

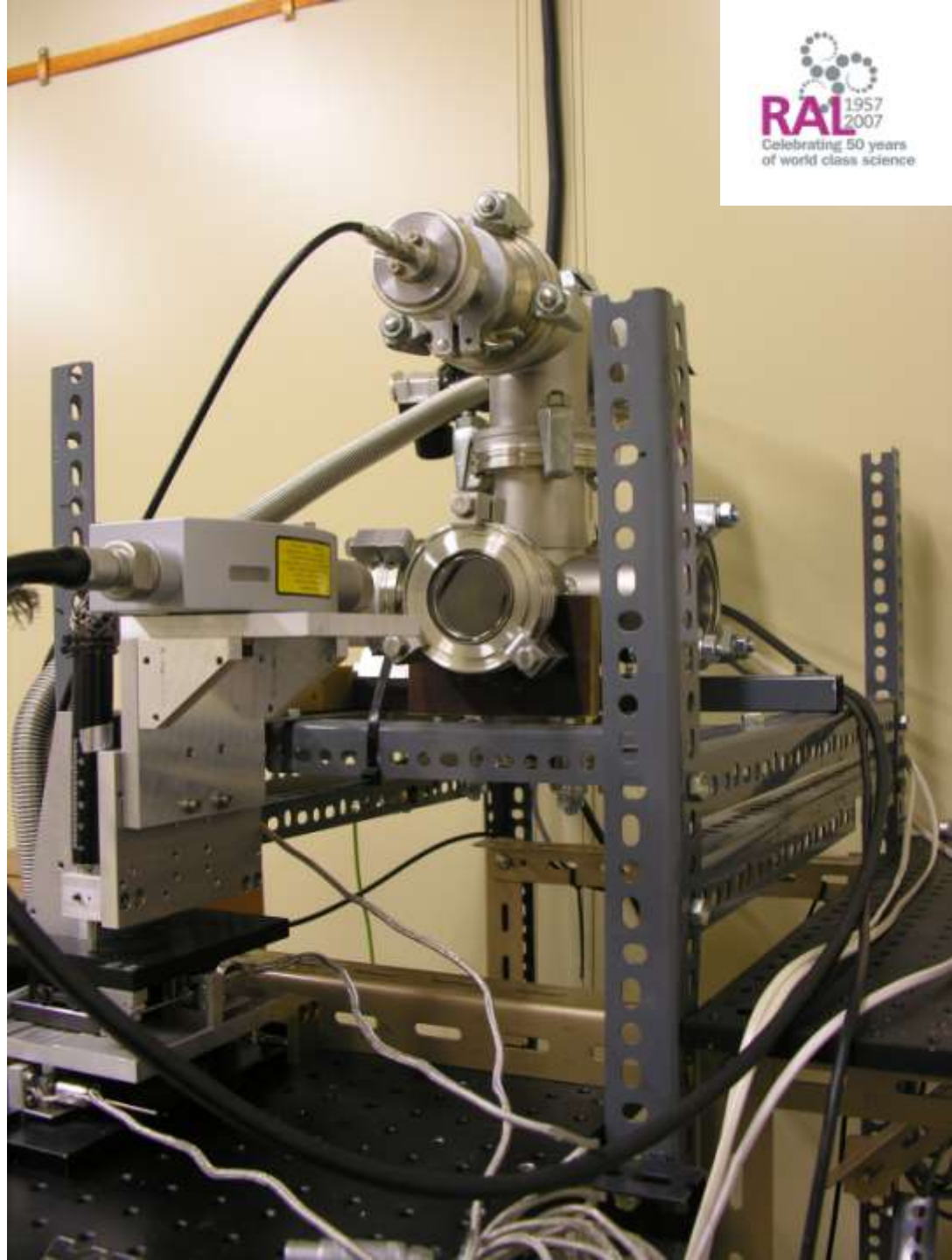
# Overview of solid target studies for a Neutrino Factory

Goran Skoro

UKNF Target Studies Web Page:  
<http://hepunx.rl.ac.uk/uknf/wp3/>

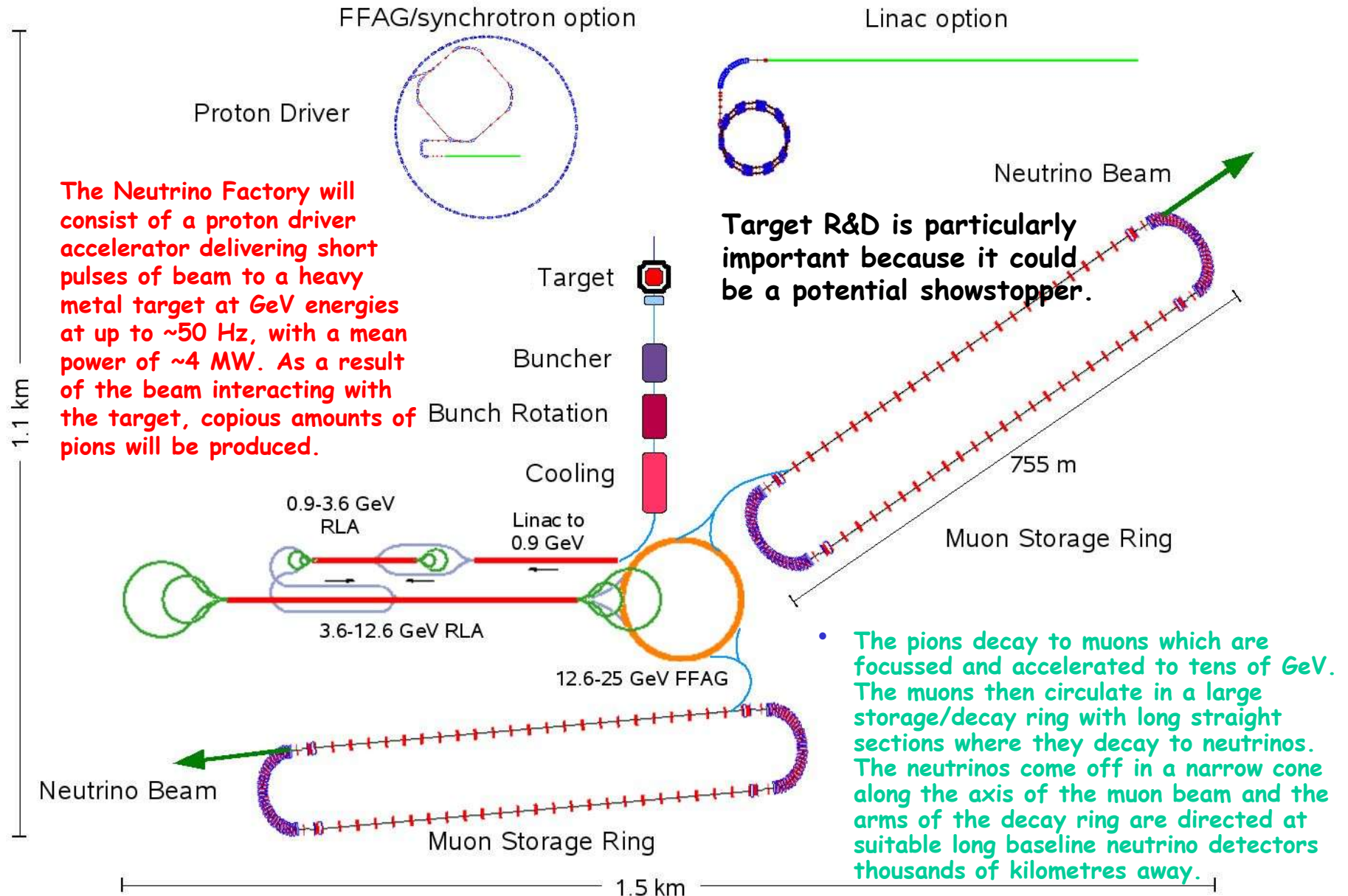
17 November 2010

University of Sheffield



# Neutrino Factory

There are proposals to build a Neutrino Factory in the US, Europe or Japan, in order to understand some of the basic properties of neutrinos.



The Neutrino Factory will consist of a proton driver accelerator delivering short pulses of beam to a heavy metal target at GeV energies at up to ~50 Hz, with a mean power of ~4 MW. As a result of the beam interacting with the target, copious amounts of pions will be produced.

Target R&D is particularly important because it could be a potential showstopper.

- The pions decay to muons which are focussed and accelerated to tens of GeV. The muons then circulate in a large storage/decay ring with long straight sections where they decay to neutrinos. The neutrinos come off in a narrow cone along the axis of the muon beam and the arms of the decay ring are directed at suitable long baseline neutrino detectors thousands of kilometres away.

## High power targets - important for many future facilities!

### Options:

~~Static Solid Targets~~

- Moving Solid Targets

~~Flowing liquid (with beam windows)~~

- Free liquid jet

### Some of the ongoing target projects

MiniBooNE Target. 30 kW beam power.

NUMI Target. 0.4 - 1 MW beam power.

CNGS Target. 0.75 MW beam power.

JPARC  $\nu$  Horn Target. 0.75 MW beam power.

SNS Mercury Target. 1 MW beam power.

But, in the case of Neutrino Factory target we will have extreme conditions:

4 MW, 10 GeV, 50 Hz, 3 x 2ns bunches.

**...and we need something completely different!\***

\*Although the Neutrino Factory is 4 MW, 'only' 0.75 MW ends up in the target. This is the reason we think solid target is a possibility. But, 'neutrino targets' need to be small; shock and cooling are serious problems -> moving target.

- Why solid?
  - lots and lots of experience
  - both liquid targets: looking at solids again

- Candidate materials

- tantalum
- tungsten

- Issues:

- radiation damage
- shock (main problem)
- temperature rise (~100K per pulse)

- R&D:

- a number (200-500) of ~2x20cm bars
- particle jet (early days)

→ Pulsed-Current Studies of Ta & W Wires at RAL

→ Flowing Tungsten Powder Targets at RAL

- Why liquid?

- shock not an issue

- Candidate materials

- mercury, Pb-Bi

- Issues:

- free jet never used before
- leakage of radioactive mercury
- rad. damage (corrosive chemical production, polonium production)

- R&D:

- CERN MERIT experiment

**Traditional view:** solid targets safe up to only 50-70 J/g deposited energy (below 1-2 MW beam power)

Empirical evidence is that some materials survive 500-1000 J/g,  
 ⇒ May survive 4 MW if rep rate ≥ 10 Hz.

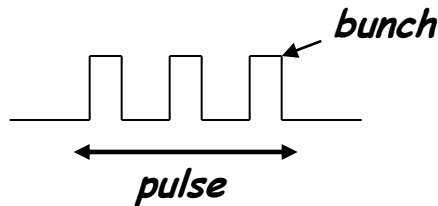
Solid targets in FNAL p-bar source: "damaged but not failed" for peak energy deposition of 1500 J/g!!!

**Reason for optimism!**



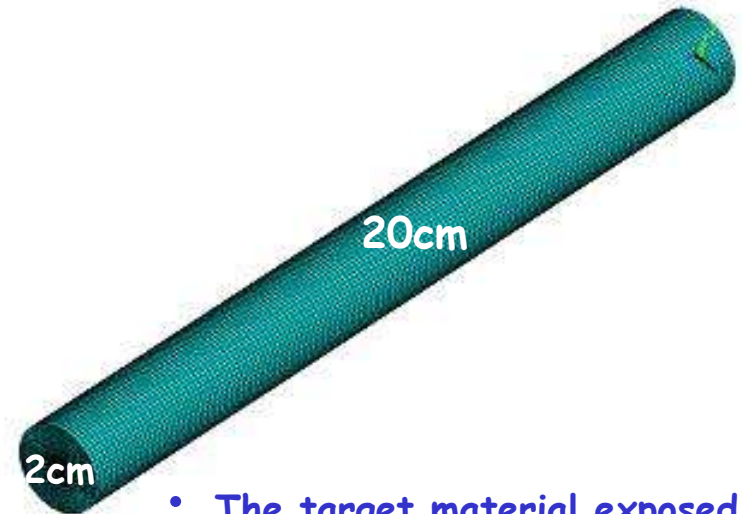
# High Temperature Solid Neutrino Factory Target - options -

- **Individual bars (200 - 500)**
- Cooling: radiation (started with this)
- The target is bombarded at up 50 Hz by a proton beam consisting of ~2ns long bunches in a pulse of tens of micro-s length.



Beam: protons,  
5 - 15 GeV

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



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

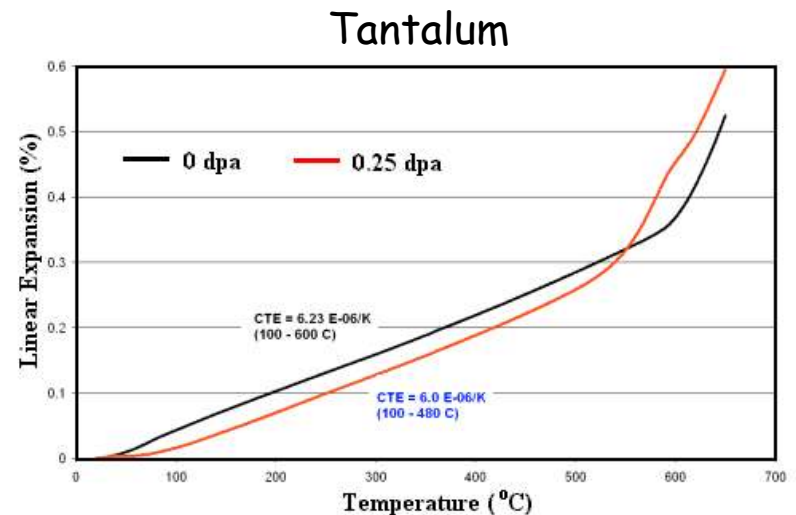
**ISS baseline (adopted by IDS-NF)\*:**  
**4 MW, 10 GeV, 50 Hz,**  
**3 bunches per pulse, 2 ns rms.**

\*<https://www.ids-nf.org/wiki/FrontPage/Documentation?action=AttachFile&do=get&target=IDS-NF-002.pdf>

## Issue: Radiation damage

- Lots of experience (ISIS):
  - used tantalum for > 10 years, tungsten ~ 5 years
  - targets changed after ~ 12 dpa\*
  - ~ 2-5 years at Neutrino Factory, depending on number of targets
  - no signs of swelling or embrittlement
  - Ta examined in detail; W still to be done

- Still to be done
  - tensile strength after irradiation
  - will be done by Nick Simos at BNL



\* dpa = displacements per atom; number of times that an atom is displaced for a given fluence; calculated measure of the radiation exposure

## Issue: Shock (Thermal stress)

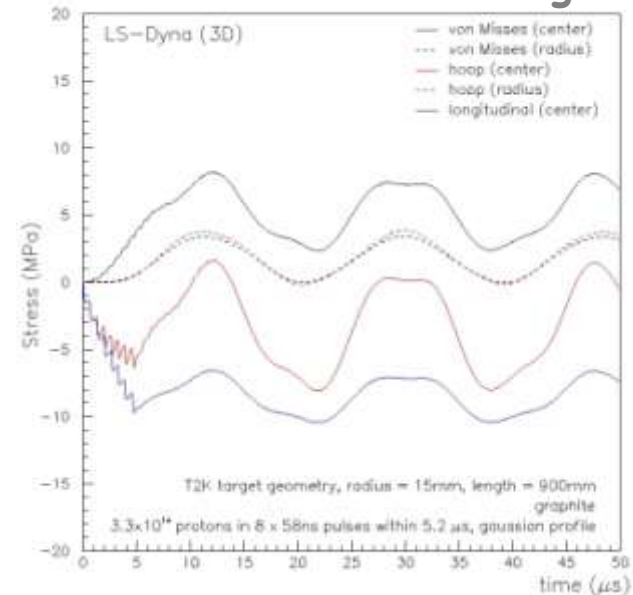
- In-beam lifetime/fatigue tests impossible
- Shock can be modelled: Finite Element Software (FES) →
- Target surface motion can be measured for (every) beam pulse and used as an indication what's happening inside the target (evaluation of the constitutive equations with the help of FES)

### What to do?

#### Original approach (R. Bennett)

- Simulate the level of shock in the real target by passing a pulsed current through a very thin wire
- Perform lifetime/fatigue tests
- Measure the wire surface motion (comparison with target surface motion)

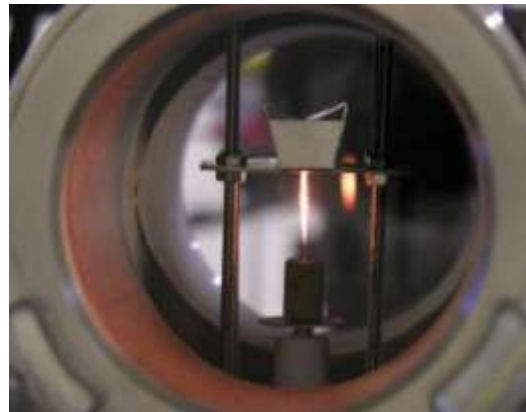
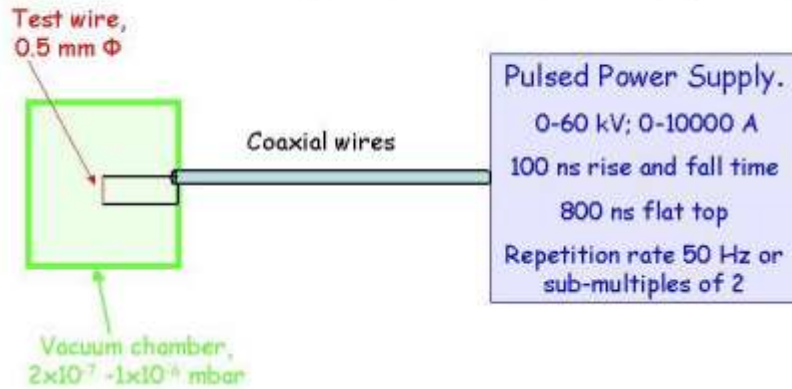
### Stress in the T2K target



FE simulations: prediction and interpretation of tests results

# Current pulse - wire tests at RAL

Schematic circuit diagram of the wire test equipment



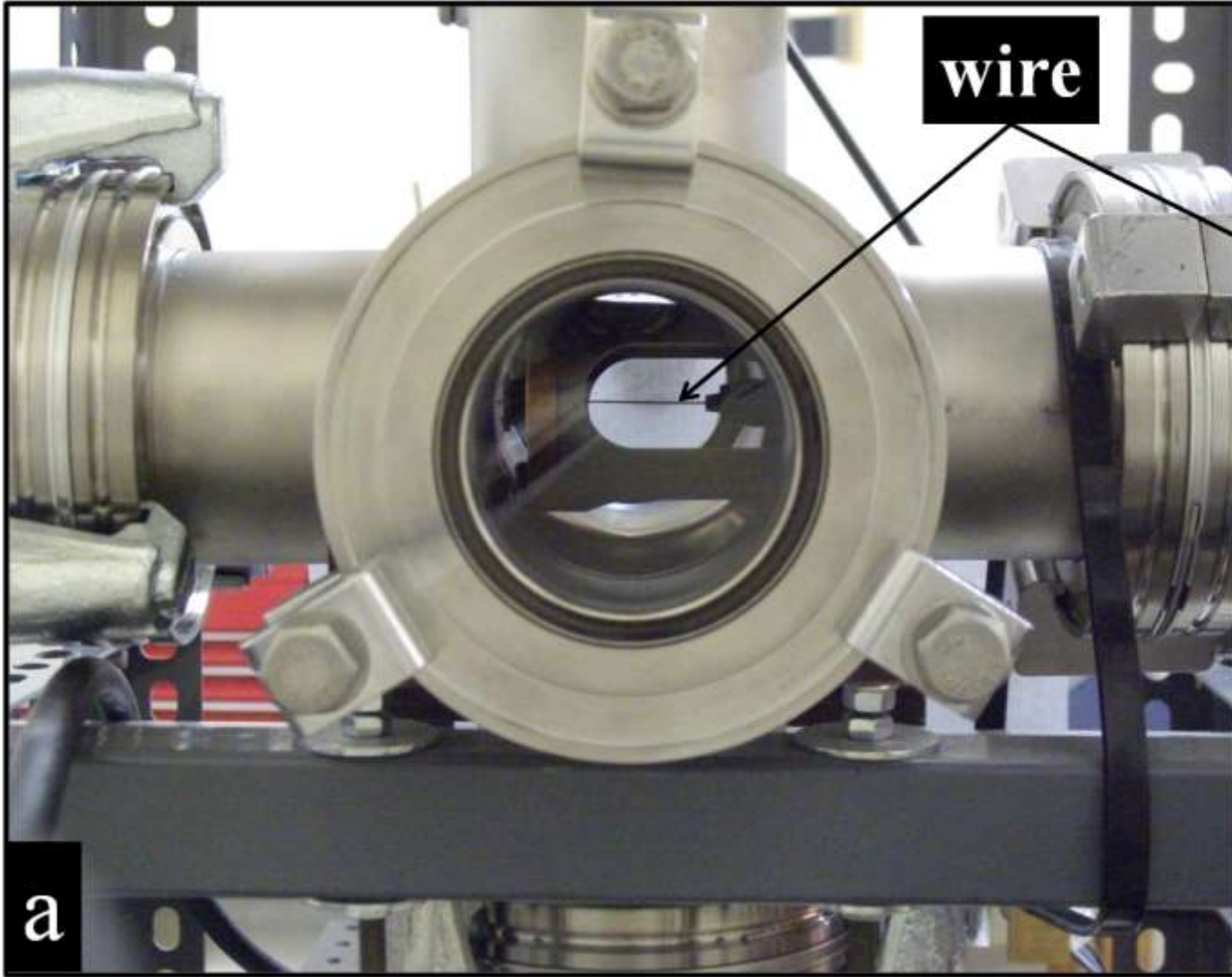
Tantalum wire - weak at high temperatures



