Advanced Materials for Next-generation Collimators

WP8 (ColMat) Highlight Talk

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EuCARD 3rd Annual Meeting
WUT Warsaw –*April 24-27, 2012*

Outlook

- Context and (Task 8.2) Objectives
- Status of Task 8.2 Activities
  - R&D on Novel Materials
  - Advanced Numerical Simulations
  - Material Testing
  - Phase II Prototype Design and Manufacturing
- Future Outlook
- Conclusions

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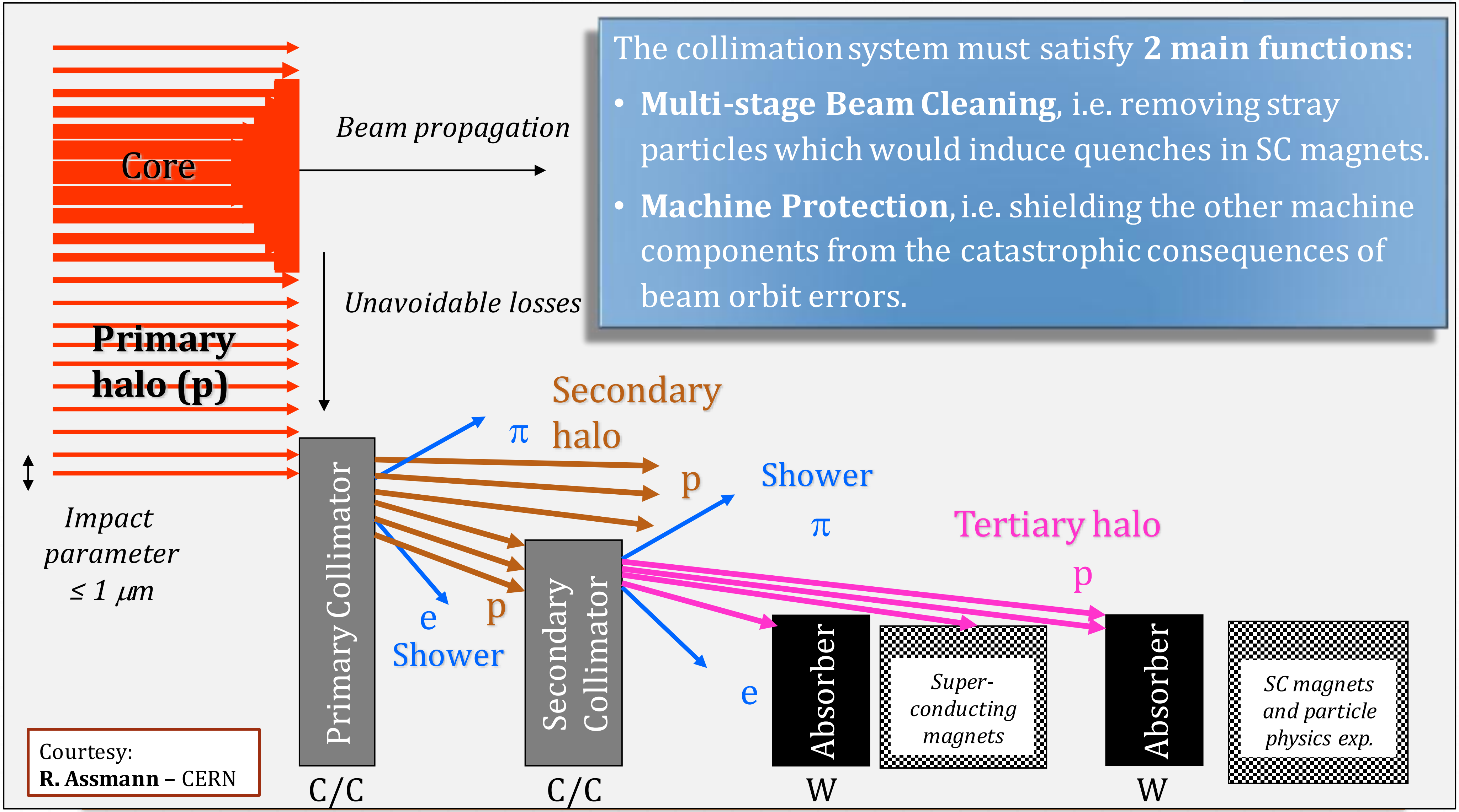
Context

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.



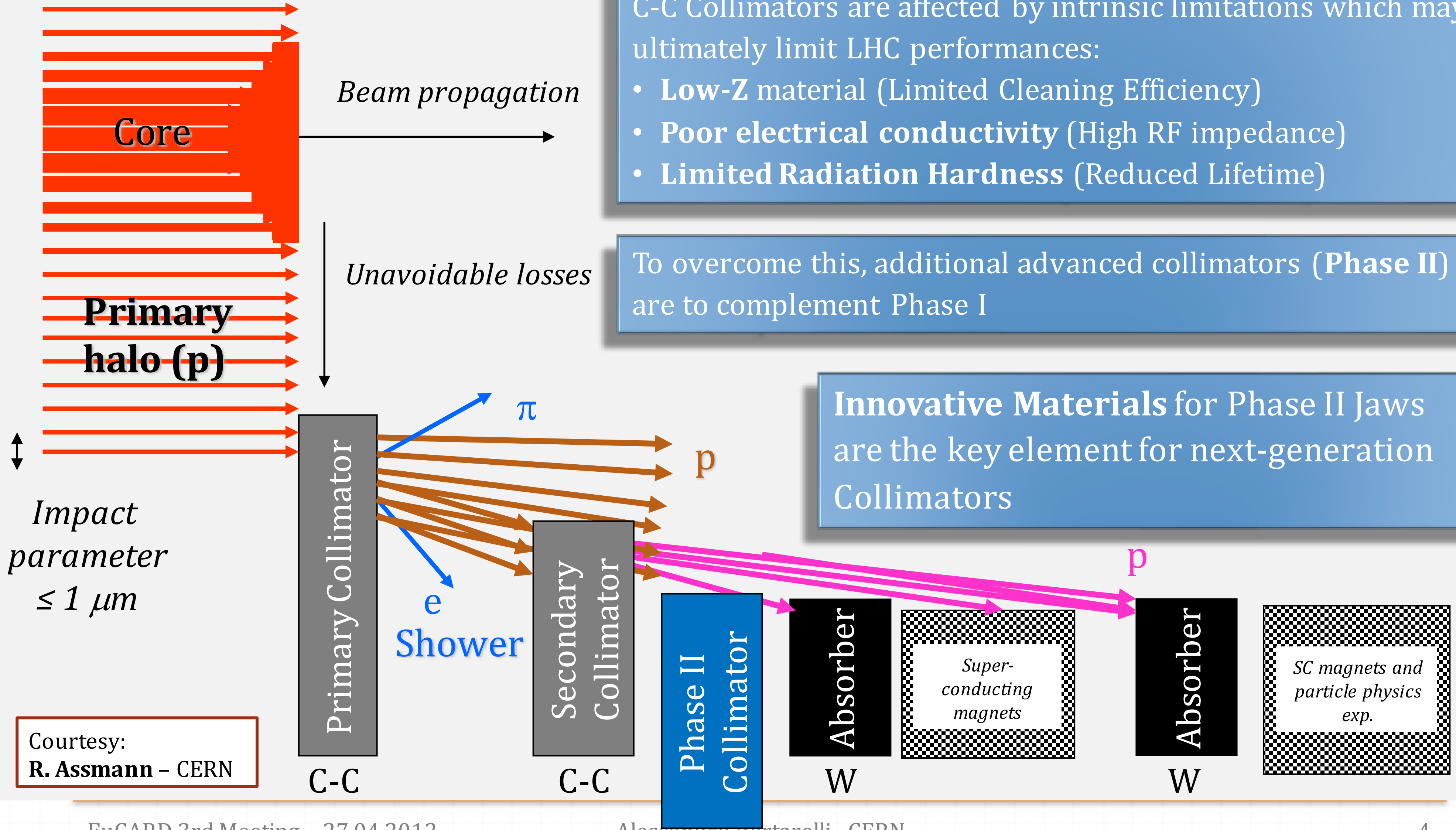
Context

C-C Collimators are affected by intrinsic limitations which may ultimately limit LHC performances:

- **Low-Z** material (Limited Cleaning Efficiency)
- **Poor electrical conductivity** (High RF impedance)
- **Limited Radiation Hardness** (Reduced Lifetime)

To overcome this, additional advanced collimators (**Phase II**) are to complement Phase I

Innovative Materials for Phase II Jaws are the key element for next-generation Collimators

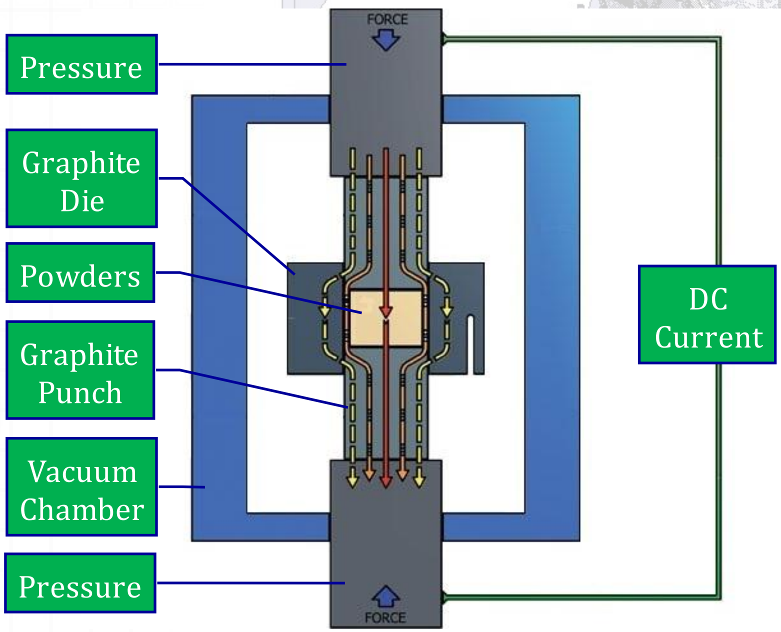


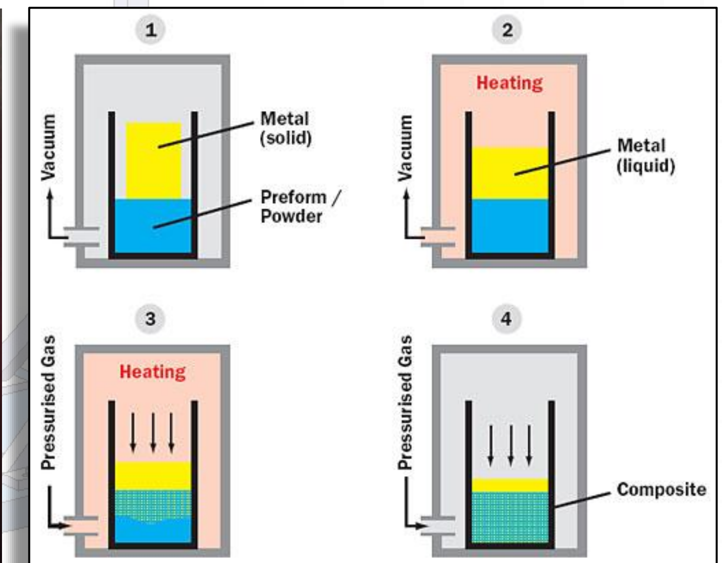
Courtesy:
R. Assmann – CERN

Task 8.2 Activities

Metal Matrix Composites

- R&D focuses on **Metal Matrix Composites (MMC)** with Diamond or Graphite reinforcements as they have the potential to combine the properties of Diamond or Graphite (high ***k*,** low ρ and low ***CTE***) with those of Metals (**strength**, γ, …**)**.
- Sintering techniques include **Rapid Hot Pressing** (**RHP**) and **Liquid Infiltration. Spark Plasma Sintering** (**SPS**) will come soon.
- Materials being investigated are **Copper-diamond** (**Cu-CD**), **Molybdenum-diamond** (**Mo-CD**), **Silver-diamond** (**Ag-CD**), **Molybdenum Graphite (Mo-Gr)**





Cu-CD Composite

- Developed by **RHP-Technology** (Austria)
- Produced by Rapid Hot Pressing (**RHP**).
- 60% Diamond, 40% Cu

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

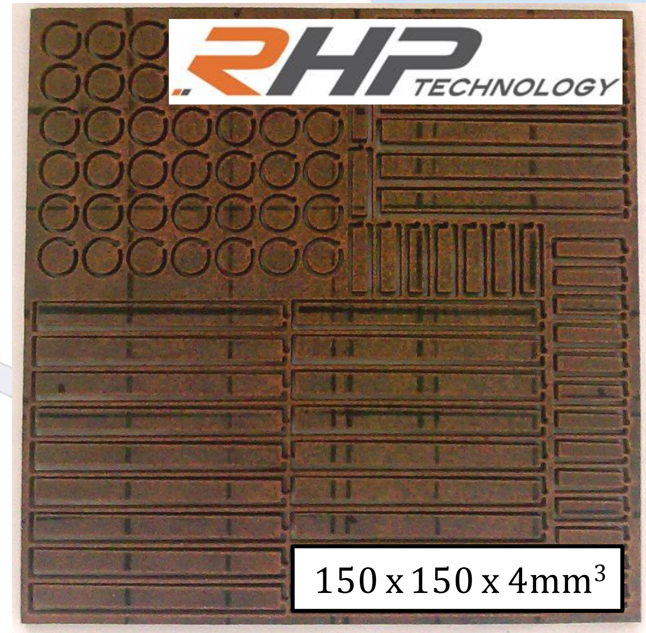
↑ Good thermal (**~490 W/mK**) and electrical conductivity (**~12.6 MS/m**).

