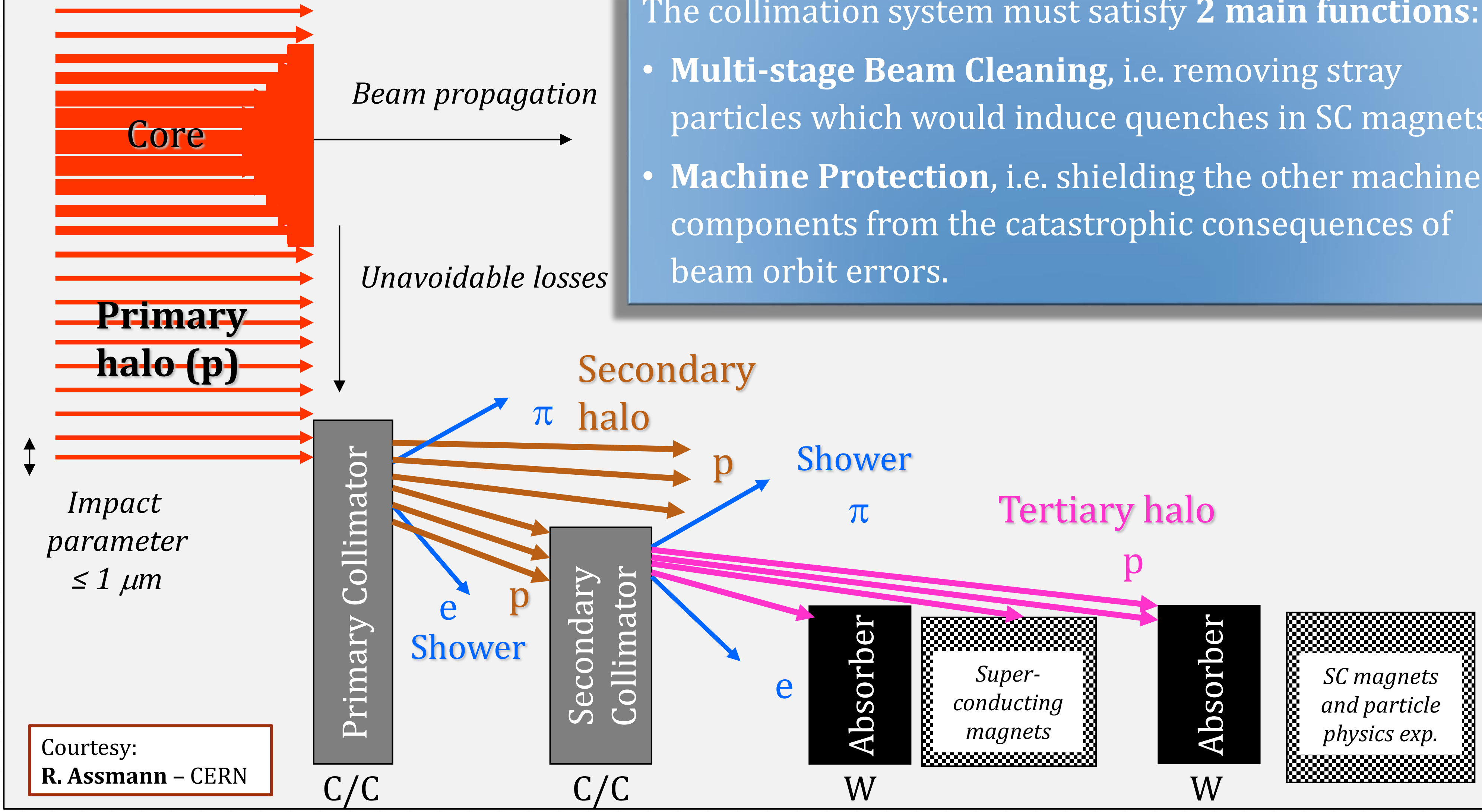
Collimators impedance/ LHC Impedance



What is a Collimator?

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.

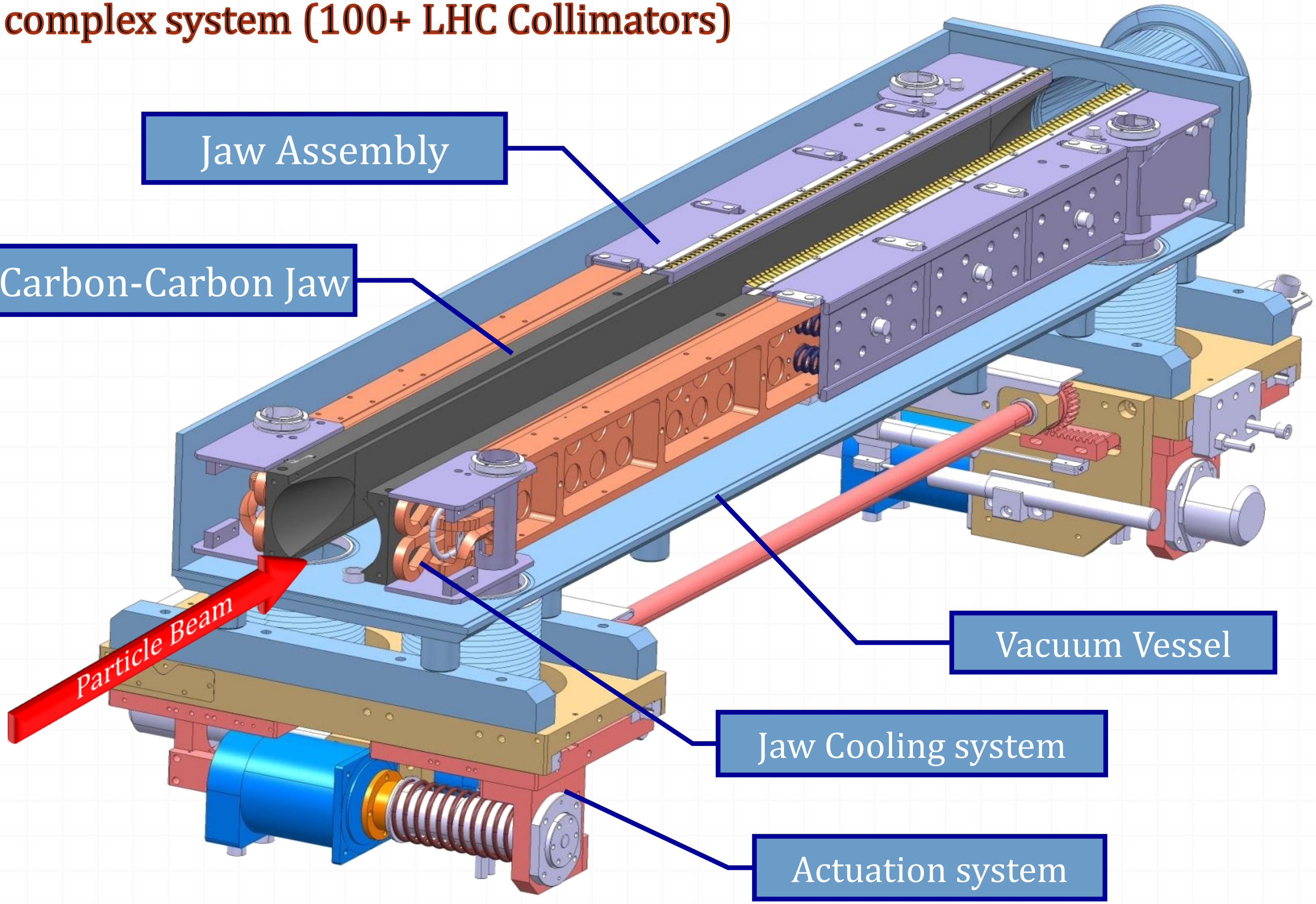


Courtesy:
R. Assmann – CERN

What is a Collimator?

