Tests Using
The "Little Wire Test" Equipment

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1. Fatigue Life of Tungsten at High Temperatures and High Strain Rates.
2. Fatigue Life of Tungsten at High Temperatures and Low Strain Rates (quasi-static).
3. Emissivity of Tungsten and Surface Roughness
4. Oxidation of Tungsten at High Temperatures

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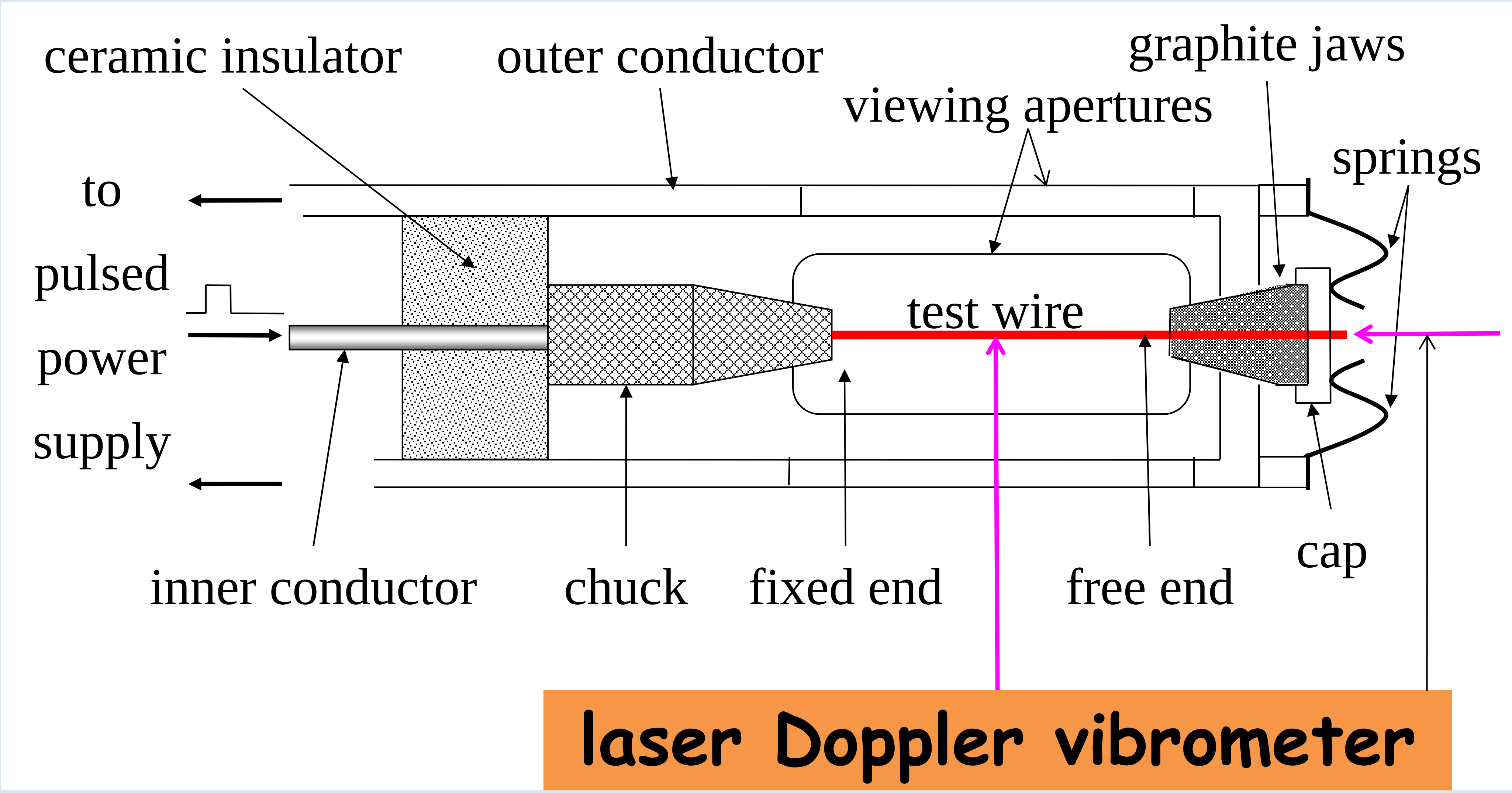
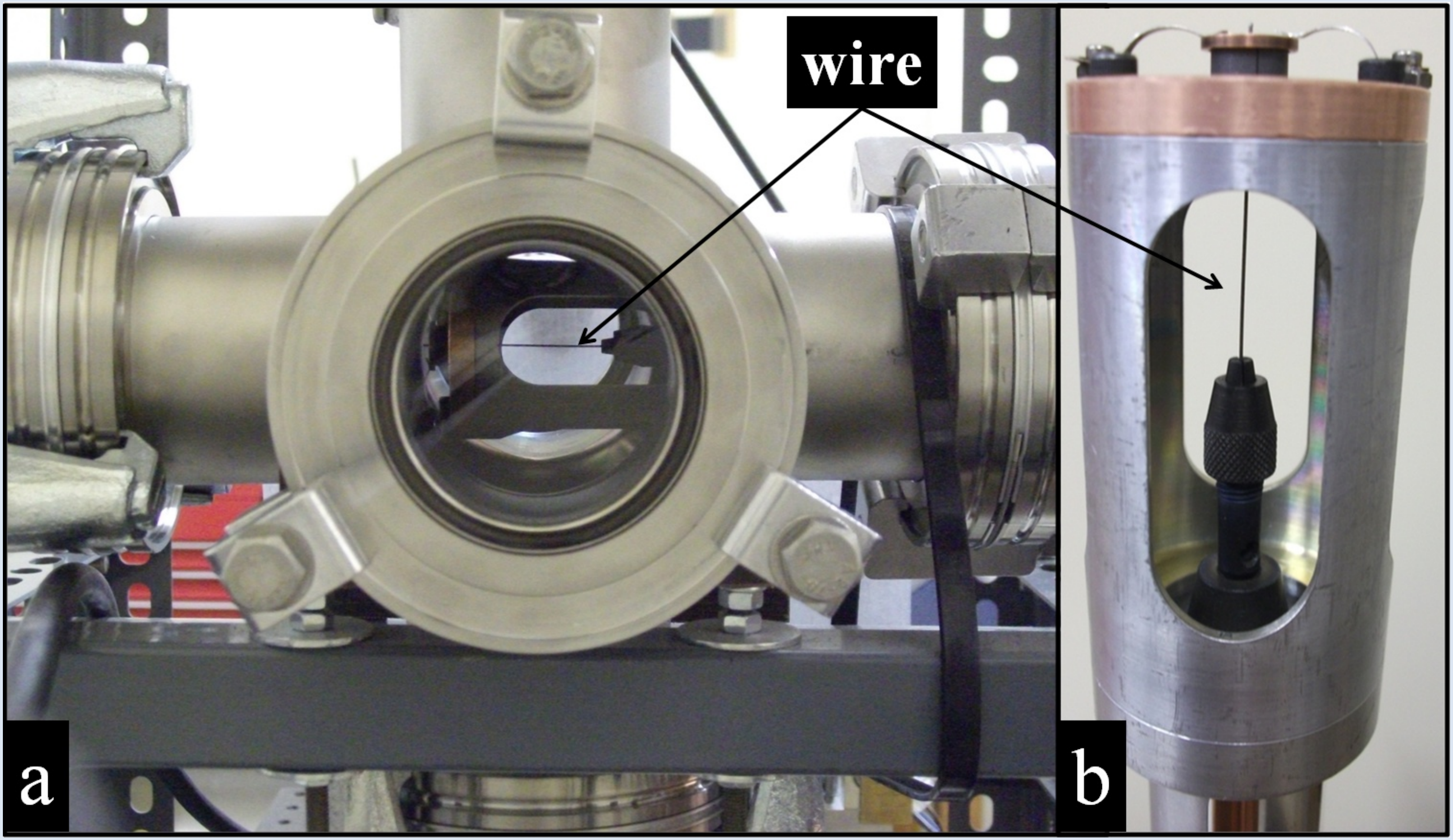
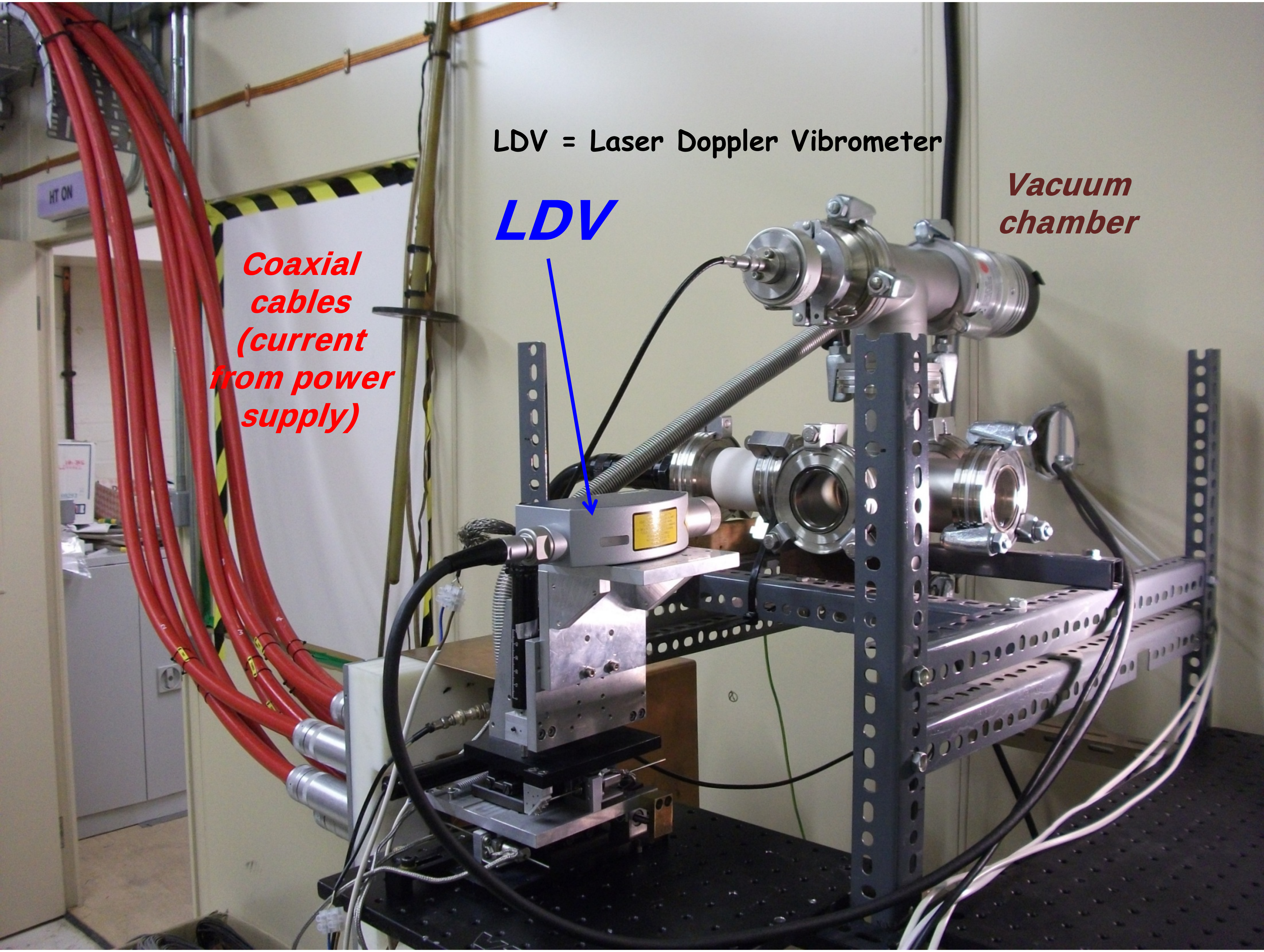
Schematic diagram of "The Little Wire"