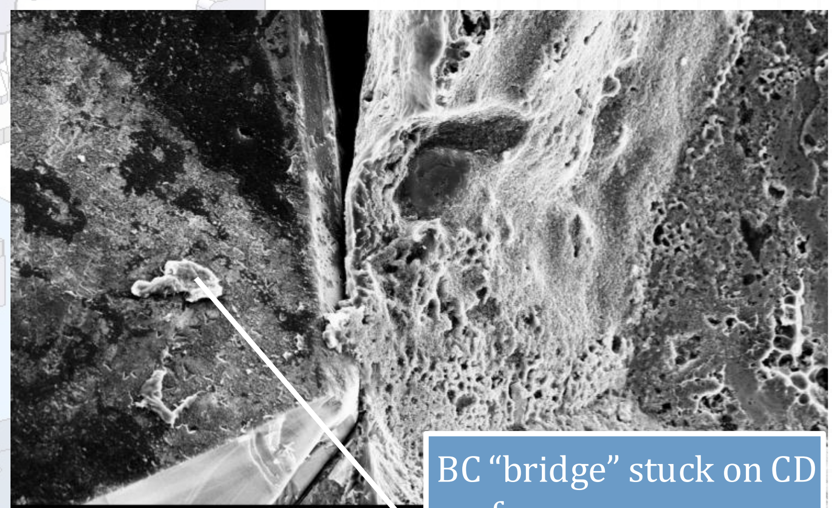
↓ No direct interface between Cu and CD (lack of affinity). Limited bonding surface assured by Boron Carbides hampers mechanical strength (**~120 MPa**).

↓ 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**)




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

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Ag-CD Composite

- Developed by **EPFL**, Switzerland.
- Manufactured by Liquid Infiltration
- ~60% Diamond, ~40% Ag-Si alloy

↑ Excellent bonding between Ag and CD assured by SiC formation on diamond.

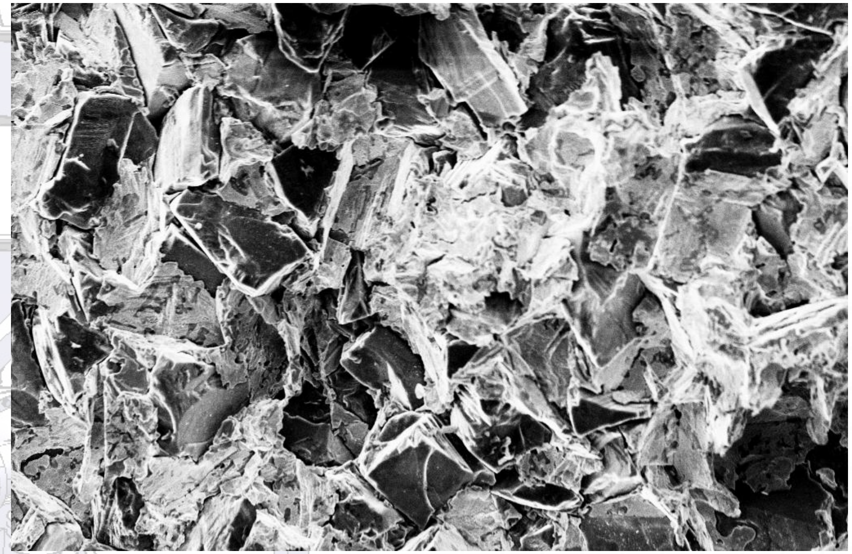
↑ High Flexural Strength (**~500 MPa**) and toughness.

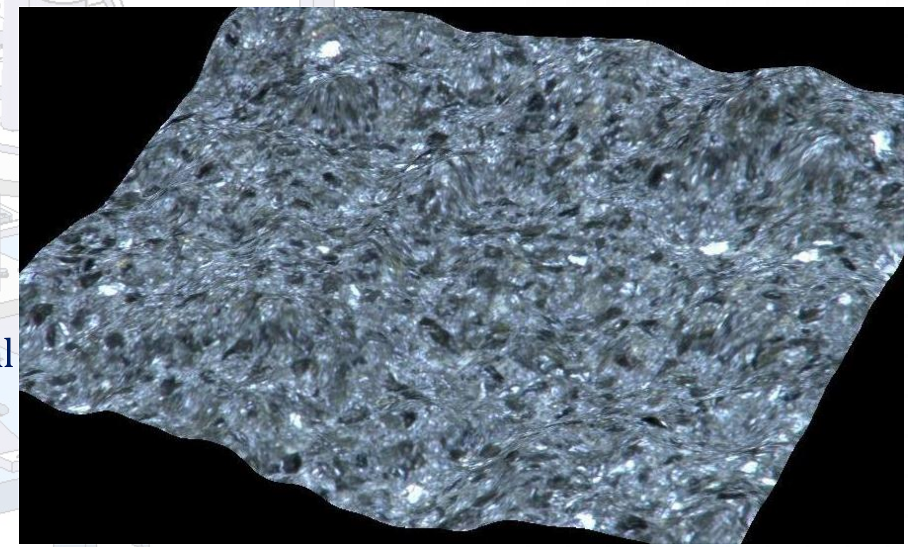
↑ High Electrical Conductivity.

↓ Max $T_{Service}$ limited by low-melting eutectic phase Ag-Si (**840 °C**).

↓ Hard to manufacture large components (>100 mm)

↓ Material non homogeneities induced by liquid metal infiltration intrinsic limitations.





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Mo-CD Composites

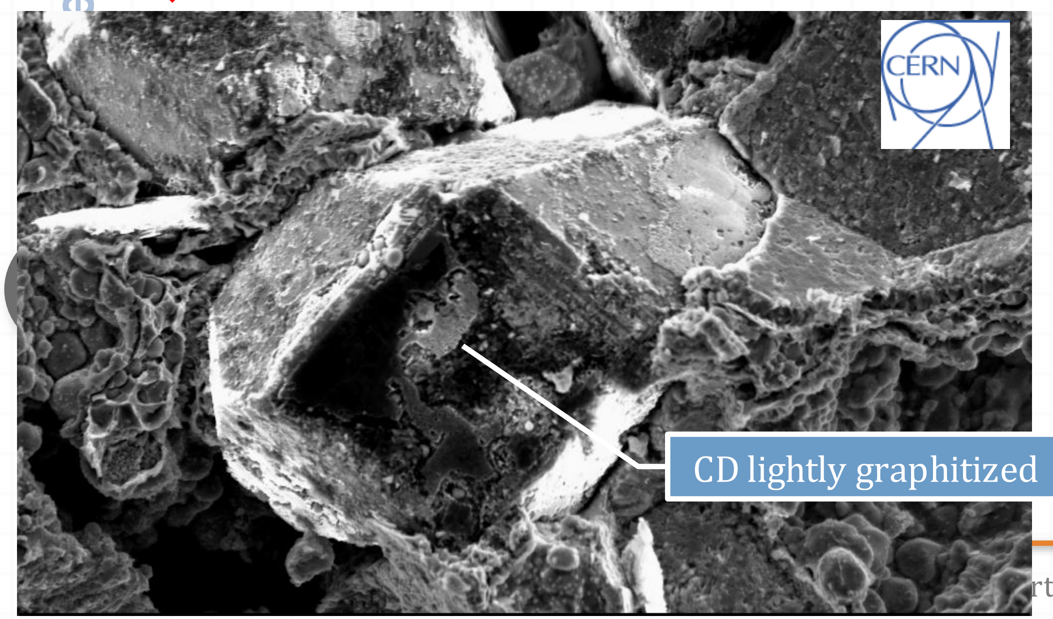
- Co-developed by **CERN** and a SME, **Brevetti Bizz**, Verona, Italy
- High sintering T of Mo (~**1700 °C**) leads to diamond graphitisation. 2 alternative processes: **Liquid Phase Sintering** (**LPS**) or **Assisted Solid-state Sintering** (**ASS**)

LPS

↑ Addition of low-melting phase (Cu) to fill in the pores between Mo and CD

↑ Good mechanical strength (400+ MPa) and fair Thermal Conductivity (185 W/mK)

↓ Max $T_{Service}$ limited by low-melting phase (Cu)



ASS

↑ Addition of activating elements (Ni, Pd) enhances Mo sintering at low T (~1300 °C)

↑ Absence of low-melting phase increases $T_{Service}$ up to ~2600 °C

↓ Large diamond particles interfere with Mo compaction.

↓ Diamond graphitization not fully avoided.

Mo-Gr Composites

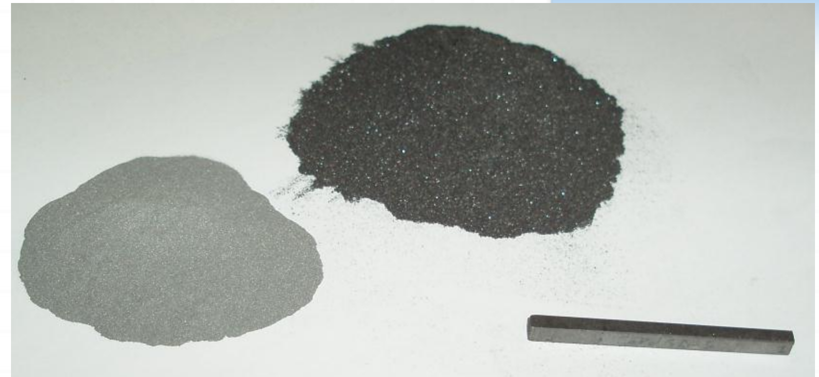
- Co-developed by **CERN** and **Brevetti Bizz**.

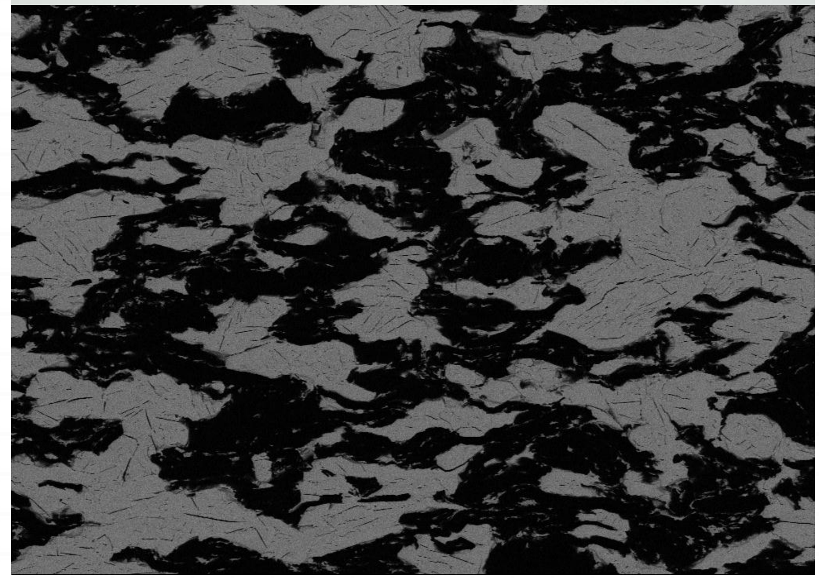
Why Graphite?

