Interactions between materials and particle beams, and simulation methods at EN-MME and PoliTo

F. Carra
On behalf of EN-MME and ARIES WP14/17

Workshop on coupling simulation
of beam impact on accelerator components

11/12/2018

Outline

- Beam-matter interactions
- Material regimes…
- …and how to simulate/test them
  - Elastic
  - Plastic
  - Shock
  - Spallation
  - Hydrodynamic tunnelling
- Conclusions

Beam impact: quasi-instantaneous heating

- Energy deposition time $t_d \ll \tau, T$
- Heat diffusion during the energy deposition **can be neglected**, and the temperature variation is:

$$S = C\frac{\partial\Theta}{\partial t} \quad \Longrightarrow \quad \Delta\Theta = \frac{S \cdot t_d}{C}$$

for $C \neq f(\Theta); S \neq f(t)$

- Material expansion during heat deposition prevented by its mass inertia: **isochoric heating**
- **Dynamic stress waves** arising

Wave equation:

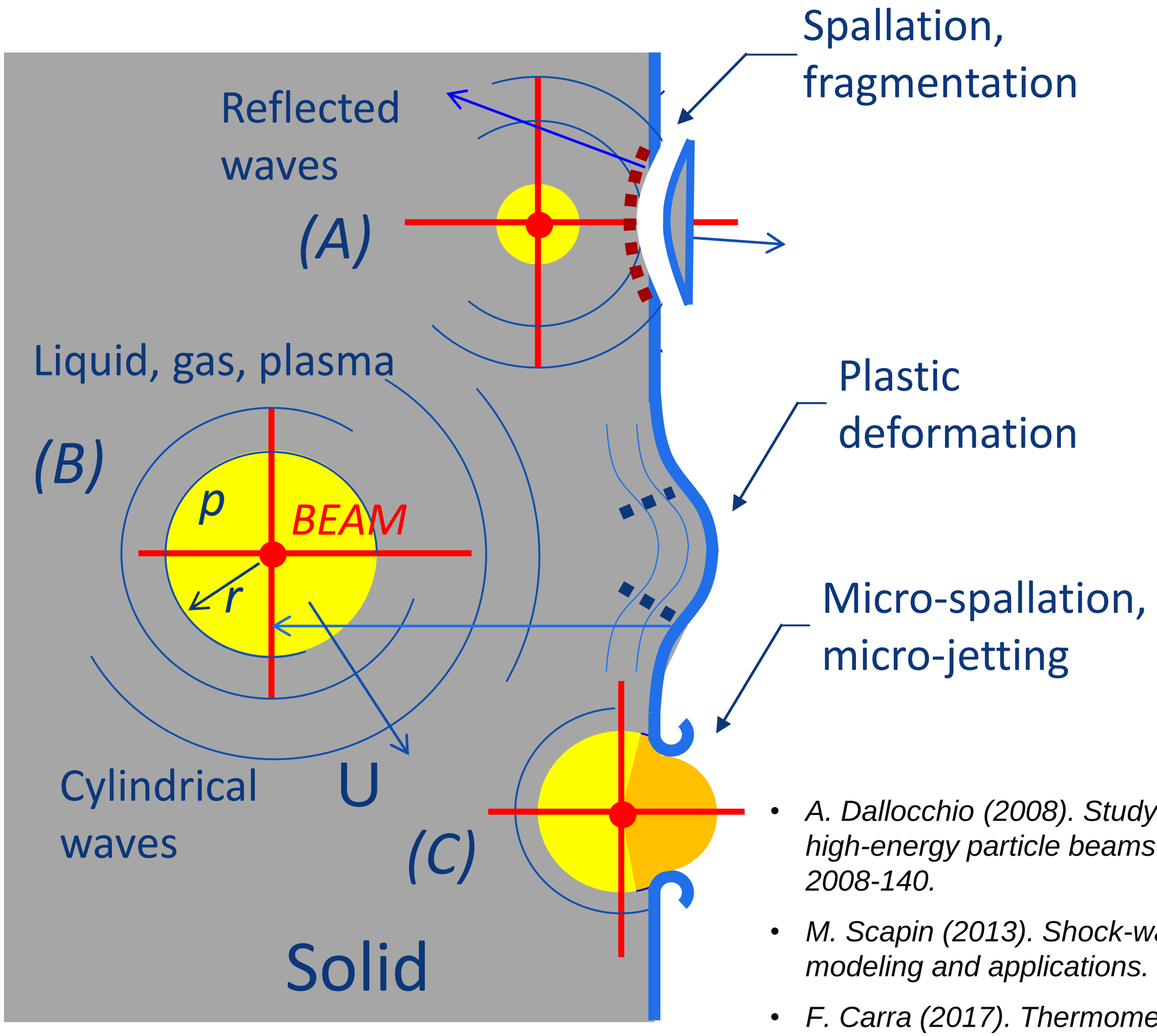
$$\frac{\partial\sigma_{ij}}{\partial x_j} = \rho\frac{\partial^2 u_i}{\partial t^2}$$

- In the **linear elastic case**

$$\frac{1}{c^2}\frac{\partial^2 u_i}{\partial t^2} = \nabla^2 u_i$$

c: speed of sound

Phenomena induced by a particle beam hitting a target

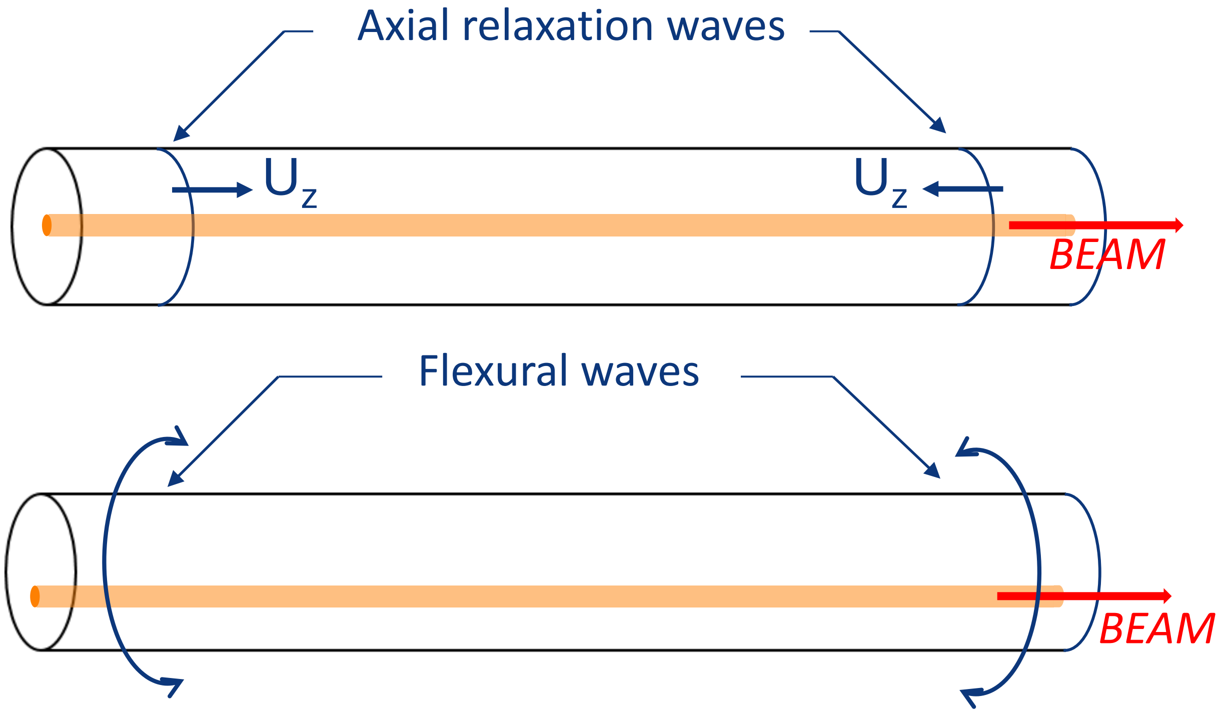


Cylindrical spreading loss

- **Far from the impact point**
  - $P \propto r^{-1/2}$ (for spherical: r^{-1})
  - $E \propto r^{-1}$ (for spherical: r^{-2})
- **Close to the impact**
  - Logarithmic singularity

- *A. Dallocchio (2008). Study of thermomechanical effects induced in solids by high-energy particle beams: analytical and numerical methods. CERN-THESIS-2008-140.*
- *M. Scapin (2013). Shock-wave and high strain-rate phenomena in matter: modeling and applications. PhD thesis, 10.6092/polito/porto/2507944.*
- *F. Carra (2017). Thermomechanical Response of Advanced Materials under Quasi Instantaneous Heating. PhD thesis, https://zenodo.org/record/1414090.*