"The Little Wire" Equipment




LDV = Laser Doppler Vibrometer
Vacuum chamber
LDV
Coaxial cables (current from power supply)
HT ON

Operating Principle

- Magnitude and frequency of wire oscillations measured using LDV
  - Characteristic frequency gives a direct measure of the **material Elastic Modulus**
  - Induced **dynamic stress** is calculated via LS-DYNA simulation and verified by cross-comparison with measured surface velocities

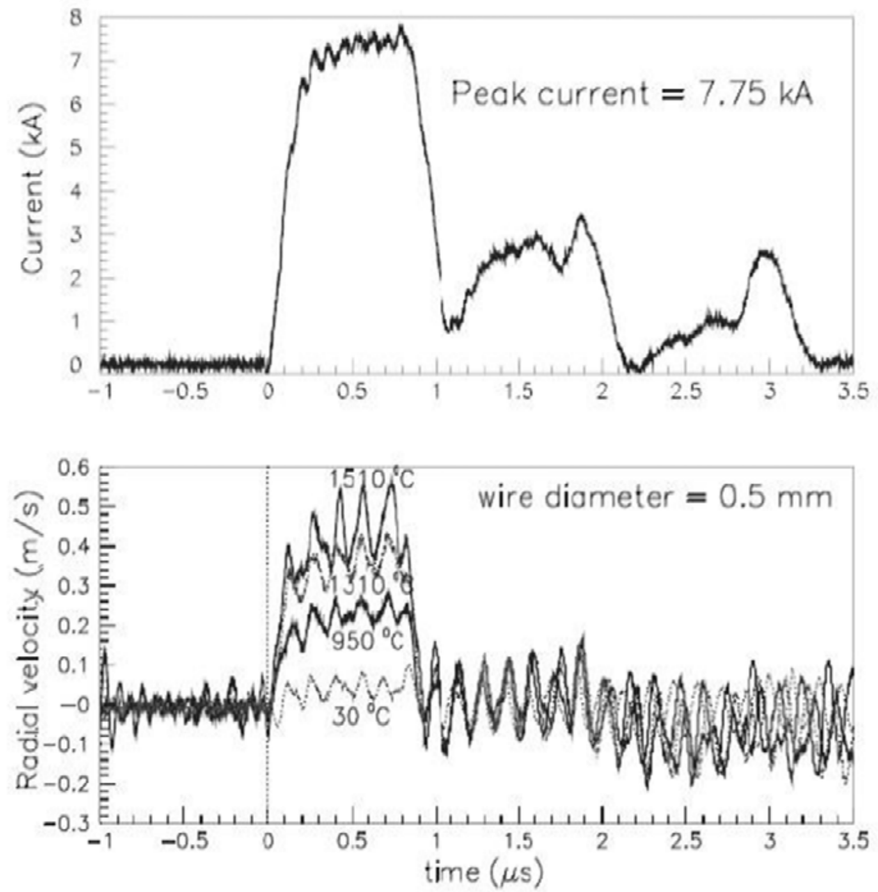


Fig. 7. (Top) The current pulse shape; (bottom) measured radial velocity of the 0.5 mm diameter tungsten wire as a function of time at different temperatures.

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Why High Strain-Rate Measurements?

- The main issue for beam-facing materials used in target systems (targets, beam windows, beam dumps, containment vessels, etc.) is the magnitude and the rate of change of **deposited energy density** (J/cc).

- In a regime where beam pulse length is short compared to characteristic expansion times and thermal conduction timescales we can make the following simplifications:

$$\Delta T \approx E_{den}/\rho.Cp \qquad \text{Thermal Stress} \approx \alpha.E.\Delta T$$

- With increasing beam power, and decreasing pulse length, the estimate of material strength and corresponding lifetime based on simple, quasi-static equations is no longer accurate.

- In these cases the **materials respond 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**.

