Advanced Numerical Methods for Simulation of Shock-waves Induced by High Energy Particle Beams

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4TH HIGH POWER TARGETRY WORKSHOP
MALMÖ, 4 MAY 2011

- Introduction
  - Thermally Induced Dynamics
  - Simulation Tools
  - Material Modelling & Algorithms of Solution
- Engineering Case Study:
  - Beam Induced Damage on LHC Tungsten Collimator
- Experimental Validation:
  - CERN HiRadMat Facility
- Conclusions

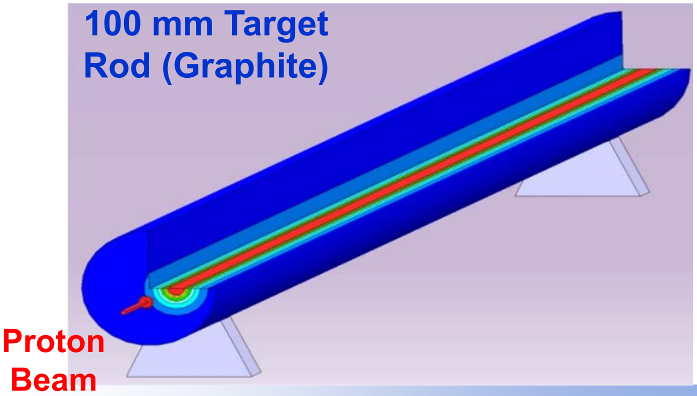
Outline

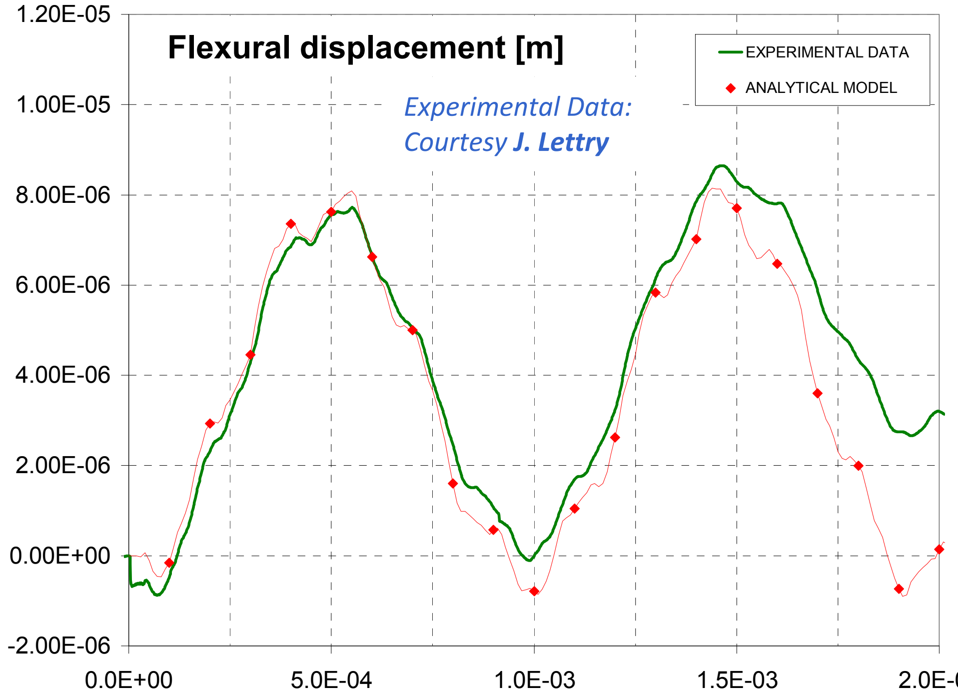
- Rapid interactions of particle beams with solids induce **Dynamic Responses** in matter.
- **Three** main Dynamic Response **Regimes** exist, depending on several parameters:
  - **Deposited Energy and Energy Density**
  - **Interaction Duration**
  - **Material Strength ...**

Regime 1: Stress waves and vibrations in the elastic domain

- *Low deposited energy density.*
- *Negligible changes in density.*
- *Wave at Elastic Speed of Sound (C_0)*
- *Treated via analytical approach or with standard FEM codes (implicit or explicit)*

Example: CNGS target rods





A. Bertarelli, A. Dallocchio et al.; Journal of Applied Mechanics -- May 2008 -- Volume 75, Issue 3

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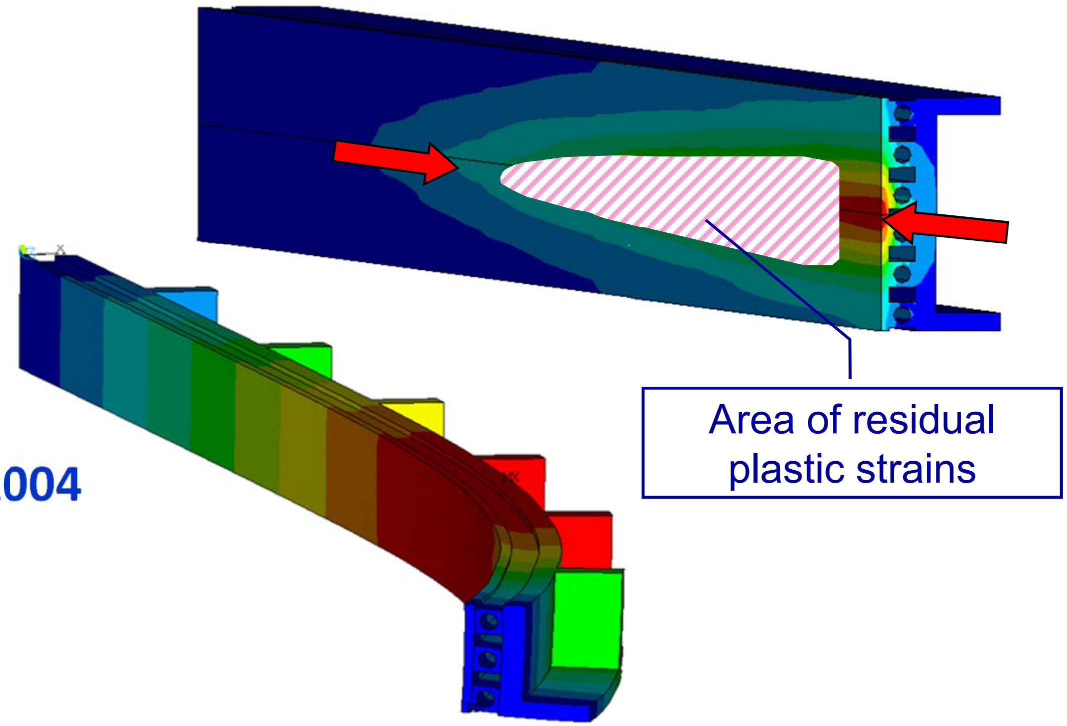
- **Three** main Dynamic Response **Regimes** exist, depending on several parameters:
  - **Deposited Energy and Energy Density**
  - **Interaction Duration**
  - **Material Strength ...**

Regime 2: Stress waves and vibrations in the elastic/plastic domain

- *Medium deposited energy density.*
- *Permanent deformations appear.*
- *Wave slower than sound speed.*
- *Can be treated with standard FEM codes (implicit or explicit).*



Example: Collimator Metal support
After SPS - TT40 robustness test in 2004

A. Dallocchio; *PhD Thesis -- CERN-THESIS-2008-140*

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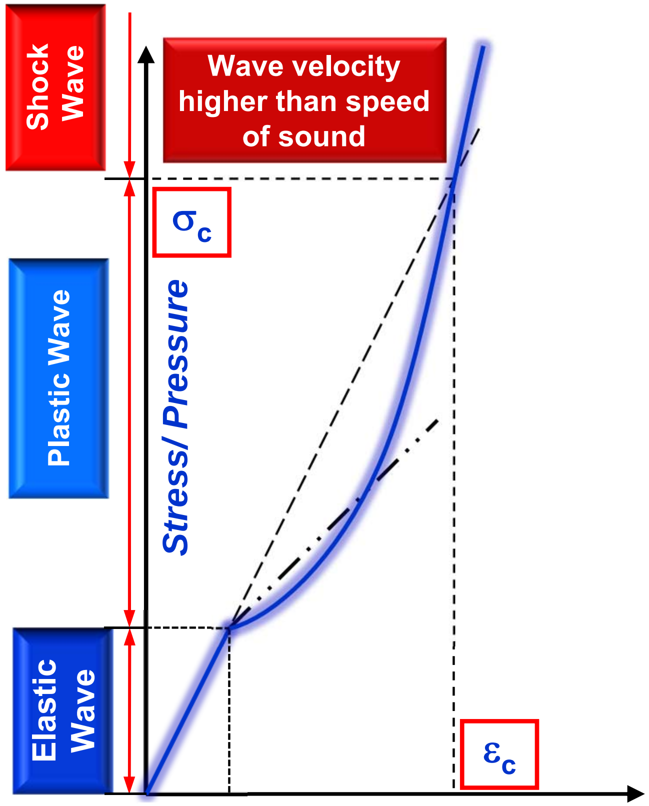
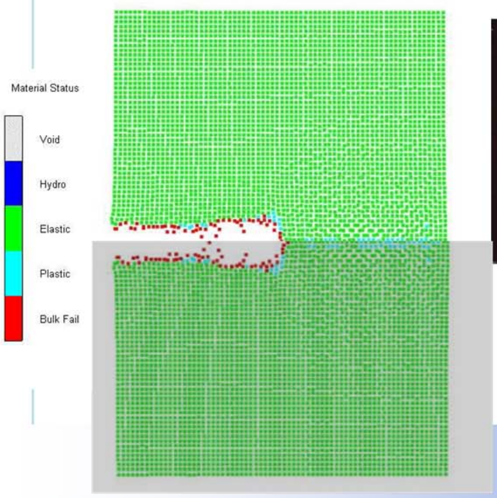
- **Three** main Dynamic Response **Regimes** exist, depending on several parameters:
  - **Deposited Energy and Energy Density**
  - **Interaction Duration**
  - **Material Strength …**

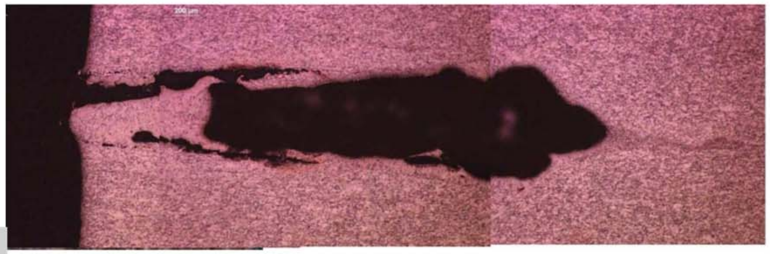
Regime 3: Shock Waves

- *High deposited energy density.*
- *Strains and pressure exceed a critical value.*
- *Wave faster than elastic sound speed. Change of density.*
- *Require special numerical tools.*



Example: Cu Target hit by ^{238}U beam at GSI





*Comparison between simulated beam impact in Autodyn and Metallurgical analysis of impacted Cu target (Courtesy **H. Richter / J. Lettry**)*

Shock waves in beam-induced accidents …

- For **W** shock waves are produced at ε_c **> 15%** and for **Cu** at ε_c **> 7.5%** (assuming uniaxial strain)
- Strains are intimately related to temperature changes, e.g. for Tungsten:

$$\varepsilon_m \propto \alpha(T_m - \mathrm{T_R}) \text{ with } \overline{\alpha}_{0-3000} \cong 6.8\times10^{-6} K^{-1} \text{ and } T_m = 3340^o C \Rightarrow \varepsilon_m \cong 2.3\% < \varepsilon_c$$

- **Shock waves do not appear (in metal based materials) unless changes of phase occur!!!**

… and the tools to treat them

- **Standard structural mechanics tools** (e.g. Ansys) are **unable** to treat problems with changes of phase and of density.
- A new class of numerical simulation tools is necessary ⇨ **Hydrocodes**.
- A Hydrocode is a non-linear numerical tool developed to study very fast, very intense loading on materials and structures.
- Originally it assumed a hydrodynamic behaviour of material (no strength ⇨ *fluid-like material*).
- Up-to-date Hydrocodes keep material strength into account.

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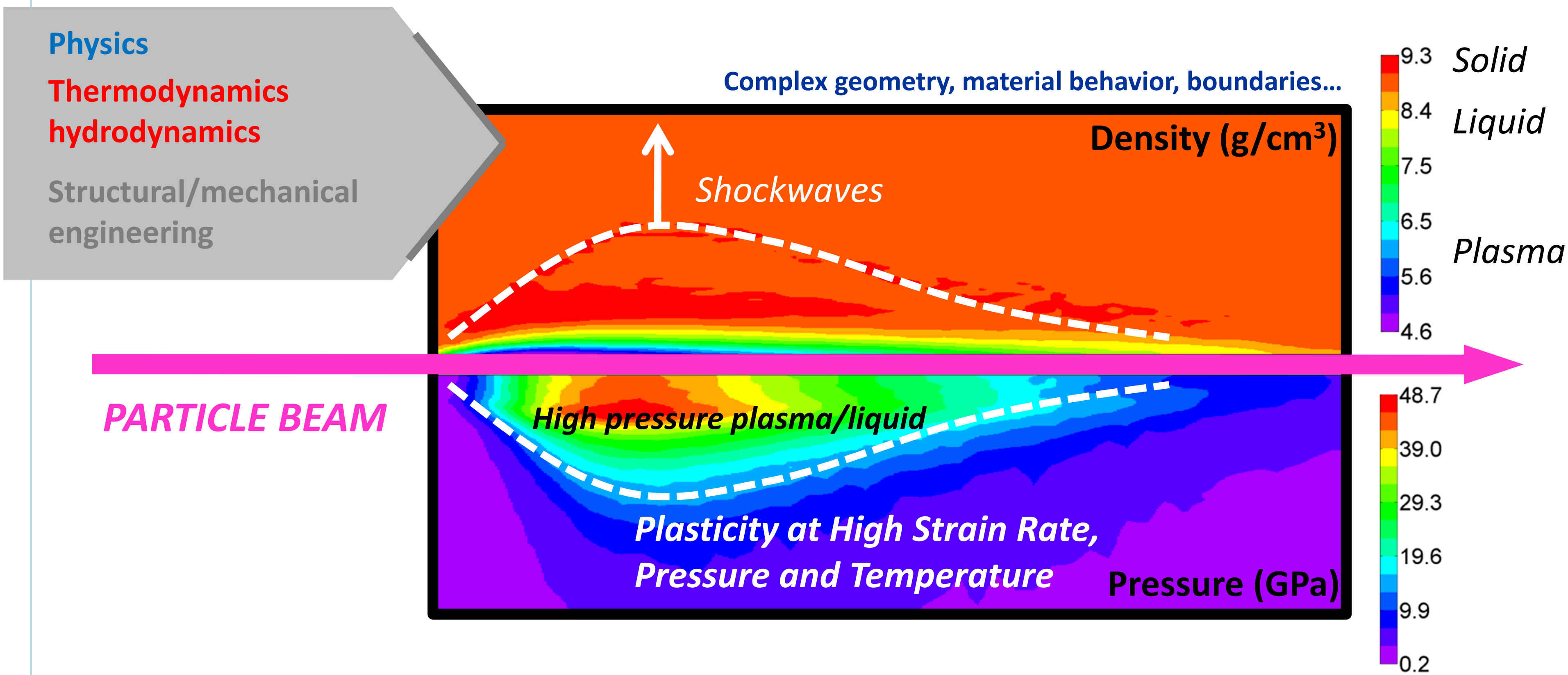
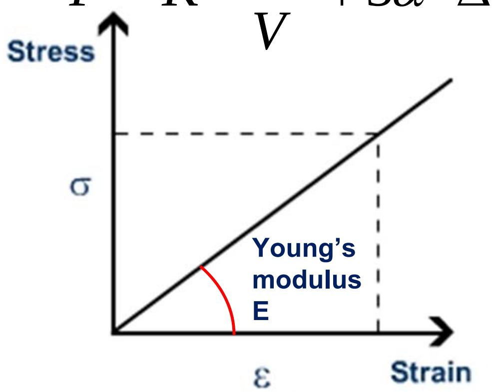
To investigate this phenomenon, a fundamental aspect is the development of methodologies of analysis of the complete problem. To do this, it is essential to look to a **multidisciplinary approach**.



