Advanced Materials for Next-generation Beam Intercepting Devices

Alessandro Bertarelli, CERN
on behalf of the EN/MME Collimator Design Team

Workshop on Machine Protection – CERN, June 6-8, 2012

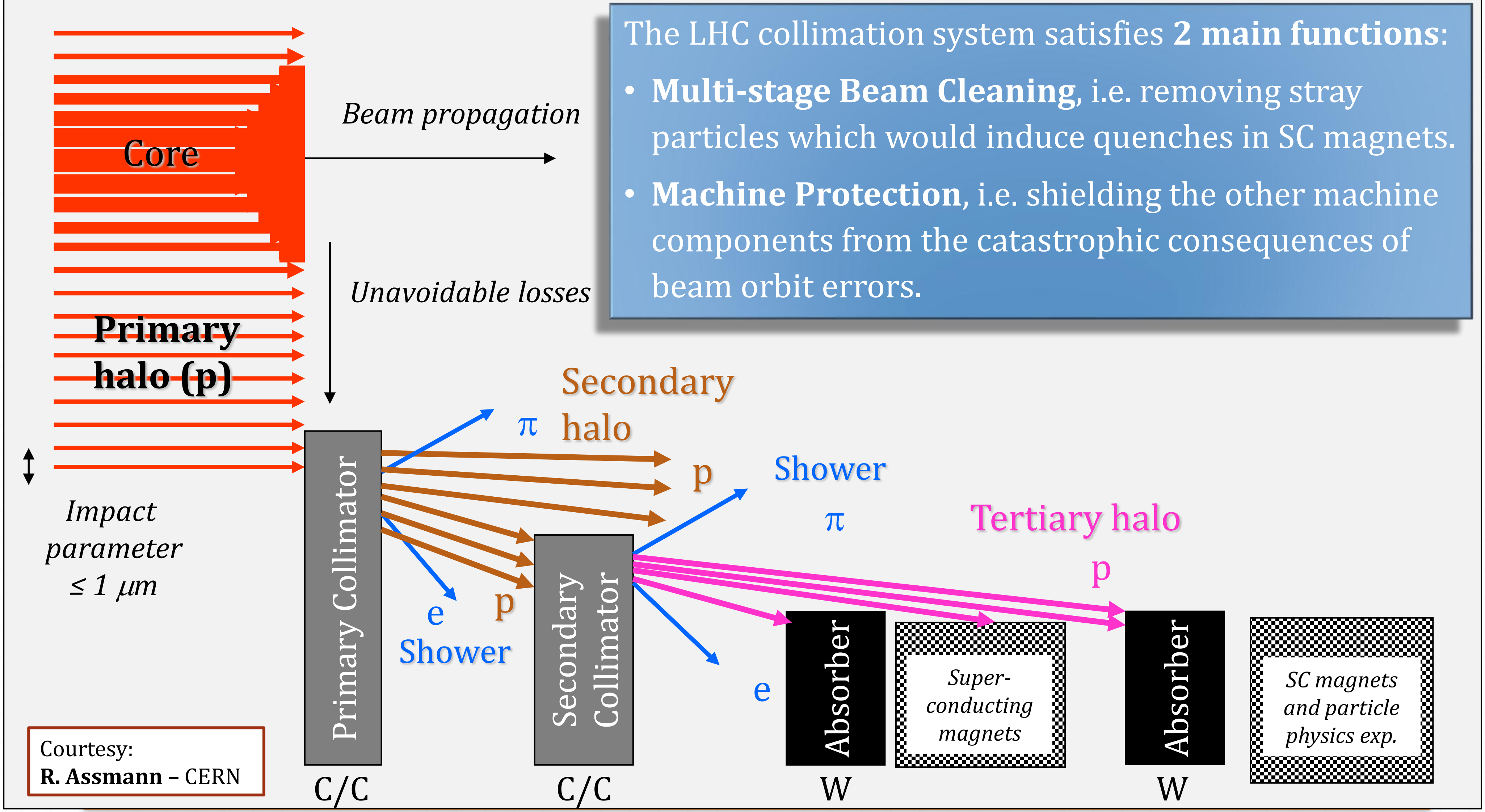
Outlook

- Context and Objectives
- R&D Activities
  - R&D on Novel Materials
  - Advanced Numerical Simulations
  - Material Testing
  - Prototyping and Manufacturing
- Conclusions

Context (LHC Collimators)

The LHC collimation system satisfies **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.

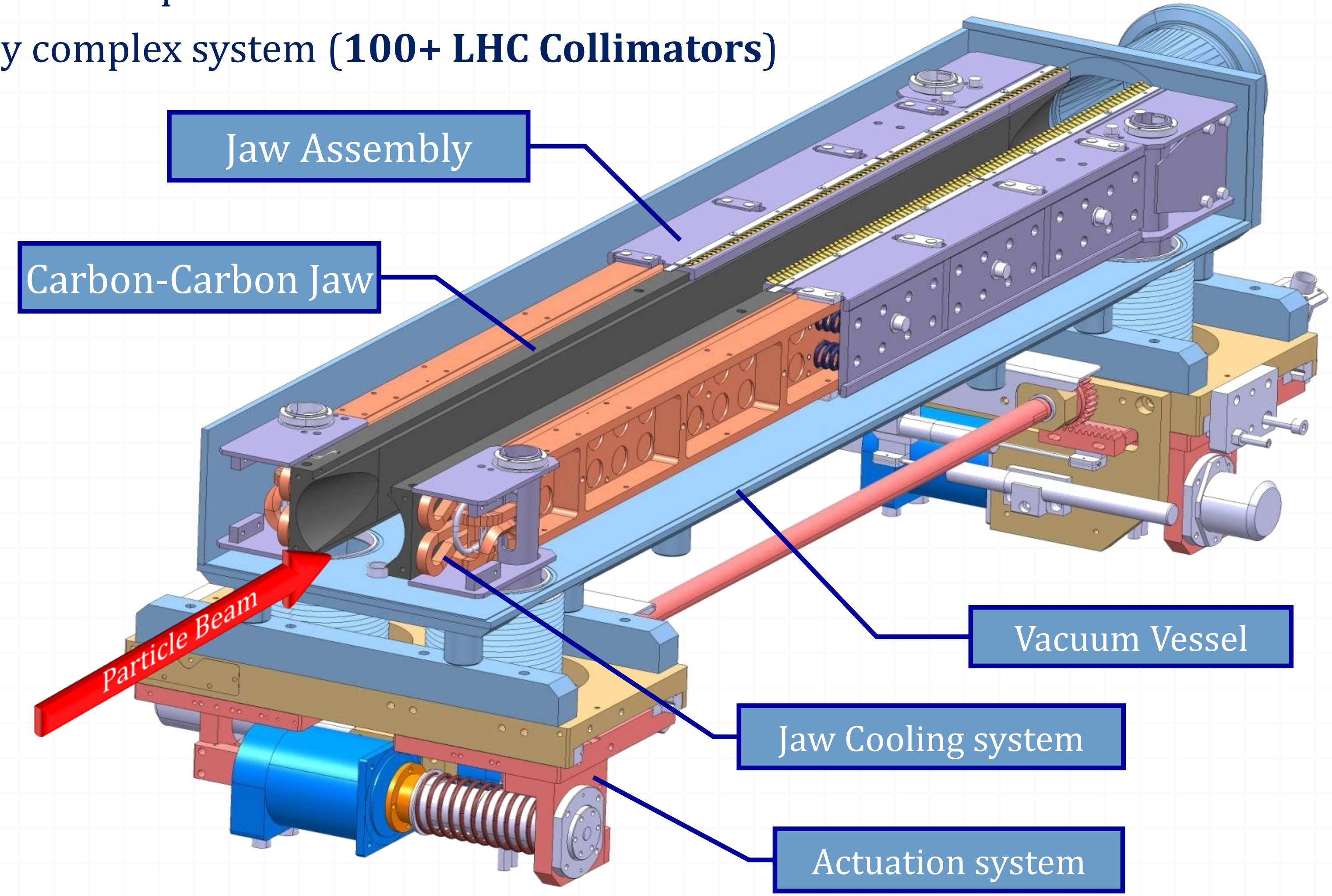


Courtesy:
R. Assmann – CERN

Context (LHC Collimators)

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

Secondary Collimator (TCSG) Cutaway



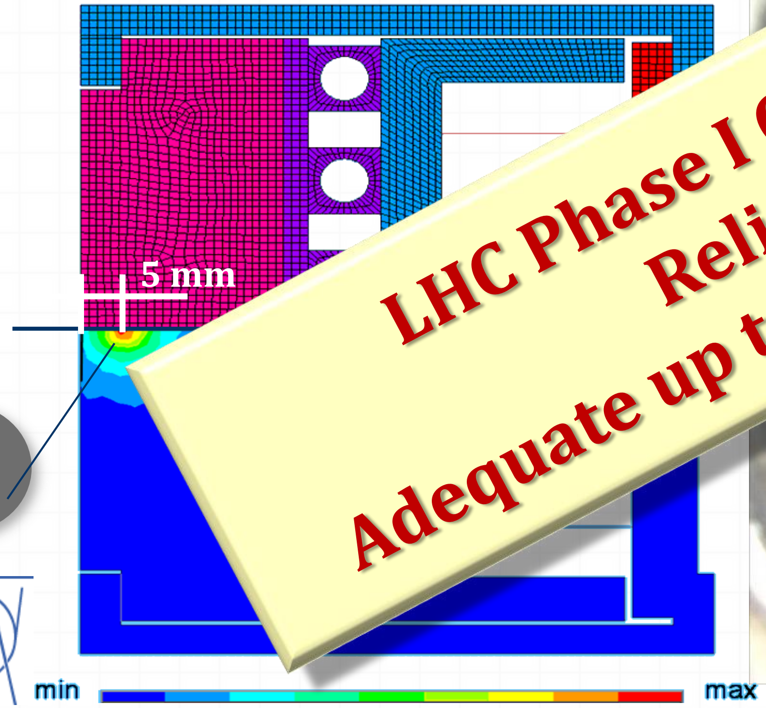
Engineering Department

EN

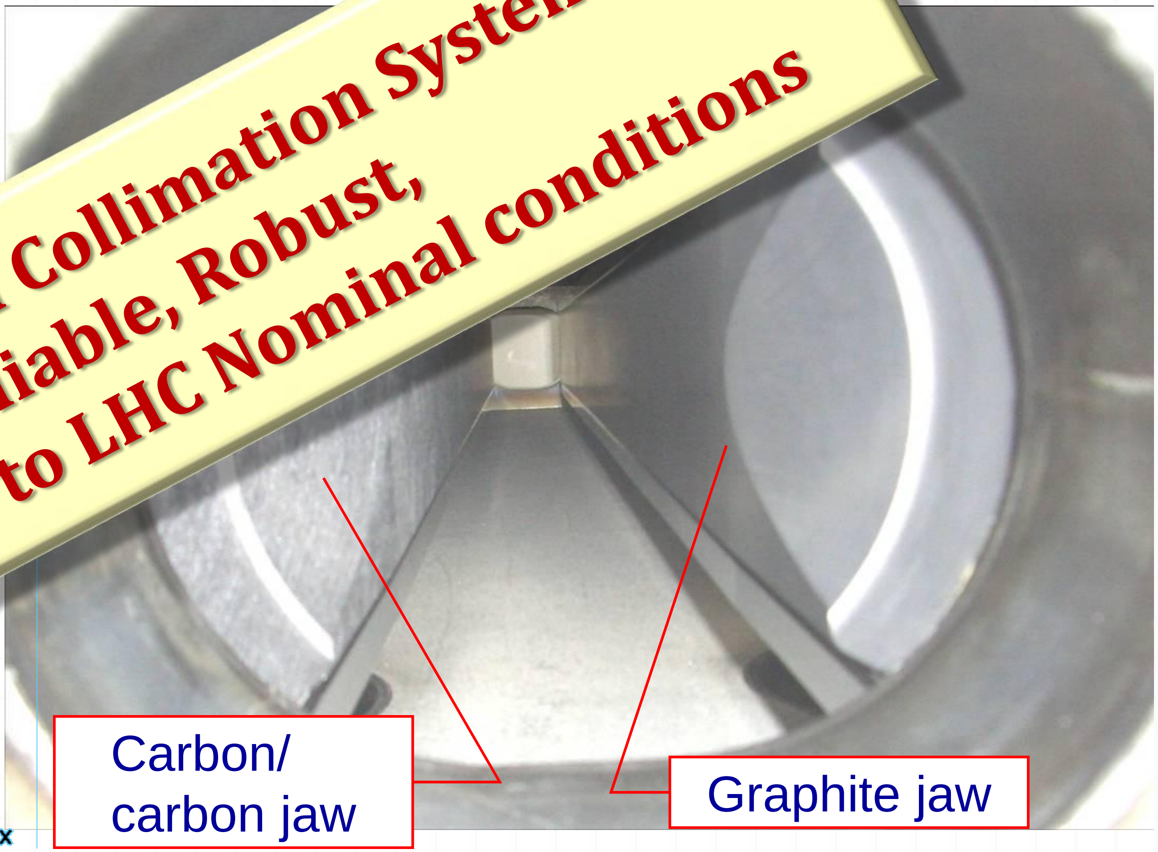
Context (LHC Collimators)

Robustness Test at 450 GeV, 3.2x10^{13} protons per shot

- **5 full intensity pulses** ranging from 1 to 5 mm, 7.2 μs …
- Each impact energy equivalent to more than **½ kg of TNT**



LHC Phase I Collimation System
Reliable, Robust,
Adequate up to LHC Nominal conditions



