

LS-DYNA Simulations of Thermal Shock in Solids

Goran Skoro

University of Sheffield

Contents:

Introduction

LS-Dyna results

- Neutrino Factory target
- Test measurements (current pulse; tantalum wire)
- ISOLDE test
- T2K target + (current pulse; graphite wire)

Summary, Plans

Introduction

NF R&D Proposal

- The target is bombarded at up to 50 Hz by a proton beam consisting of ~ 1 ns long bunches in a pulse of a few micro-s length.
- The target material exposed to the beam will be ~ 20 cm long and ~ 2 cm in diameter.
- Energy density per pulse ~ 300 J/cc.
- Thermally induced shock (stress) in target material (tantalum).
- Knowledge of material properties and stress effects: measurements and simulations!

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
 - Useful for large deformations where mesh would become highly distorted
 - Expensive and specialised
- **LS-Dyna**
 - Uses Explicit Time Integration
 - suitable for dynamic e.g. Impact problems
 - Should be similar to Fluid Gravity code
- **ANSYS**
 - Uses Implicit Time Integration
 - Suitable for 'Quasi static' problems

LS-DYNA

- **General purpose explicit dynamic finite element program**
- **Used to solve highly nonlinear transient dynamics problems**
 - Advanced material modeling capabilities
 - Robust for very large deformation analyses
- **LS-DYNA solver**
 - Fastest explicit solver in marketplace
 - More features than any other explicit code

Material model used in the analysis

- **Temperature Dependent Bilinear Isotropic Model**
 - 'Classical' inelastic model
 - Nonlinear
 - Uses 2 slopes (elastic, plastic) for representing of the stress-strain curve
 - Inputs: density, Young's modulus, CTE, Poisson's ratio, temperature dependent yield stress, ...
- **Element type: LS-DYNA Explicit Solid**
- **Material: TANTALUM, Graphite (T2K)**

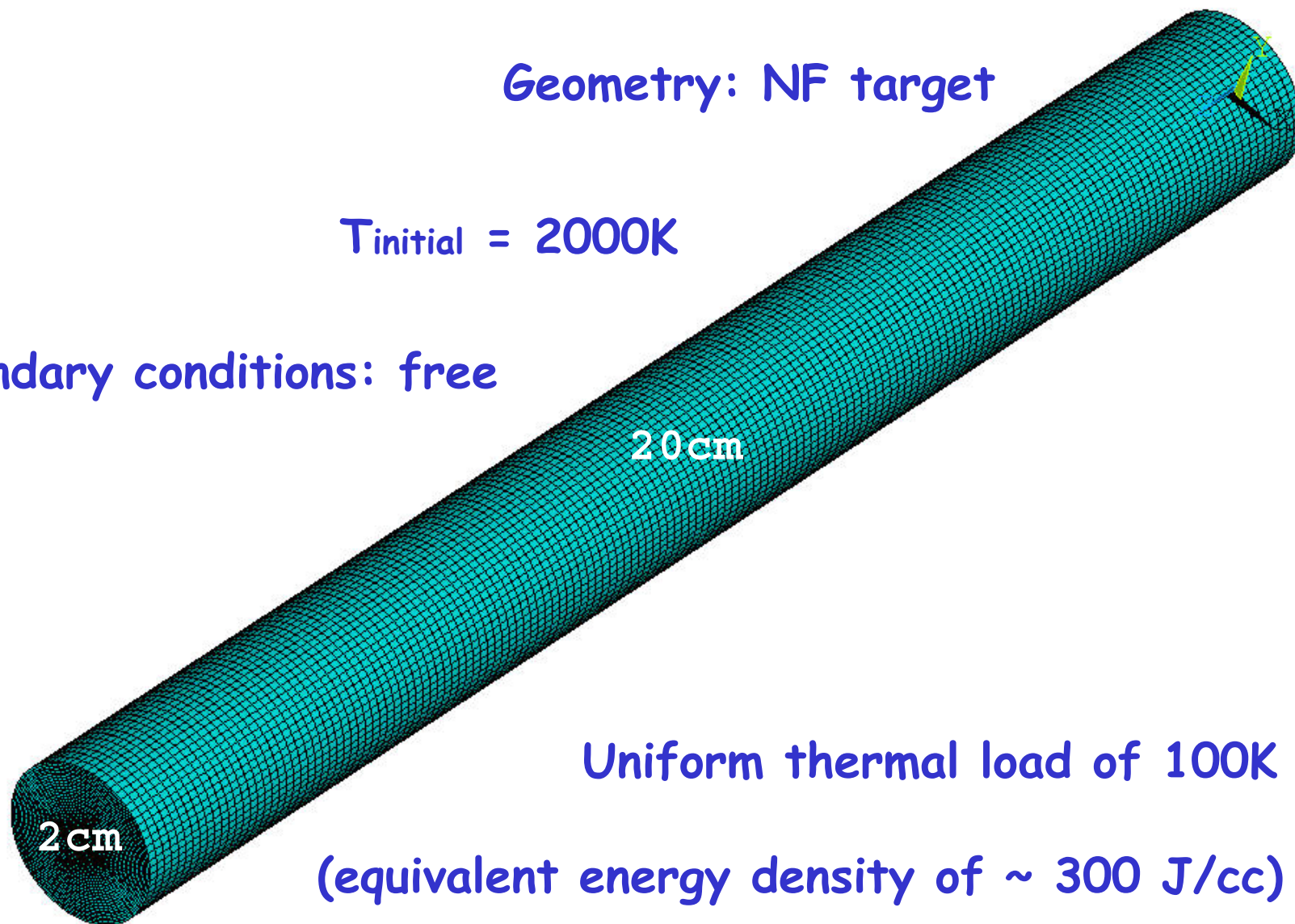
First studies (NuFact05 Proceedings)

- Because the target will be bombarded at up 50 Hz by a proton beam consisting of ~ 1 ns long bunches in a pulse of a few micro-s length we have studied:
- The effect of having different number of bunches in a pulse;
- The effect of having longer bunches (2 or 3 ns);
- The effect of different length of a pulse.

