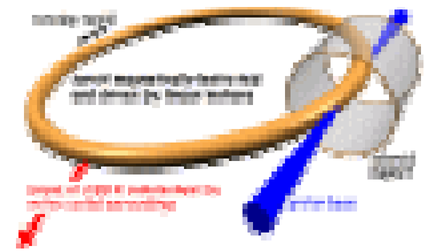

Studies of solid high-power targets

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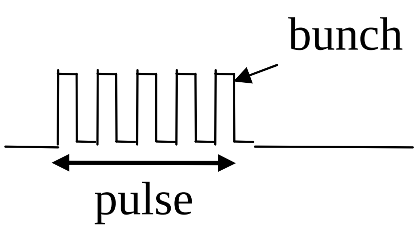
University of Sheffield

HPT Meeting

May 01 – 02, 2008
Oxford, UK

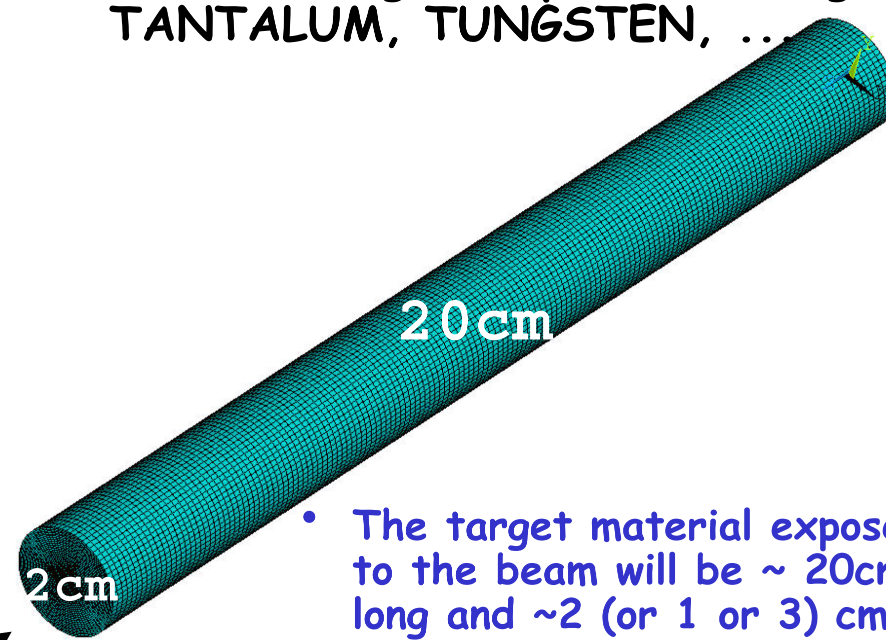
Solid Neutrino Factory target

- 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.



Beam: protons, 3 – 30 GeV

Candidates for high temperature target:
TANTALUM, TUNGSTEN, ...



- The target material exposed to the beam will be ~ 20cm long and ~2 (or 1 or 3) cm in diameter.

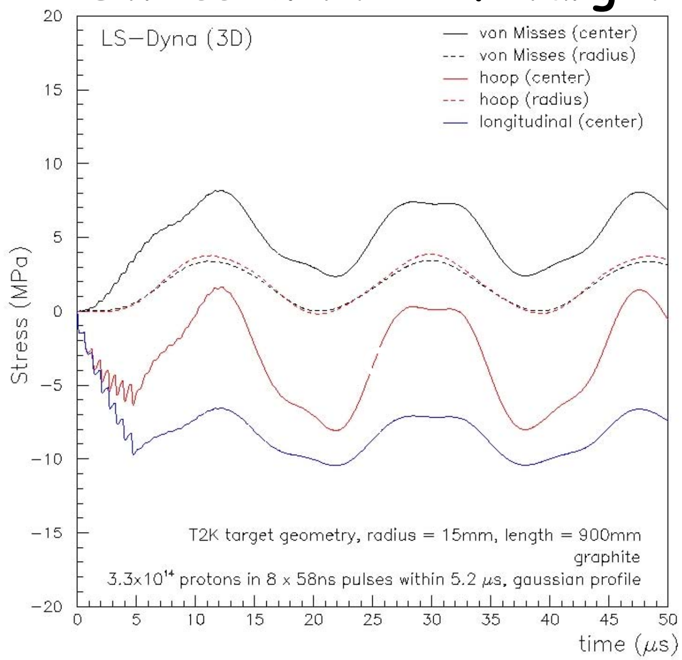
- Energy density per pulse ~ 300 J/cc.

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

One of the main problems: Thermal Shock (Stress)

- In-beam lifetime/fatigue tests hardly possible
- Shock can be modelled: Finite Element Software (FES) →
- Target surface motion can be measured for (every) beam pulse and used as an indication what's happening inside the target (evaluation of the constitutive equations with the help of FES)

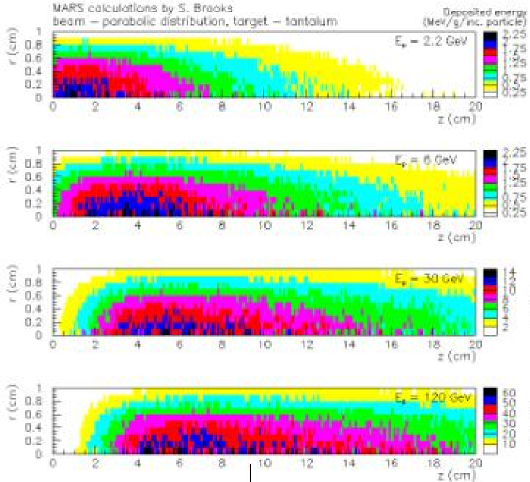
Stress in the T2K target



- Simulate the level of shock in the real target by passing a pulsed current through a very thin wire
- Lifetime/fatigue tests
- Measurements of the wire surface motion

