



# Simulation of material deformation due to multiple beam pulses on beryllium target.

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Summer Students at Fermilab - Final Report

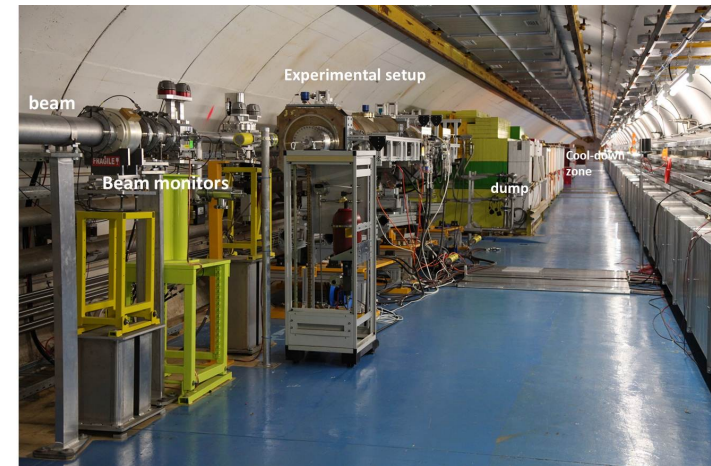
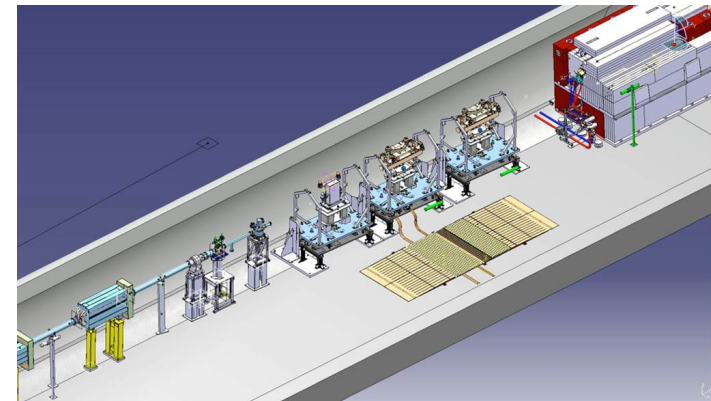
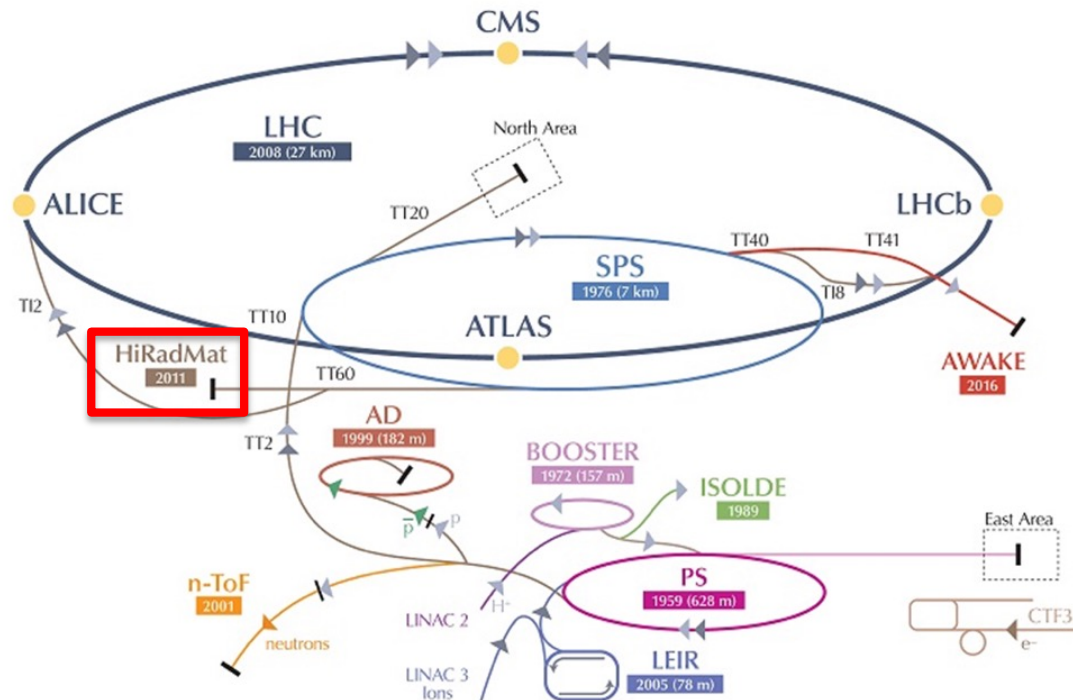
25<sup>th</sup> September 2018

Supervisor:

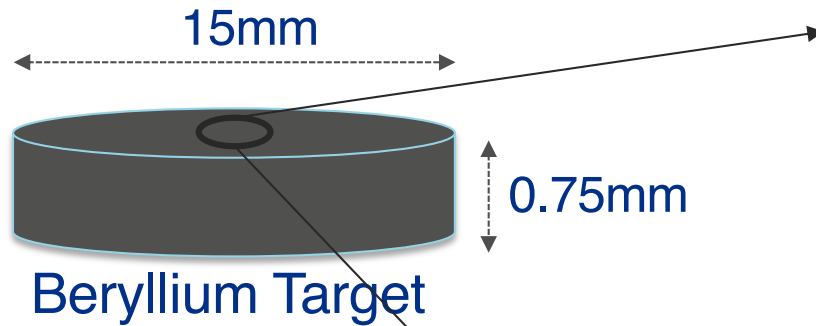
Sujit Bidhar

# Background - HighRADMat test at CERN

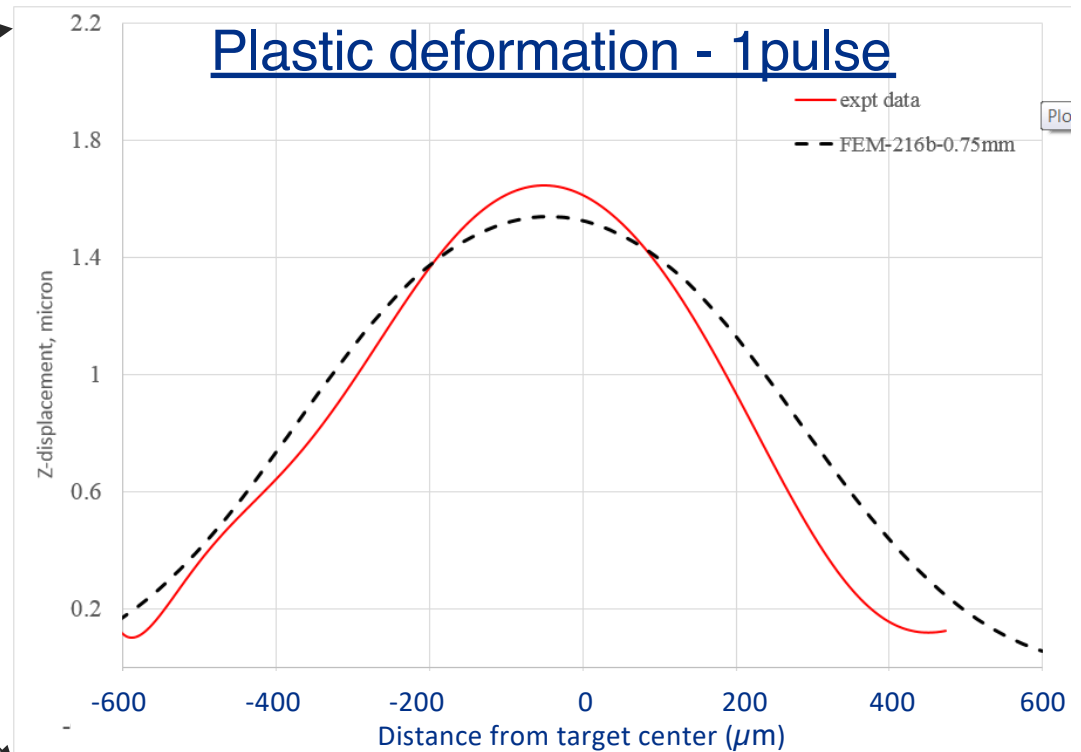
Evaluate the effect of high-intensity pulsed beams on materials or accelerator component assemblies in a controlled environment.