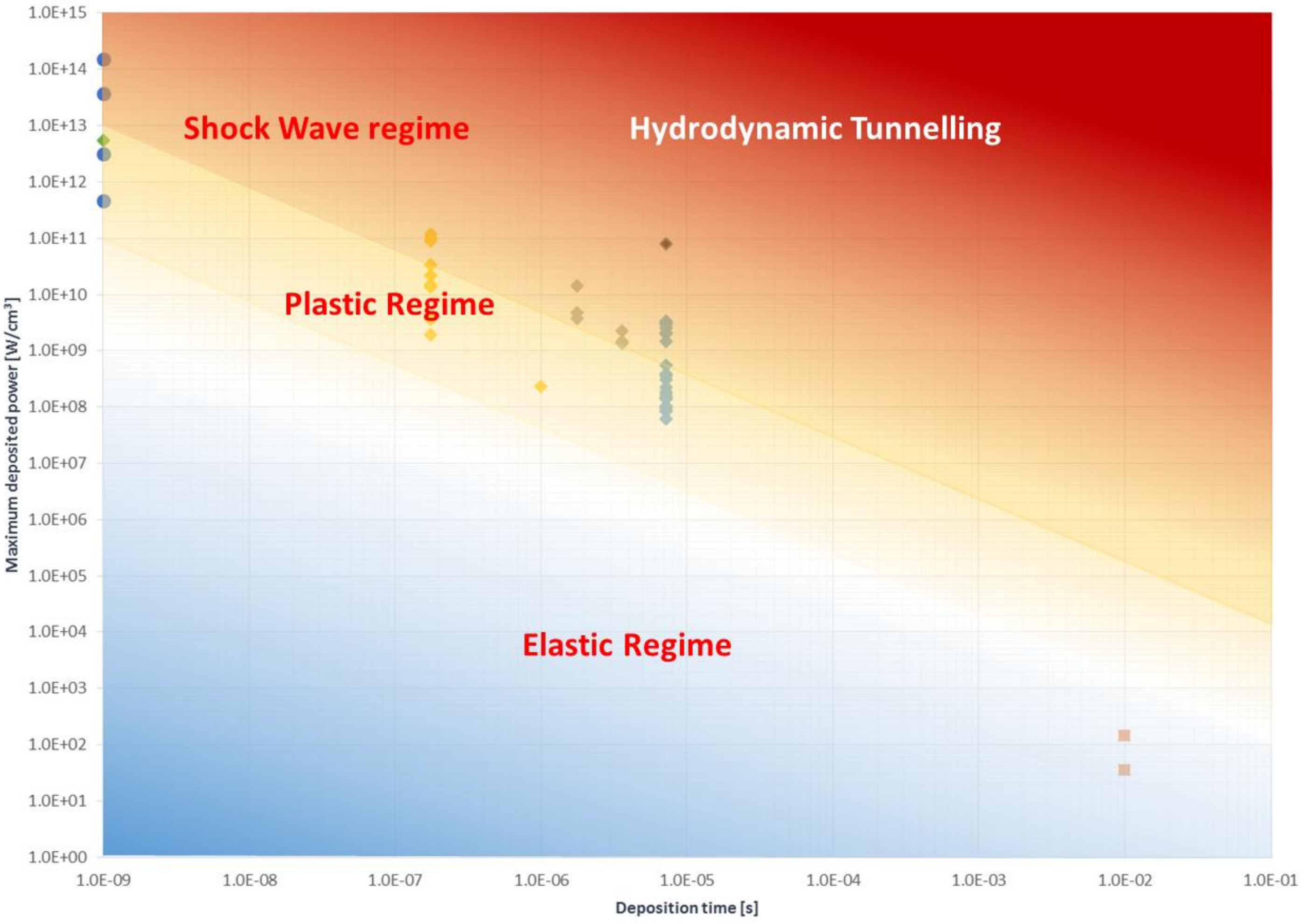
Phenomena induced by a particle beam hitting a target



- Additionally, other wave families typically generate at the boundaries (solid/gas and solid/solid interfaces): Rayleigh, Lamb, Love, Stoneley, etc.

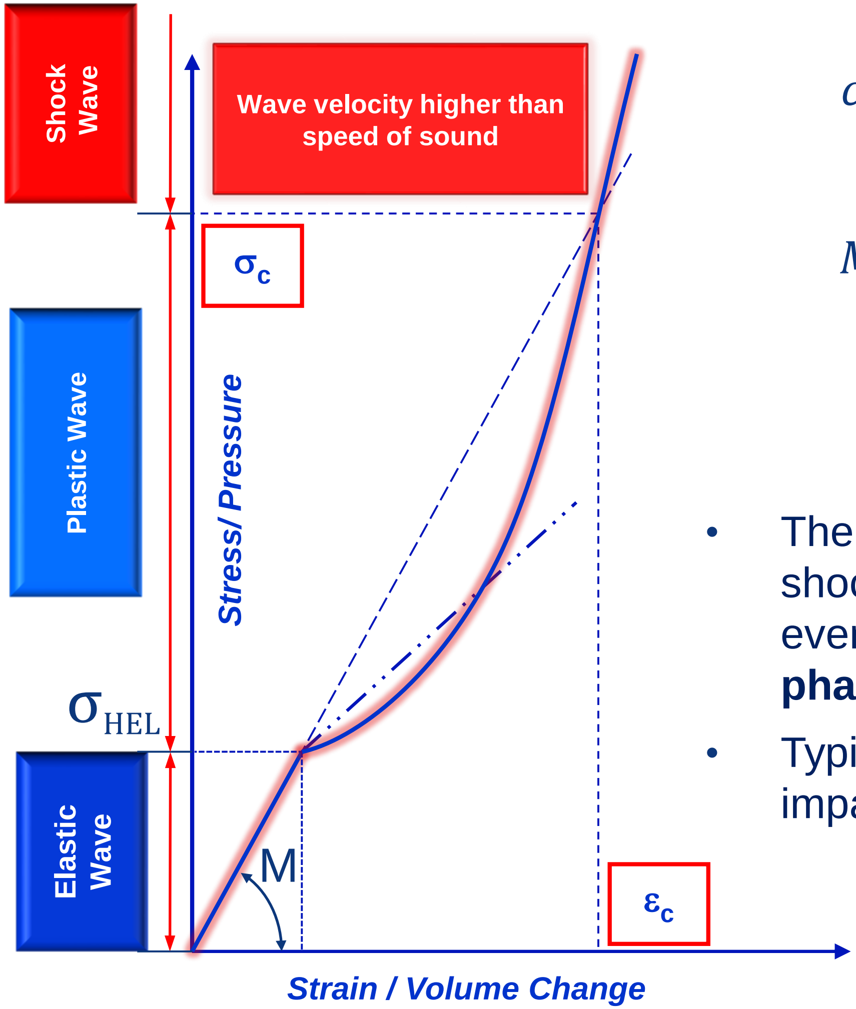
- *A. Bertarelli, A. Dallocchio and T. Kurtyka (2008). Dynamic Response of Rapidly Heated Cylindrical Rods: Longitudinal and Flexural Behavior, J. Appl. Mech., Vol. 75, issue 3, 031010.*

Material regimes after beam impact



- *A. Bertarelli (2016). Beam-induced damage mechanisms and their calculation. CERN Yellow Reports, v. 2, p. 159, Jan. 2016. ISSN 00078328.*

Material regimes after beam impact



$$c = \sqrt{\frac{M}{\rho}}$$

$$M = \lambda + 2\mu = K + \frac{4}{3}G = \frac{(1-\nu)E}{(1+\nu)(1-2\nu)}$$

- The energy required to trigger the shock regime in particle-induced events involves multiple **changes of phase**
- Typically: **plasma state** at the beam impact

Simulation tools

ANSYS

Linear Equation of State

Autodyn and LS-Dyna

Polynomial and tabular Equations of State

ANSYS: good for the elastic and (to some extent) the plastic regimes

Autodyn, LS-Dyna: can cover all regimes, including those with shock, changes of phase, explosion, fragmentation

Both requires, for the beam impact case, 3D energy density maps, computed with **FLUKA, Geant4, Mars**, etc.

Static Failure Strength

$$\sigma < \sigma_{ult}$$

Dynamic Failure Models

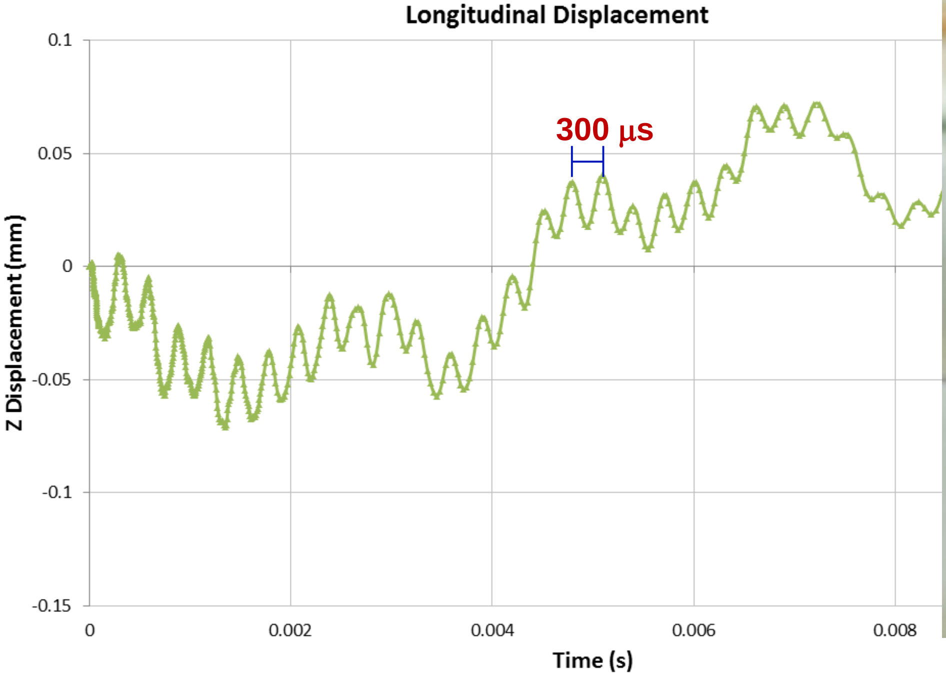
Damage $D = f(\varepsilon, \dot{\varepsilon}, T, \bar{\sigma} \ldots) < 1$