FE simulations: prediction and intrepretation of tests results

Simulations… as realistic as possible

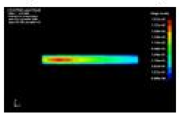


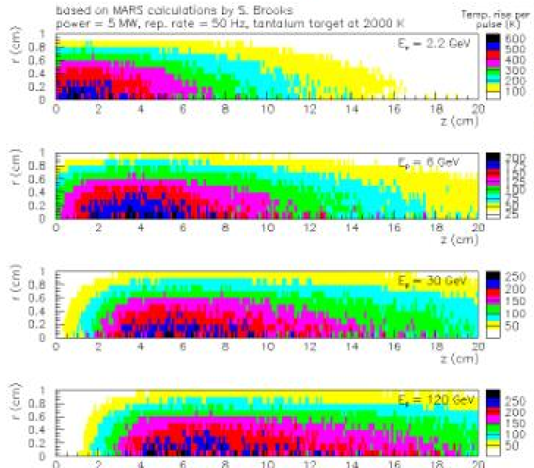
High energy particle cascade calculations (MARS)

Energy deposition in solid target

Temperature rise in solid target

Input for thermal stress calculations (LS-DYNA)

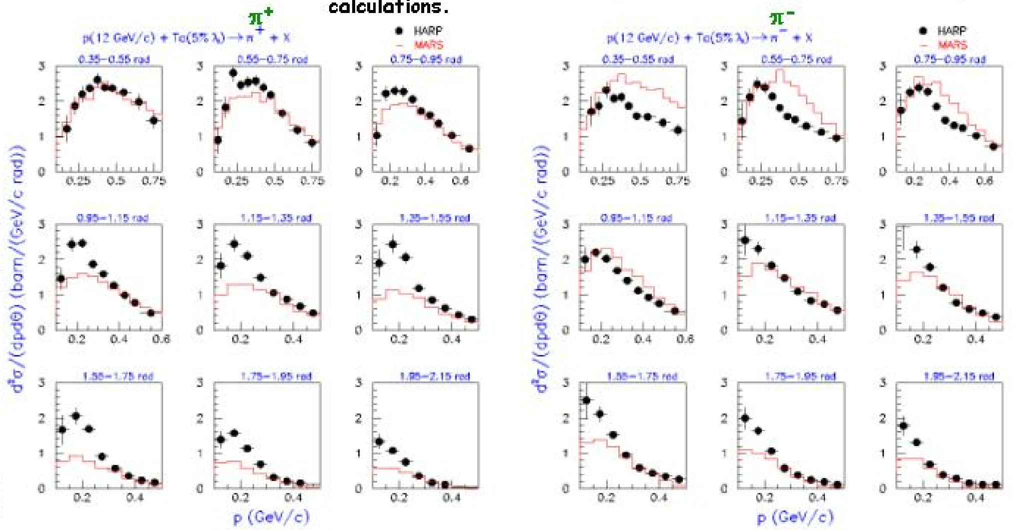




Here: TANTALUM,
Beam power = 5 MW, repetition rate = 50 Hz

MARS vs. HARP

Comparison between experimental data from HARP experiment and Monte Carlo calculations (MARS15) on pion production in proton – tantalum interactions will help to tune all the Neutrino Factory related calculations.



Beam momentum = 12 GeV/c

We are most interested in the HARP results for beam momentum of 12 GeV/c because this is closest value to the 'standard' beam energy (10 GeV) we use in UKNF simulations.

The agreement between MARS and HARP is relatively good.

LS-DYNA simulations

Material model used in the analysis

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

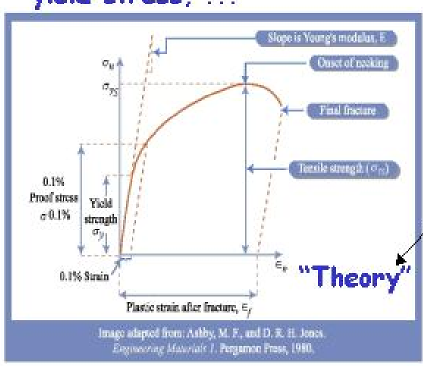
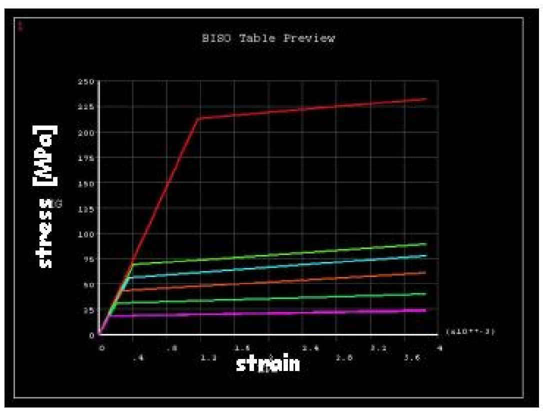


Image adapted from: Ashby, M. F., and D. R. H. Jones. *Engineering Materials 1*. Pergamon Press, 1980.



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.

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

Geometry

- 0.5mm diameter; 3cm long wire; supported at bottom, free at top

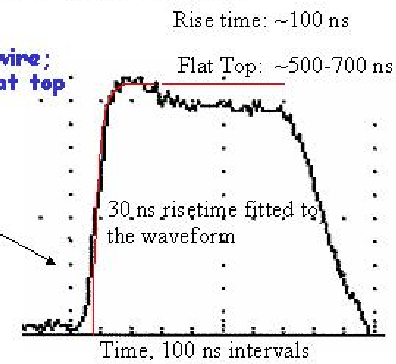
Loads

- Current pulse: ~ 5-10 kA, exponential rise

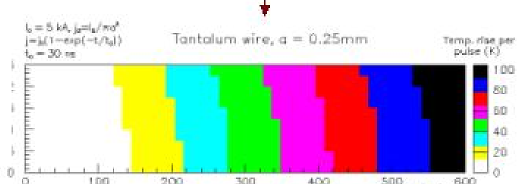
The power supply planned for the test purpose can deliver up to 8kA and the pulse waveform has a rise time of about 100ns and a flat top of about 500ns. The shape of the pulse waveform is exponential $I = I_0(1 - e^{-\gamma t})$ with time constant $t_0 = 1/\gamma = 30$ns. Assuming that an electric field 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, $J_1(x)$ and $J_0(x)$ 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.