# Background - HighRADMat test at CERN



Beam Parameters	
Beam energy	440 GeV
Max. bunch intensity	$1.2 \times 10^{11}$
No. of bunches	1 – 288
Max. pulse intensity	$3.5 \times 10^{13}$ ppp
Max. pulse length	7.2 $\mu$ s
Gaussian beam size	$1\sigma$ : 0.1 – 2 mm



FEM simulation → matches with experimental data for single pulse

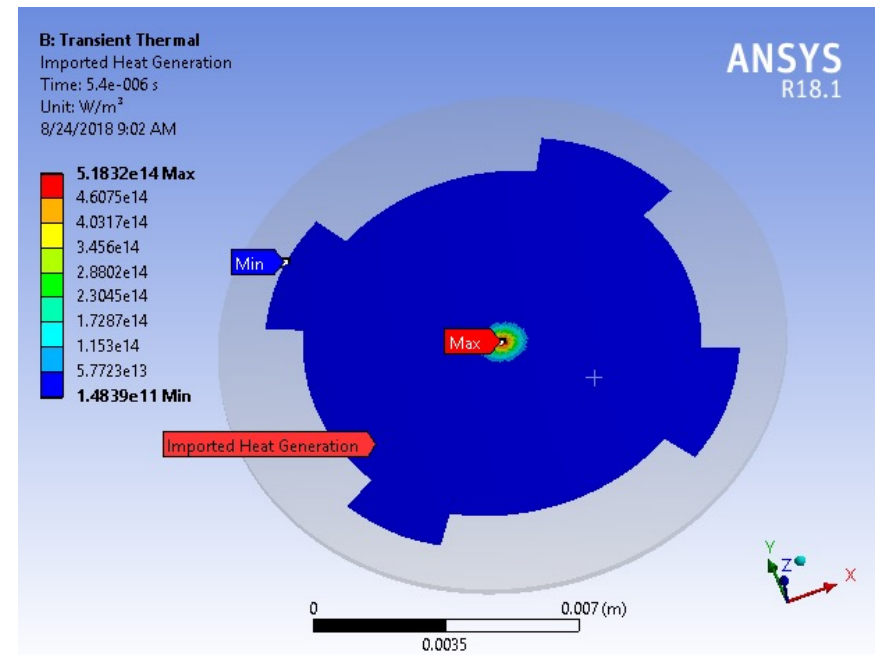
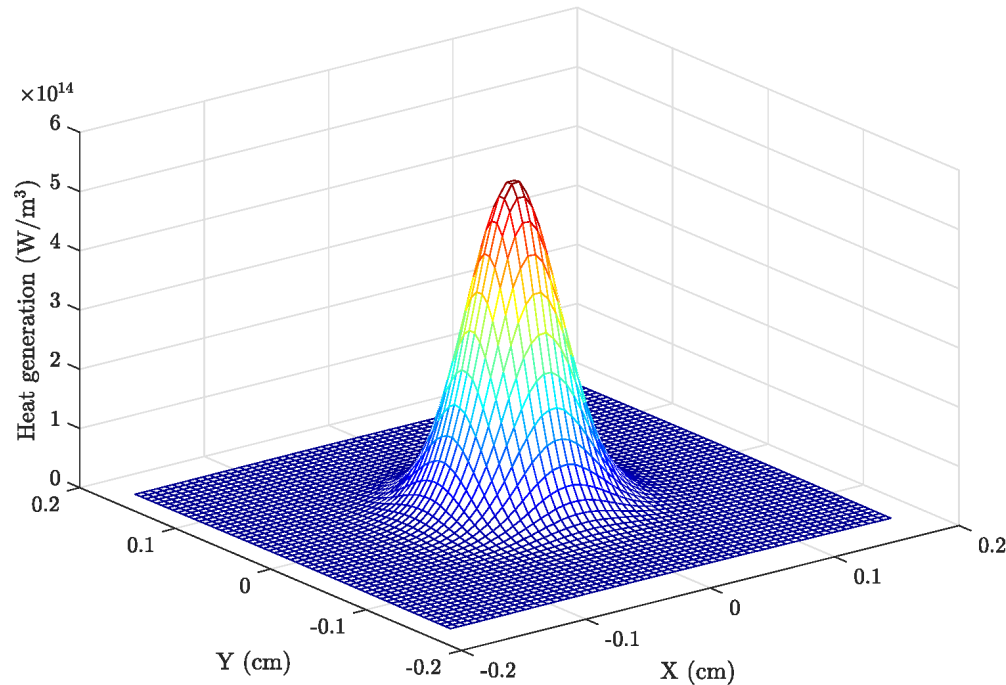
# Objectives

- Use commercial finite element software to simulate **material deformation** due to multiple pulsed beam on beryllium target.
- Implement **user material subroutine** for Equation of State of beryllium.



# Analysis Steps

1. Transient Thermal analysis using ANSYS Workbench
  - Input: proton beam heat generation table from MARS simulation



## 2. Structural analysis using LS-DYNA

- Import: nodal temperature profile (function of time) from thermal analysis

# Johnson-Cook Model

$$\sigma_y = (A + B\varepsilon_p^n)(1 + c \ln \dot{\varepsilon}^*)(1 - T^{*m})$$

Separate effects of:

