High-Power Targets for Neutrino Factories and Muon Colliders

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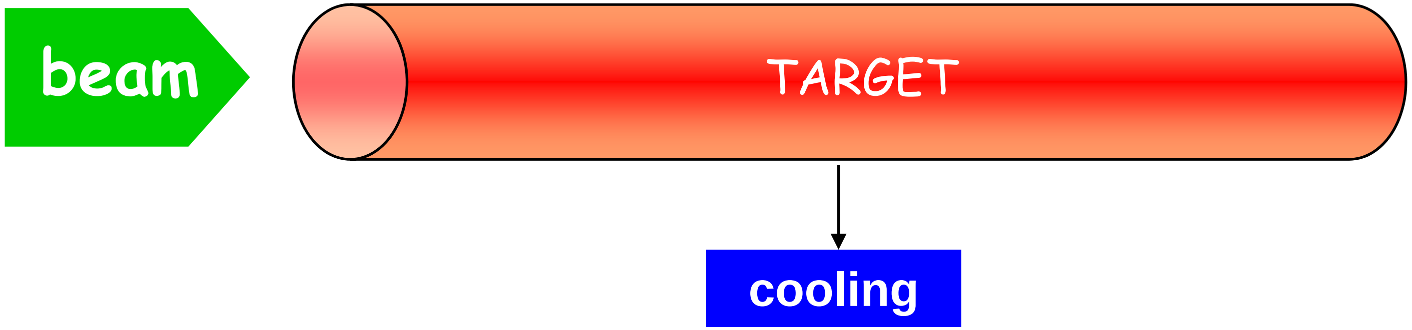
Topical Workshop on the Neutrino Factory and Muon Collider, the Physics and the R&D Programmes
Cosener's House, Abingdon, Oxfordshire, UK, 22-24 October 2007

Outline

1. Principles of high-power target design.
2. Some examples of high-power targets.
3. Neutrino Targets.

The most obvious effect of a beam hitting a target is heating – therefore must **cool the target**



Cooling is made easier if the target is large –

i.e. a low energy density

Water is a very effective coolant.

(Power stations have hundreds of MWs of water cooling.)

Target Problem Areas

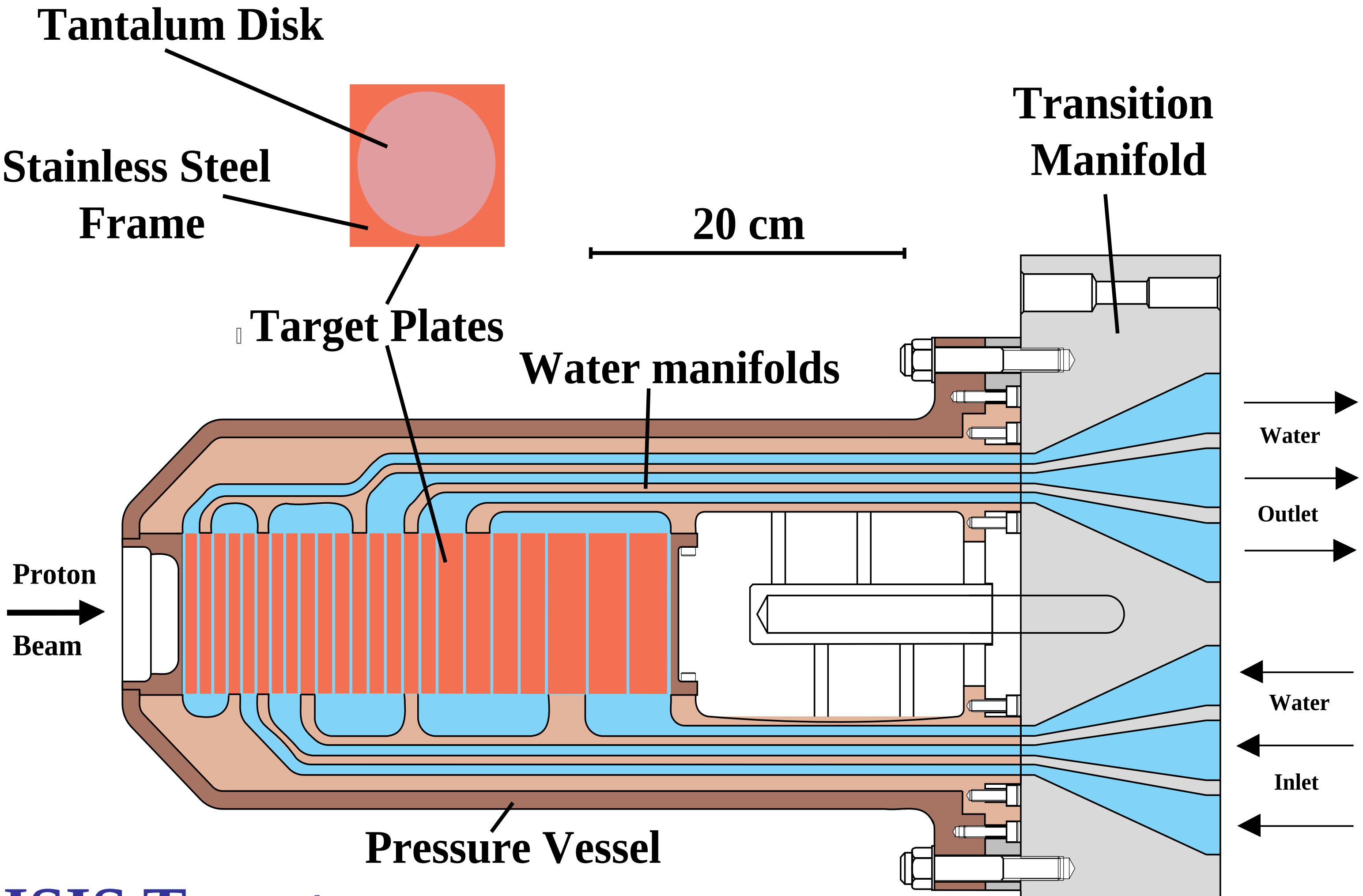
1. Cooling.
2. Thermal shock for pulsed beams.
3. Radiation Damage.

In all cases the severity of the problem increases with the energy density (power density) in the target – until it becomes very difficult to achieve sufficient cooling, etc.

To solve the problem of very high energy (power) densities it is necessary to have a moving or flowing liquid target.

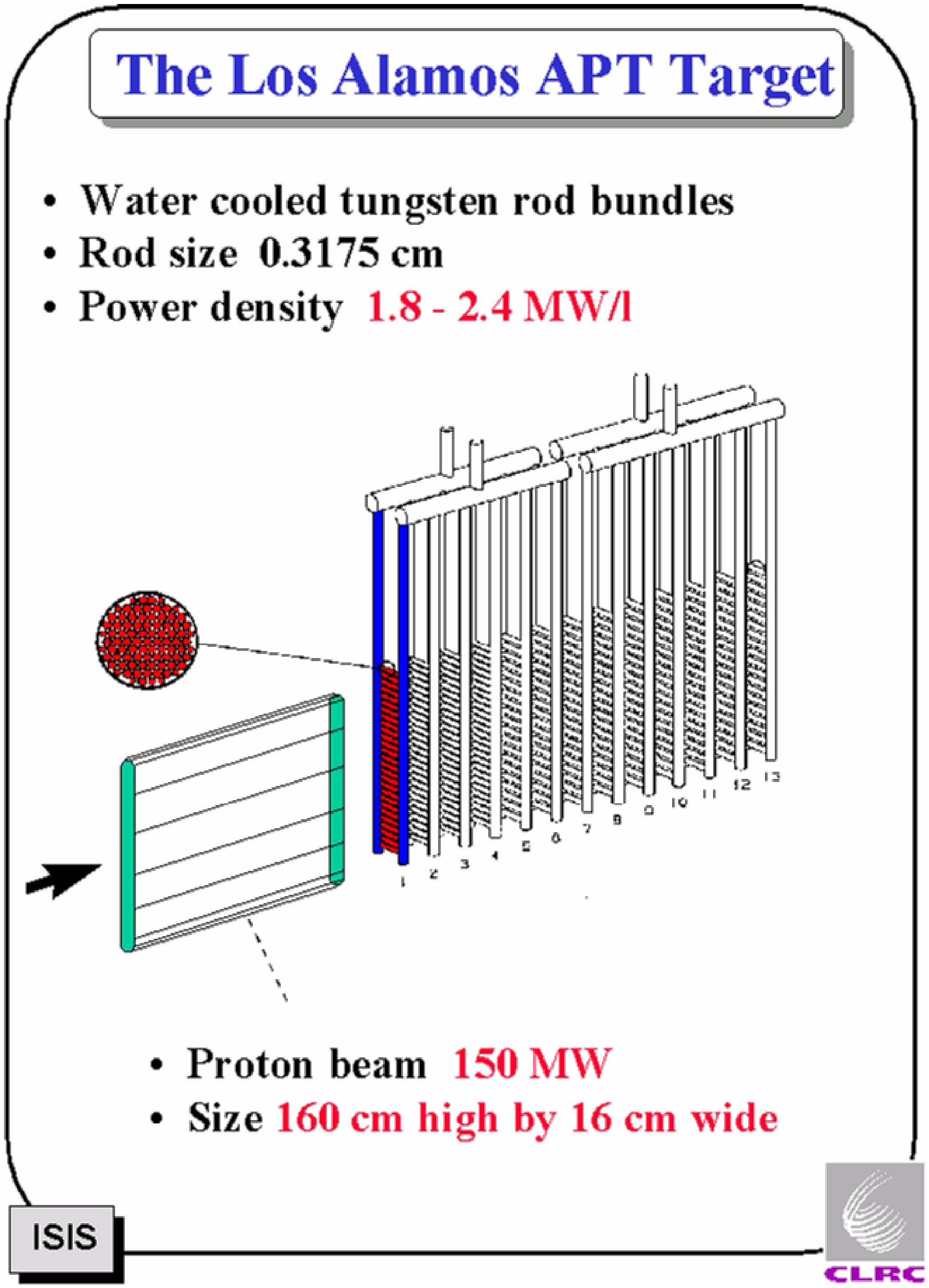
Let us look at a number of examples of existing and proposed targets.

Here is an example of a relatively low energy density pulsed target with conventional water cooling. 200 kW average at 50 Hz into a 10x10x30 cm^2 target (peak power ~500 W cm^{-3}).



The ISIS Target

An example of a high power (up to 200 MW), but low power density target.



The Los Alamos APT Target

- Water cooled tungsten rod bundles
- Rod size 0.3175 cm
- Power density 1.8 - 2.4 MW/l

- Proton beam 150 MW
- Size 160 cm high by 16 cm wide

Tim Broome, RAL

And an example of very high energy density, but very low average power – **the Pbar Target at FNAL.**

The beam is very small, σ = 140 μm.

The peak energy density during the pulse is >3000 J g^{-1} - or 25000 J cm^{-3} (Inconel).

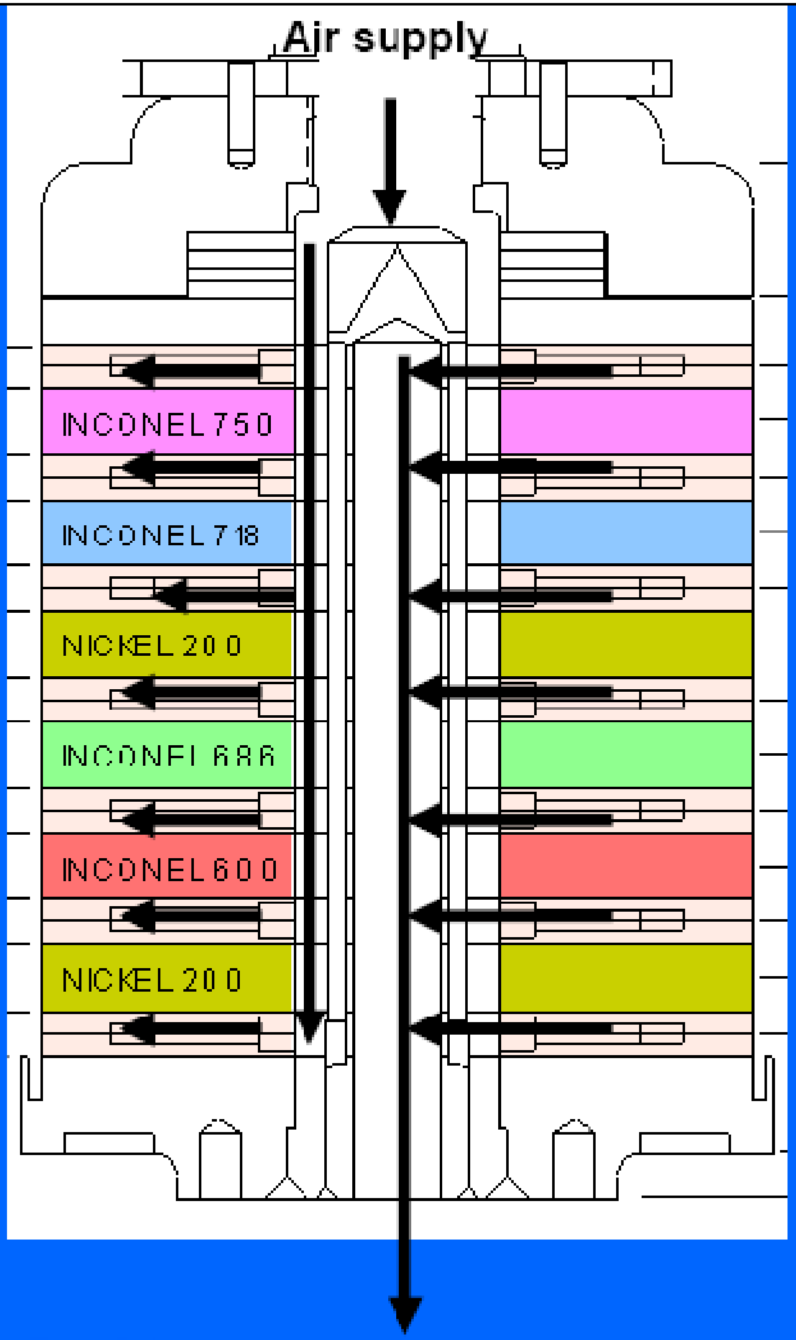
With tantalum have achieved >40000 J cm^{-3}.

With these energy densities the target melts during the pulse and then solidifies before the next pulse. But one sees spalling at the beam entry and exit.

Pictures from Anthony Leveling - presentation at the 3rd High-Power Target Workshop, Bad Zurzach, Switzerland, September 2007.

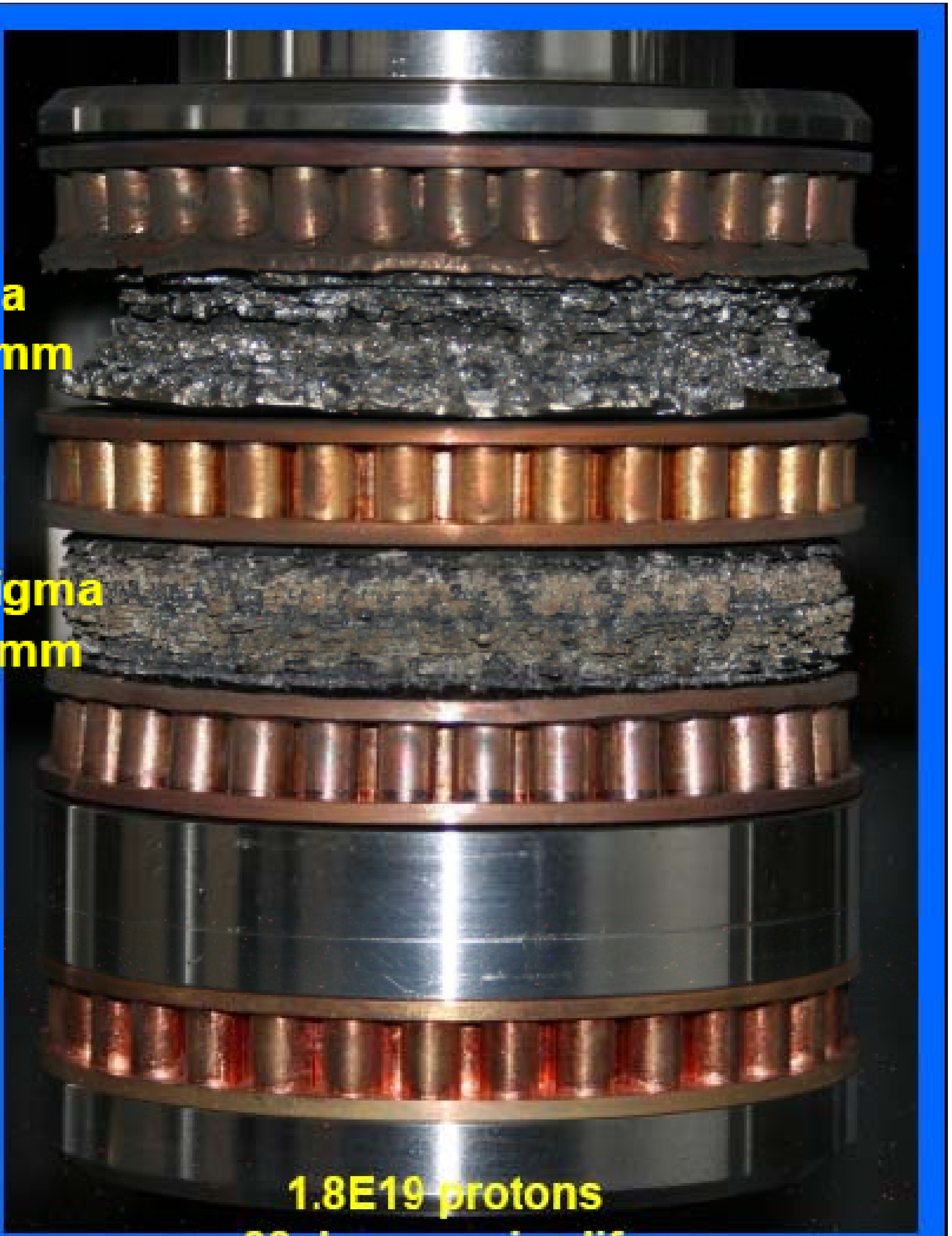
3.1E19 protons – 525 day service life
1/03 to 7/04

Target 2
Six 0.95 X 10 cm diameter target disks
Seven copper cooling disks



Air exhaust

Target 8



Top disk - 200 micron beam sigma
with beam sweeping radius ~0.3 mm

Middle disk – 140 micron beam sigma
With beam sweeping radius ~0.6 mm

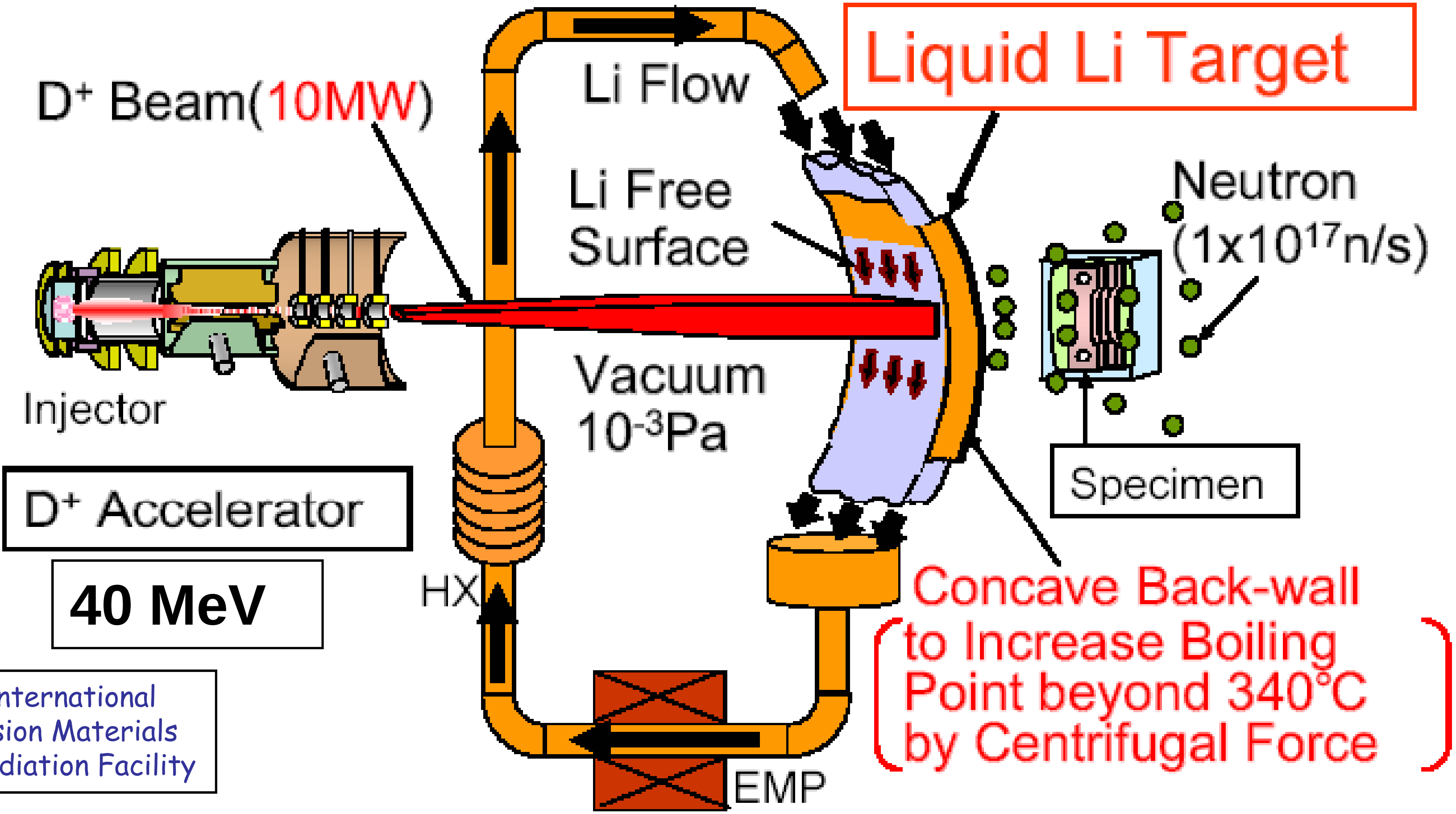
Beam sweeping system
commissioned late 4/07

1.8E19 protons
88 days service life
5/07 to present

IFMIF Target of Flowing Lithium

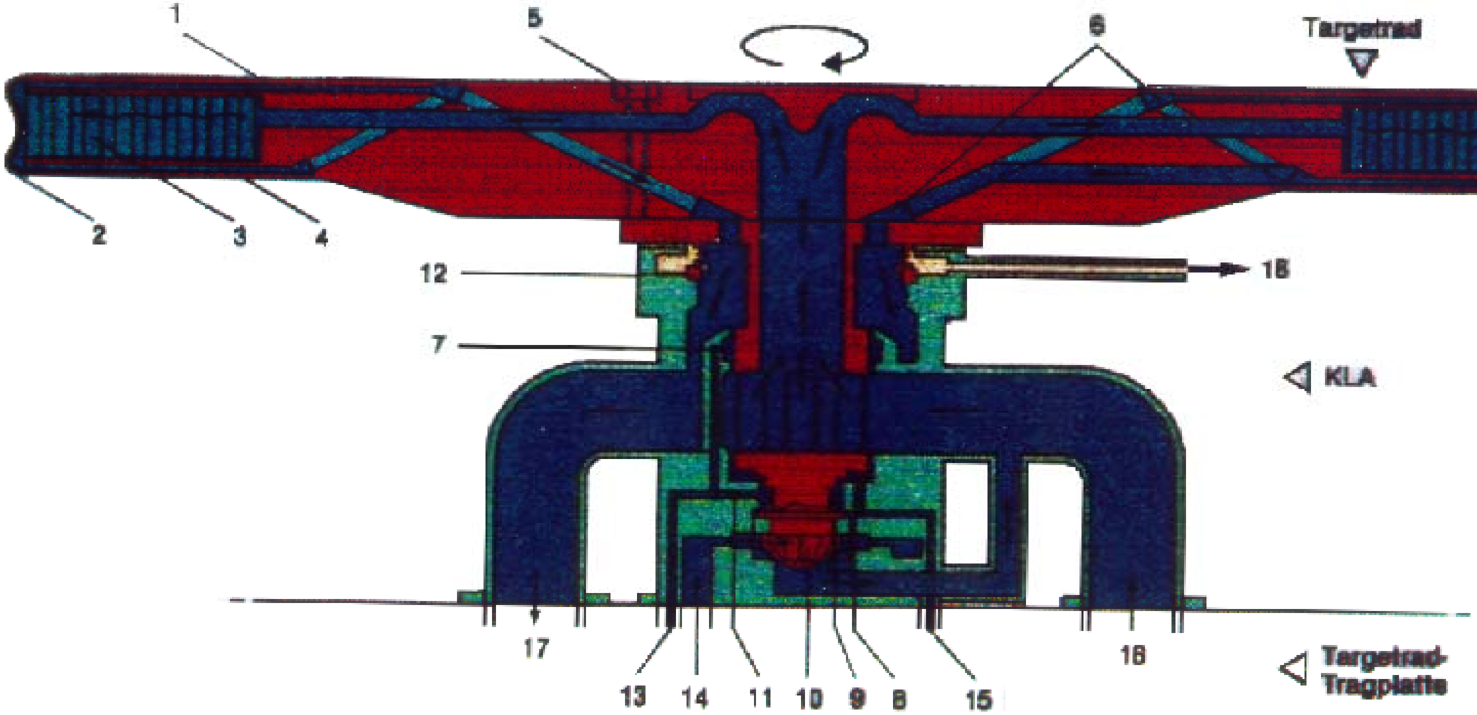
Concept of D-Li Neutron Source

High-speed liquid Li flow along concave back-wall is selected as Li target to handle high heat load (1GW/m^2) of 10MW D$^+$ beams.