- Low CTE
- Low Density
- High Thermal Conductivity (grade-dependent)
- High Melting (degradation) point
- High Shock wave damping

Comparison with Mo-CD:

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





- Mo-Gr still under intense R&D program.
- Margin of improvements by optimizing base materials, composition and processes.

Mo-Gr/Mo Sandwich

- Co-developed by **CERN** and **Brevetti Bizz**.
- Molybdenum – Graphite core with layers of pure Mo.
- Sandwich structure drastically increases electrical conductivity.
- Up 1 mm thick Mo layer perfectly bonded.

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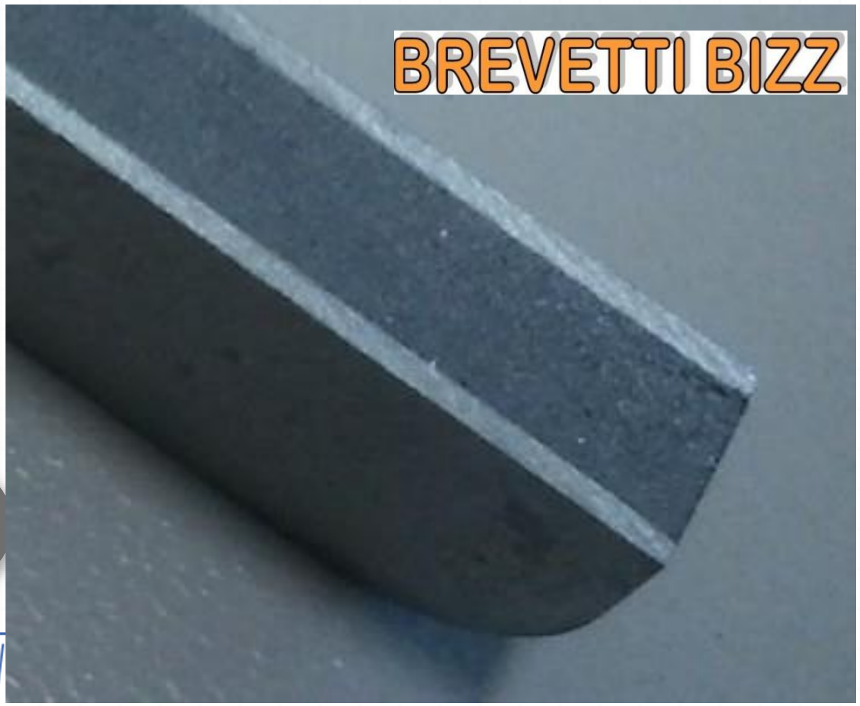
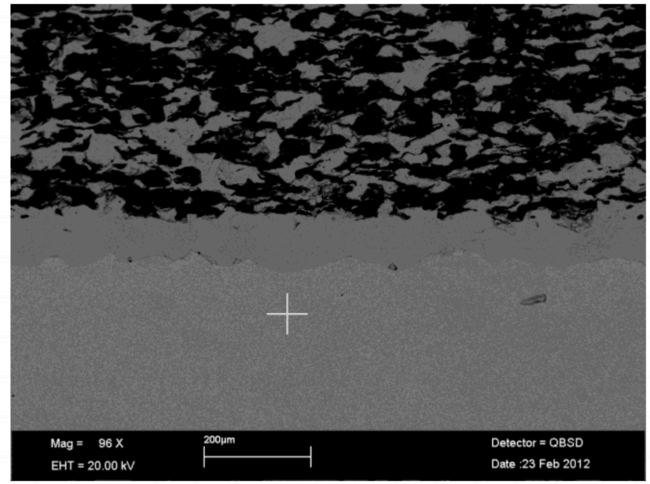
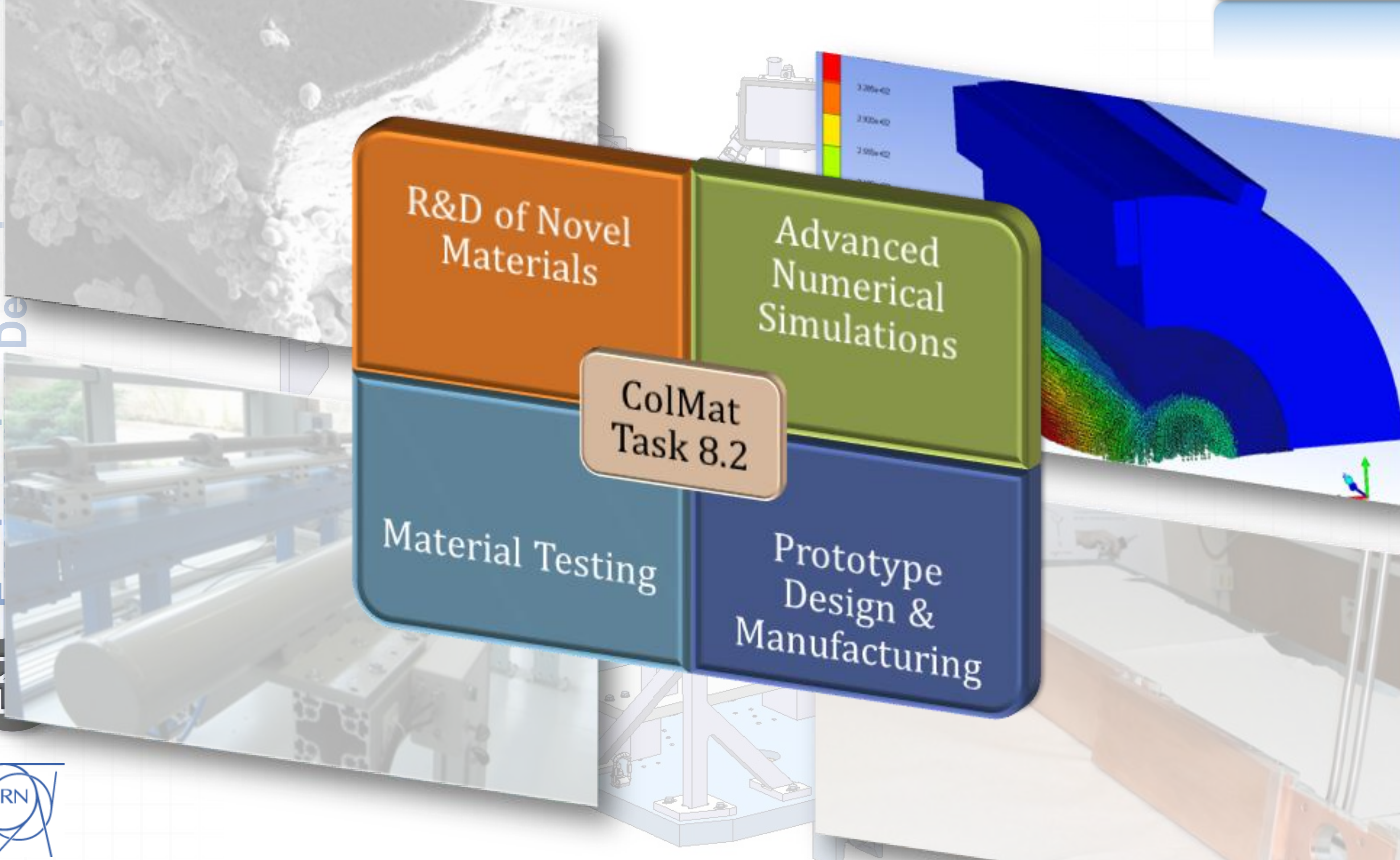




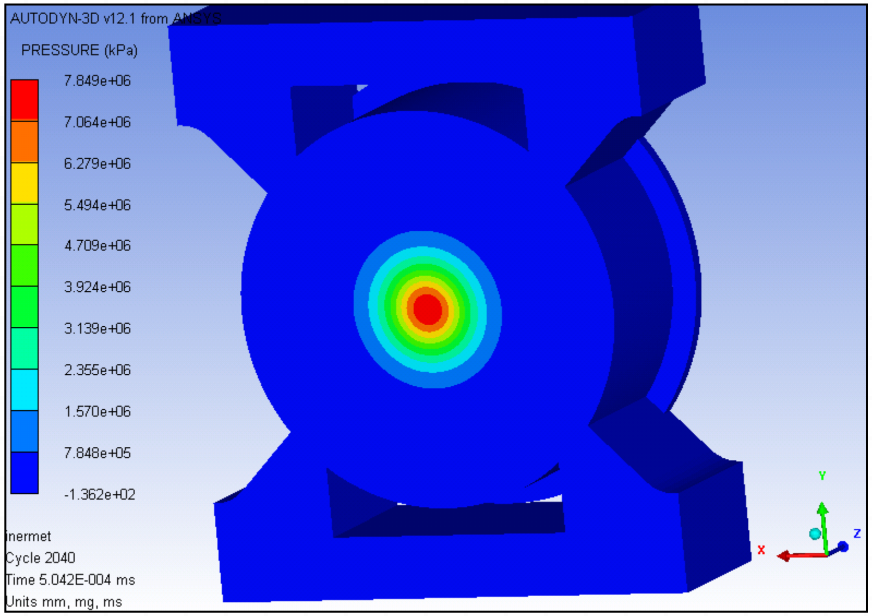
Density (g/cm3)	Electrical Conductivity (MS/m)	Thermal Conductivity (W/mK)	Flexural Strength (MPa)
6.68	18	under characterization	260

Task 8.2 Activities



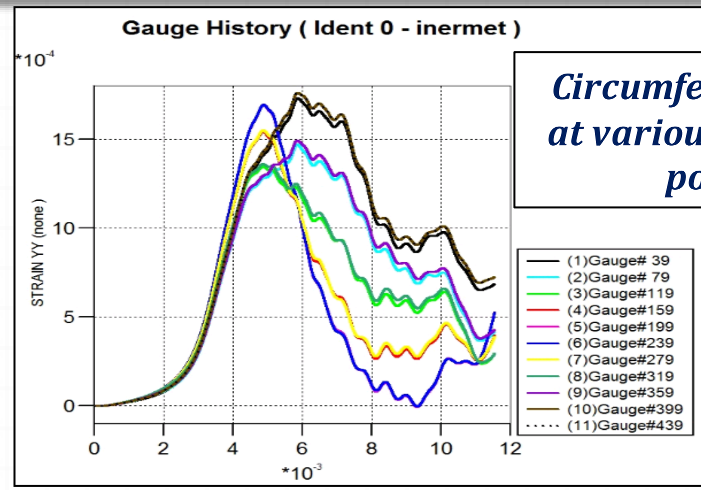
Shock-wave Analysis

Extensive Complex Calculations of Beam-induced Shockwaves with advanced non-linear tools (**Hydrocodes – Autodyn**)

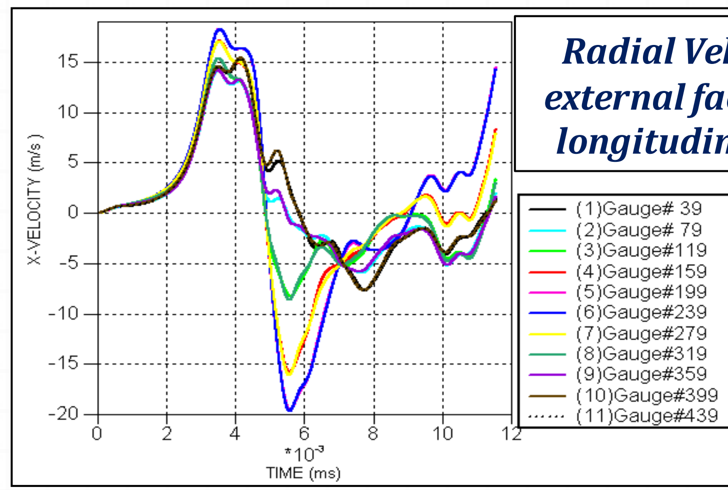


Pressure wave after 500 ns (peak ~8 GPa)

