10th – 12th JULY 2019
Hosted by CERN, Geneva, Switzerland

HiRadMat
High-Radiation to Materials

INTERNATIONAL HIRADMAT WORKSHOP

Shock-wave and high strain-rate phenomena in high energy particle beam impacts

Lorenzo Peroni

POLITECNICO DI TORINO

*with contributions by **M. Scapin***

Exchange scientific concepts and ideas linked to the goals of HiRadMat

TOPICS TO INCLUDE:
ACCELERATOR PHYSICS
CONDENSED MATTER PHYSICS
ENGINEERING
MATERIALS SCIENCE
PLASMA PHYSICS

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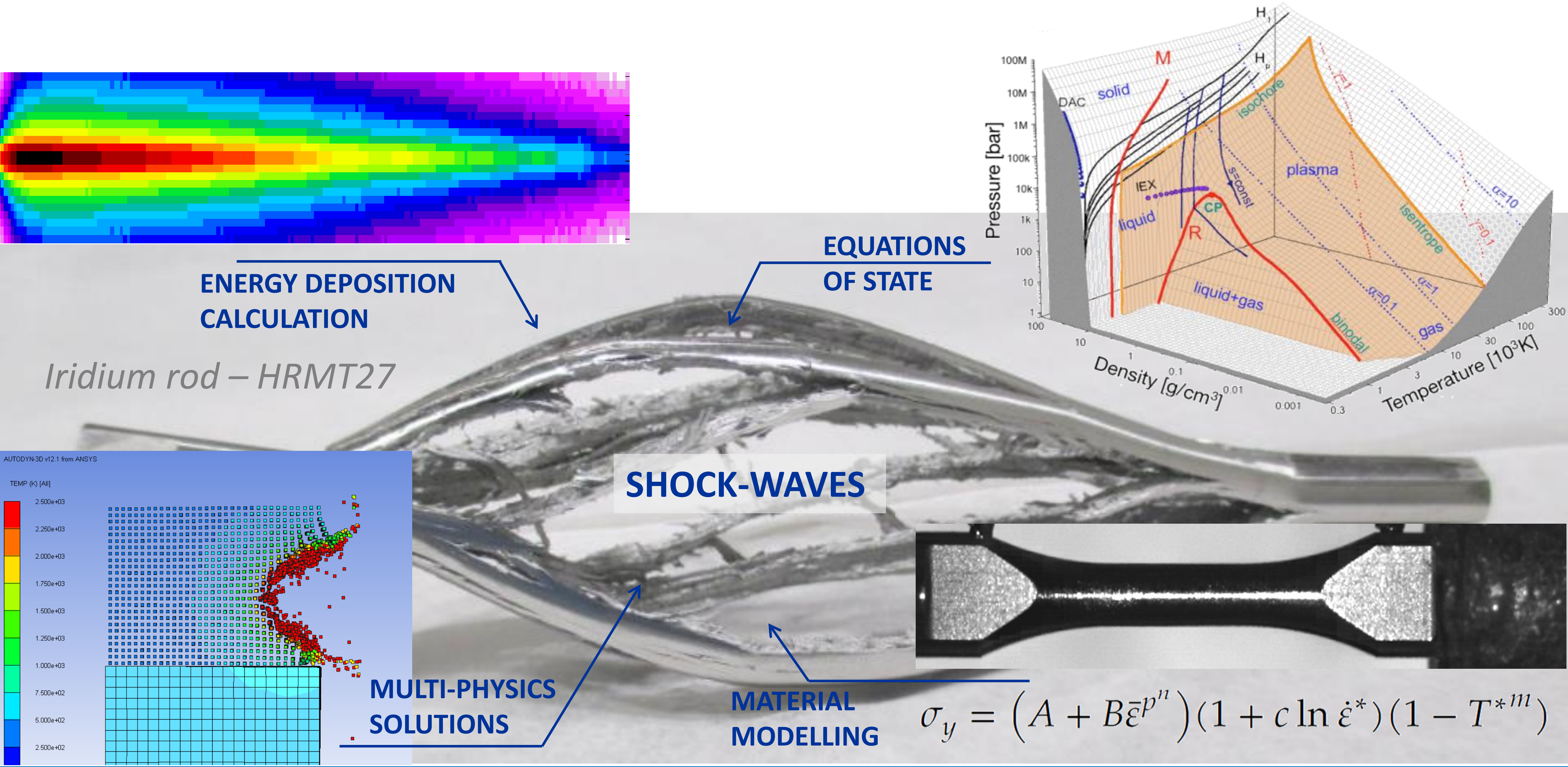
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

ARIES

EN ENGINEERING DEPARTMENT



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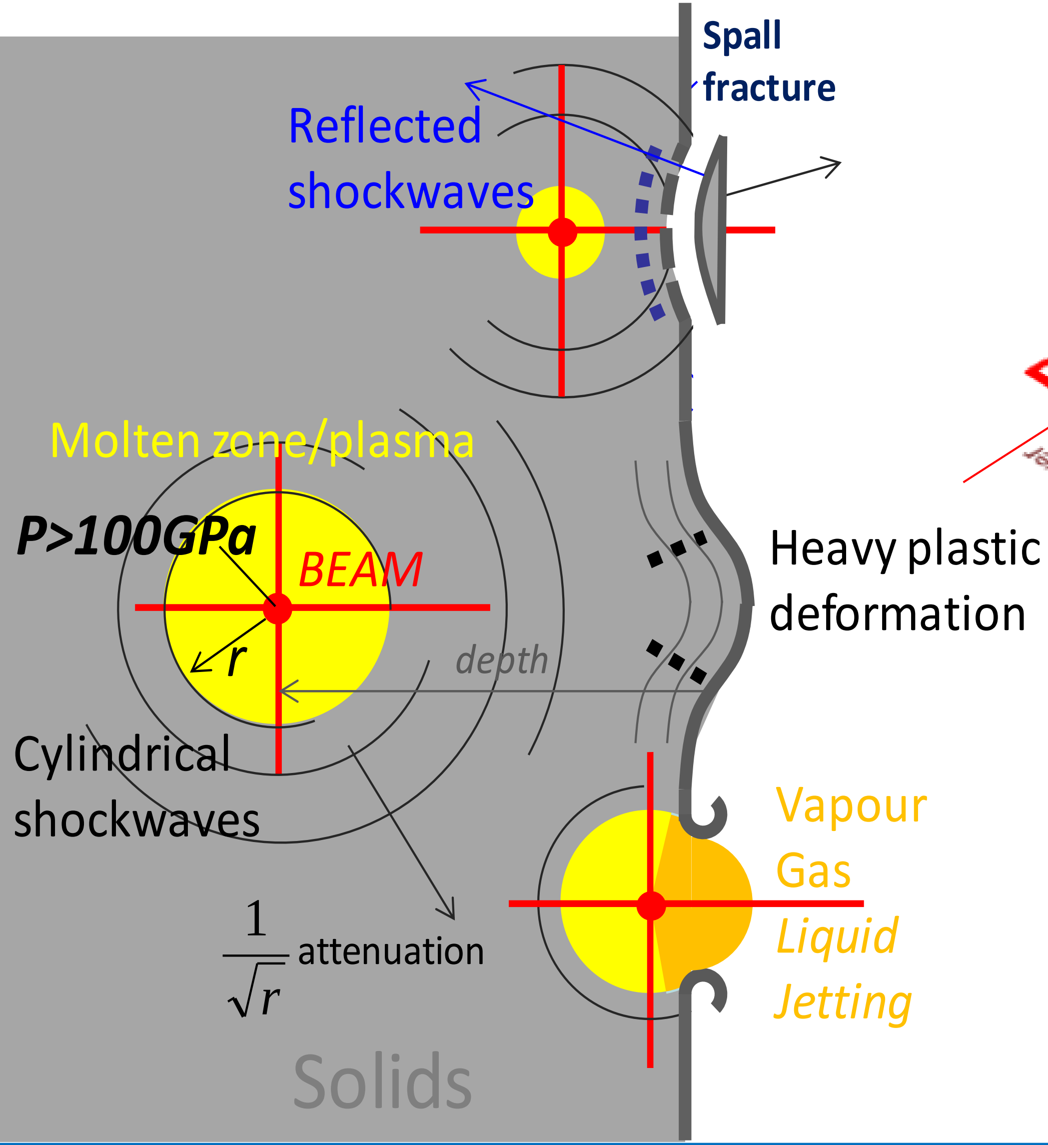
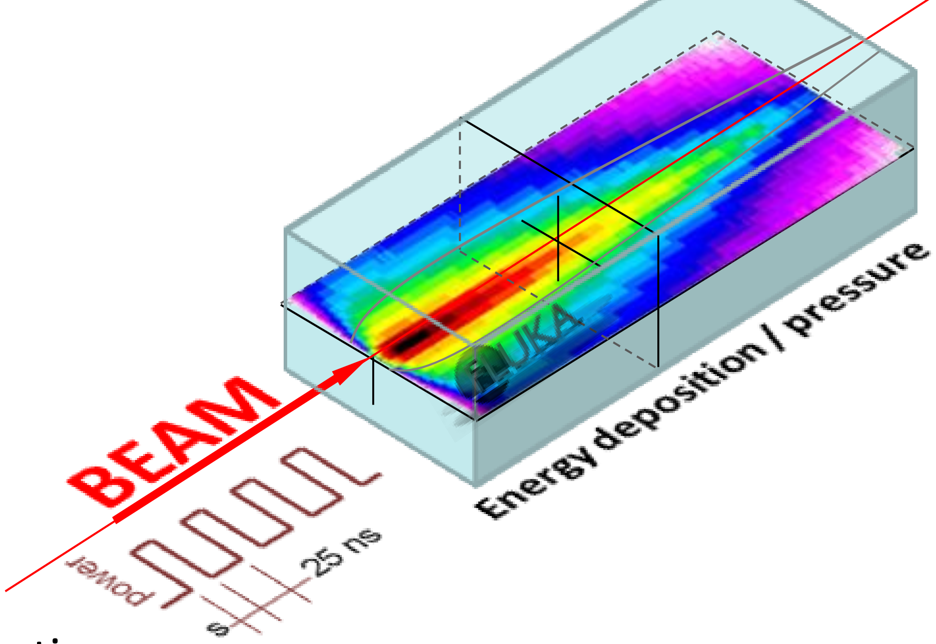
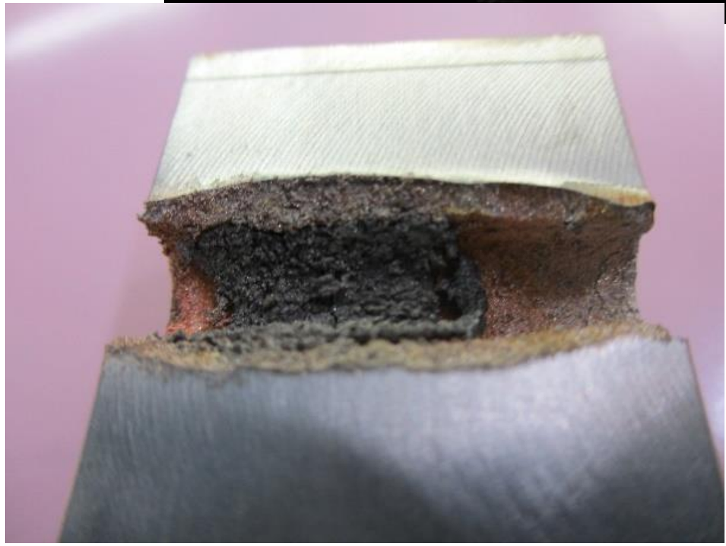
Outline





"**Interaction** of high energy, high intensity particle **pulses** with matter leads to **sudden temperature rises** (with possible changes of phase) and large **thermal deformations in very short times** (initially **prevented by mass inertia**), with propagation of **intense pressure waves,** possibly leading to **extensive mechanical damage**" *A. Bertarelli*



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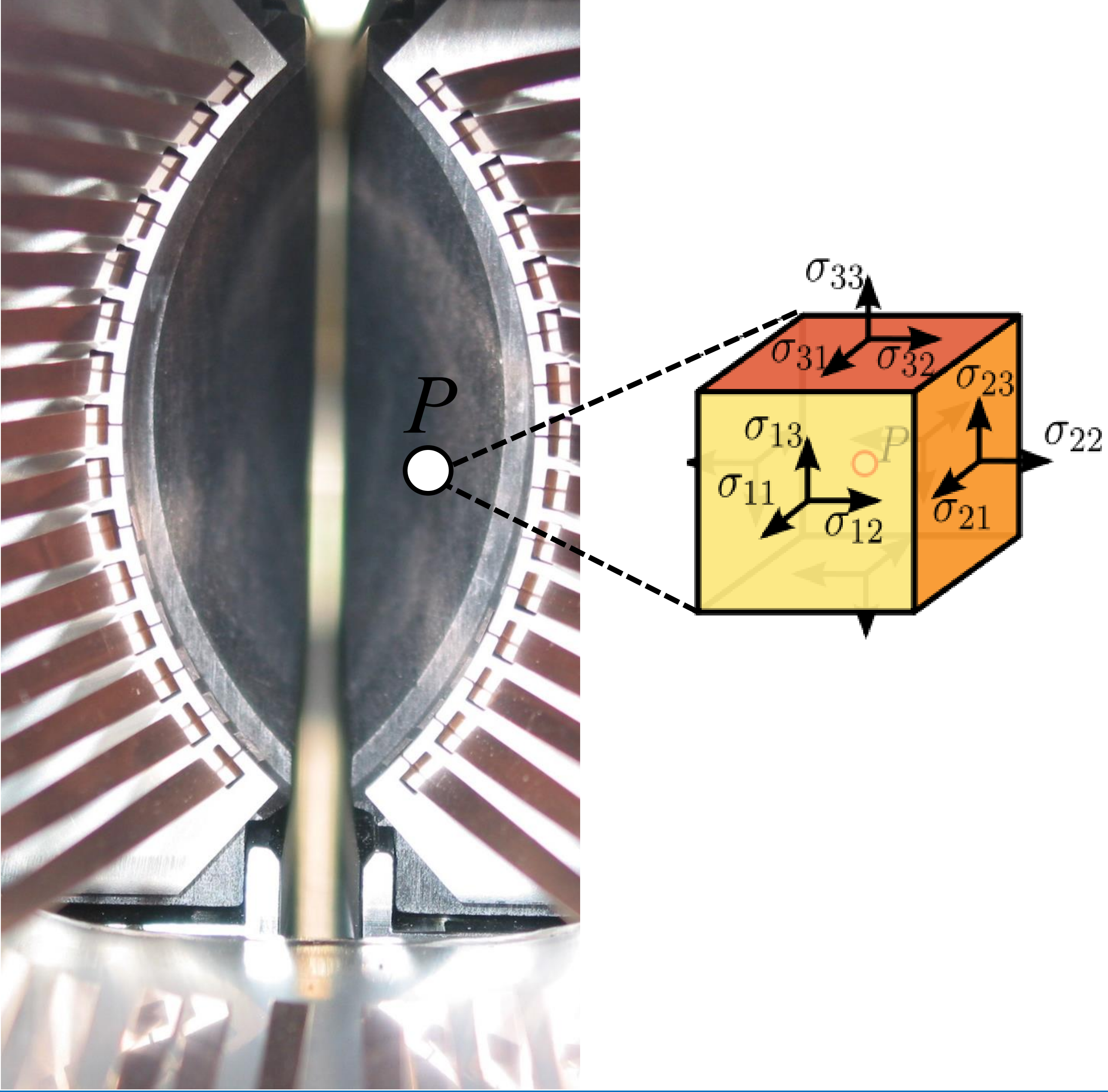
Material behaviour in beam impacts scenarios