Spallation $p < p_s(\varepsilon, \dot{\varepsilon}, T, D, c_0, K_c, Y)$

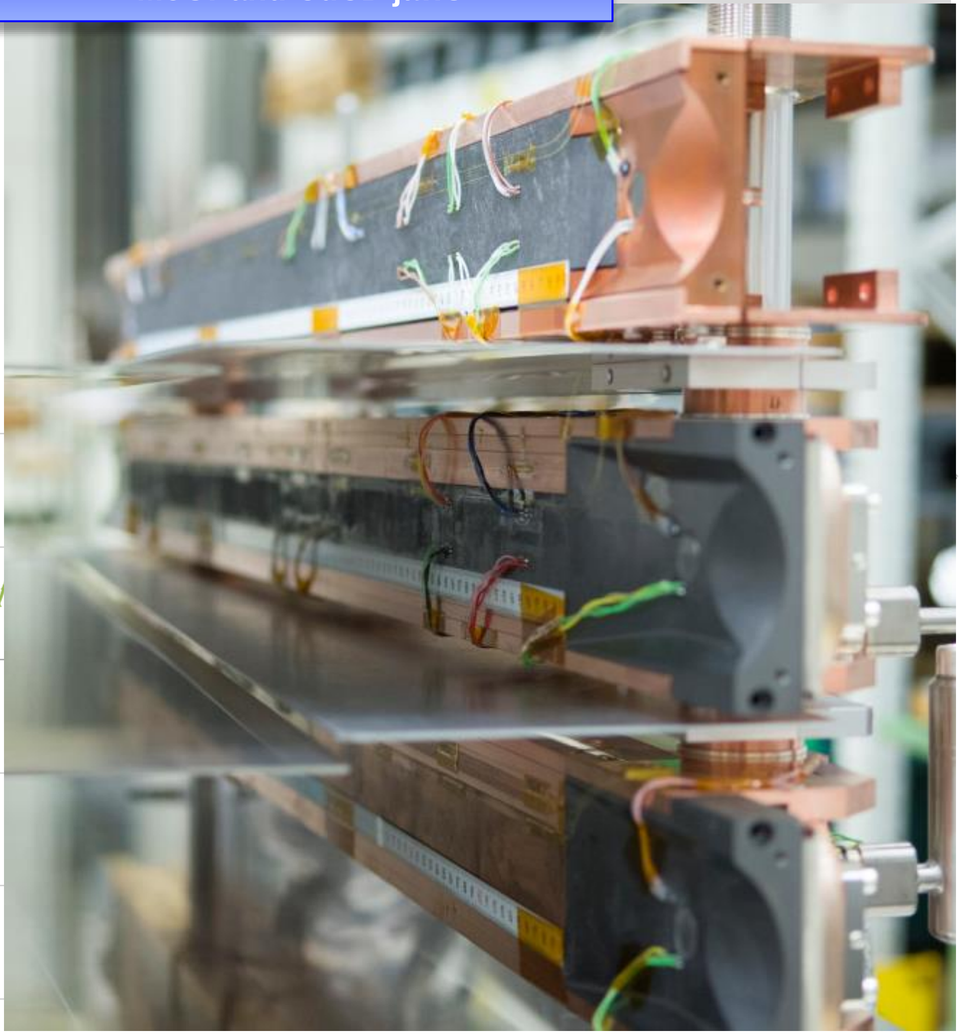
Elastic regime: collimator jaw

Accidental case: beam injection error

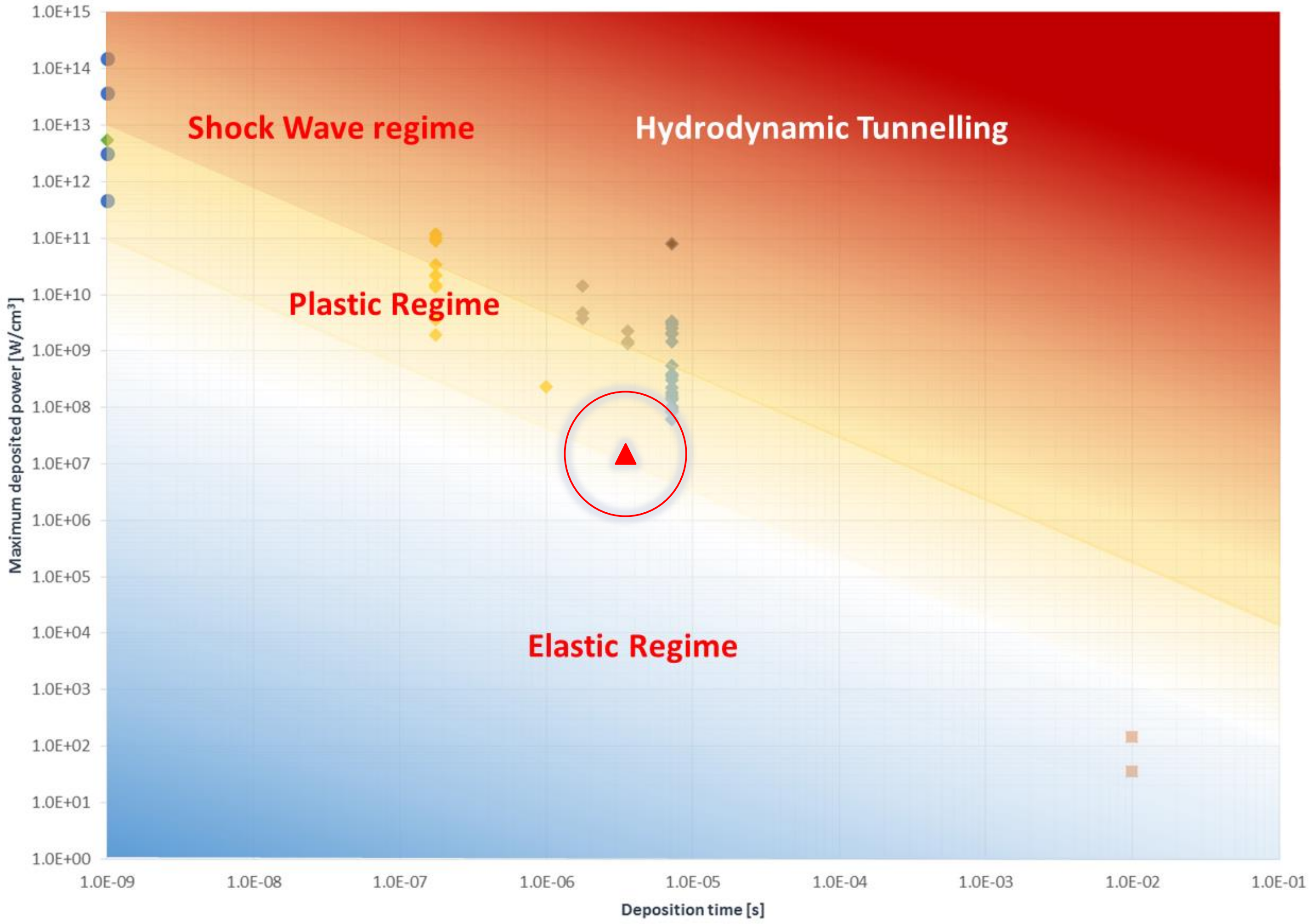
- Longitudinal waves: 3 kHz
- Transversal waves: 45 kHz
- Flexural waves: 80 Hz (displacement free surface 1 mm)



HRMT-23 "Jaws" experiment: CFC, MoGr and CuCD jaws



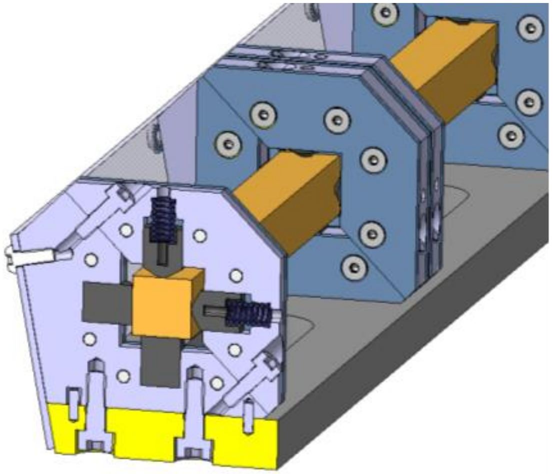
Where are we in the P/t diagram?



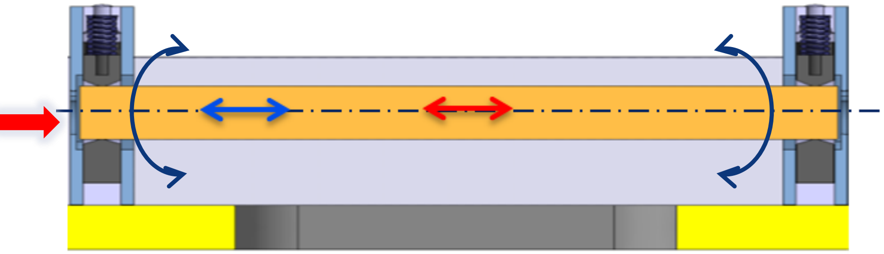
- *F. Carra (2017). Thermomechanical Response of Advanced Materials under Quasi Instantaneous Heating. PhD thesis, https://zenodo.org/record/1414090.*

Plastic regime: HRMT-36

- Specimens of simple geometry (**slender bars,** length **120** or **247 mm**) tested to generate simple wave signals, easy to acquire and benchmark. **Some low-Z samples coated** (Mo, Cu, TiN)
- **Simply supported** bars, axially **free** to expand.
- Mainly **square cross section** (8×8 to 12×11.5 mm^2) to disentangle anisotropy and simplify PIE