Dynamic Young's Modulus of Tungsten

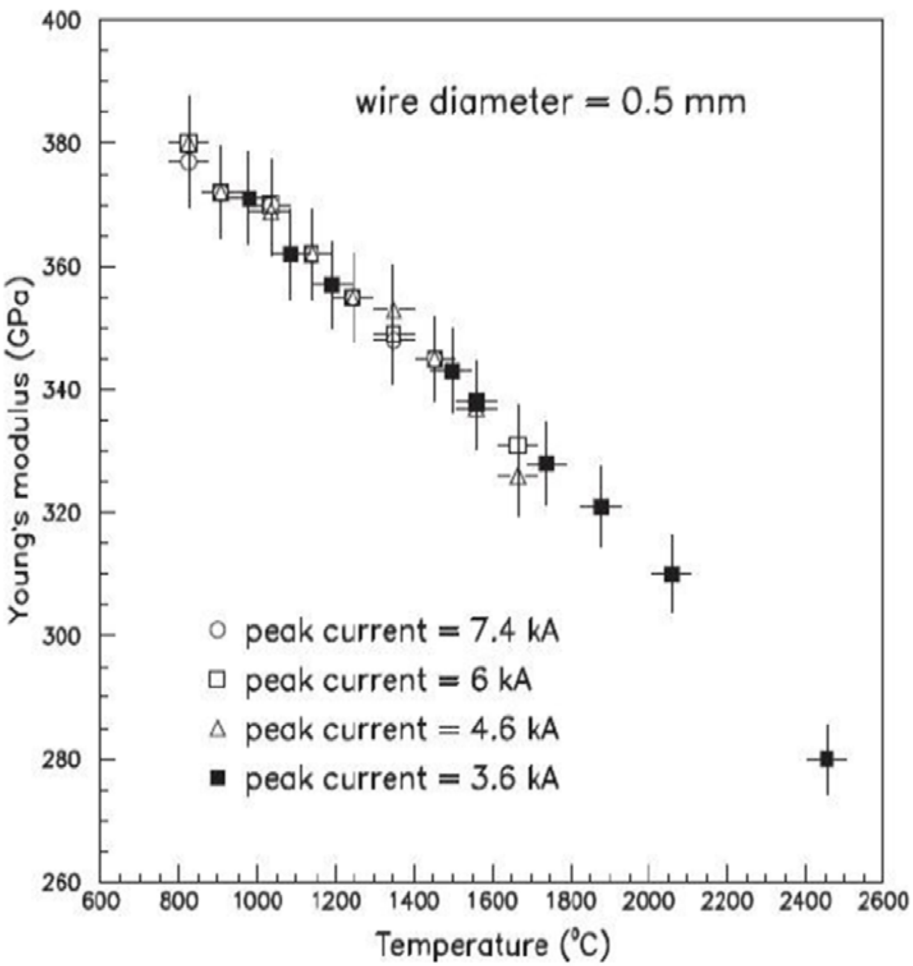

Fig. 8. Young's modulus of a 0.5 mm diameter tungsten wire as a function of temperature for four different peak currents.

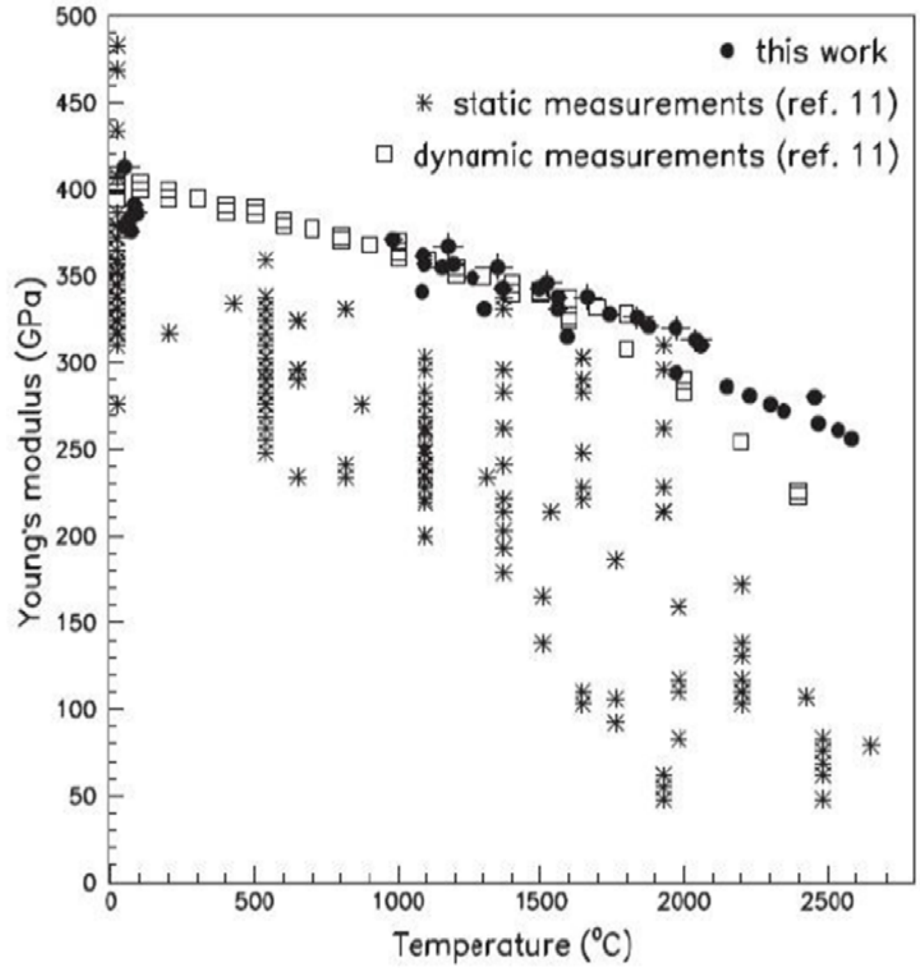

Fig. 10. Comparison between our experimental results and previous results [11] on tungsten Young's modulus.

