# Computational Tools II: Explicit Simulations

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MECHANICAL & MATERIALS ENGINEERING
FOR PARTICLE ACCELERATORS AND DETECTORS

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# Outline

- More on Implicit vs. Explicit codes
- Material constitutive models
- Examples of explicit simulations for particle accelerators
  - Design & Fabrication
  - Response to accidental cases with beam
- Summary

# Implicit vs Explicit codes

| Implicit codes | Explicit codes |
|---|---|
| Unconditionally stable | Conditionally stable |
| Large time steps | Small time steps |
| Matrix inversion | «Lumped» matrix multiplication |
| Coupled equations | Uncoupled equations |
| Convergence problem | «Keep going» |

- What about **explicit codes drawbacks**?
  - **Conditionally stable method**: instabilities if time step “too large”
  - Time step shall be sufficiently lower than **a critical time step**
  - Critical time step: minimum time step needed for a stress wave to propagate between one element and the adjacent one

$$\Delta t < \frac{L}{c} \sim L\sqrt{\frac{\rho}{E}}$$

$L - element\ length$
$c - wave\ propagation\ speed$
$E - Young's\ modulus$
$\rho\ - mass\ density$

# Implicit vs Explicit codes

$$\Delta t < \frac{L}{c} \sim L\sqrt{\frac{\rho}{E}}$$

**Example**

- 1x1x1 mm$^3$ elements
- Material: steel ($\rho$ 7.8 g/cm$^3$, E 210 GPa)
- Critical time step: **0.2 μs**!

- Even for a "standard" mesh size and material, critical time step very small!
- If the time domain of the simulated phenomenon **is very short**, this is not a huge problem:
  - **Particle beam impact on targets:** duration ~ few μs → **some hundreds of cycles/integration steps**
- If the simulated phenomenon **is "slow" transient or static**, this can be a big problem for an explicit simulation:
  - Bending oscillation of a structure with first mode 50 Hz → duration n * 20 ms → **>10$^5$ cycles**
  - Quasi-static problem, duration of tens of seconds → **>10$^8$ cycles**

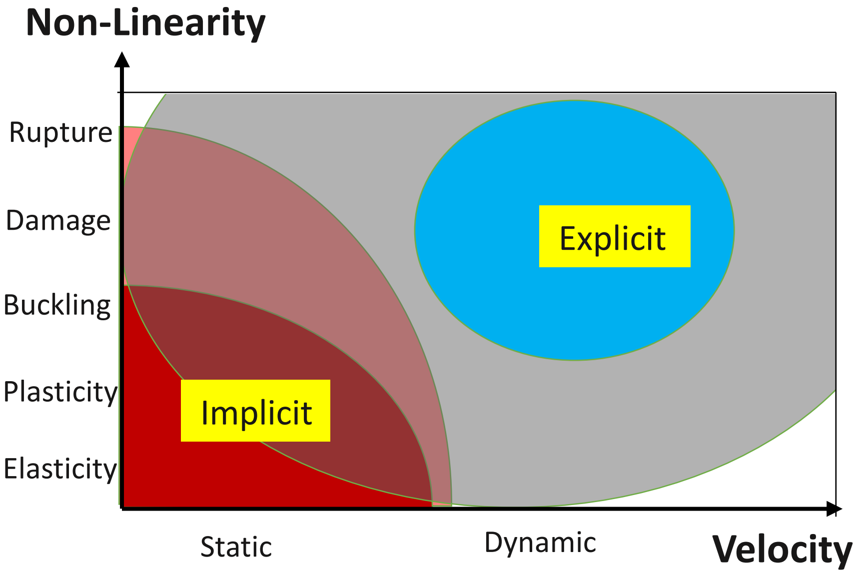
# Implicit vs Explicit codes

**Implicit**

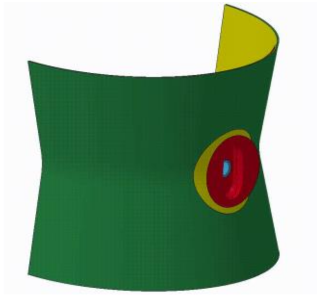
**Explicit**

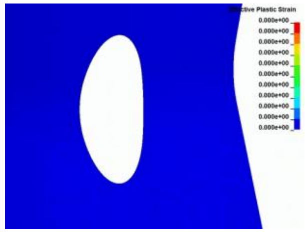
- **Structural dynamics/statics:**
  Low frequency response, vibration, static application, springback
  quasi-static, boundary conditions affect the structure slowly, for low strain rates/velocity,

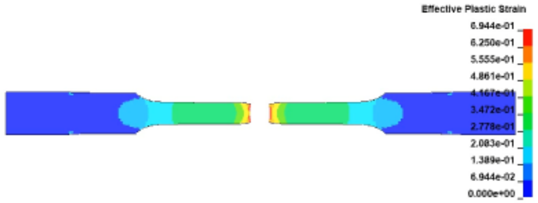
- **Short time dynamics:**
  High frequency response, wave propagation
  For large deformation, dynamic problems, for high strain rates/velocity, highly non-linear problems

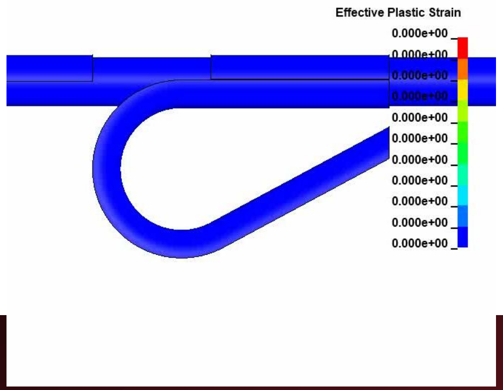


What about those?

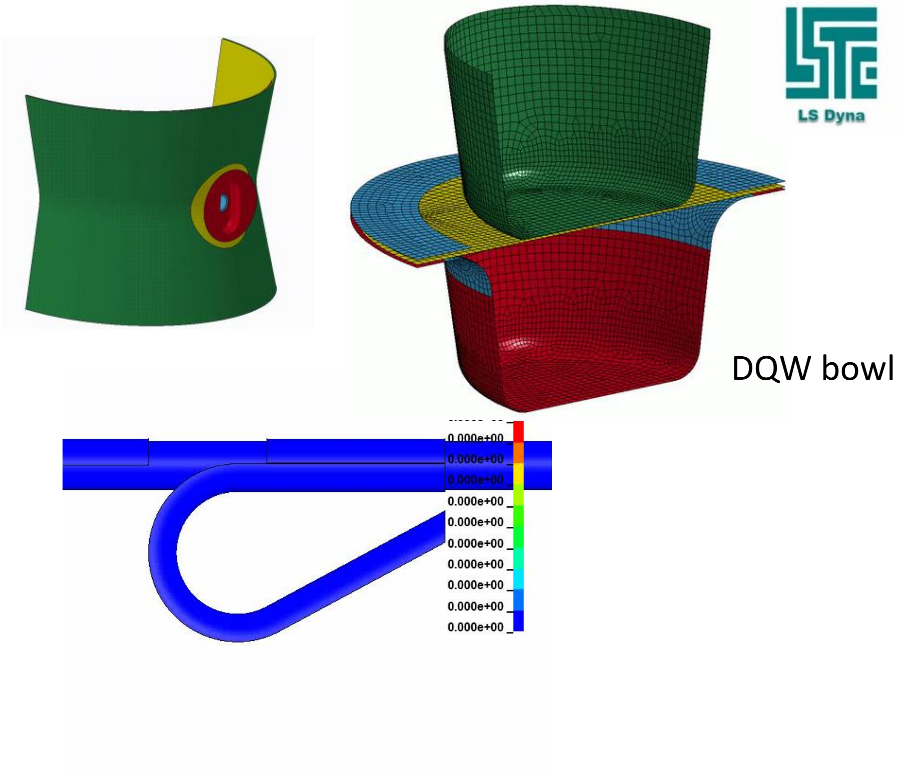




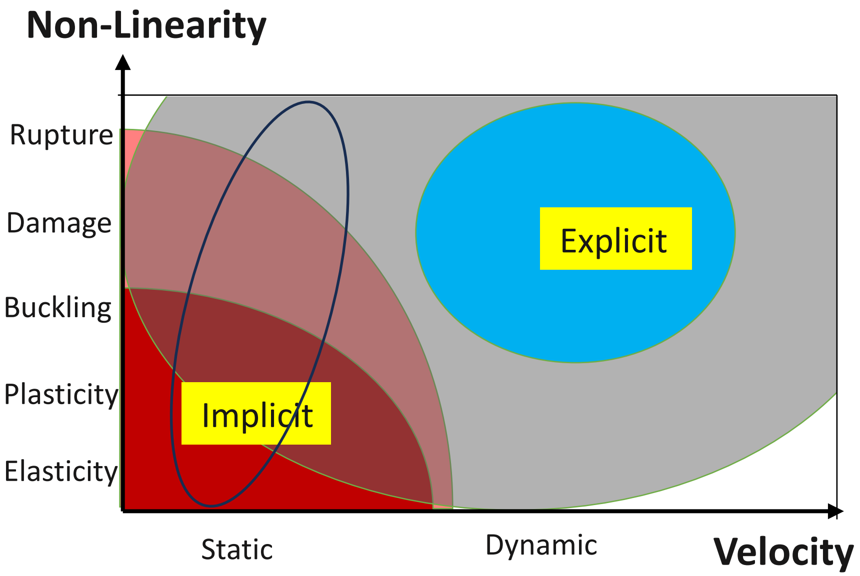




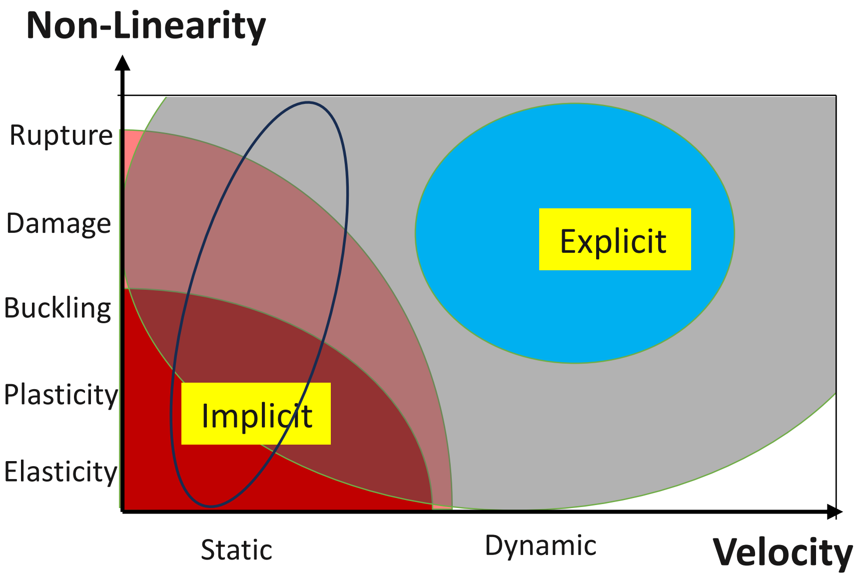
# Implicit vs Explicit codes



- Simulating **fabrication processes with large plastic deformations**: slow, but with strong non-linearities!
- We are in this “blurred” region between Implicit & Explicit, no evident answer!



# Implicit vs Explicit codes



- At CERN, to simulate forming, deep drawing, bending, etc. we resort to **Explicit codes**
- We need then to overcome the limitation related to the small time step / **too long computing time**

$$\Delta t < \frac{L}{c} \sim L\sqrt{\frac{\rho}{E}}$$

$$n \cdot \Delta t = t_{tot}$$

$n - number\ of\ cycles, \propto \boldsymbol{computing\ time}$

$t_{tot} - \boldsymbol{physical\ phenomenon\ duration}$

# Explicit codes: dealing with long simulations

…and… increasing/optimizing the
mesh size is always important!

$$\Delta t < \frac{L}{c} \sim \textcolor{red}{\bigcirc\!\!\!\!\!L}\sqrt{\frac{\rho}{E}}$$

Either we (artificially) increase the density → **“mass scaling”**

$n - number\ of\ cycles, \propto \boldsymbol{computing\ time}$

$t_{tot} - \boldsymbol{physical\ phenomenon\ duration}$

$$n \cdot \Delta t = t_{tot}$$

Or we (artificially) decrease the
phenomenon duration → **“time scaling”**

# Explicit codes: dealing with long simulations

How to reduce your simulation time?