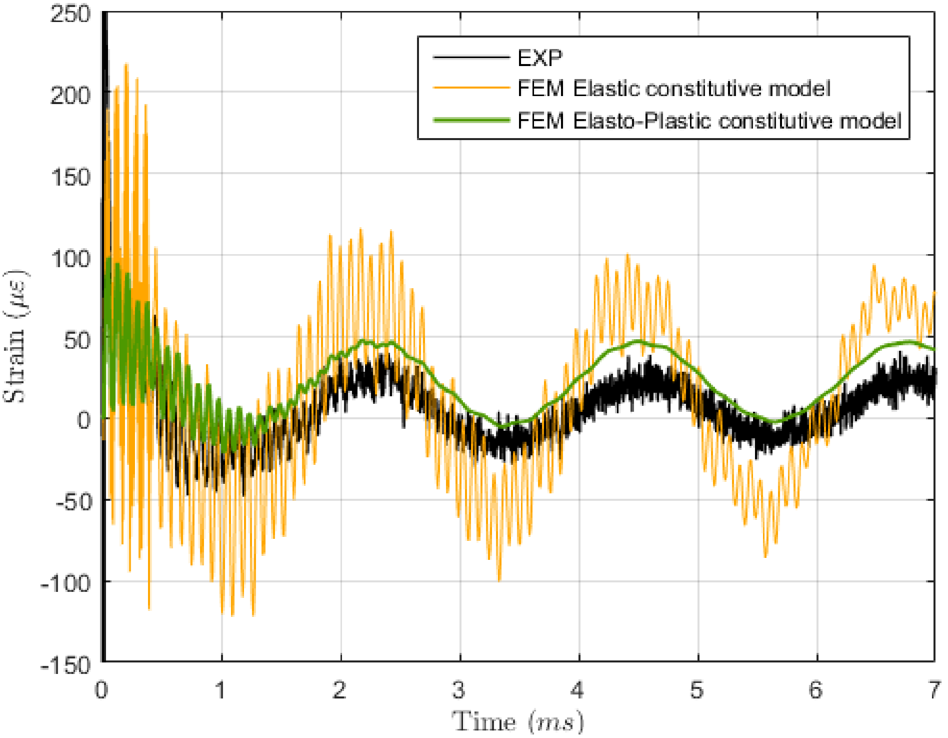


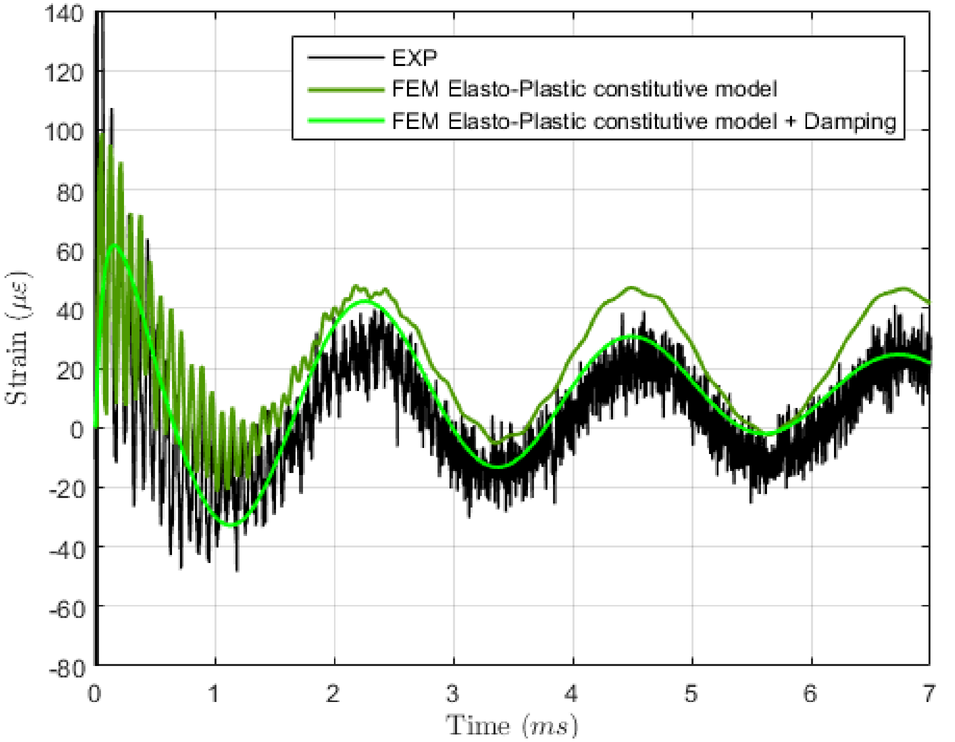
Plastic regime: HRMT-36



- Material: **CuCD**
- Pulse intensity: **1 bunch, 1.43E11 p/b**
- Sigma: **0.5 mm** Offset: **3.1 mm**

- Longitudinal strain at z = l/2 with elastic / elasto-plastic constitutive model and no damping.
- Longitudinal strain at z = l/2 with elasto-plastic constitutive model and damping ratio ζ = 8% (Rayleigh)

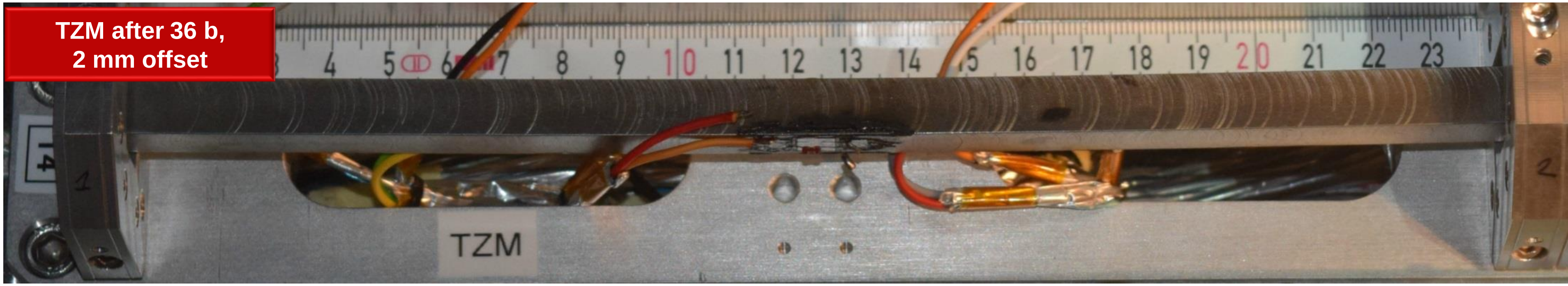




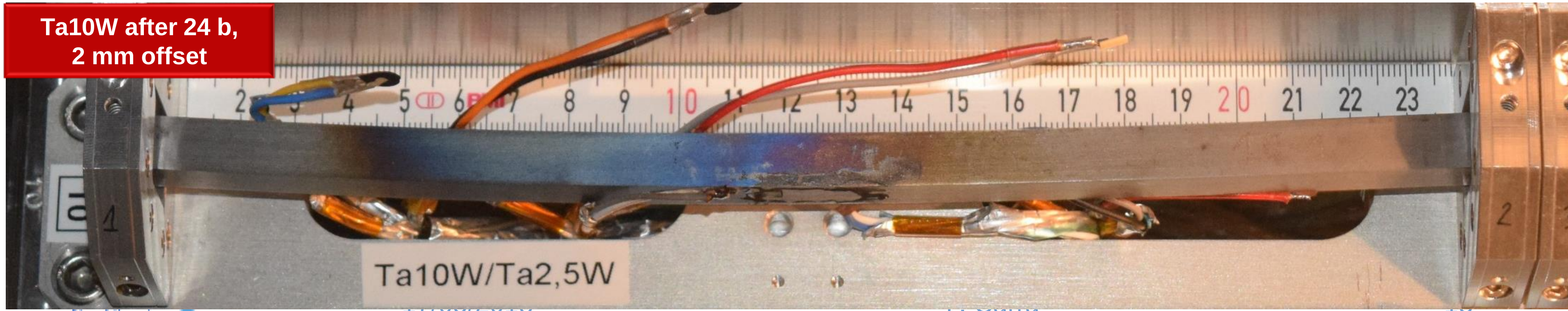
Plastic regime: HRMT-36

- HRMT-36: Permanent Deformation induced on high-Z materials

**IT180 after 24 b,
2 mm offset**



**TZM after 36 b,
2 mm offset**



**Ta10W after 24 b,
2 mm offset**

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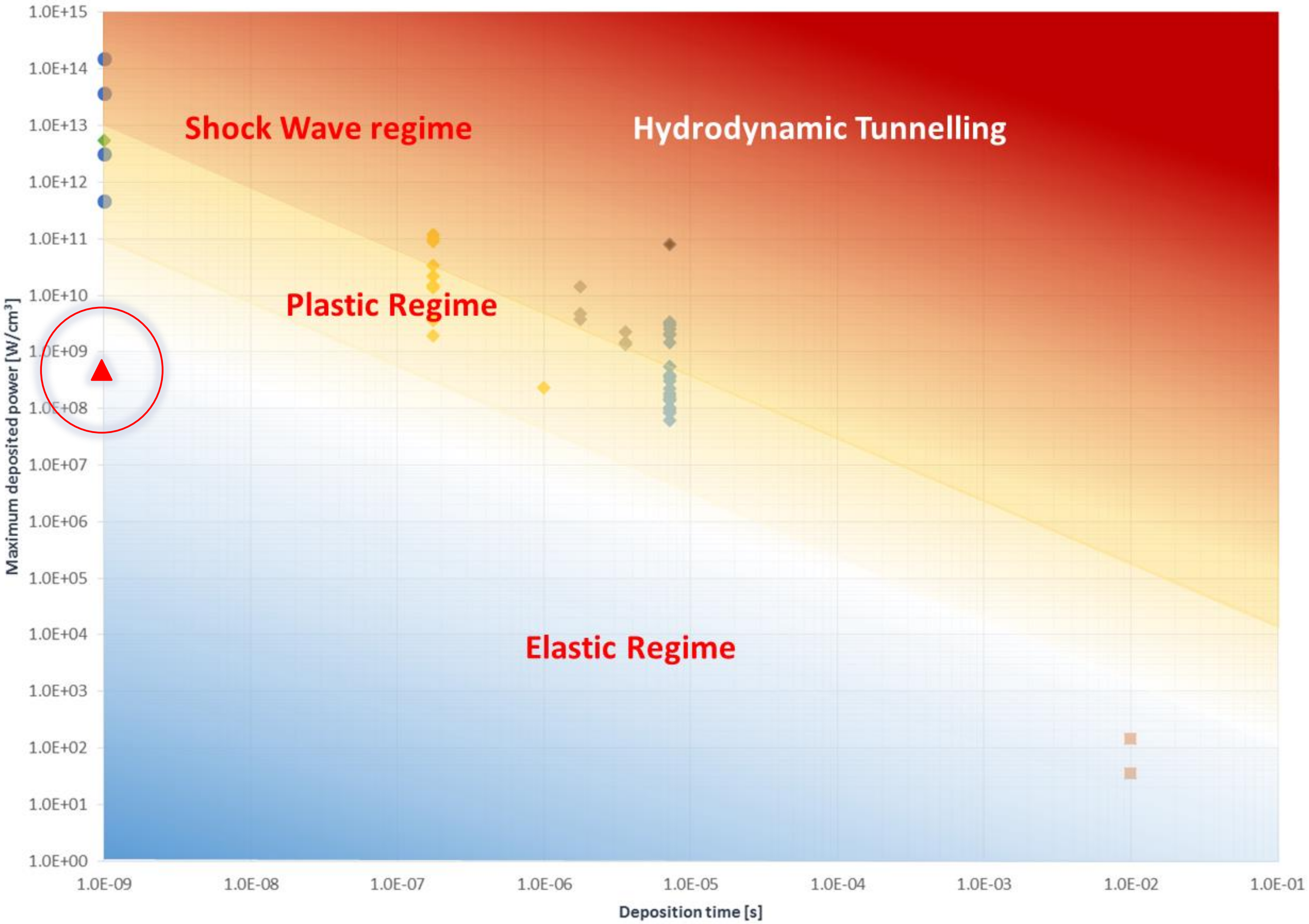


- *A. Bertarelli et al. (2018). Dynamic testing and characterization of advanced materials in a new experiment at CERN HiRadMat facility. J. Phys.: Conf. Ser. 1067 (082021).*

