# MATERIAL RESPONSE TO HIGH POWER BEAMS

GORAN ŠKORO

UKNF Target Studies Web Page:

http://hepunx.rl.ac.uk/uknf/wp3/

4th HIGH POWER TARGETRY WORKSHOP

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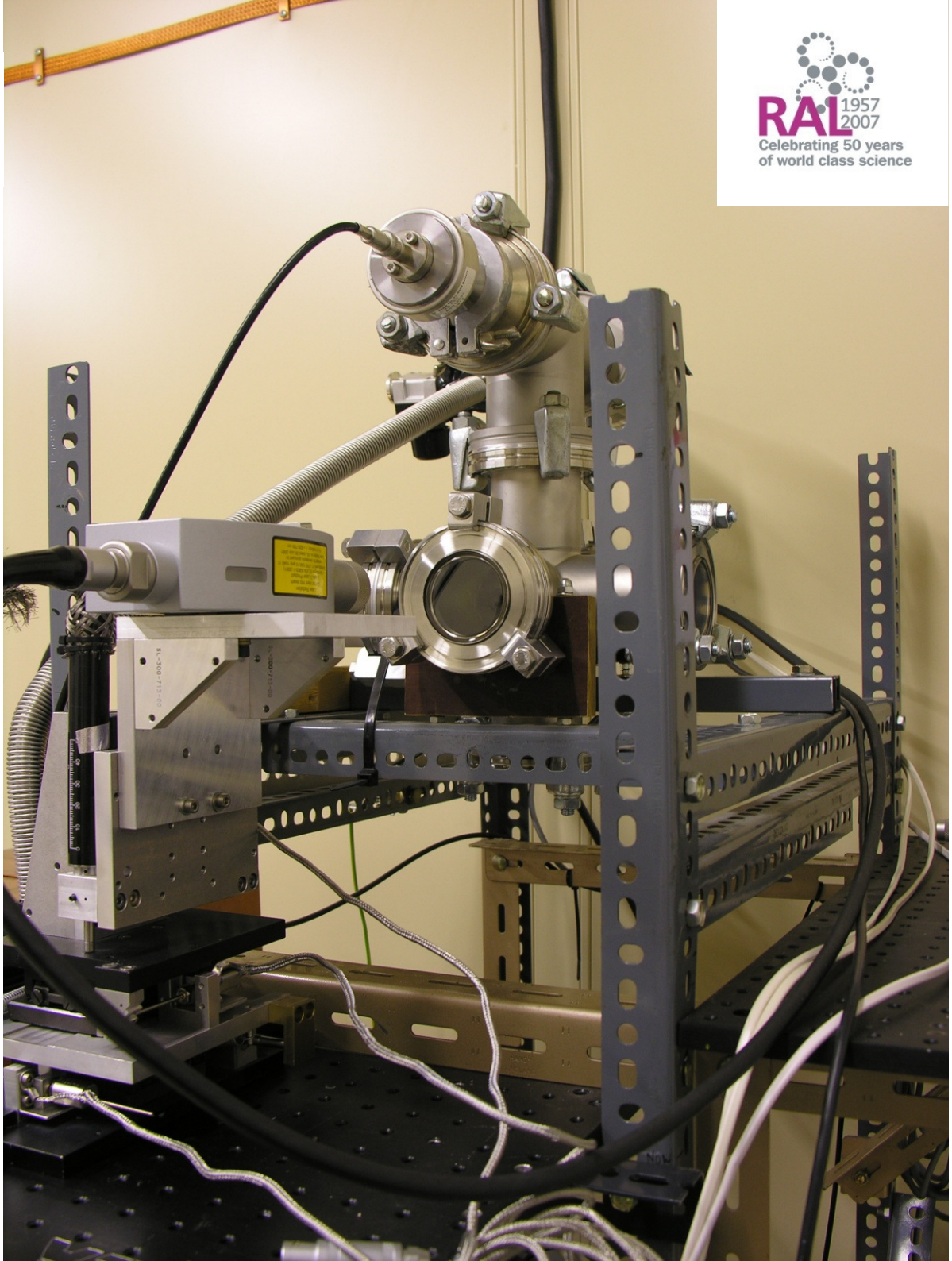

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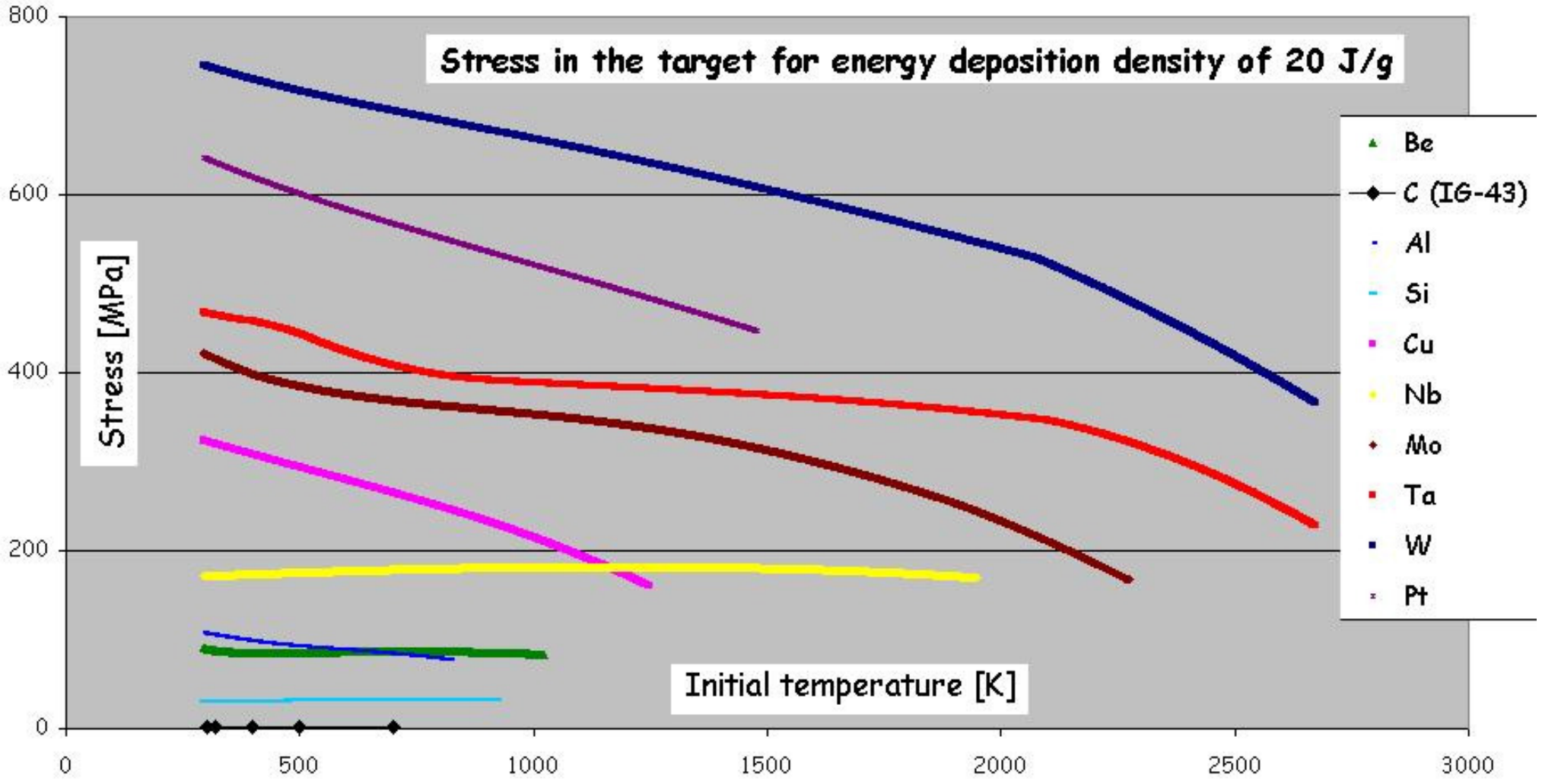
**The main issue for the materials (solids) used in the target systems (targets, beam windows, beam dumps, the pipes for contained liquid/powder jets, etc.) is the magnitude and the rate of change of deposited energy density.**

## Thermal Stress ~ $\alpha E \Delta T/(1-\nu)$ $\Delta T = EDD/Cp$



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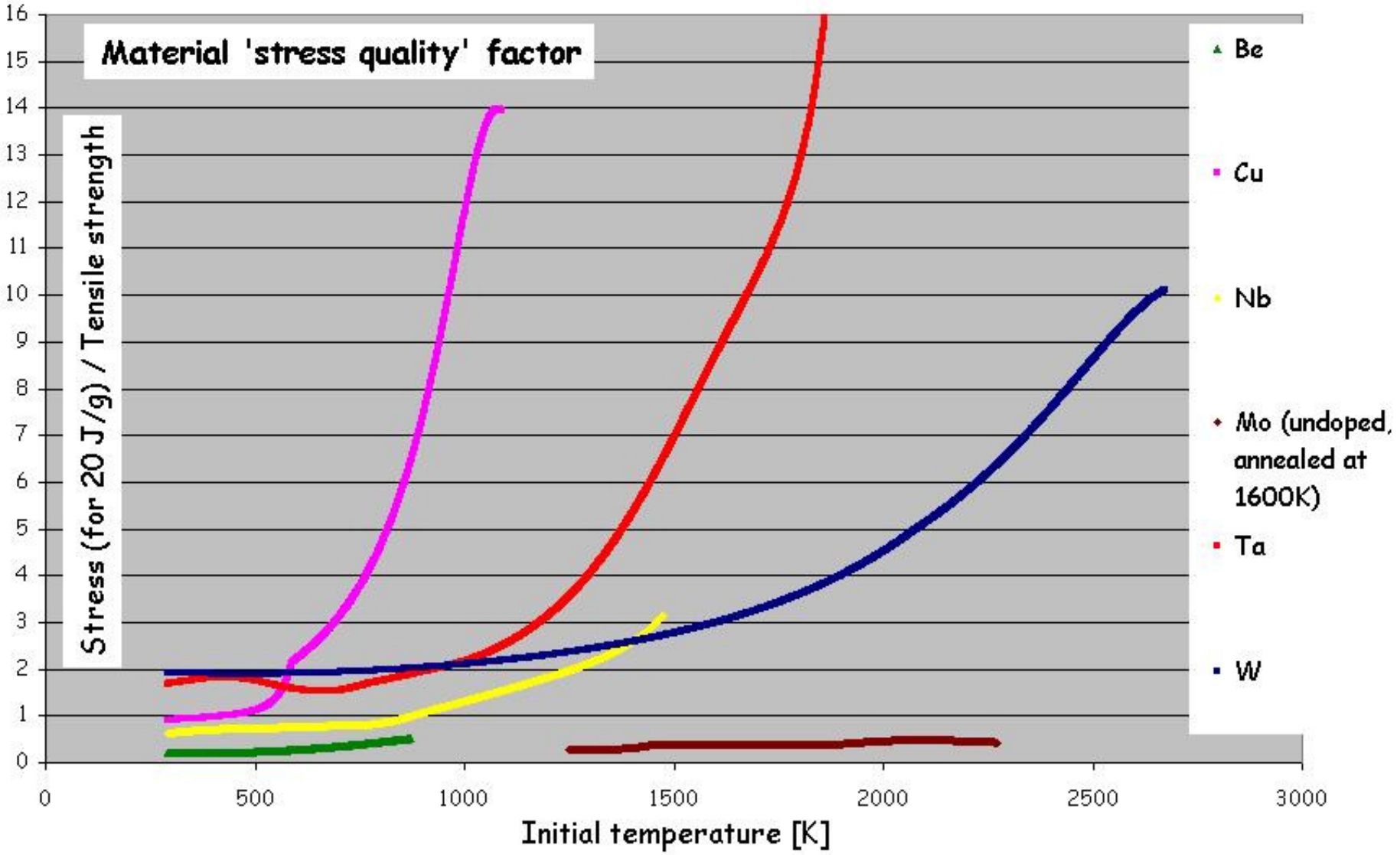
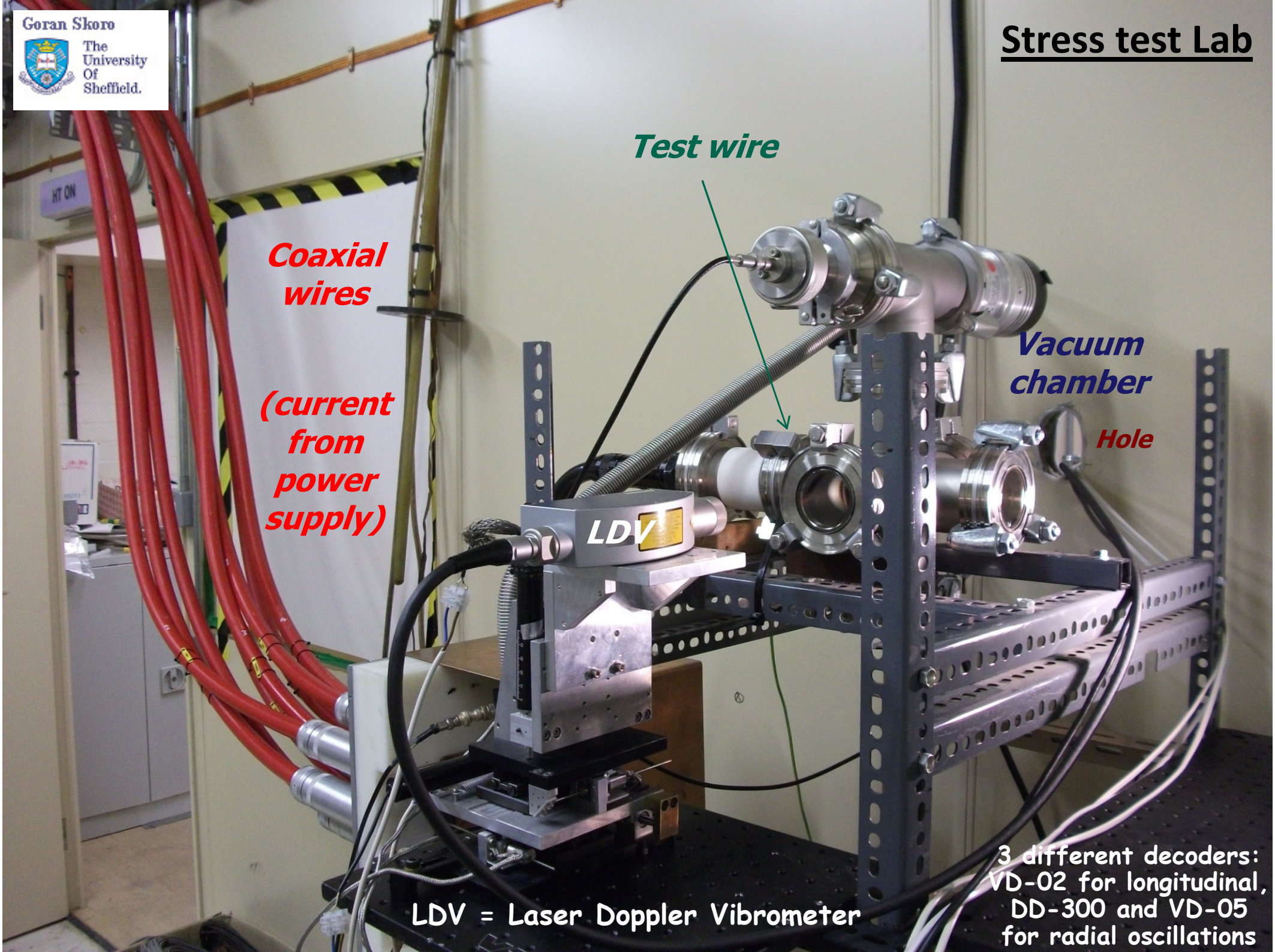