Standard FEM Codes

Linear Elastic Behaviour

$$P = K \cdot \frac{\Delta V}{V} + 3\alpha \cdot \Delta T$$



Replaced by

Static Yield Strength

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

Replaced by

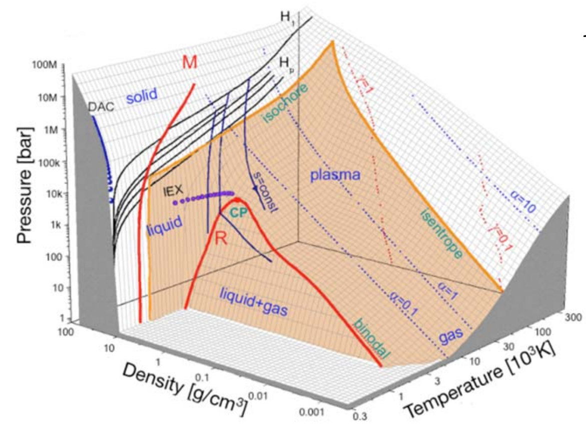
Static Failure Strength

$$\sigma_{ult} = R_m$$

Replaced by

Hydrocodes

Complex Equations of State (EOS)



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

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

Multi-parameter Strength Models

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

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

Dynamic Failure Models

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

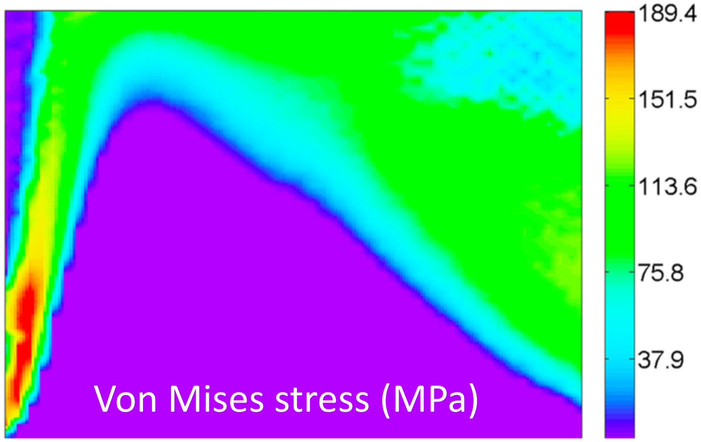
Stress tensor = hydrostatic tensor + deviatoric tensor

(change in volume) (change in shape)

$$\sigma_{ij} = s_{ij}\left(\varepsilon_{ij}^{el}, \varepsilon_{ij}^{pl}\right) + p\,\delta_{ij}$$

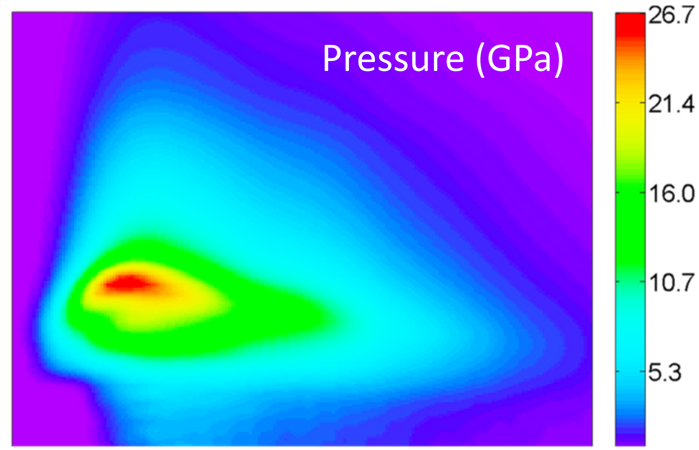
Grüneisen
Polynomial
Tillotson, Puff, GRAY
Tabular (SESAME, EOSPRO…)

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



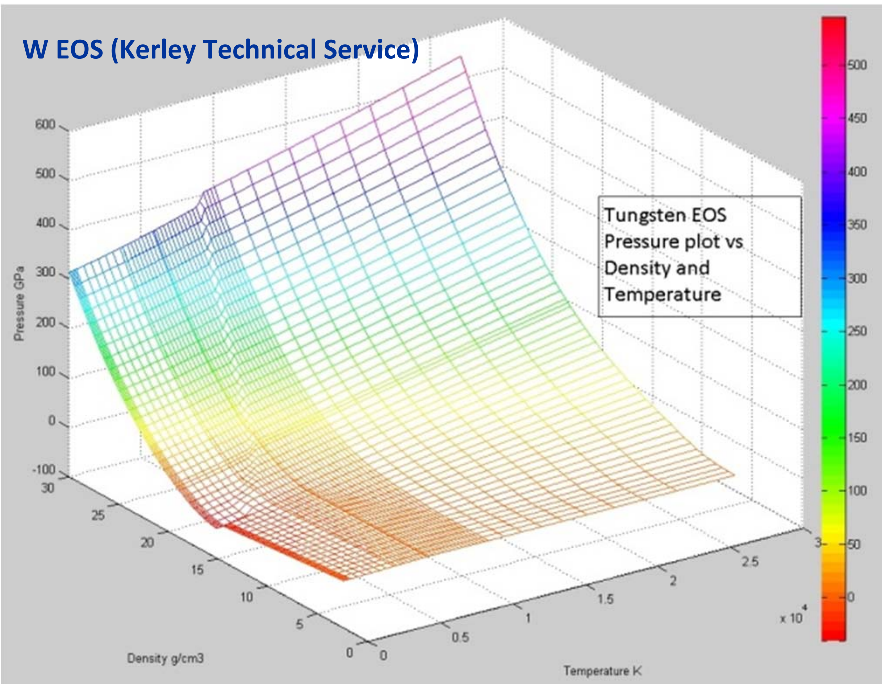
$$\sigma_y = f\left(\varepsilon_{eff}, \dot{\varepsilon}, T, p\right)$$

Johnson–Cook
Steinberg–Lund
Zerilli–Armstrong



Tabular EOS (SESAME)

Different analytical Models for different regions of ρ-T space for best fitting:



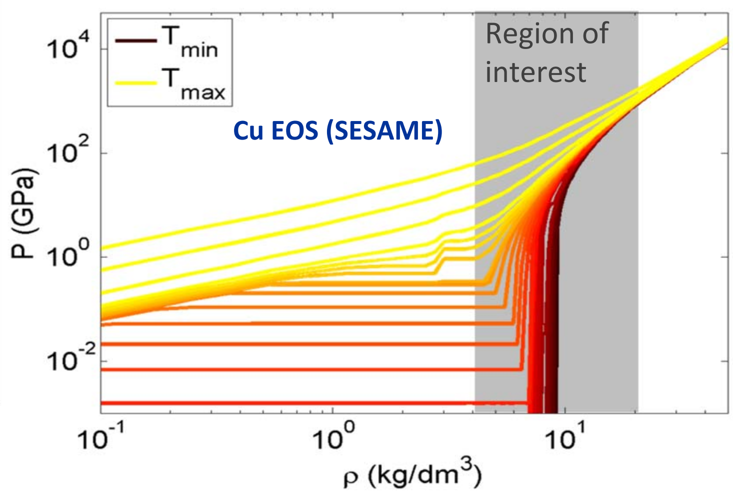
Polynomial EOS

Tabular EOS Polynomial interpolation:

- **defined over the Region of interest**
- **P=*f*(E) with *f* linear**
- **2 different polynomials for Compression (c, $\mu<0$) and Rarefaction (T, $\mu>0$);**

$$P_c = A_1\mu_c + A_2\mu_c^2 + A_3\mu_c^3 + (B_0 + B_1\mu_c)\rho_0 e$$

$$P_T = T_1\mu_T + T_2\mu_T^2 + B_0\rho_0 e$$



$$\mu = \frac{\rho - \rho_0}{\rho_0}$$

$$E = \rho_0 e$$

✓There is not a unique Failure Model
✓ Different Models for Different Failure Mechanisms and Materials

Ductile Failures on high deformable materials (Cu):

Johnson-Cook Failure

$$D=\sum\frac{\Delta\varepsilon}{\varepsilon^f}$$

$$\varepsilon^f=\underbrace{\left[D_1+D_2e^{D_3\sigma^*}\right]}_{\text{Pressure dependence}}\underbrace{\left[1+D_4\ln\left|\dot{\varepsilon}^*\right|\right]}_{\text{Strain rate dependence}}\underbrace{\left[1+D_5T^*\right]}_{\text{Temperature dependence}}$$

Ductile Failures on low deformable materials (W Alloys):

Plastic Strain Failure

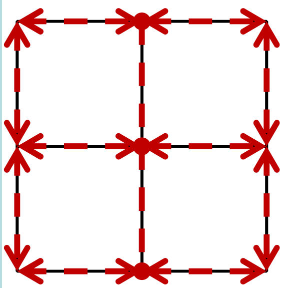
$$\begin{cases}\varepsilon_{Pl}\geq\varepsilon_{Pl}^{MAX}\\ D=1\end{cases}$$

Ductile-Brittle Failures with very high strain rates (Shock Wave propagation):

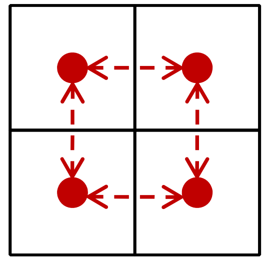
Spall Strength (Failure due to Rarefaction Wave)

$$\begin{cases}P\leq P^{\min}\\ D=1\end{cases}$$

✓Identification of Parameters Depends on Failure Conditions
✓Need for Specific tests to Validate Failure Models

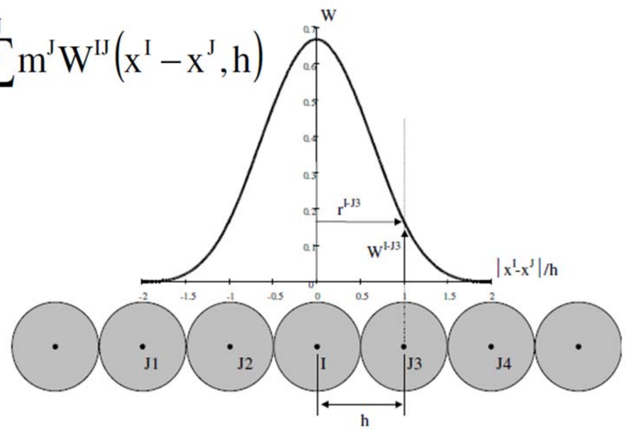


Lagrangian Mesh: multi-node elements with shared nodes.



SPH Mesh: single-node elements interaction modeled via Weighting Function (W) and Smoothing Length (h); Density (ρ) expressed as a function of W and h.

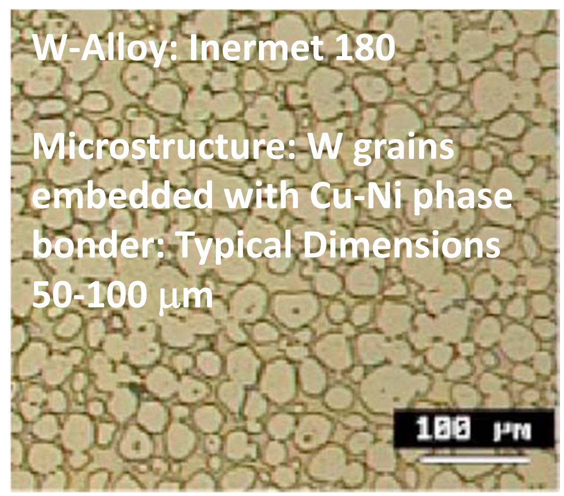
$$\rho^I = \sum^N m^J W^{IJ}\left(x^I - x^J, h\right)$$



Possibility to study crack propagation inside the target and motion of expelled fragments/liquid droplets.

SPH Tips and Tricks:

Mesh size:
Accurate damage assessment (splashing) vs. CPU Time



Time Step
5-10 times smaller w.r.t. Lagrangian mesh.

Algorithms of Solution

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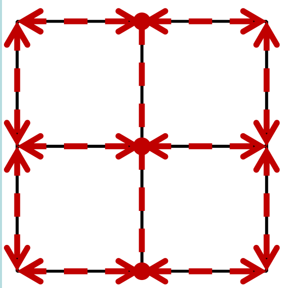

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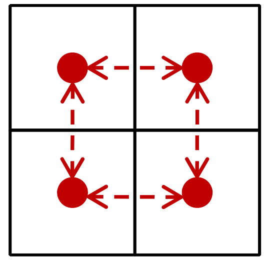

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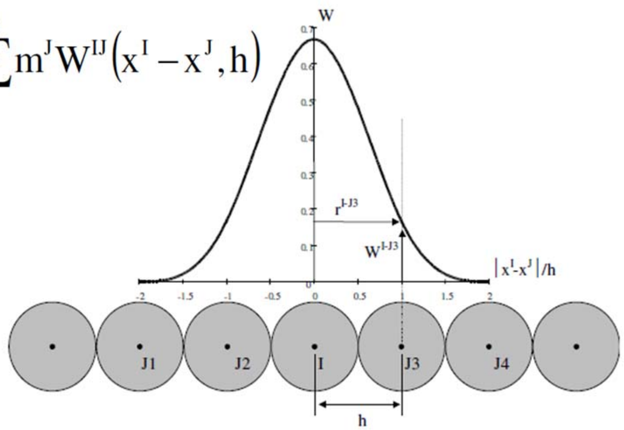
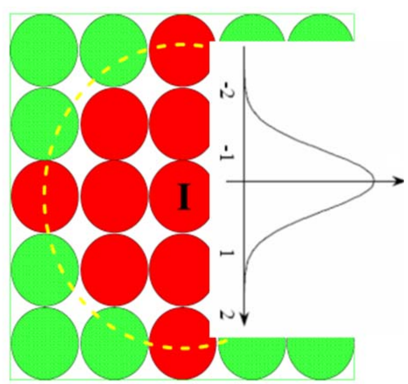


Possibility to study crack propagation inside the target and motion of expelled fragments/liquid droplets.

