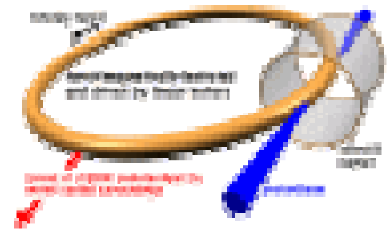


Modelling shock in solid targets

Goran Skoro

(UKNF Collaboration, University of Sheffield)

NuFact 06

UC Irvine, August 24-30, 2006

Estimation of the thermal stress in materials

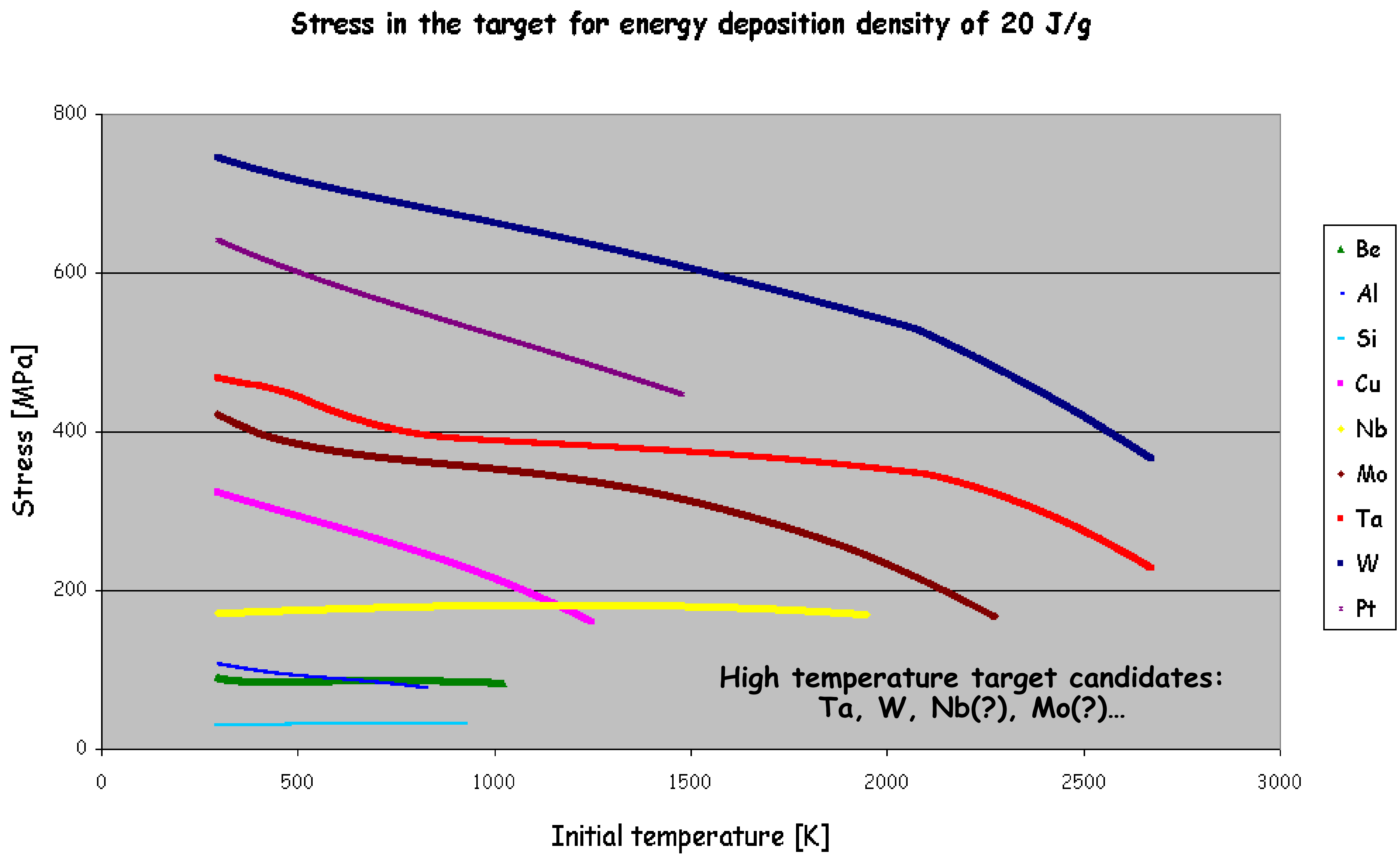
Thermal Stress ~ $\alpha E \Delta T/(1-\nu)$

$\Delta T = EDD/C_p$

α - thermal expansion coefficient
E – elastic modulus
ΔT- temperature rise
ν - Poisson's ratio
EDD – energy deposition density
C_p – specific heat

α=f(T); E=f(T); ν=f(T); Cp=f(T) !!!

Thermal stress as a function of temperature for different materials?



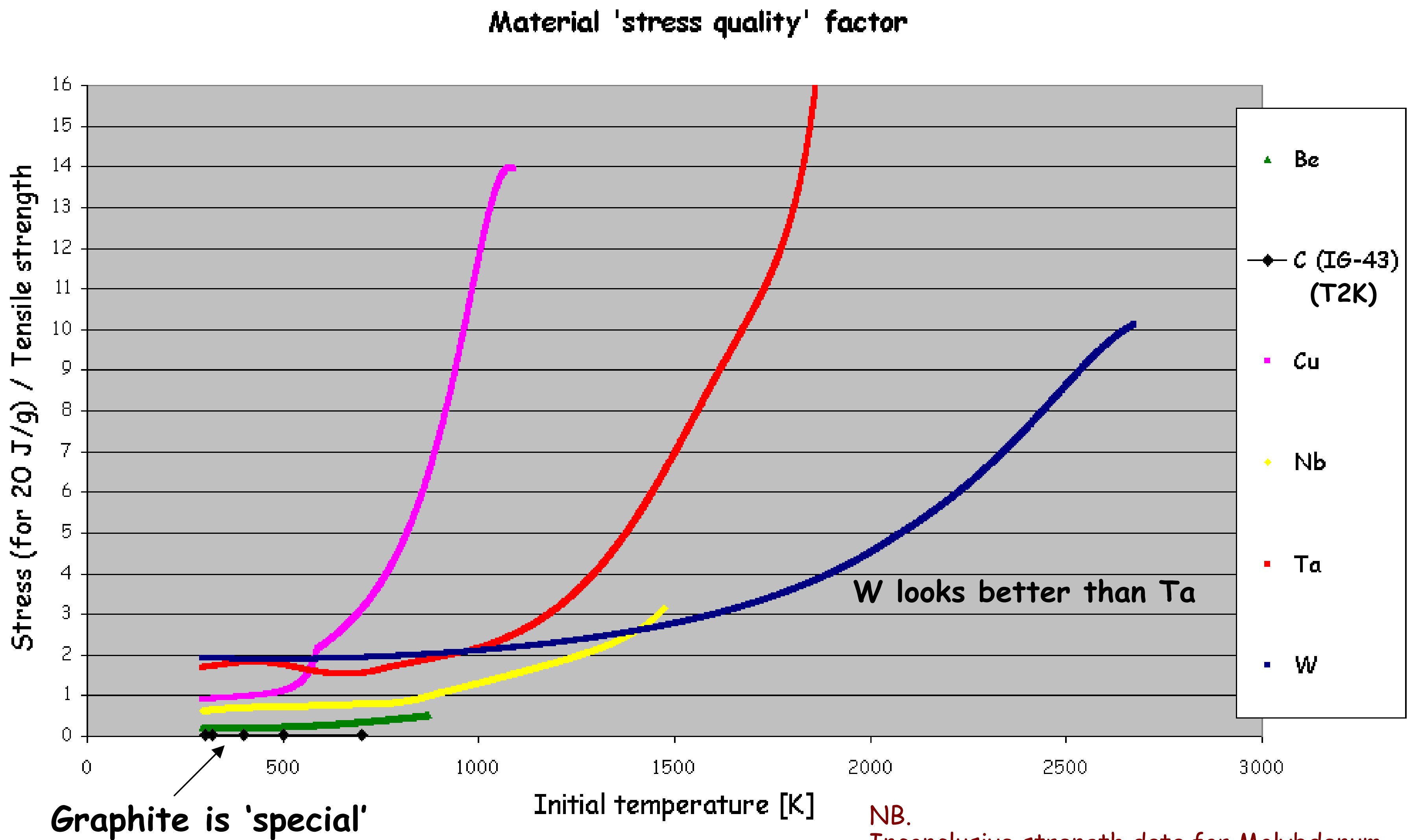
20 J/g corresponds to ~ 300 J/cc in Ta (and W)

- energy density for 4-5 MW beam power, 6-10 GeV protons -

Assuming that the tensile strength (=f(T)) is a measure of material mechanical strength we can introduce

'stress quality' factor = thermal stress/tensile strength

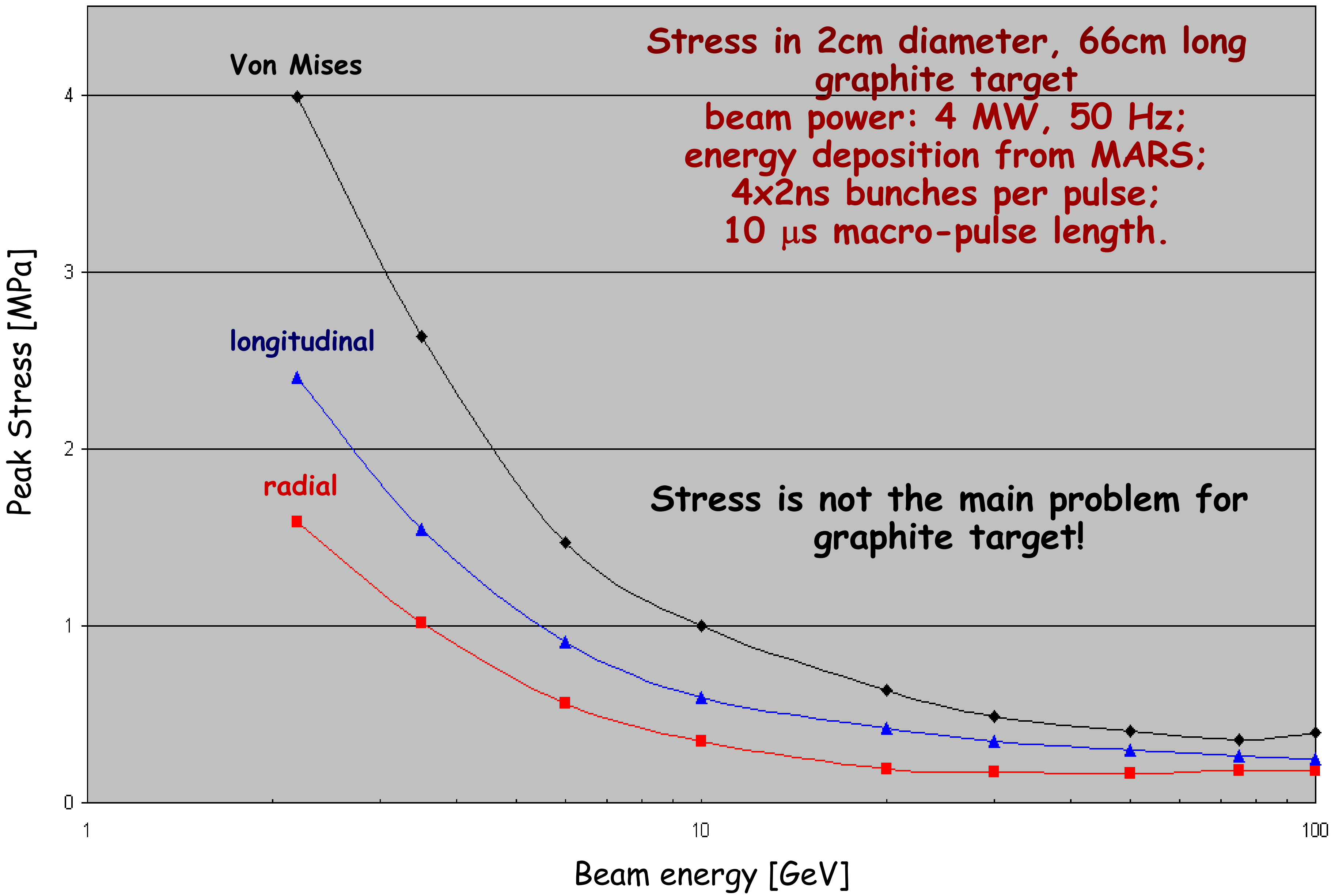
lower value of stress quality factor -> 'better' candidate for solid target



NB.
Inconclusive strength data for Molybdenum. Looks interesting in general (it is valuable alloying agent). Almost all ultra-high strength steels contain Mo in amounts from 0.25 to 8% .