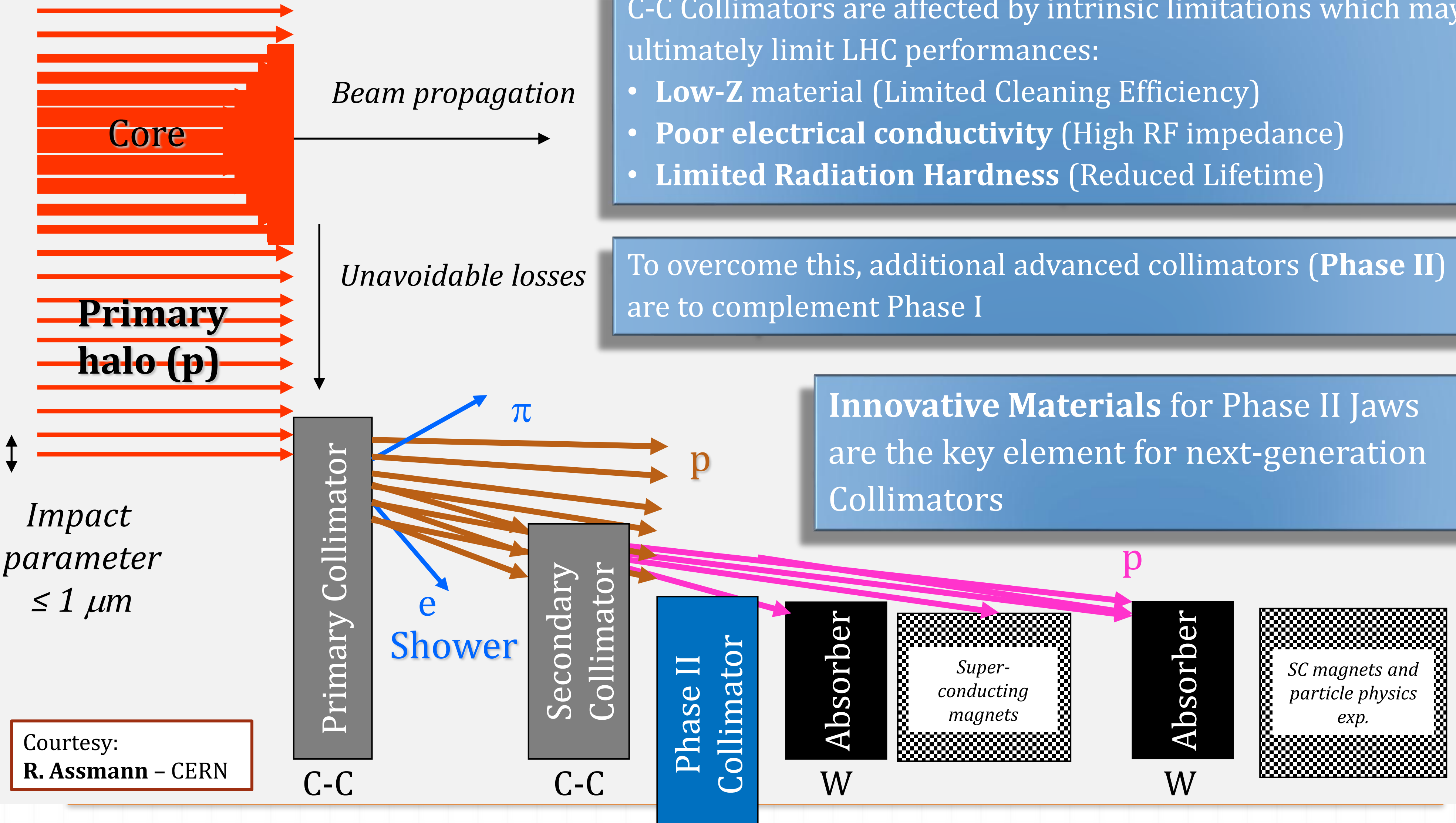
Context

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



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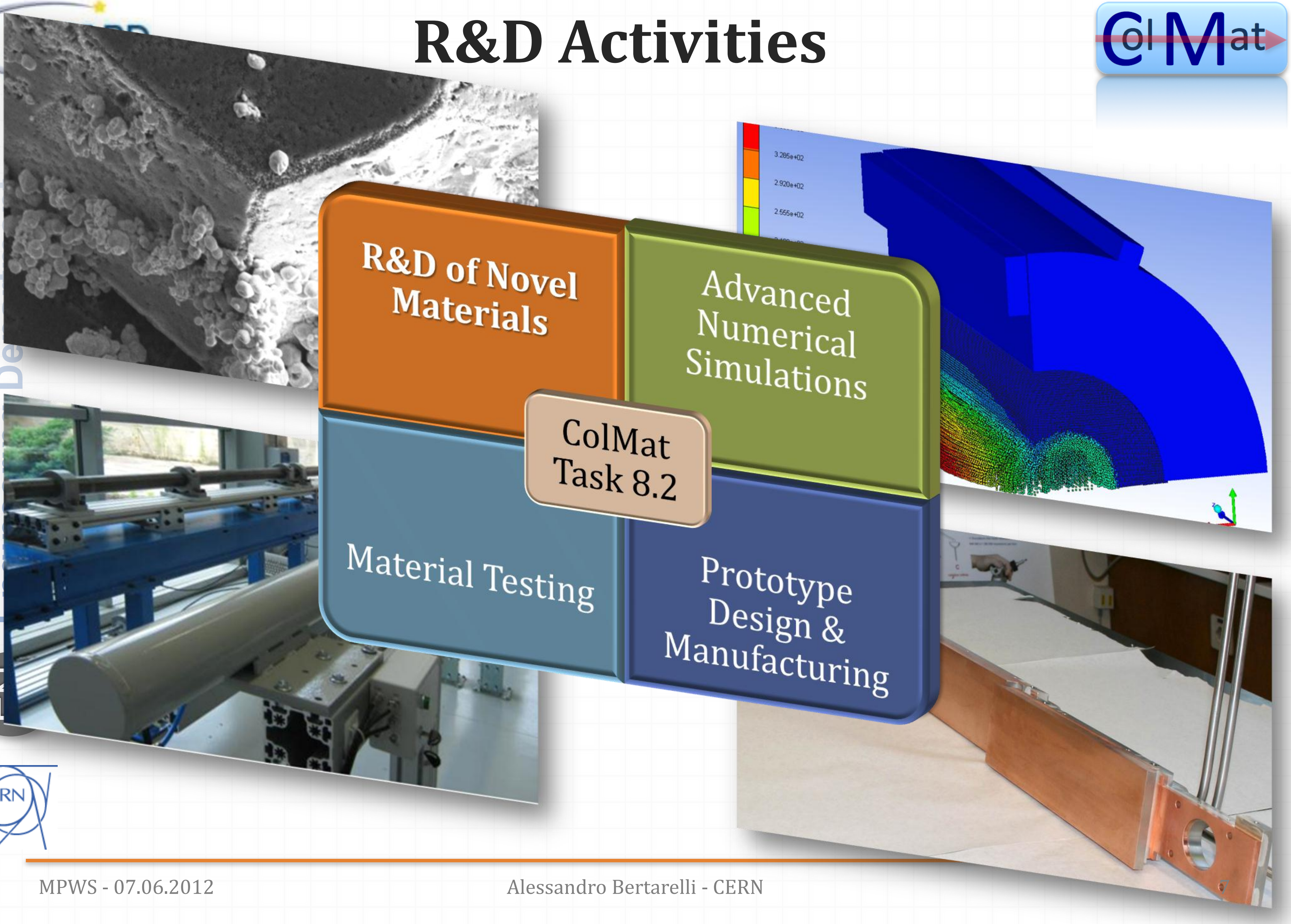
R&D Activities



R&D of Novel Materials

Advanced Numerical Simulations

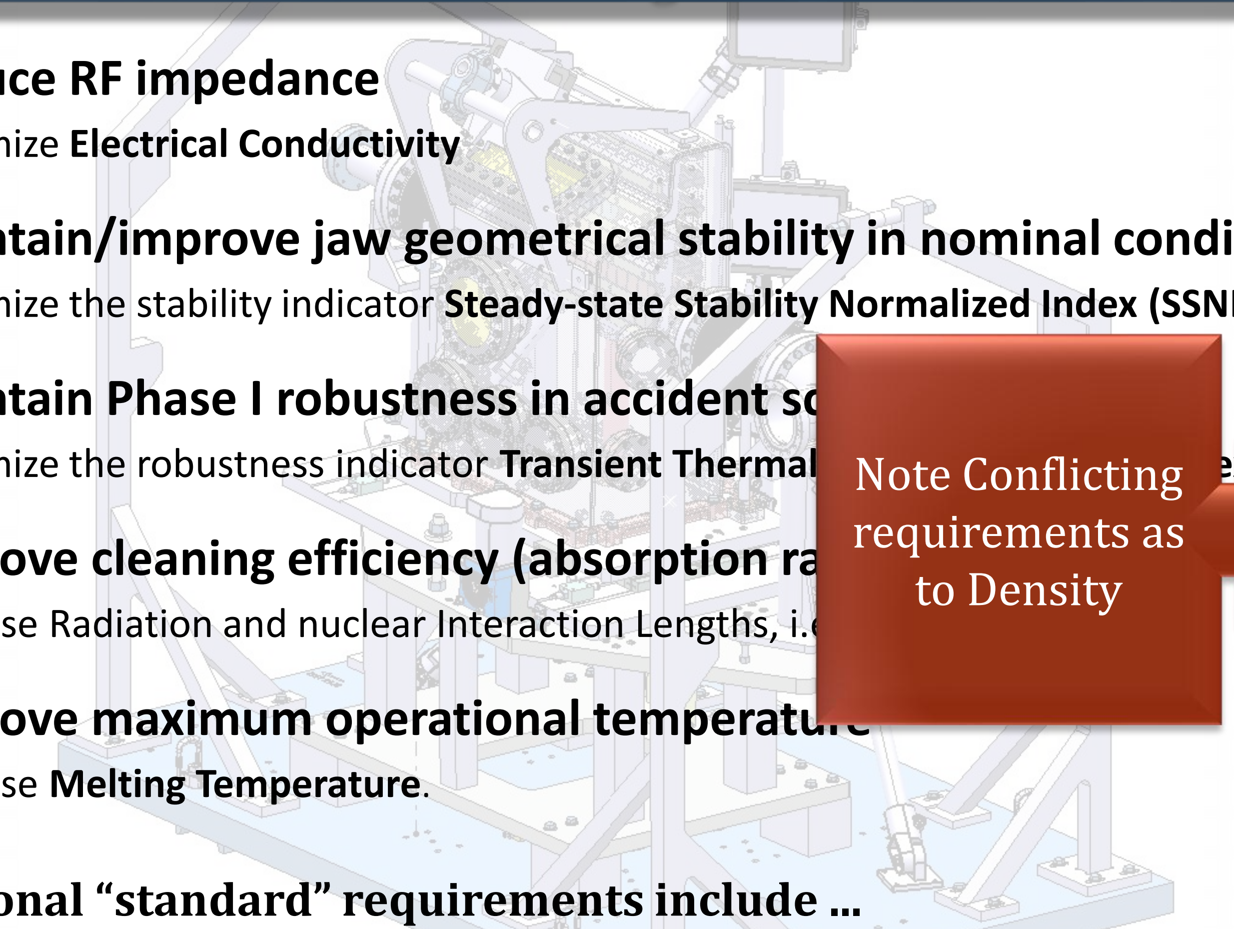
ColMat Task 8.2

Material Testing

Prototype Design & Manufacturing

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 accident sc**

  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

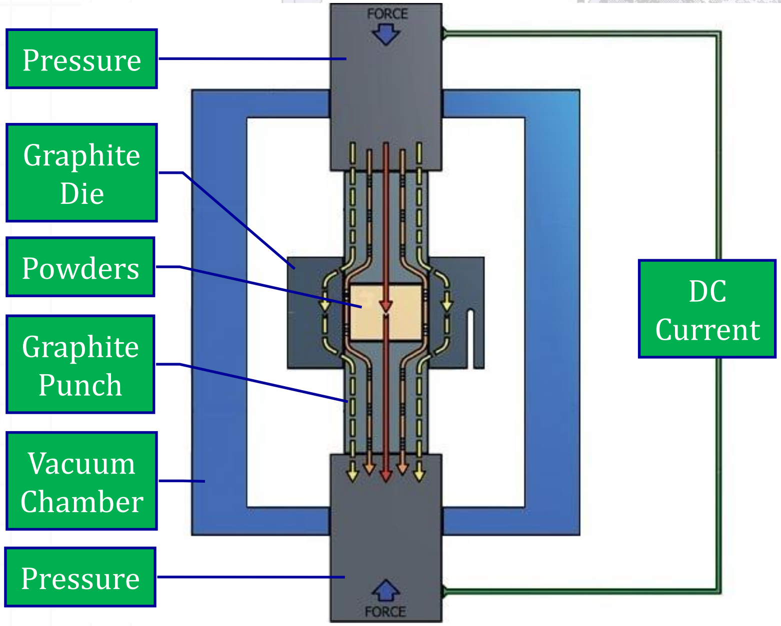
Note Conflicting requirements as to Density

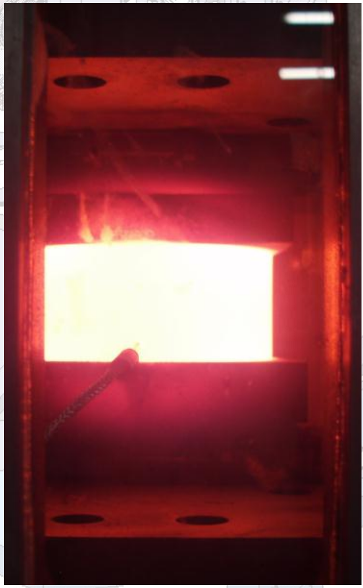
Additional "standard" requirements include ...

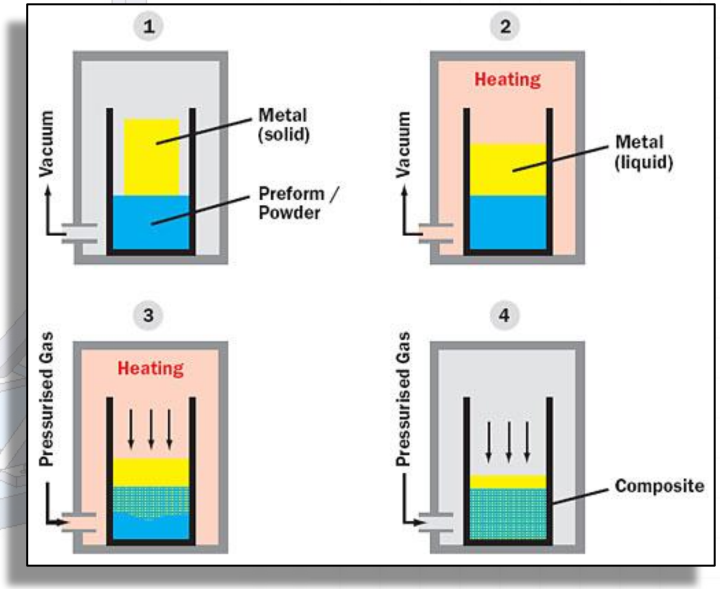
- Radiation Hardness, UHV Compatibility, Industrial producibility of large components, Possibility to machine, braze, join, coat ..., Toughness, Cost ...

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**) to come soon.
- Materials being investigated are **Copper-diamond** (**Cu-CD**), **Molybdenum-diamond** (**Mo-CD**), **Silver-diamond** (**Ag-CD**), **Molybdenum Graphite (Mo-Gr)**







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,** still under development, shows overall very promising figures of merit.

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**).

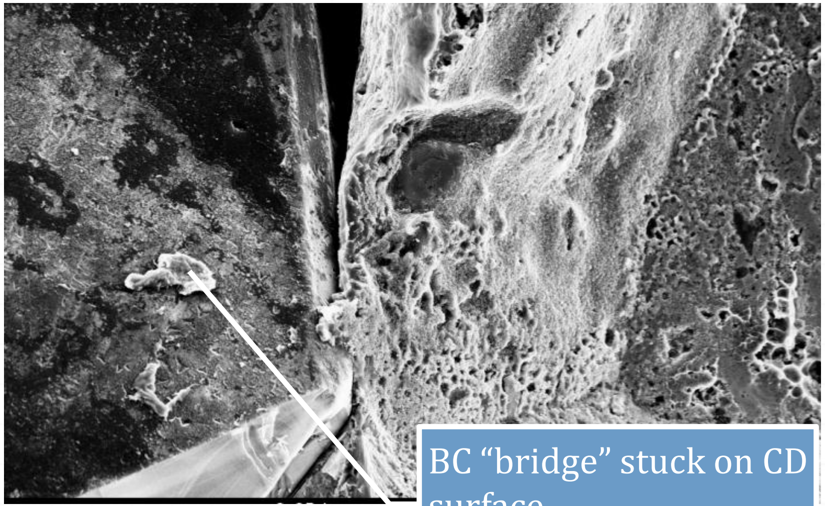
↓ No direct interface between Cu and CD (lack of affinity). Limited bonding surface assured by Boron Carbides hampers mechanical strength (**~120 MPa**).

↓ 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 ~**6x10^{-6} K^{-1} at RT** up to **~12x10^{-6} K^{-1} at 900 °C**)

150 x 150 x 4mm^3

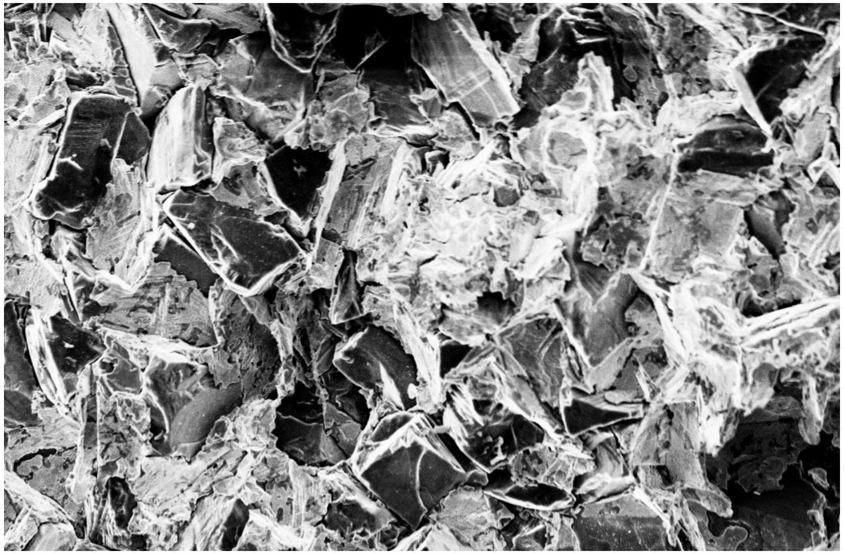


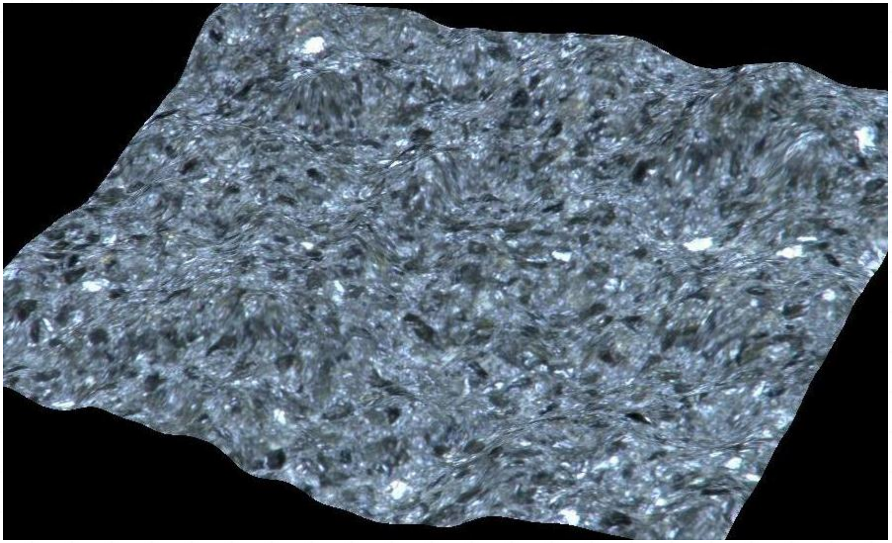
BC “bridge” stuck on CD surface.
No CD graphitization

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.





Mo-CD Composites

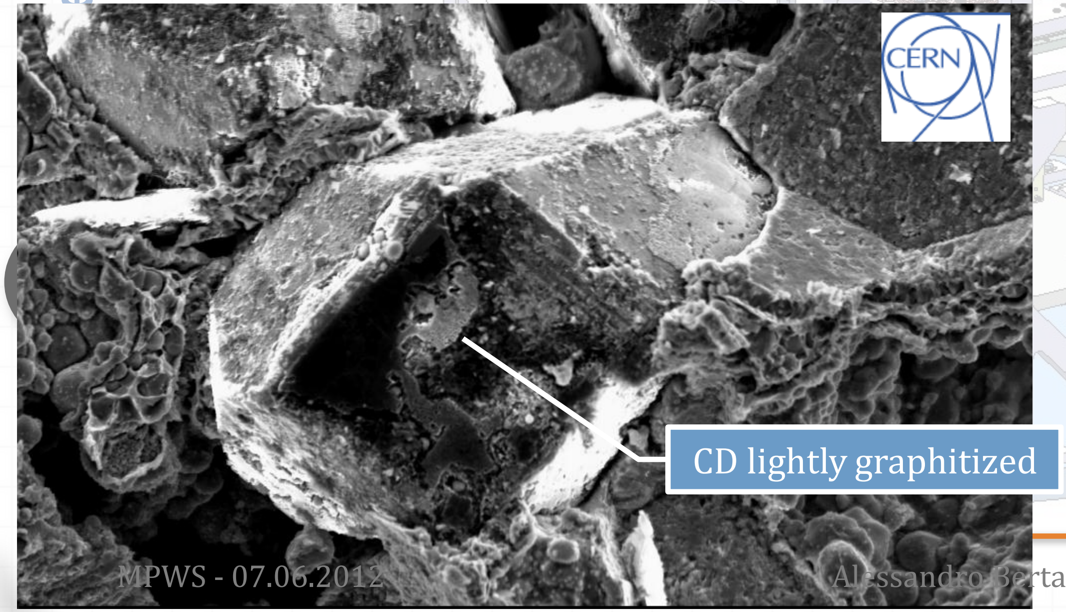
- Co-developed by **CERN** and a SME, **Brevetti Bizz**, Verona, Italy
- High sintering T of Mo (~**1700 °C**) leads to diamond graphitisation. 2 alternative processes: **Liquid Phase Sintering** (**LPS**) or **Assisted Solid-state Sintering** (**ASS**)

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.