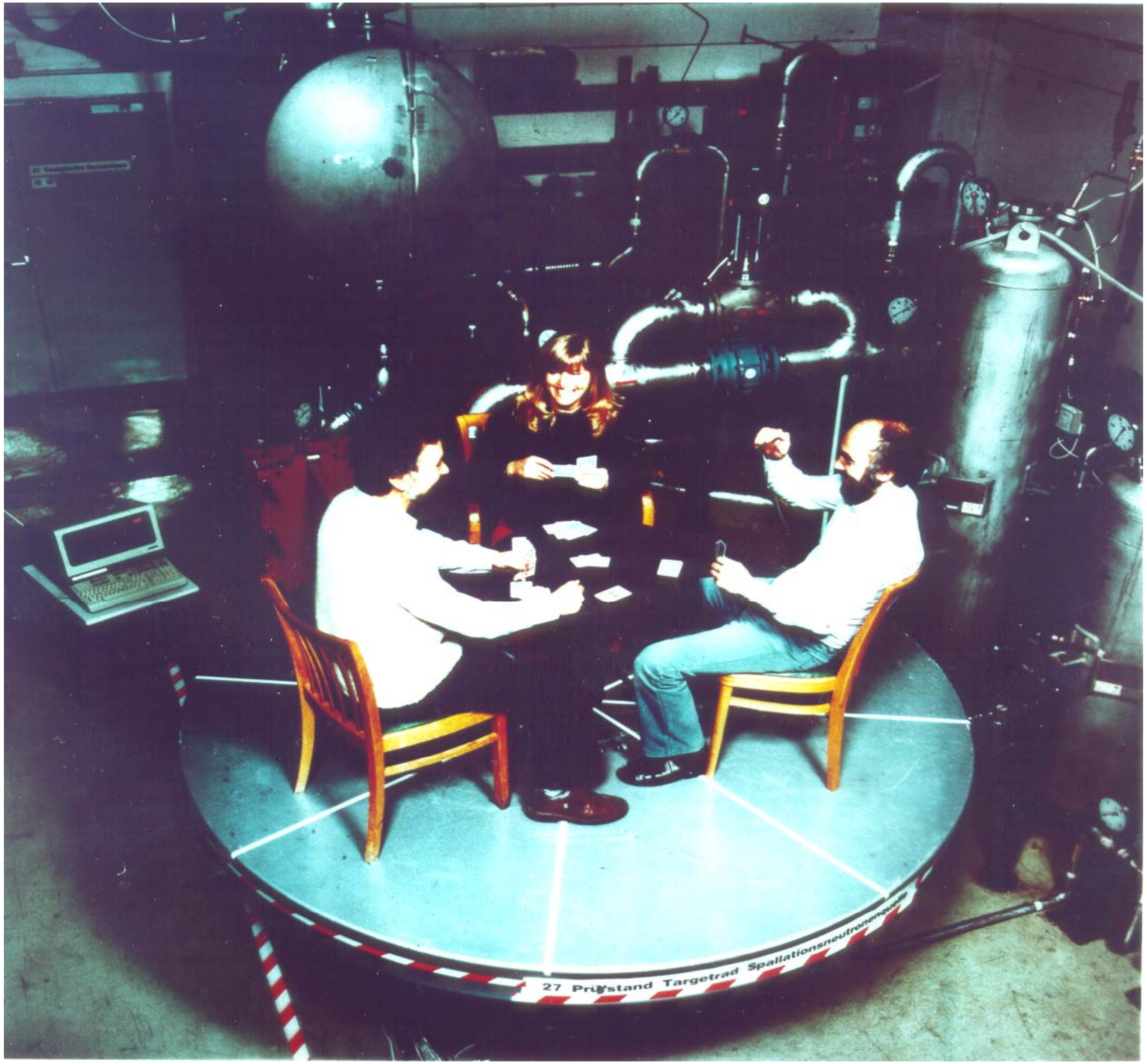


International Fusion Materials Irradiation Facility

A large rotating disc, water cooled for neutrons. Dissipating 900 W average, 500 W cm^{-3} peak.

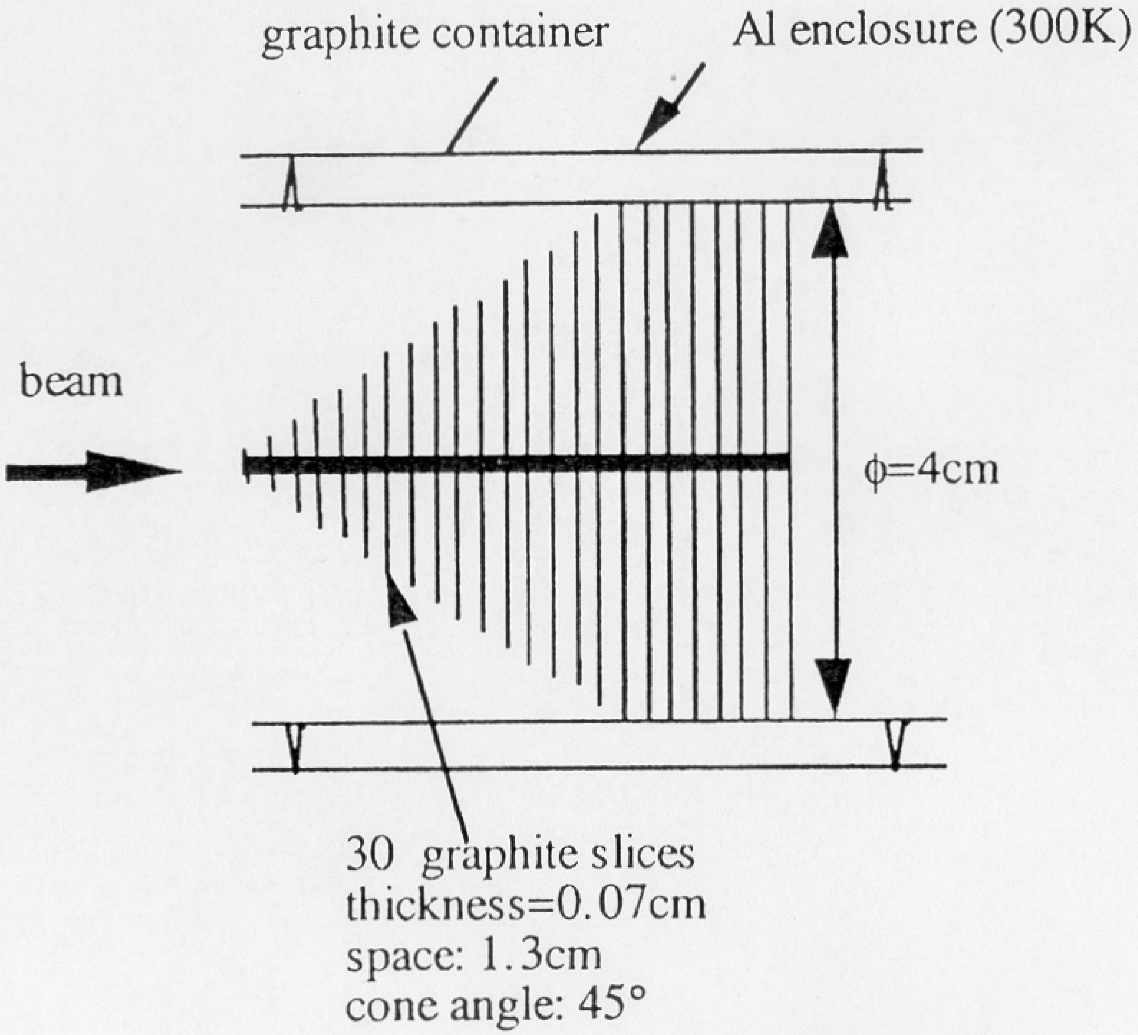


Section through SNQ Target



SNQ Target Wheel

Heavy ions because of their short range produce very high energy densities in the target (5000 W cm^{-3}, 2 kW beam power). The graphite target at GANIL overcomes the problem by allowing the target to become very hot and radiating the power and by extending the effective surface area by making a coned shaped target consisting of discs.

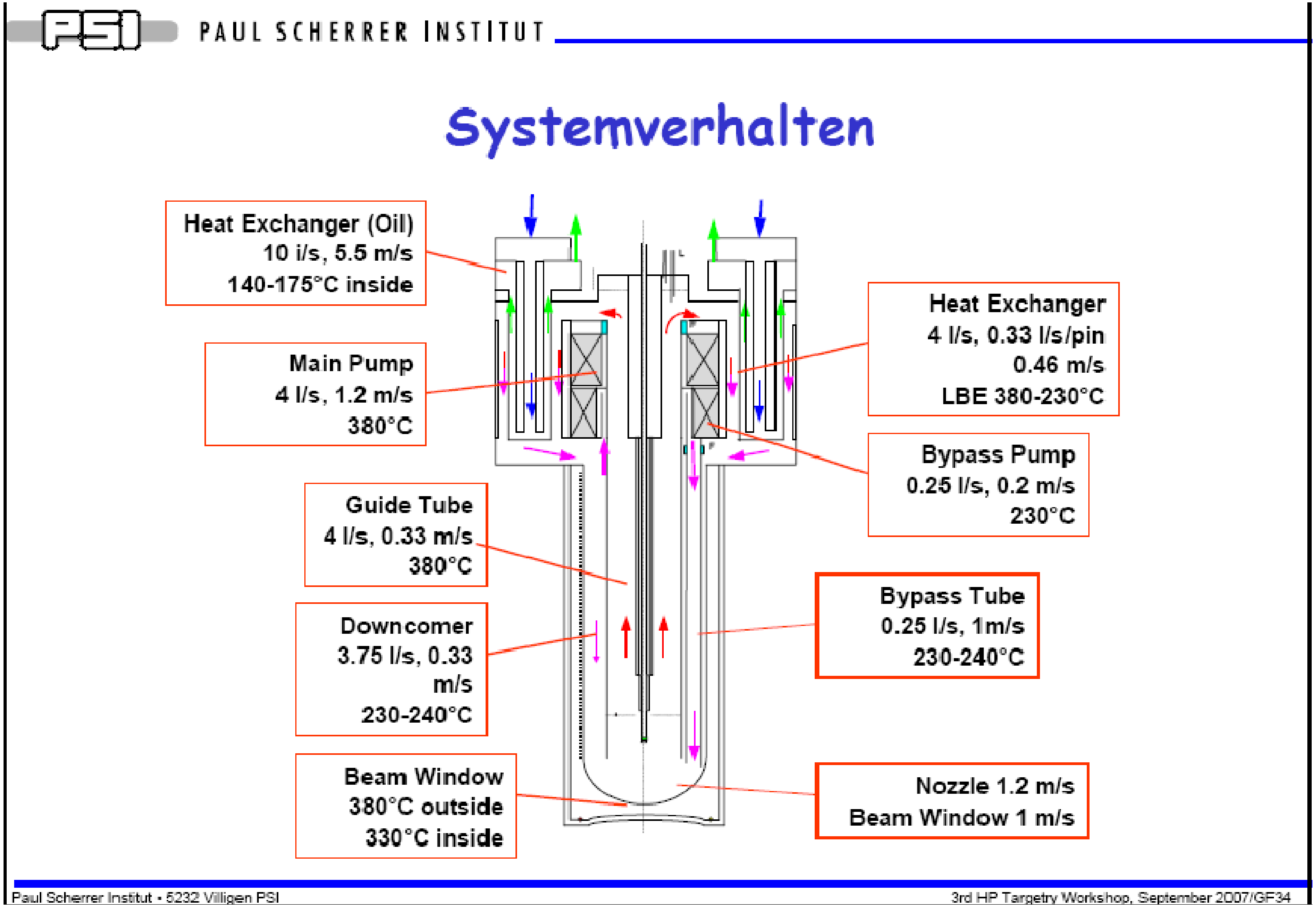


Schematic representation of the conical target.

SPIRAL Heavy Ion Target for Radioactive Ion Beams

MEGAPIE Target at PSI

Flowing liquid metal Lead bismuth eutectic) target for neutron production.
Power dissipated in the target = 415 kW mA^{-1} of beam, gives 600 kW.



PAUL SCHERRER INSTITUT

Systemverhalten

Heat Exchanger (Oil)
10 l/s, 5.5 m/s
140-175°C inside

Main Pump
4 l/s, 1.2 m/s
380°C

Guide Tube
4 l/s, 0.33 m/s
380°C

Downcomer
3.75 l/s, 0.33 m/s
230-240°C

Beam Window
380°C outside
330°C inside

Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
LBE 380-230°C

Bypass Pump
0.25 l/s, 0.2 m/s
230°C

Bypass Tube
0.25 l/s, 1m/s
230-240°C

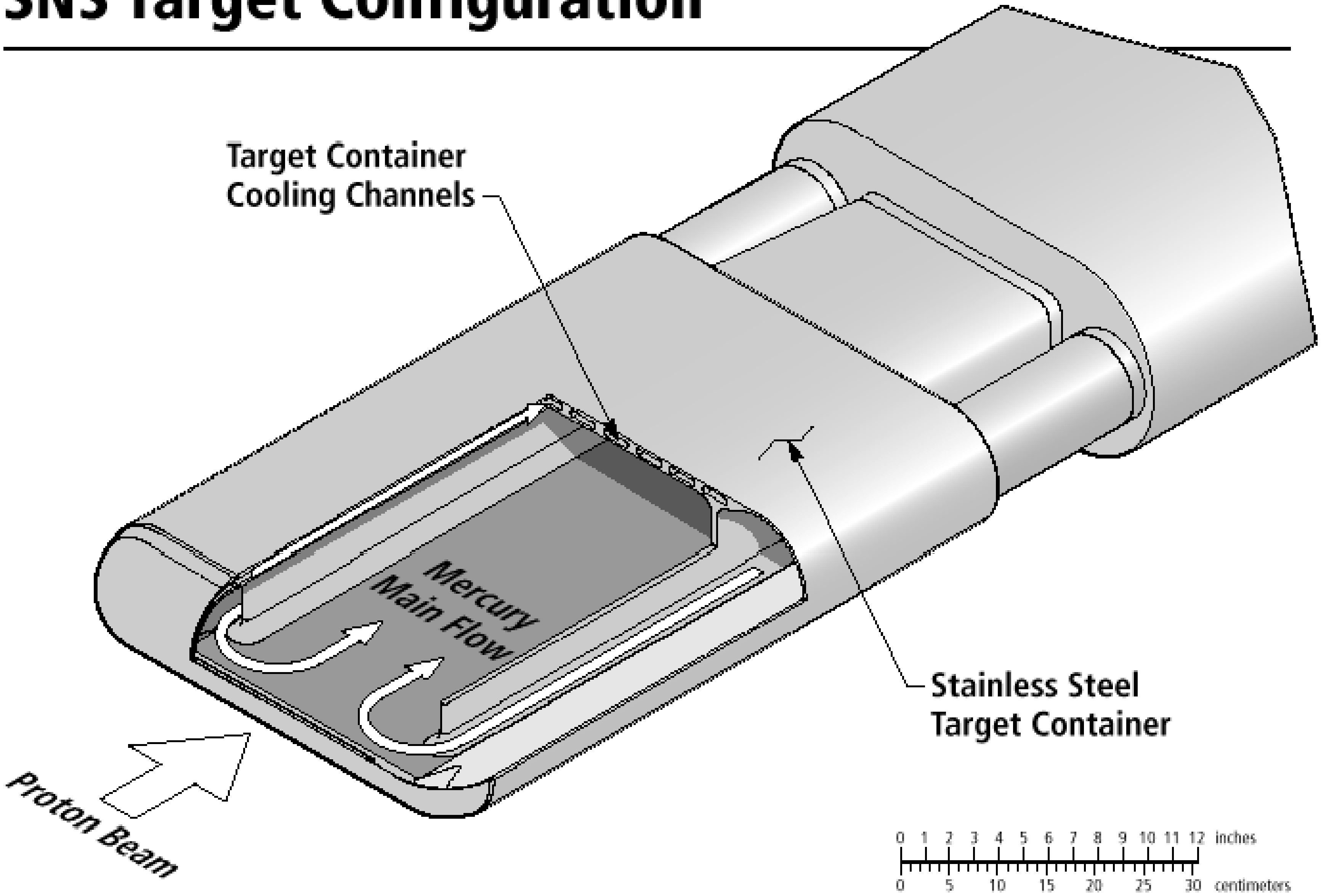
Nozzle 1.2 m/s
Beam Window 1 m/s

Paul Scherrer Institut • 5232 Villigen PSI

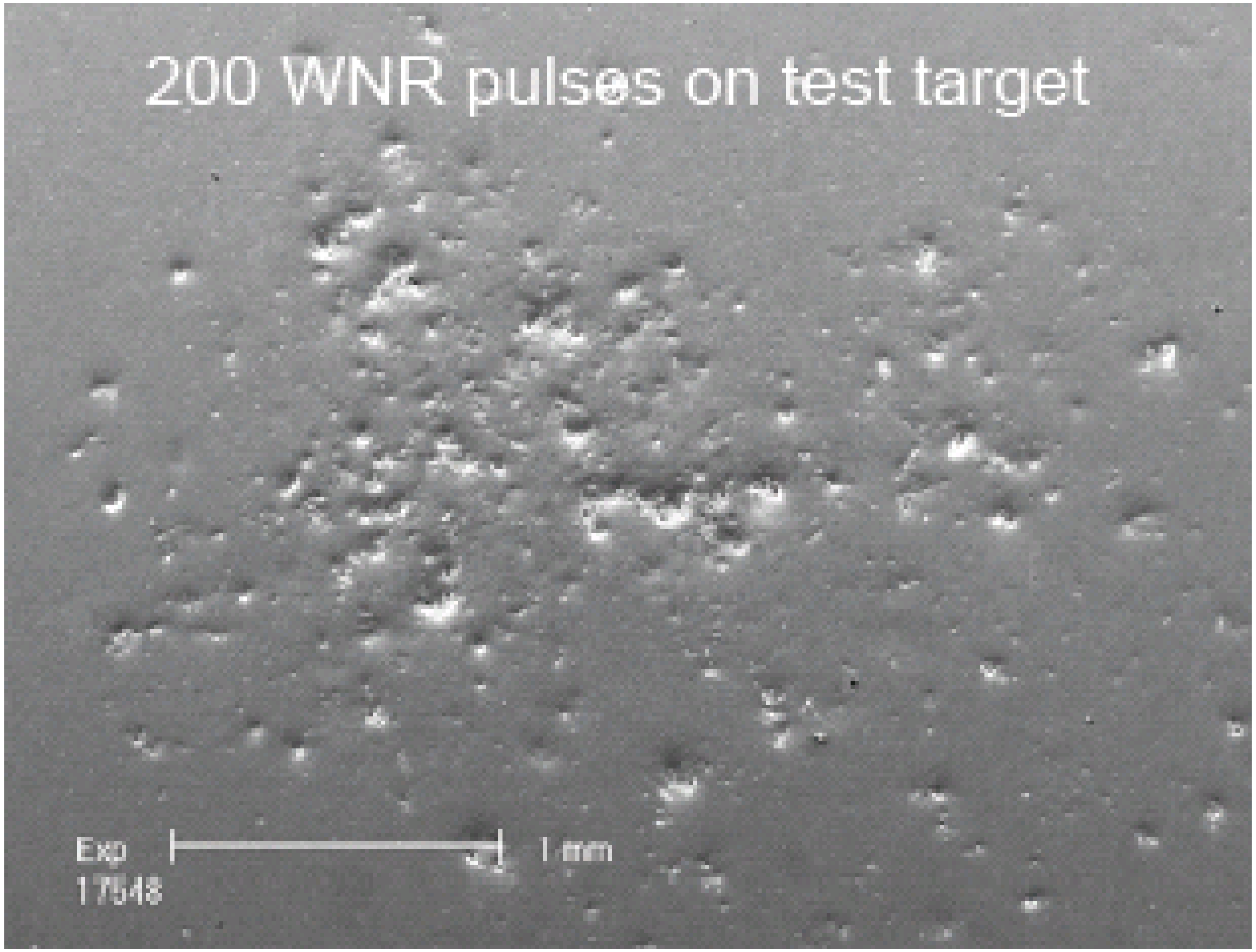
3rd HP Targetry Workshop, September 2007/GF34

Contained flowing mercury target for pulsed neutrons

SNS Target Configuration



Currently suffering from shock effects in the mercury. Cavitation causes pitting of the surface of the container and leads to a limited life of a few weeks at full power (1 MW of beam).



Current High-Power Target Studies, excluding NF

There are several high-power targets being considered or studied for neutron, electron and radioactive beam facilities.

SNS, JSNS (and ESS) (pulsed sources): Contained mercury targets – cavitation problems – hardening surfaces and bubbles of helium gas to reduce the problem.
PSI (cw source): Contained liquid metal (LBE) and solid tungsten.

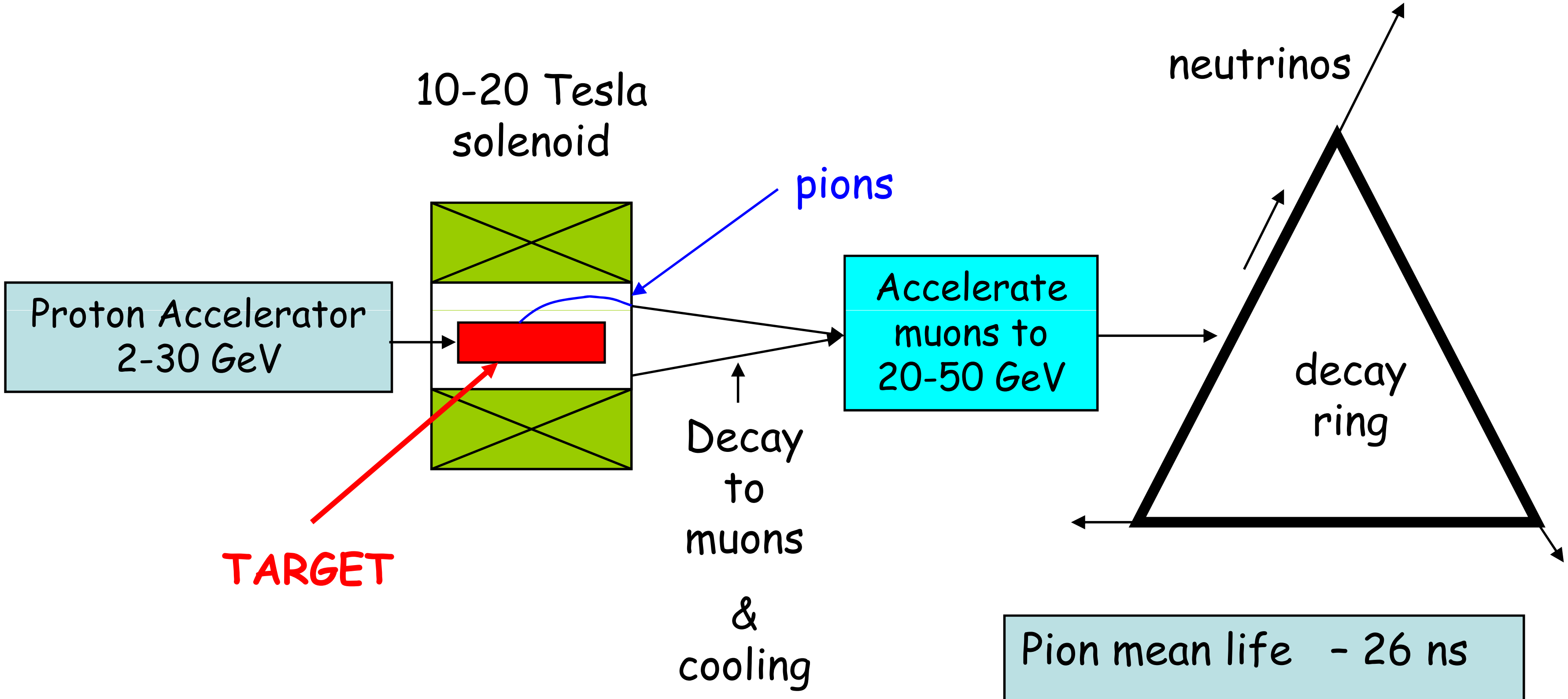
Neutron Irradiation Studies: IFMIF – liquid lithium jet.
GNEP Material Test Station – LBE cooled tungsten.

Linear Collider: Beam Dump, Positron target.

Radioactive Beams –RIA: Solid tungsten for neutron source and thin liquid lithium jet. Fair. BigRIPS.

EURISOL: Mercury

Targets for a Neutrino Factory



Pion mean life – 26 ns

Muon mean life - 2.2 μs

Simple schematic diagram of the neutrino factory, as seen by the target. The muon collider is basically similar but with a intersecting beam storage ring.

Targets currently being studied for Neutrino Factories

1. Mercury Jet – US/CERN/RAL – MERIT Experiment at CERN
2. Solid Tantalum Toroid or Bars - RAL
3. Solid Metal with low thermal expansion – BNL
4. Flowing Metal Powder - RAL
5. Small Solid Metal Spheres – CERN
6. Graphite Targets – Generally low energy density and power of a few tens of kW even if the beam power is in the MWs.

Neutrino Factory and Muon Collider Targets

- ☐ I believe the requirements of both are very similar.
- ☐ They may become different if the requirement for the small emittance muon beams with the collider significantly alters the design of the front end - perhaps increasing the luminosity and hence requiring less current on the target, etc?
- ☐ Very important to design the target and capture system as a unit.