Stress in graphite target

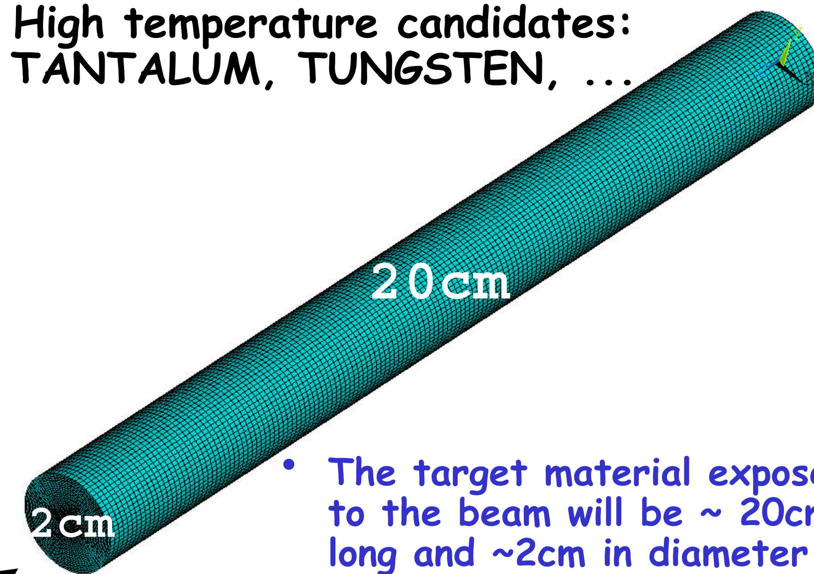
LS-DYNA



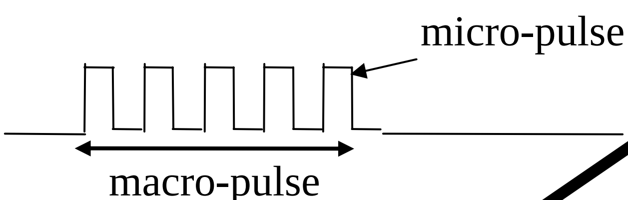
Simulations of the shock in the solid Neutrino Factory target

- Rotating toroidal ring (operating at ~2000 K);
- Individual bars...
- Cooling: radiation
- The target is bombarded at up 50 Hz by a proton beam consisting of ~1ns long bunches in a pulse of a few micro-s length.

High temperature candidates:
TANTALUM, TUNGSTEN, ...



- The target material exposed to the beam will be ~ 20cm long and ~2cm in diameter (in tantalum case).



- Energy density per pulse ~ 300 J/cc.

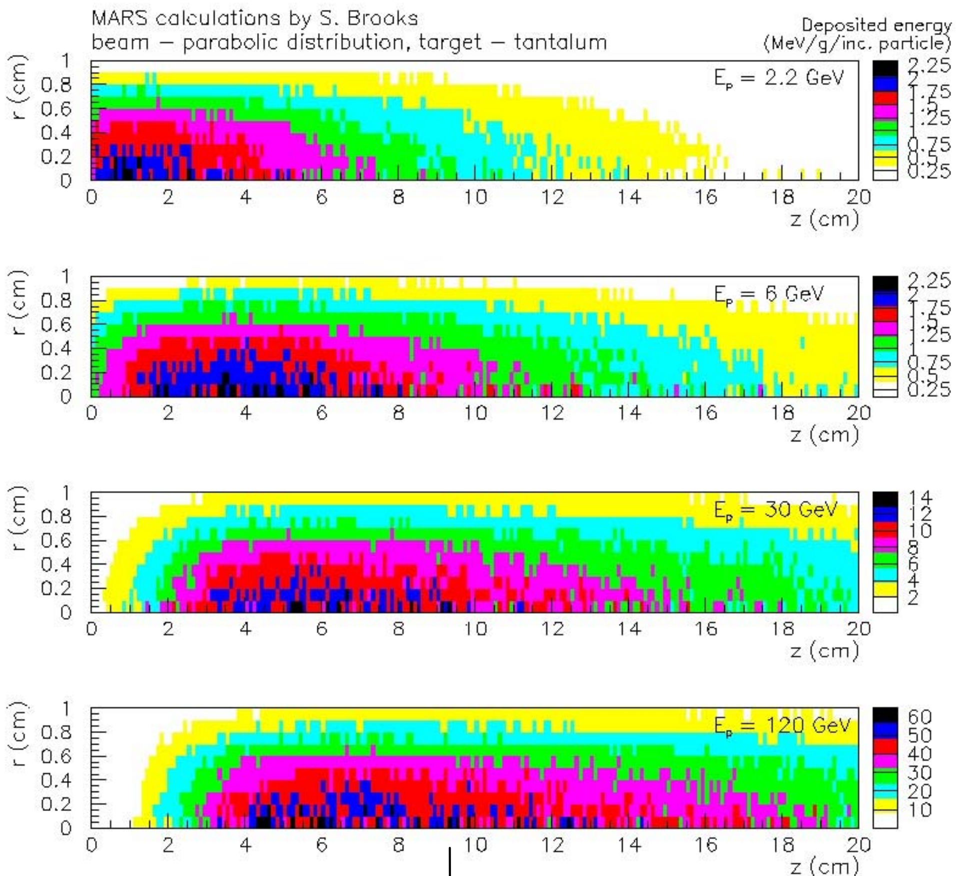
Beam: protons, 3 – 30 GeV

ISS baseline (April 2006):
4 MW, 10 GeV, 50 Hz,
4 bunches per pulse, 2 ns rms.

Simulations... as realistic as possible

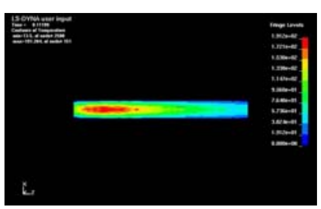
High energy particle cascade calculations (MARS)

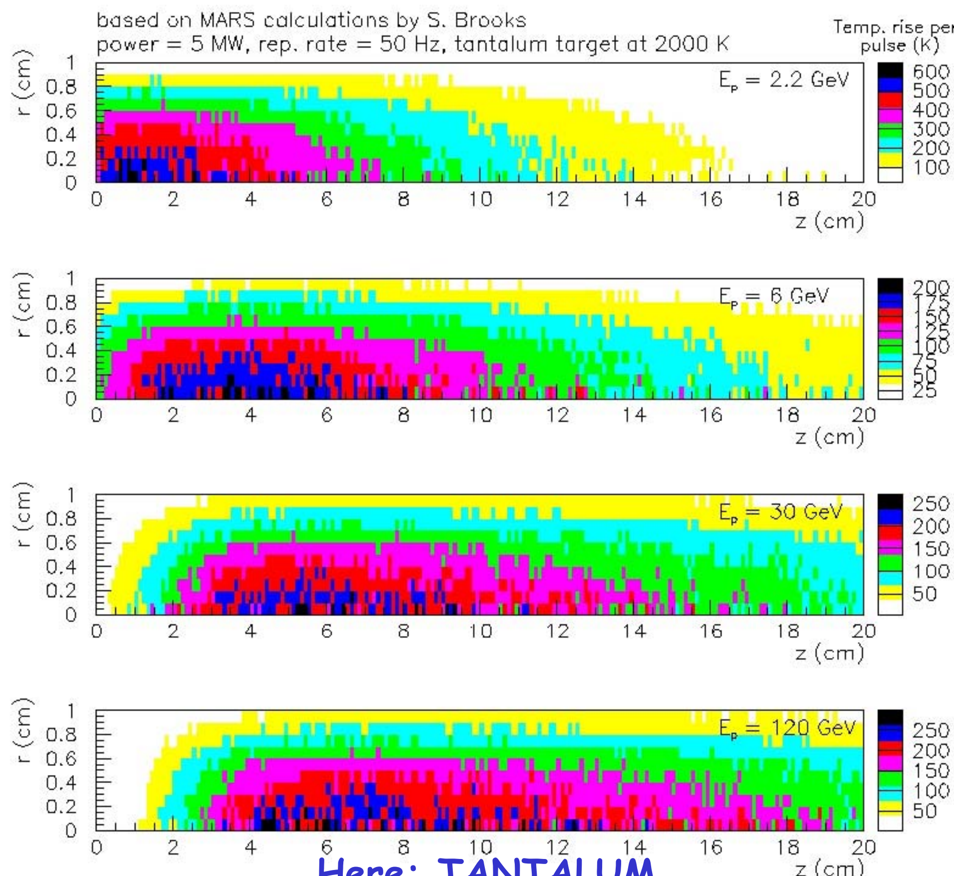
Energy deposition in solid target



Temperature rise in solid target

Input for thermal stress calculations (LS-DYNA)





Here: TANTALUM,
Beam power = 5 MW, repetition rate = 50 Hz

LS-DYNA simulations

Material model used in the analysis

- Temperature Dependent Bilinear Isotropic Model
- Uses 2 slopes (elastic, plastic) for representing of the stress-strain curve
- Inputs: density, Young's modulus, CTE, Poisson's ratio, yield stress, ...