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Yield Strength Measurements

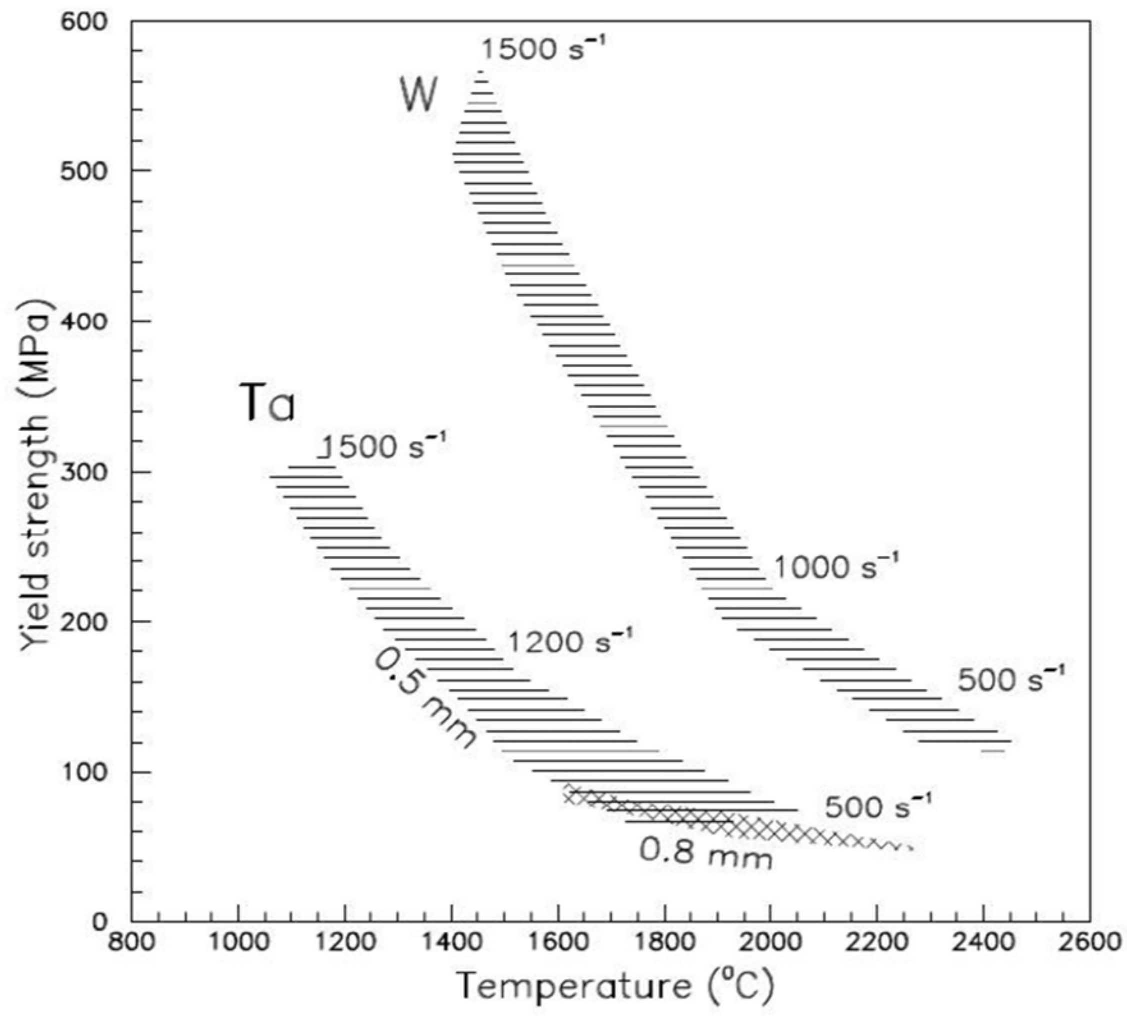


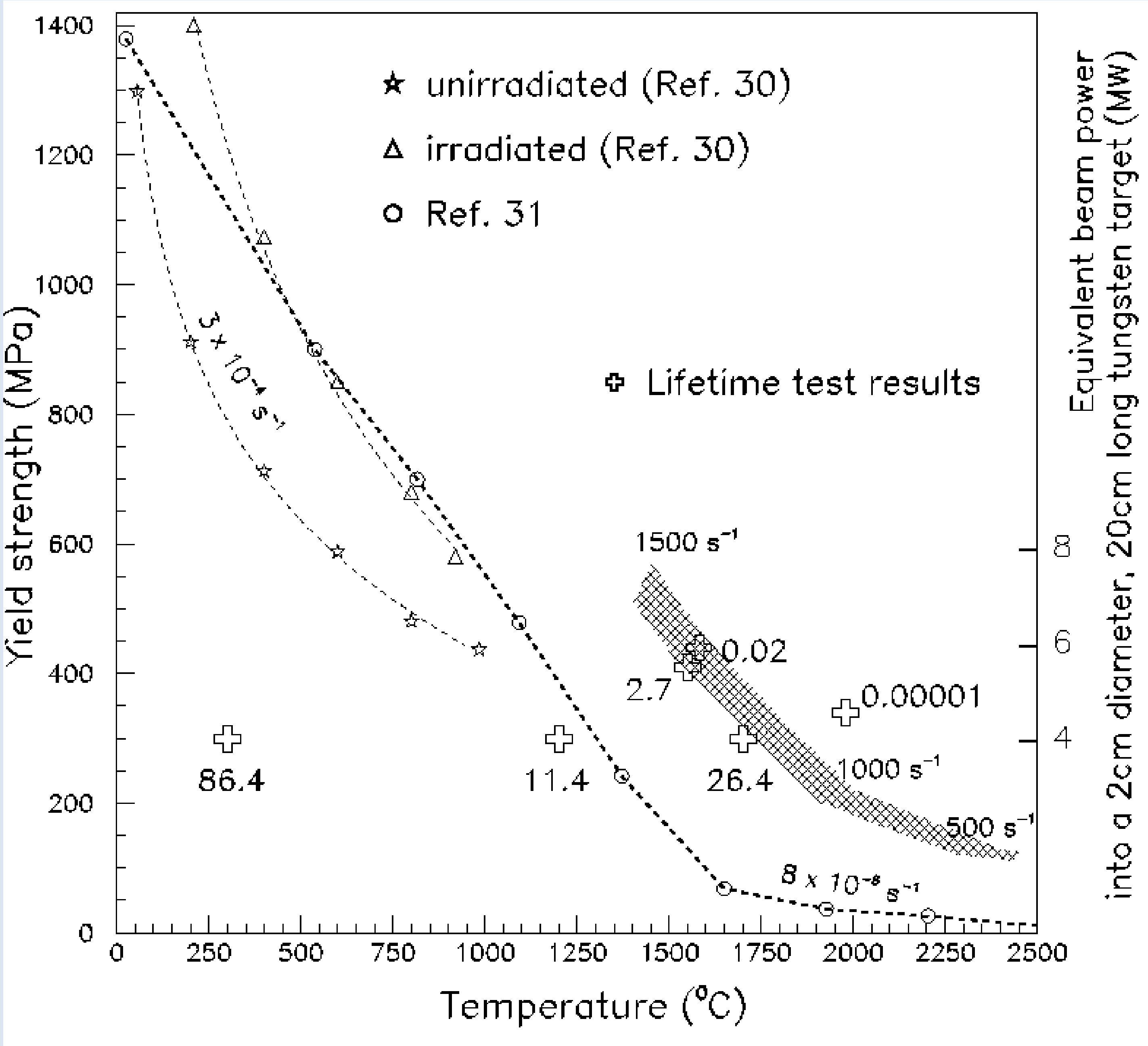
Figure 2. The yield strength versus peak temperature for tantalum wires of 0.5 and 0.8 mm diameter and for tungsten wires of 0.5 mm diameter [5]. The upper edge of the bands indicates the stress at which the wire started to bend and the lower edge indicates where the wire was not deformed. The characteristic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

Lifetime Evaluation (Cycles to failure)

Strength of Tungsten versus Temperature and Lifetime, ✚ in Millions of Pulses

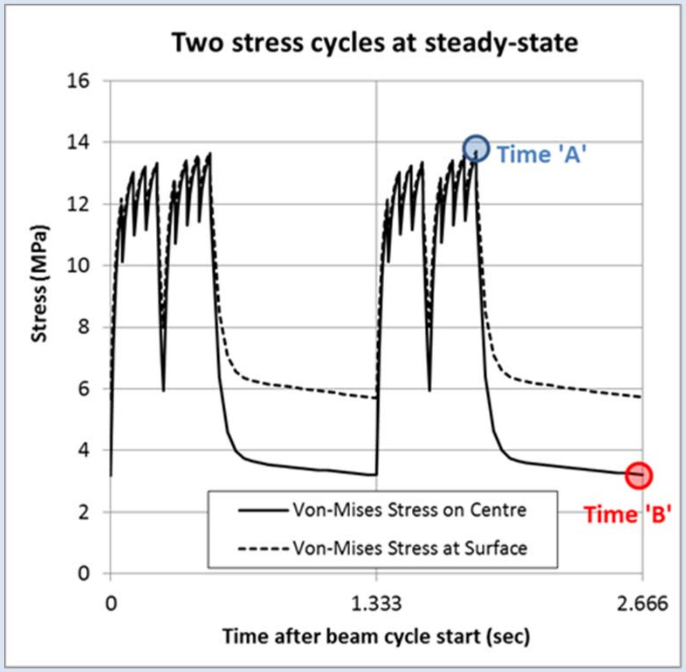
Strain rates shown in s^{-1}.



