CCLRC

Rutherford Appleton Laboratory

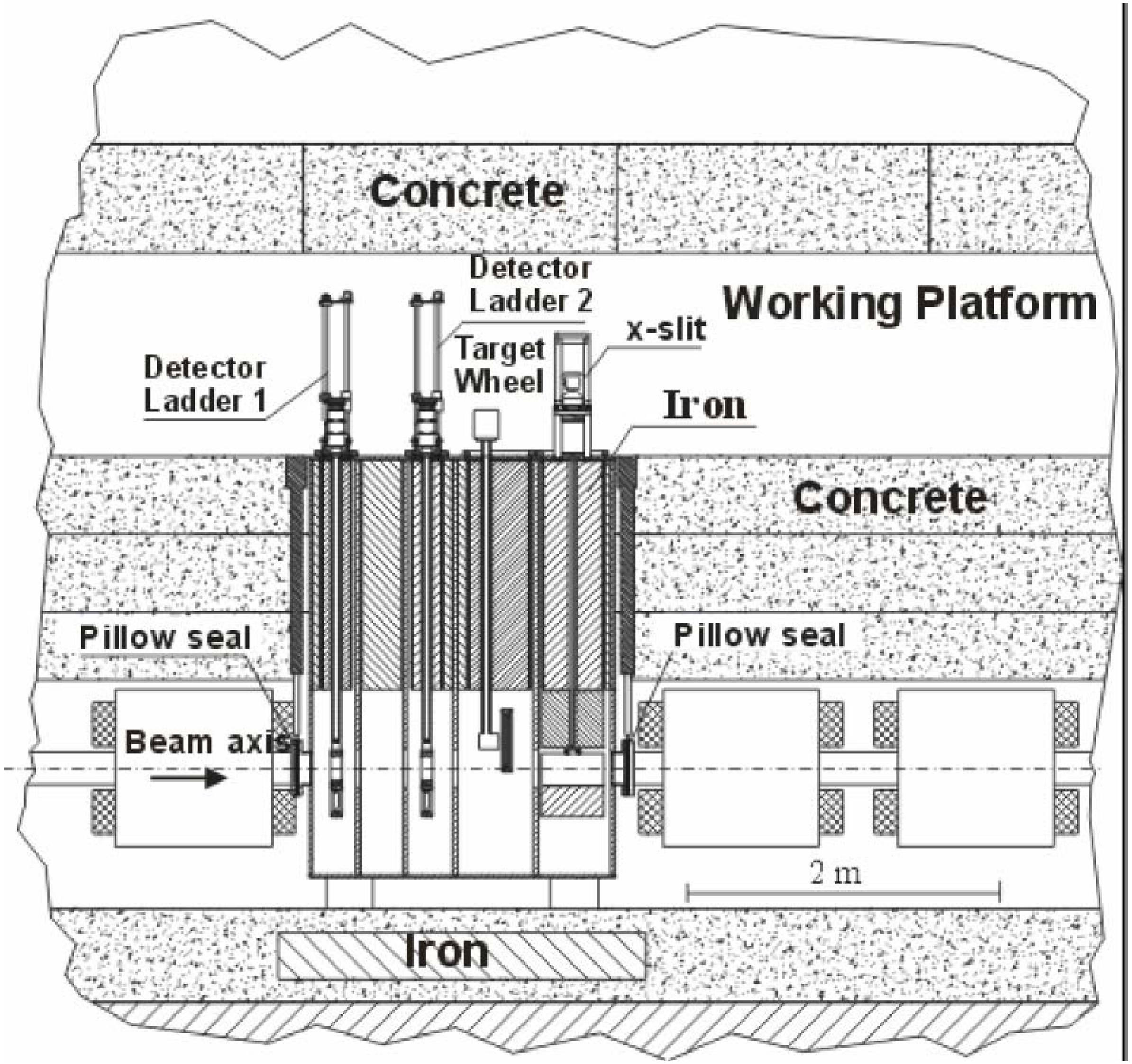
Shock wave studies in solid targets

FAIR Super-FRS production targets

Synergy with some targets for other accelerator facilities

Chris Densham
Engineering Analysis Group

Layout of Super-FRS target area



Super-FRS production targets

Slow extraction

- ions extracted over few seconds
- Slowly rotating graphite wheel probably OK

Fast extraction – the wish list!

- U^{238} beams of up to 10^{12} ions/pulse
- Pulse lengths 50-60 ns
- Beam spot sizes $\sigma_x = 1$ mm, $\sigma_y = 1$ mm
- Power densities 40 kJ/g
- $\Delta T = 30{,}000^\circ C$

→ Instantaneous evaporation of any material

Fast-extracted beams:
Target options under consideration:

- Increase beam spot size – obvious easy option
- For low projectile Z and low intensities - use a PSI style rotating graphite wheel (as planned for slow extraction)
- For highest intensities – windowless liquid metal jet

CCLRC work programme for FAIR

Study of:

Solid (graphite) target
Liquid Li target
Beam Dump

Informal agreement between CCLRC and GSI:

Chris Densham, Mike Fitton, Matt Rooney (CCLRC),
Helmut Weickl, Klaus Sümmerer, Martin Winkler,
Bernhard Franzke (GSI)

CCLRC work programme for FAIR: Solid Target

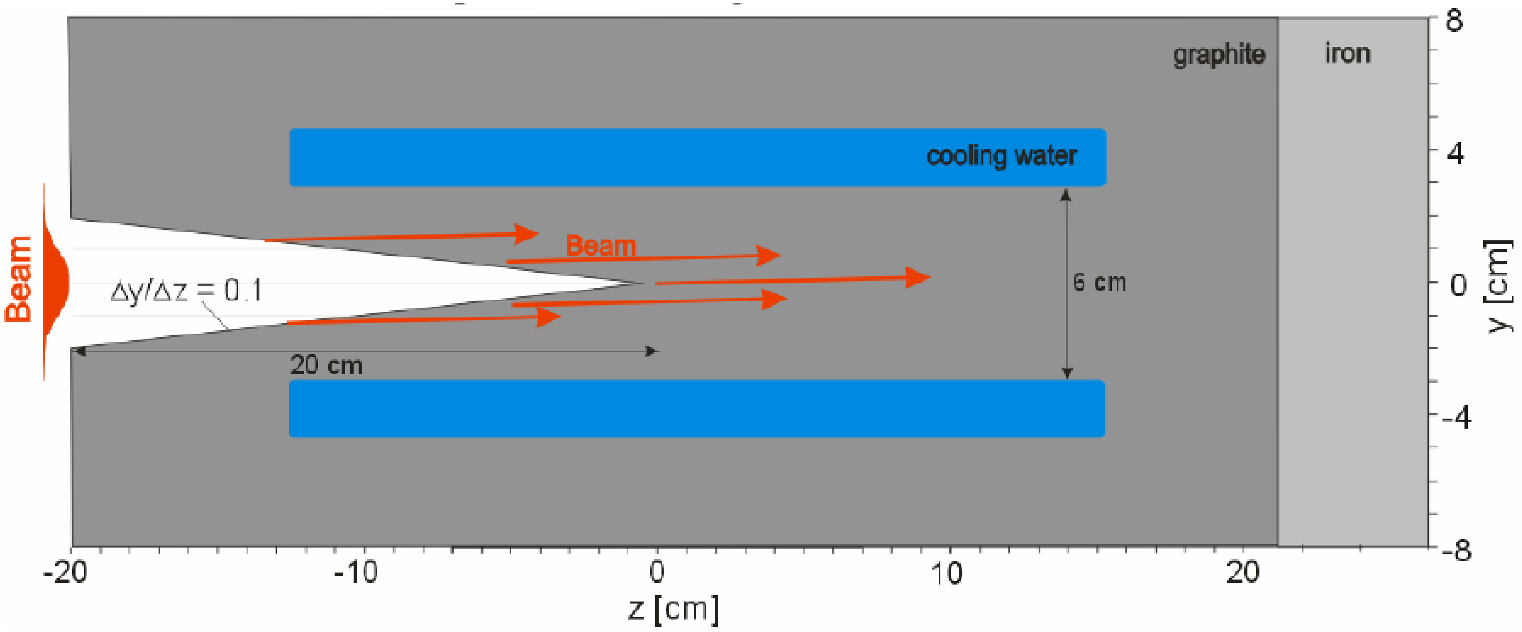
- For a U^{238} beam, $\sigma_x = 1$ mm, $\sigma_y = 2$ mm on a graphite target:
- What are the maximum positive and negative stress waves that traverse the graphite after the impact of the ion pulse?
- What are the technical limits of these shock stresses?
- What is the expected lifetime of a graphite target?
- What U beam spot size would give a target lifetime of 1 year?

CCLRC Work Programme for FAIR: Liquid Metal target

- For high intensity, high Z, highly focussed beam
- Simulation of liquid lithium target to determine limiting factors of design is required.
  - Simulations should include
    - Free surfaces (predict ejection of Lithium)
    - Shock waves
    - 3D
    - An appropriate EOS model

- Experiments similar to RIA, but with pulsed beam would be necessary for validation.