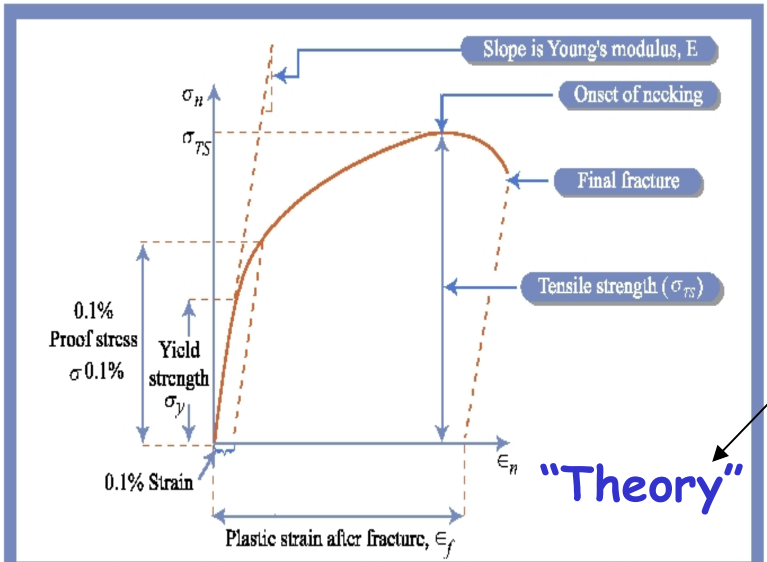
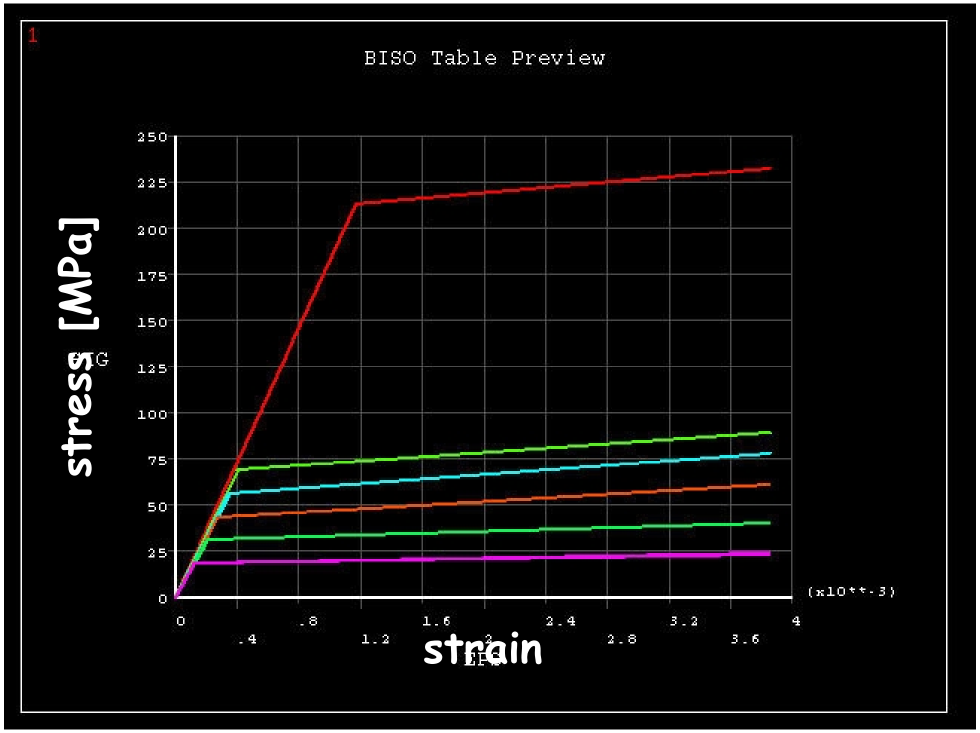


Image adapted from: Ashby, M. F., and D. R. H. Jones. *Engineering Materials 1*. Pergamon Press, 1980.

"Theory"

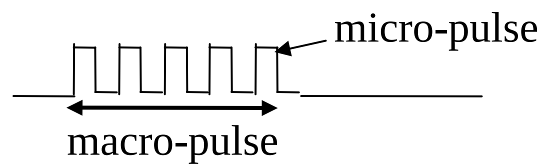


LS-DYNA input (estimate; especially for T> 1000K)

Problems with material data:

- reliable data can be found for temperatures up to 1000K (but inconclusive);
- no data (practically) at high temperatures.

LS-DYNA simulations (TANTALUM)

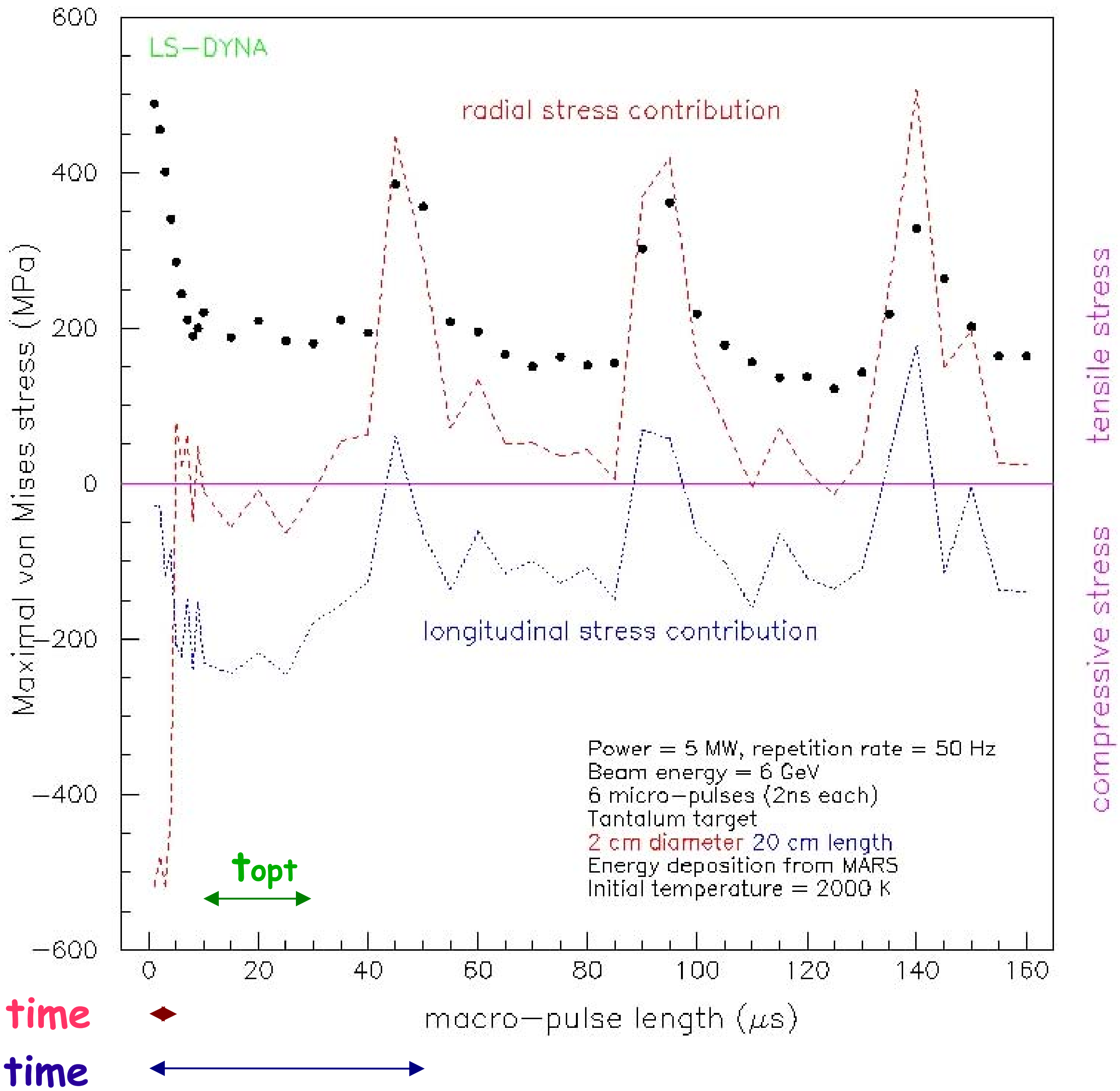


characteristic time
(shock transit time)
=
characteristic length / speed of sound in material

factor of 2 difference in shock magnitude

optimal macro-pulse length (t_{opt})

(let's say)
from 10 to 30 μs



radial characteristic time

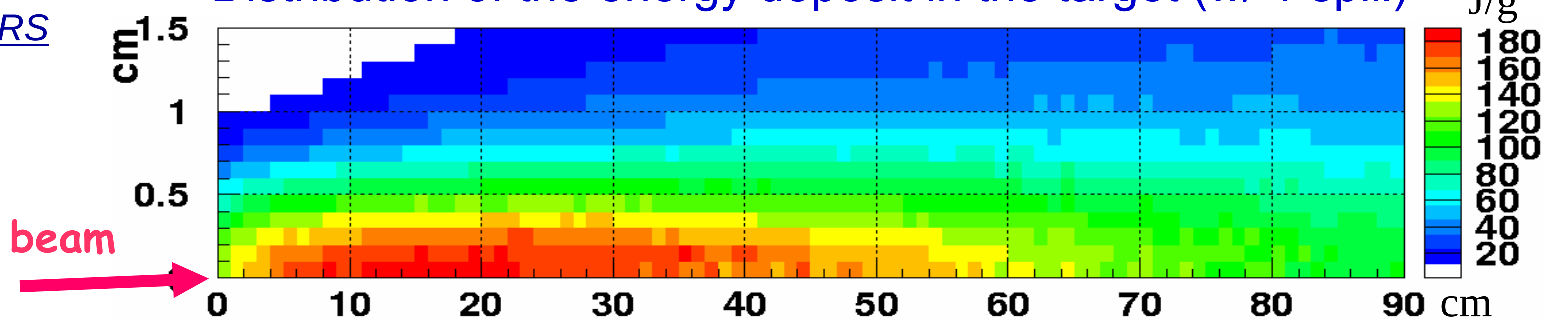
longitudinal characteristic time

"Proof": T2K target results

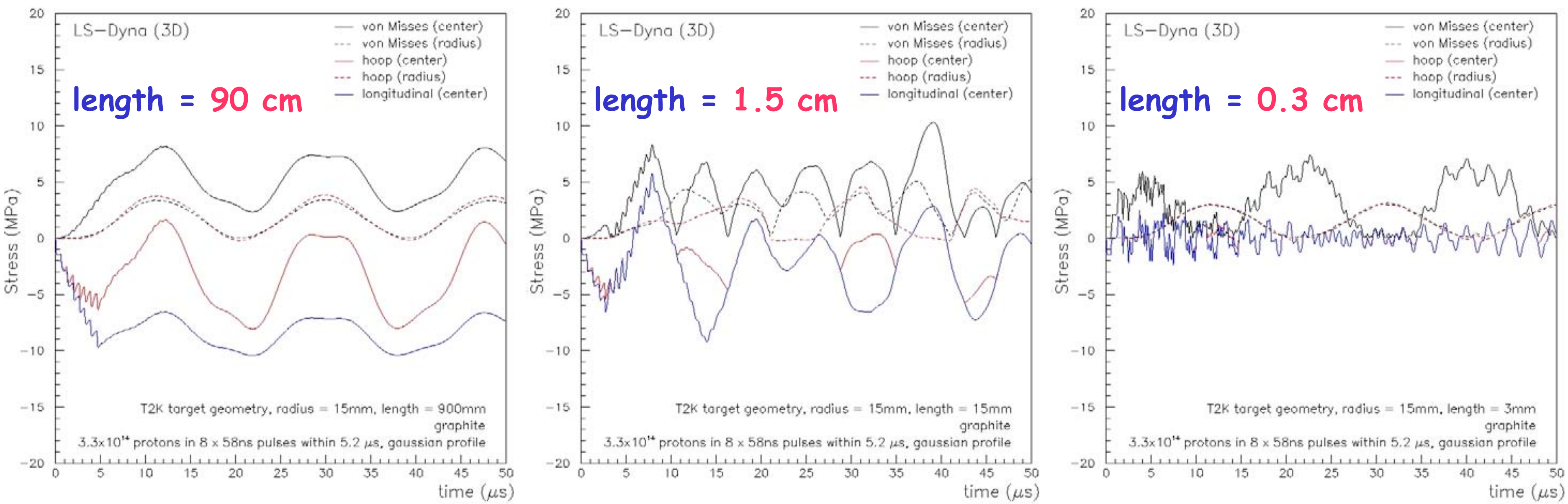
- Graphite Bar Target : r=15mm, L=900mm (2 interaction length)
  - Energy deposit … Total: 58kJ/spill, Max:186J/g → $\Delta T \approx 200K$

Distribution of the energy deposit in the target (w/ 1 spill)

MARS



macro-pulse length = 5 μs characteristic time (radial) = 10 μs



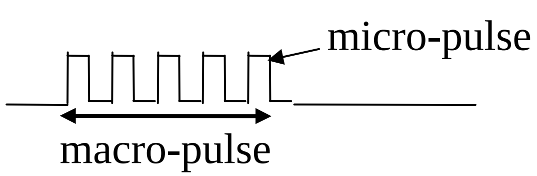
Slicing of the target does not help if shock transit time is bigger than macro-pulse length