- Energy density; temperature rise across the wire



- Lorentz force induced pressure wave

Comparison with existing experimental results

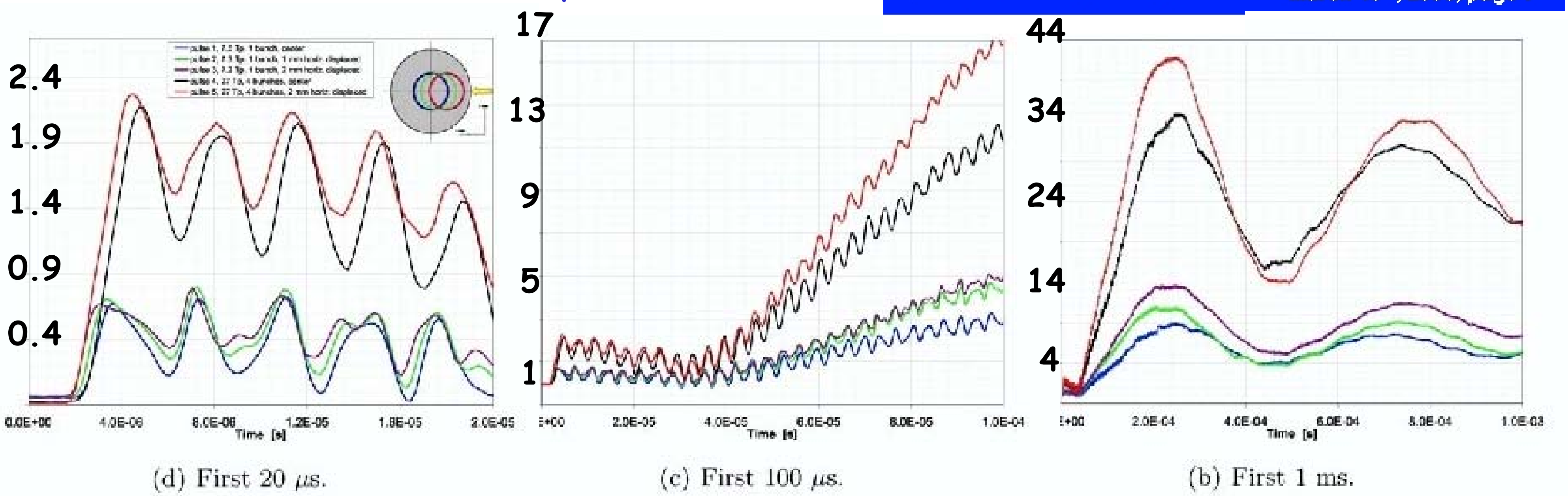
Tests at the ISOLDE

Tantalum Cylinder, 1x10 cm

Roman WILFINGER
ISOLDE, CERN & TU Vienna

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

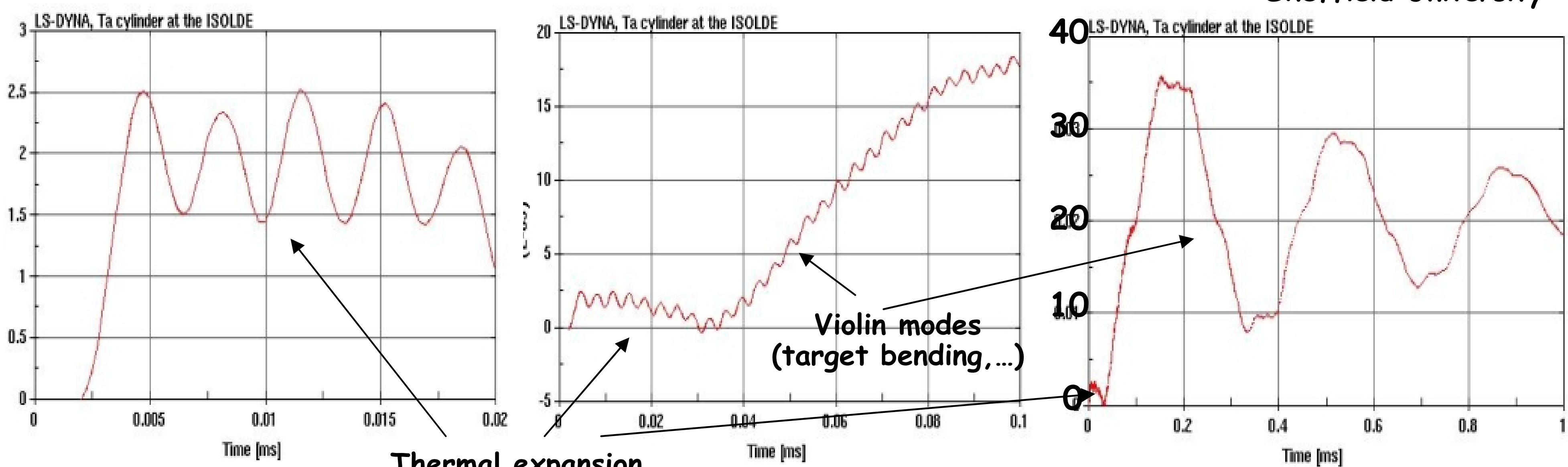
surface displacement [μm]



LS-DYNA simulations

Goran SKORO,
Sheffield University

surface displacement [μm]