Hydrostatic ← | → *Deviatoric*

Solids only
Elasticity, Plasticity

Stress tensor

$$\sigma_{ij} = \frac{\sigma_{kk}}{3}\delta_{ij} + s_{ij}$$

Pressure — Equivalent stress

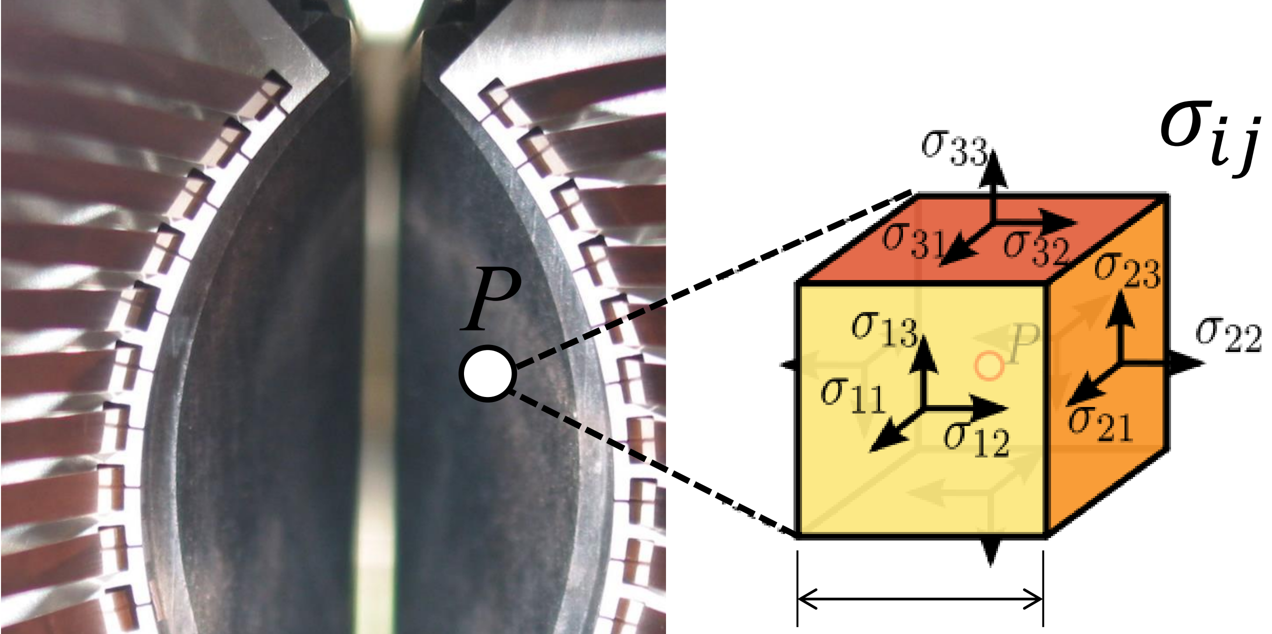
Strain tensor

$$\varepsilon_{ij} = \frac{\varepsilon_{kk}}{3}\delta_{ij} + e_{ij}$$

Density — Plastic strain

Why shock-waves?

Why shock-waves?

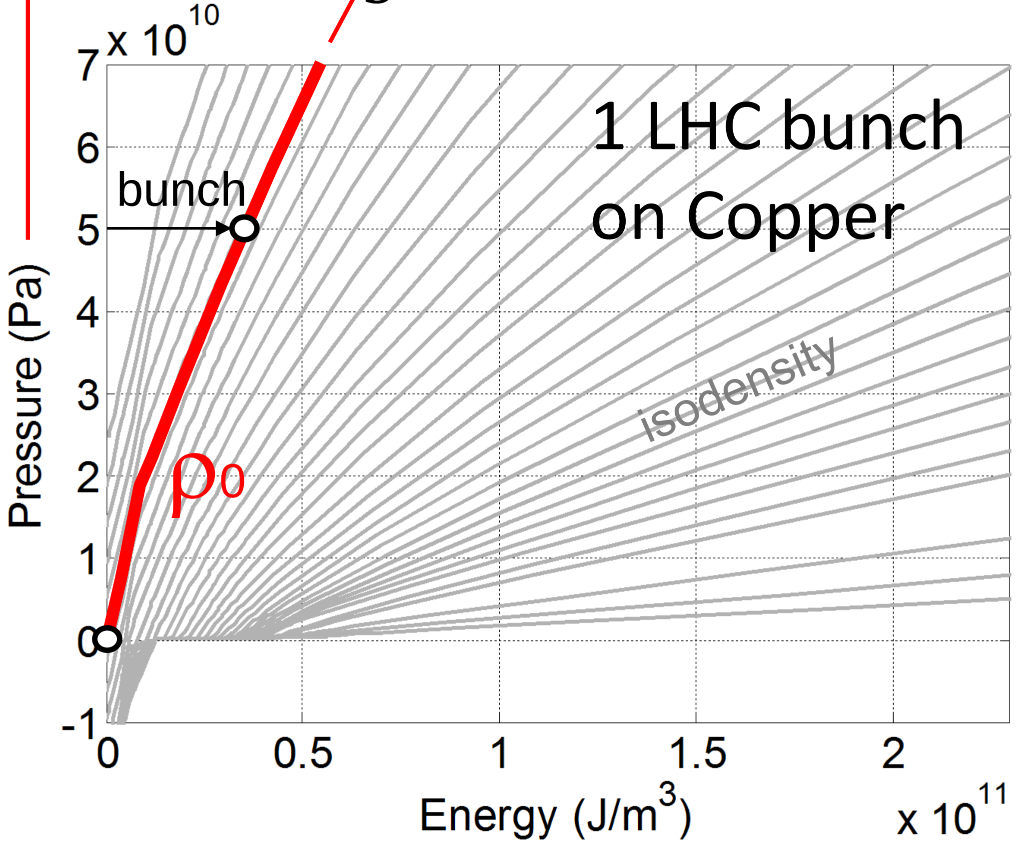


$$\sigma_{ij} = \frac{\sigma_{kk}}{3}\delta_{ij} + s_{ij}$$

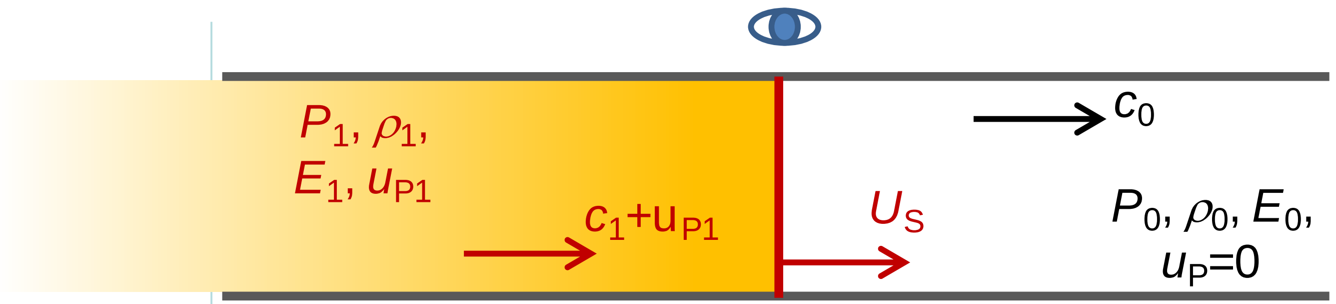
$$\varepsilon_{ij} = \frac{\varepsilon_{kk}}{3}\delta_{ij} + e_{ij}$$

During the energy deposition phase the deformation of the material is limited by the inertia

$$t_{dep} \ll \frac{L_C}{c}$$

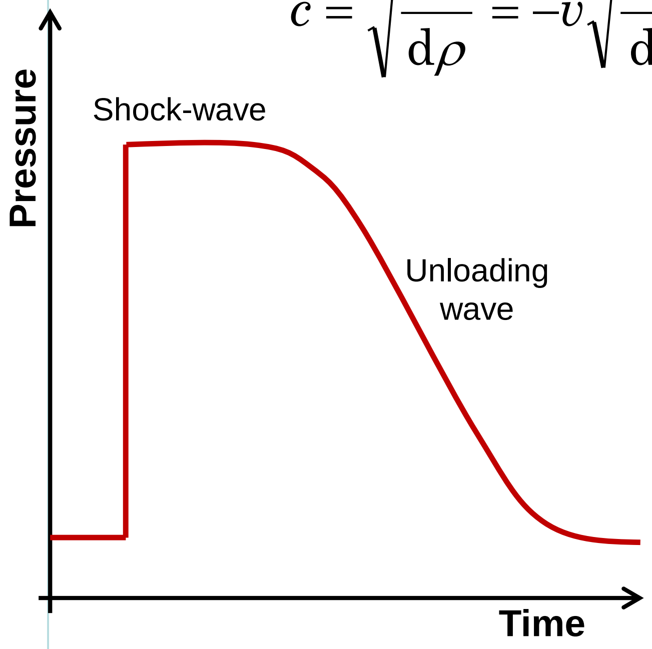


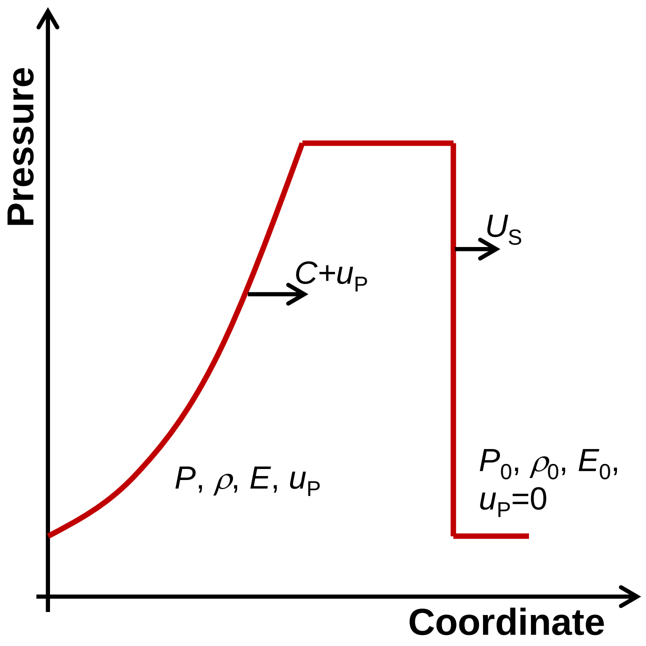
Propagating surface continuous in displacements, but discontinuous in pressure, density, velocity, …



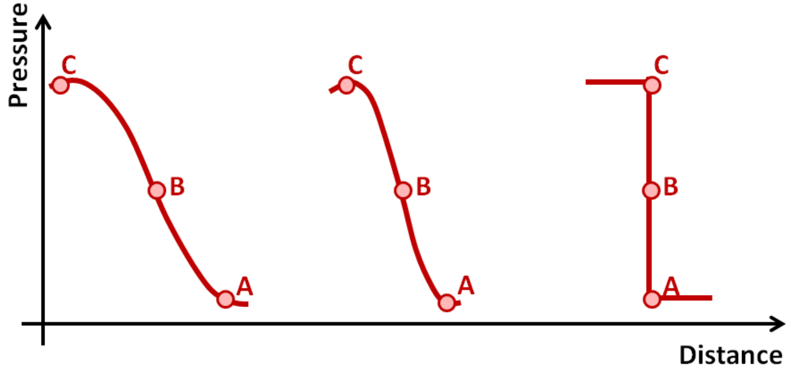
No signals move ahead the shock front and any disturbance can catch the shock front from behind: the shock front is supersonic relative to the undisturbed material and subsonic relative to the shocked material

$$c=\sqrt{\frac{\mathrm{d}P}{\mathrm{d}\rho}}=-v\sqrt{\frac{\mathrm{d}P}{\mathrm{d}v}}$$