SPH Tips and Tricks:

Failure Model for Tungsten: Spall Strength

Failure due to Rarefaction Shock-Wave

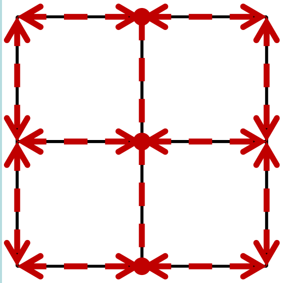


Failure model:

Distance between Interacting SPH Particles must be < 2h (to avoid energetic errors); Plastic Strain Failure Models could leads to energetic instabilities.

Algorithms of Solution

Smoothed Particle Hydrodynamics (SPH) Mesh



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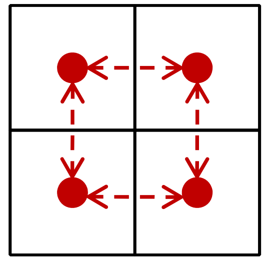

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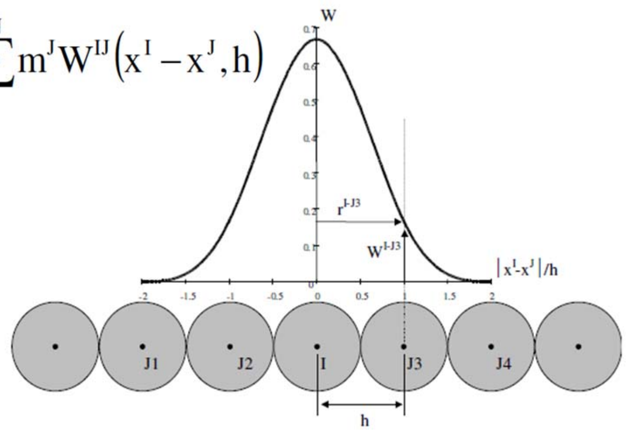
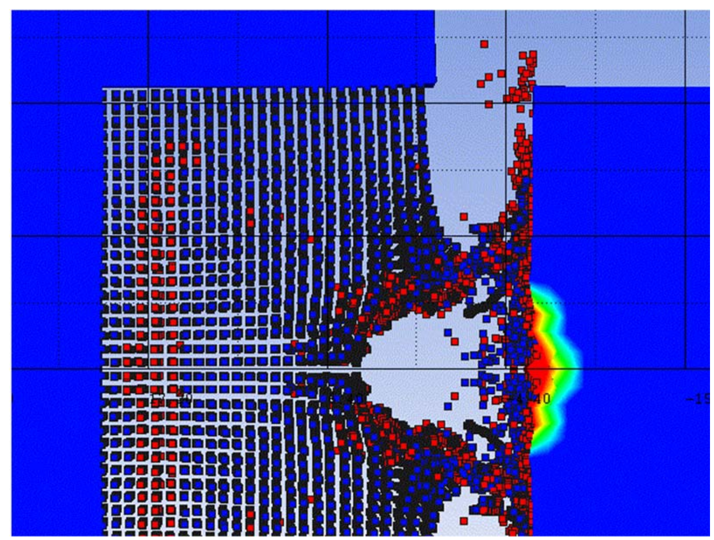


Possibility to study crack propagation inside the target and motion of expelled fragments/liquid droplets.

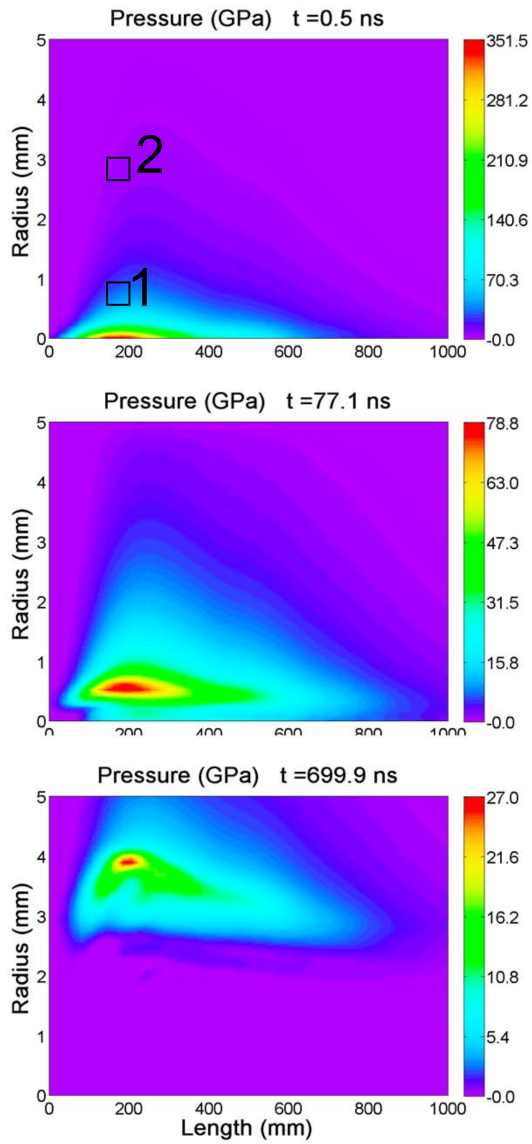
SPH Tips and Tricks:

SPH-Lagrangian Mesh Interaction:
Effects of highly energetic droplets 10^2-10^3 m/s