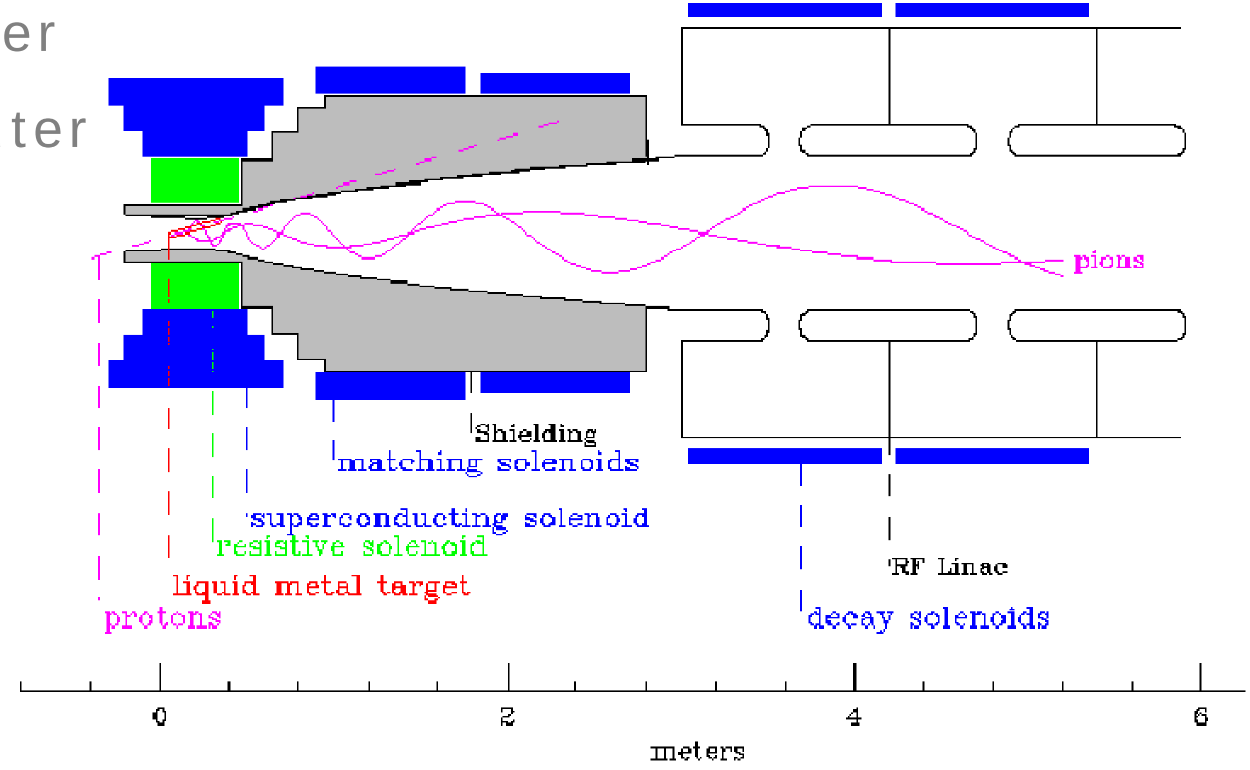
Pion Capture

- Two capture methods proposed:

  US: 20T solenoid

  CERN: magnetic horn (as used for "conventional" neutrino beams)

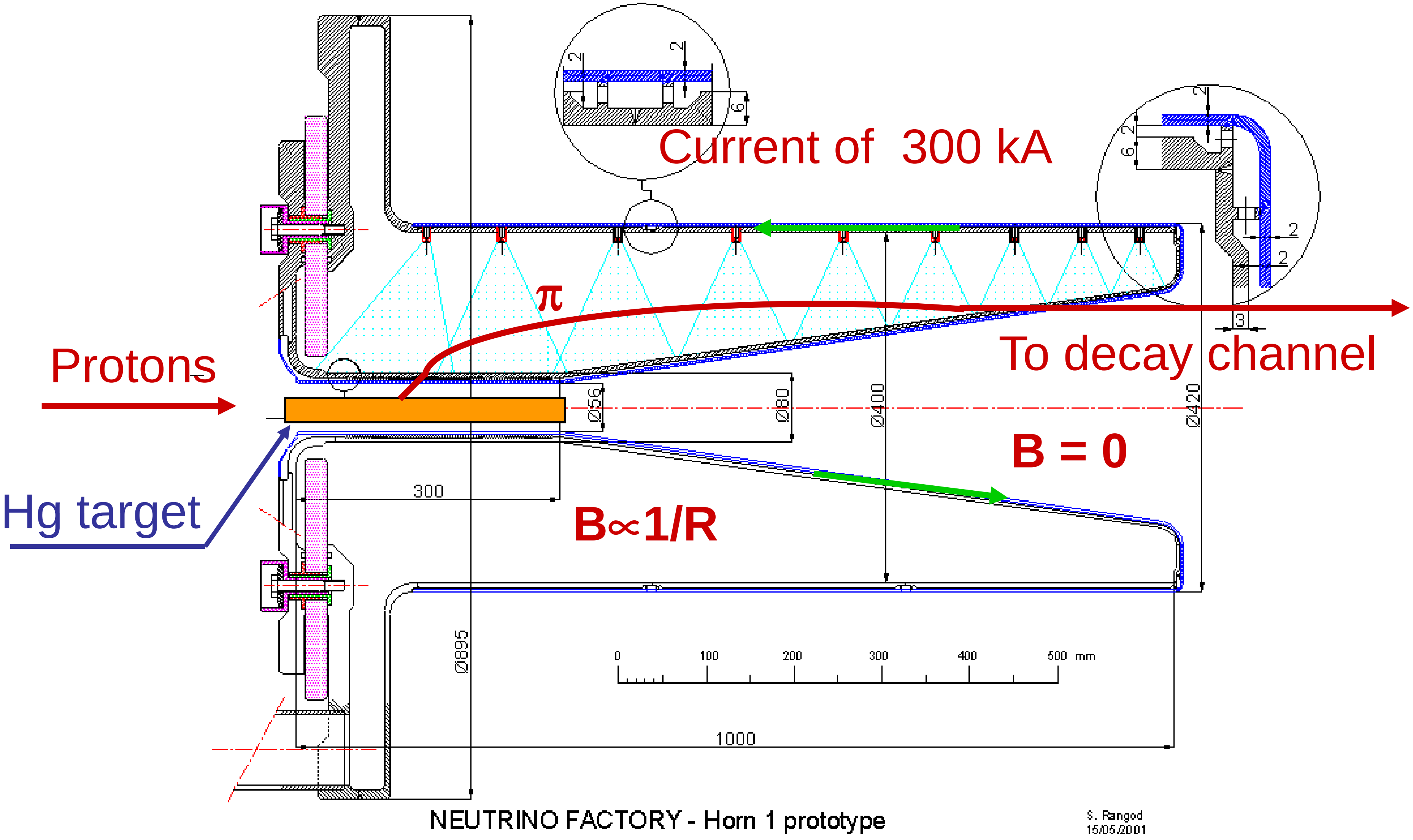
- Each feeds pions into ~1.5T solenoid decay channel
- 20T solenoid formed from a resistive inner core and superconducting outer
- Inner core shields outer



"Old" 20T capture solenoid layout

Rob Edgecock, RAL

Horn Capture



Current of 300 kA

π

Protons

Hg target

To decay channel

B = 0

B∝1/R

Rob Edgecock, RAL

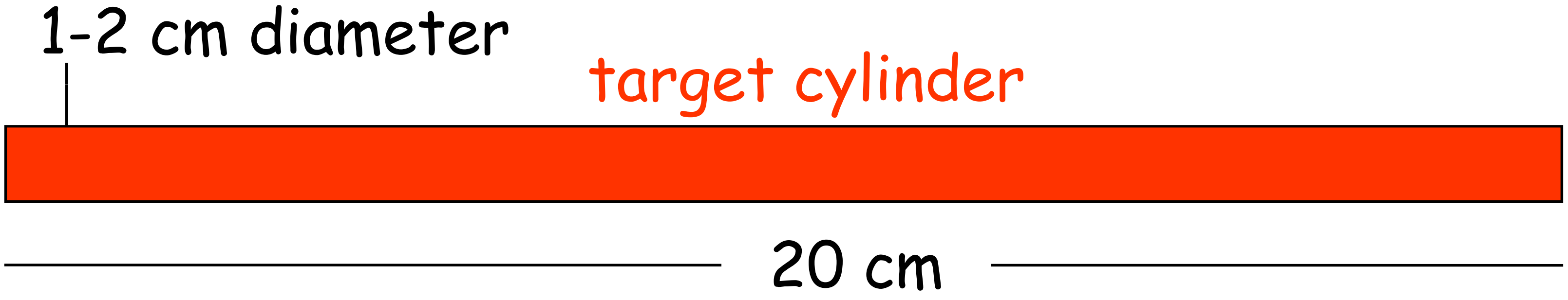
The Target

Proton beam

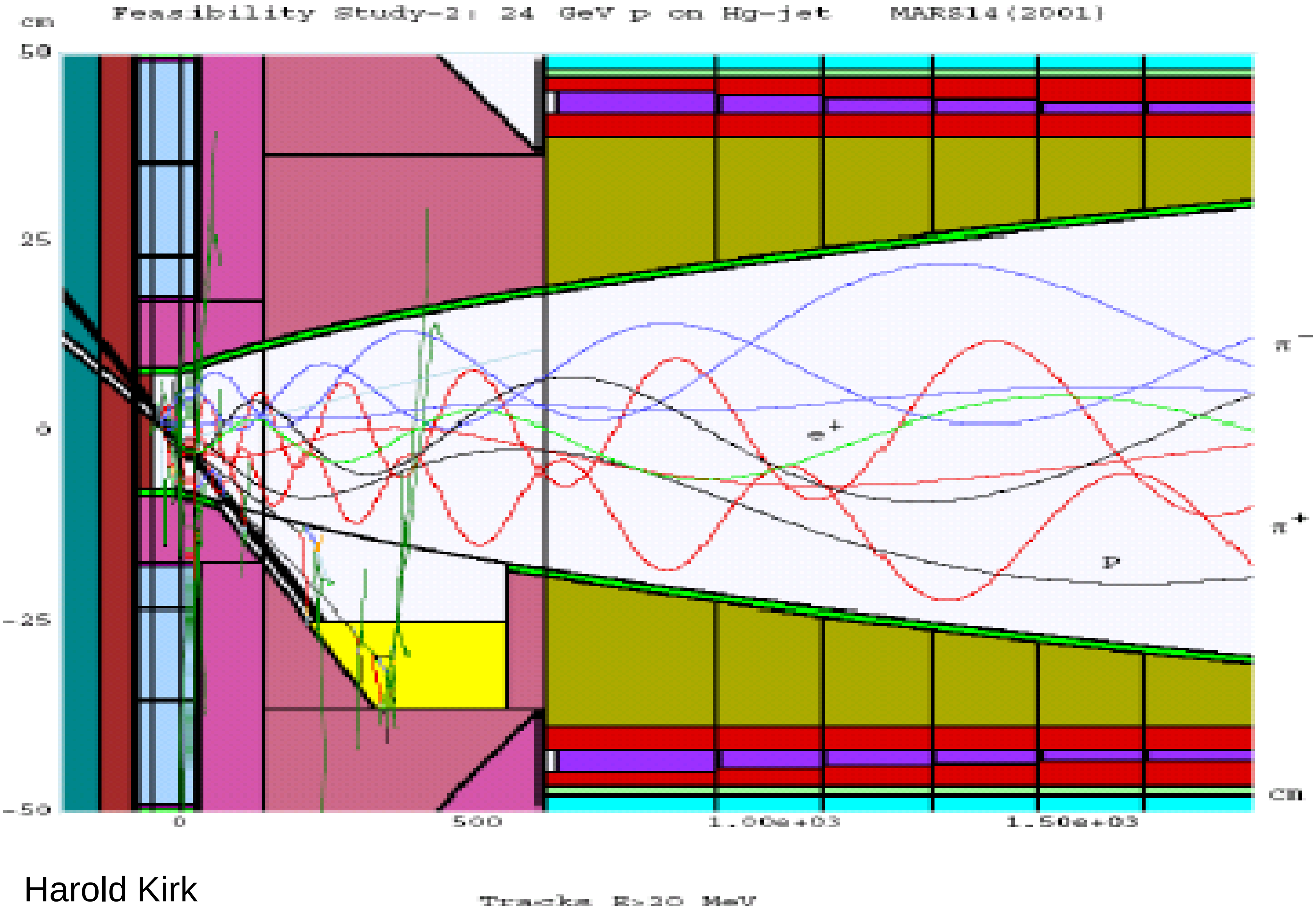
Energy	2-30 GeV
Current	2-0.03 mA
Power	4 MW
Pulse	~2ns – 50μs
	50 Hz

Target (high *z* material such as lead, mercury or tungsten)

Dimensions	20 cm long (2 interaction lengths), 1-2 cm diameter
Power Dissipation	~1 MW
Power Density	~4-16 kW/cm^3 (average)
Energy Density	~300-1200 J/cm^3/pulse



THE FREE MERCURY JET



Harold Kirk

Tests at BNL and CERN

- Calculations of injecting the mercury jet into a magnetic field showed small perturbations.
- The field provides damping of the motion in the jet. Tests (CERN) at Grenoble show this.
- Tests with a proton beam at BNL showed that the jet broke up.

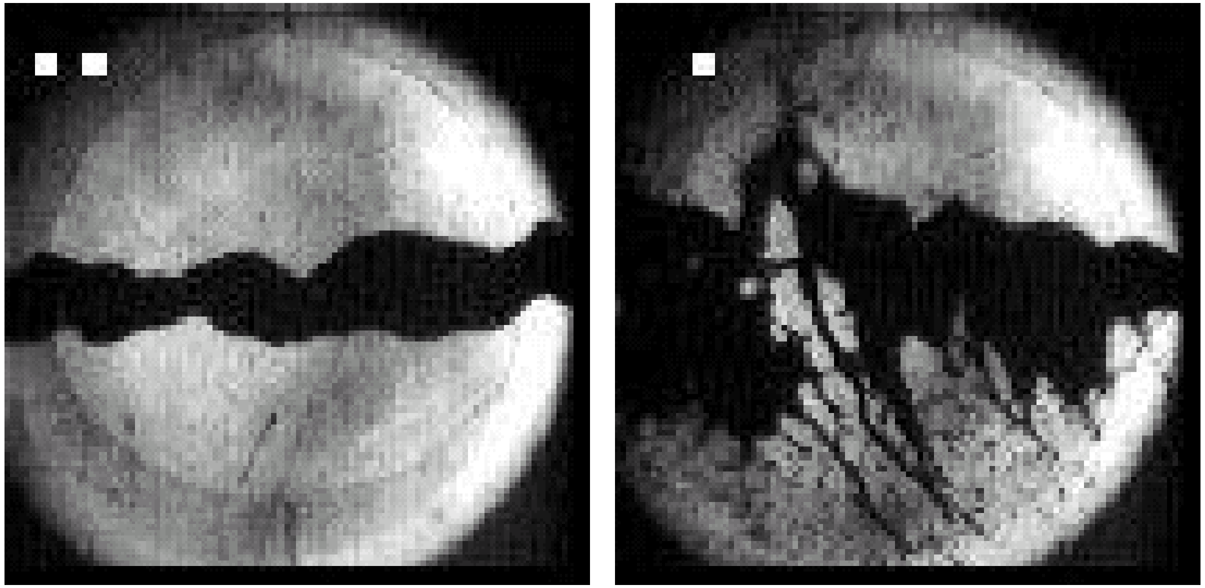
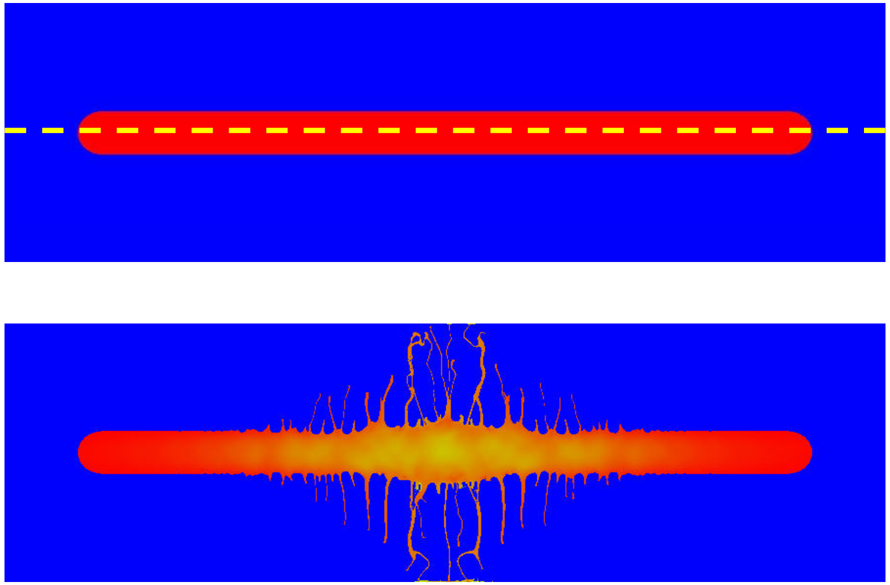


Figure 3.7: Breakup of a 1-cm-diameter mercury jet in a 24-GeV proton beam (BNL E951).

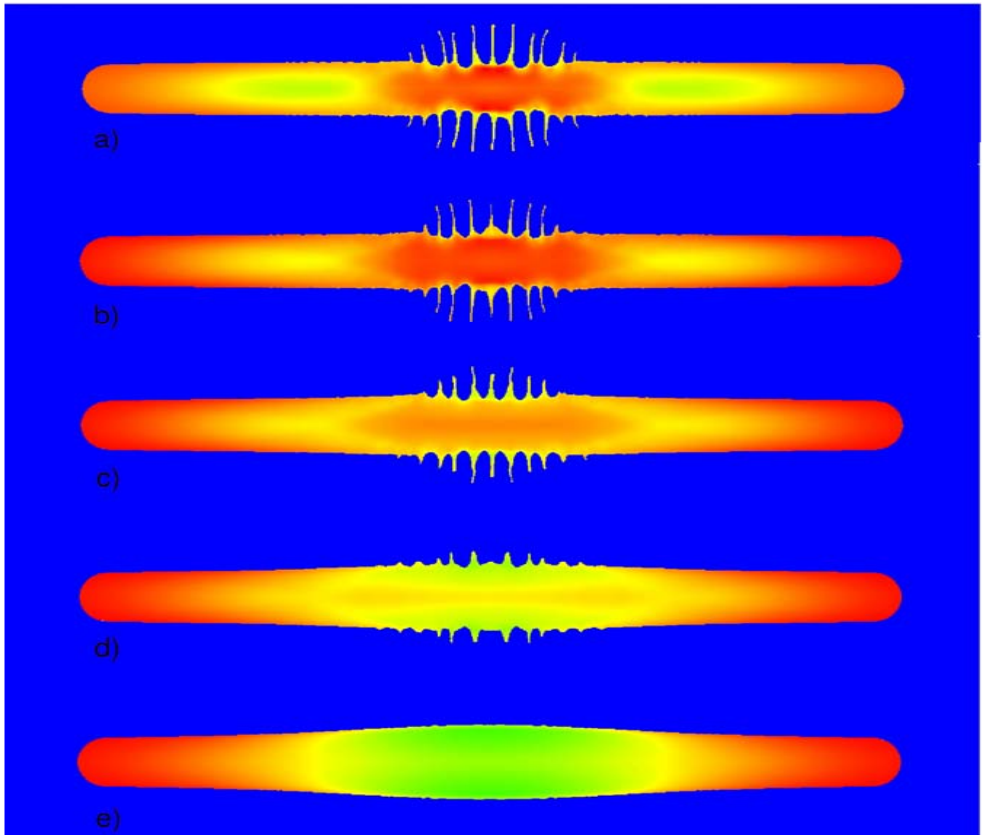
Calculations of Thermal Shock in a Free Mercury Jet, Roman Samulyak, BNL

Richtmyer-Meshkov instability and MHD stabilization



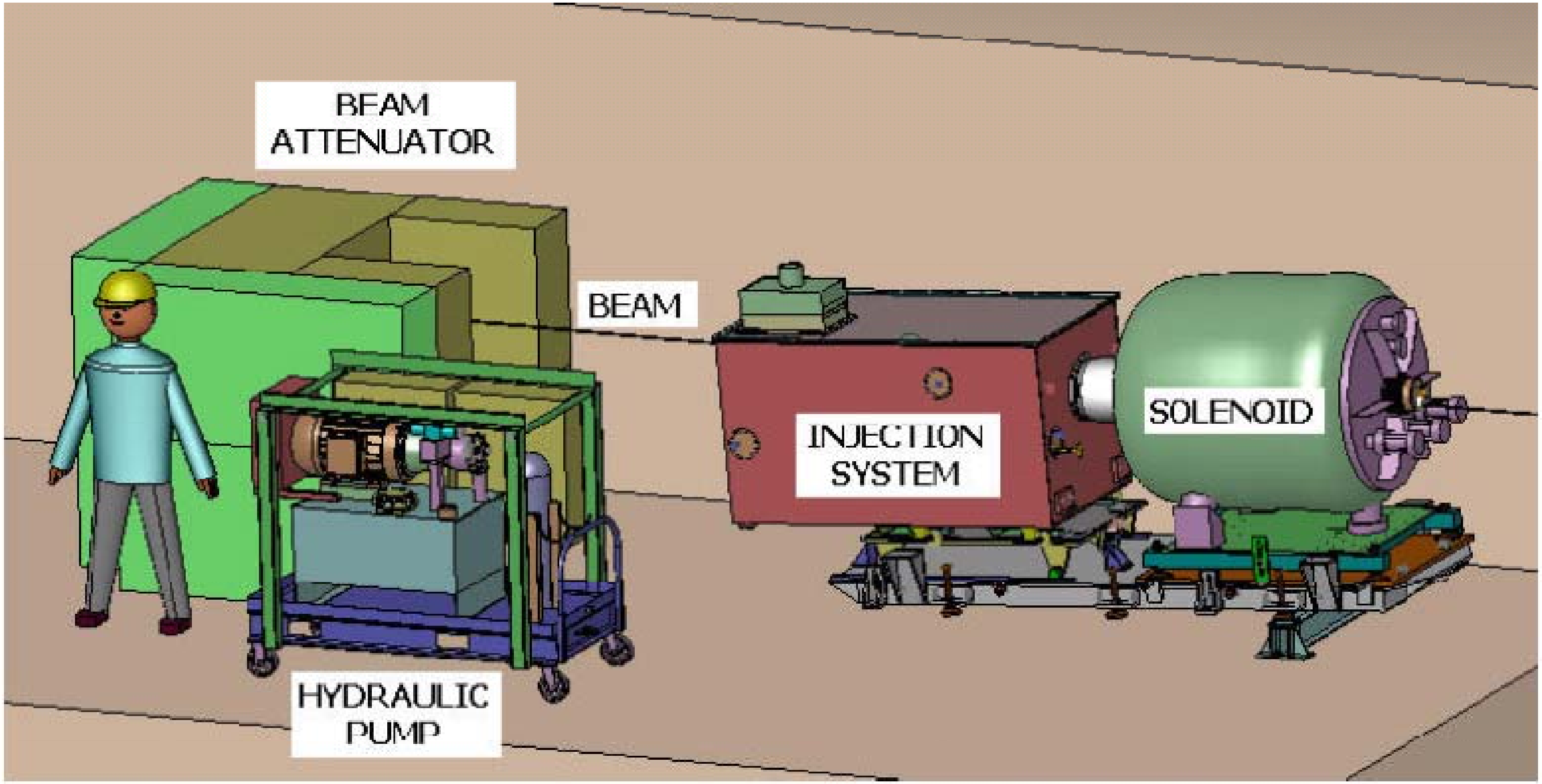
Simulation of the mercury jet – proton pulse interaction during 100 microseconds, B = 0

Effect of different axial magnetic fields



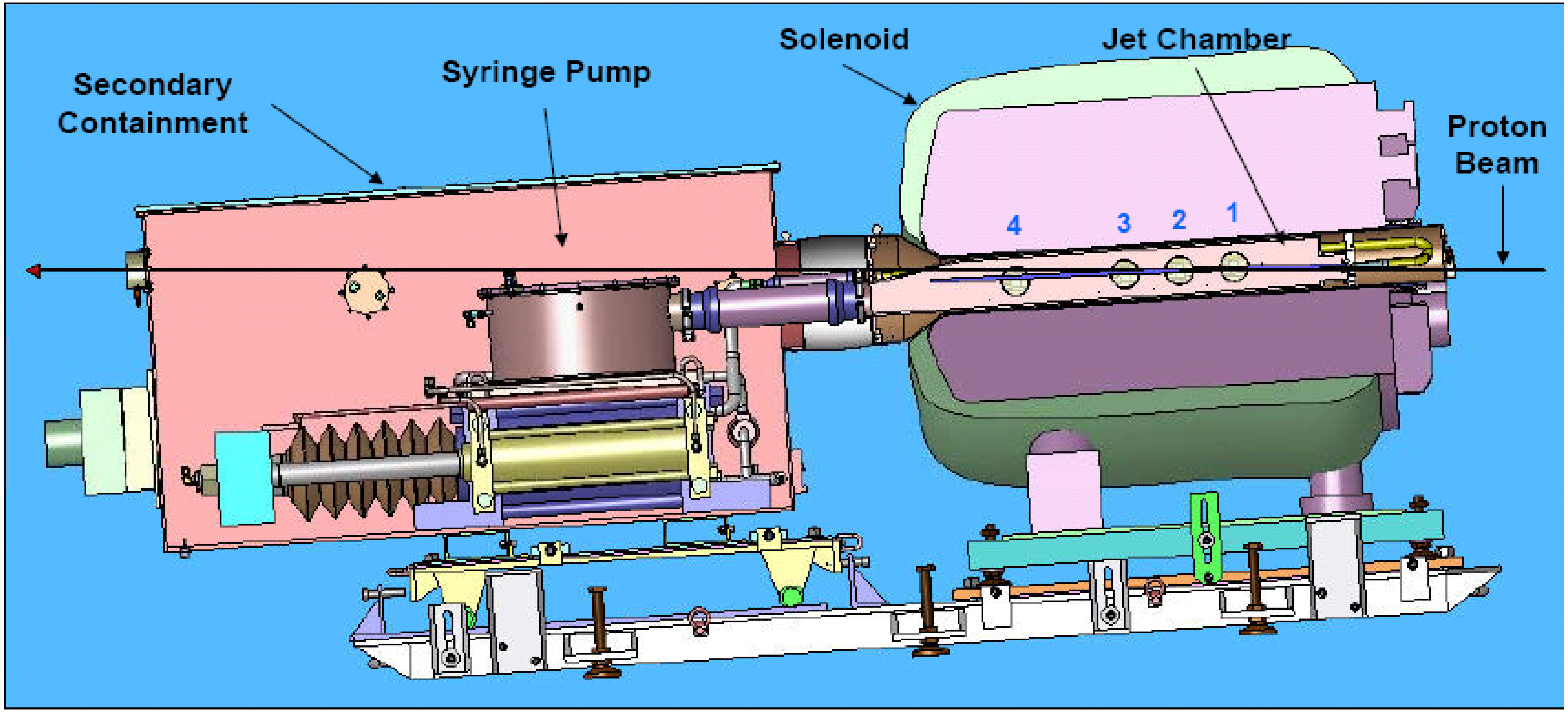
a) B = 0 b) B = 2T c) B = 4T
d) B = 6T e) B = 10T

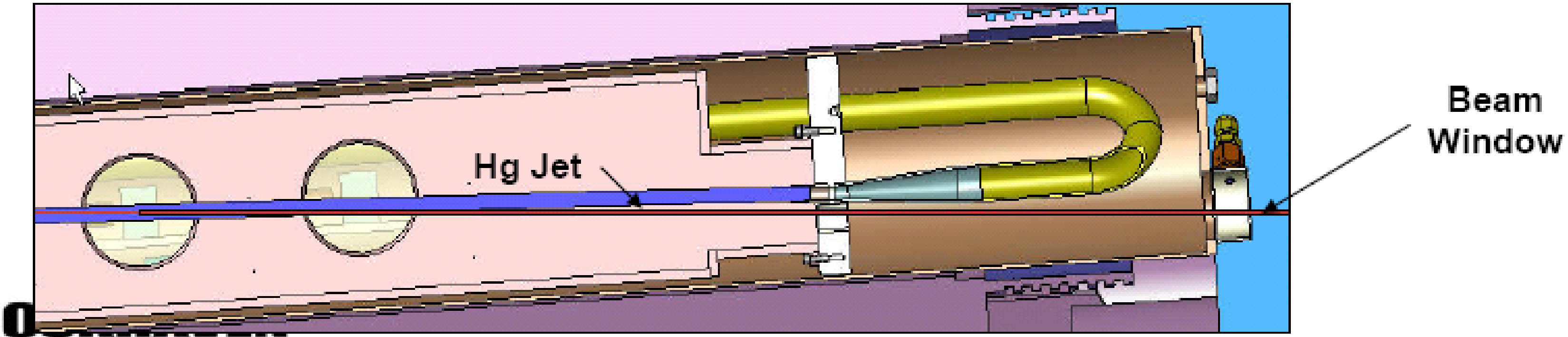
The MERIT (nTOF11) Experiment



MERcury Intense Target

Sectional view of the MERIT Experiment

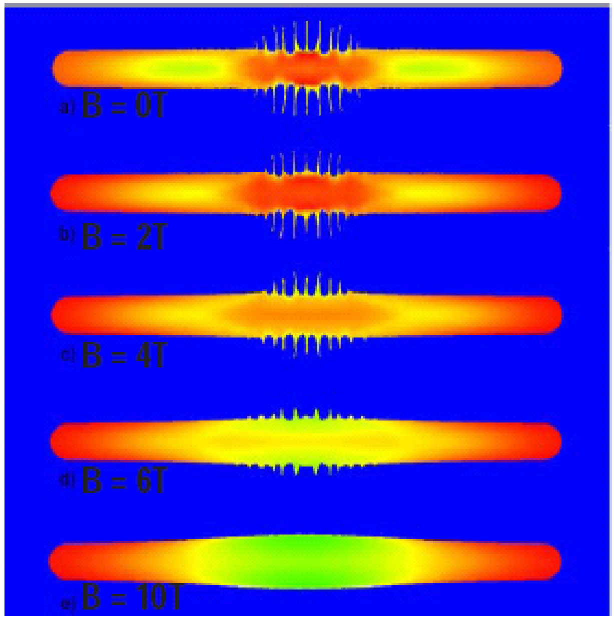




MERIT Scientific Goals

Milestone towards demonstration of a 4MW target concept

Study MHD effects of pion capture scheme with Hg-jet and 15T solenoid



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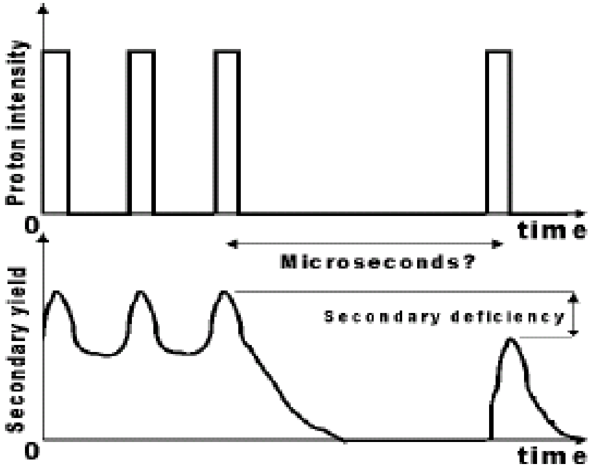
Study jet disruption and cavitation by varying the PS spill structure