Impact of 20 bunches at 440 GeV (3E12 p) on a Tungsten cylindrical specimen



Circumferential Strain at various longitudinal positions



Radial Velocity on the external face at various longitudinal positions

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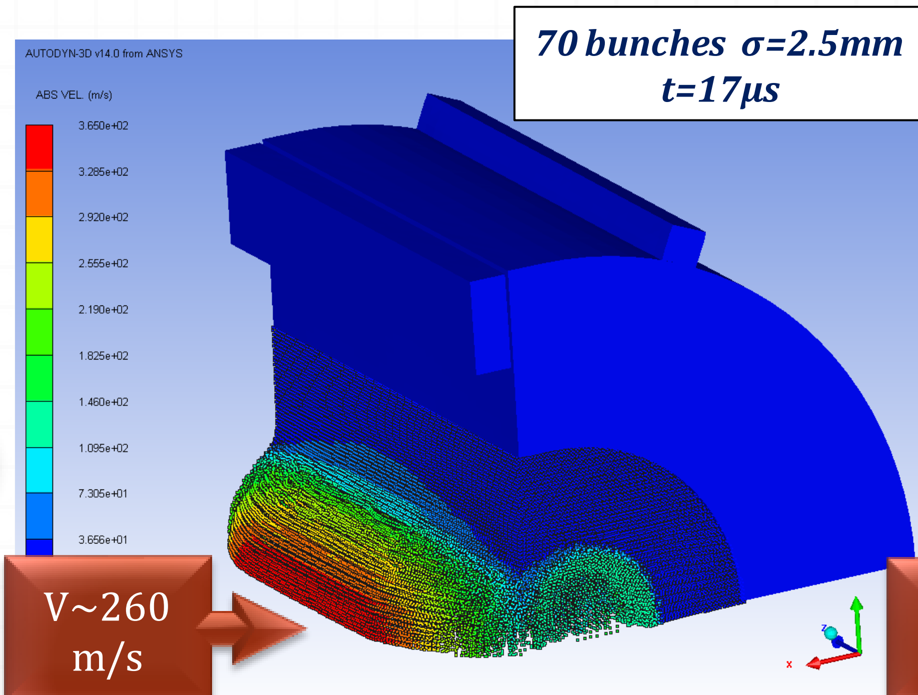
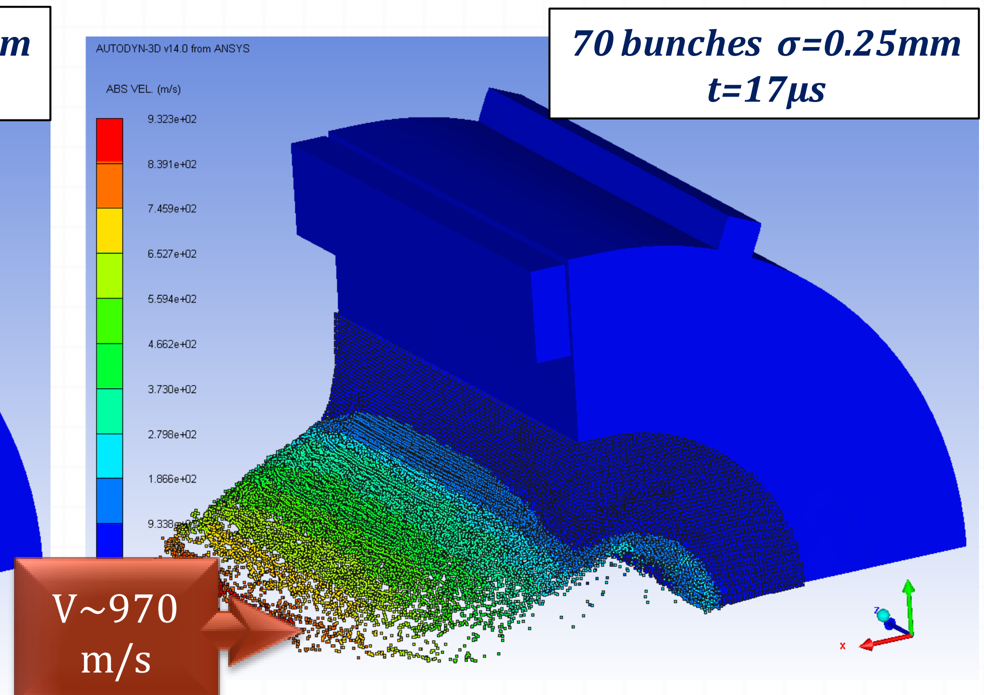
SPH Analysis

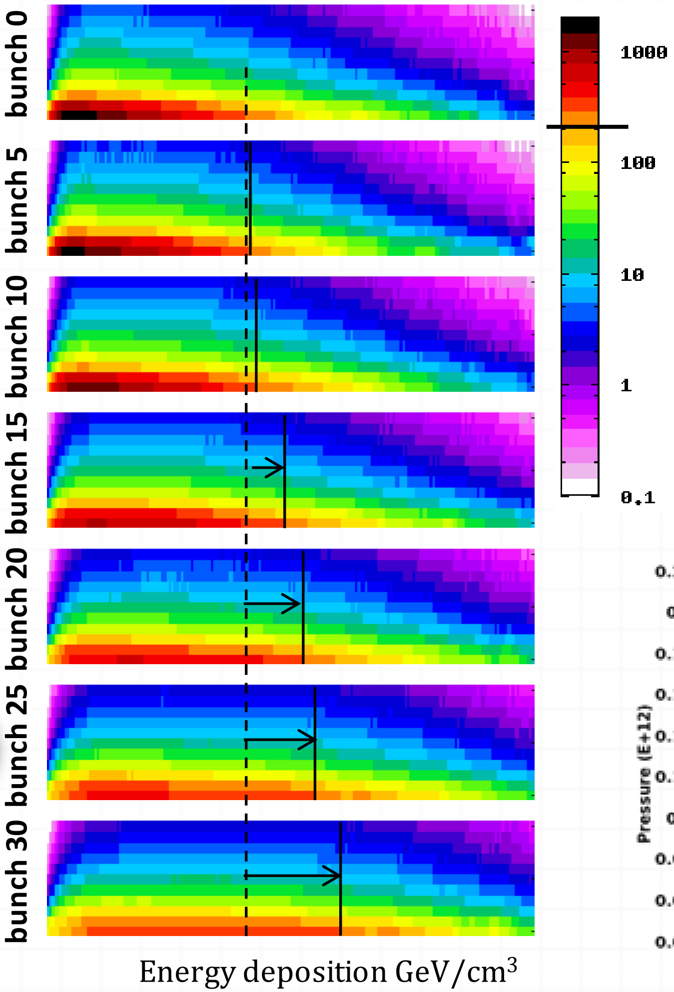
- **SPH (Smooth Particle Hydrodynamics)** calculations allow to determine disruptive effects such as:
  - Material fragmentation
  - Projections of very fast particles
  - Material density changes during deposition
  - Particle impacts on adjacent components

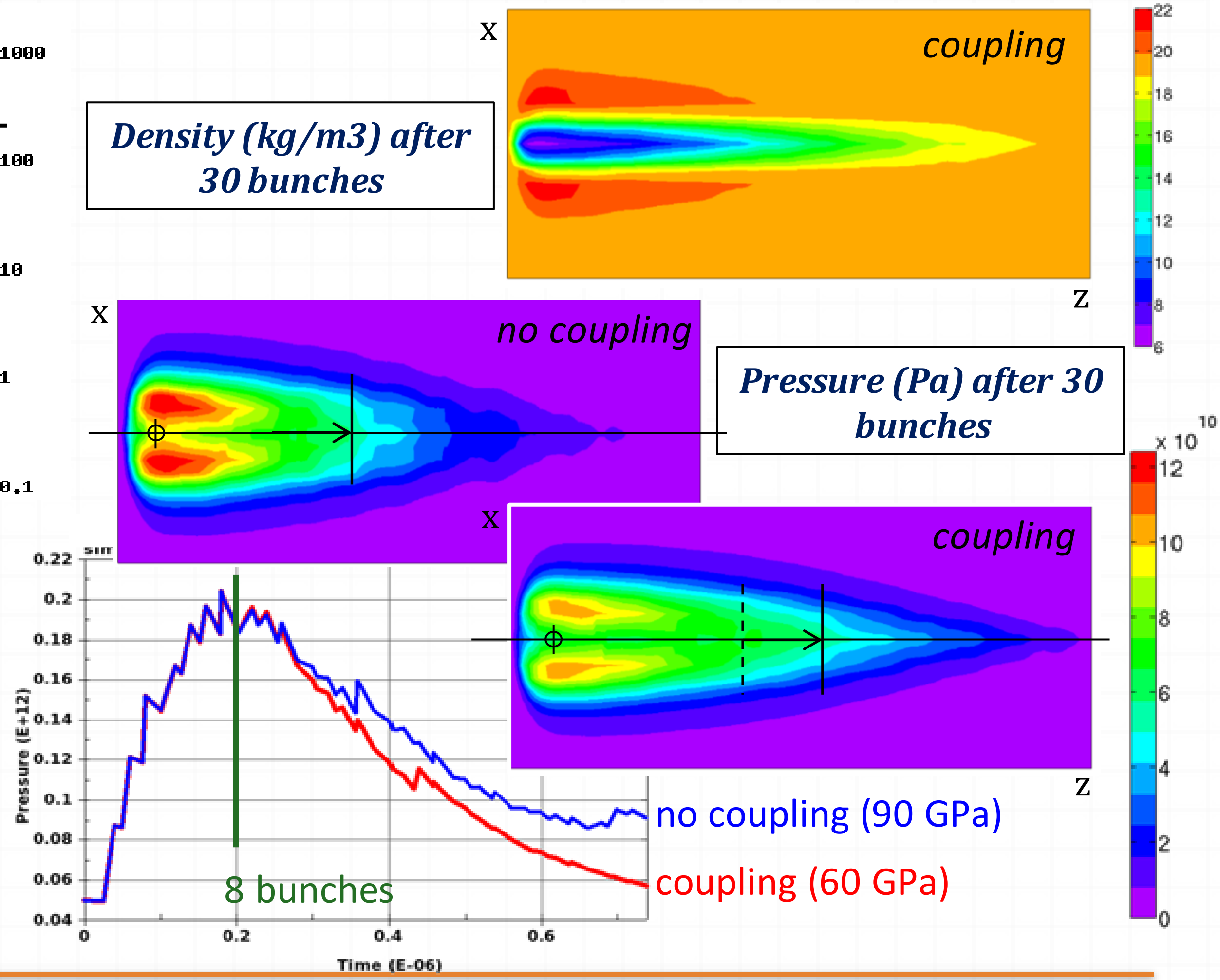




FLUKA/LS-Dyna Coupling

A complex simulation program carried out at **Politecnico di Torino** to couple FLUKA and Hydrocodes (LS-Dyna) to study effects of changing density during beam impact (**tunnelling effect**)



