Innovative collimator materials

WP8 Highlight Talk

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Outline

- ✓ Objectives & activities
- ✓ Advanced collimator design
- ✓ Materials R&D
- ✓ Radiation damage
- ✓ Numerical simulations
- ✓ Future outlook
- ✓ Conclusions

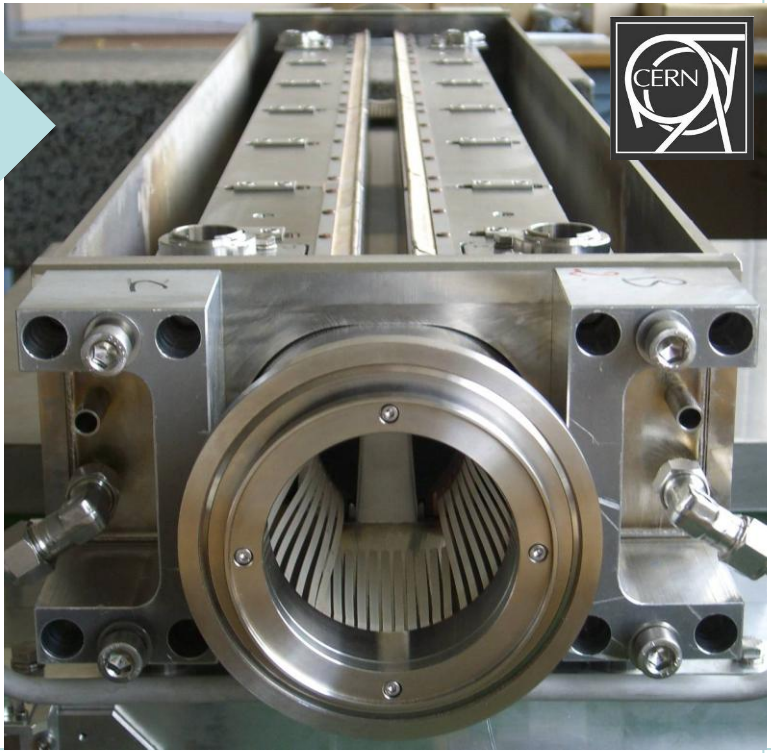
New challenges arise for the materials that are placed close to or into the high intensity beams. Full intensity and performance can only be reached if collimation works reliably with excellent efficiency.

Damage must be avoided or, if it cannot fully be excluded, handled in a safe manner.

Focus on the most critical component: **collimator jaw**

Jaw materials (goals)

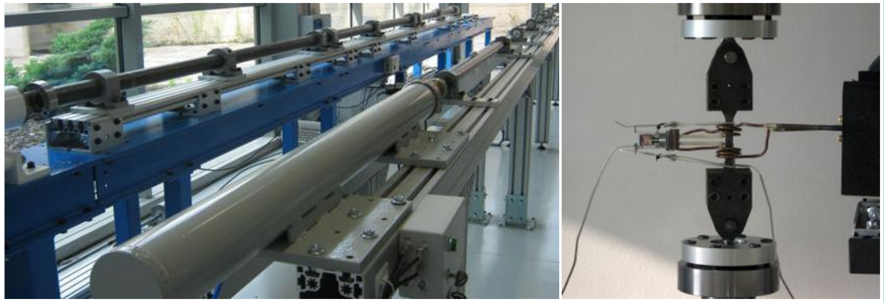
- ✓ *tailored electrical conductivity to improve RF stability*
- ✓ *high thermo-mechanical stability and robustness*
- ✓ *strong resistance to particle radiation.*
- ✓ *higher density (high-Z) to improve collimation efficiency*



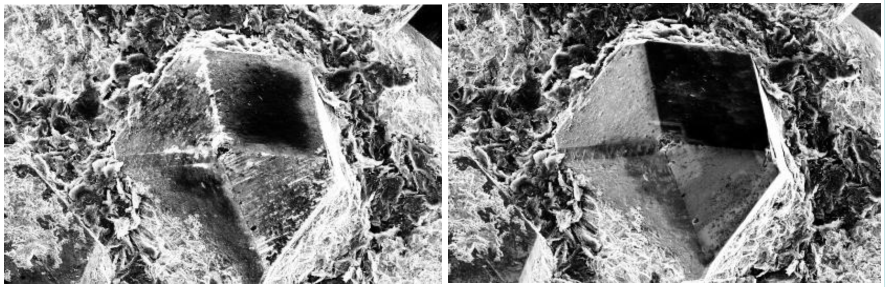
Objectives

Activities

- ✓ Identify, characterize and model materials under extreme conditions



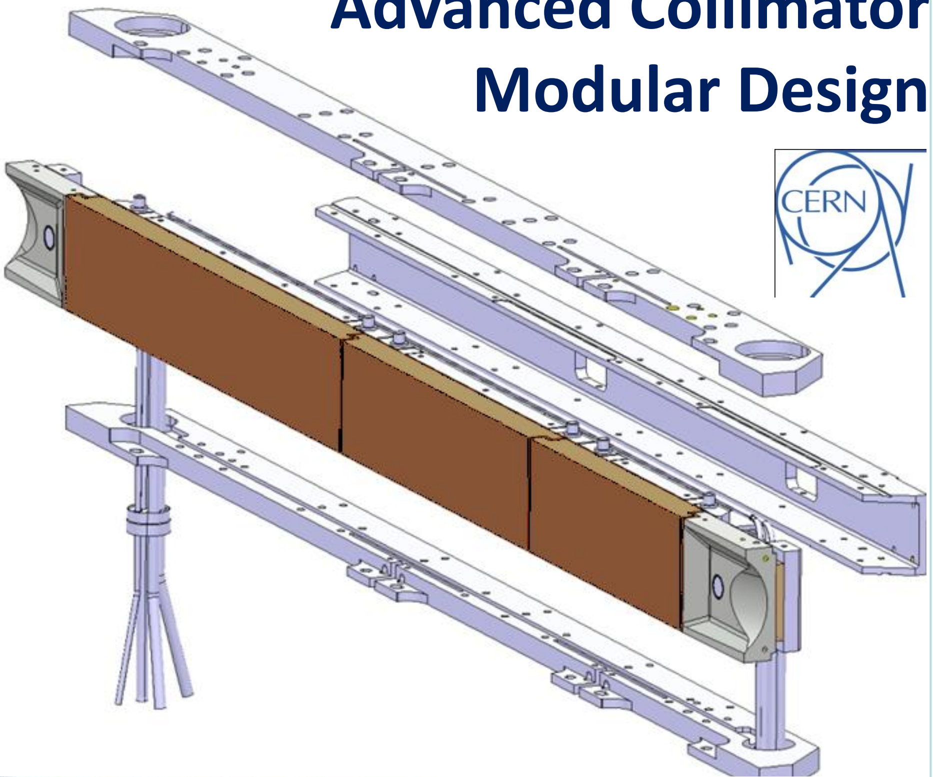
- ✓ Predict residual dose rates for irradiated materials and their life expectancy



- ✓ Design, construct and test collimator prototype(s) for upgraded LHC performances

Advanced Collimator Modular Design

A common baseline for the jaw assembly allows the use of **alternative materials** for the jaw (3 sector jaw): *maximized thermal dissipation and geometrical stability*



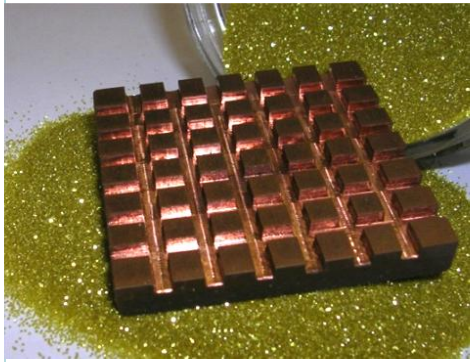
Prototype manufacturing status:

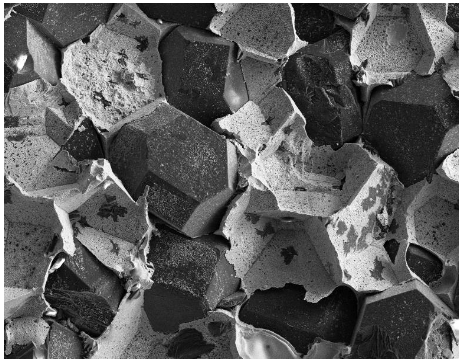
- ✓ all jaw components manufactured
- ✓ jaw sectors successfully brazed (Glidcop/Copper/Stainless Steel)
- ✓ metrological controls completed
- ✓ qualification procedure ongoing