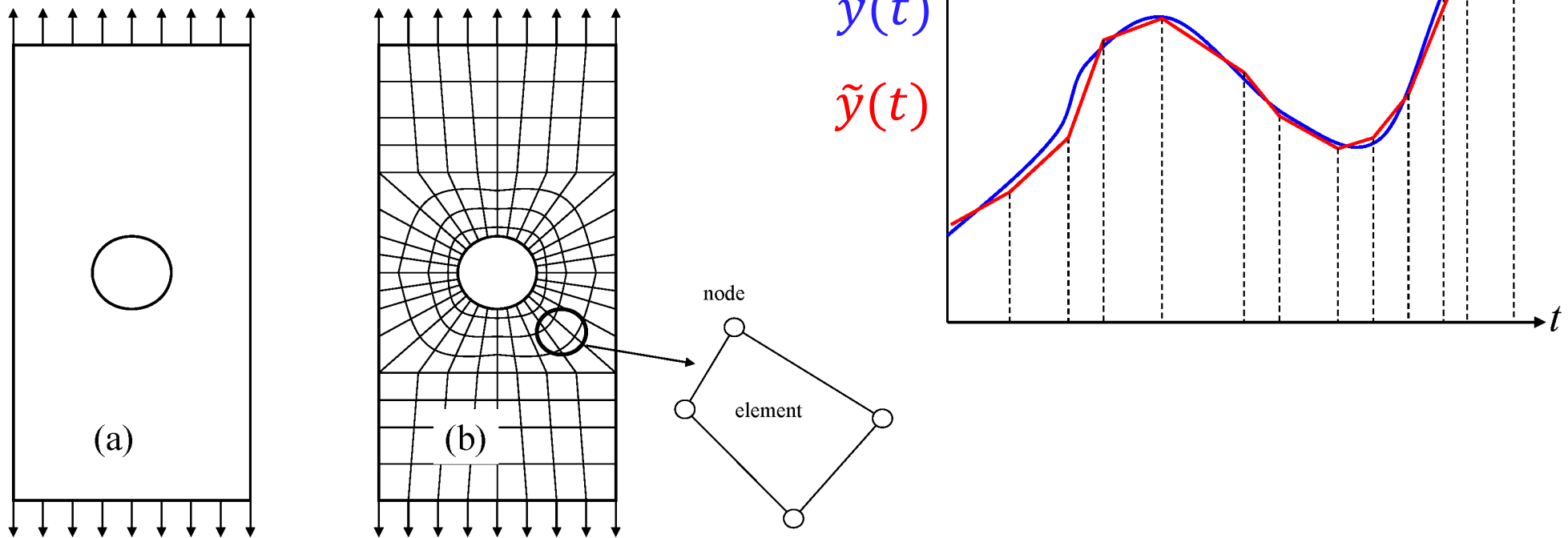
- Temperature
- Strain Rate
- Hardening

↓  
5 material constants

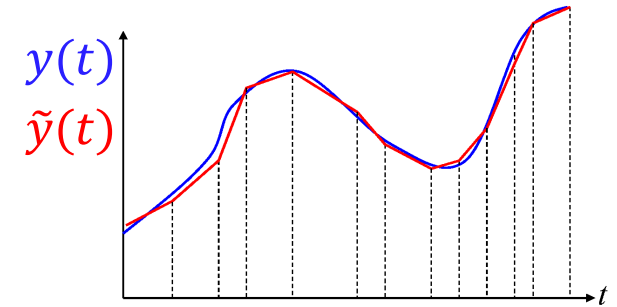
- $\varepsilon_p$  = effective plastic strain
- $\dot{\varepsilon}^* = \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0}$  = effective plastic strain rate
- $T^* = \frac{T - T_0}{T_m - T_0}$

# FEM overview (1)

- Subdivision of a large problem into smaller → Elements
- Simple equations for each elements assembled into a larger system
- Approximate values of the unknowns at discrete number of points over the domain



# FEM overview (2)



- Implicit

$$y_{n+1} = f(y_{n+1}, y_n)$$

$$Ma'_{n+1} + Cv'_{n+1} + Kd'_{n+1} = F_{n+1}^{ext}$$

$$d'_{n+1} = d_n^* + \beta a'_{n+1} \Delta t^2$$

$$v'_{n+1} = v_n^* + \gamma a'_{n+1} \Delta t$$

$$a'_{n+1} = M^{*-1} F_{n+1}^{res}$$

- Explicit

$$y_{n+1} = f(y_n)$$

$$Ma_n + Cv_n + Kd_n = F_n^{ext}$$

$$Ma_n = F_n^{ext} - F_n^{int}$$

$$a_n = M^{*-1} F_n^{res}$$

$$\left( a_{ni} = \frac{F_n^{res}{}_i}{M_i^*} \right)$$

$$v_{n+1} = v_{n-1} + a_n \frac{\Delta t_{n+1} + \Delta t_{n-1}}{2}$$

$$d_{n+1} = d_n + v_n \Delta t_n$$



# Time Step overview

- Implicit:
  - Time step → Load step
  - Step size depends on convergence criteria
- Implicit
  - No limit to step size
  - Iterative
  - The computational time per load step is relatively high

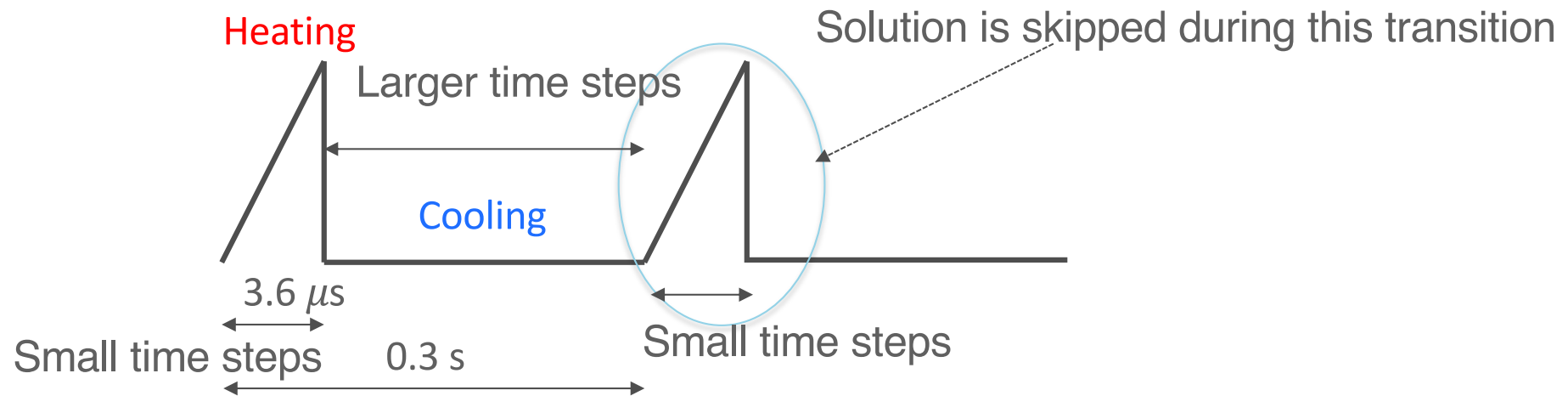
- Explicit:
  - Time step → actual time

$$\Delta t = \frac{L}{\sqrt{E/\rho}}$$

- Explicit
  - Requires small time steps
  - Not-iterative
  - The computational time per load step is relatively low
  - More efficient
  - Good for dynamic problems (impact and shock problems)

# LS-DYNA analysis

- **Heating** in the first  $3.6 \mu\text{s}$  → explicit solver
  - **Cooling** until  $0.3 \text{ s}$  → implicit solver
- } 6 times

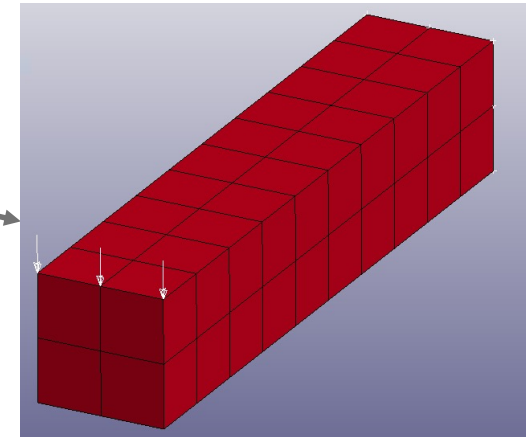


In multiple pulse simulation LS-DYNA had problems **switching** from **implicit** to **explicit** analysis