MERIT: 180 J/g

- 30TP@24GeV protons
- 1cm diam. 20m/s Hg-jet
- 1.2×1.2 mm^2 beam size rms



Pump-Probe with Particle Detectors

Goals of the MERIT Experiment

- Study single beam pulses with intensities up to 30TP
- Study influence of solenoid field strength on Hg jet dispersal (B_o from 0 to 15T)
- Study 50 Hz operations scenario
- Study cavitation effects in the Hg jet by varying PS spill structure—Pump/Probe
- Confirm Neutrino Factory targetry concept

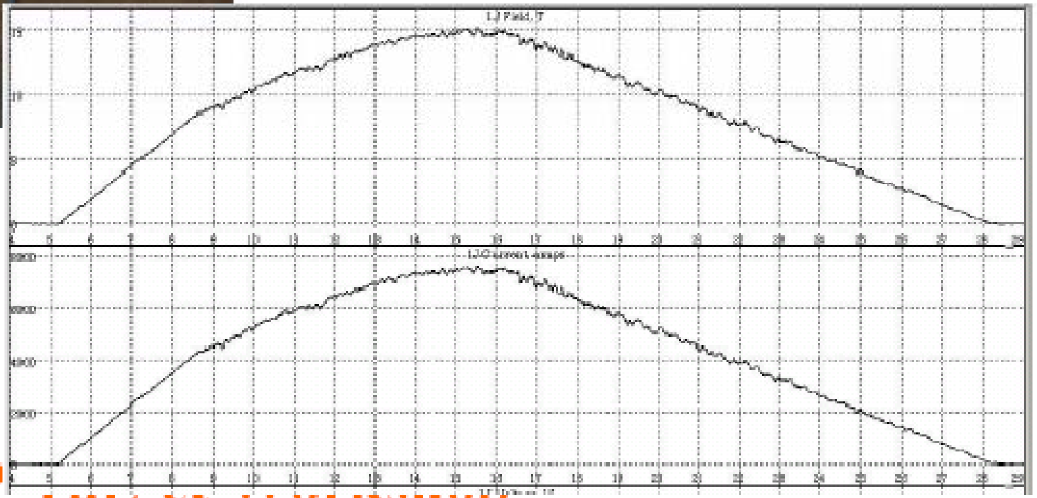
Profile of the Experiment

- 14 and 24 GeV proton beam
- Up to >30 x 10^{12} protons (TP) per 2μs spill
- Proton beam spot with r ≤ 1.5 mm rms
- 1cm diameter Hg Jet
- Hg Jet/proton beam off solenoid axis
  - Hg Jet 33 mrad
  - Proton beam 67 mrad
- Test 50 Hz operations
  - 20 m/s Hg Jet

The Pulsed Solenoid

CVIP December 2005

15T at MIT March 30, 2006



The Hg Injection System

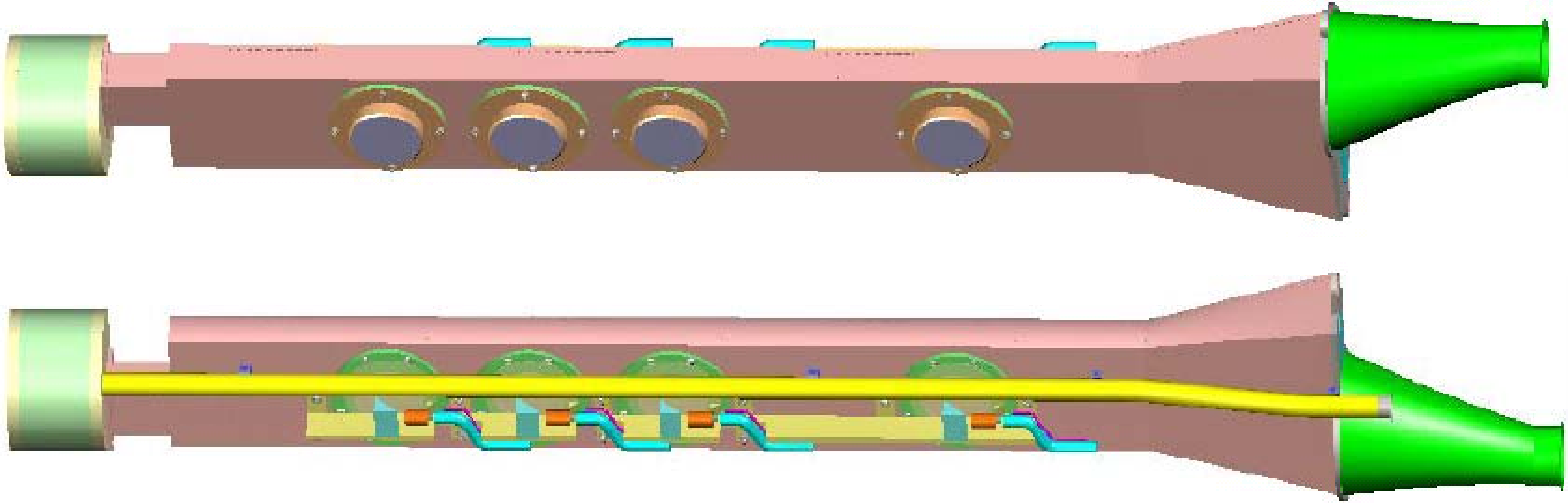
Syringe pump

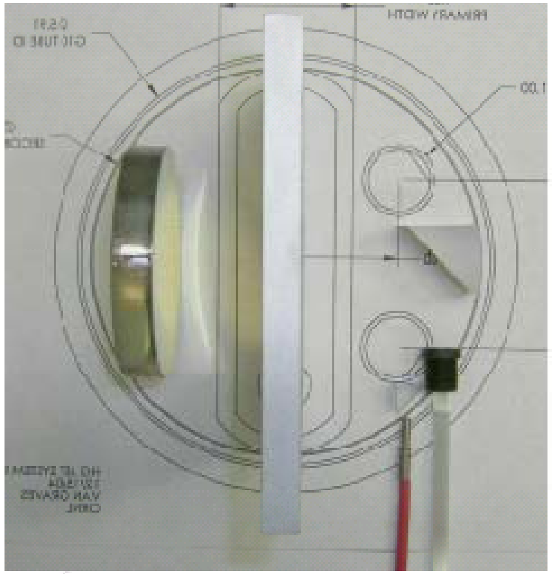
Hydraulic power unit w/control system

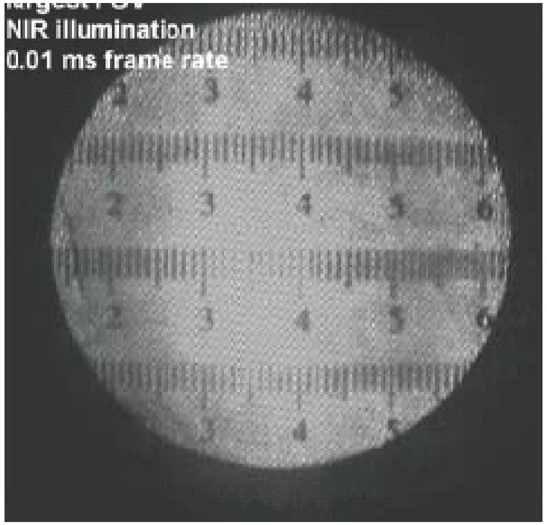
Optical diagnostic system

Baseplate support structures

Optical Diagnostics in Secondary Containment







One set of optics per viewport

T.Tsang, BNL

Advantages

1. Jet destroyed every pulse but reforms for the next pulse. No direct shock problem.
2. No beam power limit?

3.Disadvantages

4. Limit macro-pulse length?
5. Possible damage to chamber walls by fast break up of the jet?
6. Erosion of the nozzle and pipework by the high velocity mercury?
7. Chemical erosion of nozzle and pipe under irradiation?
8. Need beam windows.
9. Safety issues with mercury.

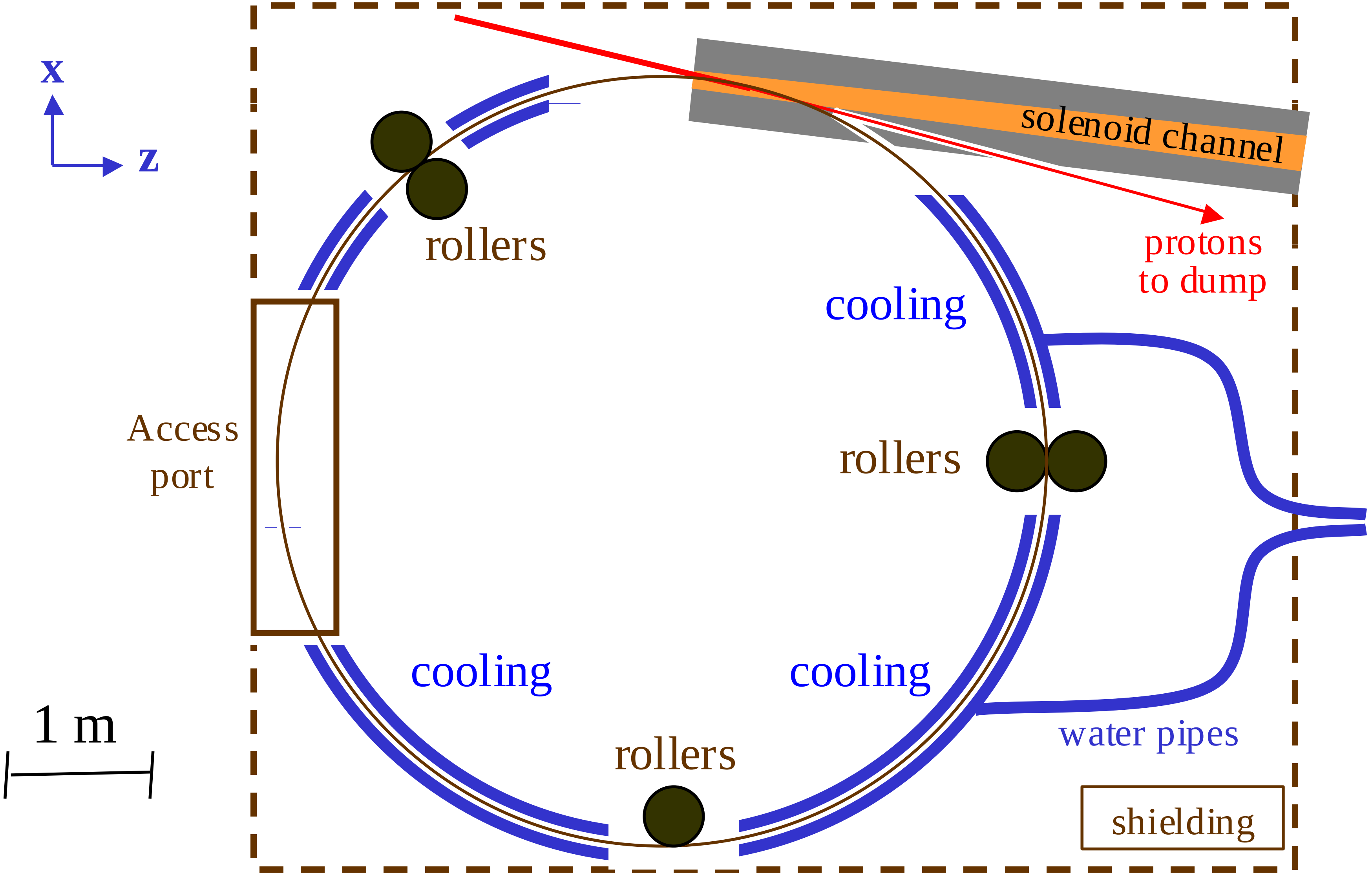
SOLID TARGETS

A Cu-Ni Rotating Band Target

Bruce King & Robert Weggel
(BNL), Nikolai Mokhov (FNAL),
Scott Moser (St. Joseph's)

Radiation Cooled Rotating Toroid, Magnetically Levitated (RAL)

Plan View of Targetry Setup



Target Specifications

Target dimensions: 0.6 cm thick x 6 cm high x 15.7 m circumference
=> heat removal of 40 -- 80 W/cm^2
=> water cooling OK

Material properties: Cu-Ni alloy (e.g. Olin 715)
elect. conductivity ~ 5% of Cu
interaction length = 15 cm

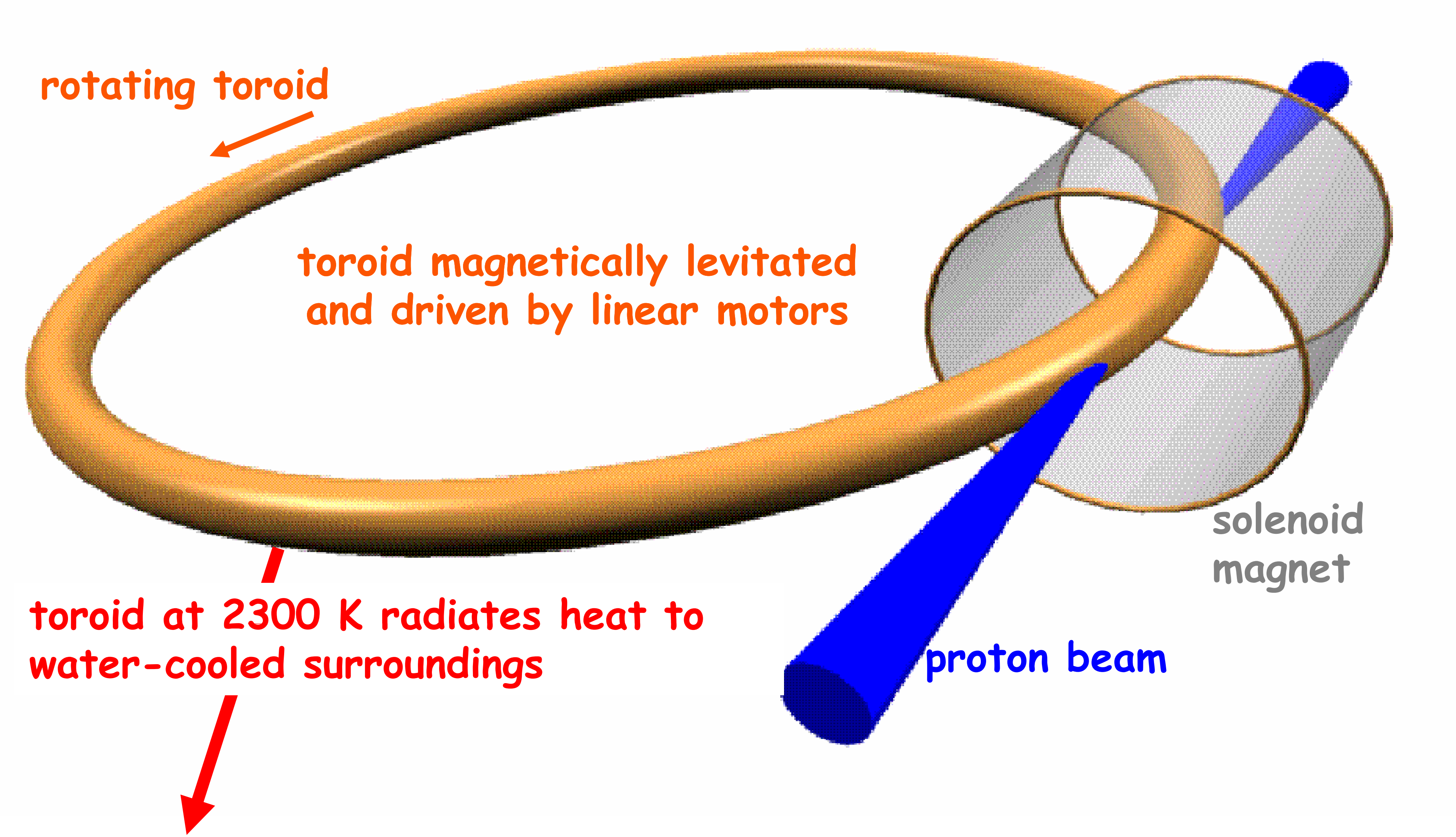
Target Rotation: velocity = 3 m/sec (=> heat from ~2 pulses overlap)

Solenoidal Magnet: (Bx,By,Bz) = (0,0,20) Tesla
bore diameter = 15 cm

Proton Beam: spot size: $\sigma_x = 1.5$ mm, $\sigma_y = 10$ mm
10^{14} 16 GeV protons/pulse @ 15 Hz (4 MW)

The Radiation Cooled Rotating Toroid

RAL, UK



rotating toroid

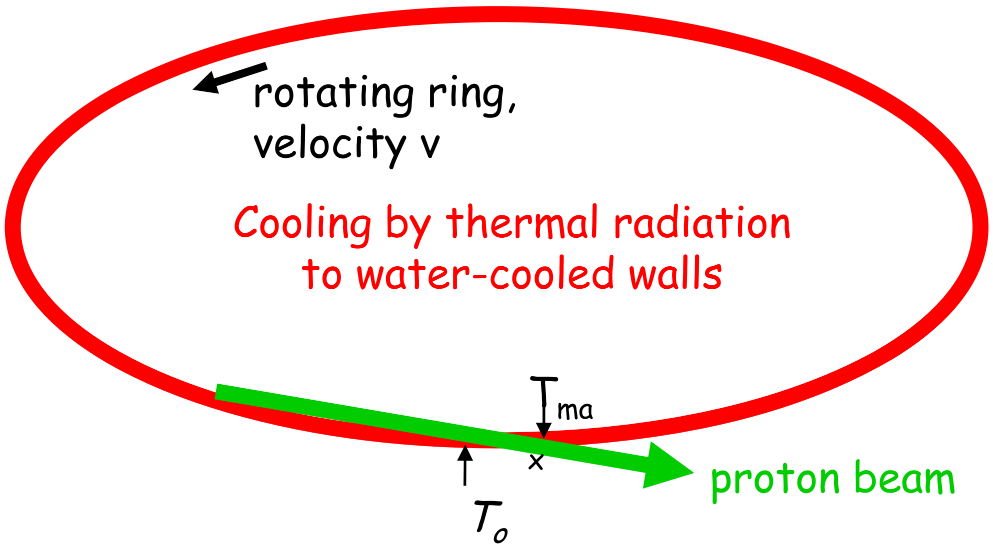
toroid magnetically levitated and driven by linear motors

toroid at 2300 K radiates heat to water-cooled surroundings

solenoid magnet

proton beam

Schematic Diagram of the Levitated Toroid



- toroid operates at 2000-2500 K
- radiation cooled
- rotates in a vacuum
- vacuum chamber walls water cooled
- no windows
- shock? Tests using electron beam simulation and high current pulses in thin wires indicate no problem.

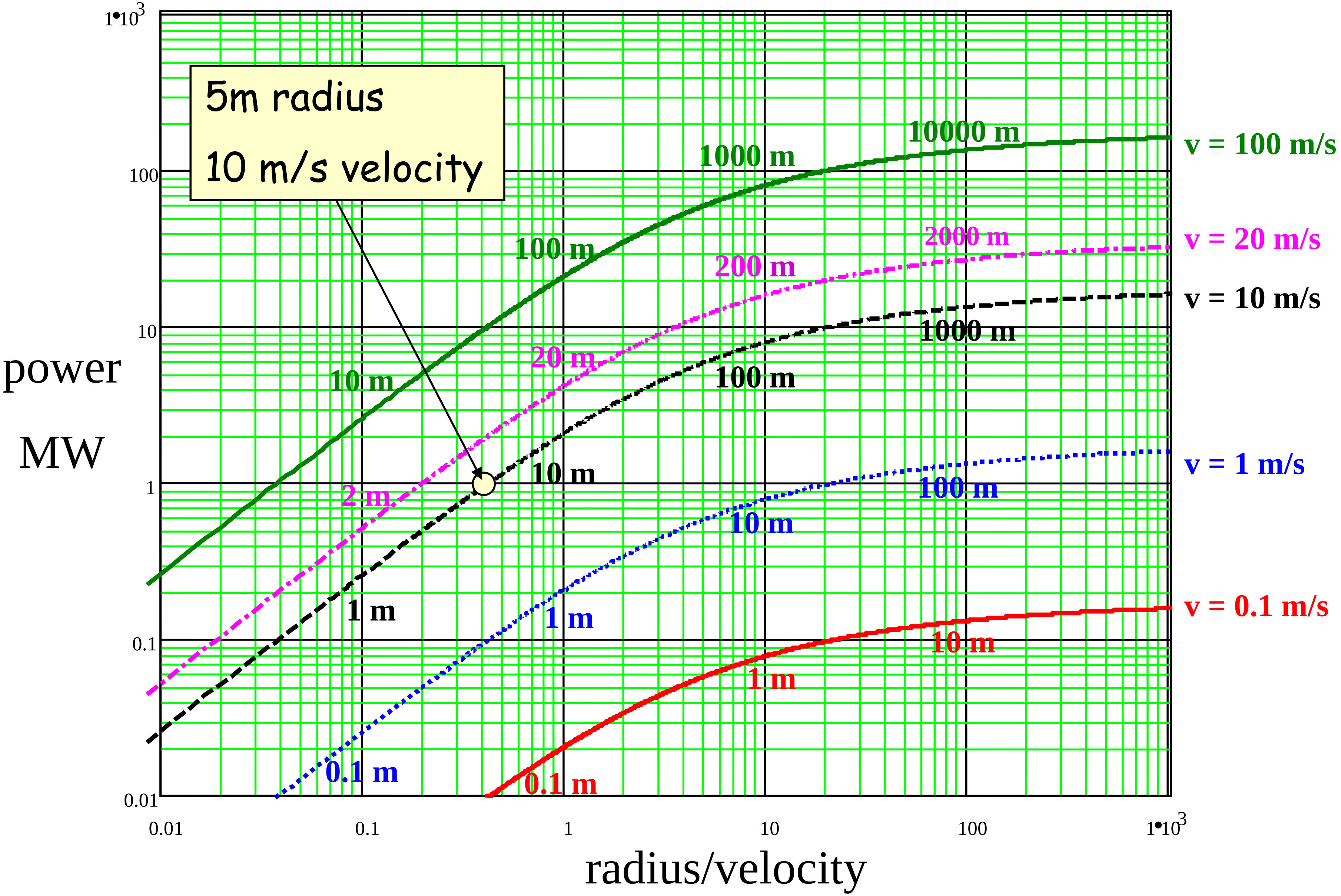
Advantages

- No windows
- Cooling in the walls
- Simple concept
- No mechanical friction

Disadvantages

- Large rotating toroid or many individual targets
- Problems if toroid breaks
- Thermal shock - toroid breaks
- Very radioactive

POWER DISSIPATION

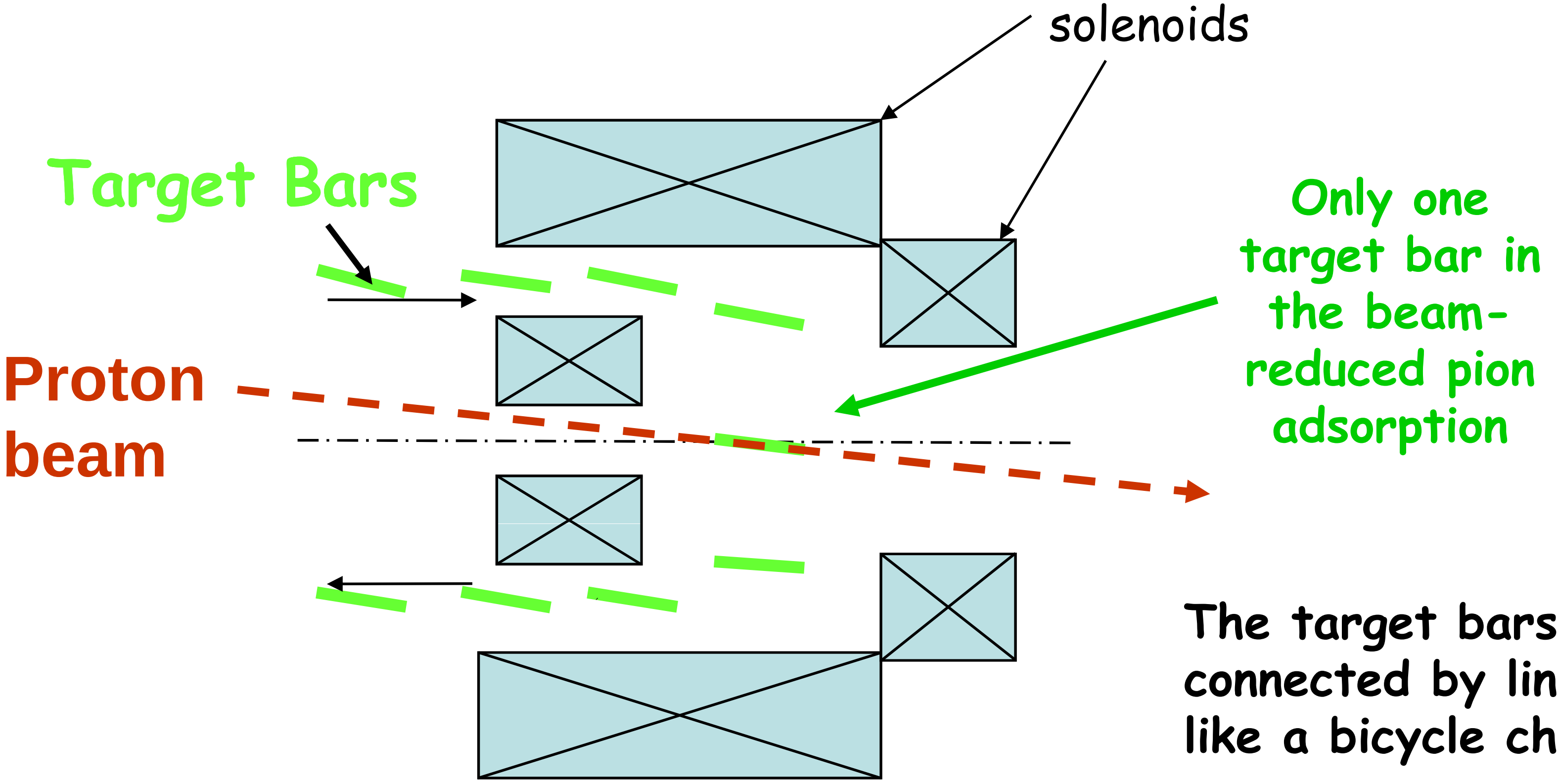


5m radius

10 m/s velocity

The alternative concept to the toroid-

Individual Bar Targets



solenoids

Target Bars

Proton beam

Only one target bar in the beam-reduced pion adsorption

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

Schematic diagram of the target and collector solenoid arrangement

The primary purpose of the tests at RAL is to address the problem of thermal shock at high temperatures.