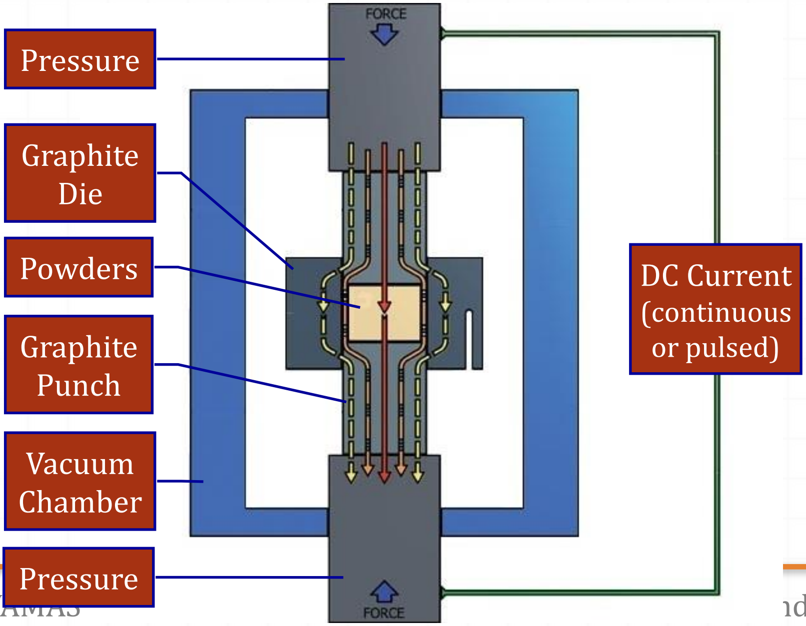
- Several types of collimators at multiple locations required.
- Very complex system (100+ LHC Collimators)

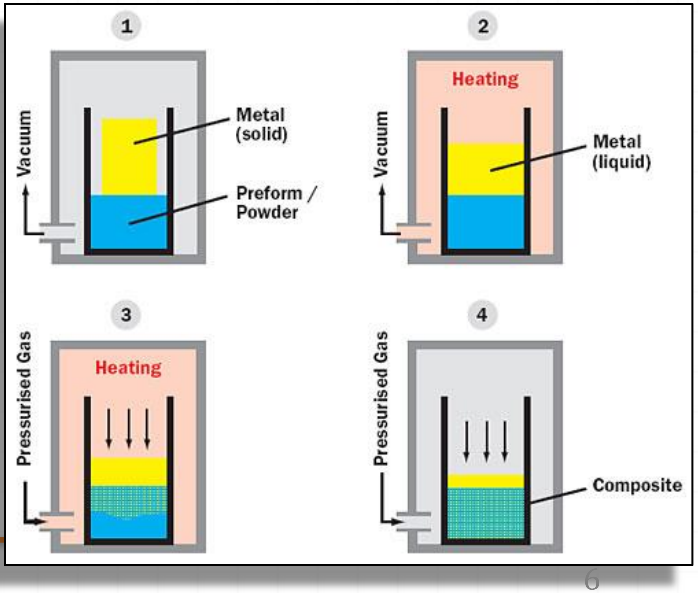
Secondary Collimator (TCSG) Cutaway



Metal Matrix Composites

- Material development program carried out pursuing **two complementary paths**:
  - **EuCARD** by **CERN**, **RHP-Technology**, **EPFL**, **Polito**, **GSI**, **NRC-KI** (superseded by **EuCARD^2**)
  - **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 ρ** and **low CTE**) with those of Metals (**strength**, **ductility**, γ, …).
- Production techniques include **Rapid Hot Pressing** (**RHP**), **Spark Plasma Sintering** (**SPS**), **Liquid Phase Sintering** and **Liquid Infiltration**.

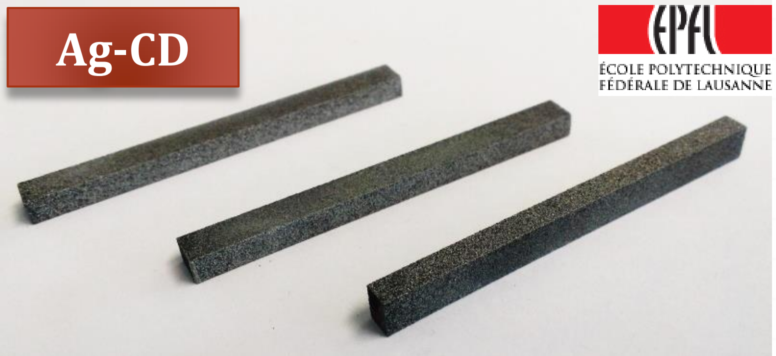




Metal Matrix Composites

- 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 is **easy to machine**, is **versatile** and can be **coated with** a **Mo layer** dramatically **increasing electrical conductivity** …

RHP TECHNOLOGY



Copper-Diamond Composite

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

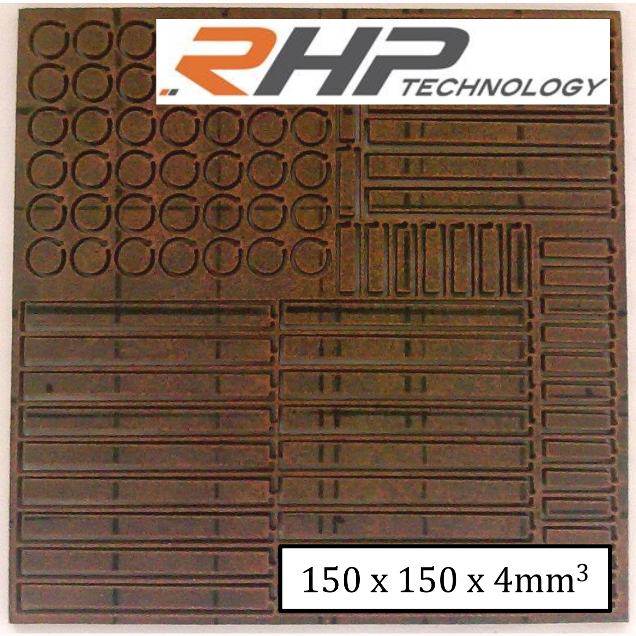
↑ No diamond degradation (in reducing atmosphere graphitisation starts at **~ 1300 °C**)

↑ Very good thermal (**~490 $Wm^{-1}K^{-1}$**) and electrical conductivity (**~12.6 MSm^{-1}**).