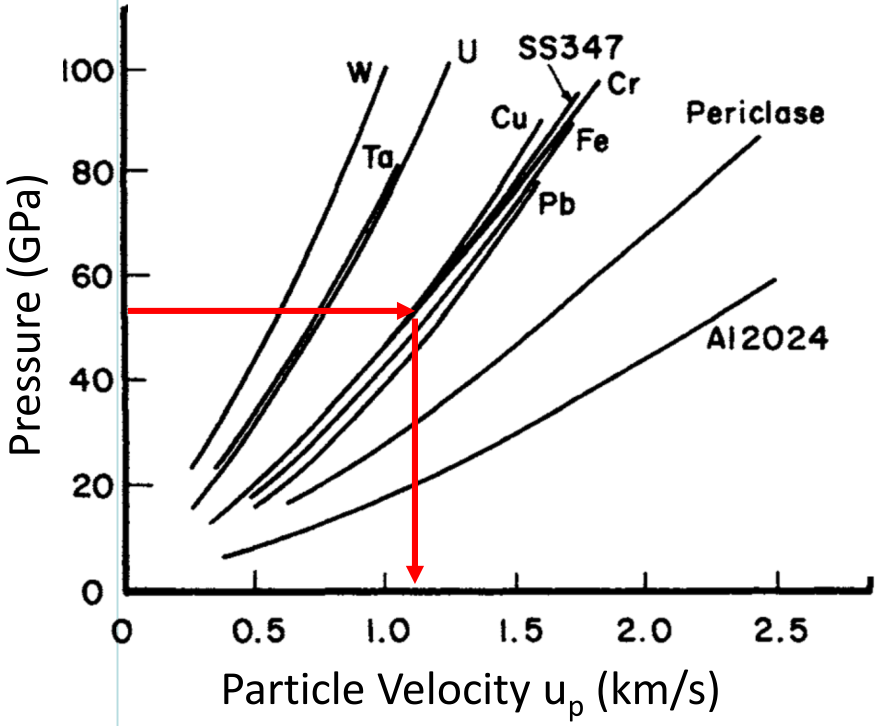
A shock front is spontaneously generated starting from a quite smooth signal

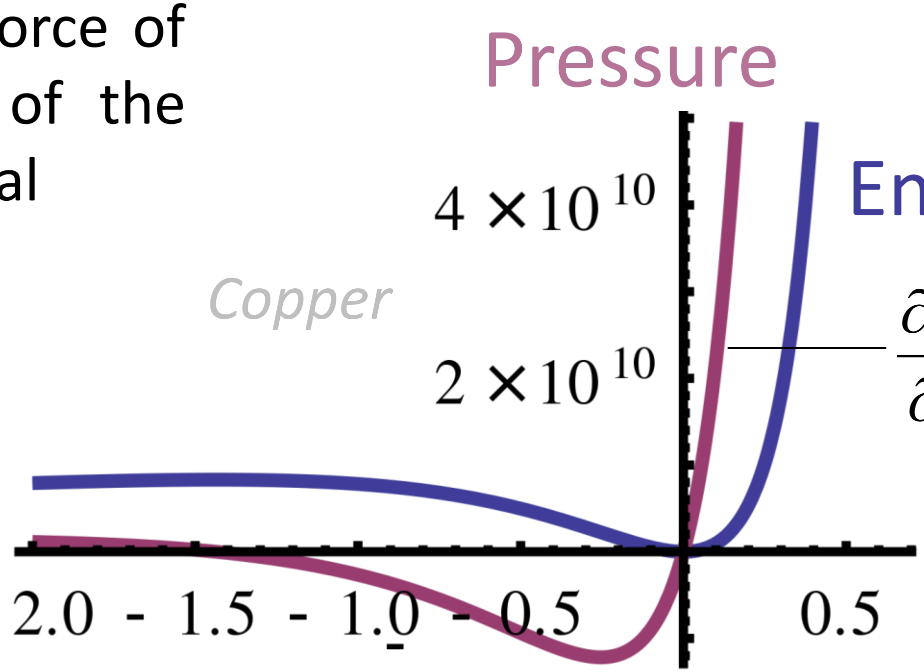


The unloading wave (rarefaction wave), generated from the rear, travels faster than the shock front and can reach the shock front reducing it intensity

Shock-waves (I)

The EOS depends from the force of interaction between atoms of the lattice structure of the material



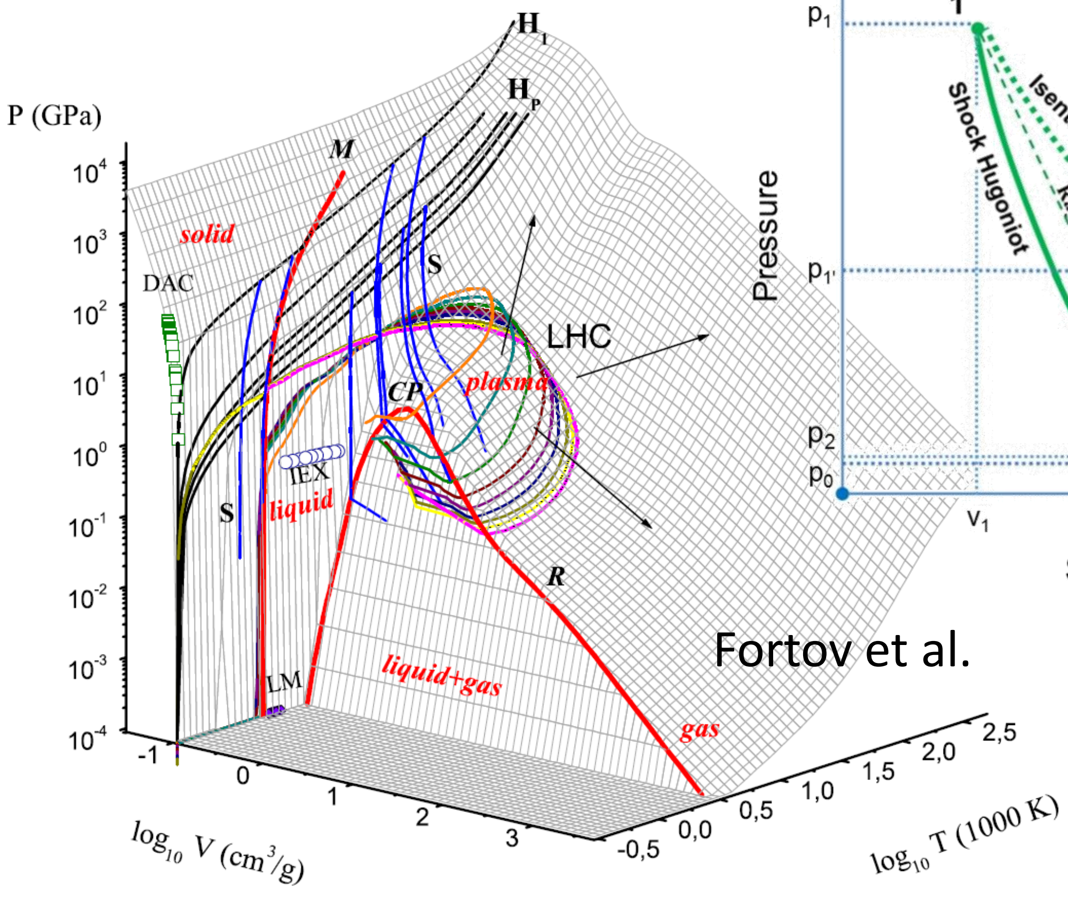


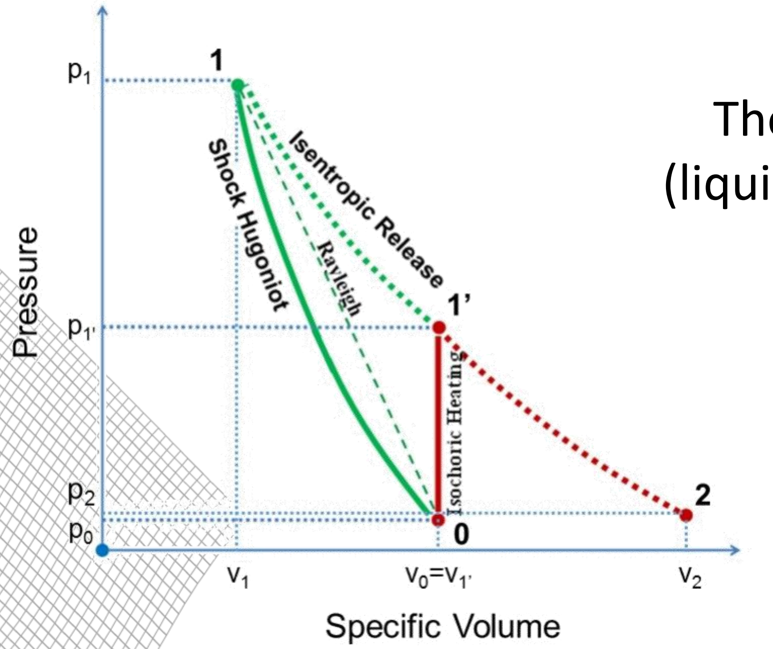
$$\frac{\partial P}{\partial v} < 0 \qquad \frac{\partial^2 P}{\partial v^2} > 0$$

$$1 - \frac{\rho_0}{\rho} = 1 - \frac{v}{v_0}$$

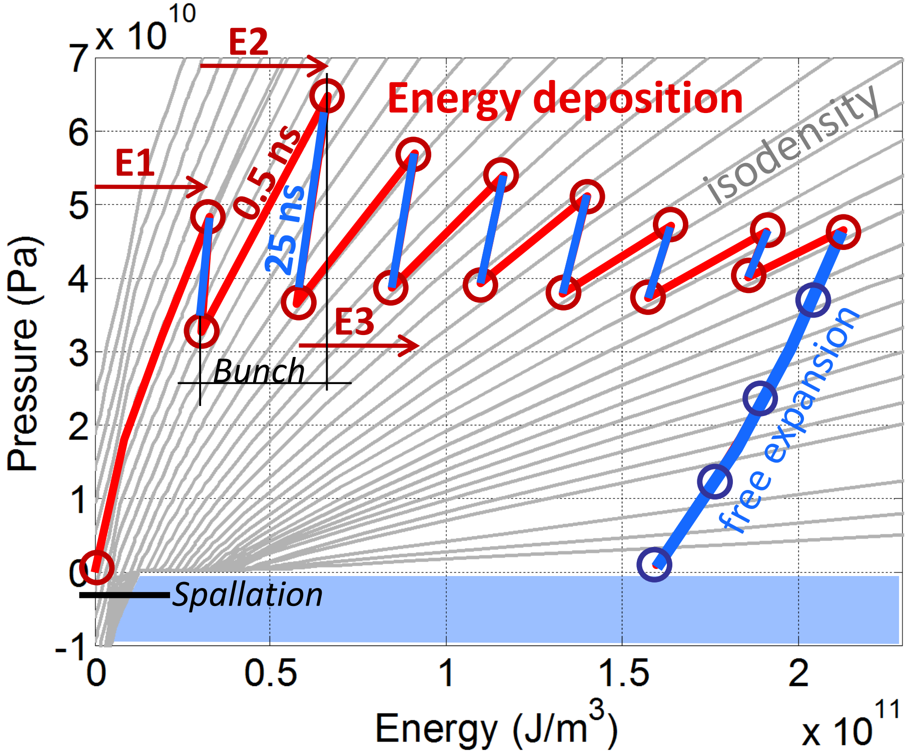
Such an EOS is defined as stiffening: the pressure grows faster than linearly with the volume. This implies that the wave velocity *c* increases if the pressure increases.

The EOS must include solid and fluid phases (liquid, gas, vapour and plasma) and describes the relation between pressure, density, temperature and energy





Fortov et al.



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

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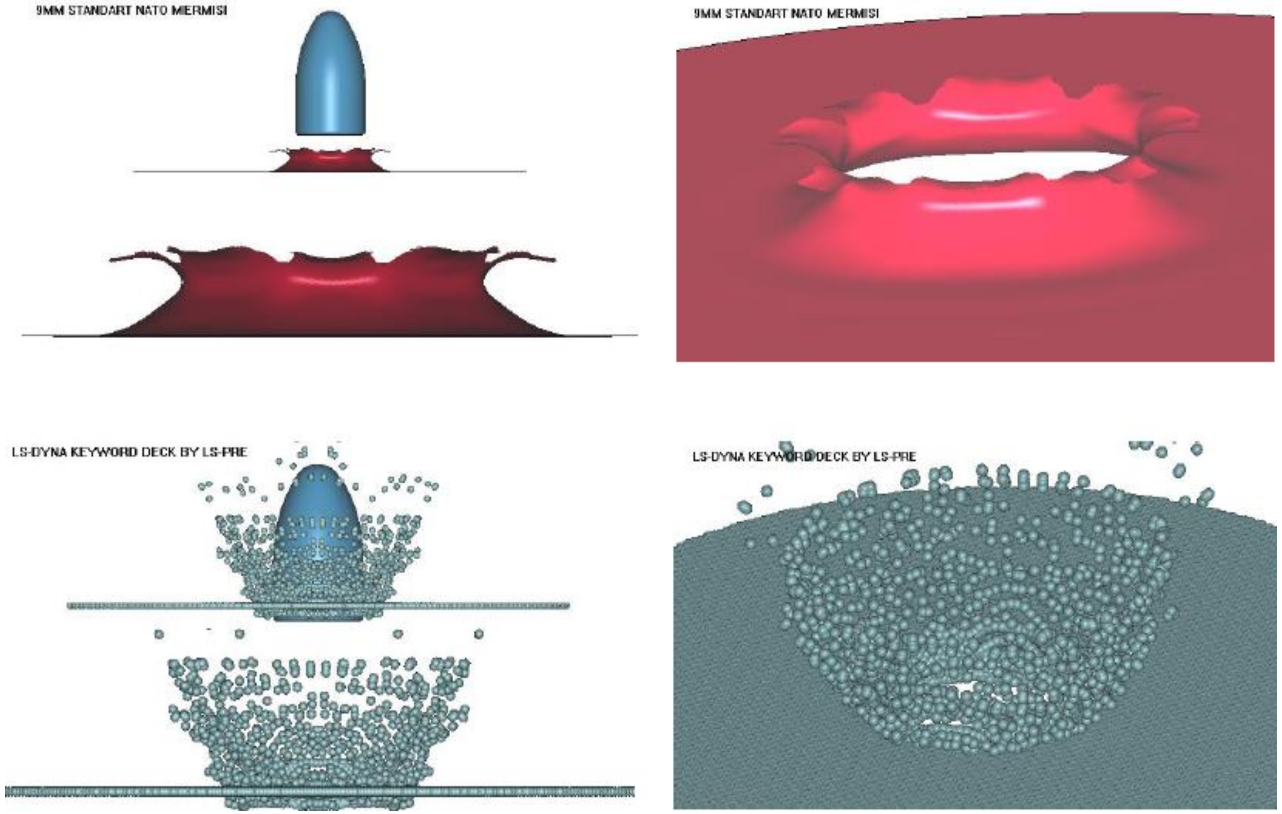
Shock-waves (III)