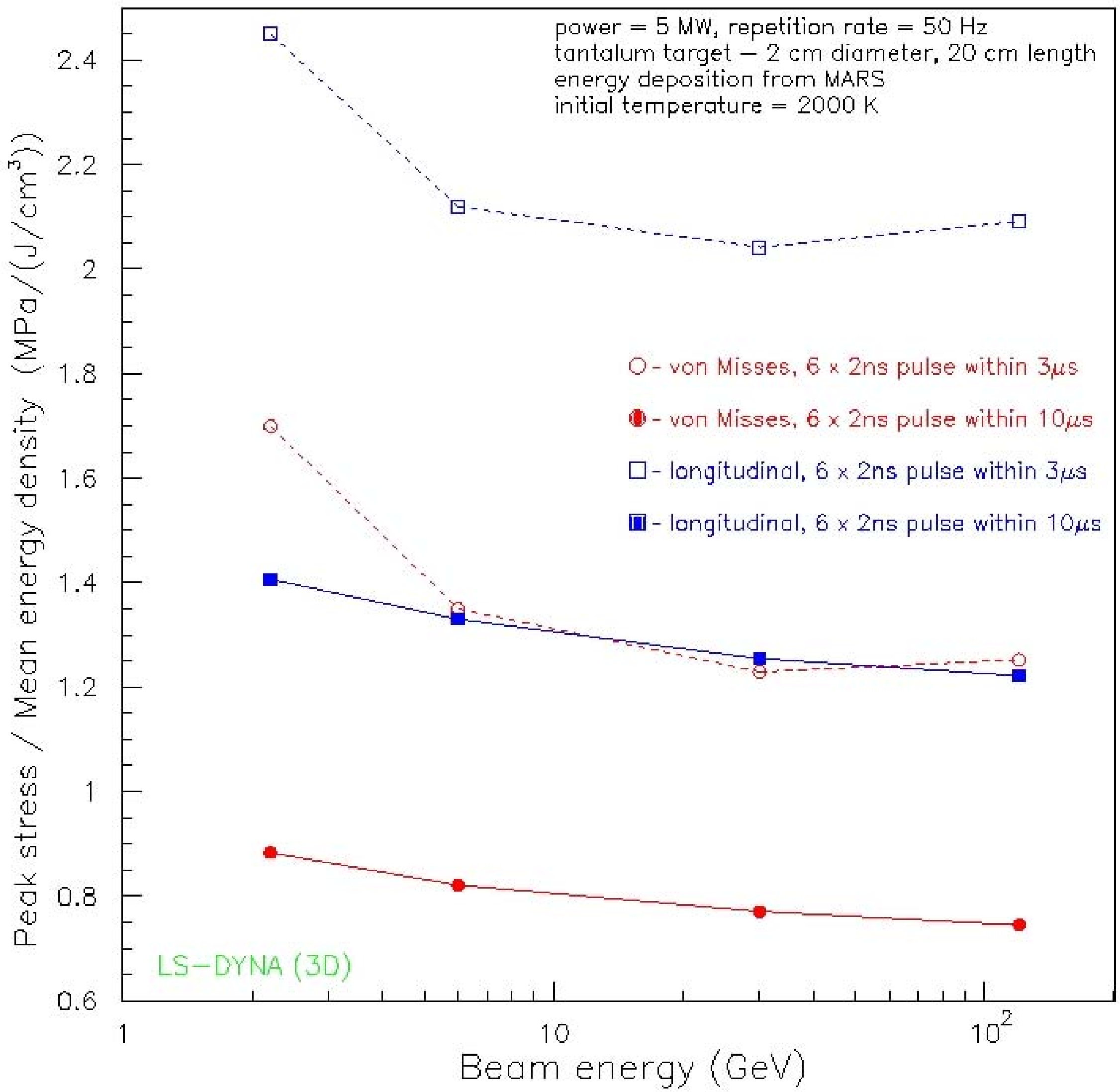
LS-DYNA simulations (TANTALUM)

Peak stress as a function of beam energy
(normalized on mean energy density)

for fixed beam power (5 MW) and repetition rate (50 Hz)

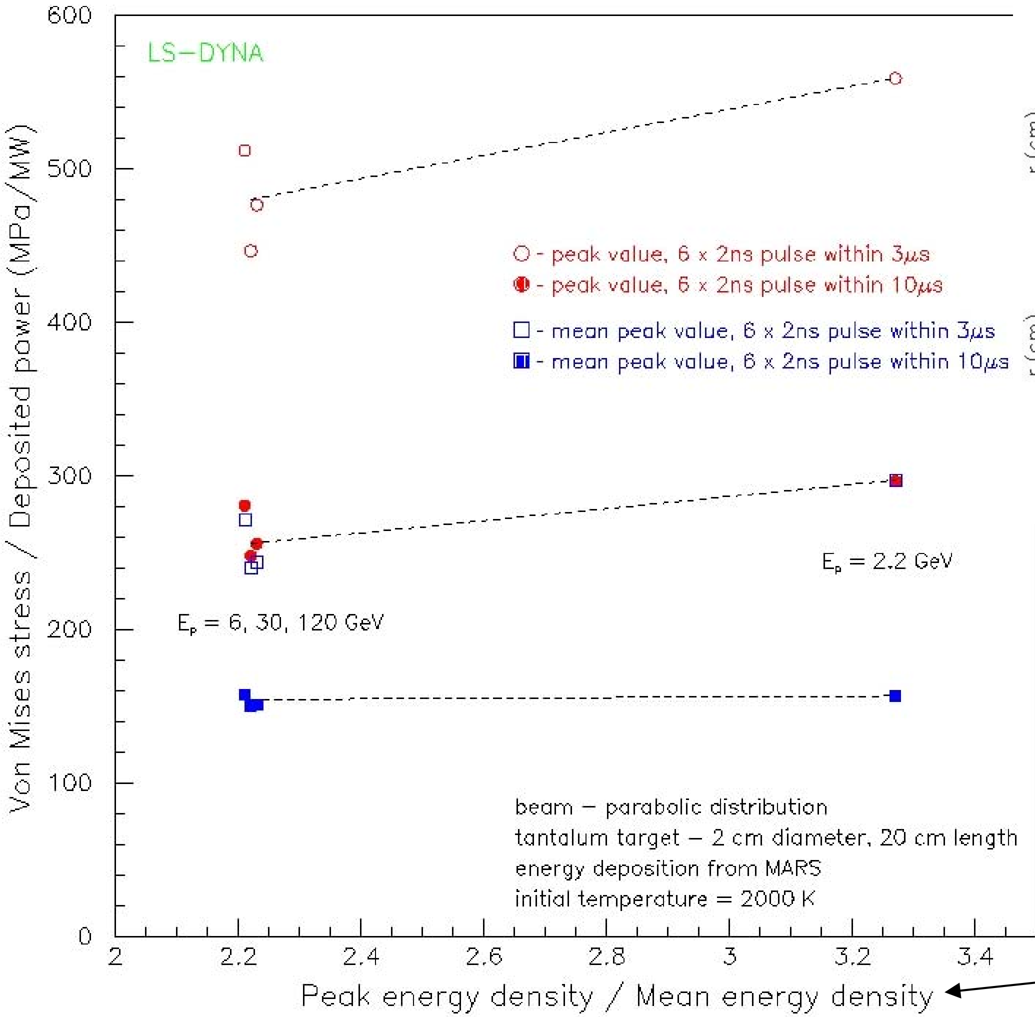
for 2 different macro-pulse lengths (3 μs) and (10 μs)

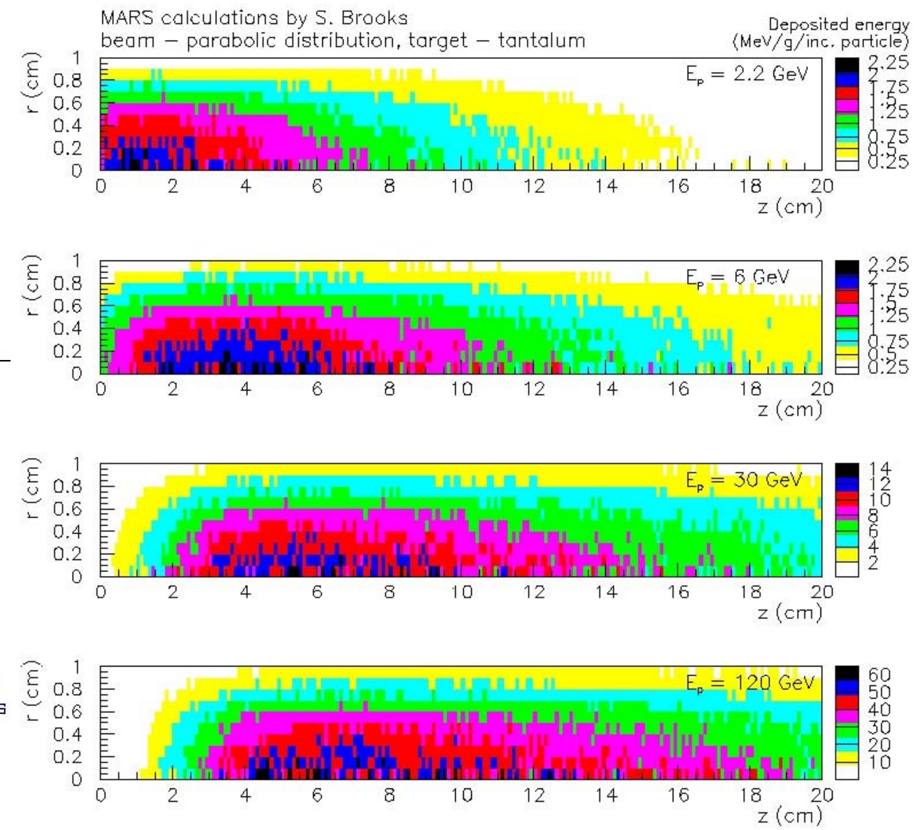




LS-DYNA simulations (TANTALUM)

Stress per deposited power
- at the level of 250 MPa per MW -

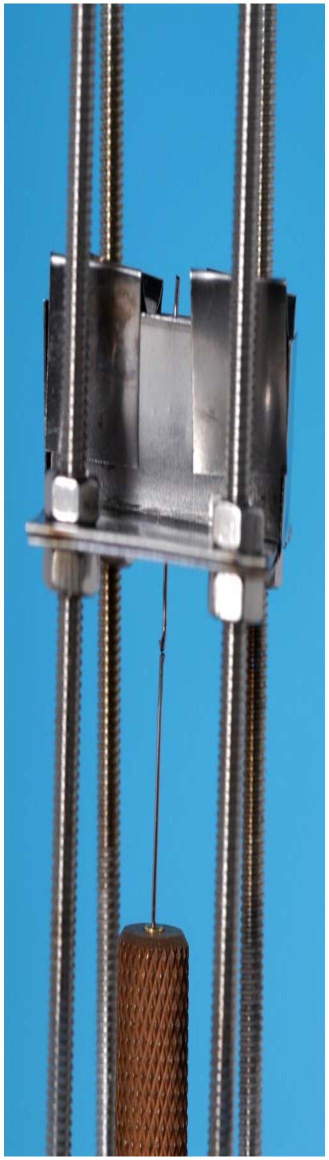




'mean peak value' = averaged peak (von Mises) stress across the target

measure of 'concentration' of deposited energy

Status of simulations of the current pulse – wire tests at RAL



Experiment (Tantalum wire)

The wire is 0.5 mm diameter, tantalum.

Originally it protruded from the graphite top connection by 0.5 mm and ended up protruding 3 mm.

The wire ran for 16 hours at 3.125 Hz repetition rate.

The wire was run at 100 C rise per pulse for the first 6.5 hours, ... The last 5 hours was at 4900 A, pulse, corresponding to a temperature rise or 150 C per pulse.

The peak temperature ... was estimated to be ~1300 C.

One can see that the wire has become reduced in radius in parts and is thicker in others.