Geometry: NF target

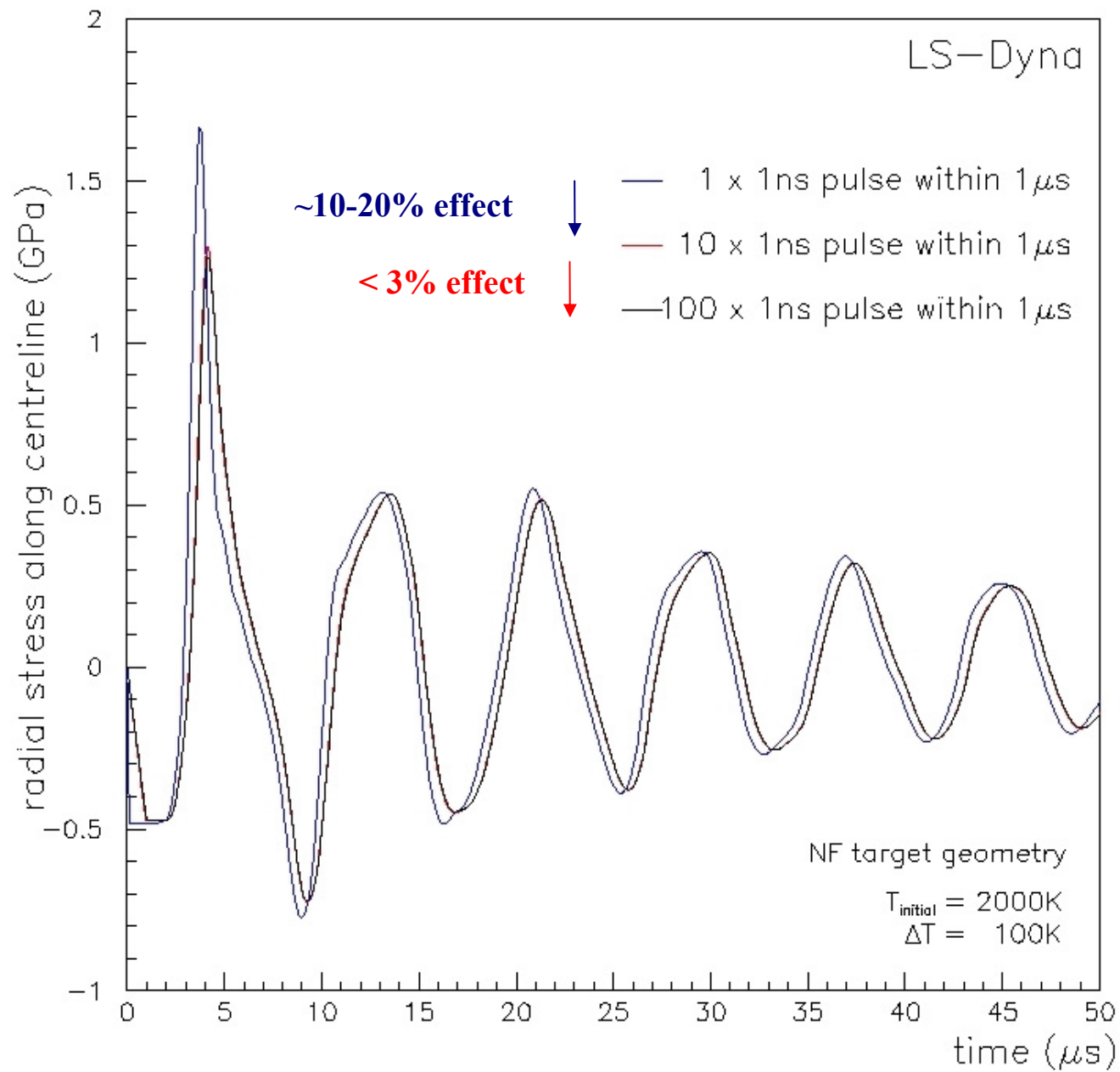
$T_{\text{initial}} = 2000\text{K}$

Boundary conditions: free

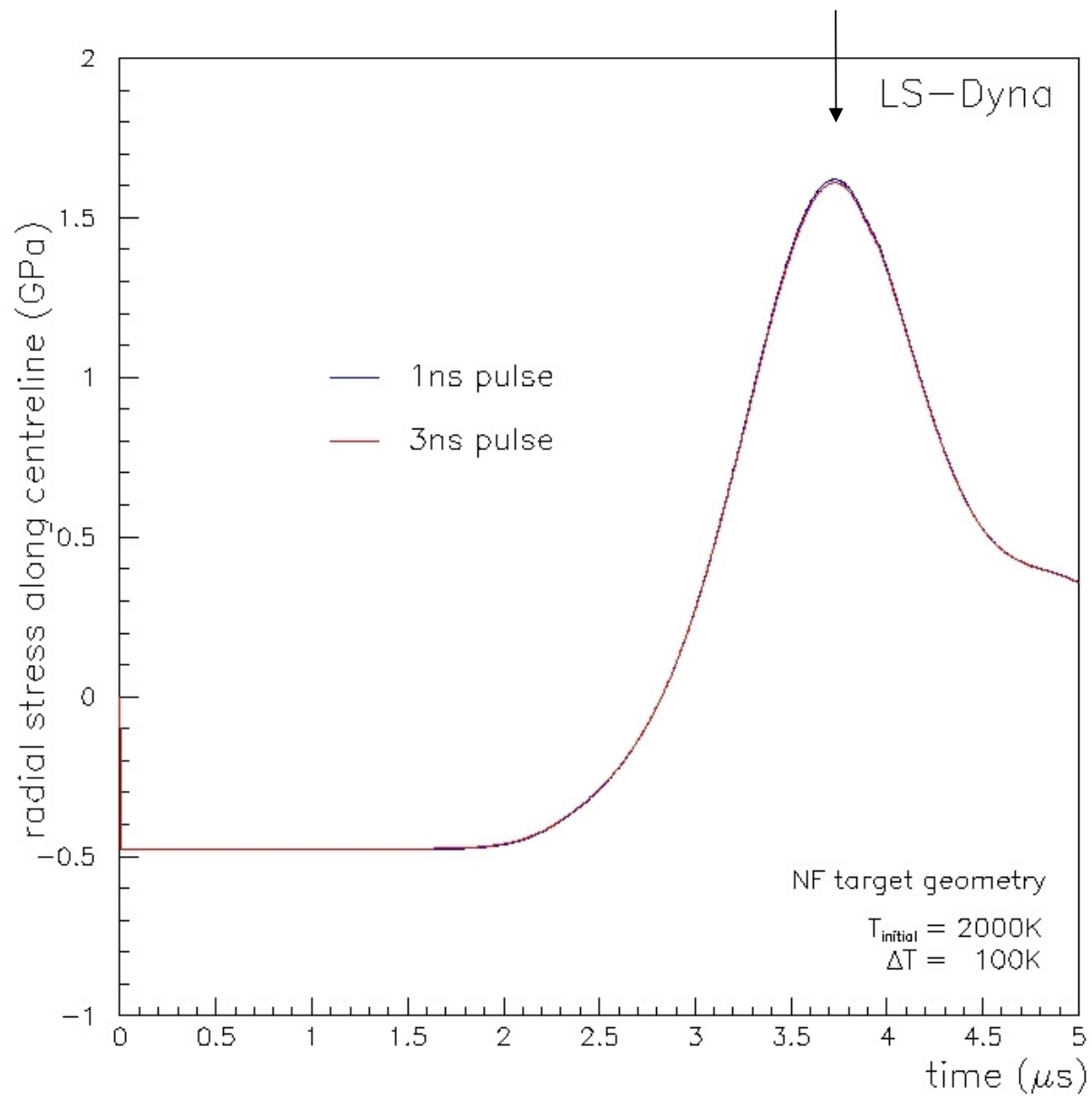