**Tungsten - much better!!!**

The Finite Element Simulations have been used to calculate equivalent beam power in a real target and to extract the corresponding lifetime.  
(procedure is described on following slides)

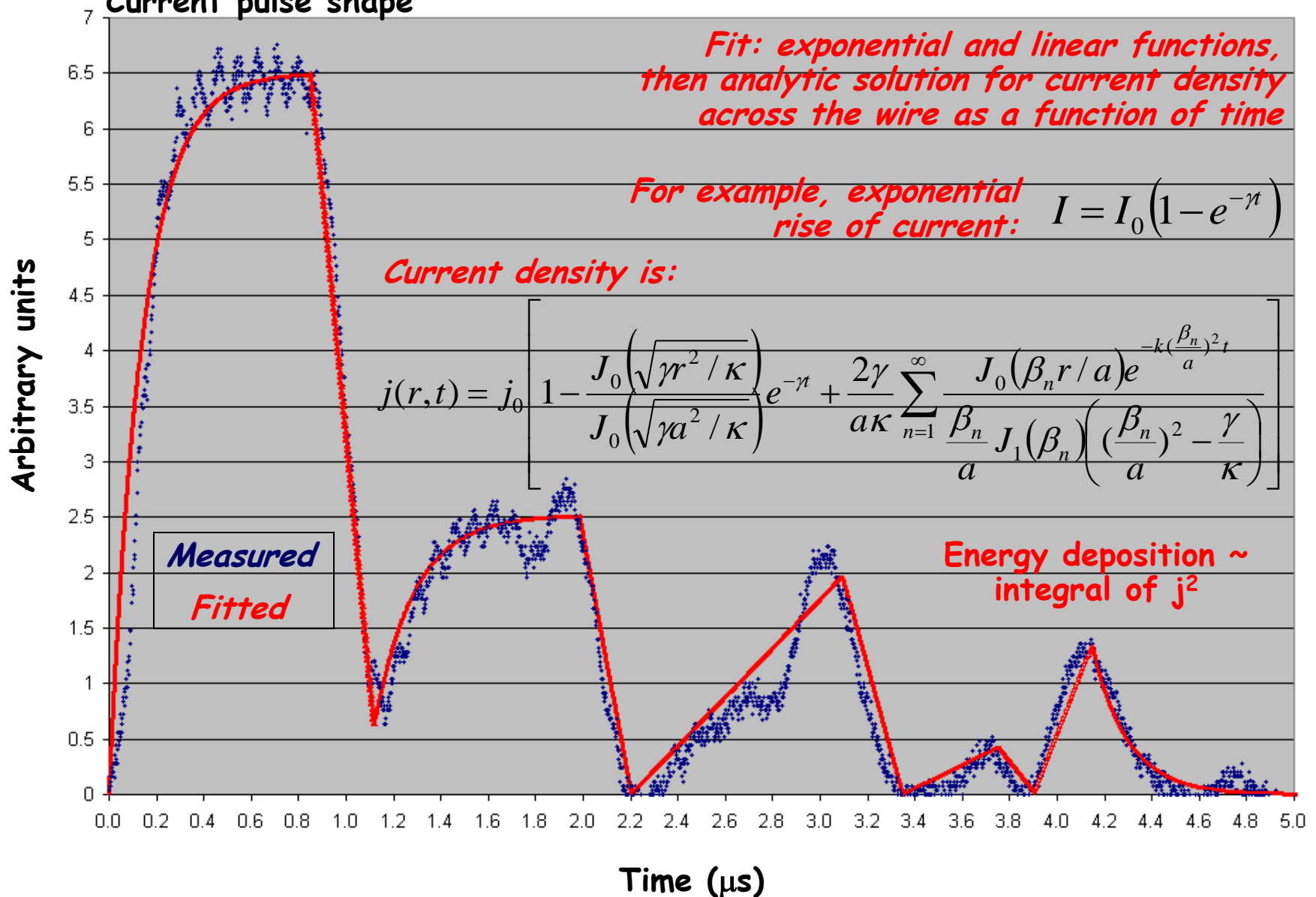
# Current pulse - wire tests at RAL



## Energy deposition - current pulse

+ Lorentz force induced pressure wave

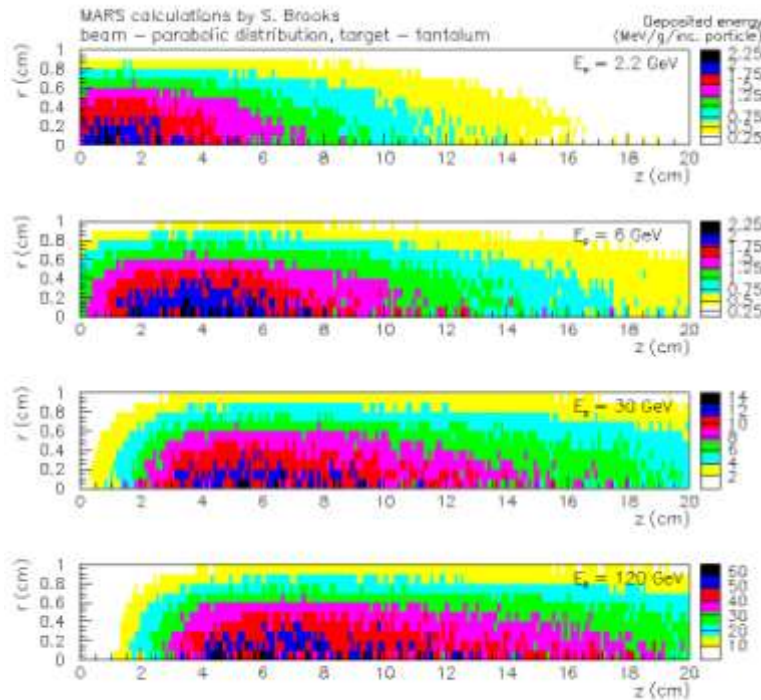
### Current pulse shape



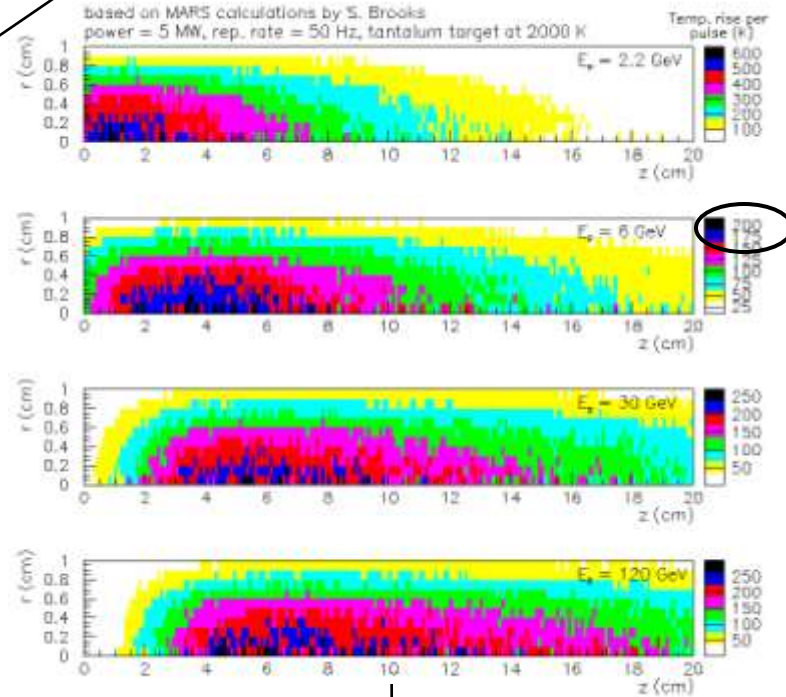
# Simulations of stress in a real target

High energy particle cascade calculations  
(MARS)

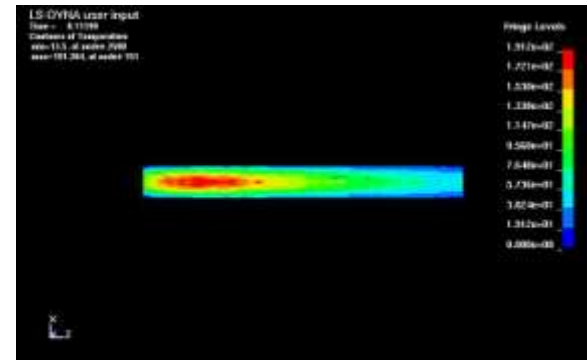
Energy deposition in solid target



Temperature rise in solid target



Input for thermal stress calculations (LS-DYNA)

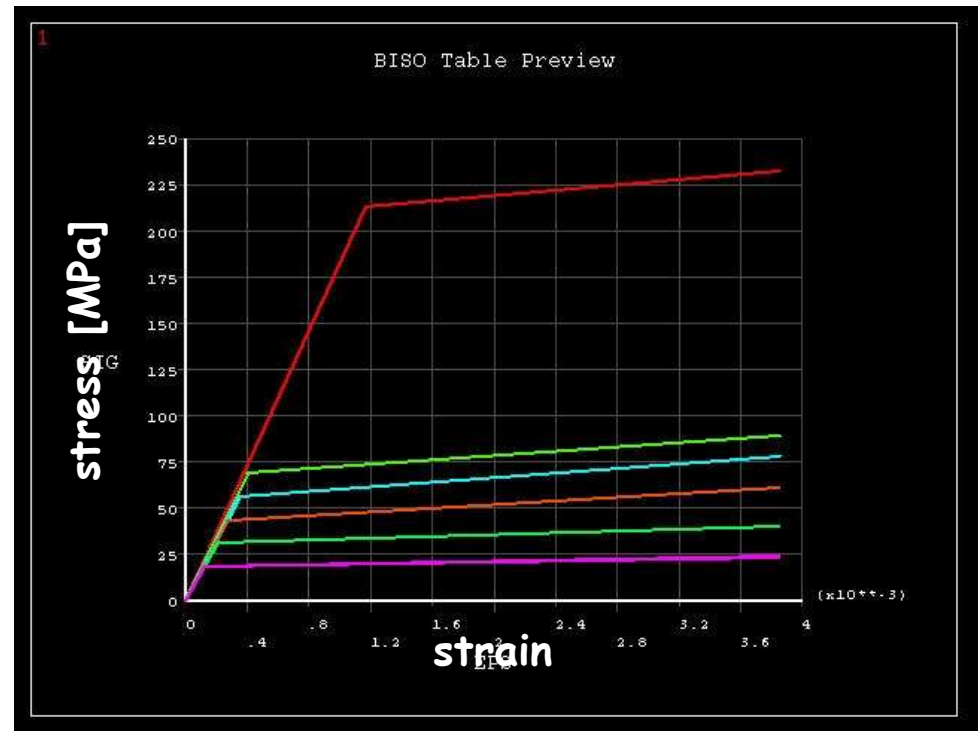
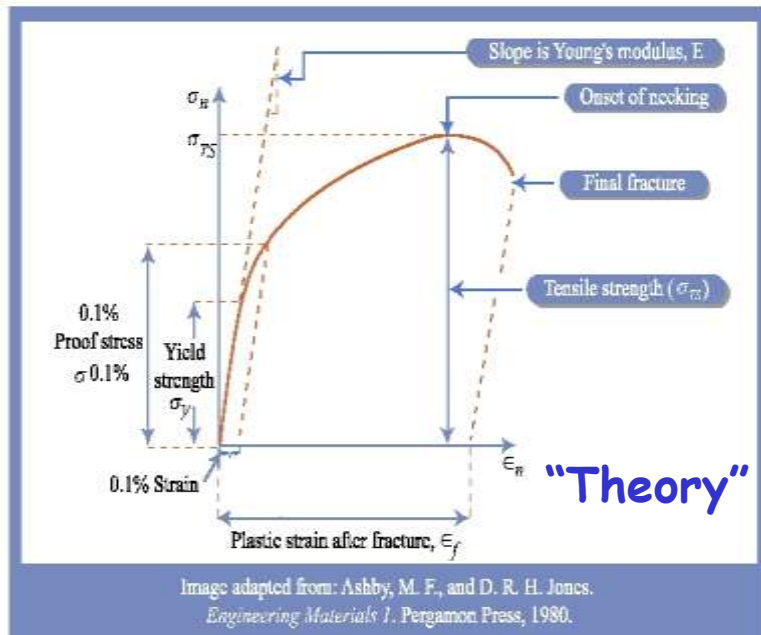


Here: Tantalum,  
Beam power = 5 MW, repetition rate = 50 Hz

# Finite element simulations: LS-DYNA

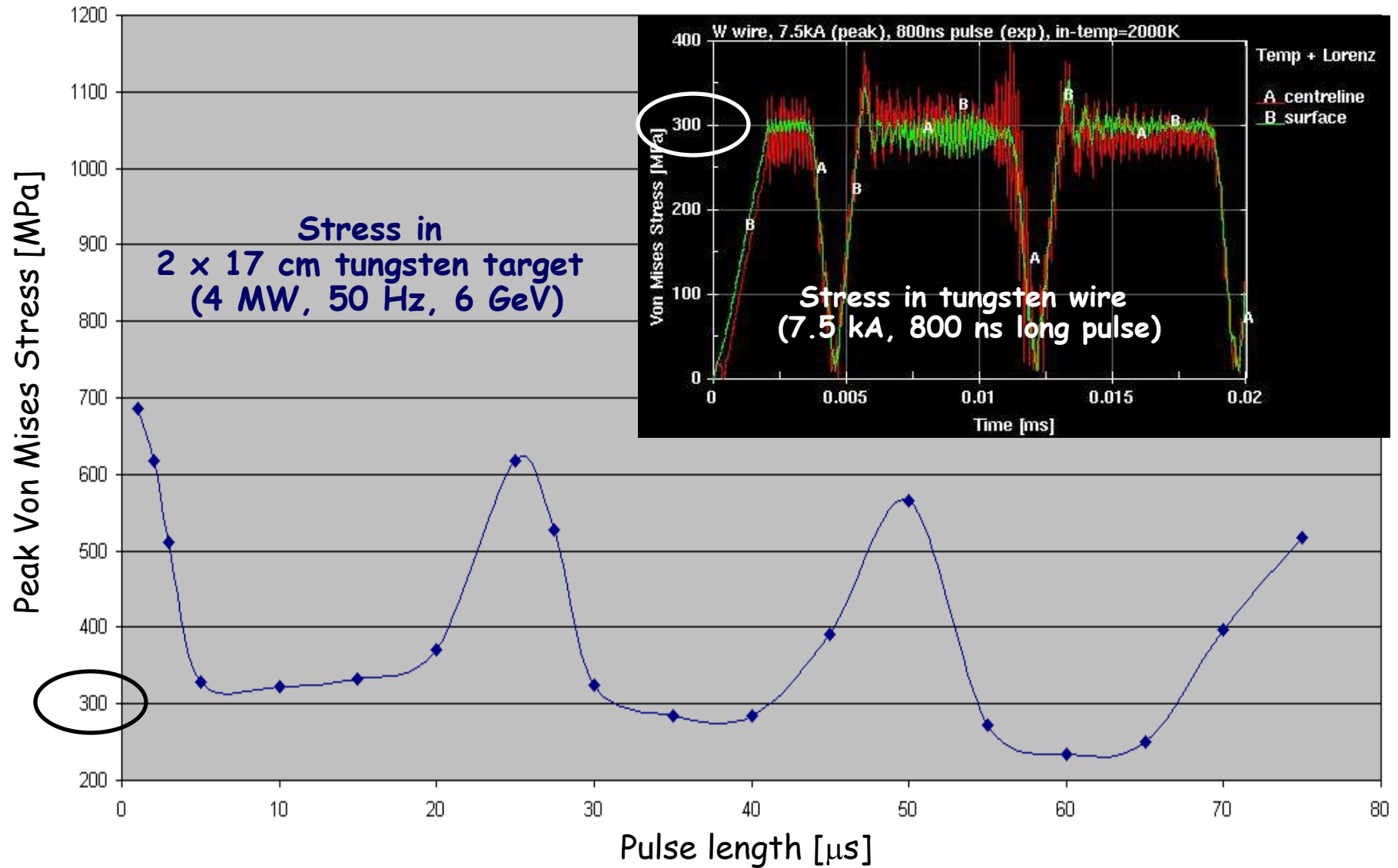
## Material model used in the analysis

- 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, ...



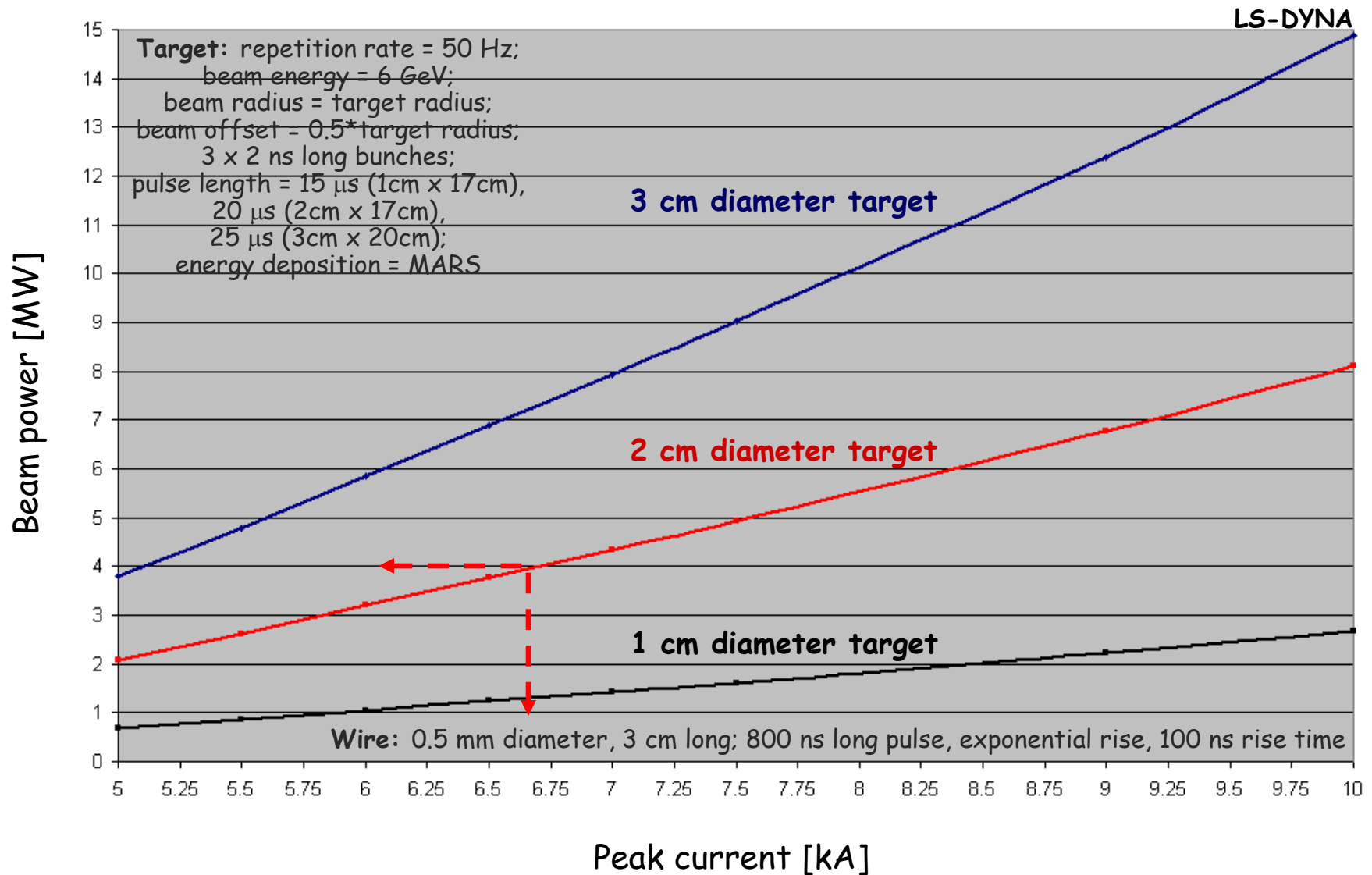
LS-DYNA

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



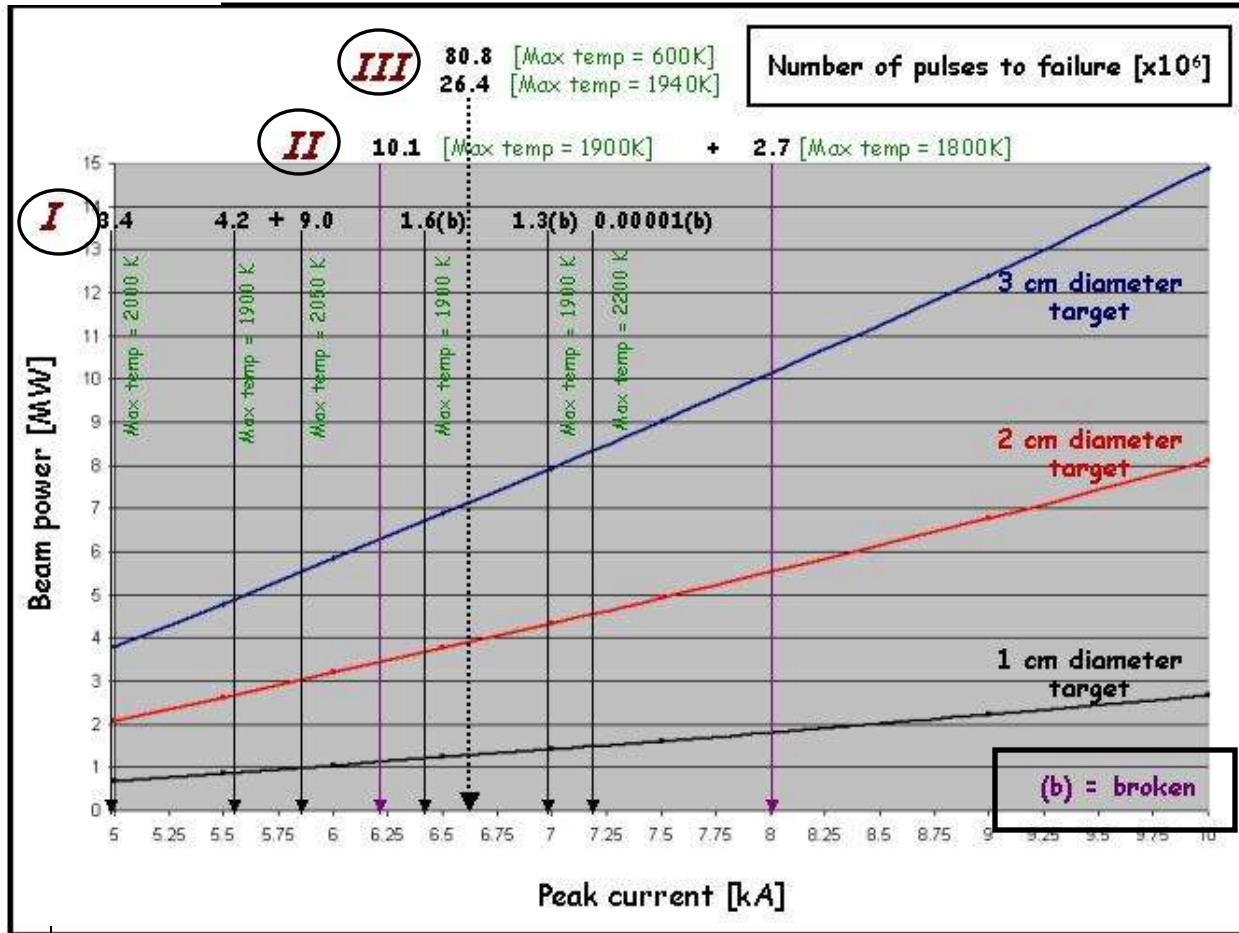
# Stress in real target vs. stress in tungsten wire