LS-DYNA simulations

Geometry

- 0.5mm diameter; 40mm long wire; supported at bottom, free at top

Loads

- Current pulse: ~ 5 kA, exponential rise

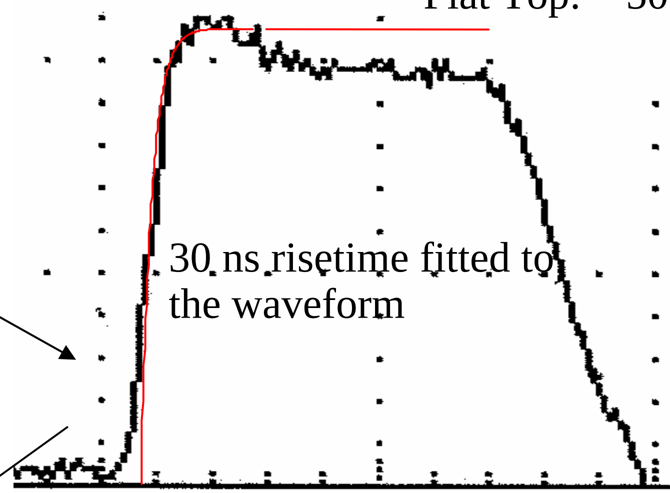
The power supply planned for the test purpose can deliver up to 8kA and the pulse waveform has a rise time of about 100ns and a flat top of about 500ns. The shape of the pulse waveform is exponential $I = I_0(1 - e^{-\gamma t})$ with time constant $t_0 = 1/\gamma = 30$ns. Assuming that an electric field is instantaneously applied across the conductor of radius a and that current density j is circularly symmetric about the axis of the conductor the corresponding diffusion equation can be obtained by using Maxwell's equations. The solution of the diffusion equation for the case of an exponential rise in current density at $r = a$ has the form:

$$j_z = j_{z0}\{1 - \frac{J_0(\sqrt{\gamma r^2/\kappa})}{J_0(\sqrt{\gamma a^2/\kappa})} e^{-\gamma t} + \frac{2\gamma}{a\kappa} \sum_{n=1}^{\infty} \frac{J_0(\beta_n r/a) e^{-\kappa(\frac{\beta_n}{a})^2 t}}{\frac{\beta_n}{a} J_1(\beta_n)[(\frac{\beta_n}{a})^2 - \frac{\gamma}{\kappa}]}\},$$

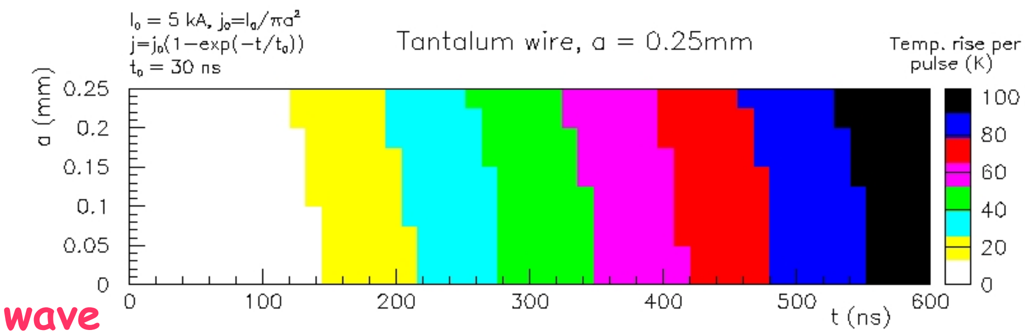
where j_{z0} is the current density at $r = a$, β_n are the roots of the Bessel functions of the first kind, $J_1(*)$ and $J_0(*)$ are the corresponding Bessel functions, $\kappa = 1/\mu_0\sigma$ with μ_0 being the permeability of free space and σ is the electrical conductivity.

Rise time: ~100 ns

Flat Top: ~500 ns



- Energy density; temperature rise across the wire



- Lorentz force induced pressure wave

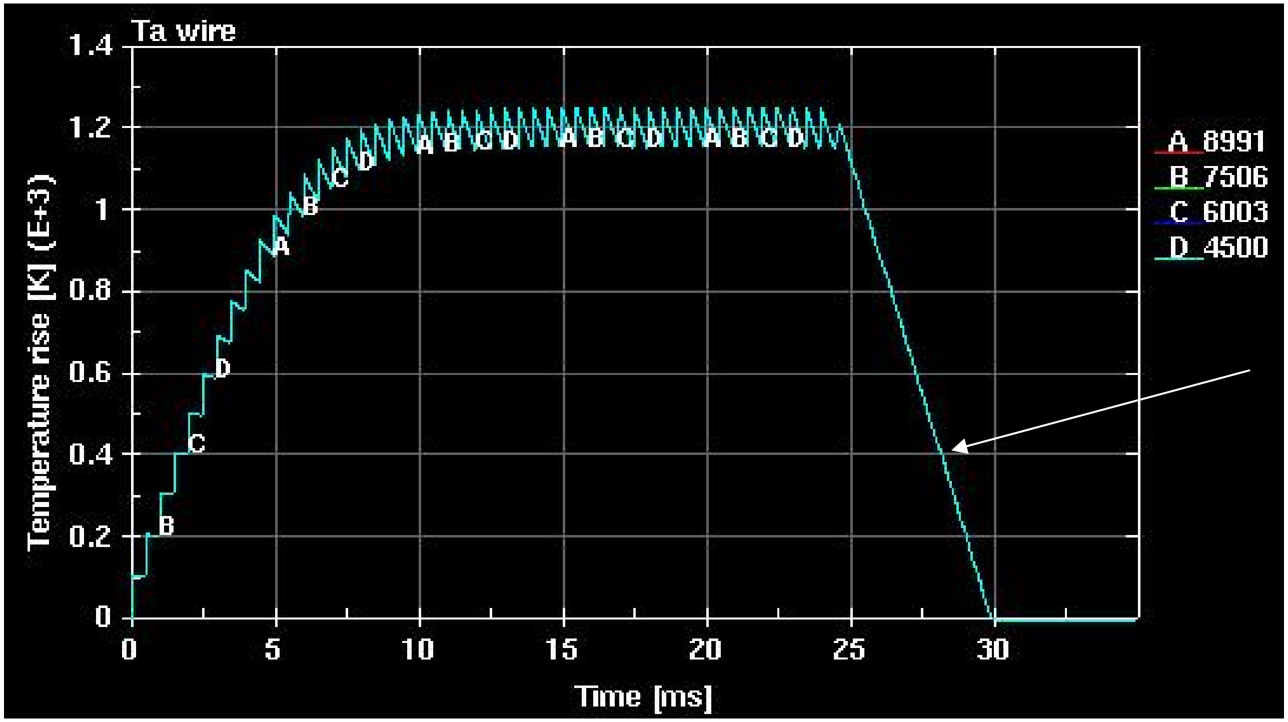
LS-DYNA simulations

Multiple pulses

- Pulse time (heating) ~ 600 ns; temperature rise per pulse ~ 110 C
- Time between pulses (cooling) ~ 300 ms; LS-DYNA needs 115 h to complete 1 pulse!

- APPROXIMATION: Time between pulses (cooling)~ 500 μs; 50x longer than (longitudinal) characteristic time!

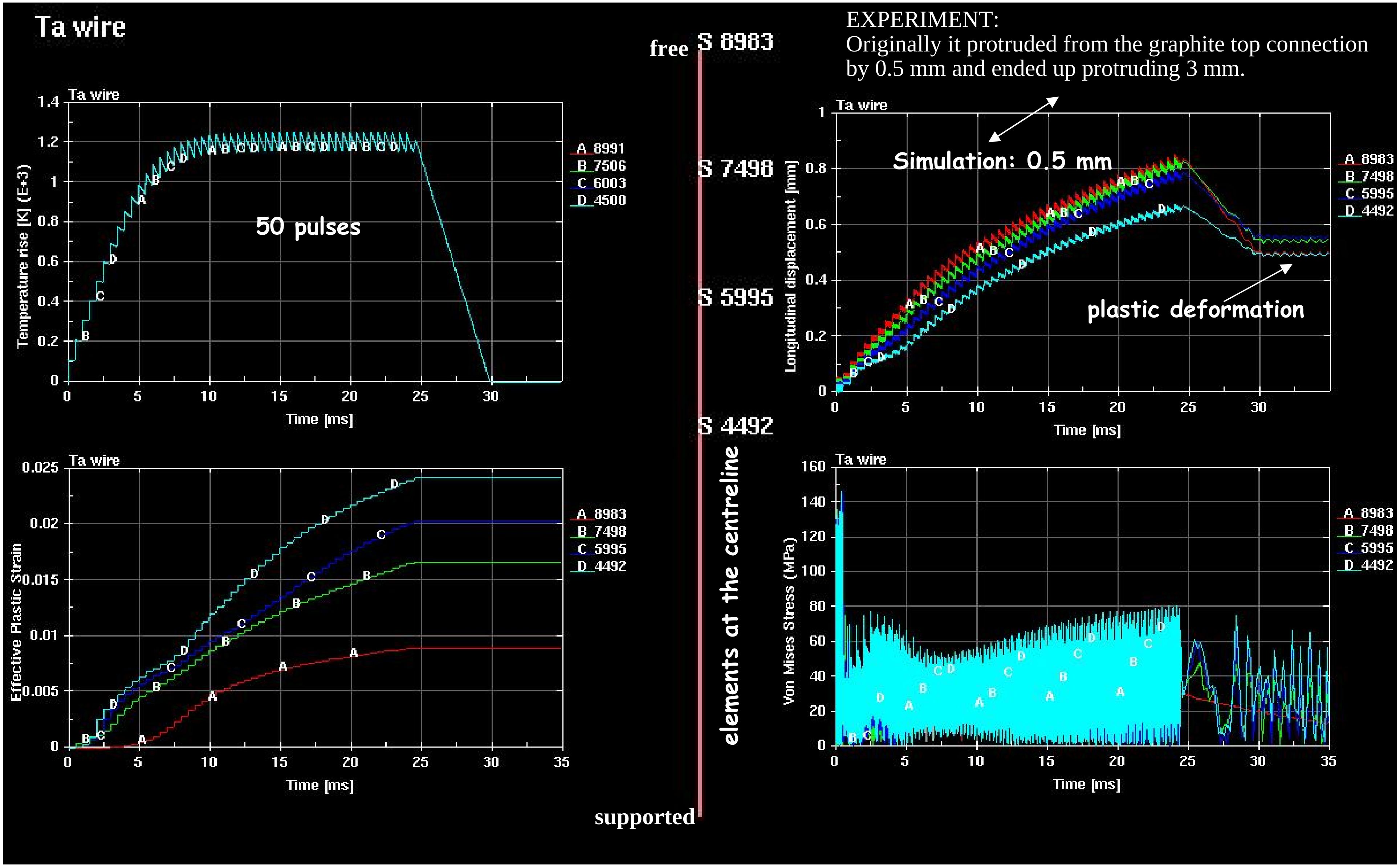
- 50 pulses (16 h to complete);
- temperature rise ~ 1300 C



final cooling ↔ 500x longer time than (longitudinal) characteristic time.