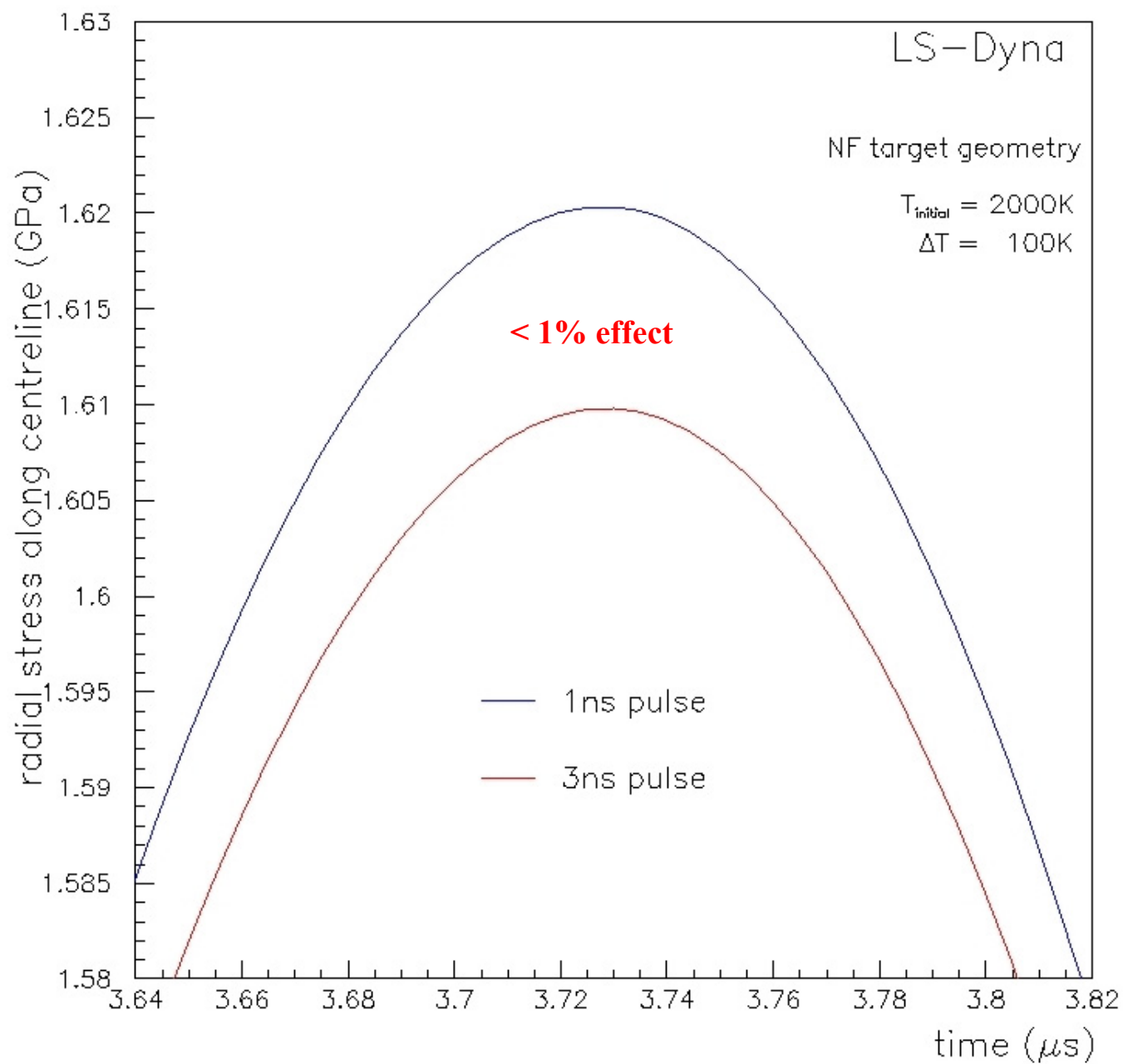
Uniform thermal load of 100K

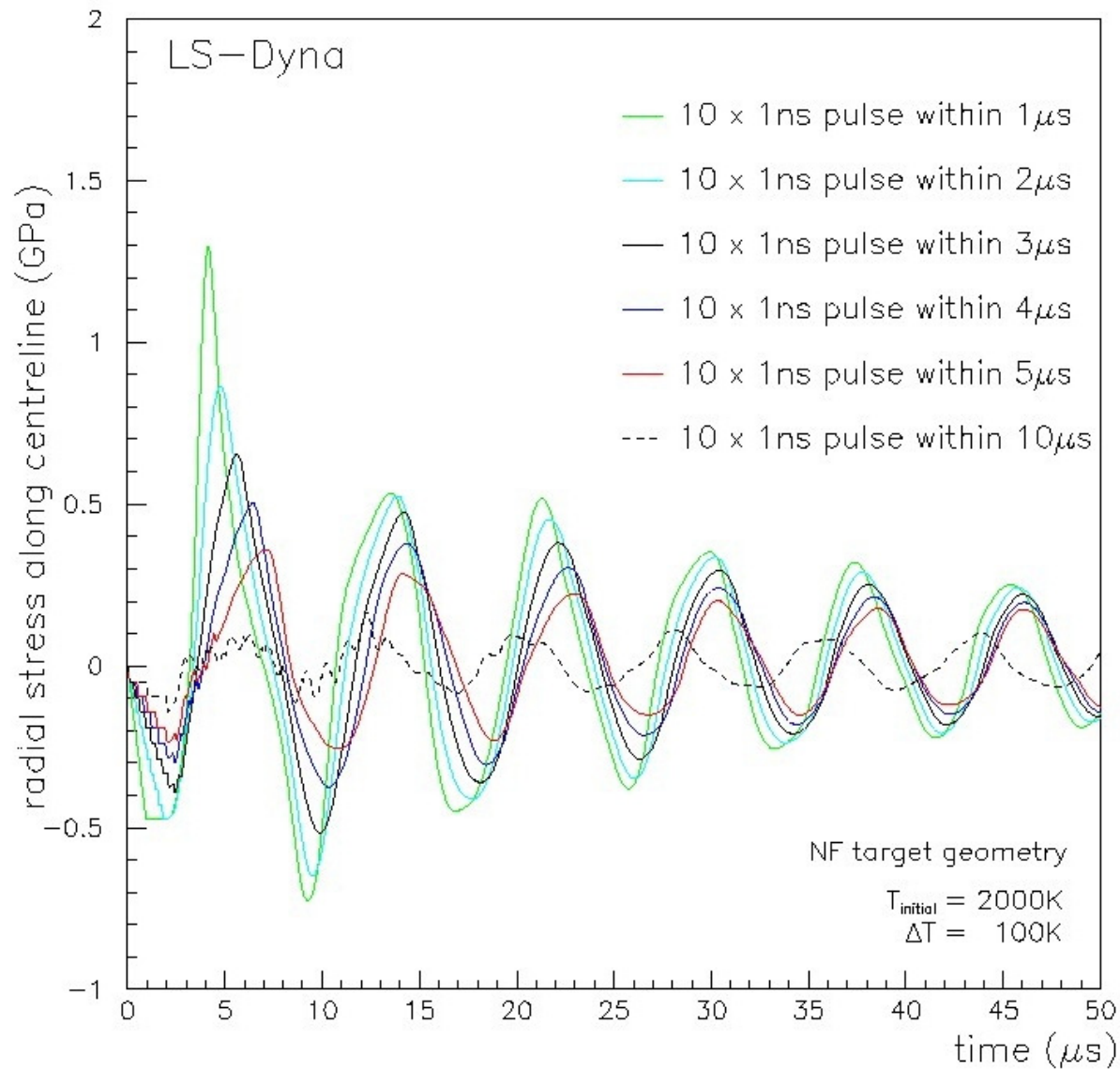
(equivalent energy density of $\sim 300 \text{ J/cc}$)