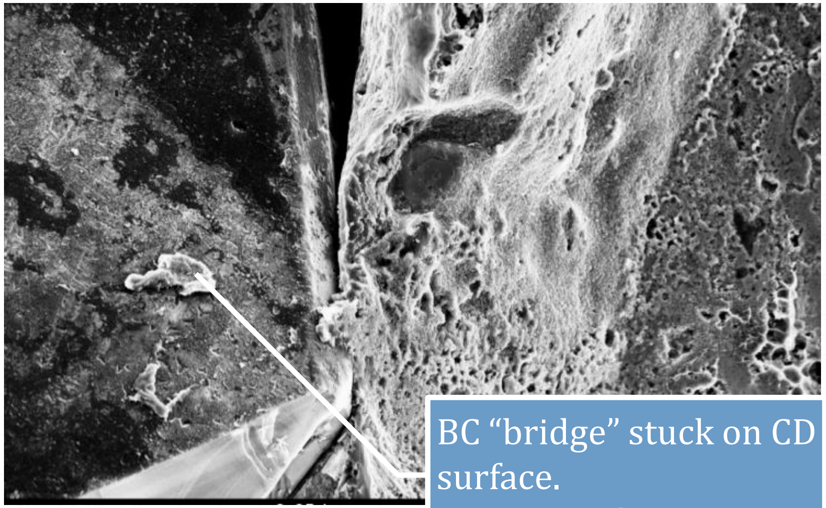
↔ No direct interface between Cu and CD (lack of affinity). Partial bonding bridging assured by Boron Carbides limits mechanical strength (**~120 MPa**).

↓ Cu low melting point (**1083 °C**) 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**)



150 x 150 x 4mm^3



BC “bridge” stuck on CD surface.
No CD graphitization

Molybdenum-Graphite Composites

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

Why Graphite?

- Low CTE
- Low Density
- High Thermal Conductivity (natural graphite flakes)
- Very High Service Temperatures (also allowing elevated processing temperatures)
- High Shockwave Damping

Composite Features

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

⬆ Low Density (can be tailored)

⬆ **Very high thermal conductivity**

⬆ Highly stable (forms MoC_{1-x} carbides)

↔ Fair electrical conductivity

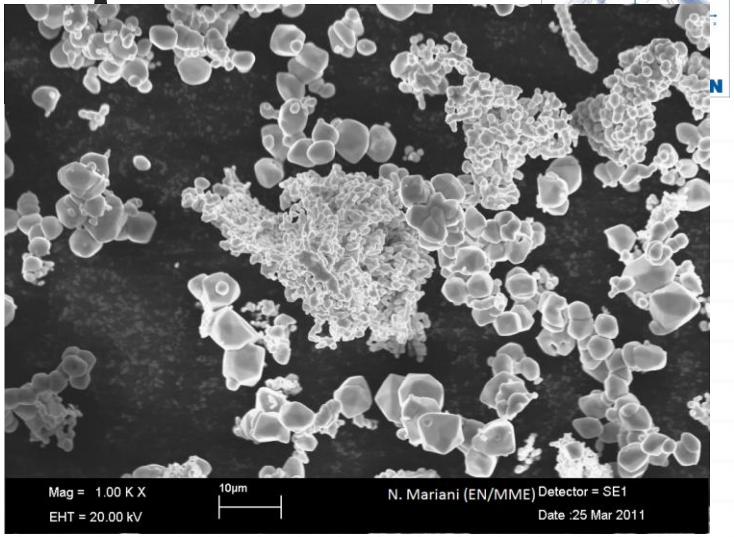
⬇ Mechanical strength to be improved …

Why Molybdenum?

- Refractory metal
- High mechanical strength
- Density lower than Tungsten

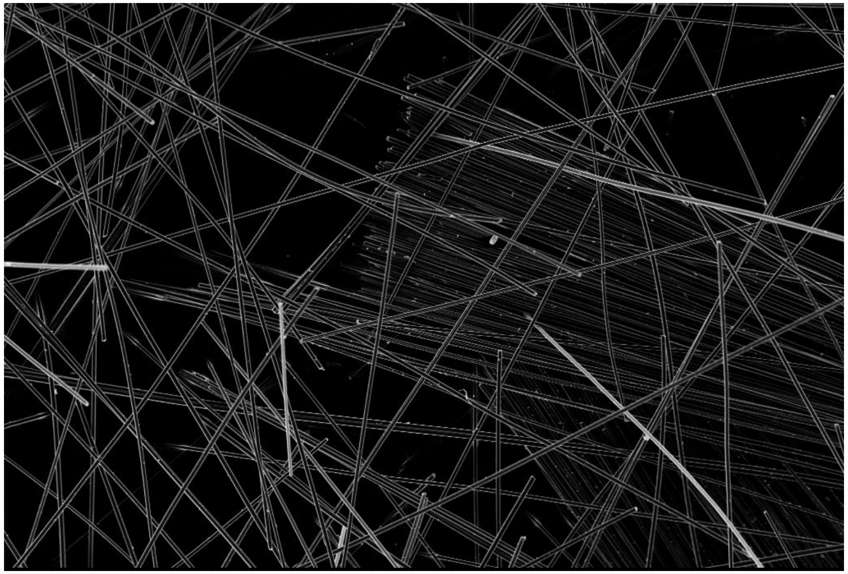
Molybdenum-Graphite Composites

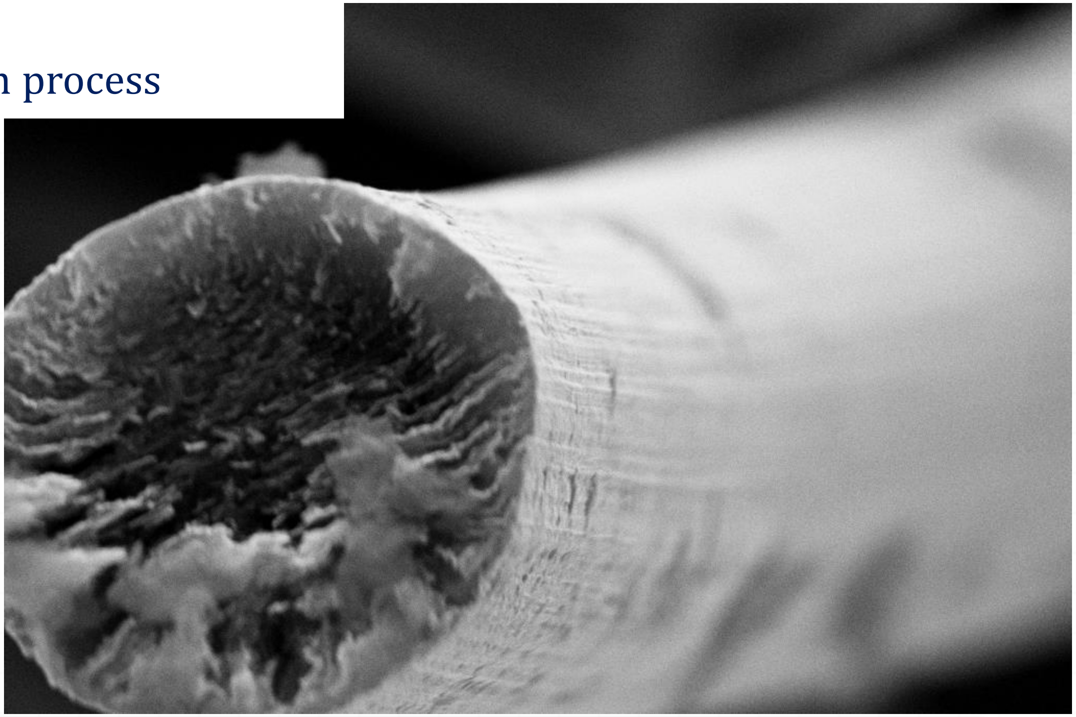
- Addition of **mesophase pitch-base carbon fibers**
- **Liquid Phase** Spark Plasma **Sintering (>2500° C)**



Advantages of Carbon Fibers addition

- Increase mechanical strength
- Contribute to high thermal conductivity (mesophase pitch grade)
- Along with MoC_{1-x} , catalyze graphitization process