## Time scaling

**accelerate your process duration**

- ➢ Artificially increasing the tool/object velocity (higher than in real process)

But **accelerating too much** can introduce **artificial dynamic effects**. How to check it?

- Visual inspection – severe dynamic effects can be seen in the simulation graphics;
- Check if Energy Ratio=1,(Energy Ratio = total energy / (initial energy + External work)); peaks of variation should be small
- Kinetic Energy / Internal Energy should be low

**Note:** Parameters which depends on the velocity such strain rate should be adjusted in this case!

## Mass scaling

**add mass to the system** to increase the time step defined by the Courant's stability criteria (critical timestep criterion)

- ➢ Artificially increasing the material density for selected parts/elements (manual method)
- ➢ Automatic mass scaling proposed by software (selective scaling: add mass only to the elements with the lowest time step)

But **adding too much mass** can introduce **artificial dynamic effects**. How to check it?

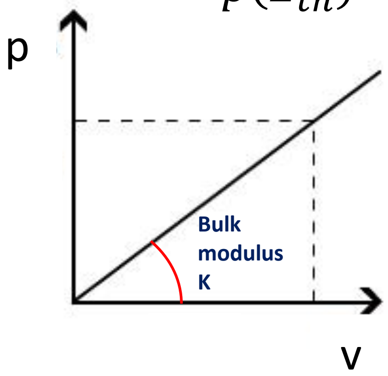
- Check value of added mass
- Limit percent increase (percentage of extra mass added in relation to the system mass, less than 5%)

# Material constitutive models

## Implicit

### Linear Equation of State

$$p(E_{th}) = \frac{\alpha K}{\rho_0 c_v} E_{th}$$



### Strain-rate-independent Yield

$$\sigma = f(\varepsilon, T)$$

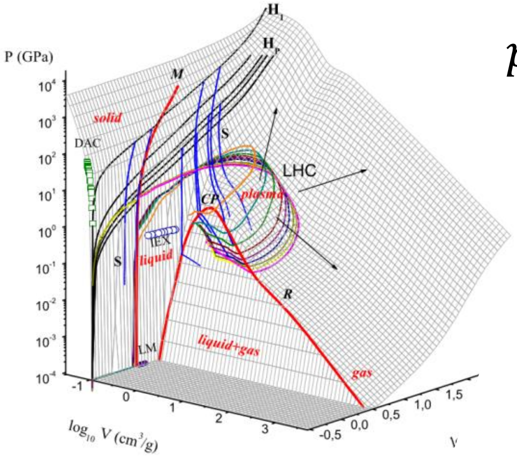
- ✓ Hollomon
- ✓ Ludwik
- ✓ Multilinear
- ✓ …

### Static Failure Strength

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

## Explicit

### Polynomial and tabular Equations of State



$$p = f(\rho, E_{th}, T)$$

- ✓ Phase changes
- ~~ate transitions
- regions

**More sophisticated material models: but also more difficult to build / retrieve!**

### Multi-parameter Yield Models

$$\sigma = f(\varepsilon, \dot{\varepsilon}, T)$$

- ✓ Johnson-Co
- ✓ Steinberg-Guinan
- ✓ Johnson-Holmquist
- ✓ ….

### Dynamic Failure Models

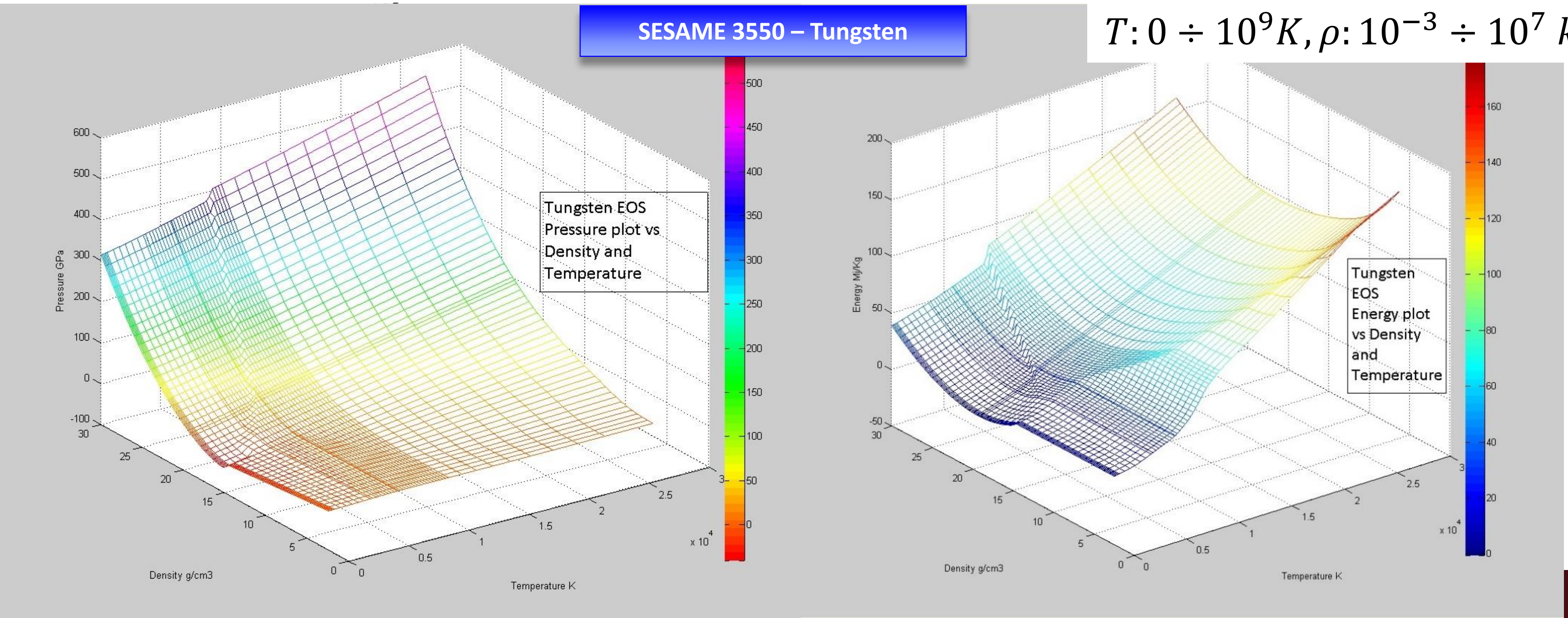
Damage $D = f(\varepsilon, \dot{\varepsilon}, T, \bar{\sigma} \dots) < 1$

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

# Material constitutive models: EOS

- The EOS expresses the relation **pressure / density / energy** (or T)
- Explicit simulations often used when change of phase is involved (melting, vaporization, plasma) → need to take into account **phase transformations**!
- Most sophisticated type of equation of state: Tabular EOS. At CERN, we have access to the **most complete tabular EOS library in the world** (**SESAME** from Los Alamos National Laboratory)

$T: 0 \div 10^9 K, \rho: 10^{-3} \div 10^7\ kg/m^3$



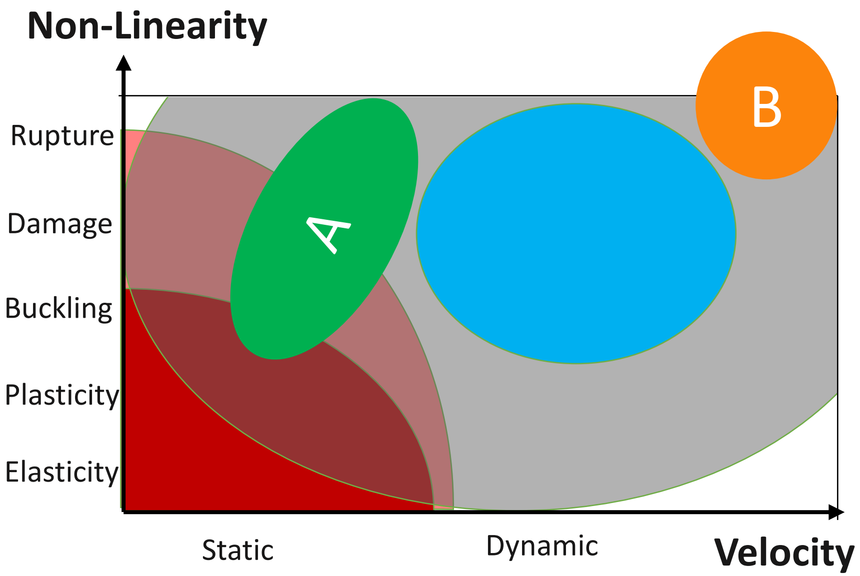
# Explicit simulations at CERN

In MME, we resort to **explicit codes in two main fields**:

1. Optimization / tuning of **large-deformation manufacturing processes** (e.g. forming, deep drawing, bending, etc.), objectives:
    - Choice of the best material
    - Design of fabrication tools
    - Definition of process parameters (loading history, temperature, friction coefficients, annealing treatments, etc.)
    - Benchmarking with post-production metrology
2. Response of accelerator components to **accidental or operational beam-impacts**
    - Assess survival of the component
    - Exclude major failure of the containment (vacuum tank, cooling circuit)
    - Evaluate presence of hydrodynamic tunnelling

# Explicit simulations at CERN

1. Optimization / tuning of **large-deformation manufacturing processes** (e.g. forming, deep drawing, bending, etc.) → **Region "A"** → relatively long process duration, very high non-linearities
2. Response of beam intercepting devices (BID) to **accidental or operational beam-impacts** → **Region "B"** → Very short duration, extreme non-linearities with changes of phase



# Examples of Explicit simulations

# Optimization / tuning of large-deformation manufacturing processes

LS-DYNA

# Hydroforming

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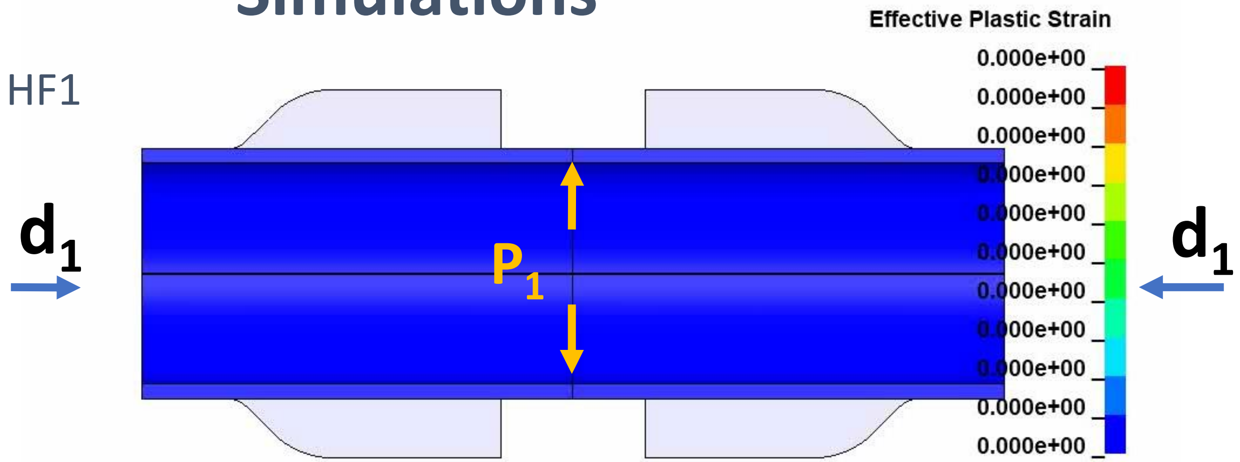
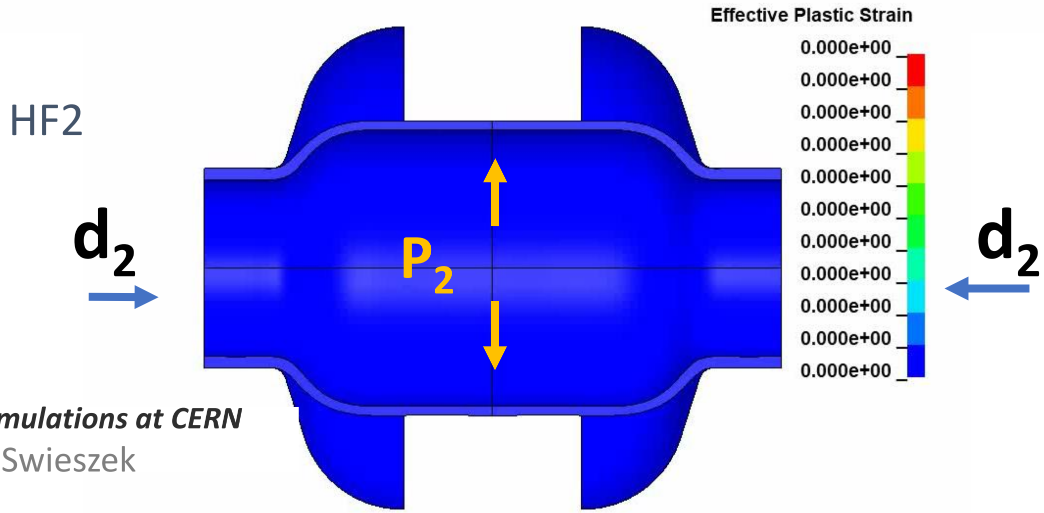
atic