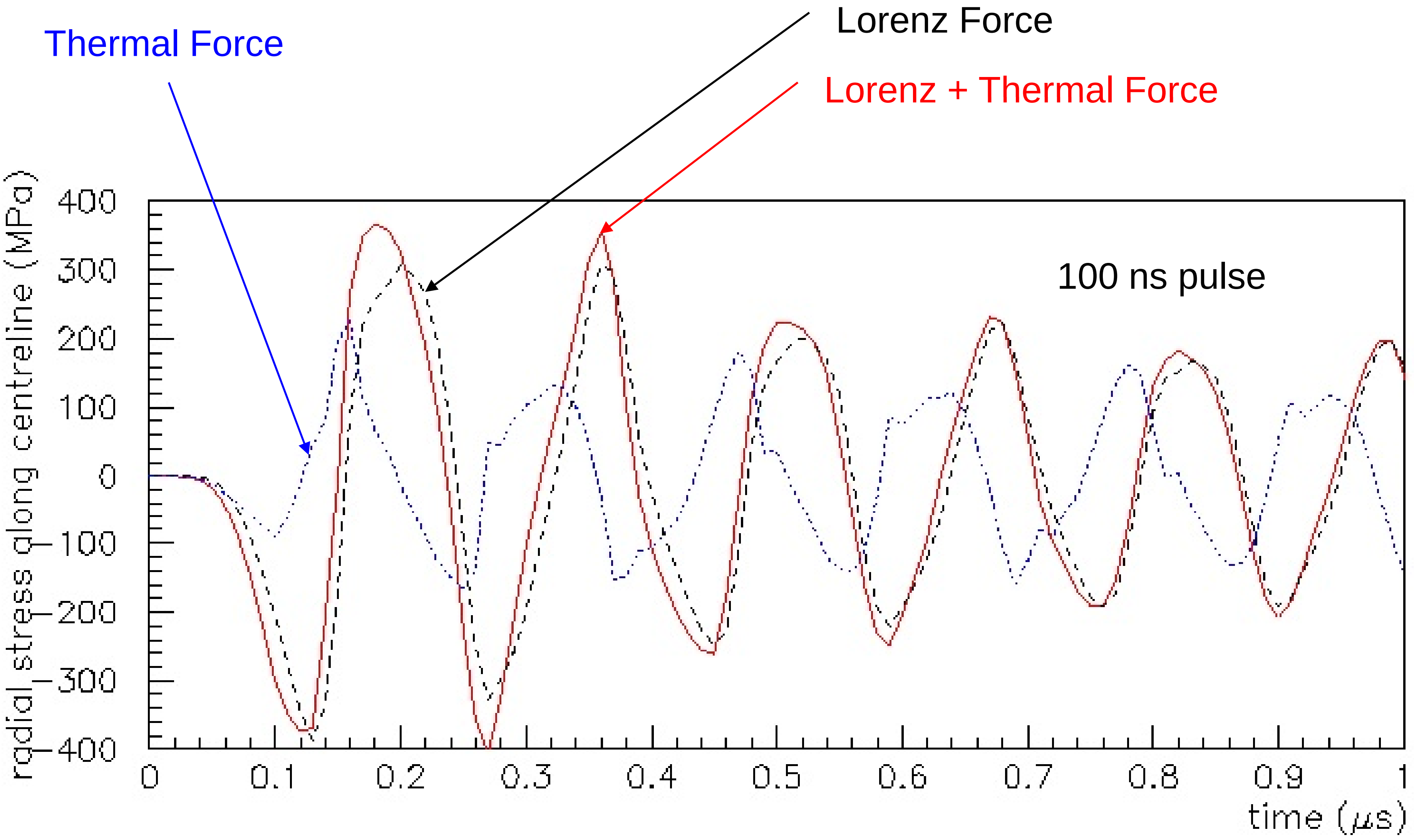
To find a refractory material that will withstand the thermal stresses/fatigue and have a long life of ~1-10 years.

1 year corresponds to 10^6 pulses on an individual target bar.

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

The solution

- ❑ Produce shocks by passing high current pulses through thin wires.



Typical radial stress in the wire from thermal and Lorentz forces

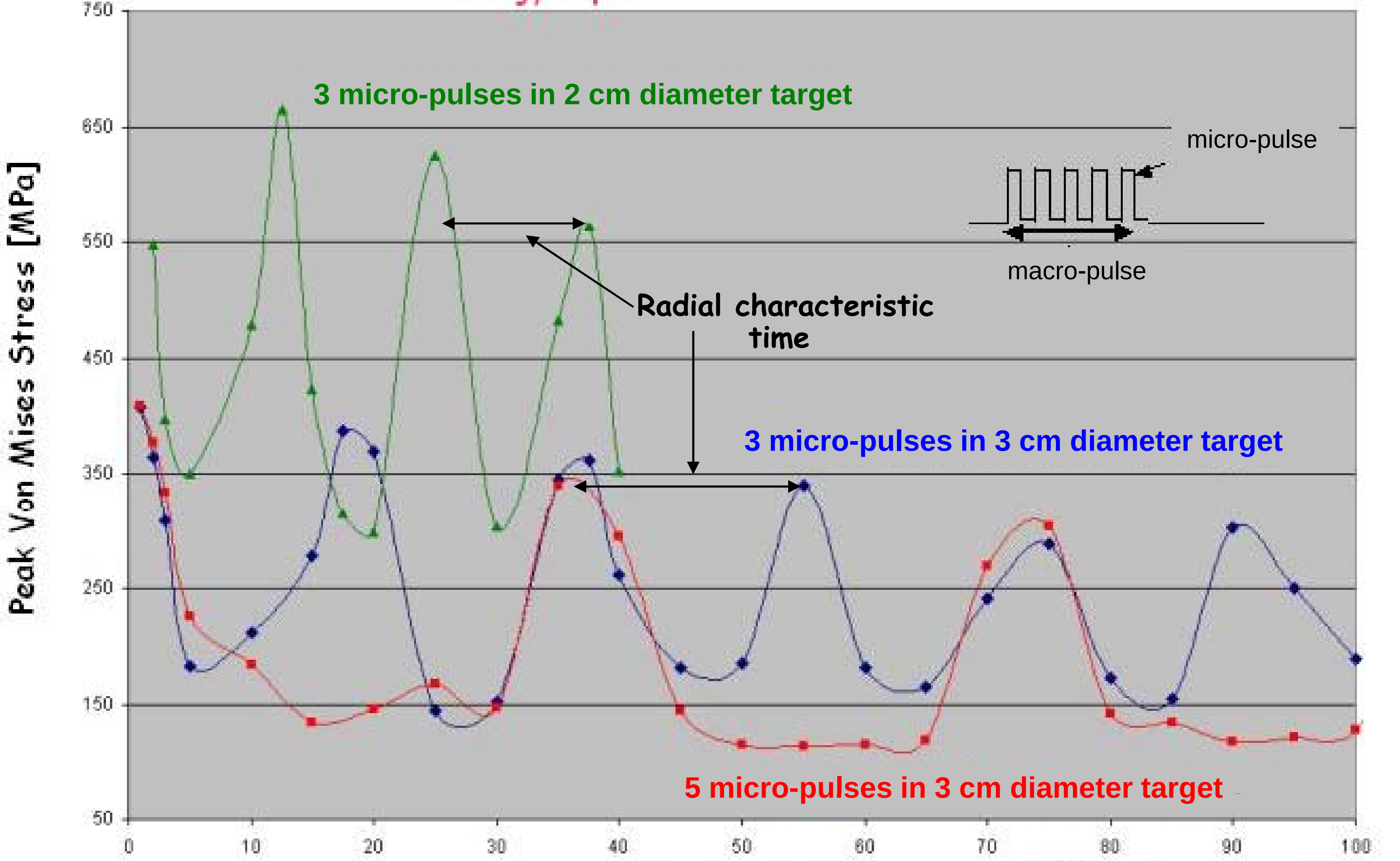
Goran Skoro

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



Macro-pulse length, µs

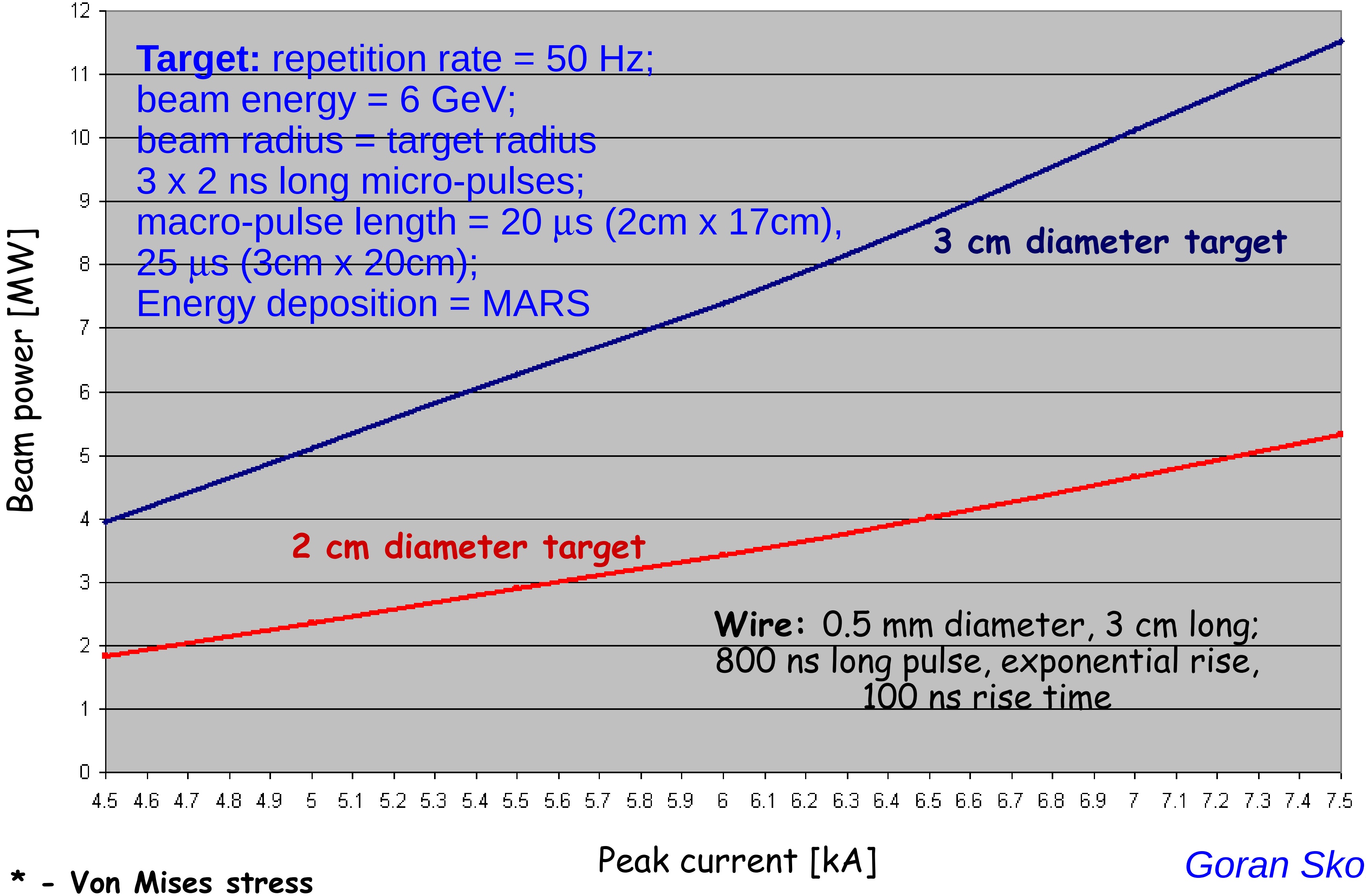
NB.
The bunches are equidistant.

Goran Skoro

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

Results

LS-DYNA

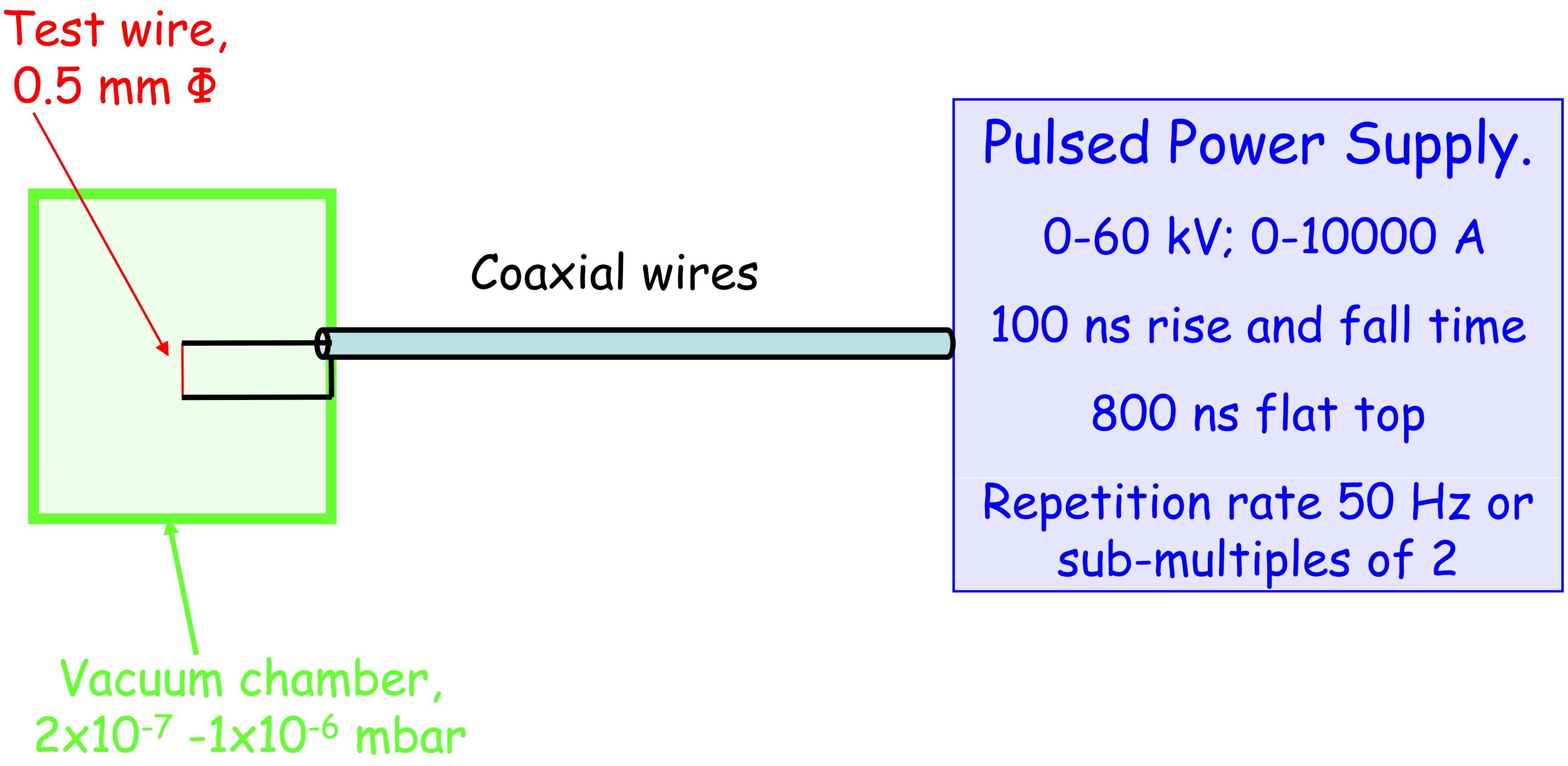


Target: repetition rate = 50 Hz;
beam energy = 6 GeV;
beam radius = target radius
3 x 2 ns long micro-pulses;
macro-pulse length = 20 µs (2cm x 17cm),
25 µs (3cm x 20cm);
Energy deposition = MARS

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

Pulsed Power Supply.

0-60 kV; 0-10000 A

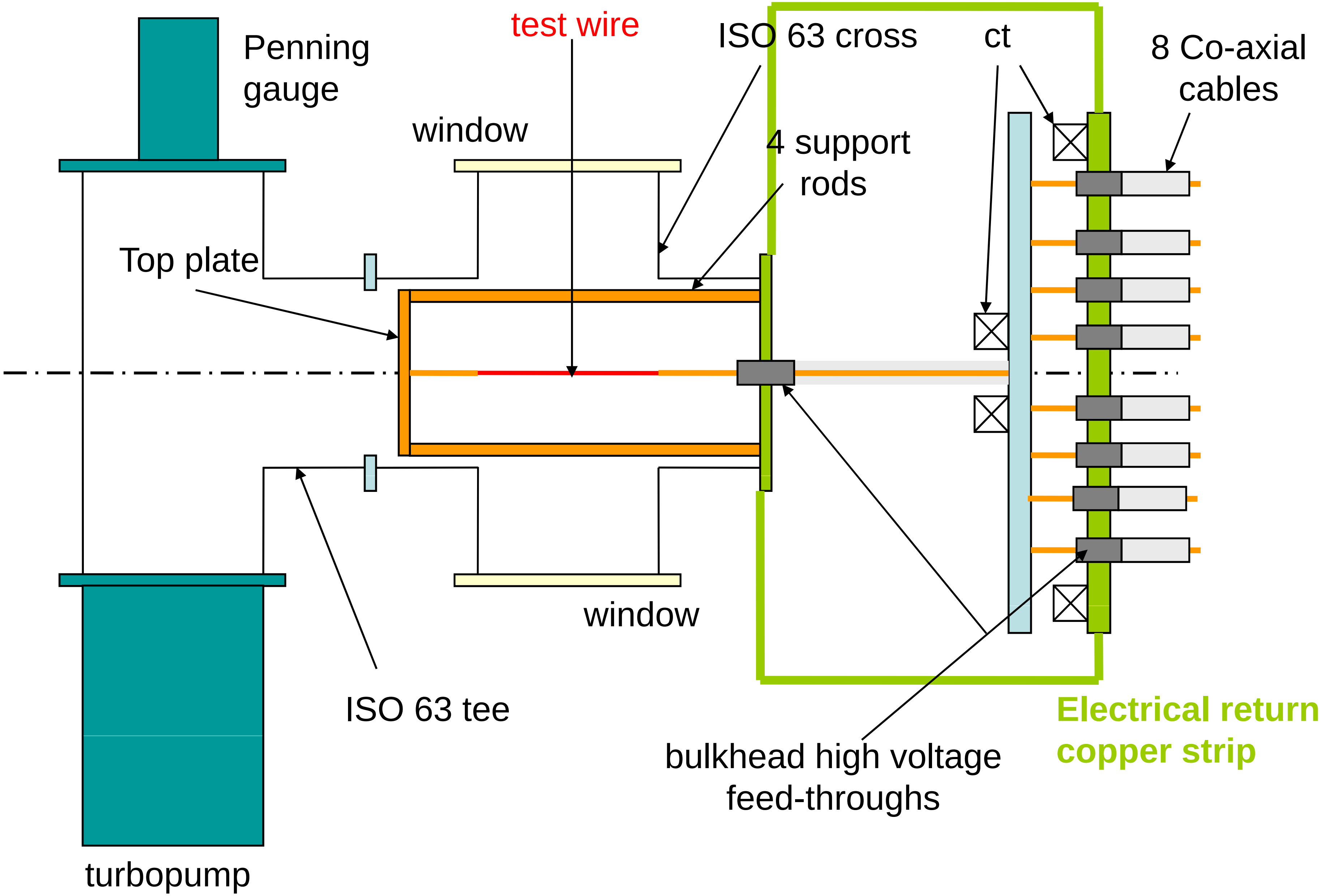
100 ns rise and fall time

800 ns flat top

Repetition rate 50 Hz or sub-multiples of 2

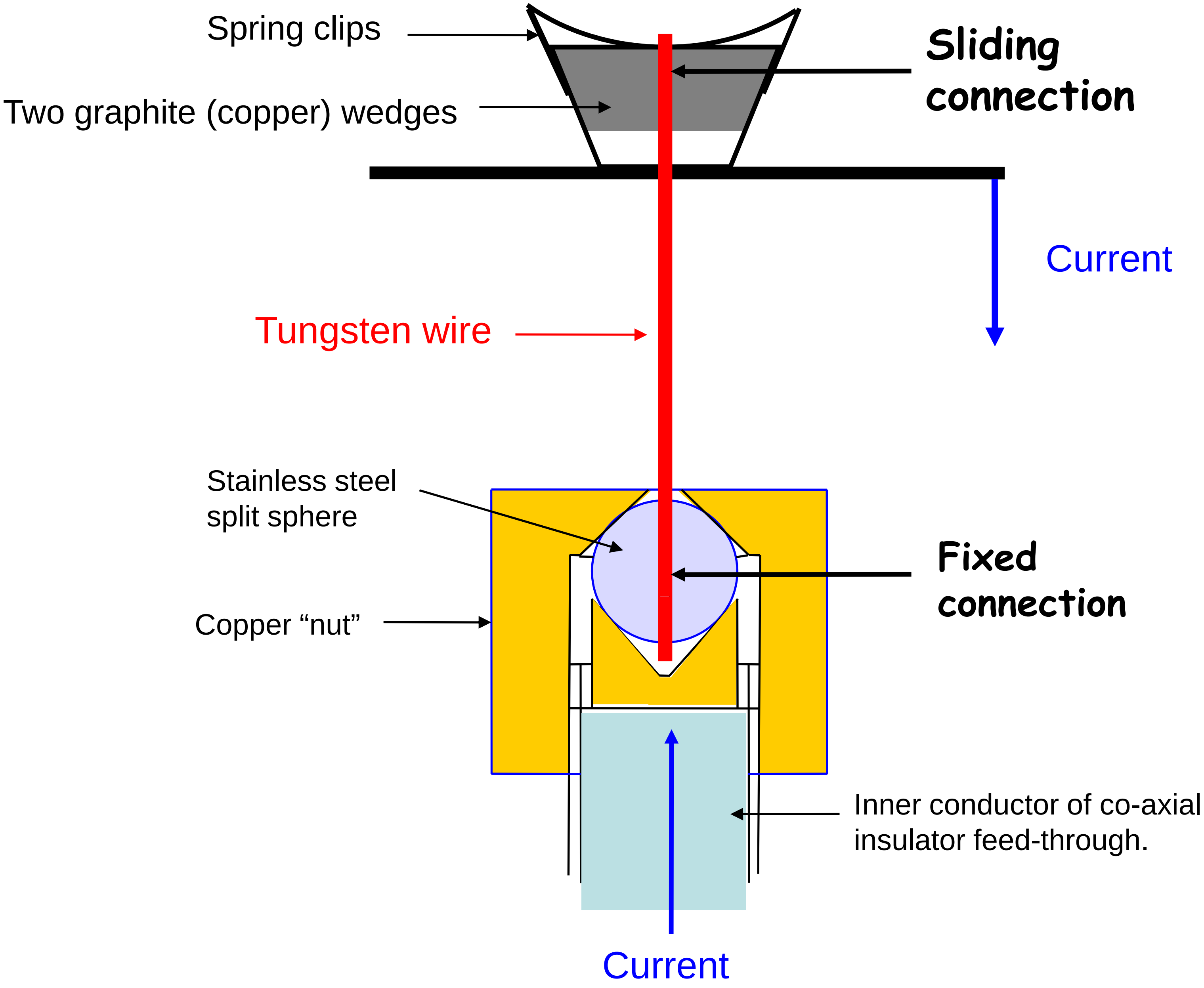
Vacuum chamber,
2×10^{-7} -1×10^{-6} mbar

Schematic circuit diagram of the wire test equipment



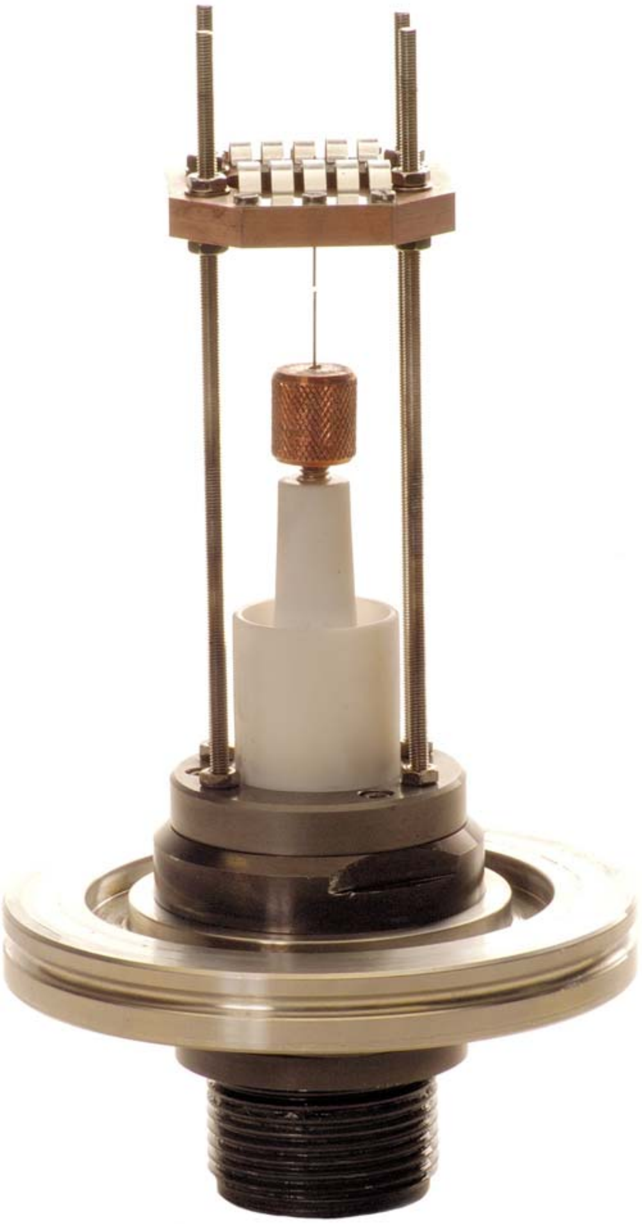
Schematic section of the wire test assembly