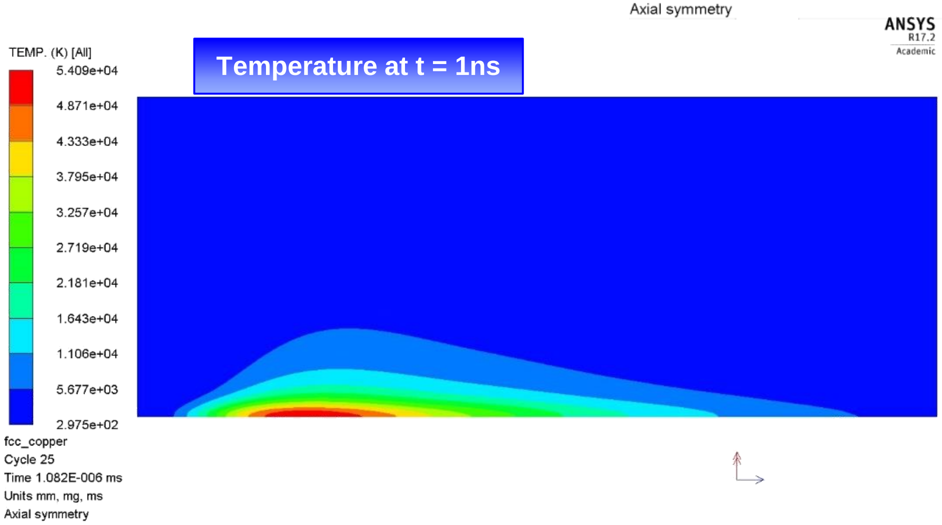
Shock regime: FCC

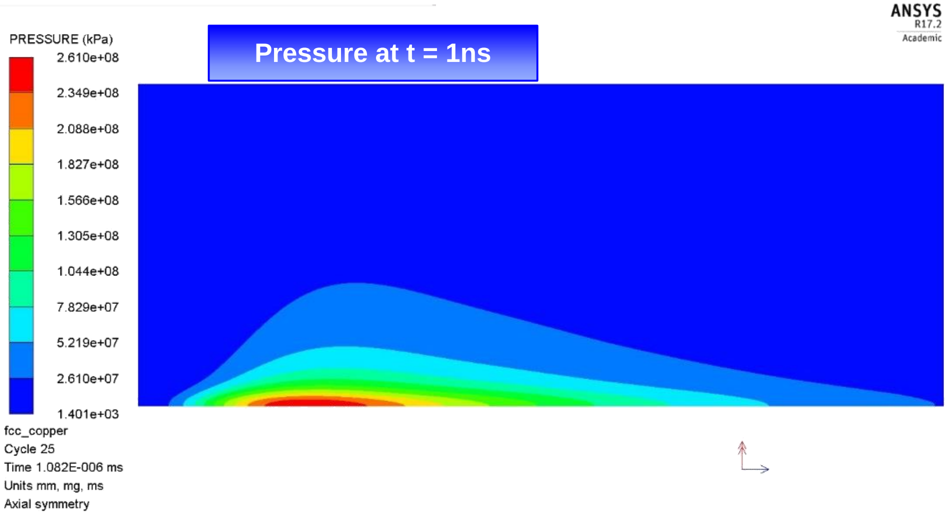
- **1 FCC proton bunch** impacting on a copper cylinder (*L = 1 m, D = 8 mm*)

SOUNDSPEED (m/s)

EOS	Strength Model		Failure Model		Beam Parameters	
SESAME 3320	Johnson-Cook		Johnson-Cook		E_k	50 TeV
	G	46 GPa	D_1	0.54	t_d	0.5 ns
	A	90 MPa	D_2	4.89	n_{tot}	1×10^{11} p
	B	292 MPa	D_3	-3.03	E_{tot}	230 kJ
	n	0.31	D_4	0.014	E_{max}	310 kJ/cm^3
	C	0.025	D_5	1.12	σ_x, σ_y	0.1×0.1 mm^2
	T_m	1356 K	T_m	1356 K		
	$\dot{\varepsilon}_0$	1 s^{-1}	$\dot{\varepsilon}_0$	1 s^{-1}		

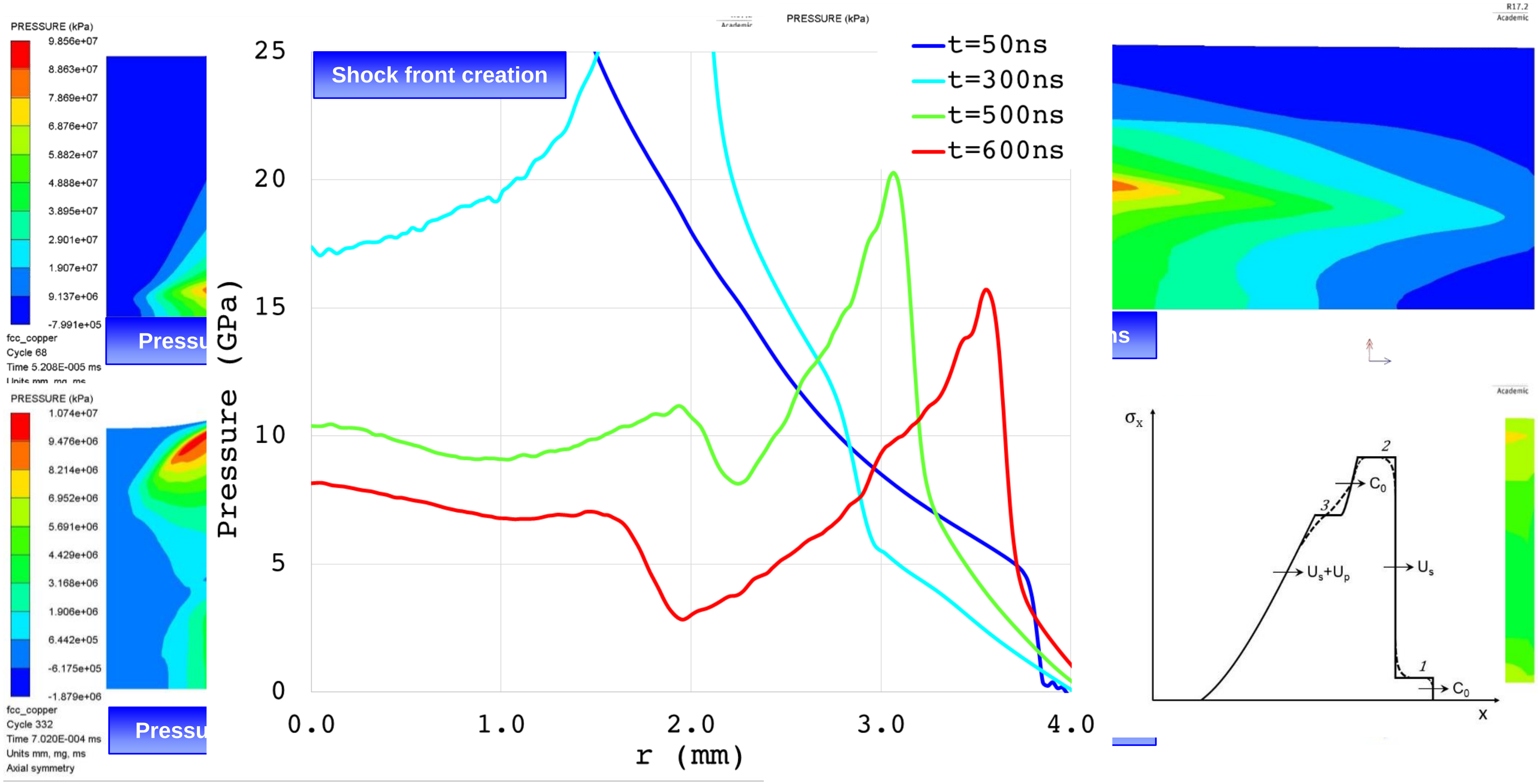
Units mm, mg, ms
Axial symmetry


Temperature at t = 1ns


Pressure at t = 1ns

Shock regime: FCC

- **1 FCC proton bunch** impacting on a copper cylinder (*L = 1 m, D = 8 mm*)



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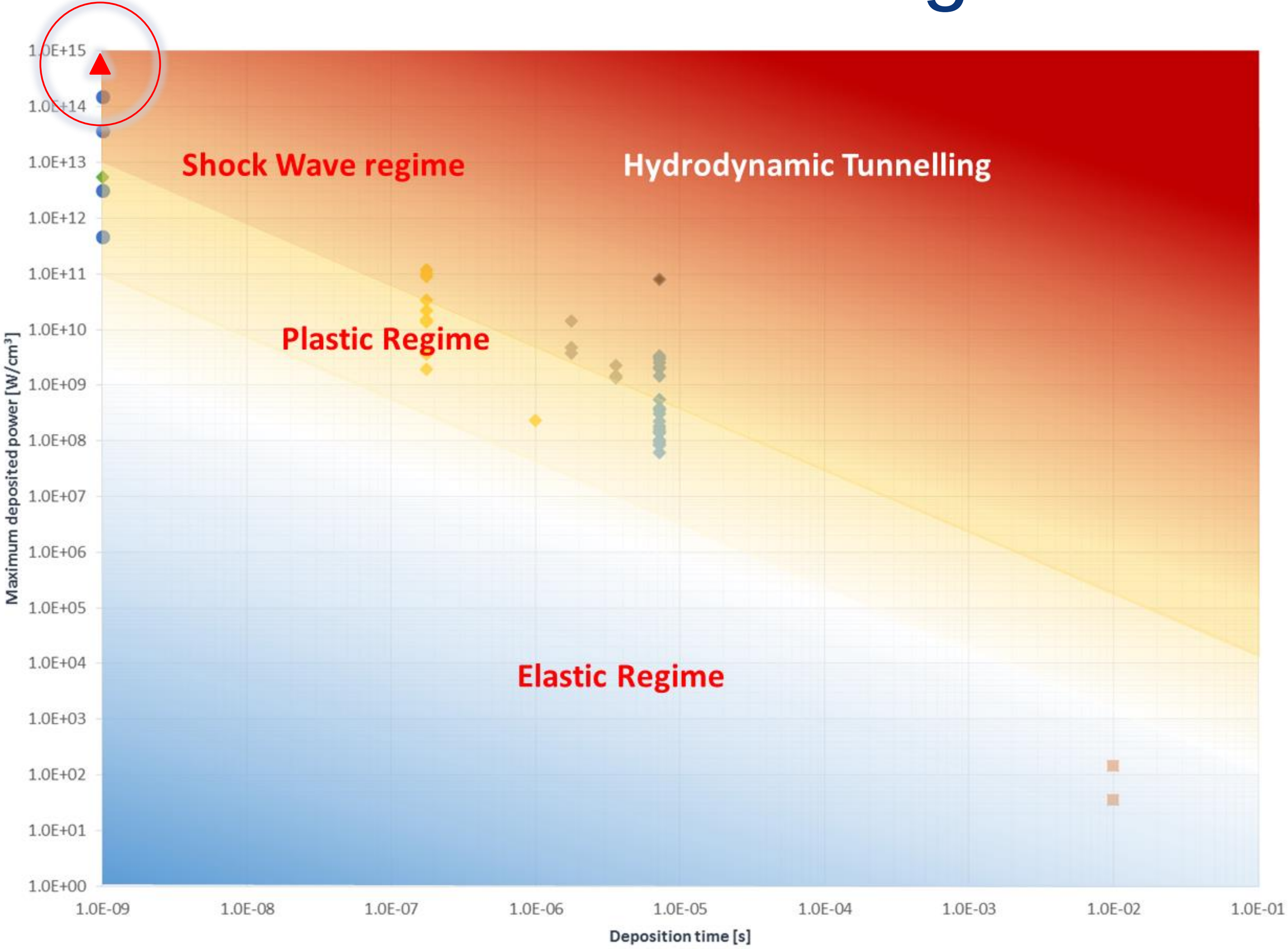