CD lightly graphitized

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)

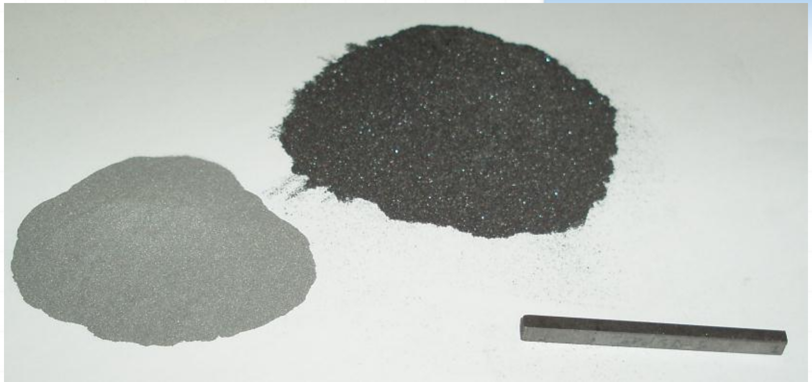
⬆ Lower Density

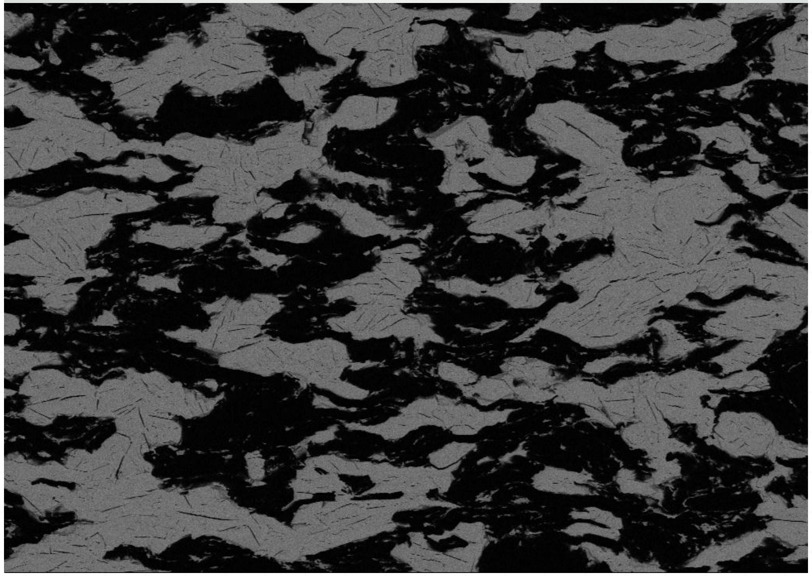
↔ Similar Thermal Conductivity

⬆ No reinforcement degradation

⬆ Lower Costs

⬇ Mechanical strength not yet satisfactory

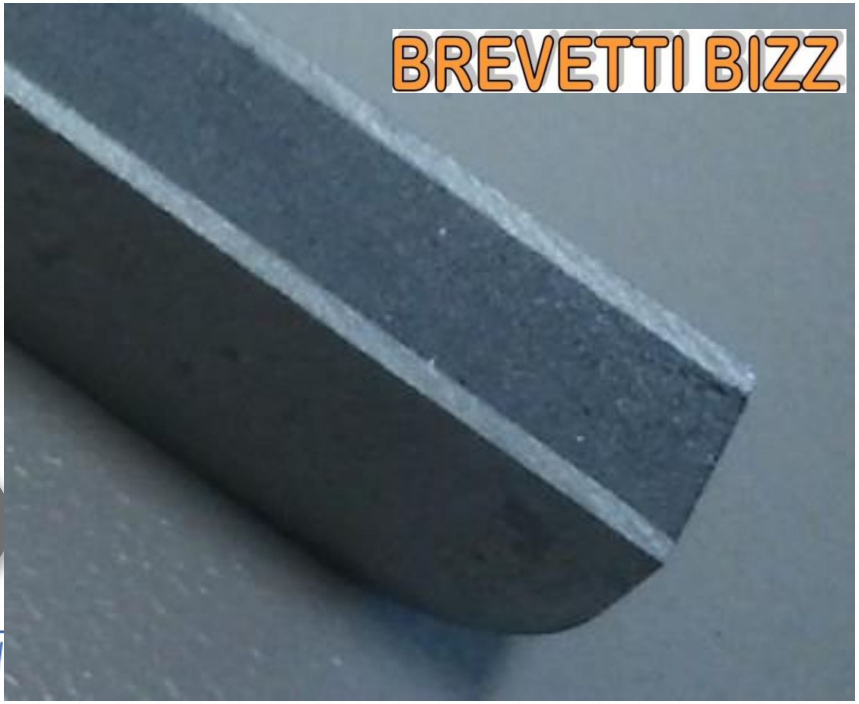


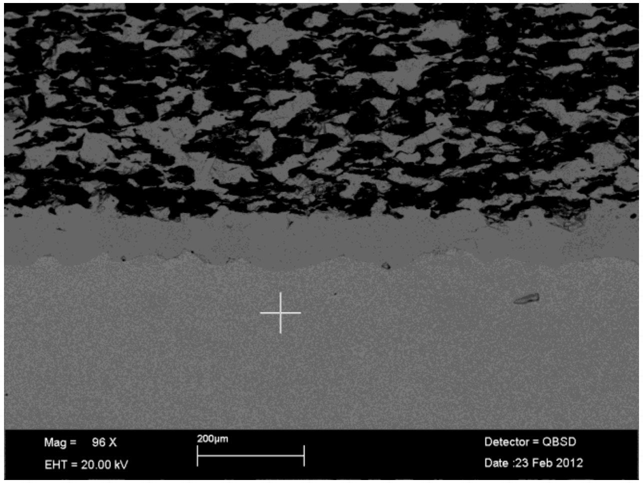


- Mo-Gr still under intense R&D program.
- Margins of improvements by optimizing base materials, composition and processes.

Mo-Gr/Mo Sandwich

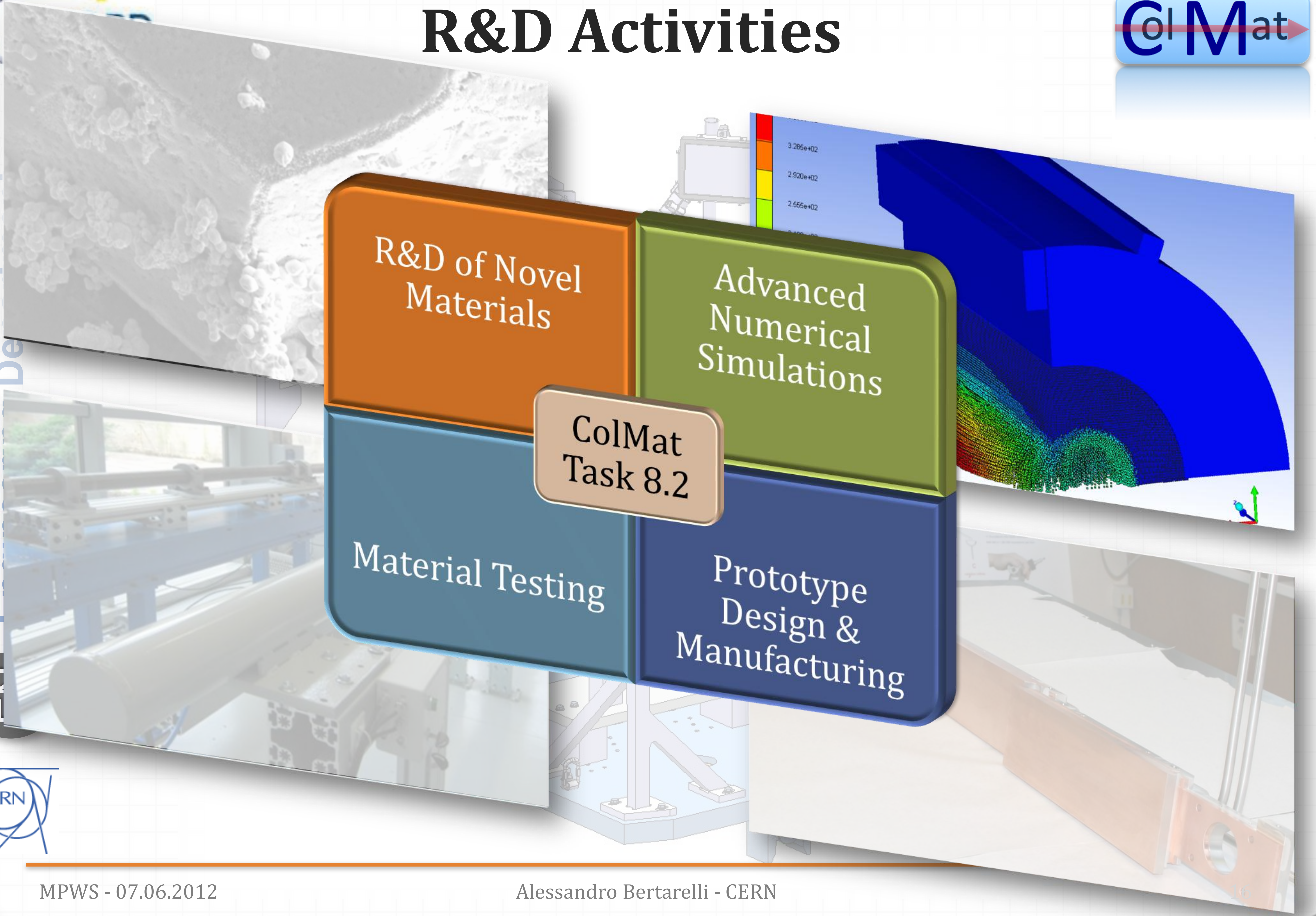
- Co-developed by **CERN** and **Brevetti Bizz**.
- Molybdenum – Graphite core with pure Mo cladding.
- Sandwich structure drastically increases electrical conductivity.
- Up 1 mm thick Mo layer perfectly bonded.





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

R&D Activities



R&D of Novel Materials

Advanced Numerical Simulations

Material Testing

Prototype Design & Manufacturing

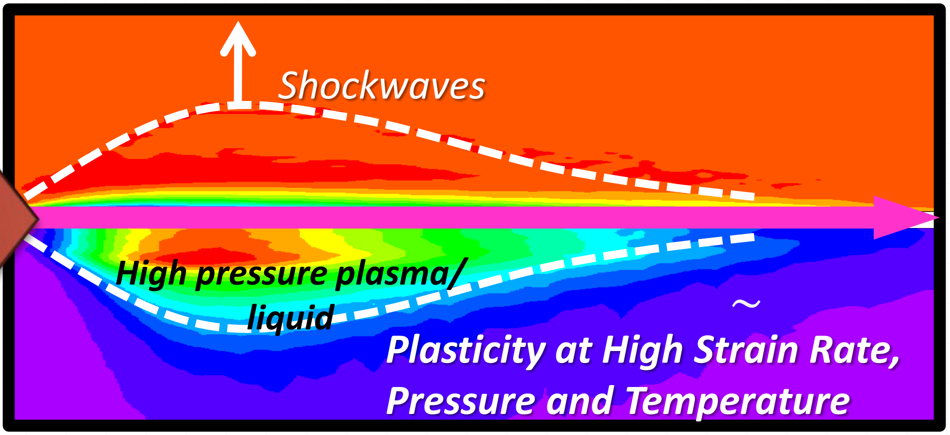
ColMat Task 8.2

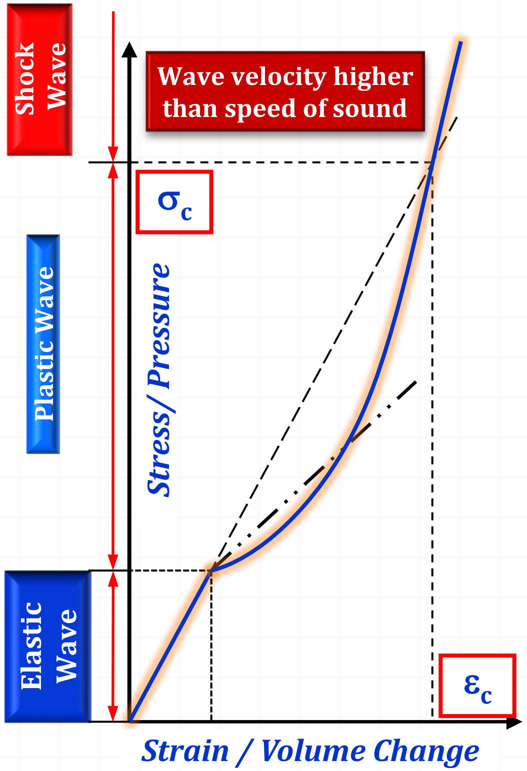
Thermally Induced Dynamics

- Rapid interactions of particle beams with solids induce **Dynamic Responses** in matter.
- **Three** main Dynamic Response **Regimes** exist, depending on several parameters:
  - **Deposited Energy**
  - **Interaction Duration**
  - **Material Strength ...**

Regime 1: stress waves and vibrations in the elastic domain
Regime 2: stress waves and vibrations in the plastic domain
Regime 3: Shock Waves

- High Deposited Energy
- Strain, pressure exceed a critical value
- Wave faster than elastic sound speed.
- Changes of Density
- **Phase Transitions**

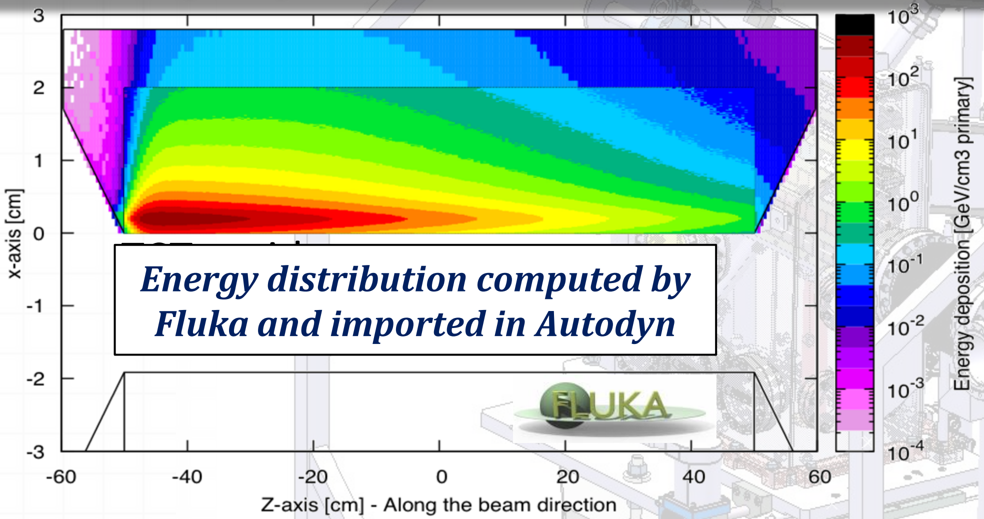




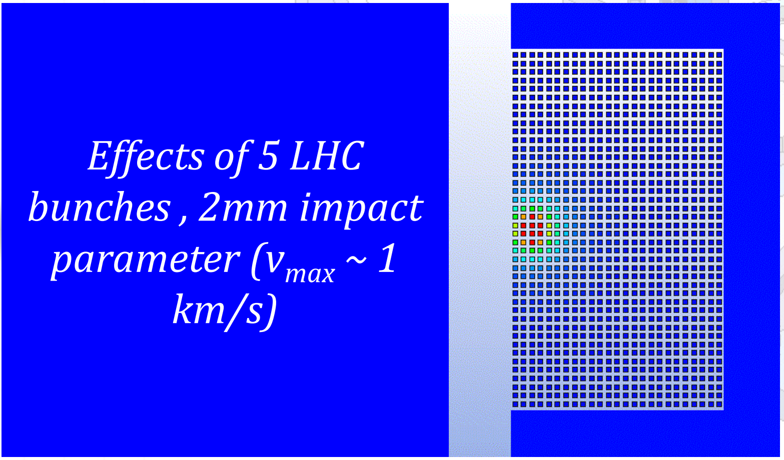
Shock Waves can only be treated with advanced numerica tools (**Hydrocodes**).
Hydrocodes require extended knowledge of complex material **Consitutive Models**

Shock-wave Analysis

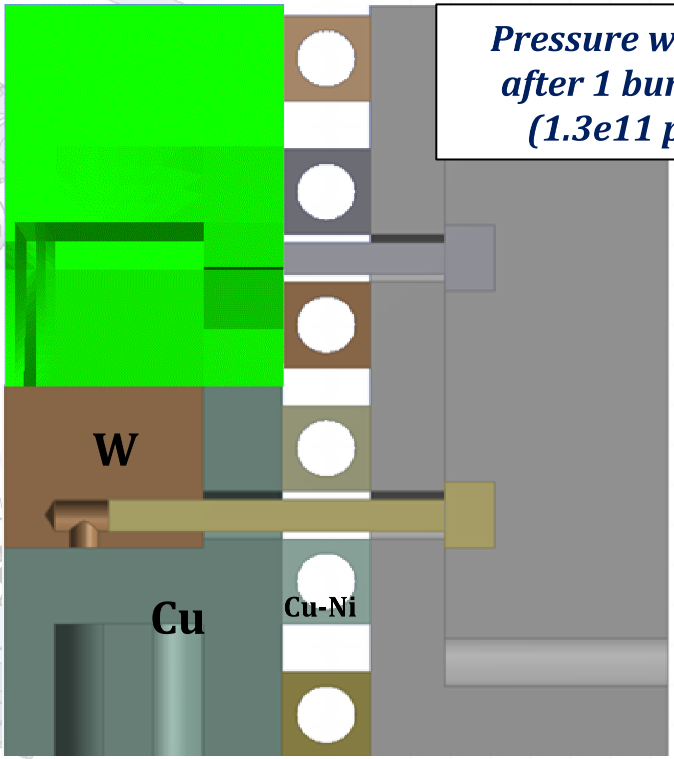
Impact of LHC bunches (1.3e11) at 5 TeV on a Tertiary (Tungsten) Collimator simulated with **Autodyn** hydrocode.