# Hydroforming

LS-DYNA

## Simulations

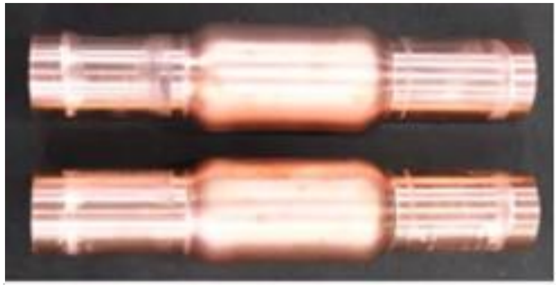




***Simulations at CERN***

J. Swieszek

## Manufacturing



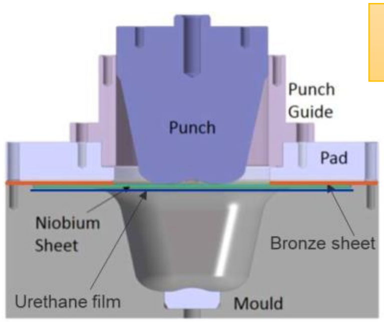
4x Seamless cavities produced in few hours

***Produced by KEK***

M. Yamanaka, A. Yamamoto

# Deep drawing

- Also used in the manufacturing of RF cavities of complex shape
- Example: superconductive RFD crab cavity for HL-LHC (niobium)



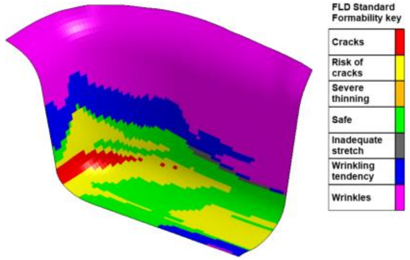
Niobium forming

**Lot-1 (forming OK)**

**Lot-2 (forming NOK)**

**Very different outcome!**

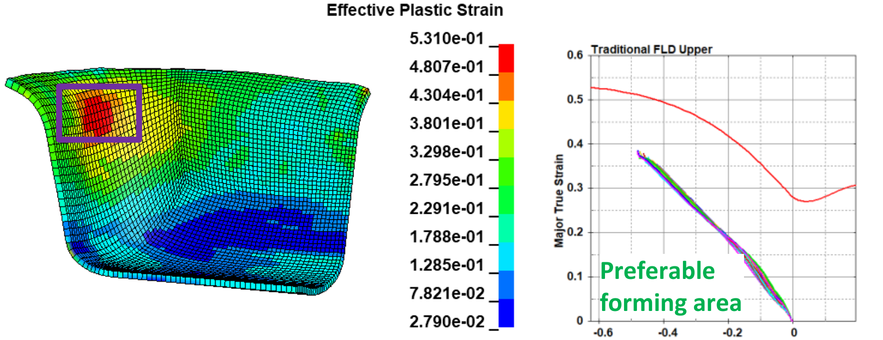
- Same material specification
- Same material supplier
- **2 different material lots**
- Same tooling
- Same operators
- Same forming procedure
- Same press machine



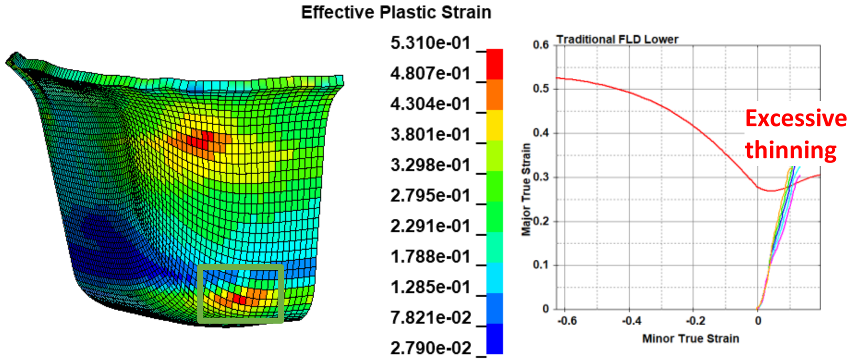
**Why?**

# Deep drawing

In-depth analysis of material used!
Activities in full synergy with EN-MME Material, Metrology & NDT section

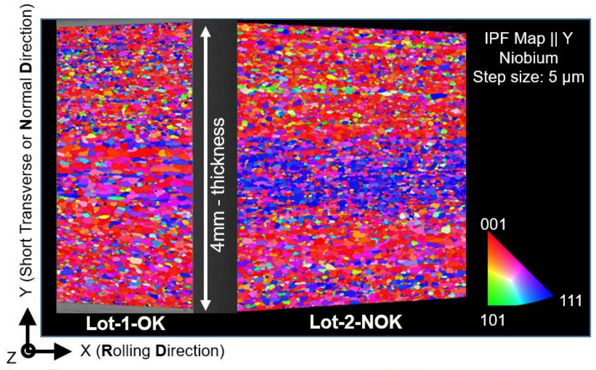


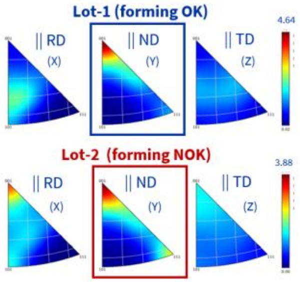
REGION 1. MAX strain



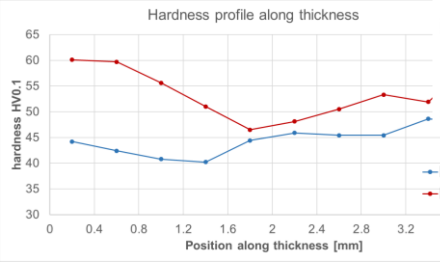
REGION 2. Failure strain

***Simulations at CERN***
J. Swieszek





***Crystallographic orientation and texture***
A. Gallifa Terricabras, S. Pfeiffer



***Hardness profiles***

**R&D NIOBIUM FORMING**
Nb material model
- Anisotropy
- Strain rate sensitivity

Improved failure model

# Particle beam impacts on accelerator structures

# Particle beam impacts

- When a **particle beam hits an accelerator structure**, it transfers its kinetic energy to the structure under the form of heat
- We call this case **"quasi-instantaneous heating"** because the duration of the impact (ns, μs) is very small compared to the time constants of the problem:

$$\boldsymbol{t_d <, \ll \tau_{th}, \tau_{mech}}$$

$$\tau_{th} = \frac{L^2}{a} \quad \left(a = \frac{k}{\rho c_p}\right)$$

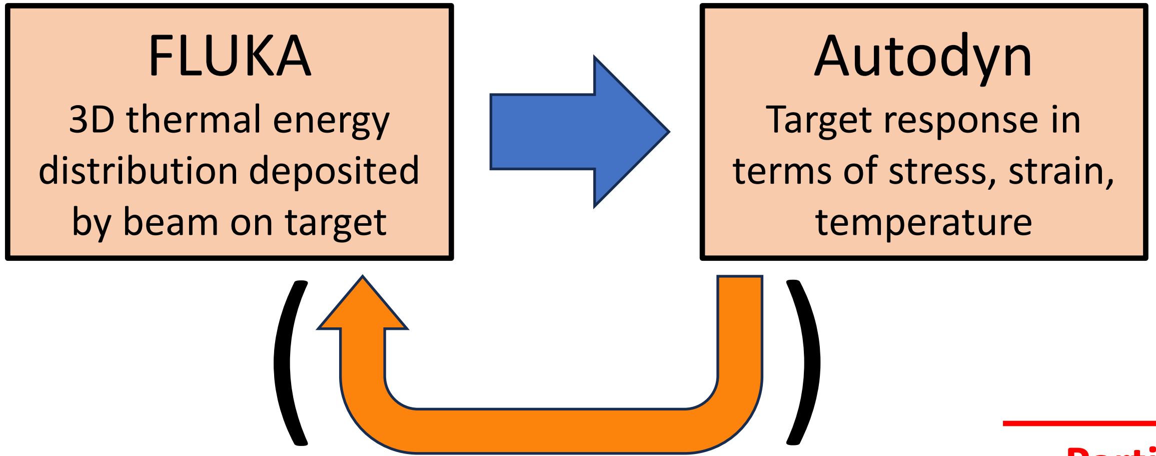
$$\tau_{mech} = \frac{L_c}{c}$$

*$\tau_{th}$: thermal time constant*
*$\tau_{mech}$: mechanical time constant*
*$L_c$: characteristic dimension of the system*
*a: thermal diffusivity*
*k: thermal conductivity*
*$\rho$: density*
*$c_p$: specific heat*
*c: wave speed (speed of sound in the elastic domain)*

- Short time phenomenon, high non-linearity (melting, vaporization, fragmentation) → typical domain of **explicit codes**!
- Tool of preference for this scenario, at CERN, is **Autodyn** (self-implemented SESAME EOS, etc.)

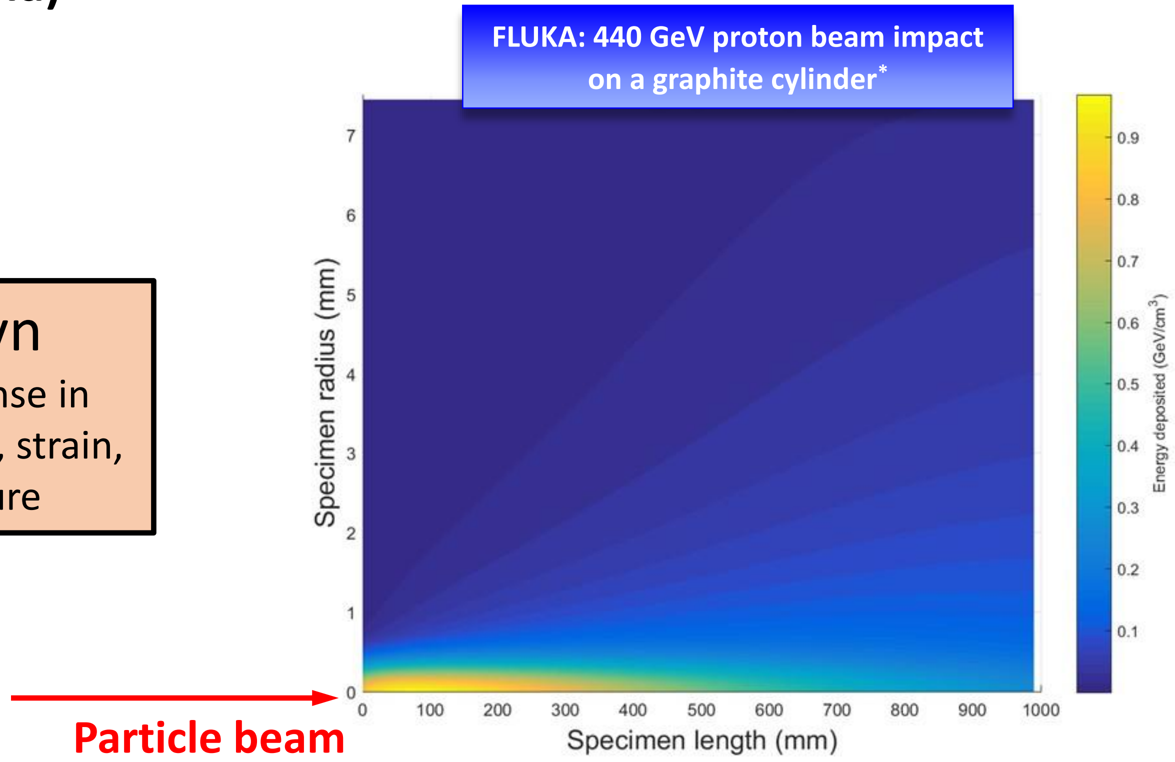
# Particle beam impacts

- Thermal energy deposited on the target can be evaluated through Monte-Carlo interaction and transport codes *e.g*. **GEANT4**, **MARS**, **FLUKA** (CERN, SY-STI)
- 3D energy density FLUKA maps used as an **input for the thermomechanical simulations (Autodyn, LS-Dyna)**