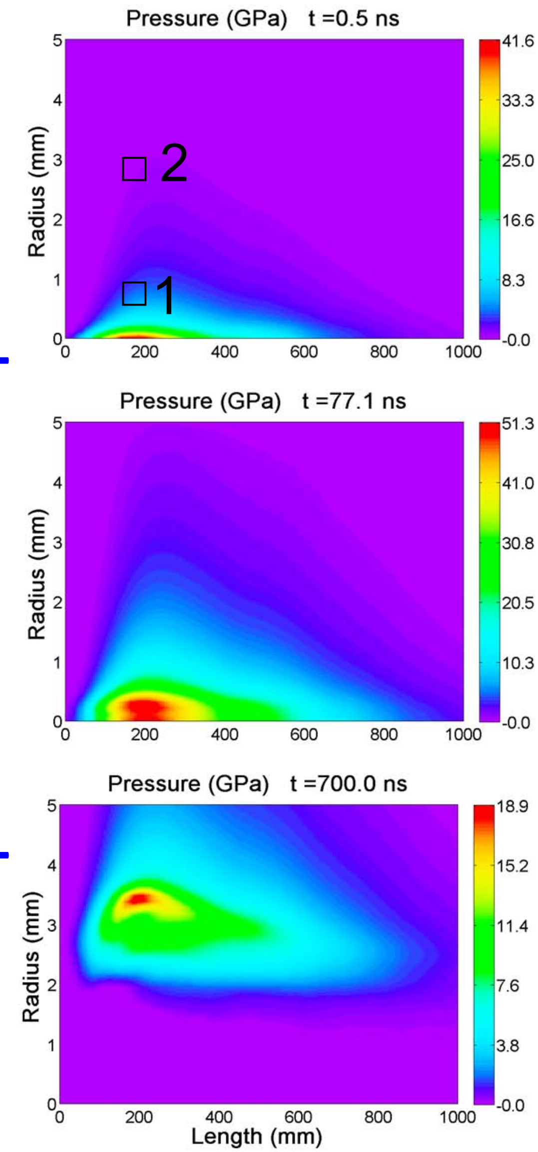


Algorithms of Solution

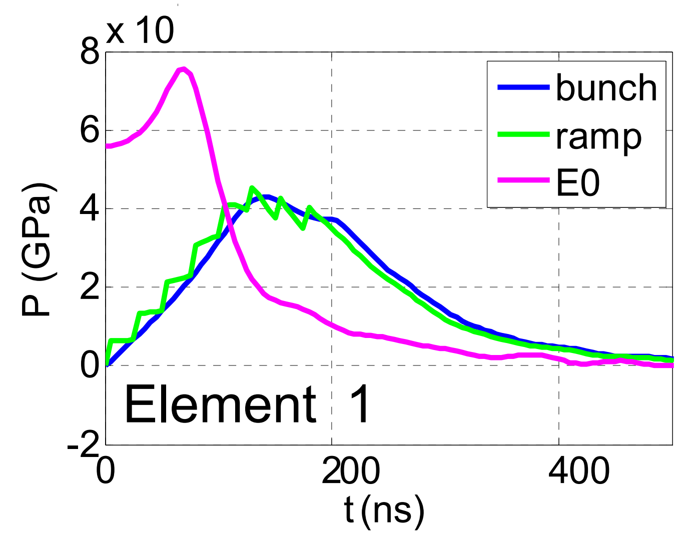
Deposition as initial condition E_0

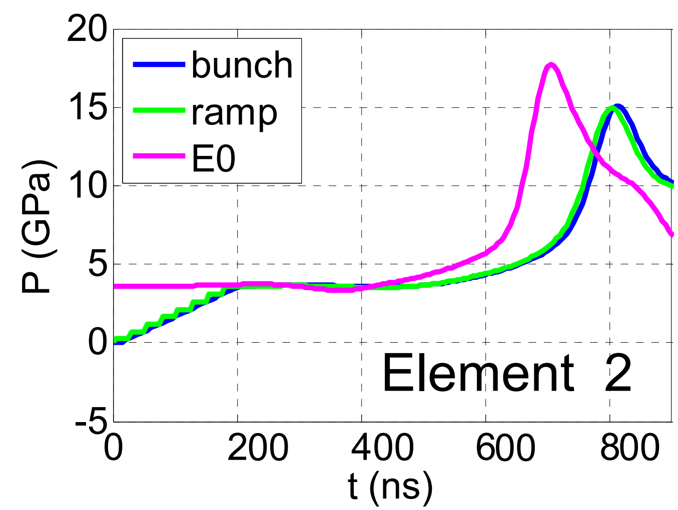


Deposition as 8 bunches profile



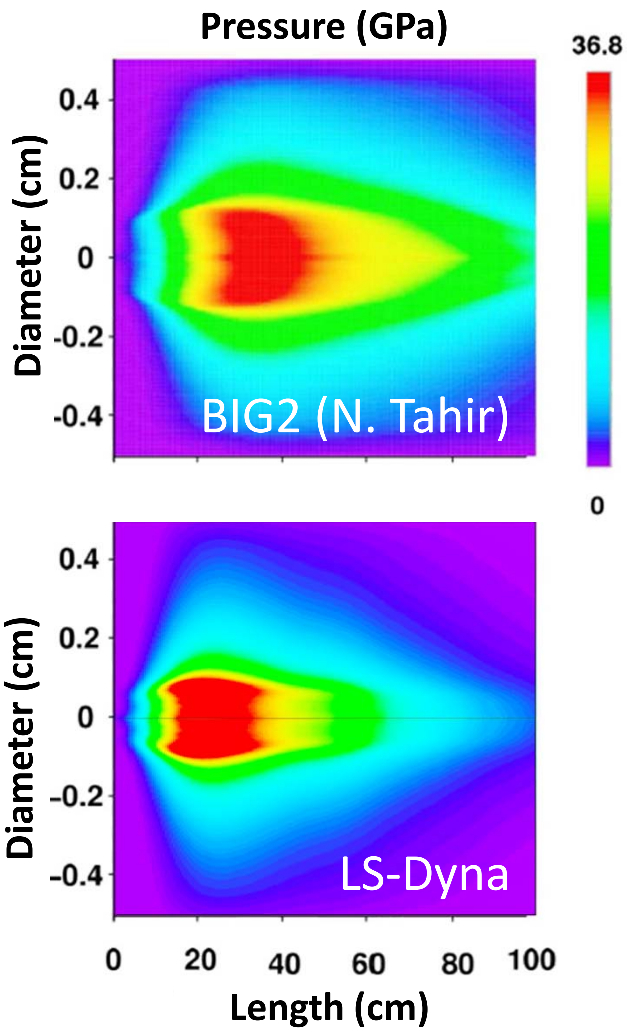
Cu thin rod hit by 8 LHC bunches

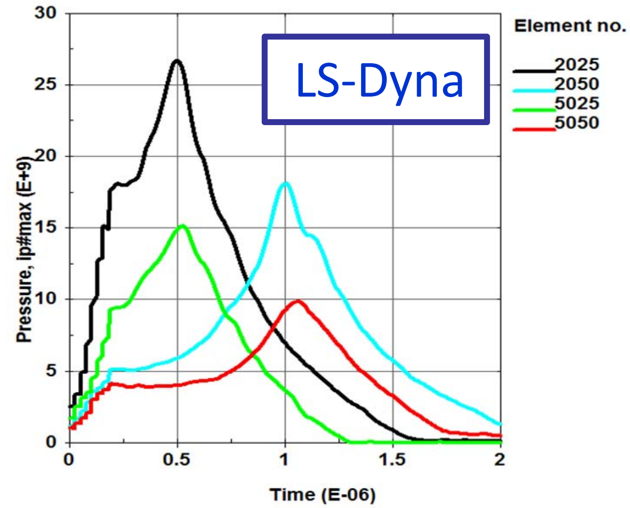


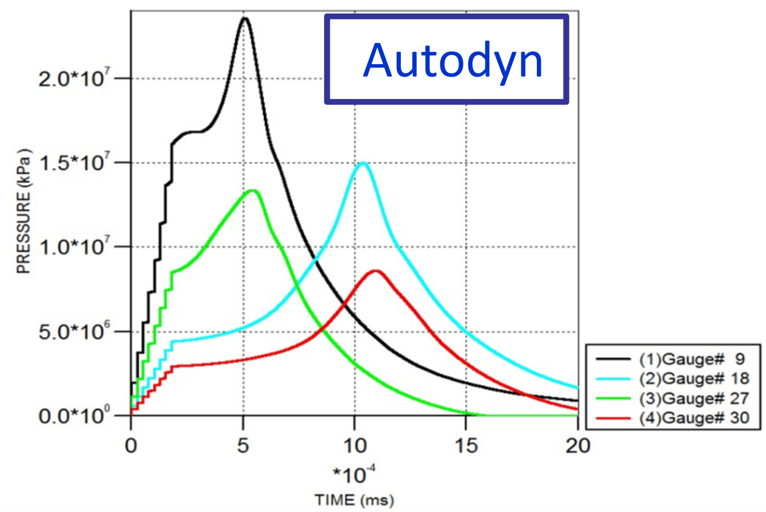


Energy Deposition

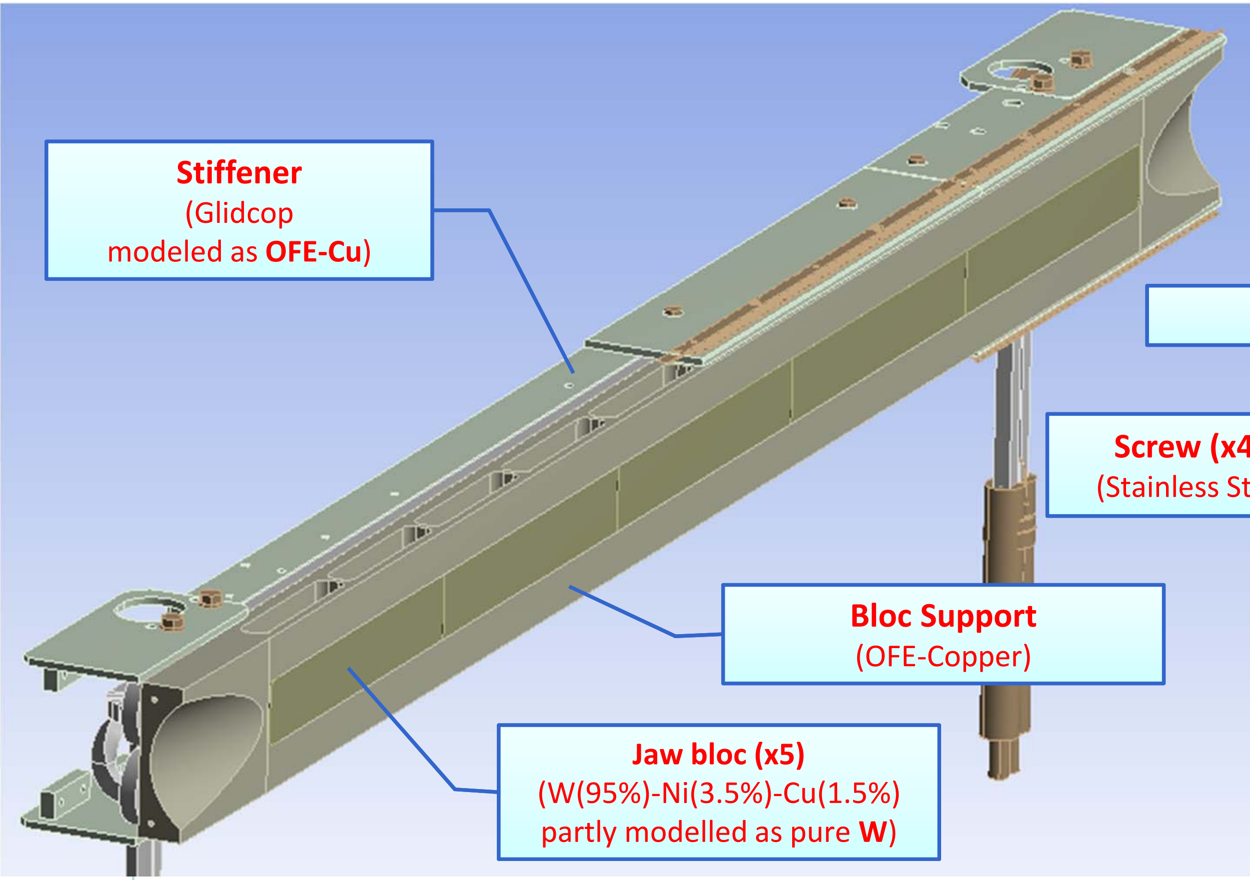
CERN (Autodyn), Politecnico di Torino (LS-Dyna) and GSI (BIG-2)

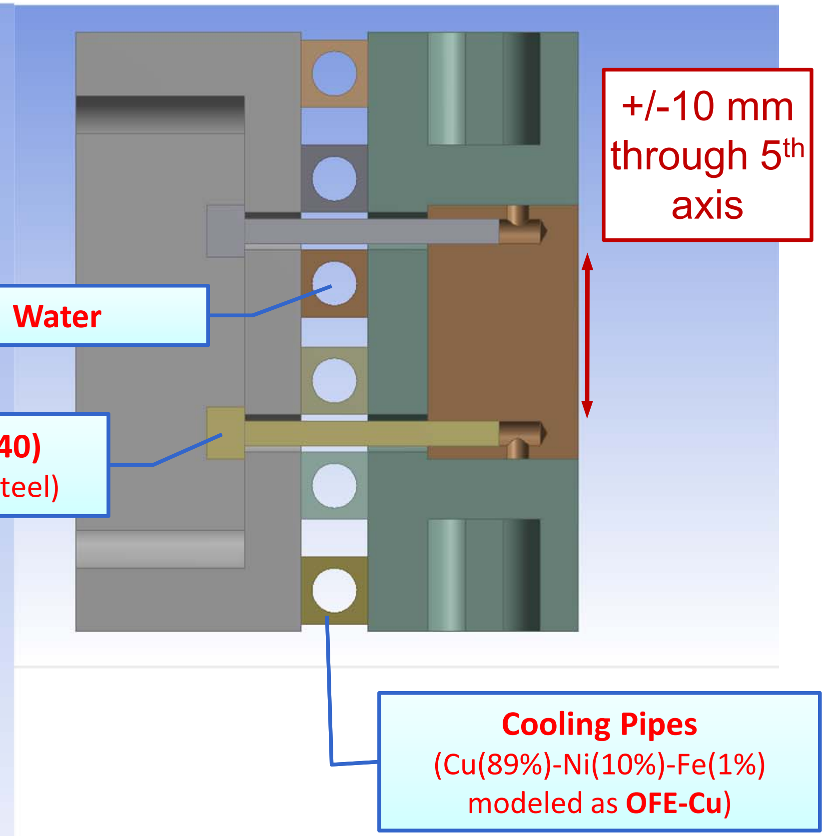






M. Scapin, A. Dallocchio, L. Peroni, "Thermo-mechanical modeling of high energy particle beam impact". ACE-X 2010, Paris. Under review for publication on "Numerical Modeling of Materials Under Extreme Conditions", Springer.





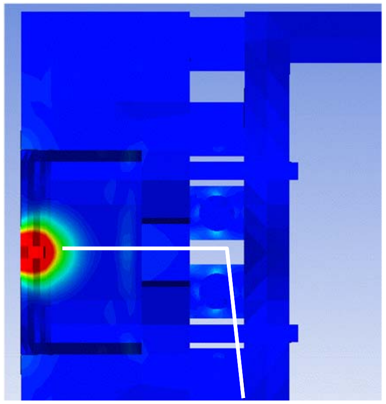
Material	EOS	Strength model	Failure model
Tungsten	Tabular (SESAME)	Johnson-Cook	Plastic strain/ Hydro (Pmin)
Copper OFE	Polynomial	Johnson-Cook	Johnson-Cook
Stainless steel AISI 316	Shock	Johnson-Cook	Plastic strain
Water	Shock	-	Hydro (Pmin)

Engineering Case Study

Case	Beam Energy [TeV]	Norm. Emittance [μm rad]	Impacting Bunches	Particles per Bunch	Bunch spacing [ns]	Impact Depth [mm]	Deposited Energy on Jaw [kJ]	TNT Equivalent [g]
1	3.5	3.50	1	$1.3x10^{11}$	-	2	38.6	9.2
2	5	7	1	$1.3x10^{11}$	-	2	56.2	13.4
3	5	3.5	1	$1.3x10^{11}$	-	2	56.5	13.5
4	5	1.75	1	$1.3x10^{11}$	-	2	56.6	13.5
5	5	1.75	2	$1.3x10^{11}$	25	2	111.3	26.6
6	5	1.75	4	$1.3x10^{11}$	25	2	216.1	51.6
7	5	1.75	8	$1.3x10^{11}$	25	2	**429.8**	**102.7**

Three different **damage scenarios**, with increasing severity:

- **Level 1** (***Collimator need not be replaced***). Permanent jaw deformation and damage are limited.
- **Level 2** (***Collimator must be replaced***). Collimator and other components (e.g. Screws) are fatally compromised.
- **Level 3** (***Long down time of the LHC***). Catastrophic damage to collimator leading to water leakage into beam vacuum (pipe crushing, tank water circuit drilling ...)

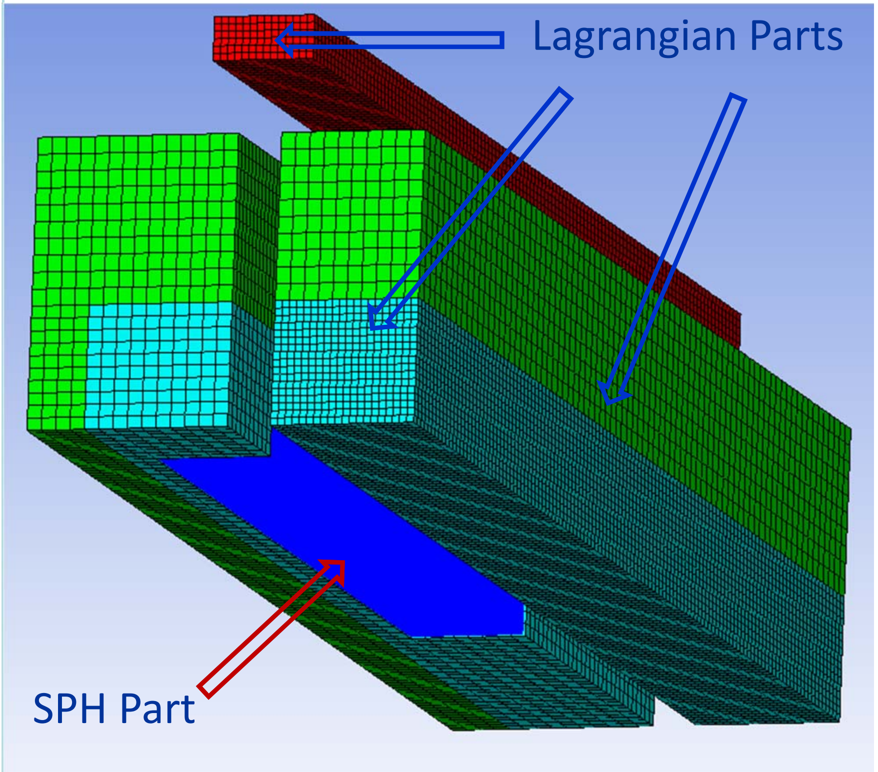


Jaw Damaged Area (red)
Level 1 : H ≤ 8 mm
Level 2: H > 8 mm

Engineering Case Study

✓SPH Simulations

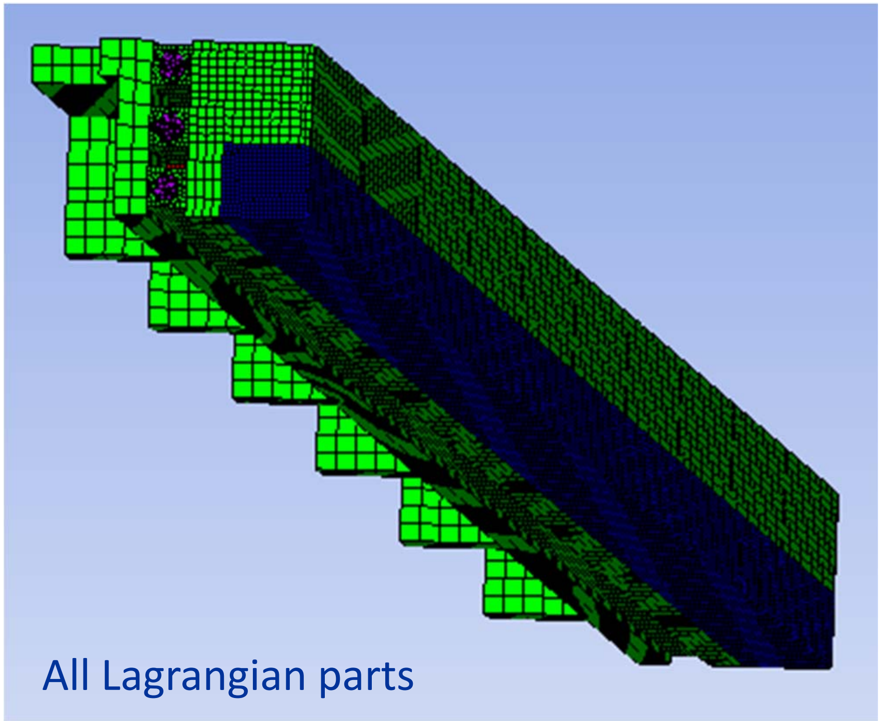
First W Sector of Jaw (Length 200 mm)



SPH Mesh: W Insert LOCAL Damage due to Beam Impact; Surrounding Lagrangian parts for Boundary Conditions