CCLRC work programme for FAIR
Beam Dump



- Primary beam is stopped in graphite
- Secondary beam stopped in subsequent Fe layer
- Calculate temperatures / shock waves in C/Fe interface and coolant pipes
- Optimise design to maximise lifetime

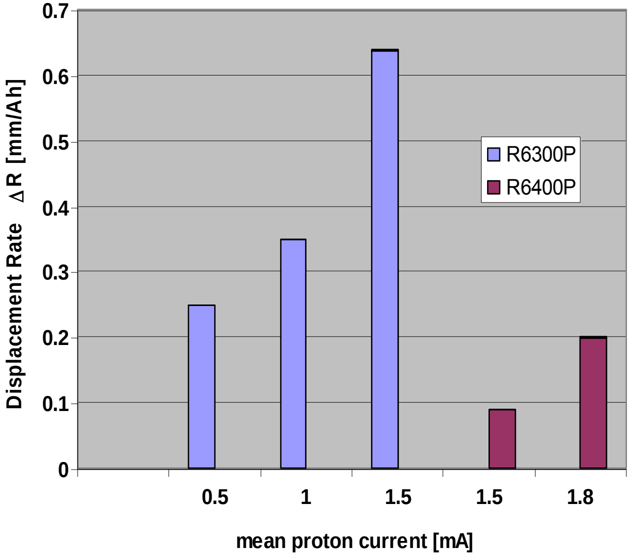
The PSI muon production target

- Rotating graphite disc
- CW Proton beam
- Considerable experience gained at PSI, e.g. bearings, materials

- Planned to adapt design for FAIR – want c.4 g/cm^2

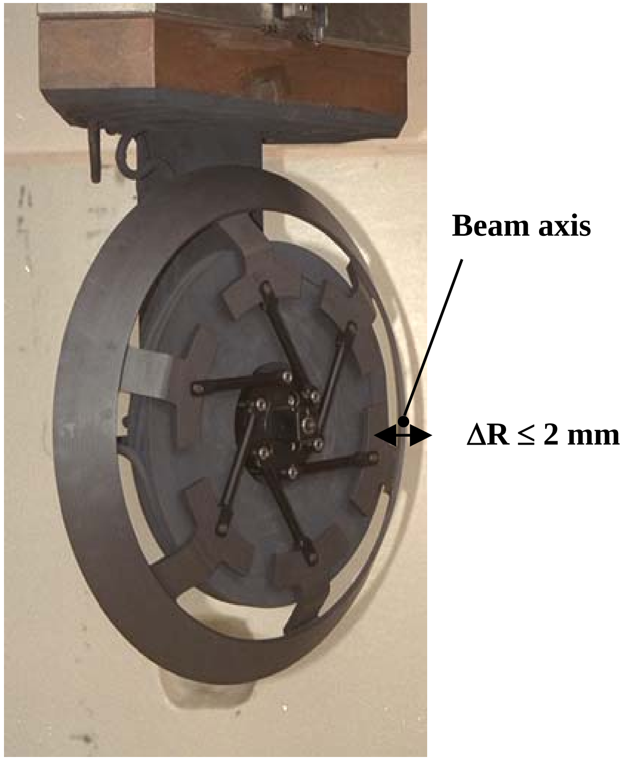
LIFETIME OF THE ROTATING POLYCRYSTALLINE GRAPHITE TARGET CONES

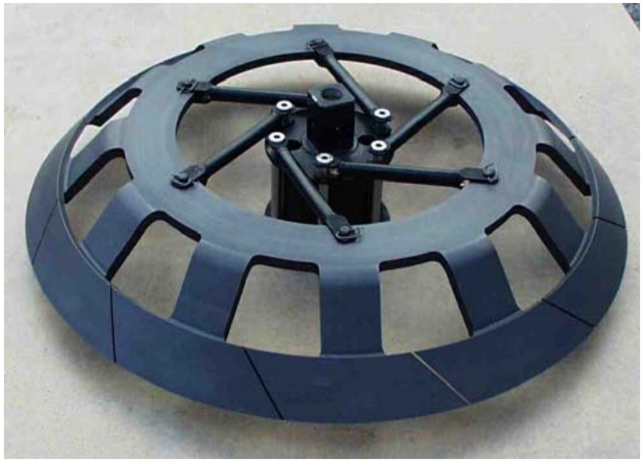
Radiation-induced anisotropic shrinkage of polycrystalline graphite causes deformation of the shape and hence leads to a radial wobble. The radial displacement amplitude ΔR must be ≤ 2mm for the operation of the target.



Measured radial displacement rates for the targets made from the graphite grades R6300P and R6400P *)

*) SGL Carbon, D-53170 Bonn, Germany





A new design of graphite wheel. The target cone is subdivided into 12 segments separated by gaps of 1mm at an angle of 45° to the beam direction: This allows unconstrained dimensional changes of the irradiated part of the graphite.

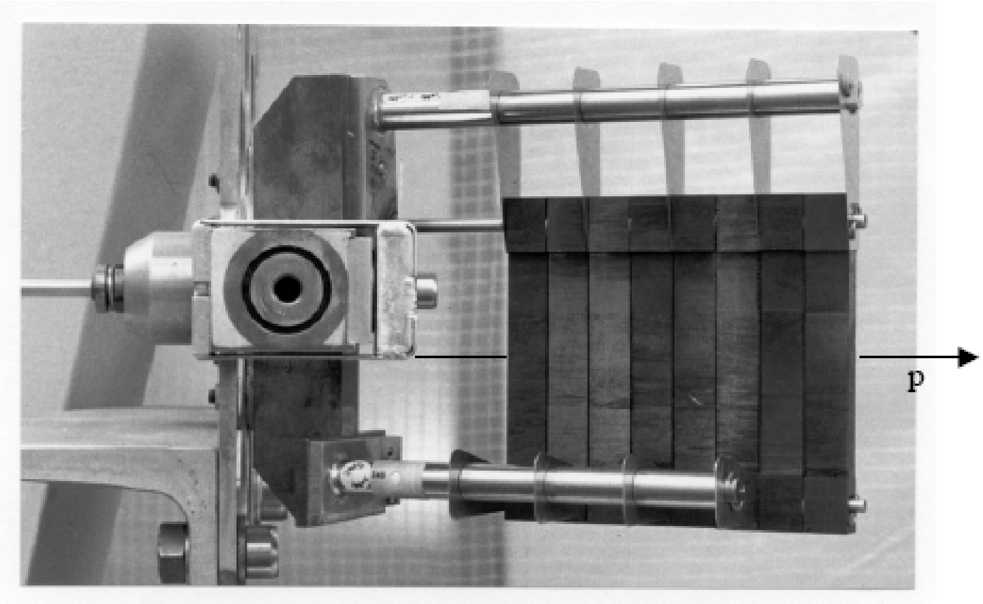
LIFETIME OF THE PYROLITIC GRAPHITE TARGETS DUE TO IRRADIATION-INDUCED DIMENSIONAL CHANGES

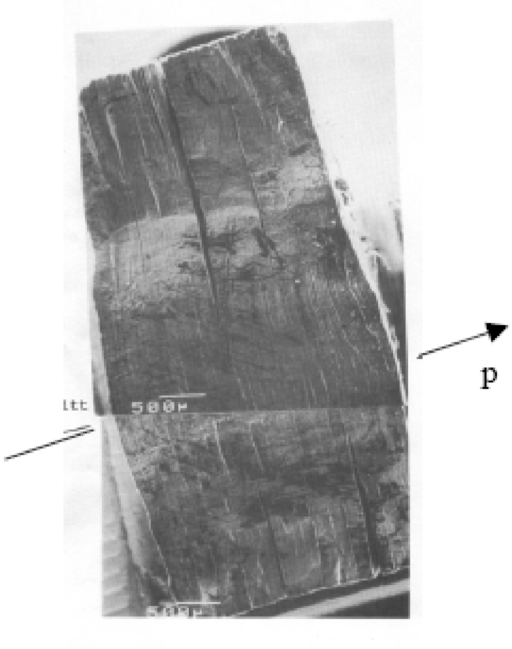
Operational parameters:

Proton current: 100 μA
Peak current density: 1000 μA/cm^2
Peak temperature: 1800 K

Lifetime limits:

Proton fluence: $\approx 10^{22}$ p/cm^2
Integrated beam current: $\approx$ 50 mAh
Irradiation-induced swelling: $\approx$ 10 %
Irradiation damage rate: $\approx$ 1 dpa