Prototype of LHC Collimator Phase II

Materials R&D: metal-CD composites

Development of Metal-Diamond composites to maximize mechanical and thermal properties along with **radiation hardness** and **thermal stability**





First solutions: Copper Diamond

Hot Pressing **(RHP)**

Liquid Infiltration **(EPFL)** of Al-CD and Ag-CD as possible alternatives

Molybdenum Diamond MoCD

Mo:	high thermal stability high mechanical properties high melting point
CD:	high thermal conductivity low density and Z number

Challenge:

sintering of Mo-CD composites at low temperature to avoid diamond degradation

Liquid Phase Sintering (Cu):

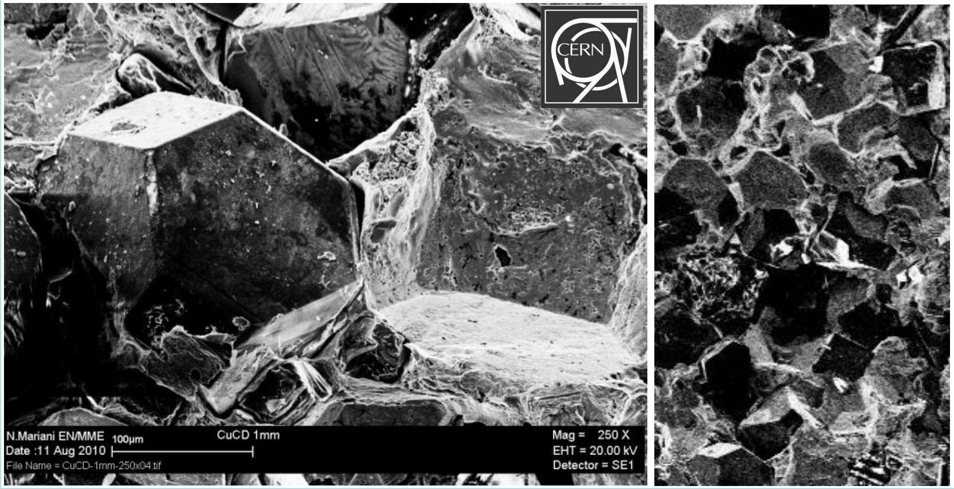
- ✓10-20% Cu phase;
- ✓sintering at 1100°C (Cu melts);
- ✓R&D Program Run since Aug 2010 to Feb 2011

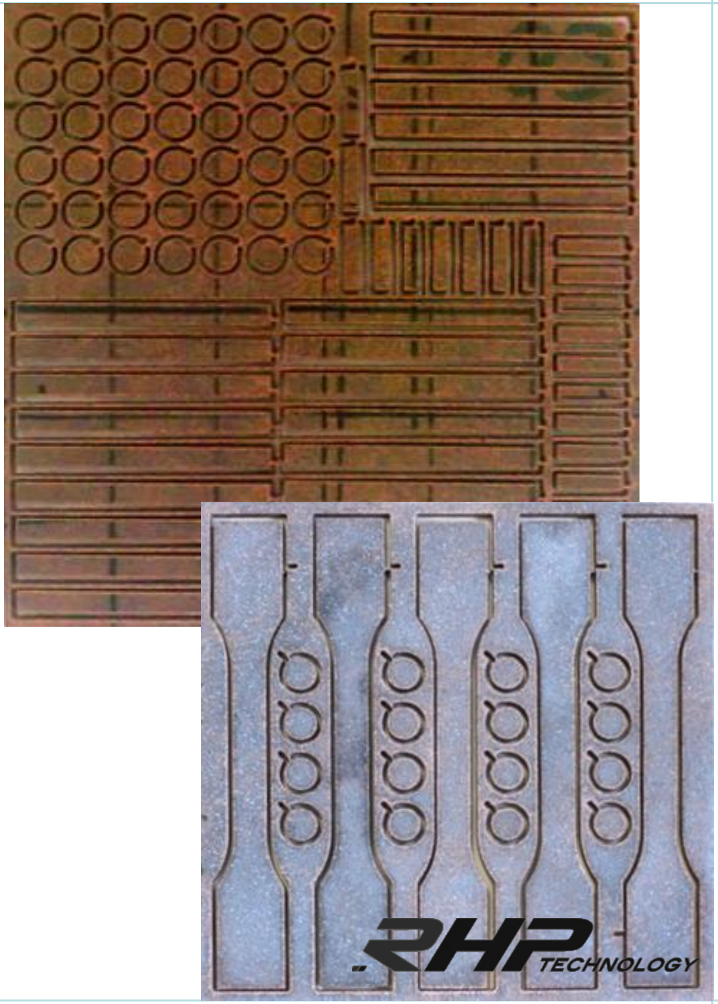
Assisted Solid State Sintering (Pd):

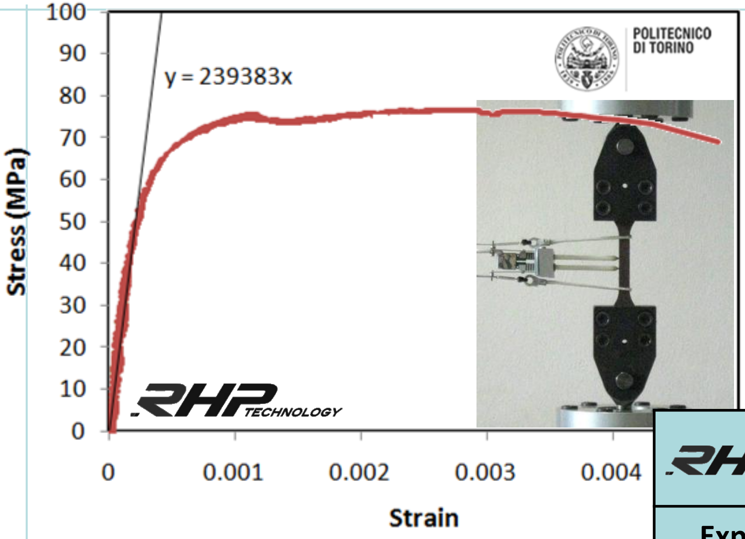
- ✓0.5% Pd powder;
- ✓sintering at 1300°C;
- ✓R&D Program Run since Mar 2011

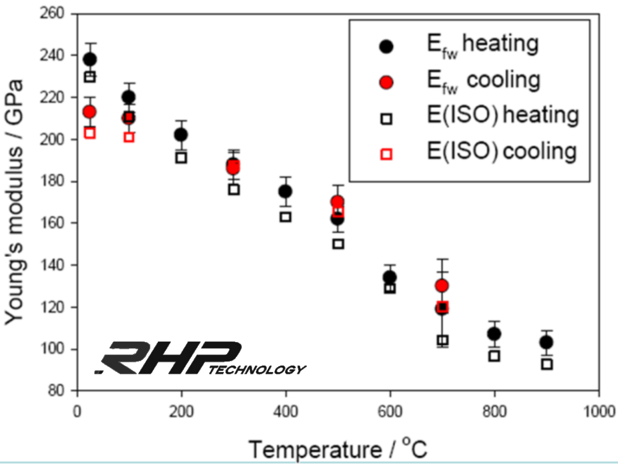
Materials R&D: CuCD composites

- ✓ manufacturing of Cu-CD plates with 60 vol.%
- ✓ water jet cutting of samples for:
  - ✓ thermal diffusivity
  - ✓ CTE
  - ✓ mechanical testing
  - ✓ measurement of mechanical properties at high temperature









Thermo Physical properties measured at **RHP** (ρ, CTE, C_p estimated by ROM, K) and at **CERN** (б).