**As the beam power increases, and the beam pulse length decreases, the estimate of material strength and corresponding lifetime based on simple, quasi-static equations is no longer accurate. In these cases the materials are tested dynamically and they behave differently than under quasi-static loading.**

**In order to address this problem the fundamental material properties and corresponding strength have to be measured under dynamic conditions.**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Stress test Lab
Test wire
Coaxial wires
(current from power supply)
Vacuum chamber
Hole
LDV
LDV = Laser Doppler Vibrometer
3 different decoders:
VD-02 for longitudinal,
DD-300 and VD-05
for radial oscillations

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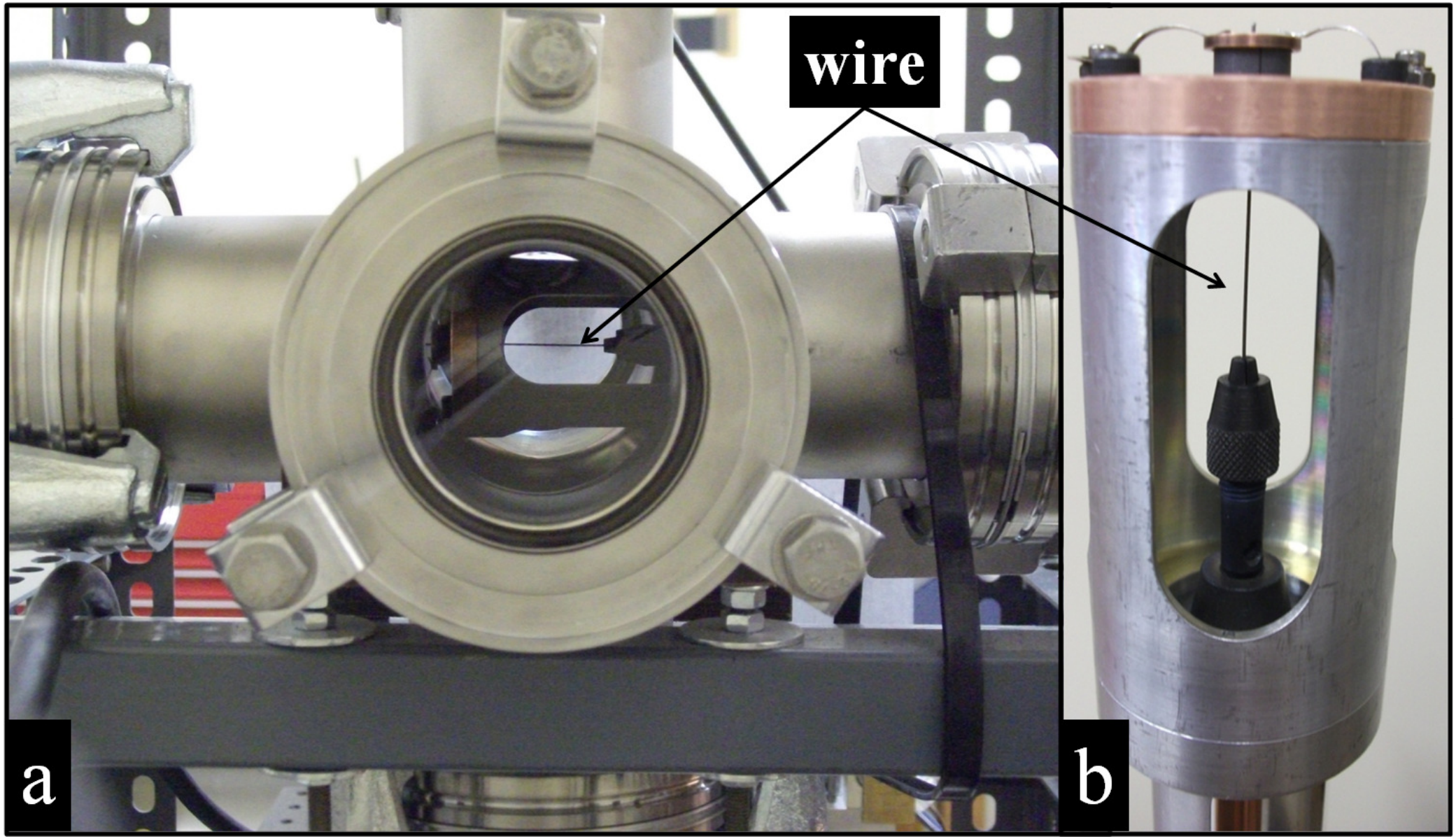
# Current pulse – wire tests at RAL



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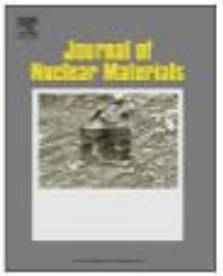

# Dynamic Young's moduli of tungsten and tantalum at high temperature and stress ☆

G.P. Škoro [a,*], J.R.J. Bennett [b], T.R. Edgecock [b,c], S.A. Gray [b], A.J. McFarland [b], C.N. Booth [a], K.J. Rodgers [b], J.J. Back [d]

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[b] STFC, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK
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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 $s^{-1}$) and very high temperatures (up to 2650 °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 °C.

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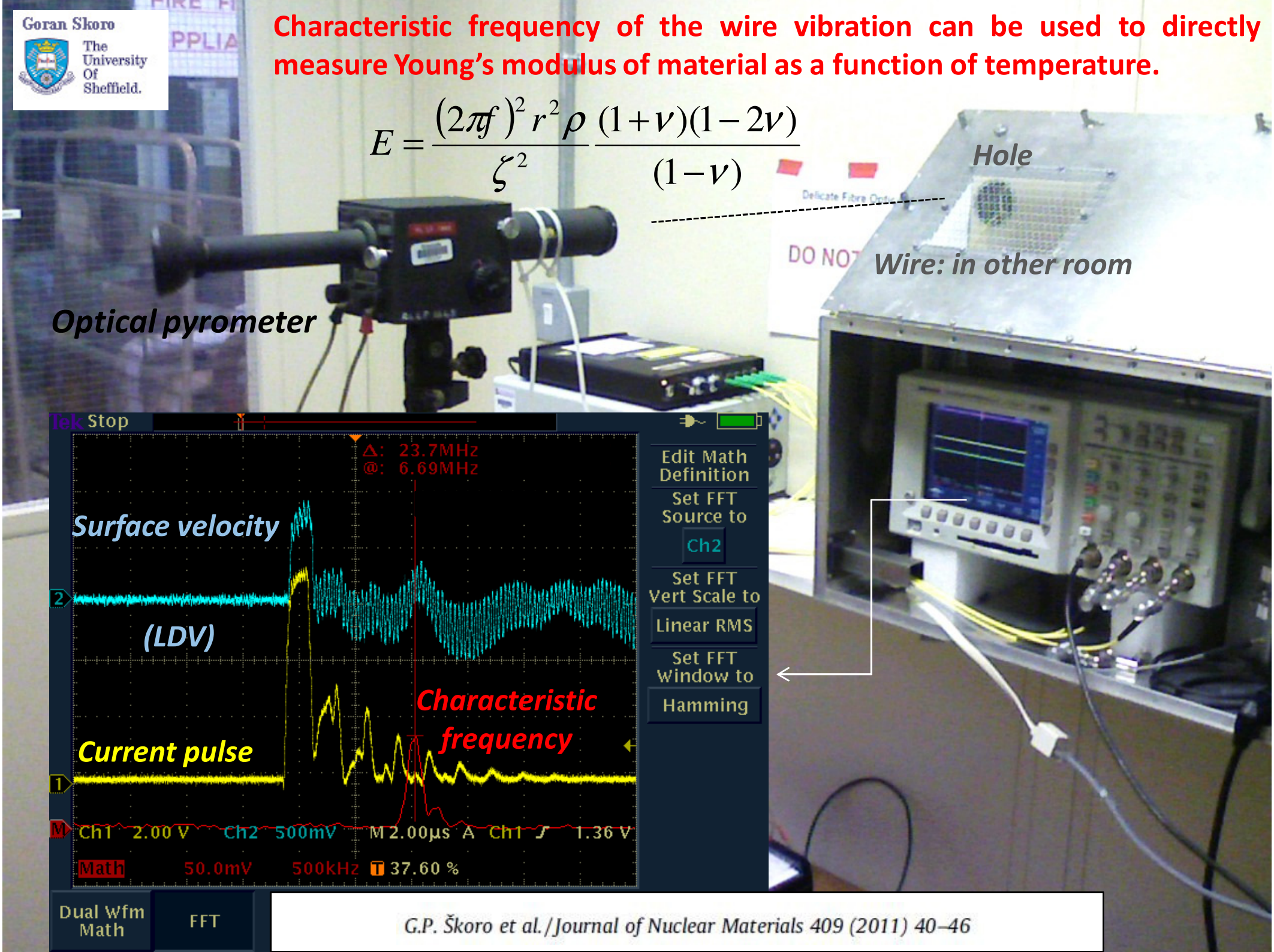
**Characteristic frequency of the wire vibration can be used to directly measure Young's modulus of material as a function of temperature.**

