Thermal Shock Measurements and Modelling for Solid High-Power Targets at High Temperatures

J. R. J. Bennett[1], G. Skoro[2], J. Back[3], S. Brooks[1], R. Brownsword[1], C. J. Densham[1], R. Edgecock[1], S. Gray[1] and A. J. McFarland[1]

[1] Rutherford Appleton Laboratory, Chilton, Didcot, Oxon. OX11 0QX, UK
[2] Department of Physics and Astronomy, University of Sheffield, Sheffield. S3 7RH, UK
[3] Department of Physics, University of Warwick, Coventry. CV4 7AL, UK

roger.bennett@rl.ac.uk

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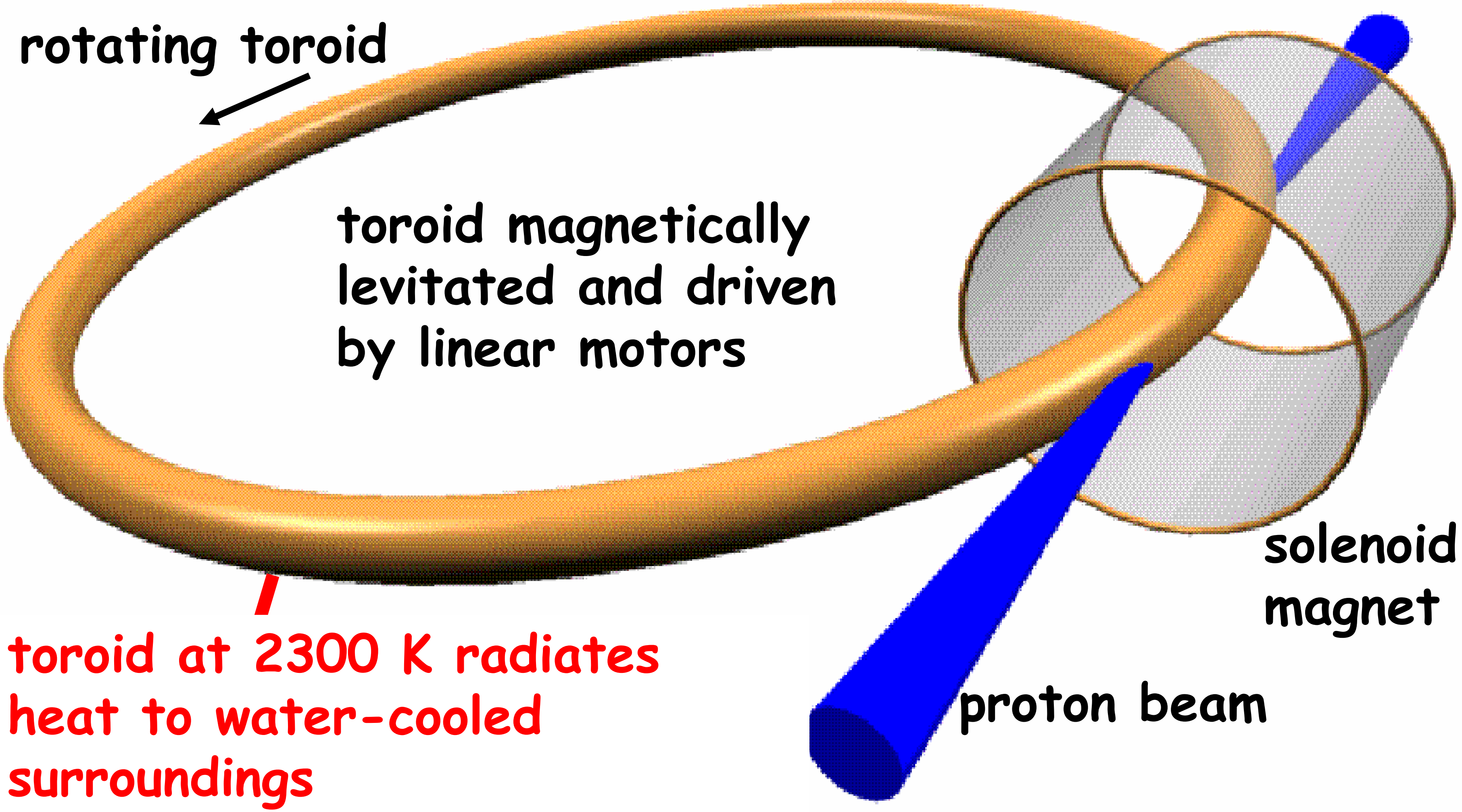
OUTLINE

1. Introduction
2. Wire tests - an update from NuFact06
3. Fatigue and Creep
4. *Longitudinal* versus *Transverse* Bar Feed

The original RAL Target concept -

(after Bruce King)

Schematic diagram of the radiation cooled rotating toroidal target



rotating toroid

toroid magnetically
levitated and driven
by linear motors

solenoid
magnet

proton beam

toroid at 2300 K radiates
heat to water-cooled
surroundings

The alternative concept -

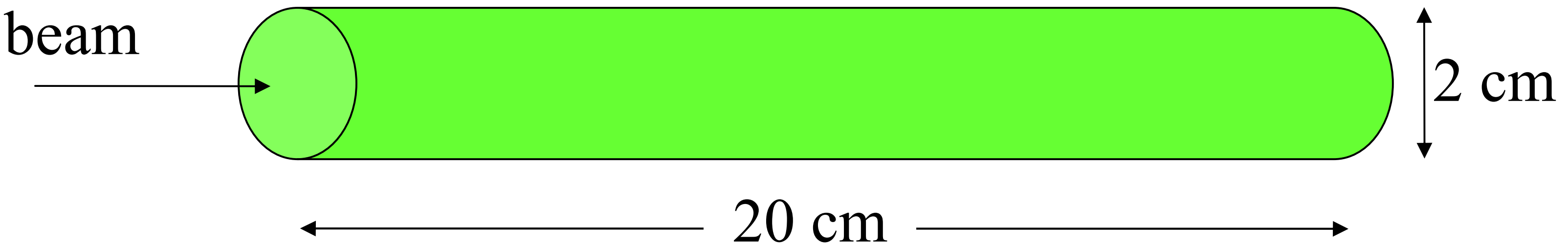
Individual Bar Targets

Target Parameters

Proton Beam

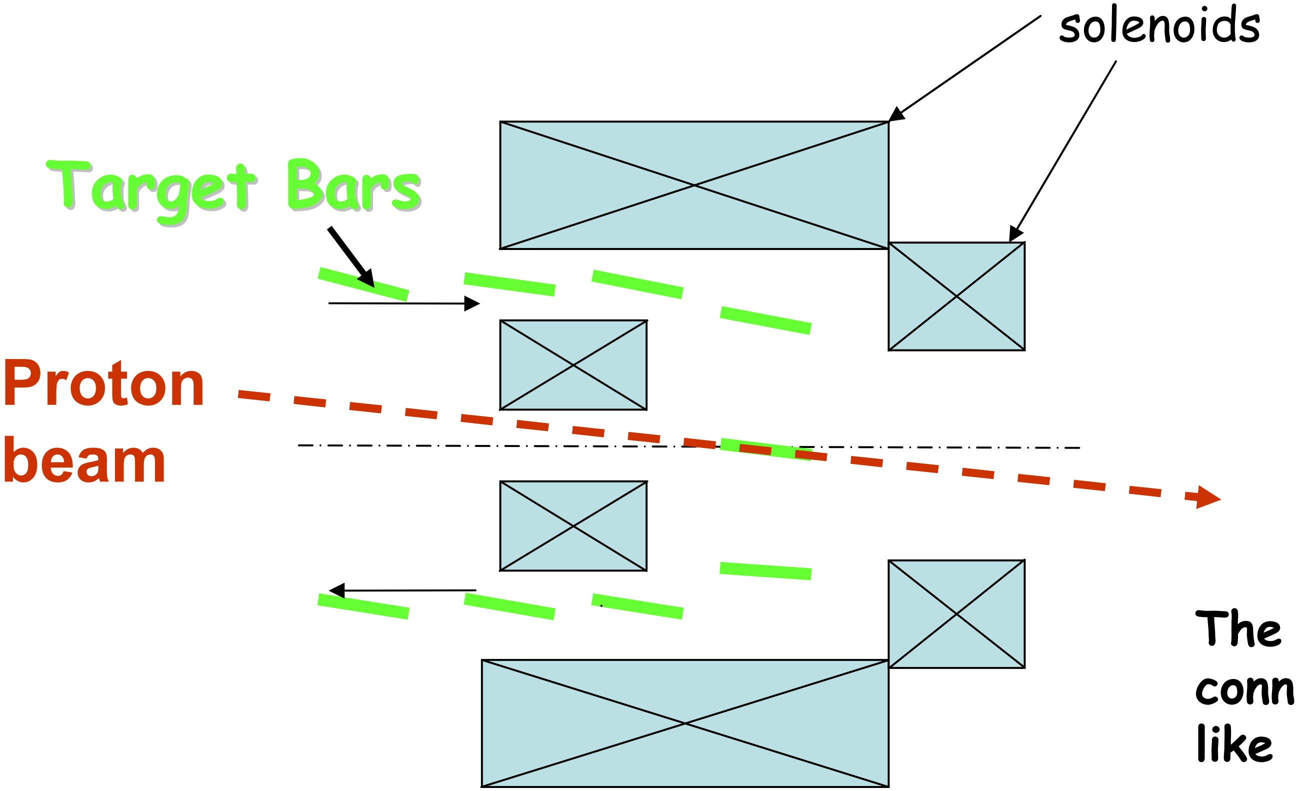
pulsed	50 Hz
pulse length	~40 μs
energy	~10 GeV
average power	~4 MW

Target (not a stopping target)



mean power dissipation	1 MW
energy dissipated/pulse	20 kJ (50 Hz)
energy density	300 J cm^{-3} (50 Hz)

Schematic diagram of the target and collector solenoid arrangement



The target bars are connected by links - like a bicycle chain.

The value of the peak stress is:

$$\sigma_{\max} = \pm E \alpha T$$

With typical values for tungsten:

E = 300 GPa a = 0.9x10^{-5} K^{-1} T = 100 K

0.2% Yield Strength = ~20 MPa at 2000 K

UTS = ~100 MPa

s_{max} = 270 MPa

Stress exceeds UTS

FAILURE EXPECTED!!

Real Life is not this simple.