Characteristic time = radius / speed of sound in the tantalum







~ RAL proton driver

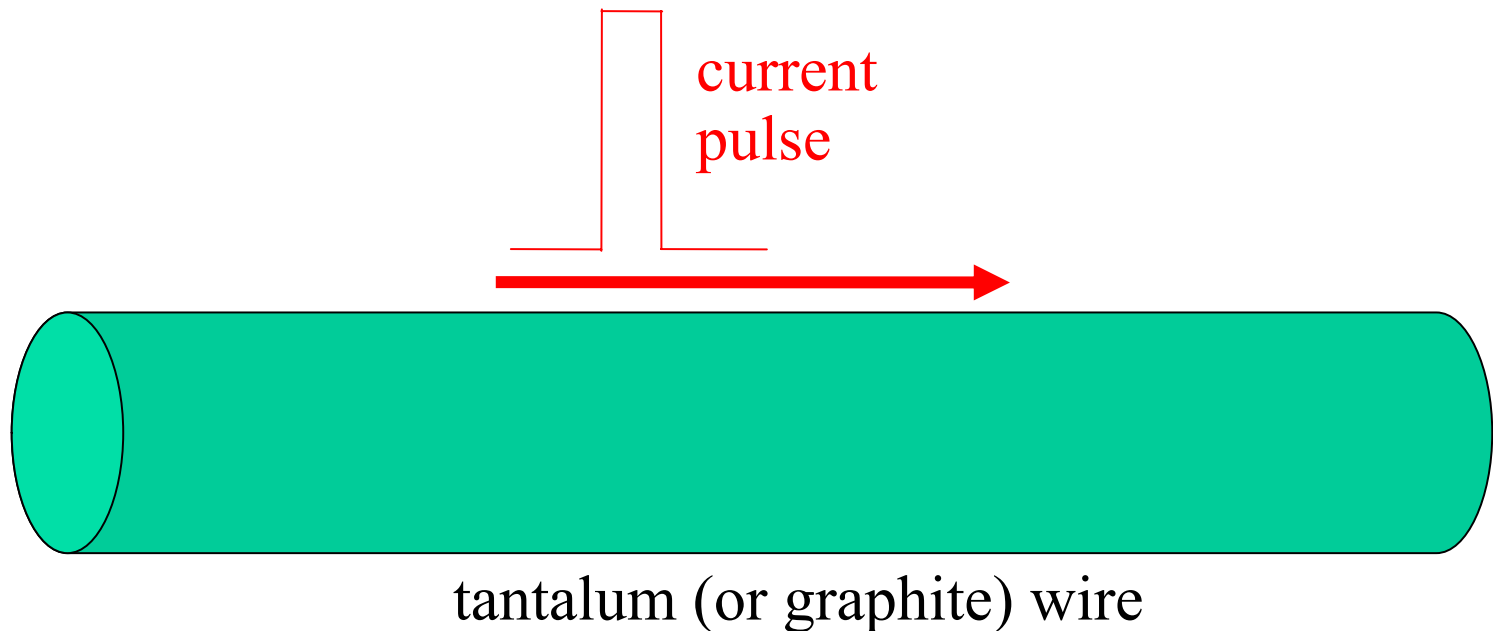
Important parameters: Energy deposition rate and shock transit time!

BUT,

- At high temperatures material data is scarce...
- Hence, need for experiments to determine material model data :
- Current pulse through wire (hopefully, equivalent to ~ 300 J/cc);
- Use **VISAR** to measure surface velocity;
- Use results to extract material properties at high temperatures...
- and test material 'strength' under extreme conditions....

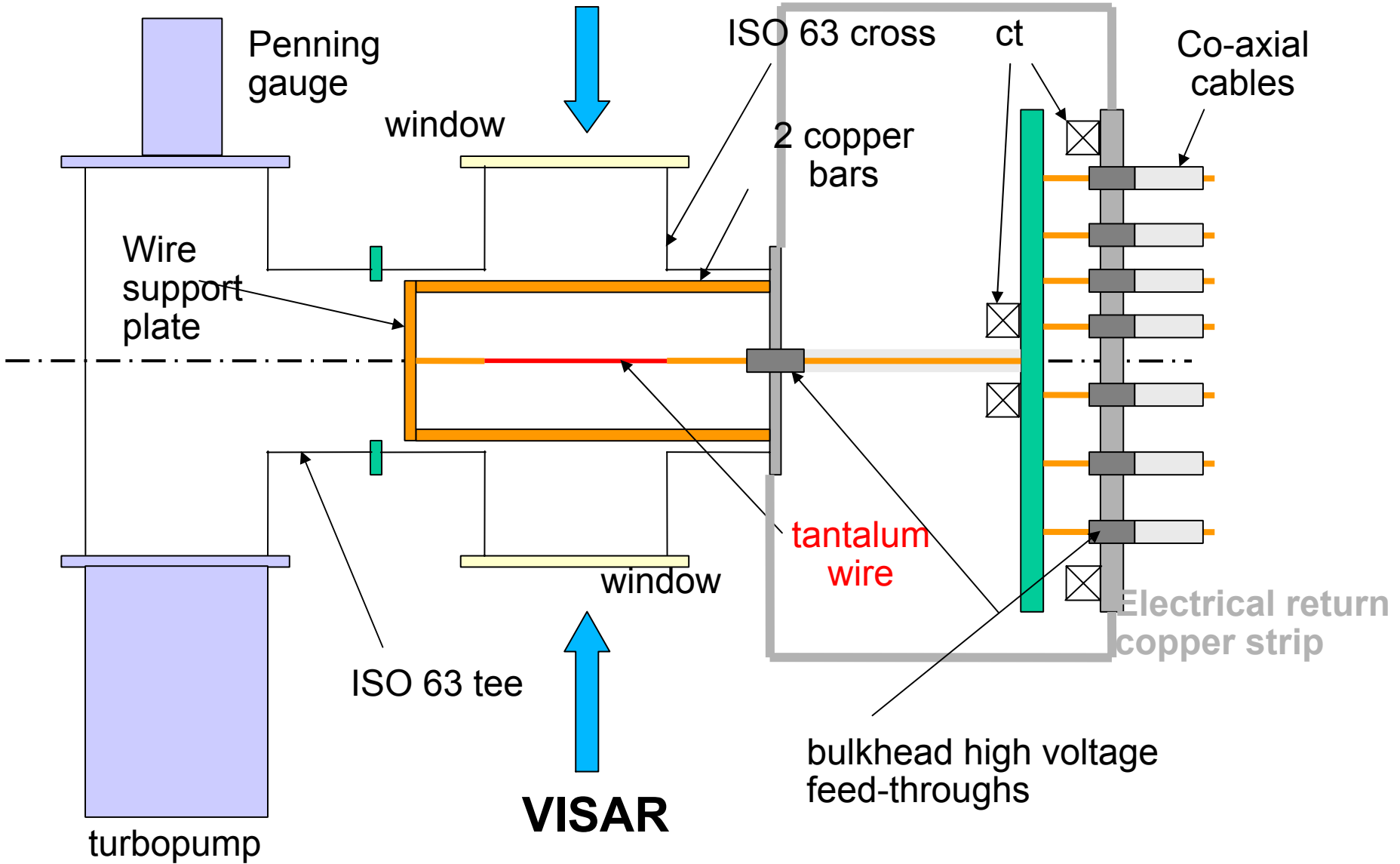
Shock wave experiment at RAL

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



Energy density in the Ta wire needs to be $\varepsilon_0 = 300 \text{ J cm}^{-3}$ to correspond to 1 MW dissipated in a target of 1 cm radius and 20 cm in length at 50 Hz.