Mo-Gr-CF Microstructures

- Homogeneous distribution of graphite, fibers and fine MoC_{1-x} grains
- Recrystallization of graphite and CF
- Highly Oriented **Graphene** planes
- Strong fiber-matrix bonding

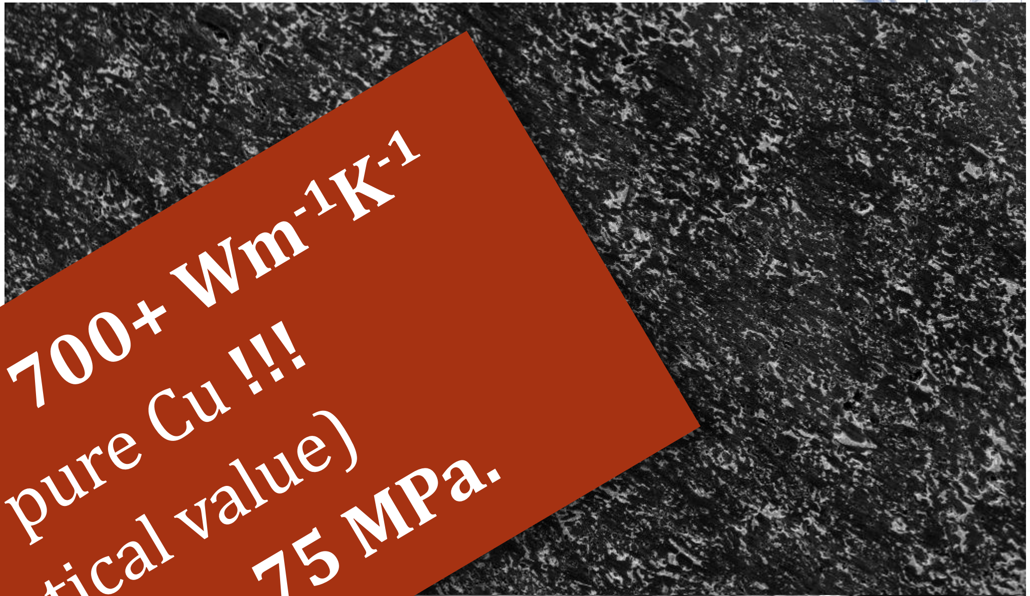
➔ **Improved Mechanical St**

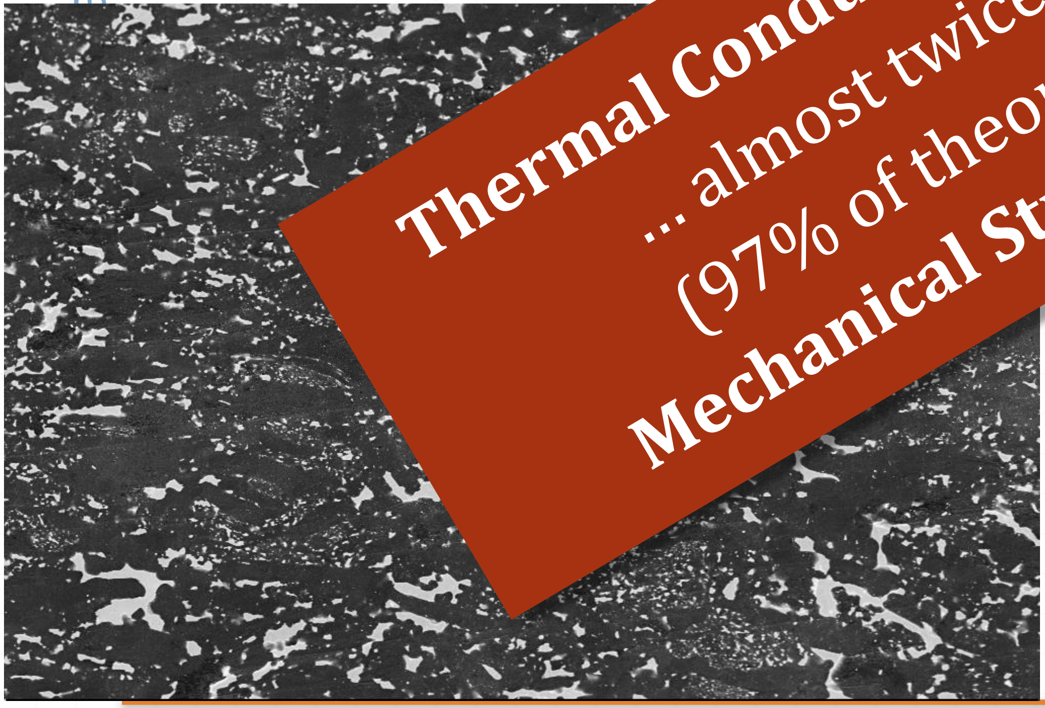
Thermal Conductivity 700+ $Wm^{-1}K^{-1}$

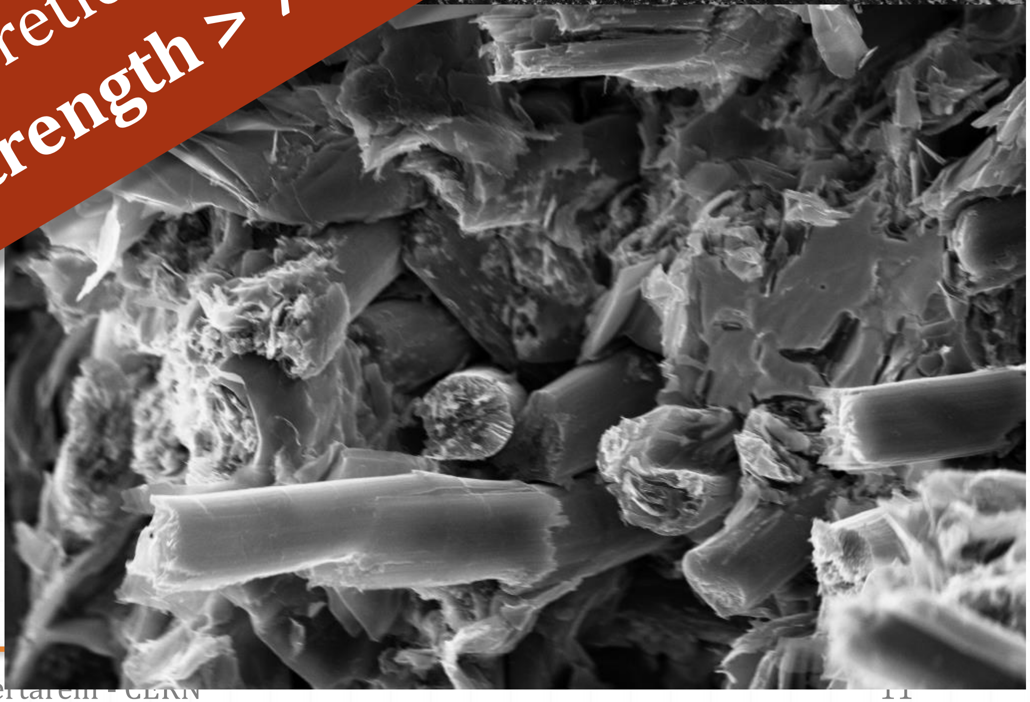
… almost twice pure Cu !!!

(97% of theoretical value)

Mechanical Strength > 75 MPa.