**Isostress\* lines for tungsten target and wire (operating at 2000 K)**

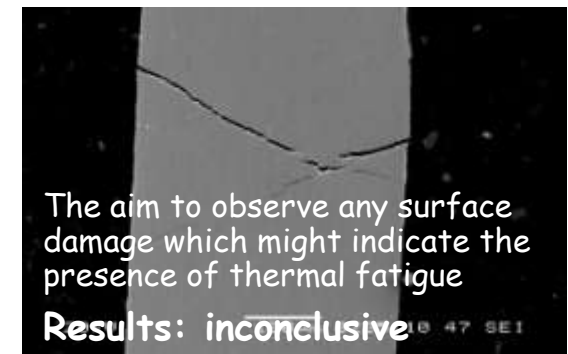
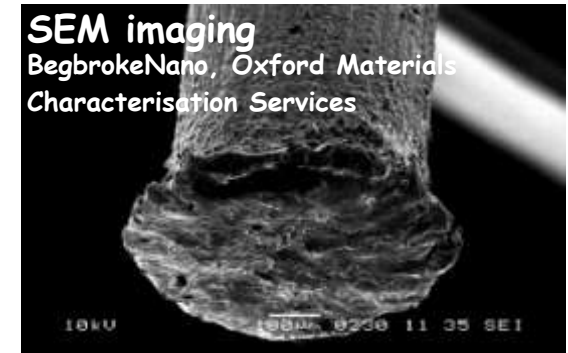


\* - Von Mises stress

# Lifetime/fatigue tests results



I, II, III -> 'chronology'.  
We have got better with the tests over time (better clamping of the wire; better understanding of 'violin modes' -> better alignment of the wire)



More than sufficient lifetime demonstrated:  
 > 10 years for 2cm diameter target  
 > 20 years for 3cm diameter target

Next:  
 Measure stress;  
 Confirm modelling.

Better at lower temperature!

based on LS-DYNA simulations

**Coaxial  
wires**

**(current  
from  
power  
supply)**

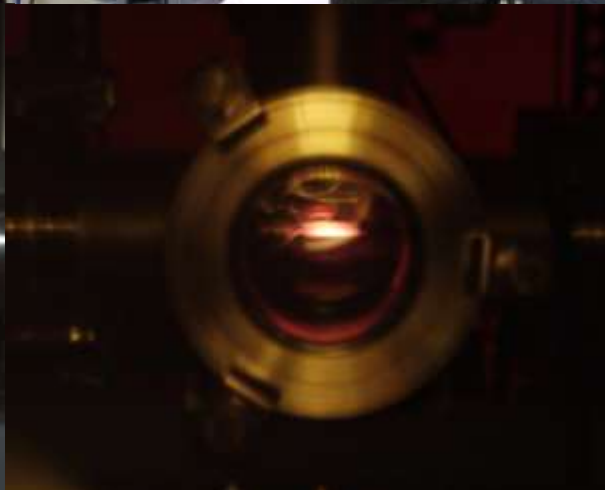
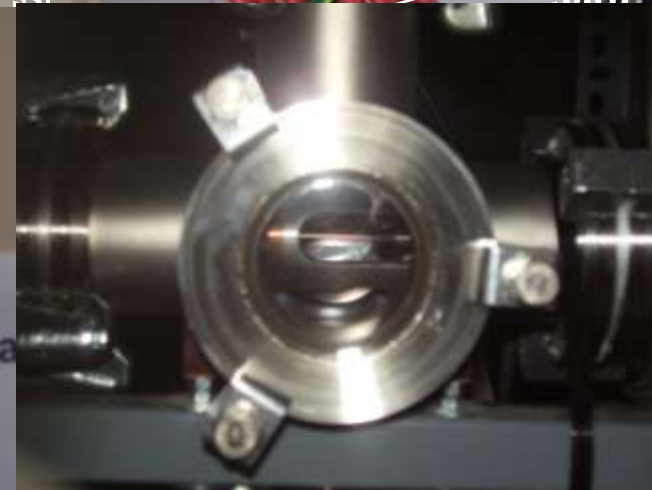
**Test wire**

**Vacuum  
chamber**

**Hole**

**LDV**

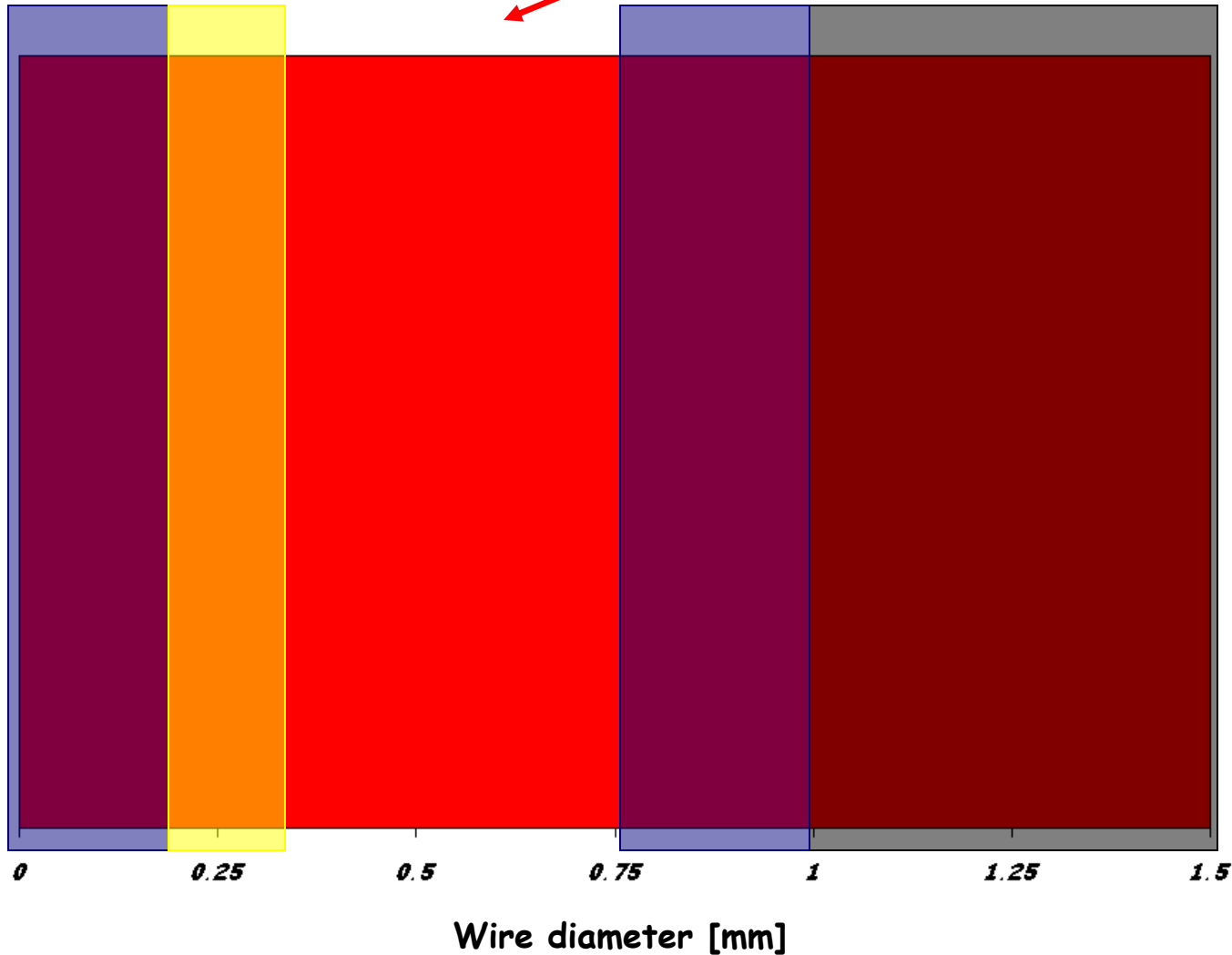
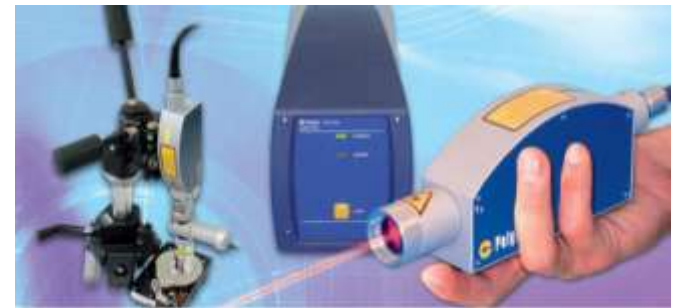
with calculations



Tungsten wire at 2000 K

# Laser Doppler Vibrometer (LDV)


3 different decoders: VD-02 for longitudinal, DD-300 and VD-05 for radial oscillations



Current < 10 kA

Shock ~ NF target

Freq. and Amp. range

 - excluded

# Longitudinal oscillations

0.5 mm diameter tungsten wire  
4.5 cm length



*Fundamental frequencies*

$$f_n = (2n + 1) \frac{c}{4l} = \frac{(2n + 1)}{4l} \sqrt{\frac{E}{\rho}}$$

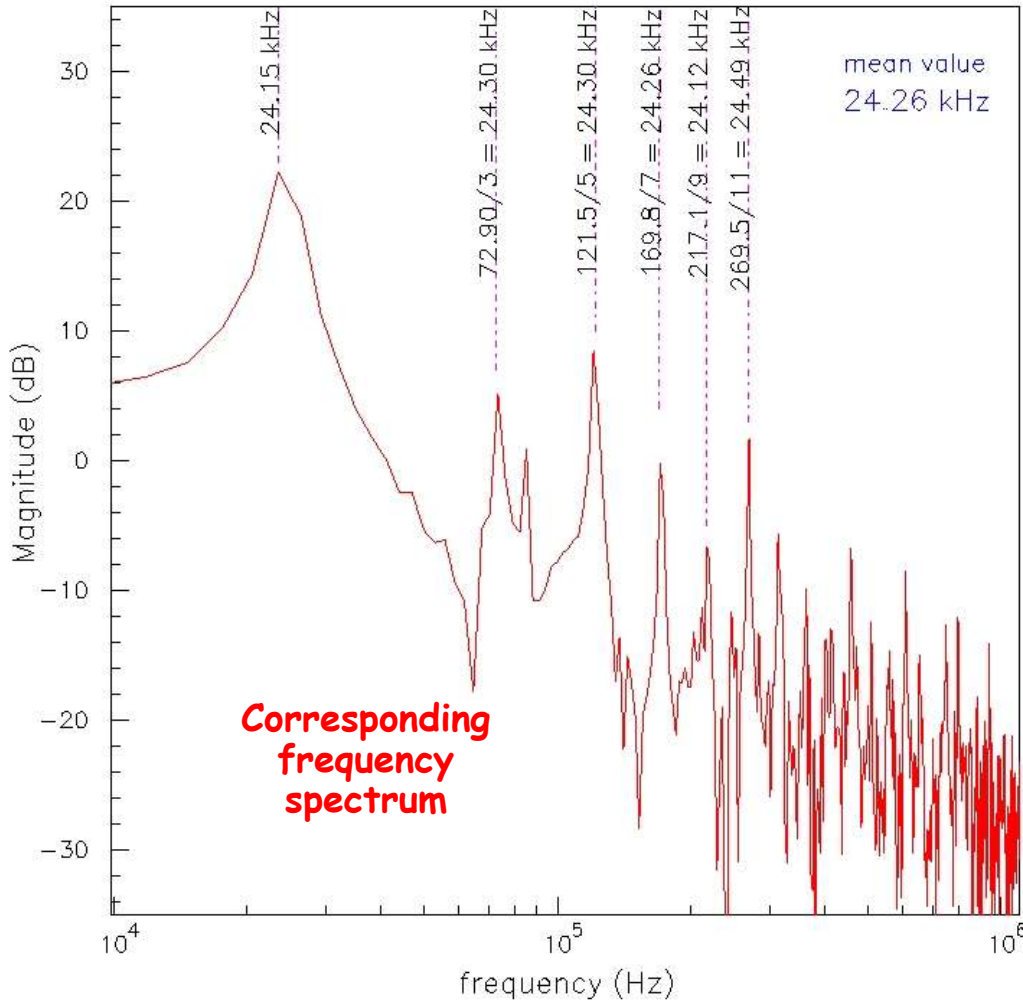
*c - speed of sound*

*l - wire length*

*E - Young's modulus*

*ρ - density*

Vibrometer, VD02, end of wire, length = 4.5 cm, diameter = 0.5 mm

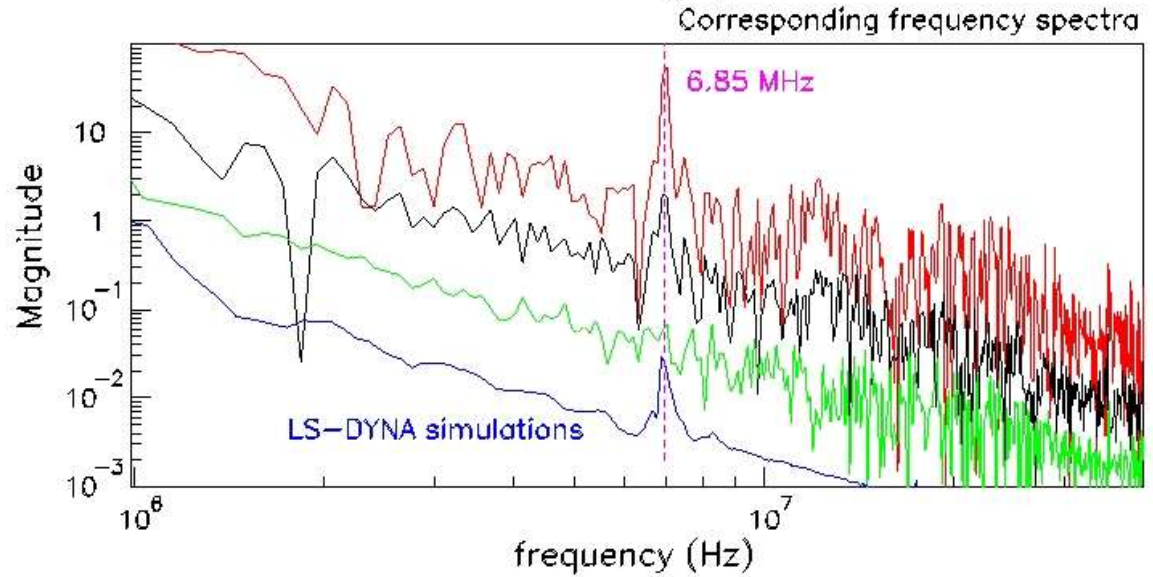
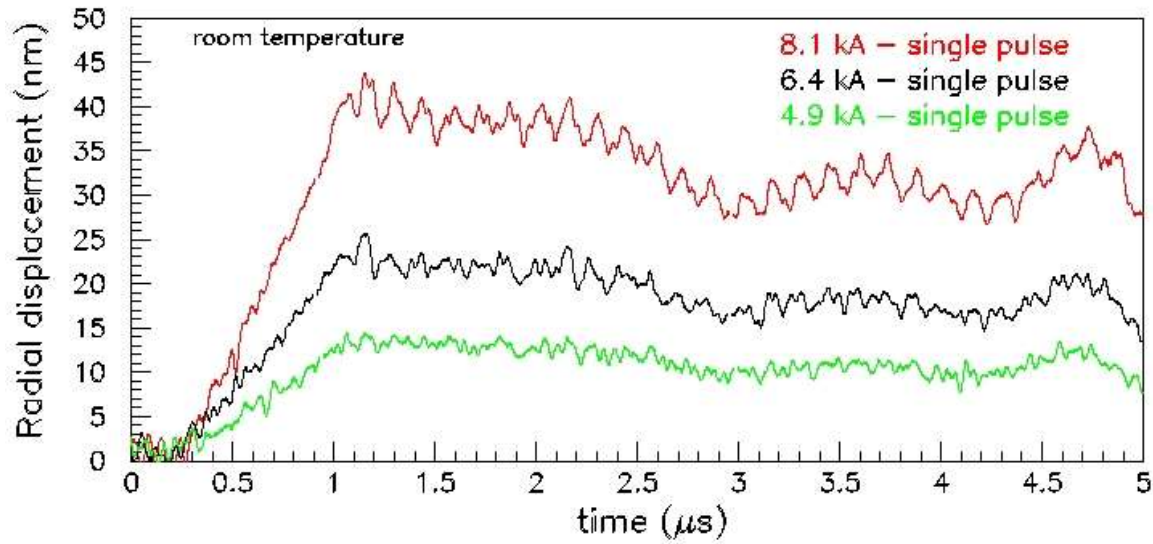