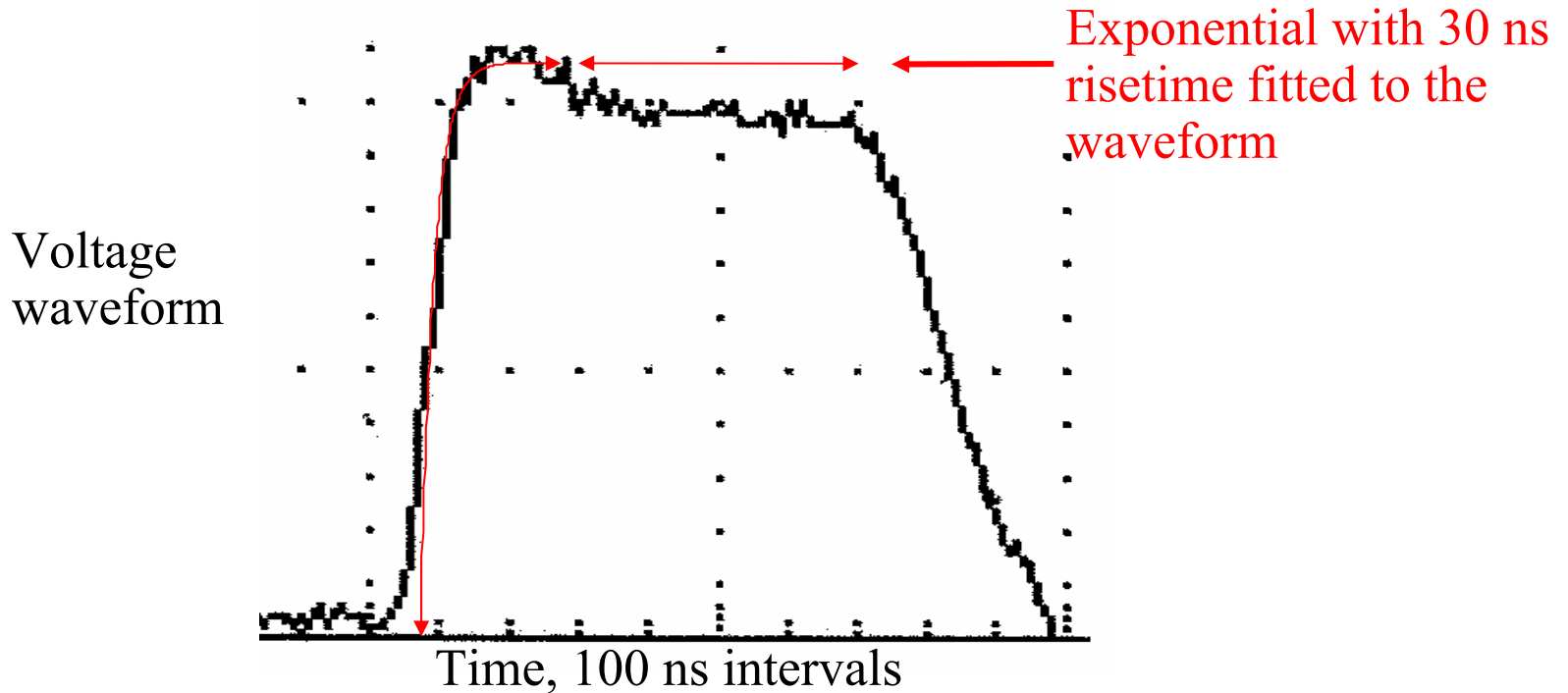
Schematic section of the wire shock-wave test assembly



JRJ Bennett (RAL)