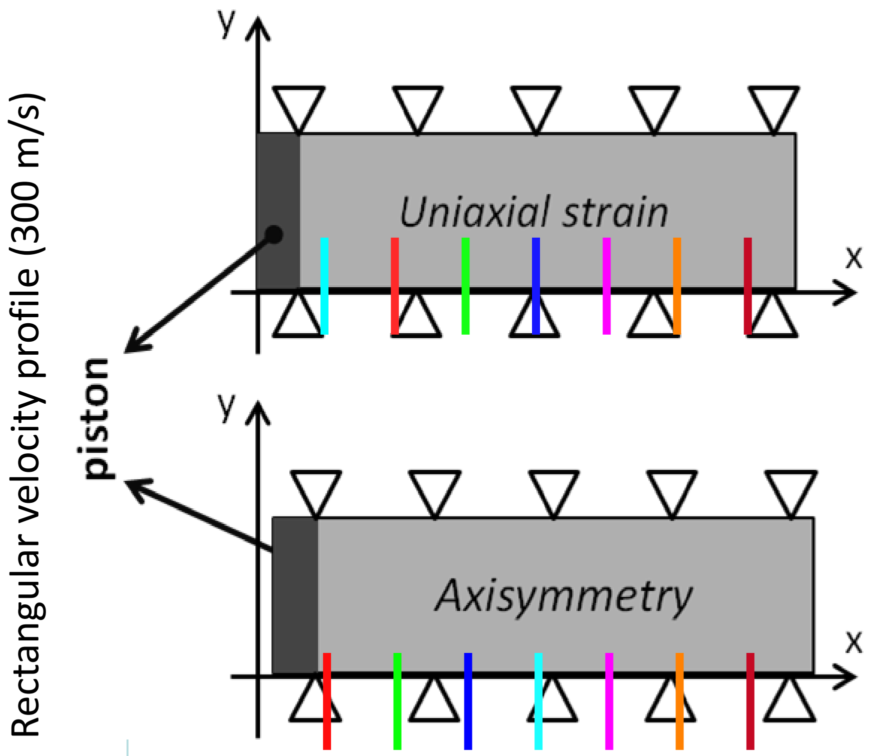
Hydrocodes (LS-Dyna, Autodyn)

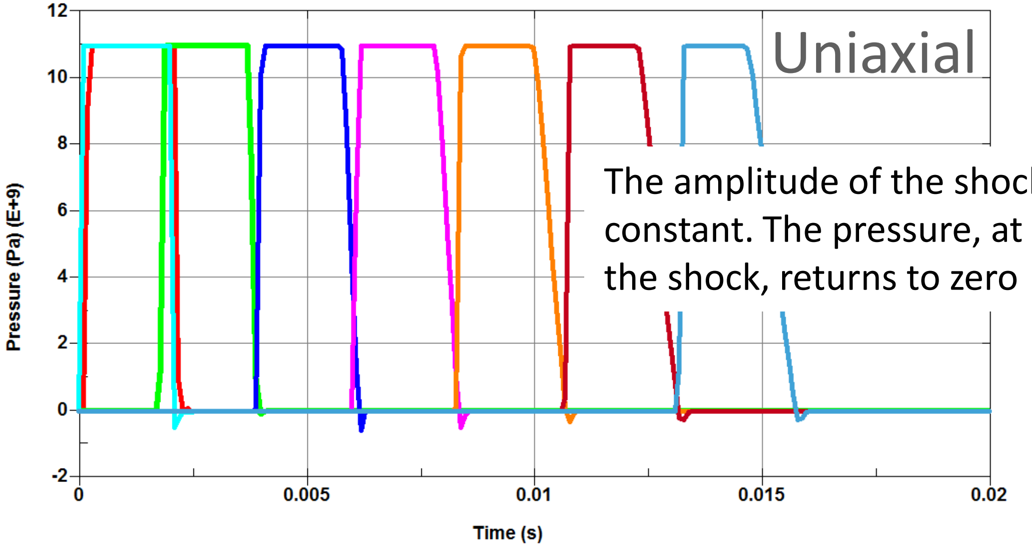
Hydrocodes are **nonlinear tools**, initially developed for high speed mechanical impacts, where solids can be approximated as **fluids (deviatoric stresses neglected)**.
Simulations can be performed using different meshing schemes, **Lagrangian** and **SPH as example**.

Lagrangian mesh moves and distorts with the material it models as a result of forces from neighbouring elements.
Most efficient solution for structures.
Very slow when element incurs in large distorsion.

SPH (**Smooth Particle Hydrodynamic**): mesh-free method, with single node elements, ideally suited for problems with extensive material damage and separation.
Possibility to study crack propagation inside a body and motion of ejected fragments/liquid droplets.
SPH elements must be generally very small to accurately model the material.
Compromise to be found between accuracy and calculation time.

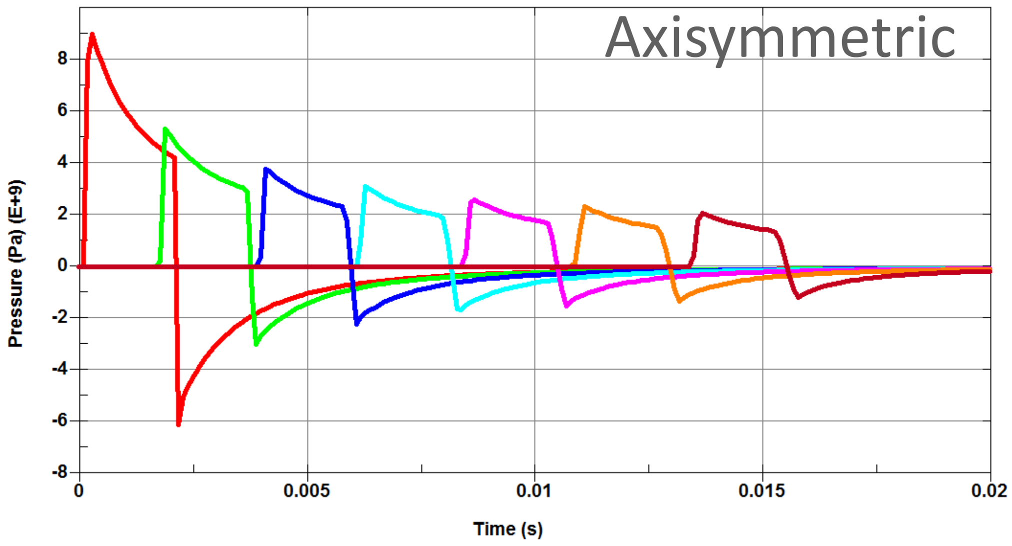






The amplitude of the shock remains constant. The pressure, at the end of the shock, returns to zero

Strong reduction in the shock amplitude due to the fact that the elements are situated at increasing radii. At the end of the shock the pressure reaches negative values: if no limits are imposed, the material can reach high values of negative pressure



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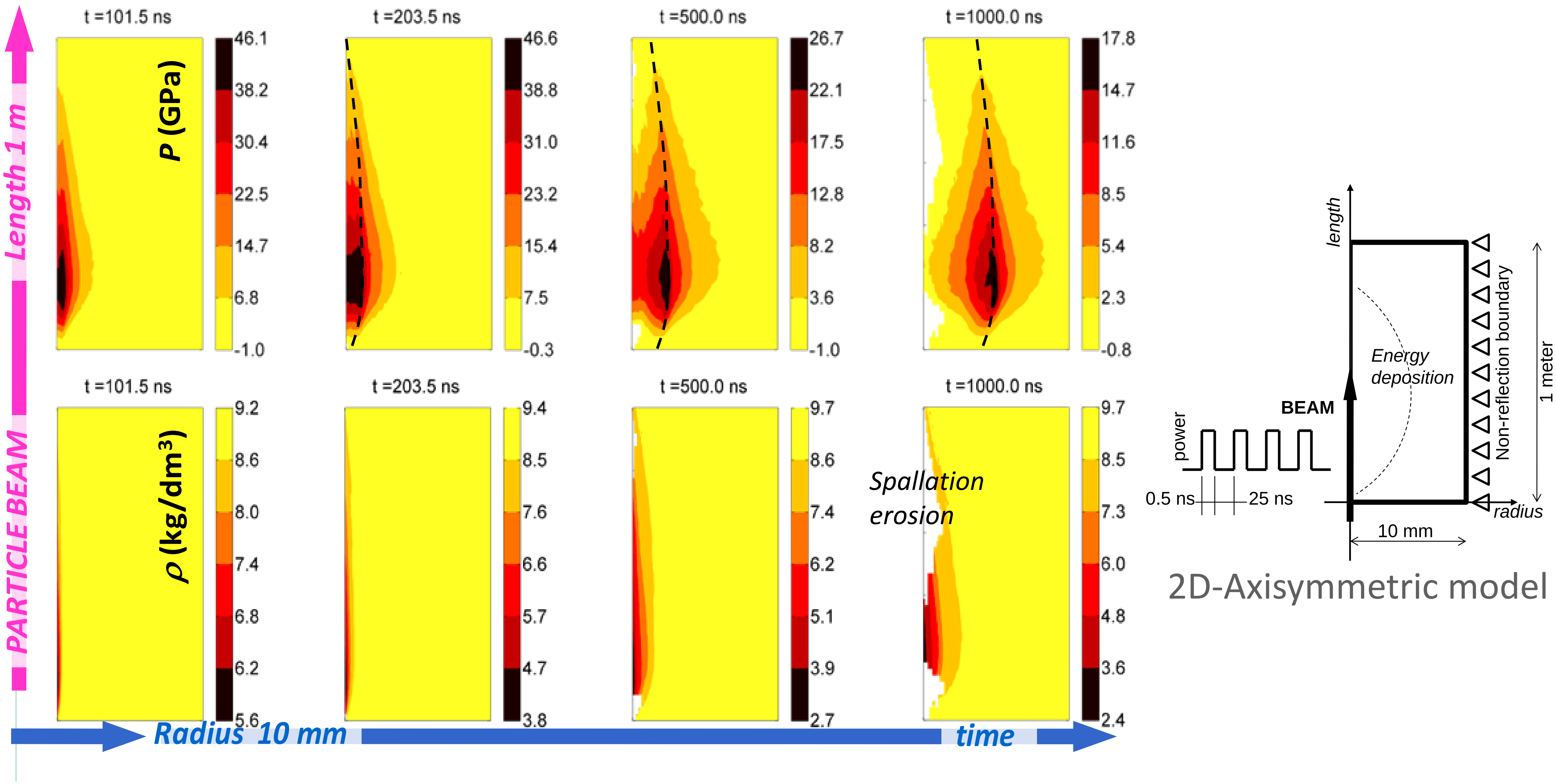
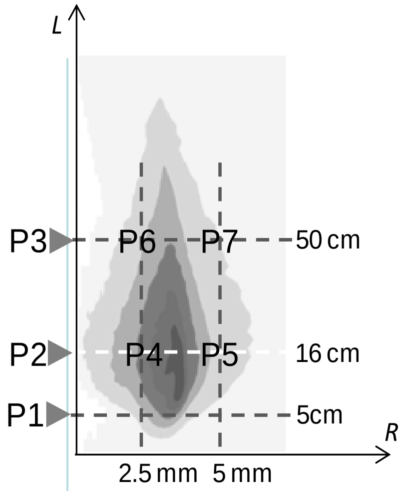
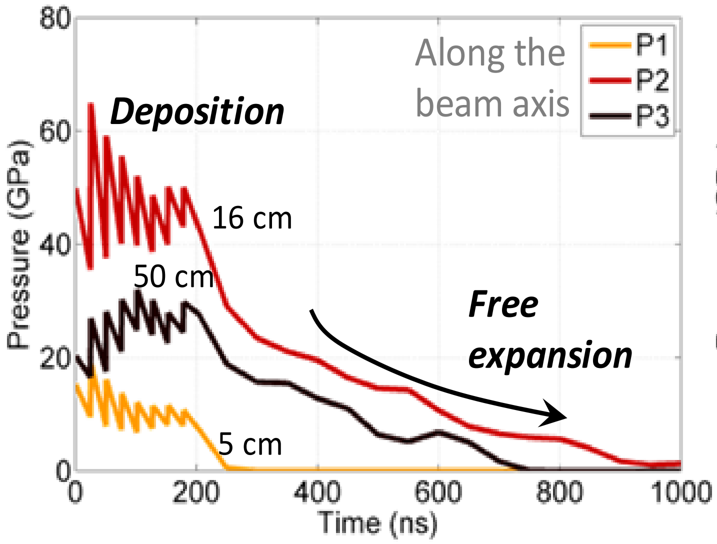
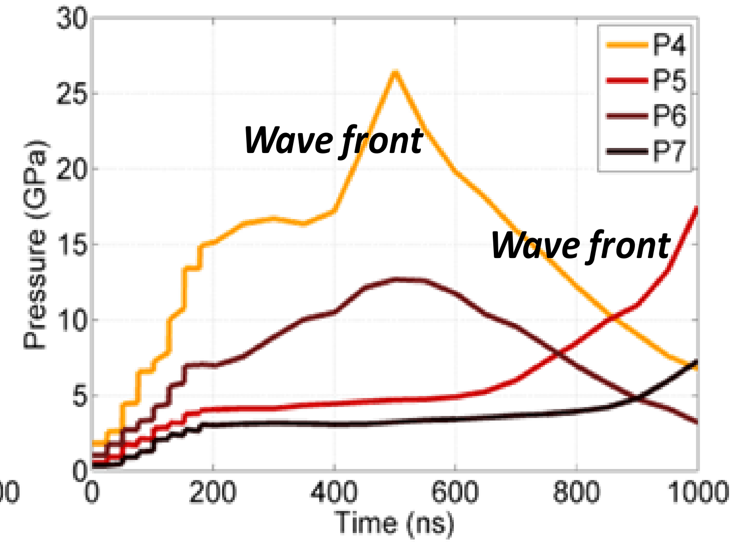
Uniaxial VS Cylindrical