-

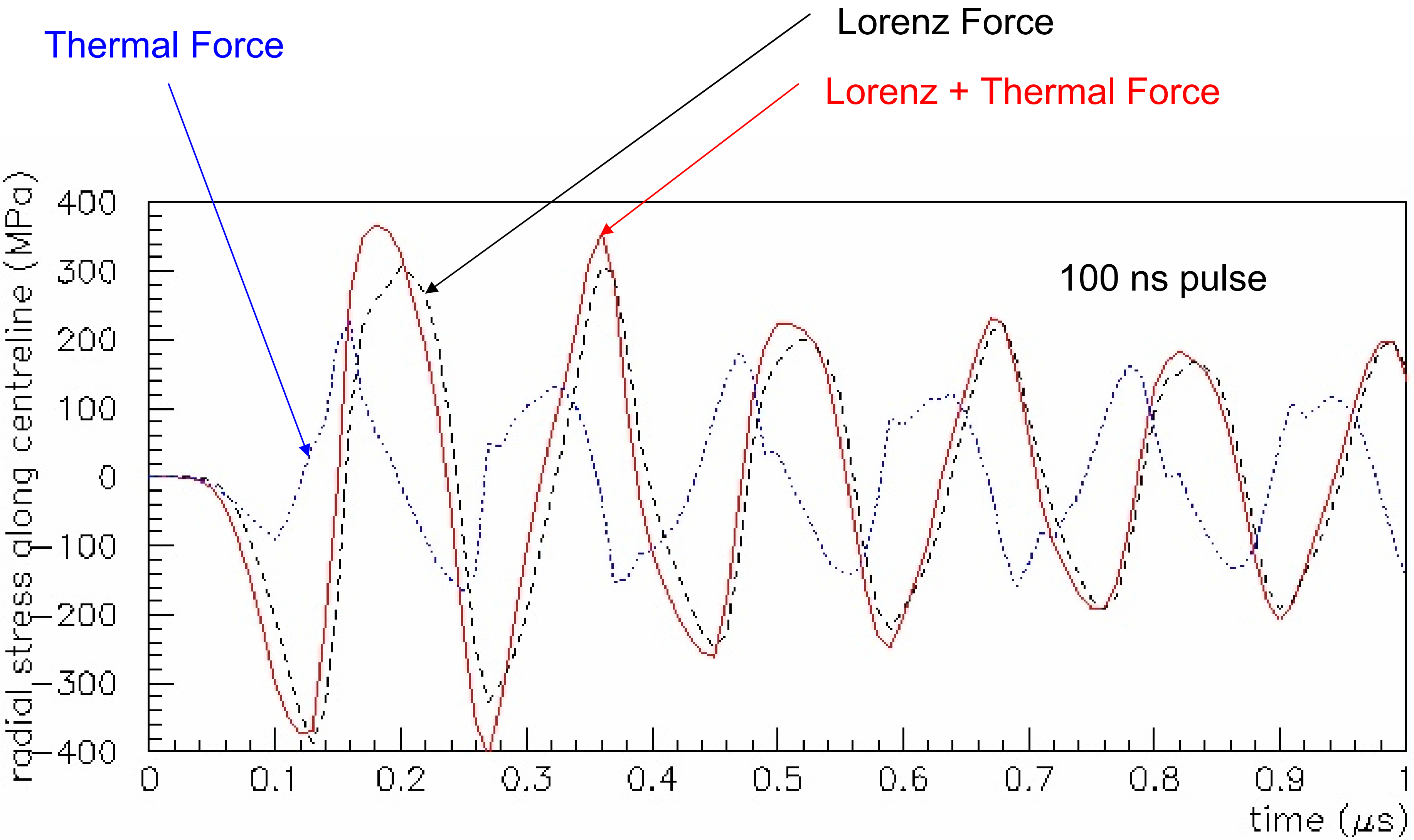
The Pbar target at FNAL withstands 40,000 J cm^{-3}!

-

The NF target has only 300 J cm^{-3}

- It is not possible to test the full size targets in a proton beam and do a life test.

- Produce shock by passing high current pulses through thin wires.



Thermal Force

Lorenz Force

Lorenz + Thermal Force

100 ns pulse

Typical radial stress in the wire from thermal and Lorenz forces

Goran Skoro

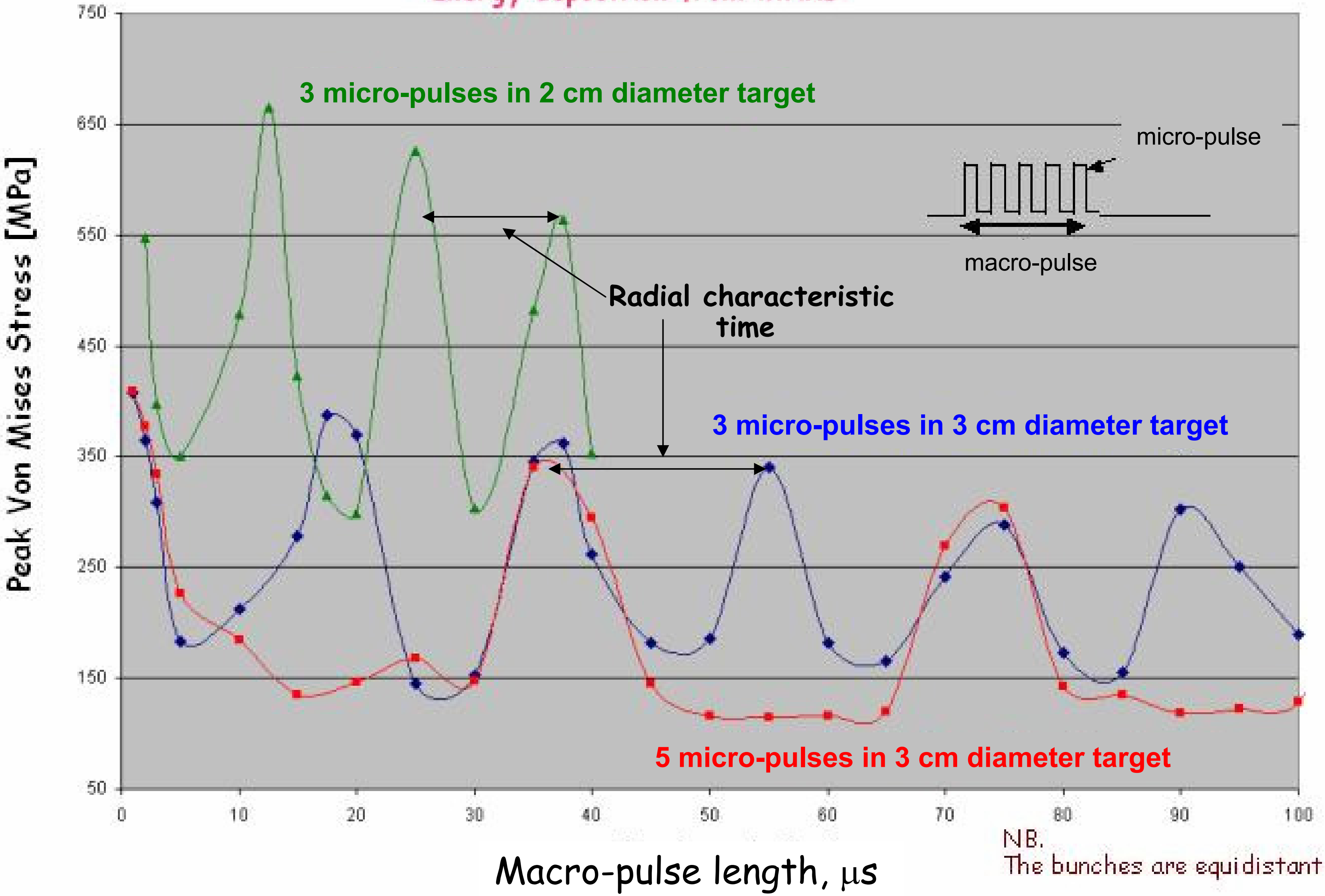
Results

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

Beam radius = Rod radius

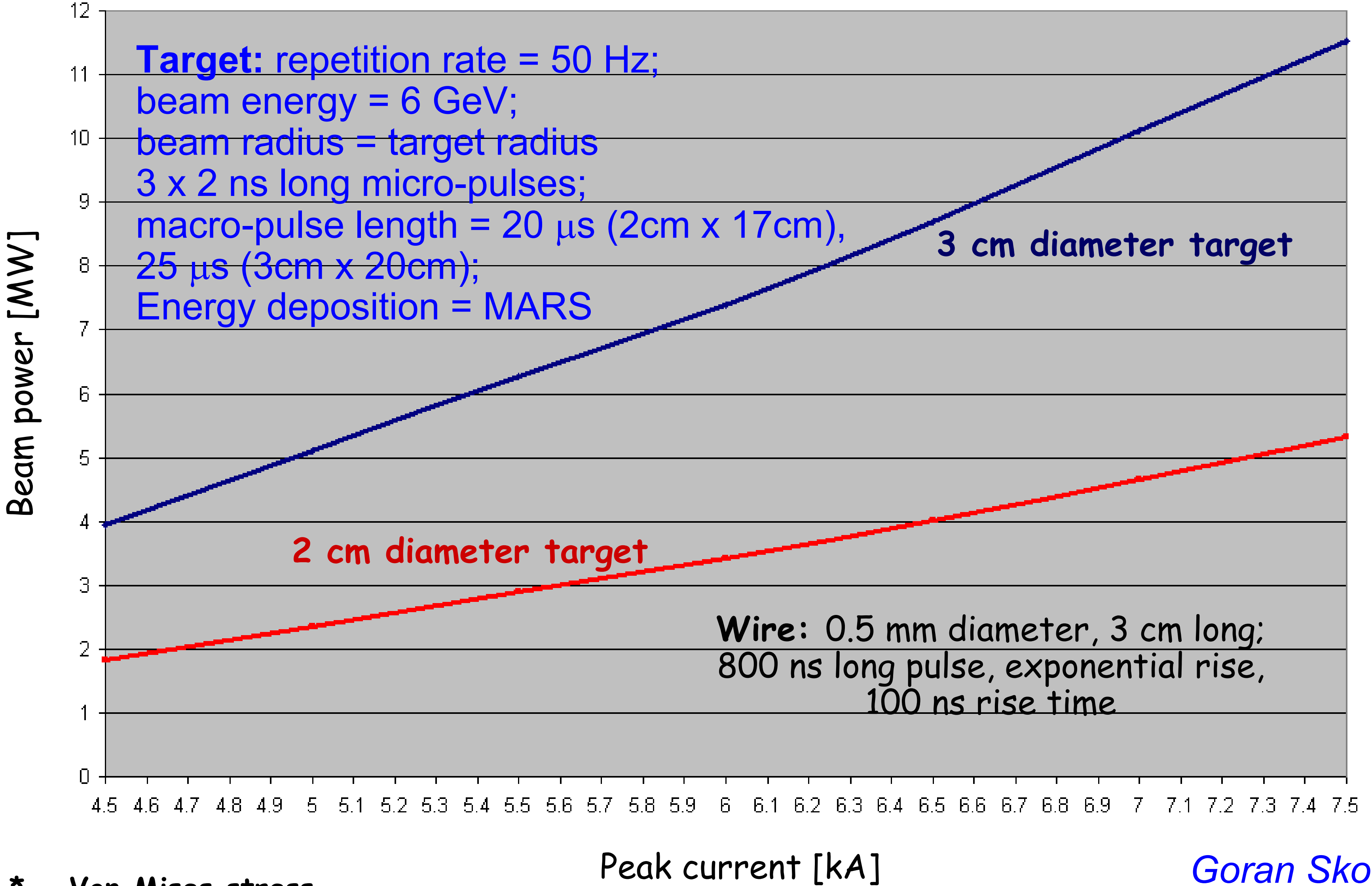


N.B.
The bunches are equidistant.

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

Results

LS-DYNA

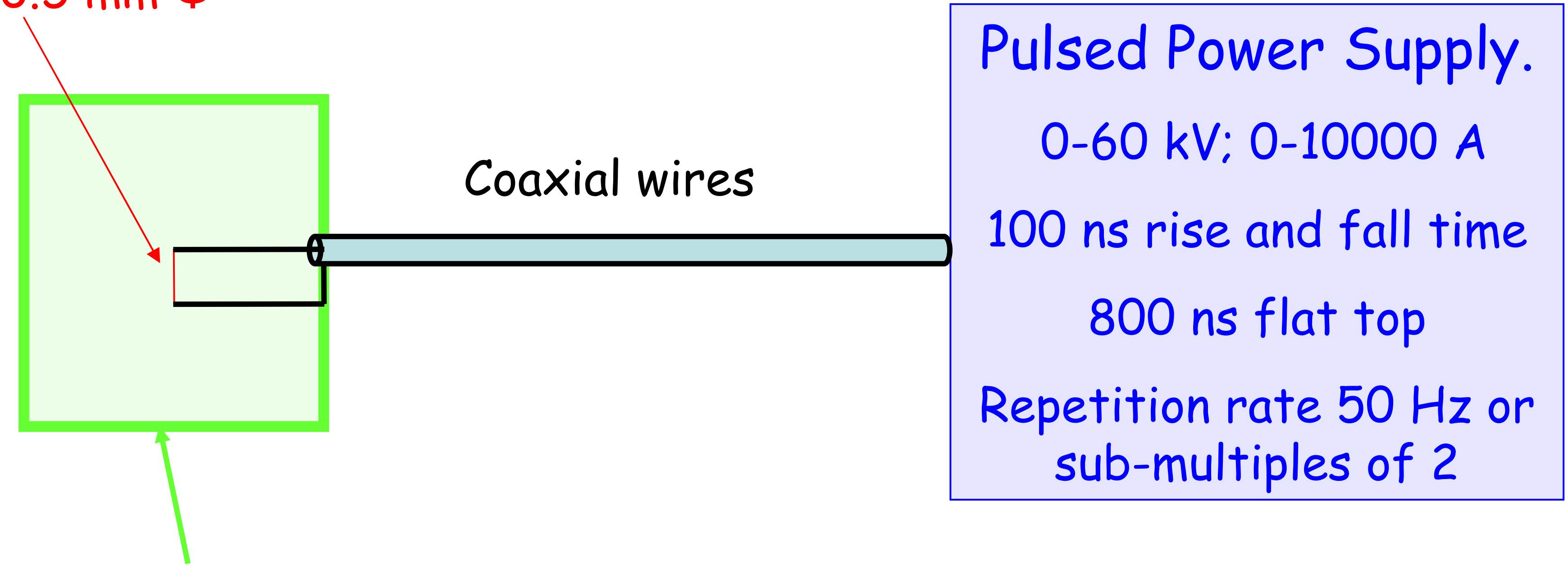


Target: repetition rate = 50 Hz;
beam energy = 6 GeV;
beam radius = target radius
3 x 2 ns long micro-pulses;
macro-pulse length = 20 μs (2cm x 17cm),
25 μs (3cm x 20cm);
Energy deposition = MARS

Wire: 0.5 mm diameter, 3 cm long;
800 ns long pulse, exponential rise,
100 ns rise time

* - Von Mises stress

Goran Skoro



Test wire,
0.5 mm Φ

Coaxial wires

Vacuum chamber,
2×10^{-7} -1×10^{-6} mbar

Pulsed Power Supply.