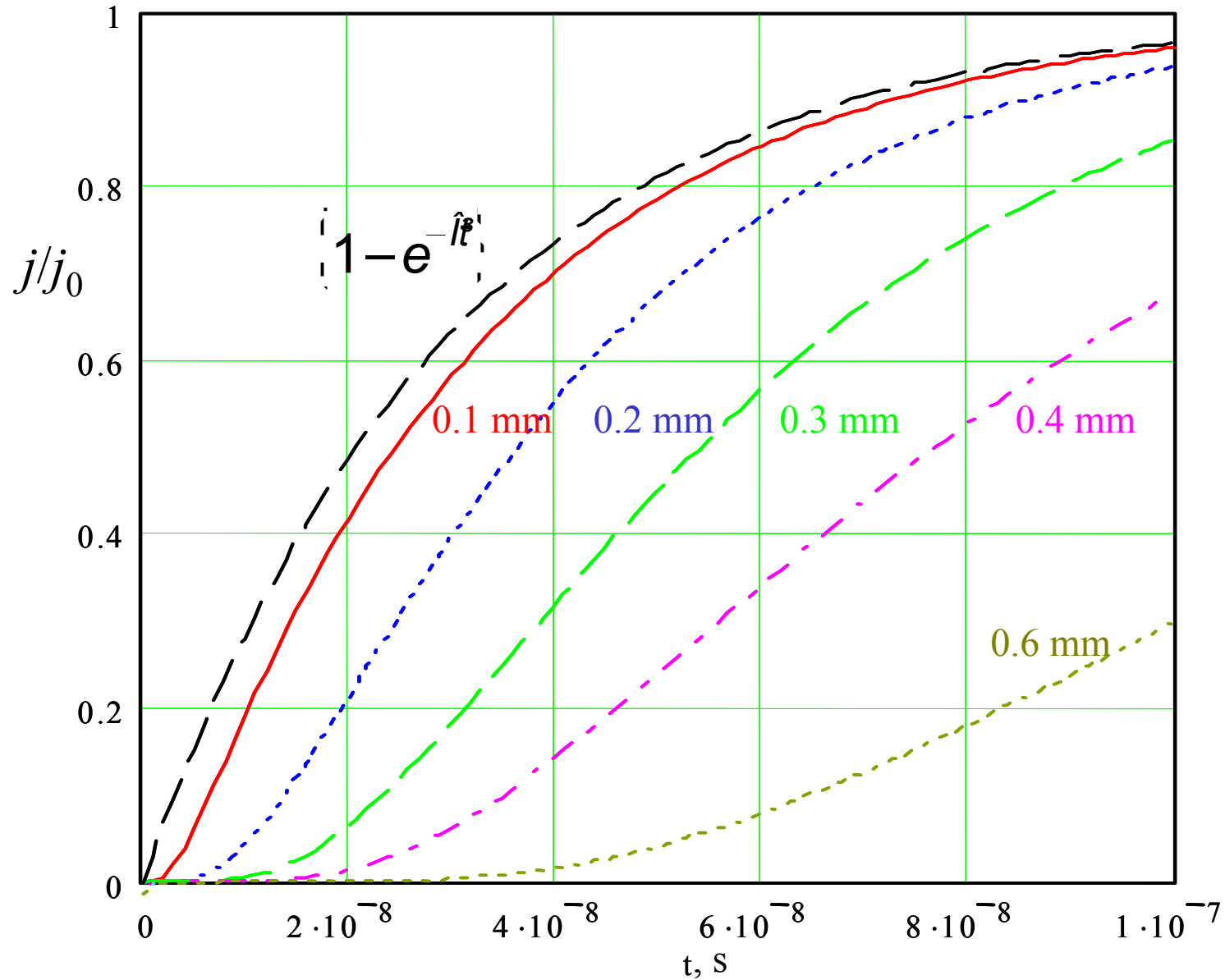
Doing the Test

The ISIS Extraction Kicker Pulsed Power Supply



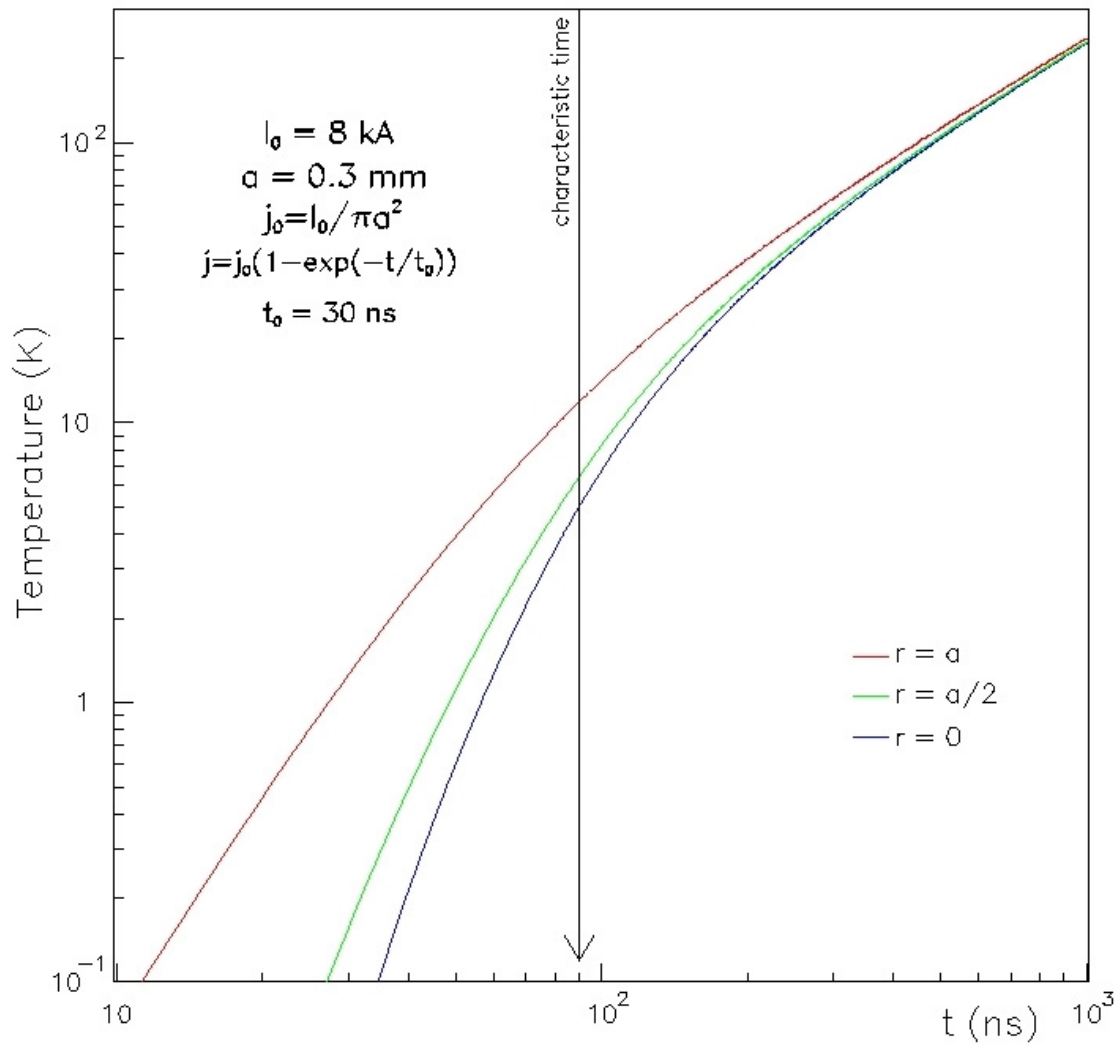
Rise time: ~ 100 ns

Flat Top: ~ 500 ns



Current density at $r = 0$ versus time (t , s), for different wire radii (a , mm).