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




G.P. Škoro et al./Journal of Nuclear Materials 409 (2011) 40–46

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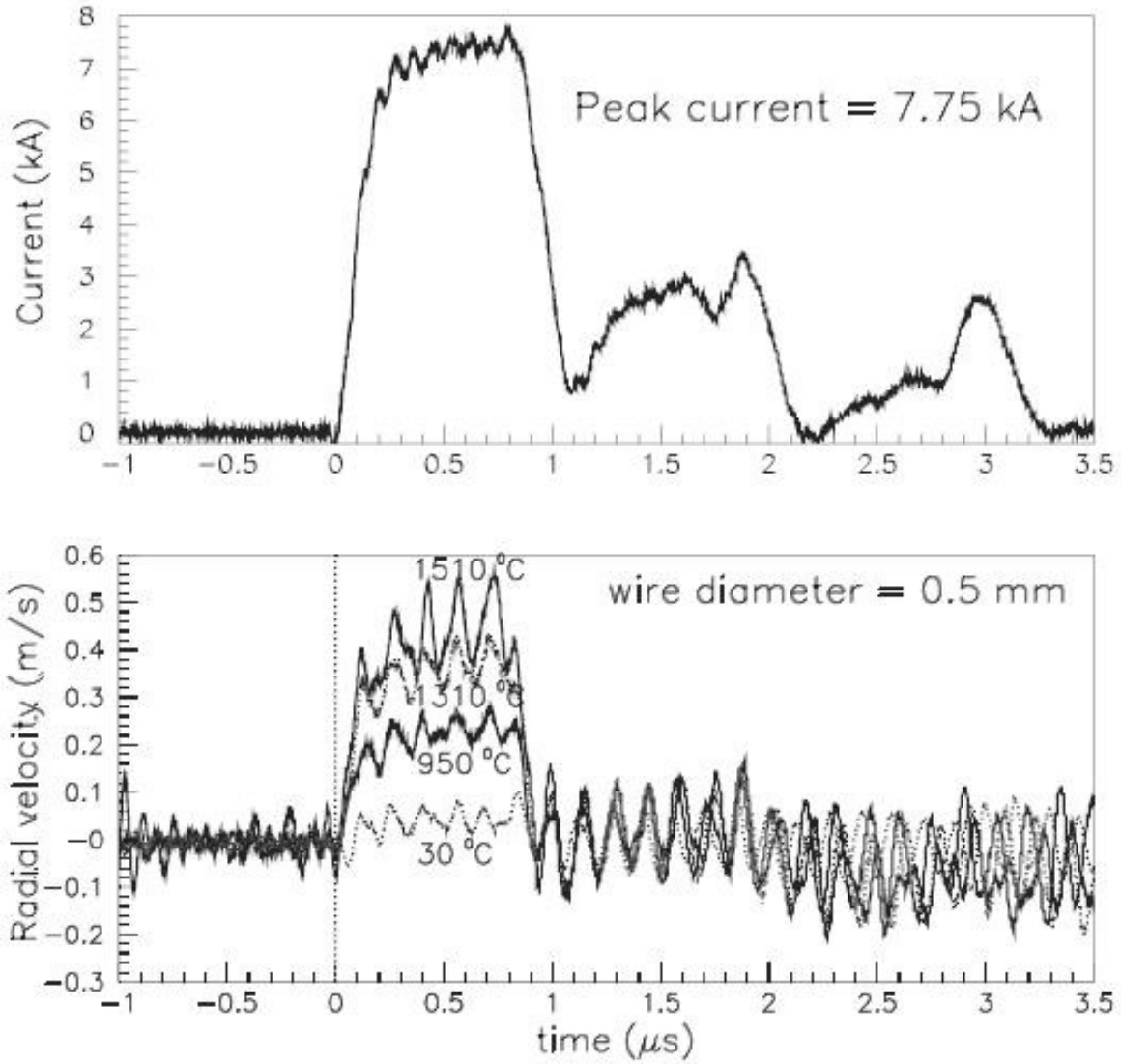


**Fig. 7.** (Top) The current pulse shape; (bottom) measured radial velocity of the 0.5 mm diameter tungsten wire as a function of time at different temperatures.

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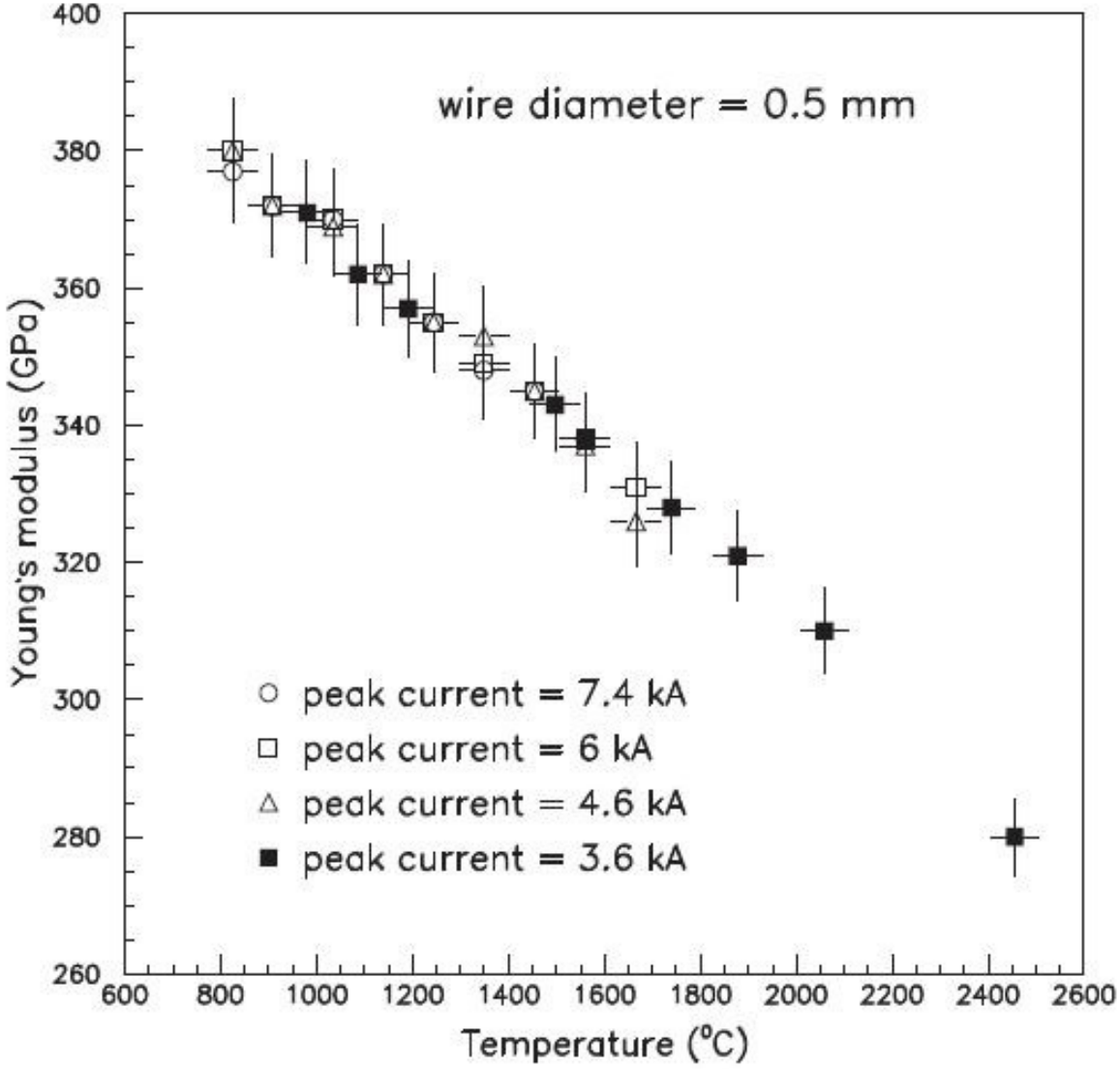


**Fig. 8.** Young's modulus of a 0.5 mm diameter tungsten wire as a function of temperature for four different peak currents.

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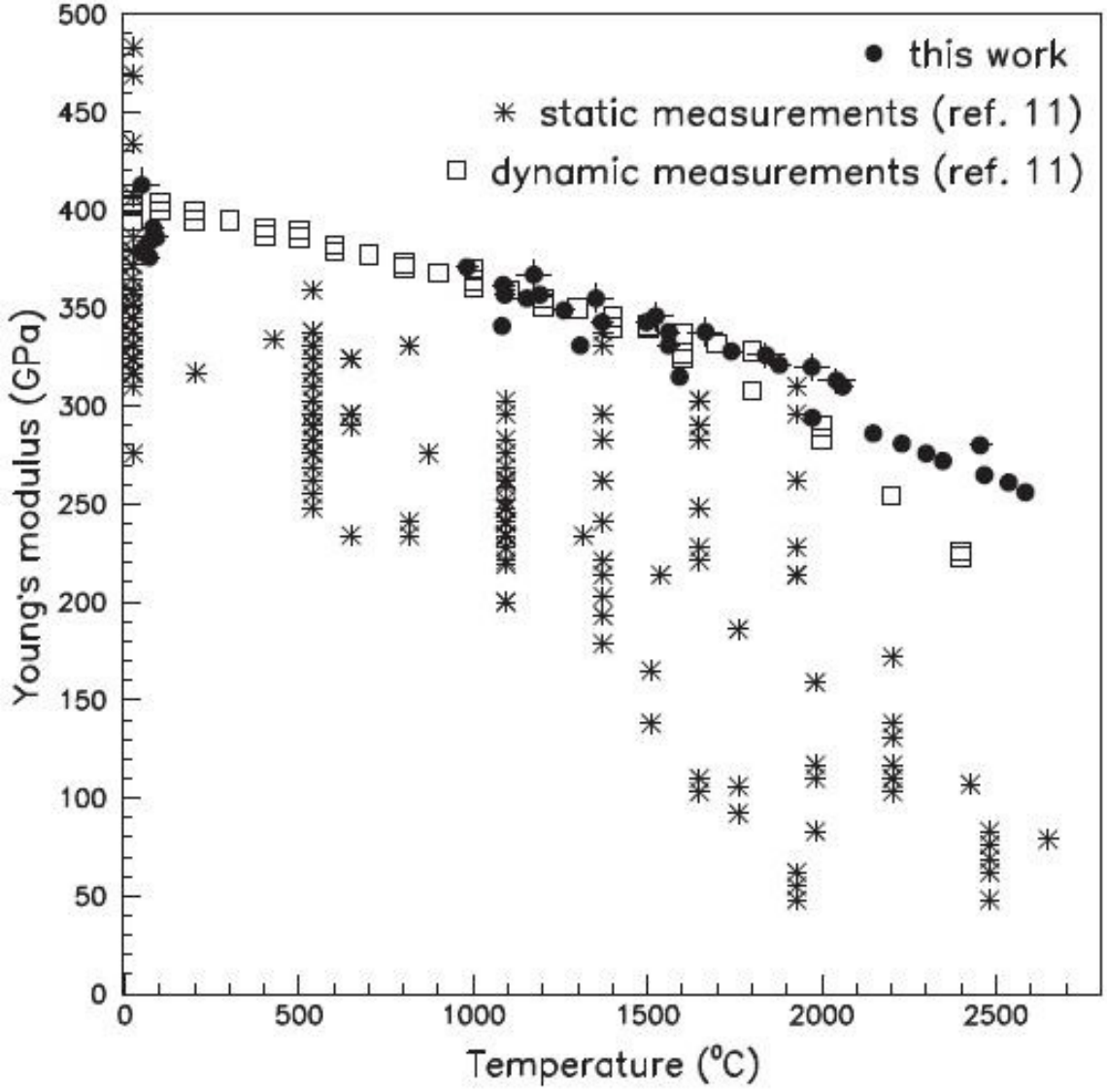


**Fig. 10.** Comparison between our experimental results and previous results [11] on tungsten Young's modulus.

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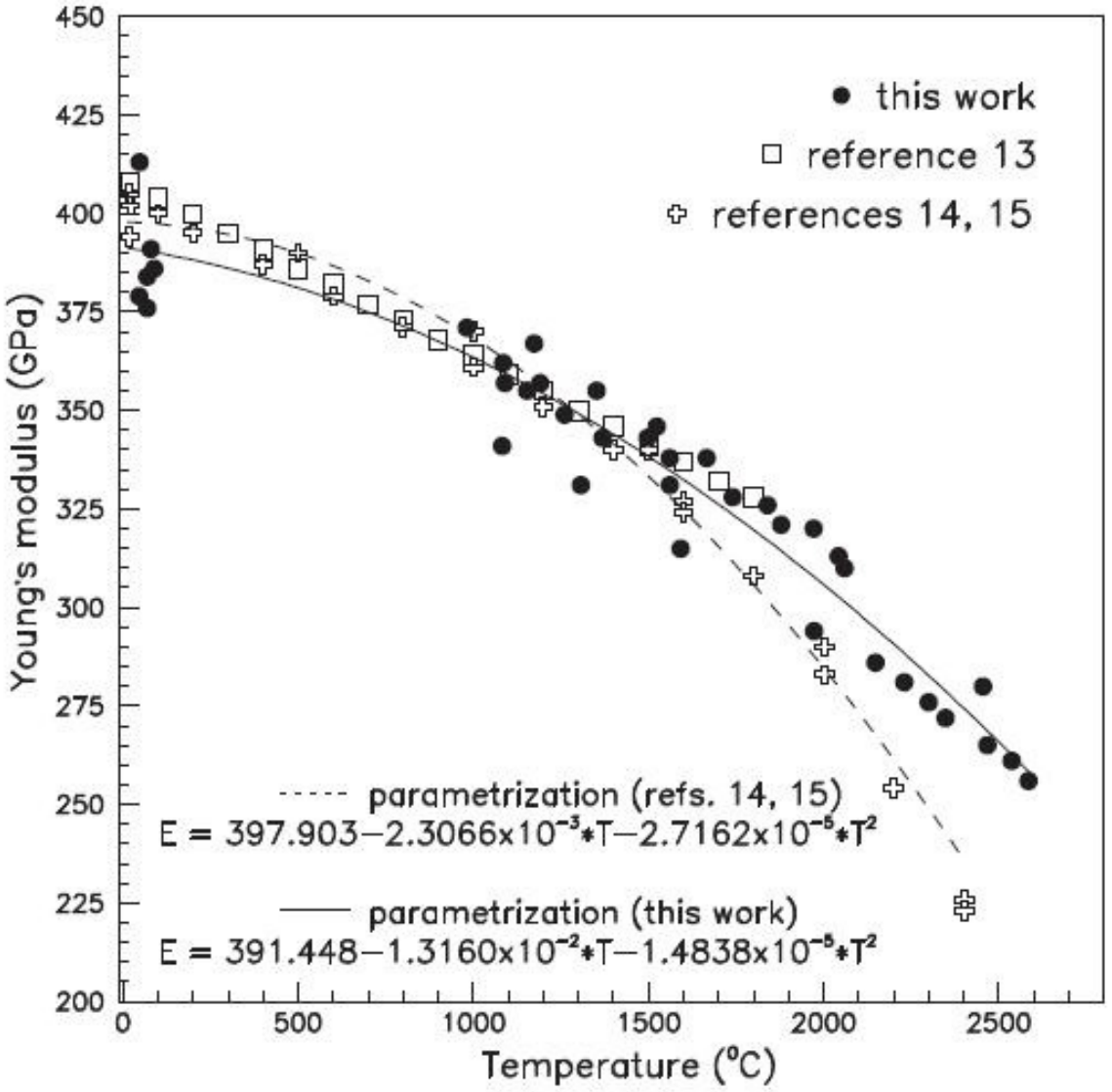


**Fig. 12.** Comparison between these experimental results and previous results of dynamic measurements [13–15] of Young's modulus for tungsten.