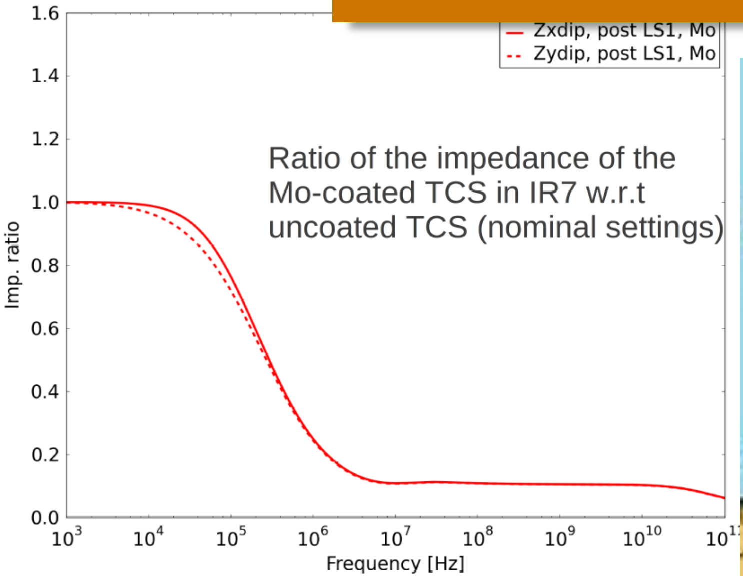




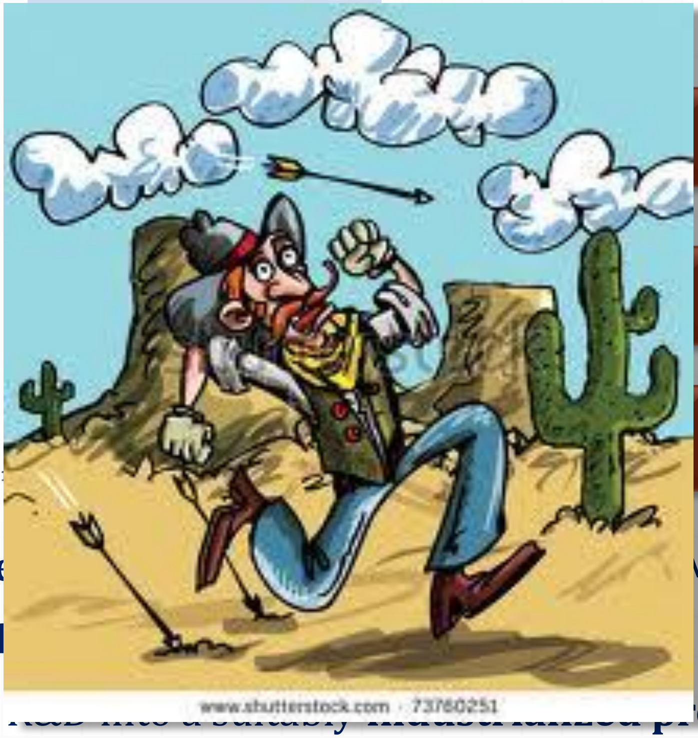
Mo-coated Mo-Gr

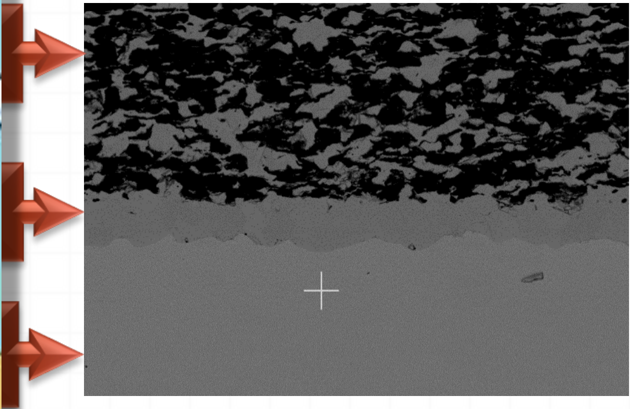
- Co-developed by **CERN** and **Brevetti Bizz.**
- Molybde
- **Sandwic**
- Excellent

We must cross the valley of death in a dreadfully short time!



Ratio of the impedance of the Mo-coated TCS in IR7 w.r.t uncoated TCS (nominal settings)





- Collimator **impedance reduce** … Mo-Gr.
- Wish to **install** soon **a full coll**
- 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)**

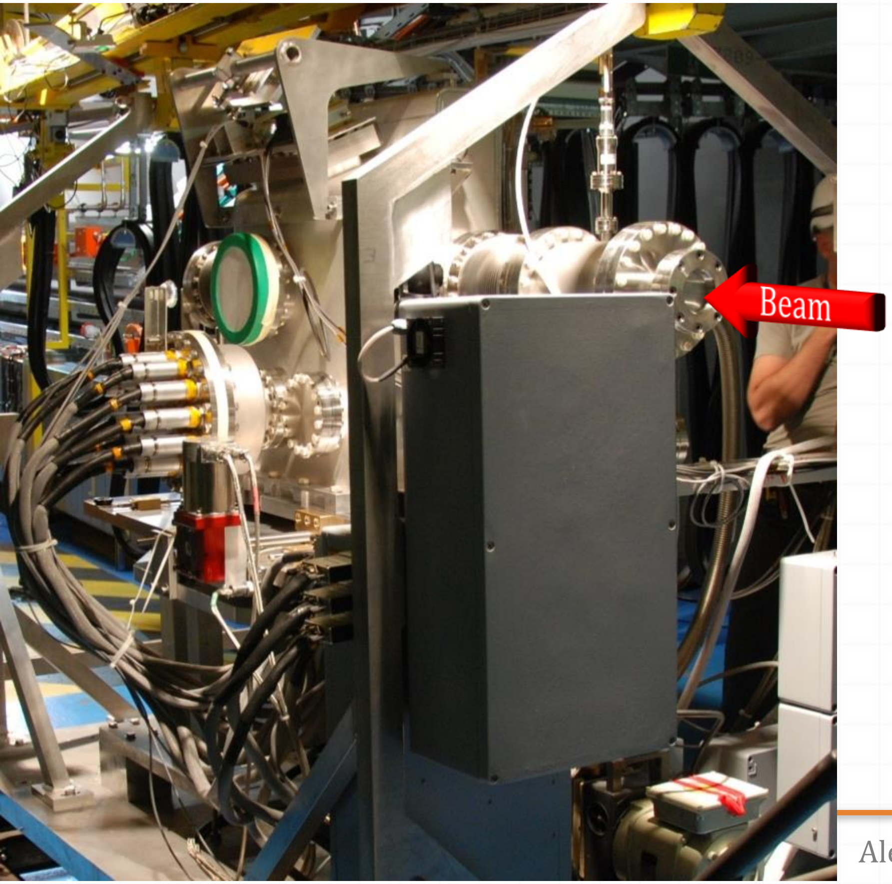
Material Tests in HiRadMat

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**).

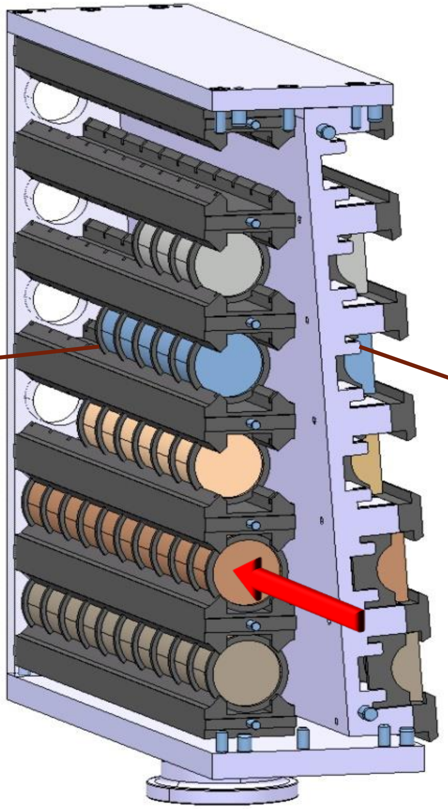
HRMT14 Experiment

- **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.