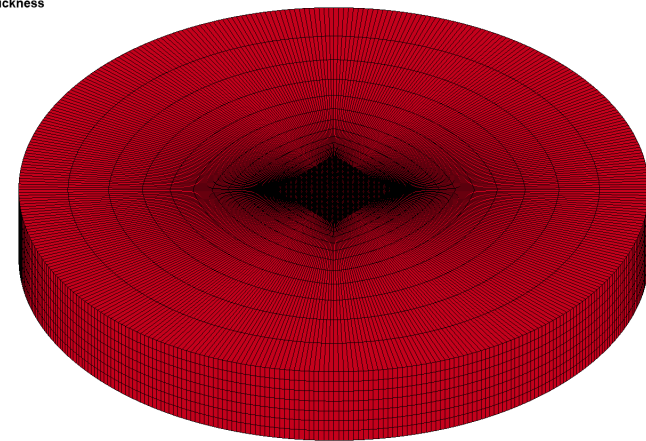
Arrived near  $0.3 \text{ s}$ , the last time step was always too big to go beyond the next  $3.6 \mu\text{s}$  of the explicit analysis → no control over time step size

# Status

- Familiarize with LS-DYNA and in particular its options regarding implicit and explicit analysis.
- Use simplified model to optimize time steps
  - same element size
  - same load curves
  - same solver options
- Implement in actual model