Results

Tantalum wire: 0.5 mm diameter, 40 mm long

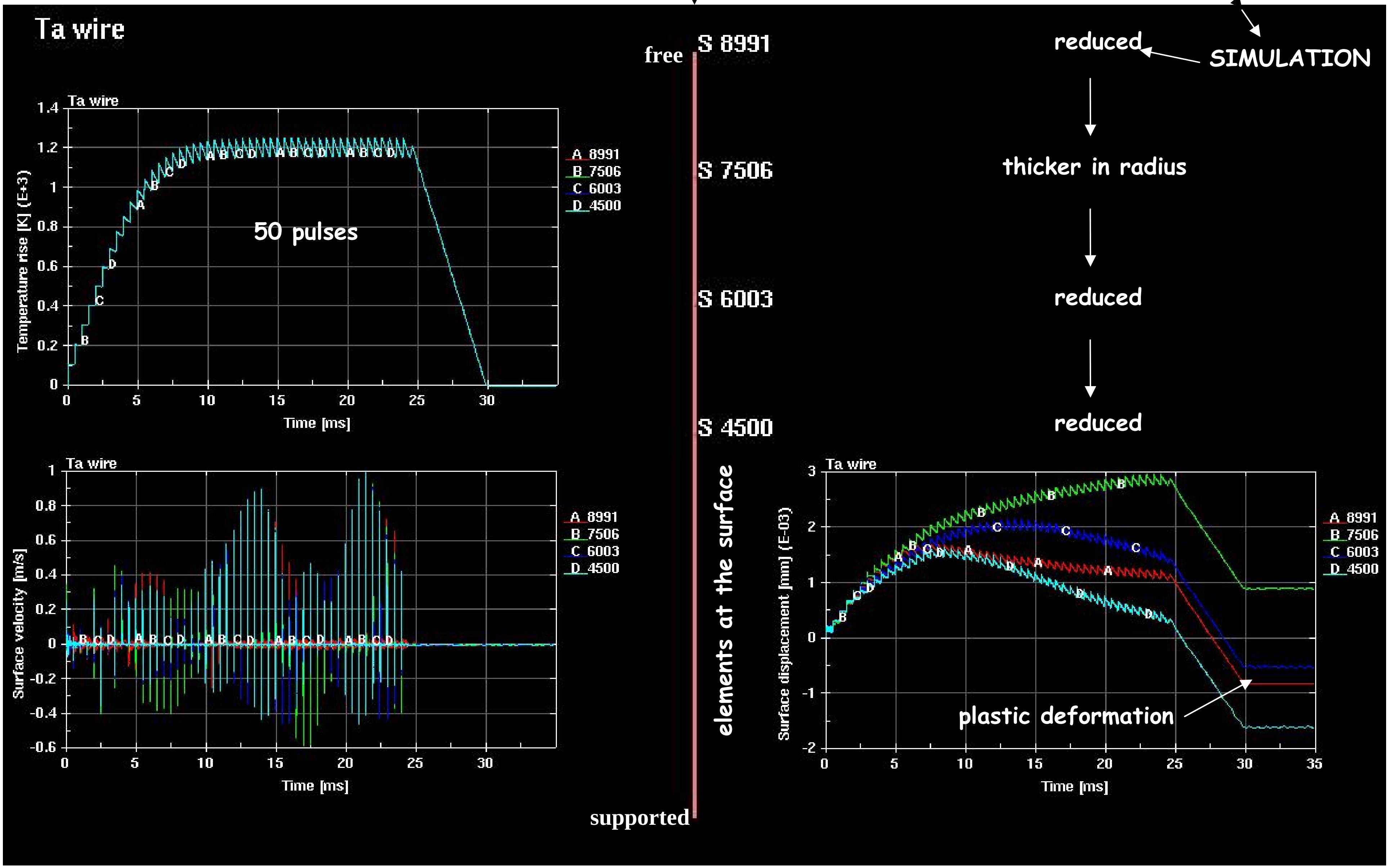


LS-DYNA

Results

Tantalum wire: 0.5 mm diameter, 40 mm long

EXPERIMENT:
One can see that the wire has become reduced in radius in parts and is thicker in others.



LS-DYNA

Tungsten wire test

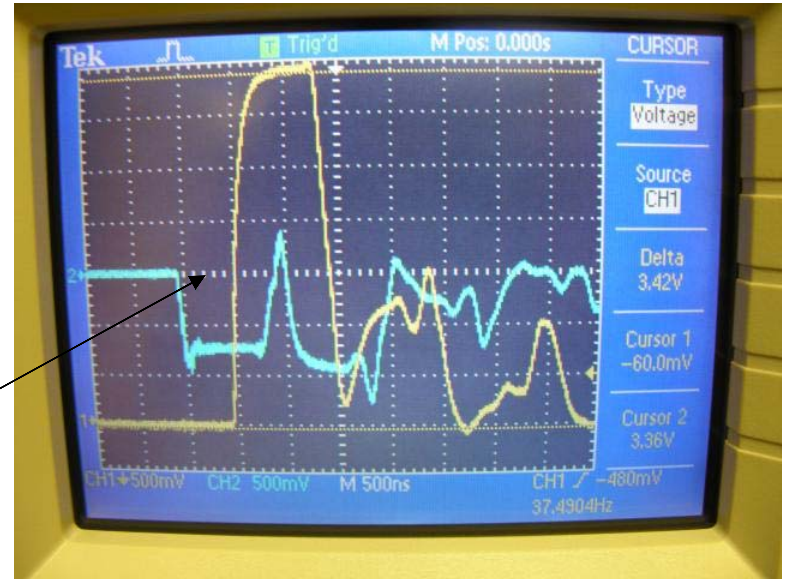
Geometry

- 0.5mm diameter; 30mm long wire

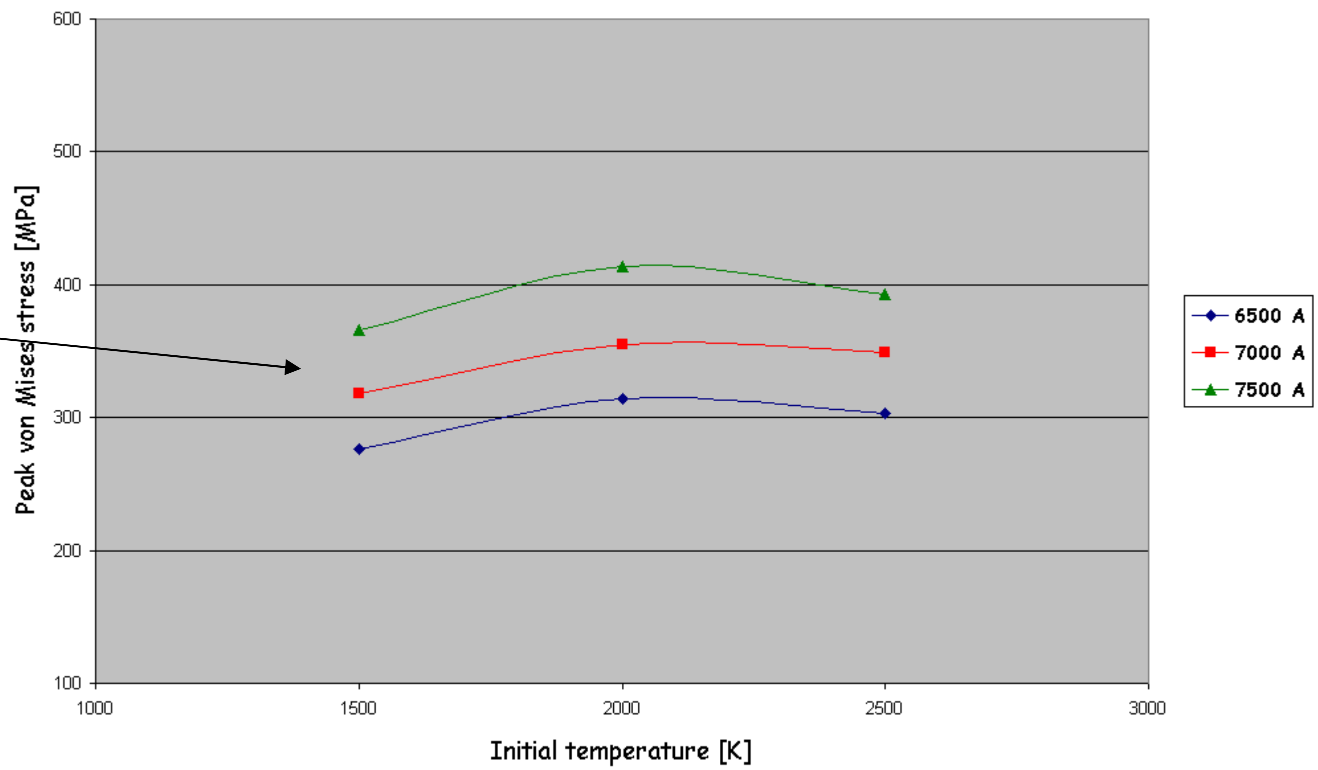
Loads

- Current pulse: ~7 kA, 800 ns long

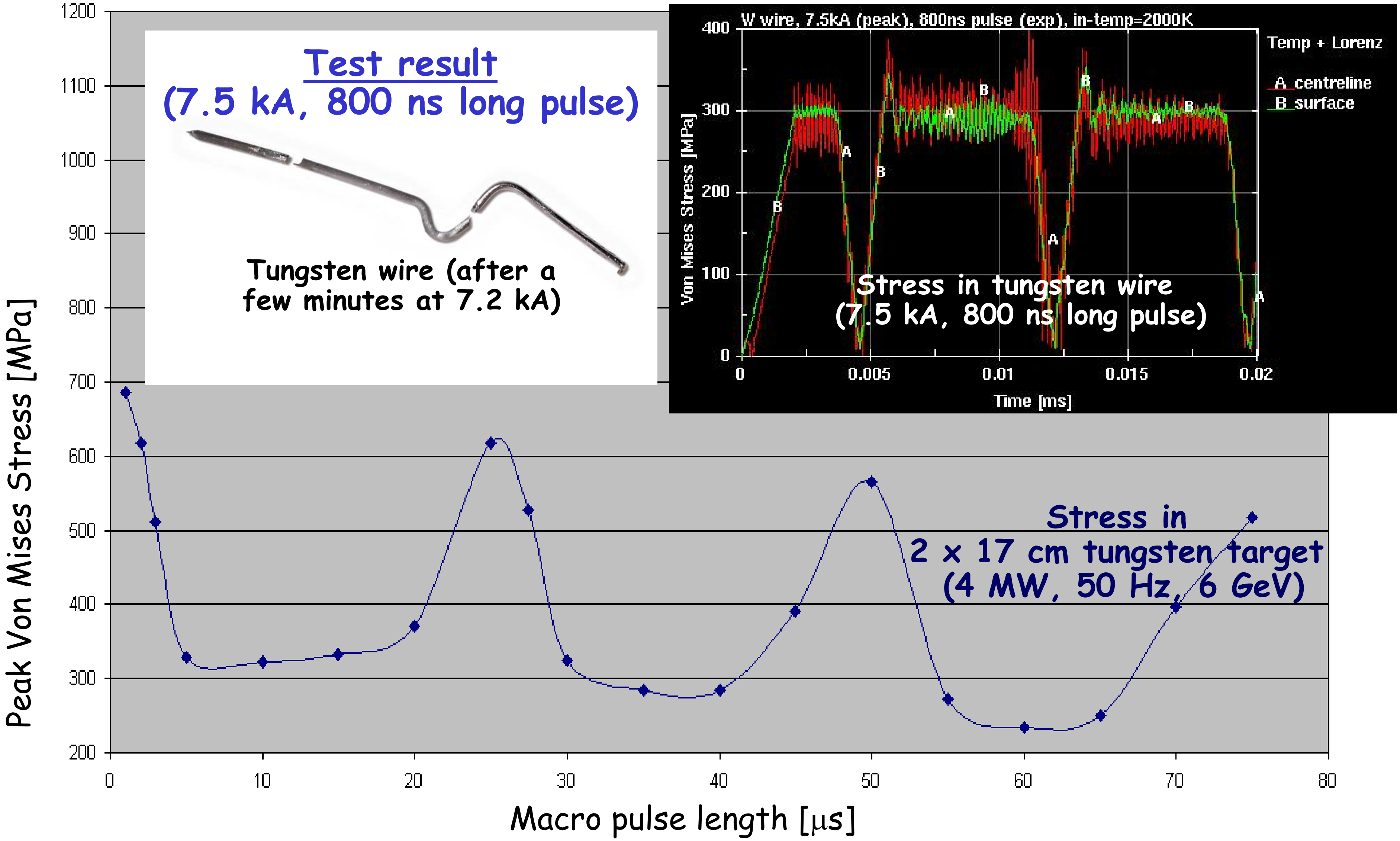
Initial temperature = 2300 K



Peak current can be 'tuned' to have a wanted value of the peak stress in the wire