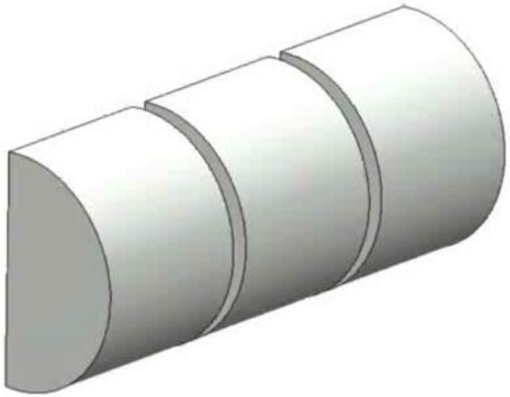


High Intensity Samples (Type 2)

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

HRTM14: High Intensity Tests

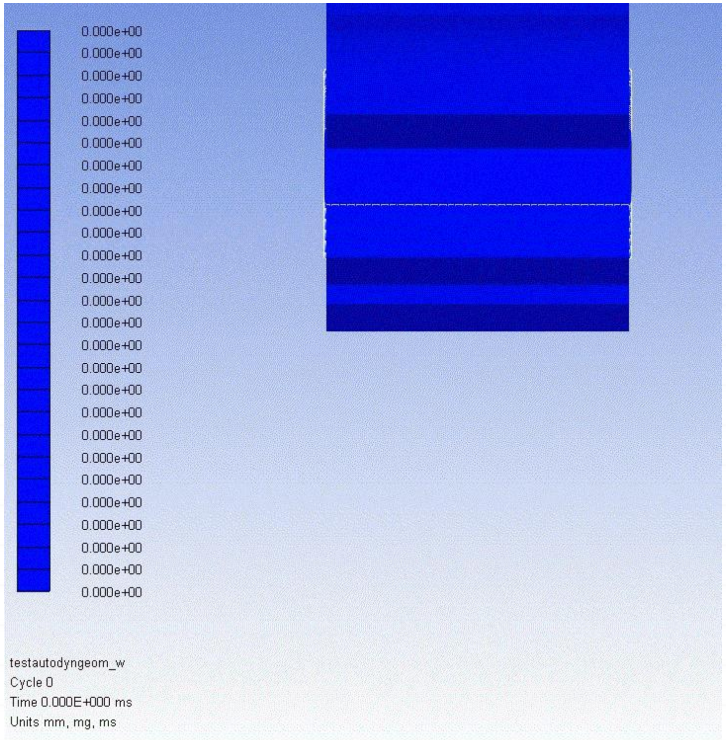
Inermet samples as seen from viewport and camera



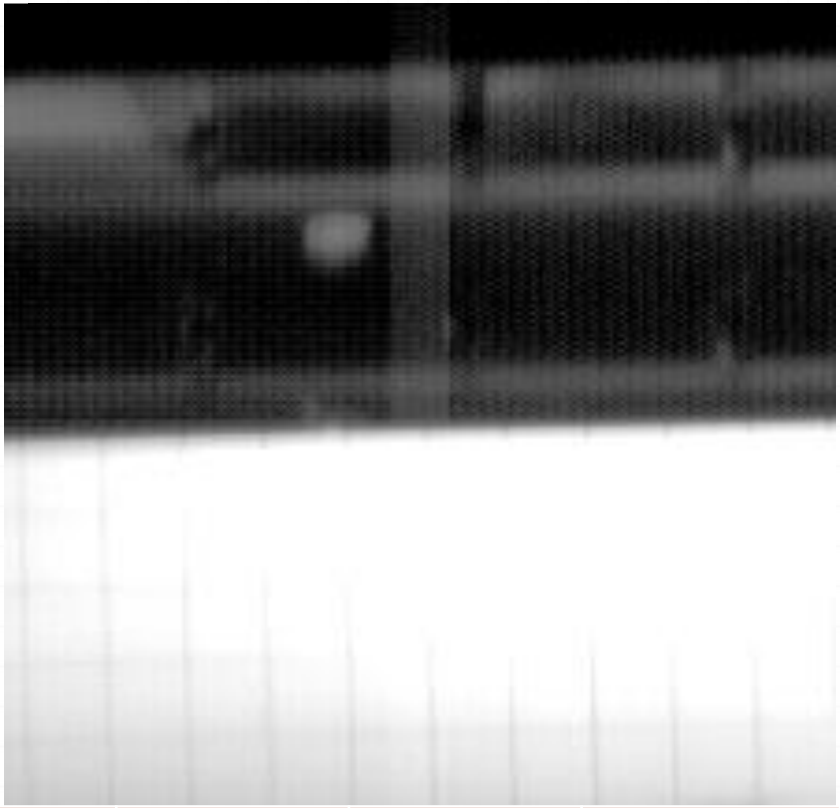
HRMT14: High Intensity Tests

Inermet : comparison Autodyn (SPH) between simulation and experiment

Beam

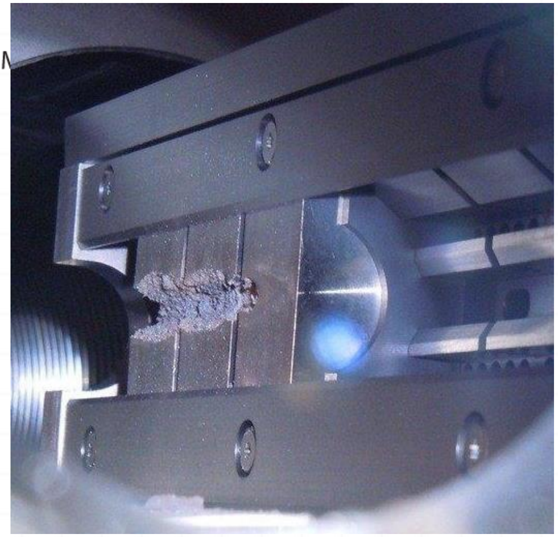


```
testautodyngeom_w
Cycle 0
Time 0.000E+000 ms
Units mm, mg, ms
```

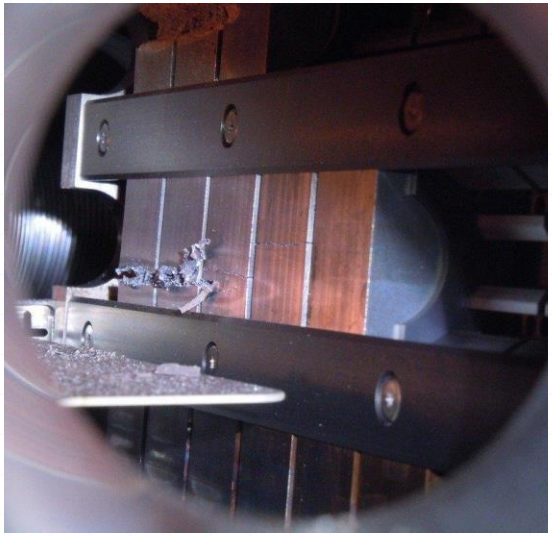


Case	Bunches	p/bunch	Total Intensity	Beam Sigma	Specimen Slot	Velocity
Simulation	60	1.5e11	9.0e12 p	2.5 mm	9	**316 m/s**
Experiment	72	1.26e11	9.0e12 p	1.9 mm	8 (partly 9)	**~275 m/s**