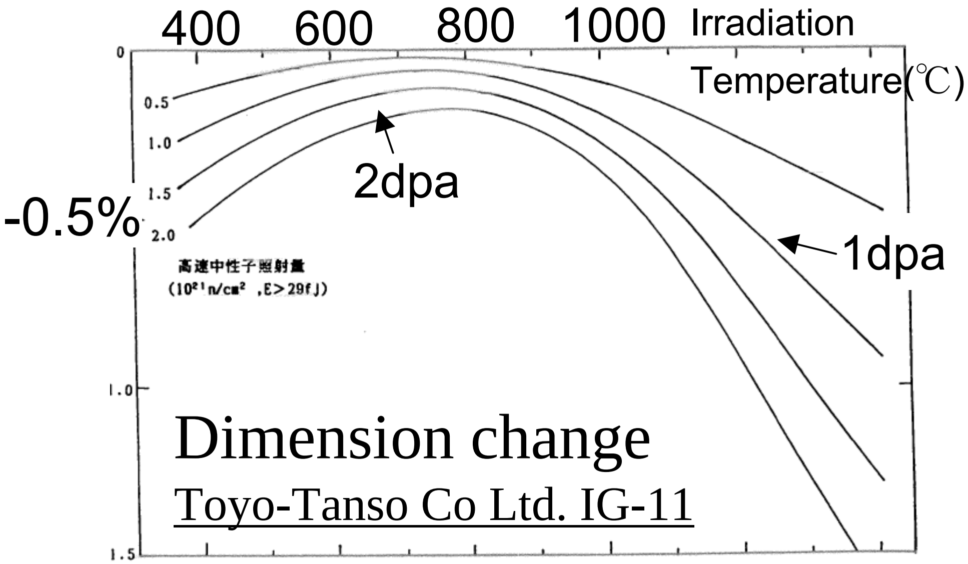




Target slab after irradiation

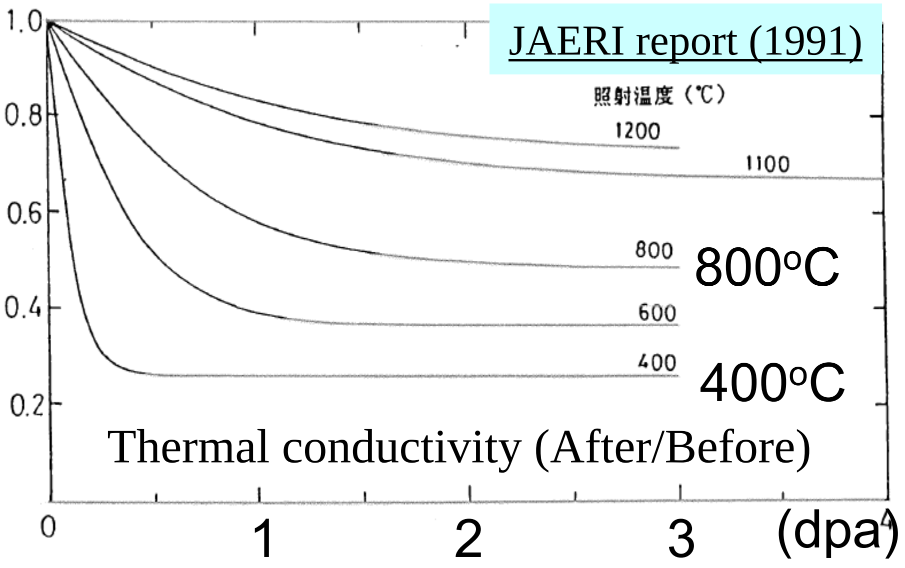
Irradiation Effect of Graphite

- Expected radiation damage of the target
  - The approximation formula used by NuMI target group : 0.25dpa/year
  - MARS simulation : 0.15~0.20 dpa/year
- Dimension change … shrinkage by ~5mm in length in 5 years at maximum. ~75μm in radius
- Degradation of thermal conductivity … decreased by 97% @ 200 °C
  70~80% @ 400 °C
- Magnitude of the damage strongly depends on the irradiation temperature.
  - It is better to keep the temperature of target around 400 ~ 800 °C



Dimension change

Toyo-Tanso Co Ltd. IG-11



JAERI report (1991)

Thermal conductivity (After/Before)

Current / Future projects where shock waves may be an issue

	Material	Beam	Peak power density J/cc/pulse	Pulse length
ESS (next generation ISIS)	Hg	Few GeV protons	20	1×10^{-6} s
T2K/JPARC target + window	Graphite +Ti	30-50 GeV p	344	5×10^{-6} s
GSI/Fair target + dump	Li + Graphite	Heavy ions	30000	5×10^{-9} s

T2K experiment

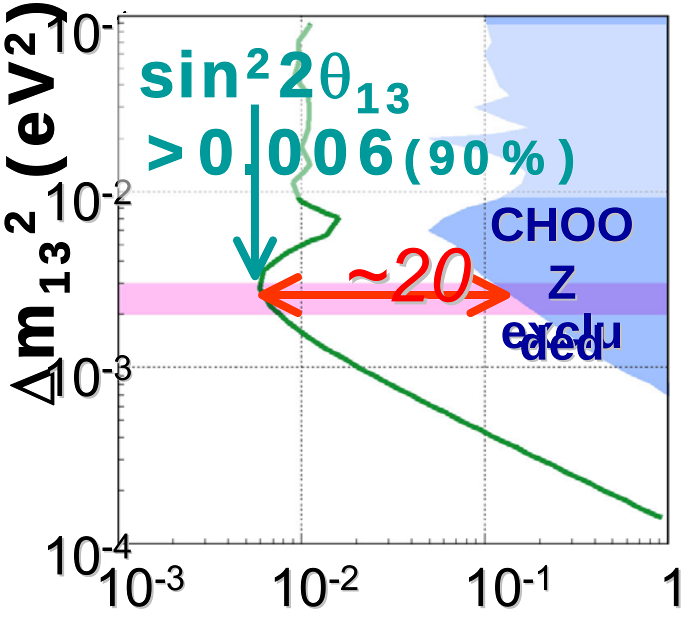
Long baseline neutrino oscillation experiment from Tokai to Kamioka.

Super-K: 50 kton Water Cherenkov

~1GeV ν_μ beam ($\times$100 of K2K)

J-PARC 0.75MW 50GeV PS

Sensitivity on ν_e appearance



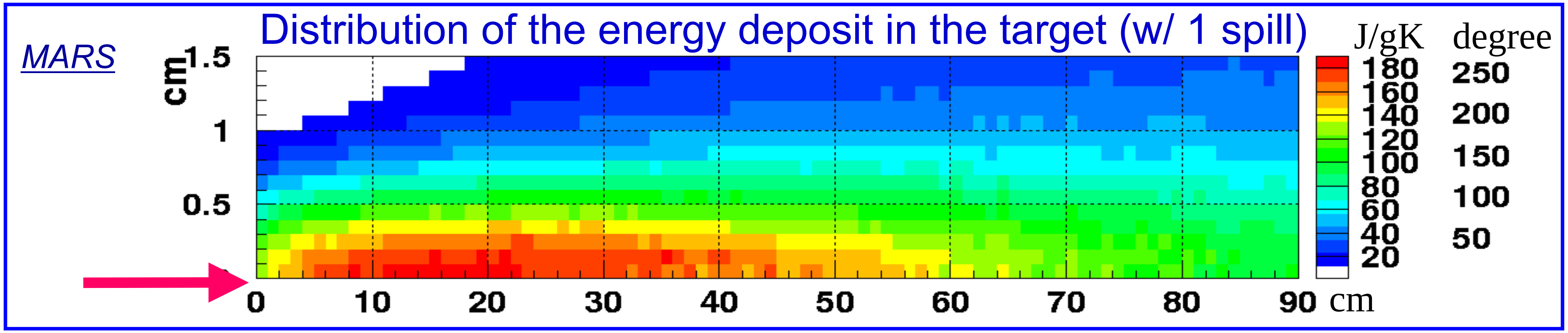
$\sin^2 2\theta_{13} > 0.006$ (90%)

Physics motivations

- **Discovery of $\nu_\mu \rightarrow \nu_e$ appearance**
- **Precise meas. of disappearance $\nu_\mu \rightarrow \nu_x$**
- **Discovery of CP violation (Phase2)**