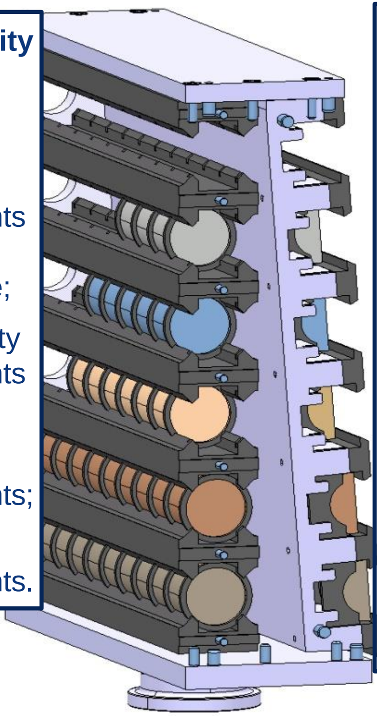
- *F. Carra (2017). Thermomechanical Response of Advanced Materials under Quasi Instantaneous Heating. PhD thesis, https://zenodo.org/record/1414090.*

Spallation: HRMT-14

- Testing of 6 materials, with two different shapes: cylinders and half-moons
- Half-moons adopted to generate and record extreme events such as spallation, micro-spallation, micro-jetting with a **high-speed camera**
- Benchmarking done with **Autodyn (SPH method)**

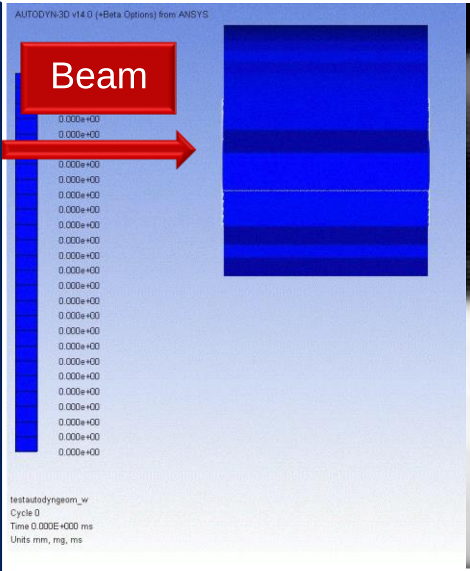
Medium Intensity Samples (Type 1)

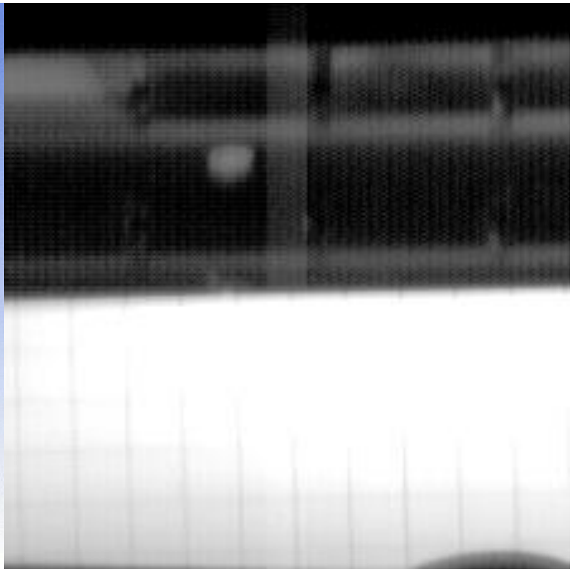
- Strain measurements on sample outer surface;
- Radial velocity measurements (LDV);
- Temperature measurements;
- Sound measurements.



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.





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**

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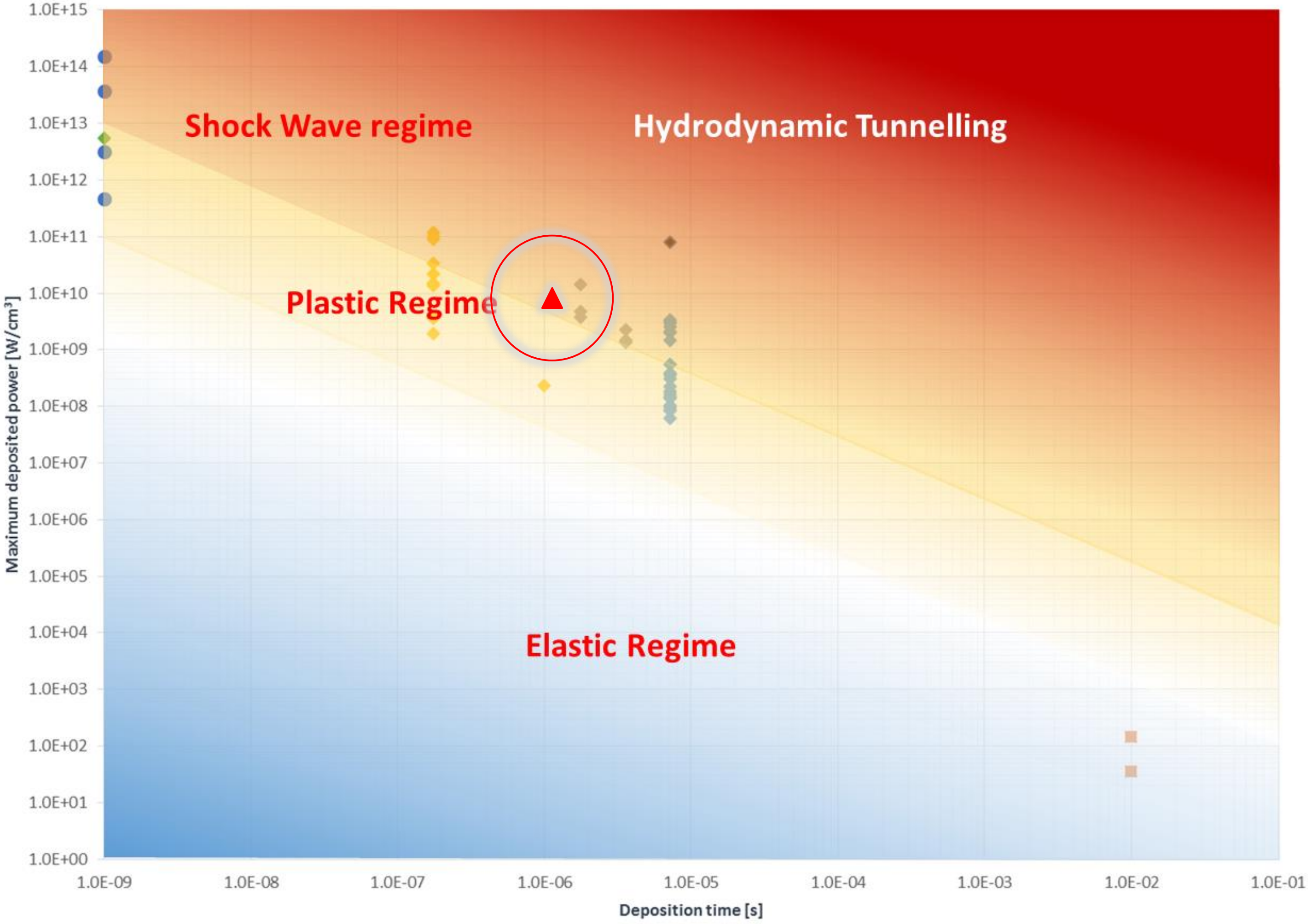
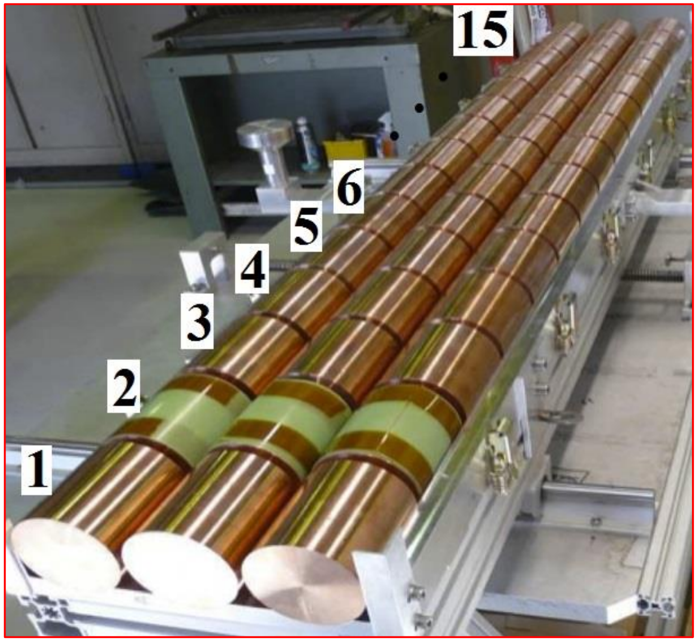
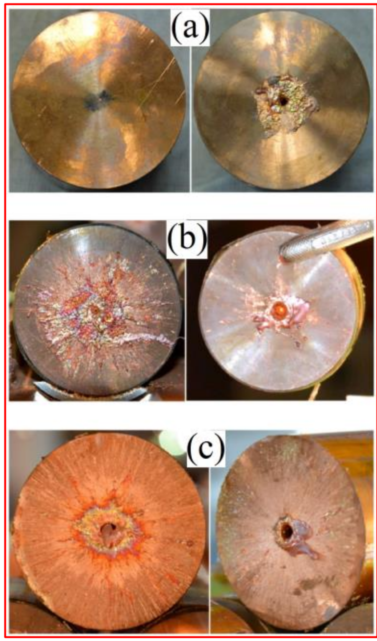