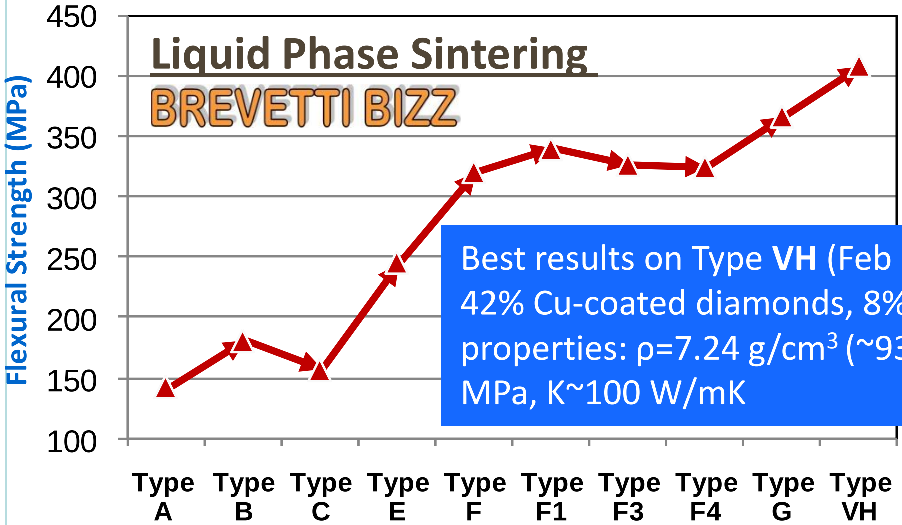
Measurement of RT thermal diffusivity of 40 samples (**RHP**): 218 +/- 18 mm²/s.

RHP TECHNOLOGY	Density (g/cm³)	C_p (J/KgK)	K (W/mK)	CTE (10^{-6} K^{-1})	σ %IACS (MS/m)
Expected value	5.61	442	615 (H&J)	6.25 (Turner)	23.7% (13.7) (by LW formula)
Measured	**5.33**	**~ 420**	**~ 490 ±40**	**6-8**	**21.7% (12.6)**
% of Th. Value	95.02%	95%	~ 80 %	-	~ 91.5 %

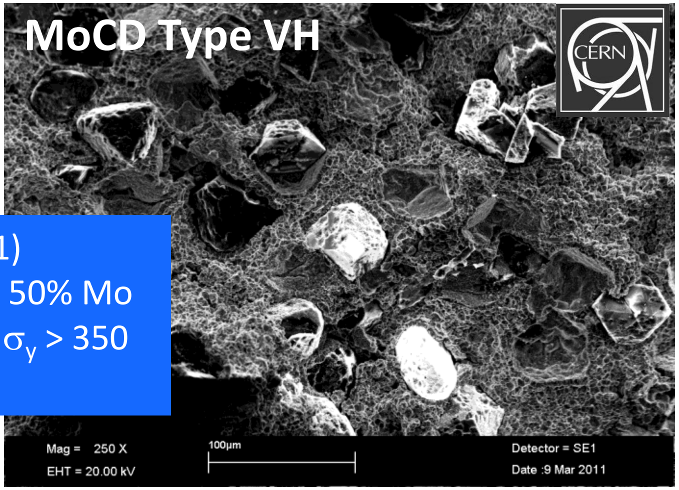
EPFL	Volume fraction	Young's modulus (GPa)	Bending strength (MPa)
CuCD 1	0.77	216	136
CuCD 2	0.76	204	120

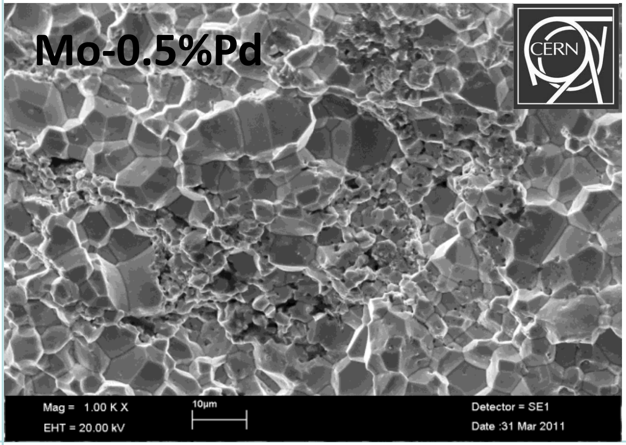
Materials R&D: CuCD composites

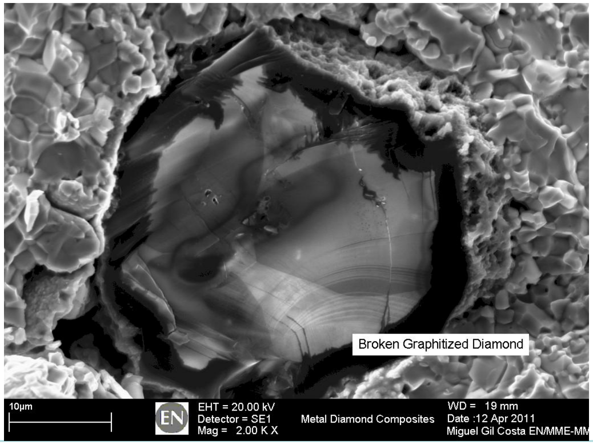
Materials R&D: MoCD composites



Best results on Type **VH** (Feb 2011)
42% Cu-coated diamonds, 8% Cu, 50% Mo
properties: ρ=7.24 g/cm^3 (~93%), σ_y > 350 MPa, K~100 W/mK







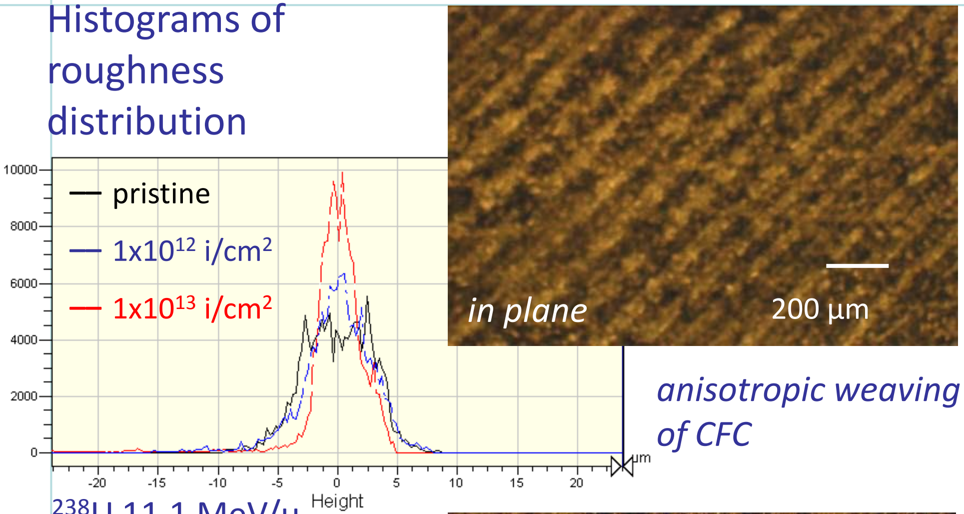
Assisted Solid State Sintering (Pd)

R&D ongoing, promising results on Mo-0.5%Pd system

properties:
ρ=10.07 g/cm^3 (~98.5%)
σ_R > 400 MPa

Ion-induced damage in C/C composites

Histograms of roughness distribution



anisotropic weaving of CFC

^{238}U 11.1 MeV/u

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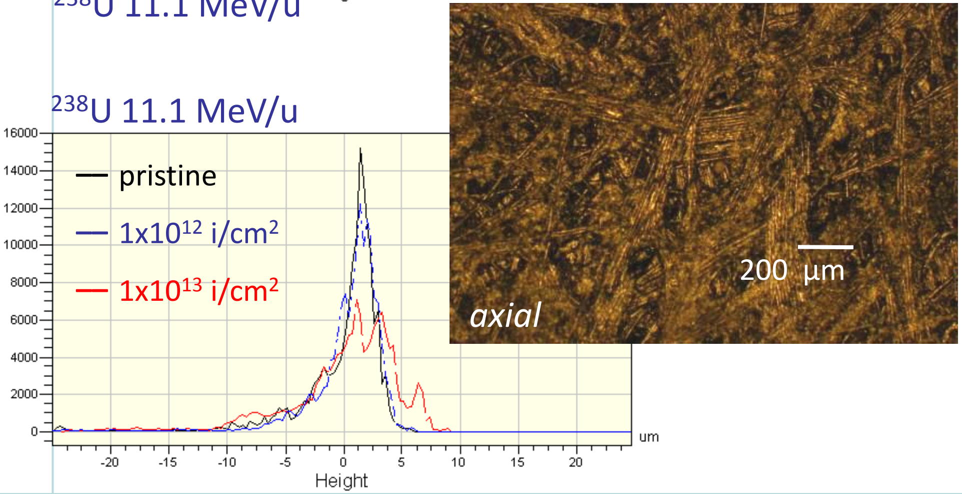
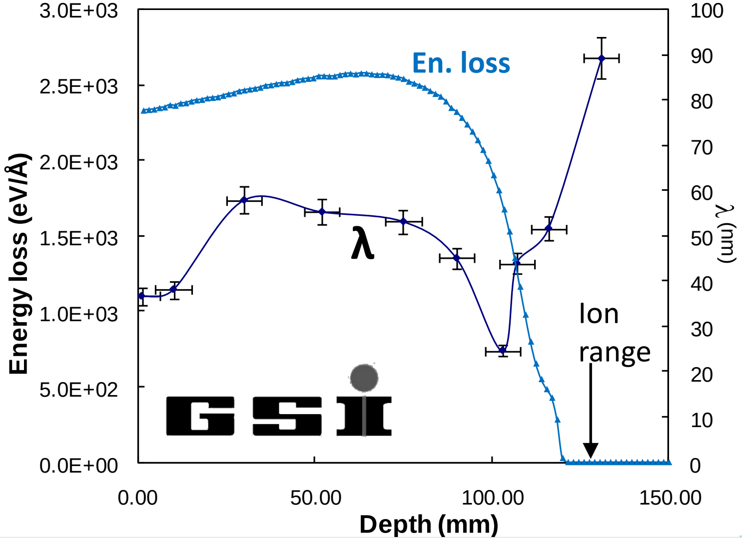