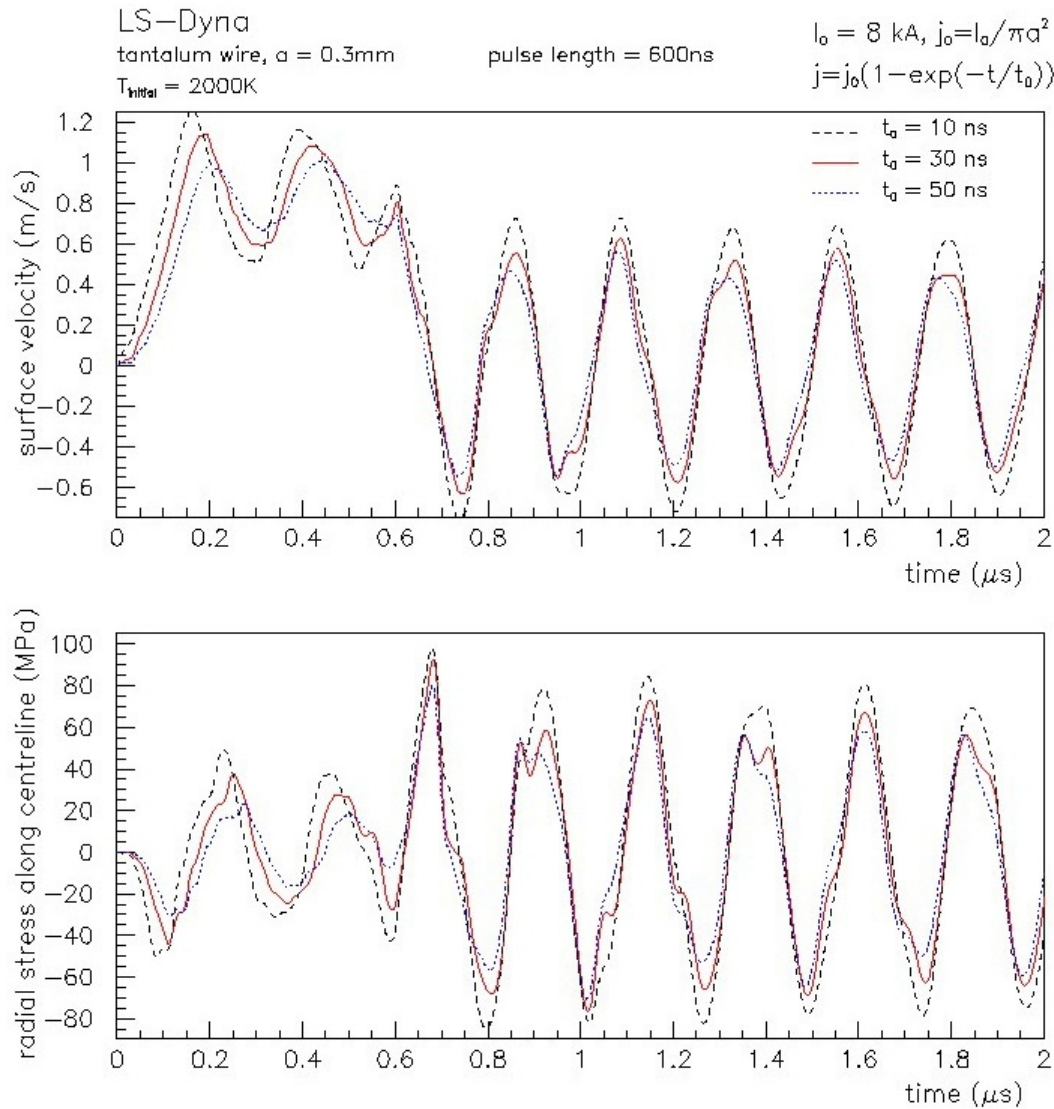
Pulse time profile - exponential rise of the current



Temperature rise

wire diameter = 0.6 mm;
shock transit time ~ 100 ns

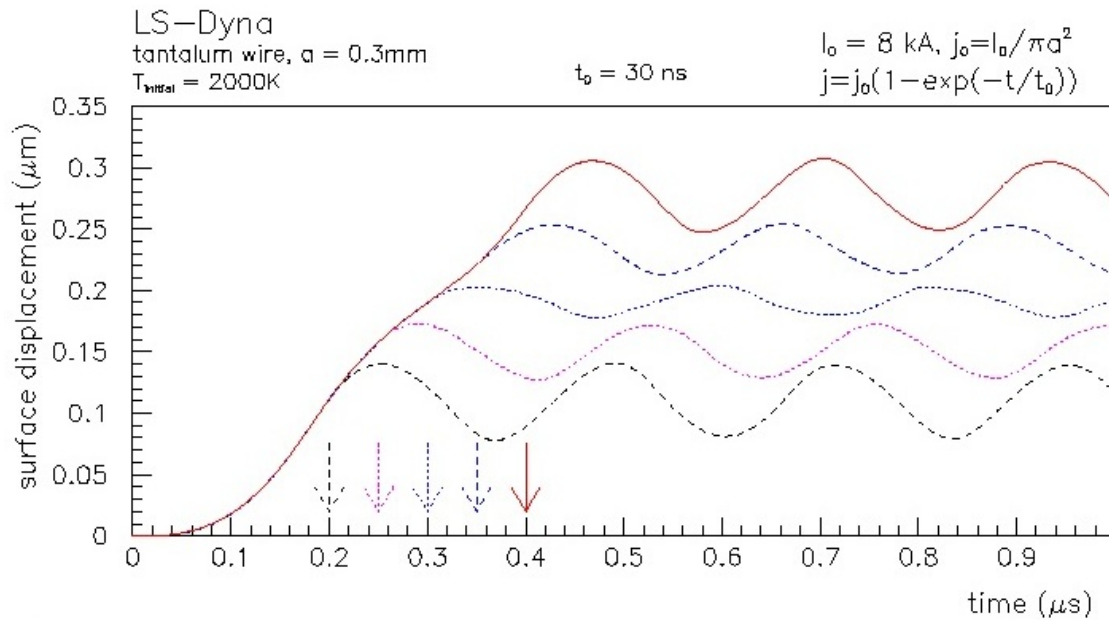
Pulse time profile - exponential rise of the current