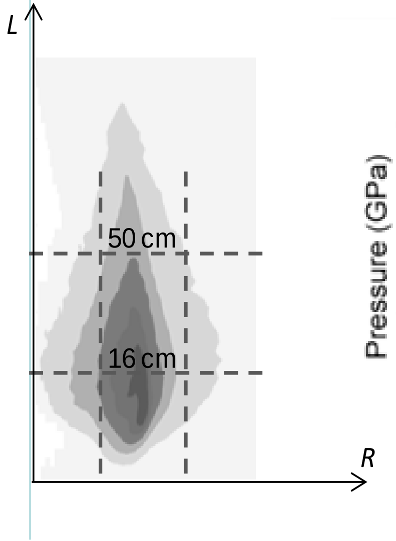
Example: copper bar

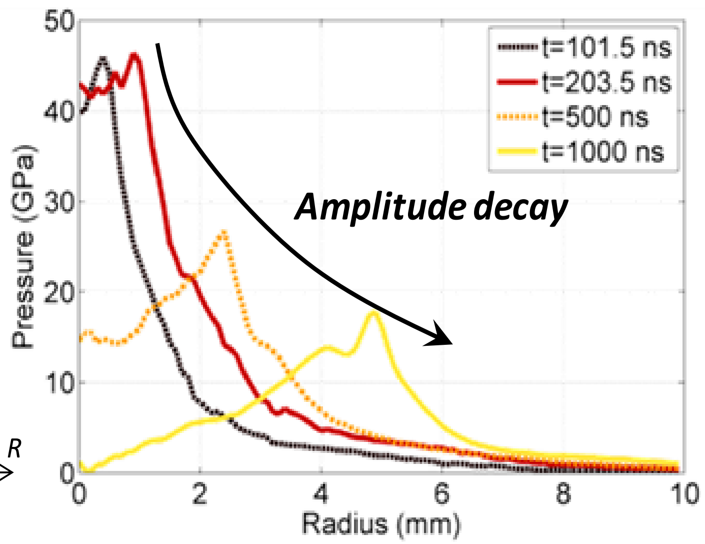


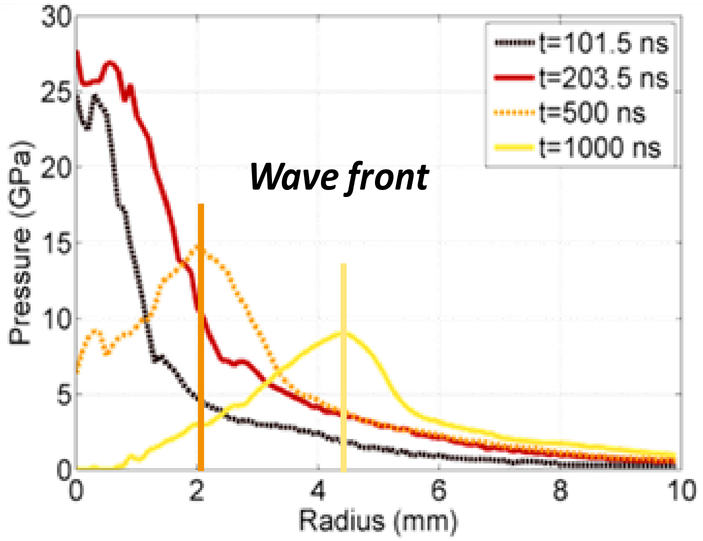




For elements situated along the beam axis (high deposition) the maximum pressure increases is during the deposition phase, which is followed by free expansion.



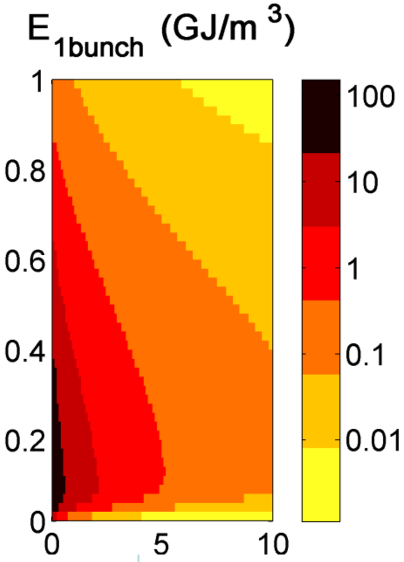


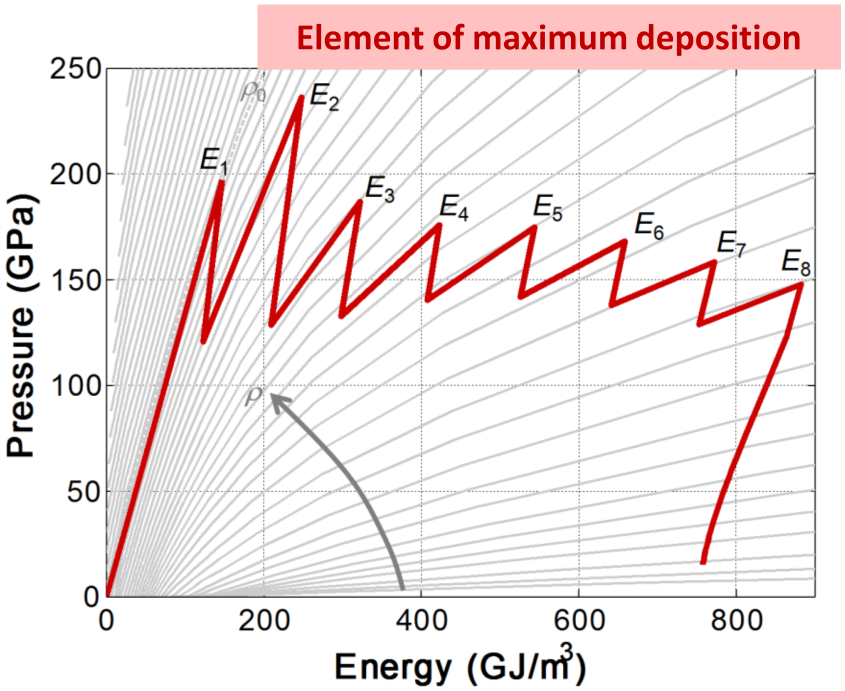


For elements situated far from the beam axis, the maximum pressure increase is reached at the arrival of the shock front and it is followed by the unloading phase.

Example: copper bar (II)

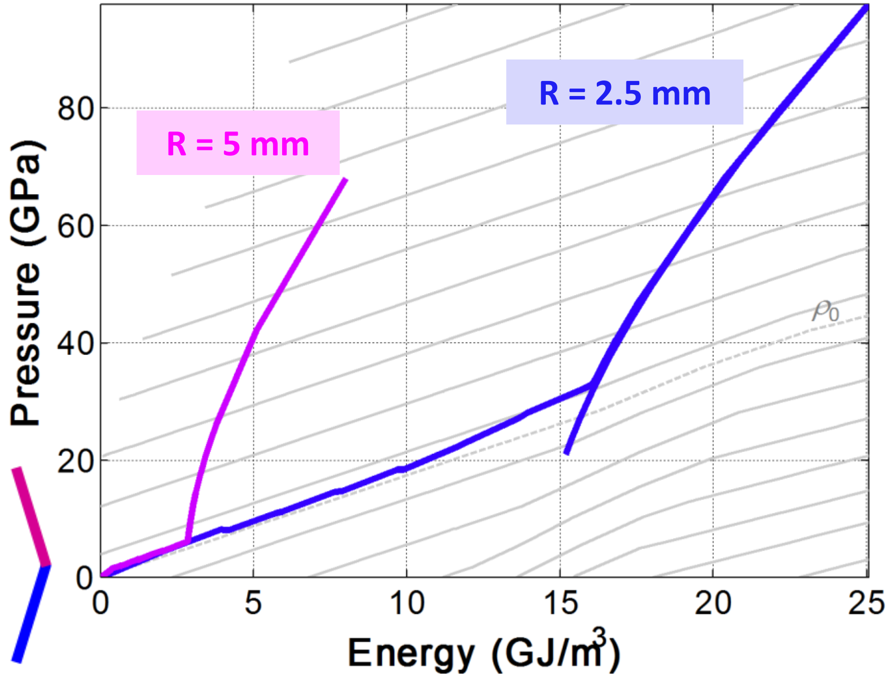
Example: tungsten bar

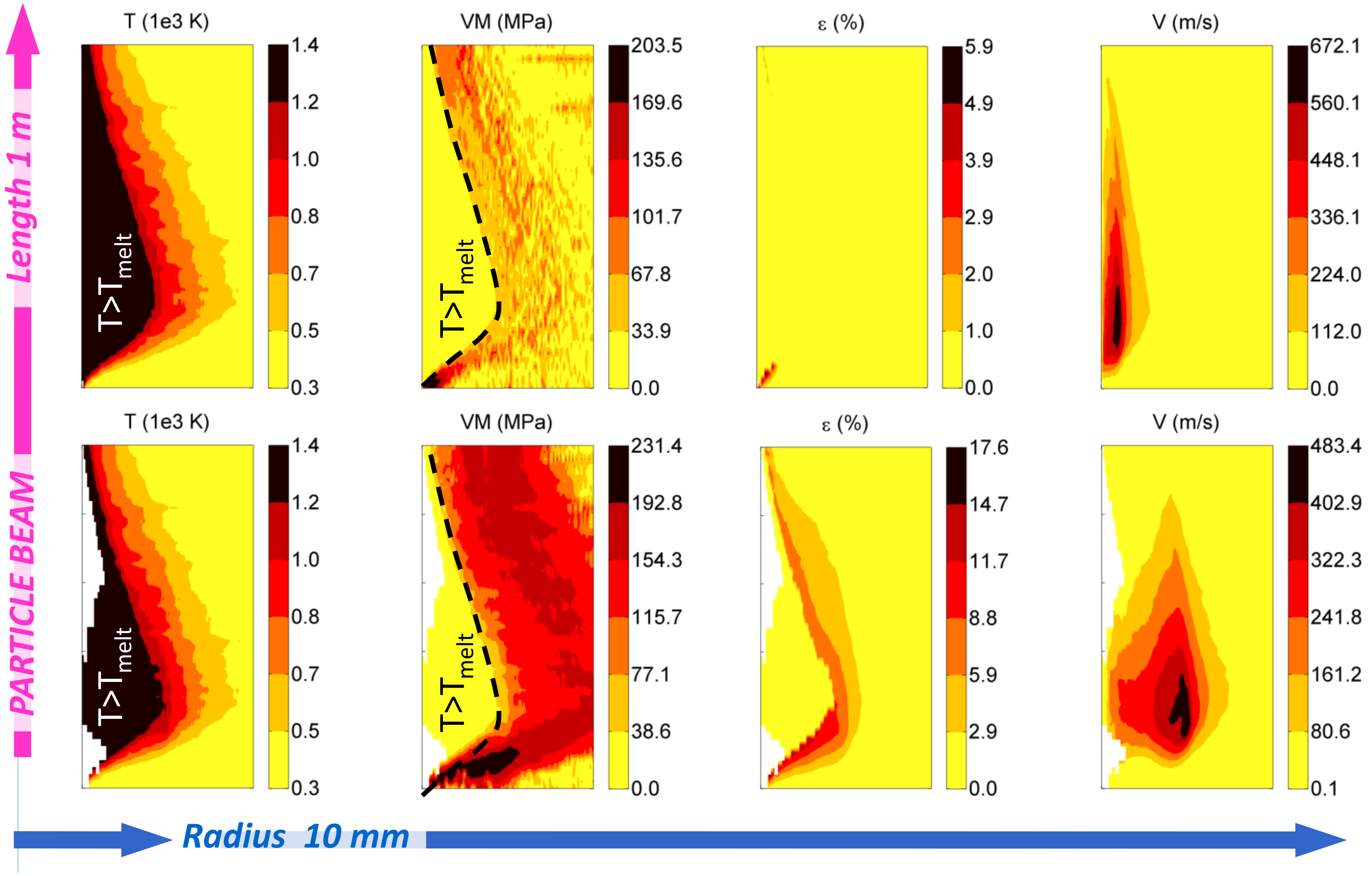




Isochoric deposition: the deposition time is higher than the thermodynamic time of the system

The elements remains quite undisturbed until the shock front reach them producing a significant compression





The high pressure reached in the portion of the component with high level of deposited energy produces heavy plastic deformation beyond the shock front in a very short time (plastic strain-rate in the order of 10^4 s^{-1})