Vertical Section through the Wire Test Apparatus

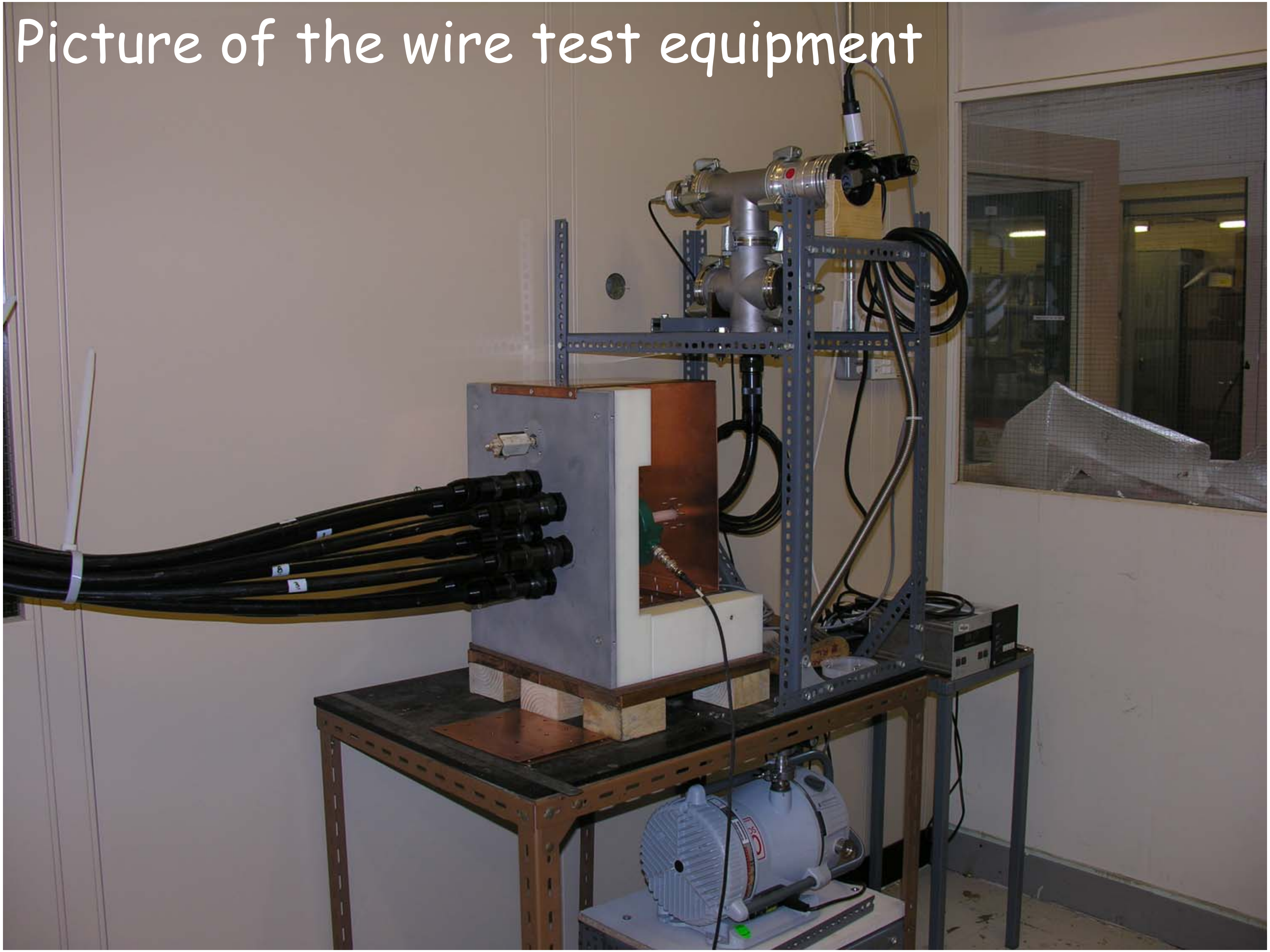


W26

Tungsten Wire Assembly



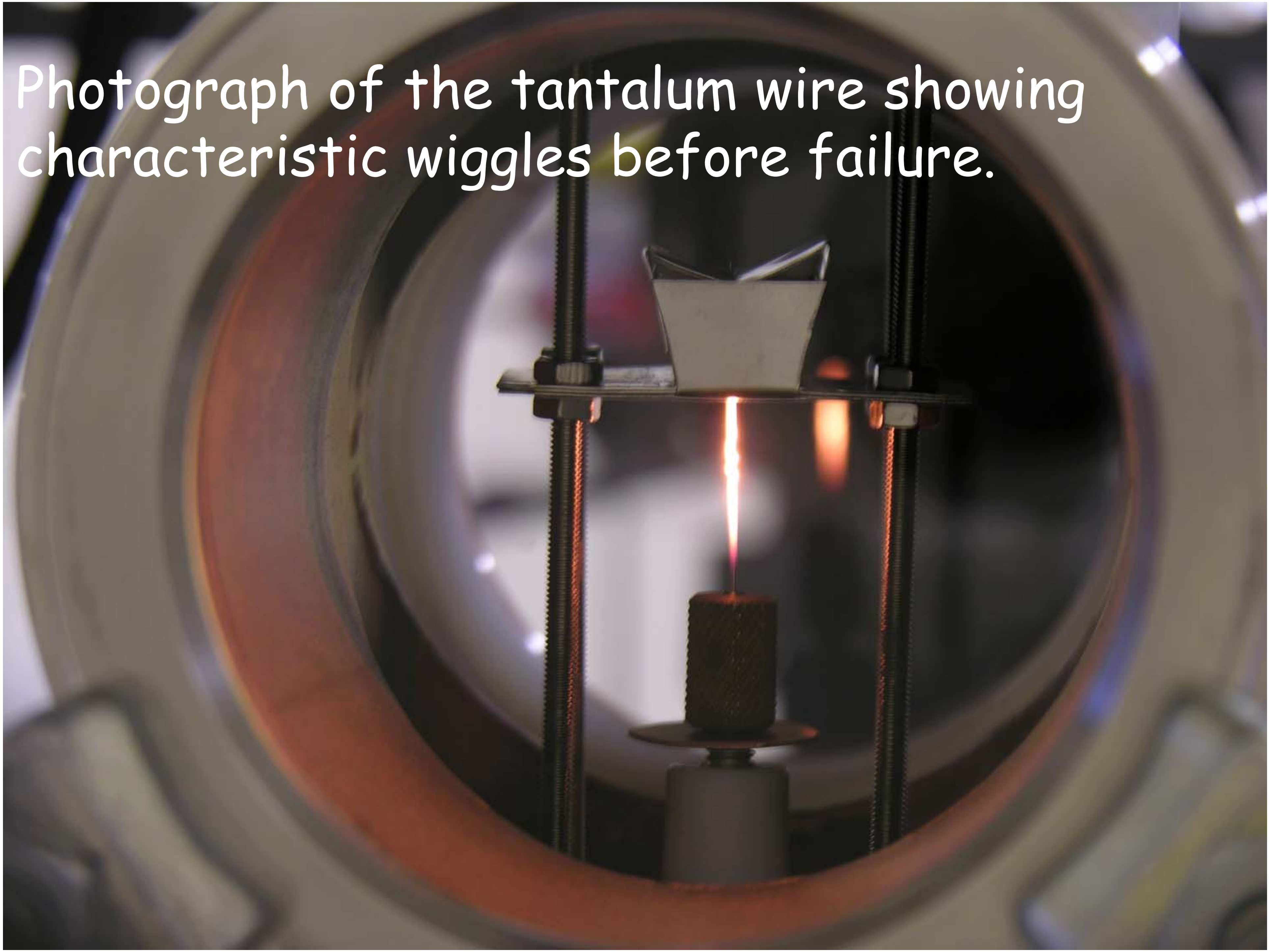
Picture of the wire test equipment



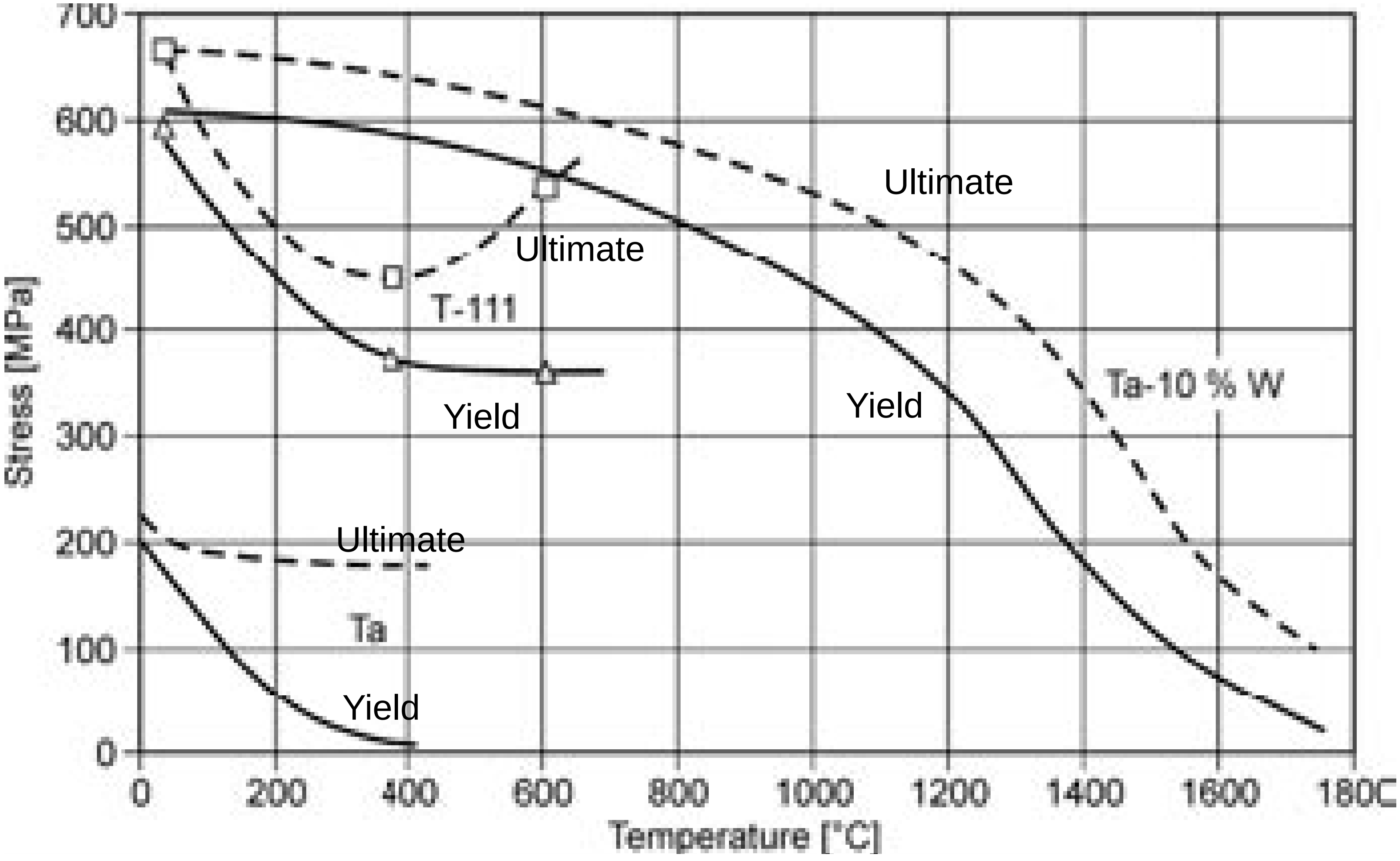
Tests on Tantalum Wire

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

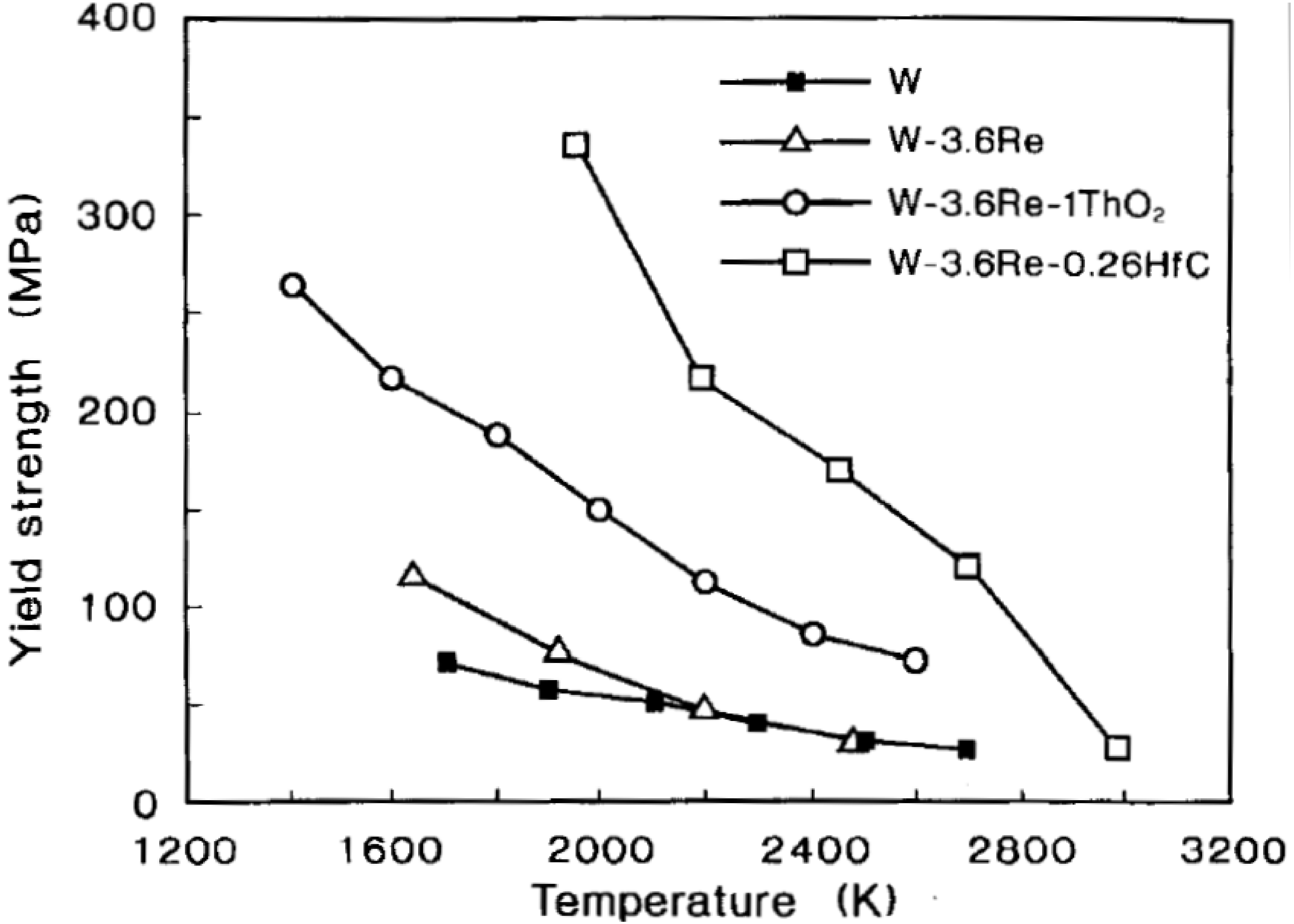
Tantalum is not a suitable material since it too weak at high temperatures (1600-2000 K).



Photograph of the tantalum wire showing characteristic wiggles before failure.



Yield and Ultimate Strength of Tantalum and alloys versus Temperature.



Yield Strength of Tungsten and some Alloys versus Temperature

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	$>3.4\times10^6$ 16,500	Broke	2.3	4.8
W08	6400	150	1900	$>1.6\times10^6$	Wire stuck to top connection (cu blocks)	3.9	8.4
W09	5560 5840	120 130	1900 2050	4.2×10^6 9×10^6	Top connector failed	3 3.3	6.4 7.0
W15	6400	180	1950	1.3×10^6	Wire stuck to top connection (cu blocks)	3.9	8.4
W26	6200 7520-8000	140 ~230	2000 ~1800	10×10^6 3×10^6	Broke	3.6 ~6	7.8 ~12
W28	6560	180	1900	26.4×10^6	Crack appeared	4.1	8.8
W30	4720	93	1870	$>54.5\times10^6$	Not broken	2.2	4.5

"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.

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.
3. Tests at BNL, (Nick Simos).

SEM ANALYSIS OF 4 SAMPLES OF TUNGSTEN WIRE.

Chris Salter

With the aim to observe any surface or internal damage which might indicate the presence of thermal fatigue. Micro-cracks can indicate fatigue.

Samples. 4 wires were supplied, W31 to W34.

The following techniques were used to characterise the samples:

- SEM imaging of the wires as delivered using both the secondary electron and the back-scattered electron signal.
- With some energy dispersive analysis to determine the nature of some of the features observed.
- The same samples were mounted in cold setting resin and polished, again observed using the SEM.

Results and Discussion

Wire W31; Unbroken wire

An extensive search found no surface signs of any fatigue cracks. However, the surface of the tungsten wire had been thermally etched in the central region, with extensive removal of material from the grain boundary regions.

Also, No signs of cracks in the sections.

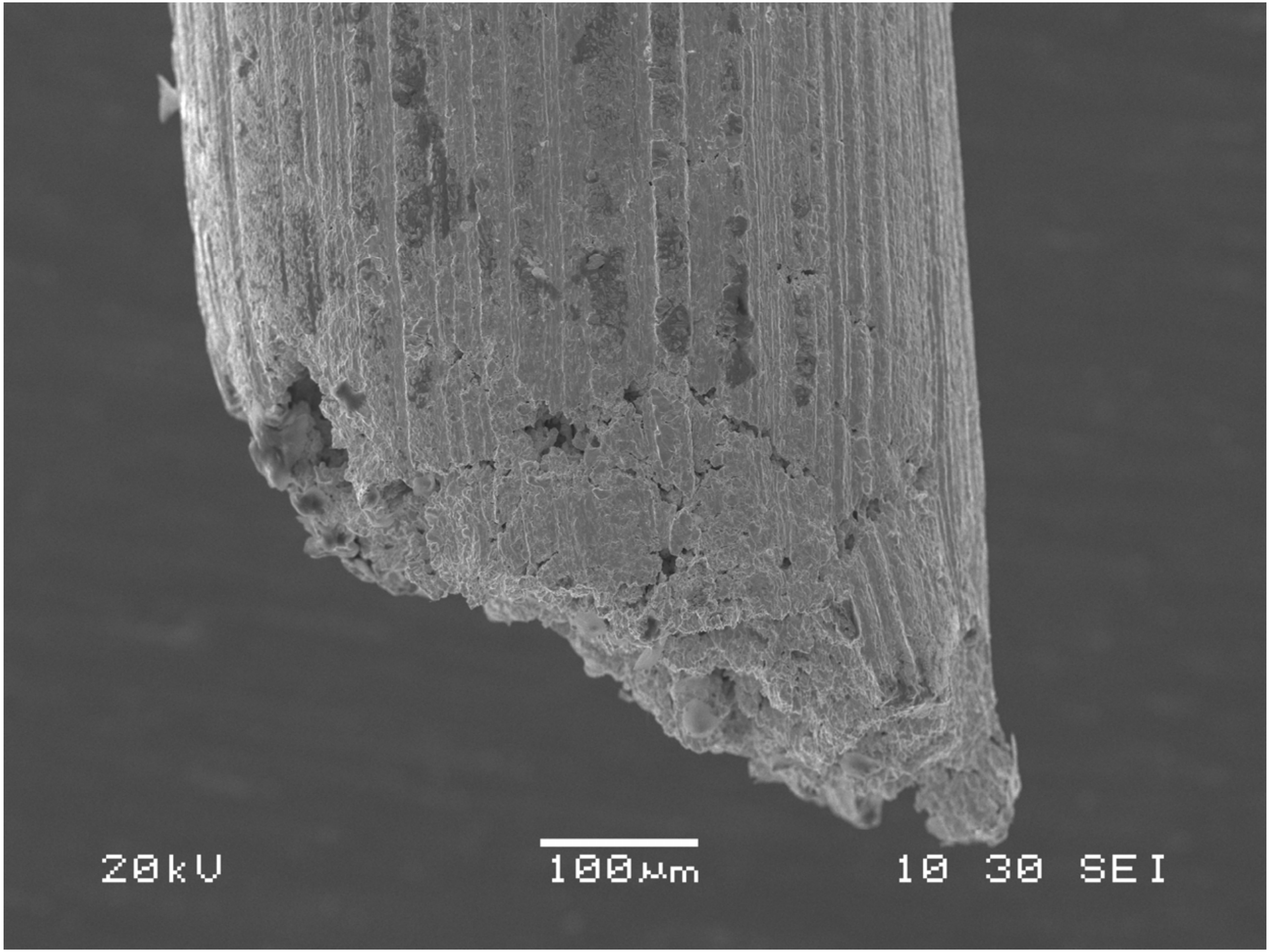
Wire W32 and 33; Broken.

No signs of fatigue micro-cracks. But wire severely melted at brake.

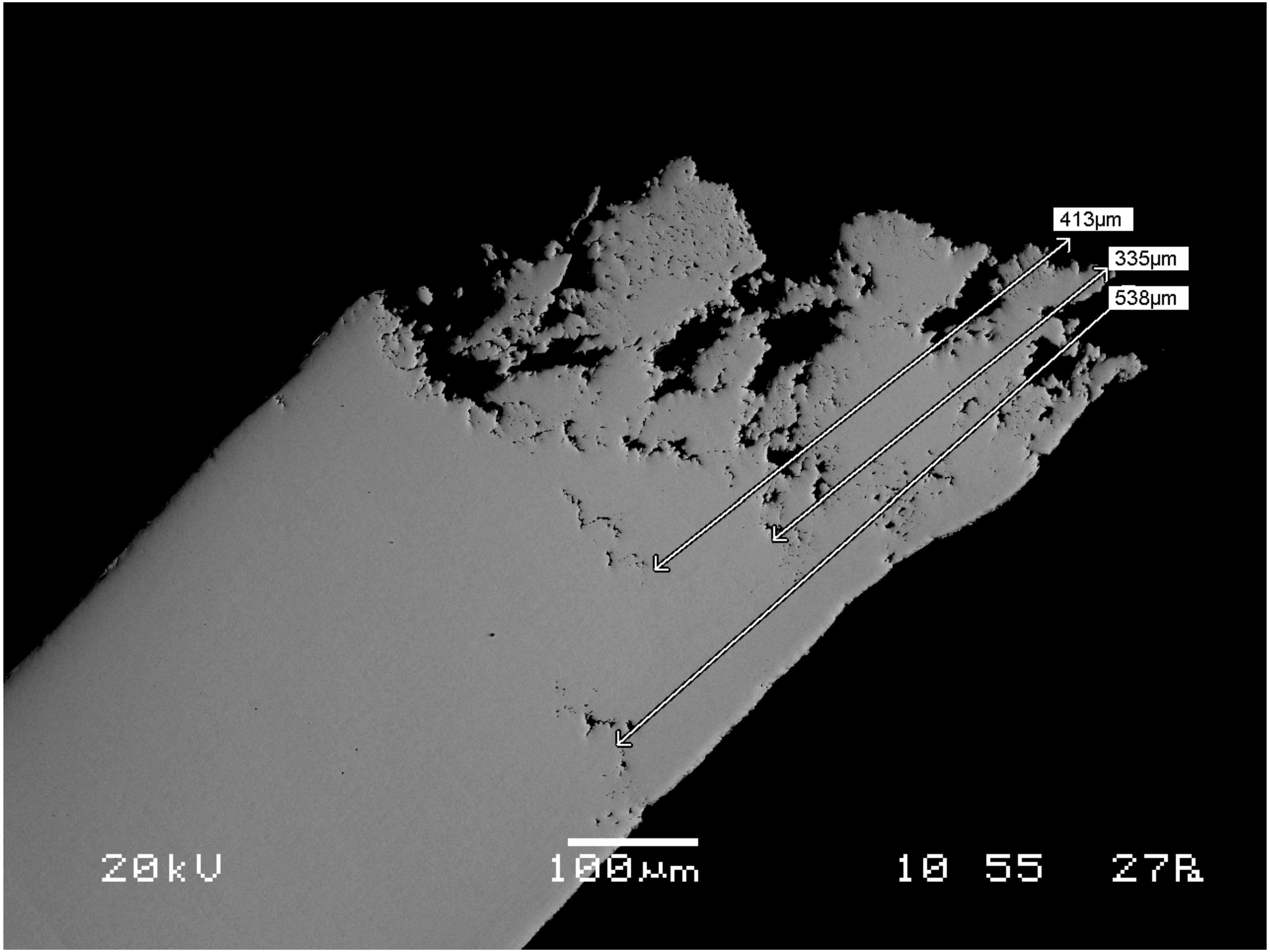
Wire W34; Crack just appeared in thermal test, Broke on cooling.

Massive cracking near the brake in the wire.

Is this a sign of fatigue stress?



W34



W 34. Section

Conclusions

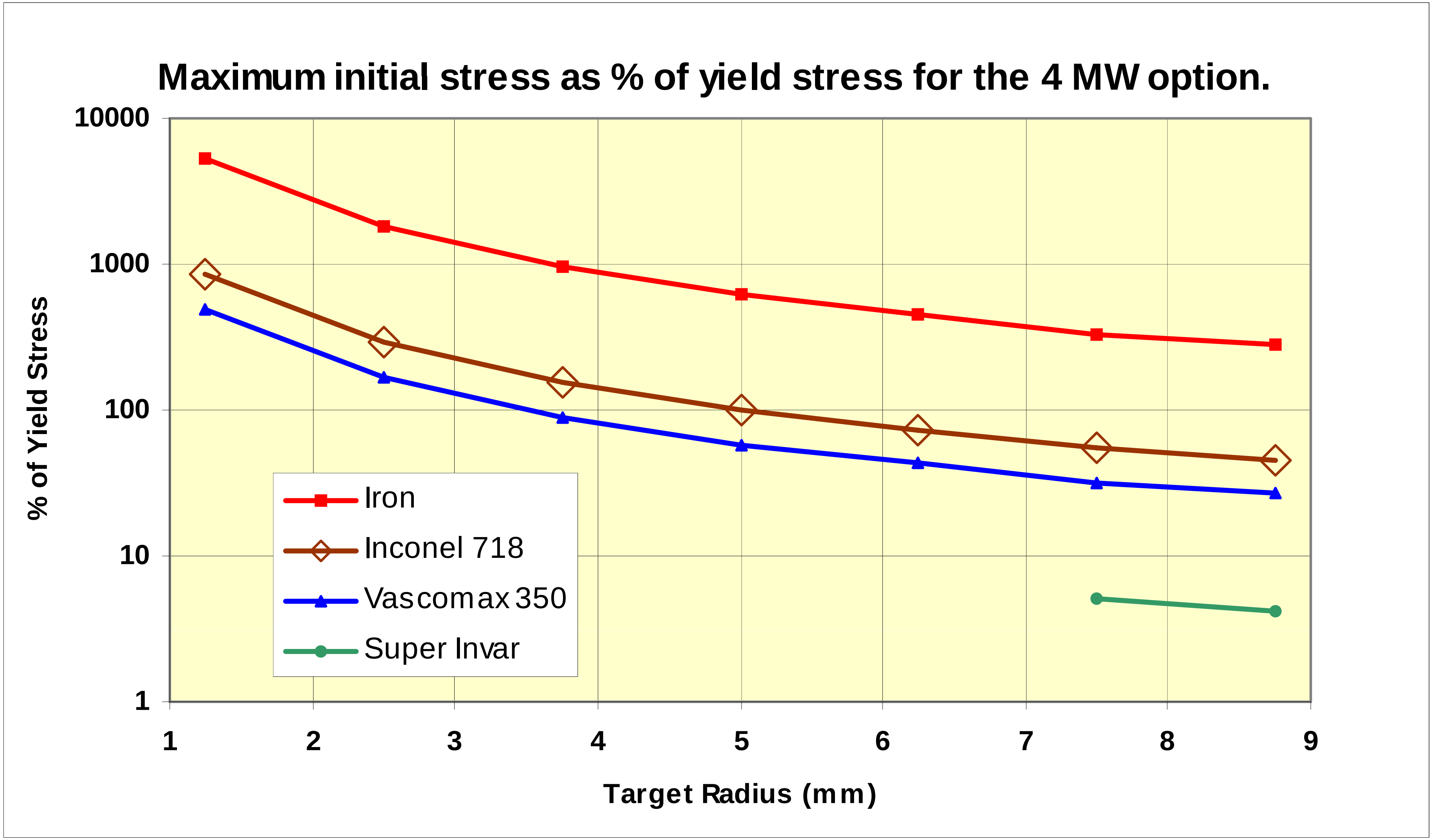
I believe that the viability of solid tungsten targets at high-temperature for a long life (~10 years) has been demonstrated with respect to thermal shock and fatigue and will not suffer undue radiation damage.