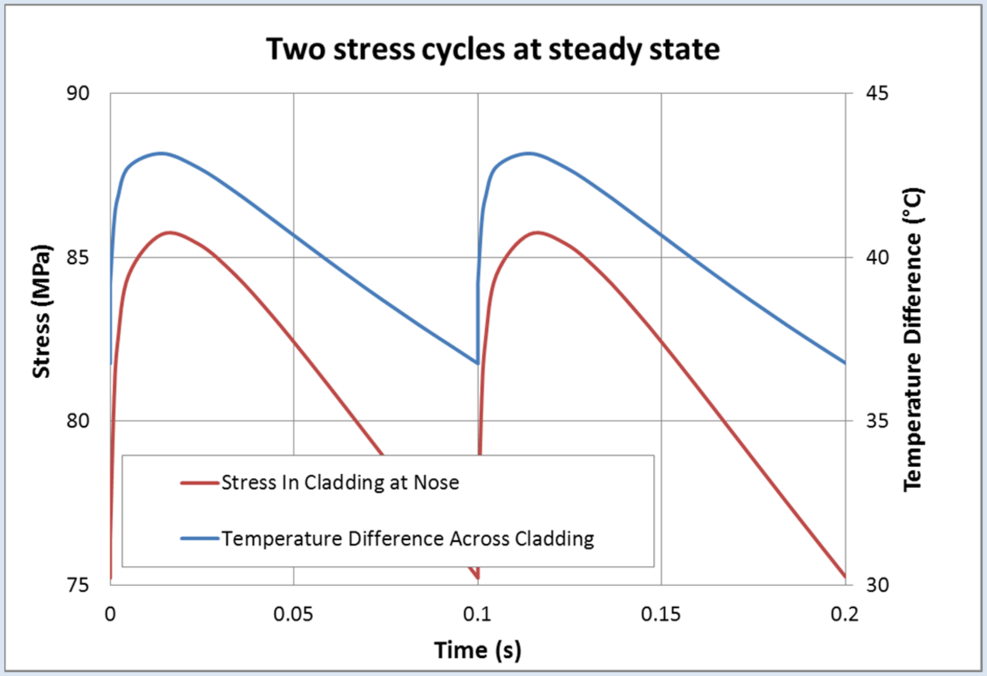
Why Low Strain-Rate Measurements?

- In some target applications the rate of change of stress and Strain are 'low'. i.e. we have a 'quasi-static' state of stress:

e.g. Proposed Mu2e Target:
Unusually long (~50 msec) beam spills give rise to quasi-static cycles



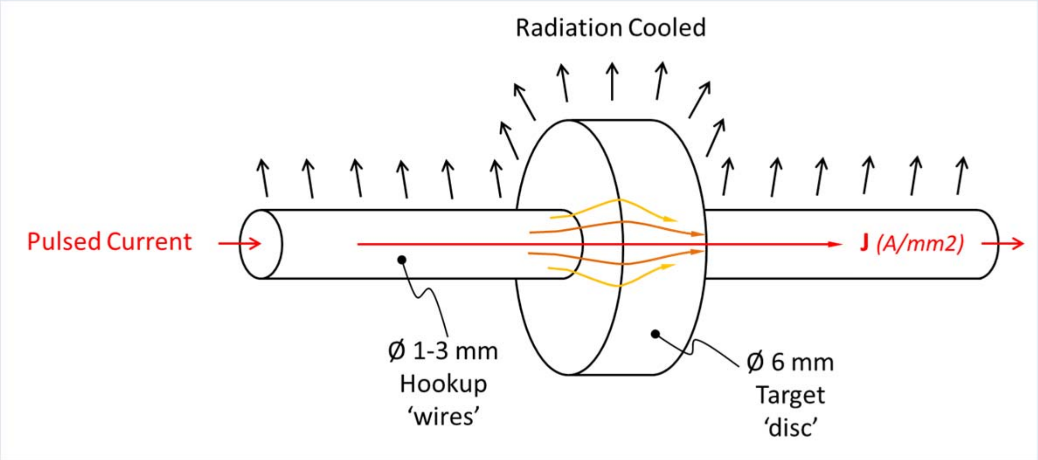
e.g. ISIS target Cladding:
Stresses rise and fall between pulses on the timescale of thermal conduction

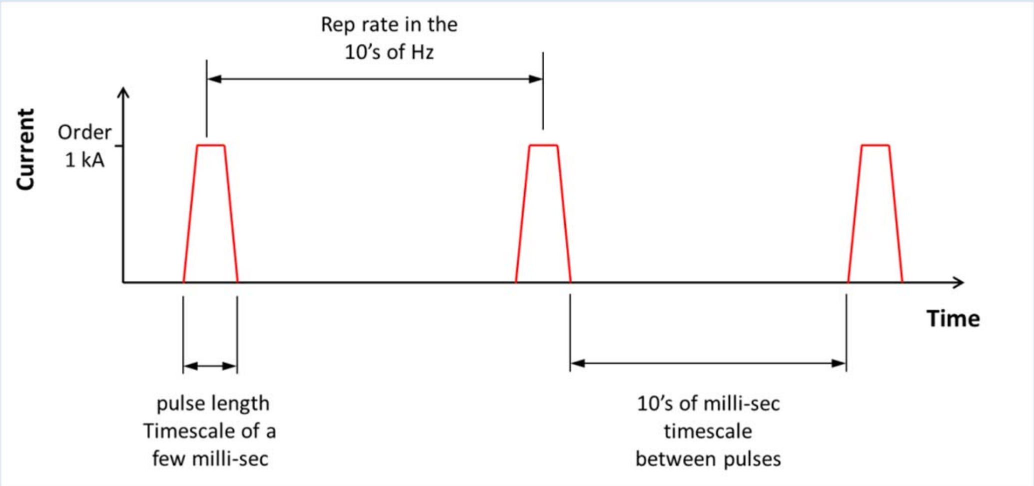


Low Strain Rate Tests in the Little-Wire Test Rig

Operating Principle:

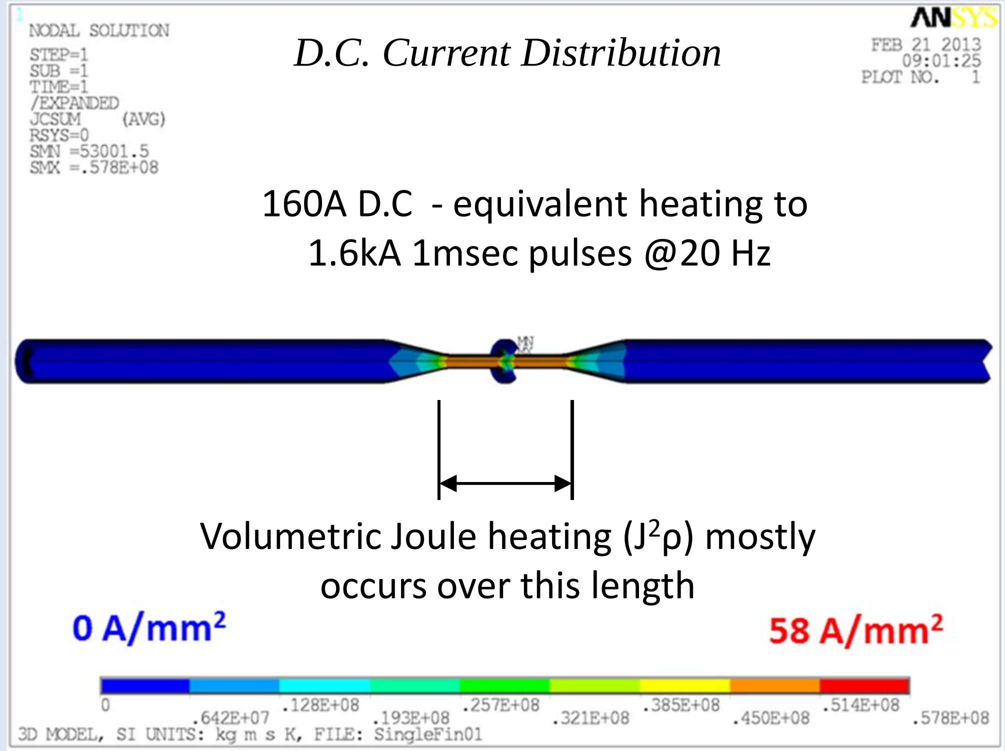
- ❑ Use resistive (Joule) heating from an electric current pulse to preferentially heat the centre of a disk
- ❑ Pulse length long enough to give 'static' stress field
  (do not want inertial stresses)
- ❑ Inter pulse gap long enough for transient stress component to decay
  (on the timescale of thermal conduction)
- ❑ Rep rate of 10's of Hz
  (to allow accelerated testing of target lifetime cycles)