Energy distribution computed by Fluka and imported in Autodyn



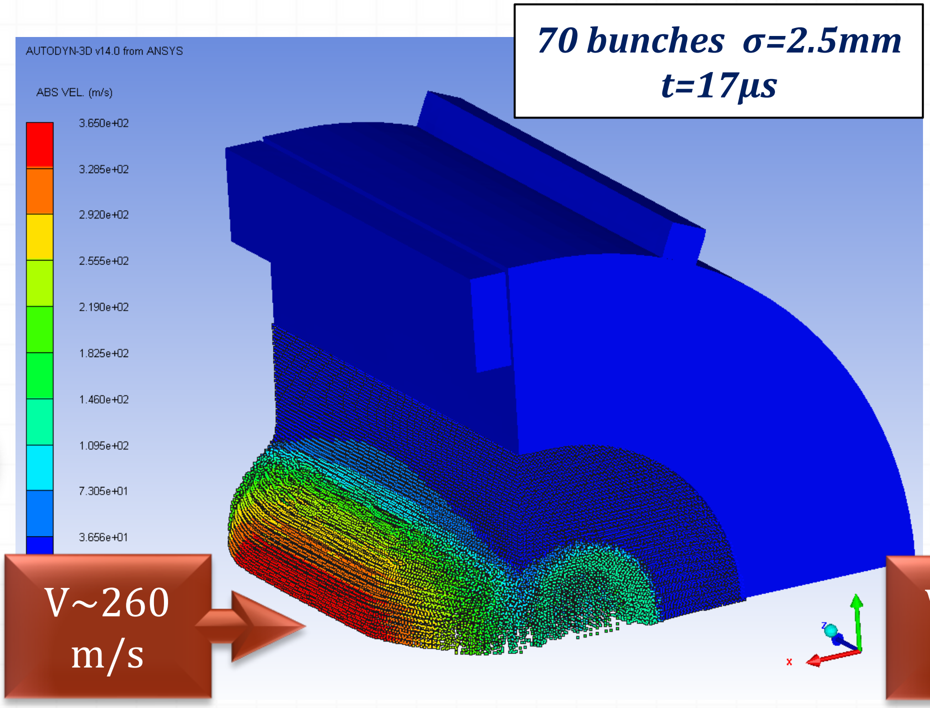
Effects of 5 LHC bunches , 2mm impact parameter (v_{max} ~ 1 km/s)



Pressure wave after 1 bunch (1.3e11 p)

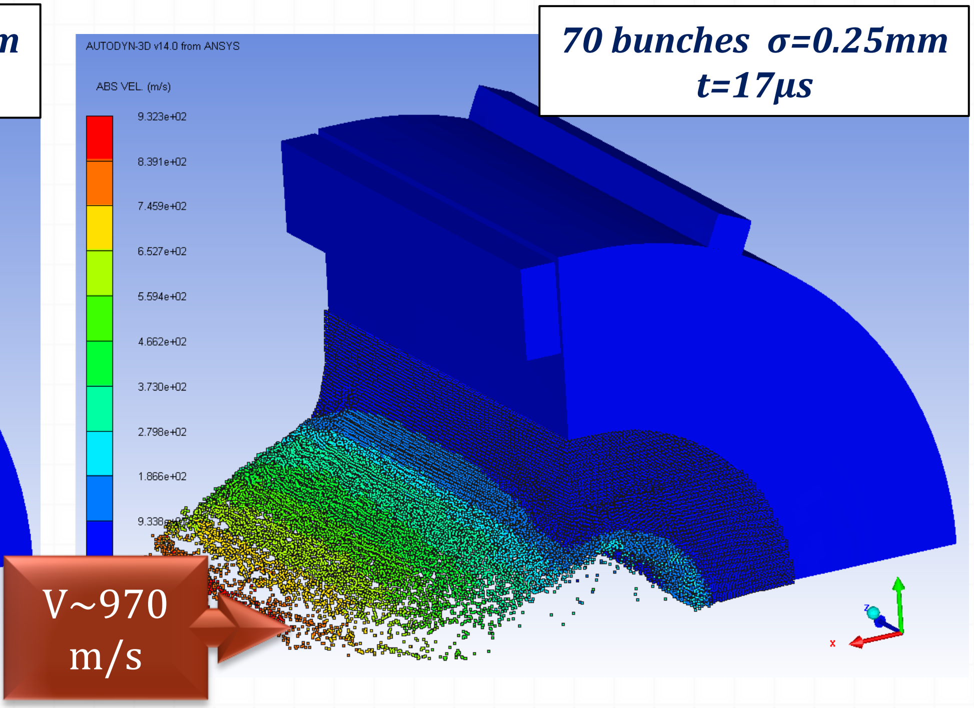
SPH Analysis

- **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



70 bunches σ=2.5mm
t=17μs

V~260 m/s

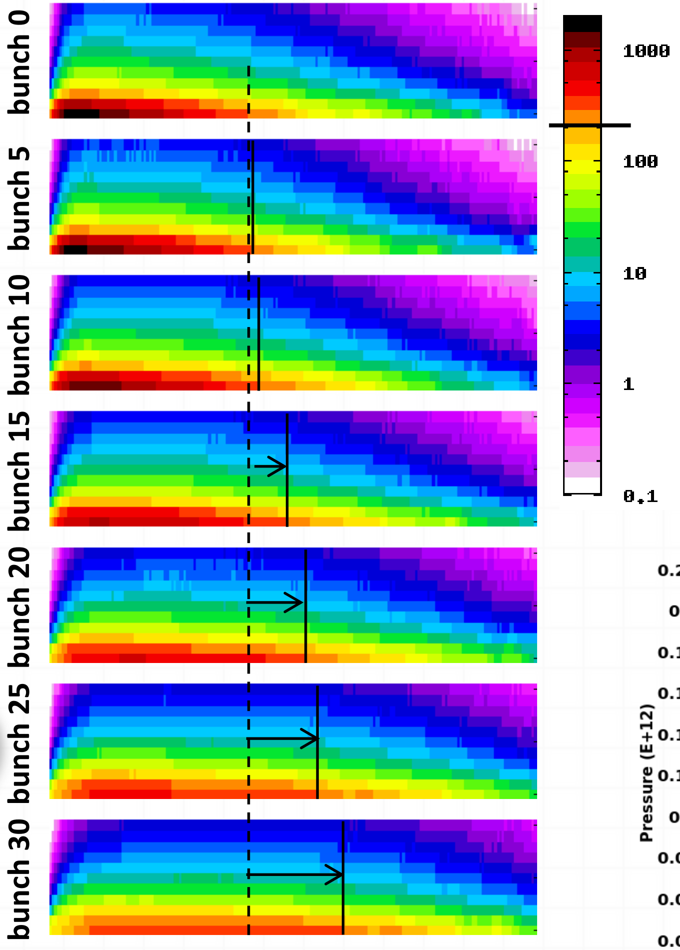


70 bunches σ=0.25mm
t=17μs

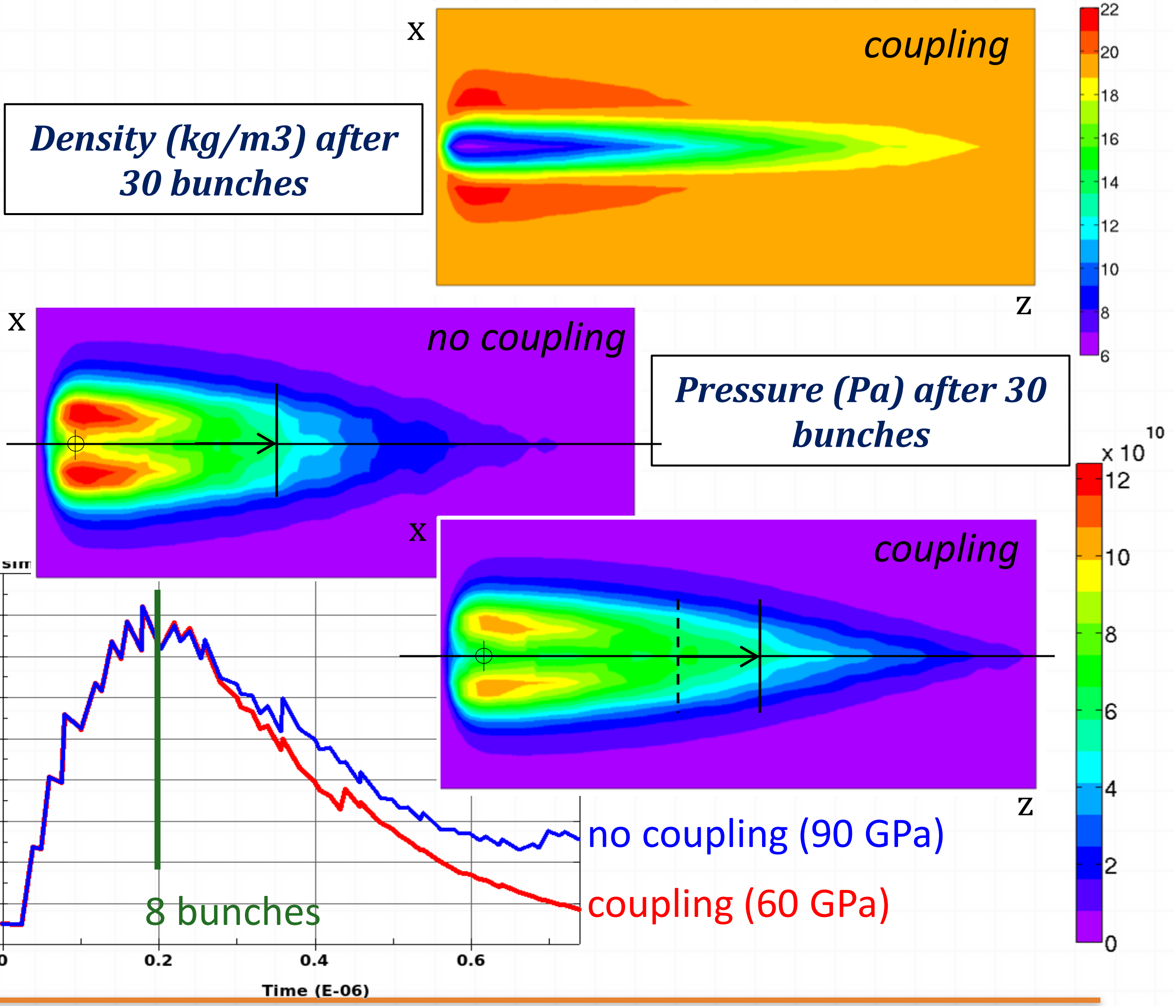
V~970 m/s

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**)