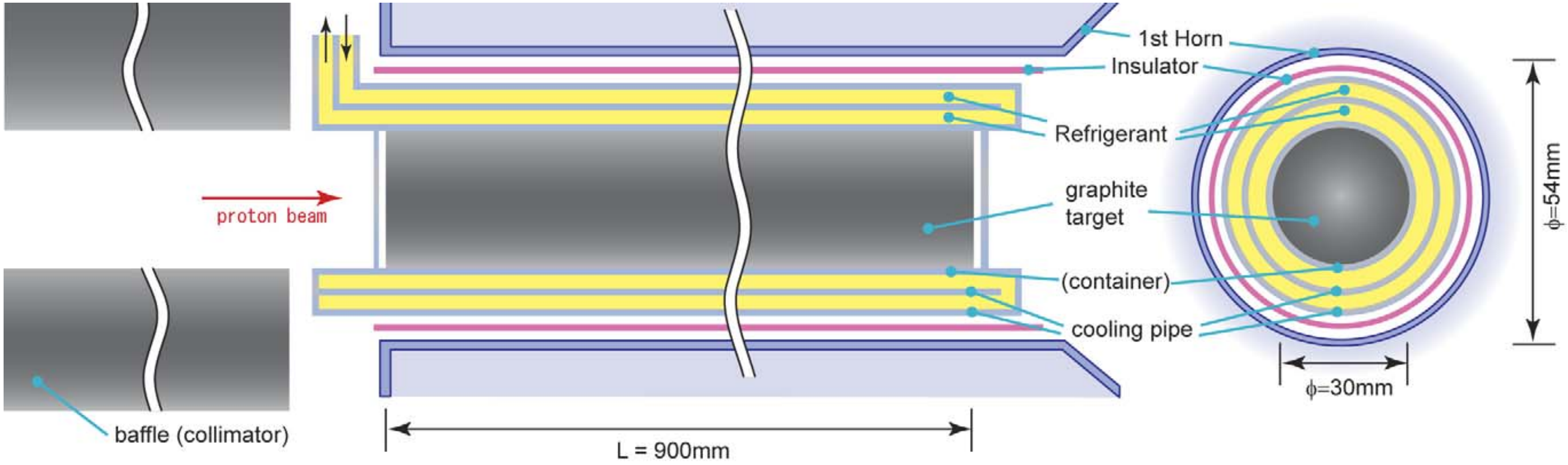
T2K target conceptual design

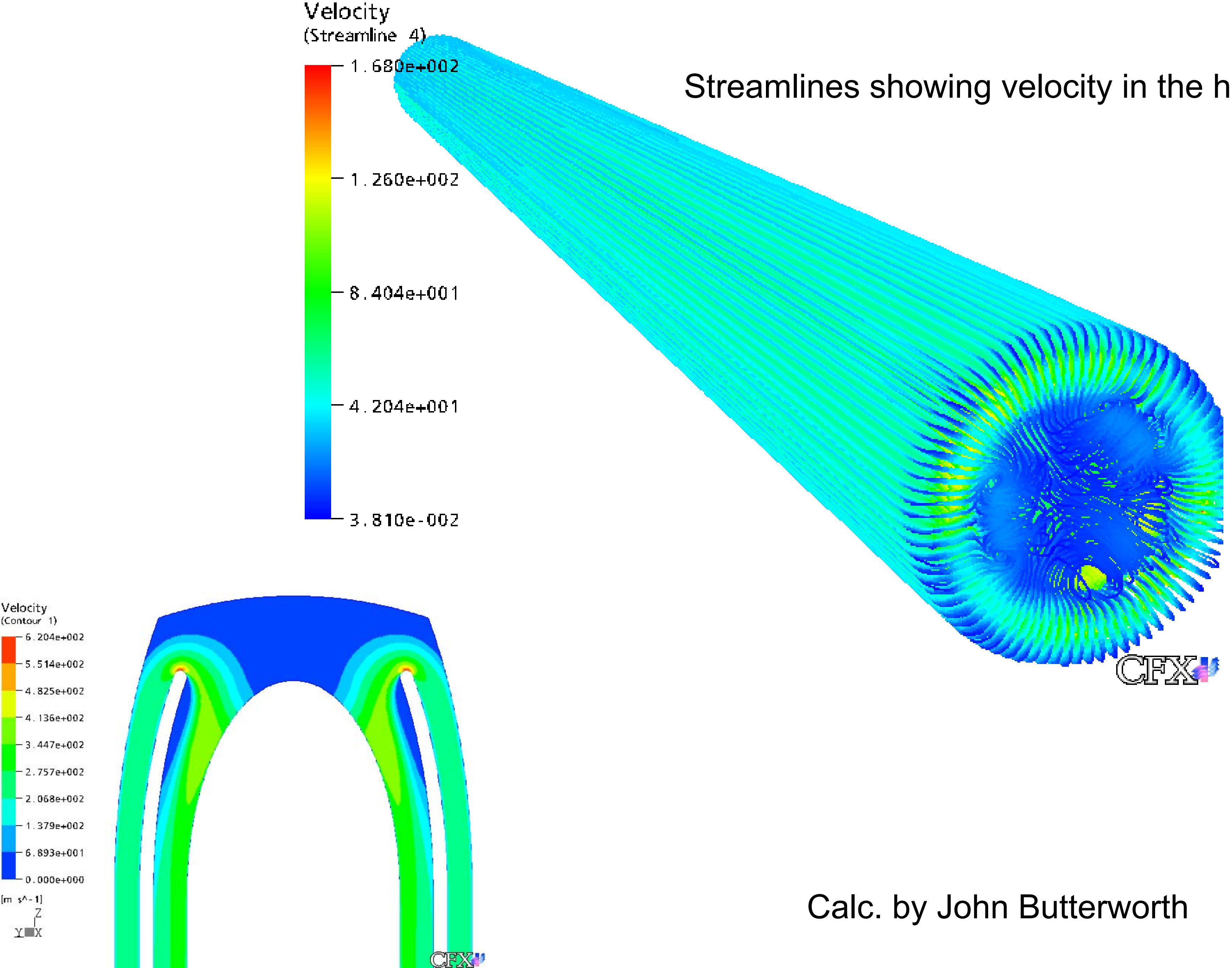
- Graphite Bar Target : r=15mm, L=900mm (2 interaction length)
  - Energy deposit … Total: 58kJ/spill, Max:186J/g → ΔT ≈ 200K



Distribution of the energy deposit in the target (w/ 1 spill)

- Co-axial 2 layer cooling pipe.
  - Cooling pipe: Graphite / Ti alloy (Ti-6Al-4V), Refrigerant: Helium (Water)





Streamlines showing velocity in the helium.

Calc. by John Butterworth

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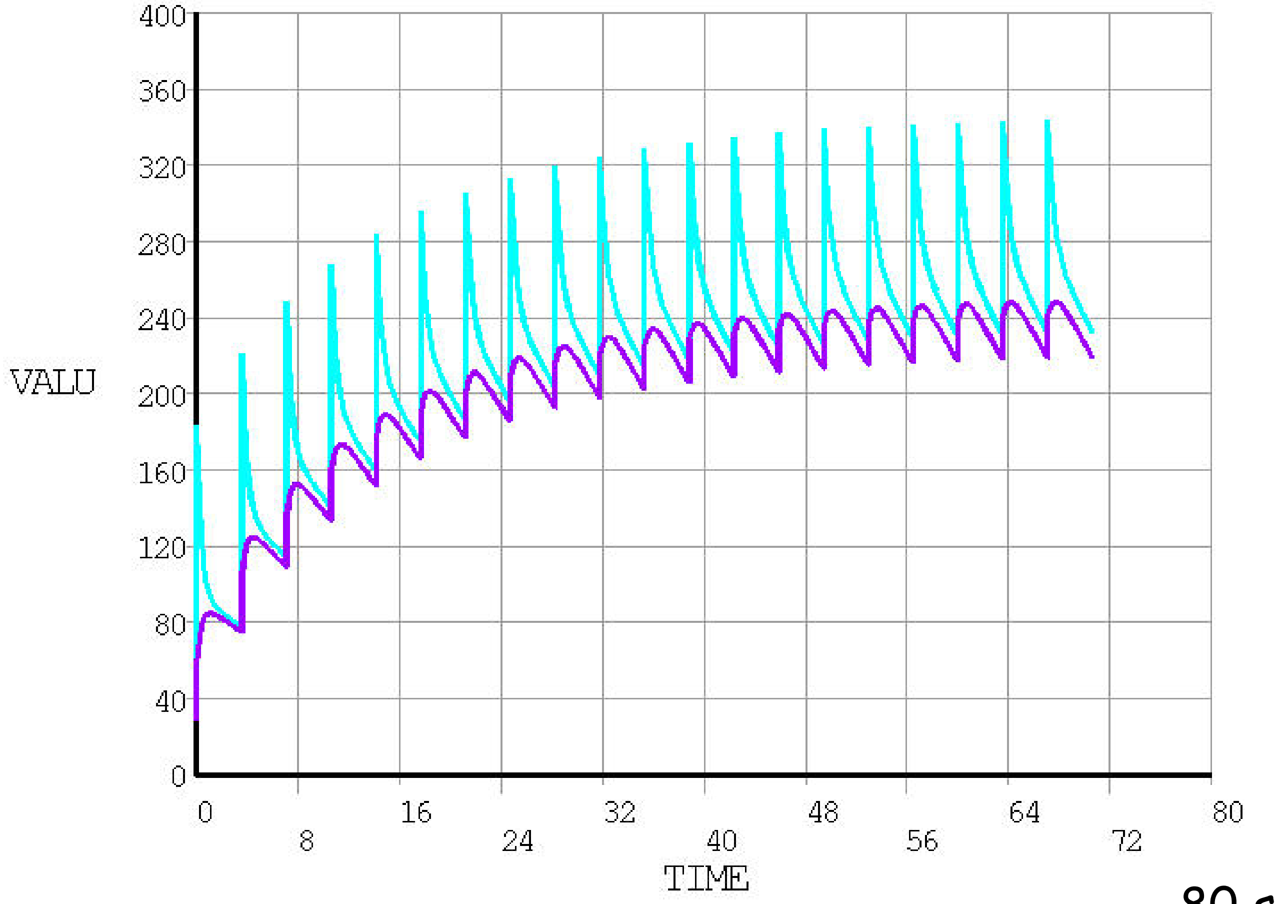
POST26