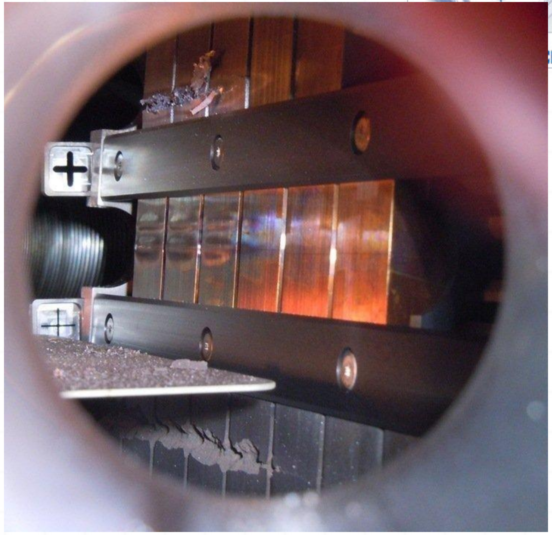
HRMT14: High Intensity Tests



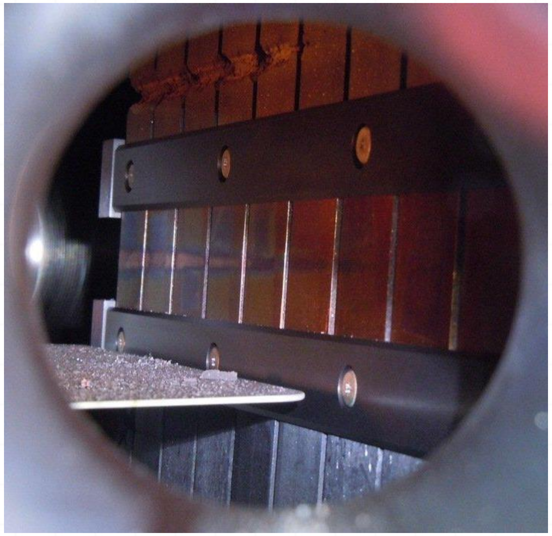
Inermet 180, 72 bunches



Molybdenum, 72 & 144 bunches

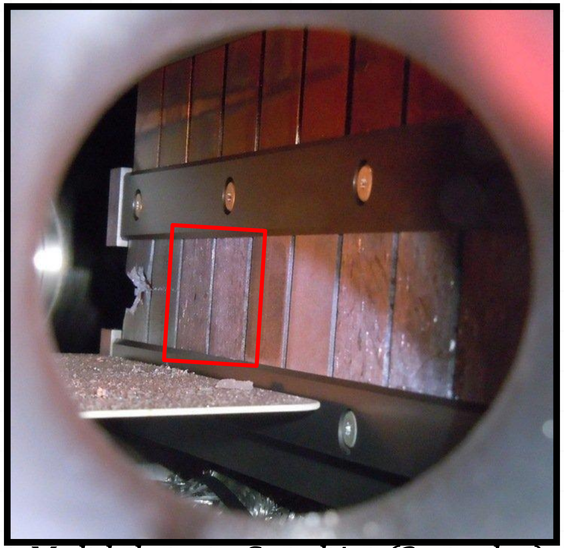


Glidcop, 72 bunches (2 x)



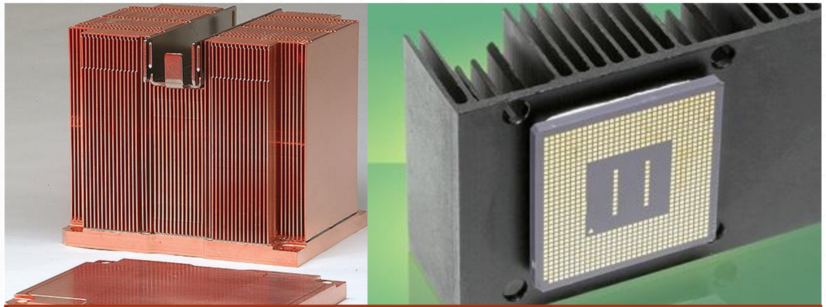
Copper-Diamond
144 bunches

Molybdenum-Copper-Diamond
144 bunches



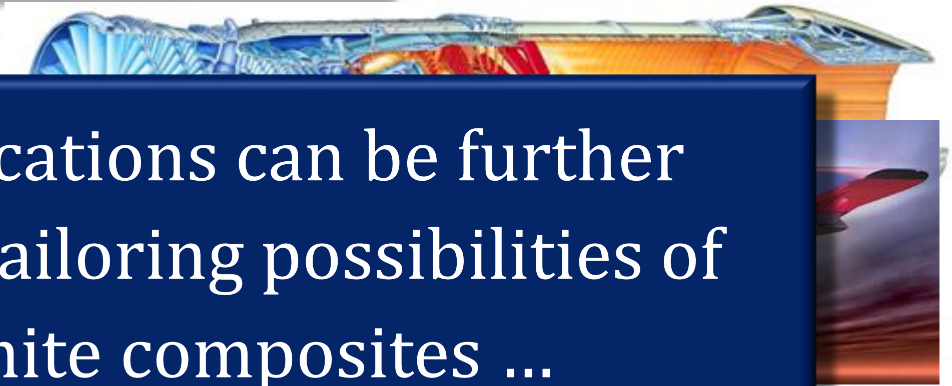
Molybdenum-Graphite (3 grades)
144 bunches

Mo-Gr Further Applications …



Thermal Management for High Power Electronics

Fusio



Potential range of applications can be further expanded thanks to the tailoring possibilities of Molybdenum-Graphite composites …

Advanced Braking Systems

Solar Energy Applications

Summary and Perspectives

- Bringing LH new generation of collimators
- An ambitio n two complementary paths : EuC evetti Bizz.
- Cu-CD, Ag-C ed.
- Outstandin mal conductivity (700+ Wm^{-}
- RF studies s ance by a factor 10.
- A full LHC C d in the LHC ...
- ... this calls f gram while progressing
- Newly developed materials are appealing for a broad range of industrial applications and have the potential for a real impact on society …

CERN

Thank you for your attention!

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**

  γ

- **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 temperatu**

  Increase **Melting Temperature**.