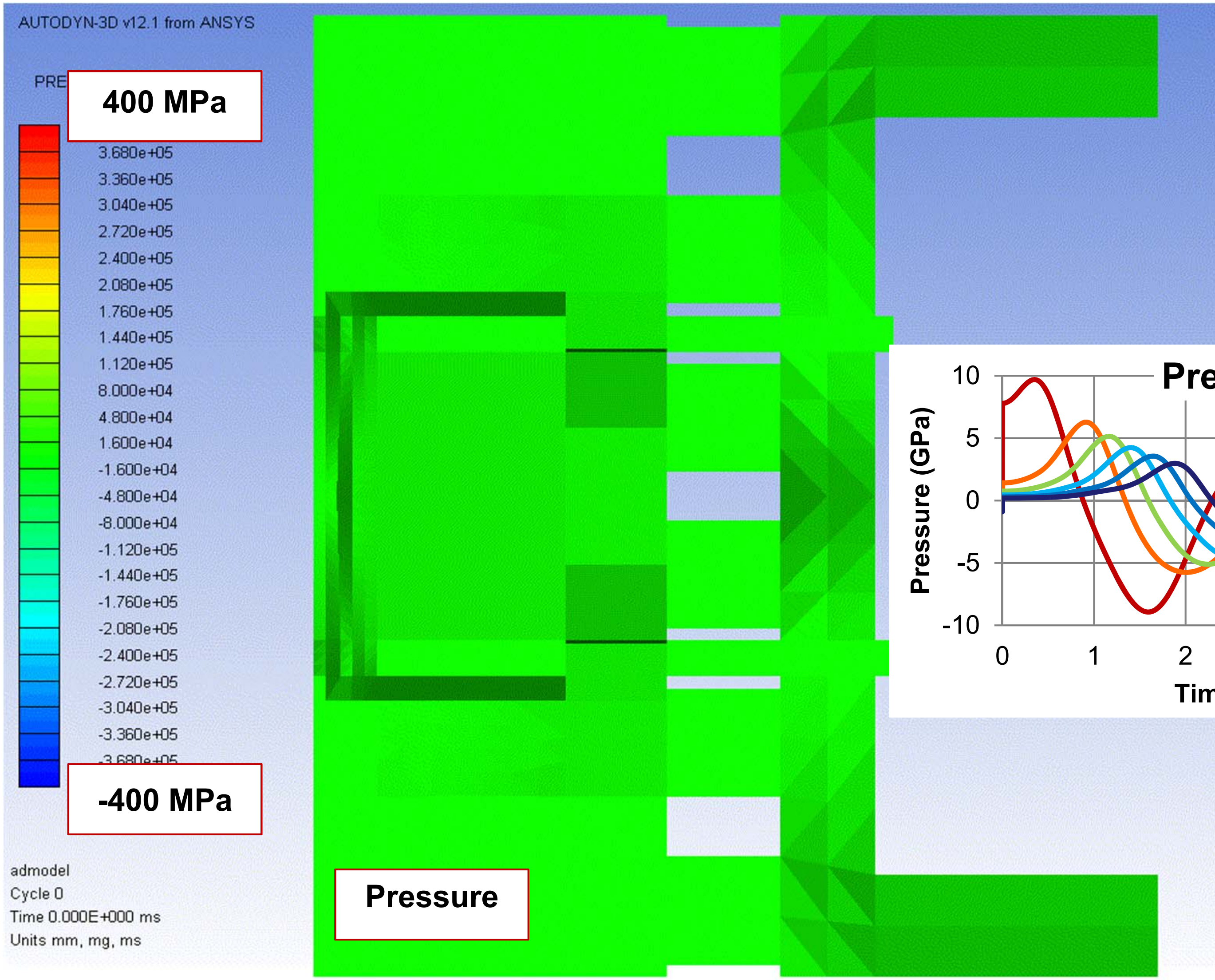
✓Lagrangian Simulations

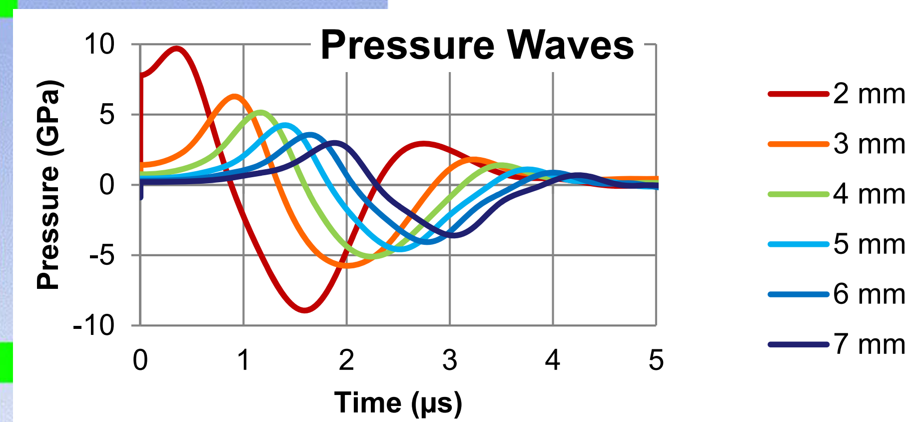
Complete Jaw (Length 500 mm)



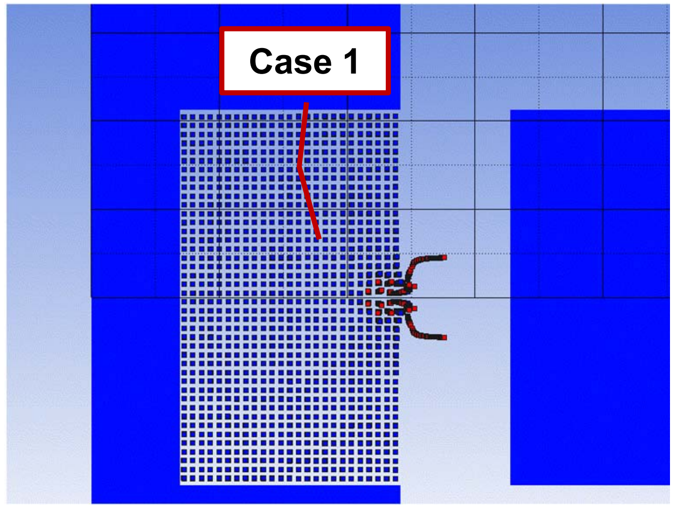
Lagrangian Mesh: Shock Wave propagation along the entire structure (W inserts, Cu Jaw, Cooling Pipes, Stiffener)

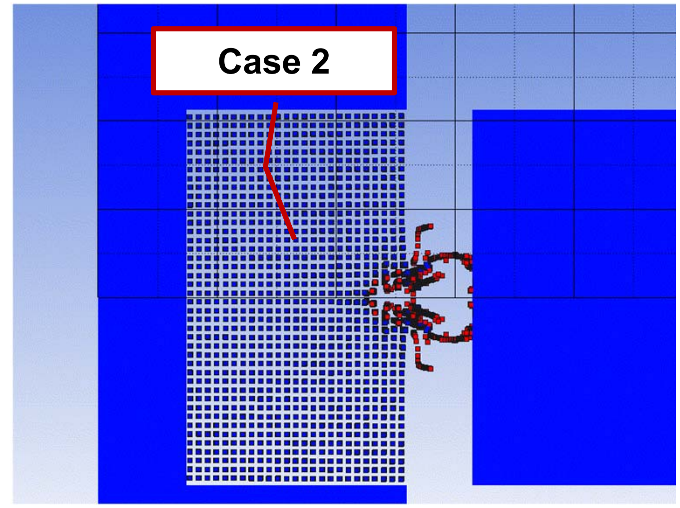
Single-bunch @ 5 TeV.

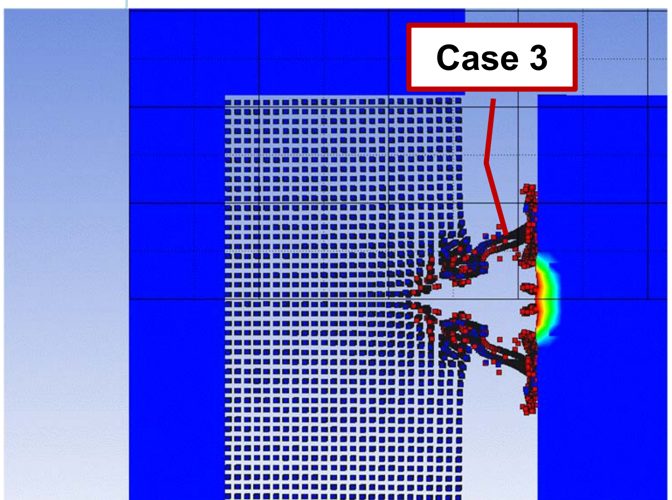


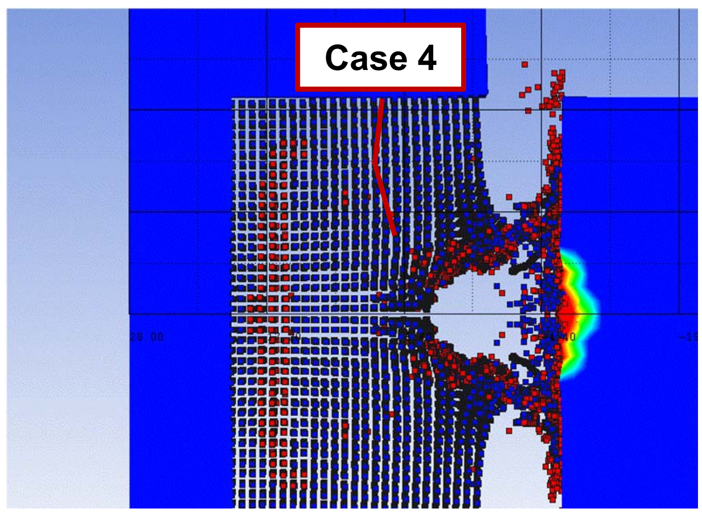


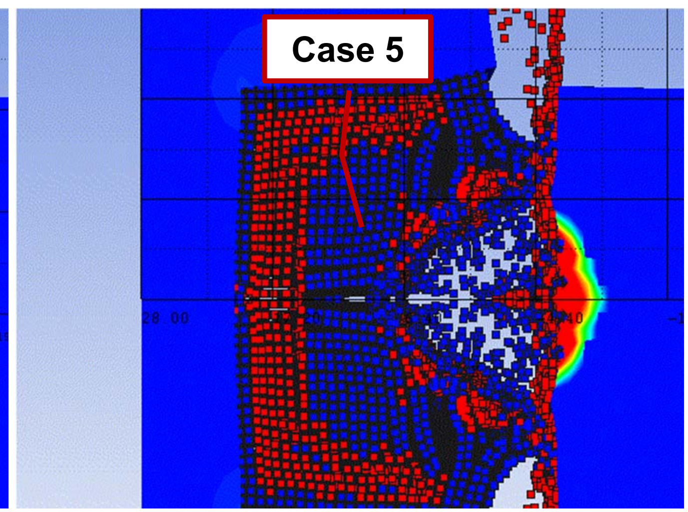
1) 1 Bunch @ 3.5TeV
2) 1 Bunch @ 5TeV
3) 2 Bunches @ 5 TeV
4) 4 Bunches @ 5 TeV
5) 8 Bunches @ 5 TeV