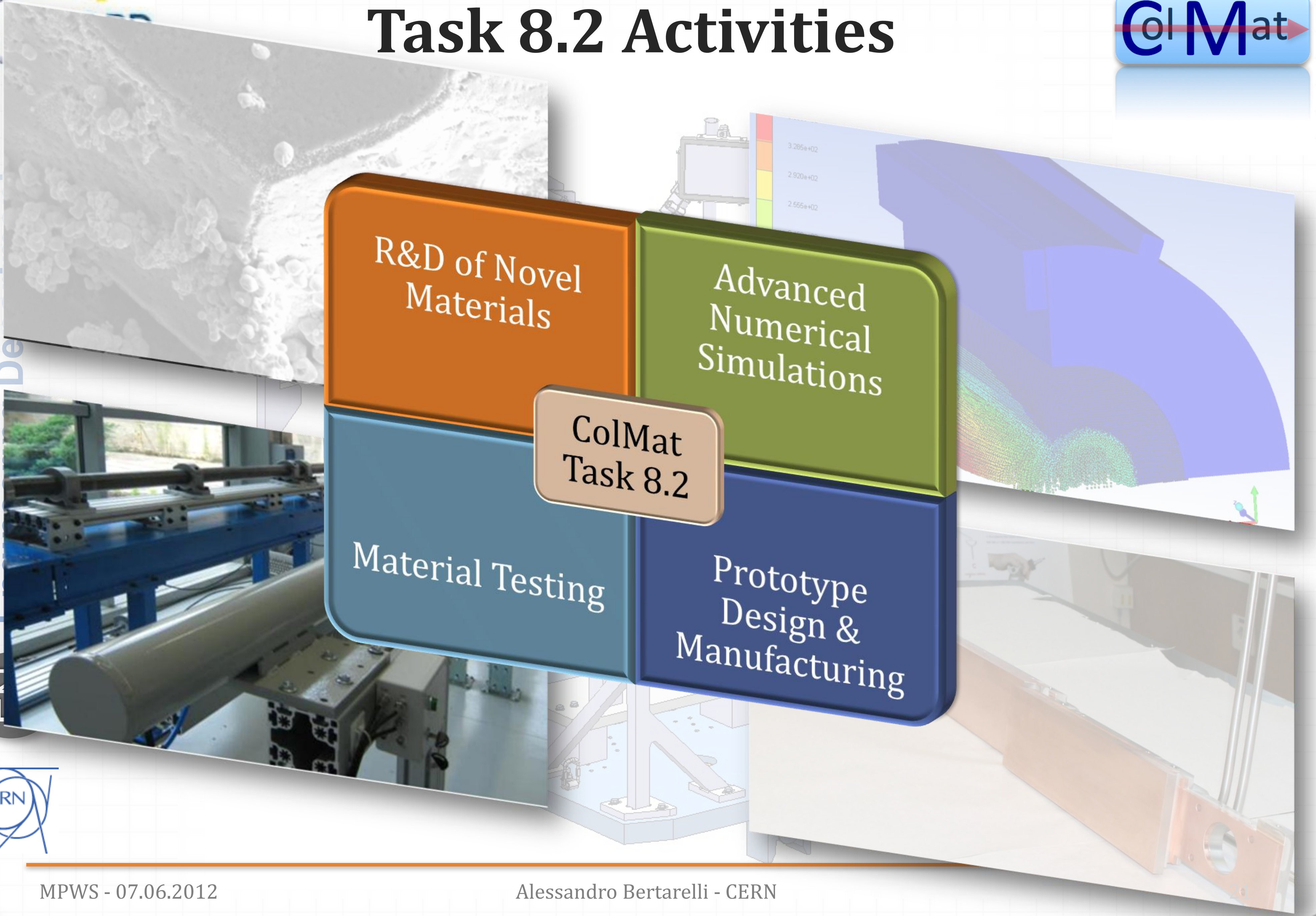
Energy deposition GeV/cm^3



Density (kg/m3) after 30 bunches

Pressure (Pa) after 30 bunches

Task 8.2 Activities



R&D of Novel Materials

Advanced Numerical Simulations

ColMat Task 8.2

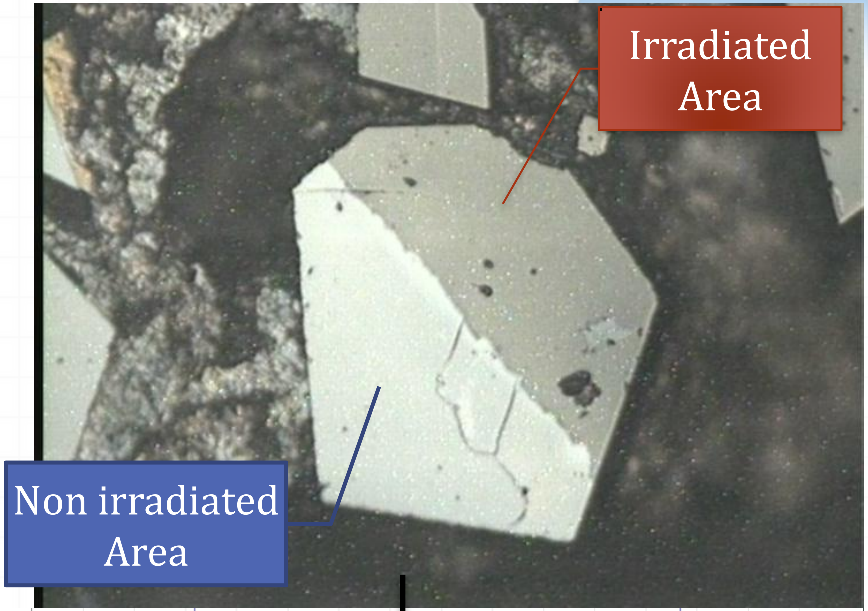
Material Testing

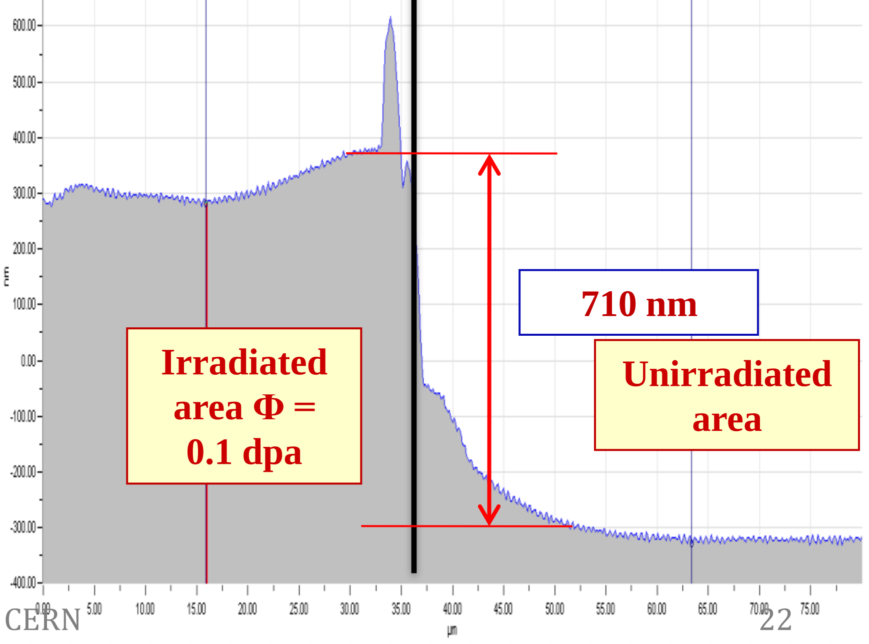
Prototype Design & Manufacturing

Cu-CD Irradiation

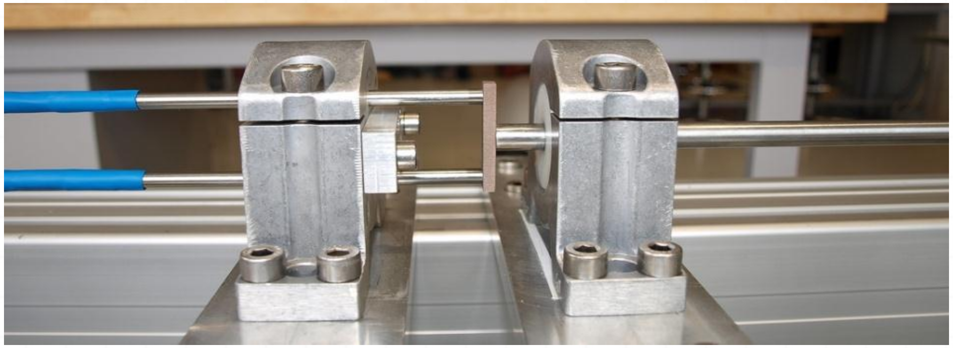
- **Irradiation studies** on Cu-CD at **RRC-KI**
- Proton Beam: 30 MeV, $\Phi = 10^{17}$ p/cm^2,
  - Estimated dpa level $10^{-4} - 10^{-3}$
- Carbon-Ion Beam: 26 MeV, $\Phi = 10^{16}$ i/cm^2,
  - Estimated dpa level 10^{-1}
- Properties measured **before and after irradiation**.
- **Material strength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

Swelling Measurement on Diamond carried out by Carbon-Ion Irradiation

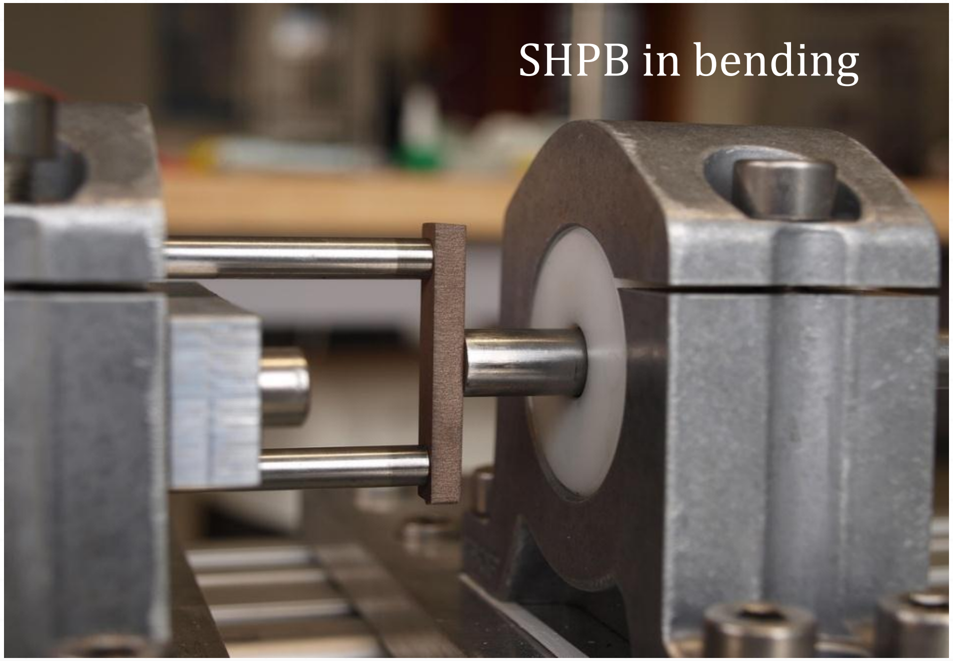


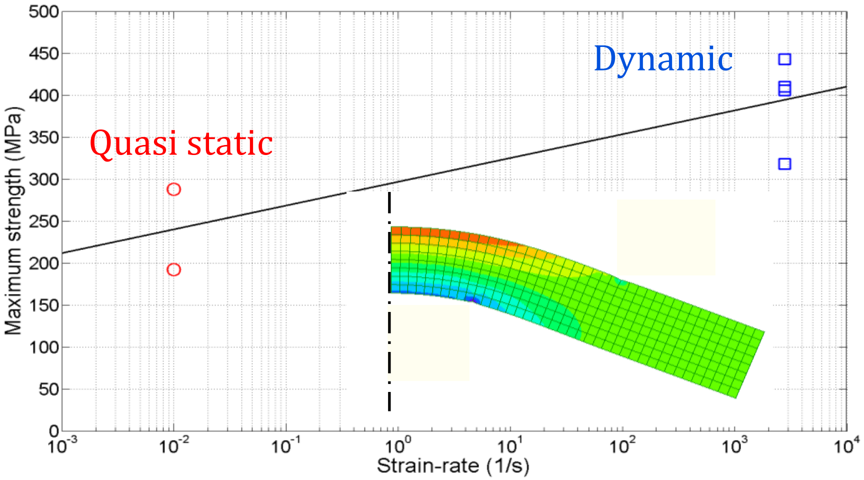


MoCD Mechanical Tests



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





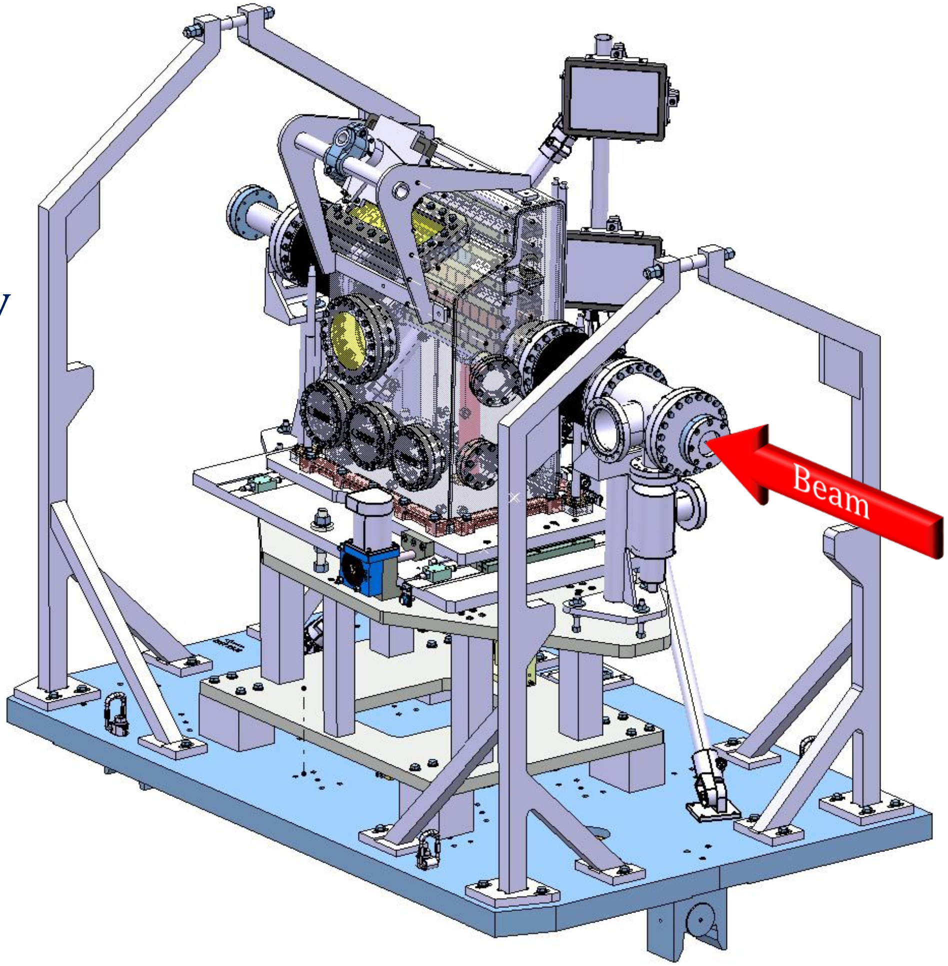
The value of strength and strain-rate are evaluated with an elastic field approximation

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).

HiRadMat
High-Radiation to Materials

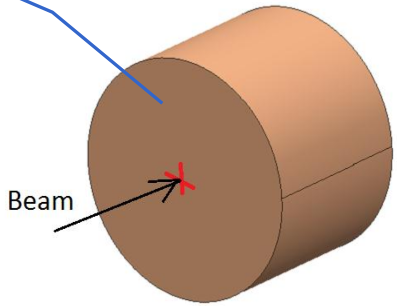


Material Tests in HiRadMat

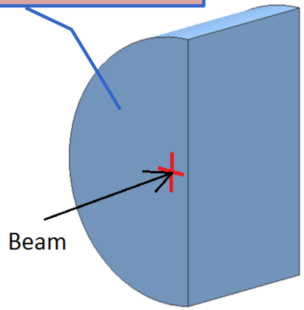
What to do in HiRadMat?

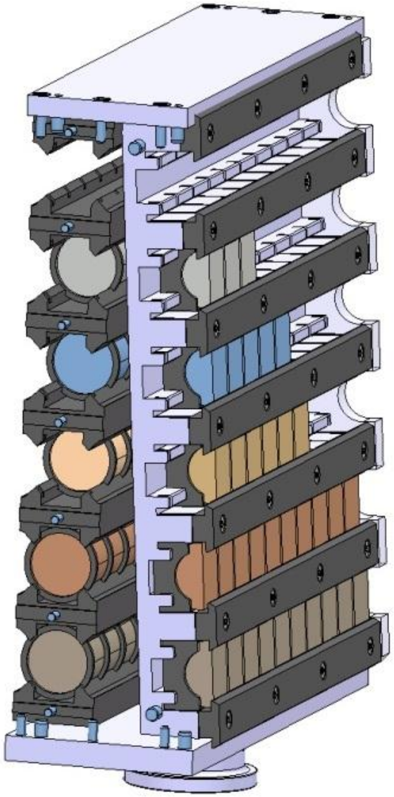
- Characterize **six different materials** (Inermet 180, Glidcop, Molybdenum, Copper-Diamond, Molybdenum-Diamond, Molybdenum-Graphite)
- **Medium intensity** and **High intensity** tests, with different material samples for each material (Type 1, Type2)
- Each sample holder tier can host up to **10 specimens**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

Type 1 Sample (Ø 40 mm L30 mm)



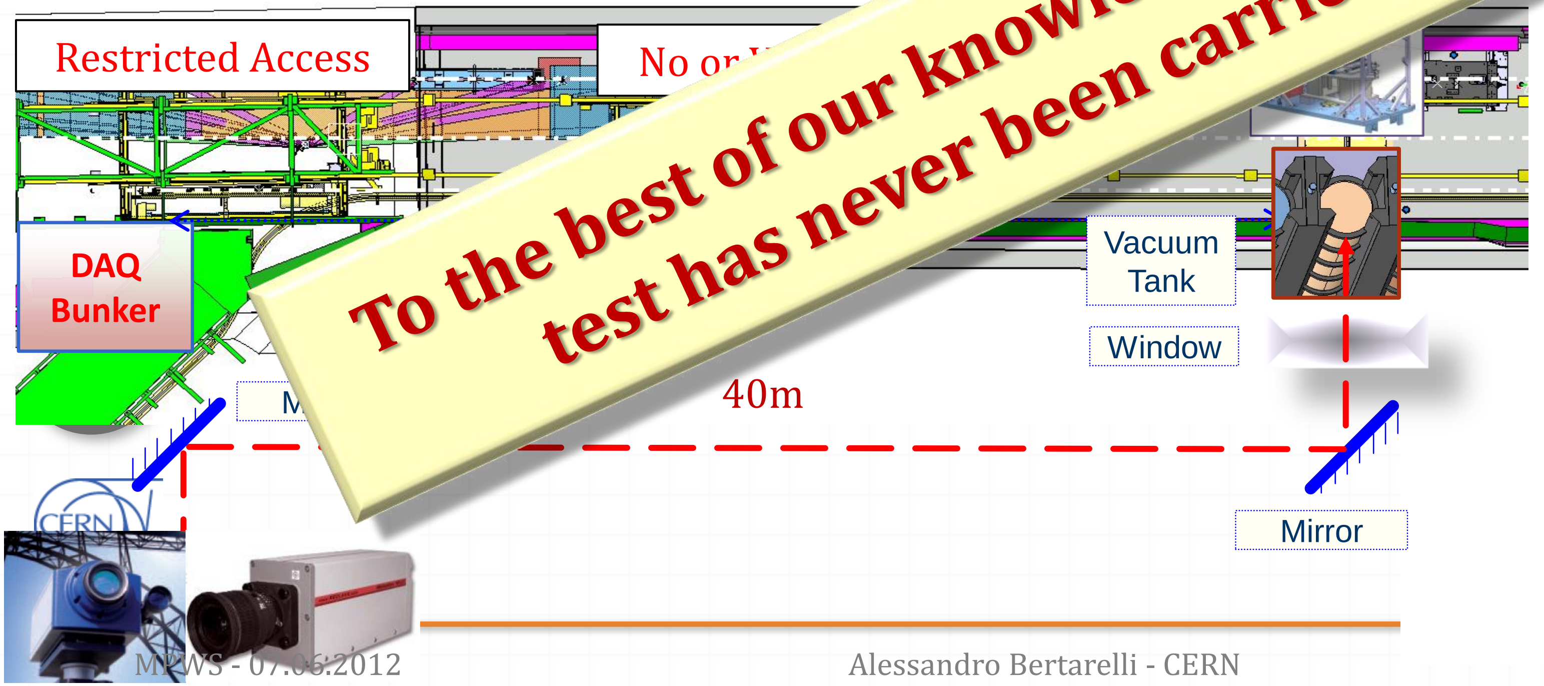
Type 2 Sample (Ø 40 mm, L30 mm, Surf. Offset 2 mm)