Thermal expansion

NuFact target

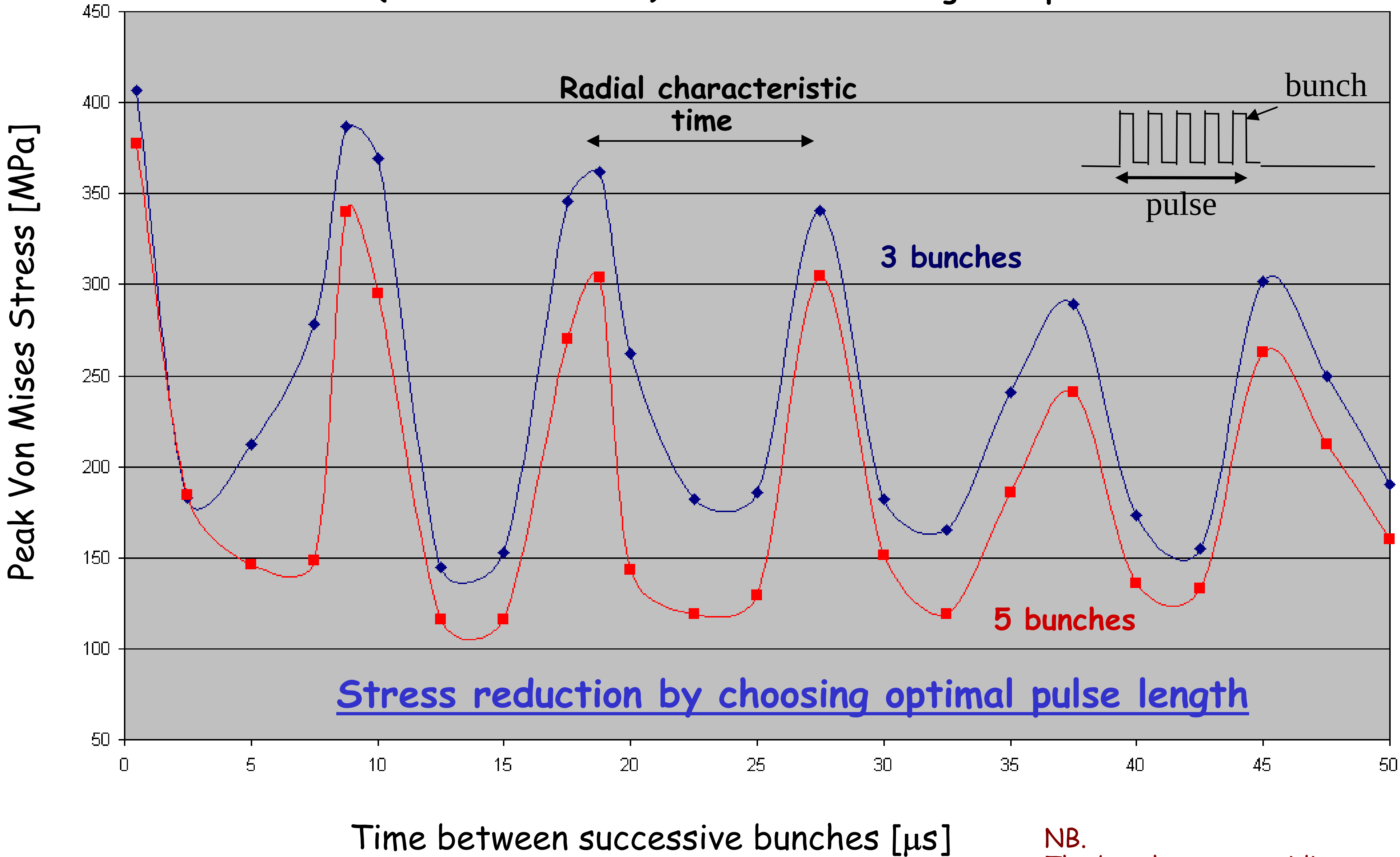
LS-DYNA

Power = 4 MW, repetition rate = 50 Hz,
Beam energy = 6 GeV (*parabolic distribution*)
2 ns long bunches
Energy deposition from MARS