Future Programme

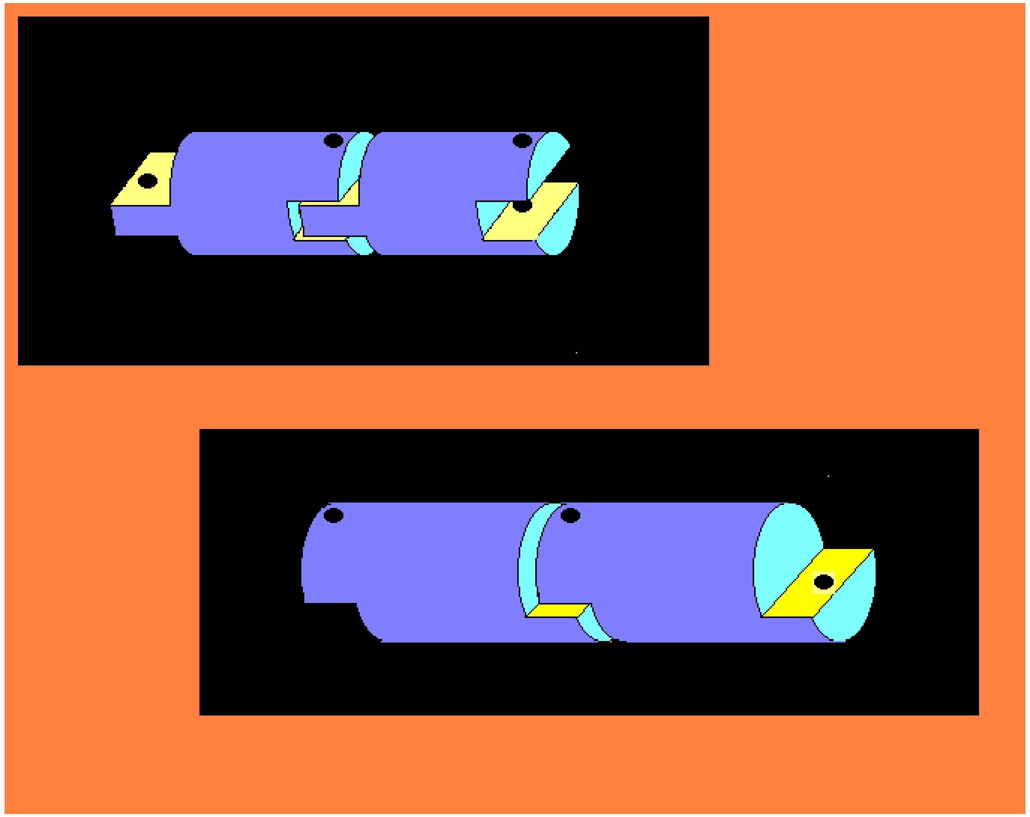
1. Continue wire tests with Tungsten and Graphite.
2. Continue modelling computations.
3. Continue SEM measurements.
4. VISAR measurements to asses the properties of tungsten, and any changes, during the wire tests. (Effect of thermal shock.)
5. Tests with a proton beam to confirm wire tests and VISAR measurements - but limited number of pulses.
6. Radiation damage studies.
7. Test alloys of tungsten.
8. Design & build a model of the target bar system.
9. Design the solenoid.
10. Design and cost the complete target station including the beam dump.

Solid Metal with low thermal expansion - BNL

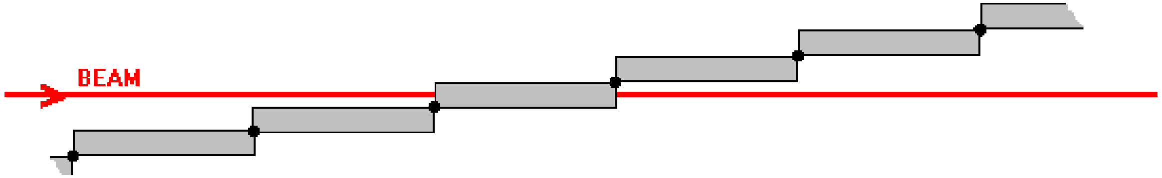
No thermal expansion = No shock



H.G. Kirk and P. Thieberger



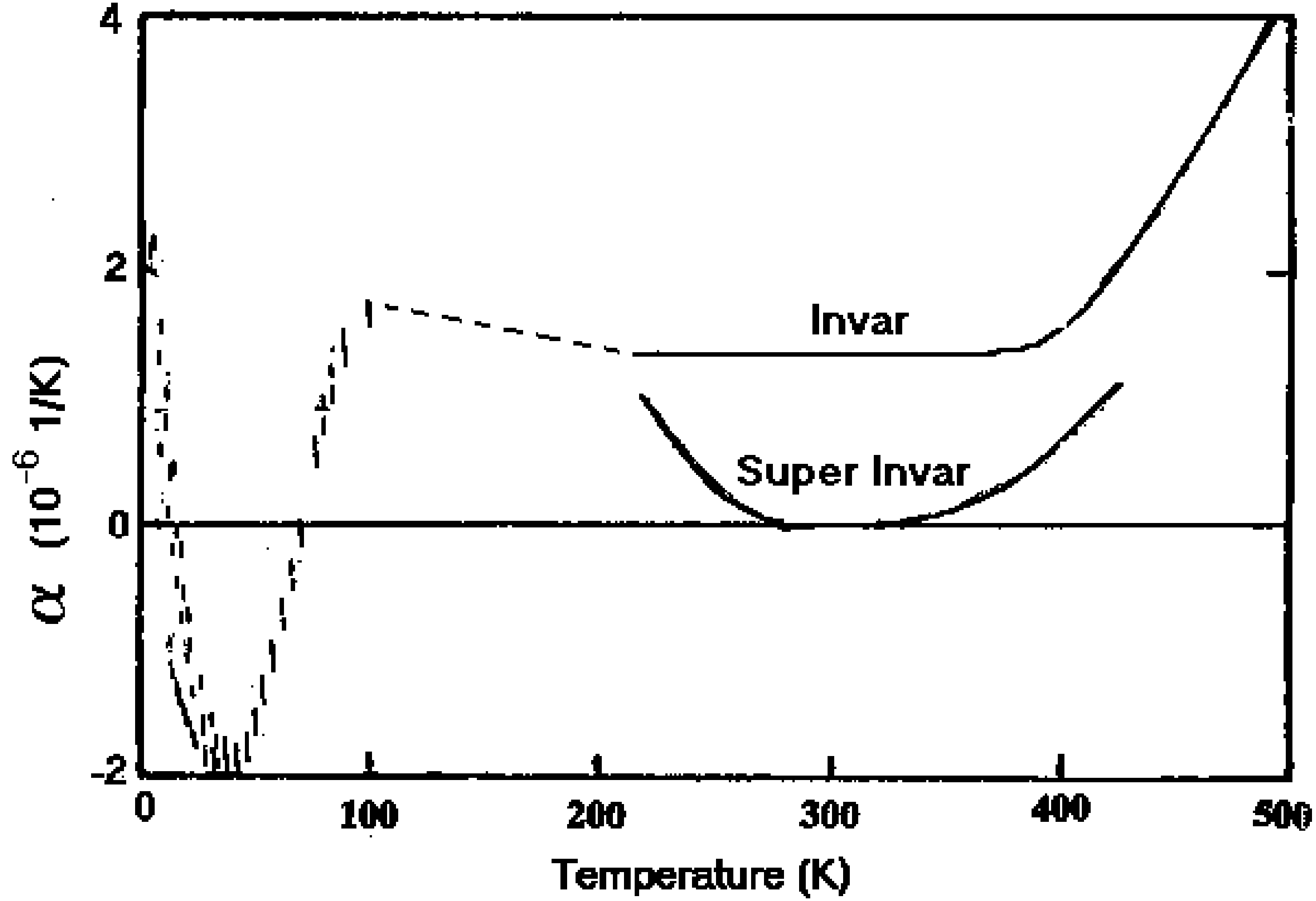
Schematic examples of metallic chain links showing rather compact designs with large metal to gap volume rtatios.



Schematic example of a chain with long links that would allow the beam to be coaxial with the target.

Examples of target velocities and lengths according to assumptions explained in the text.

	Velocity (continuous motion)	Minimum length (continuous motion)	Average Velocity (intermittent motion)	Minimum length (intermittent motion)
	m/s	m	m/s	m
Super Invar - 1 MW Option	7.5	175		
Vascomax C-350 - 1 MW Option	0.85	16.8	1.0	18
Super Invar - 4 MW Option	12.0	274		
Vascomax C-350 - 4 MW Option	3.0	34		



Thermal expansion coefficients versus temperature.

Comparison of advantages and disadvantages the three alloys considered.

MATERIAL	ADVANTAGES	DISADVANTAGES
Super Invar	Largest margin for thermal shock tolerance. Absence of large magnetic forces.	Narrow temperature range and low heat conductivity leading to the need for long chains or cables. The largest uncertainty regarding deleterious effects of radiation damage.
Vascomax C-350	Largest tensile strength. Good heat conductivity allowing the use of relatively short chains or cables.	The material is ferromagnetic and will be subject to large magnetic forces
Inconel 718	Good fatigue endurance limit similar to Vascomax C-350. Absence of large magnetic forces.	Poor heat conductivity (similar to Super Invar) requiring long chains of cables, but not as long as for Super Invar since the temperature range is not as small.

Unfortunately the advantageous properties are lost at fairly modest irradiations

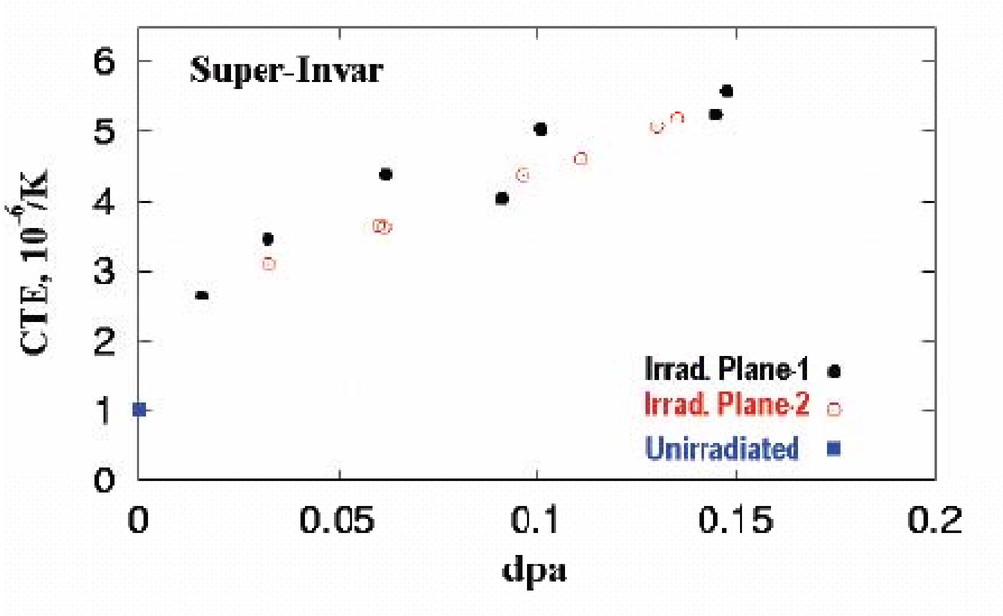
But they can be restored by heating to ~500°C.

This work is continuing.

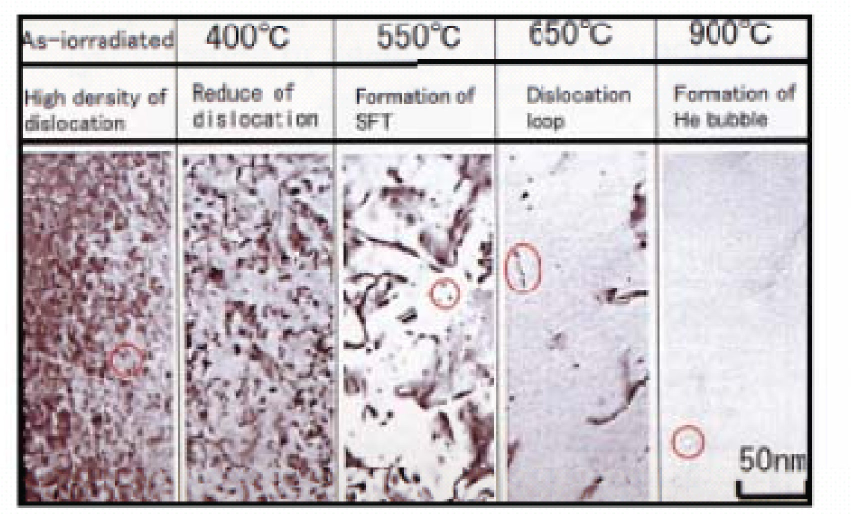
Irradiation studies on super-Invar

- “invar” effect found in Fe-Ni alloys → low CTE
  - “inflection” point at around 150 C

Effect of modest irradiation



Annealing or defect mobility at elevated temperature

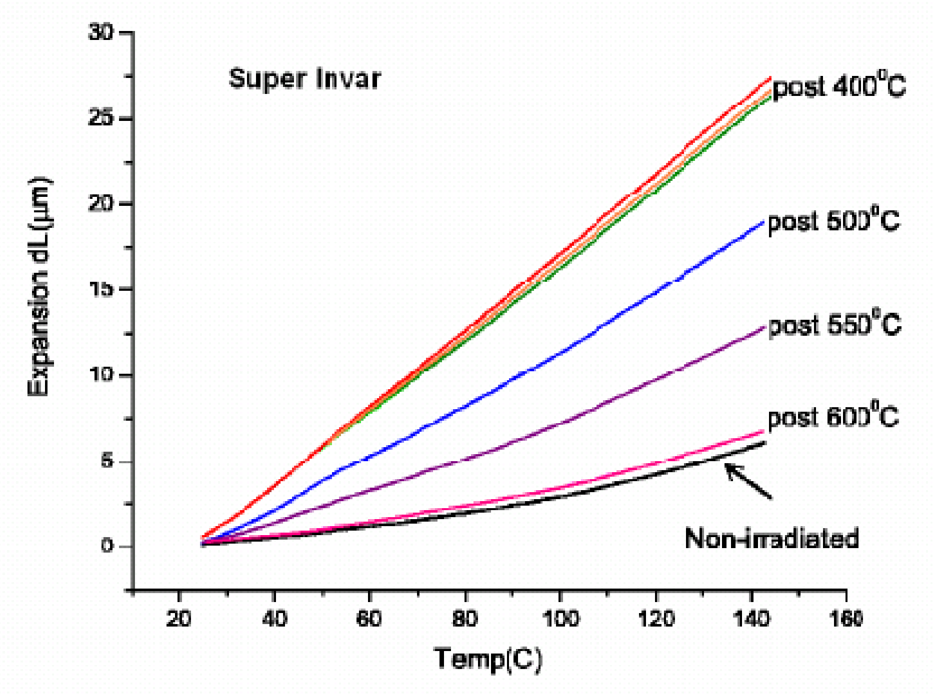


Y. Ishiyam et. al., J. Nucl. Mtrl. 239 (1996) 90-94

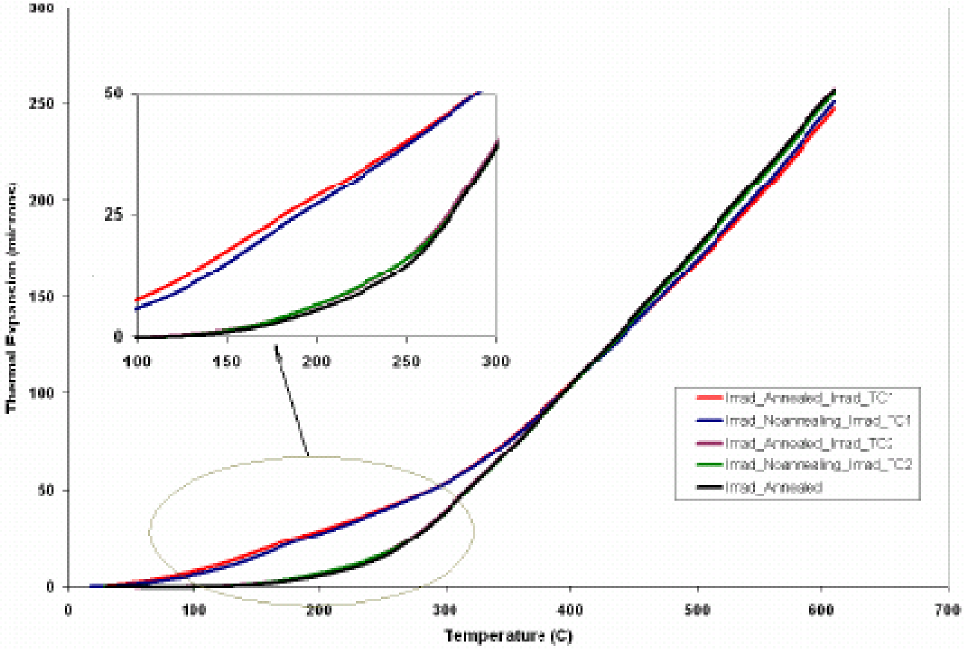
Nick Simos

“annealing” of super-Invar

Following 1st irradiation

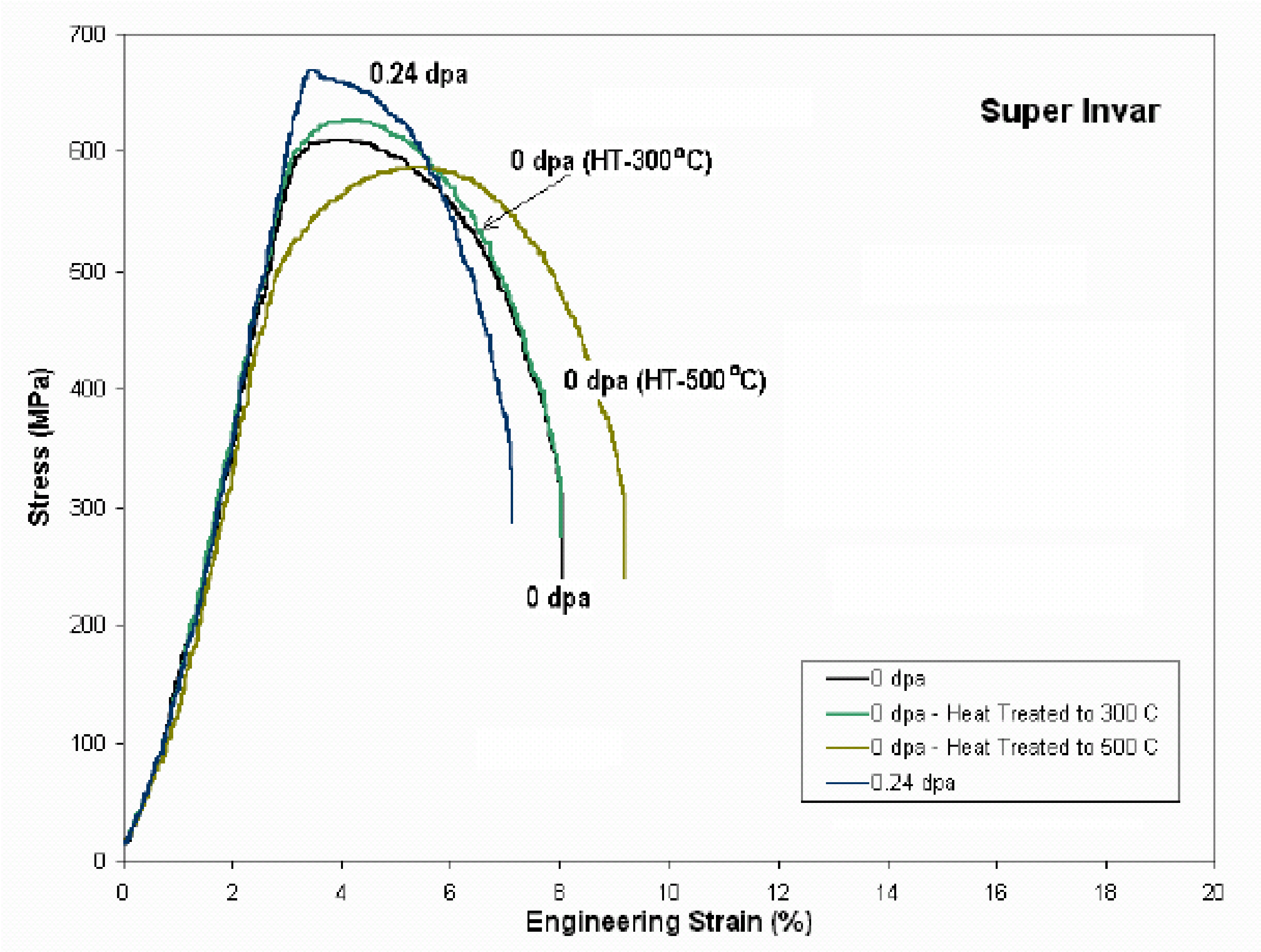


Following annealing and 2nd irradiation



ONGOING 3rd irradiation phase: neutron exposure

Irradiation & temperature effects on Super-Invar

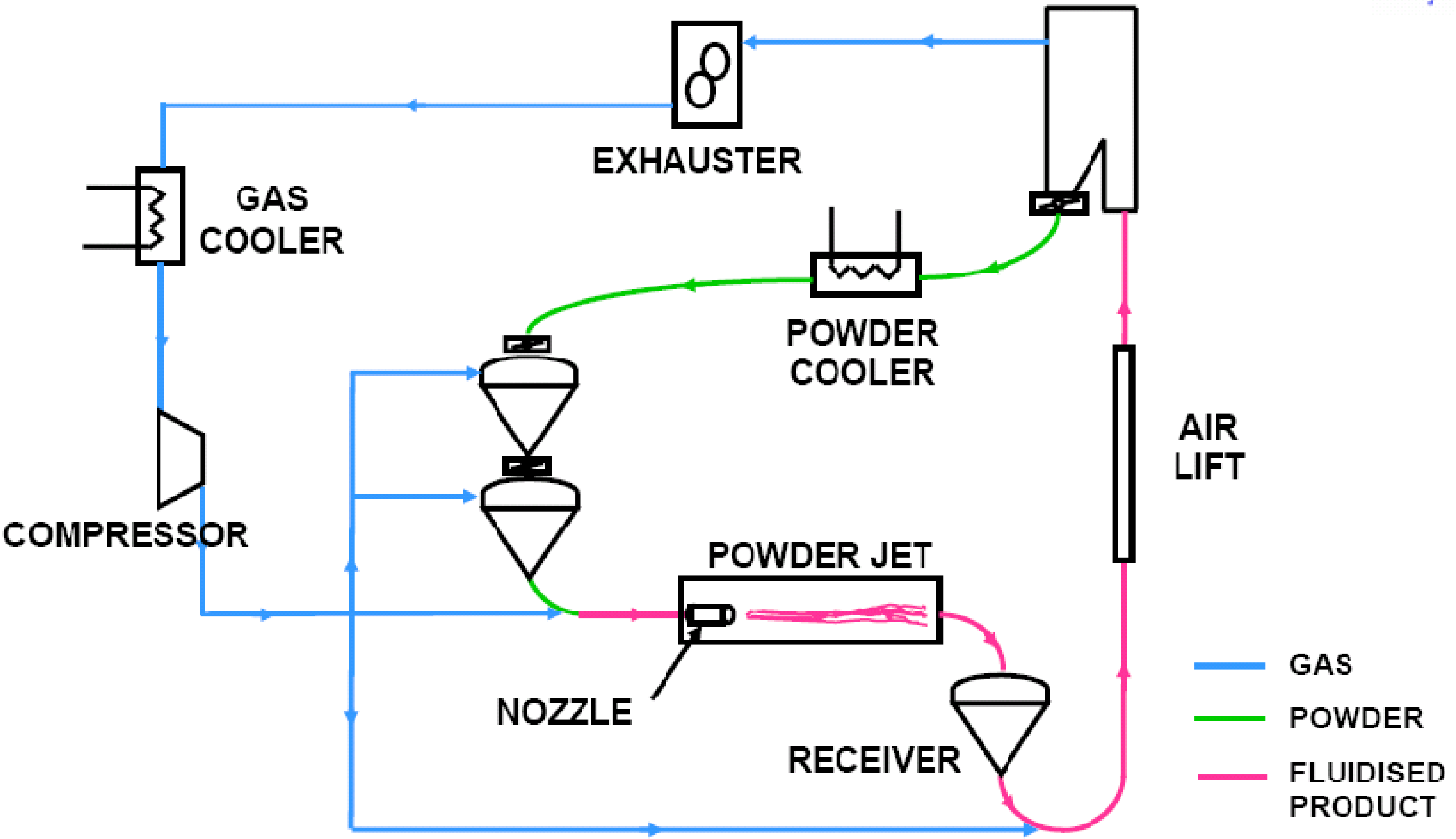


Flowing Metal Powder Targets - RAL

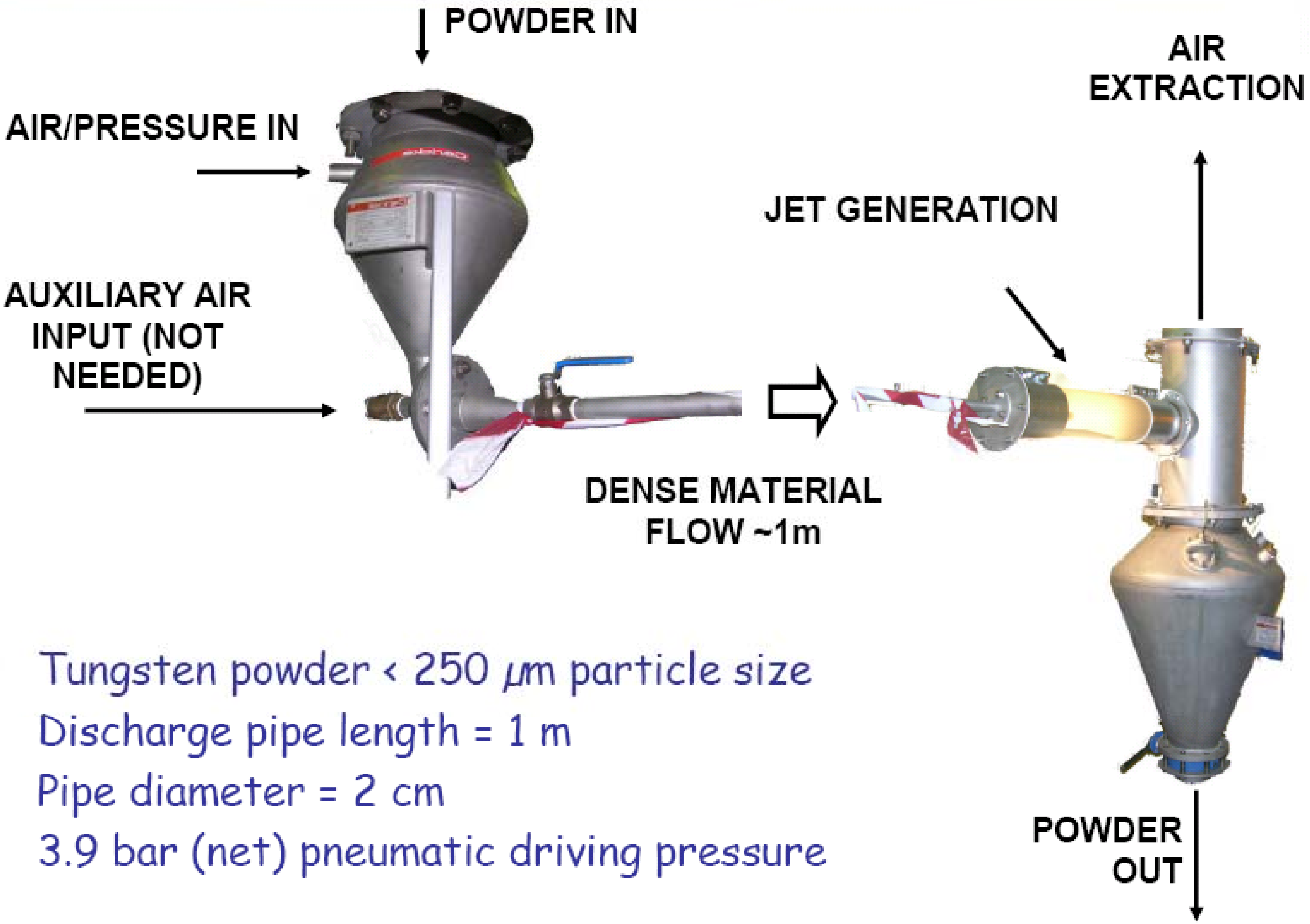
- ☐ Metal powder in a liquid or gas.
- ☐ The small particle size avoids the shock problems.
- ☐ Similar in many respects to liquid metal targets.