T2K graphite target temperature progression during first 80 seconds

ANSYS

DEC 10 2004
13:18:33
PLOT NO. 1



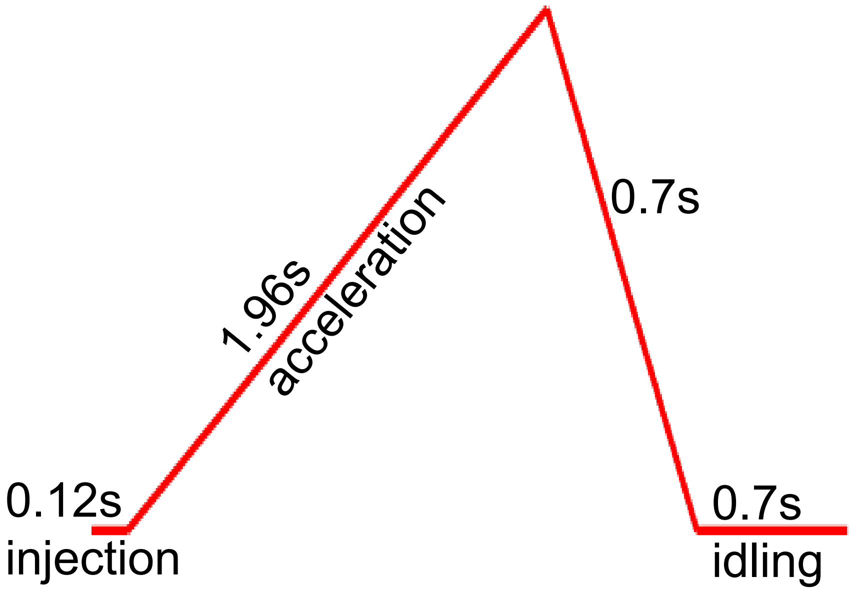
80 s

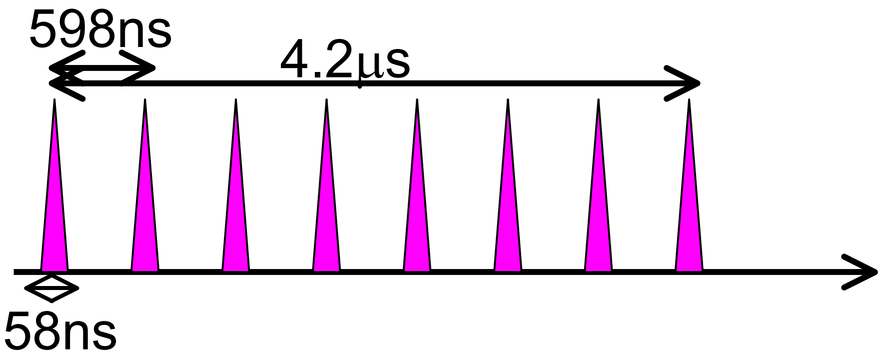
Helium cooled

Primary Beam

- **50 GeV (40 at T=0)**
- **single turn fast extraction**
- **$3.3\mathrm{x}10^{14}$proton/pulse**
- **3.53 sec cycle**
- **750kW (~2.6MJ/pulse)**
- **8 (15) bunches**
- **$\varepsilon=6\pi$ (7.5π)mm.mr @ 50 (40) GeV**

Default acceleration cycle for 50GeV





Total ~3.53s (from TDR)
Idling time is to adjust total power.
If beam loss, power consumption allow,
this can be reduced.

Codes used for study of shock waves

- Specialist codes eg used by Fluid Gravity Engineering Limited – Arbitrary Lagrangian-Eulerian (ALE) codes (developed for military)
  - Developed for dynamic e.g. impact problems
  - ALE not relevant? – Useful for large deformations where mesh would become highly distorted
  - Expensive and specialised
- LS-Dyna
  - Uses Explicit Time Integration (ALE method is included)
    - suitable for dynamic e.g. Impact problems i.e. $\Sigma F=ma$
  - Should be similar to Fluid Gravity code (older but material models the same?)
- ANSYS
  - Uses Implicit Time Integration
  - Suitable for ‘Quasi static’ problems ie $\Sigma F\approx 0$

Implicit vs Explicit Time Integration

- Implicit Time Integration (used by ANSYS) -
  - Finite Element method used
  - Average acceleration calculated
  - Displacements evaluated at time $t+\Delta t$
  - Always stable – but small time steps needed to capture transient response
  - Non-linear materials can be used to solve static problems
  - Can solve non-linear (transient) problems…
  - …but only for linear material properties
  - Best for static or 'quasi' static problems ($\Sigma F \approx 0$)

Implicit vs Explicit Time Integration

- Explicit Time Integration (used by LS Dyna)
  - Central Difference method used
  - Accelerations (and stresses) evaluated at time *t*
  - Accelerations -> velocities -> displacements
  - Small time steps required to maintain stability
  - Can solve non-linear problems for non-linear materials
  - Best for dynamic problems ($\Sigma F = ma$)

Can ANSYS be used to study proton beam induced shockwaves?

- **Equation of state giving shockwave velocity:**

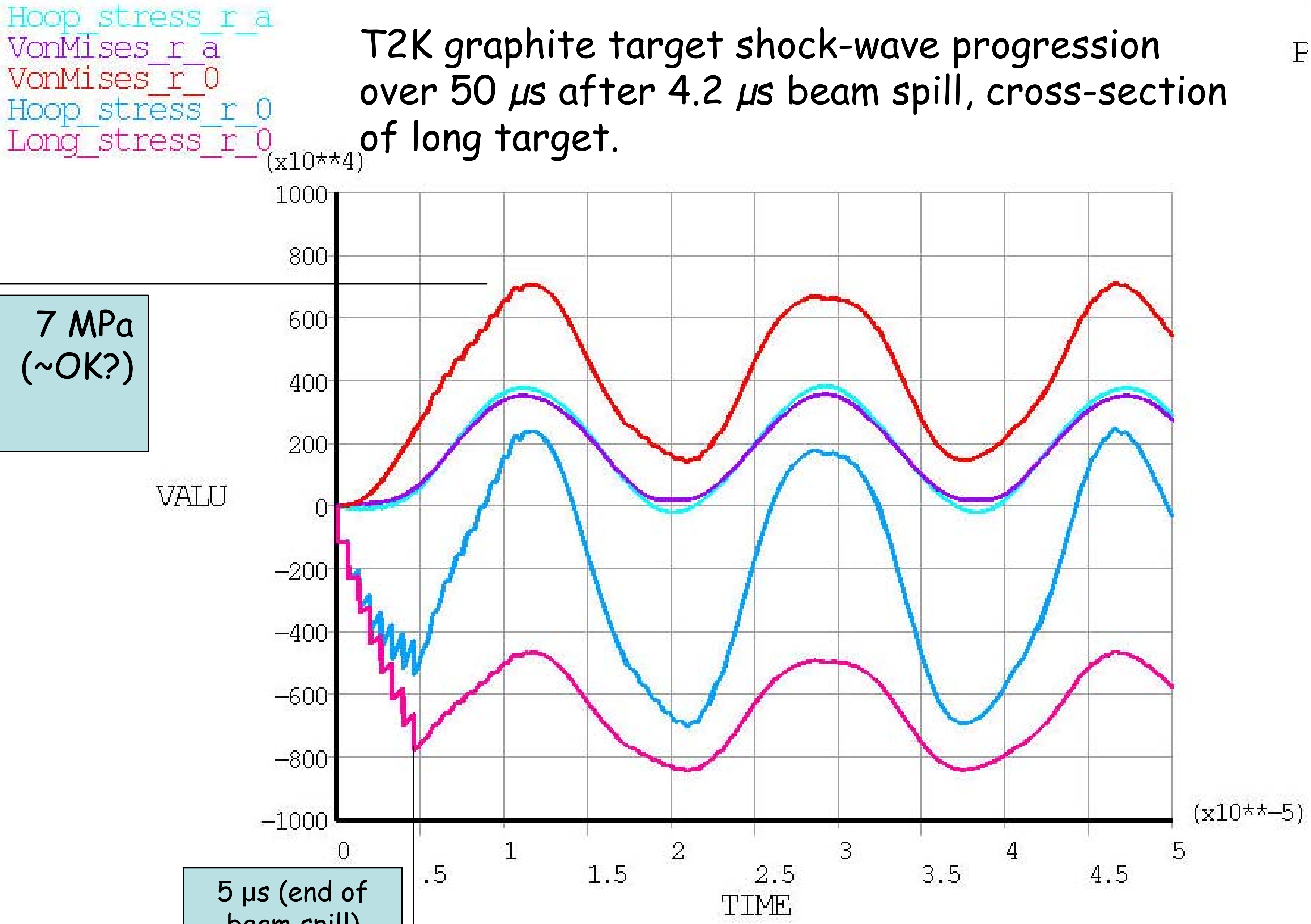
$$u_s = c_0 + s u_p + q u_p^{\ 2}$$

For tantalum c_0 = 3414 m/s

Cf: ANSYS *implicit* wave propagation velocity :

$$c = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{185.7 \times 10^9}{16600}} = 3345 m/s$$

T2K graphite target shock-wave progression over 50 μs after 4.2 μs beam spill, cross-section of long target.



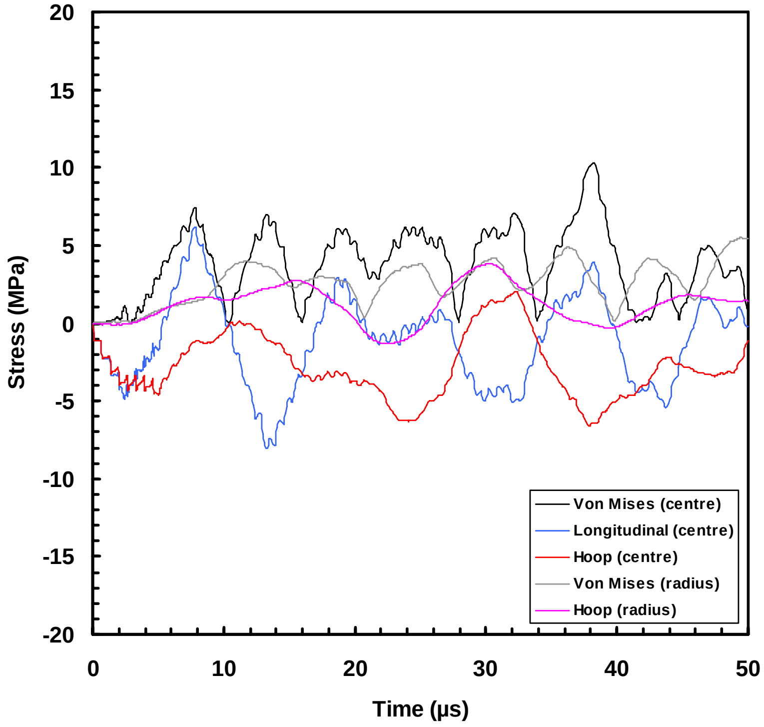
7 MPa (~OK?)