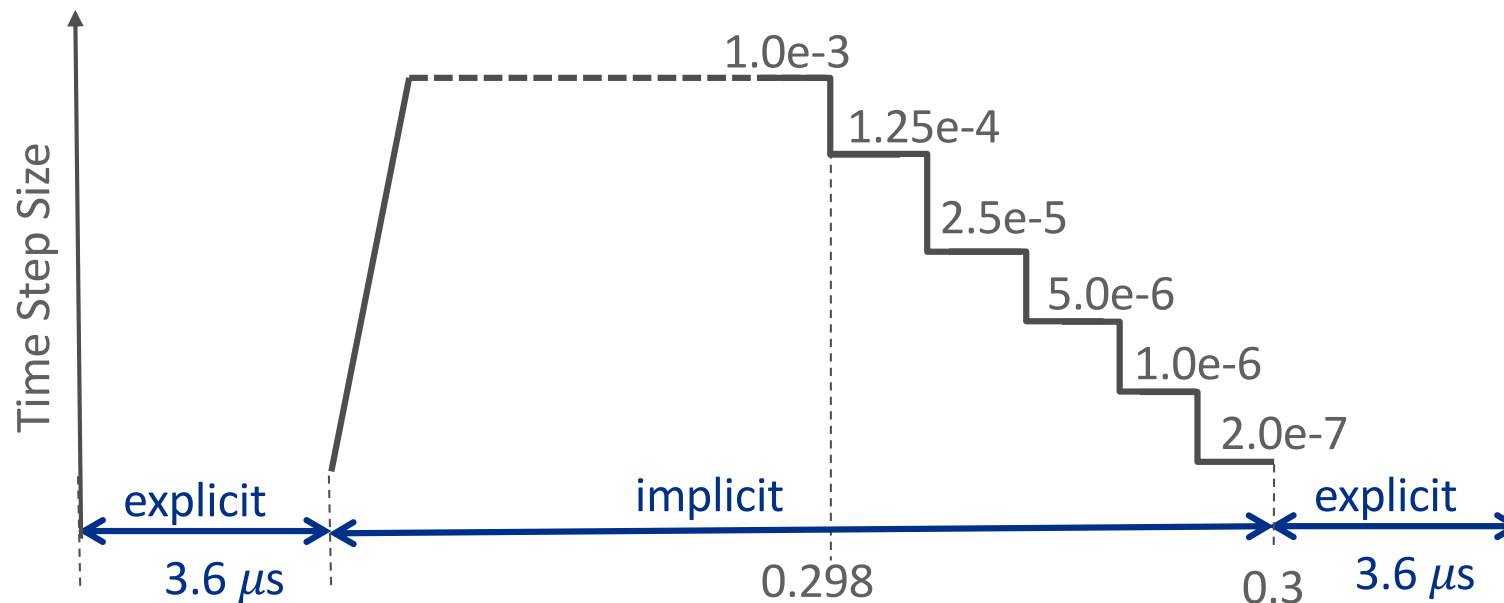


Be - 2 mm thickness

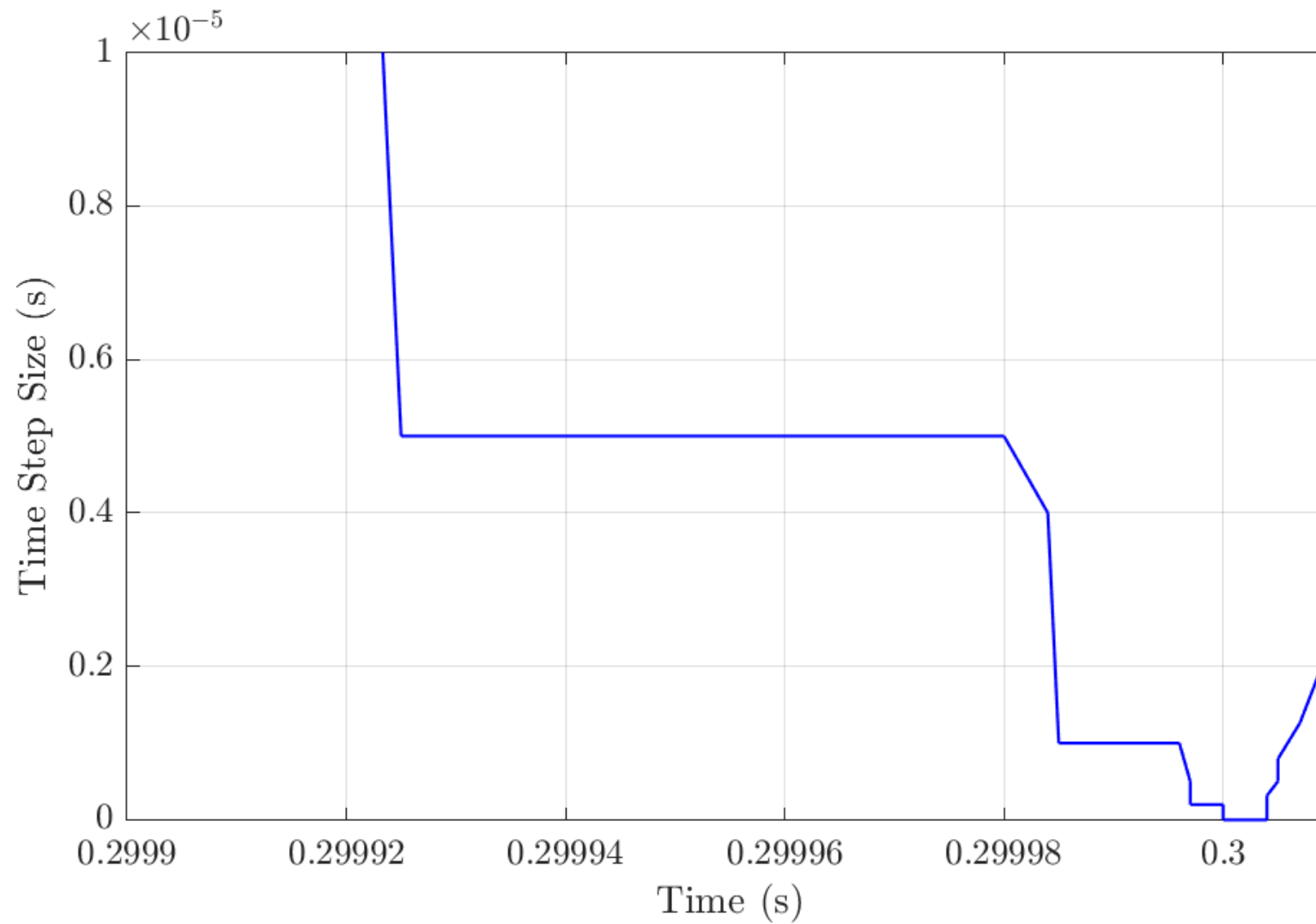


# Methodology

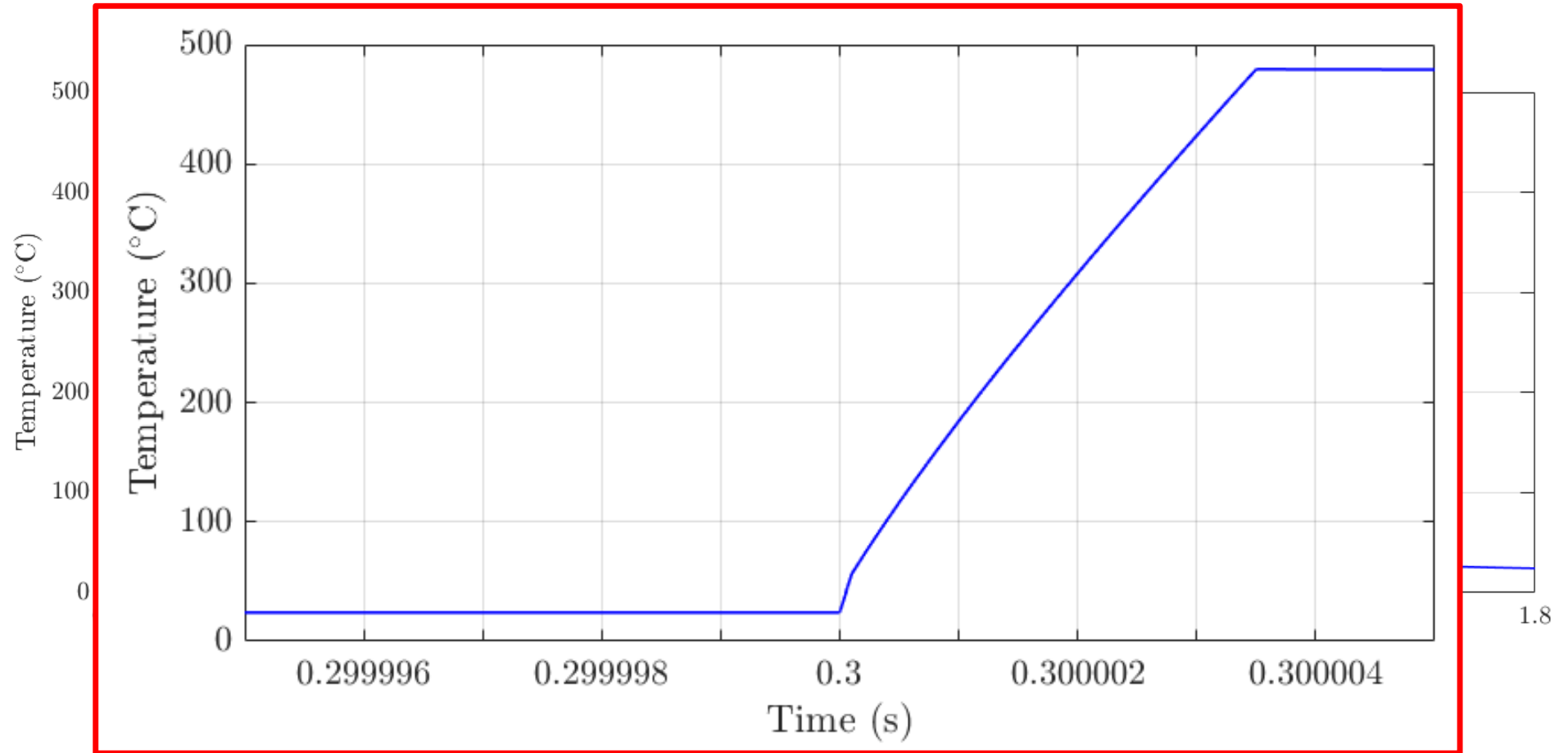
- Decrease the maximum time step size in implicit analysis just before the explicit analysis.



# Results – Time Step Size

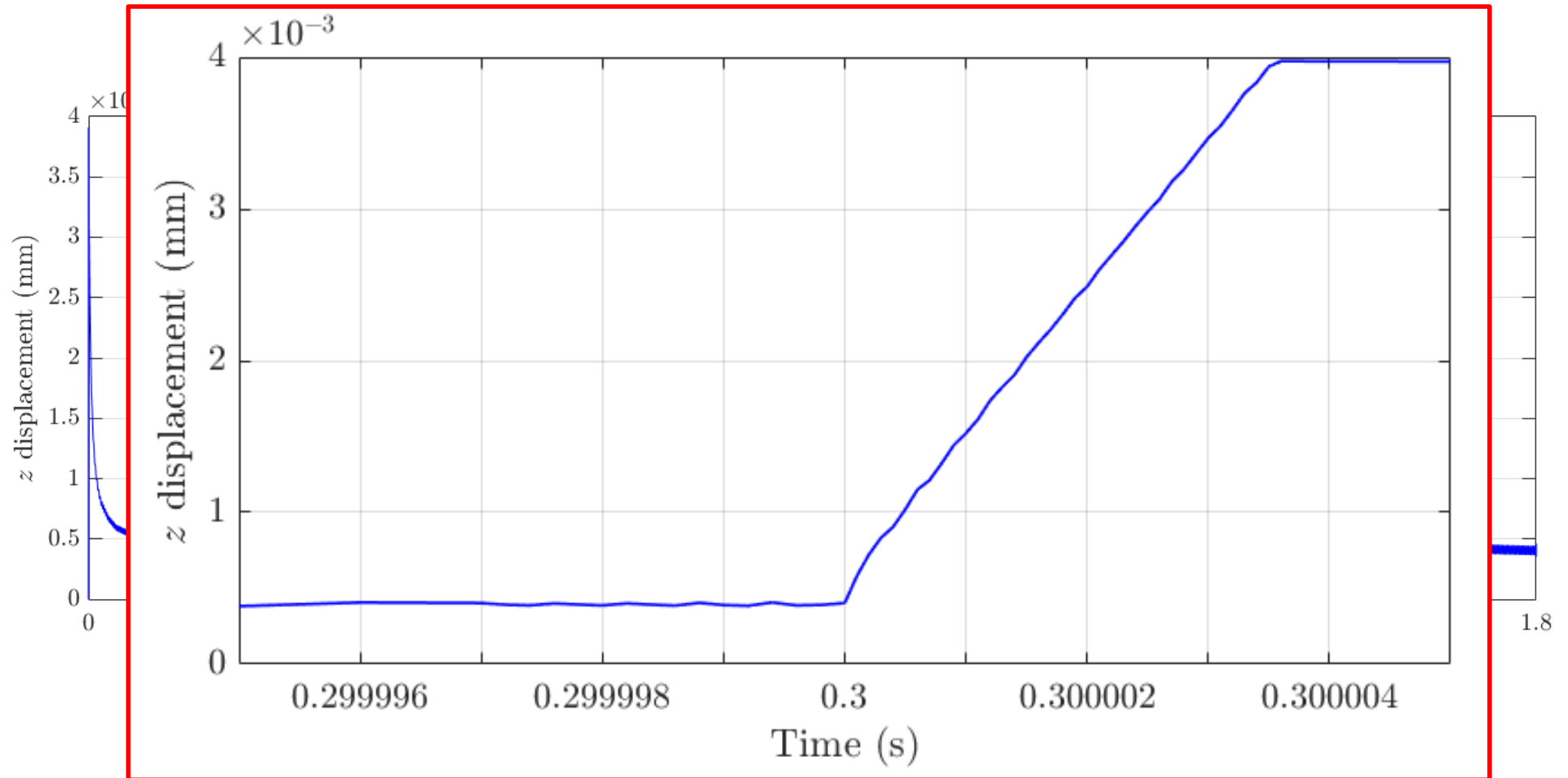


# Results – Temperature load





# Results – Displacements



# Results – Plastic Strain

## Be - 2 mm thickness

Time = 0.3  
Contours of Effective Plastic Strain  
min = 0, at elem# 1  
max = 0.00124866, at elem# 43660  
section min = 0, near node# 15618  
section max = 0.00119151, near node# 49298