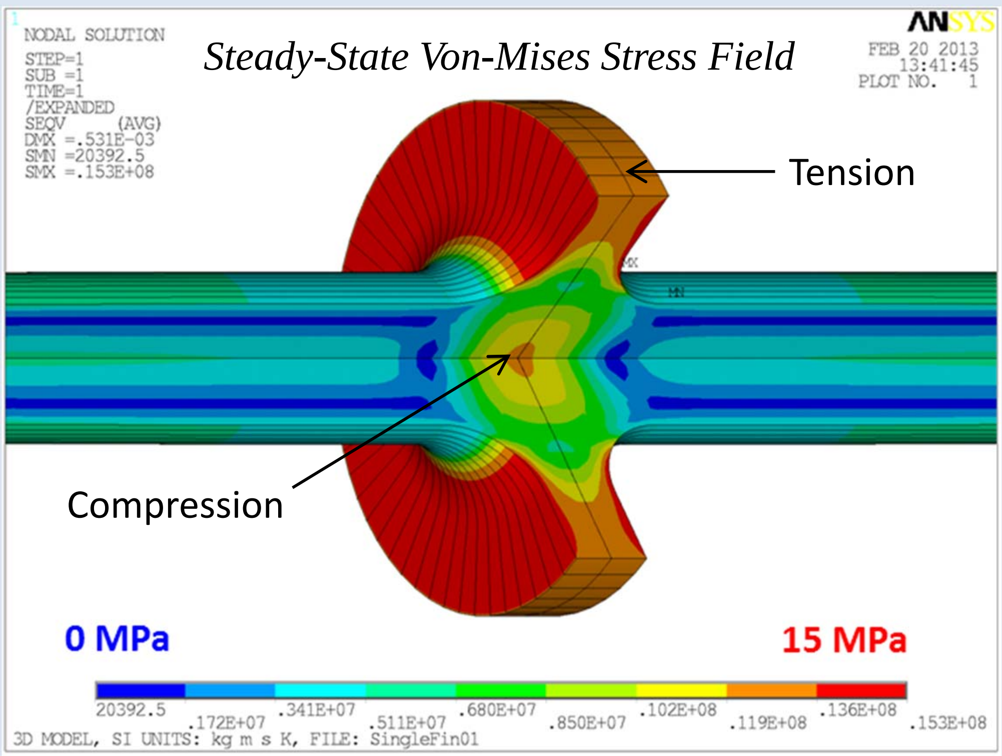


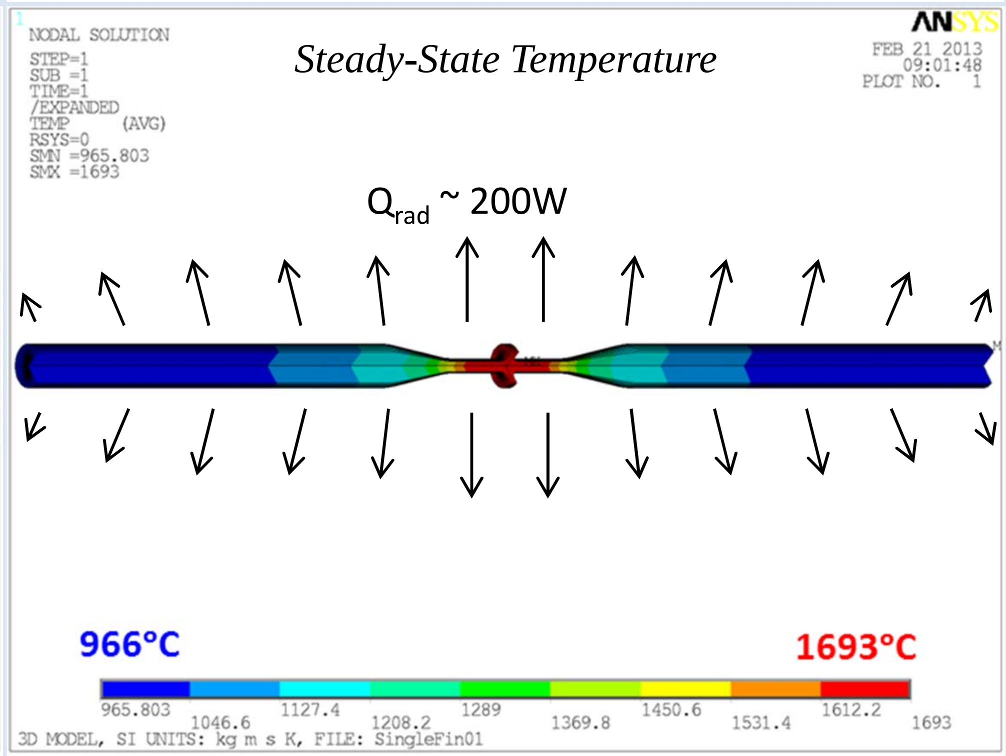


Sample Geometry Concept

- Example: Mu2e Target Test
  - Machine features into a 6mm diameter 160mm long tungsten bar i.e. this is a 'full size' test
  - Means we can test the stock material / surface treatment that we intend to use for the real target!