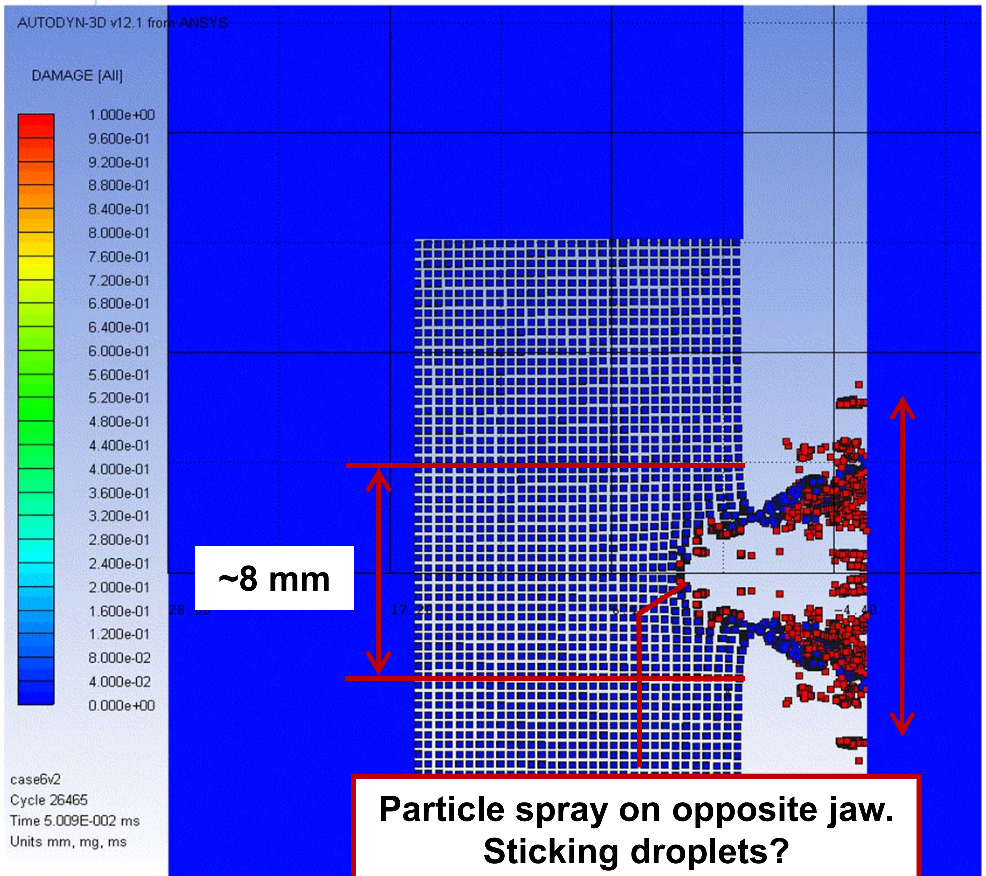


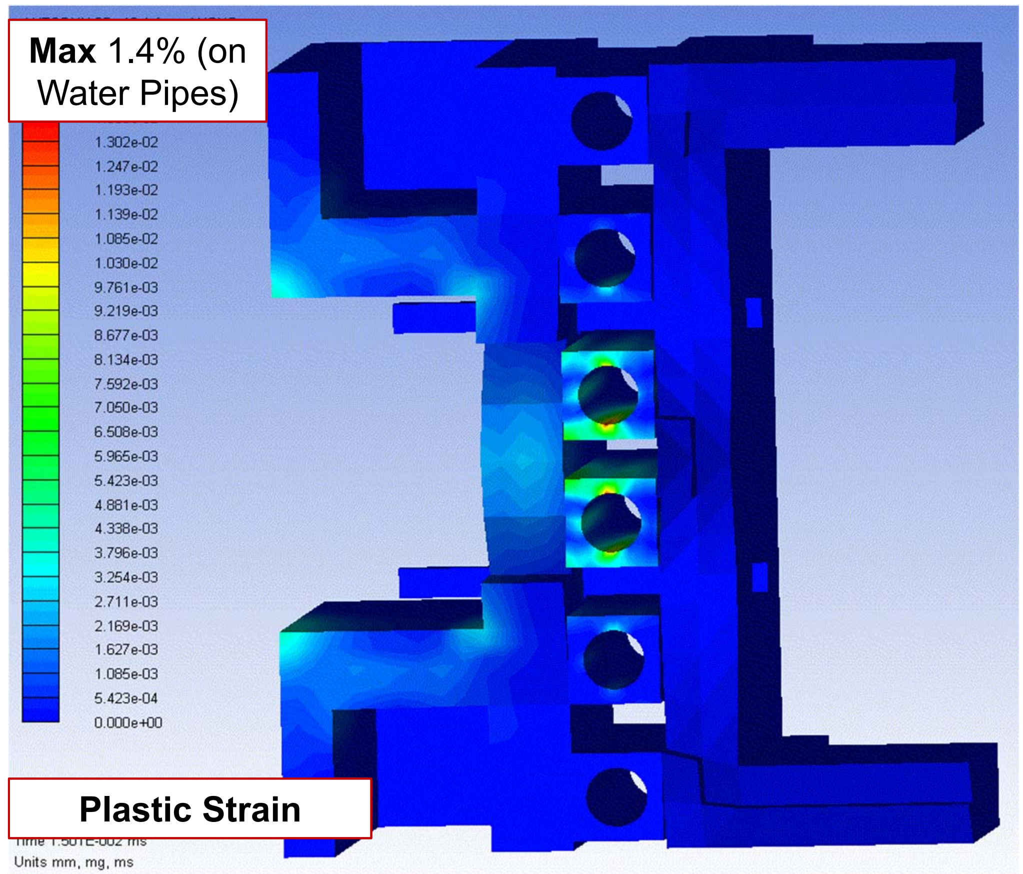




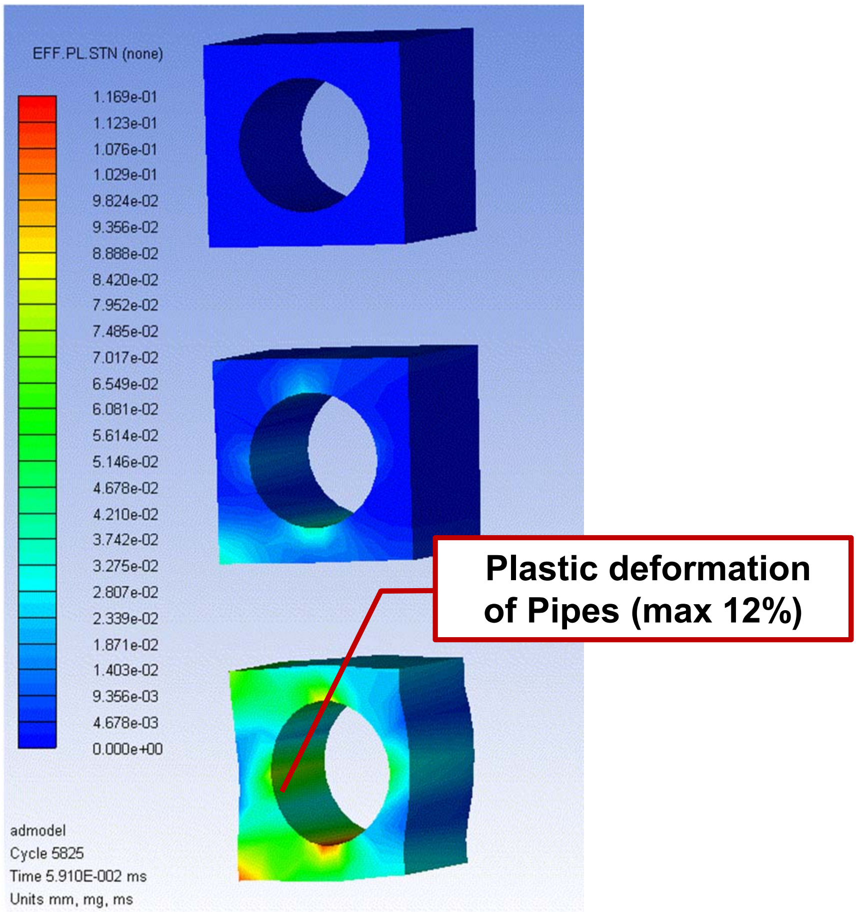
Damage Level 1 (In-situ spare surface)

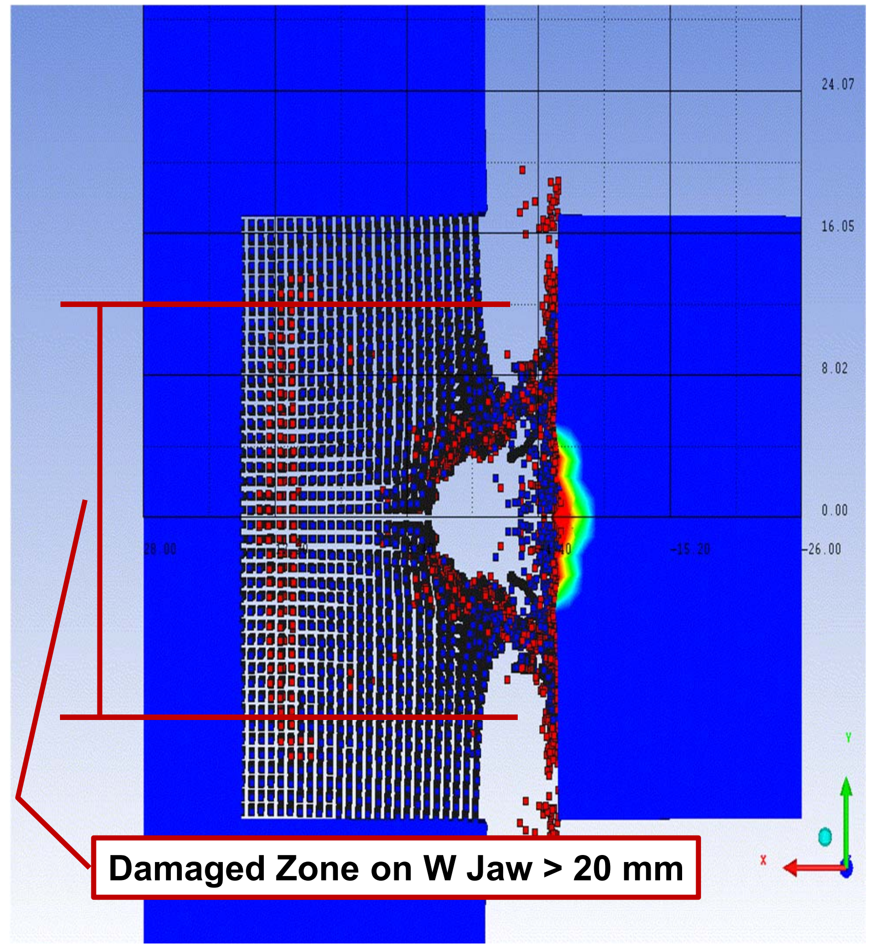
- **1 LHC Bunch @ 5TeV**.
- **Plastic deformations** on cooling pipes and screws remain limited.
- 8mm damage on impacted jaw.
- **Particle Spray** on a larger area on opposite jaw.





- **4 LHC Bunches @ 5TeV** impacting at 2mm from jaw surface
- Severe **plastic deformations** on cooling pipes and screws.
- Permanent damage to opposite jaw due to particle spray.

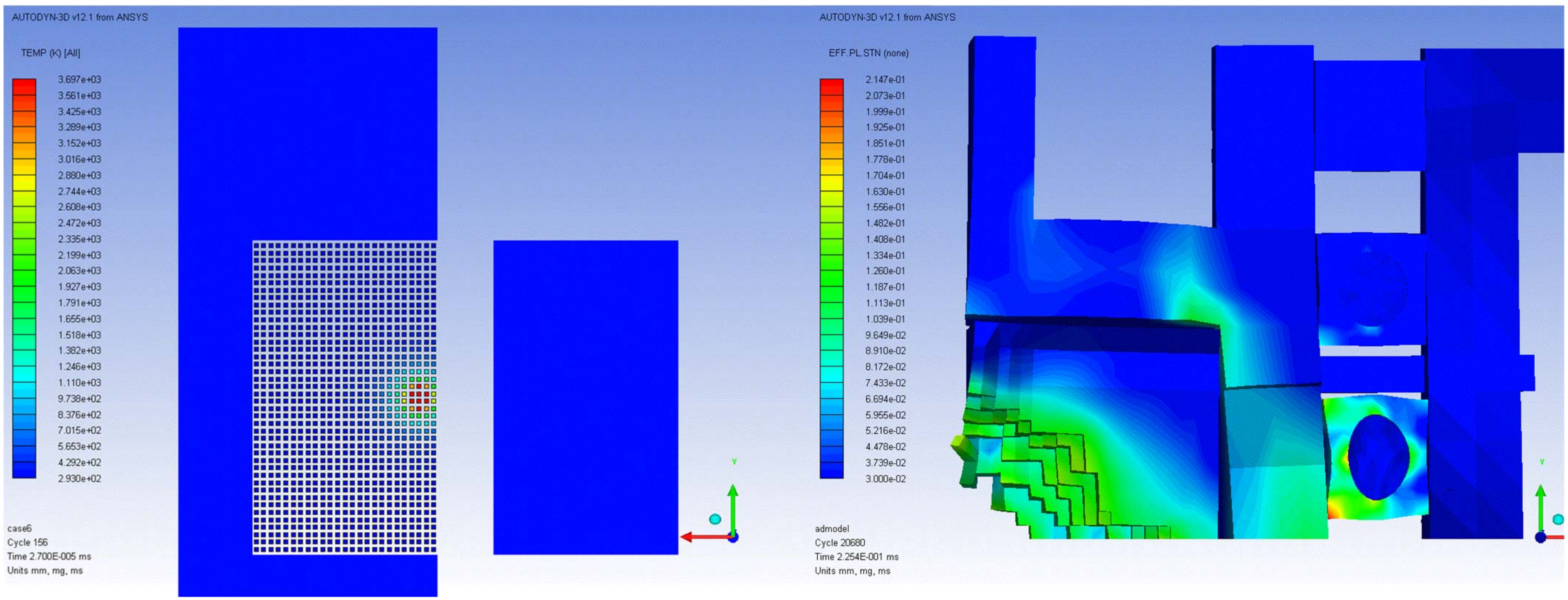




Engineering Case Study

Damage Level 3 (Catastrophic Damage)

- **8 LHC Bunches at 5 TeV**.
- High probability of **water leakage** due to very severe plastic deformations on pipes.
- Impressive **jaw damage** :
  - Extended eroded and deformed zone.
  - Projections of hot and fast solid tungsten bullets (T≈2000K, V_{max} ≈ 1 km/s) towards opposite jaw. Slower particles hit tank covers (at velocities just below ballistic limit).
  - Risk of “bonding” the two jaws due to the projected resolidified material.



Flies in the ointment

- 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.
- There is no "fit-any-material" **Strength** or **Failure Model**. There is a generalized lack of experimental data for these models under extreme conditions (e.g intense beam impacts).
- Approximations and extrapolations are inevitable for each of the three "ingredients" of the Hydrocode tools.
  Data for pure metal (more easily available) are often used in place of alloys.
- **All presented results are unavoidably affected by these uncertainties.**
- **Only dedicated experimental tests can provide the correct inputs for simulations.**

  ➔ **HiRadMat Facility at CERN**

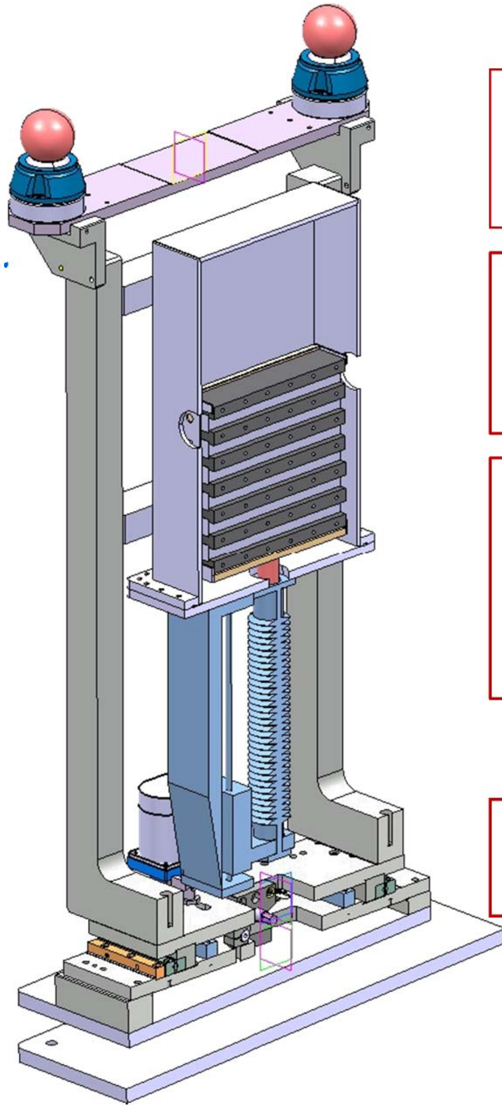
Experimental Validation

HiRadMat:

High **Rad**iation to **Mat**erials Project: development of a new facility at CERN.

Multi-bunch beam impact tests using SPS Beam up to 450 GeV.

Material Test Bench



Several Material candidates ("standard" + advanced).

- **Metals**
  - GlidCop, W, Mo
- **Ceramics**
  - Graphite, SiC
- **Metal-Diamond Composites**
  - CuCD, MoCD...

Material Properties
(EOS, Strength and Failure Models)

Numerical Simulation of the HiRadMat tests
(FLUKA, LSDYNA, AUTODYN)

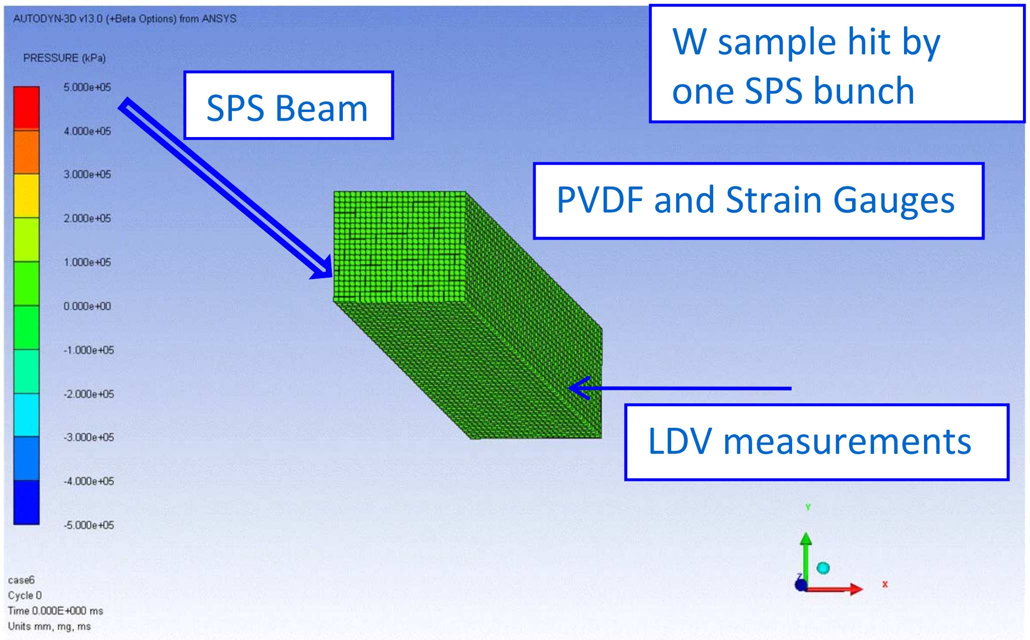
Experimental Measurements
(LDV Laser Interferometer, PVDF, Strain Gauges, Thermal probes
+ post mortem analysis)

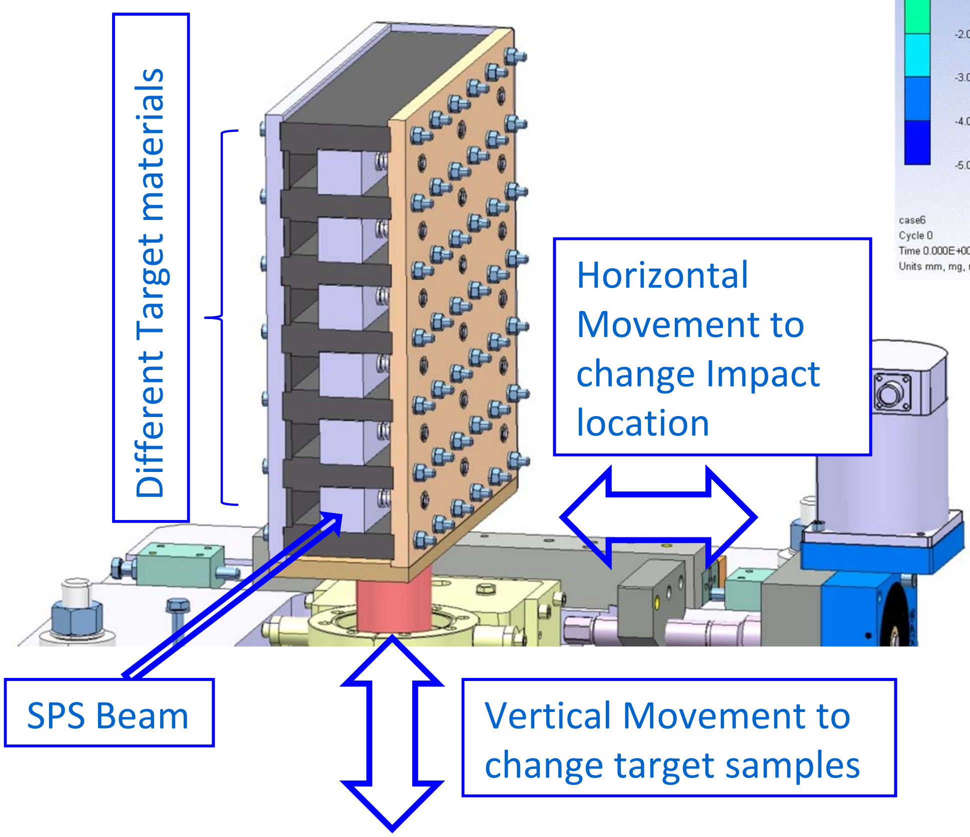
Validation of Material Models and of Numerical Tools.