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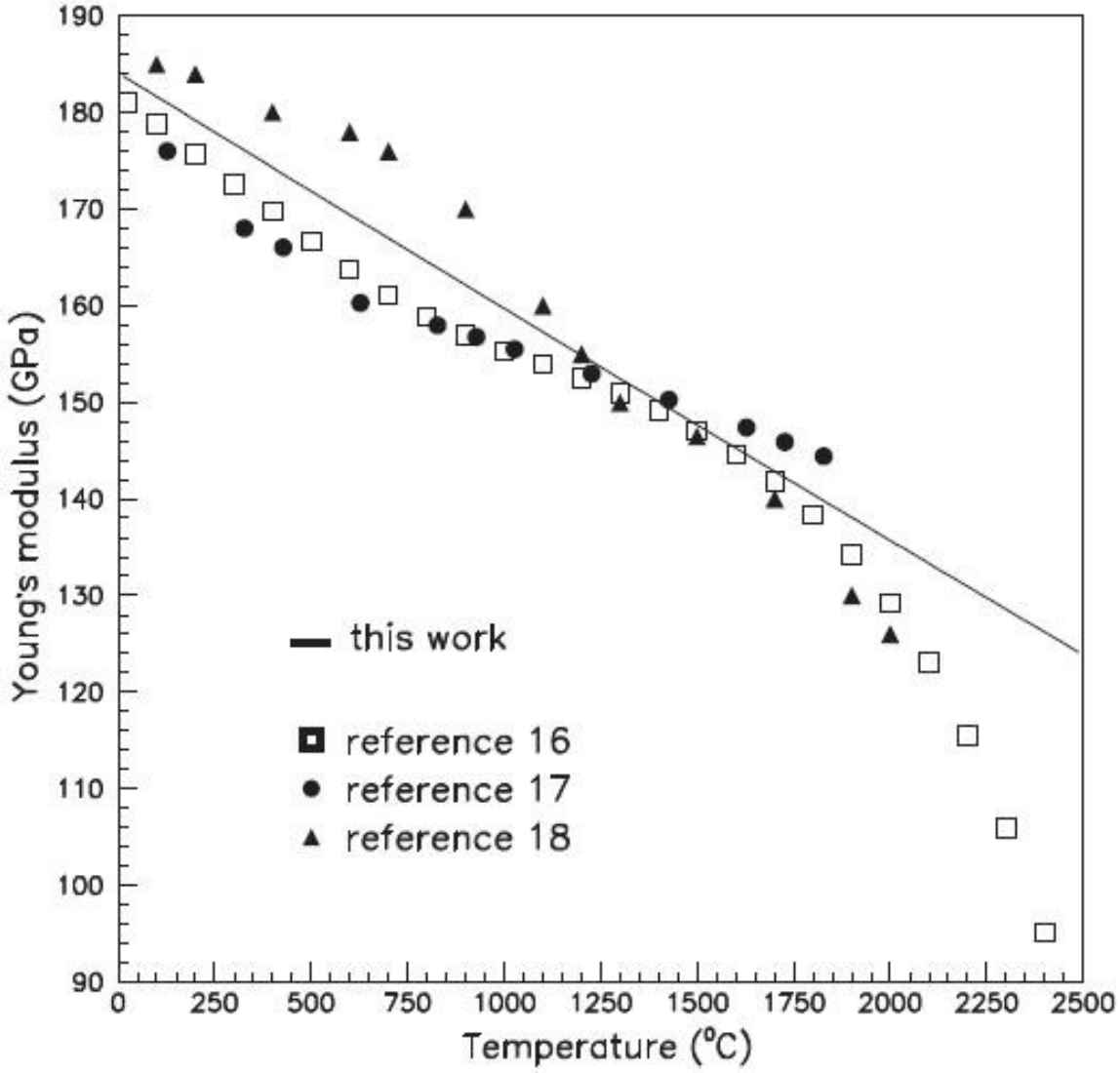


**Fig. 13.** Comparison between the new experimental data and previous results [16–18] on tantalum Young's modulus.

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# Lifetime and strength tests of tantalum and tungsten under thermal shock for a Neutrino Factory target

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Tantalum
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Thermal shock
Material strength
Target lifetime
Neutrino Factory

ABSTRACT

A description of tests on tantalum and tungsten wires to evaluate their lifetime and strength under the thermal shock that will be experienced when a solid target is bombarded with short pulses of high energy protons in a Neutrino Factory is given. The results of lifetime tests and measurements of dynamic strength characteristics at high temperatures, stresses and strain rates using a laser Doppler vibrometer are given. The tests show that a solid tungsten target will have a life of at least 3 years, which, with other beneficial characteristics, make it an excellent candidate for the Neutrino Factory.

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CORRECTED PROOF

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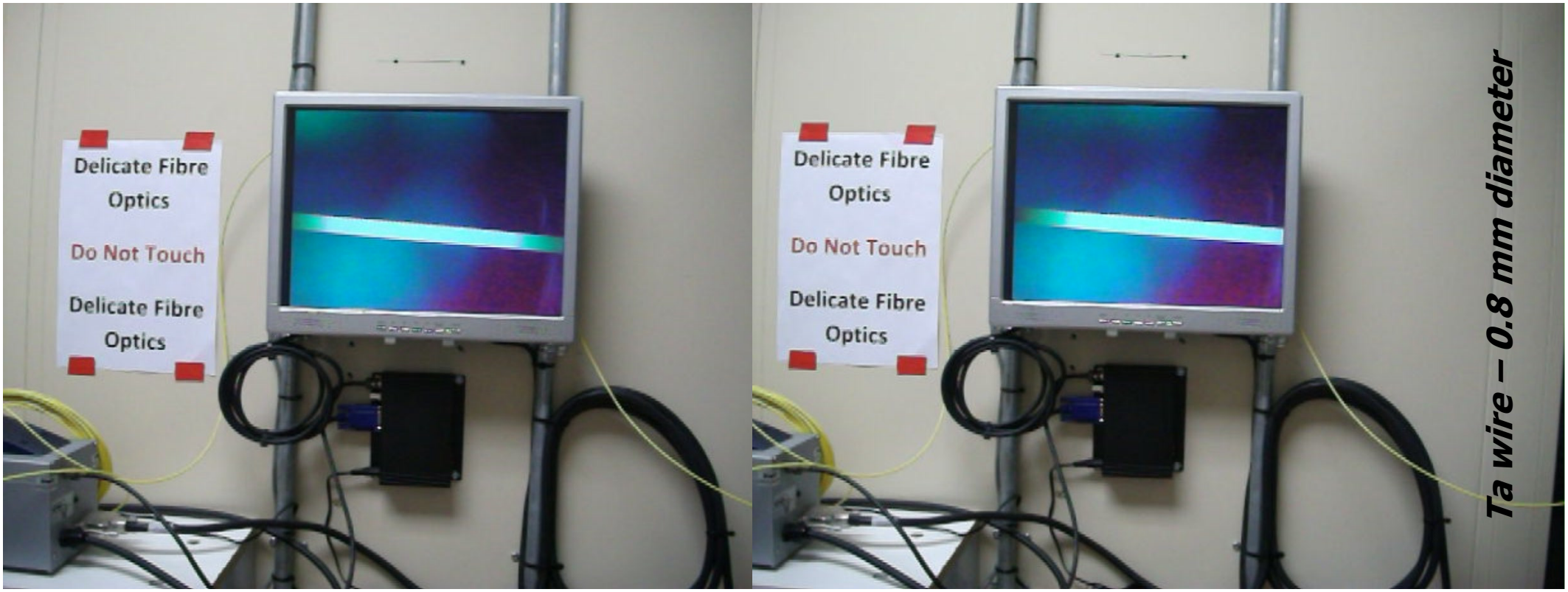
# Direct measurements of material strength

**35 kV** **45 kV**




**~ 1000 °C**

J.R.J. Bennett, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.03.036

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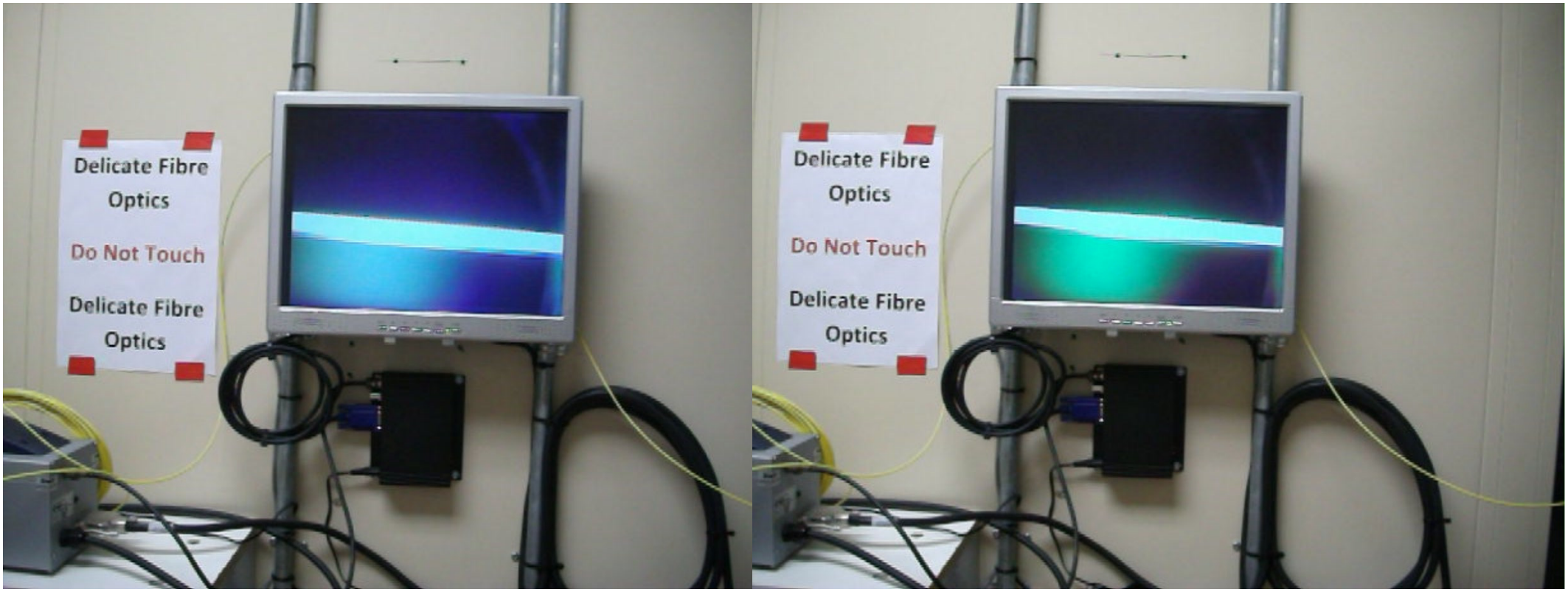
# Direct measurements of material strength