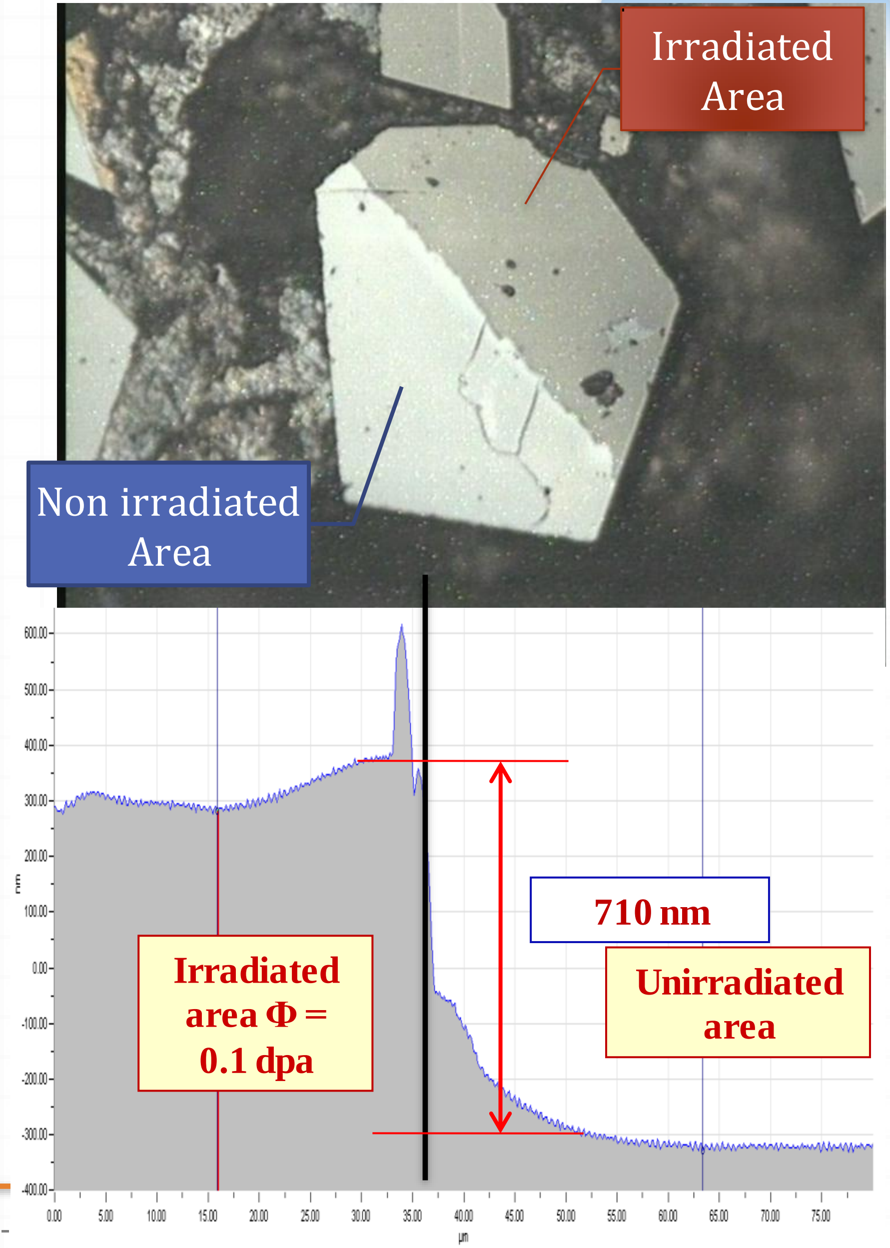


Task 8.2 Activities

Cu-CD Irradiation

- **Irradiation studies** on Cu-CD at **RRC-KI**
- Proton Beam: 30 MeV, $\Phi = 10^{17}$ p/cm^2,
  - Estimated dpa level $10^{-4} – 10^{-3}$
- Carbon-Ion Beam: 26 MeV, $\Phi = 10^{16}$ i/cm^2,
  - Estimated dpa level 10^{-1}
- Properties measured **before and after irradiation**.
- **Material strength and elongation** to come soon.

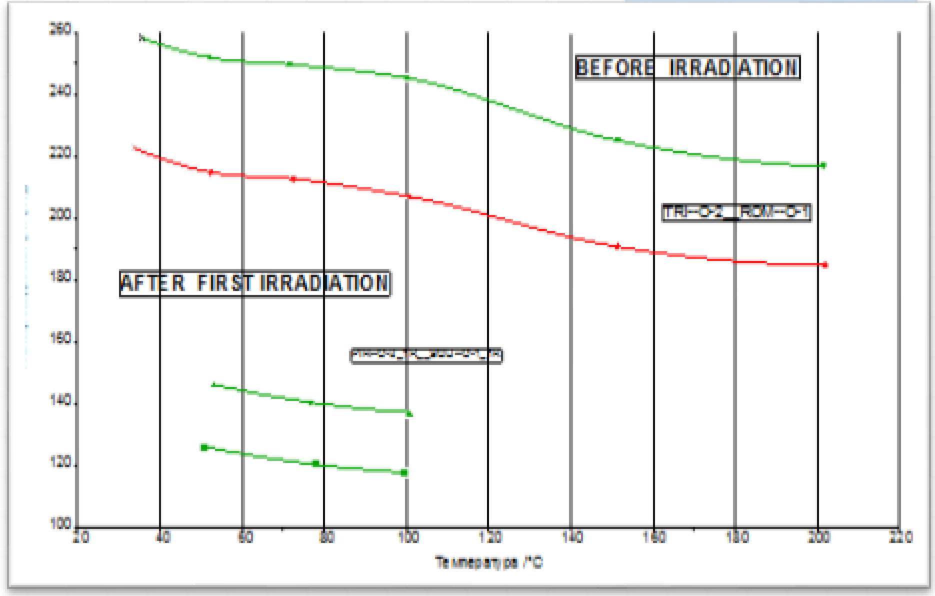
Swelling Measurement on Diamond carried out by Carbon-Ion Irradiation



CuCD Irradiation

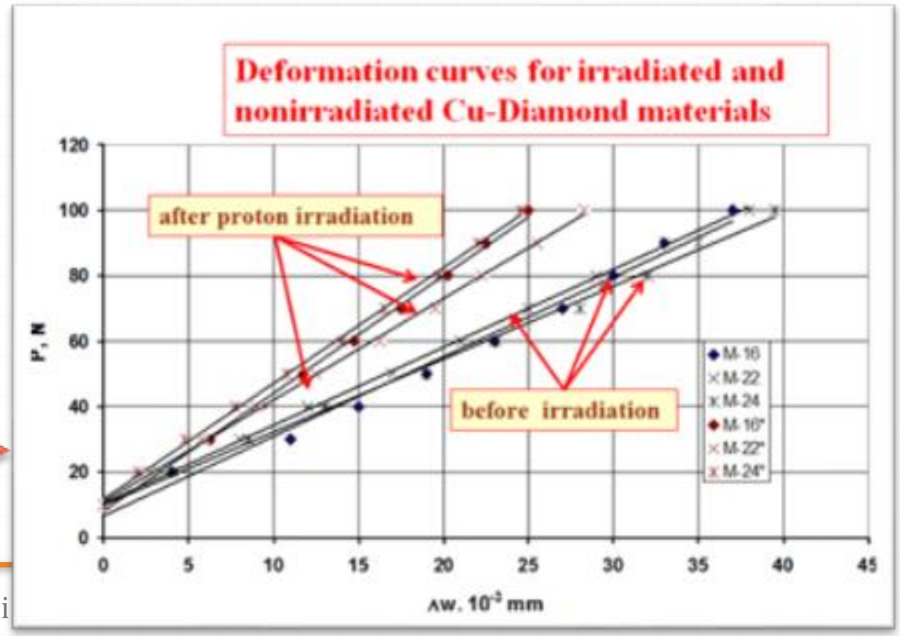
Effect of Proton Irradiation (30 MeV, $\Phi = 10^{17}$ p/cm^2) on Physical Properties

Thermal Conductivity Reduction



Property at T_a	Before Irradiation	After Irradiation	Variation %
CTE [ppm/m/K]	7,8	8,3	+ 6%
k [W/m/K]	490	279	– 43%
γ [MS/m]	10 ± 0.2	9.8 ± 0.2	–
E [GPa]	240 ± 50	330 ± 30	+ 40%

Young's Modulus Increase



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MoCD Mechanical Tests

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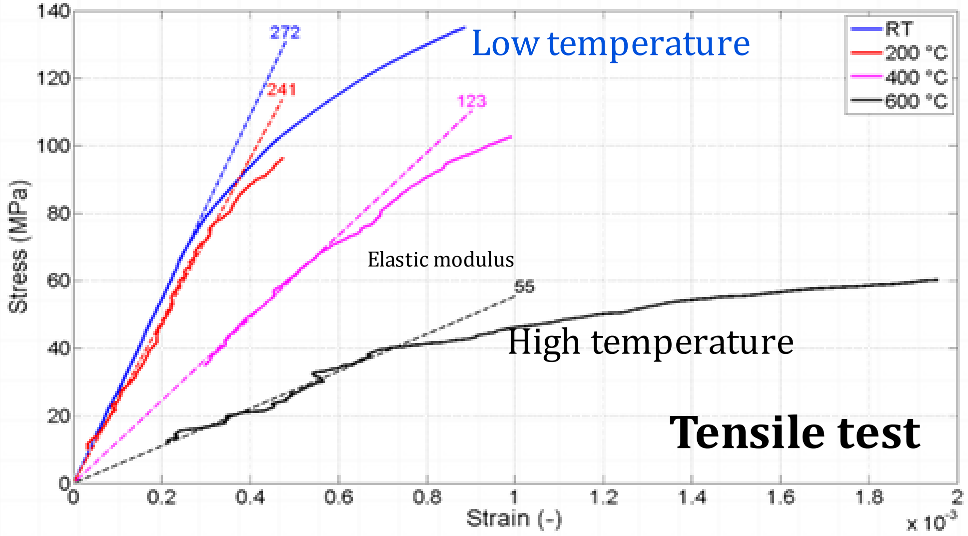
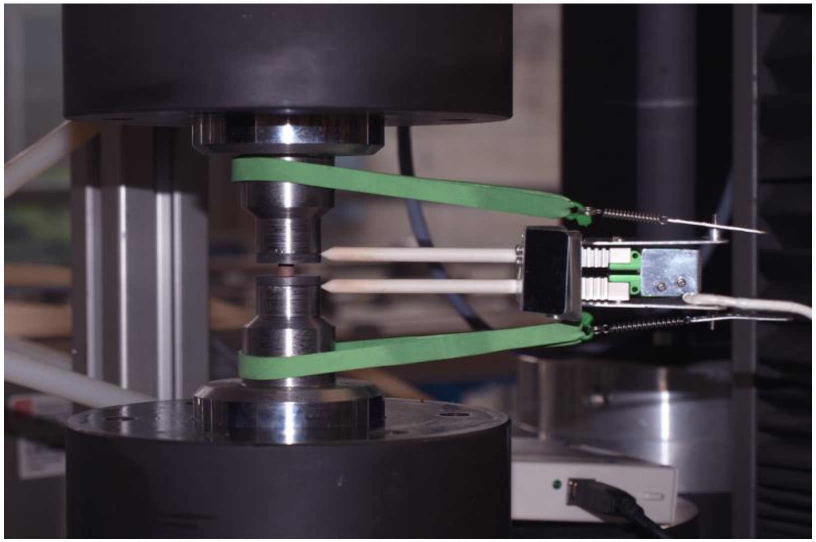
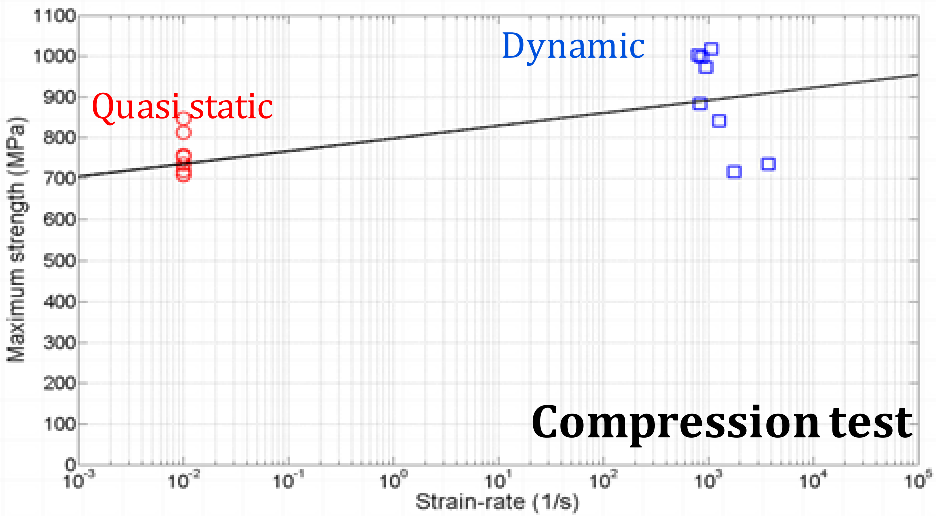


Quasi-static Tensile test on MoCD performed at different temperatures

Compression test on small cylinder specimens of MoCD performed at different strain-rates