Anisotropic behavior of C/C under irradiation

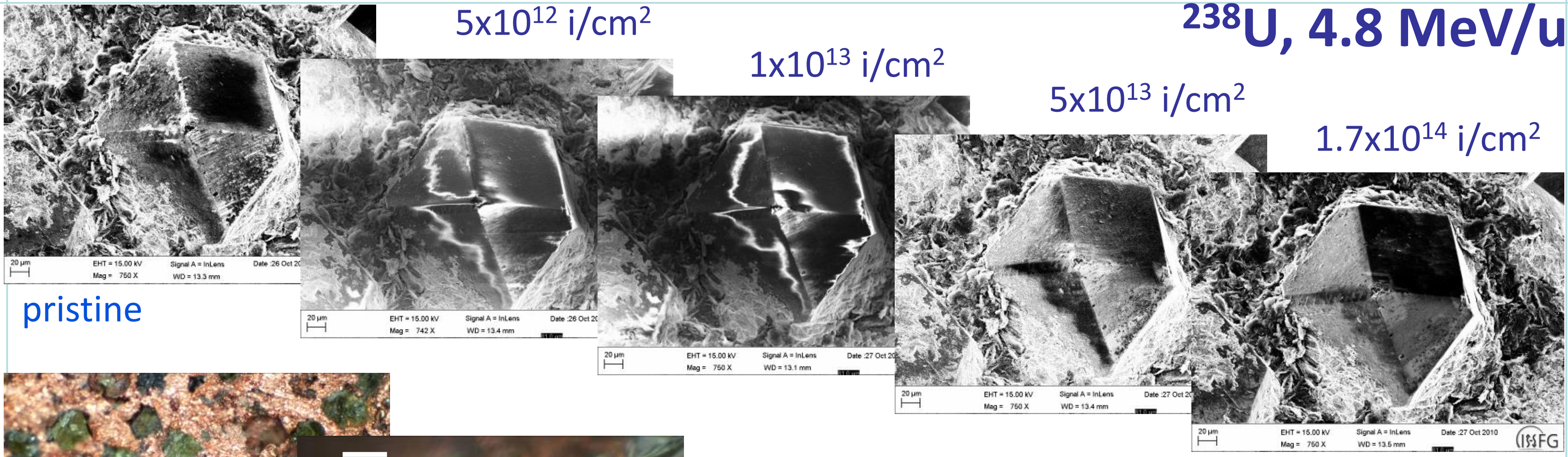
Fiber controlled properties
- ✓ swelling
- ✓ thermal conductivity

Variation of phonon mean free path (λ) for a carbon fiber, within depth of irr. C/C
1×10^{13} 238U/cm^2, 11.1 MeV/u



Ion-induced damage in CuCD composites

^{238}U, 4.8 MeV/u



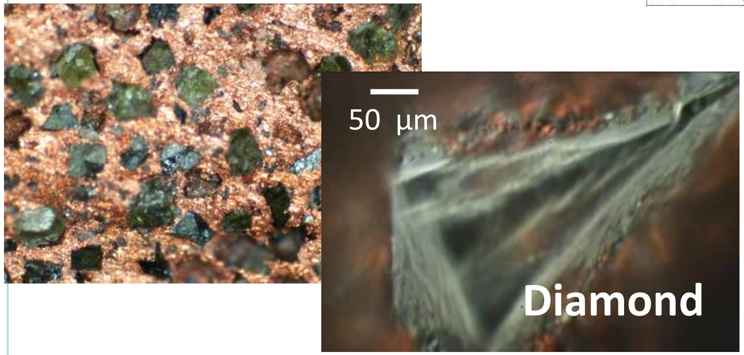
pristine

5x10^{12} i/cm^{2}

1x10^{13} i/cm^{2}

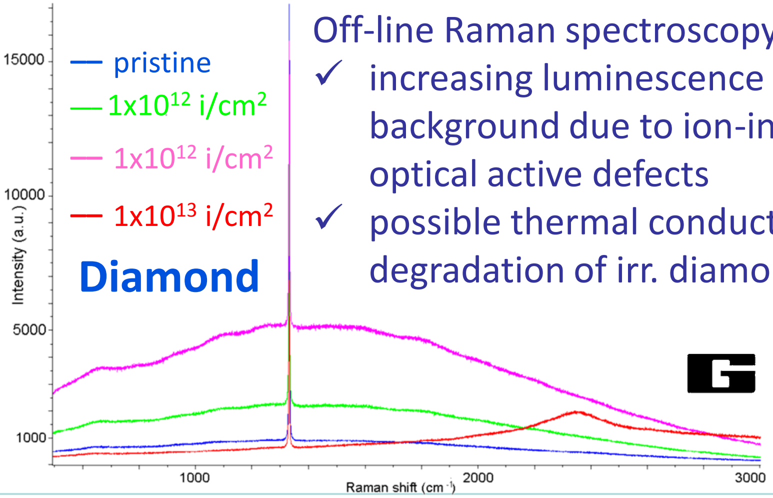
5x10^{13} i/cm^{2}

1.7x10^{14} i/cm^{2}



In-situ SEM during ion irradiation shows:

- ✓ no detachment or cracks at interfaces
- ✓ charge trapping at ion induced defects in diamonds



Off-line Raman spectroscopy shows:

- ✓ increasing luminescence background due to ion-induced optical active defects
- ✓ possible thermal conductivity degradation of irr. diamonds

Rapid interactions of particle beams with solids induce **Dynamic Responses** in matter.

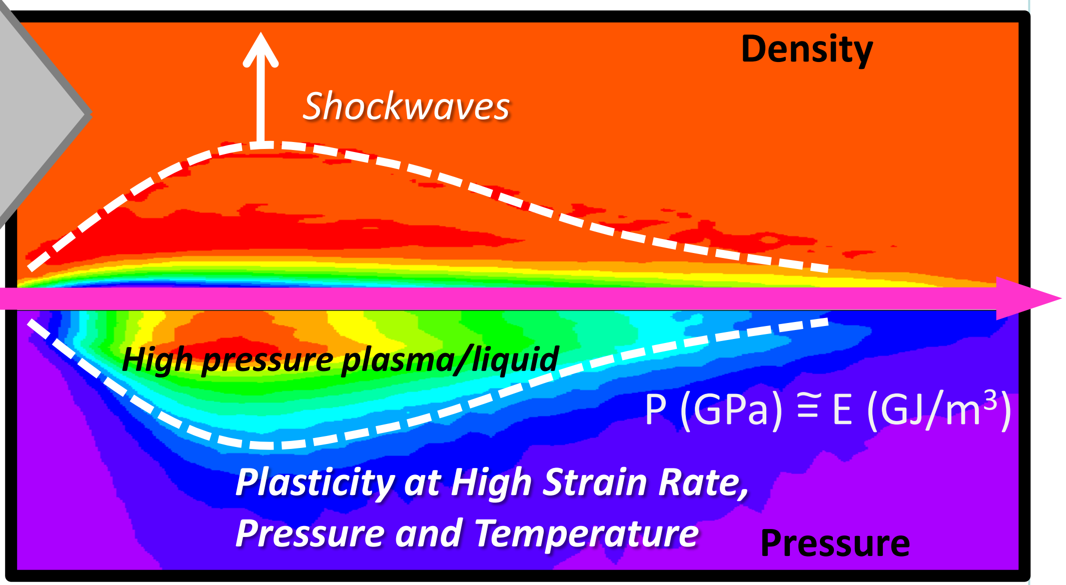
Three main dynamic response **regimes** exist, depending on several parameters:

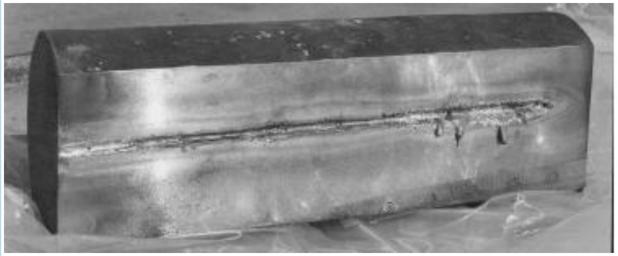
- ✓ **deposited energy and energy density**
- ✓ **interaction duration**
- ✓ **material strength ...**

✓stress waves and vibrations in the elastic domain
✓stress waves and vibrations in the plastic domain
✓Shockwaves!