  T_m

Note Conflicting requirements as to Density

Additional “standard” requirements include …

- Radiation Hardness, UHV Compatibility, Industrial feasibility of large components, Possibility to Machine, Braze, Join, Coat ..., Toughness, Cost …

Material Ranking

Material	C-C	Mo	Glidcop ®	Cu-CD	Ag-CD	Mo-Gr
Density [g/cm^3]	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**

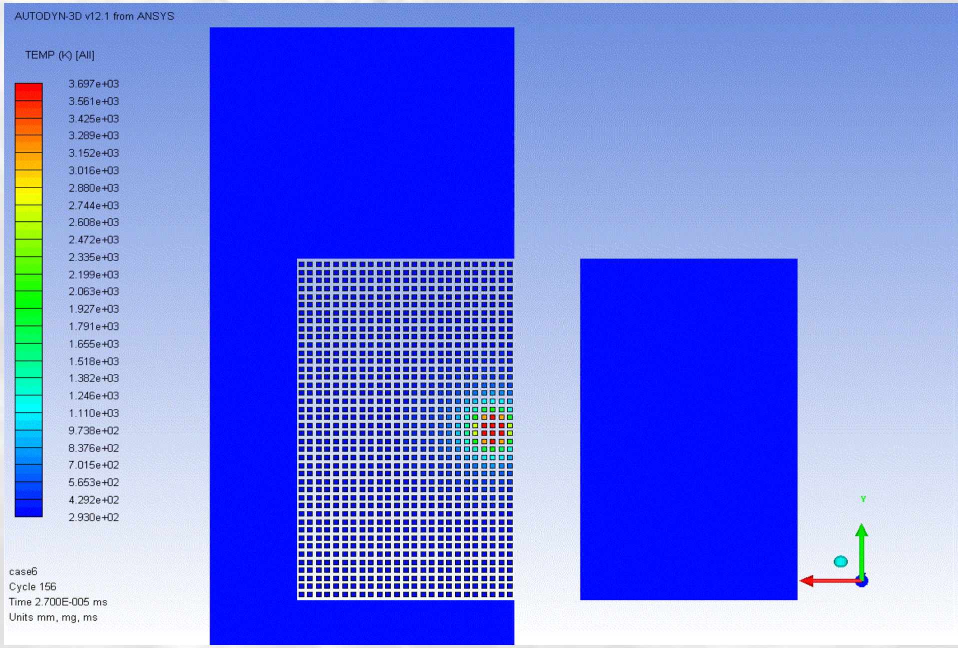
** Estimated values*
*** with Mo coating*

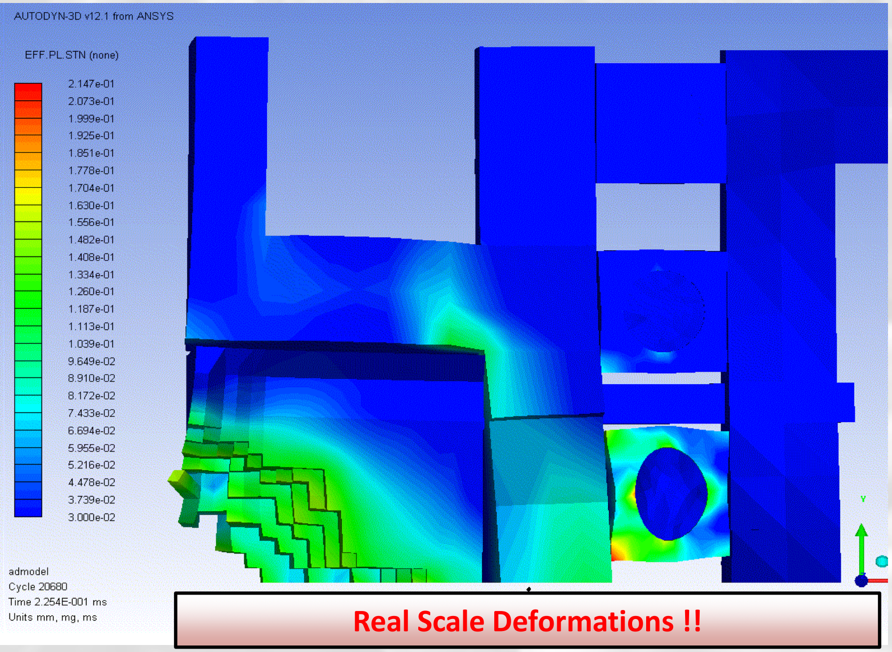
- **C-C** stands out as to thermo-mechanical performances. Adversely outweighed by poor electrical conductivity, low Z, expected degradation under irradiation.
- **High-Z metals (Cu, Mo)** possess very good electrical properties. High density adversely affects their thermal stability and accident robustness.
- **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.

Example of an Accidental Impact

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**, $\mathbf{V_{max} \approx 1\ km/s}$) 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.

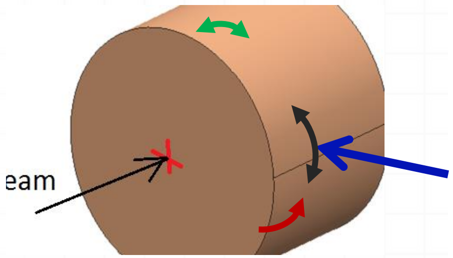


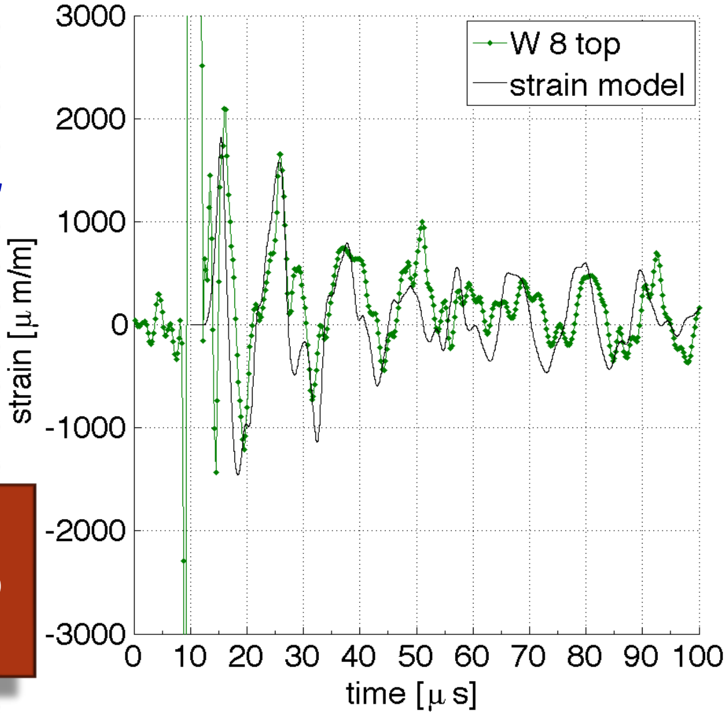


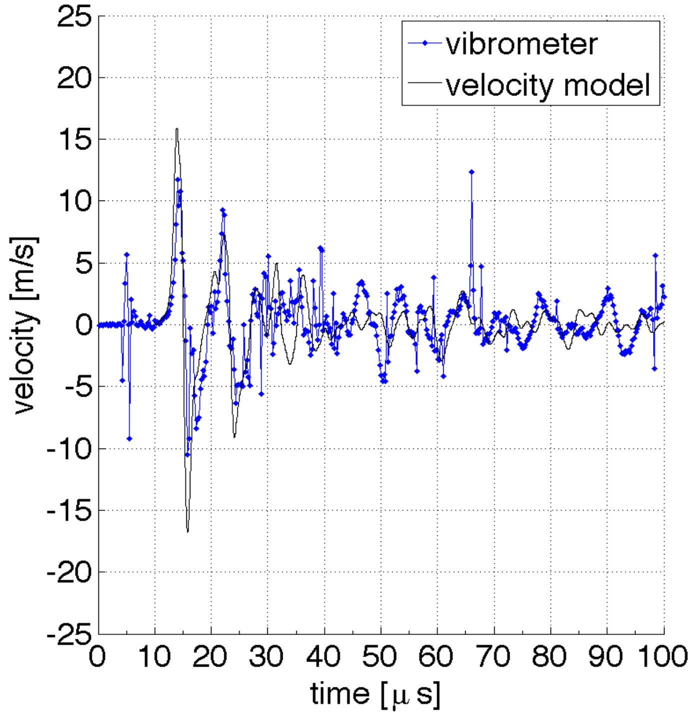
Real Scale Deformations !!

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