MoCD Mechanical Tests

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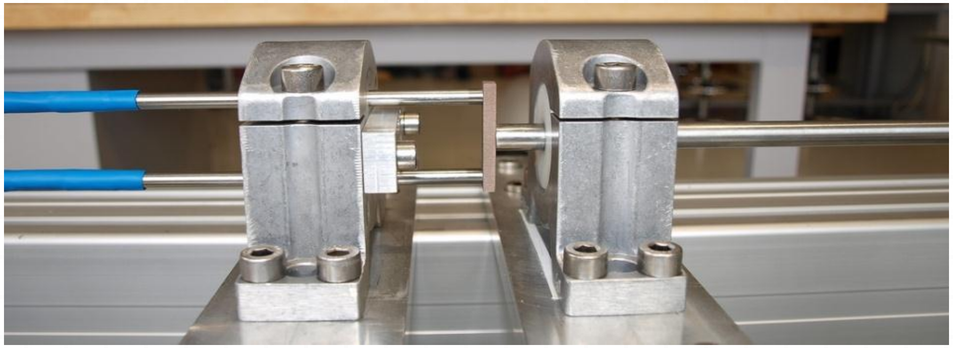
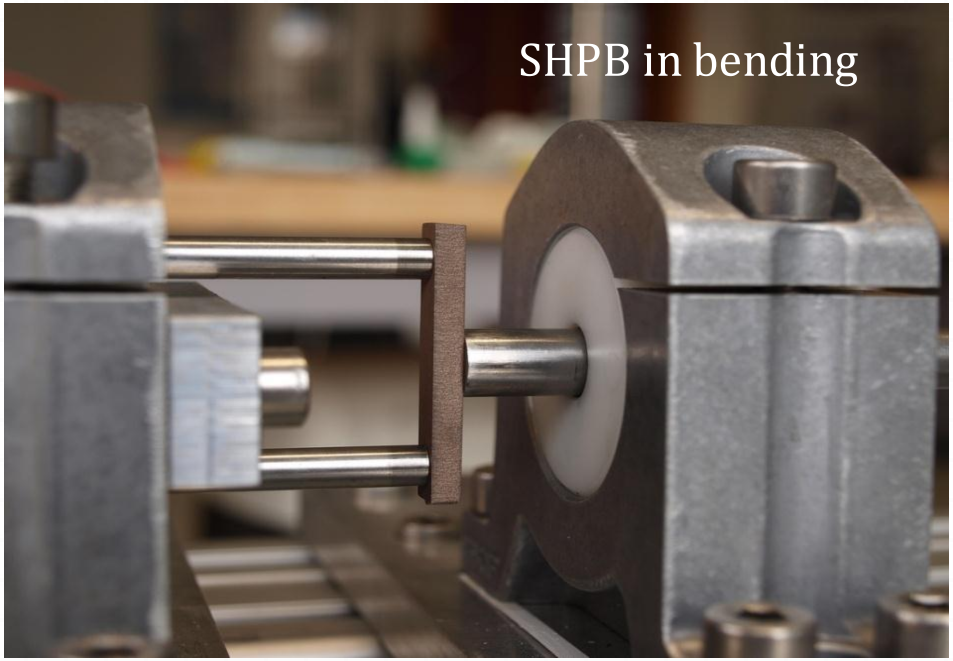
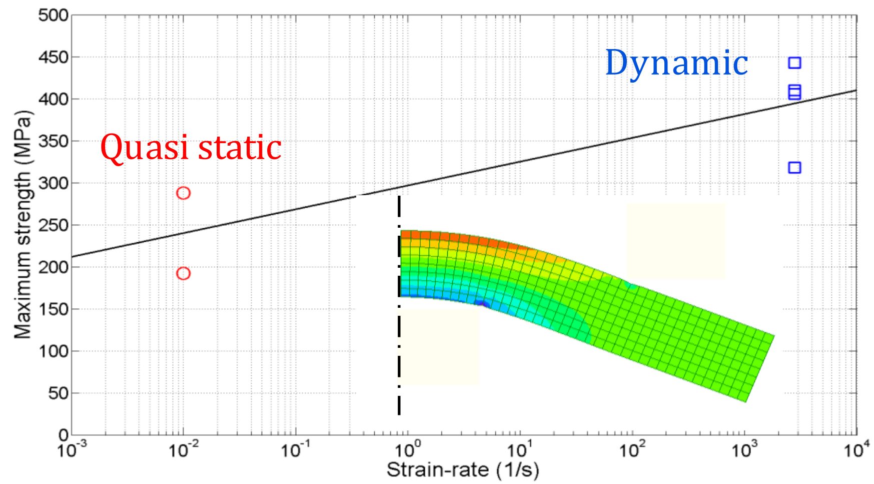


New SHPB (Split Hopkinson Pressure Bar) setup suitable for dynamic testing of brittle high strength material



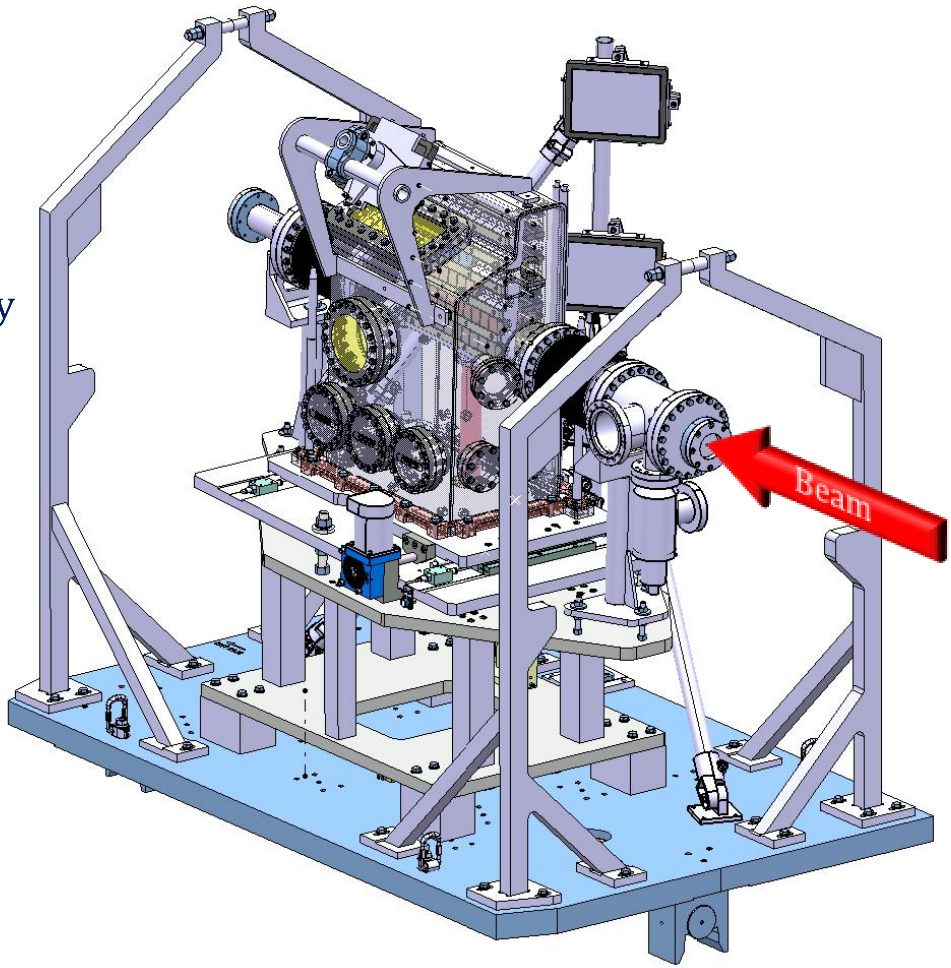


The value of strength and strain-rate are evaluated with an elastic field approximation

Material Tests in HiRadMat

Why HiRadMat Tests?

- To **test** traditional and novel materials under the **Extreme Conditions** they may encounter in case of accidental beam impacts.
- To quantify **Material Damage** for LHC Operating Scenarios.
- To fully characterize **Novel Materials** currently under development for Phase II Collimators.
- To **benchmark** advanced numerical simulations, in-depth but based on limited and scarce literature data on material constitutive models.
- To collect, mostly in real time, experimental data on **Constitutive Models** of Materials (Equations of State, Strength Models, Failure Models).



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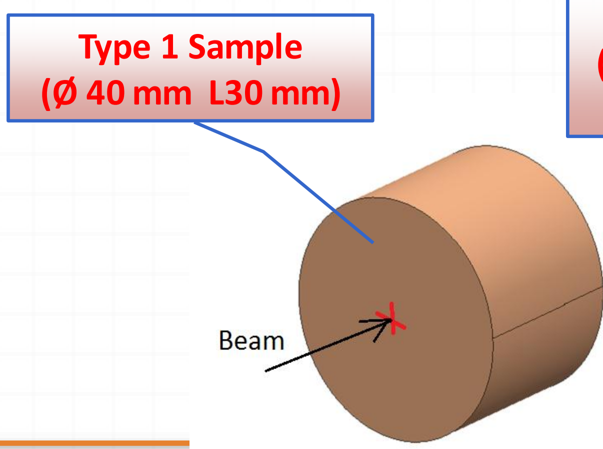
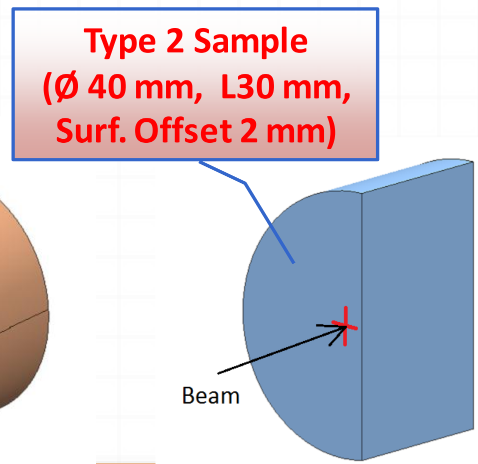
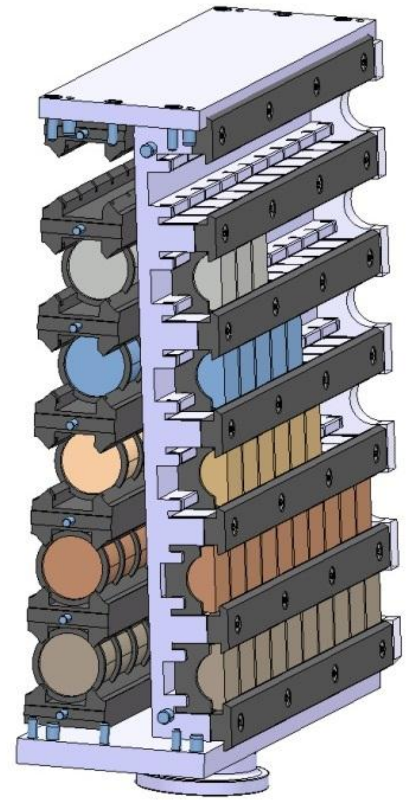
Material Tests in HiRadMat

What to do in HiRadMat?