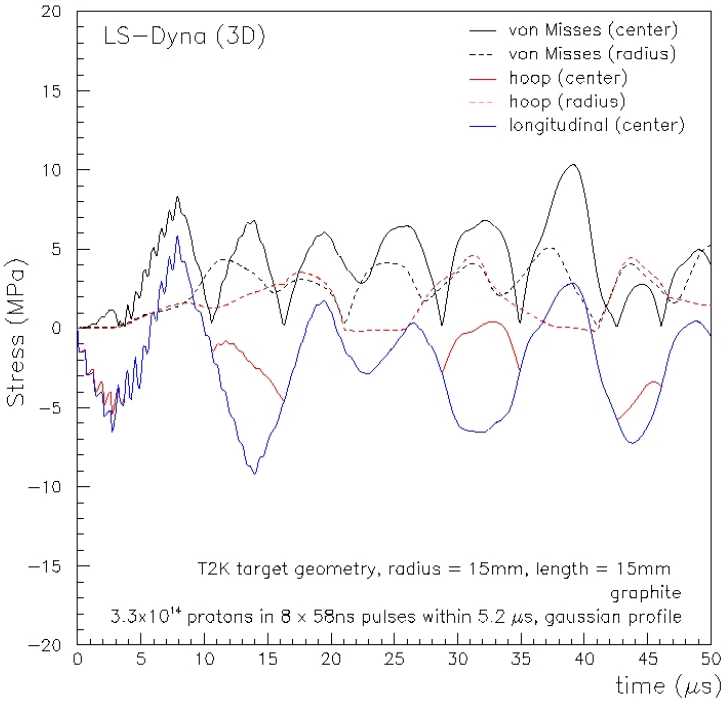
5 µs (end of beam spill)

2 g/cm^2 graphite stress wave plots from 50 GeV protons

Max Von Mises Stress: **Ansys – 7MPa**
LS-Dyna – 8Mpa

Max Longitudinal Stress: **Ansys – 8.5MPa**
LS-Dyna – 10MPa

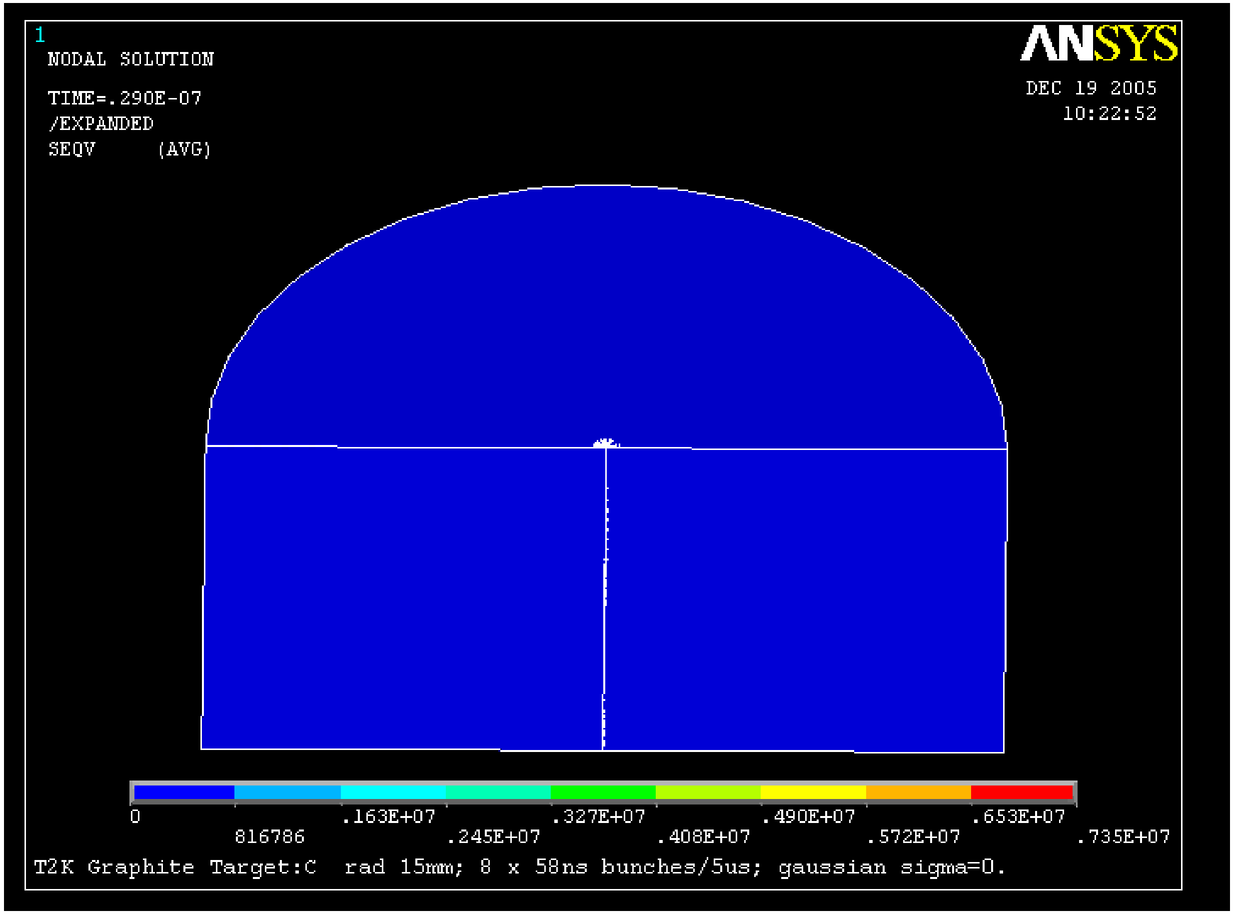




Ansys
(RAL)

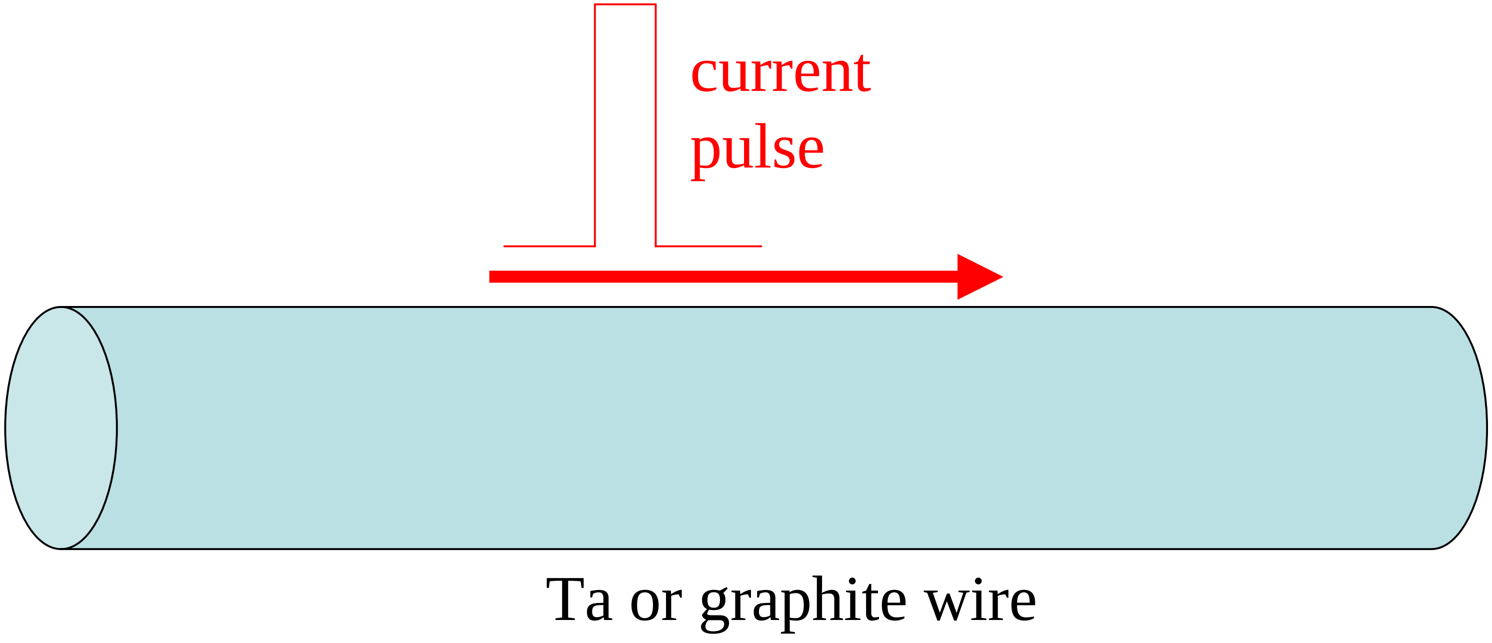
LS-Dyna
(Sheffield)

Stress and Deformation in 2 g/cm2 graphite disc over 10μs



Shock wave experiment at RAL

Pulsed ohmic-heating of wires may be able to replicate pulsed proton beam induced shock.