**FLUKA**
3D thermal energy distribution deposited by beam on target

**Autodyn**
Target response in terms of stress, strain, temperature



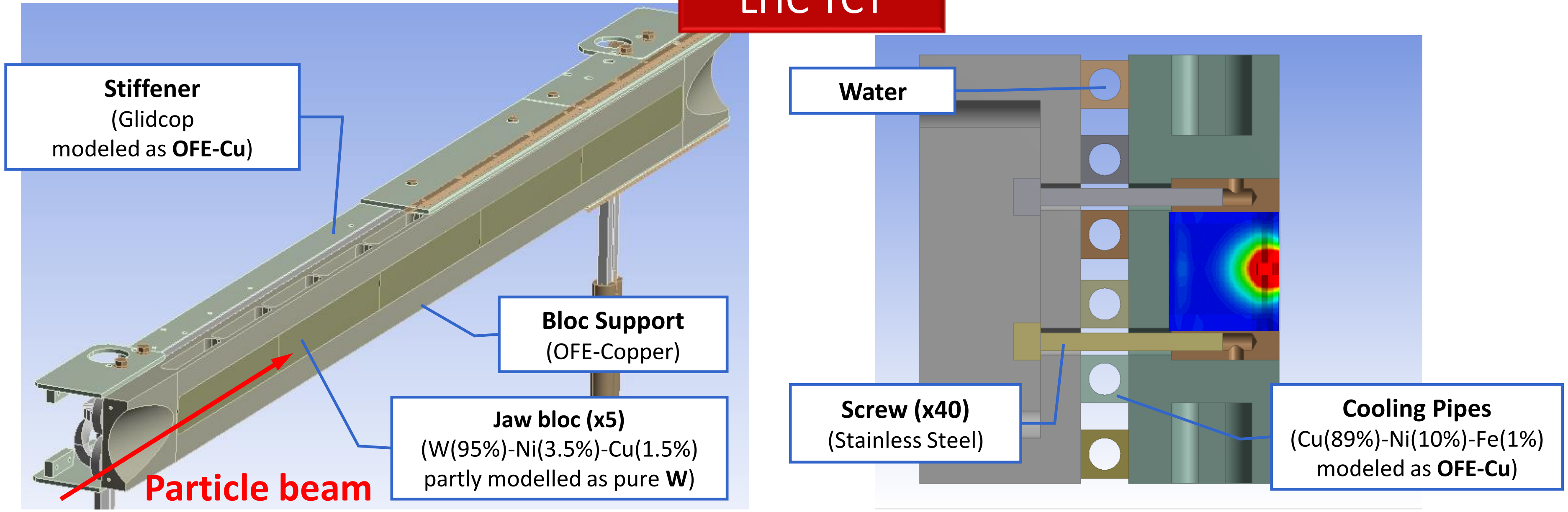
**FLUKA: 440 GeV proton beam impact on a graphite cylinder***

**Courtesy of M. Frankl, CERN, SY-STI*

# Particle beam impacts on LHC collimators

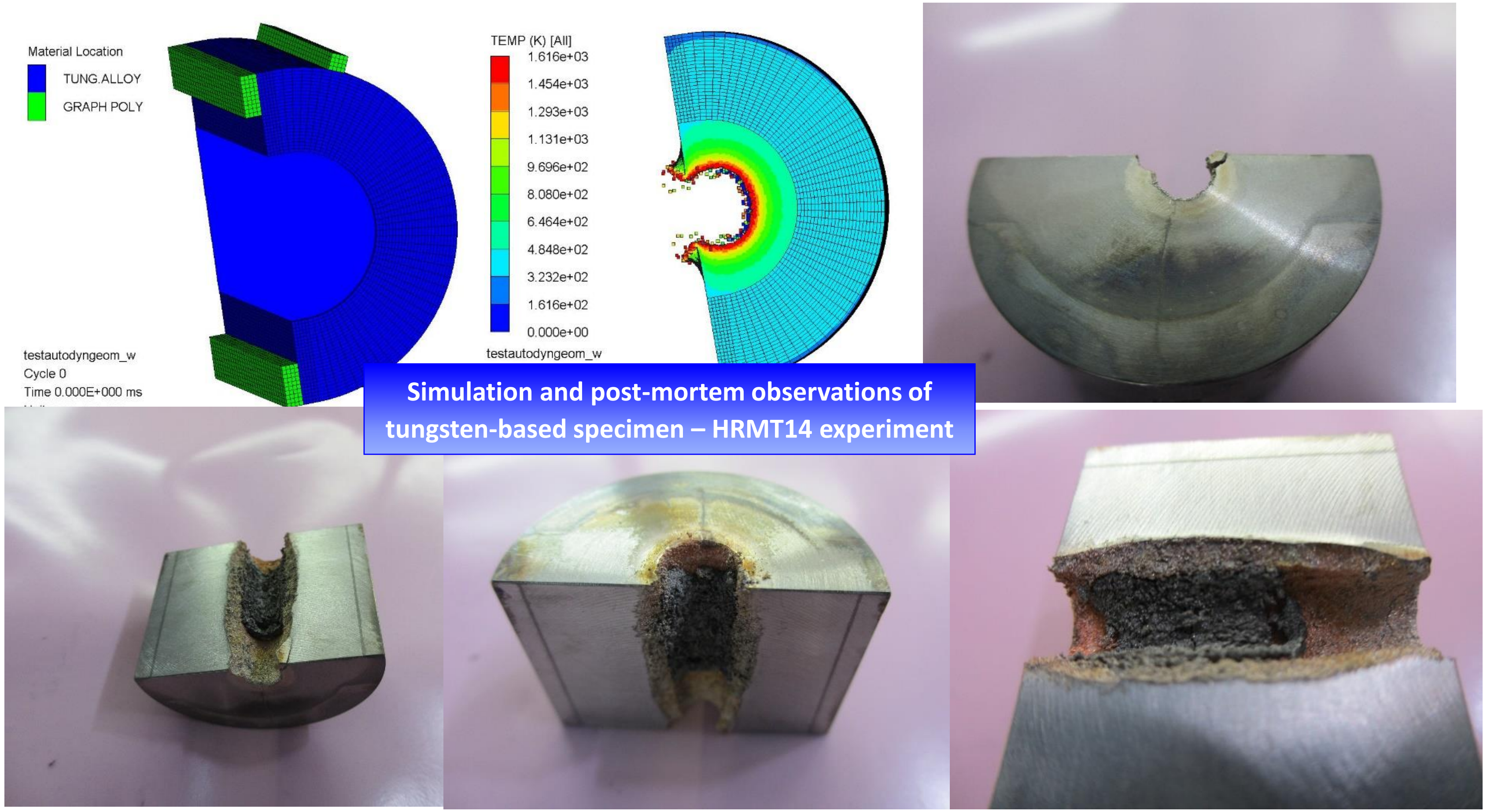
- **LHC collimators**: objects intercepting the external halo of the circulating proton beam (steady state load)
- **In accidental cases**: direct beam impact on the collimator absorber!
- Most critical case is on **tertiary collimators** (tungsten-based, dense absorber)

LHC TCT



# Particle beam impacts on LHC collimators: material testing

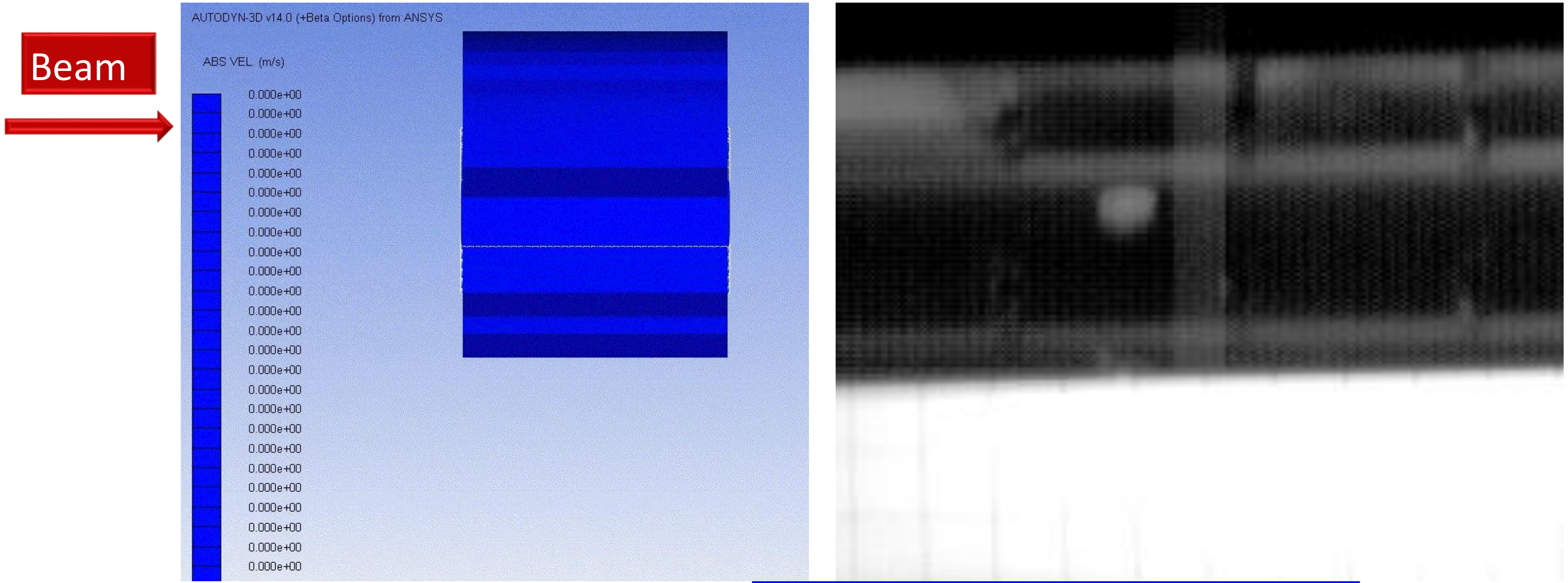
- Materials can be tested in these conditions at CERN: **HiRadMat facility**