Physics
Thermodynamics
hydrodynamics
Structural/mechanical engineering

PARTICLE BEAM



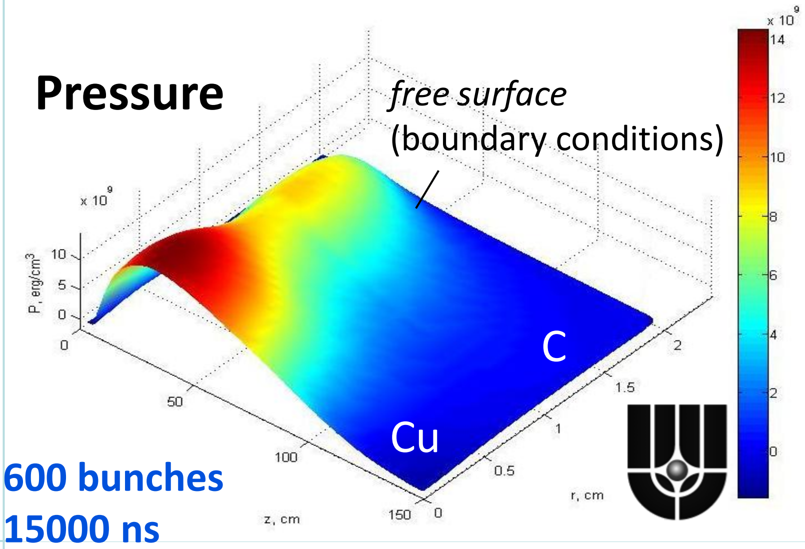


Complex geometry, material behavior, boundaries…

Numerical simulations

In the irradiation with high-energy particles the exchange of kinetic energy (elastic collisions between PKA and atoms inside the crystalline lattice) leads to formation of cascade and sub-cascade of atomic collisions.

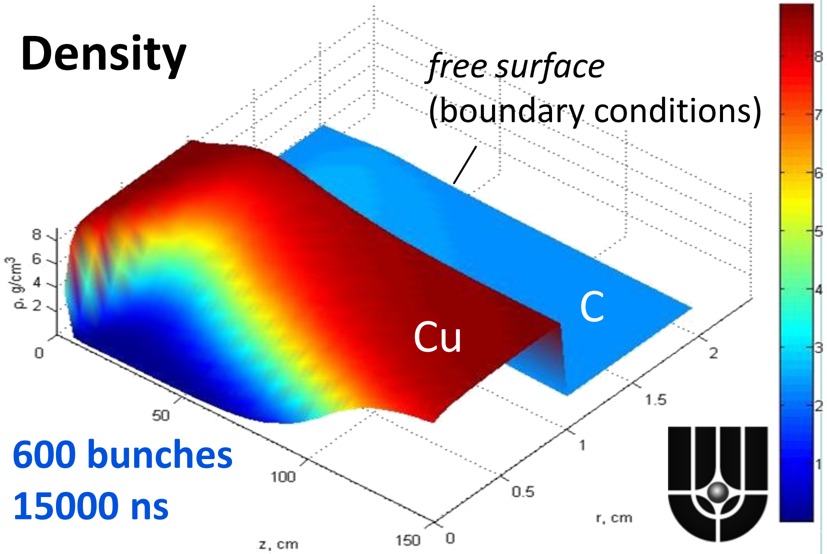
During development and relaxation of cascades and sub-cascades point defects are produced and accumulated (t~10^{-11}sec) **leading to serious degradation of physical mechanical properties**.


Pressure

free surface (boundary conditions)

600 bunches
15000 ns

Shockwave propagation in ("sandwich structure materials") Cu–C at 450 GeV proton beam


Density

free surface (boundary conditions)

600 bunches
15000 ns

The theoretical model, developed at **Kurchatov Institute** for the investigations of shockwaves propagation in the collimator materials takes into account *ionization*, *electronic excitation*, and *energy transfer* from excited electronic subsystem to the ionic subsystem

Shockwaves in irradiated materials

Simulations with hydrocodes were developed in order to reproduce the behavior of actual and novel materials in shockwaves regime and for prevision and future comparison between experimental (HiRadMat) and numerical results

1 st step **FLUKA**

- ✓ **energy deposition calculation of a single beam bunch by Montecarlo analysis (Fluka team CERN)**

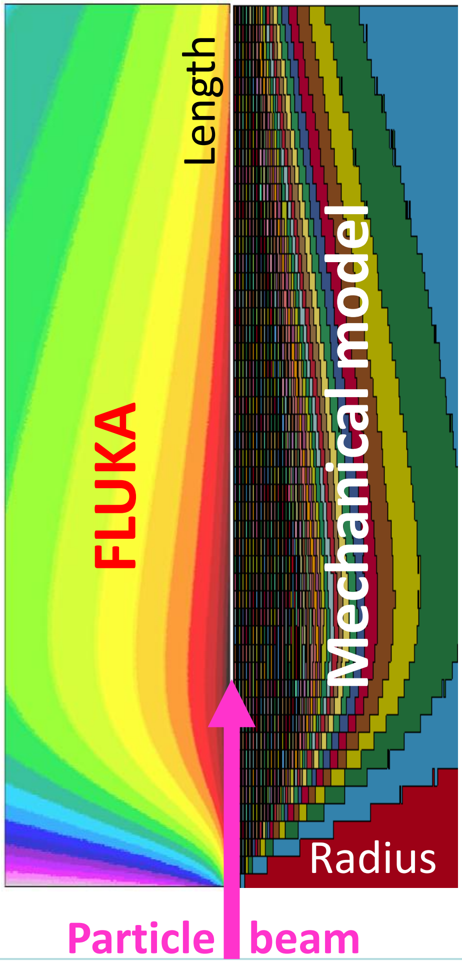
Coupling…

- ✓ **calculation of mechanical response of the structure**
- ✓ **energy deposition as power vs time history: bunch profile of 0.5 ns of constant power, 25 ns of void, 0.5 ns of constant power… PULSE TRAIN)**
- ✓ **explicit integration (time step magnitude 0.01 ns)**
- ✓ **lagrangian/eulerian/SPH approach**