Fringe Levels

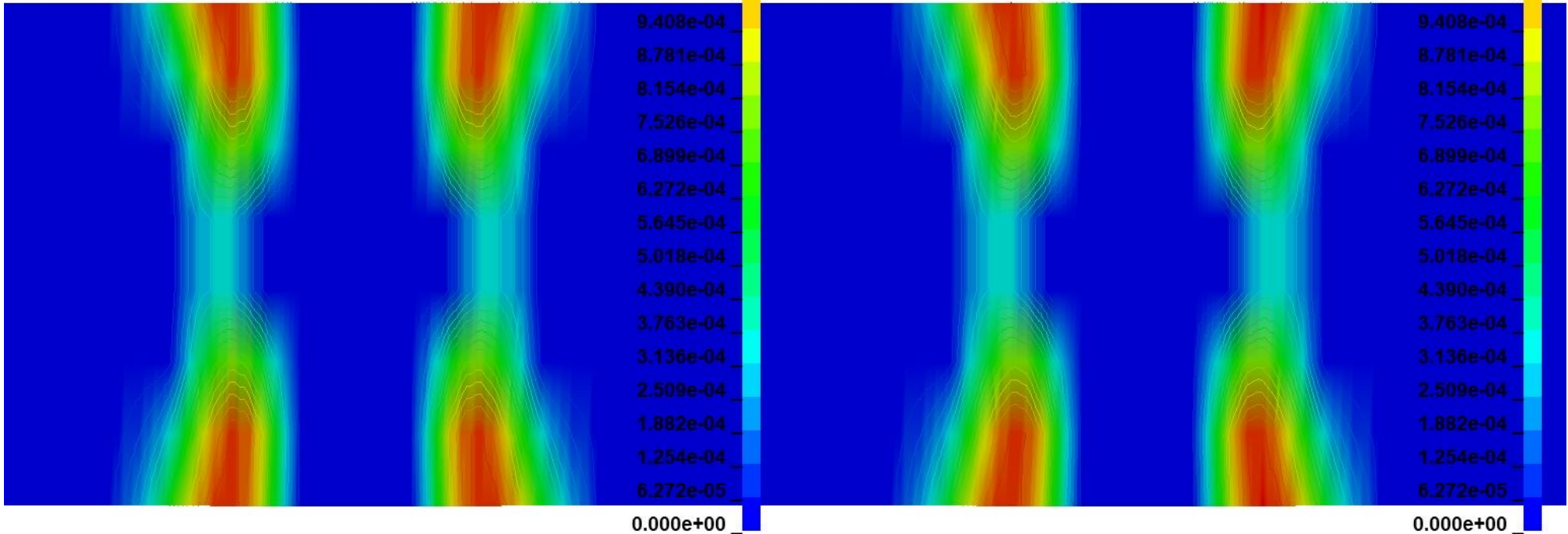
1.254e-03  
1.192e-03  
1.129e-03  
1.066e-03  
1.004e-03  
9.408e-04  
8.781e-04  
8.154e-04  
7.526e-04  
6.899e-04  
6.272e-04  
5.645e-04  
5.018e-04  
4.390e-04  
3.763e-04  
3.136e-04  
2.509e-04  
1.882e-04  
1.254e-04  
6.272e-05  
0.000e+00

## Be - 2 mm thickness

Time = 1.8  
Contours of Effective Plastic Strain  
min = 0, at elem# 1  
max = 0.00125439, at elem# 52978  
section min = 0, near node# 15602  
section max = 0.00119677, near node# 49298

Fringe Levels

1.254e-03  
1.192e-03  
1.129e-03  
1.066e-03  
1.004e-03  
9.408e-04  
8.781e-04  
8.154e-04  
7.526e-04  
6.899e-04  
6.272e-04  
5.645e-04  
5.018e-04  
4.390e-04  
3.763e-04  
3.136e-04  
2.509e-04  
1.882e-04  
1.254e-04  
6.272e-05  
0.000e+00