- Characterize **six different materials** (Inermet 180, Glidcop, Molybdenum, Copper-Diamond, Molybdenum-Diamond, Molybdenum-Graphite)
- **Medium intensity** and **High intensity** tests, with different material samples for each material (Type 1, Type2)
- Each sample holder tier can host up to **10 specimens**
- Extensive **real time data acquisition** (in situ and remote)
- **Post mortem** analyses







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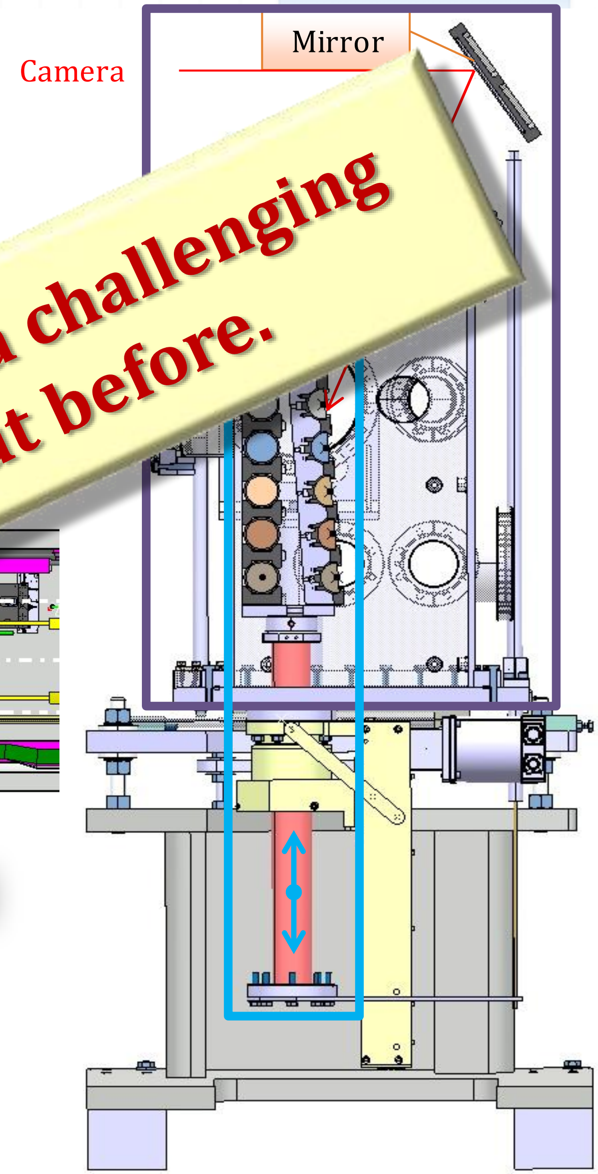
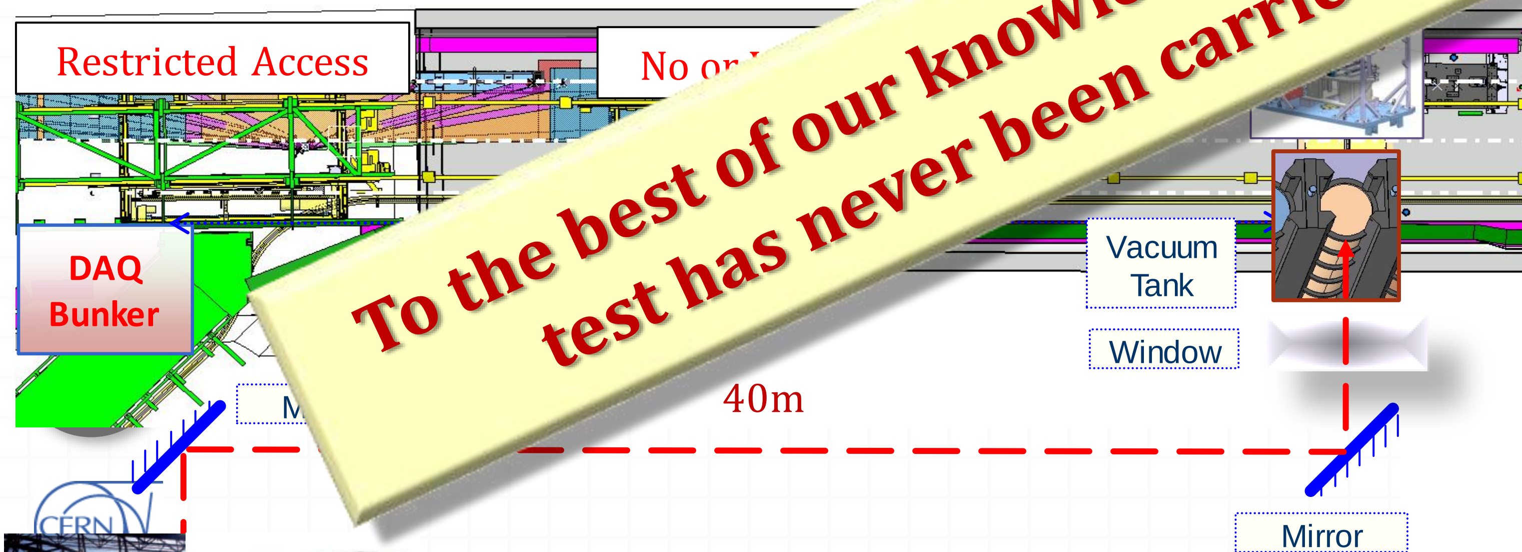
HiRadMat Test DAQ

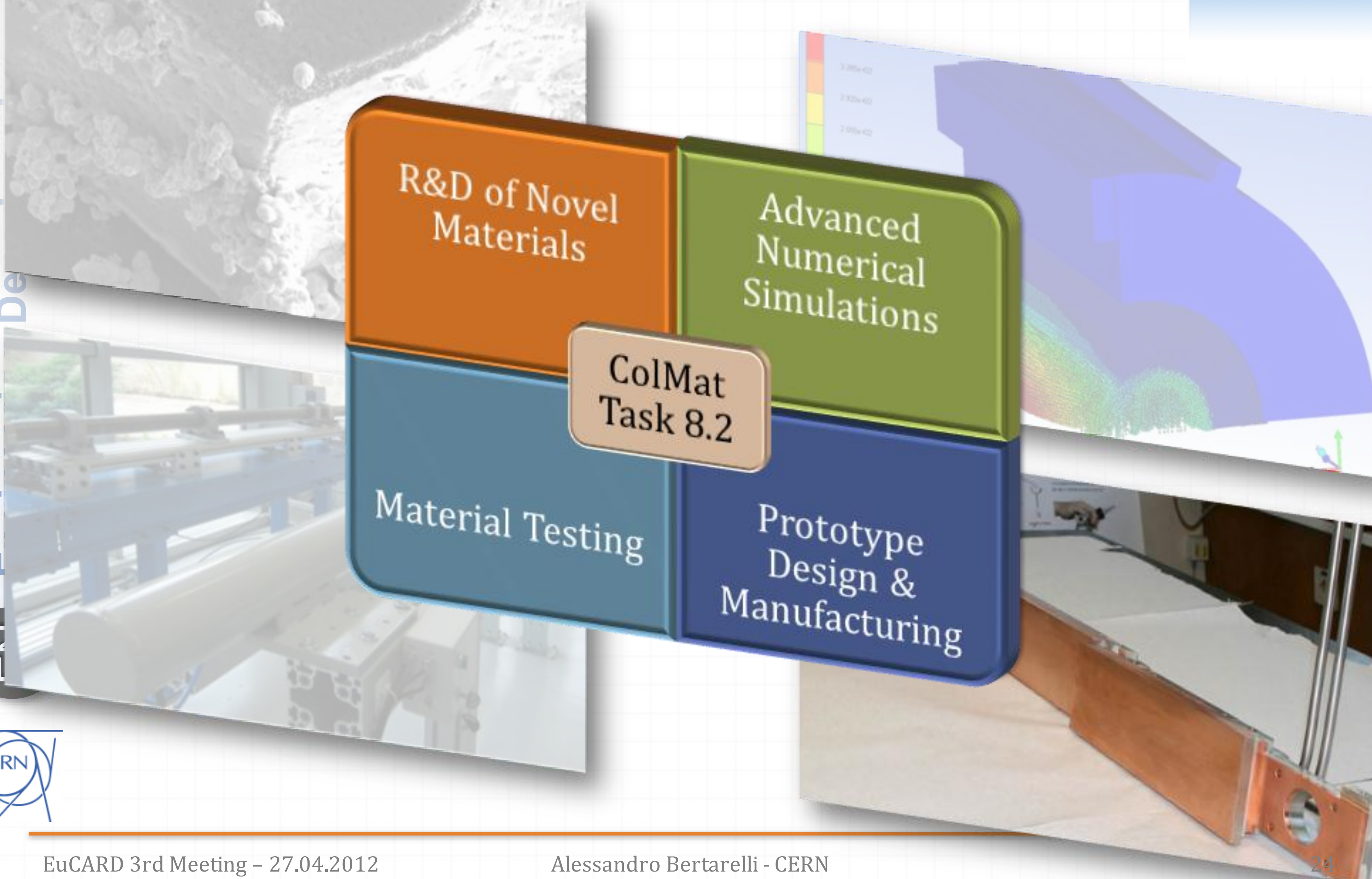
- **Laser Doppler Vibrometer** (remote): measures radial velocity of outer cylindrical surface (type 1 samples). Sampling rate 5 MHz
- **High Speed Camera** (remote): acquires live images of impacted type 2 samples. Capture rate up to 30 kfps
- **Strain gauges** (in situ): measures circumferential and axial st… generated on outer surface (type 1 and 2). Sampling rat…
- **Temperature** and **vacuum** sensors, **microph**…

To the best of our knowledge, such a challenging test has never been carried out before.

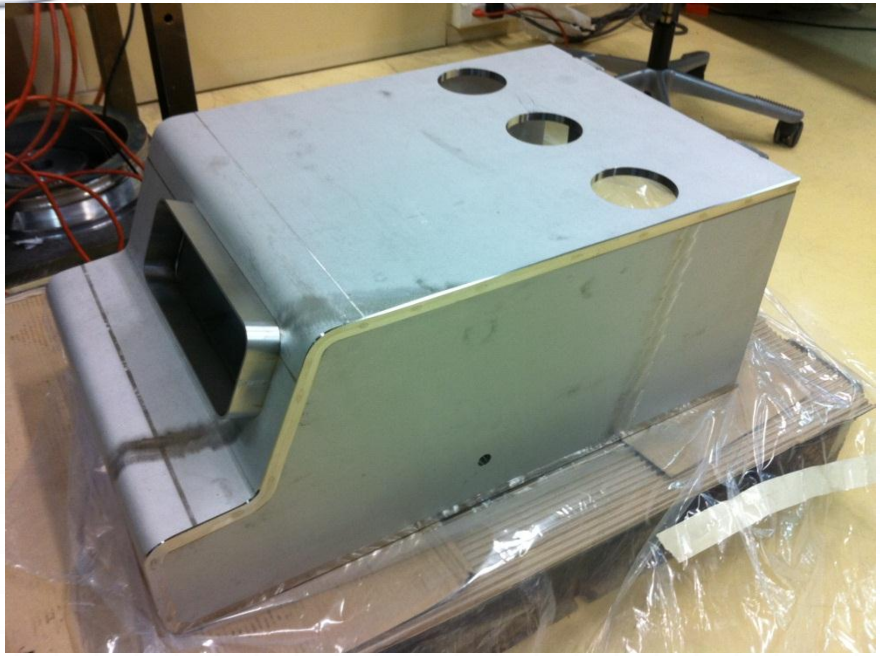




Task 8.2 Activities

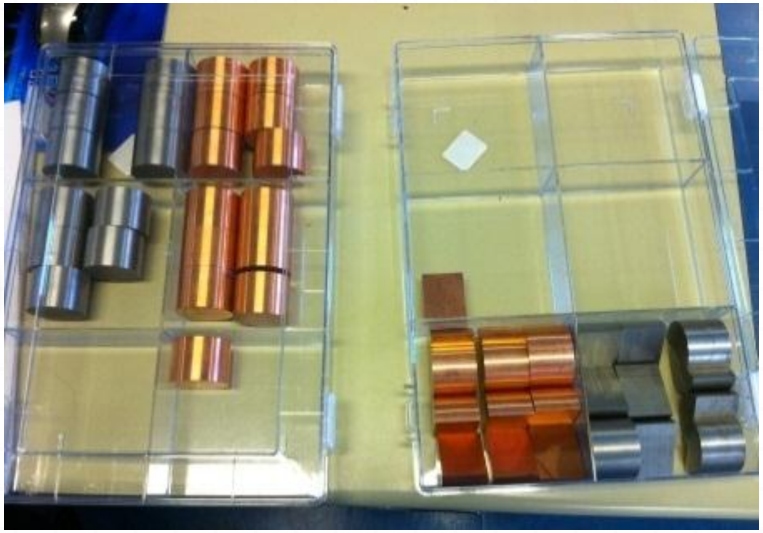


HiRadMat Sample Holder



Project Status

- Design very advanced, details finalization.
- Manufacturing has started.
- All main data acquisition choices made.
- New LDV purchased.
- Material samples ordered and partly delivered.