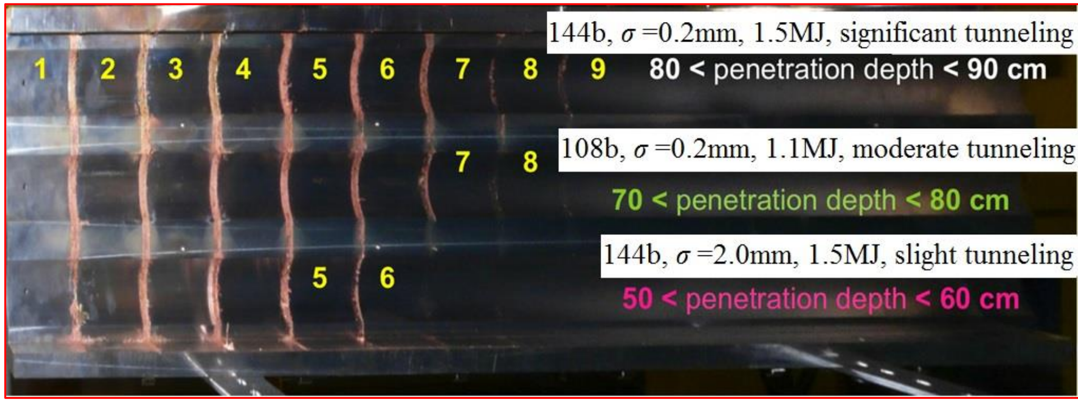
- *A. Bertarelli et al. (2013). An experiment to test advanced materials impacted by intense proton pulses at CERN HiRadMat facility. Nuclear Instruments and Methods in Physics Research B, Vol. 308, pp. 88–99.*

Hydrodynamic tunneling: HRMT-12

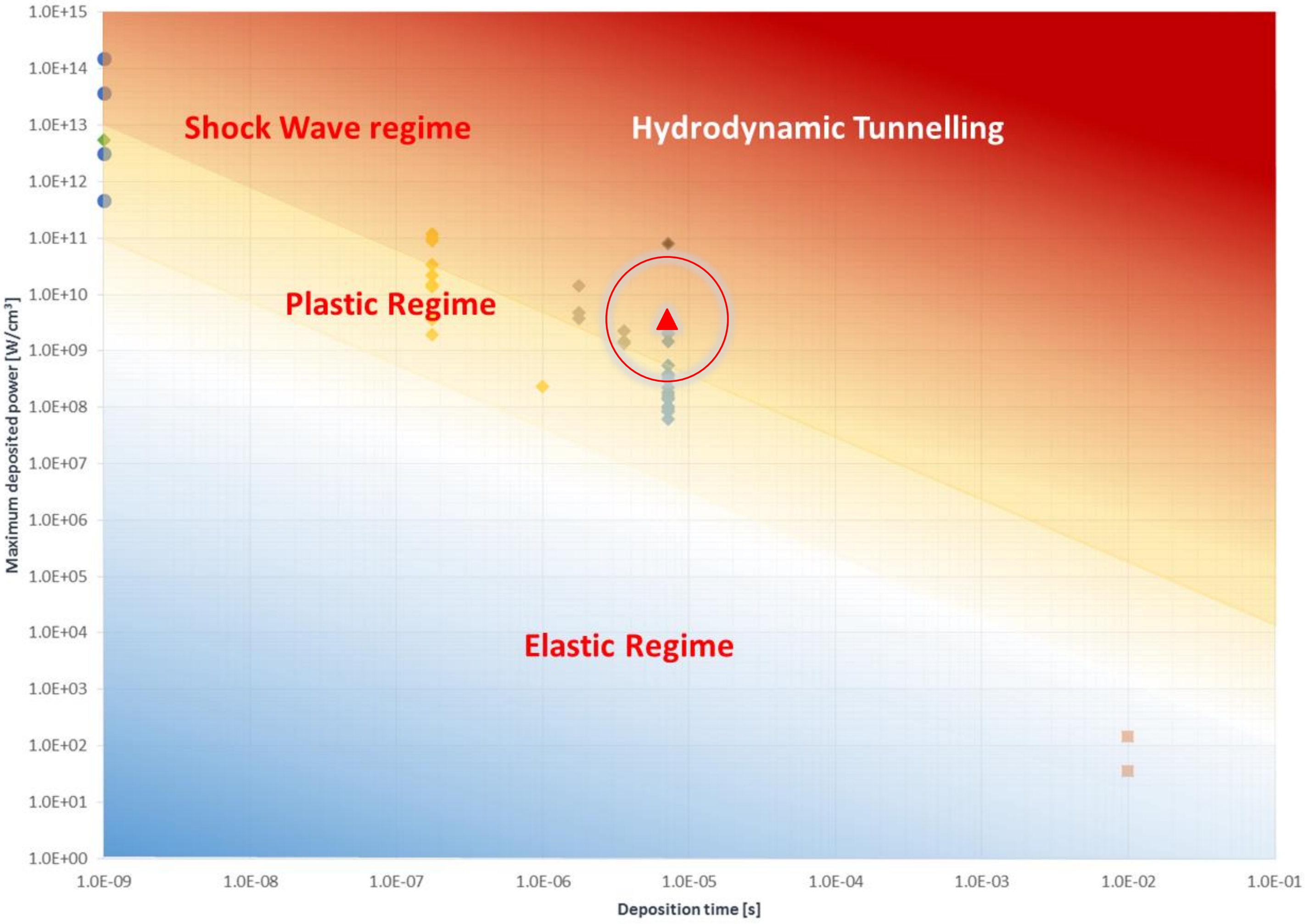
- Related to the multi-bunch case
- Because of the material density reduction during the impact time, **the beam penetrates more and more in the material**
- **It requires iterations between the energy transport code and the FE code**
- Benchmarking with **FLUKA and Autodyn of the HRMT-12 case** (144 SPS bunches on copper), originally studied with Fluka and BIG-2 by Tahir → paper under publication on PRAB (accepted with minor revisions) ***see presentation from Yuancun***.







Where are we in the P/t diagram?



- *Y. Nie et al. (2018). Simulation of hydrodynamic tunneling induced by high-energy proton beam in copper coupling computer codes . Under publication on PRAB.*

FLUKA/LS-Dyna coupling at PoliTo

THE ENERGY DEPOSITION IS DENSITY DEPENDENT

At the beginning:

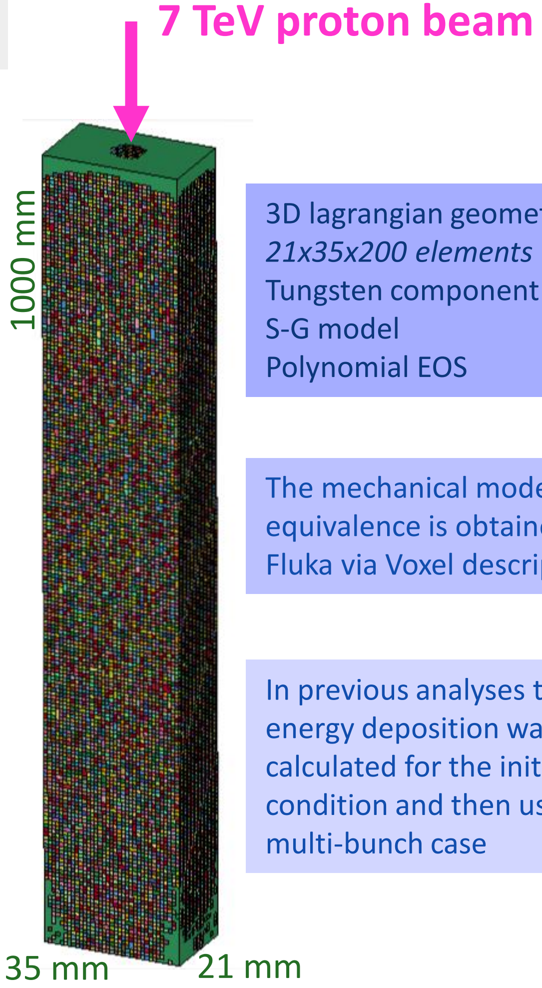
- ✓ Start with the density of the pristine material

For each step:

- ✓ take as input the density map resulting from the LS-DYNA calculations;
  - define discrete density levels: each level is an independent FLUKA material;
- ✓ use 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;
- ✓ take as input the energy map resulting from the FLUKA calculations;
  - define discrete energy levels; interpolate the SESAME EOS for getting the polynomial coefficient;
- ✓ analyze the results;

RESTART a new mechanical analysis (1 or more bunches)