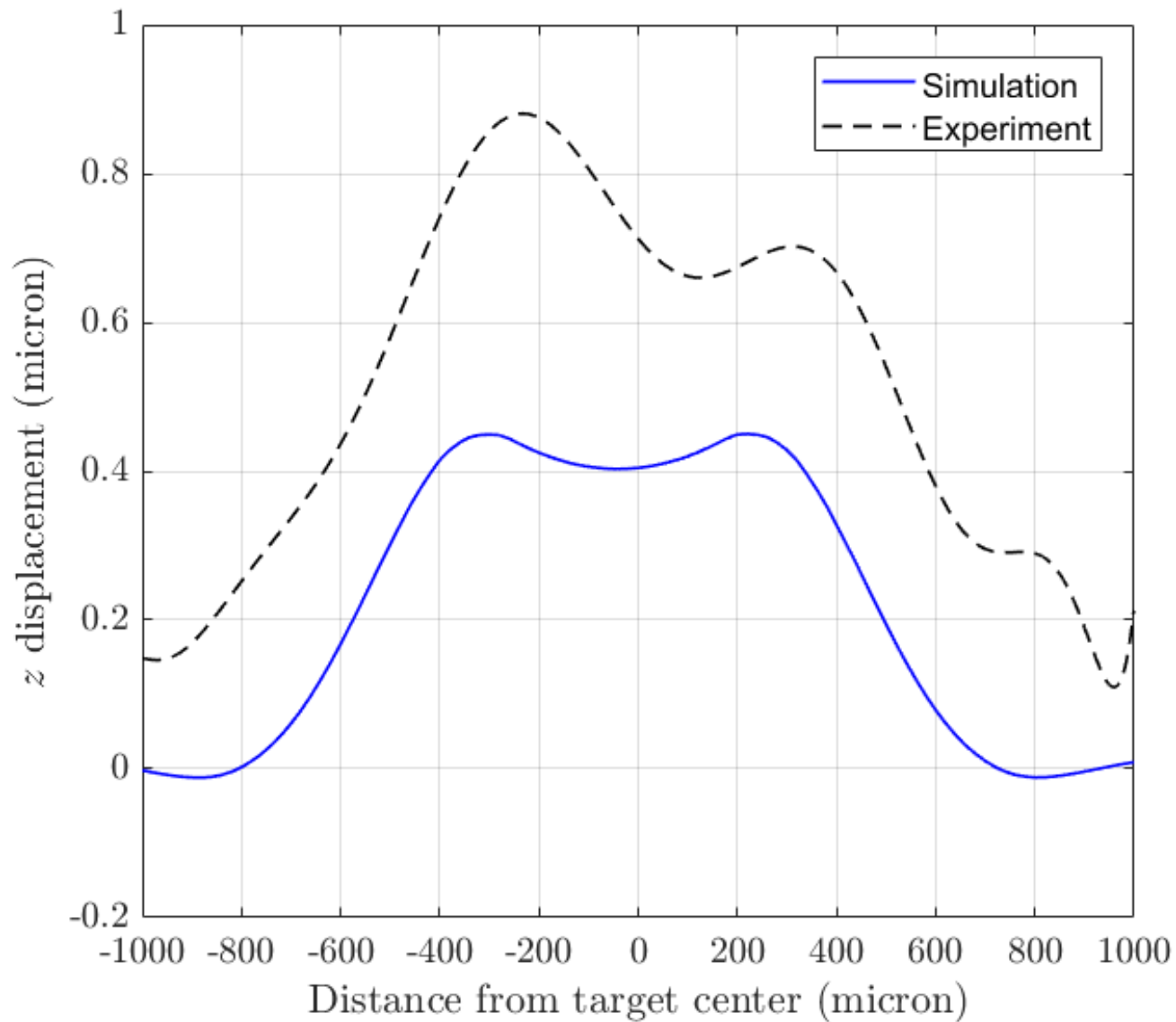


$t = 0.3 \text{ s}$



$t = 1.8 \text{ s}$

# Comparison FEM vs. Experimental Results



# Results – Plastic Strain

**Be - 2 mm thickness**

Time = 3.5998e-006

Contours of Effective Plastic Strain

min = 0, at elem# 1

max = 0.00116733, at elem# 43660

section min = 0, near node# 15603

section max = 0.00110416, near node# 49298

Fringe Levels

1.167e-03

1.109e-03

1.051e-03

9.922e-04

9.339e-04

8.755e-04

8.171e-04

7.588e-04

7.004e-04

6.420e-04

5.837e-04

5.253e-04

4.669e-04

4.086e-04

3.502e-04

2.918e-04

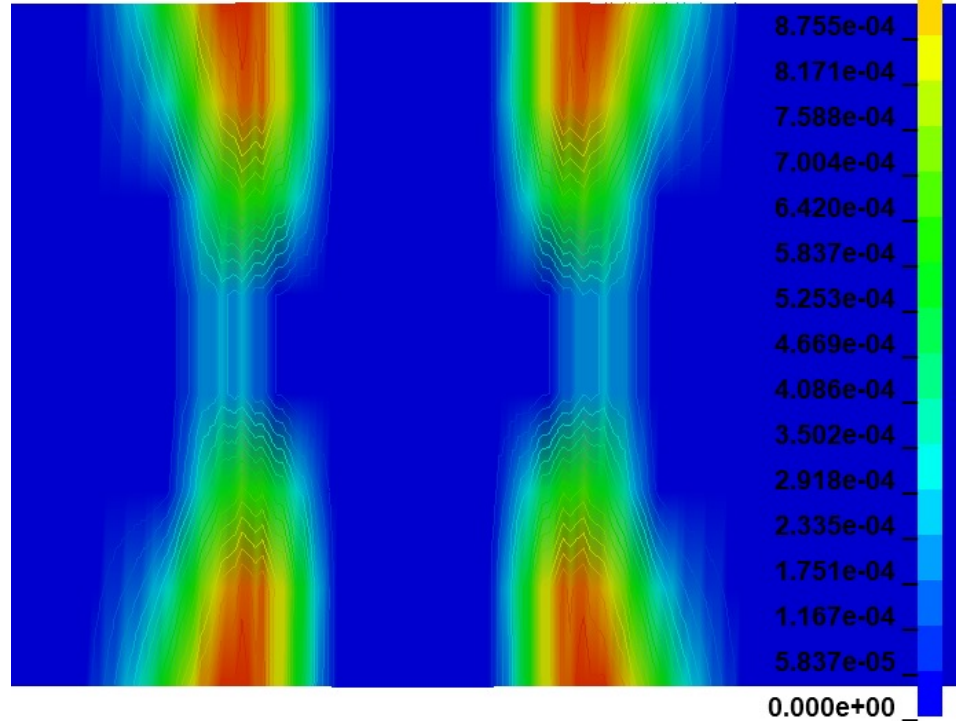
2.335e-04

1.751e-04

1.167e-04

5.837e-05

0.000e+00



$t = 3.6 \mu s$

# Results – Strain Rate

**Be - 2 mm thickness**

Time = 3.5998e-006

Contours of Z-strain-Strainrate

min = -119.46, at elem# 94857

max = 1378.7, at elem# 58443

section min = -113.578, near node# 110098

section max = 1370.71, near node# 69298

Fringe Levels

1.379e+03

1.304e+03

1.229e+03

1.154e+03

1.079e+03

1.004e+03

9.292e+02

8.543e+02

7.794e+02

7.045e+02

6.296e+02

5.547e+02

4.798e+02

4.049e+02

3.300e+02

2.551e+02

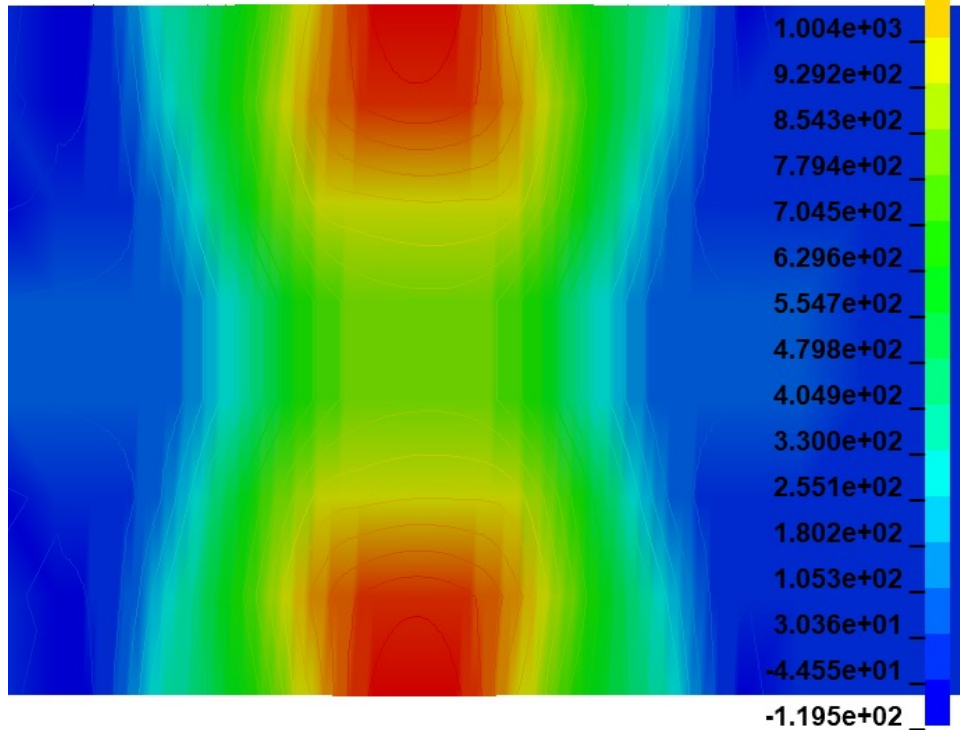
1.802e+02

1.053e+02

3.036e+01

-4.455e+01

-1.195e+02



$$t = 3.6 \mu s$$

# Equation of State (EOS) - Introduction

Functional relationship among the thermodynamic variables for a system:

$$f(P, V, T) = 0$$

$P$  = pressure

$V$  = volume (or  $\rho = 1/V$ , density)

$T$  = temperature (or  $E$ , internal energy)

Johnson-Cook model has fixed density.