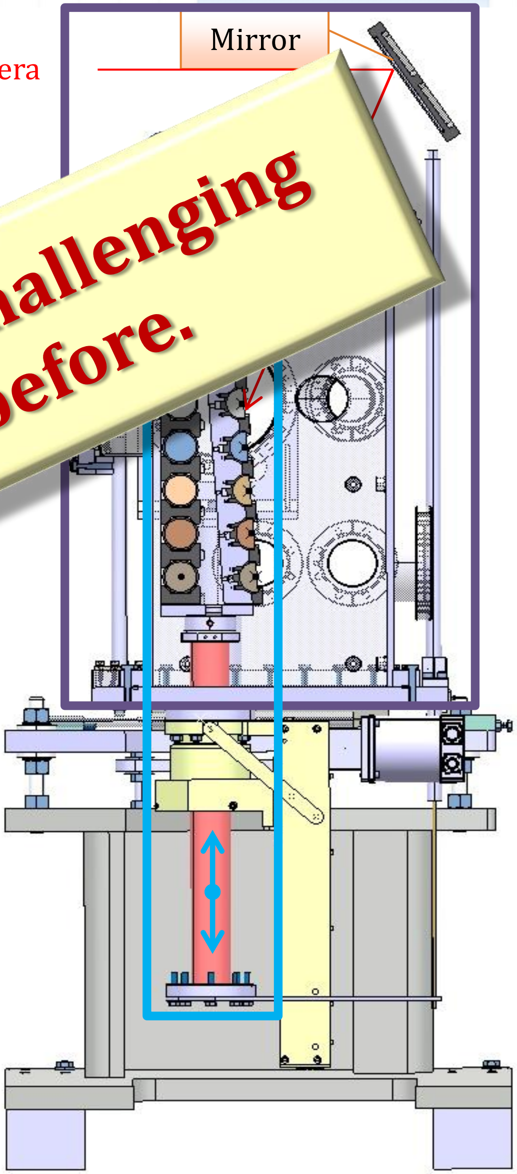




HiRadMat Test DAQ

- **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

R&D of Novel Materials

Advanced Numerical Simulations

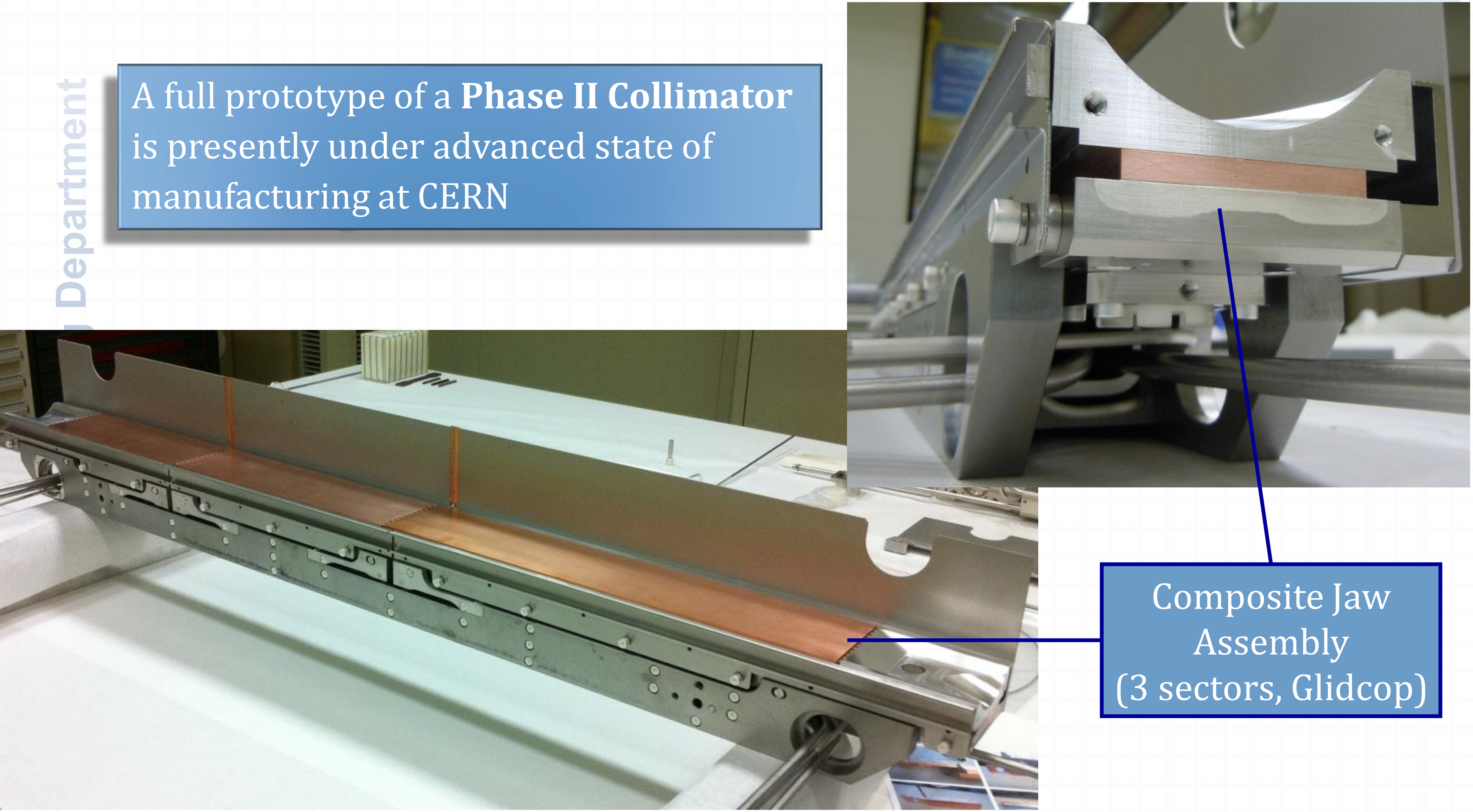
ColMat Task 8.2

Material Testing

Prototype Design & Manufacturing

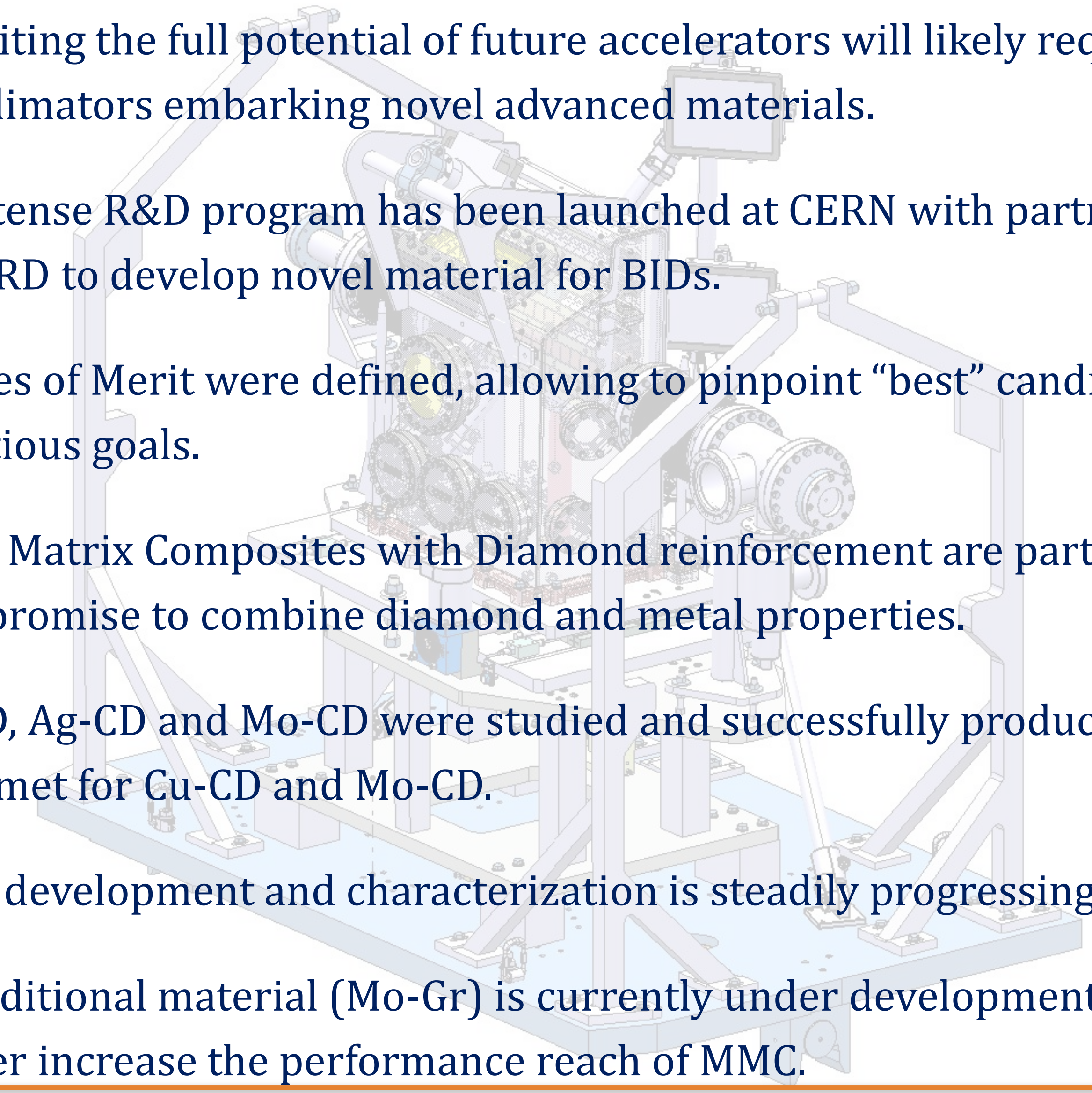
Phase II Prototype

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



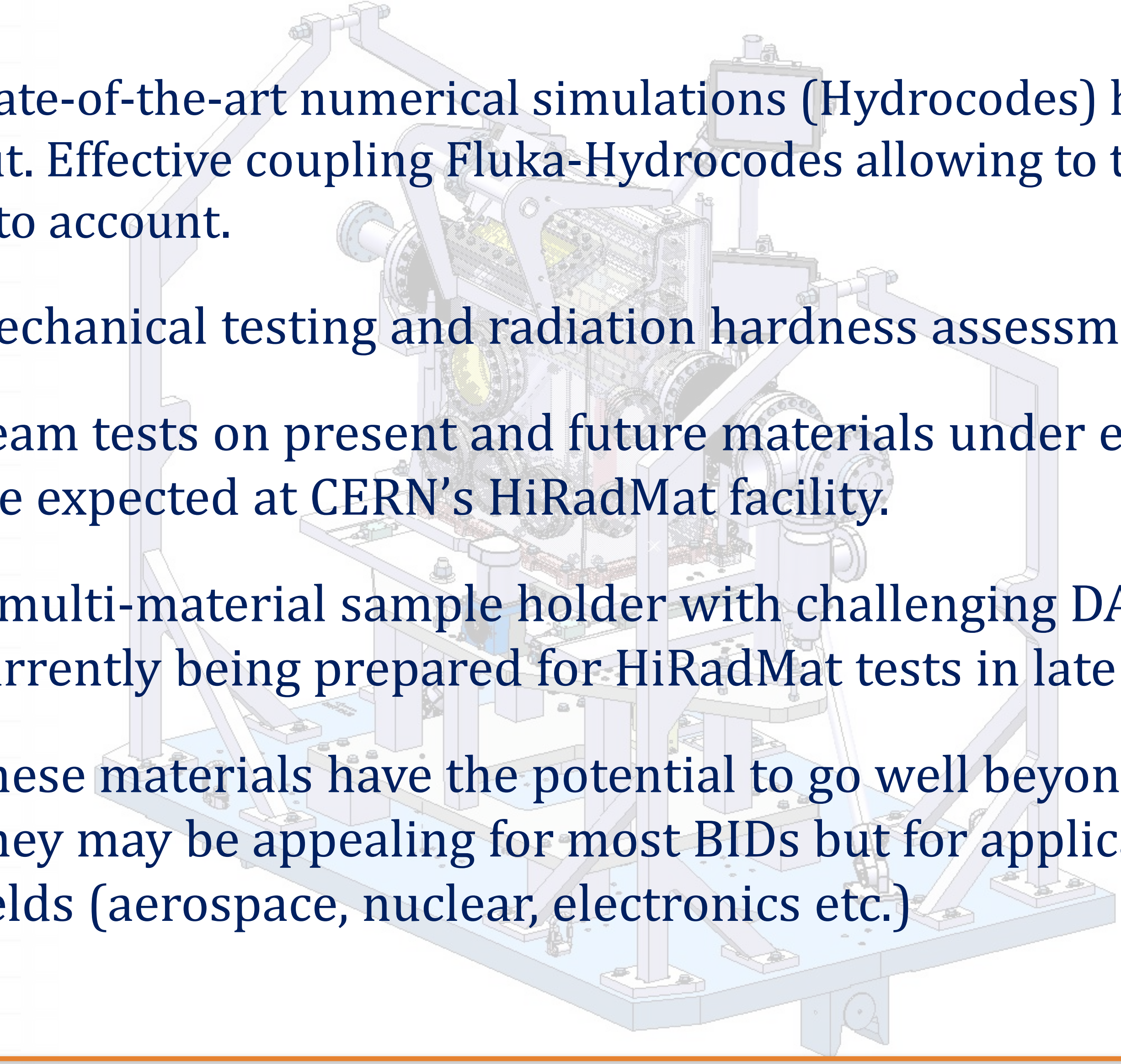
Composite Jaw Assembly
(3 sectors, Glidcop)

Conclusions I



- Exploiting the full potential of future accelerators will likely require a new generation of collimators embarking novel advanced materials.
- An intense R&D program has been launched at CERN with partners partly within the EuCARD to develop novel material for BIDs.
- Figures of Merit were defined, allowing to pinpoint “best” candidates and to set ambitious goals.
- 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 development and characterization is steadily progressing.
- An additional material (Mo-Gr) is currently under development and promises to further increase the performance reach of MMC.

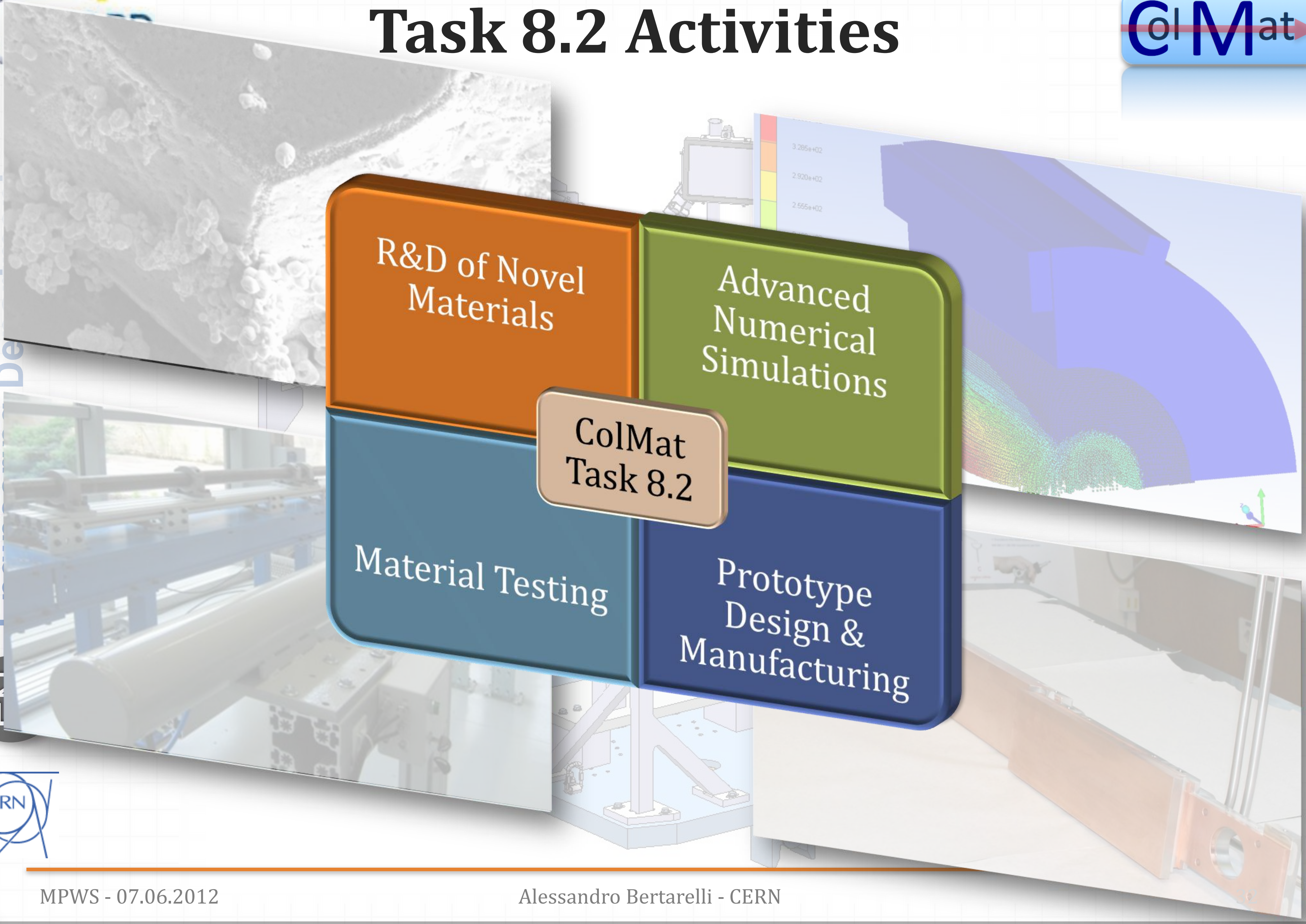
Conclusions II



- State-of-the-art numerical simulations (Hydrocodes) have been carried out. Effective coupling Fluka-Hydrocodes allowing to take tunnelling effect into account.
- Mechanical testing and radiation hardness assessment is ongoing.
- Beam tests on present and future materials under extreme conditions are expected at CERN's HiRadMat facility.
- A multi-material sample holder with challenging DAQ system is currently being prepared for HiRadMat tests in late 2012.
- These materials have the potential to go well beyond LHC Collimators. They may be appealing for most BIDs but for applications in other fields (aerospace, nuclear, electronics etc.)