Courtesy L. Peroni, M. Scapin

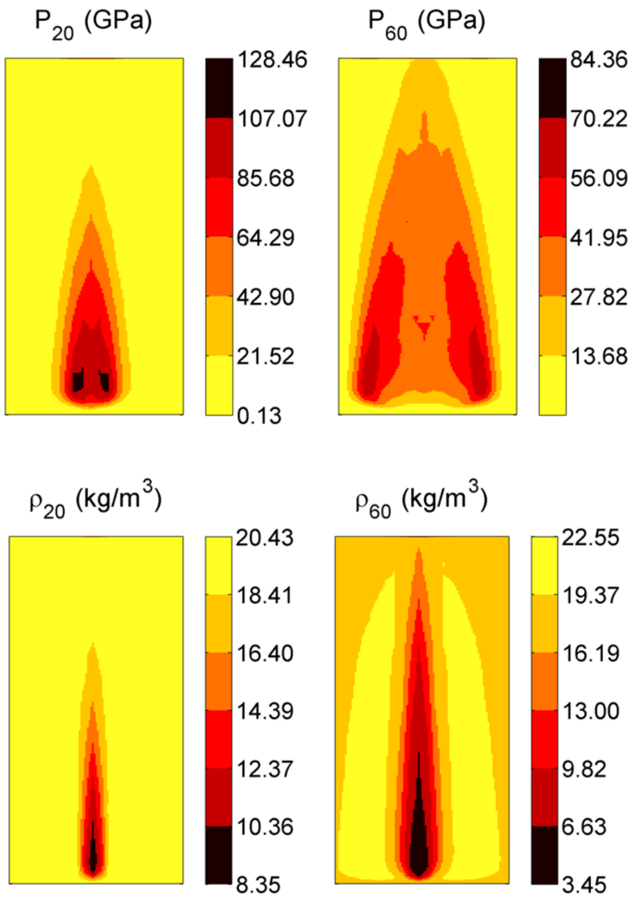


3D lagrangian geometry
21x35x200 elements
Tungsten component
S-G model
Polynomial EOS

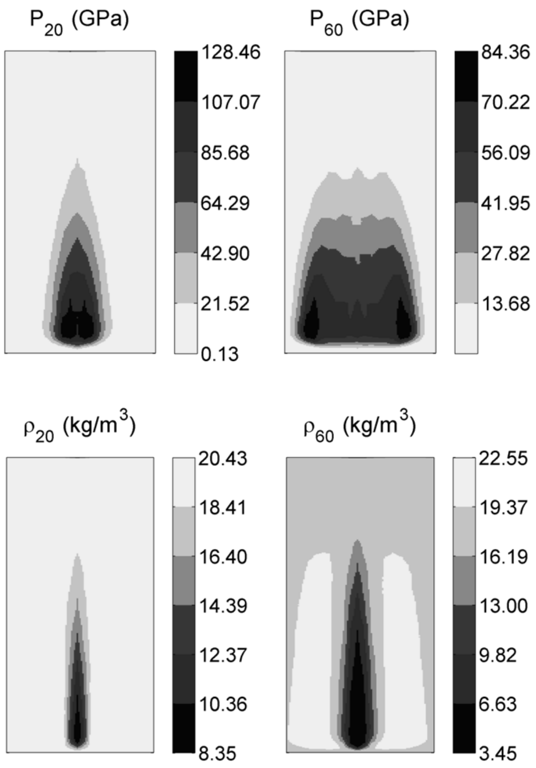
The mechanical model equivalence is obtained in Fluka via Voxel description

In previous analyses the energy deposition was calculated for the initial condition and then used in a multi-bunch case

FLUKA/LS-Dyna coupling at PoliTo



Coupled



Uncoupled

60 LHC bunches on W target

Courtesy L. Peroni, M. Scapin

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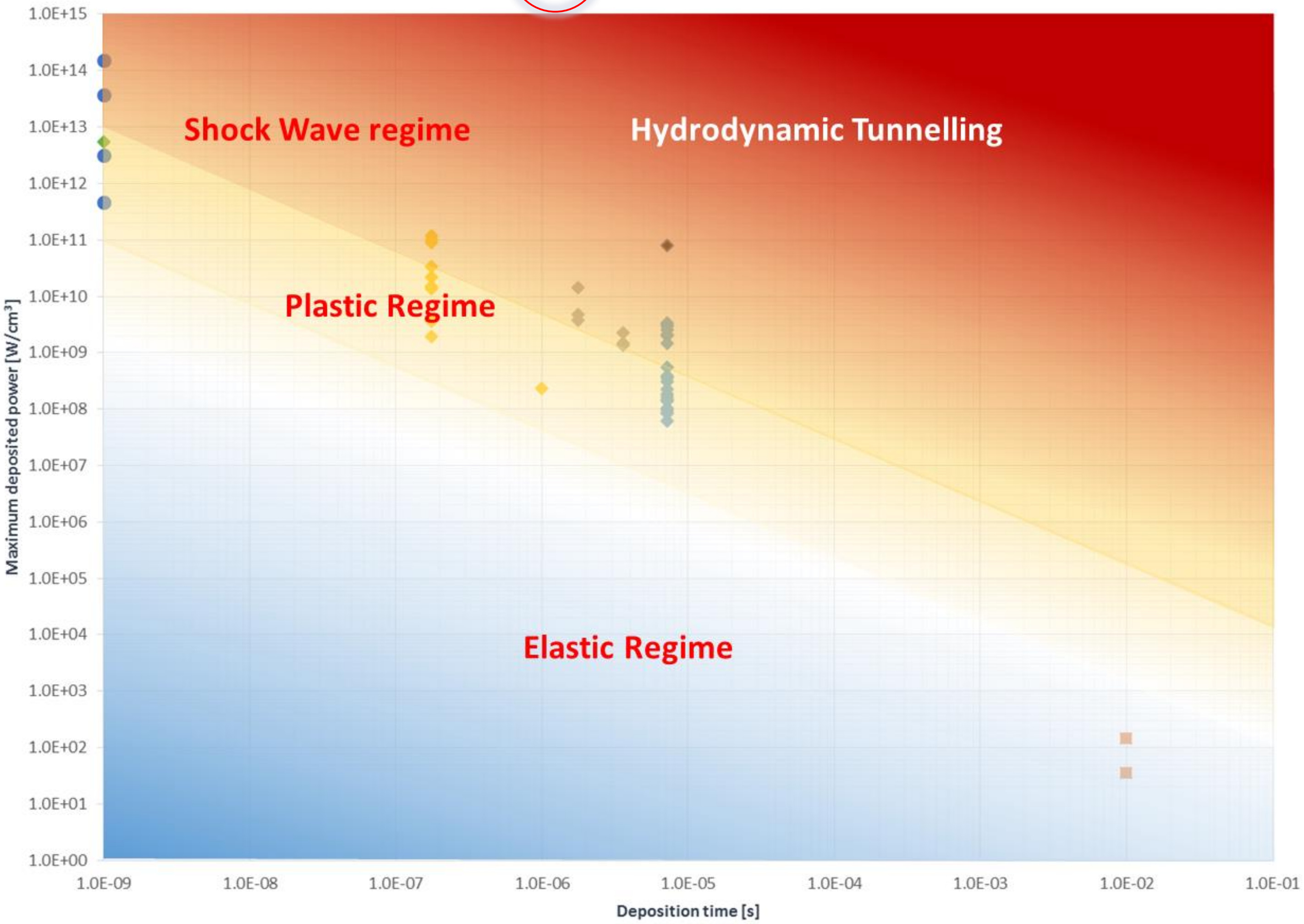


- *M. Scapin, L. Peroni, V. Boccone, F. Cerutti (2013). A LS-Dyna/FLUKA coupling for the numerical simulation of high energy particle beam interaction with matter. Proceedings of Computational Methods for Coupled Problems in Science and Engineering V, Spain, ISBN 9788494140761.*

Conclusions

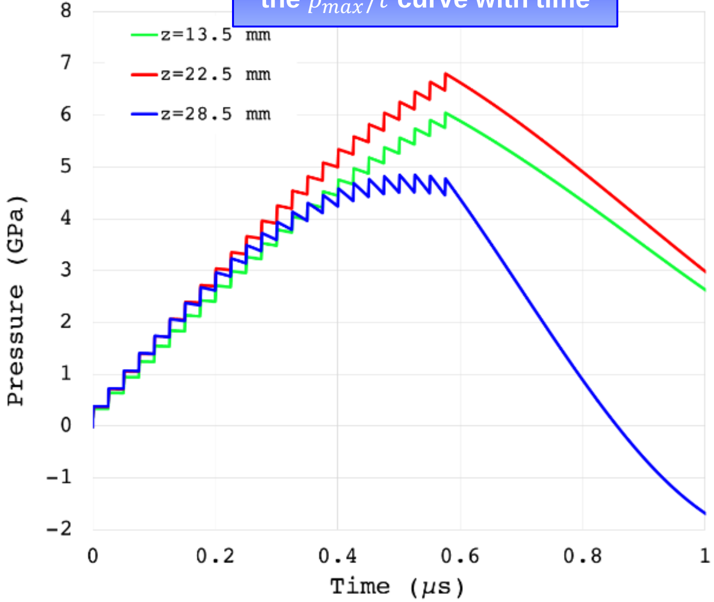
- In the design of beam intercepting devices, we want typically to remain in the **elastic regime of the material**
- In some cases, for example in accidental scenarios, **a limited extent of plasticity (without failure) can be accepted**
- Both conditions can be effectively treated with an implicit code like **ANSYS**
- With the increase of stored energy in future accelerators, scenarios involving changes of phase, shock wave regime, hydrodynamic tunnelling, spallation, etc. will become more and more relevant
- Those can be studied only with an explicit code such as **Autodyn** (or LS-Dyna, BIG-2, etc.)
- **The coupling between the energy transport code and the explicit code is needed** when, during the impact, one of the following conditions is triggered:
  - Change of geometry
  - Change of beam particle distribution in space
  - Change of density of the target
- At EN-MME, in collaboration with TE-MPE and the FLUKA team, a **manual coupling between Autodyn and FLUKA** was successfully implemented and tested on the HRMT-12 case
- At PoliTo, **an automatic coupling between LS-Dyna and FLUKA** was also implemented in 2013

Thanks for your attention

Cylindrical shock waves

- **Radial decay** proportional to $r^{-1/2}$
- Bunched structure of the beam: the **slope p_{max}/t decreases**
- **Rarefaction waves originating from the center and free faces**, decreasing even more the pressure

Shock regime provoked by particle beam impact is difficult to reach!


Cu cylinder – flattening of the p_{max}/t curve with time

- **FCC**: circular collider of 100 km under construction at CERN. Particle energy 10 times bigger than the LHC, t_d (1 bunch): 0.5 ns → **energy densities of 10^9 J/cm^3 achievable!**
- **Case study**: **1 FCC proton bunch** impacting on a copper cylinder (*L = 1 m, D = 8 mm*)
- Simulation performed with **Autodyn** (significant nonlinearities and changes of phase expected)