2 nd step **Hydrocode**

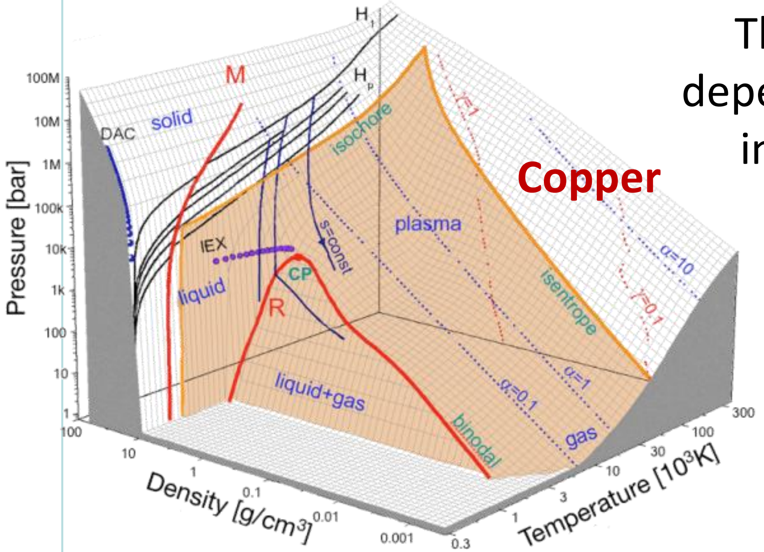
No bunch interactions

No material degradation due to irradiation

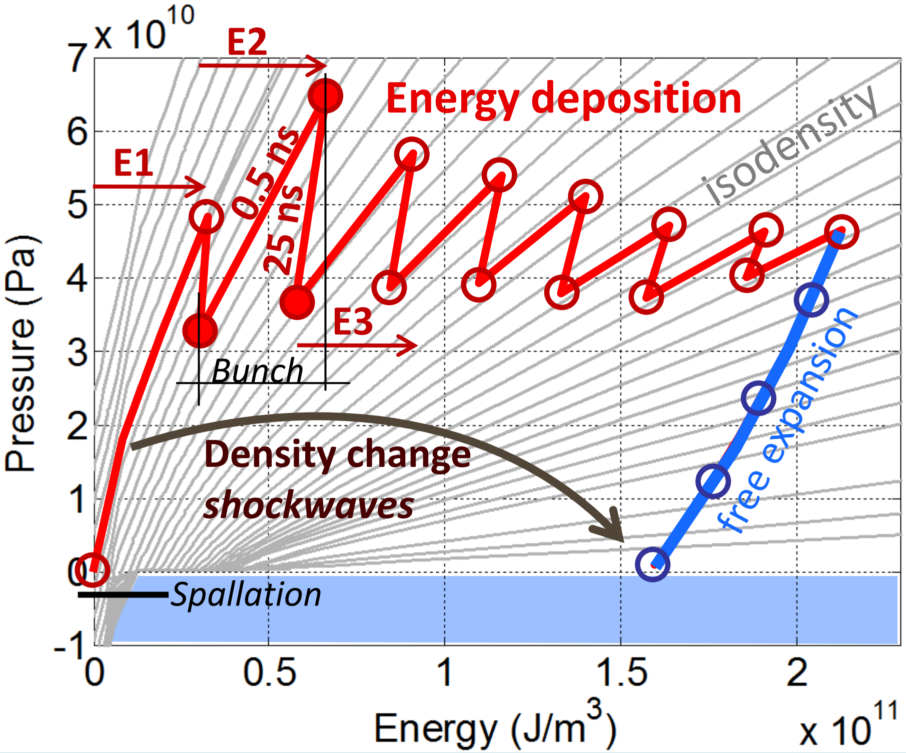


Hydrocode numerical simulations

Equation 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?)

Pressure gradients produce plasticity!

Johnson-Cook

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

Steinberg-Guinan

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

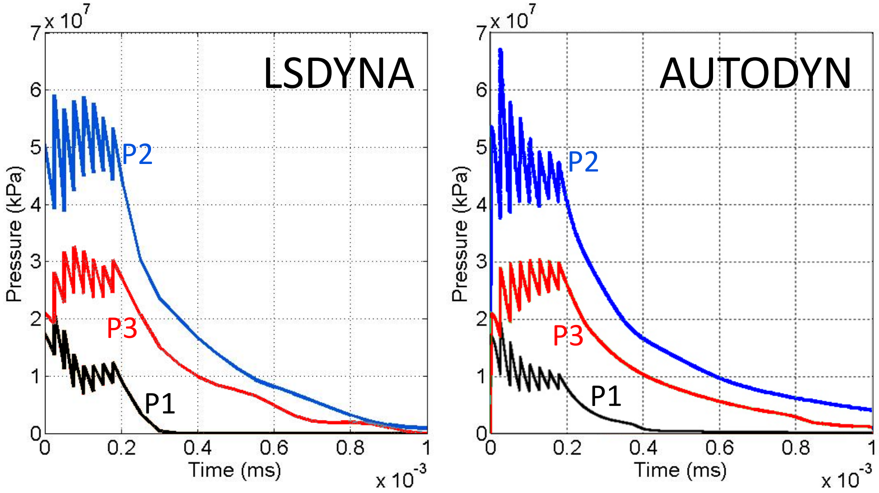
When the temperature reaches the value of the melting temperature the shear strength of the material model becomes zero **and the material starts to be considered like a fluid (pure hydrodynamic behaviour)**

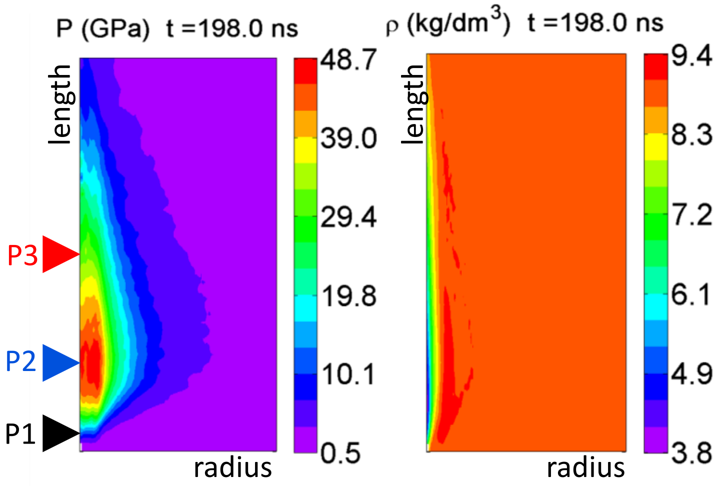
These models have typically been tested and calibrated with experiments on Hopkinson bars, Taylor cylinders, and with high-explosive (HE)–driven shock or compression waves at pressures ***up to a few tens of GPa*** *and strain rates of* 10^3 *to* 10^5 s^{-1}

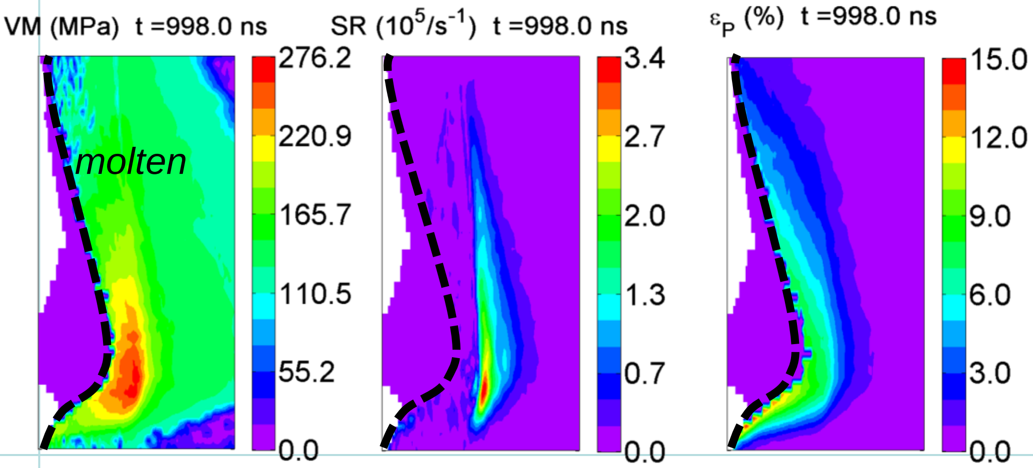
$P_{\mathrm{expected}} \sim E_{\mathrm{deposited}} > 100$ GPa!

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?