**35 kV** **45 kV**




**~ 1400 °C**

J.R.J. Bennett, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.03.036

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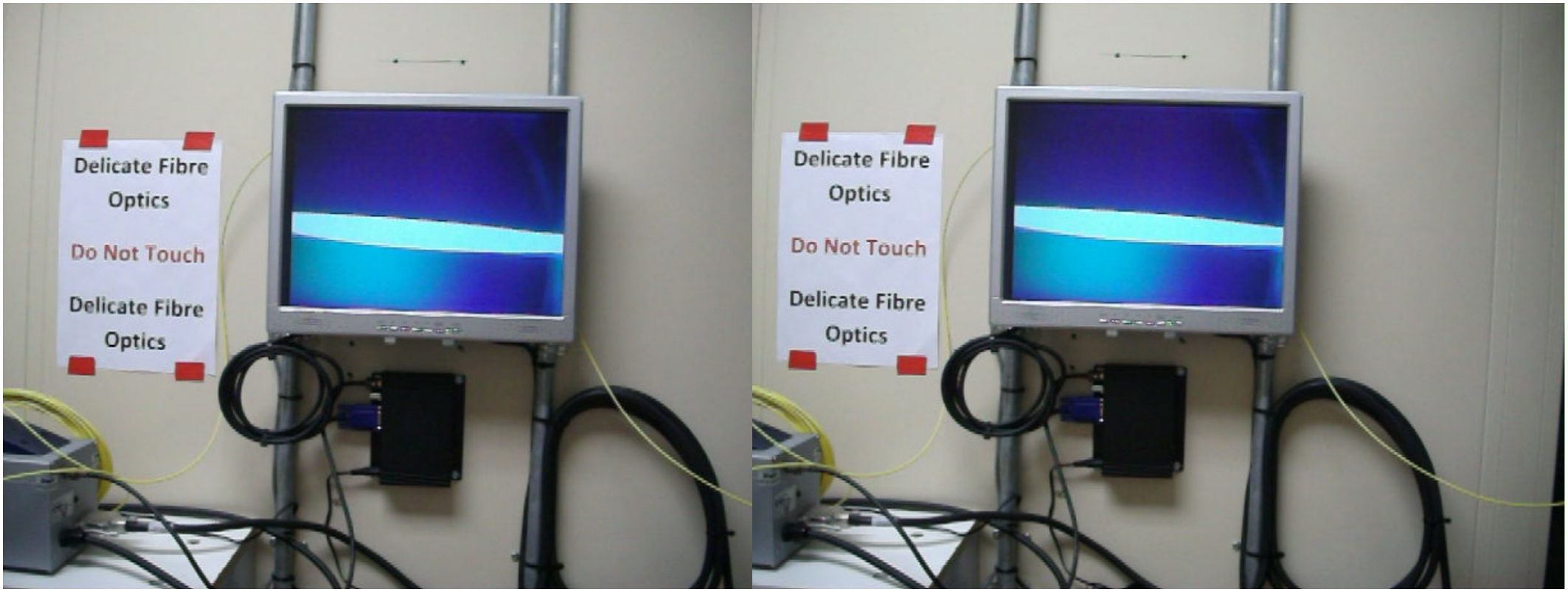
# Direct measurements of material strength

**35 kV** **45 kV**




**~ 1800 °C**

J.R.J. Bennett, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.03.036

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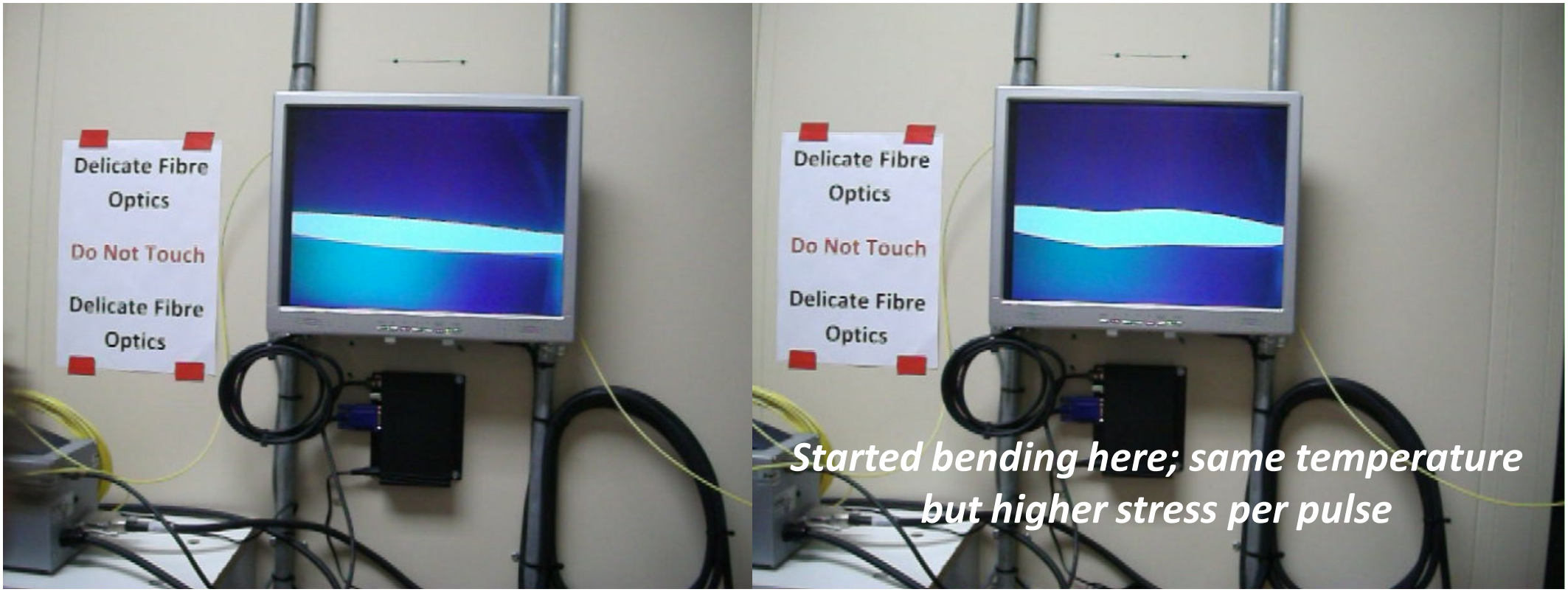
# Direct measurements of material strength

**35 kV** **45 kV**




**~ 2100 °C**

J.R.J. Bennett, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.03.036

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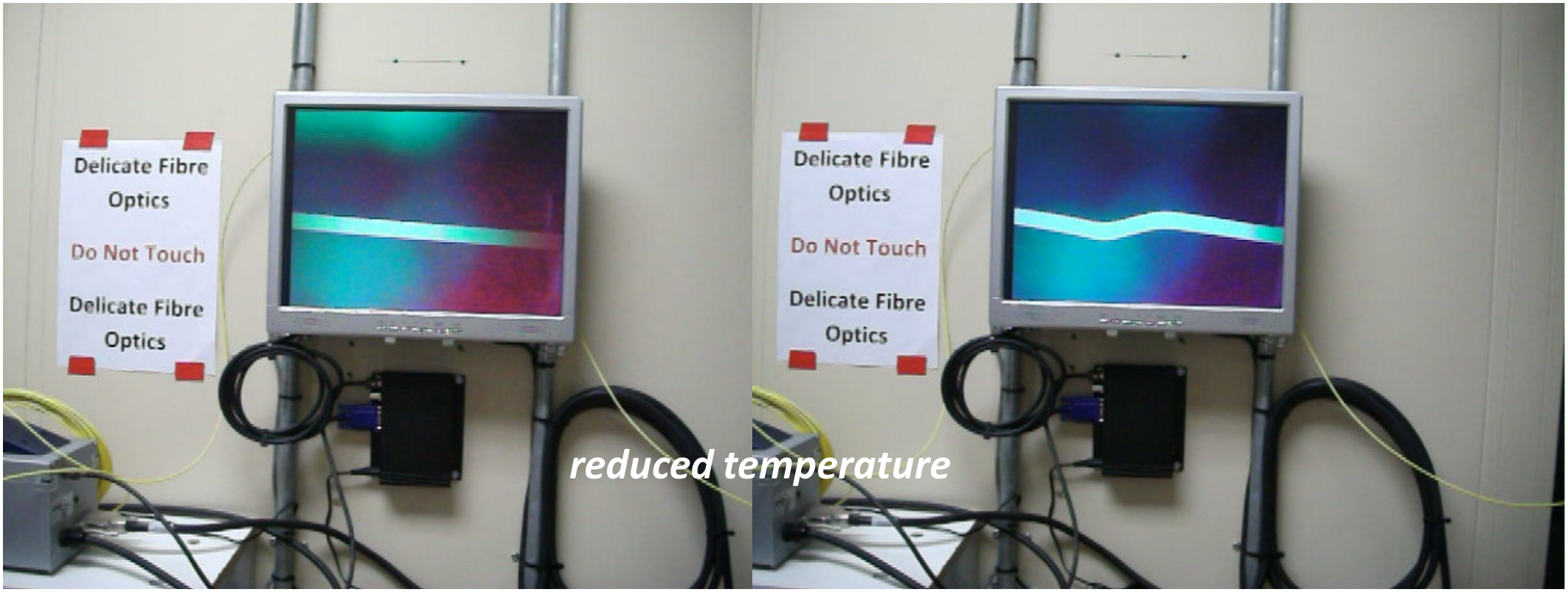
# Direct measurements of material strength

**35 kV** **45 kV**




**Plastic deformation: stress is bigger than yield strength of tantalum**

**LS-DYNA was used to calculate stress in the wire per pulse…**

J.R.J. Bennett, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.03.036

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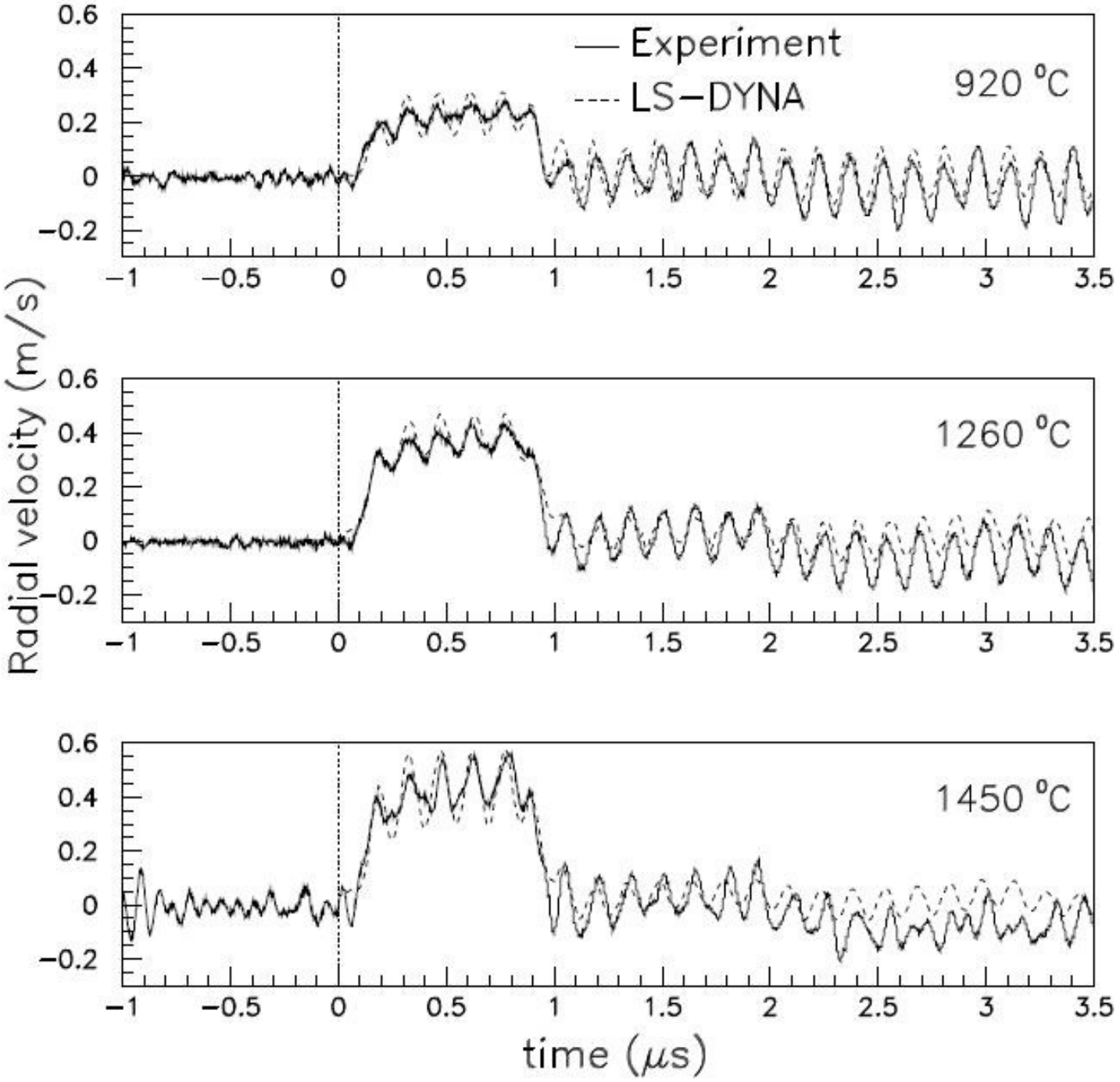


Figure 1. The measured and calculated radial velocity of a 0.5 mm diameter tungsten wire at peak temperatures of 920, 1260 and 1450$^0$C [5].