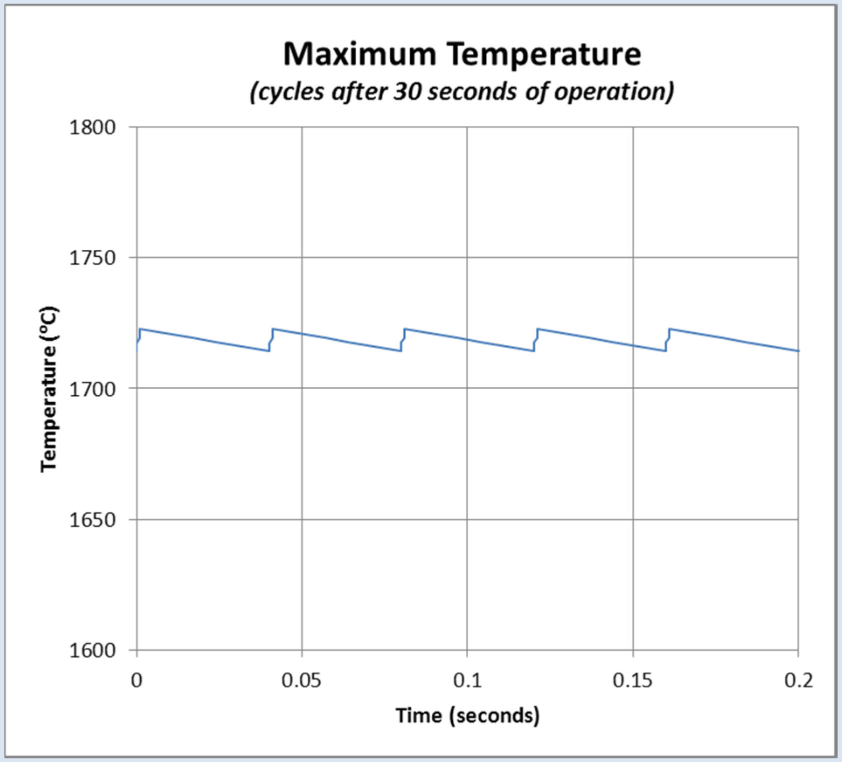


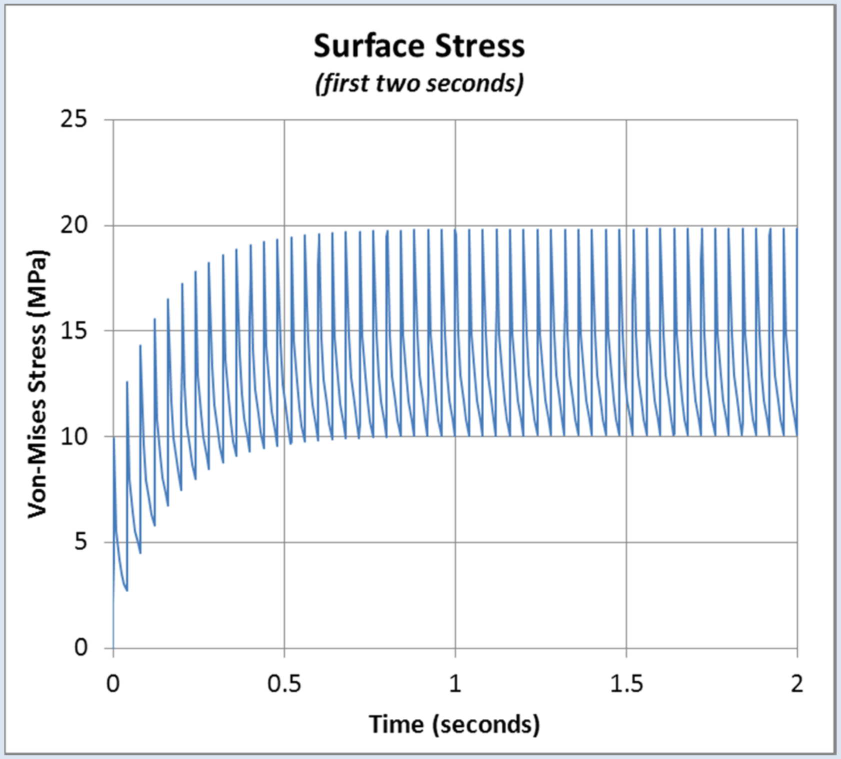




Tuneable Temperature and Stress Cycles

- Can tune the sample geometry to achieve representative temperature and stress cycles for a given application
- Can fine tune the stress cycle and operating temperature online by varying the peak current and rep rate.

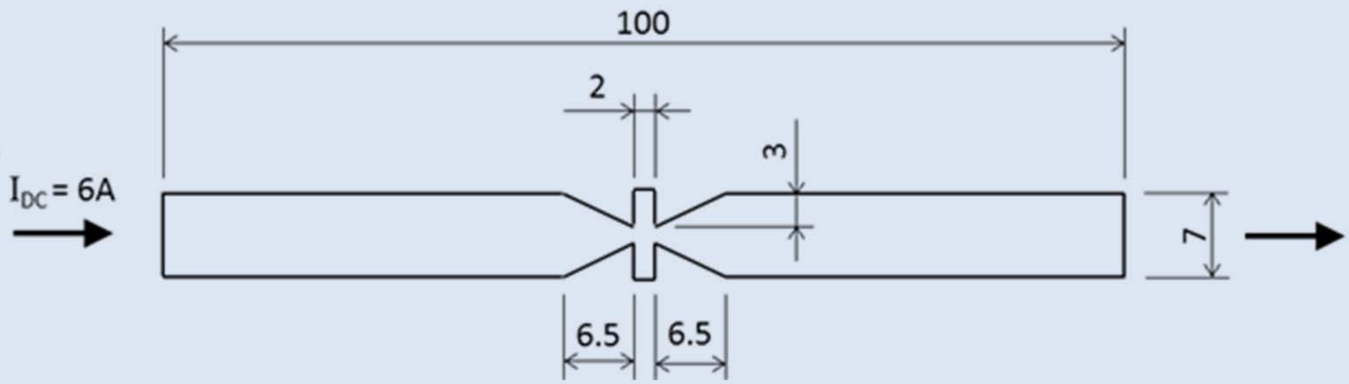




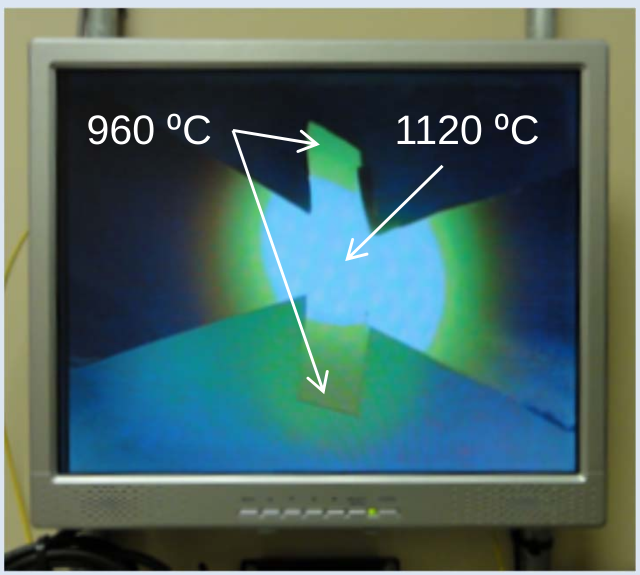
Example: Temperature and stress cycles in the proposed Mu2e test specimen (1.6 kA, 1 msec half sine-wave current pulses @ 25Hz) Tuned to match the target operating conditions

First Tests Using Tantalum Foil

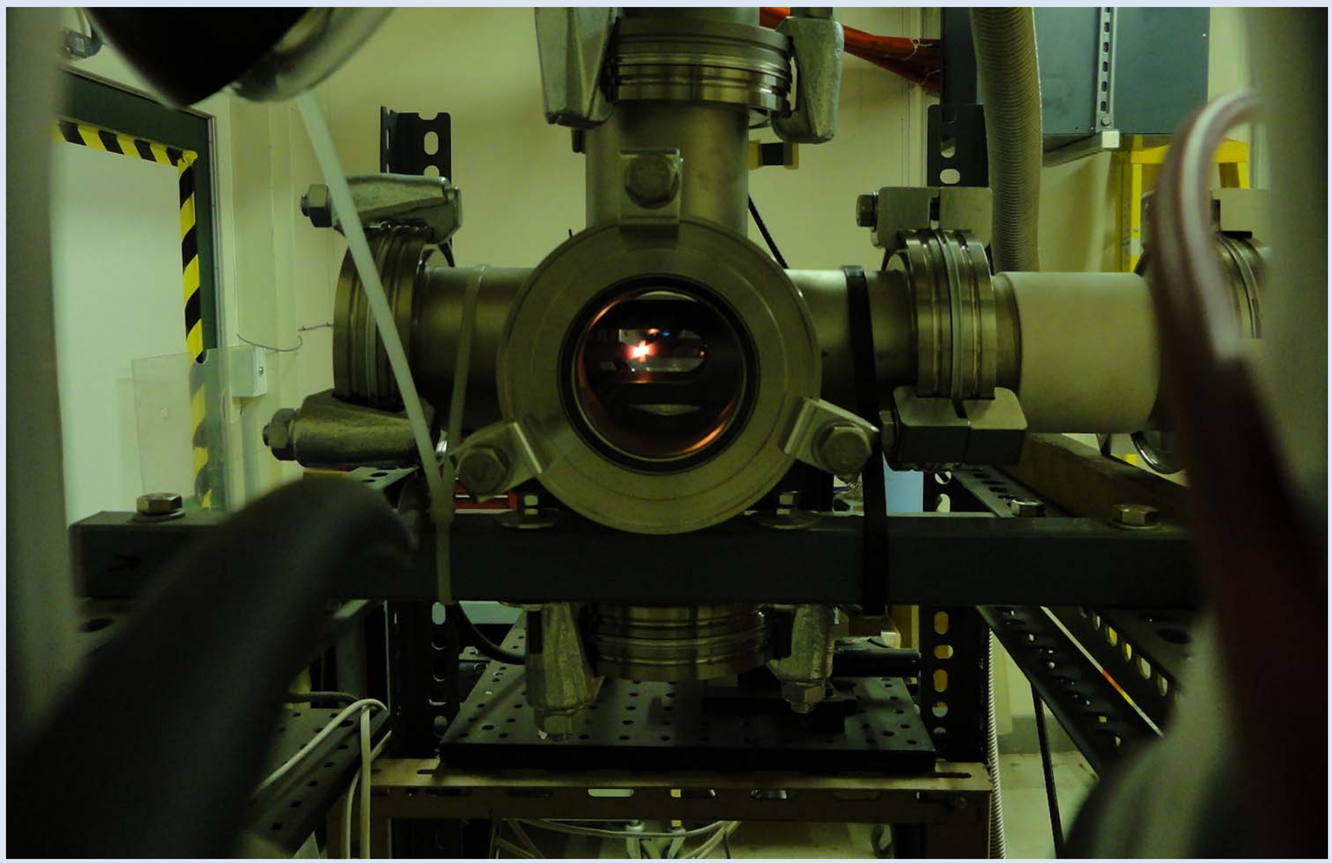
- ‘2D version’ of the proposed Mu2e test piece
- 25 µm tantalum foil
- 1×10^{-5} mbar vacuum
- DC Current = 6.0 A