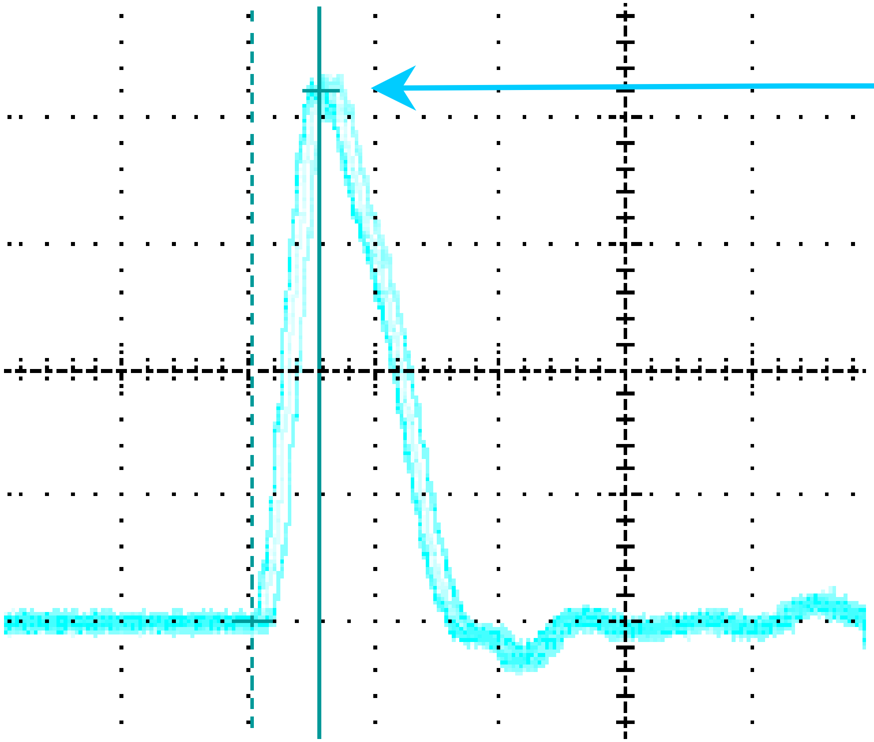


50kV, ~8kA PSU
50Hz

At ISIS, RAL

Doing the Test

The ISIS Extraction Kicker Pulsed Power Supply



8 kA

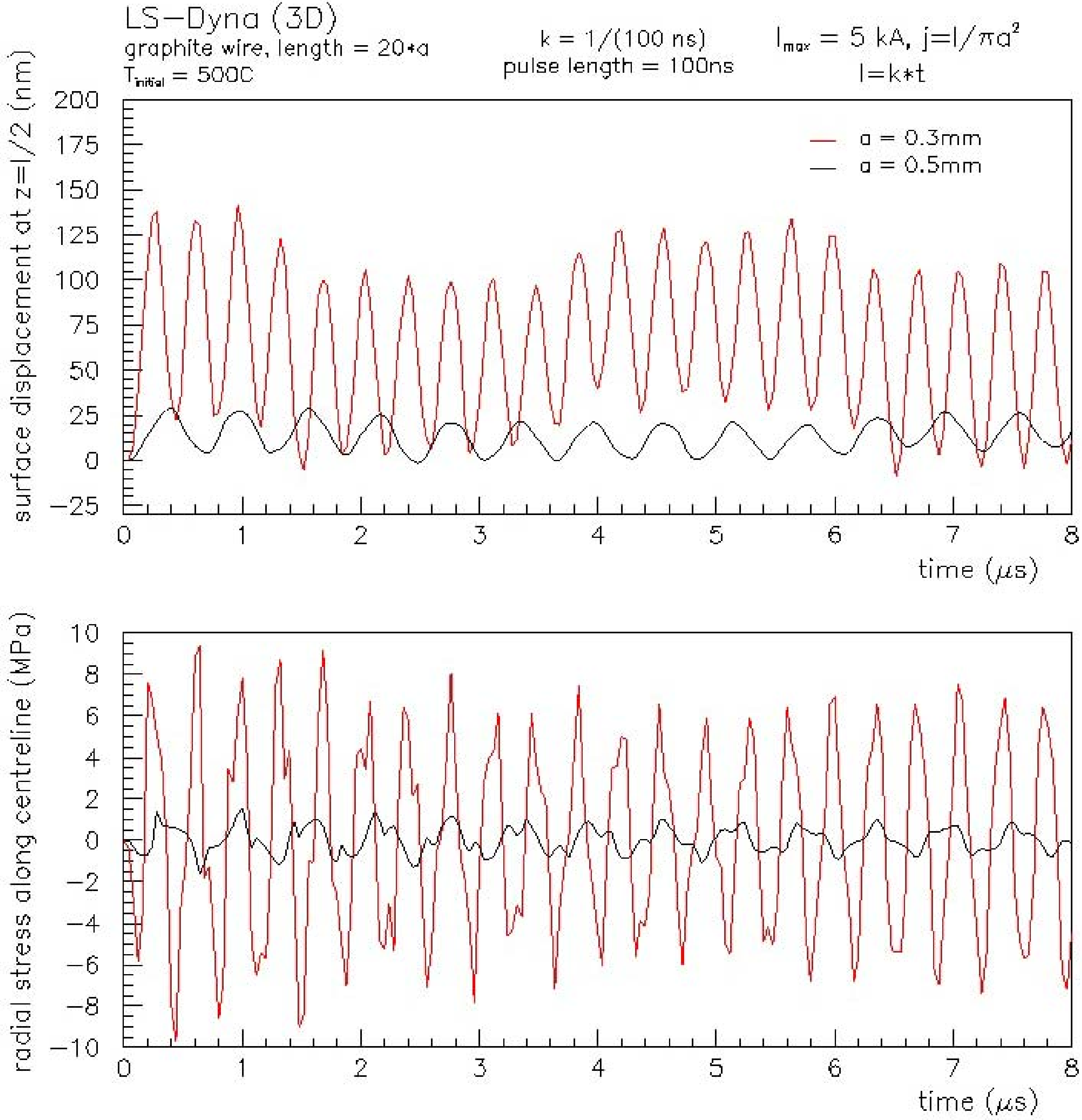
Voltage waveform

Time, 100 ns intervals

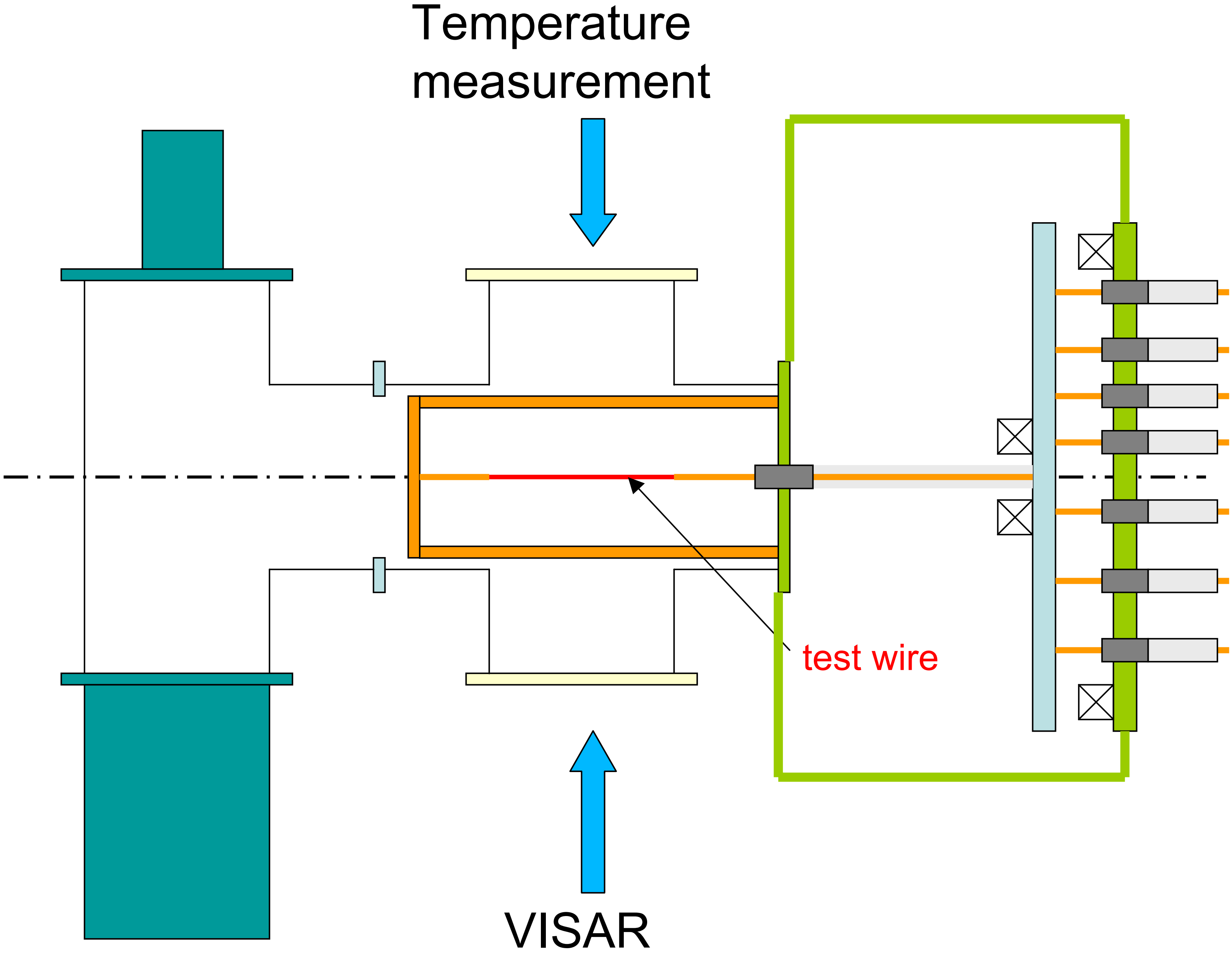
Rise time: ~50 ns   Voltage peak: ~40 kV   Repetition rate up to 50 Hz.