• *Oscillations are complicated*

▪ *Details not fully reproduced (unknown `forces` in the system)*

# Radial oscillations

Surface displacement of the 0.5 mm diameter wire measured by LDV



0.5 mm diameter wire



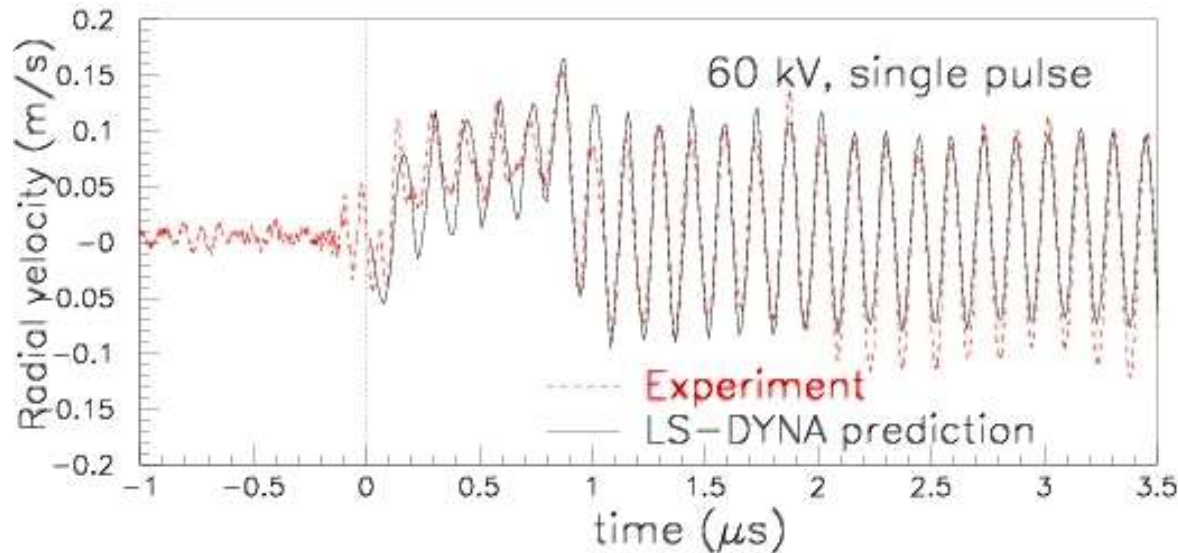
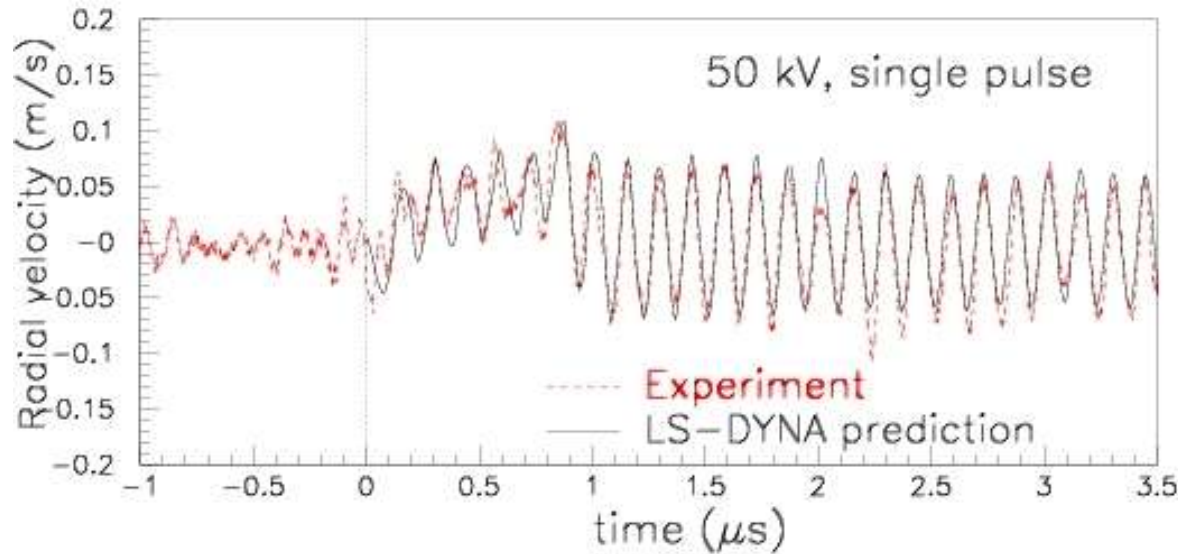
Wire



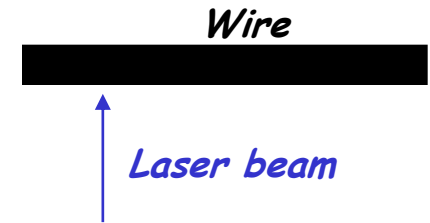
Laser beam

DD-300 decoder

## Radial oscillations



0.5 mm diameter wire

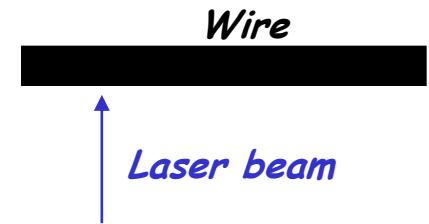


VD-05 decoder

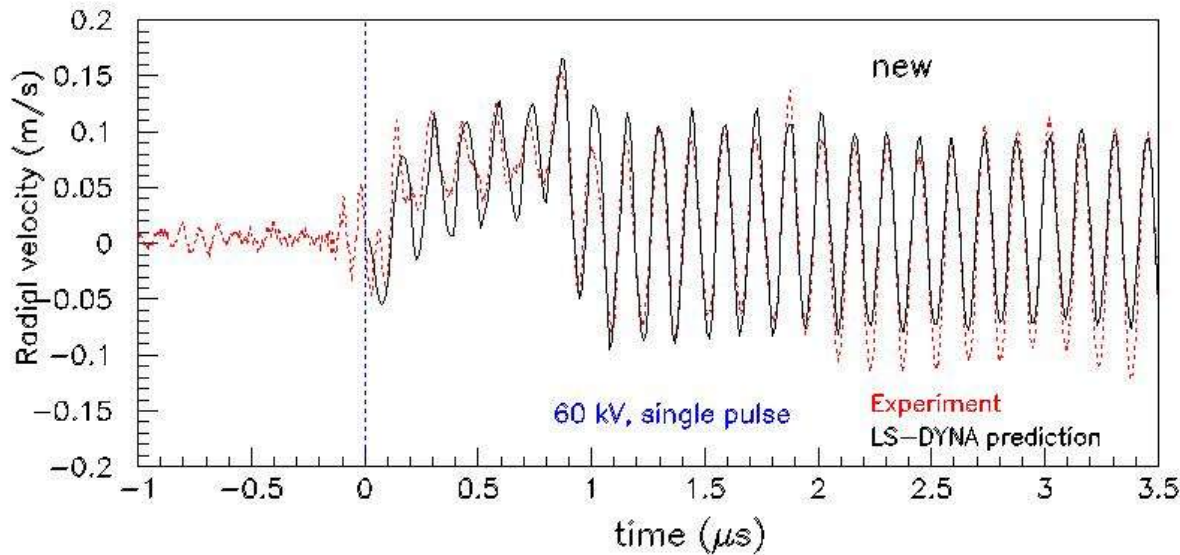
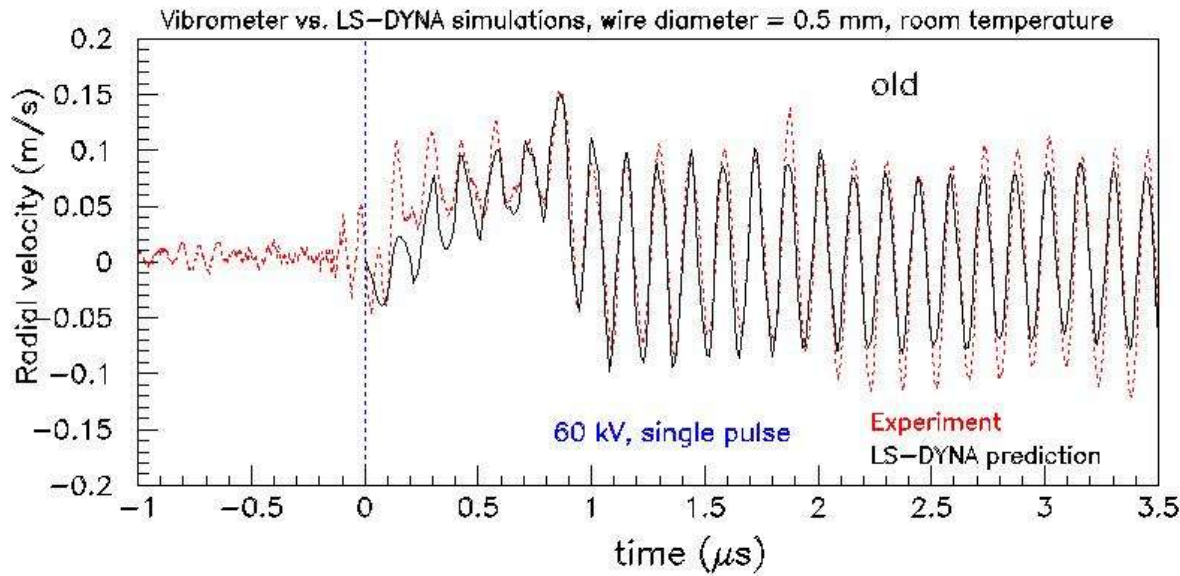
- *Details not fully reproduced*
- *Frequency is OK!*
- *Correct velocity is reproduced (level of stress is correct)*
- *Lifetime results are valid*

# Radial oscillations - update

0.5 mm diameter wire



VD-05 decoder

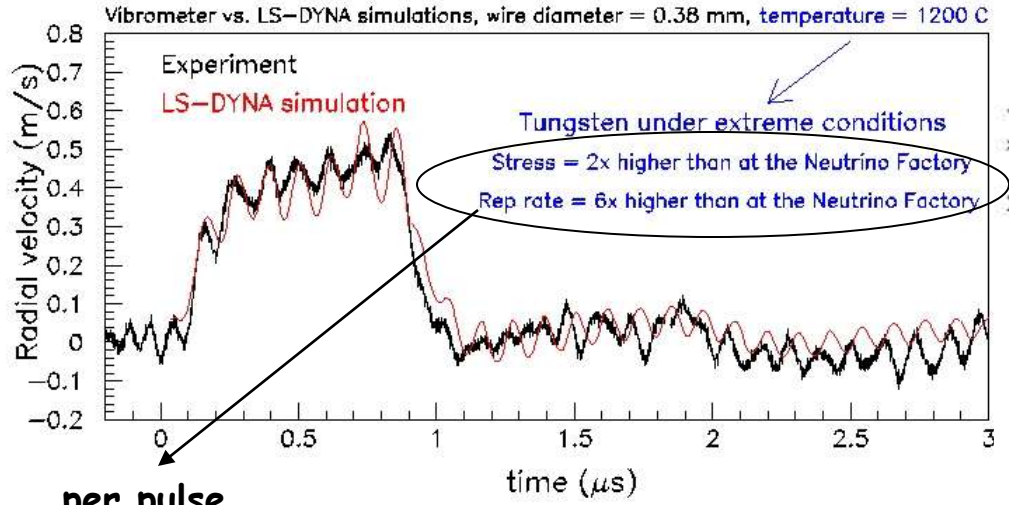
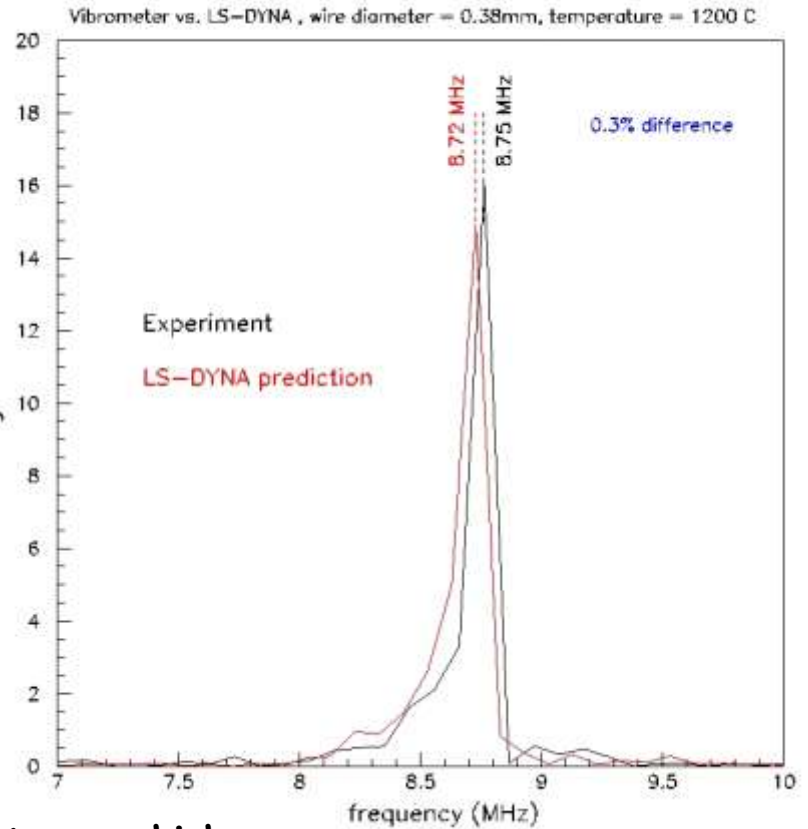
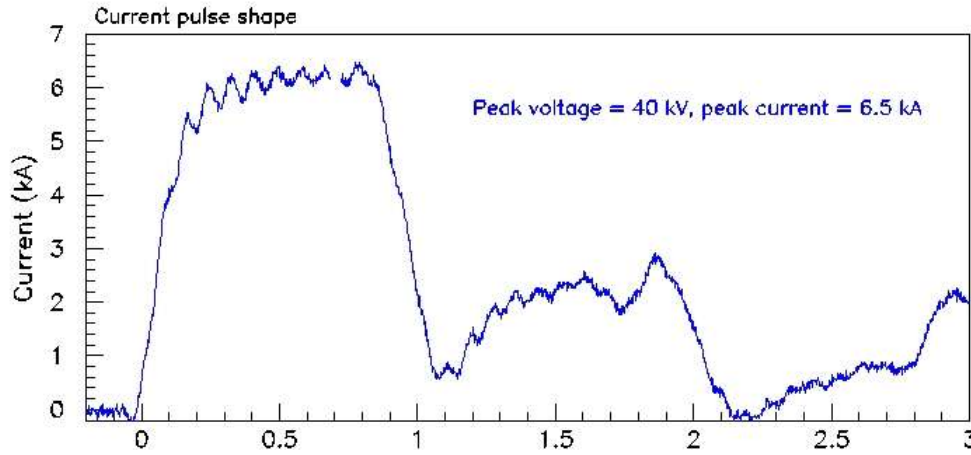
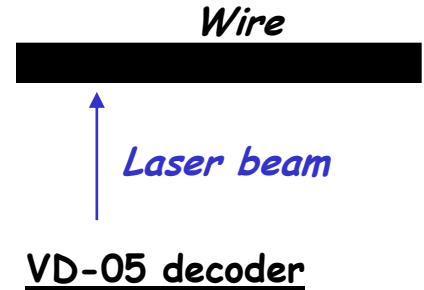


- Voltage rise time measured - better understanding of current density distribution across the wire
- Details - much better agreement!

# Radial velocity of the tungsten wire under extreme conditions

0.38 mm diameter wire

- wire is being stressed at above NF levels



per pulse  
1000 pulses - no problem

Then 1000 pulses at 3x higher stress than at NuFact, even higher...

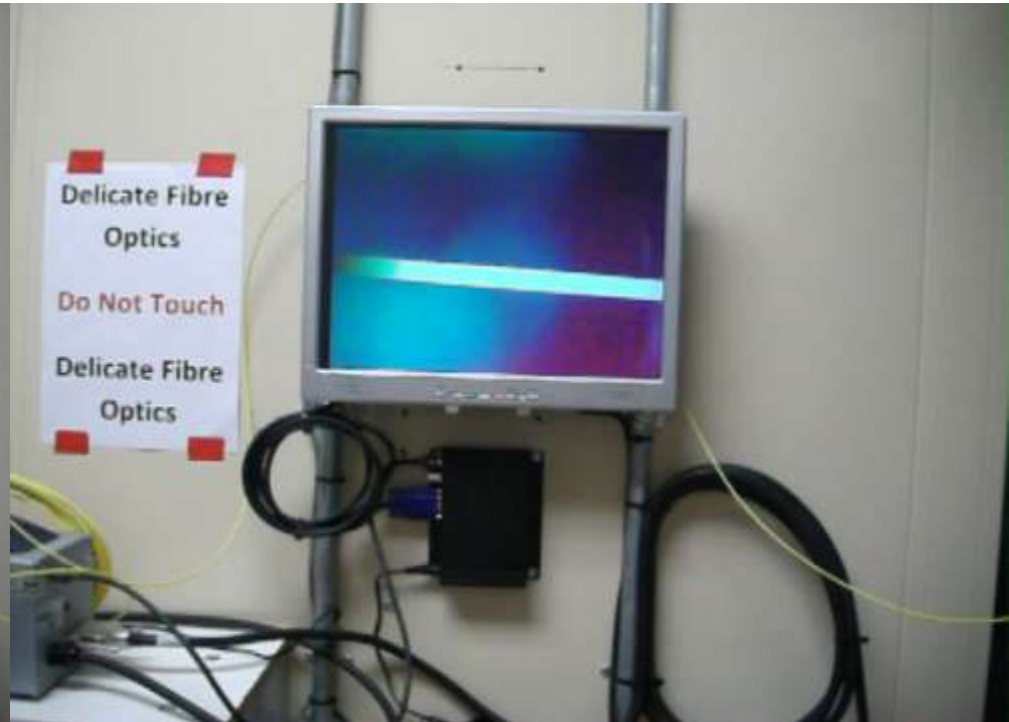
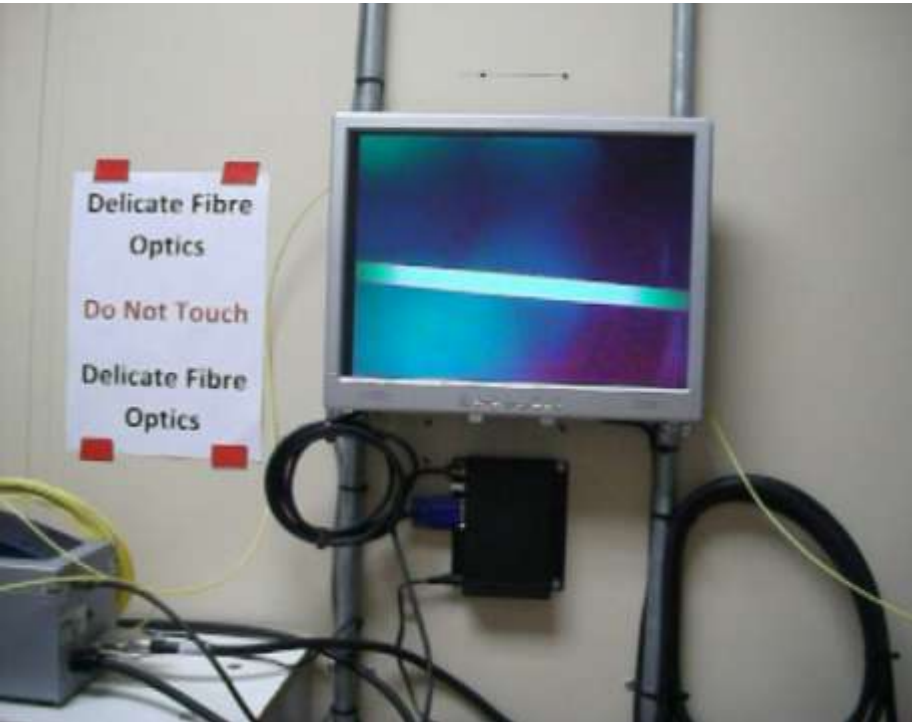
*Tungsten is strong,  
Tantalum is weak.*