TUNGSTEN target
operating at 2000 K

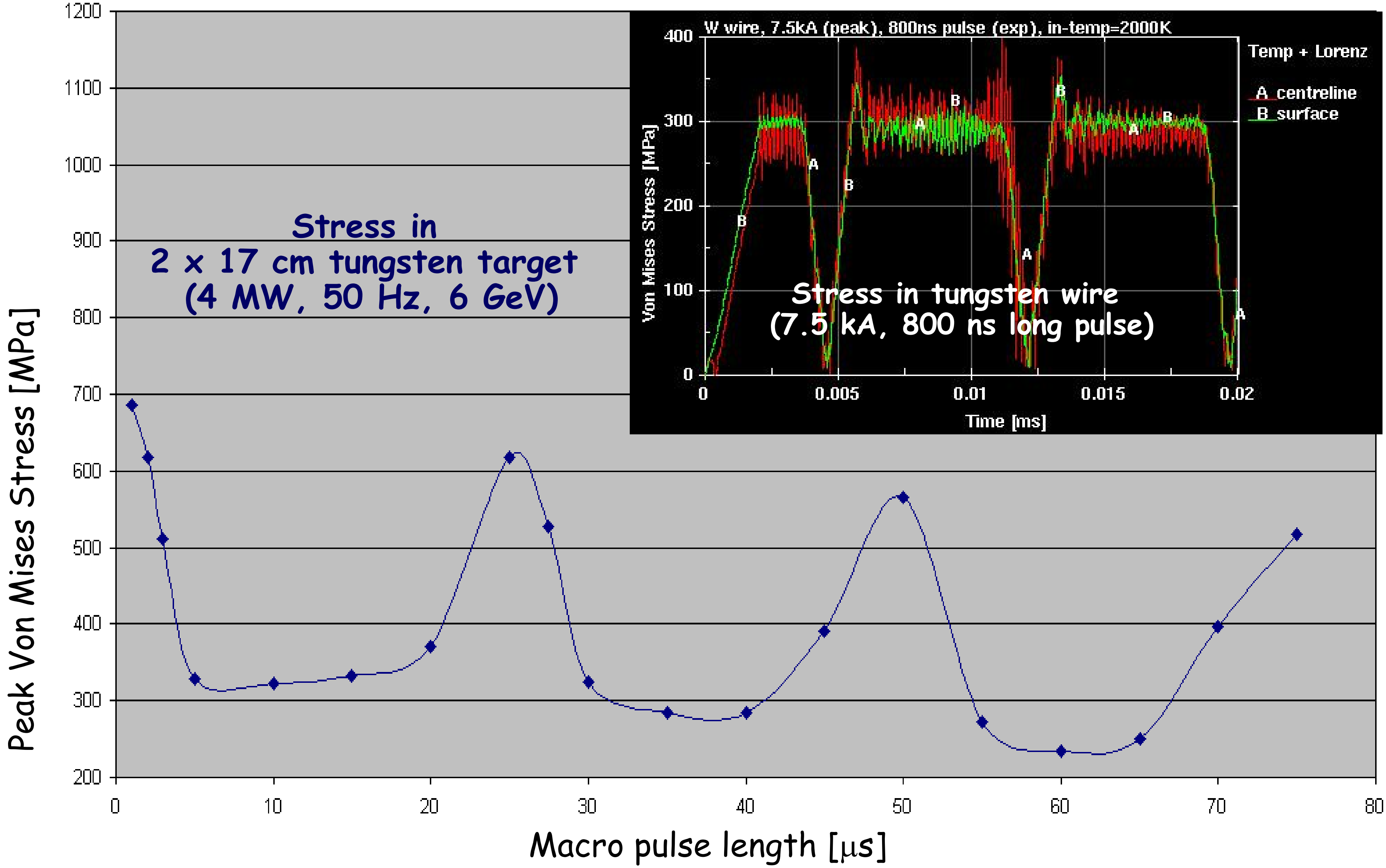
3 cm x 20 cm
Beam radius = Rod radius

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



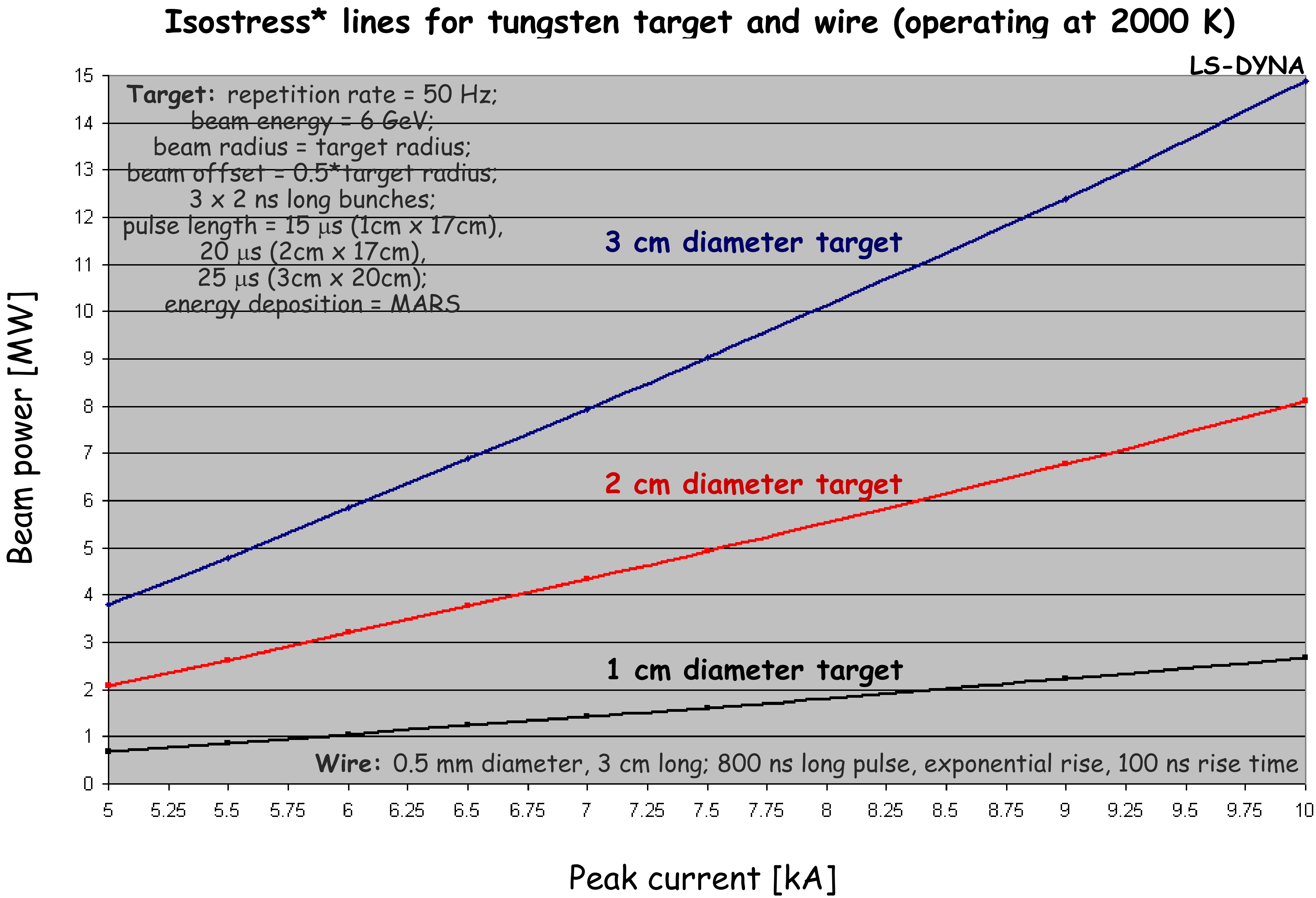
NB.
The bunches are equidistant.