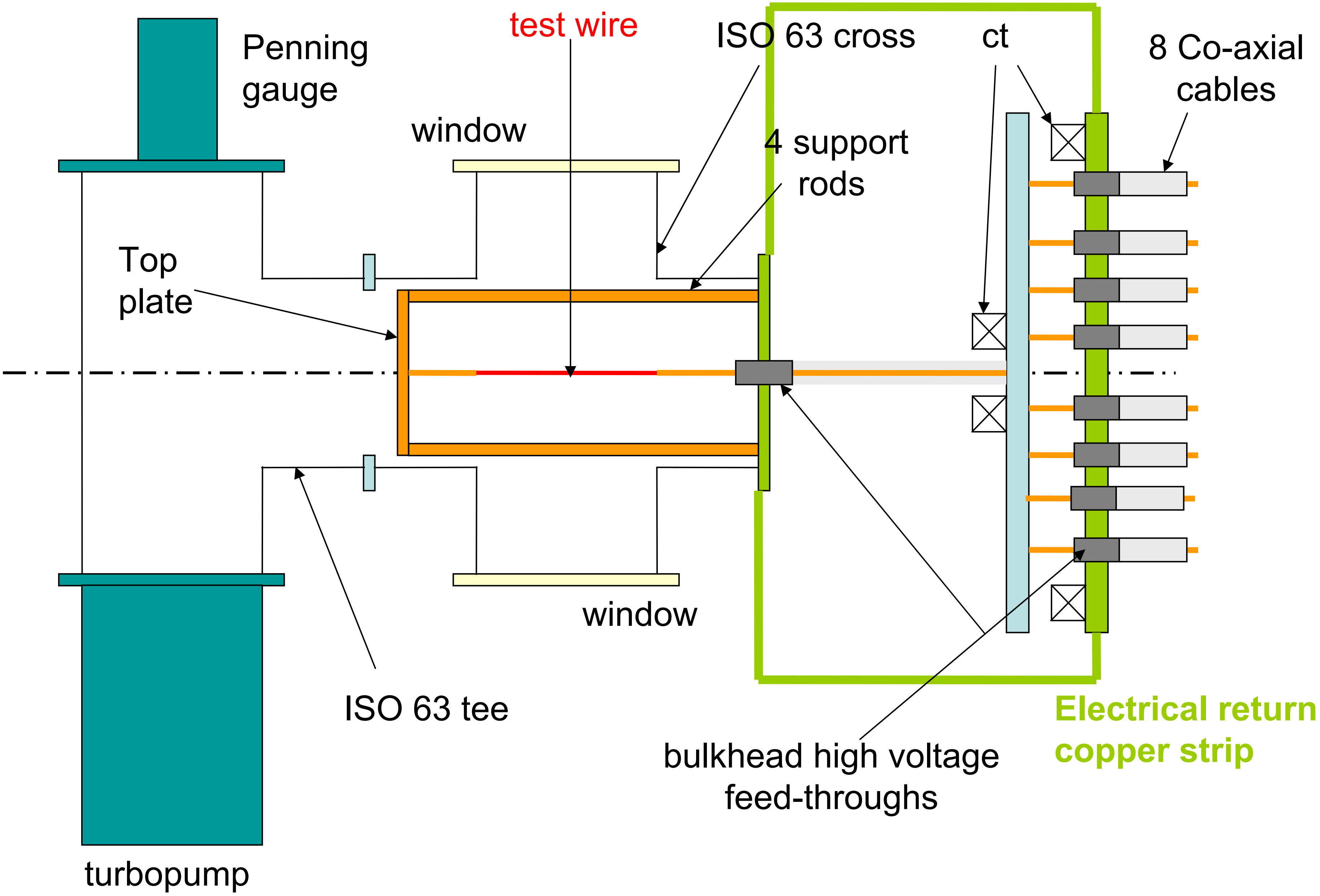
0-60 kV; 0-10000 A

100 ns rise and fall time

800 ns flat top

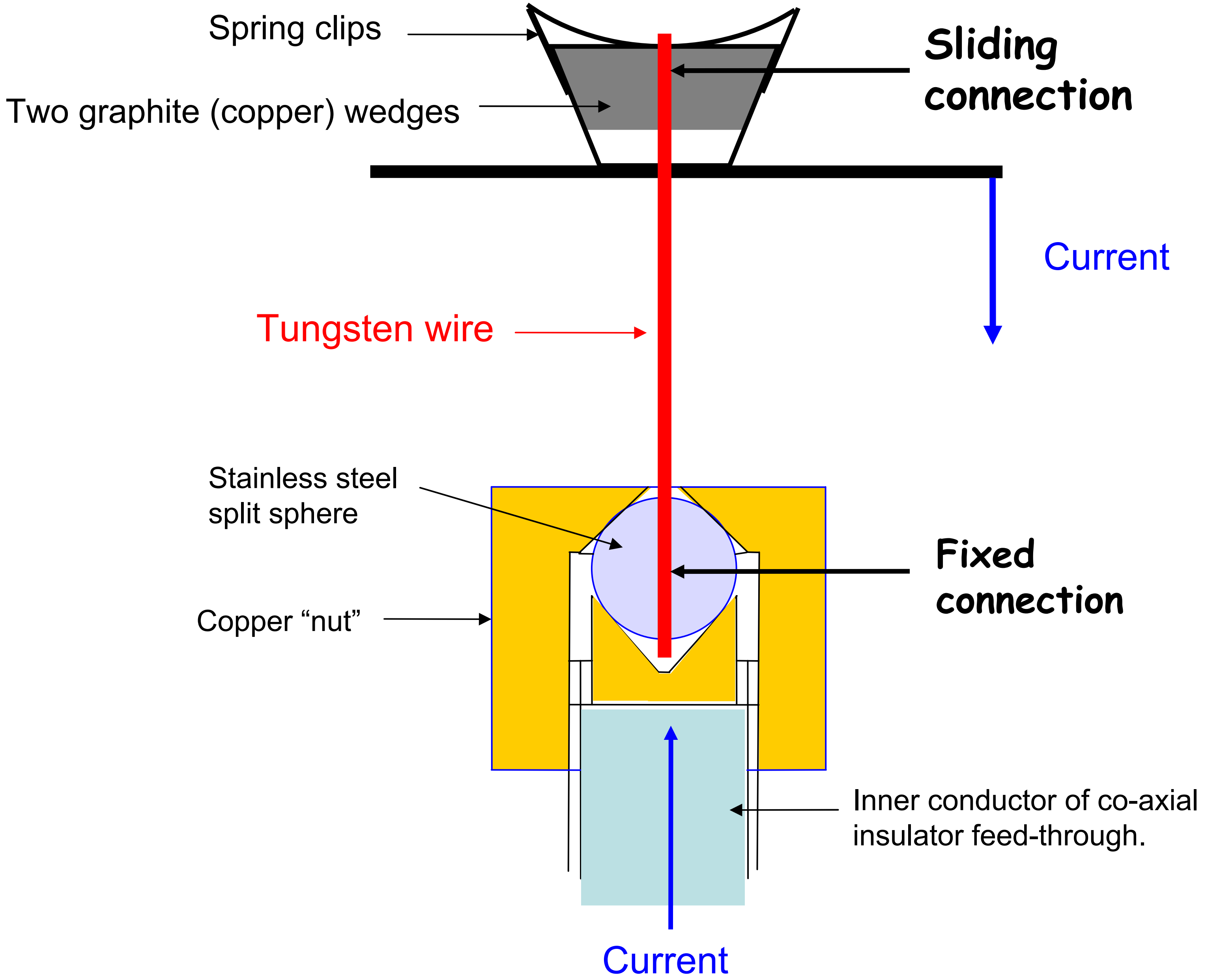
Repetition rate 50 Hz or
sub-multiples of 2