Work by Chris Denham & Ottone Caretta (RAL), Tom Davies (Exeter University) and Richard Woods (Gericke LTD)

Powder jet prototype test plant



The rig



POWDER IN

AIR/PRESSURE IN

AUXILIARY AIR INPUT (NOT NEEDED)

DENSE MATERIAL FLOW ~1m

JET GENERATION

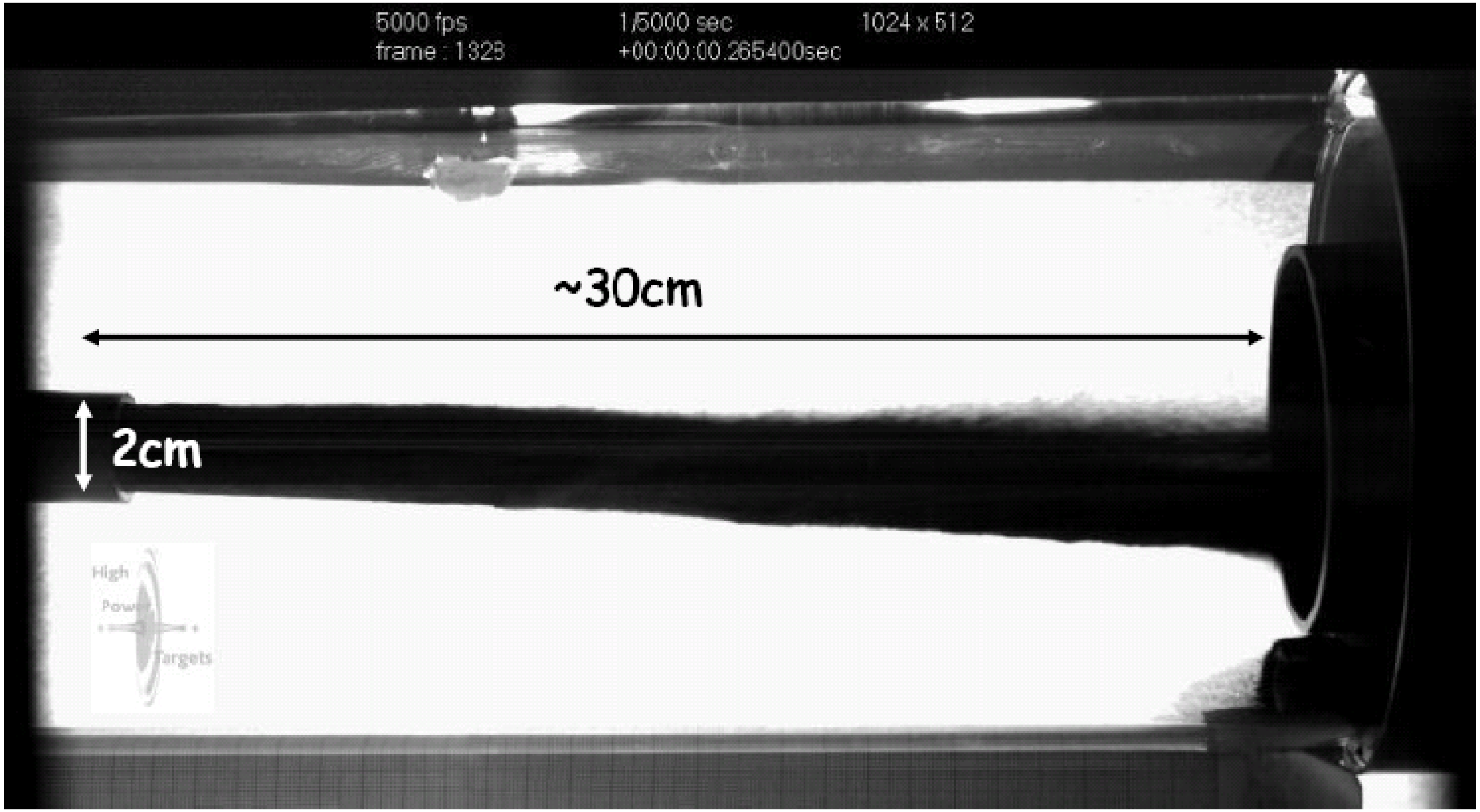
AIR EXTRACTION

POWDER OUT

- Tungsten powder < 250 μm particle size
- Discharge pipe length = 1 m
- Pipe diameter = 2 cm
- 3.9 bar (net) pneumatic driving pressure

Results from the 2nd day

(with small improvements on day 1: see Densham's presentation at NuFact 07)



Thank you to EIP at RAL for providing the video equipment used for these experiments

Observations:

- Tungsten despite being very heavy has extraordinarily good flowability characteristics

- The powder jet has similar behaviour as a fluid jet (affected by the conditions of the surrounding gas)

Tungsten powder jet – first results

P_0= 4.9 bar (abs)

P_1= 1 bar (abs)

Initial bulk density

= 8660 kg/m^3

= 45 % W (by volume)

Jet bulk density

~= 28.75 % W by vol.

Jet velocity = 10 m/s

(100 kg in 8 seconds)

Difficult to measure!

Some questions/issues:

- Electrical charge (Lorentz force)
- Eddy currents
- Elastic stress waves and thermal expansion
- Erosion
- Disposal and radiological hazard

Electrical charge (Lorentz force)

- **Electrostatic charge**
  powder charging due to friction is a well known issue in material conveying and can be avoided with careful plant design

- **Beam ionisation**
  is worth studying! (both physics studies and possibly tests)
  The number of protons in the beam is small compared with the atoms in the grains!

Eddy currents

There are 2 ways to reduce eddy currents of a conductor moving in an EM field:

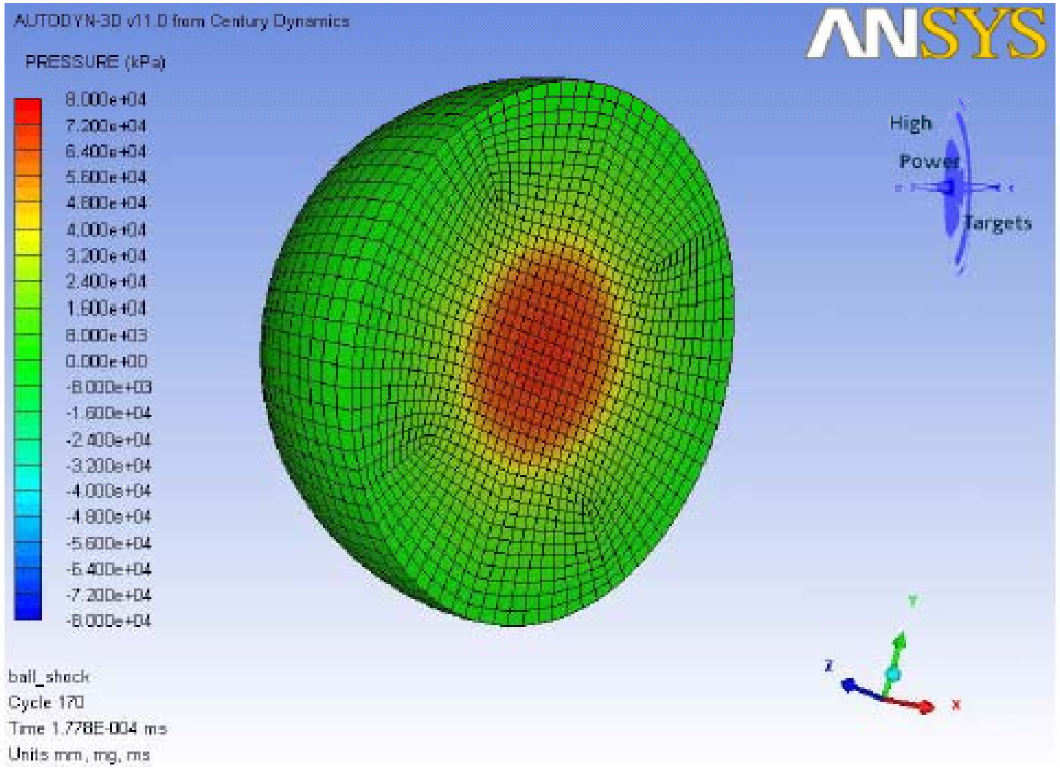
- lower the conductivity of the material
- break the conductor into smaller parts

Should not be a problem, but is worth investigating!

Elastic stress waves and thermal expansion

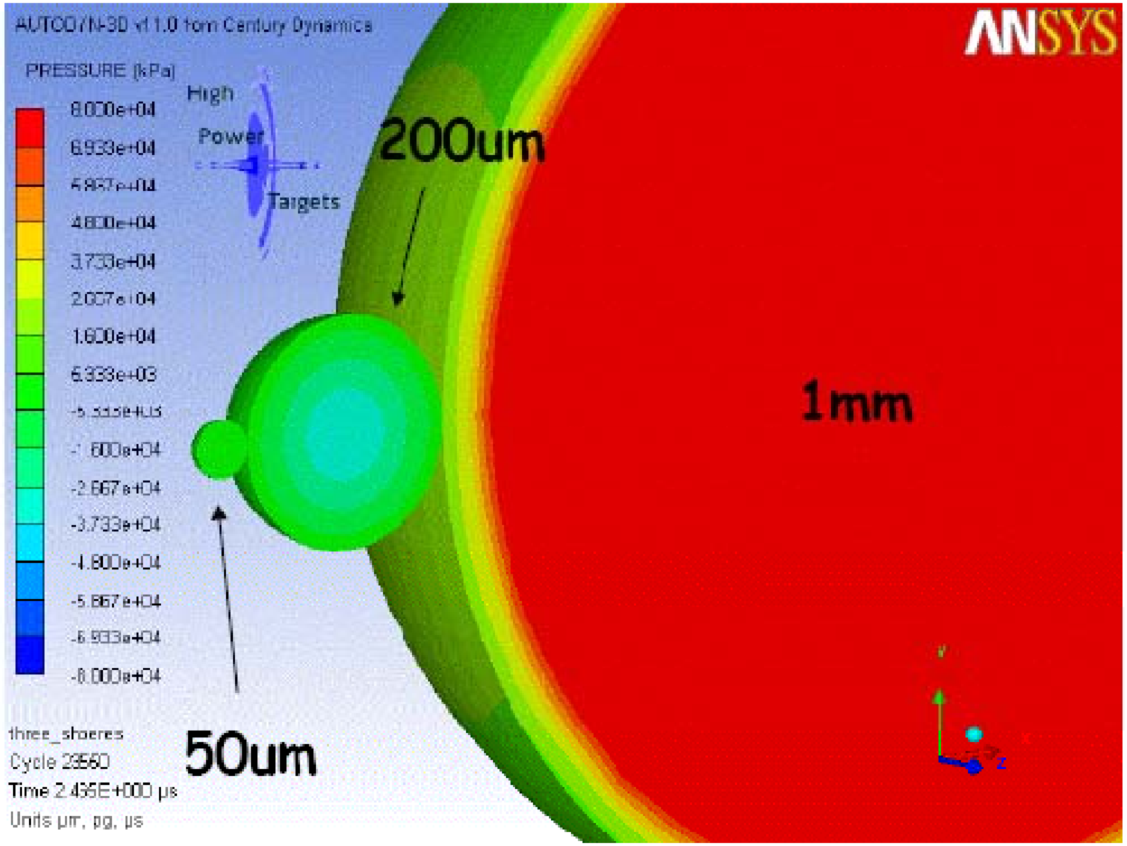
Interesting to study both with **simulations** and perhaps with **in beam tests** (such as mercury thimble at ISOLDE?)

Elastic waves should not be a problem:
Sand bags are effective at stopping bullets!



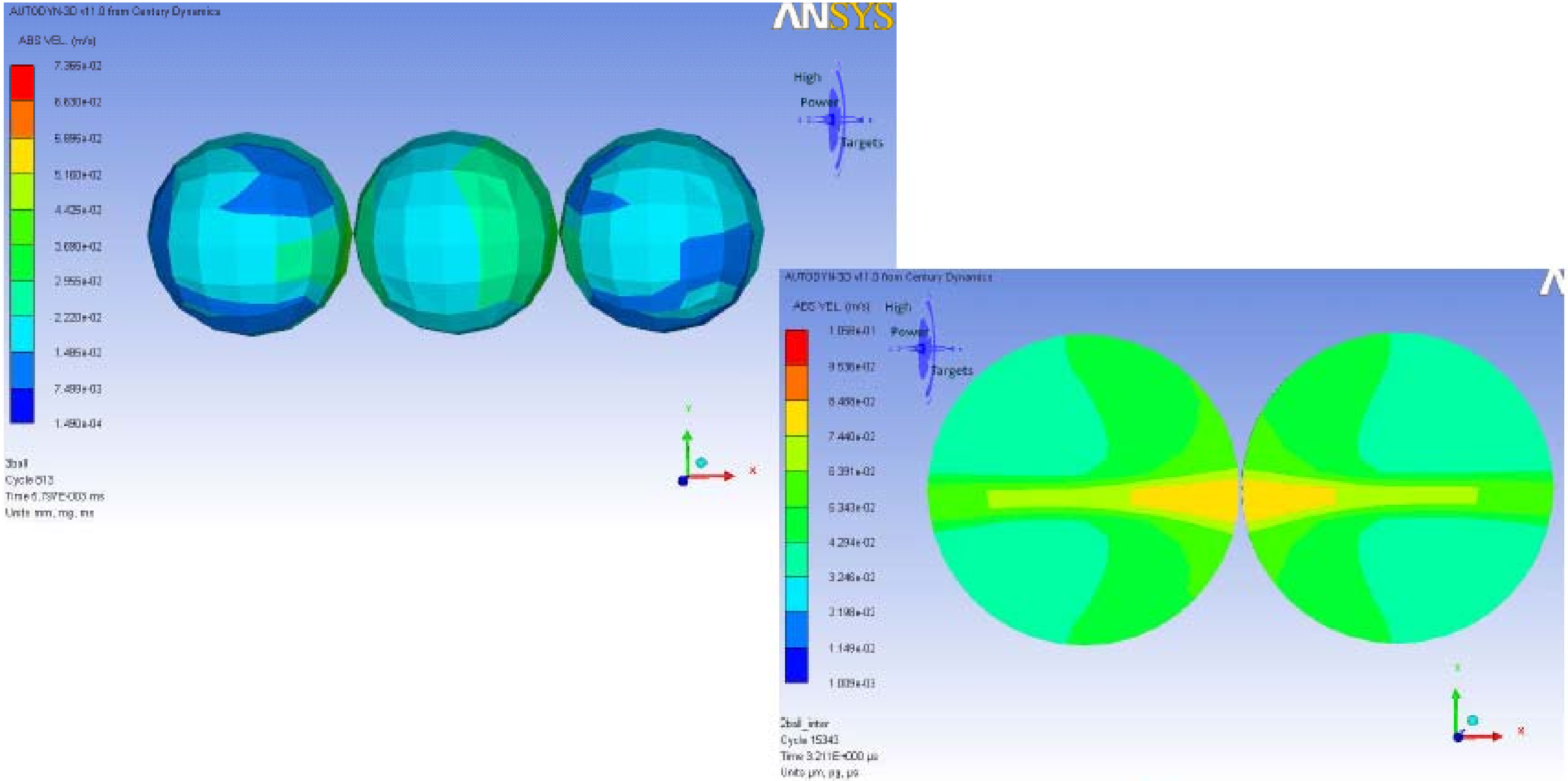
Elastic stress waves and thermal expansion

The simulations show that smaller particles have higher resonance frequencies and dissipate their energy faster than bigger particles



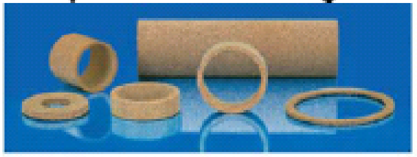
Elastic stress waves and thermal expansion

The preliminary simulations indicate small velocities due to elastic particle interaction (order of 0.5 m/s)



Powder jet: next stages

- Incorporate recirculation air lift into system
- Improve bulk density of jet (28.7% -> 45% by volume)
  - By co-axial air flow ?
  - By matching the pressure drop to the delivery pipe length?
  - By degassing the stream prior to injection (using a porous sintered material)?



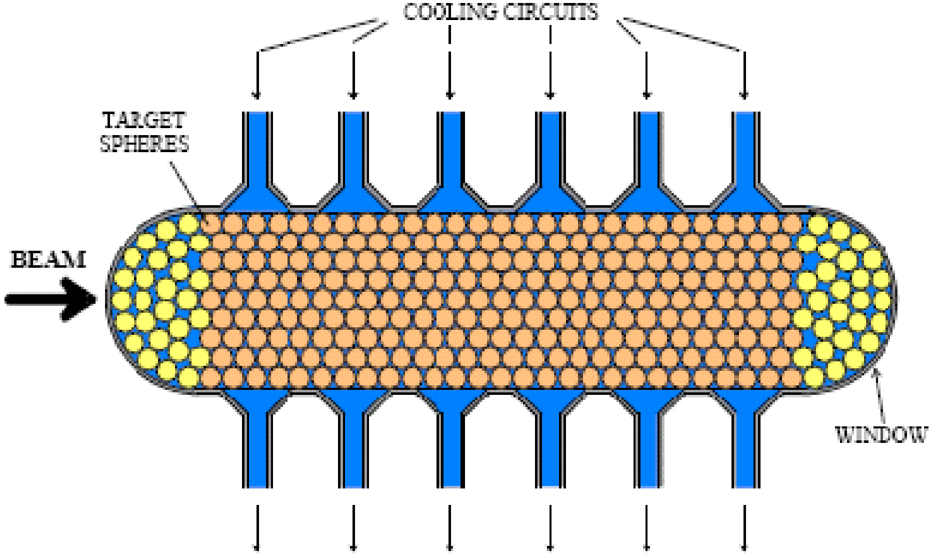
- Demonstrate shock waves are not a problem
- Demonstrate magnetic fields/eddy currents are not a problem

Small Solid Metal Spheres - Granular Targets

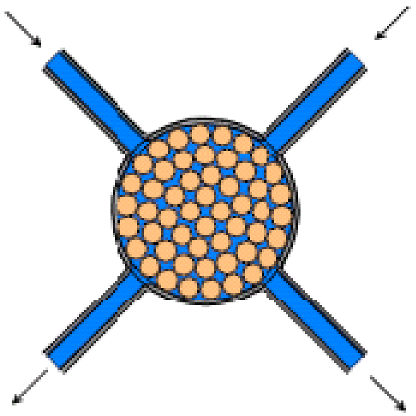
Peter Sievers - CERN

The small solid spheres avoid the shock problems

GRANULAR TARGET COOLED BY LIQUID OR GAS



TRASVERSE SECTION



P. SIEVERS, CERN
20/11/2000

COOLED GRANULAR TARGET
4 MW-BEAM

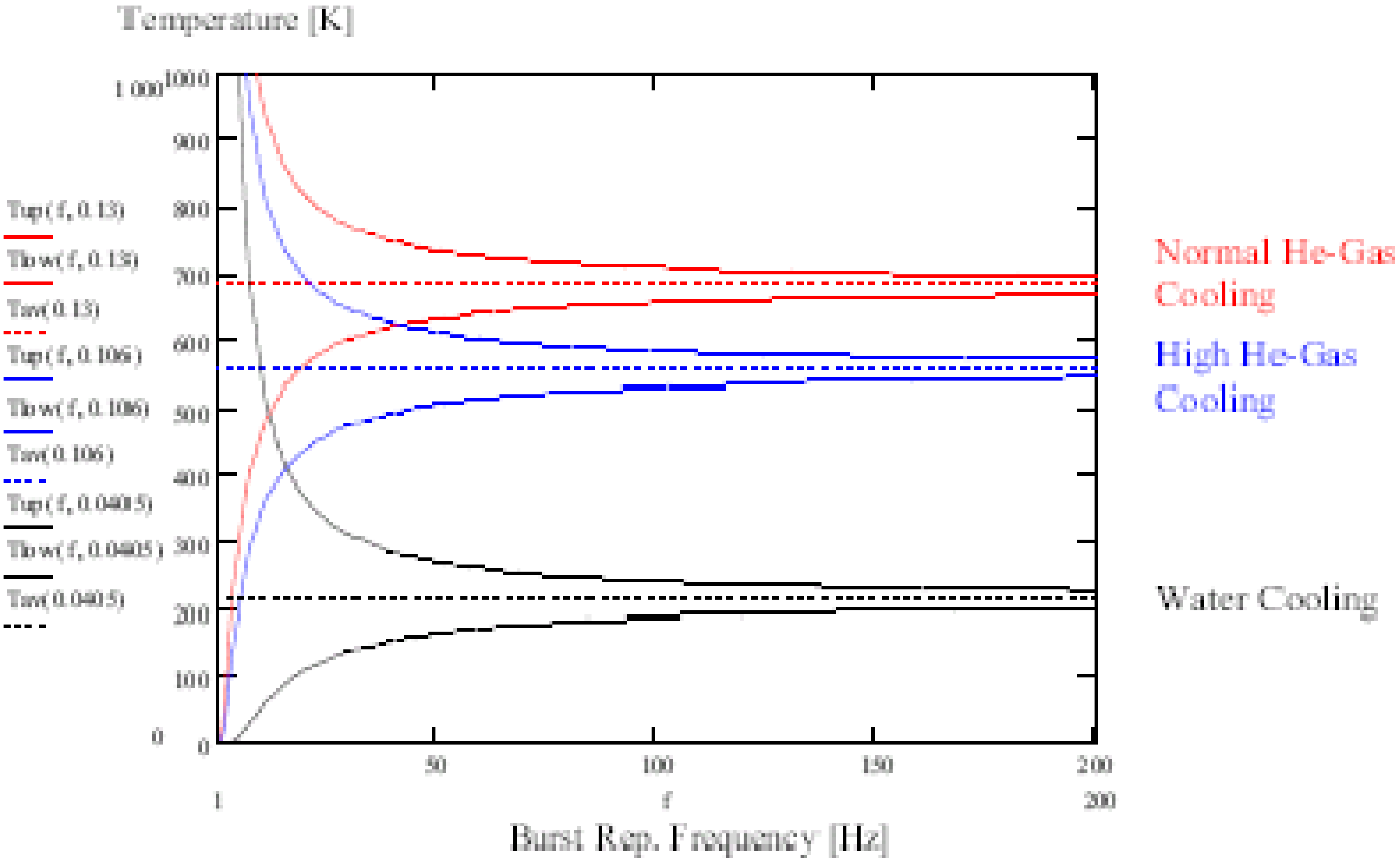
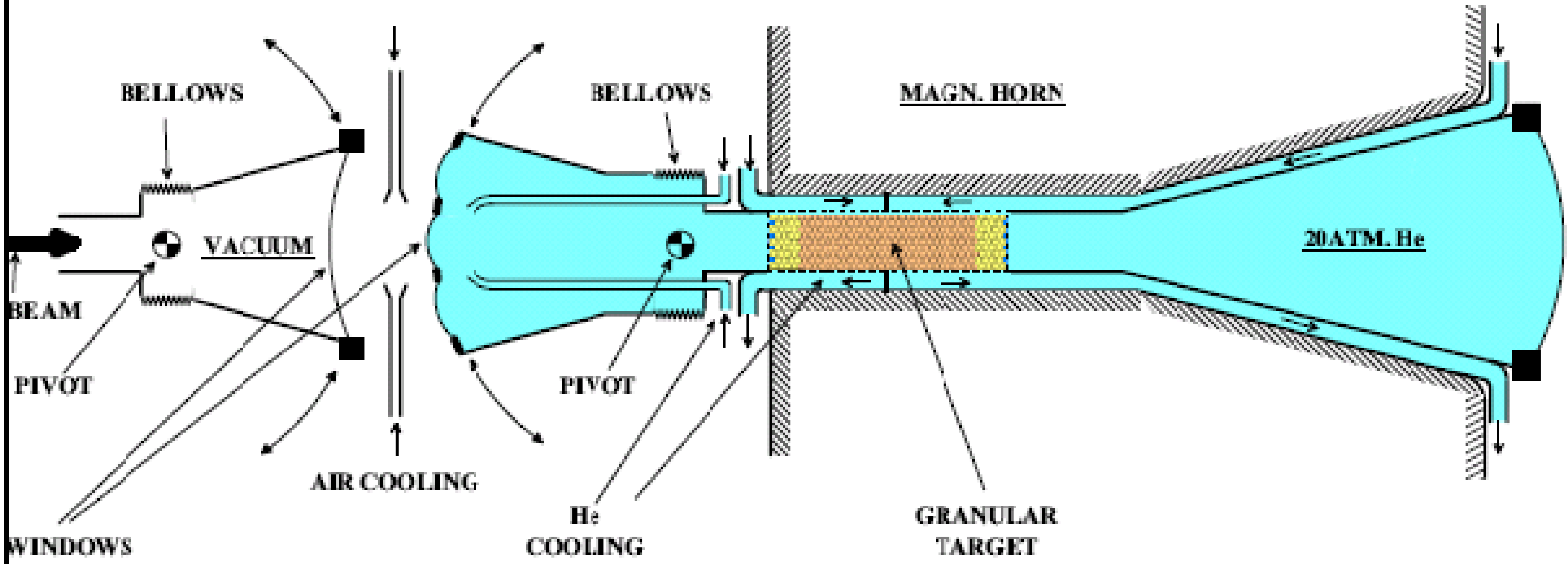


Table 1: Minimum and maximum temperature inside spheres and He-gas during the 50 Hz pulsed beam. The time average temperatures refer to a 4 MW continuous beam.

	$T_{S,}$ min.	$T_{S,}$ Max.	$T_{S,}$ average	$T_{He,}$ min.	T_{He} Max.	T_{He} average
Single target, $\dot{m}_{He}$ = 0.36 kg/s	631	731	680	505	585	544
Single target, $\dot{m}_{He}$ = 0.72 kg/s	387	487	435	240	302	270
Quadruple target, $\dot{m}_{He}$ = 0.36 kg/s	125	225	170	100	180	136

GRANULAR TARGET WITH He-GAS COOLING AND WITH WINDOWS OF EXTENDED LIFETIME



P. SIEVERS - 10/01/2002

- A sophisticated design of optics was developed to combine the pion beams from four targets.
- The work has ceased when Peter Sievers retired in 2003.
- This is the only stationary target design for high-powers.

The End

Thank you for your attention