Comparison of the simulations results: Stress in real target vs. stress in tungsten wire



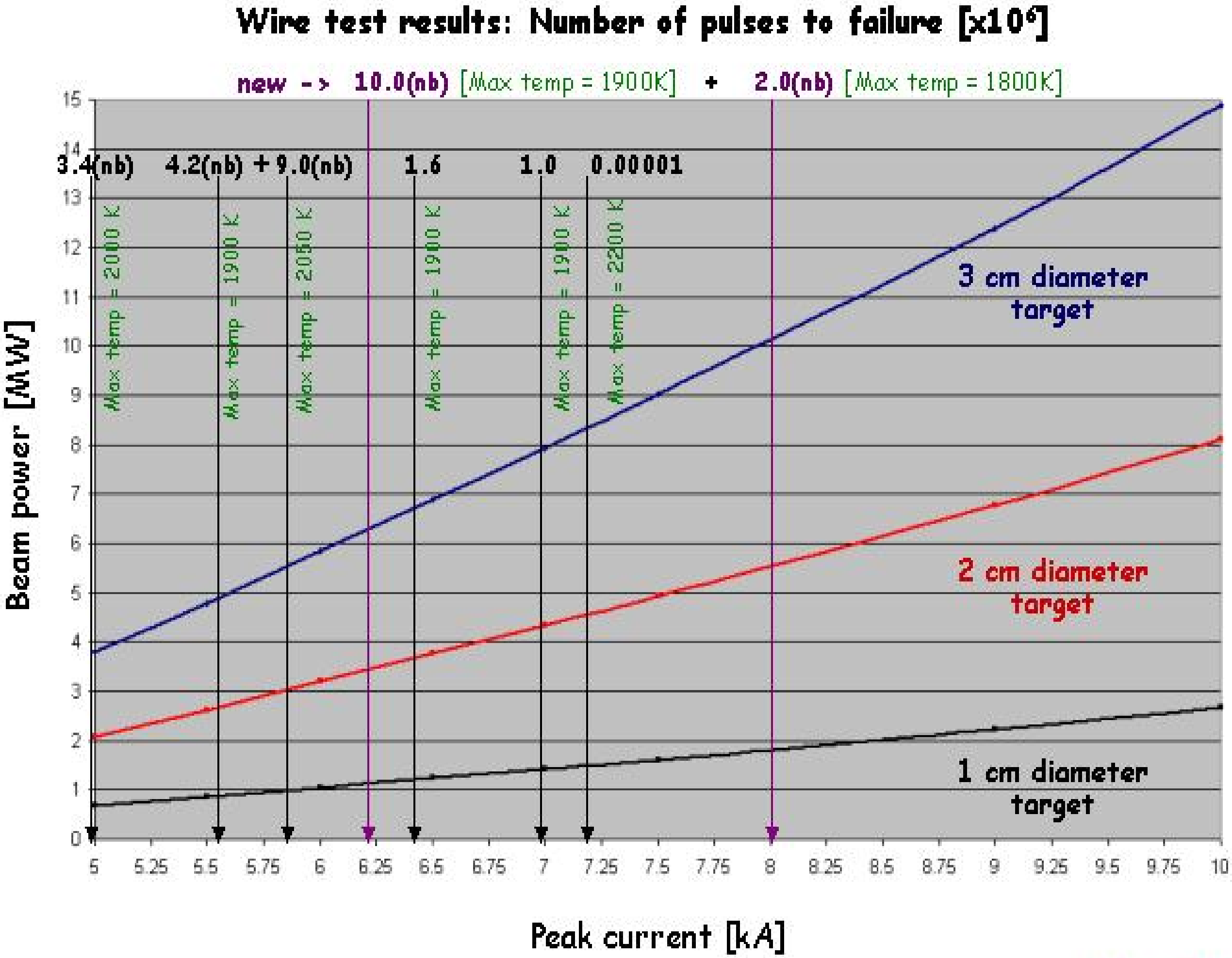
LS-DYNA

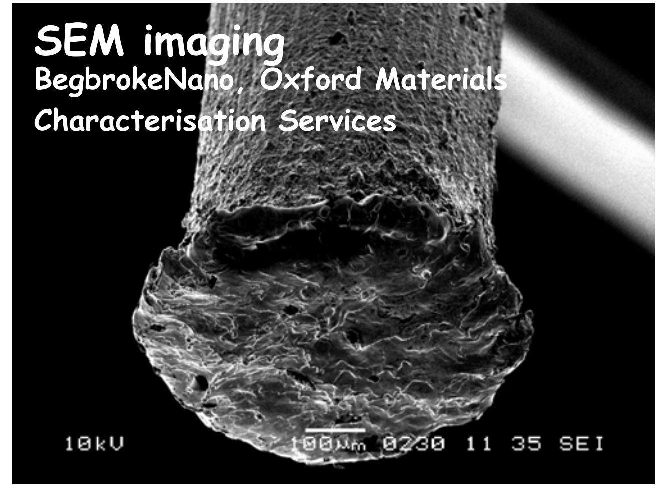
Stress in real target vs. stress in tungsten wire