**Simulation and post-mortem observations of tungsten-based specimen – HRMT14 experiment**

# Particle beam impacts on LHC collimators: material testing

- Materials can be tested in these conditions at CERN: **HiRadMat facility**



**Simulation and online observations of tungsten-based specimen – HRMT14 experiment**

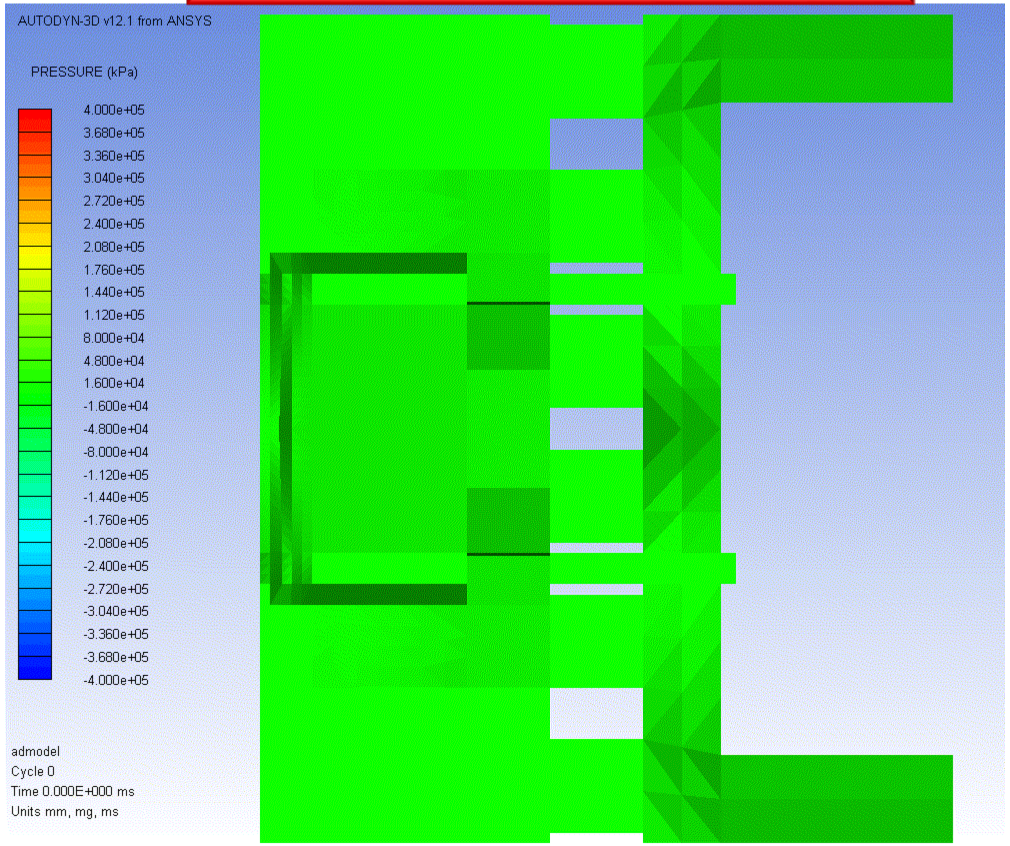
- Maximum fragment velocity:
  - Numerical 316 m/s
  - Experimental 275 m/s

# Particle beam impacts on LHC collimators

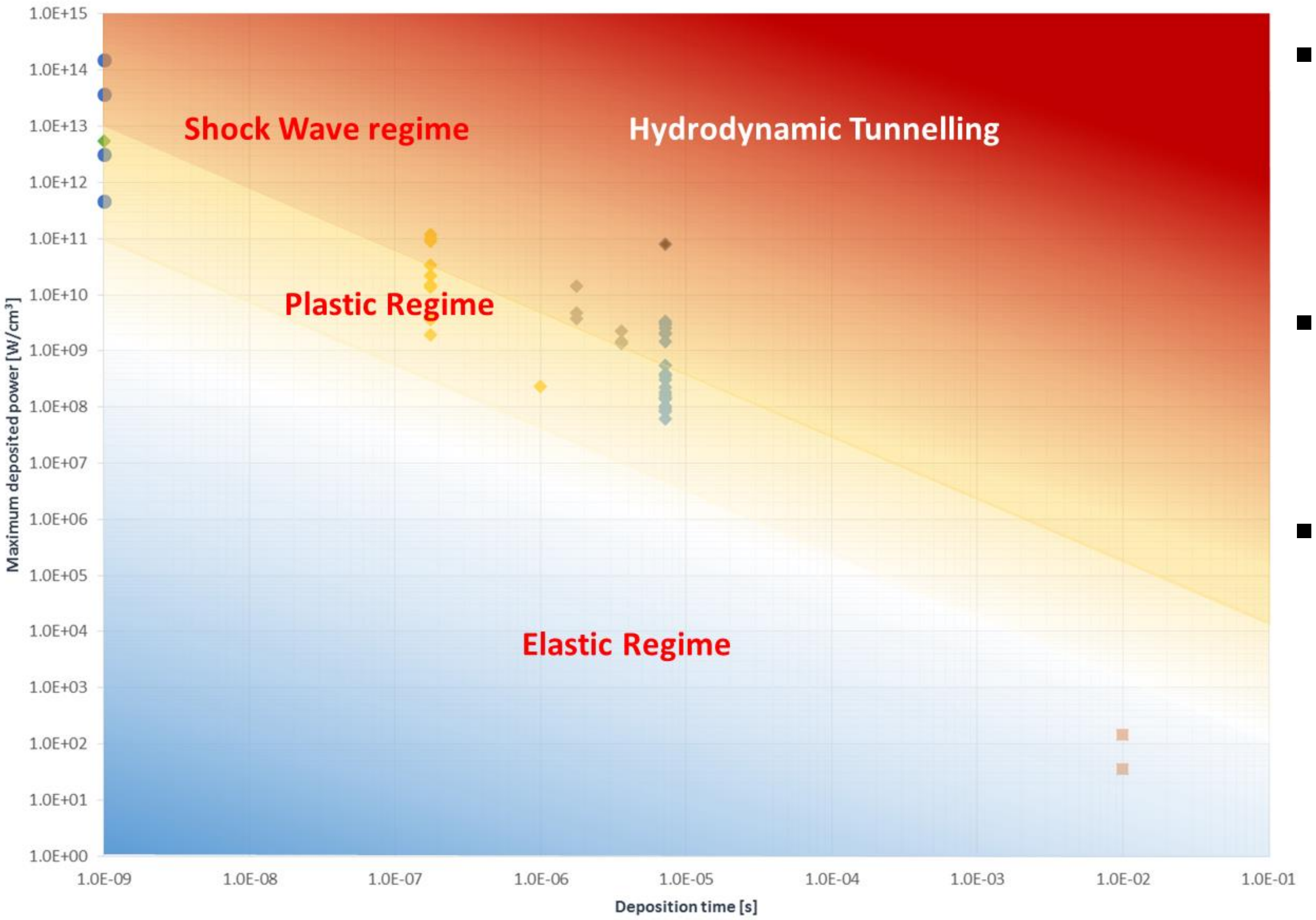
- What is the point in simulating so extreme accidental scenarios?
- Reason: we can accept failure of the absorber and replace the collimator. But **we cannot accept major failure possibly jeopardizing the close-by environment** (full vacuum sector or even outside of the tank)

- Design must ensure:
  - Resistance of the **cooling circuit**
  - Resistance of the **vacuum containment** (absorber fragments are like hot bullets!)

1 LHC bunch @5 TeV impacting TCT



# Particle beam impacts with hydrodynamic tunnelling



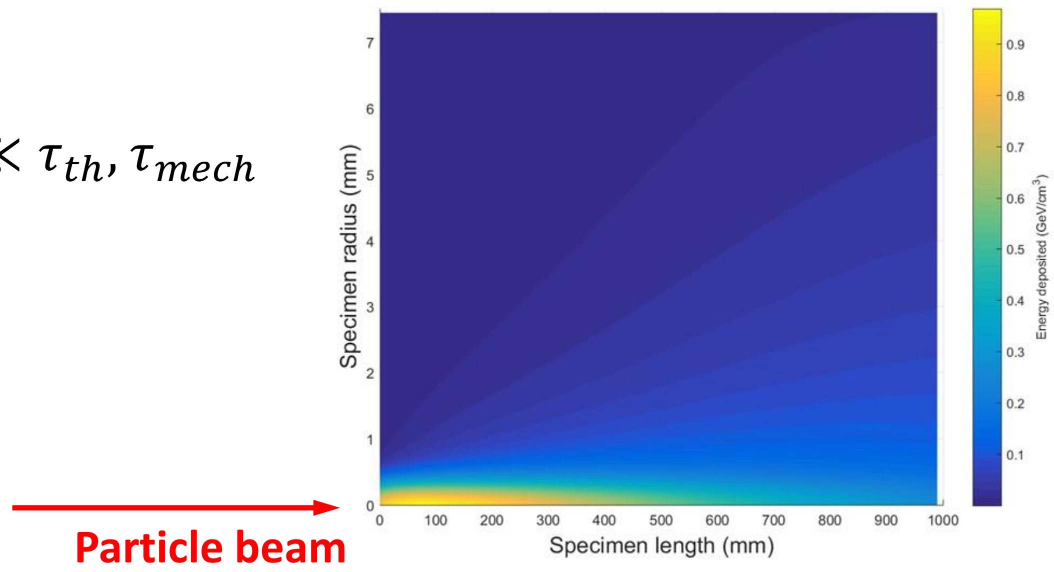
- Depending on the energy and densities, a device impacted by the particle beam will undergo **different regimes**
- Most complex to study / simulate is the **hydrodynamic tunnelling regime**
- **What's that?**

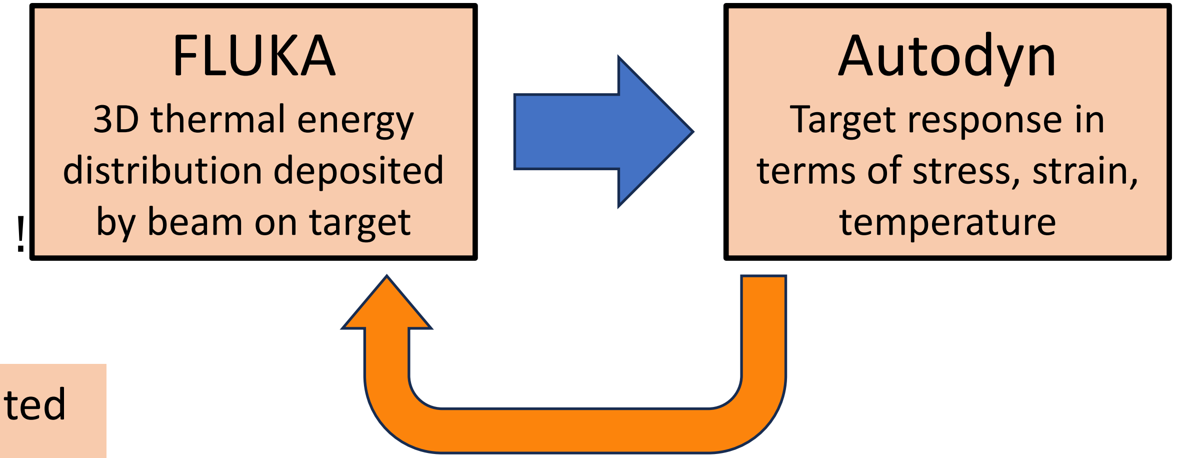
- *A. Bertarelli (2016). Beam-induced damage mechanisms and their calculation. CERN Yellow Reports, v. 2, p. 159, Jan. 2016. ISSN 00078328.*

# Particle beam impacts with hydrodynamic tunnelling

- We said, for beam impacts → $t_d <, \ll \tau_{th}, \tau_{mech}$
- With FLUKA, the simulation starts from a component with density $\rho_0$
- At the impact spot: instantaneous temperature and density change
- However, as soon as the target remains solid, the density change is small → $\rho(t) \sim \rho_0$
- At a certain time of the impact $\tau_{tu}$, change of phase occurs. There → $\rho_{\tau_{tu}} <, \ll \rho_0$ !