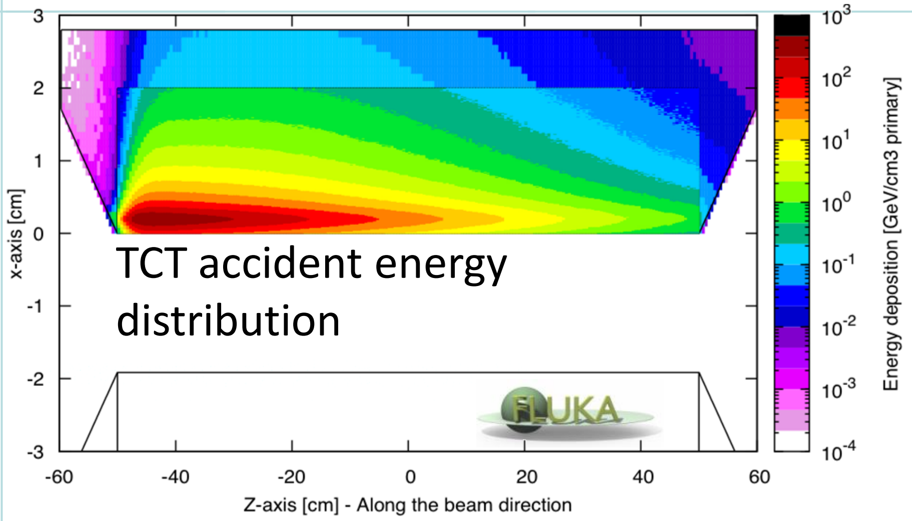


A **Copper** or Tungsten bar (10 mm radius, 1 m long) facially irradiated with **8 bunches** of 7 TeV protons (each bunch 1.11x10^{11} protons)

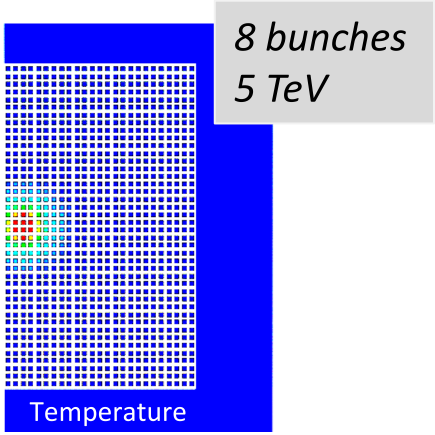
2D Axis-symmetric lagrangian and eulerian (LSDYNA, AUTODYN, BIG2)

Hydrocodes benchmarking

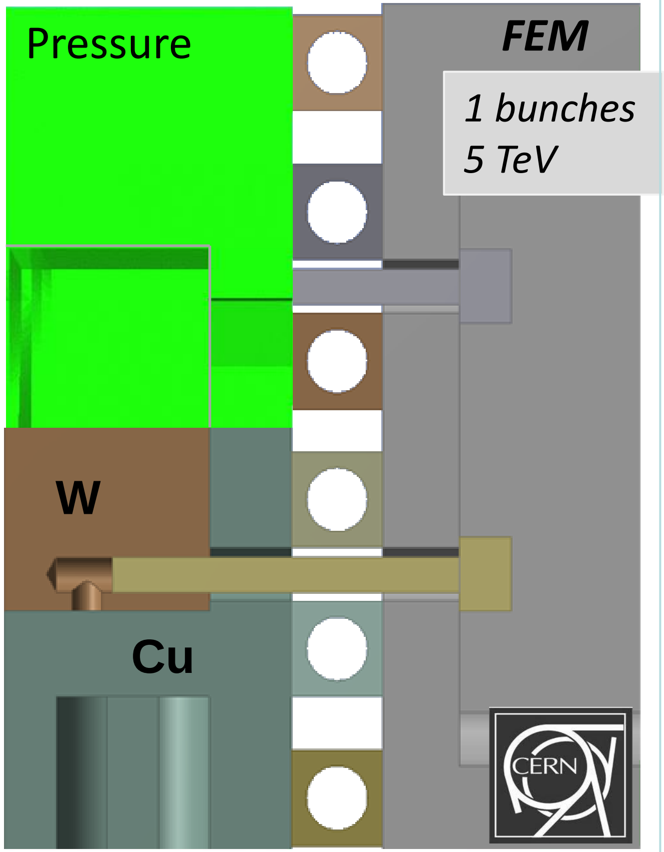
3D hydrocode example: TCT collimator


TCT accident energy distribution

Seven different cases were derived varying ***energy, intensity*** *and* ***emittance/beam size conservatively*** *assuming that all bunches have the same impact parameter* ***(d=2 mm)****, same charge* ***(1.3 x 10^{11} p)*** *and optical functions at TCTH.4R5B2*


8 bunches
5 TeV

SPH


FEM

1 bunches
5 TeV

Damage is confined to W as energy escaping W block is limited (**shock impedance** at W-Cu barrier)

Fluka-LSDyna coupling (I)

At the beginning

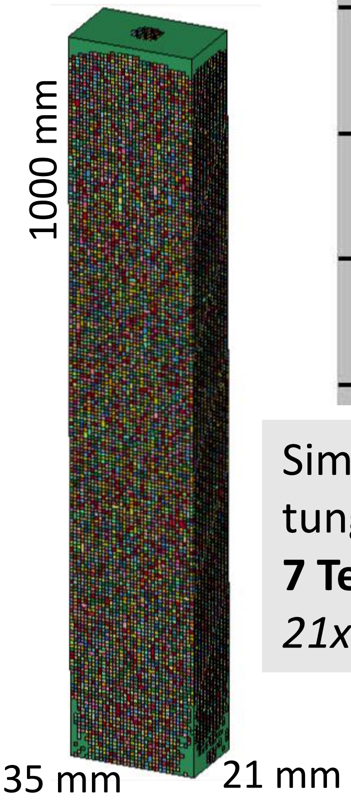
- ✓ define the correct number of primaries to achieve a good precision on the energy deposition;
- ✓ define the energy and the thresholds;

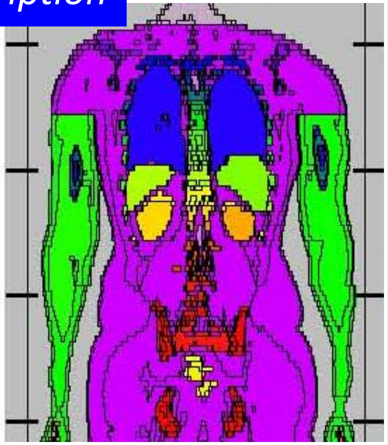
For each step

- ✓ take as input the density map resulting from the LSDyna calculations;
  - define discrete density levels: each level is an independent FLUKA material;
- ✓ using a **voxel structure** to define the regions with different density in the target block;
  - associate to each voxel the corresponding material with the correct density;
  - perform density interpolation in case of mesh deformation (FEM);
- ✓ store the energy deposition for each voxel;
- ✓ run a new mechanical analysis (1 or more bunches)