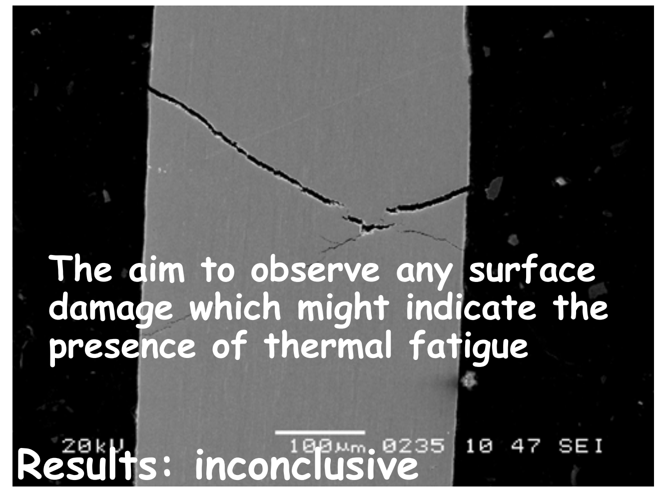


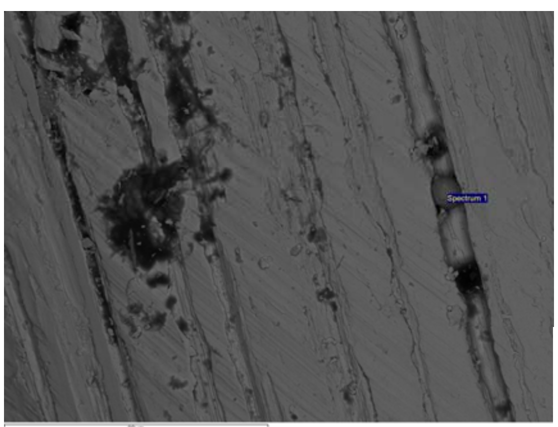
* - Von Mises stress

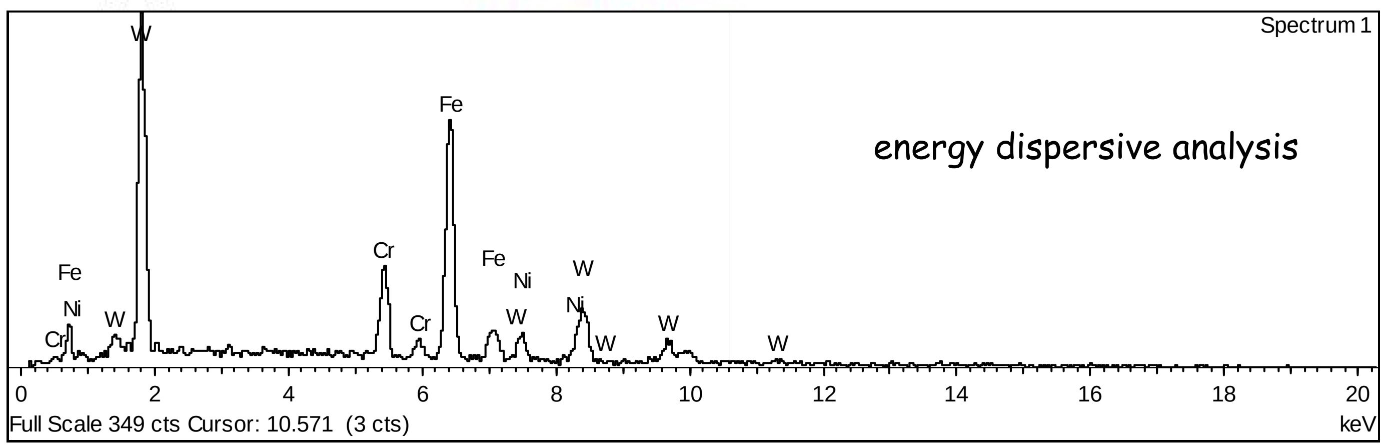
Stress in real target vs. stress in tungsten wire