J.R.J. Bennett, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.03.036

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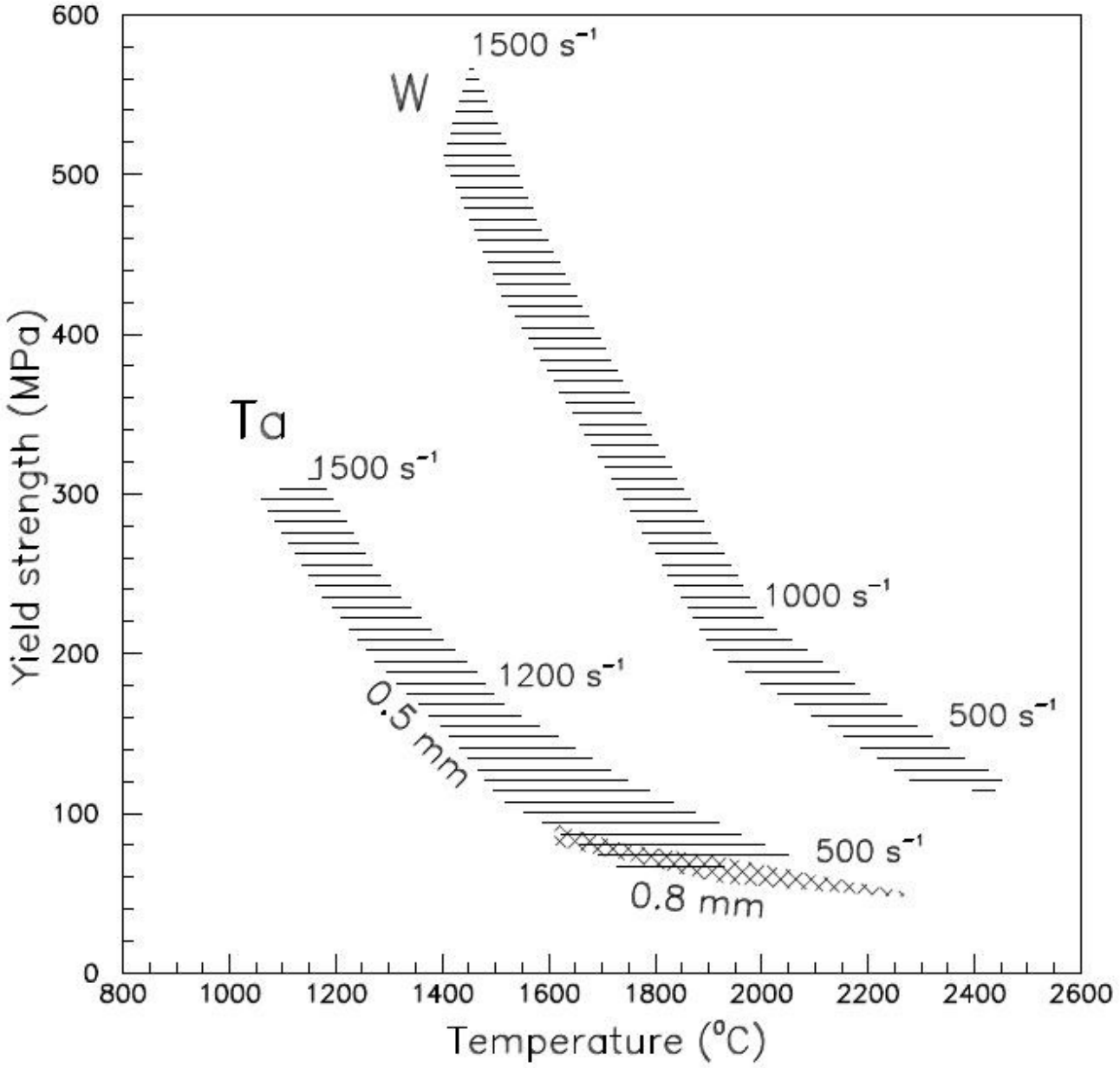


Figure 2. The yield strength versus peak temperature for tantalum wires of 0.5 and 0.8 mm diameter and for tungsten wires of 0.5 mm diameter [5]. The upper edge of the bands indicates the stress at which the wire started to bend and the lower edge indicates where the wire was not deformed. The characteristic strain rate values are indicated.

J.R.J. Bennett, et al., Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.03.036

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# Experimental results and constitutive modelling for tungsten and tantalum at high strain rates and very high temperatures☆

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[b]*STFC, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK*
[c]*University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK*

**Abstract**

Recently reported results of the high strain rates, high temperature measurements of the yield stress of tungsten and tantalum have been analyzed. The highest temperature reached in the experiment, based on heating and stressing a thin wire by a fast, high current pulse, was 2250 $^0$C and 2450 $^0$C, for tantalum and tungsten, respectively. The strain-rates in both the tungsten and tantalum tests were in the range from 500 to 1500 $s^{-1}$. The parameters for the constitutive equation developed by Zerilli and Armstrong have been determined from the experimental data and the results have been compared with the data obtained at lower temperatures.

*Keywords:* tungsten, tantalum, yield strength, high temperature, high strain rate

*Preprint submitted to Mechanics of Materials*

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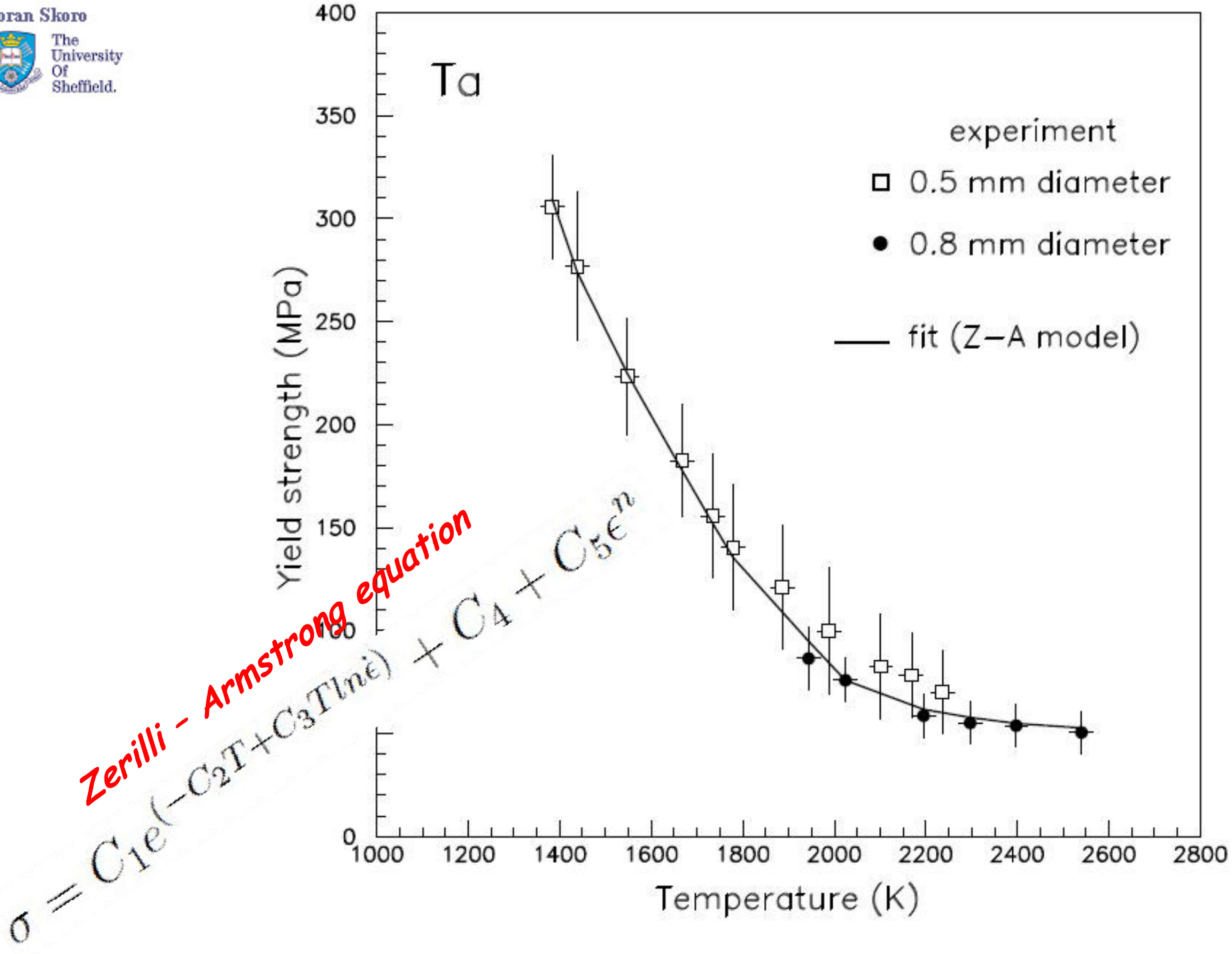


Figure 3. Experimental data on tantalum yield strength and the best fit based on Z&A model.

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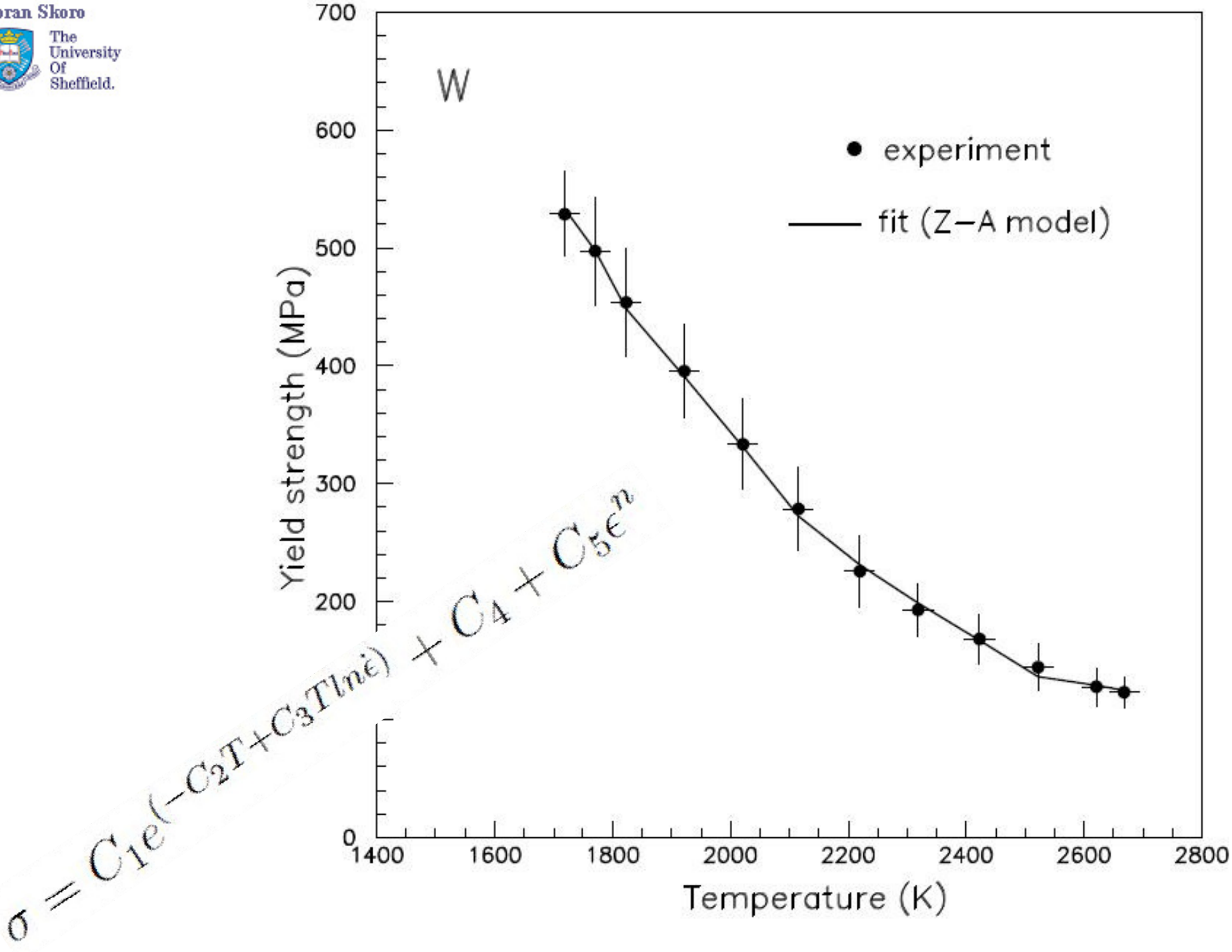


Figure 4. Experimental data on tungsten yield strength and the best fit based on Z&A model.