THANK YOU FOR YOUR ATTENTION

Task 8.2 Activities

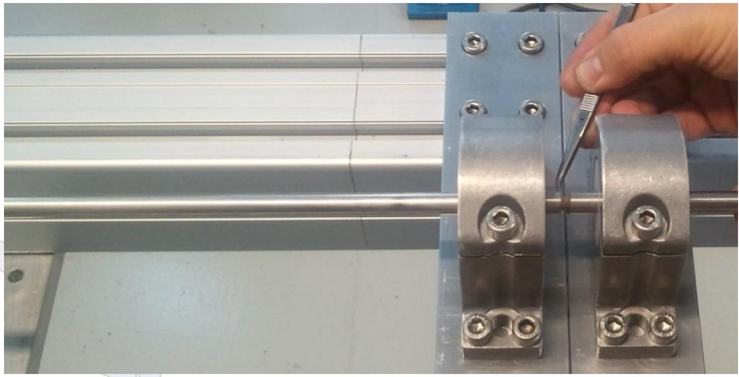


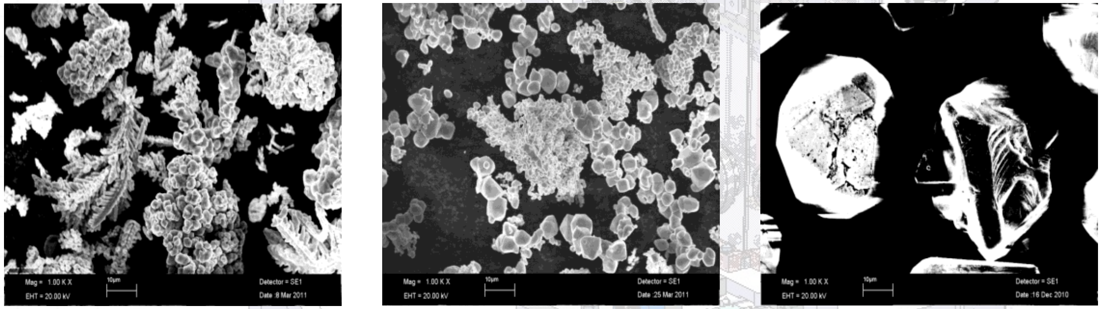
ColMat Task 8.2

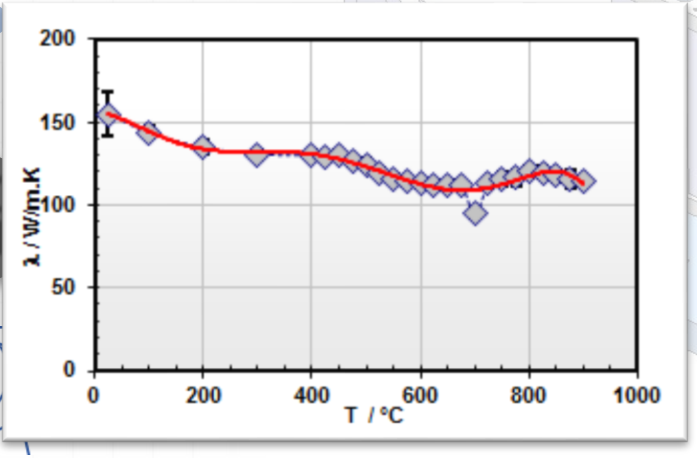
- R&D of Novel Materials
- Advanced Numerical Simulations
- Material Testing
- Prototype Design & Manufacturing

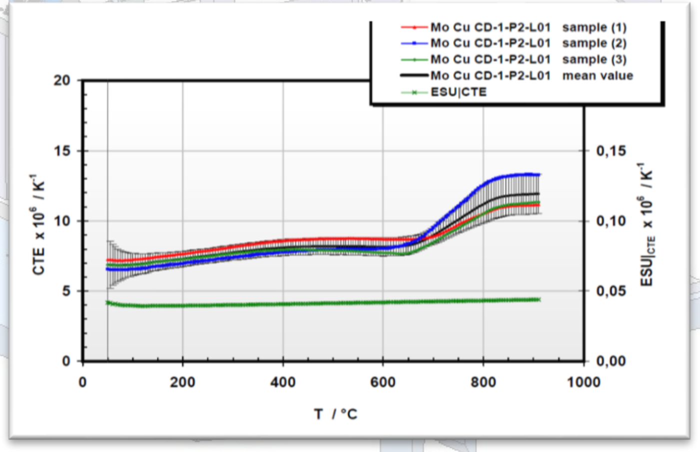
MoCD Thermo-Mechanical Tests

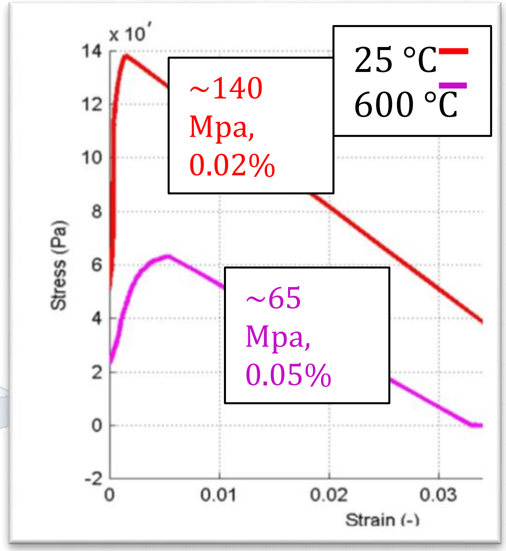
- Mechanical characterization carried out at **CERN** (quasi-static) and **Politecnico di Torino** (dynamic – Hopkinson's bar tests)
- Thermal Characterization carried out at **AIT**
- Microstructural characterization at CERN











~140 Mpa, 0.02%

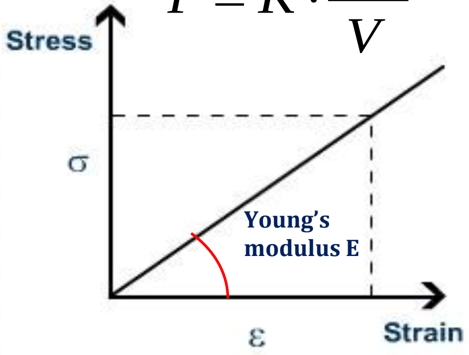
~65 Mpa, 0.05%

Material Modelling

Standard FEM Codes

Linear Elastic Behaviour

$$P = K \cdot \frac{\Delta V}{V}$$



Replaced by

Static Yield Strength

$$\sigma_y = R_{p0.2}$$

Replaced by

Static Failure Strength

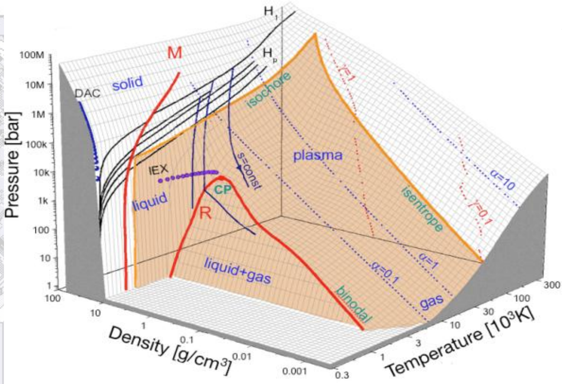
$$\sigma_{ult} = R_m$$

Replaced by

Hydrocodes

Complex Equations of State (EOS)

$$P = f\left(\rho, E(T)\right)$$



- ✓ Mie-Gruneisen
- ✓ Tabular EOS (SESAME)
- ✓ Tillotson
- ✓ ....

Multi-parameter Yield Models

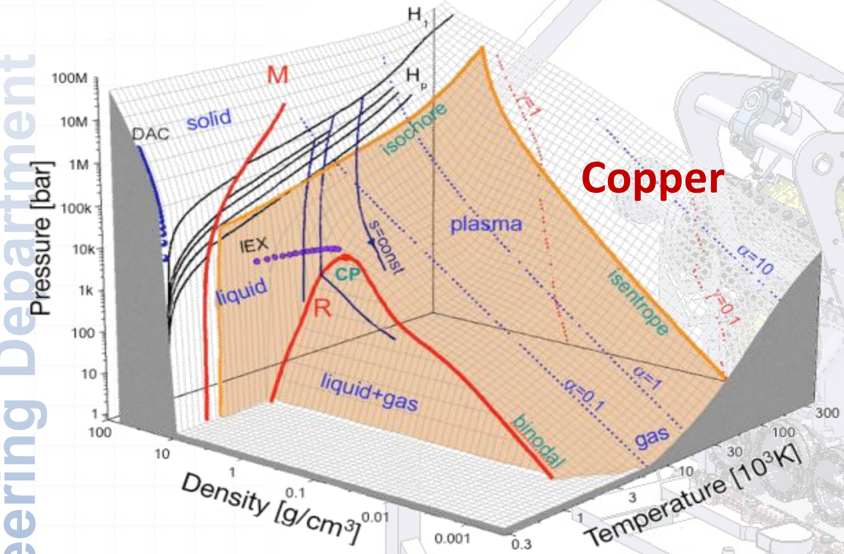
$$\sigma_y = f\left(\varepsilon, \dot{\varepsilon}, T, ...\right)$$

- ✓ Johnson-Cook
- ✓ Steinberg-Guinan
- ✓ Johnson-Holmquist
- ✓ ....

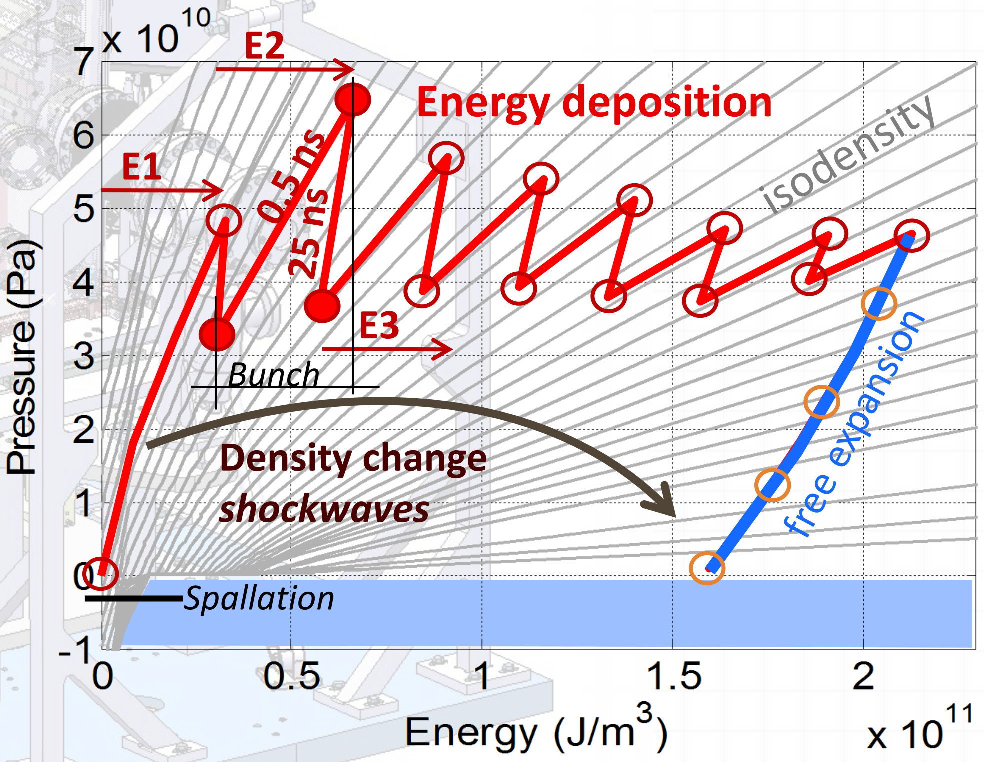
Dynamic Failure Models

$$Damage = f\left(\varepsilon, \dot{\varepsilon}, T, P_{\max}, P_{\min}, K_c ...\right)$$

Equations of state

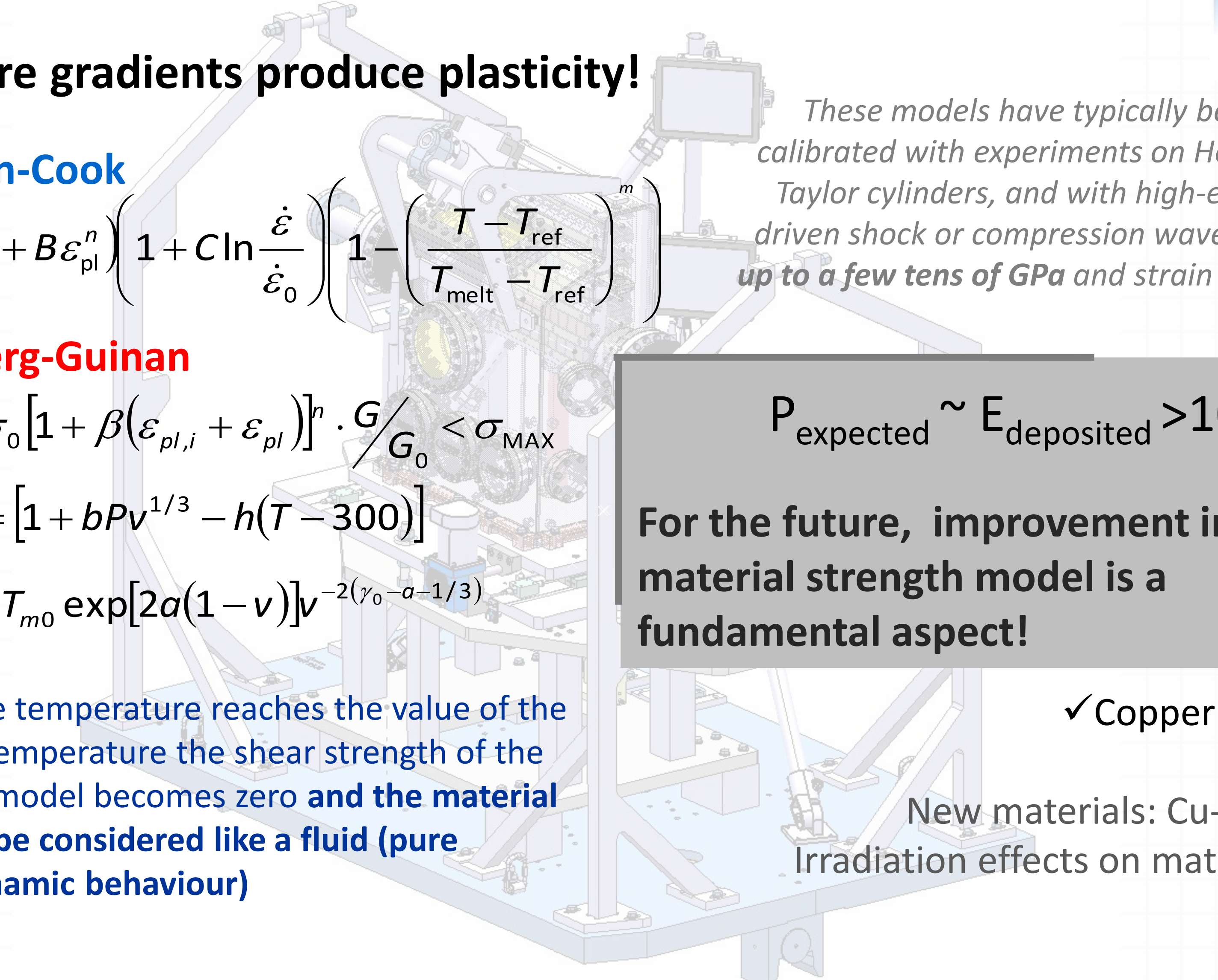


The EOS must include solid and fluid phases and the dependent variable (pressure) is defined as function of independent variables (internal energy and density)



- ✓ a new territory that of **high power explosions** and **ballistics**
- ✓ most pure material **EOS** are drawn from **military research** (mainly **Los Alamos**); unfortunately these data are frequently inaccessible as they are **classified**
- ✓ EOS for specific mixtures and alloys are often totally unavailable (Metal-CD?)

Constitutive material models



Pressure gradients produce plasticity!

Johnson-Cook

$$\sigma_y = \left(A + B\varepsilon_{\text{pl}}^n\right)\left(1 + C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\left(1 - \left(\frac{T - T_{\text{ref}}}{T_{\text{melt}} - T_{\text{ref}}}\right)^m\right)$$

Steinberg-Guinan

$$\begin{cases} \sigma_y = \sigma_0\left[1 + \beta\left(\varepsilon_{pl,i} + \varepsilon_{pl}\right)\right]^n \cdot {}^{G}\!/_{G_0} < \sigma_{\text{MAX}} \\ {}^{G}\!/_{G_0} = \left[1 + bPv^{1/3} - h(T - 300)\right] \\ T_{melt} = T_{m0}\exp\left[2a(1 - v)\right]v^{-2(\gamma_0 - a - 1/3)} \end{cases}$$

When the temperature reaches the value of the melting temperature the shear strength of the material model becomes zero **and the material starts to be considered like a fluid (pure hydrodynamic behaviour)**

These models have typically been tested and calibrated with experiments on Hopkinson bars, Taylor cylinders, and with high-explosive (HE)–driven shock or compression waves at pressures ***up to a few tens of GPa*** *and strain rates of 10^3 to 10^5 s^{-1}*

$P_{\text{expected}} \sim E_{\text{deposited}} > 100$ GPa!

For the future, improvement in the material strength model is a fundamental aspect!