Schematic circuit diagram of the wire test equipment



Schematic section of the wire test assembly

Vertical Section through the Wire Test Apparatus



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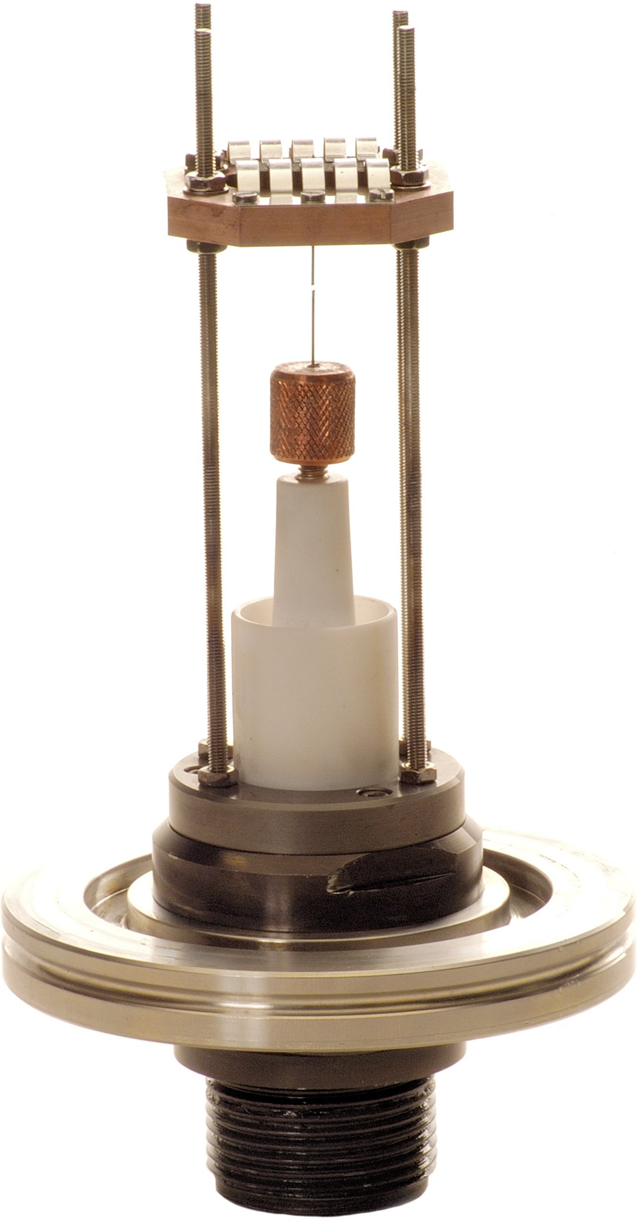
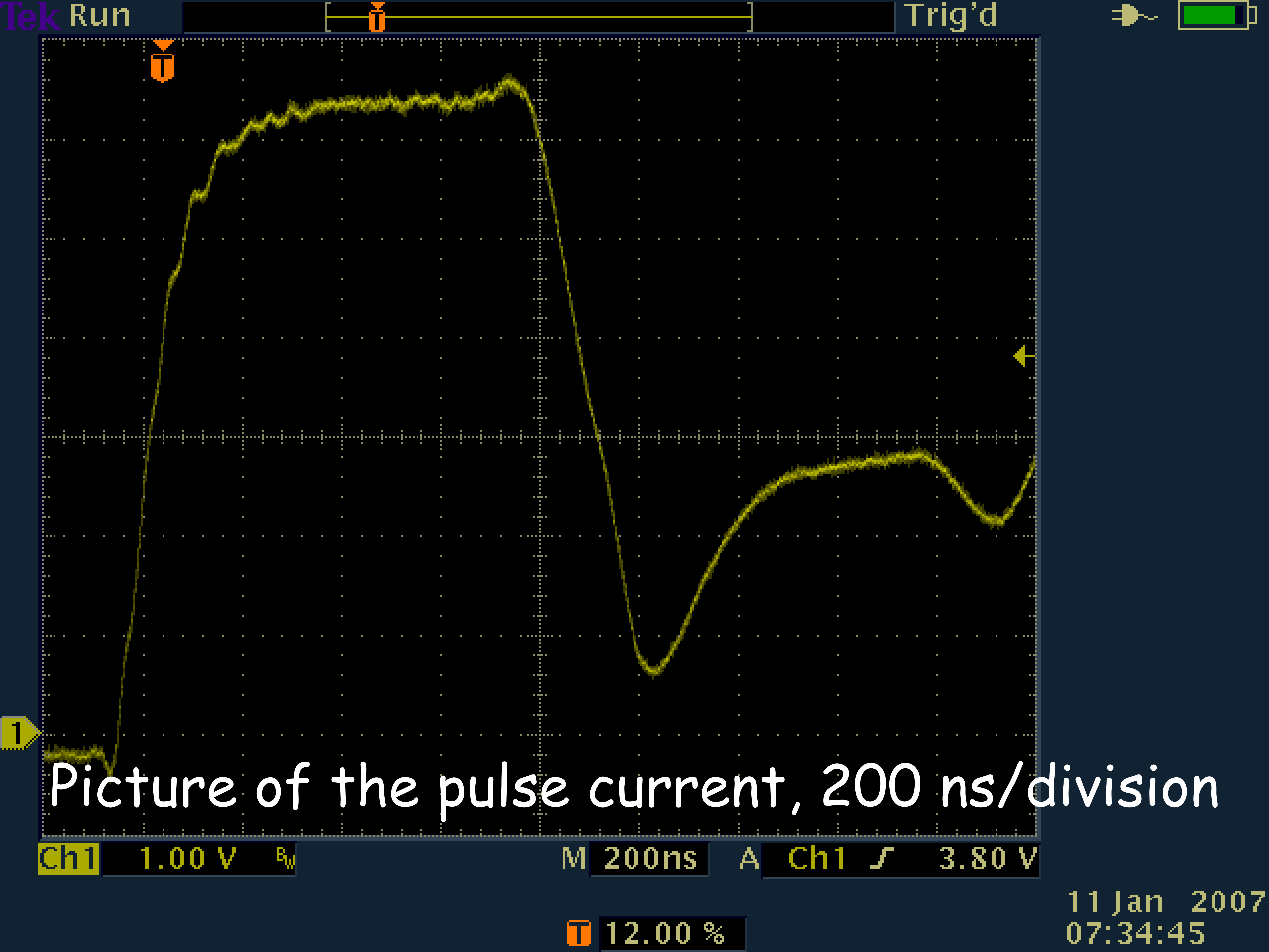
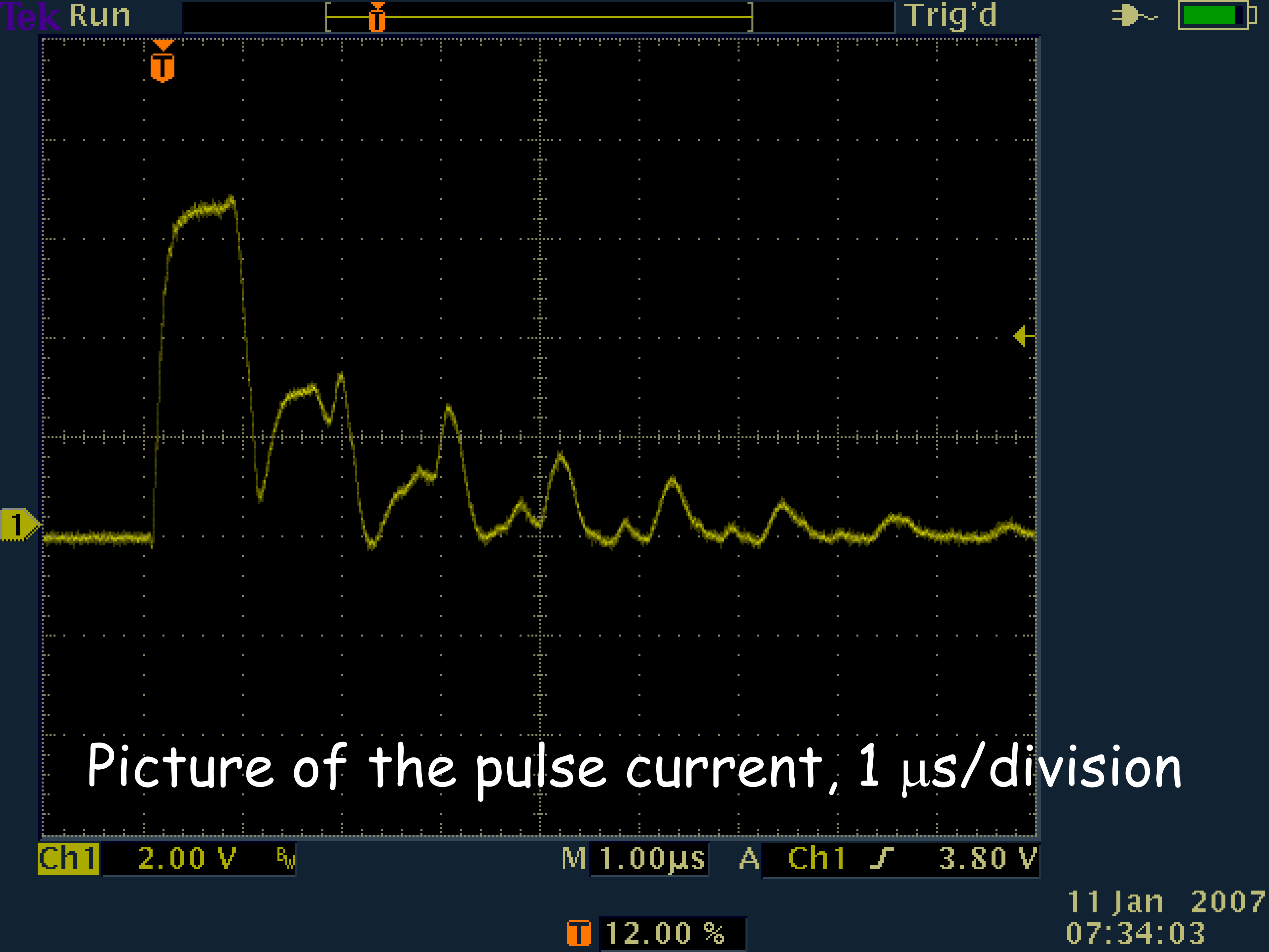
Tungsten Wire Assembly