*Courtesy of M. Frankl, CERN, SY-STI





**FLUKA**

3D thermal energy distribution deposited by beam on target

**Autodyn**

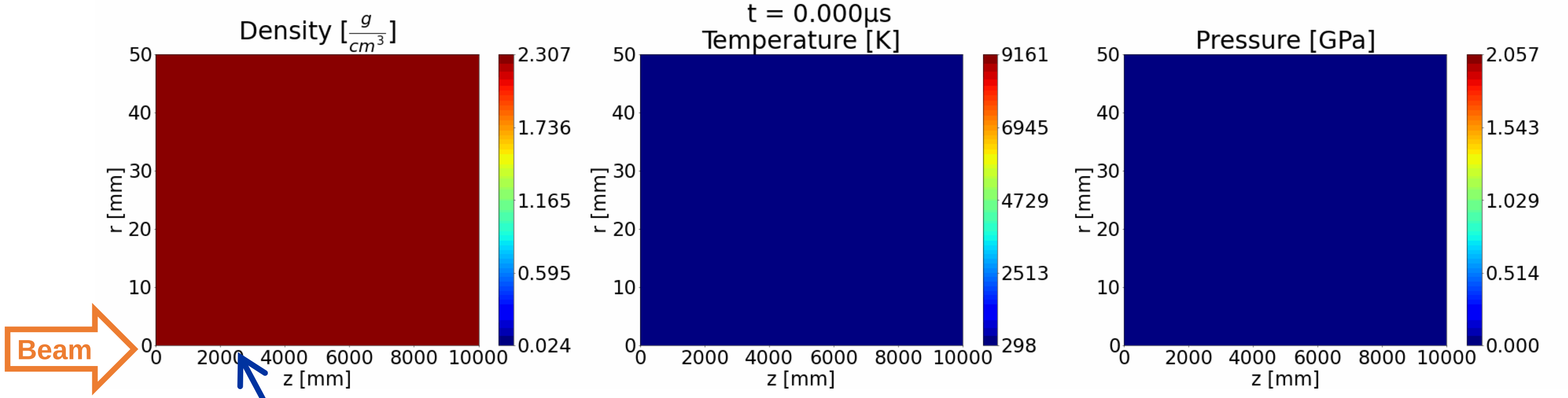
Target response in terms of stress, strain, temperature

If $t_d > \tau_{tu}$ → the FLUKA map needs to be updated with the new target density distribution

# Particle beam impacts with hydrodynamic tunnelling

In a nutshell

- **Hydrodynamic tunnelling**: the impacting beam penetrates deeper and deeper into the target, as the density of the impact region depletes over time
- If FLUKA map is not updated over time → strong underestimation of the beam penetration into the target → **could be a problem for beam dumps!**
- **Example: full HL-LHC beam impact on graphite target** ($t_d$ > 70 μs)

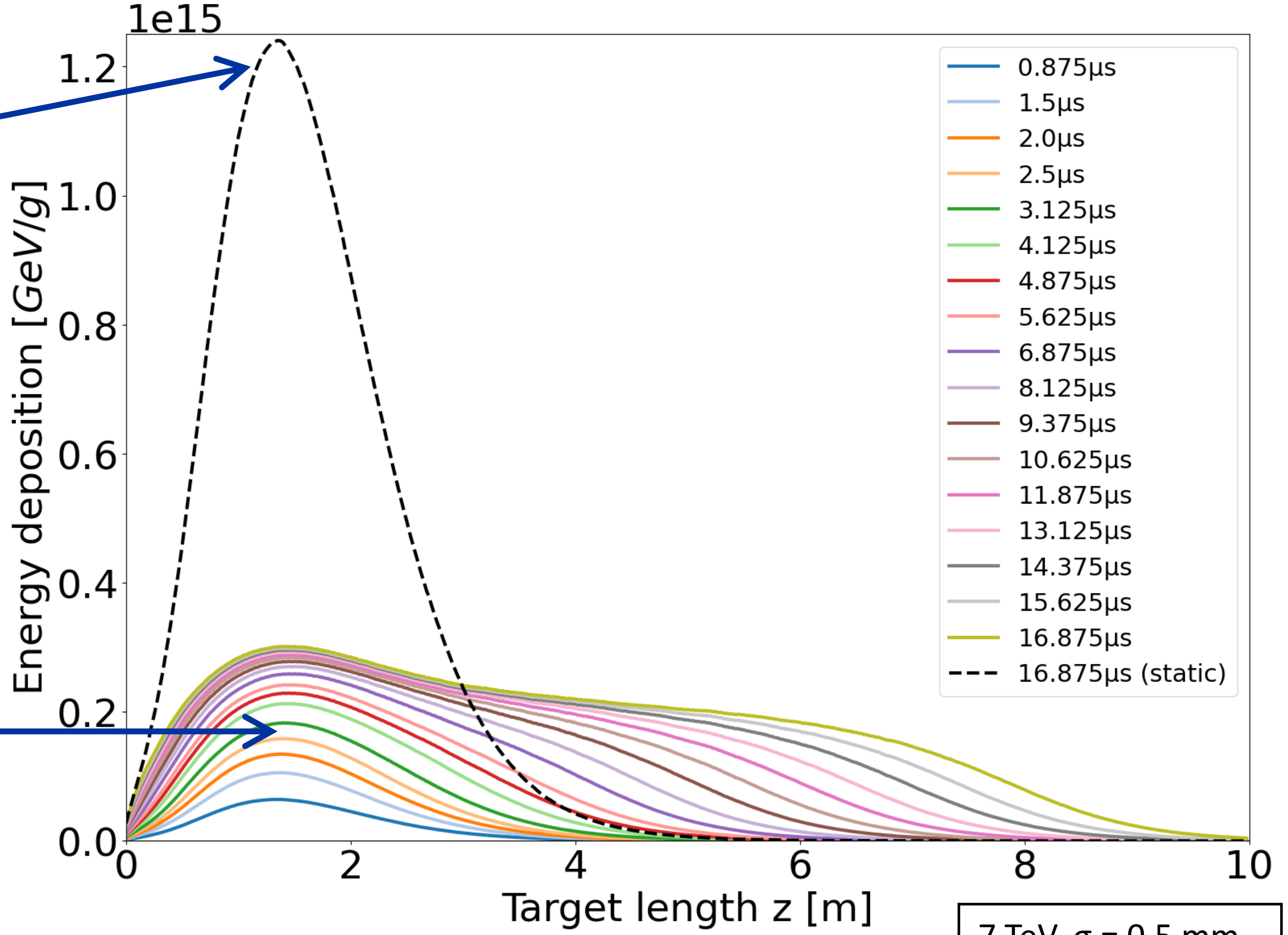


Density depleting to zero at the axis.

*Courtesy of I. Hjelle (CERN, TE-MPE) & A. Piccini (CERN, EN-MME)*

# Particle beam impacts with hydrodynamic tunnelling

No FLUKA/Autodyn coupling: **beam penetration after 70 μs into target = ~5m**



7 TeV, σ = 0.5 mm,
2.2e11 ppb

FLUKA/Autodyn coupling: beam penetration into target after 17 μs → ~10m (**and after 70 μs → ~30m!**)

**Tunnelling!**

# Computational Tools II - Summary

- At CERN, and especially in the phase of designing particle accelerator components, we **most often resort to implicit tools such as ANSYS**.
- Explicit codes usually offer a wider range of material models and possibilities for **non-linear calculations**.
- However, **defining / obtaining such models is a complex and laborious exercise**. For this reason, explicit tools are not the 1st choice at CERN.
- Specific fields that require to us the use of explicit tools such as **LS-Dyna and Autodyn** are:
  - **Large-deformation processes**, e.g. manufacturing by forming and bending
  - Accidental (or operational) **particle beam impacts on accelerator devices**
- Given the complexity of explicit simulations and material models, for this type of studies **extensive experimental testing and benchmarking** is of paramount importance.

# Bibliography

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# Symbols (1/2)

- $\Delta t$: integration time step $[s]$
- $L$: characteristic length $[m]$
- $c$: wave propagation speed $[m/s]$
- $\rho$: density $[kg/m^3]$
- $E$: Young modulus $[Pa]$
- $n$: number of integration cycles/steps$[-]$
- $t_{tot}$: total duration of the real process $[s]$
- $p$: pressure $[Pa]$
- $E_{th}$: thermal energy $[J]$
- $\alpha$: thermal expansion coefficient $[K^{-1}]$
- $K$: Bulk modulus $[Pa]$
- $c_p, c_v$: specific heat at constant pressure or volume $[J/(kg \cdot K)]$
- $\varepsilon$: strain $[-]$
- $\dot{\varepsilon}$: strain rate $[s^{-1}]$
- $T$: temperature $[K]$
- $\sigma$: stress $[Pa]$
- $\sigma_{ult}$: material ultimate strength $[Pa]$
- $D$: damage function $[-]$
- $\bar{\sigma}$: hydrostatic stress $[Pa]$

# Symbols (2/2)

- $p_s$: spallation pressure $[Pa]$
- $c_0$: sound speed $[m/s]$
- $K_c$: fracture toughness $[MPa \cdot \sqrt{m}]$
- $Y$: material yield strength in uniaxial strain state $[Pa]$
- $\tau_{th}$: thermal time constant $[s]$
- $\tau_{mech}$: mechanical time constant $[s]$
- $a$: thermal diffusivity $[m^2/s]$
- $k$: thermal conductivity $[W/(m \cdot K)]$
- $t_d$: beam impact duration $[s]$
- $\tau_{tu}$: time at which change of phase occurs $[s]$

# Thanks for your attention!

## And thanks to the many contributors:

*In random order and for sure forgetting someone:* A Piccini, J. Swieszek, G. Coladonato, T. Guillen-Hernandez, A Bertarelli, L Dassa, T. Sahner, M Timmins, M Guinchard, M Scapin, M Frankl, I. Hjelle, C. Wiesner, A Lechner, I. Lamas, O. Aberle, S. Redaelli, I. Tabian, N Vejnovic, K Artoos, A Dallocchio, B Riffaud, L Zuccalli, L Gentini, L Piacentini, I. Aviles, A Gallifa, A Amorim, A Yamamoto, N Charitonidis, F. Cerutti, L Peroni.

# Backup slides

# Modelling techniques

HYDROFORMING: 1.3 GHz single cell elliptical

**Using keywords principle** with **LS-DYNA** standalone**:**

Definition of the tube:
- *PART
- *MAT_PIECWISE_LINEAR_PLASTICITY
- *SECTION_SHELL

Definition of the die and punch:
- *PART
- *MAT_RIGID
- *SECTION_SHELL

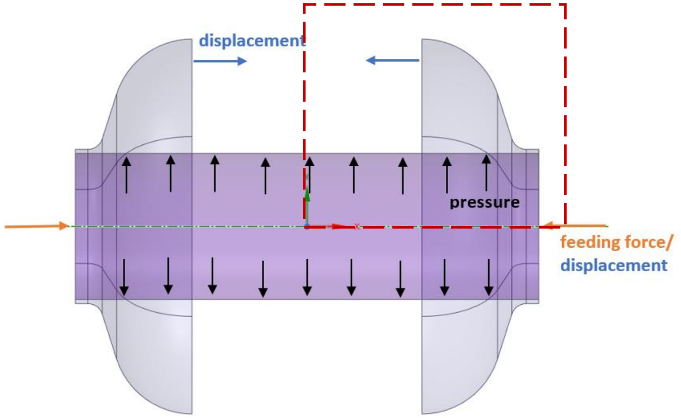
Elements will be assigned in a part
Plastic material low
Assignment of the element formulation and thickness
Tools defined as rigid

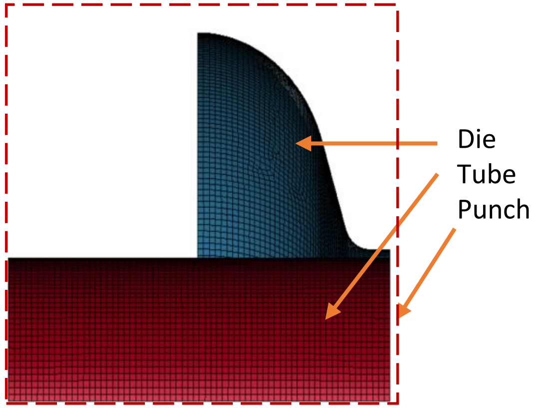
Boundary conditions:
- *BOUDARY_PRESCRIED_MOTION_RIGID
- *LOAD_SEGMENT
- *BOUNDARY SPC

Tool displacement
Applying pressure

Contact:
- * CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE

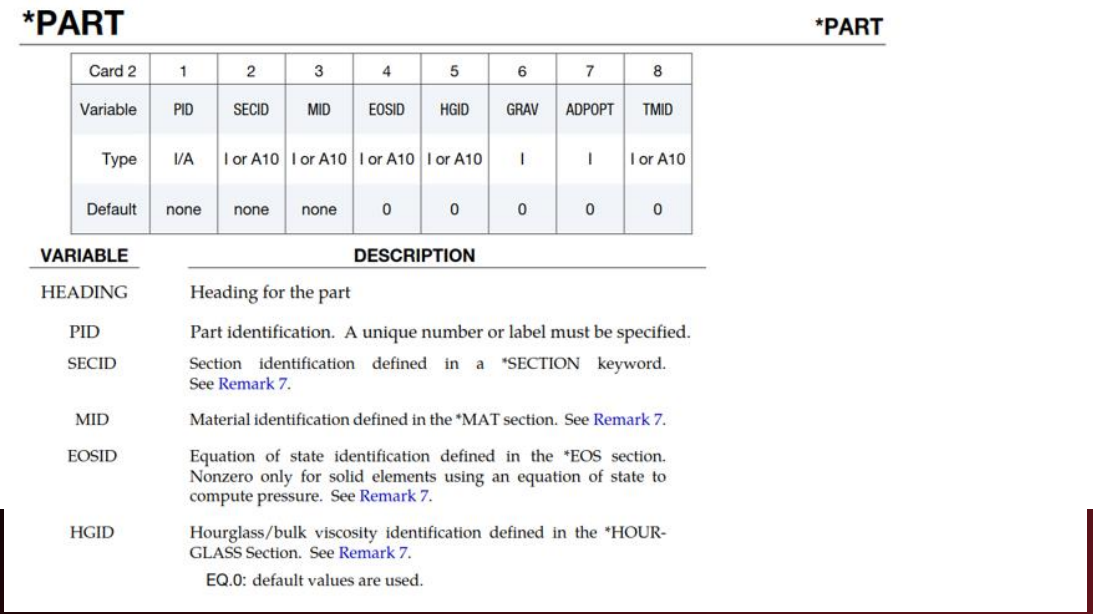
Controls and activates the output files:
- * DATABASE