*Direct measurements of material strength*

*Ta wire – 0.8 mm diameter*

**35 kV**

**45 kV**

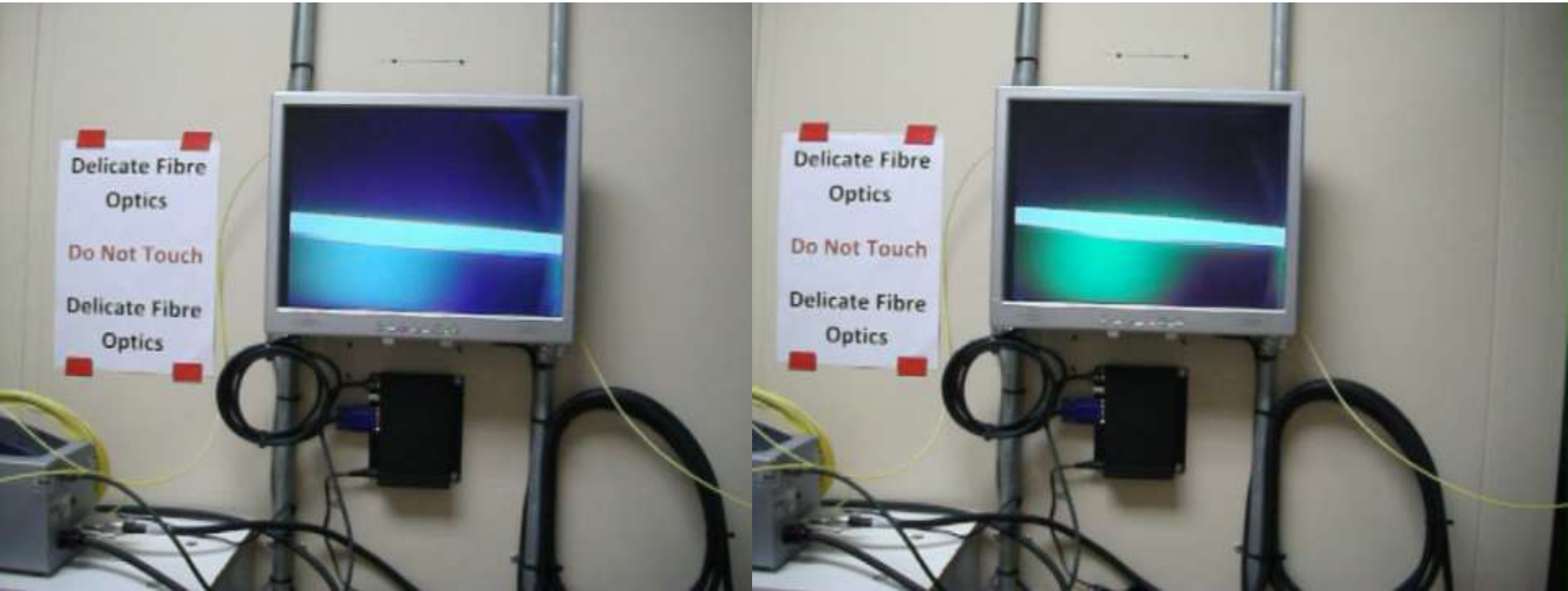


***~ 1000 °C***

## *High temperature tests - Ta wire – 0.8 mm diameter*

**35 kV**

**45 kV**

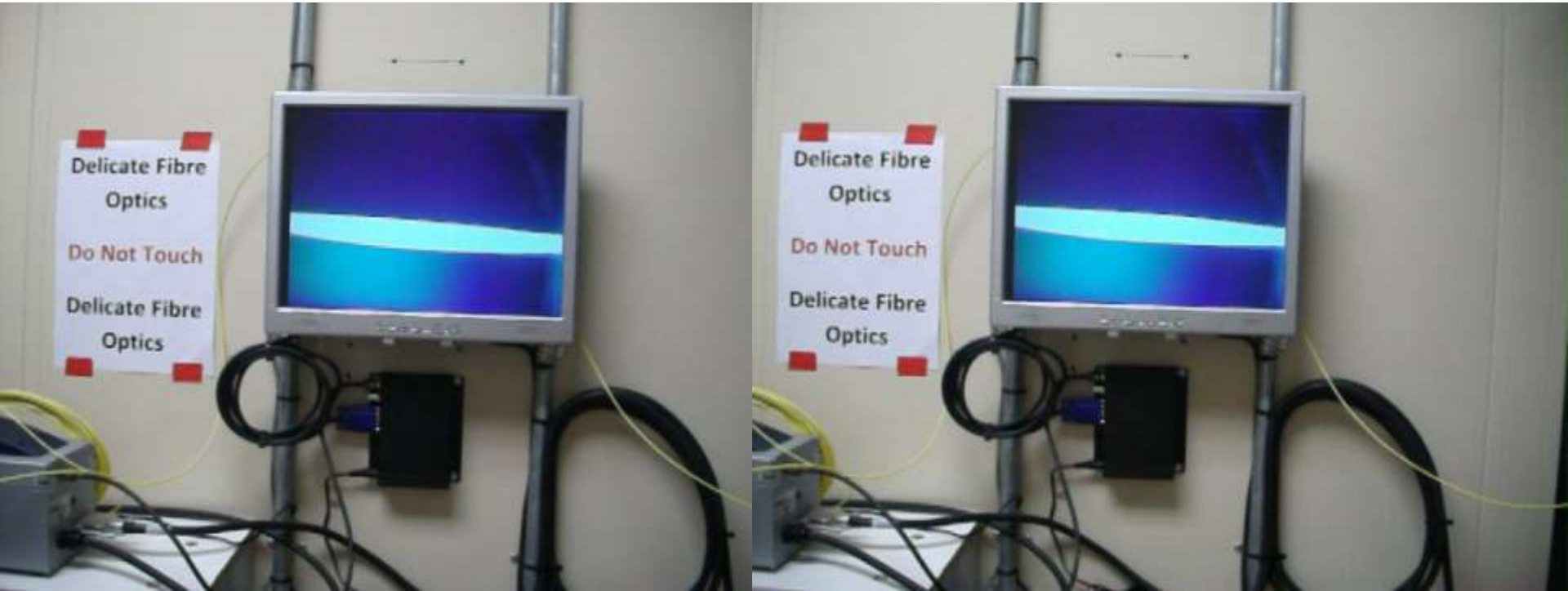


***~ 1400 °C***

# *High temperature tests - Ta wire – 0.8 mm diameter*

**35 kV**

**45 kV**

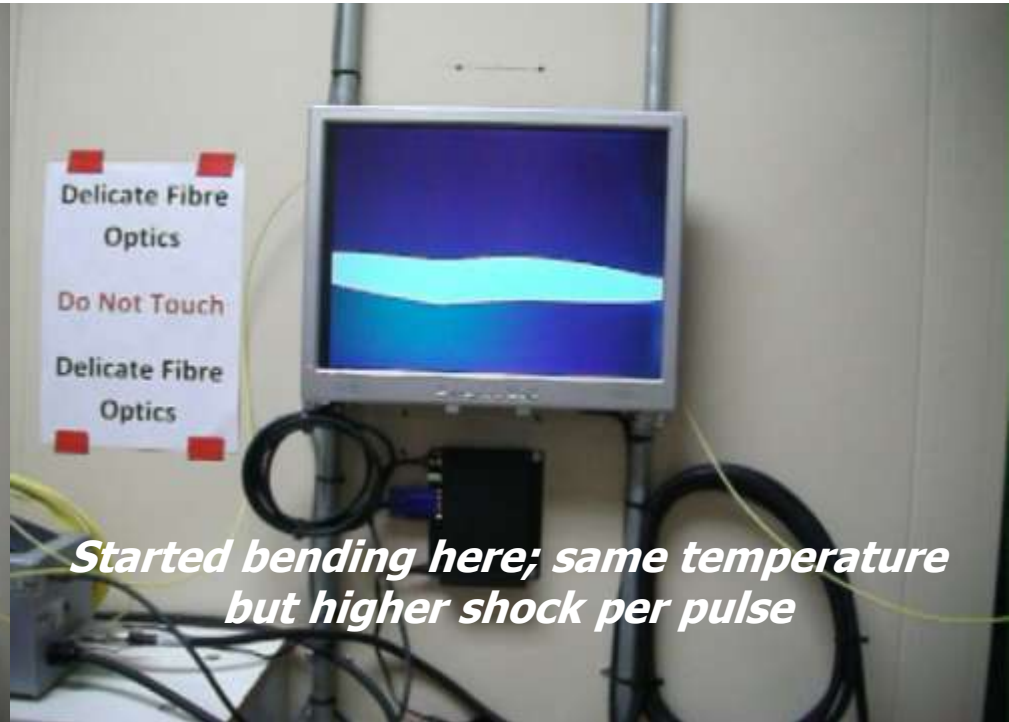
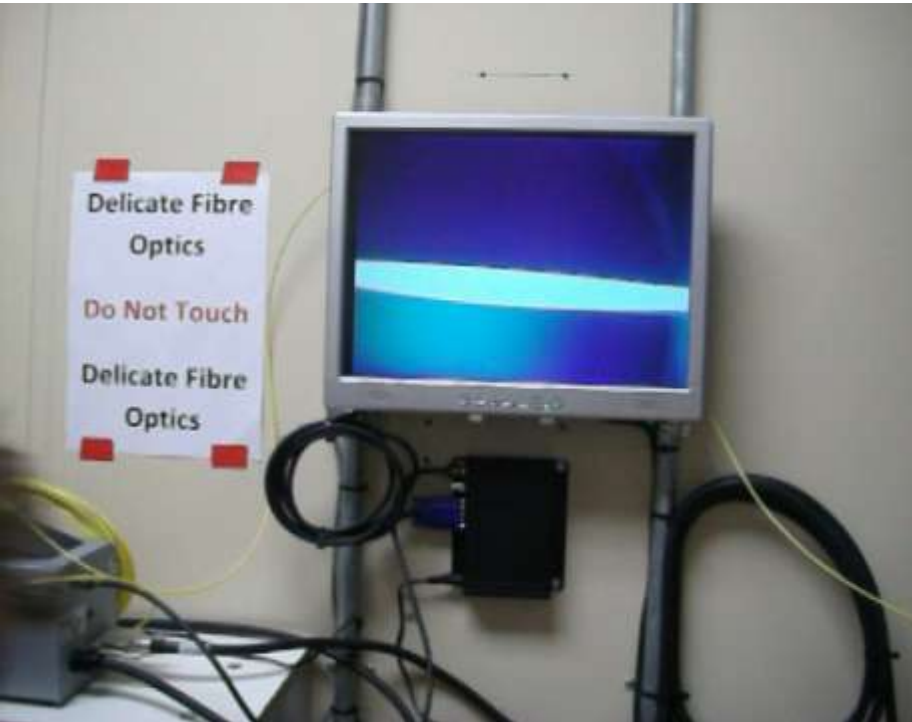


***~ 1800 °C***

# High temperature tests - Ta wire – 0.8 mm diameter

**35 kV**

**45 kV**

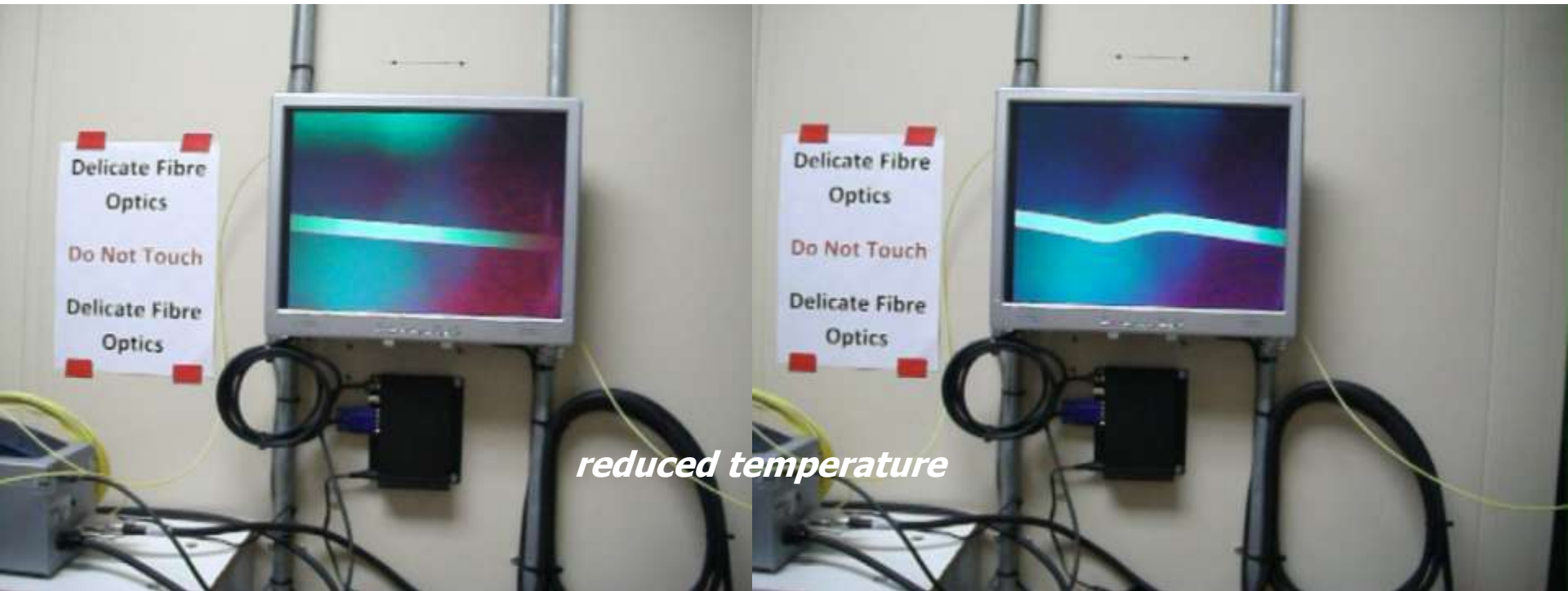


**~ 2100 °C**

## High temperature tests - Ta wire – 0.8 mm diameter

**35 kV**

**45 kV**



Plastic deformation: stress is bigger than yield strength of tantalum

LS-DYNA can be used to calculate stress in the wire per pulse...

...and estimate the strength of material

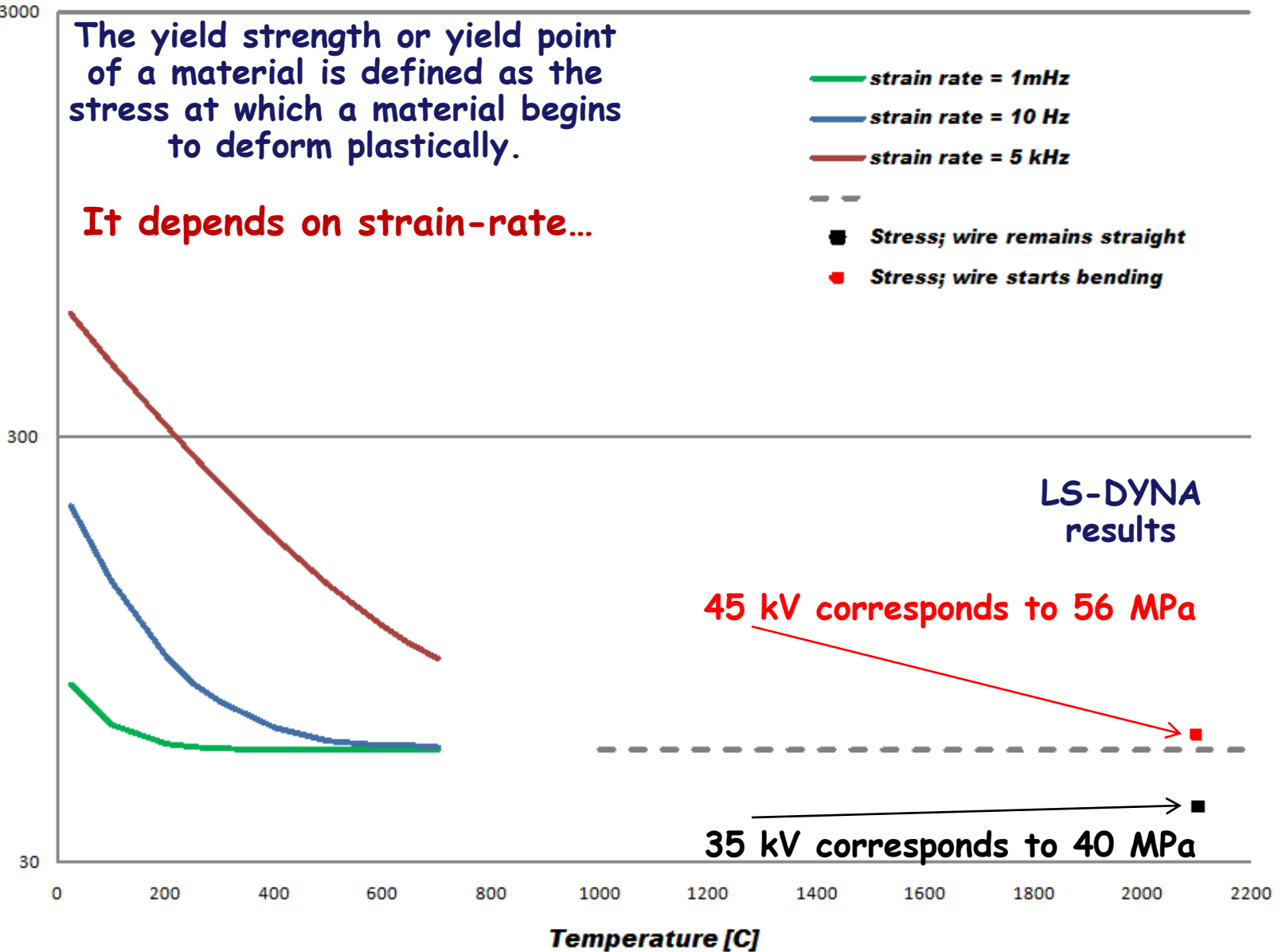
# Yield strength of tantalum - literature

The yield strength or yield point of a material is defined as the stress at which a material begins to deform plastically.

It depends on strain-rate...

- strain rate = 1 mHz
- strain rate = 10 Hz
- strain rate = 5 kHz
- —
- Stress; wire remains straight
- Stress; wire starts bending

Tantalum - Yield Strength [MPa]



## Measurements

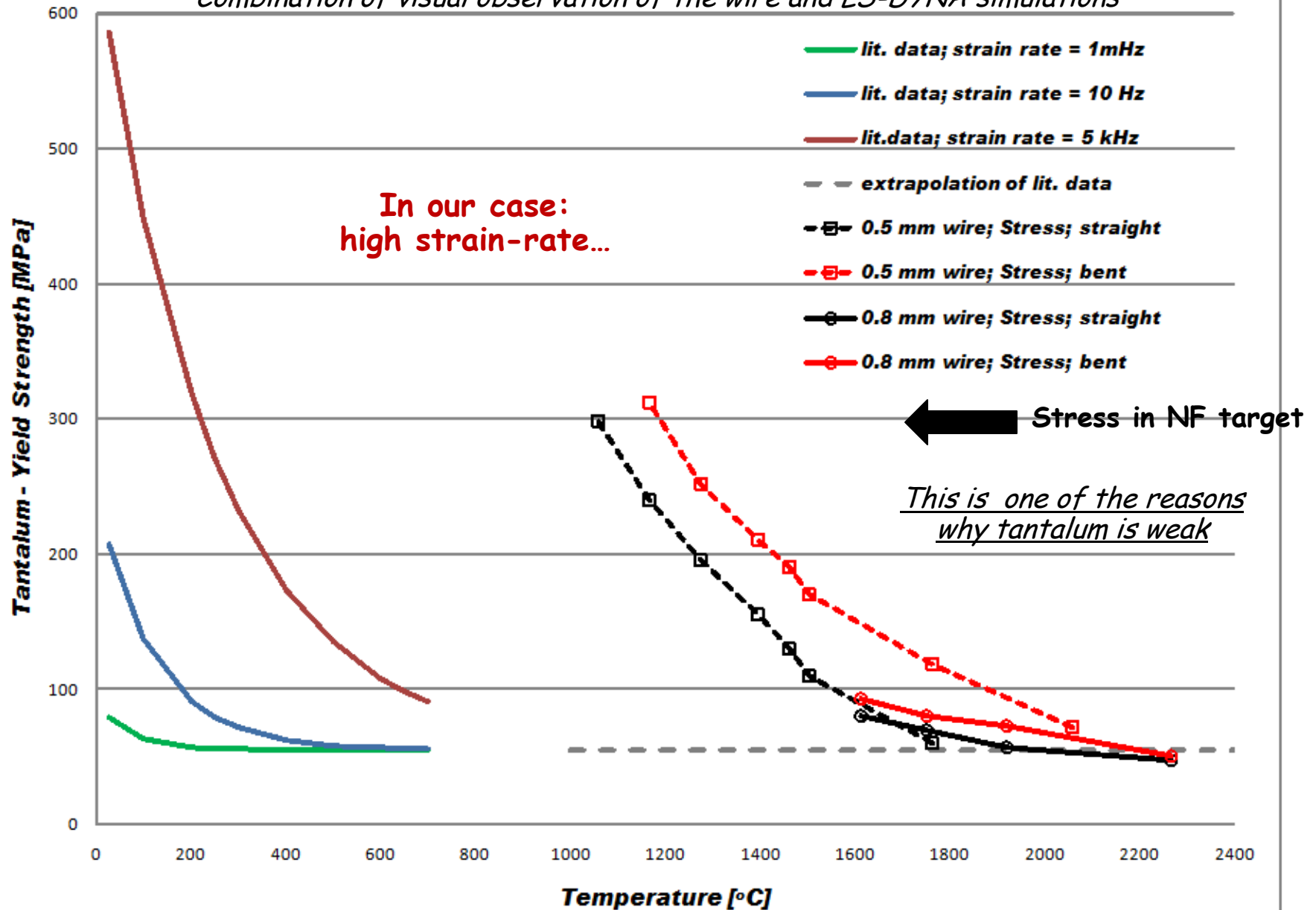
### *Bending - Illustration (3 different wires)*



*Visual observation of the wire, temperature monitoring and then LS-DYNA simulations*

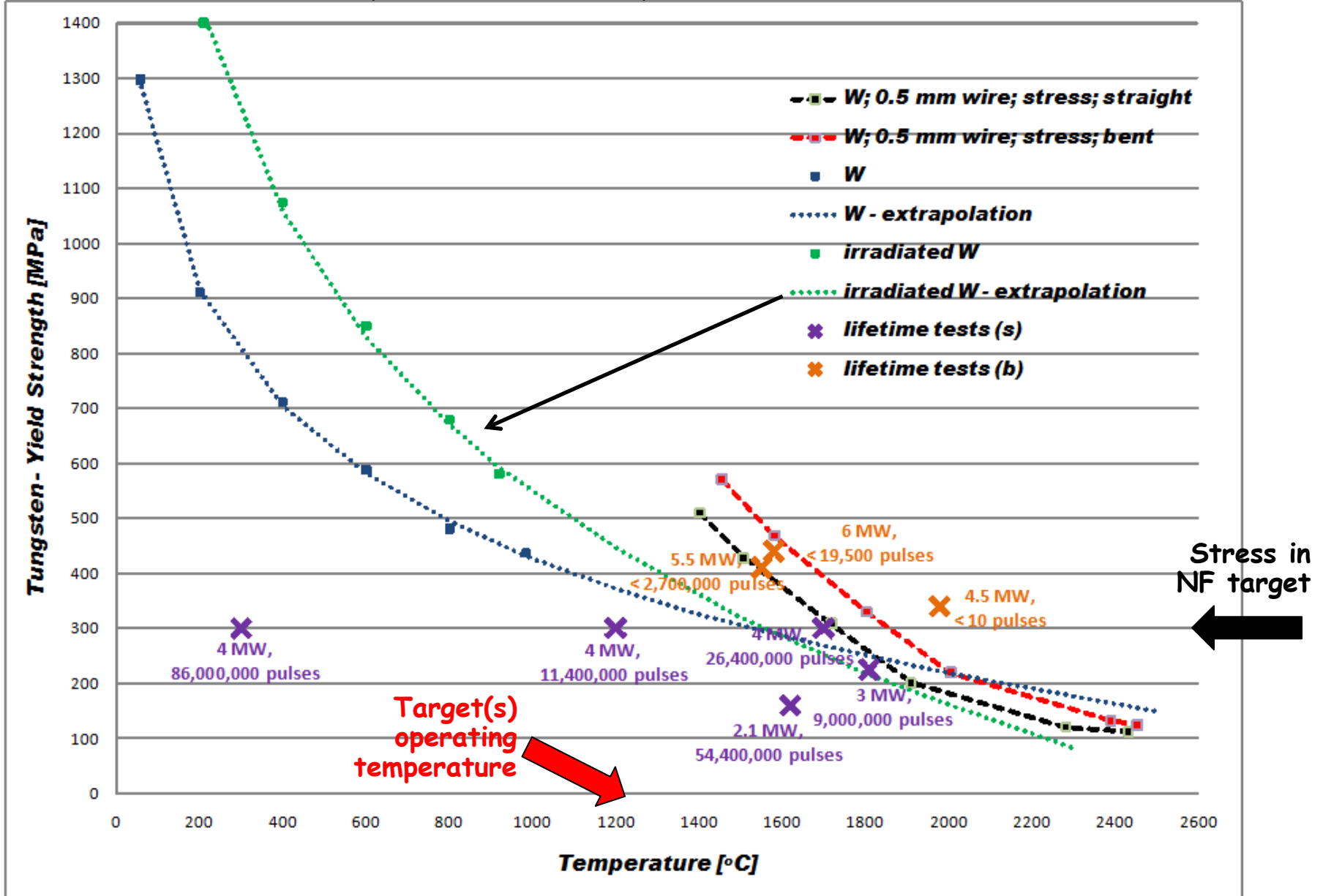
# Yield strength of tantalum - our results