Specimen Dimensions (mm)



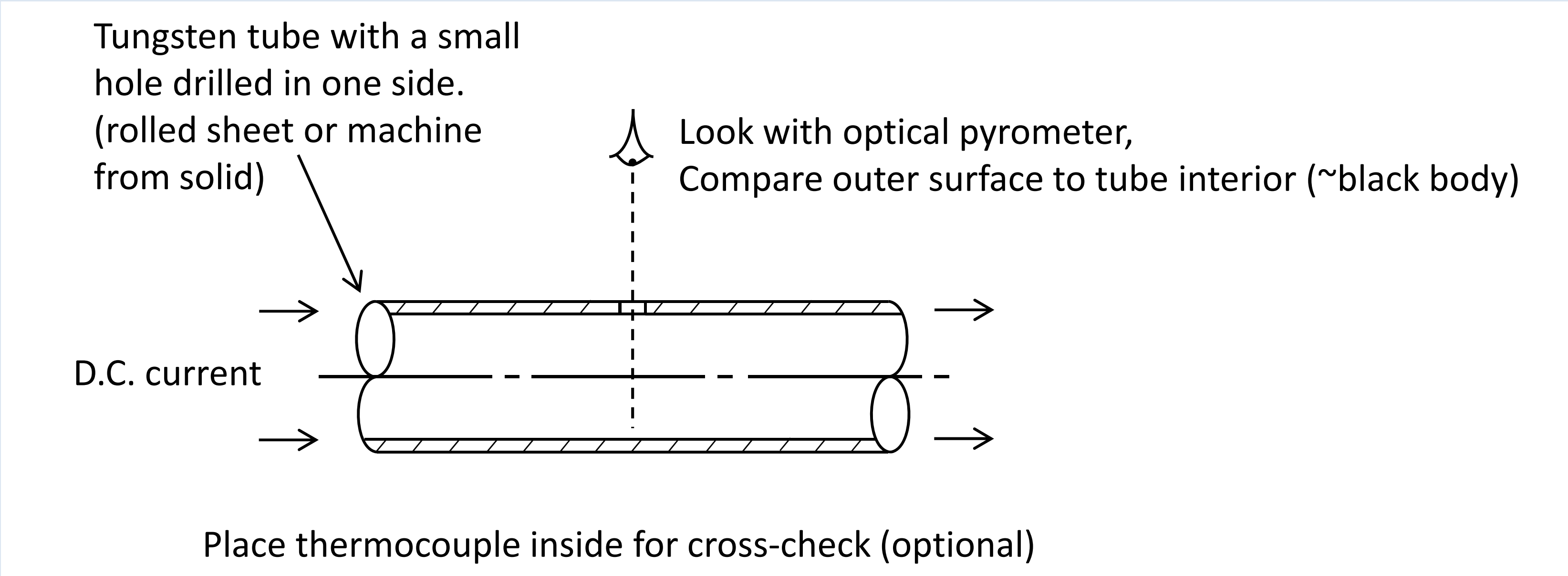
Temperature Measurements



Experimental Setup

Thermal Emissivity and Surface Roughness

- The surface roughness alters the **emissivity**. Measure the emissivity and roughen the surface - with abrasives – cut groves in the surface – etc.

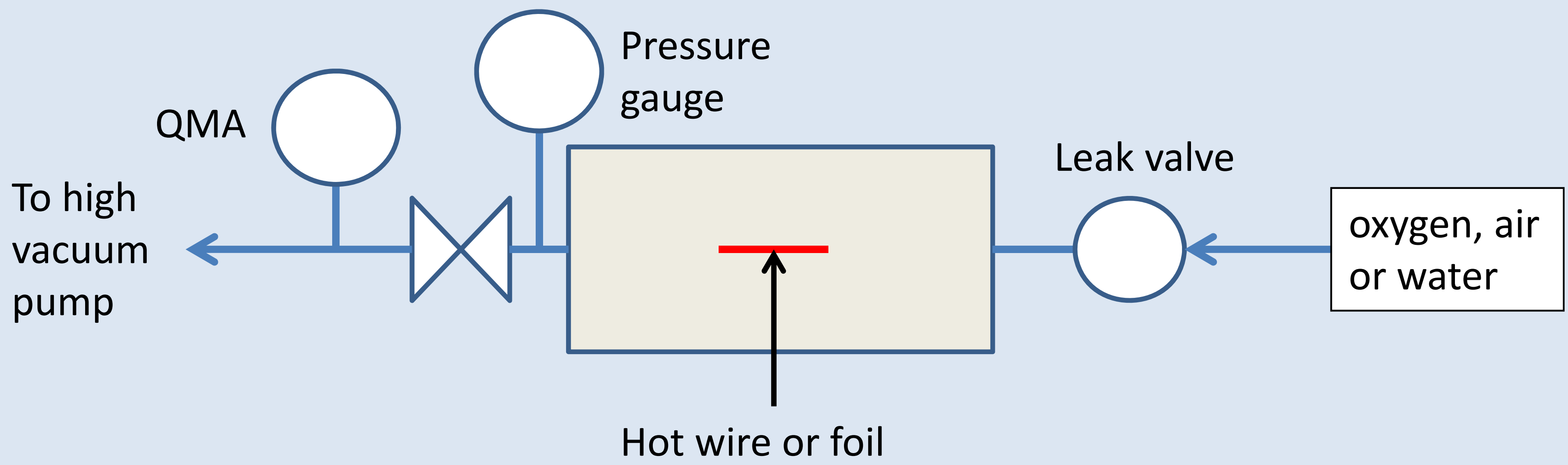


- Use an Optical Pyrometer to:
  - Measure **black body temperature** by looking through the hole – T_{bb}
  - Measure **surface temperature** – T_s

$$\varepsilon = T_s/T_{bb}$$

Oxidation

- Tungsten must be in an inert atmosphere or vacuum to avoid chemical oxidation when hot.
- We need to know the maximum vacuum pressure at which the hot tungsten will have a long life.
- There are measurements in the literature, - but *if* they are insufficient we will make our own in the measurements in the *"little wire test equipment"*.



Schematic diagram of the system

Summary of the "Little Wire Test" Equipment

The equipment is ideally suited to measuring the ultimate strength of materials at very high temperatures at all strain rates.

It has been used to determine the properties of tungsten at high strain-rate :

- ❑ Lifetime (cycles to failure) as a function of stress and temperature.
- ❑ Strength as a function of temperature.
- ❑ Young's modulus of elasticity as a function of temperature.

It is easily adaptable to a variety of other measurements:

- ❑ Lifetime evaluation at low strain-rate
- ❑ Emissivity measurements
- ❑ Oxidation Lifetime studies