Full symmetry used
All part as surfaces (shell elements)
- inner pressure
- axial displacement

Keywords definitions based on **user manual**



***PART** ***PART**

| Card 2 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Variable | PID | SECID | MID | EOSID | HGID | GRAV | ADPOPT | TMID |
| Type | I/A | I or A10 | I or A10 | I or A10 | I or A10 | I | I | I or A10 |
| Default | none | none | none | 0 | 0 | 0 | 0 | 0 |

| VARIABLE | DESCRIPTION |
|---|---|
| HEADING | Heading for the part |
| PID | Part identification. A unique number or label must be specified. |
| SECID | Section identification defined in a *SECTION keyword. See Remark 7. |
| MID | Material identification defined in the *MAT section. See Remark 7. |
| EOSID | Equation of state identification defined in the *EOS section. Nonzero only for solid elements using an equation of state to compute pressure. See Remark 7. |
| HGID | Hourglass/bulk viscosity identification defined in the *HOURGLASS Section. See Remark 7.<br>EQ.0: default values are used. |

# Failure model

## How to assess the failure?

A commonly used failure criterion:

- Maximal principal strain:

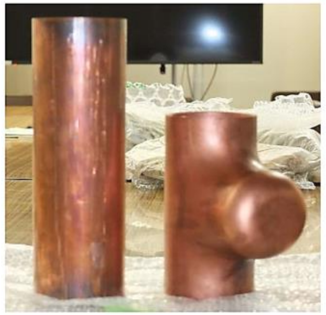
$$\varepsilon_1 \leq \varepsilon_{max}$$

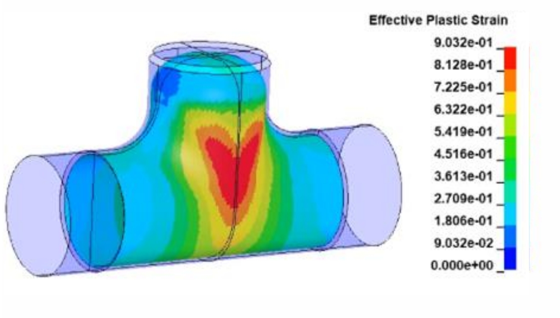
- Maximal equivalent strain:

$$\varepsilon_{eq} = \sqrt{\frac{4}{3}\varepsilon_1^2(1+b+b^2)} \leq \varepsilon_{max}$$

- Maximal thinning:

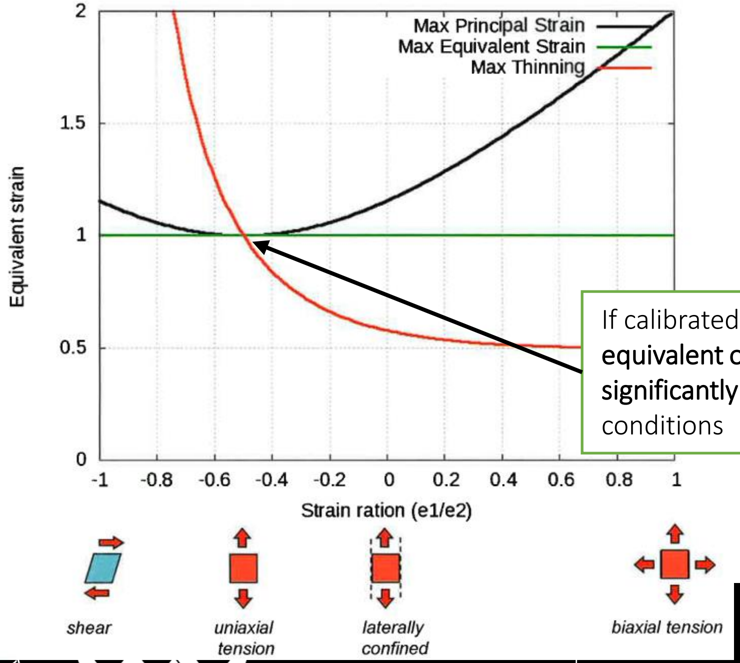
$$\varepsilon_3 \leq -\frac{\varepsilon_{max}}{2}$$





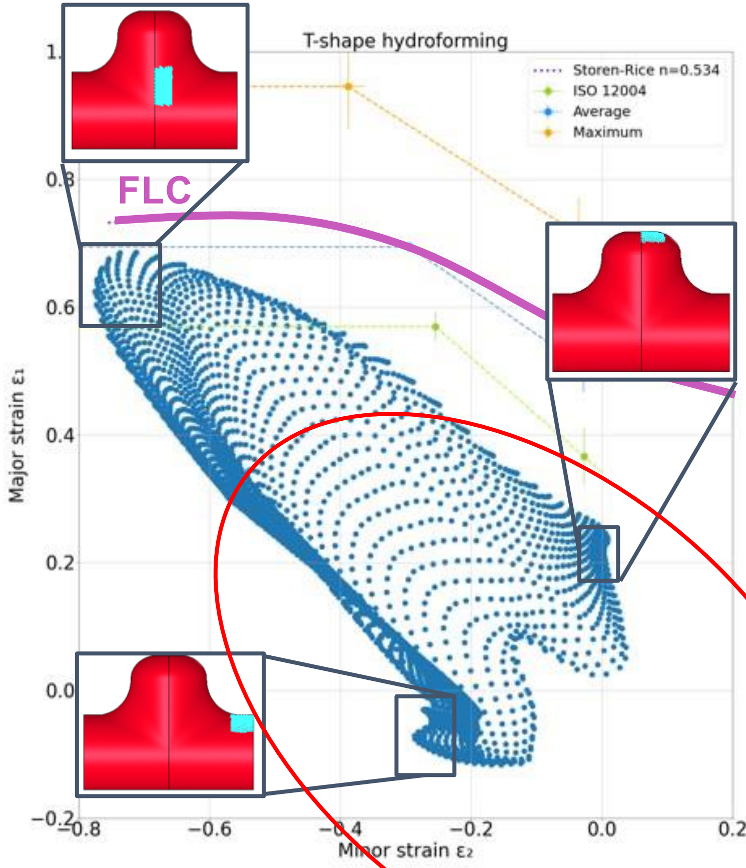
**Forming Limit Diagram**
for failure prediction

1) Simulate
2) Corelate eps1 and eps2
3) Observe part deformation paths
4) Assess feasibility



If calibrated based on uniaxial tensile (UA), **equivalent only for UA deformation**, **significantly different** for three-directional forming conditions

**Standard approach** for sheet metal forming**:**
**Failure Model** : maximum strain criteria
(Distortion Energy, **FLD** Forming Limit Diagram)

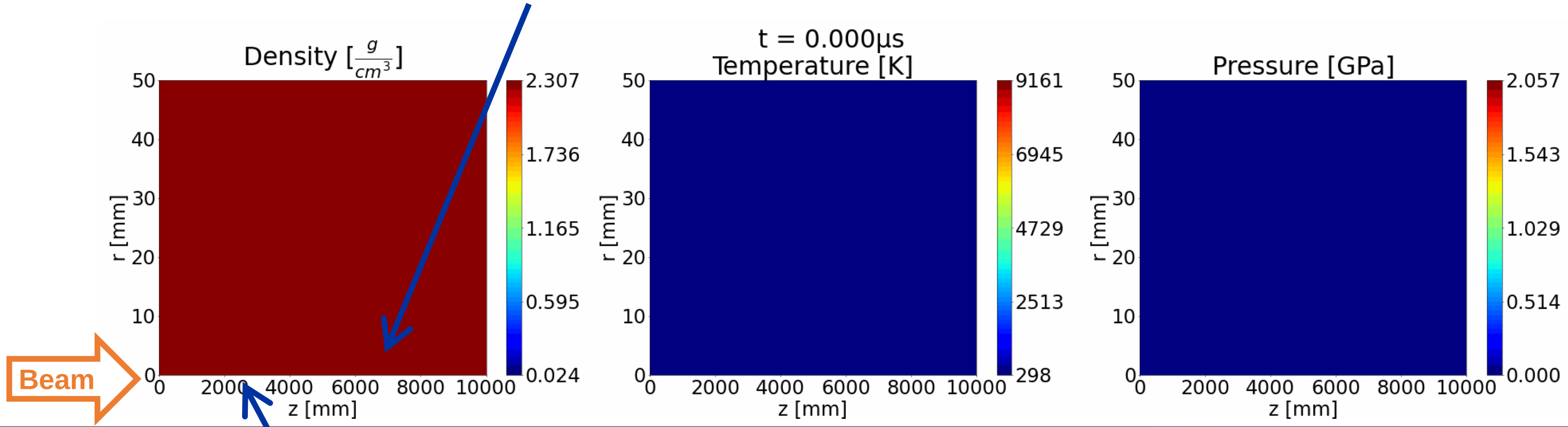


Maximal equivalent strain criterion
**Too conservative** and inaccurate for large deformation

# Hydrodynamic tunnelling

- Successive proton bunches impacting on a target depletes the material density along the beam path causing particle showers of subsequent bunches to penetrate deeper into the target.
- Due to the drastic change in density, the energy distribution calculated under nominal density will cannot be used for the full beam analysis
- **The energy distribution must be simulated again when the density change due to the beam impact is significant.**
- Done by coupling ANSYS Autodyn with the energy deposition code FLUKA iteratively. This coupling has been proven accurate by experiments conducted at HiRadMat.

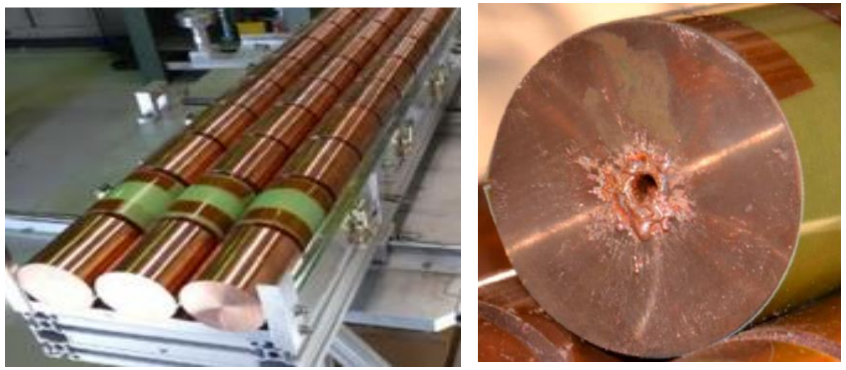
The density depletion front reaches a constant speed into the material.

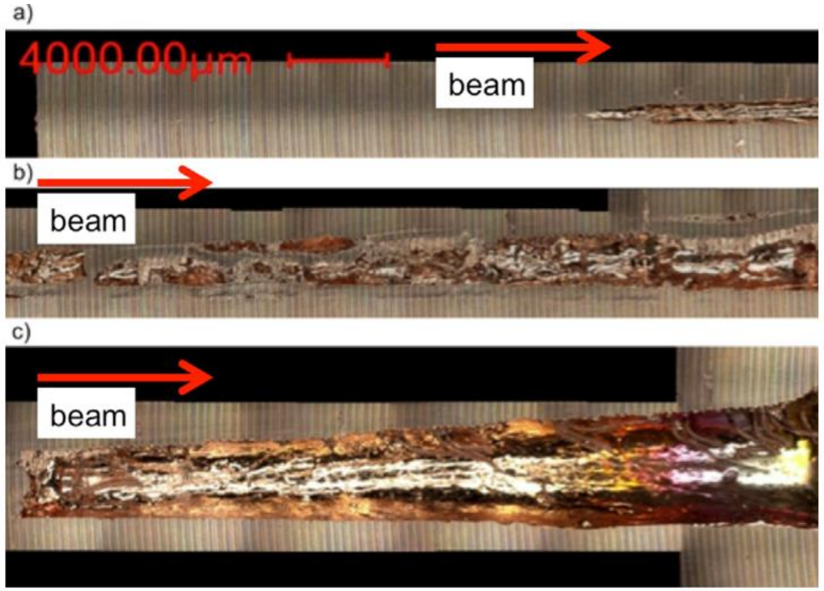


Density depleting to zero at the axis.