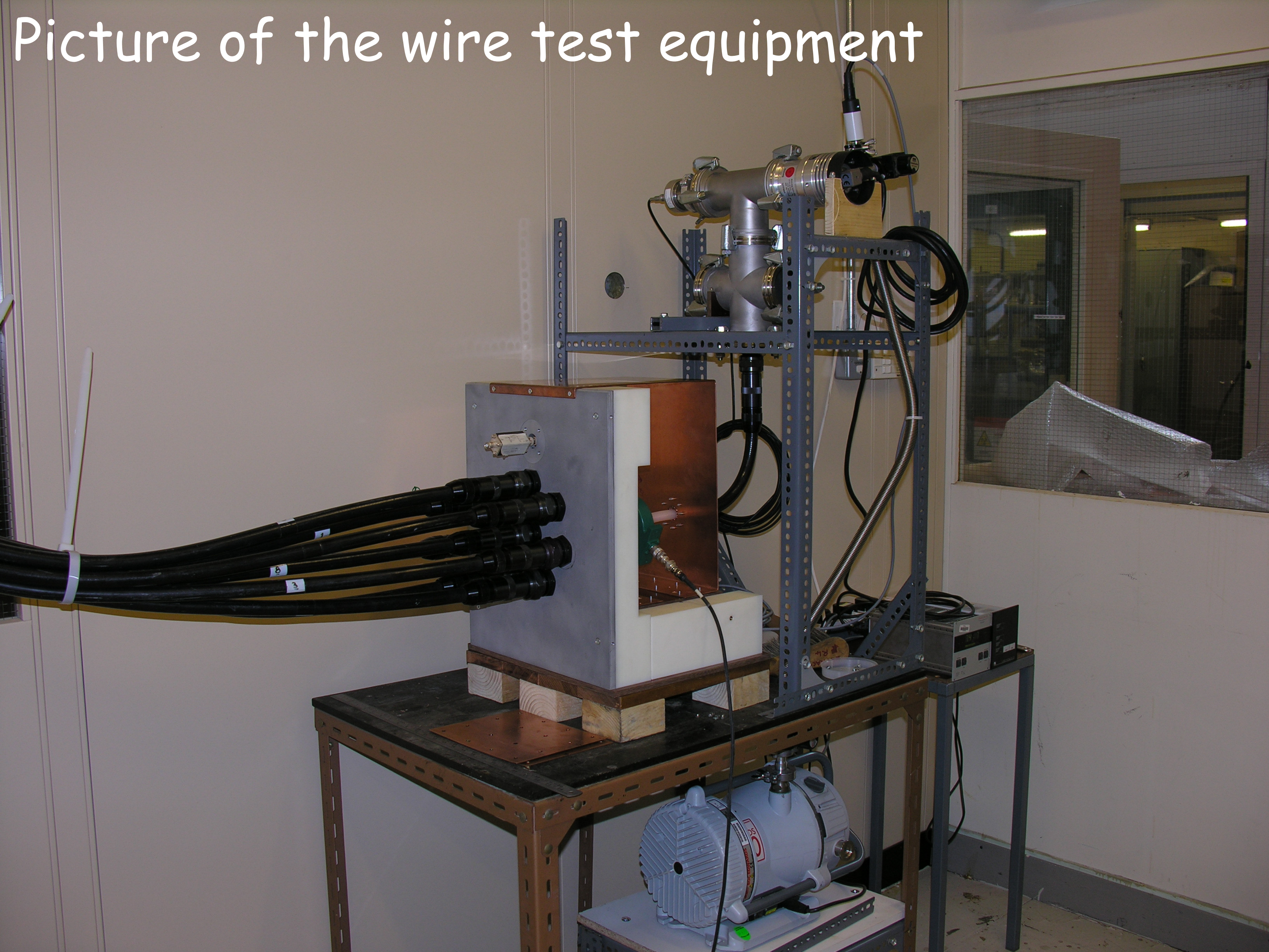


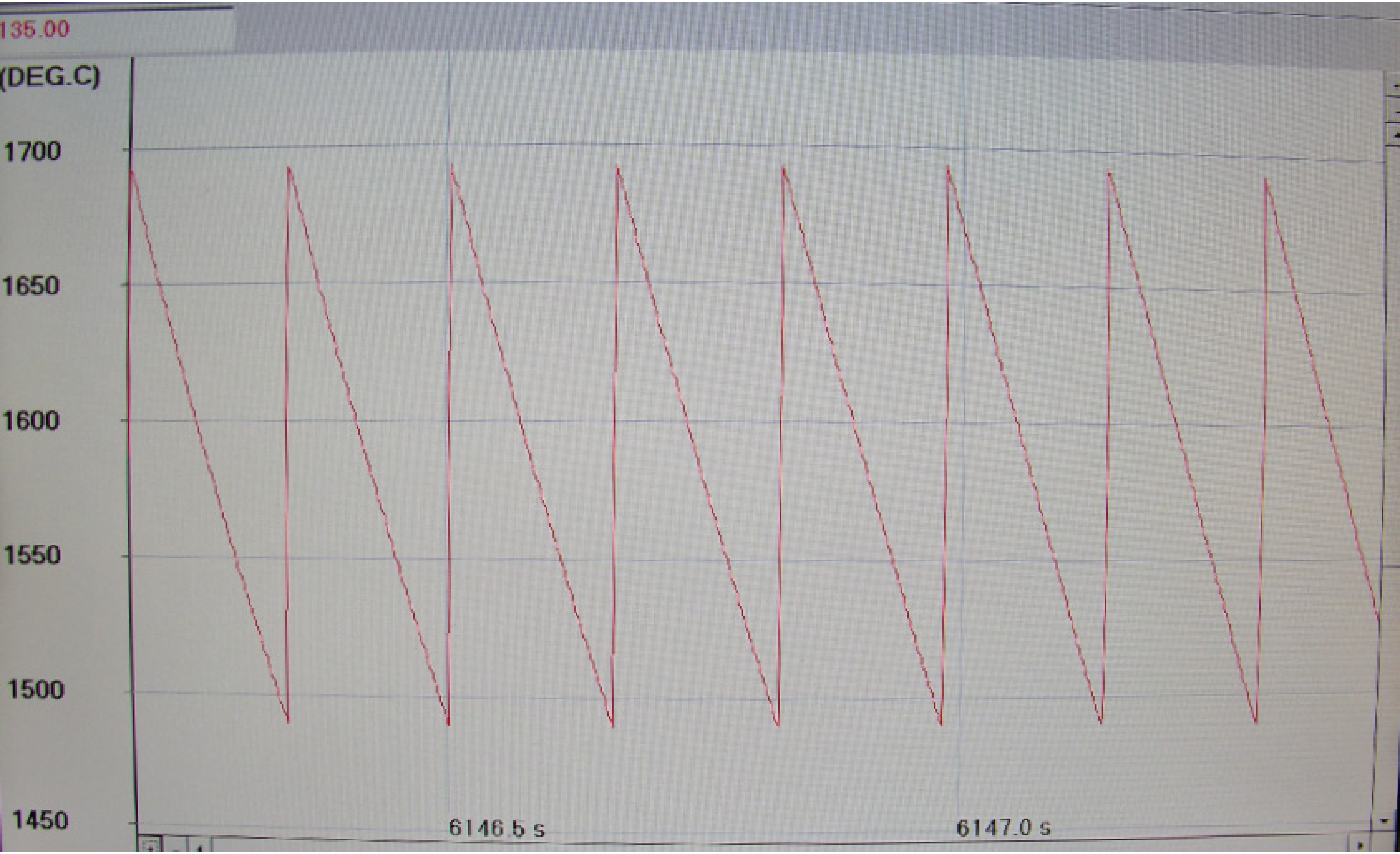
Picture of the pulse current, 200 ns/division



Picture of the pulse current, 1 μs/division

Picture of the wire test equipment





Measurement of the Pulse Temperature

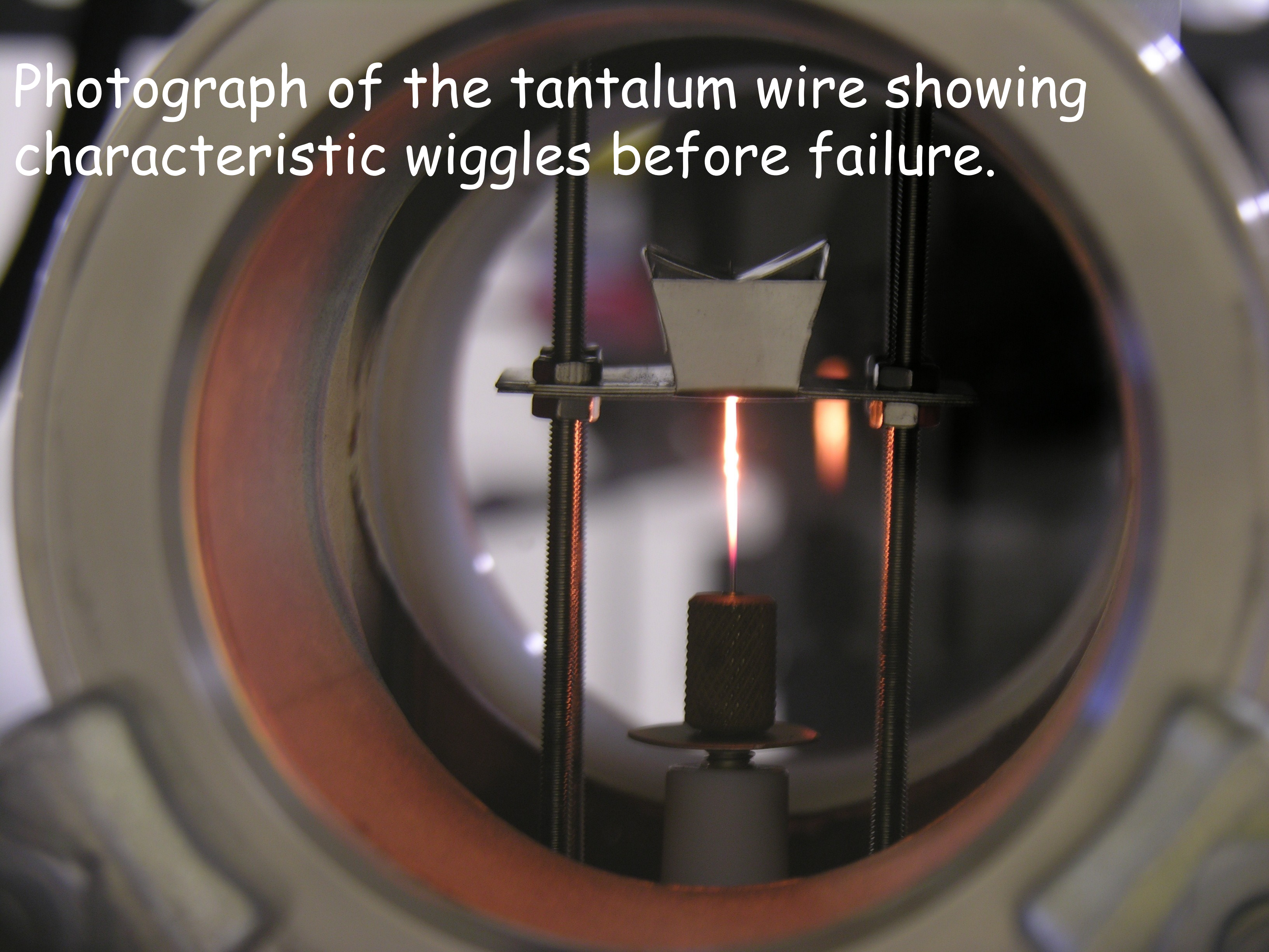
1 kHz measurement rate

Tests on Tantalum Wire

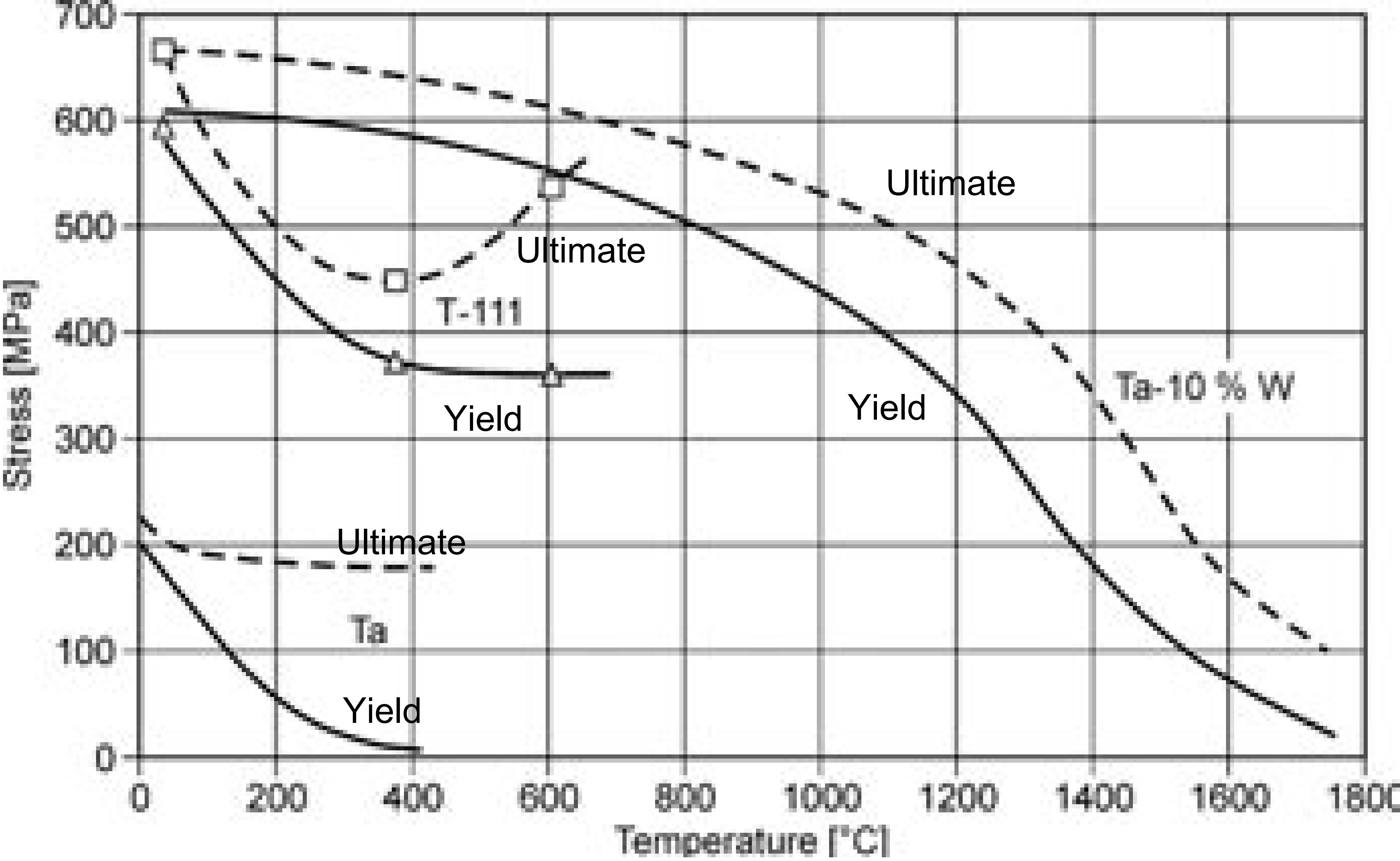
The wire lasted for a few hundred thousand pulses before breaking or bending.

Tantalum is not a suitable material since it too weak at high temperatures (1600-2000 K).