Experimental Validation

Conceptual Design of HiRadMat Sample Holder

Materials:
Glidcop, W, Mo, C, SiC, CuCD, MoCD





- **Validation of the EOS:**
  - LDV, PVDF, Strain Gauges and Thermal probes
- **Validation of Strength and Failure models:**
  - Post-Mortem Analyses
  - Specific Experimental tests for the characterization of the strength models.

Experimental Validation

- **Beam-induced structural effects** up to the melting point can be reasonably well treated with Standard FEM Codes.
- When changes of phase occur and **shock-wave phenomena** are in place, advanced tools must be used (**Hydrocodes**).
- Main aspects of complex numerical simulations have been discussed:
  - Advanced material modelling.
  - Algorithms of solution.
  - Benchmarking between numerical tools.
  - Energy Deposition.
- State-of-the-art 3D analysis of complex Collimator model carried out including:
  - Simulation of Shock-wave propagation
  - Simulation of permanent damages
  - Particle spray do to change of phase

- W and Cu are well-known materials (Los Alamos): quite good confidence in results reliability...
- ...anyway Constitutive models required by Hydrocodes are well beyond commonly available material data . ***Most important limitation of these simulations***.
- **Specific tests in HiRadMat are hence highly recommended** as well as detailed characterization of strength models via advanced experimental mechanics.
- Conceptual design of HiRadMat sample holder has been showed.
- With a suitable calibration of beam parameters (number of bunches, dimension of the spot, etc.) it would be possible, thanks to HiRadMat, to **investigate material behavior at high pressure and strain-rate with this new kind of "impacts".**
- **Coupling between FLUKA and Hydrocodes (LS-Dyna, Autodyn)** is ongoing to evaluate effects of relevant variation in material density for multi-bunch impacts.

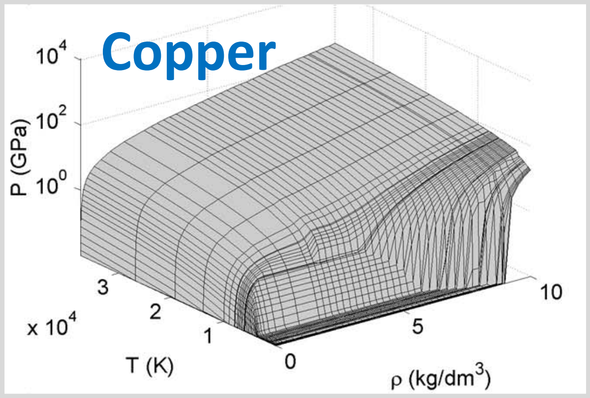
Conclusions

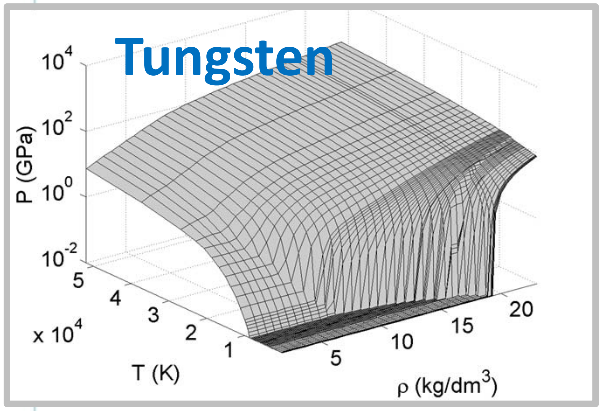
Thank you for your attention

We wish to warmly thank the FLUKA team (F. Cerutti, V. Boccone EN-STI) for the quality and quantity of their inputs.

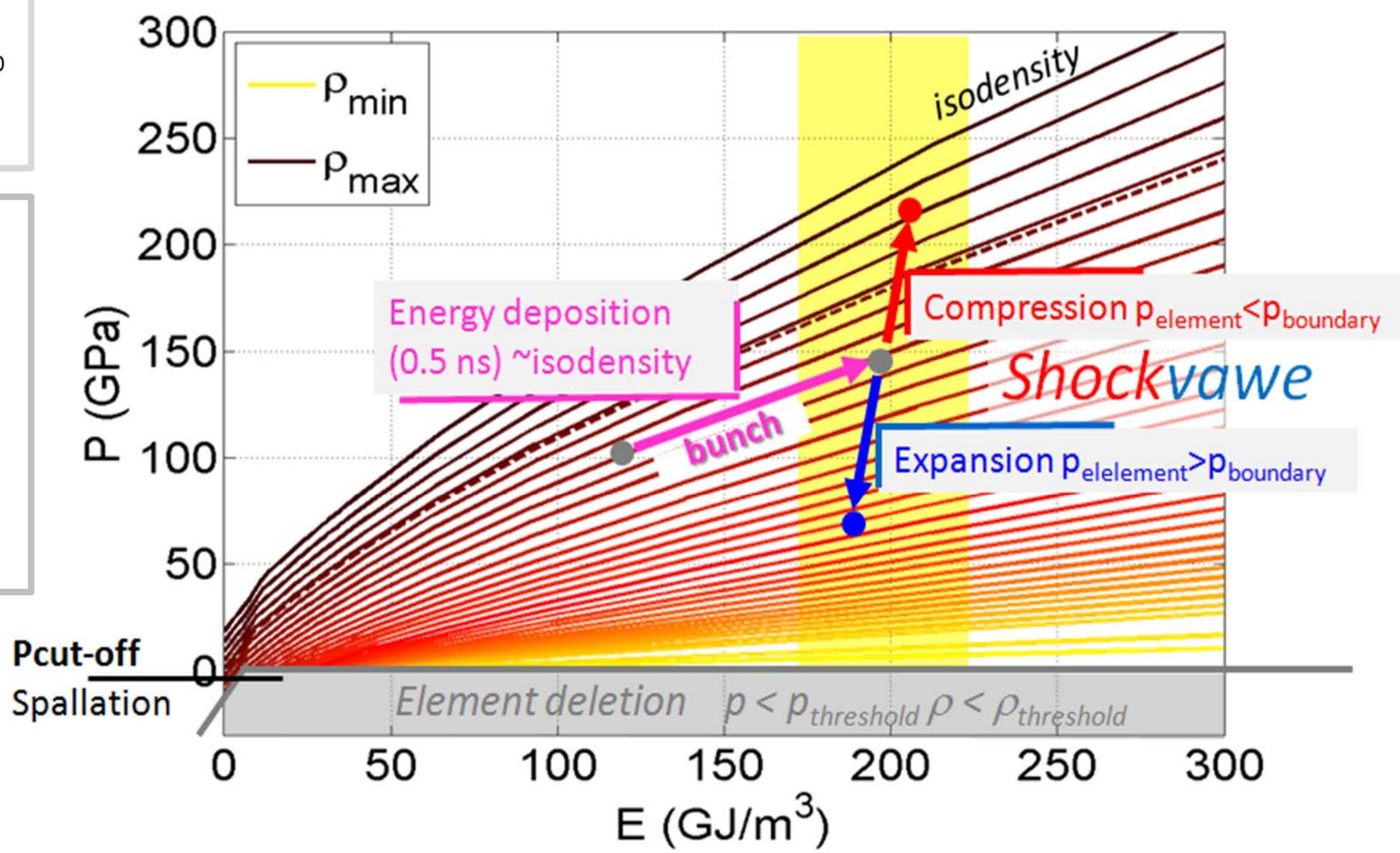
The work of H. Richter (DGS/RP) and D. Campanini (EN-MME) in developing and making available Fluka-Autodyn interfaces is also kindly acknowledged.

Bonus Slides





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



Tabular EOS

(G. Kerley)

Material Modelling

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 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}"
Remington et al.

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

Copper (FCC)
Tungsten (BCC)
New materials? Cu-Diamond, Mo-Diamond

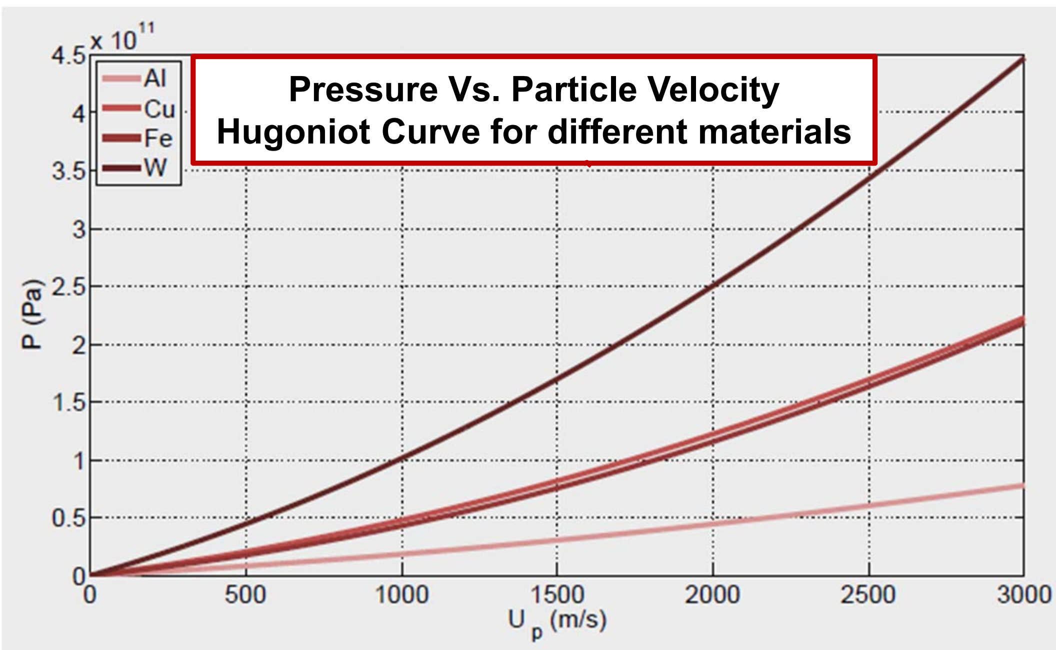
A shock Wave propagating through the interface between two solids (A and B) can be reflected and transmitted depending on the incident angle.

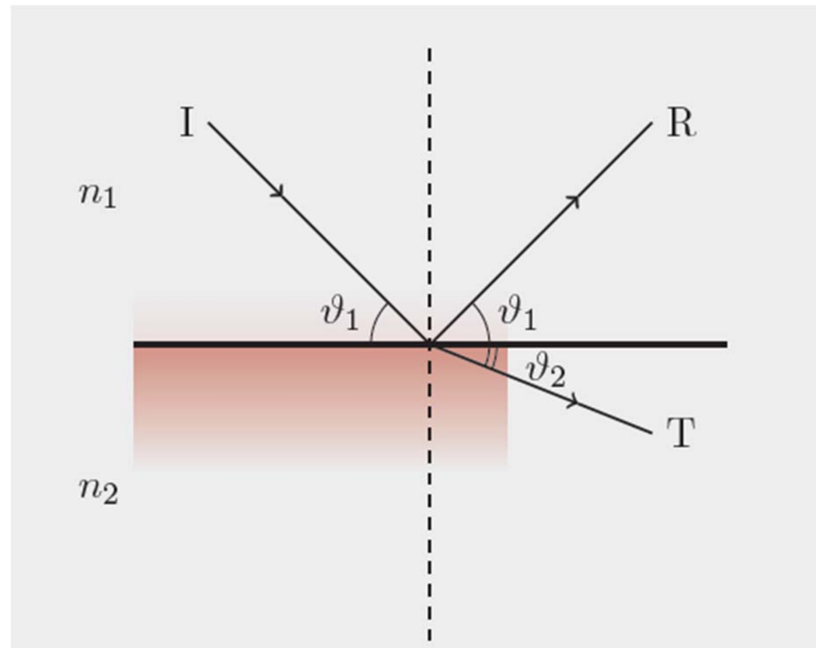
Impedance $Z=\rho_0 U_s$ (ρ_0 - initial density, U_s - sound speed inside the material)

We can define 3 cases:

- ✓ $Z_A > Z_B$ ➔ Reflected and Incident Pressure Waves have opposite sign;
- ✓ $Z_A = Z_B$ ➔ The Incident Pressure Wave is totally transmitted (No reflected Pressure Wave);
- ✓ $Z_A < Z_B$ ➔ Reflected and Incident Pressure Waves have same sign.

Through the interface W-Cu (with $Z_W > Z_{Cu}$) the Pressure Wave is reflected with opposite sign.