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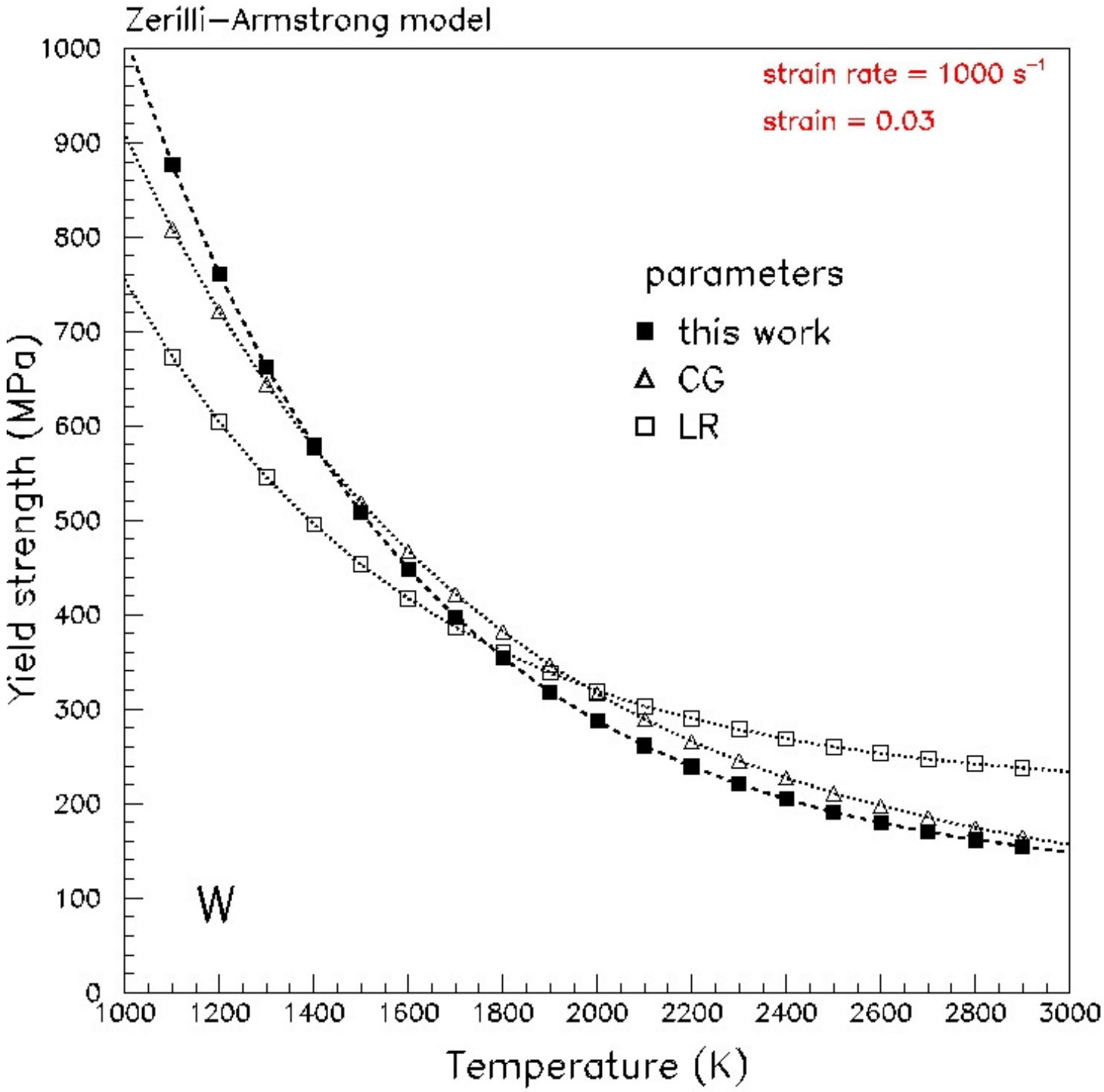


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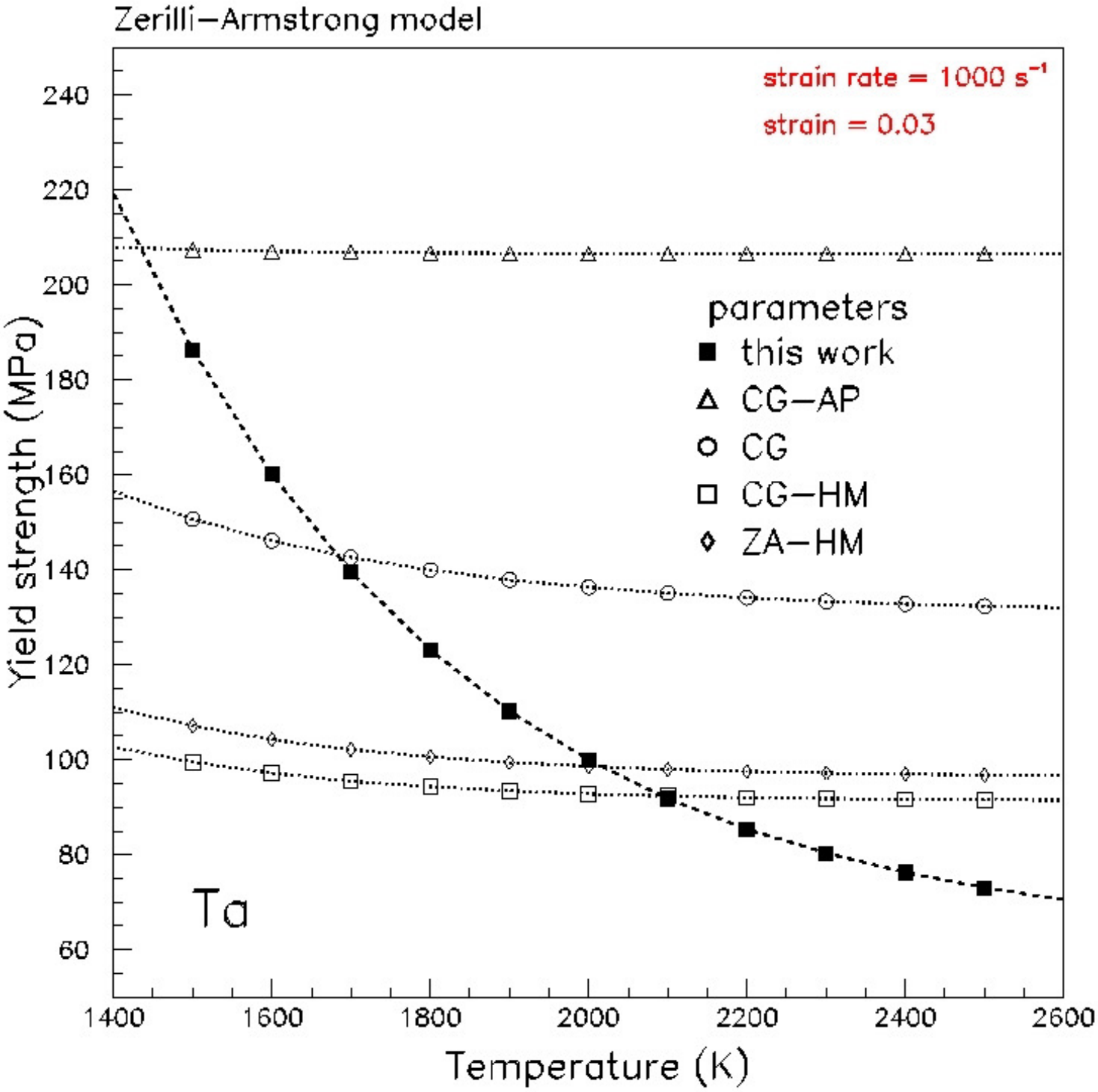


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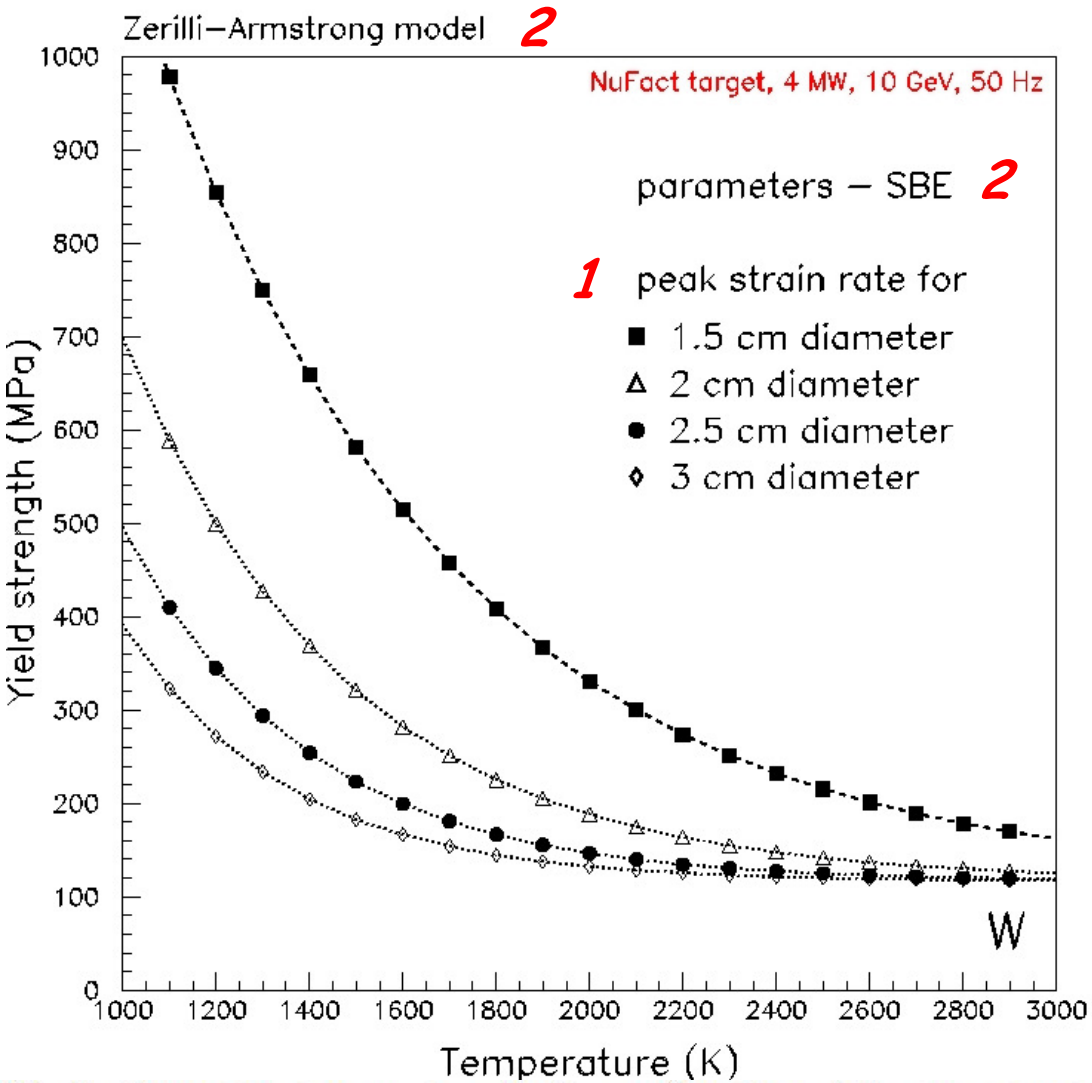


***Application(s):***

***Solid (W) Neutrino Factory target***

Table 2. Operating temperature limit as a function of the tungsten target diameter (Z-A model; ŠBE parameters).

| diameter [cm] | peak stress [MPa] 1 | Temperature [$^0$C] | Temperature [$^0$C] (safety factor = 1.5) |
|---|---|---|---|
| 1.5 | 540 | 1285 | 960 |
| 2 | 300 | 1285 | 980 |
| 2.5 | 192 | 1360 | 1040 |
| 3 | 140 | 1550 | 1090 |