*Combination of visual observation of the wire and LS-DYNA simulations*



# Yield strength of tungsten - our results

Combination of visual observation of the wire and LS-DYNA simulations



## Issue: Temperature rise

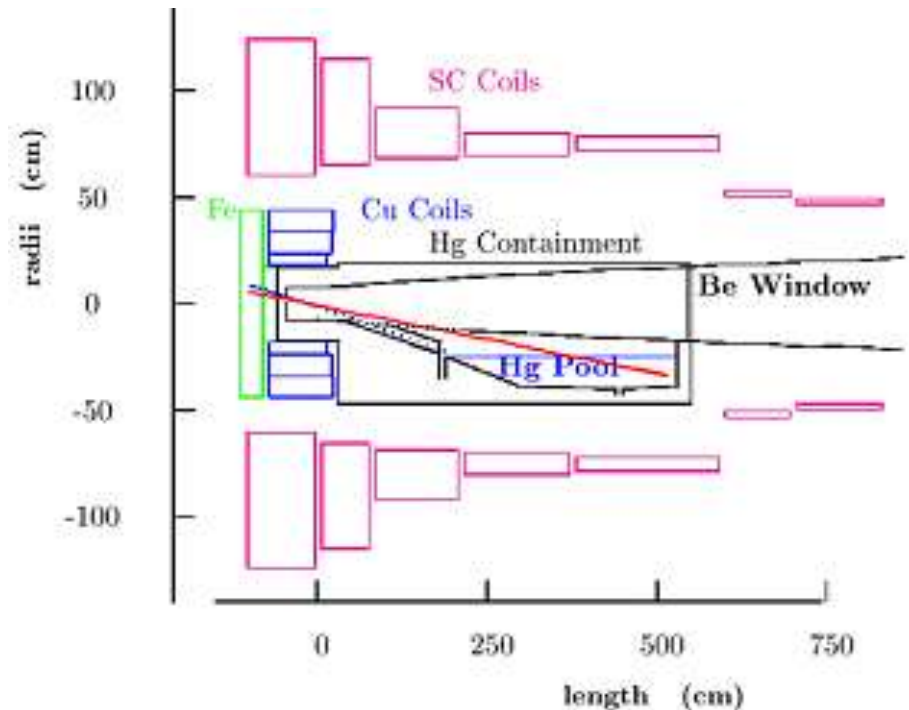
- Temperature rise/pulse: **100-200K**
- Must change target between pulses
- 200 - 400 targets: **good for shock and radiation damage**

## Solid target engineering

### Study II target station\*

*Detail of the Study 2 target station, showing the liquid mercury jet (blue) forming a pool as part of the beam dump, the proton beam (red) and the normally conducting (blue) and super-conducting (purple) coils of the pion collection solenoid.*

- Our designs have assumed this
- We tried to work out how to fit in

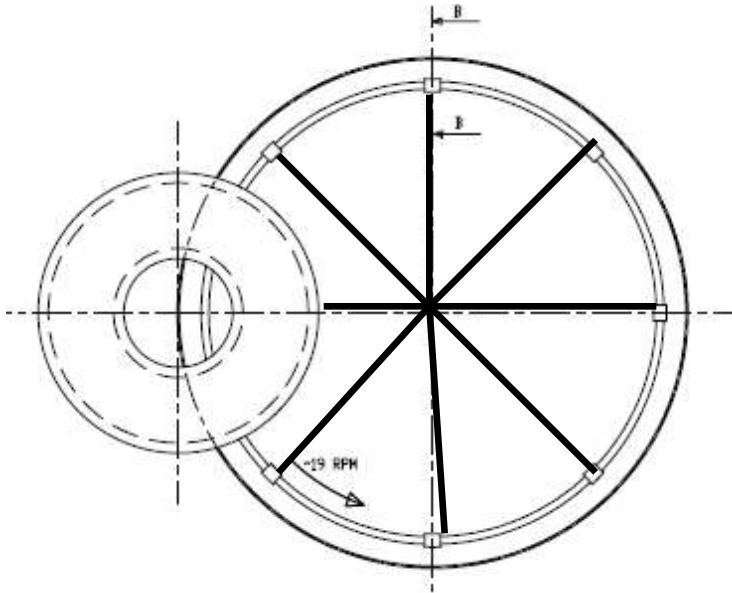


\*<http://www.cap.bnl.gov/mumu/studyii/>

Option: Wheel

- Used already at PSI, ~ 3 m radius
- no moving parts in high radiation
- solenoid must be split: **Helmholtz coil**

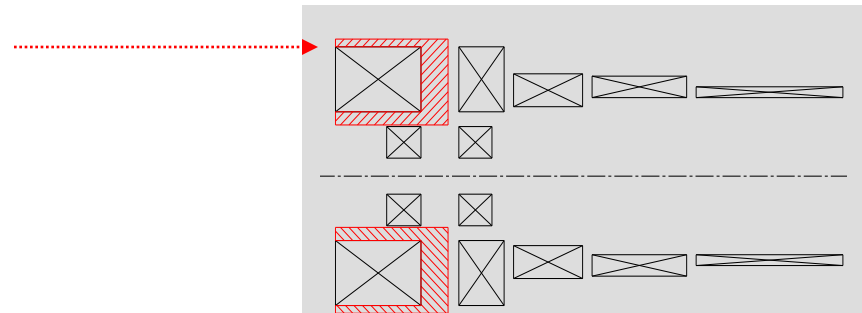
a) Spoked wheel



Huge axial forces must be transferred out to an external structure

Coils at 4.2K, external structure at room-temperature ?!

Major geometry interference issues to resolve (coils, structure, target-access)



Coil geometry with required structure volume to maintain a fully open axial gap (drawn to scale)

Remember the goal →

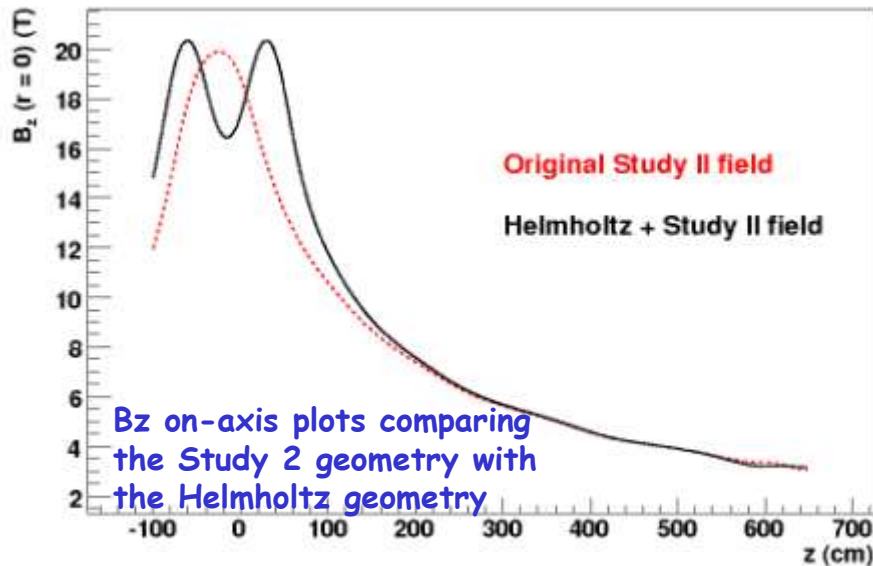
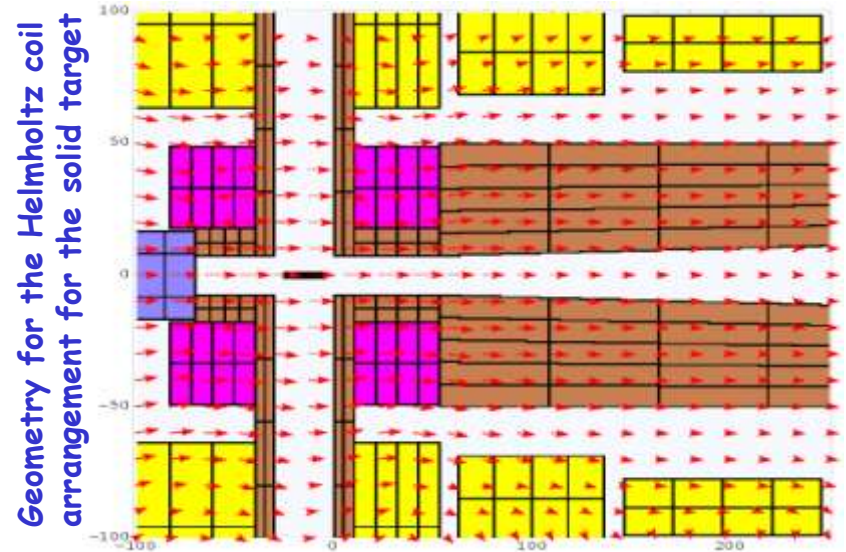
Efficient production (and capture) of secondary pions

J. Back

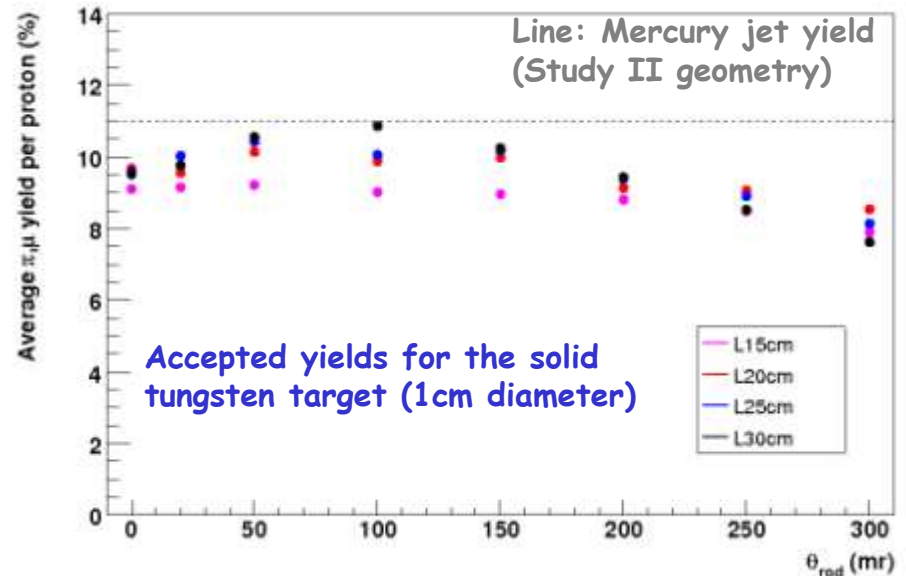
Detailed Monte Carlo simulations (MARS, ICOOL)

New coil geometry (Helmholtz) taken into account

Comparison of results for 'accepted' pion yields with a mercury jet target concept (Study II geometry)



Bz on-axis plots comparing the Study 2 geometry with the Helmholtz geometry

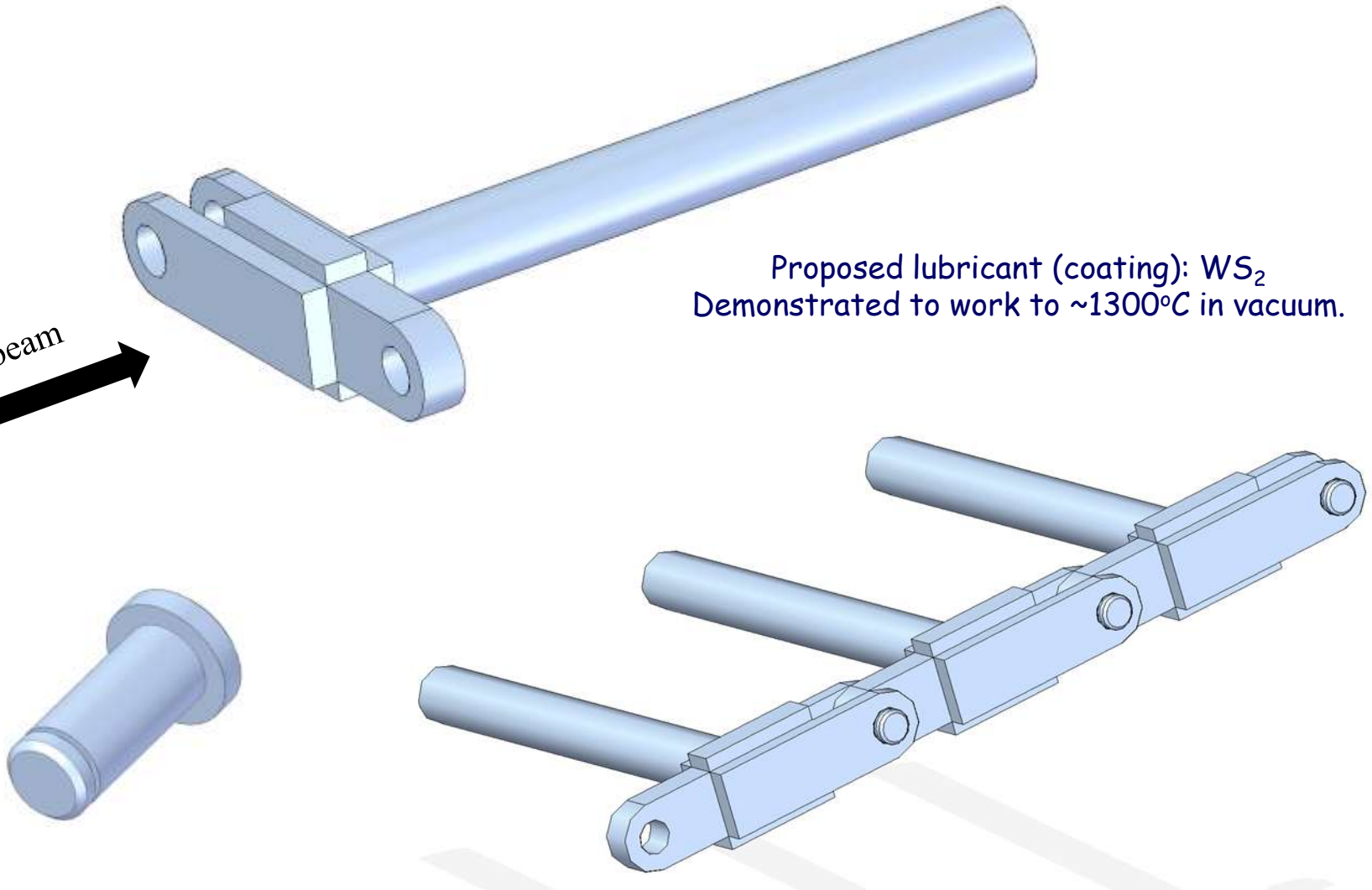


Accepted yields for the solid tungsten target (1cm diameter)

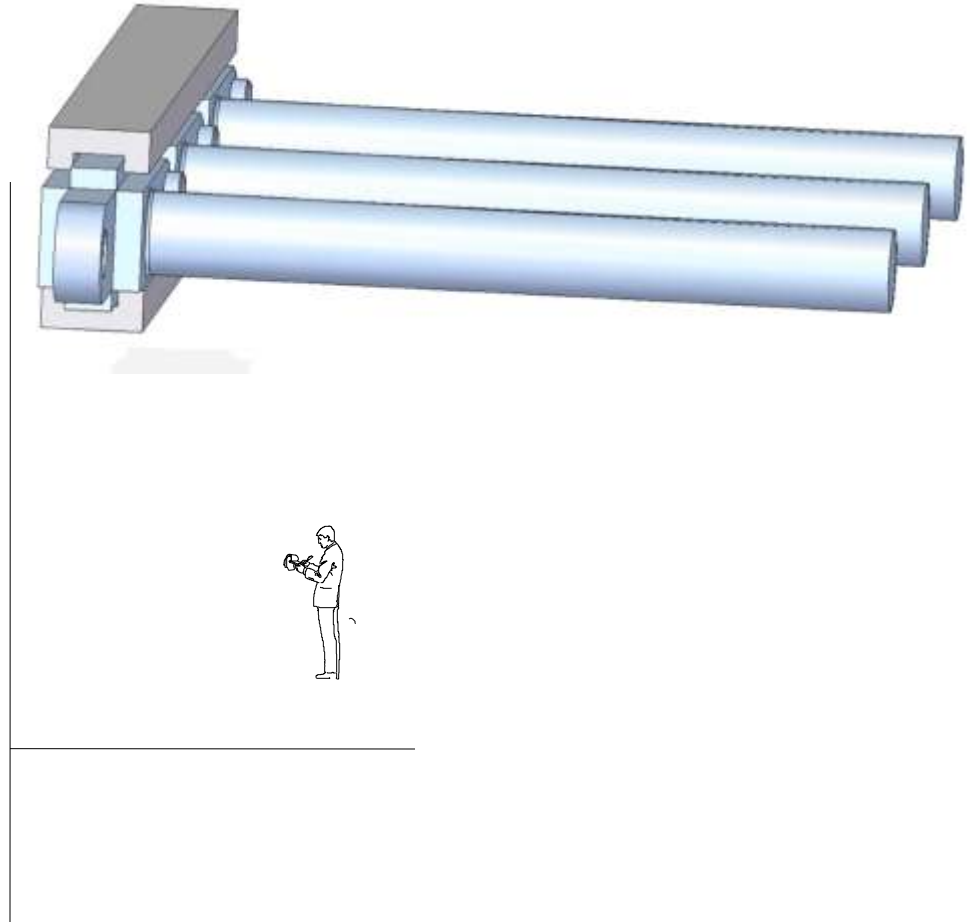
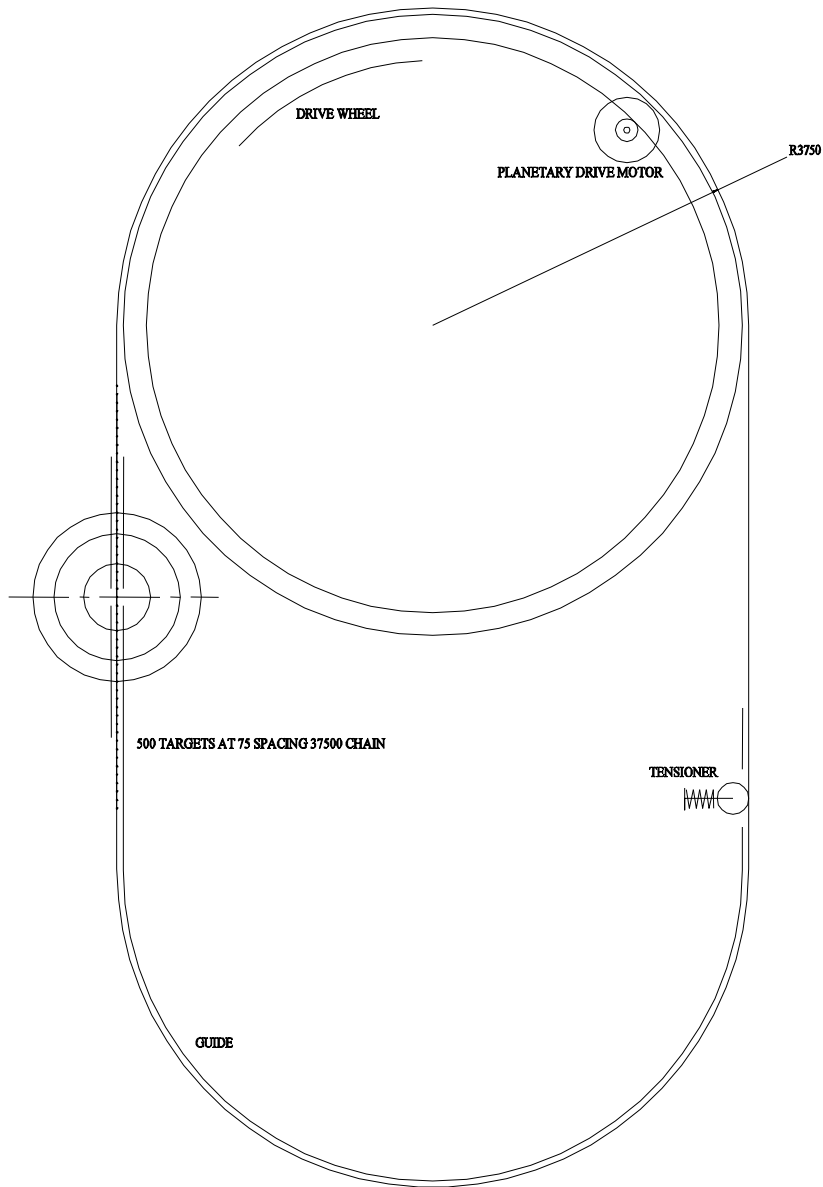
# Target change - chain

All tungsten.  
Manufacture discussed with Plansee (Austria).