mechanical model equivalence obtained in Fluka via Voxel description

FLUKA





Simplified TCT tungsten jaw
7 TeV
21x35x200 voxel

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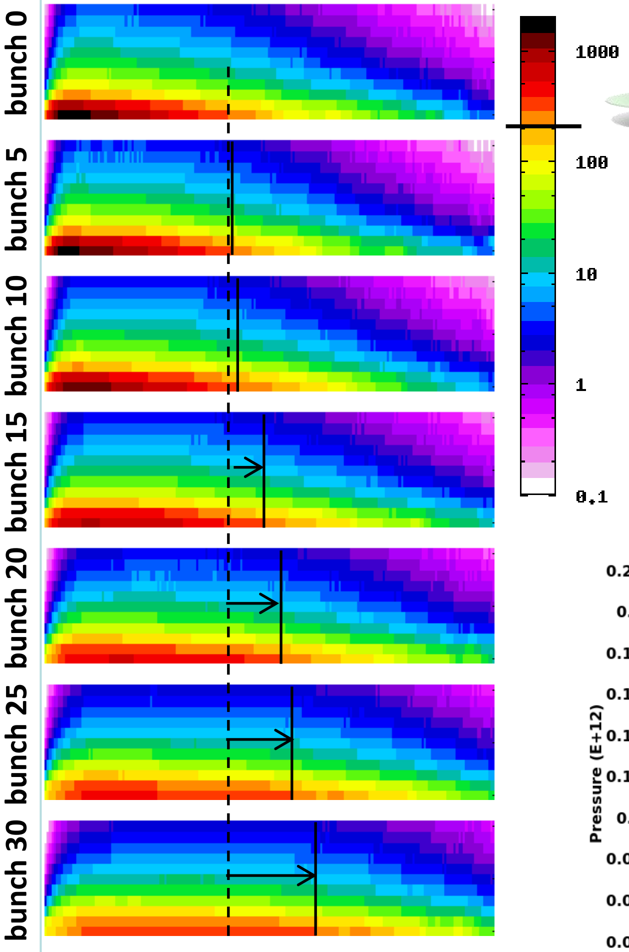
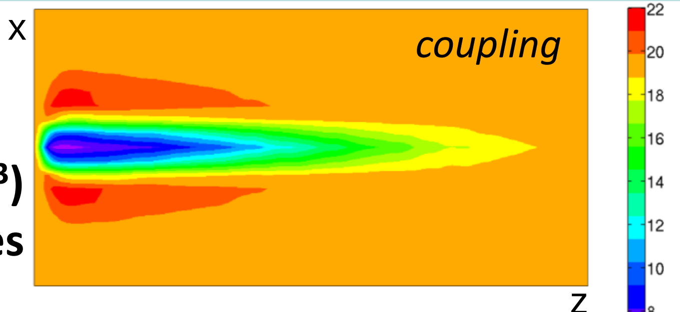
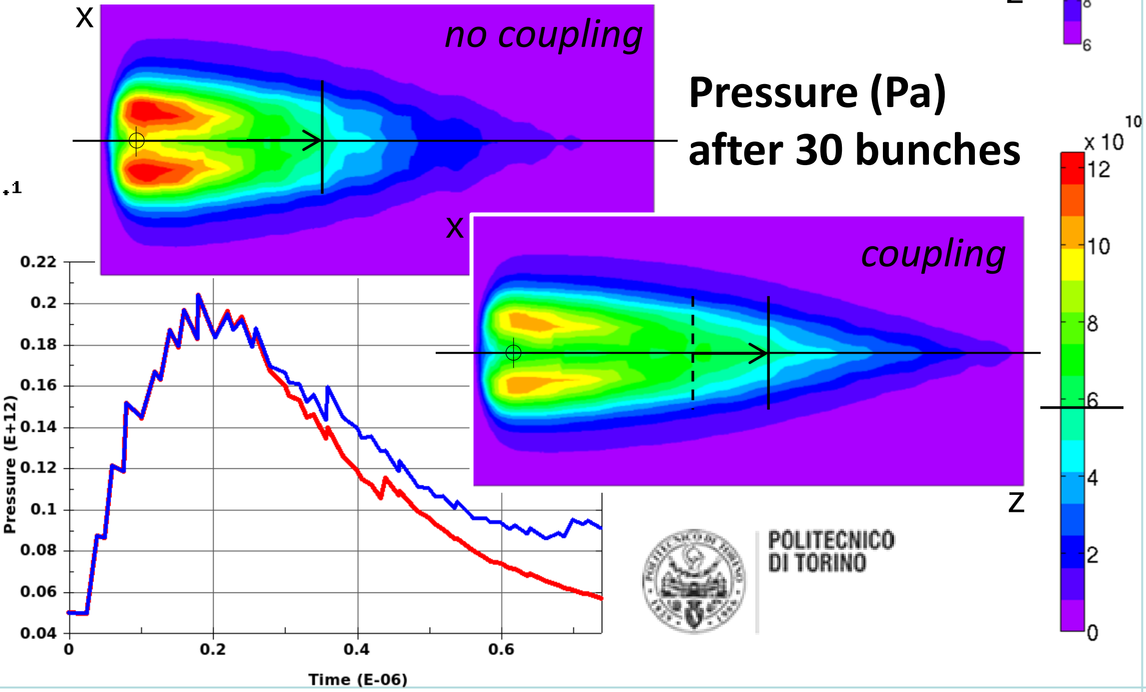


Energy deposition GeV/cm^3



Density (kg/m^3) after 30 bunches



Pressure (Pa) after 30 bunches

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Fluka-LSDyna coupling (II)

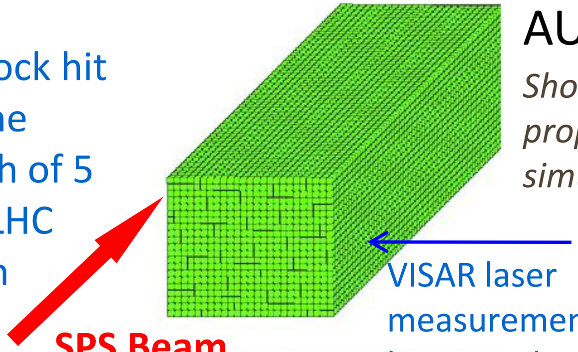
HiRadMat Material Test Bench

It is very difficult to predict structural efficiency and robustness accurately: beam-induced damage for high energy and high intensity **occurs in a regime where practical experience does not exist!**

HiRadMat Test Bench: response of advanced materials under extreme conditions

- ✓ vertical array of 6 materials samples
- ✓ movement system to change material and impact location
- ✓ SPS Beam multi-bunch impact test
- ✓ calculated pressure and velocity of gauge points
- ✓ comparison with experimental measurements

W Block hit by one bunch of 5 TeV LHC Beam



AUTODYN

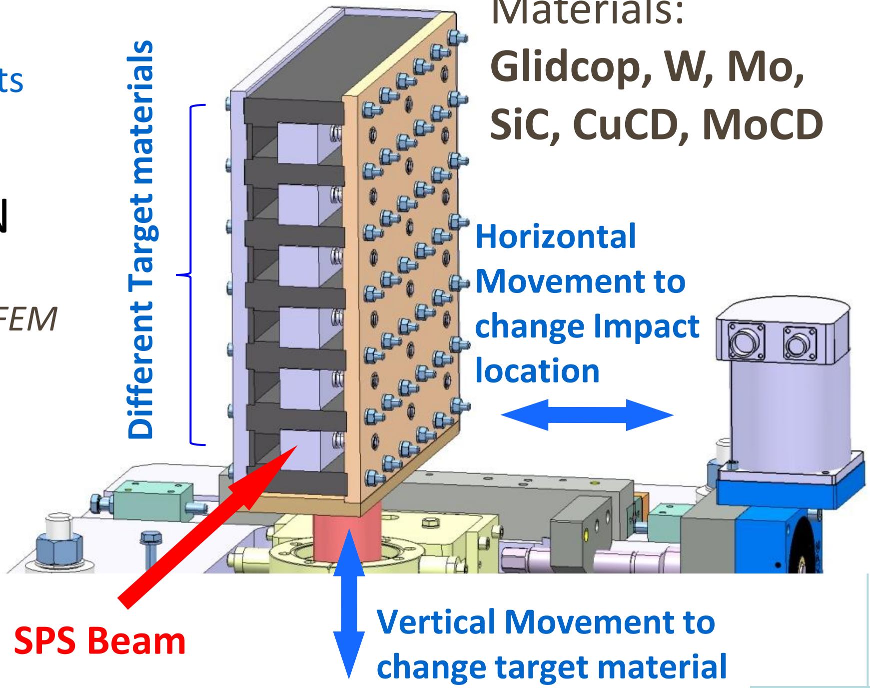
Shock-Wave propagation FEM simulation

VISAR laser measurement of horizontal displacement

SPS Beam

Materials:

Glidcop, W, Mo, SiC, CuCD, MoCD



Different Target materials

Horizontal Movement to change Impact location

SPS Beam

Vertical Movement to change target material

Present and Future Outlook

- ✓ Manufacturing of Metal-CD samples
  - ✓ Cu-CD (Hot Pressing) samples and large plates produced by **RHP** (AIT spin-off)
  - ✓ Ag-CD (Liquid Infiltration) samples produced by **EPFL**
  - ✓ Mo-Cu-CD (Liquid Phase Sintering) samples produced by **CERN\BrevettiBizz**
  - ✓ Mo-CD (Assisted Solid State Sintering) first samples produced by **CERN\BrevettiBizz**
- ✓ Irradiation studies
  - ✓ Cu-CD samples provided by **RHP** (AIT spin-off)
  - ✓ ongoing tests carried out at **GSI**
  - ✓ tests to start at **RRC-KI**
- ✓ Material characterization
  - ✓ un-irradiated Cu-CD fully characterized
  - ✓ un-irradiated Mo-Cu-CD characterization ongoing
  - ✓ un-irradiated Mo-CD characterization to start soon
- ✓ Simulations
  - ✓ coupling Fluka-Hydrocodes (**PoliTO, CERN, GSI**)
  - ✓ 2D and 3D advanced numerical simulations (**PoliTO, CERN, RRC-KI**)
- ✓ Material Constitutive Models validation
  - ✓ beam impact tests on LHC phase II collimator prototype and on material test bench

- ✓ Excellent progress in every aspect of WP Task 8.2 with important contributions from many partners
- ✓ Research development of novel materials is progressing: know-how of Metal Diamond Composites (Me-CD) growing steadily
- ✓ Irradiation studies on advanced collimator materials have started: preliminary results seemingly promising for Me-CD
- ✓ Phase II collimator full prototype production advanced, Glidcop Jaw manufactured and under testing
- ✓ State of the art numerical simulations (Hydrocodes) carried out both 2D and 3D. Effective coupling Fluka-Hydrocodes
- ✓ Experimental validation of material constitutive models to be carried out through dedicated tests in HiRadMat facility

Conclusions

Innovative collimator materials

WP8 Highlight Talk

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Thank you for your attention