Large pressure due to beam heating.

Density changes with pressure and temperature.

User defined EOS will include density change



# Equation of State (EOS) - Pressure

**Be - 2 mm thickness**

Time = 3.5998e-006

Contours of Pressure

min = -3.08497e+07, at elem# 58104

max = 1.13443e+09, at elem# 59147

section min = -2.70869e+07, near node# 26101

section max = 1.10061e+09, near node# 70102

Fringe Levels

1.134e+09

1.076e+09

1.018e+09

9.596e+08

9.014e+08

8.431e+08

7.848e+08

7.266e+08

6.683e+08

6.101e+08

5.518e+08

4.935e+08

4.353e+08

3.770e+08

3.187e+08

2.605e+08

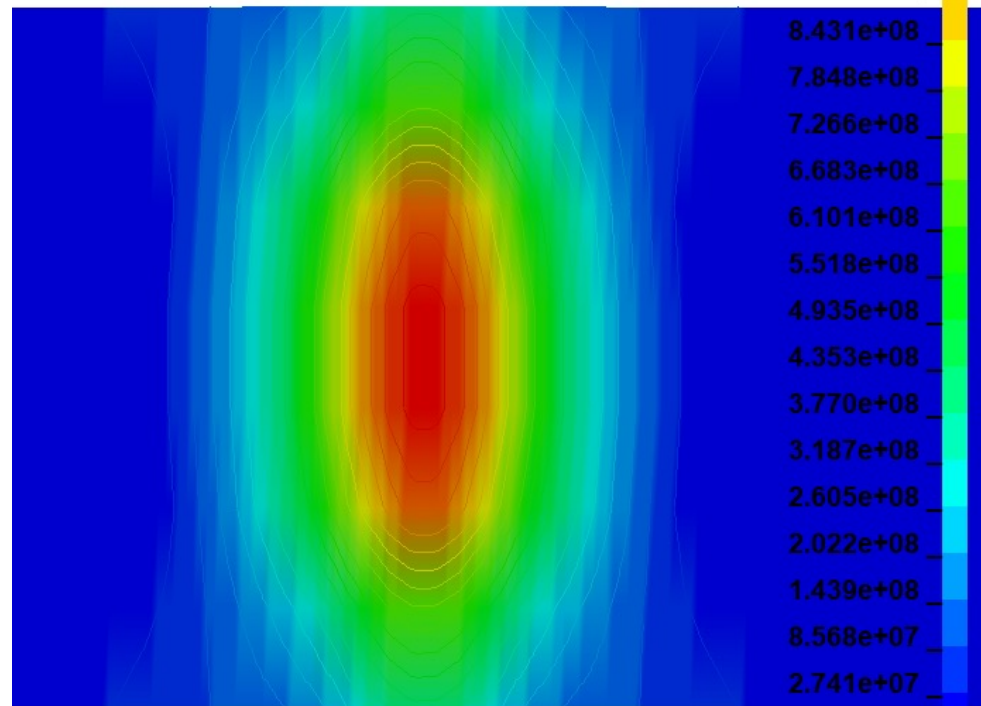
2.022e+08

1.439e+08

8.568e+07

2.741e+07

-3.085e+07



$t = 3.6 \mu s$

## Equation of State (EOS) - Model

$$P(\rho) = \frac{3}{2K_{T0}} \left( \eta^{7/3} - \eta^{5/3} \right) \left[ 1 + \frac{3}{4} (K'_T - 4) \left( \eta^{2/3} - 1 \right) \right]^*$$

$$e_M(\rho) = \frac{9}{8K_{T0}\rho_0} \left( \eta^{2/3} - 1 \right)^2 \left[ 1 + \frac{1}{2} (K'_T - 4) \left( \eta^{2/3} - 1 \right) \right]^*$$

$$\eta = \rho / \rho_0 = V_0 / V$$

$\rho_0$  = reference density

$K_{T0}$  = initial bulk modulus

$$K'_T = \frac{dK_T}{d\rho}$$

\*Gerald I. Kerley - **SANDIA REPORT - Equations of State for Be, Ni, W, and AU**

# Equation of State (EOS) – User Subroutine

1. Calculate the **bulk modulus**

$$v_R = 1/\eta = V/V_0 = \rho_0/\rho$$
$$K_T = -V \left( \frac{dP}{dV} \right)_T = -V \frac{dP}{dv_R} \frac{dv_R}{dV} = -\frac{1}{v_R} \frac{dP}{dv_R}$$

2. Update the **pressure**

$$P(v_R) = \frac{3}{2K_{T0}} \left( v_R^{-7/3} - v_R^{-5/3} \right) \left[ 1 + \frac{3}{4} (K'_T - 4) \left( v_R^{-2/3} - 1 \right) \right]$$

and **internal energy** per unit reference volume:

$$E = e_M \rho_0 = \frac{9}{8K_{T0}} \left( v_R^{-2/3} - 1 \right)^2 \left[ 1 + \frac{1}{2} (K'_T - 4) \left( v_R^{-2/3} - 1 \right) \right]$$

# Equation of State (EOS) – User Subroutine

```
subroutine ueos22s( iflag,cb,pnew,hist,rho0,eosp,specen,
& df,dvol,v0,pc,dt,tt,crv,first)
c
c*****
c| Livermore Software Technology Corporation (LSTC) |
c| ----- |
c| Copyright 1987-2008 Livermore Software Tech. Corp |
c| All rights reserved |
c*****
c
c   example scalar user implementation of the gruneisen EOS
c
c*** variables
c   iflag ----- =0 calculate bulk modulus
c                 =1 update pressure and energy
c   cb ----- bulk modulus
c   pnew ----- new pressure
c   hist ----- history variables
c   rho0 ----- reference density
c   eosp ----- EOS constants
c   specen ---- energy/reference volume
c   df ----- volume ratio, v/v0 = rho0/rho
c   dvol ----- change in volume over time step
c   v0 ----- reference volume
c   pc ----- pressure cut-off
c   dt ----- time step size
c   tt ----- current time
c   crv ----- curve array
c   first ----- logical .true. for tt,crv,first time step
c                 (for initialization of the history variables)
c
c   include 'nlqparm'
c   logical first
c
c   dimension hist(*),eosp(*),crv(lql,2,*)
c
c   Kt0 =eosp(1)
c   Ktp =eosp(2)
c
c*** calculate the bulk modulus for the EOS contribution to the sound speed
c   if (iflag.eq.0) then
c     cb=(-4*(27-49*df**(2/3))+20*df**(4/3))+3*(9-14*df**(2/3)+9*df(4/3))*Ktp)/(8*Kt0*df**(5))
c
c*** update the pressure and internal energy
c   else
c     pnew=((1.5/Kt0)*(df**(-7/3)-df**(-5/3))*(1+0.75*(df**(-2/3)-1)*(Ktp-4)))
c     pnew=max(pnew,pc)
c     specen=(9/(8*Kt0))*((df**(-2/3)-1)**(2))*(0.5*(df**(-2/3)-1)*(Ktp-4)+1)
c   endif
c
c   return
c   end
```

# Thanks for your attention