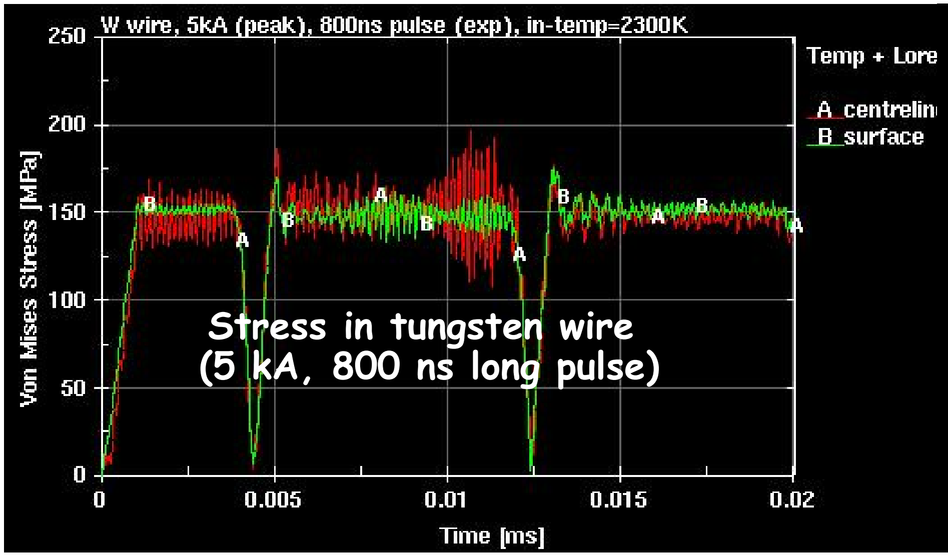


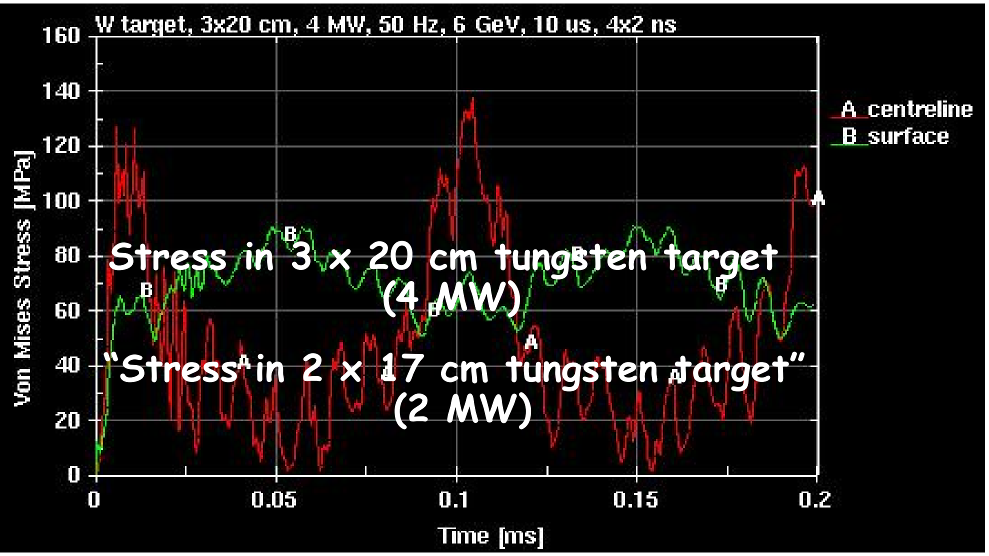
Comparison: Stress in real target vs. stress in tungsten wire



LS-DYNA

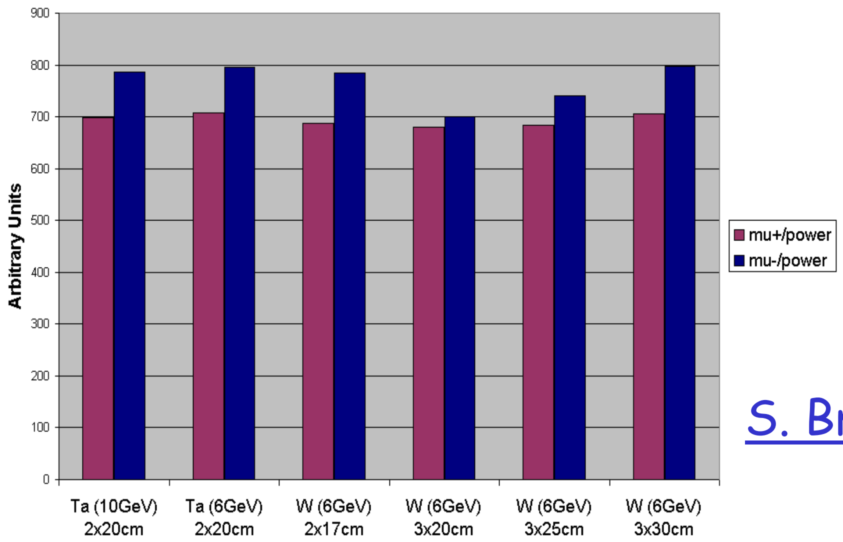
Comparison: Stress in real target vs. stress in tungsten wire



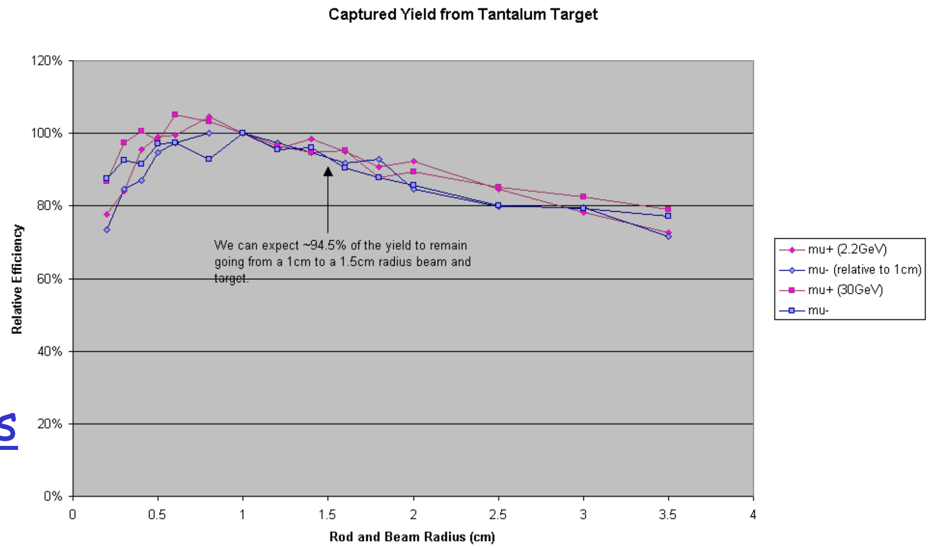


This wire had survived
over 3 million pulses at 5 kA.
Bent into this severe shape
within a few minutes at 7.2 kA.

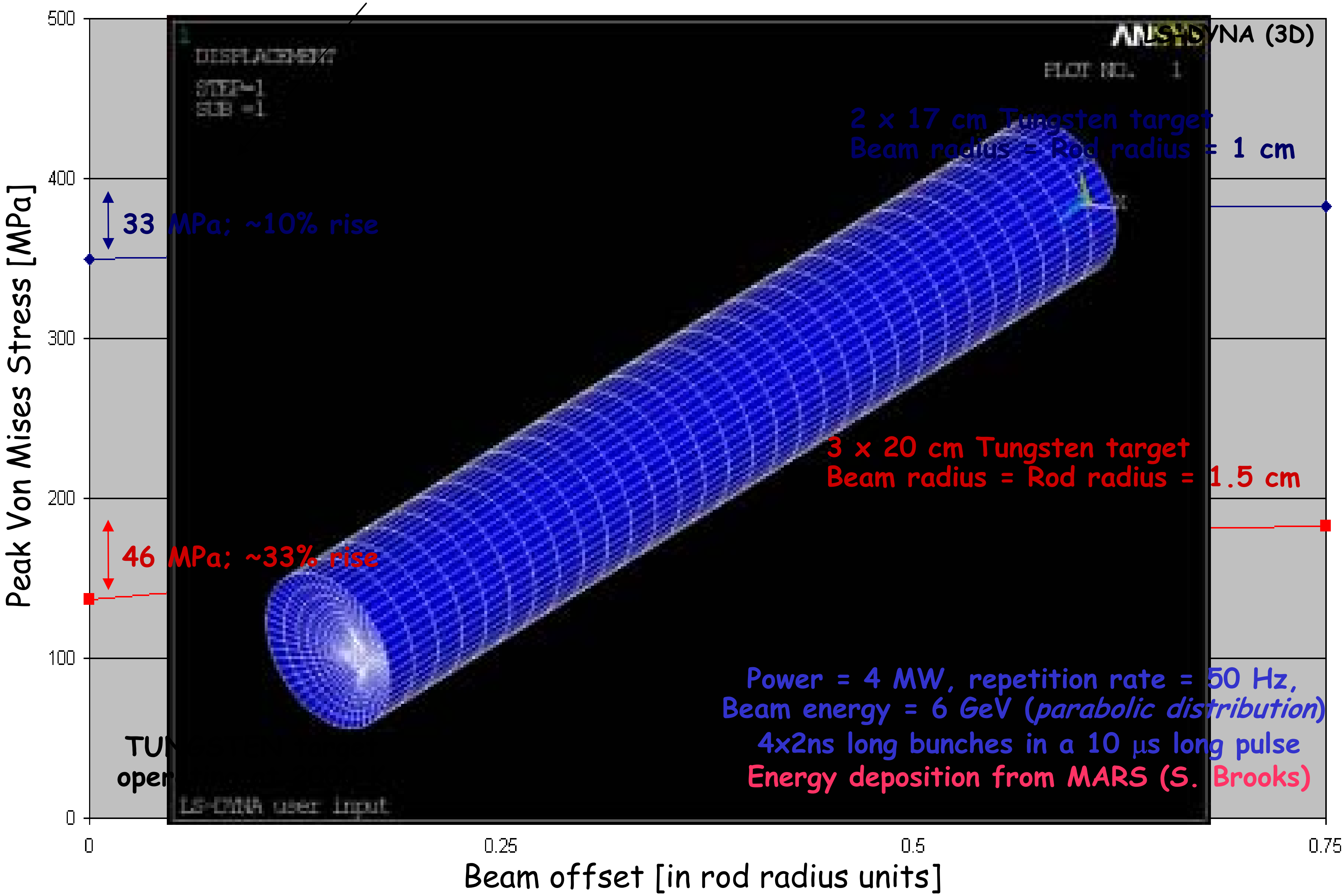
Solution: bigger target radius?
It looks possible.
Captured yield practically the same
for 1 cm radius -> 1.5 cm radius.