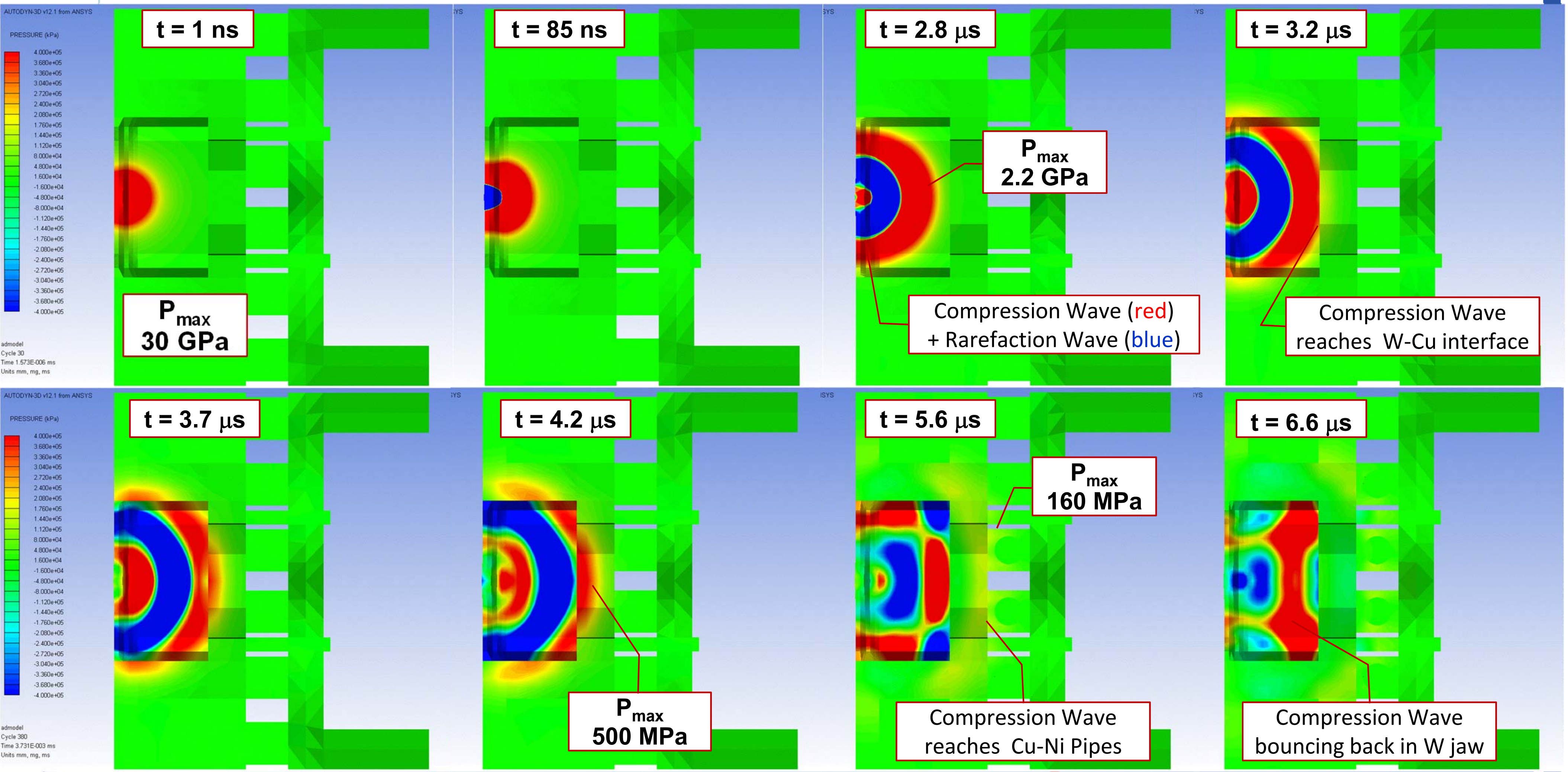




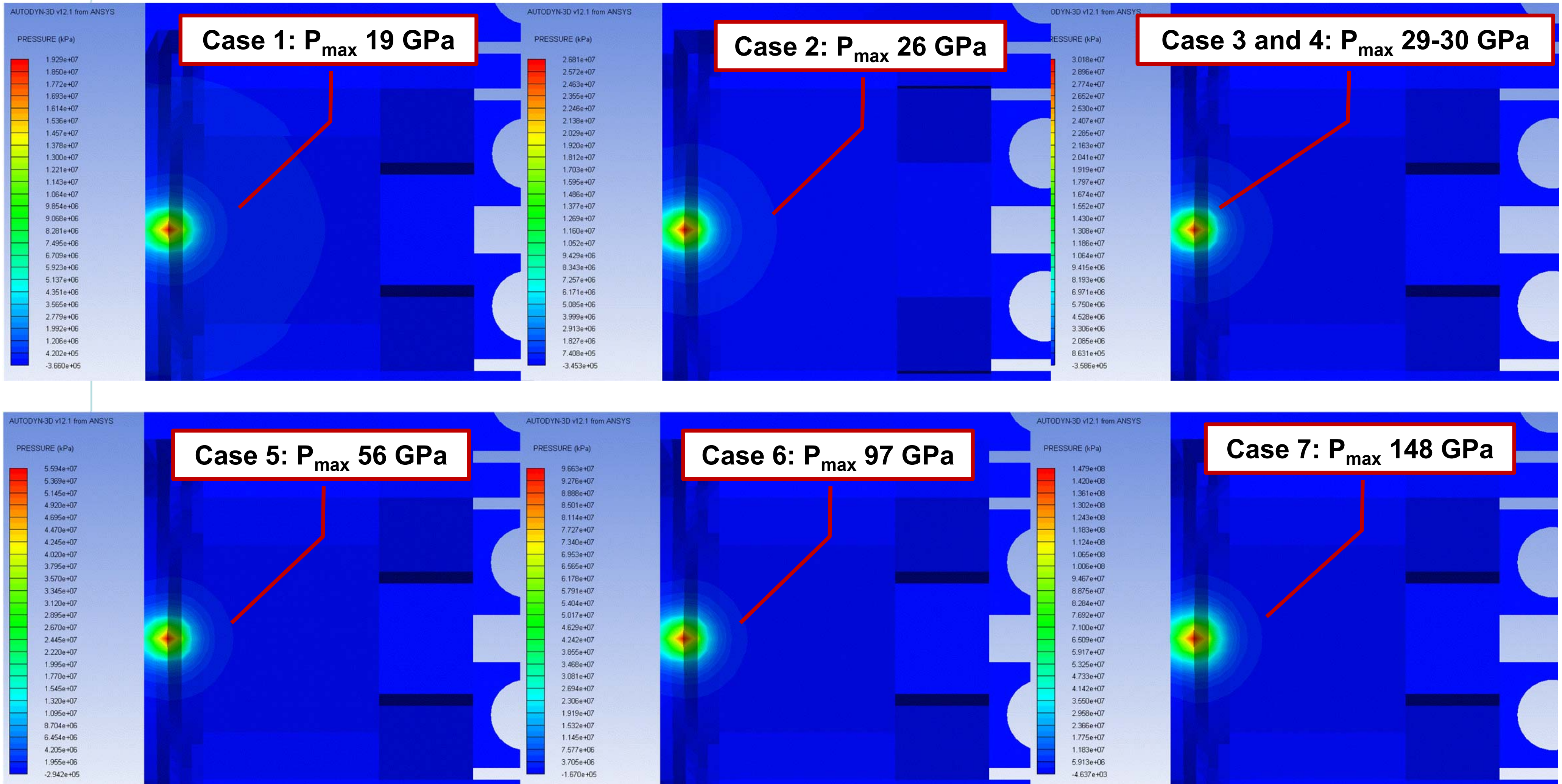
A. Dallocchio - CERN

Backup slide -- Damage Level 1 (In-situ spare surface)

- **Shock-wave propagation (5TeV Single-bunch impact)**
- Damage is confined to W as energy escaping W blocs is limited (**shock impedance** at W-Cu barrier).

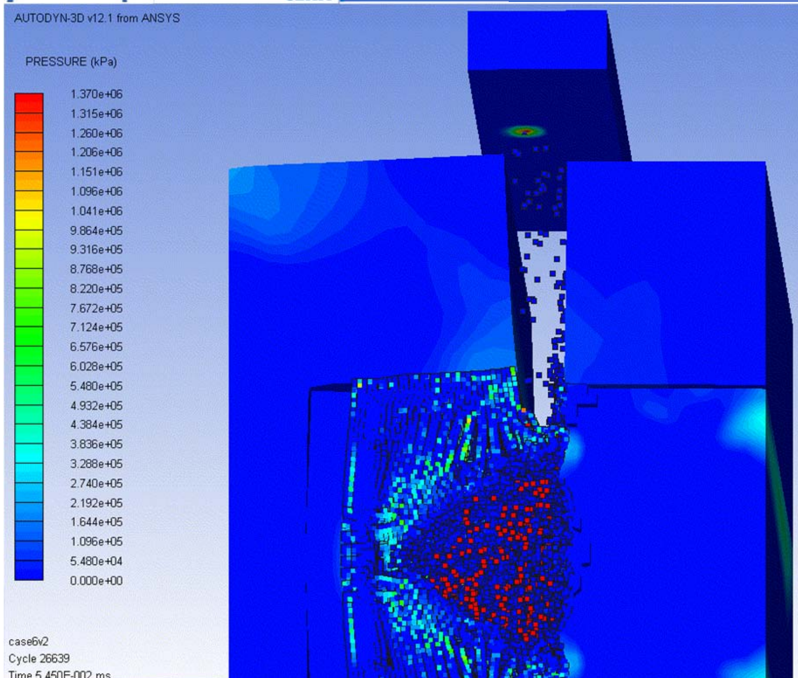


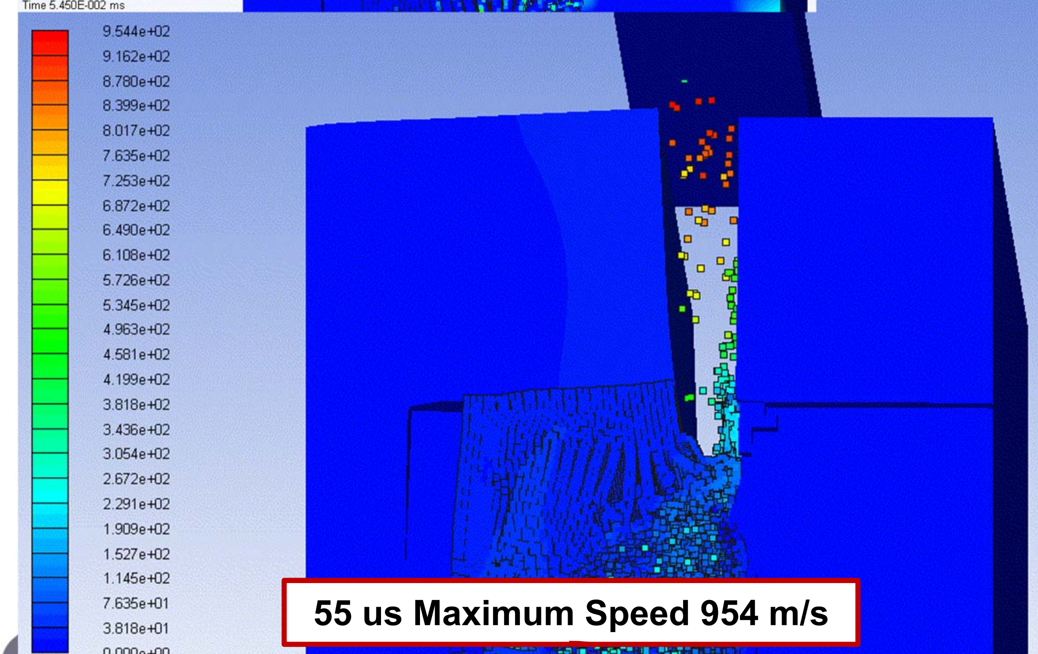
- Single-bunch cases: Maximum Pressure ≤ 30 GPa
- 8 bunches case reaches 148 GPa

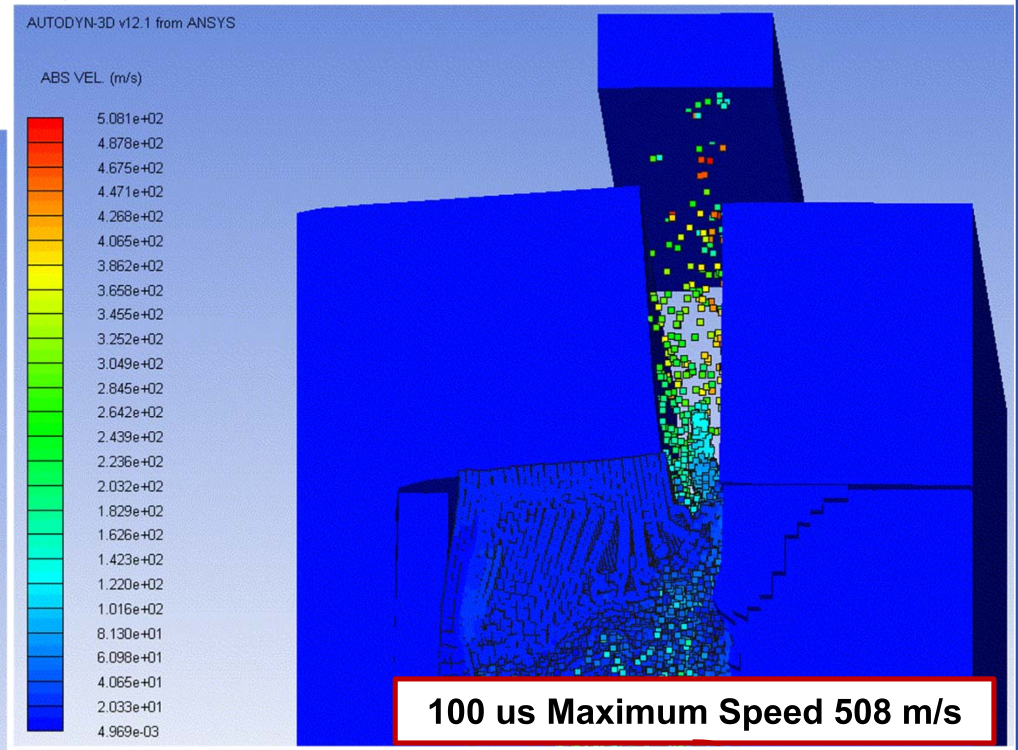


Particle Impact on Tank

- The generated particle spray hits the Stainless Steel Tank after ~55us generating a Pressure Peak about 1.37 GPa on Tank inner surface, but without plastic deformations on Tank even after 100 us
- Maximum Impacting Speed 954 m/s at 55 us, limited to few SPH particles. At 100 us the maximum speed is limited to 508 m/s.







- The maximum pressure on water in the single-bunch cases is 200 bar, above the tested value of 120 bar but without provoking damages to the copper pipes
- The energy deposited during the impact on the water is negligible, leading to an increase of temperature smaller than 0.1 K and to a pressure of less than 1 bar. Therefore the incoming pressure on water is only due to the wave propagation