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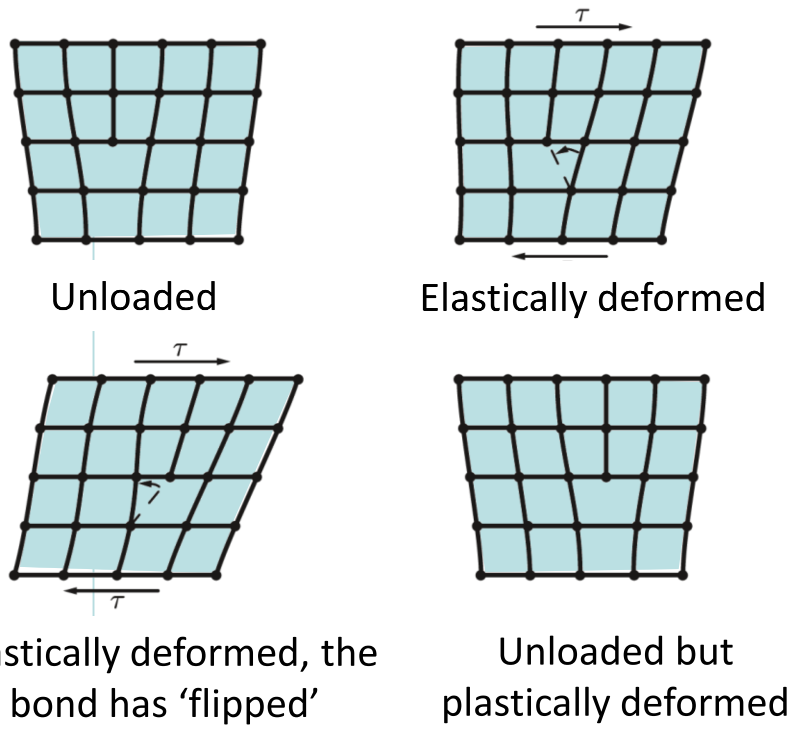
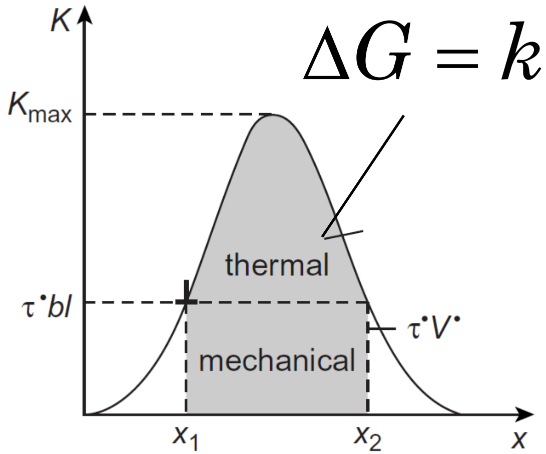
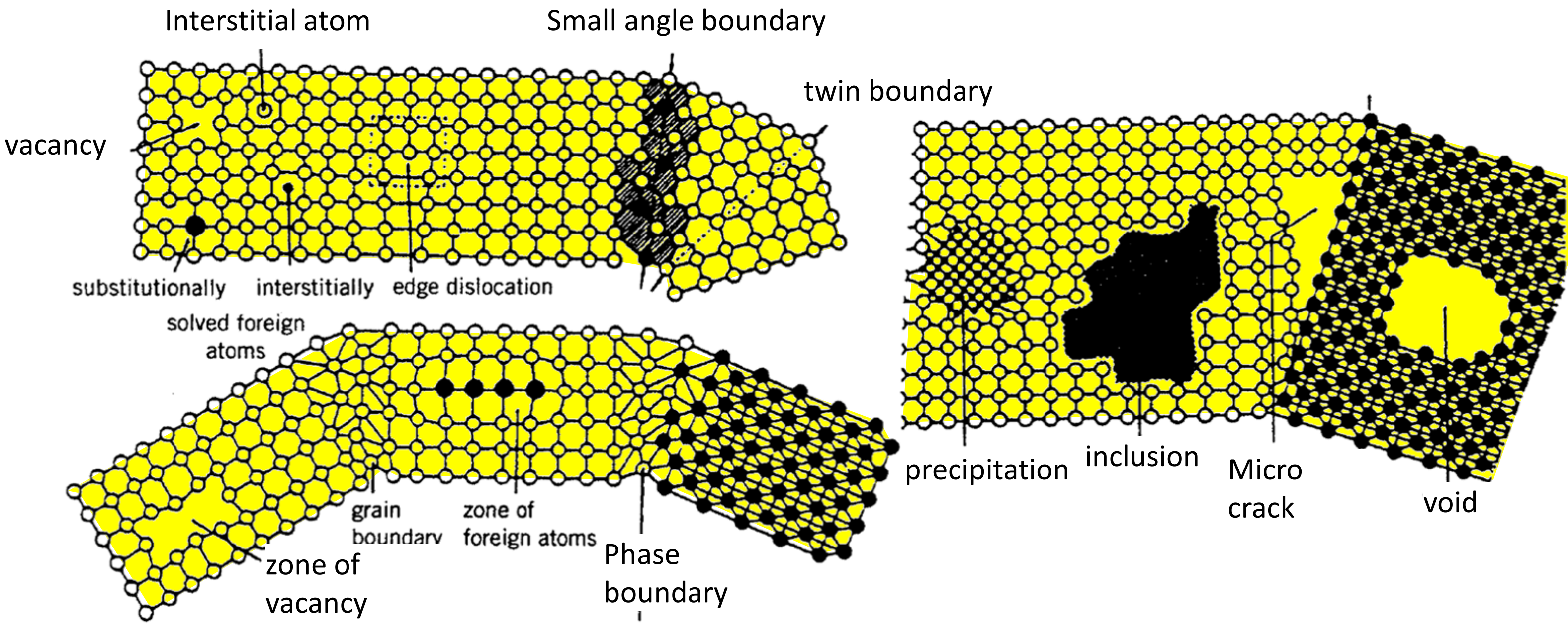
Why high strain-rate?





$$\Delta G = kT \ln \frac{\dot{\varepsilon}_0}{\dot{\varepsilon}}$$

Temperature helps the dislocation to overcome the obstacle, while strain-rate has the opposite effect

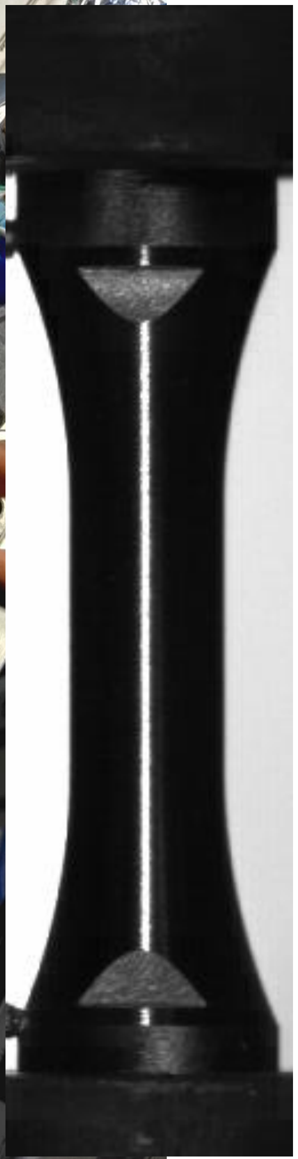


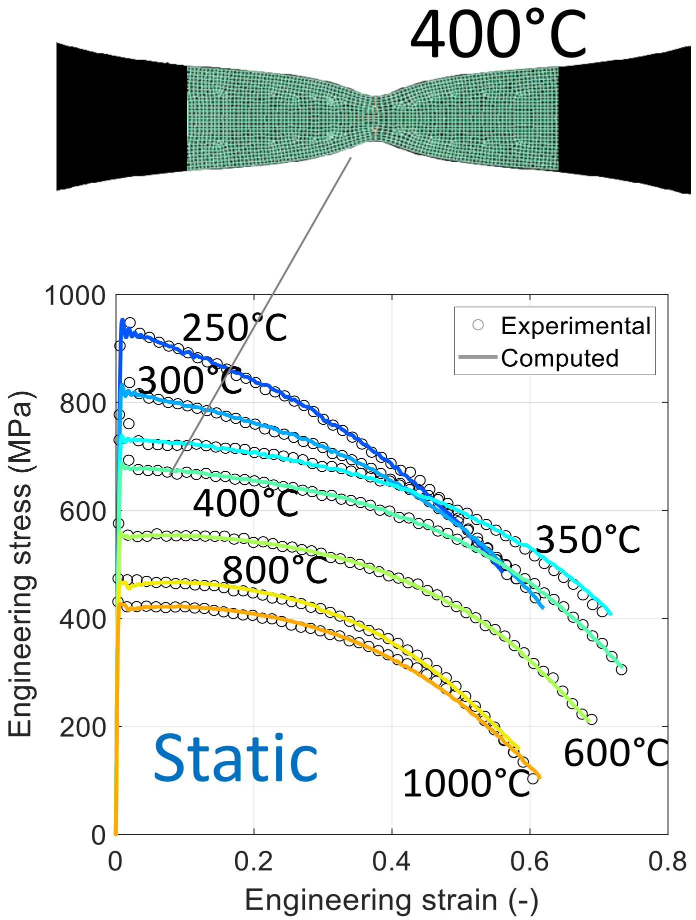
Plastic deformation is due to dislocations movement. A dislocation continuosly encounter obstacles as it moves through the lattice. These obstacles make the movement of dislocation more difficult.

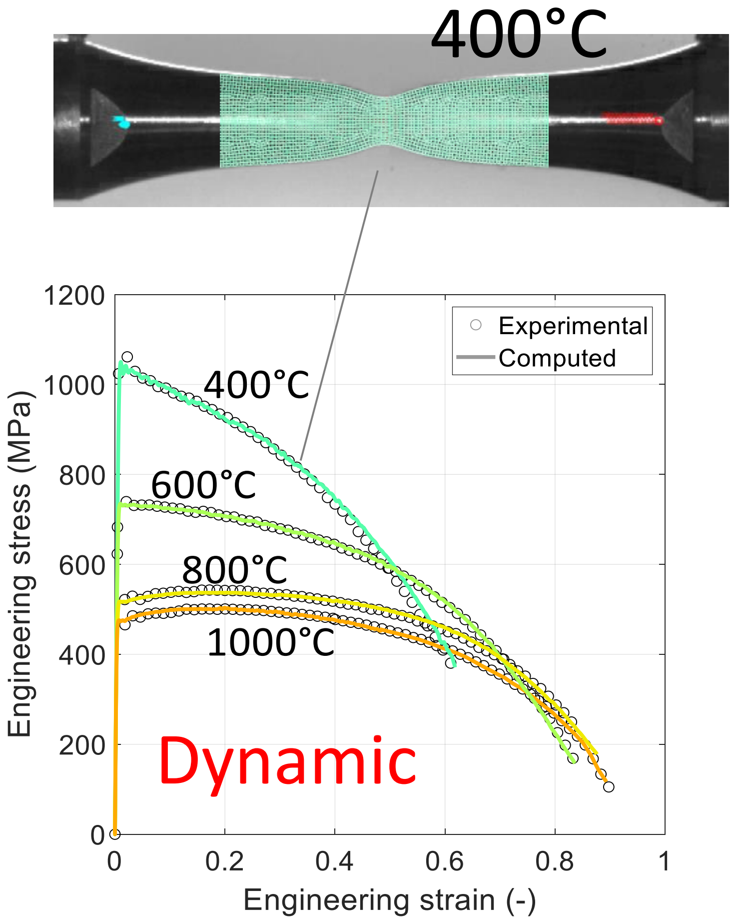
Strain-rate & temperature effects (I)

Pure tungsten sample tested in tension in 500 μs at 600°C

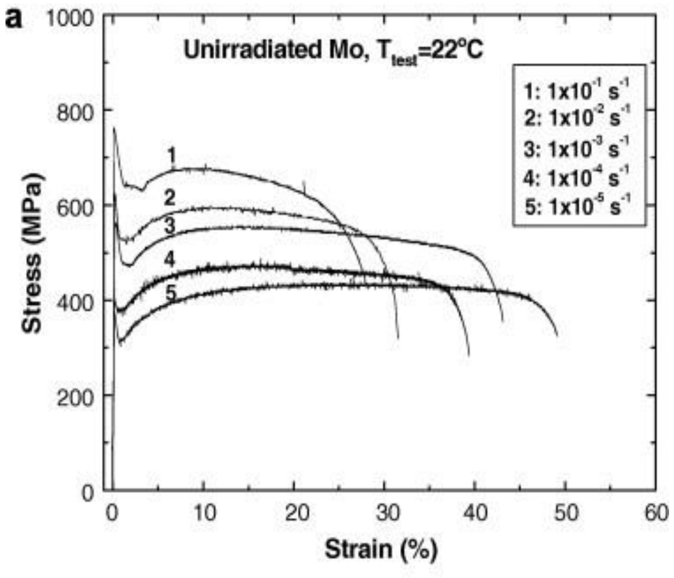
Pure tungsten

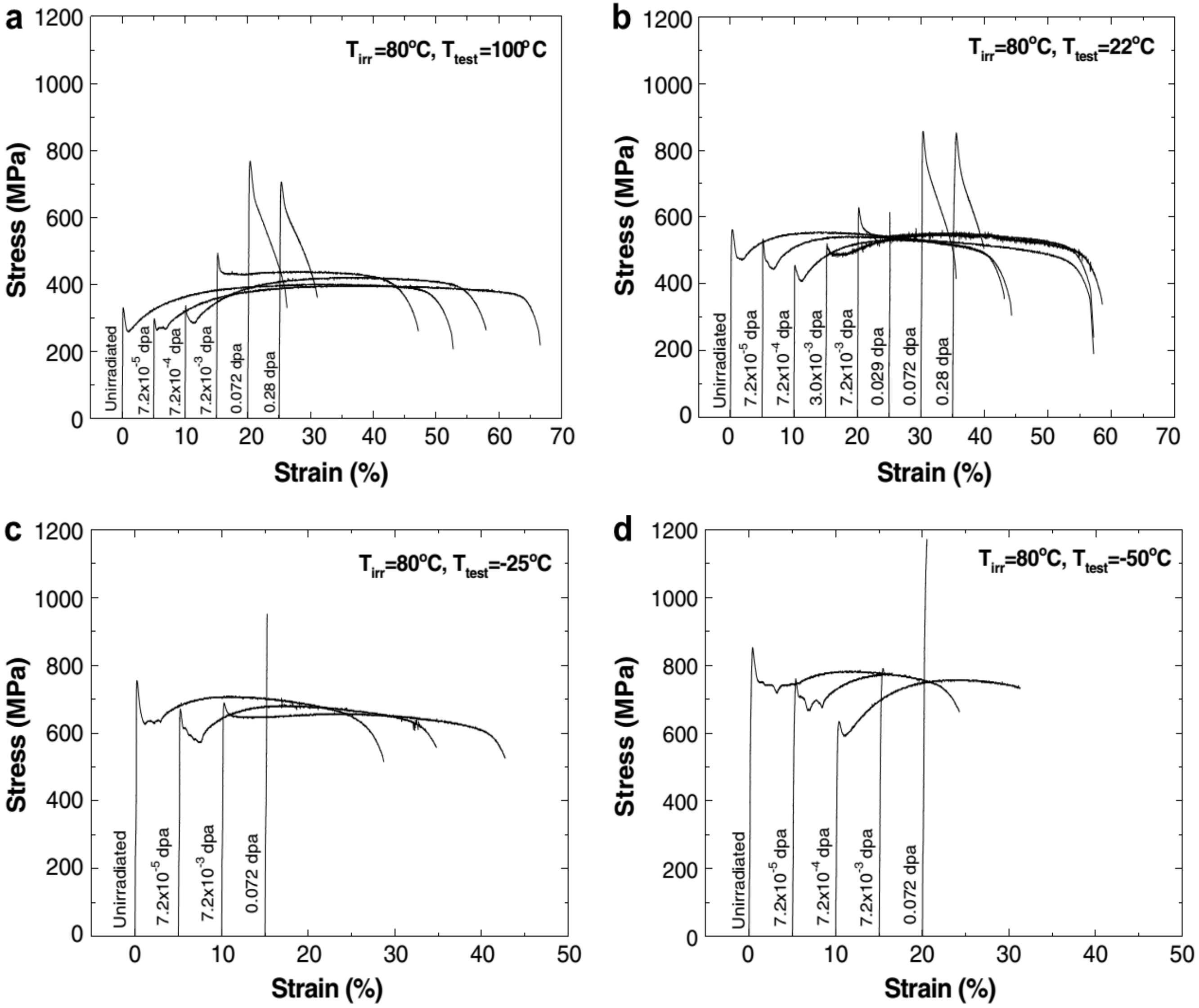






Strain-rate & temperature effects (II)