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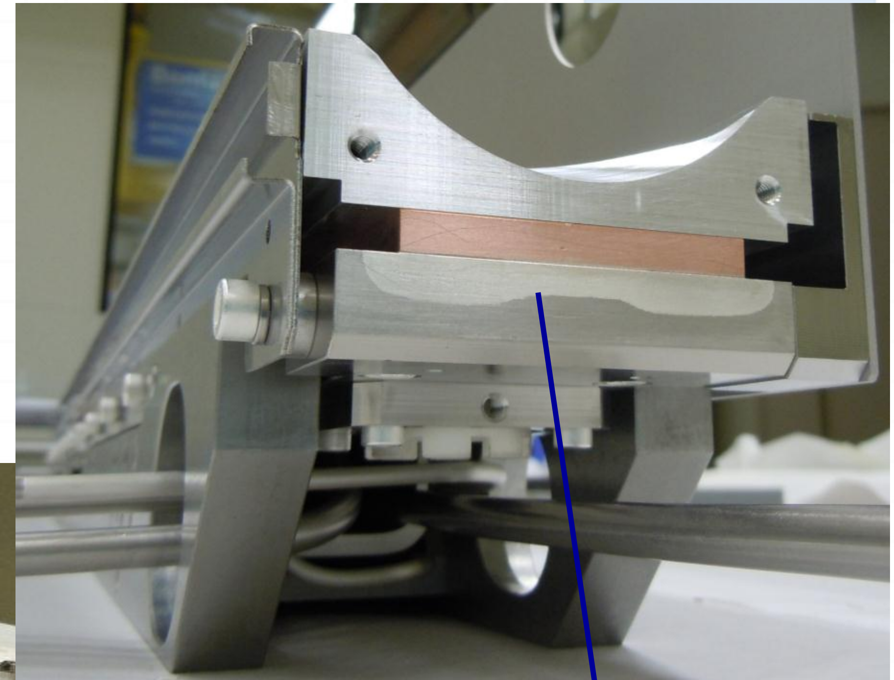
Phase II Prototype

A full prototype of a **Phase II Collimator** is presently under advanced state of manufacturing at CERN



Composite Jaw Assembly (3 sectors, Glidcop)

Conclusions I

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- Bringing LHC beyond nominal performances will likely require a new generation of collimators embarking novel advanced materials.
- ColMat Task 8.2 is focusing on the development, simulation and testing of these materials and in the production of prototypes to validate them.
- Excellent progress has been made in every aspect of this challenging and far-reaching task with important contributions from many partners.
- Metal Matrix Composites with Diamond reinforcement are particularly appealing as they promise to combine diamond and metal properties.
- Cu-CD, Ag-CD and Mo-CD were studied and successfully produced. Size challenge has been met for Cu-CD and Mo-CD.
- Their characterization is steadily progressing.

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Conclusions II

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- An additional material (Mo-Gr) is currently und nt and promises to further increase the performa
- State-of-the-art numerical simula ied out. Effective coupling Fluk effect into account.
- Radiation nd to start soon for M
- erials under extreme conditions facility.
- ple holder with challenging DAQ system is c prepared for HiRadMat tests in late 2012.
- A P se II Collimator Prototype is under finalization at CERN.

We believe this R&D program has the potential to go well beyond pure accelerator applications.

Materials being developed are potentially appealing for Nuclear, Aerospace, Thermal Management applications!

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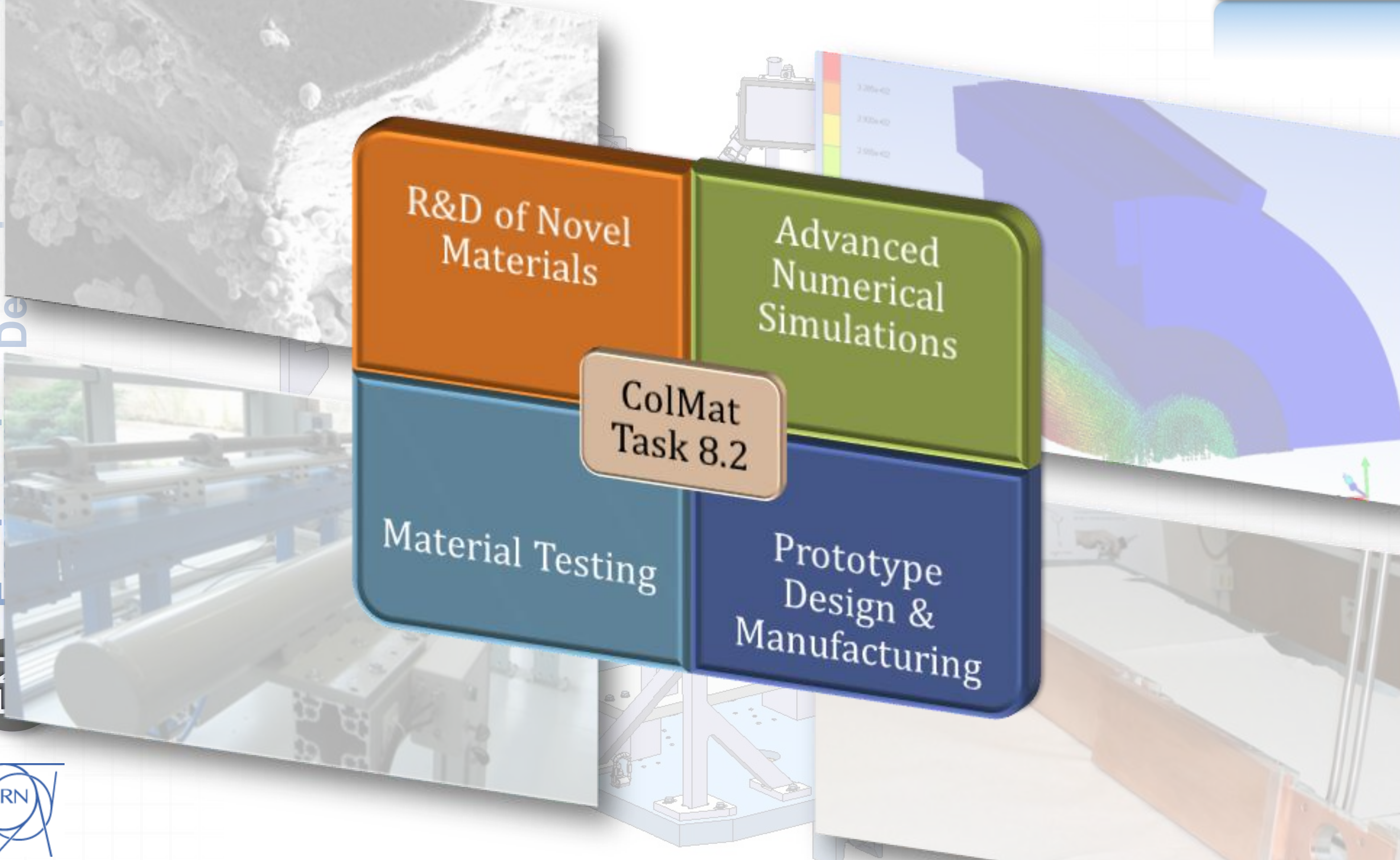
THANK YOU FOR YOUR ATTENTION

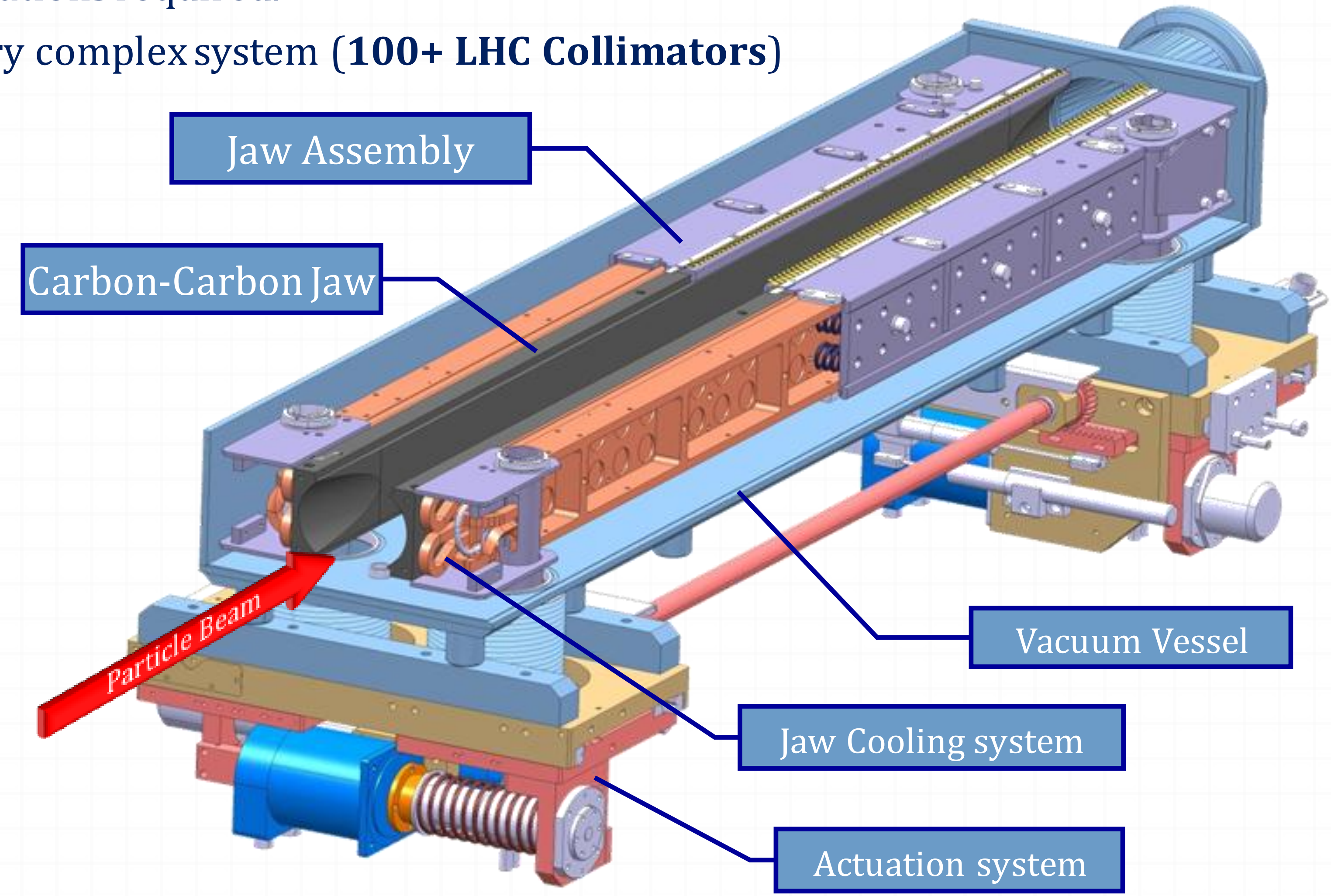
Task 8.2 Activities



Context

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

Secondary Collimator (TCSG) Cutaway



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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 temperature**
  Increase **Melting Temperature**. T_m

Note Conflicting requirements as to Density

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Additional "standard" requirements include …

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

Material Ranking

Material	C-C	Mo	Glidcop ®	Cu-CD	Mo-CD	Ag-CD	Mo-Gr
Density [g/cm^3]	1.65	10.22	8.90	~5.4	~6.9	~6.10	3.9 ÷ 5.6
Atomic Number (Z)	6	42	29	~11.4	~17.3	~13.9	10.9 ÷16.5
T_m [°C]	3650	2623	1083	~1083	~2623	~840	~2520
SSNI [kWm^2/kg]	24	2.6	2.5	13.1 ÷ 15.3	6.9 ÷ 10.9	11.4 ÷ 15.4	*7.4 **
TSNI [kJ/kg]	793	55	35	44 ÷ 51	72 ÷ 96	60 ÷ 92	*115 **
Electrical Conductivity [MS/m]	0.14	19.2	53.8	~12.6	~9.9	~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.
- **Metal-diamond composites** exhibit a balanced compromise between TSNI, SSNI, electrical conductivity , density, atomic number.
- **Molybdenum-graphite,** currently under development and characterization, shows overall very promising figures of merit.

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MoCD Thermo-Mechanical Tests

- Mechanical characterization carried out at **CERN** (quasi-static) and **Politecnico di Torino** (dynamic – Hopkinson's bar tests)
- Thermal Characterization carried out at **AIT**
- Microstructural characterization at CERN