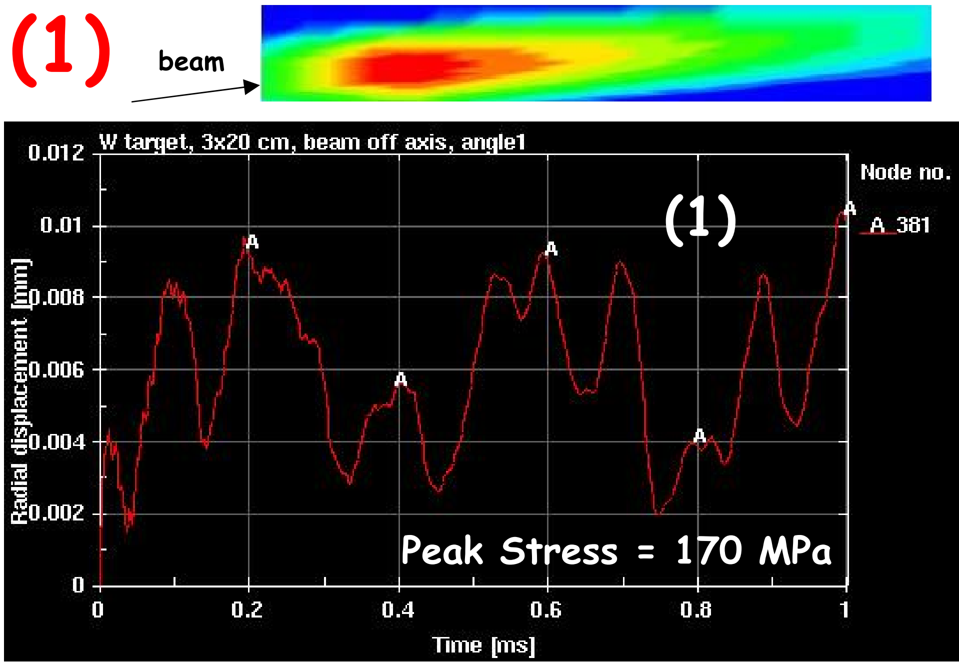


S. Brooks

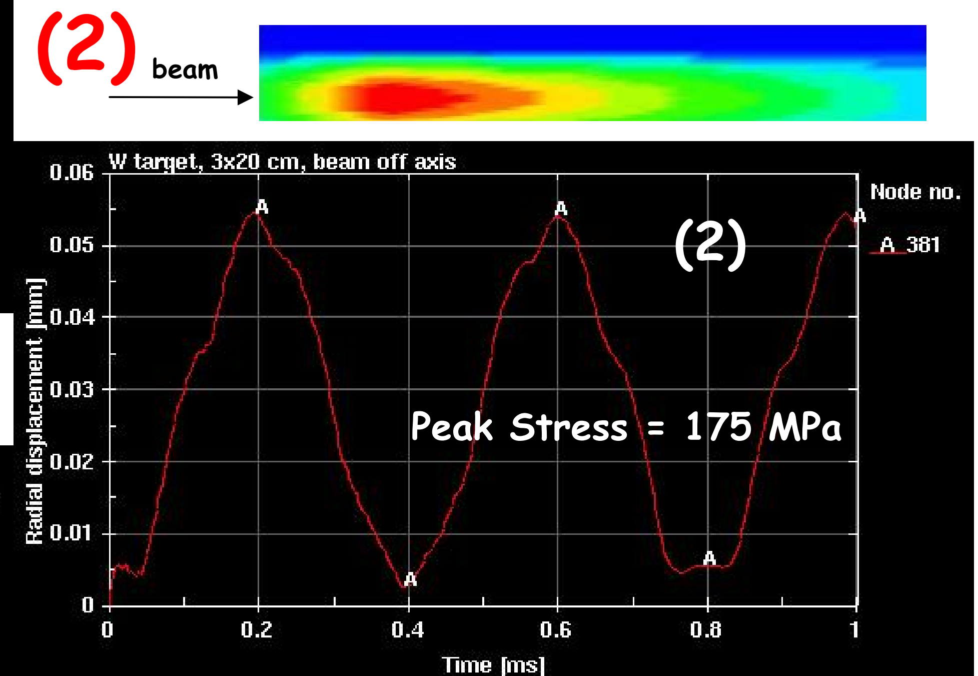


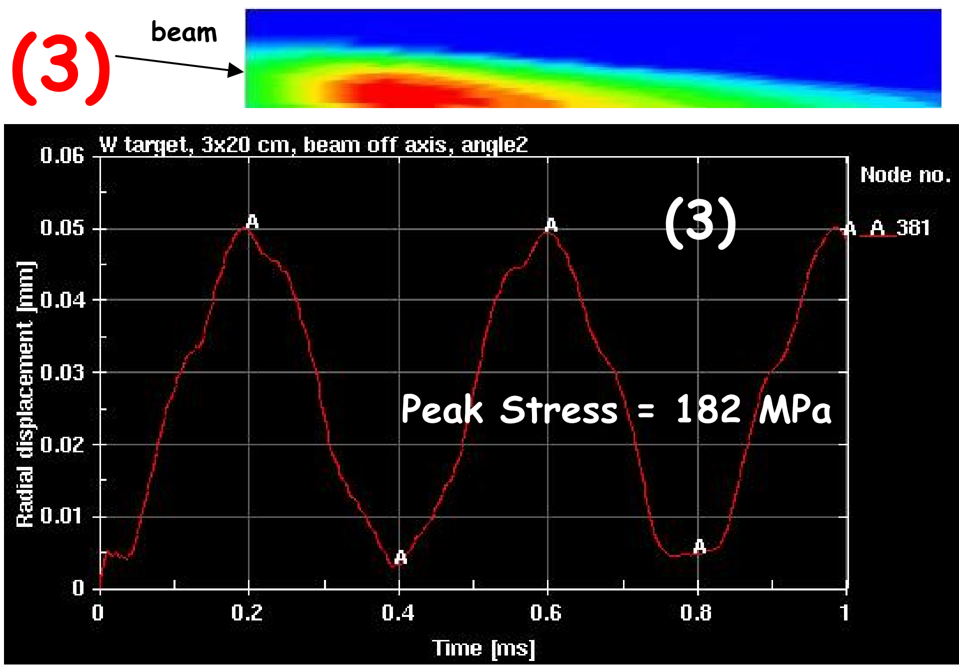
"Additional" stress in the target: for example when beam is not at a target axis (target bending, etc…)





Beam radius = rod radius;
Beam offset = 1/2 radius.





Tungsten target: 3x20 cm
Beam: 4 MW, 50 Hz,
6 GeV, 4x2ns, 10 μs

Energy deposition from MARS (S. Brooks)

LS-DYNA (3D)

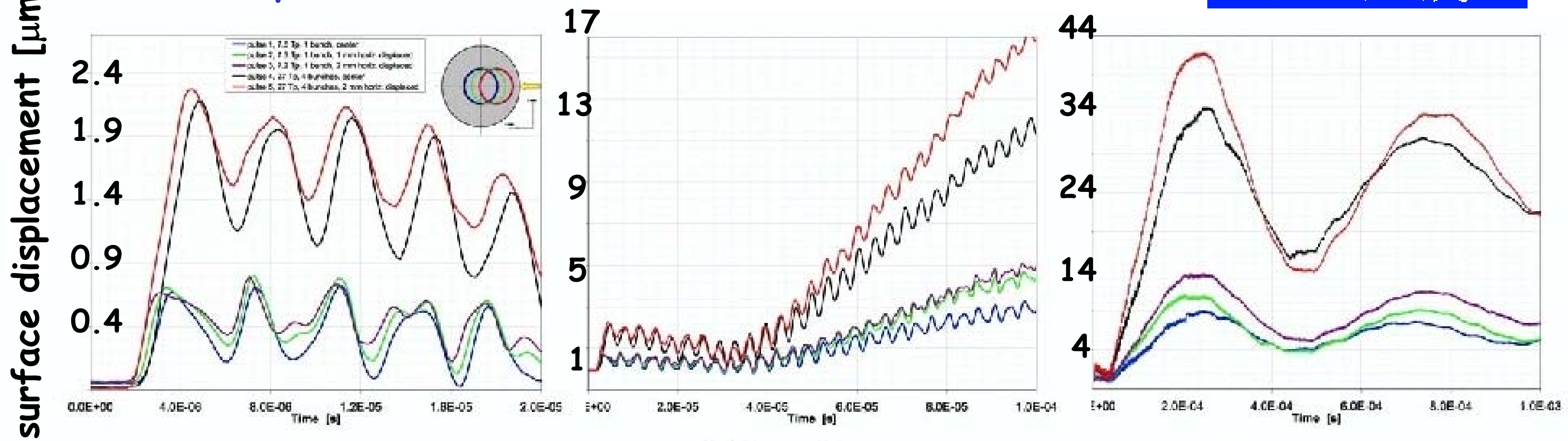
Comparison with the tests at the ISOLDE

Tantalum Cylinder, 1x10 cm

Roman WILFINGER
ISOLDE, CERN & TU Vienna

ENG / BENE Meeting,
March 16th, 2005, page 7

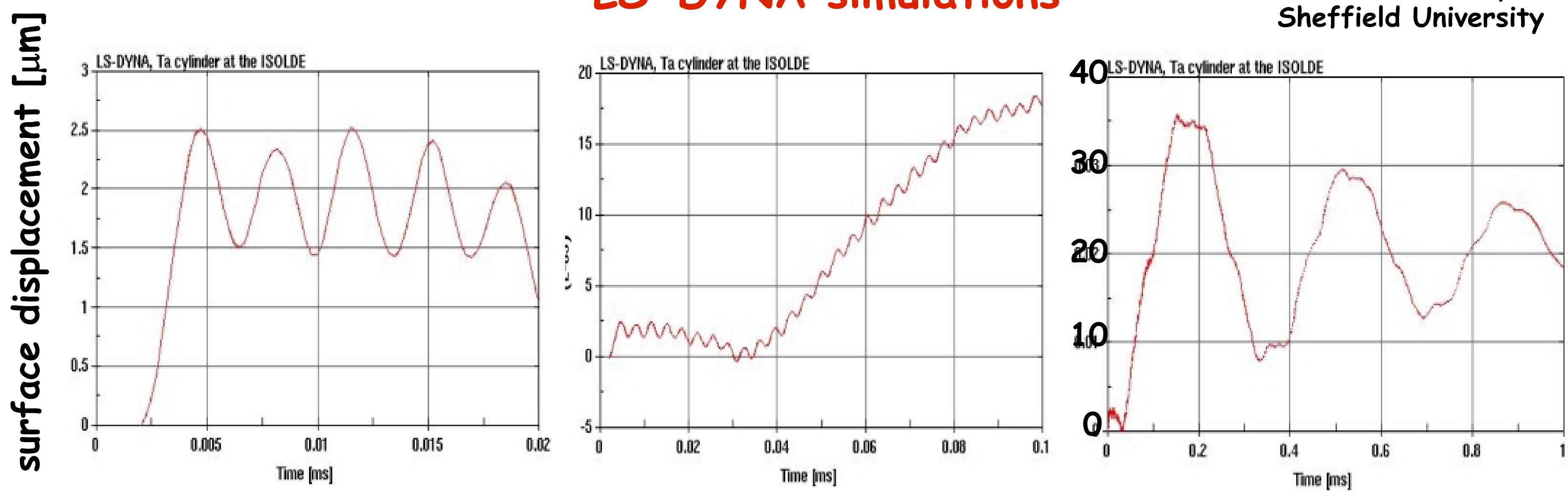
EXPERIMENT



(d) First 20 μs. (c) First 100 μs. (b) First 1 ms.

LS-DYNA simulations

Goran SKORO,
Sheffield University



Summary

- **Solid target for the Neutrino Factory:**
  - **Shock waves in candidate materials (Ta, W, C) characterised within limitations of material knowledge**
  - **Effects of beam pulse length and multiple bunches/pulse understood (stress reduction by choosing optimal macro-pulse length)**
- **Test of wire:**
  - **First estimate of the lifetime of tantalum (and tungsten) NF target**
  - **VISAR is purchased to measure surface velocity of wire and compare results with LS-DYNA calculations (this will help to extract high temperature material data from experiment)**
  - **Repeat experiment with graphite and the others candidate materials**
- **Conclusions**
  - **Nice agreement between LS-DYNA and existing experimental results**
  - **2 MW -> looks possible in 2 cm diameter target (W is better than Ta)**
  - **4 MW -> needs bigger target diameter (2 cm -> 3 cm)**