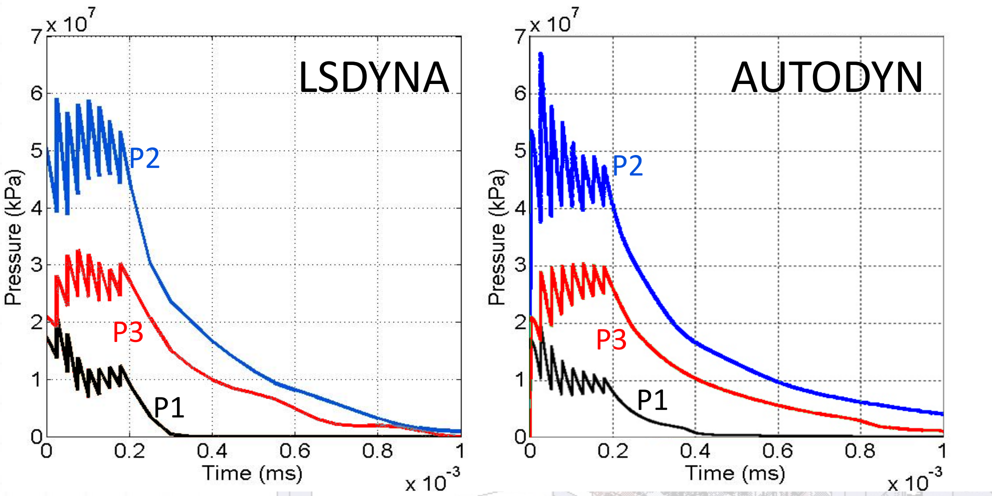
✓Copper and Glidcop

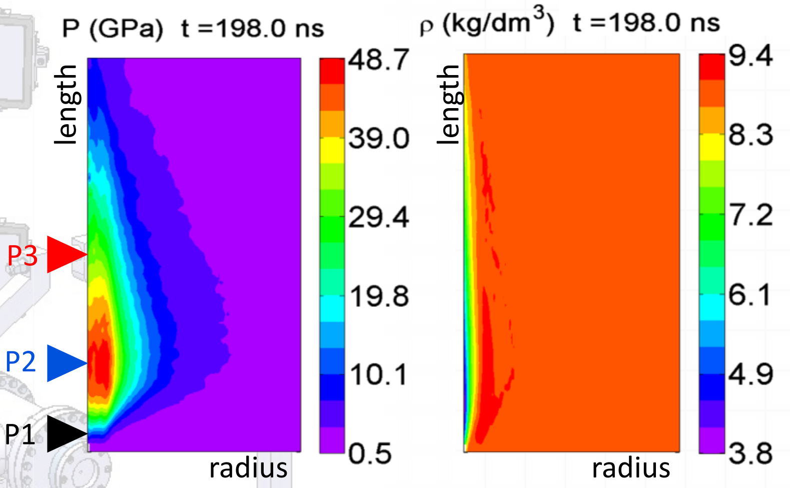
✓Tungsten

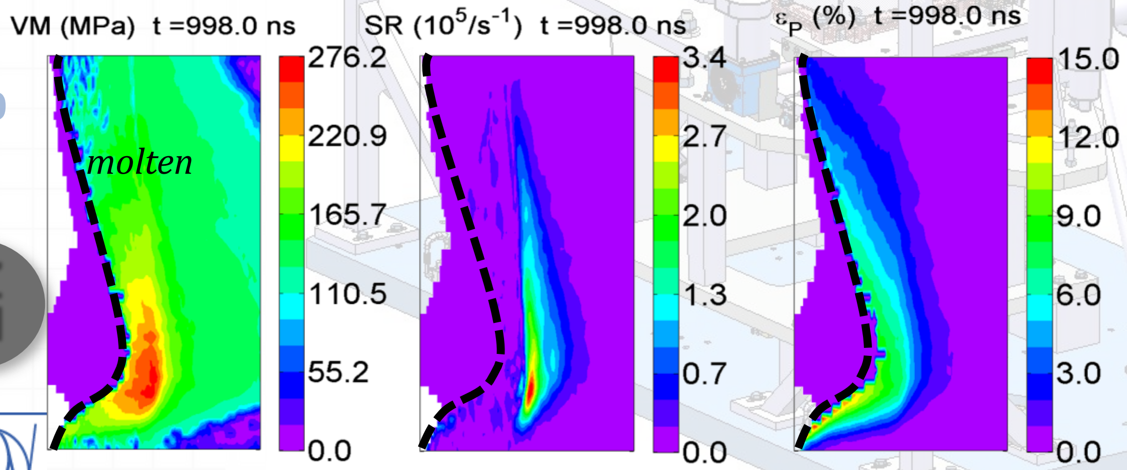
New materials: Cu-CD, Mo-CD?

Irradiation effects on material model?

Hydrocodes benchmarking







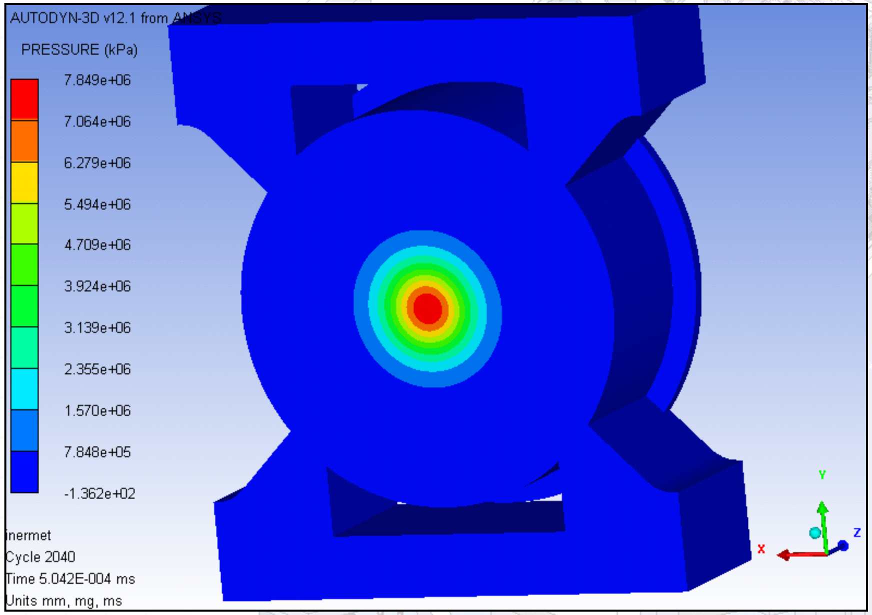
A **Copper** or Tungsten bar (10 mm radius, 1 m long) facially irradiated with **8 bunches** of 7 TeV protons (each bunch 1.11x10^{11} protons)

2D Axis-symmetric lagrangian and eulerian (LSDYNA, AUTODYN, BIG2)

POLITECNICO DI TORINO

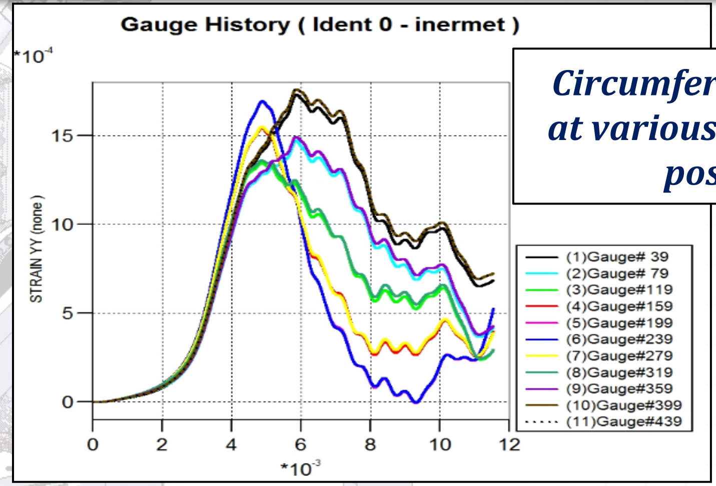
Shock-wave Analysis

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

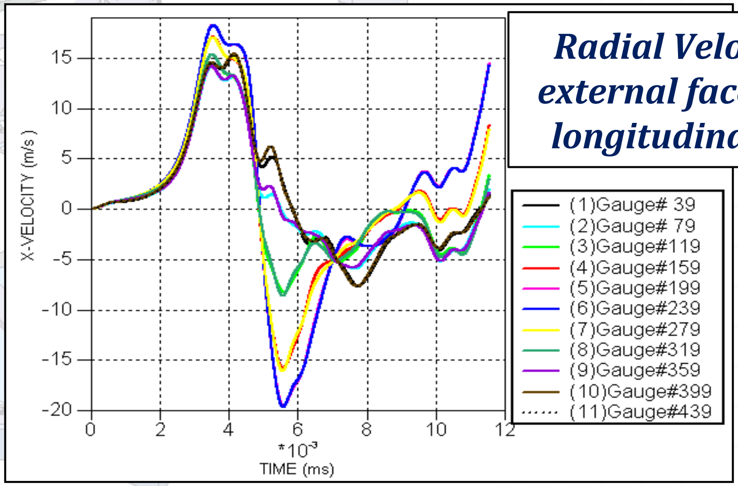


Pressure wave after 500 ns (peak ~8 GPa)

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

Engineering Department

EN

CuCD Irradiation

Engineering Department

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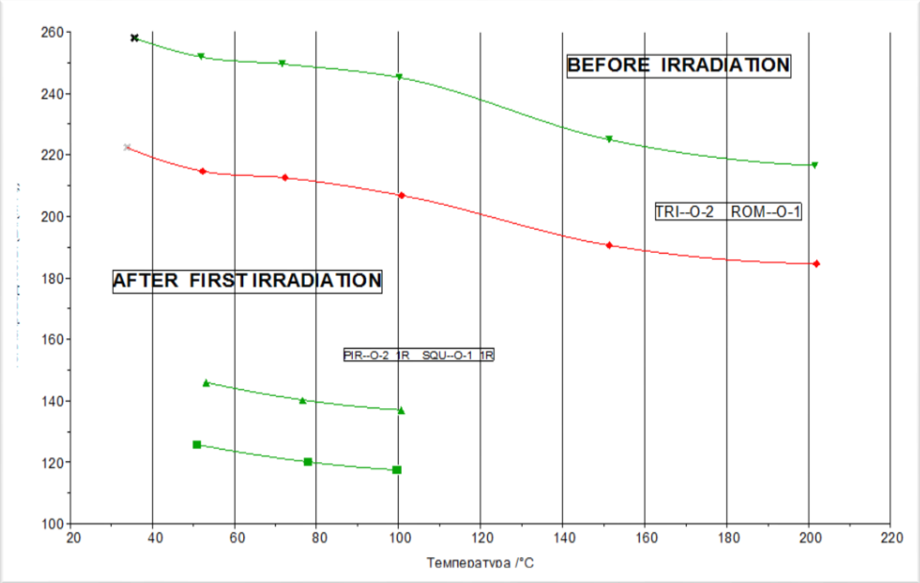
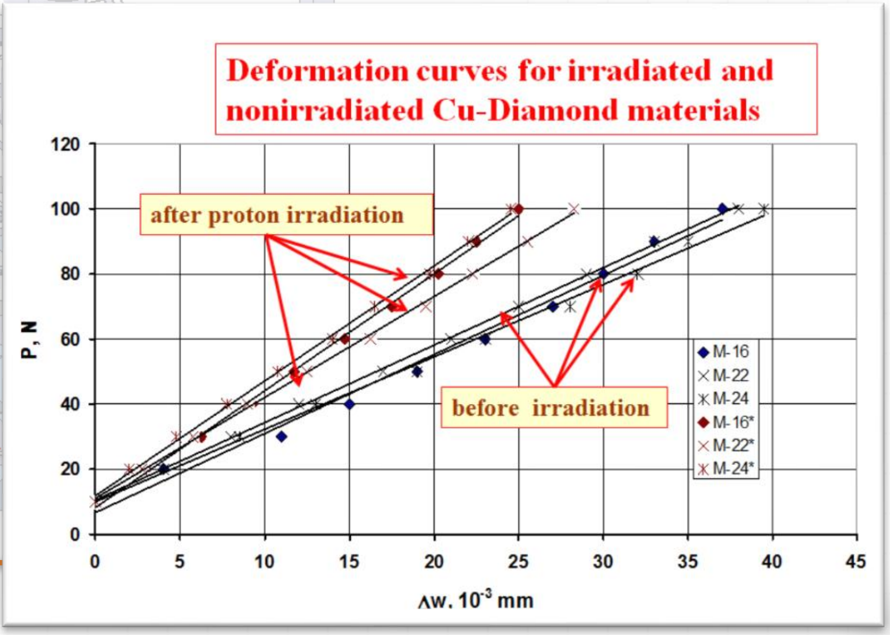
Effect of Proton Irradiation (30 MeV, $\Phi = 10^{17}$ p/cm^2) on Physical Properties

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


Deformation curves for irradiated and nonirradiated Cu-Diamond materials

MoCD Mechanical Tests

Engineering Department

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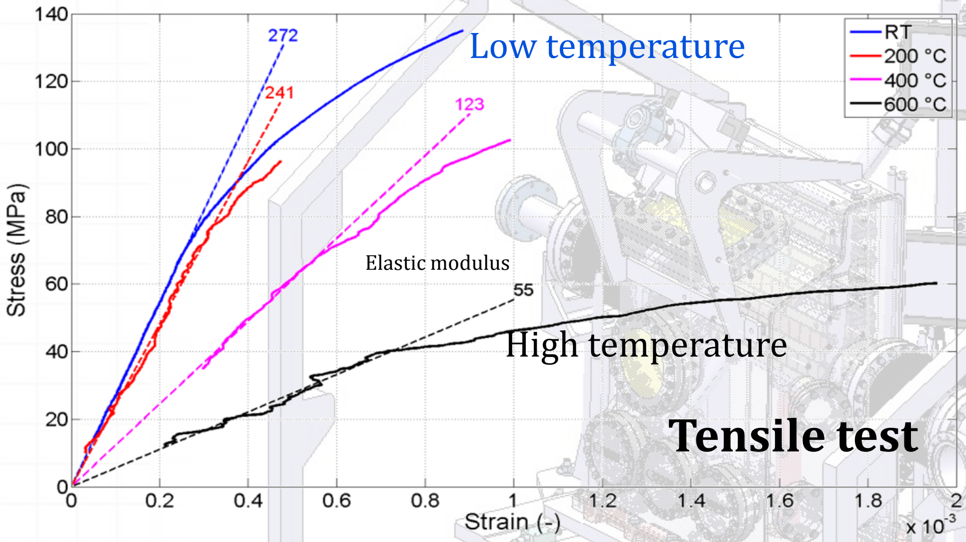
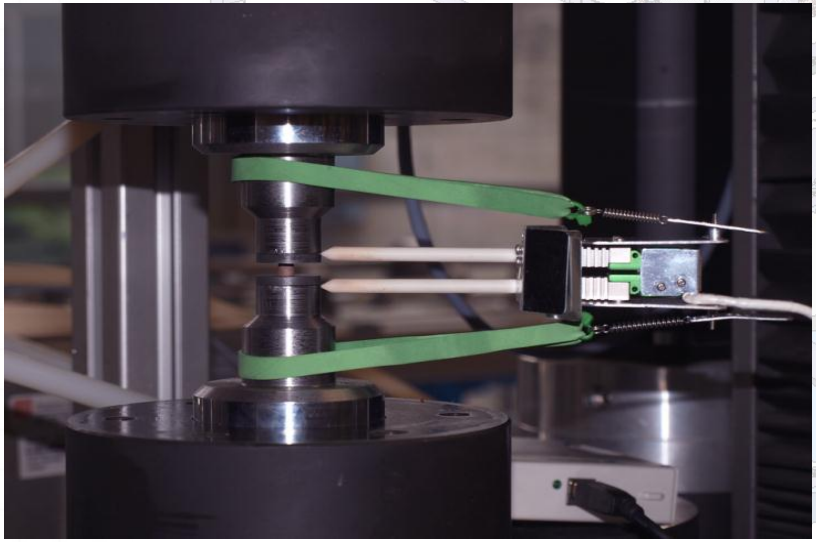
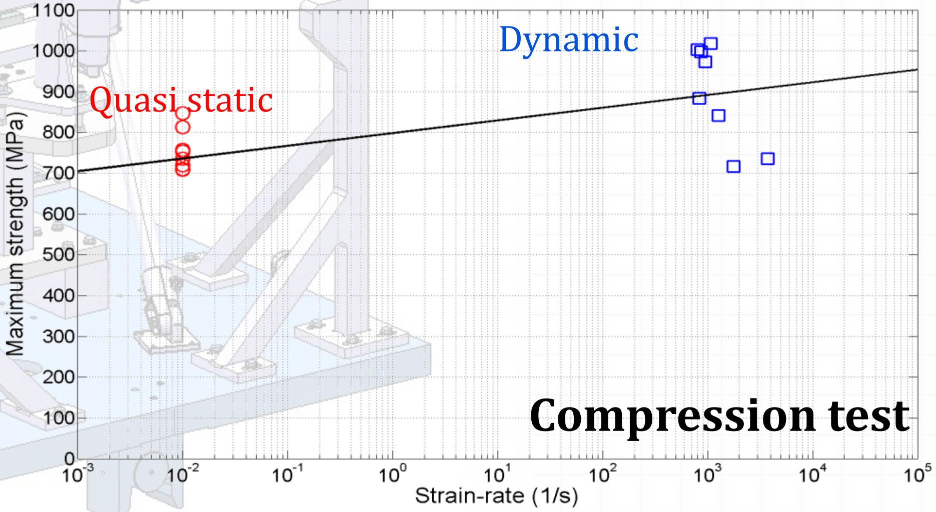


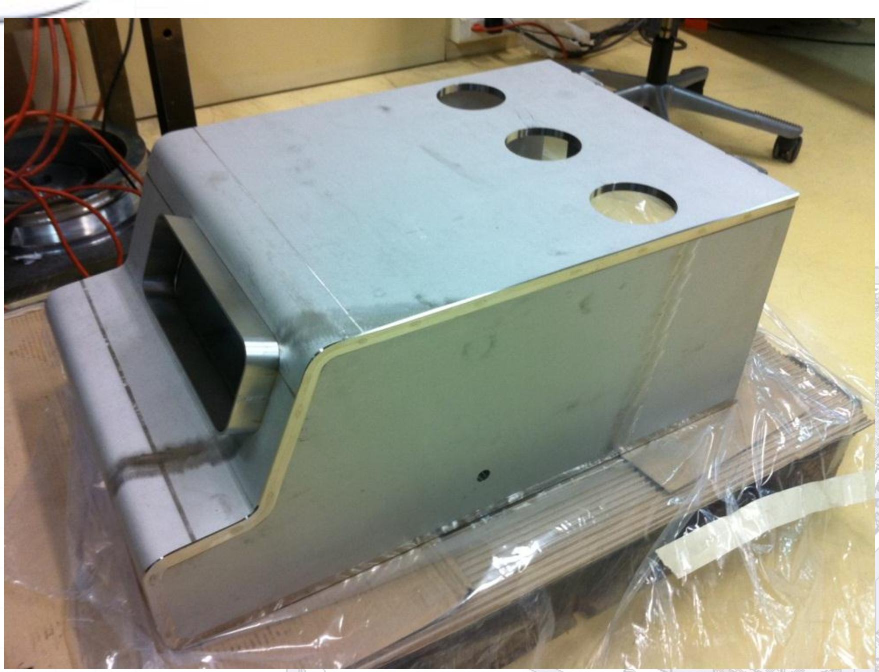
Quasi-static Tensile test on MoCD performed at different temperatures

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





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.