Low temperature neutron irradiation effects on microstructure and tensile properties of molybdenum

Meimei Li, M. Eldrup, T.S. Byun, N. Hashimoto, L.L. Snead, S.J. Zinkle

Irradiation

THE ENERGY DEPOSITION IS DENSITY DEPENDENT

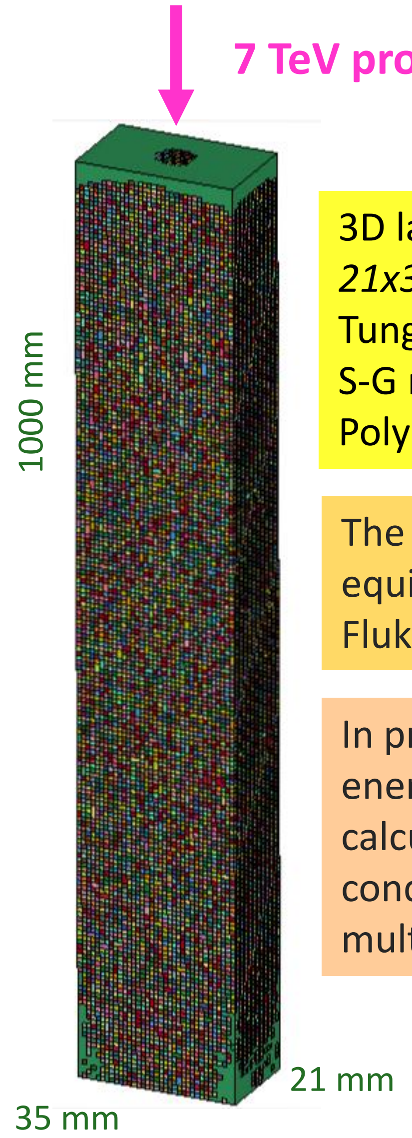
At the beginning:

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

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)

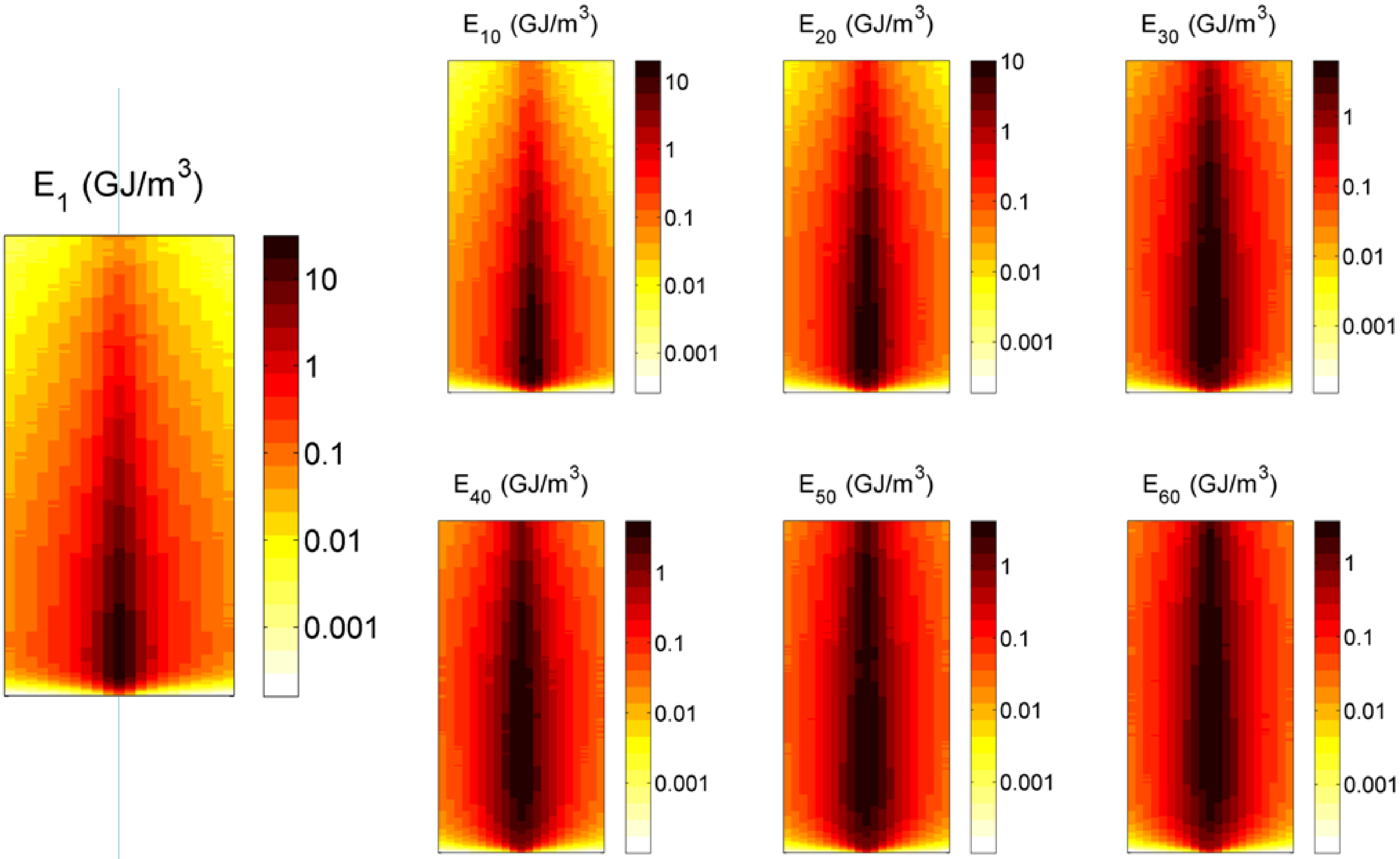


3D lagrangian geometry
21x35x200 elements
Tungsten component
S-G model
Polynomial EOS

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

LS-DYNA/FLUKA (II)

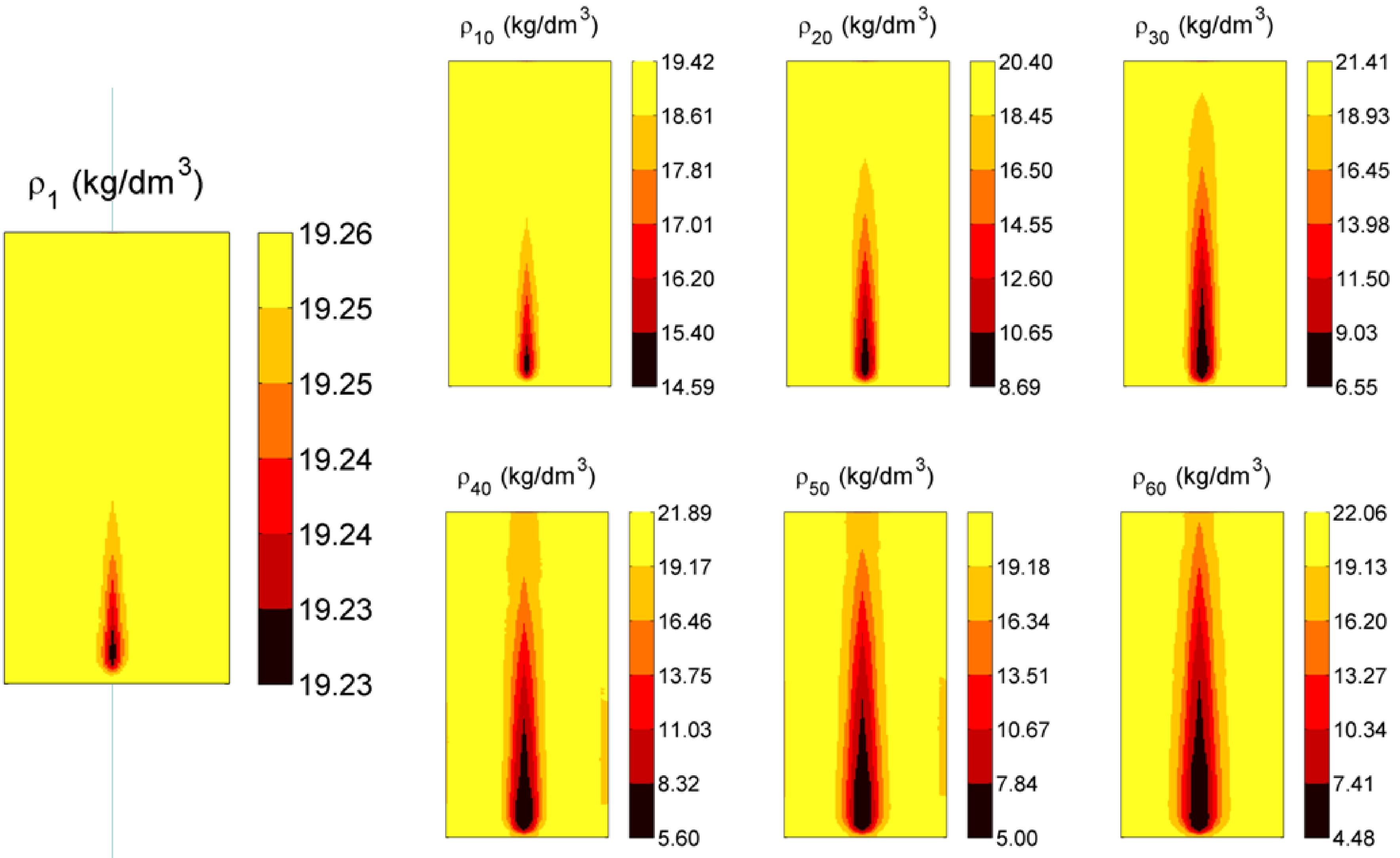


The energy distribution changes both in values and shape

The material, in which a great amount of energy is deposited, is subjected to a significant density reduction becoming more transparent to the next proton bunch

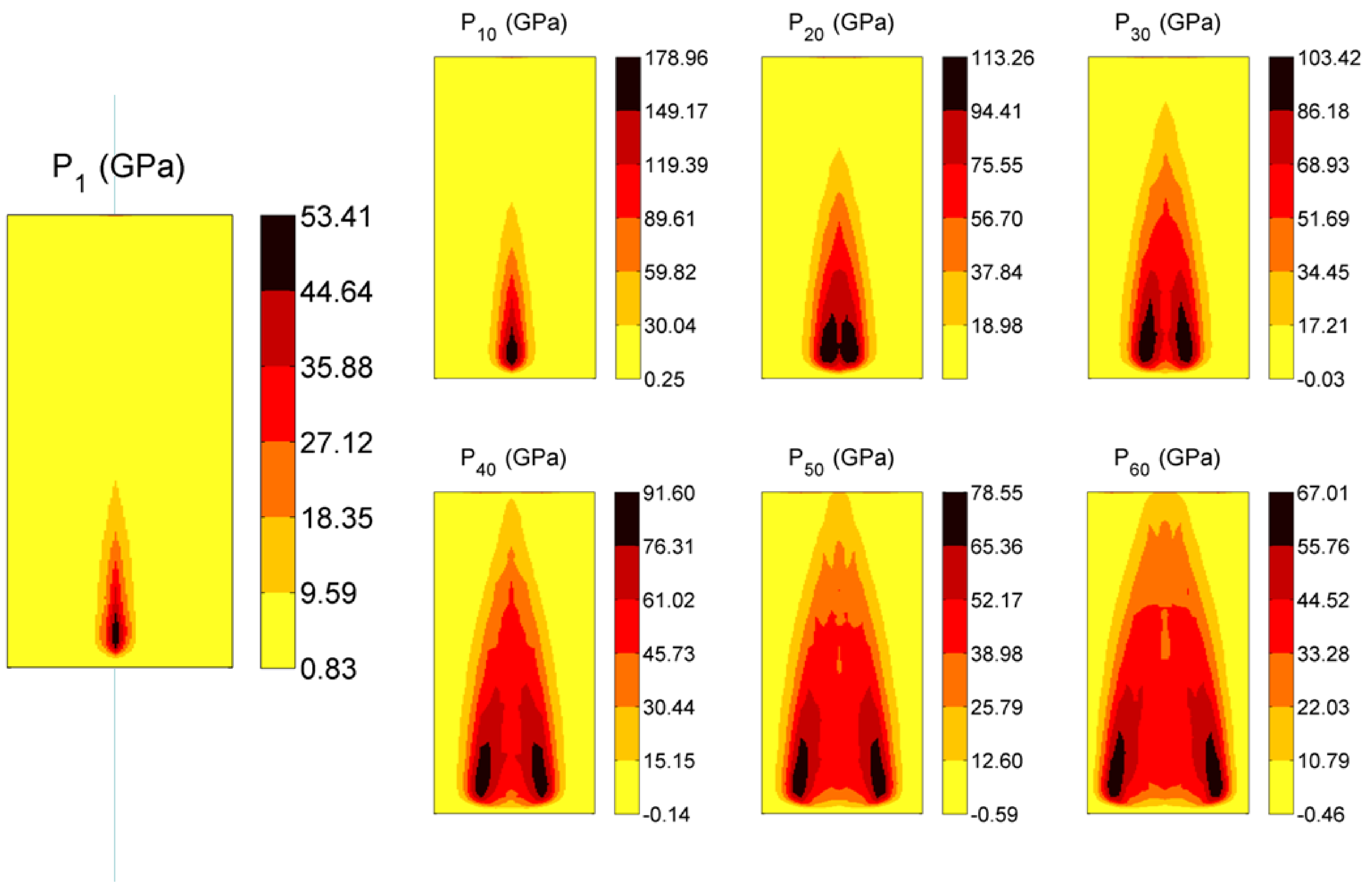
***Tunnelling* effect: the proton beam penetrates more in depth in the material in the axial direction and the energy is more diluted over the target**