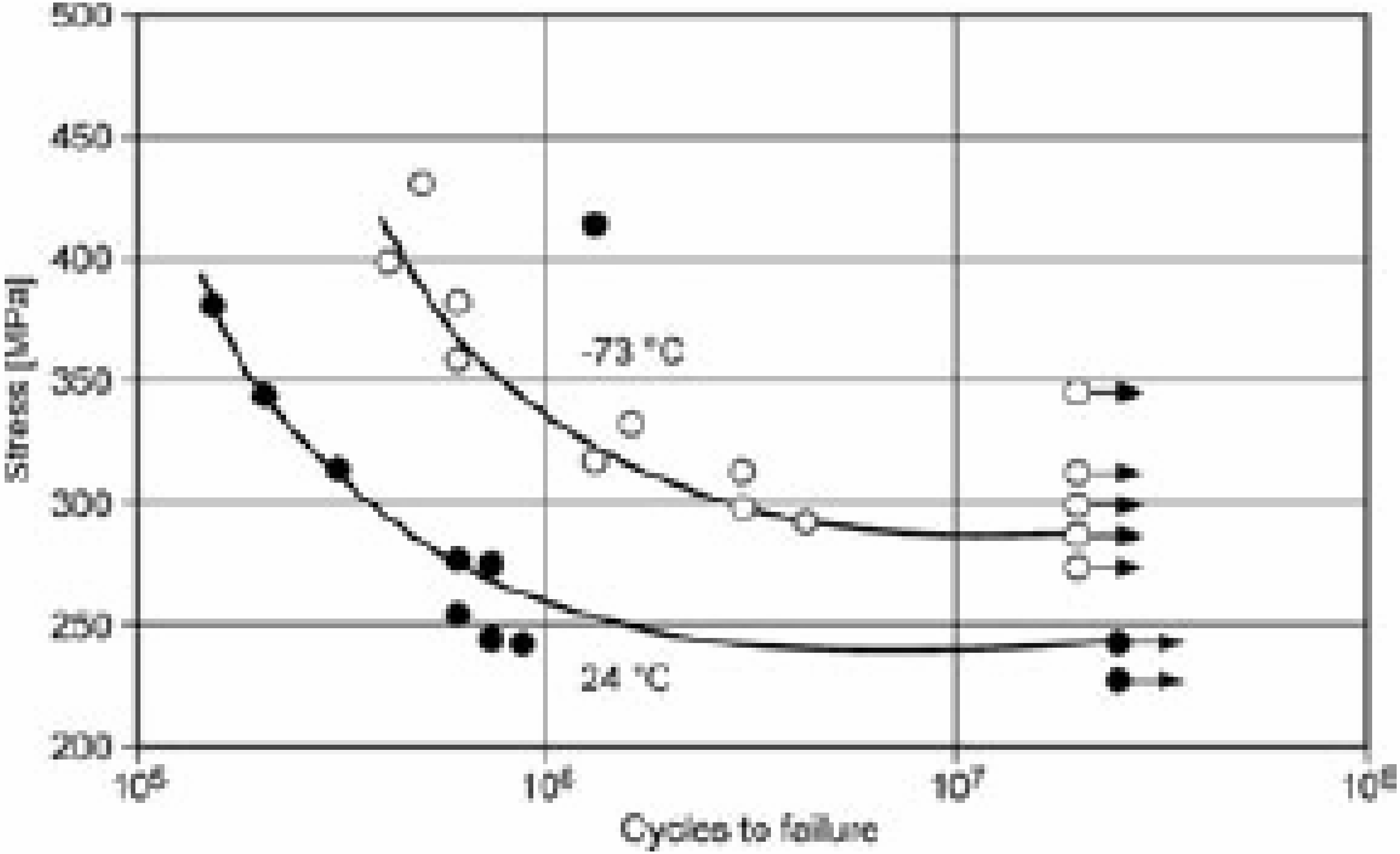
Photograph of the tantalum wire showing characteristic wiggles before failure.



A broken tantalum wire

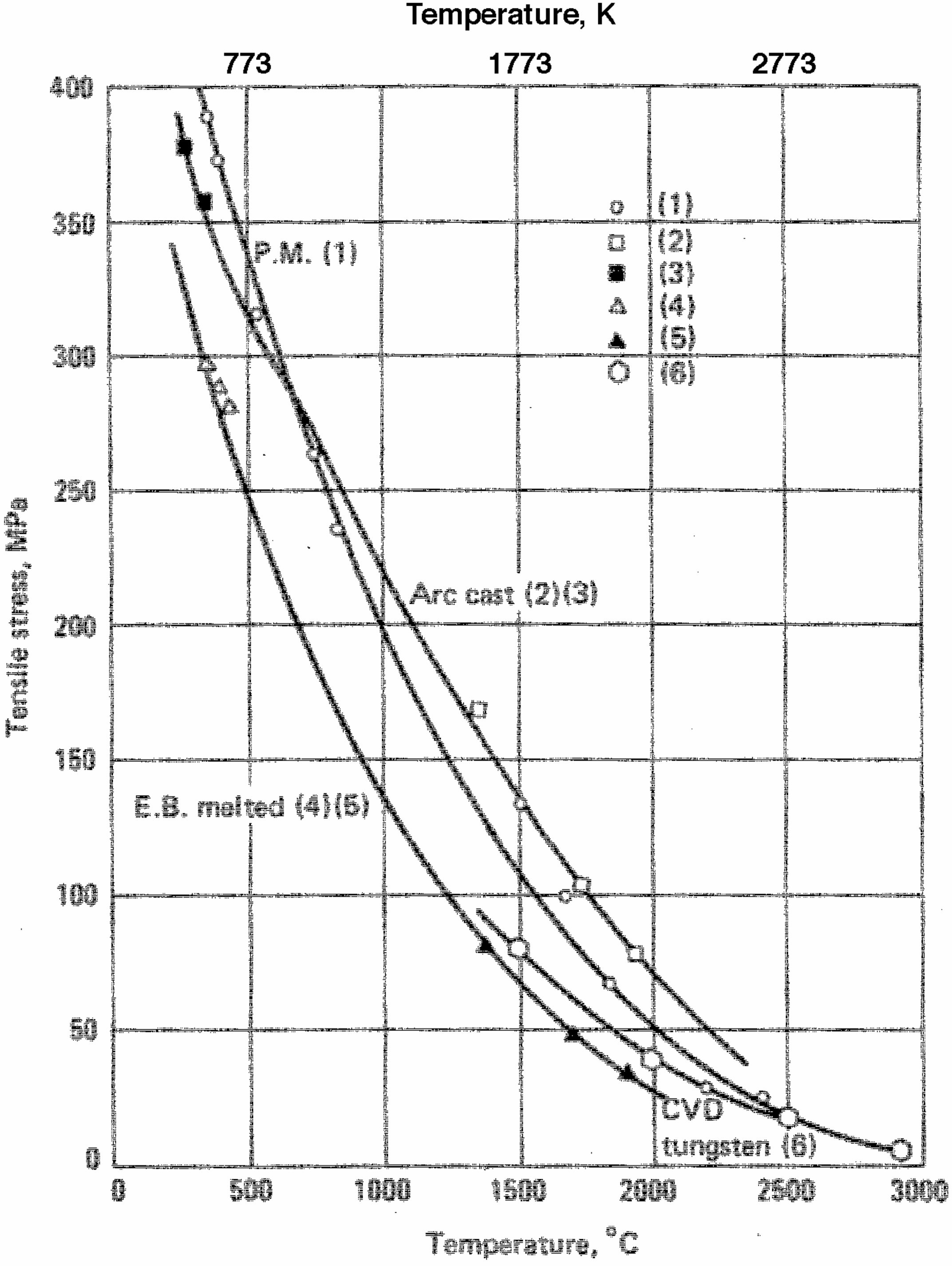


Yield and Ultimate Strength of Tantalum and alloys versus Temperature.