**OR...**

PAUL S. FOLLANSBEE

# Analysis of Deformation Kinetics in Seven Body-Centered-Cubic Pure Metals Using a Two-Obstacle Model

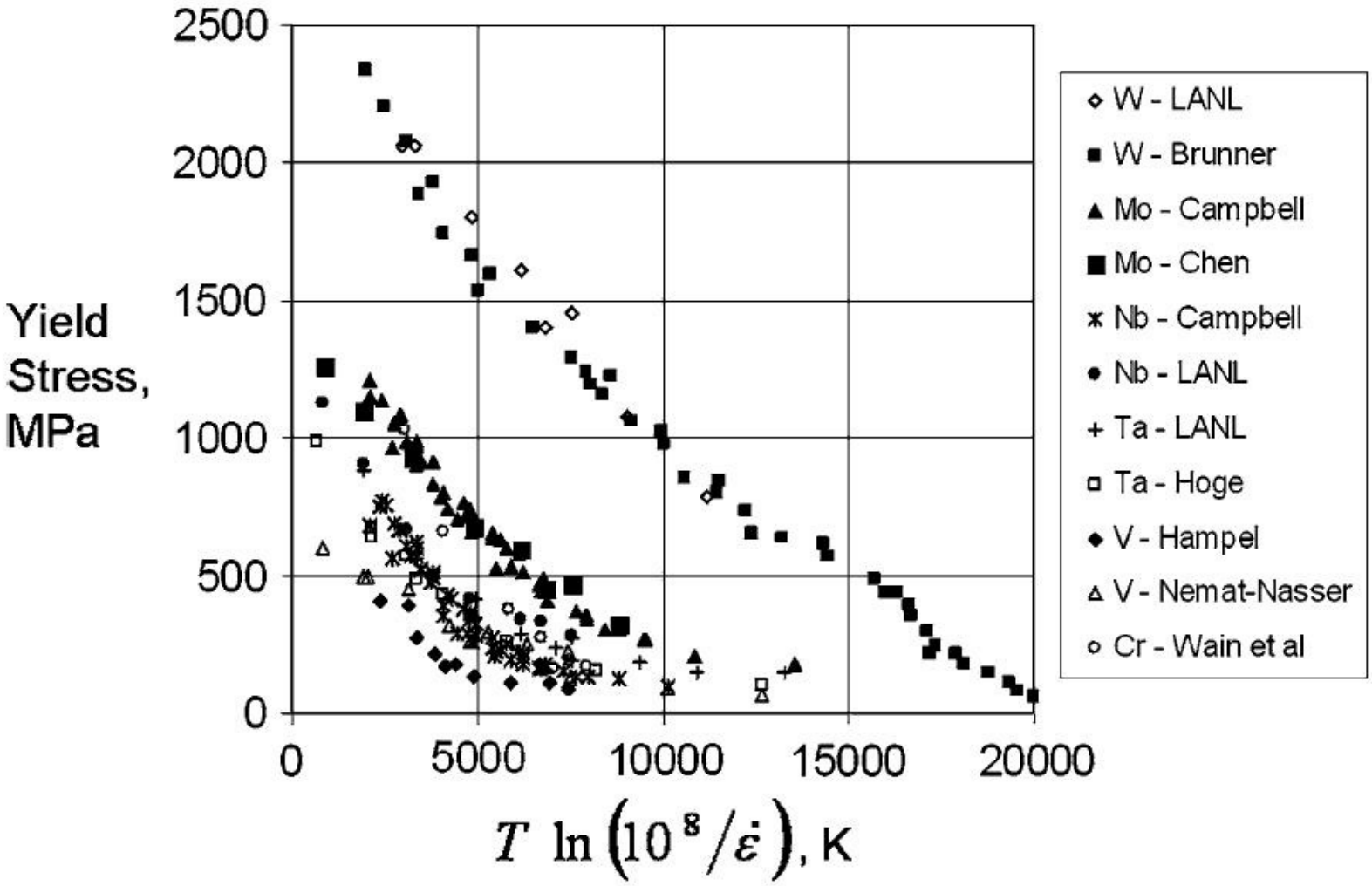


Figure 1 shows raw data for W, Mo, Nb, Ta, V, and Cr, and Figure 2 shows the data set for Fe considered here. The yield stress in both figures is plotted against

$$T \ln(\dot{\varepsilon}_0/\dot{\varepsilon}) \qquad [1]$$

which is a commonly used combination of temperature, $T$, and strain rate, $\dot{\varepsilon}$, for thermally activated processes. For all of the data, a value of $\dot{\varepsilon}_0 = 10^8\ s^{-1}$ is used.

When plotted according to Eq. [1], several common features emerge. First, most of the data sets (excluding W and Cr) show a curvature characterized by a decreasingly negative slope with increasing values of the abscissa. Second, at low values of the abscissa in some metals (*e.g.*, Fe), there appears to be a maximum (saturation) stress observed with no temperature dependence as temperature is further decreased or strain rate increased.

This latter behavior has been attributed to the initiation of deformation twinning.[23,30,31] These data points will not be included in the analysis presented here.

Included in many of the references in Tables I and II is model analysis. The common approach is to seek a single thermally activated process represented by an expression that is a variant of $\sigma \propto T \ln(\dot{\varepsilon}_0/\dot{\varepsilon})$.[16,24] Others have recognized the two extreme behaviors (low $T$ and high $\dot{\varepsilon}$ *vs* high $T$ and low $\dot{\varepsilon}$) and have proposed separate deformation mechanisms active in these regimes.[15] The model presented subsequently does not differ significantly from these approaches, although it does attempt to recognize the coexistence of two distinct obstacles restricting dislocation motion and contributing to defining the resulting deformation kinetics over a wide range of conditions.

METALLURGICAL AND MATERIALS TRANSACTIONS A
VOLUME 41A, DECEMBER 2010—3081

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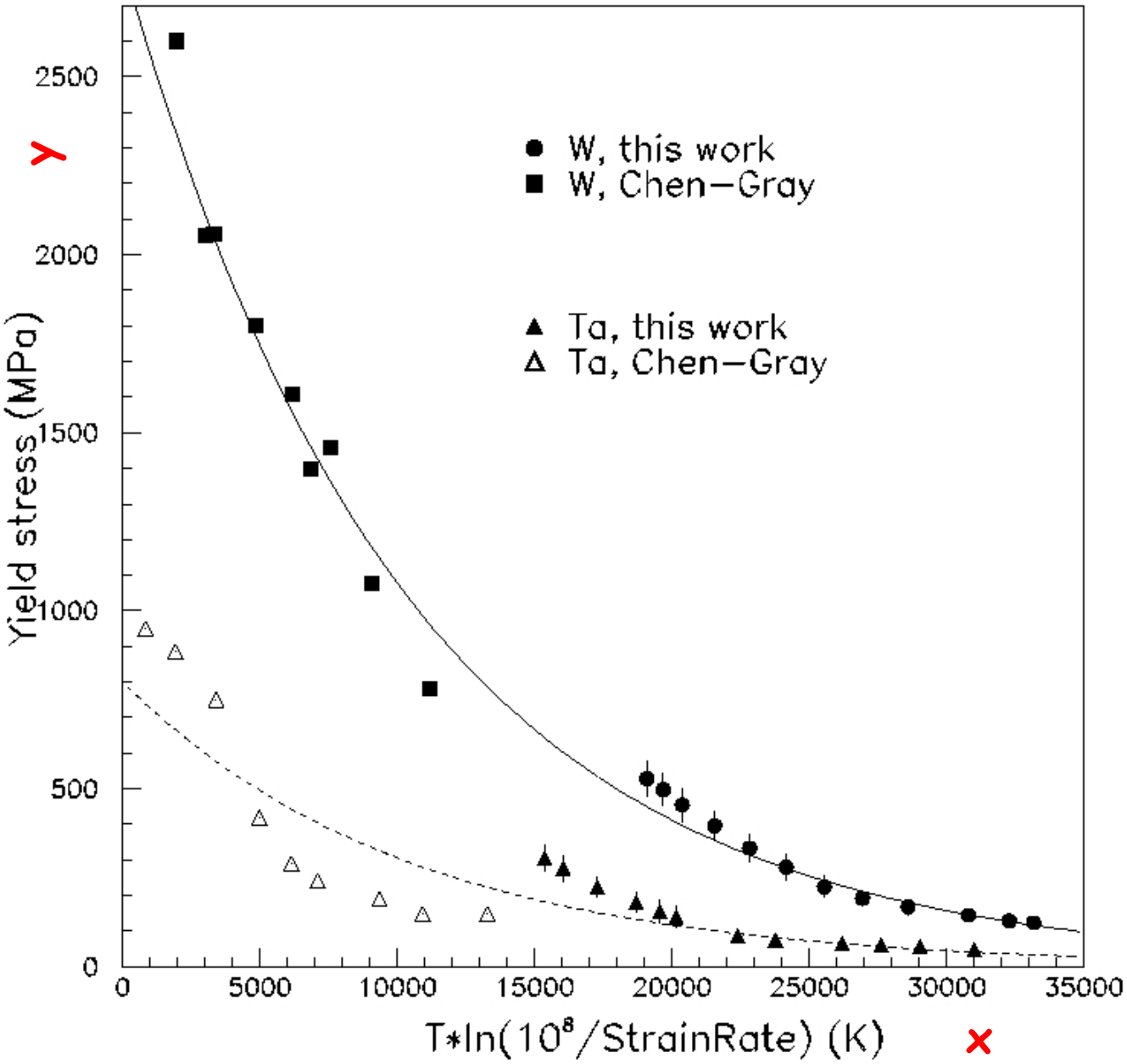
# Follansbee plot for W & Ta

## (our experimental data included)




**Fitting function:**

$y = a \bullet \exp(-bx)$

**Parameters:**

| | W | Ta |
|---|---|---|
| a | 2822 | 800 |
| b | $9.6 \times 10^{-5}$ | $9.6 \times 10^{-5}$ |

**OR...**

Constitutive Behavior of Tantalum and Tantalum-Tungsten Alloys

SHUH RONG CHEN and GEORGE T. GRAY III

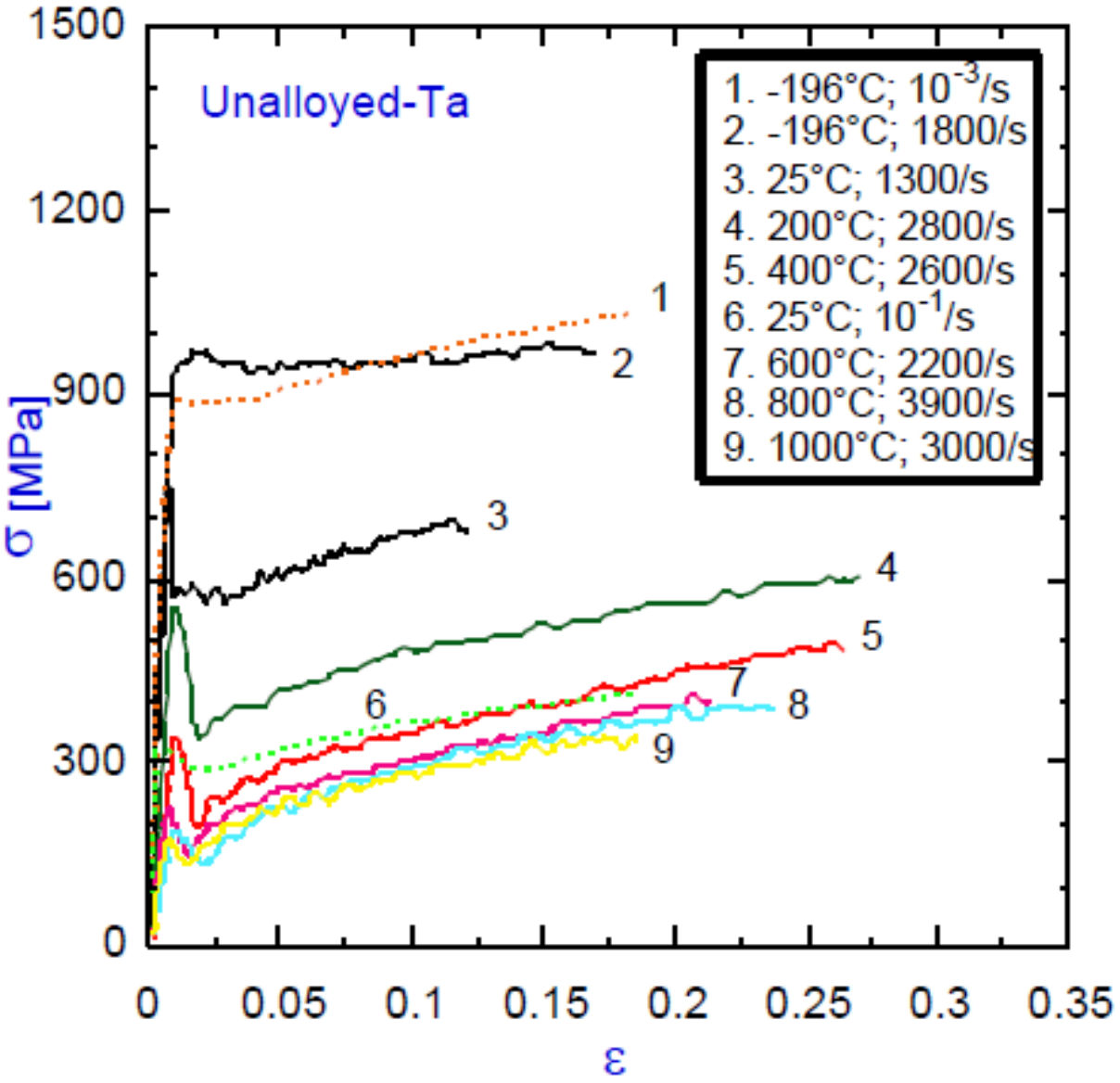



Fig. 3—Compressive stress-strain curves of the unalloyed tantalum under dynamic and quasi-static deformation at various temperatures.

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# OR...

## Contact us and we would be happy to test your sample !

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

*...not only high power targets*

*tungsten*

- new generation of `kinetic energy penetrators` (tungsten alloys)...