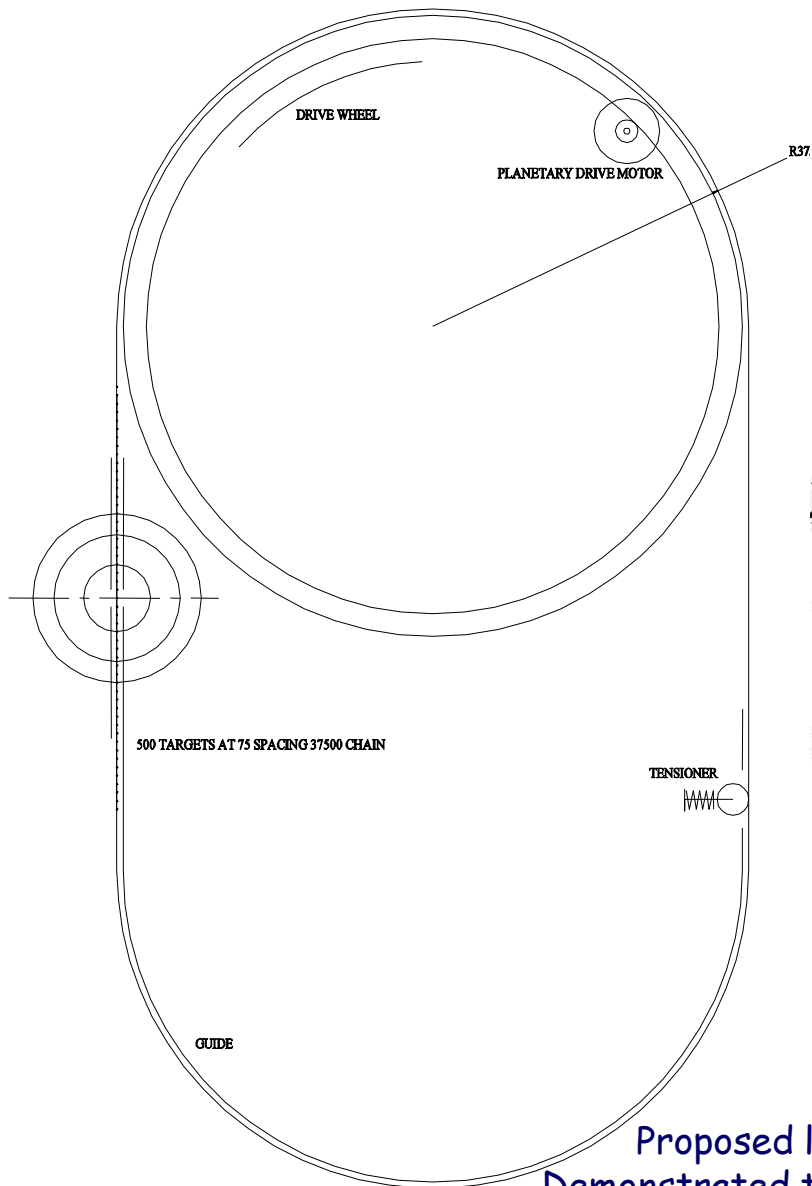
Proton beam  
→



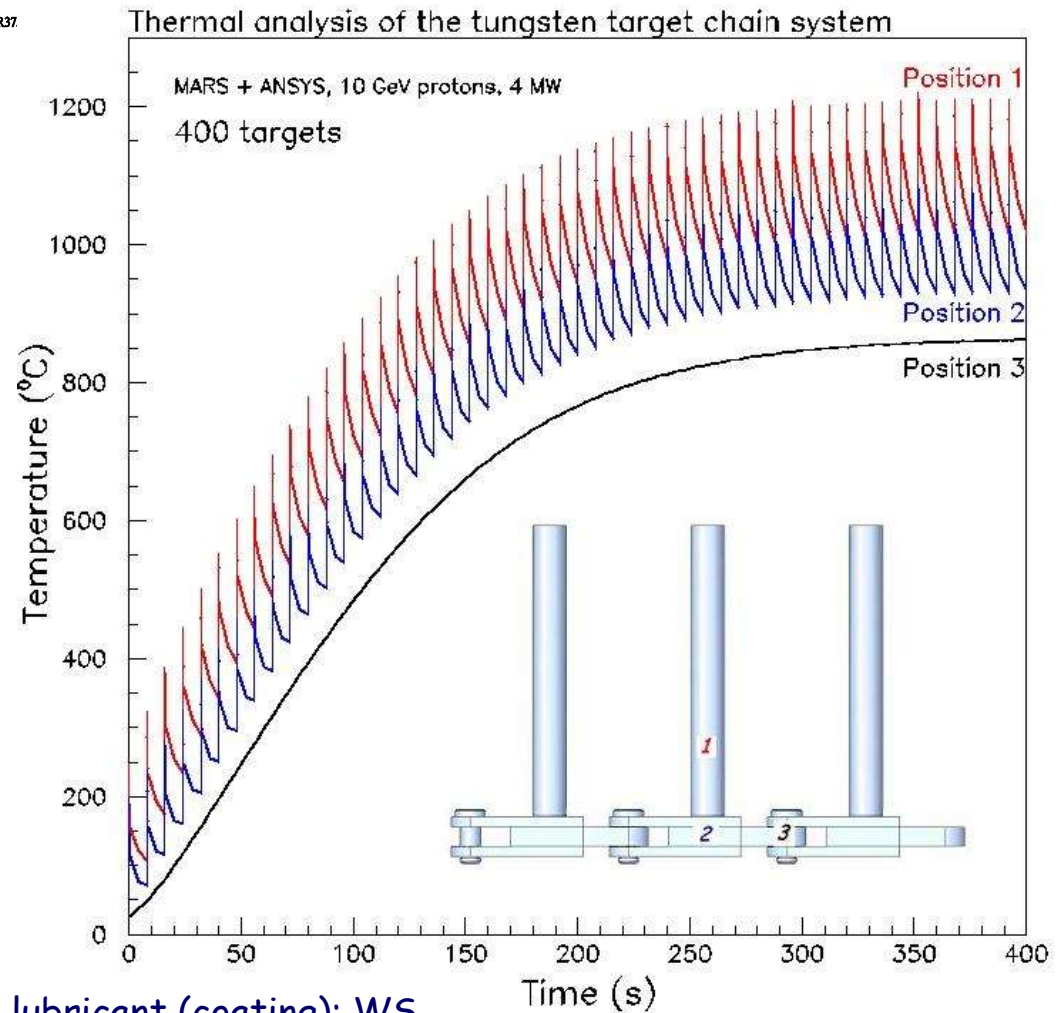
# Target change - chain



# Target change - chain

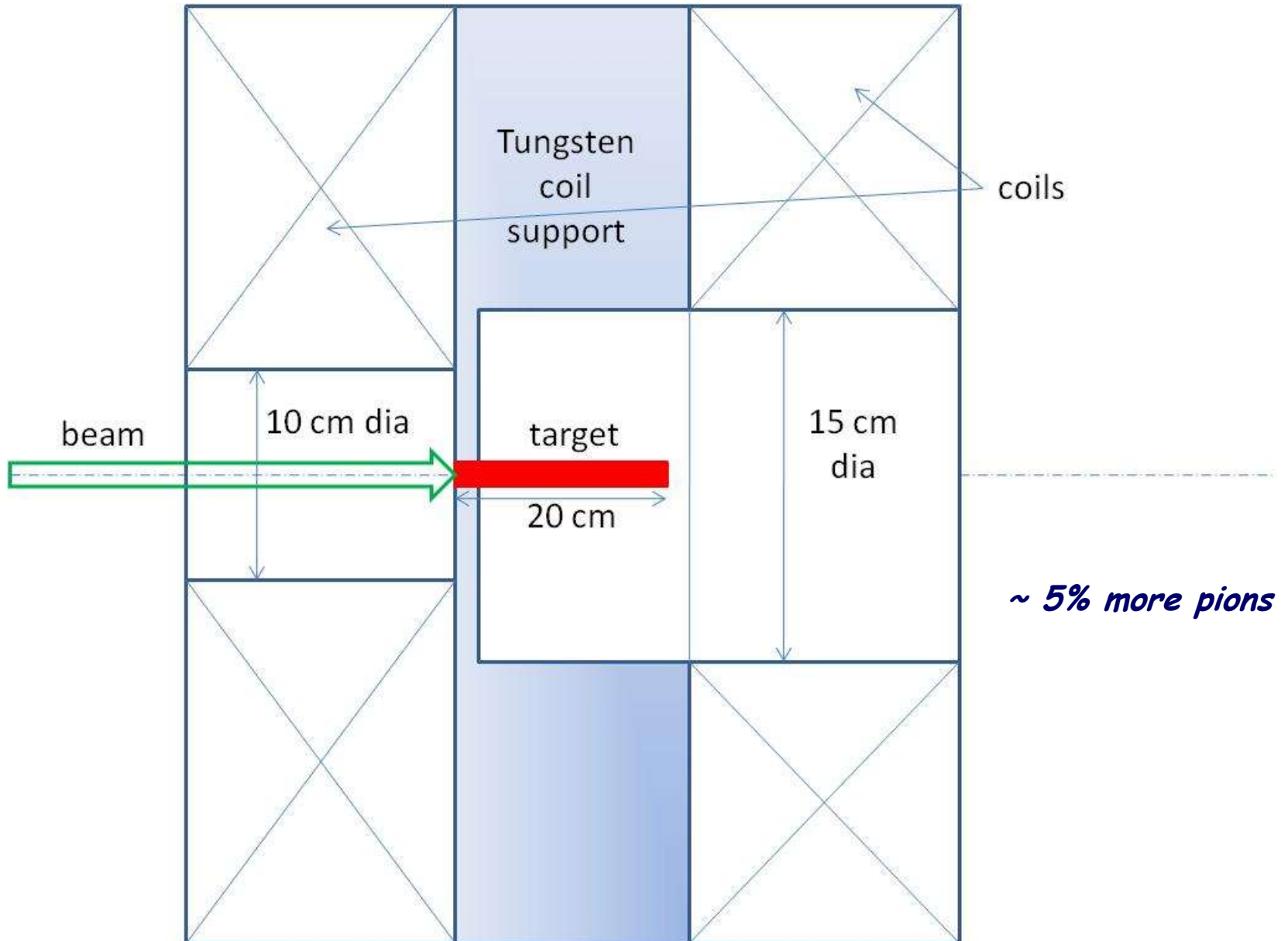


## Thermal model



Proposed lubricant (coating):  $WS_2$   
 Demonstrated to work to  $\sim 1300^\circ C$  in vacuum.

# Target change - chain

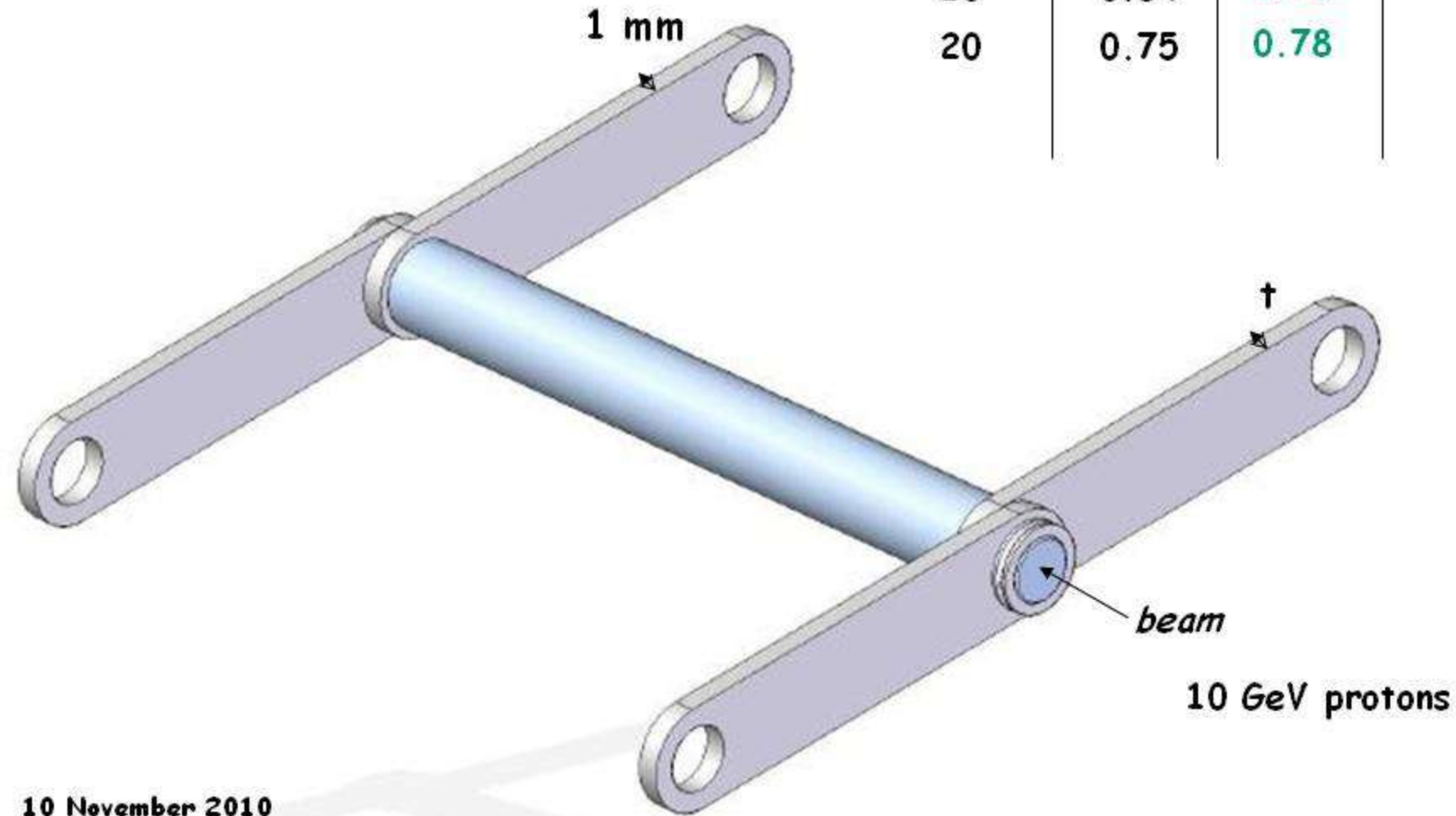


Yield (tungsten bar only) = 1

Pion yield - MARS 15

Target change - chain  
 (alternative)

t (mm)	W	yield	
		Mo	Nb
1	0.76	0.81	0.80
10	0.84	0.78	
20	0.75	0.78	



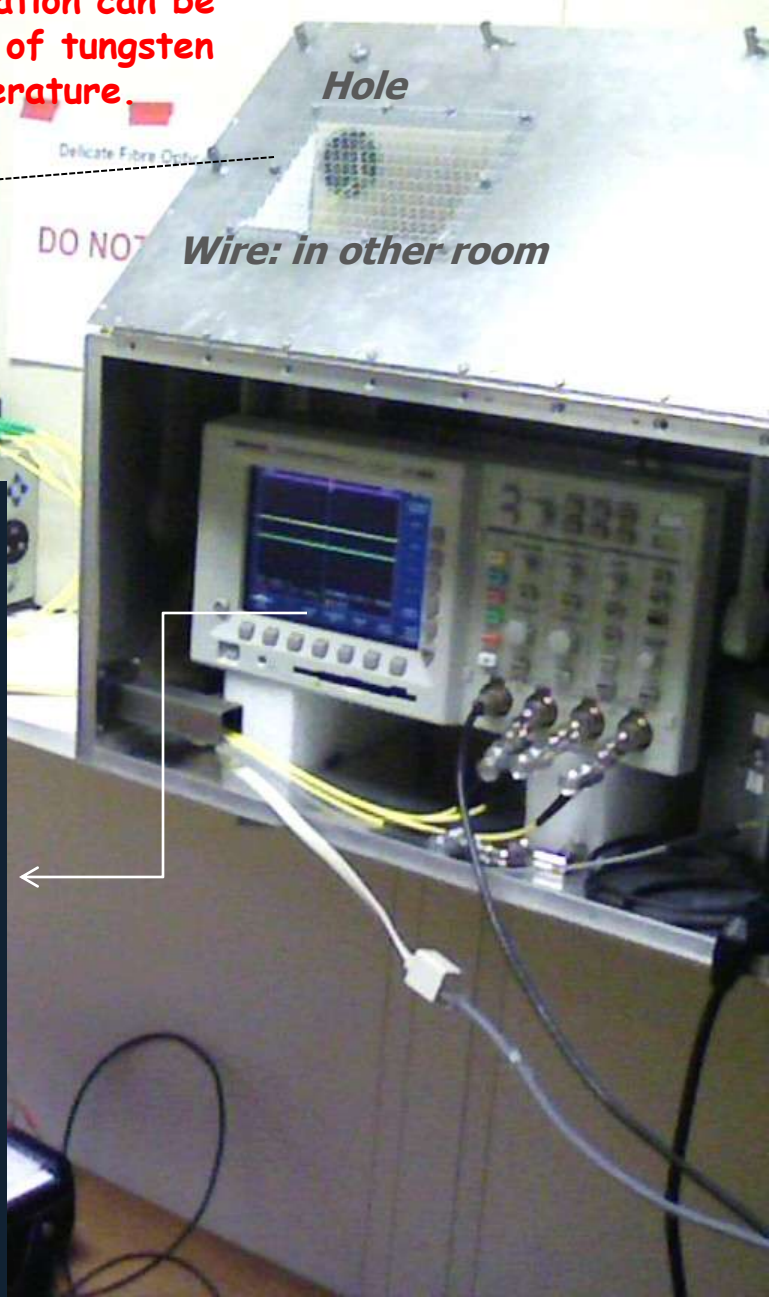
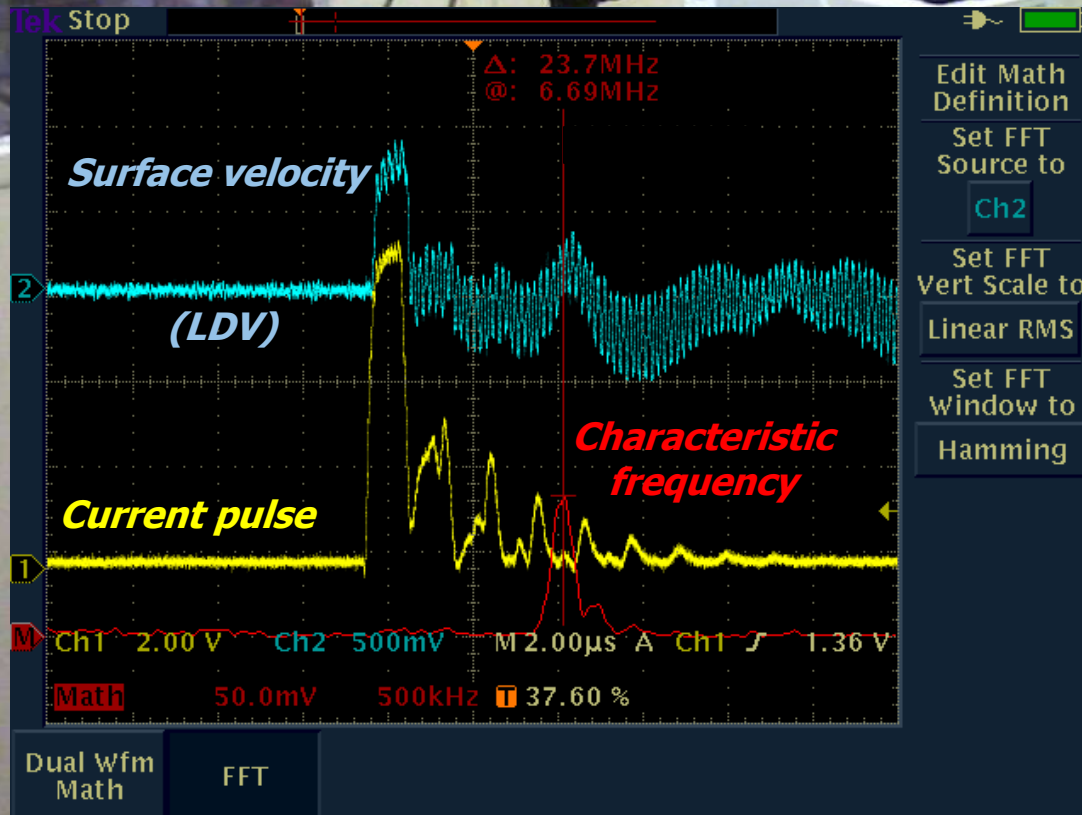
# Spin-off

Characteristic frequency of the wire vibration can be used to directly measure Young's modulus of tungsten (and tantalum) as a function of temperature.