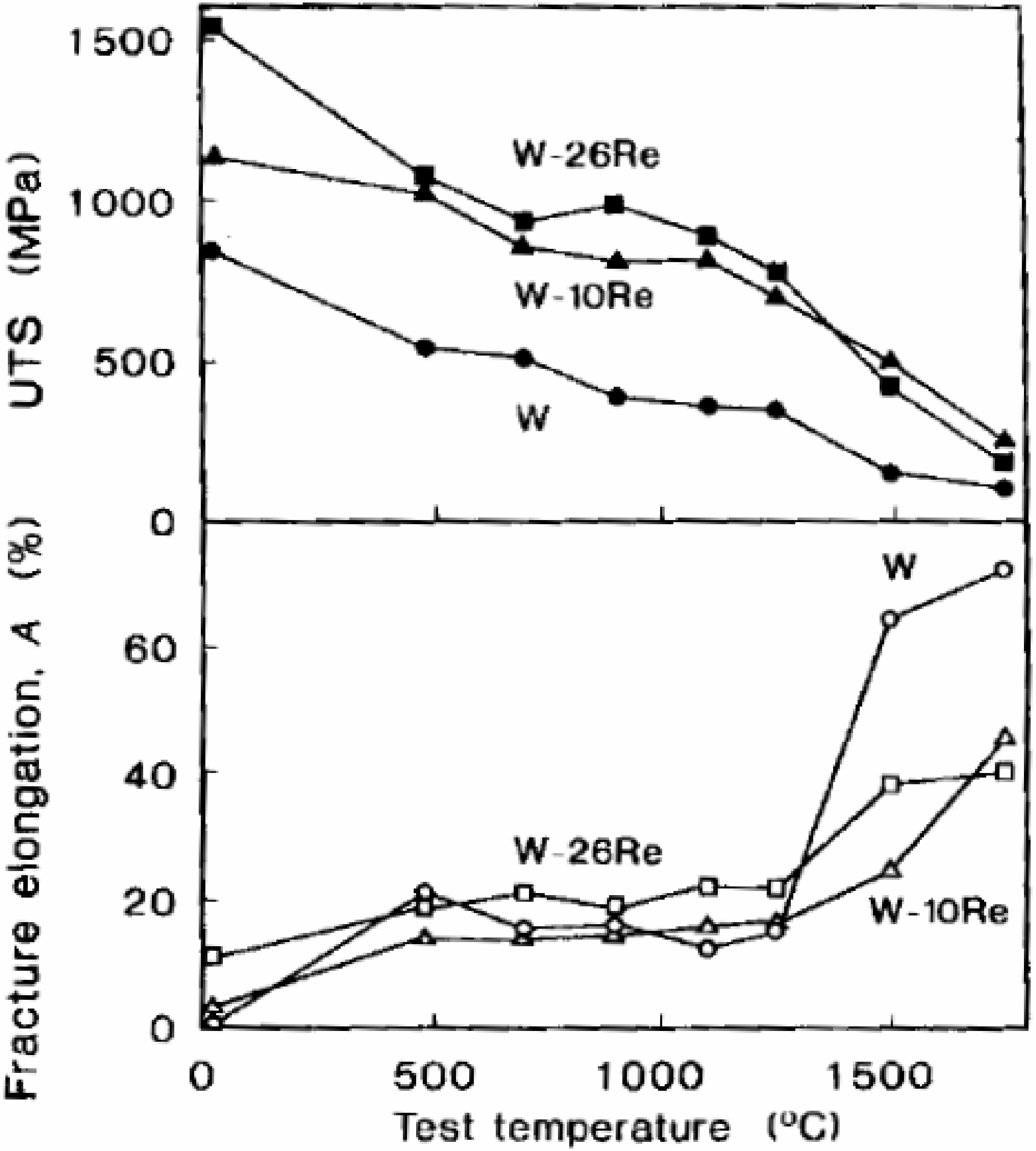


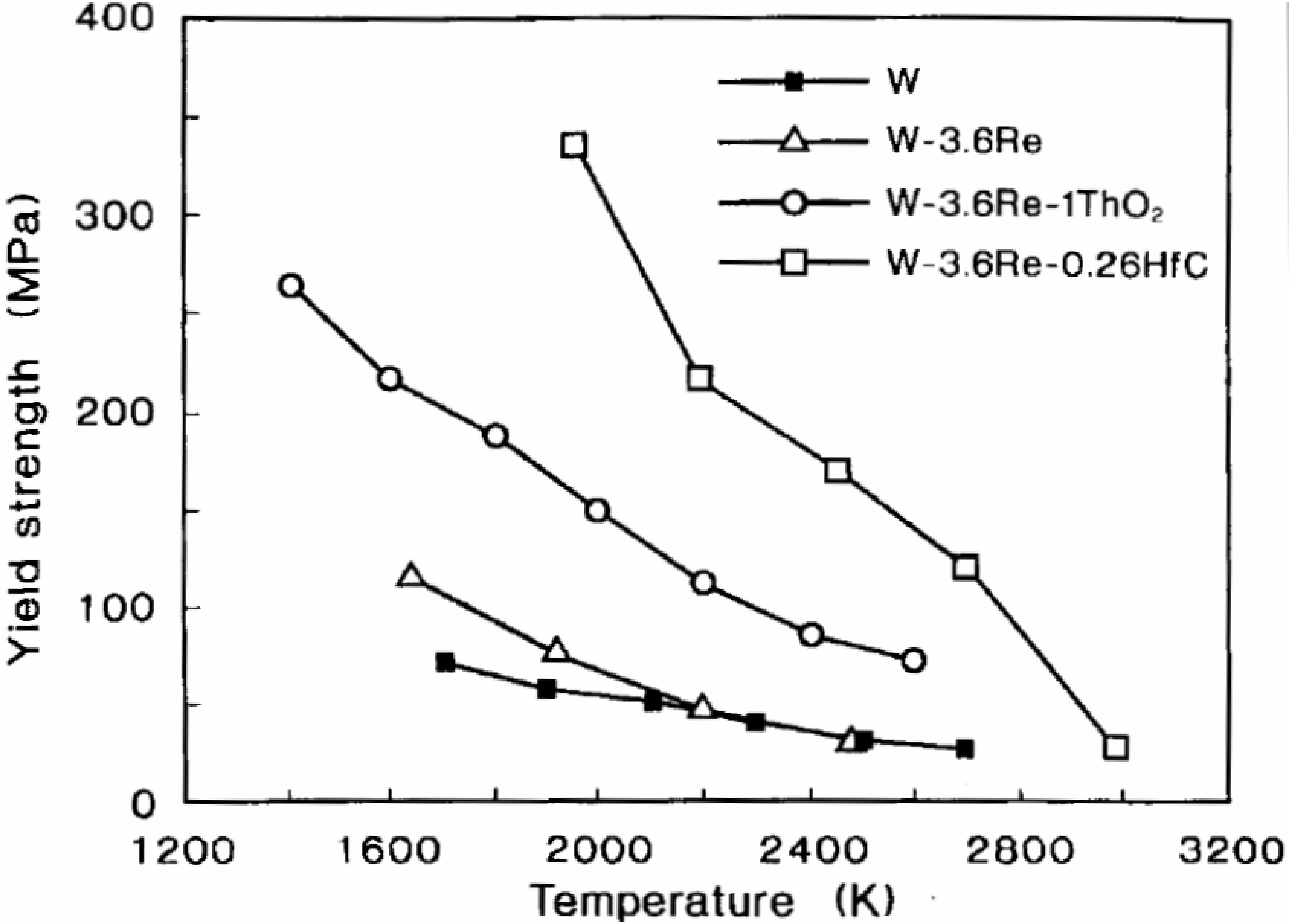
Fatigue characteristics of 1 mm thick tantalum sheet

Ultimate Tensile Strength of Tungsten Rods produced by various methods

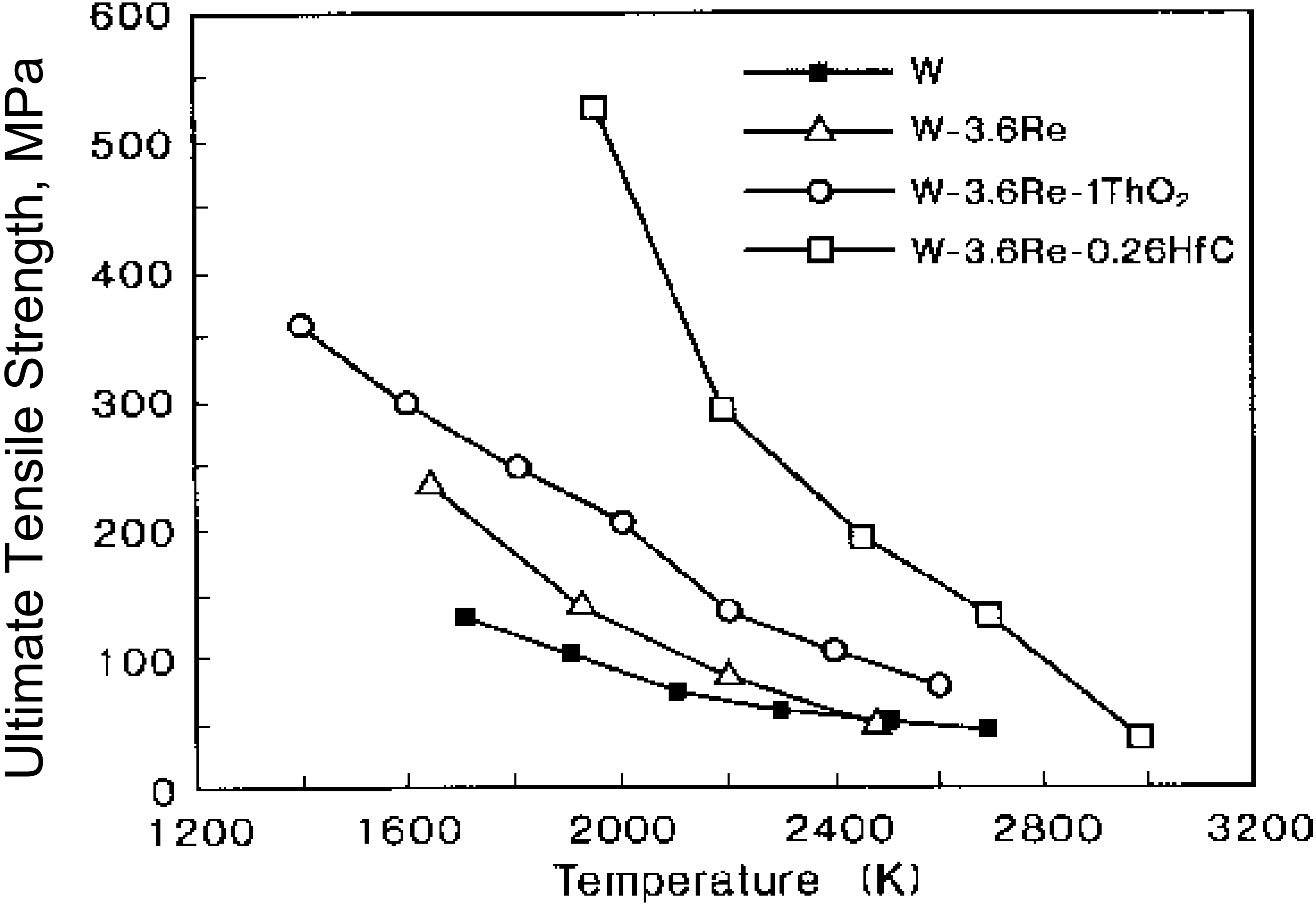


Ultimate Tensile Strength versus Temperature of Tungsten and some Alloys





Yield Strength of Tungsten and some Alloys versus Temperature



Ultimate Tensile Strength of Tungsten and some Alloys versus Temperature

Tests on Tungsten Wire

Tungsten is much stronger than Tantalum particularly at high temperatures.

So - try Tungsten

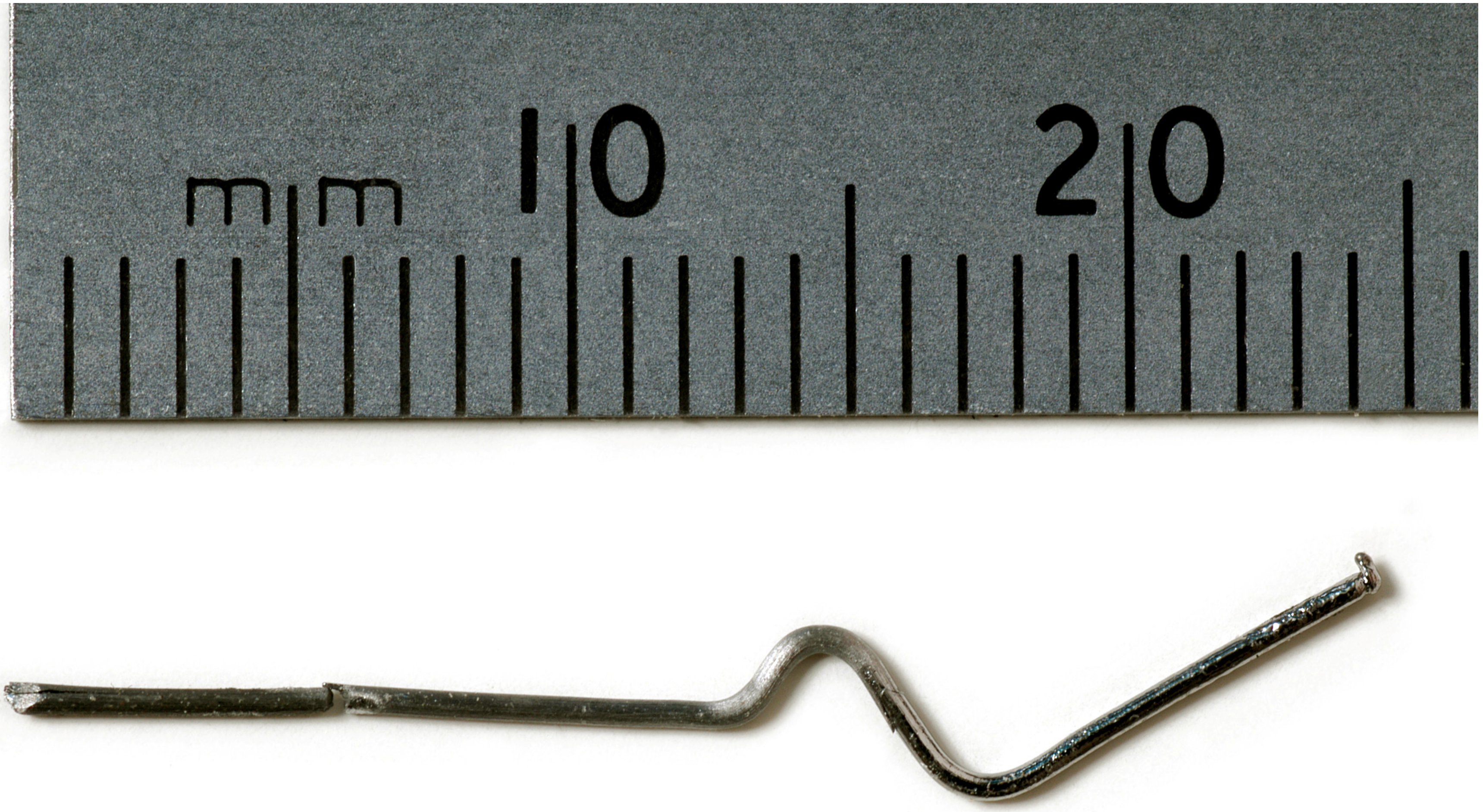
Some Results: 0.5 mm diameter Tungsten Wires

Target Number	Pulse Current A	Temp Jump K	Peak Temp K	Number of Pulses to Failure	Comments	Equivalent Power, MW, in Target Diameter	
						2 cm	3 cm
W03	4900 7200	90 200	2000 2200	>3.4x10^6 16,500	Broke	2.3	4.8
W08	6400	150	1900	>1.6x10^6	Wire stuck to top connection (cu blocks)	3.9	8.4
W09	5560 5840	120 130	1900 2050	4.2x10^6 9x10^6	Top connector failed	3 3.3	6.4 7.0
W15	6400	180	1950	1.3x10^6	Wire stuck to top connection (cu blocks)	3.9	8.4
W26	6200 7520-8000	140 ~230	2000 ~1800	10x10^6 3x10^6	Broke	3.6 ~6	7.8 ~12
W28	6560	180	1900	>19x10^6	Still running	4.1	8.8