LS-DYNA/FLUKA (III)



The density modification involves higher longitudinal coordinates increasing the number of bunches

After 60 bunches the total length of the target experiences a reduction in density in the zone around the beam axis

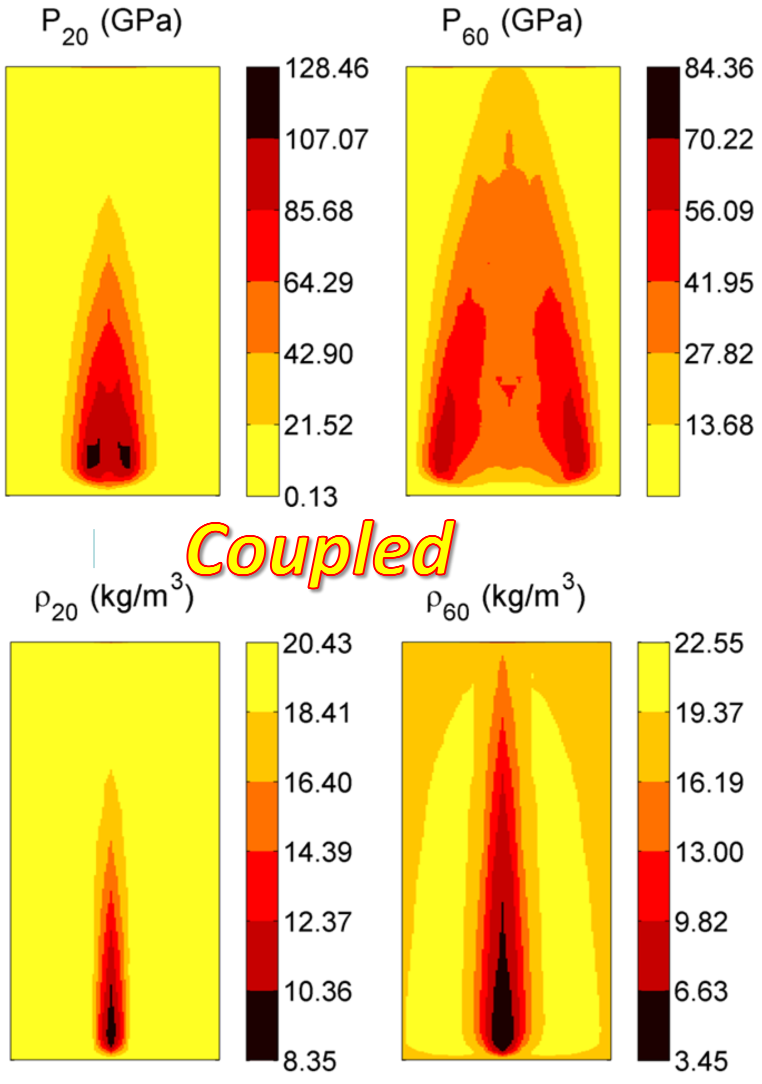


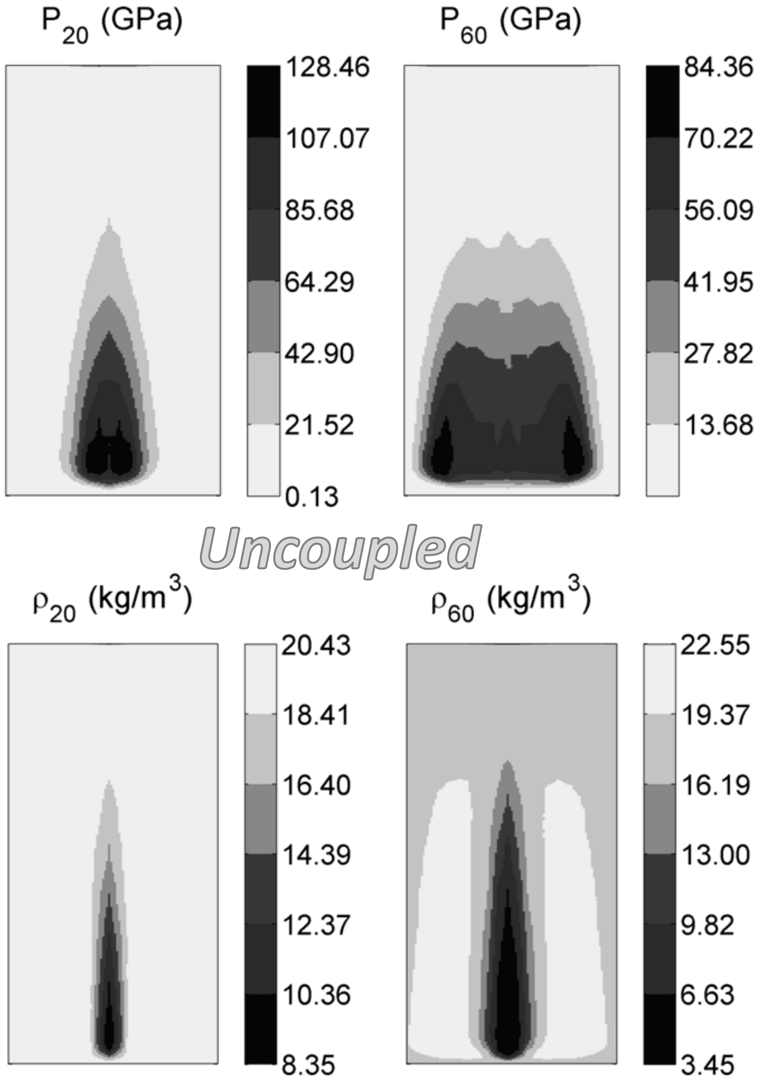
The maximum of pressure remains more or less in the same longitudinal

The pressure wave starts to travel in the *x* and *y* directions (the pressure wave is cylindrical)

The pressure increment, consequent to the next bunches, is reduced in the zone, in which the first bunch deposited a great amount of energy. On the other hand it should increase in the part of the target, in which there is an increment in density

LS-DYNA/FLUKA (IV)





The pressure decreases in the region where there is the maximum deposition at the beginning while increases in the longitudinal direction due to the more in depth penetration of the beam.

A greater reduction in density can be observed along the beam axis direction.

The state in term of pressure is completely defined on the EOS knowing the density and the energy. Considering the same density, the pressure is higher where the energy is higher. The differences between the two cases become more relevant increasing the number of bunches.

LS-DYNA/FLUKA: coupled vs. uncoupled

- ✓ When a particle beam interacts with a solid target the particles deposit their energy in the material.
- ✓ This provokes a dynamic response of the structure entailing thermal stress waves and thermally induced vibrations or even the failure of the component.
- ✓ The pressure and temperature increase and the materials could reach its melting temperature or vaporize, depending on the impact conditions.
- ✓ The high level of pressure reached produces the generation of strong cylindrical shockwaves which travel through the material,
- ✓ The part of the material, which remains solid, is characterized by high values of plastic strain, strain-rate and temperature.
- ✓ From these considerations it is clear what was the complexity of the problem, which needed of a multi-physics approach to be completely examined: hydrocodes are the numerical tools for the analysis of such scenarios

Summary

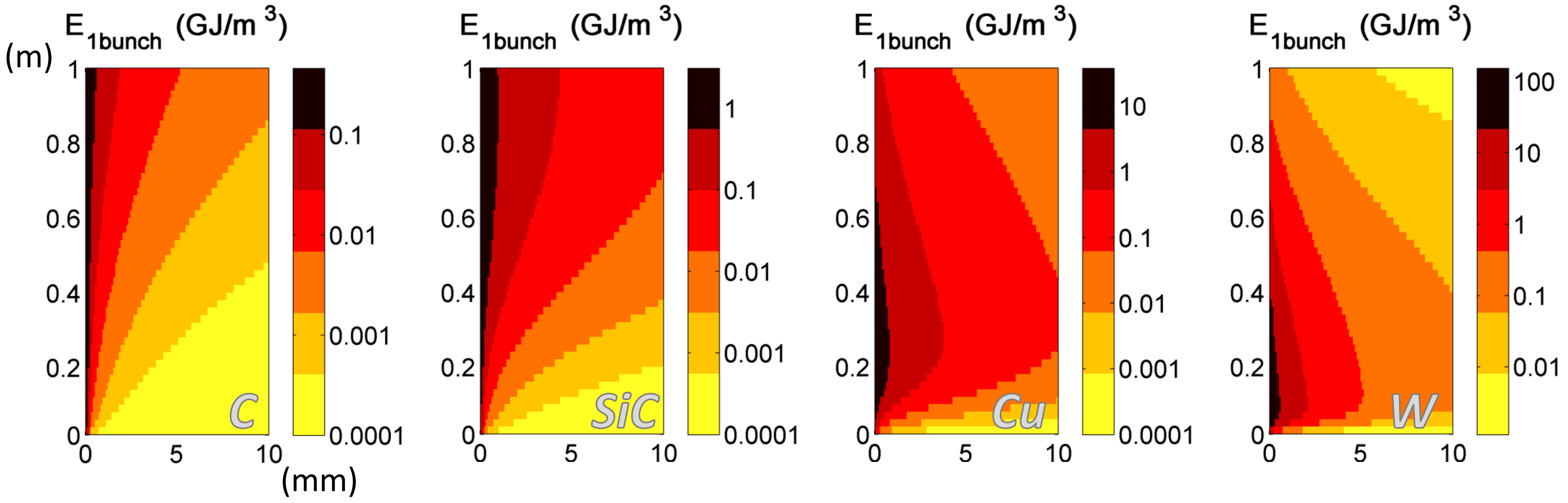
POLITECNICO DI TORINO

24th DYMAT Technical Meeting

Shock-wave and high strain-rate phenomena in high energy particle beam impacts

Thank you for your attention

The evaluation of thermal loads on the impacted material is performed by the FLUKA Team at CERN, using the statistical code, called FLUKA, based on the Monte-Carlo method.

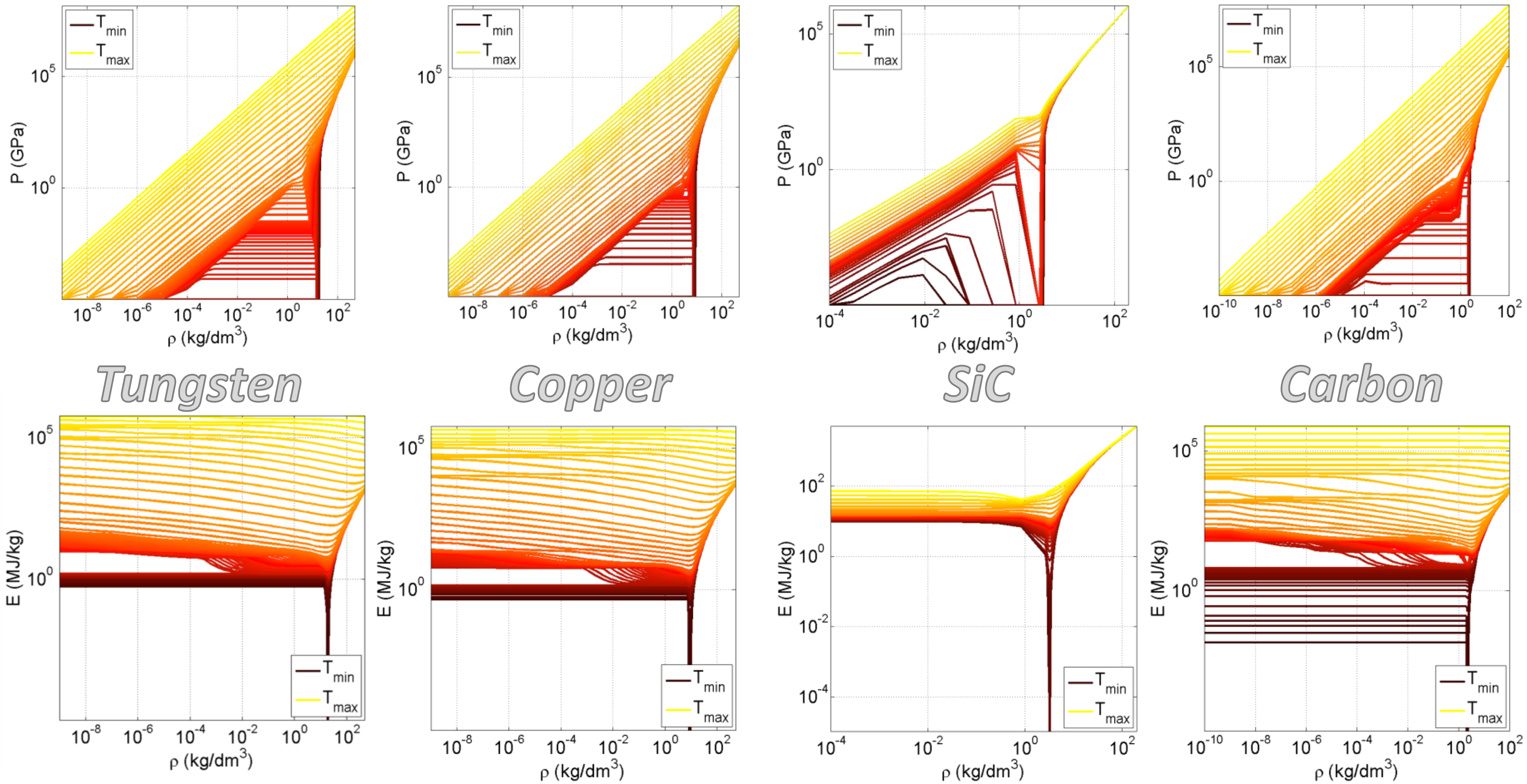


- The calculation takes into account a large number of primaries and then the results are normalized to one ideal proton.
- Hypothesis of isolated bunches: the reactions generated by the first bunch are assumed to be finished before the arrival of the second bunch and so on.
- The probability of the interaction between particles and materials is strongly density dependent: the higher the material atomic number, the higher its energy absorption.

SESAME Library

Indipendent variables → ρ, T; Dependent variables → P, E

Multi-phase & phase transitions



Equation Of State