## Experiment at HiRadMat, CERN

440 GeV, 144b, σ = 0.2 mm,
1.5e11 p$^+$, 1.5 MJ beam energy





Copper targets after impact of SPS beams. **First experimental proof of hydrodynamic tunnelling.** Taken from N. A. Tahir *et al.*, “Review of hydrodynamic tunneling issues in high power particle accelerators”, NIM B, 427 (2018), 70–86

# Hydrodynamic tunnelling – Results from some experiments and simulations

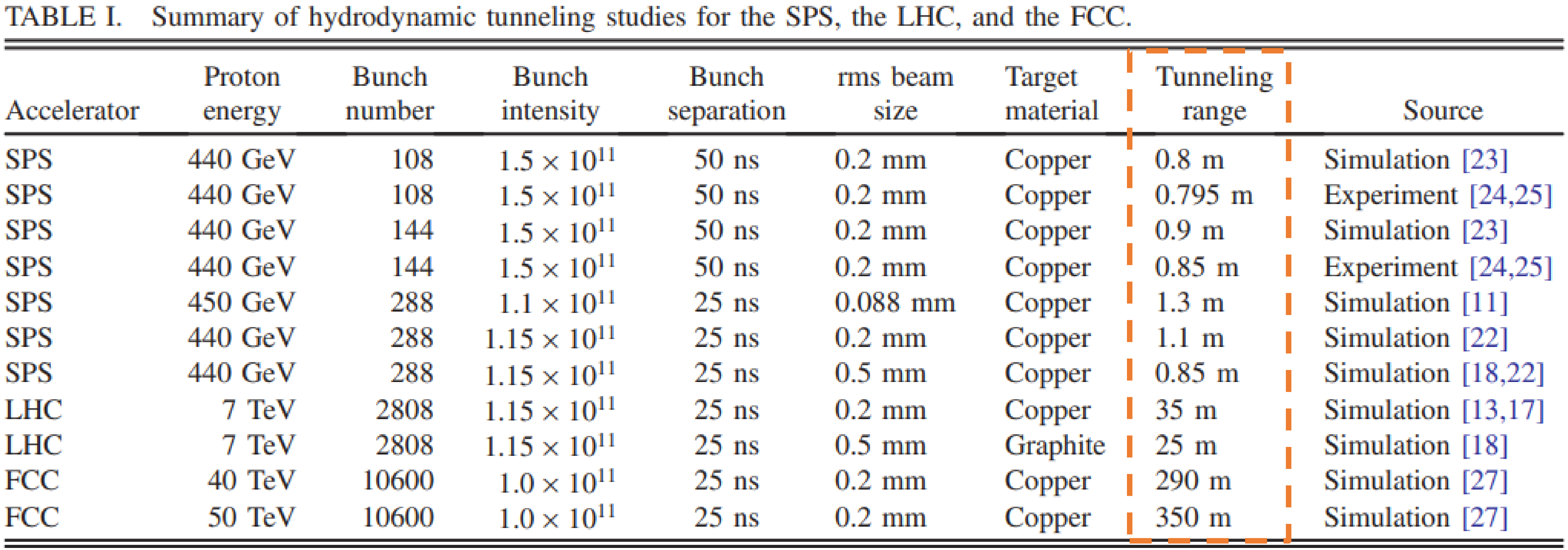


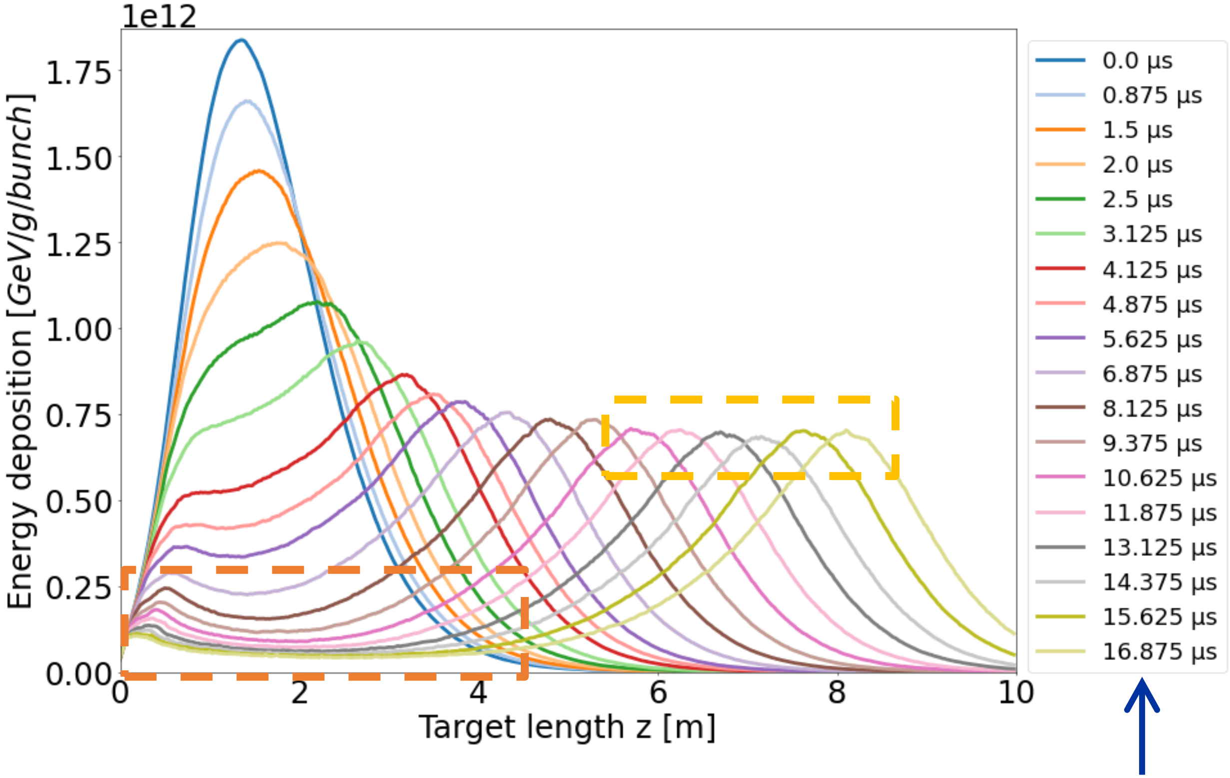
TABLE I. Summary of hydrodynamic tunneling studies for the SPS, the LHC, and the FCC.

| Accelerator | Proton energy | Bunch number | Bunch intensity | Bunch separation | rms beam size | Target material | Tunneling range | Source |
|---|---|---|---|---|---|---|---|---|
| SPS | 440 GeV | 108 | $1.5 \times 10^{11}$ | 50 ns | 0.2 mm | Copper | 0.8 m | Simulation [23] |
| SPS | 440 GeV | 108 | $1.5 \times 10^{11}$ | 50 ns | 0.2 mm | Copper | 0.795 m | Experiment [24,25] |
| SPS | 440 GeV | 144 | $1.5 \times 10^{11}$ | 50 ns | 0.2 mm | Copper | 0.9 m | Simulation [23] |
| SPS | 440 GeV | 144 | $1.5 \times 10^{11}$ | 50 ns | 0.2 mm | Copper | 0.85 m | Experiment [24,25] |
| SPS | 450 GeV | 288 | $1.1 \times 10^{11}$ | 25 ns | 0.088 mm | Copper | 1.3 m | Simulation [11] |
| SPS | 440 GeV | 288 | $1.15 \times 10^{11}$ | 25 ns | 0.2 mm | Copper | 1.1 m | Simulation [22] |
| SPS | 440 GeV | 288 | $1.15 \times 10^{11}$ | 25 ns | 0.5 mm | Copper | 0.85 m | Simulation [18,22] |
| LHC | 7 TeV | 2808 | $1.15 \times 10^{11}$ | 25 ns | 0.2 mm | Copper | 35 m | Simulation [13,17] |
| LHC | 7 TeV | 2808 | $1.15 \times 10^{11}$ | 25 ns | 0.5 mm | Graphite | 25 m | Simulation [18] |
| FCC | 40 TeV | 10600 | $1.0 \times 10^{11}$ | 25 ns | 0.2 mm | Copper | 290 m | Simulation [27] |
| FCC | 50 TeV | 10600 | $1.0 \times 10^{11}$ | 25 ns | 0.2 mm | Copper | 350 m | Simulation [27] |

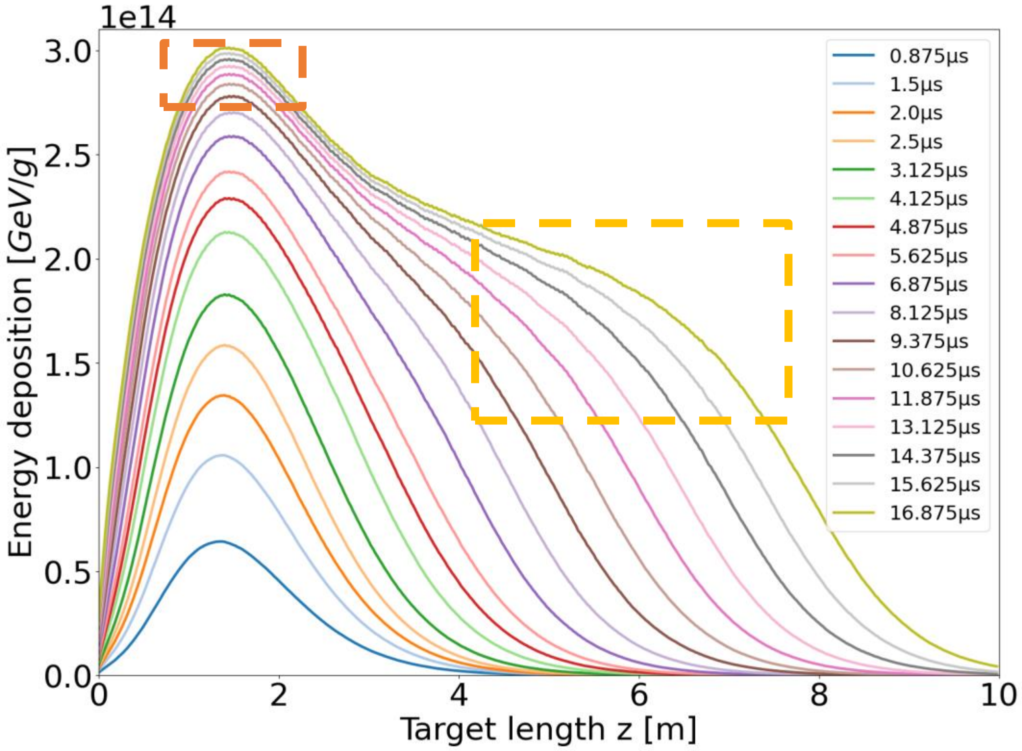
Table taken from Y. Nie *et al.*, “Numerical simulations of energy deposition caused by 50 MeV – 50 TeV proton beams in copper and graphite targets”, Phys. Rev. ST Accel. Beams 20 (2017), p.081001

# Hydrodynamic tunnelling – Distribution of energy in the material for the HL-LHC beam

Energy distribution over time. Each line is how energy is distributed at one specific timestep. First, we see an initial maximum peak, then as density is depleted the energy is deposited further into the material with a constant amplitude.



Accumulated energy over time. Each line is how the total energy is distributed in the material at the given time and how this increases over time as more bunches impact. Can see how, over time, there is close to no new energy distributed where the density is depleted to zero.



Each timestep represents a coupling step at which the energy distribution in the material was updated due to a significant change in density.

7 TeV, σ = 0.5 mm,
2.2e11 ppb