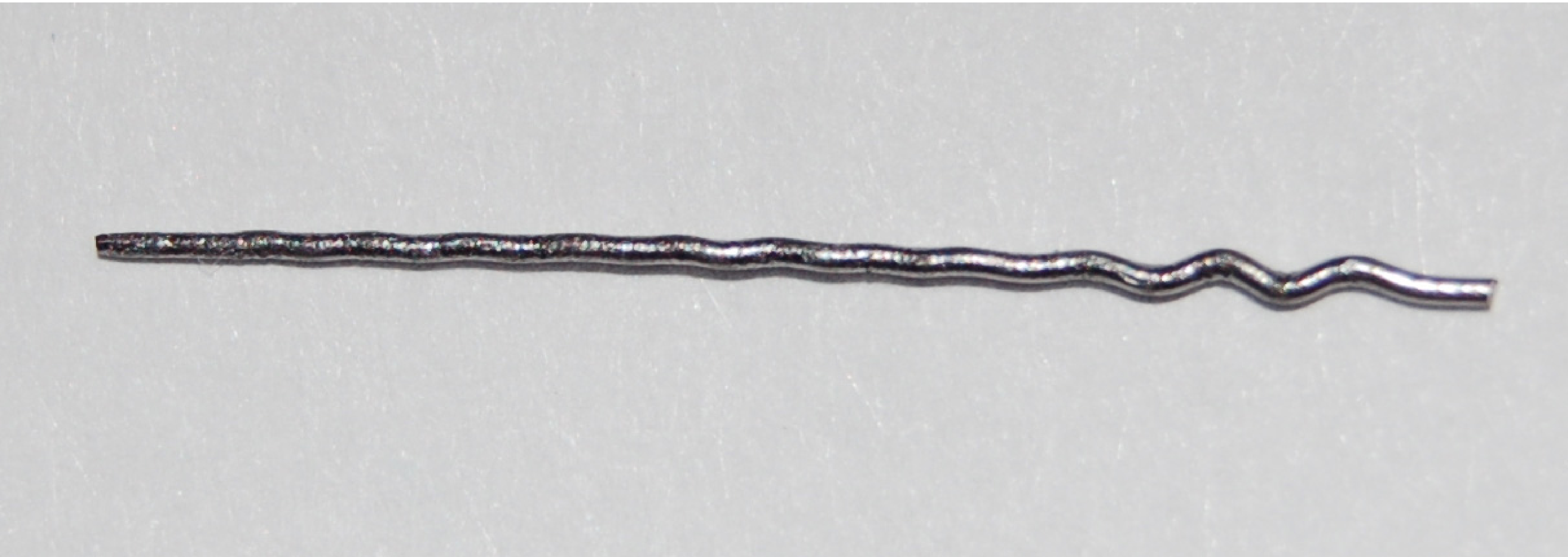
"Equivalent Target": This shows the equivalent beam power (MW) and target radius (cm) in a real target for the same stress in the test wire. Assumes a parabolic beam distribution and 3 micro-pulses per macro-pulse of 20 micro-s.

W26

Broken Tungsten Wire after 13 million pulses.



W3 Tungsten Wire, after operating at 4900 A, peak temperature 1800 K, for 3.3×10^6 pulses and then a few pulses at 7200 A at >2000 K.



W5 Tungsten Wire showing “wiggles”: 6200 A, >2000 K peak temperature, 5625 pulses.

Individual pulses are not the problem.

Failure found after **Many Pulses** - the problem is:-

Fatigue

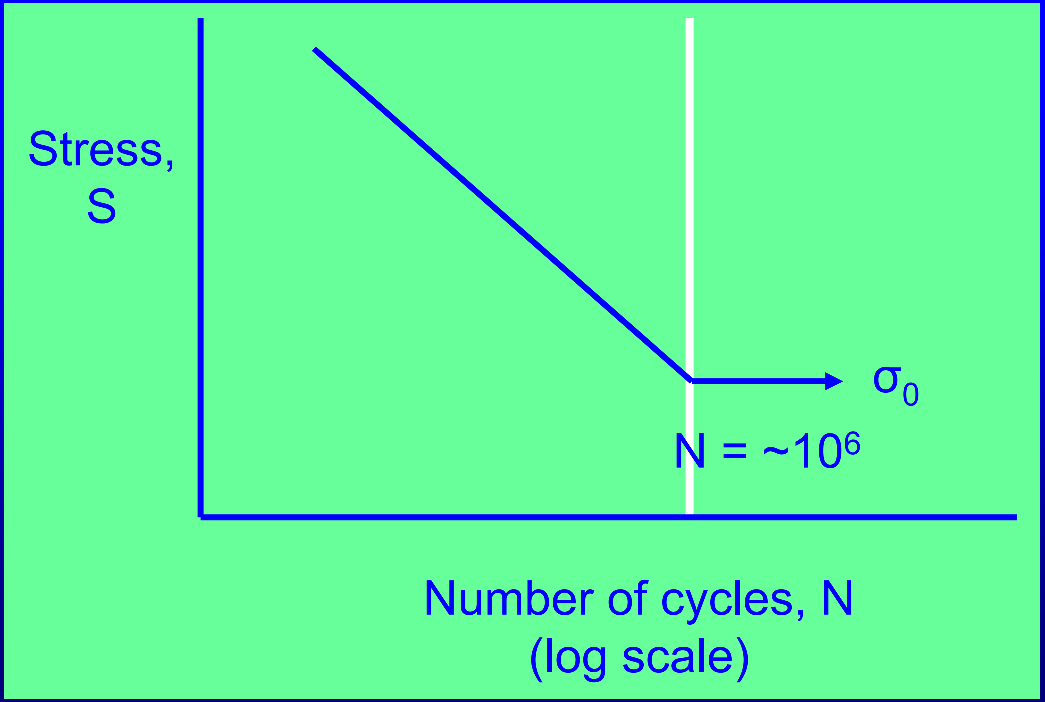
&

Creep

Fatigue and Creep

Very difficult to predict the number of cycles to failure.

S-N or Wöhler Plot – stress versus number of cycles to failure.



The Fatigue Limit Stress can be expressed by:

$\sigma_0 = 1.6\ H_v \pm 0.1H_v$

H_v - Vickers Hardness in kgf mm^{-2}

For tungsten at ~1800 K

$H_v = 50$

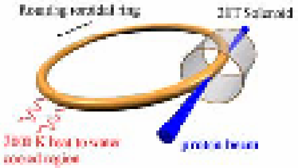
so the fatigue limit stress is

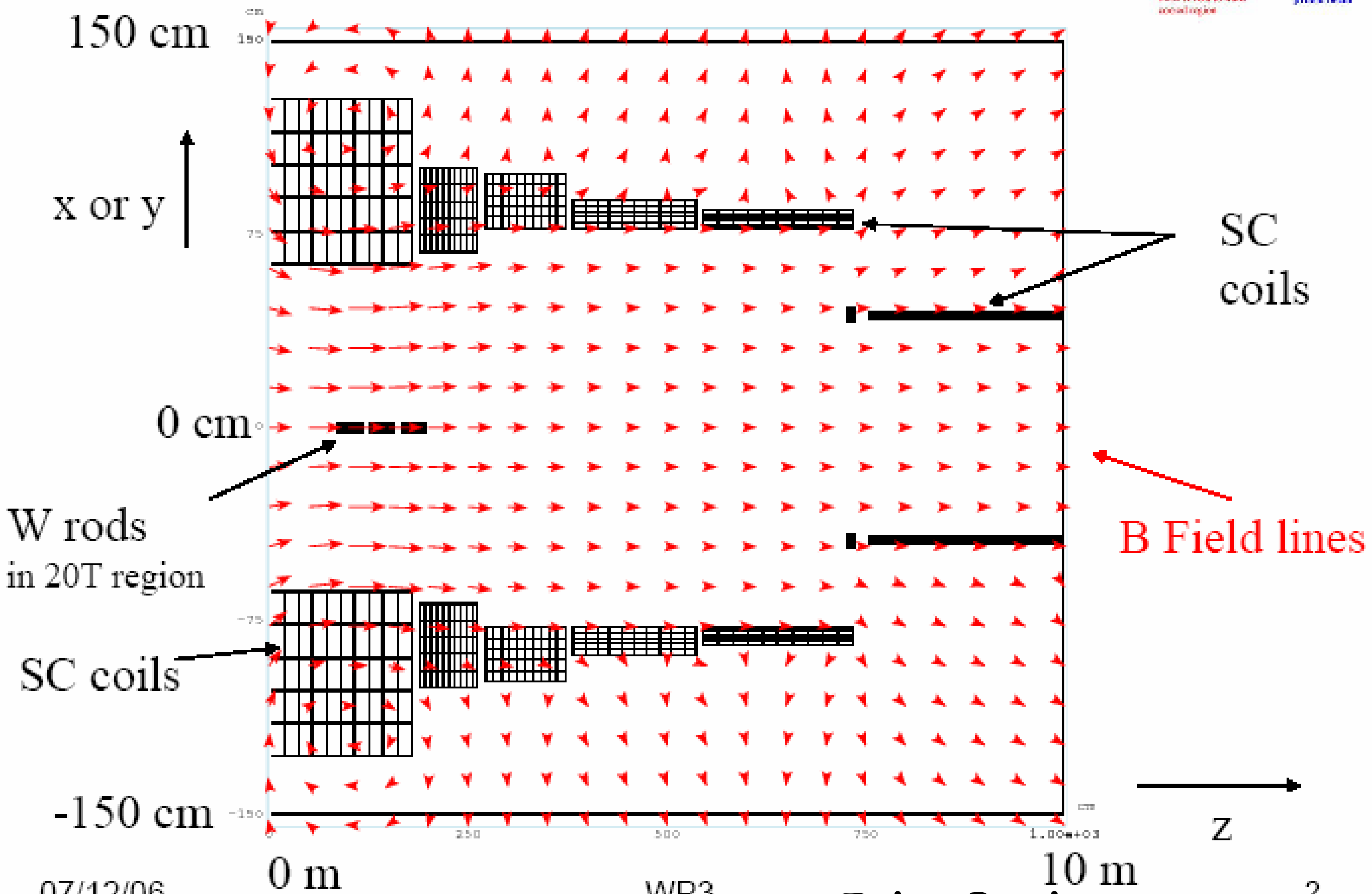
$\sigma_0 = 80$ MPa

Radiation Damage

1. Experience on the ISIS targets show that there is no serious problem up to ~12 dpa.
2. Tungsten pellets irradiated (~15-20 dpa) at PSI will be examined when cool enough.

Reminder: B Field and Geometry





SC coils

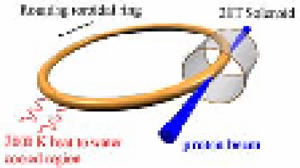
W rods in 20T region

SC coils

B Field lines

John Back

π and μ re-absorption ratios for W target



	Number of π & μ per proton per GeV at plane 2 (+ve charge, -ve charge)			Number of π & μ per proton per GeV at plane 3 (+ve charge, -ve charge)		
Rod diameter	1 cm	2 cm	3 cm	1 cm	2 cm	3 cm
1 rod	0.460	1.012	0.906	0.460	1.014	0.909
	0.482	1.035	0.917	0.481	1.035	0.915
3 rods	0.401	0.806	0.663	0.355	0.657	0.495
	0.402	0.801	0.644	0.350	0.631	0.463
1 rod/3 rods	1.15	1.26	1.37	1.30	1.54	1.84
	1.20	1.29	1.42	1.37	1.64	1.98

MARS Simulation: 10 GeV protons on 1, 2 and 3 cm diameter W rods in 20 T field.

Conclusions

I believe that the viability of solid tungsten targets at high-temperature for a long life (~10 years) has been demonstrated with respect to thermal shock and fatigue and will not suffer undue radiation damage.

Future Programme

1. Continue wire tests with Tungsten and Graphite.
2. VISAR measurements to asses the properties of tungsten, and any changes, during the wire tests. (Effect of thermal shock.)
3. Tests with a proton beam – limited number of pulses possible – to confirm wire tests and VISAR measurements.
4. Radiation damage studies.