*Optical pyrometer*

*Hole*

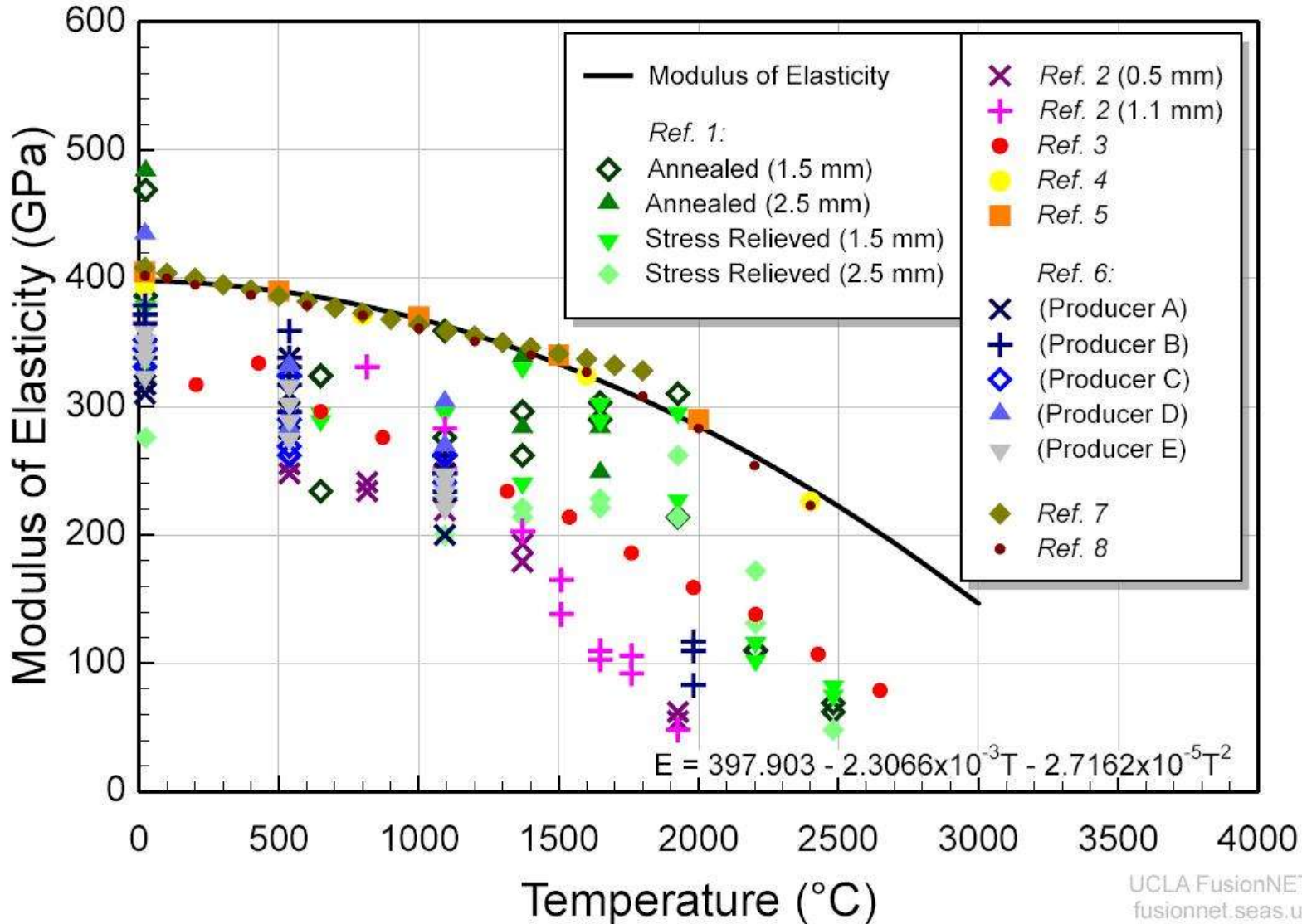
*Wire: in other room*



If we measure the frequency ( $f$ ) then:

$$E = \frac{(2\pi f)^2 r^2 \rho}{\zeta^2} \frac{(1+\nu)(1-2\nu)}{(1-\nu)}$$

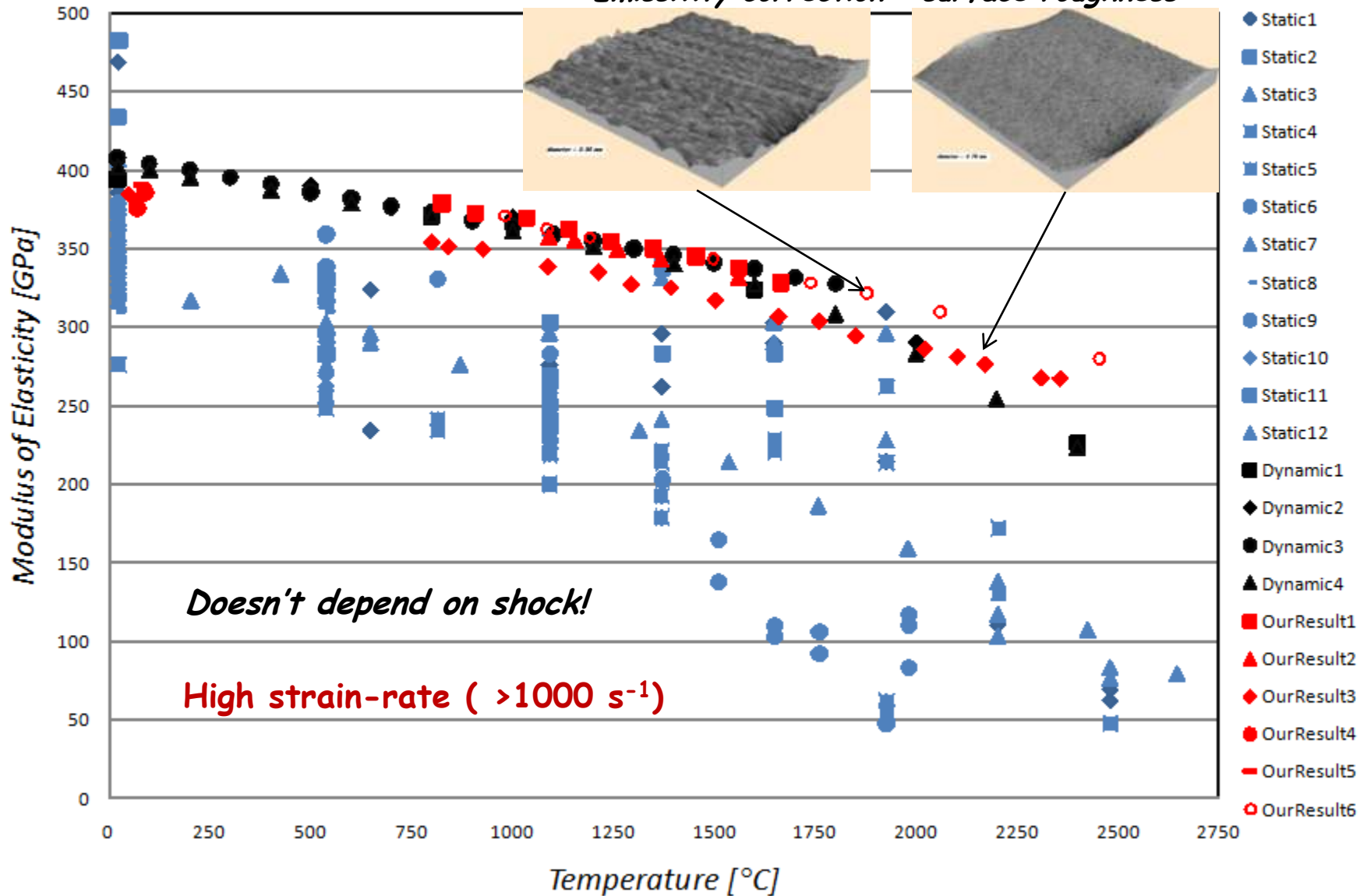
## Young's Modulus of Tungsten



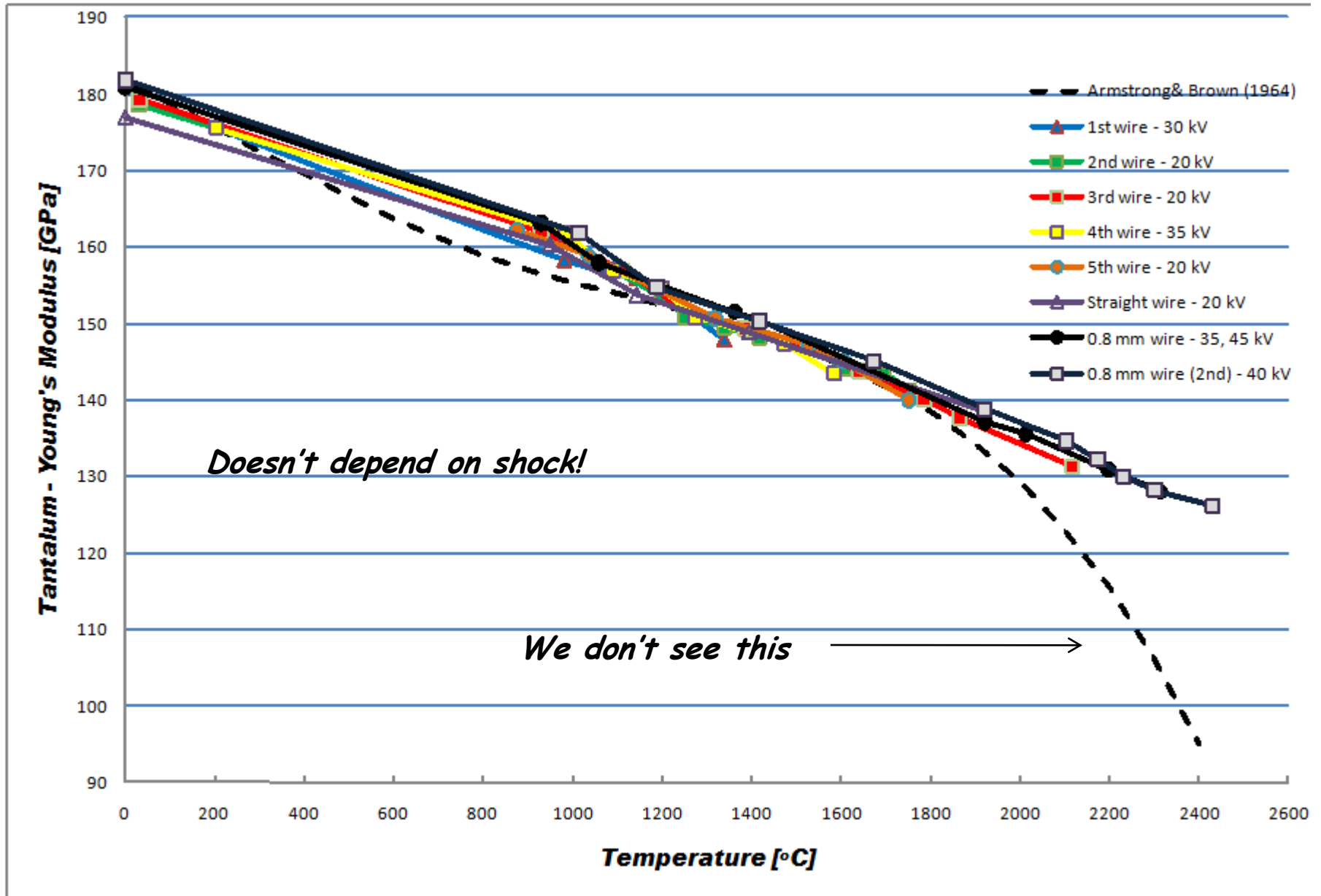
# Young's modulus of tungsten - our results

## Young's modulus of Tungsten

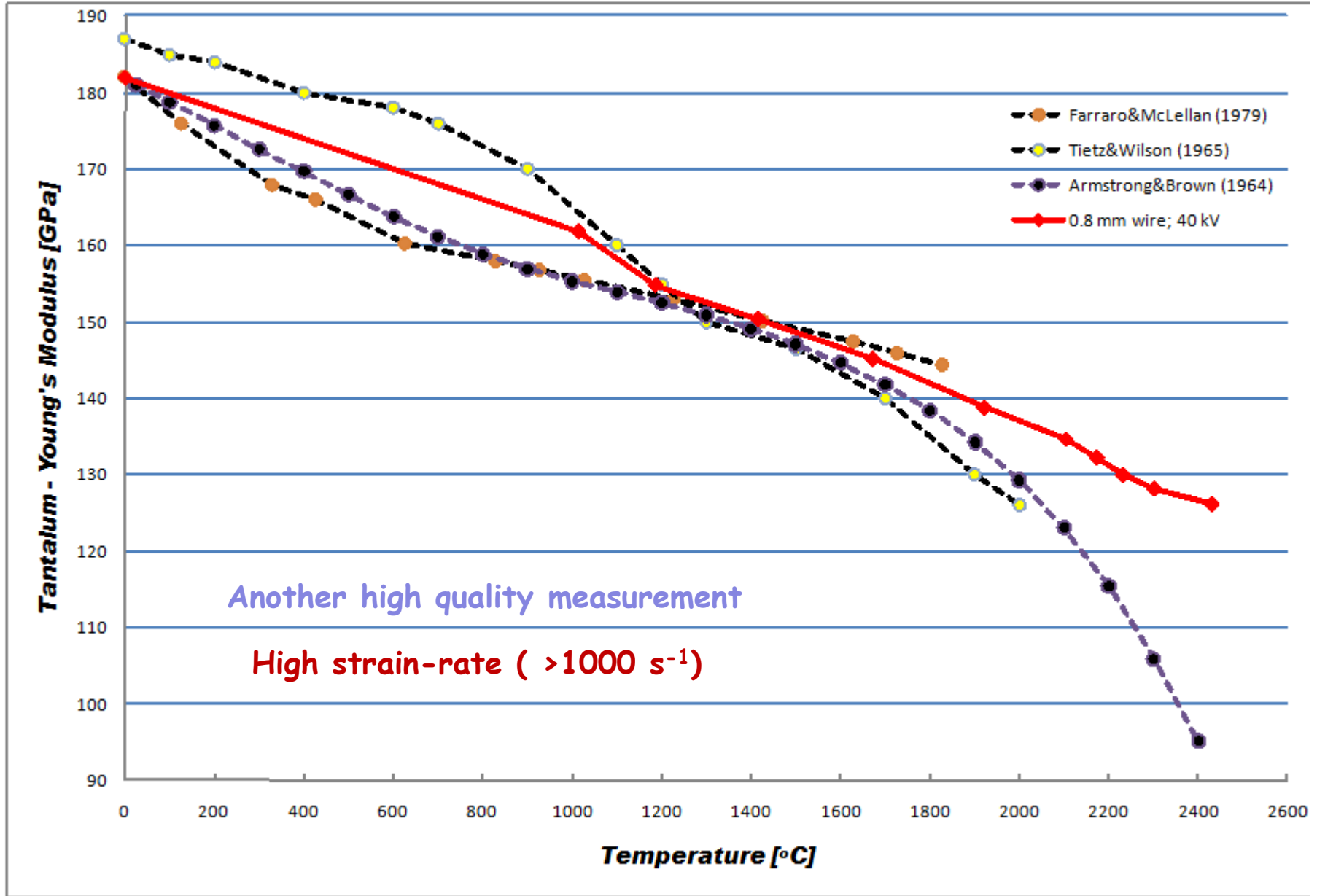
*Emissivity correction - surface roughness*



# Young's modulus of tantalum - our results



# Young's modulus of tantalum - our results vs. literature



# Summary

Dynamic Young's moduli of tungsten and tantalum at high temperature and stress<sup>☆</sup>

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**Papers:**  
← **1<sup>st</sup> - submitted to Journal of Nuclear Materials**  
**2<sup>nd</sup> - lifetime/strength tests, shock at the NuFact, etc... (NIM) - almost finished**  
**3<sup>rd</sup> - pion yields, target shape optimisation (target change)...**

## Abstract

Recently reported results of the long lifetime of the tungsten samples under high temperature and high stress conditions expected in the Neutrino Factory target have strengthened the case for a solid target option for the Neutrino Factory. In order to study in more detail the behaviour of the material properties of tungsten, a dynamic method has been used for measurement of Young's modulus at high stress, high strain-rates ( $> 1000 \text{ s}^{-1}$ ) and very high temperatures (up to  $2650 \text{ }^\circ\text{C}$ ). The method is based on measurements of the surface vibration of thin wires, stressed by a pulsed current, using a laser Doppler vibrometer. The measured characteristic frequencies under the thermal excitation have been used to obtain Young's modulus as a function of applied stress and temperature. The same procedure has been used to measure Young's modulus of tantalum up to  $2500 \text{ }^\circ\text{C}$ .

**Keywords:** tungsten, tantalum, Young's modulus, high temperature, high stress, laser Doppler vibrometer

## 1. Introduction

The answer to the fundamental question of the role of neutrinos in the creation of our universe requires precise measurements of the parameters gov-

*High temperature, high stress, high strain-rate applications*

*...not only high power targets*

*tungsten*

- blanket material in the fusion reactors;
- fuel cladding at very high temperatures in fission reactors;
- new generation of `kinetic energy penetrators` (tungsten alloys)...

<sup>☆</sup>Work supported by Science and Technology Facilities Council (UK).

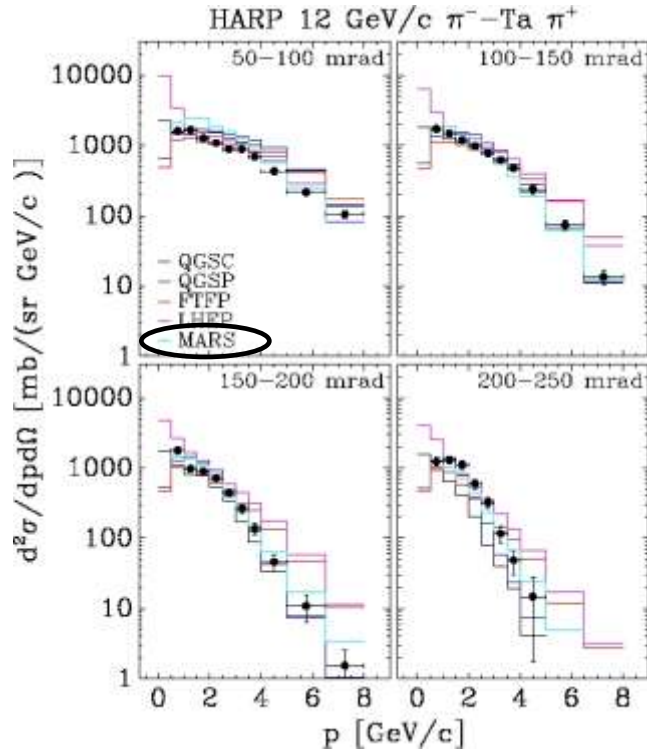
\*Corresponding author

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**Comparison of models with data, *MERIT* experiment analysis**

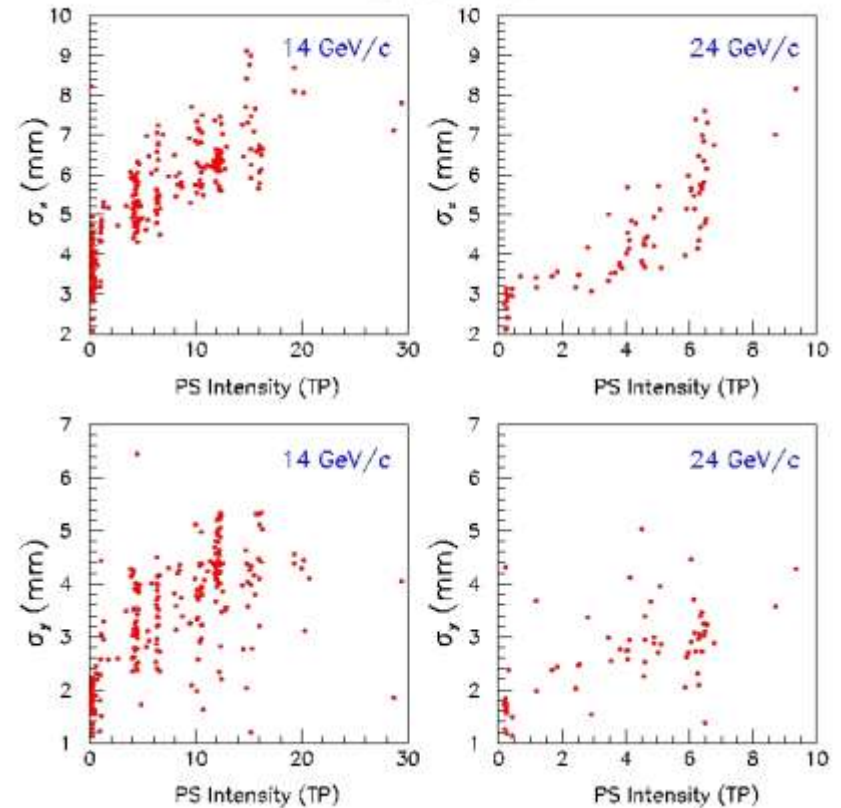
As can be seen, we rely on Monte Carlo calculations (particularly on MARS code)

Comparison between experimental data from HARP experiment and MARS results on pion production in hadron - nucleus interactions will help to tune all the Neutrino Factory related calculations



**We contribute to the analysis of the *MERIT* experimental data**

Camera 484



**Here: Results about the beam parameters dependence on beam intensity during the *MERIT* experiment run**