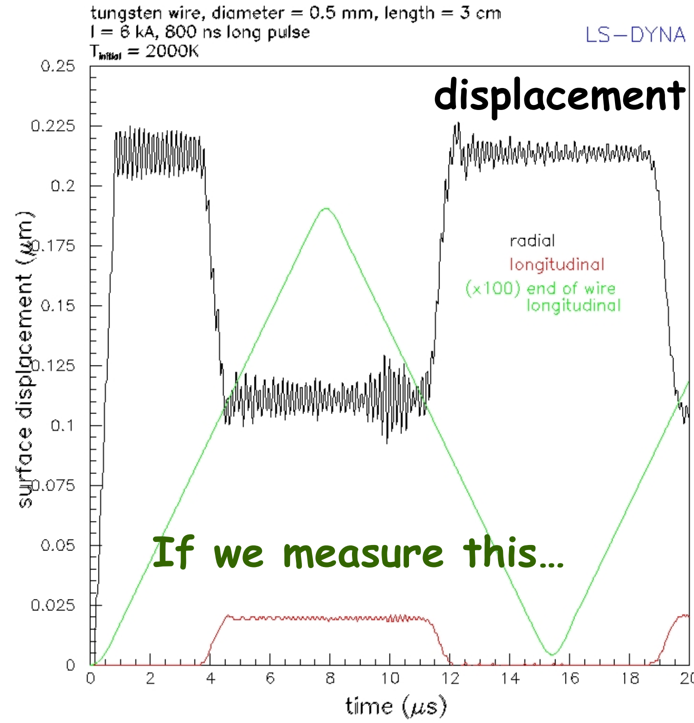


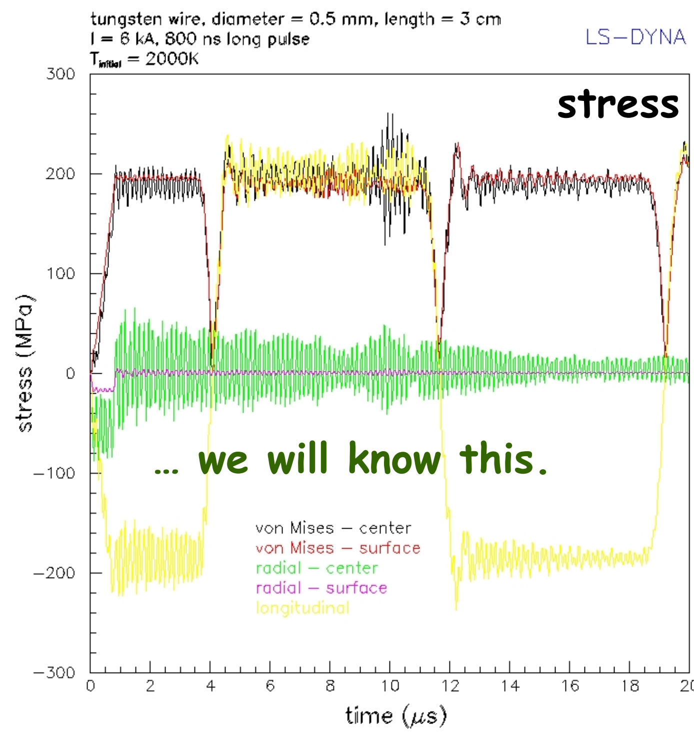
VISAR wire tests

Velocity Interferometry System for Any Reflector

Surface displacements ~ 100 nm; velocity ~ 1 m/s

LS-DYNA prediction





In-beam VISAR tests (ISIS, for example)

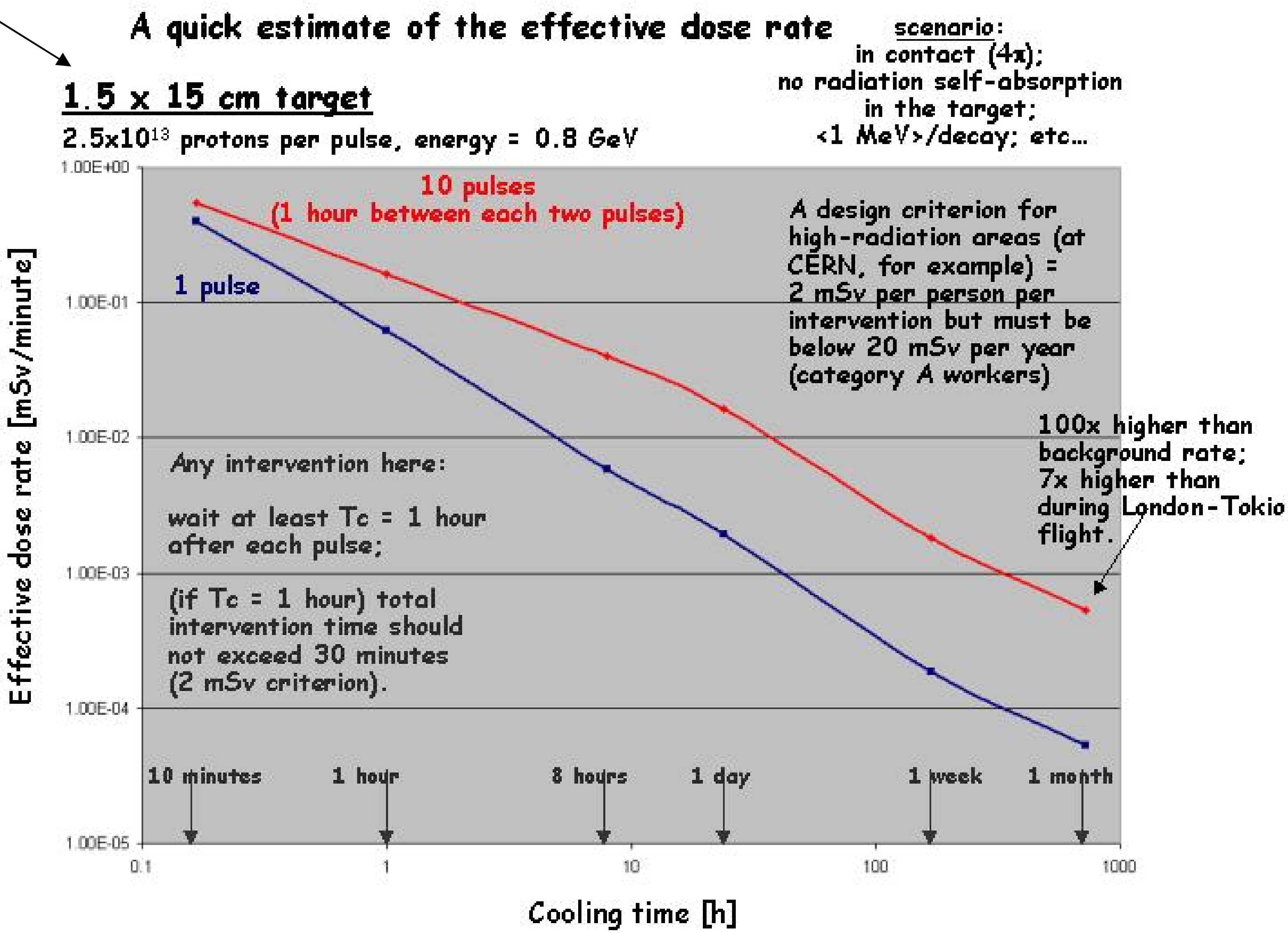
Peak Stress (ISIS, 100% beam) = **287 Mpa**

Peak Stress (Neutrino Factory, 4 MW, 2cm diameter, optimised pulse length) ≈ **300 MPa**

'optimal target dimensions'

FLUKA results on target activation for full ISIS beam power (maybe we will have only 10% of this value in so-called 10% beam dump area)

Additional focusing will be needed to achieve the required energy density



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 tungsten NuFact 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)
- MERIT:
  - We started taking part in the analysys of the data
- Important:
  - Whichever the final choice of the NuFact target (liquid/solid) we will have the solids exposed to the high power beam