+ There is a spare power supply available for use.

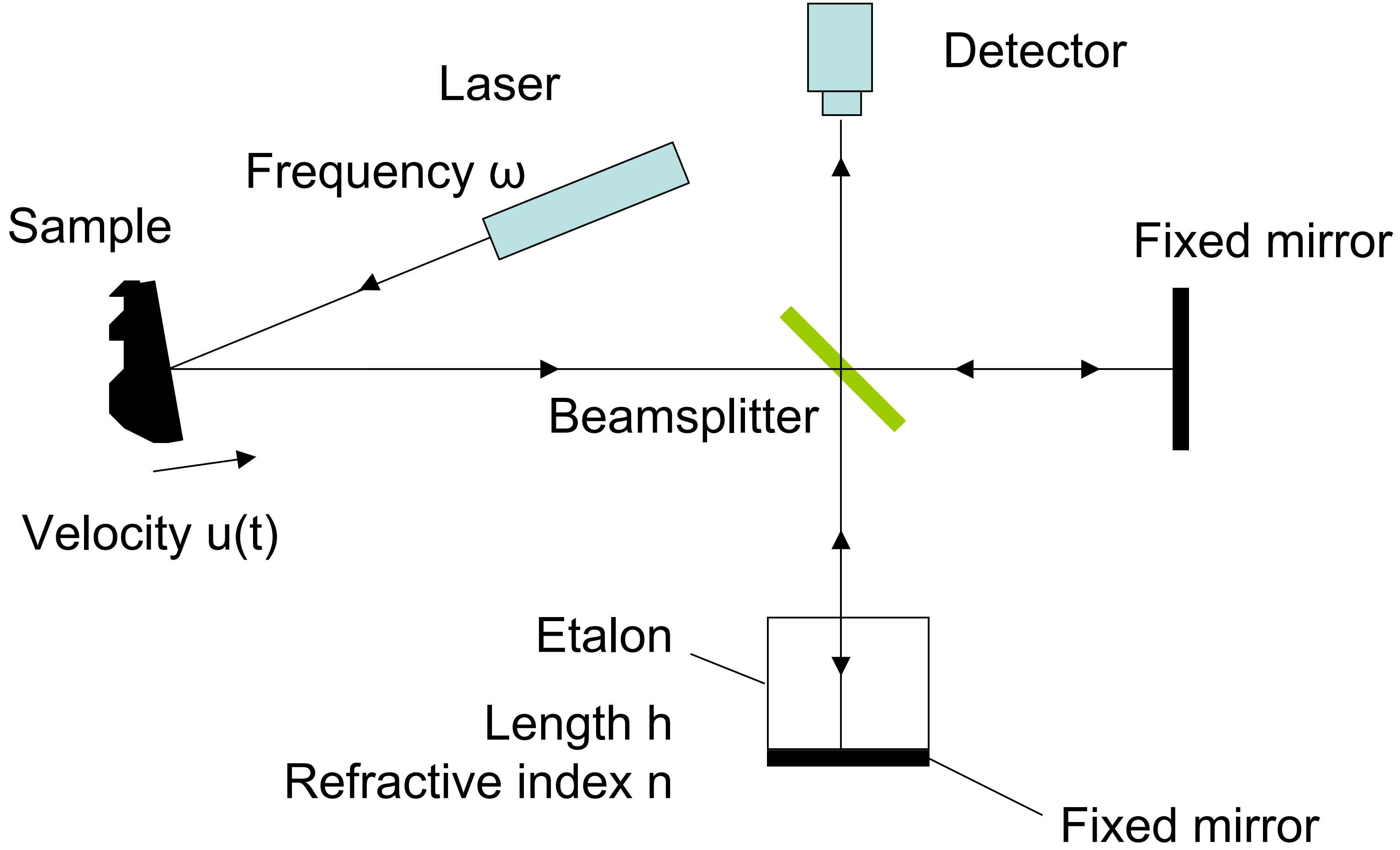
LS-Dyna calculations for shock-heating of different graphite wire radii using ISIS kicker magnet power supply



G. Skoro
Sheffield Uni


Temperature measurement
test wire
VISAR

Velocity Interferometry (VISAR) :



Detector

Laser

Frequency ω

Sample

Fixed mirror

Beamsplitter

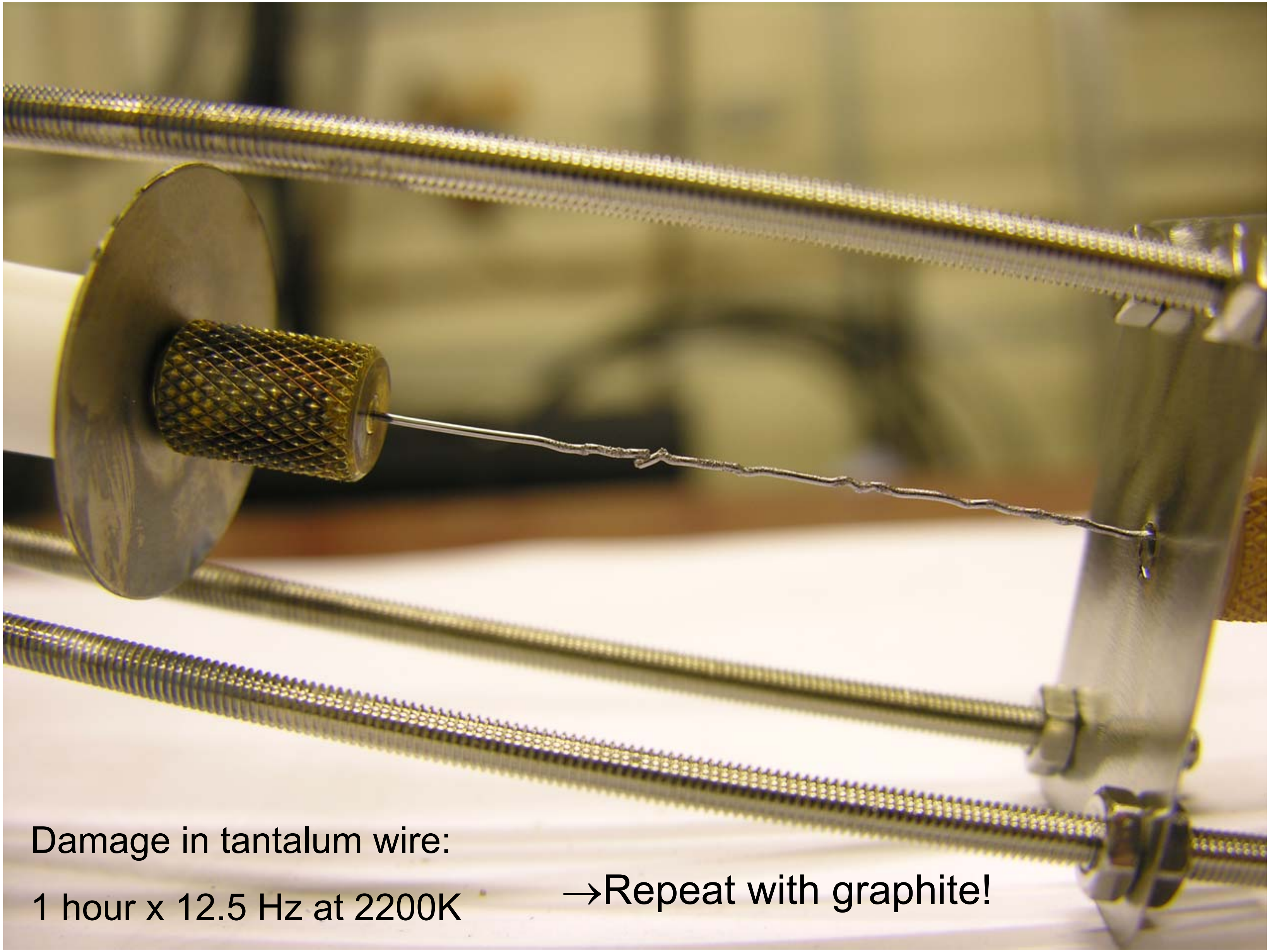
Velocity u(t)

Etalon

Length h
Refractive index n

Fixed mirror

First shock tests at RAL using tantalum wire



Damage in tantalum wire:

1 hour x 12.5 Hz at 2200K

→Repeat with graphite!