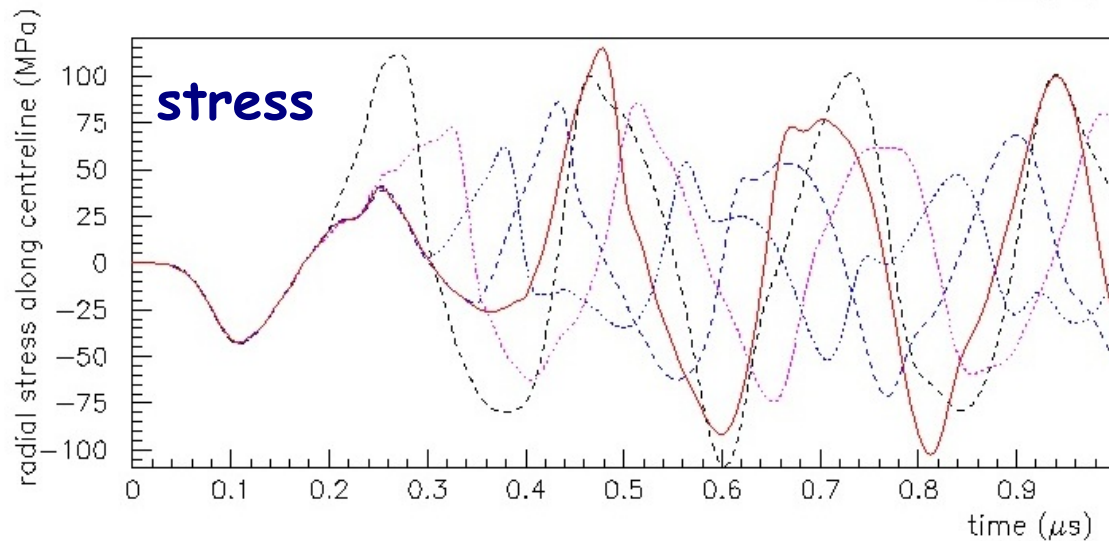
Effect of rise time

wire diameter = 0.6 mm

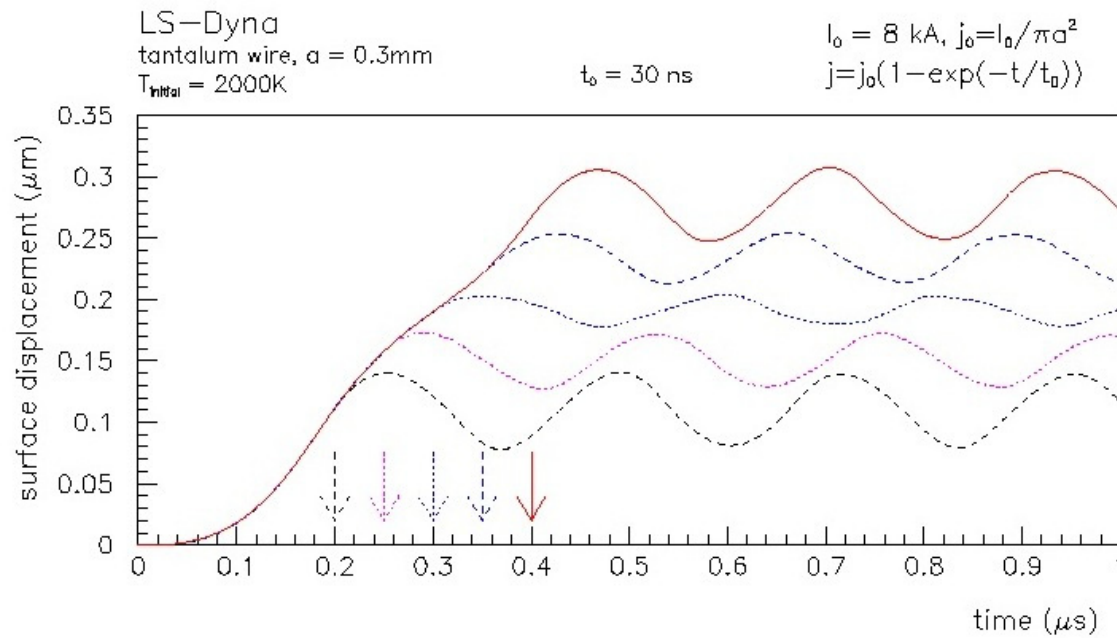
Pulse time profile - exponential rise of the current



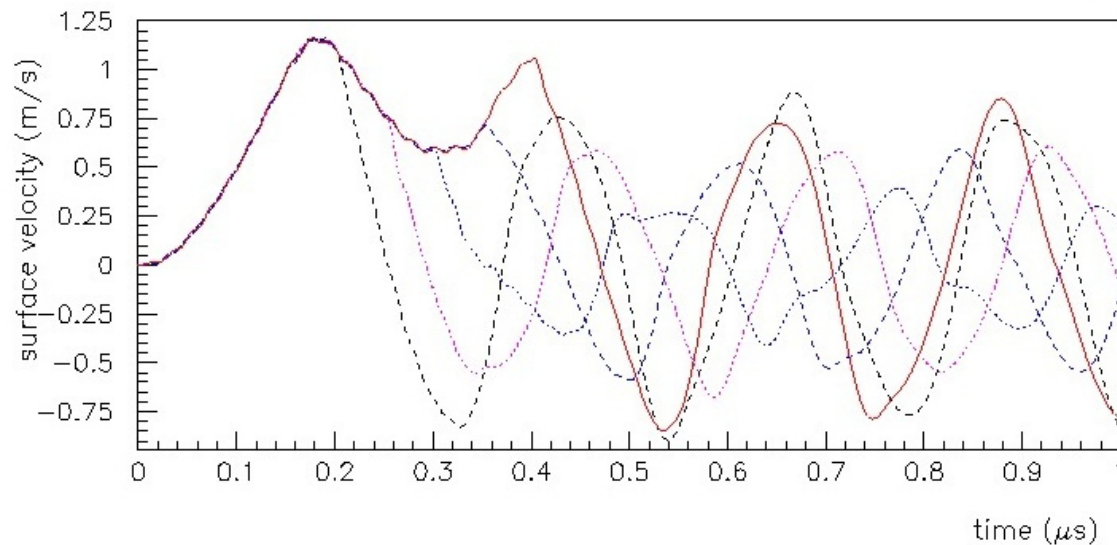
Effect of pulse length
(arrows - end of pulse)



Pulse time profile - exponential rise of the current

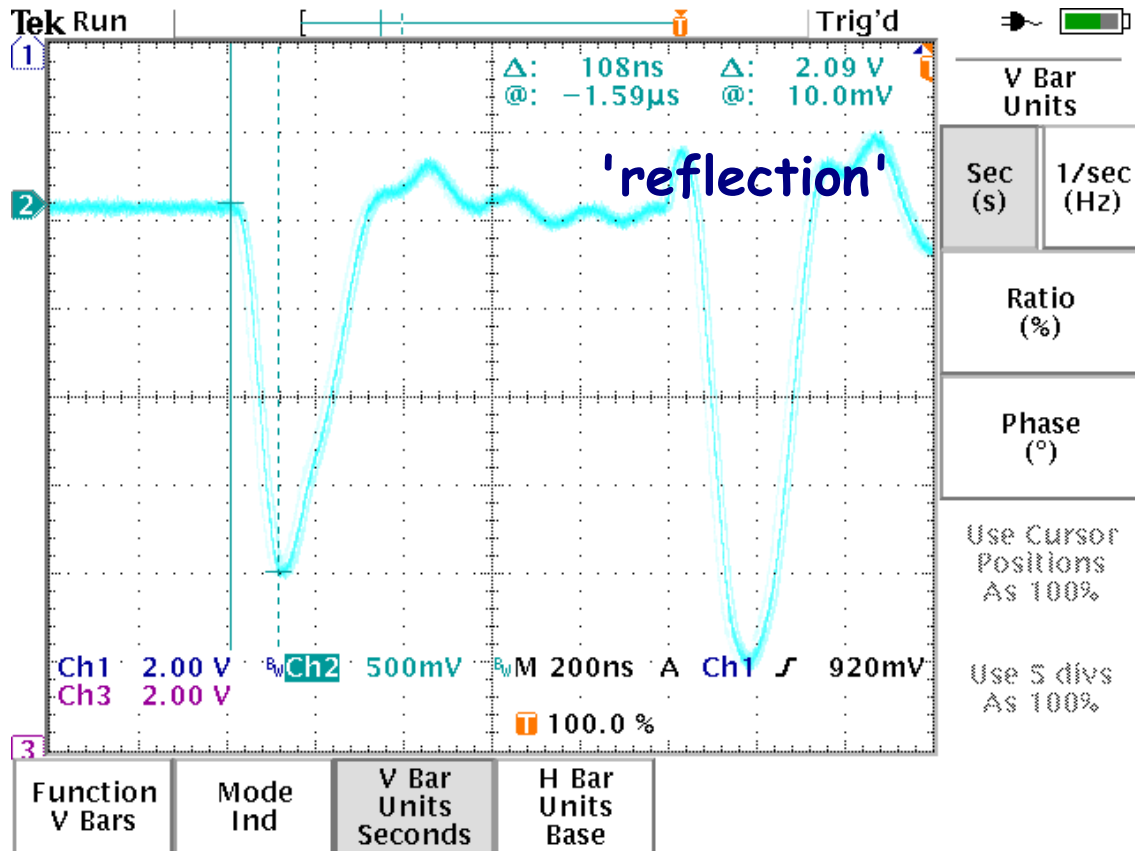


Effect of pulse length
(arrows - end of pulse)



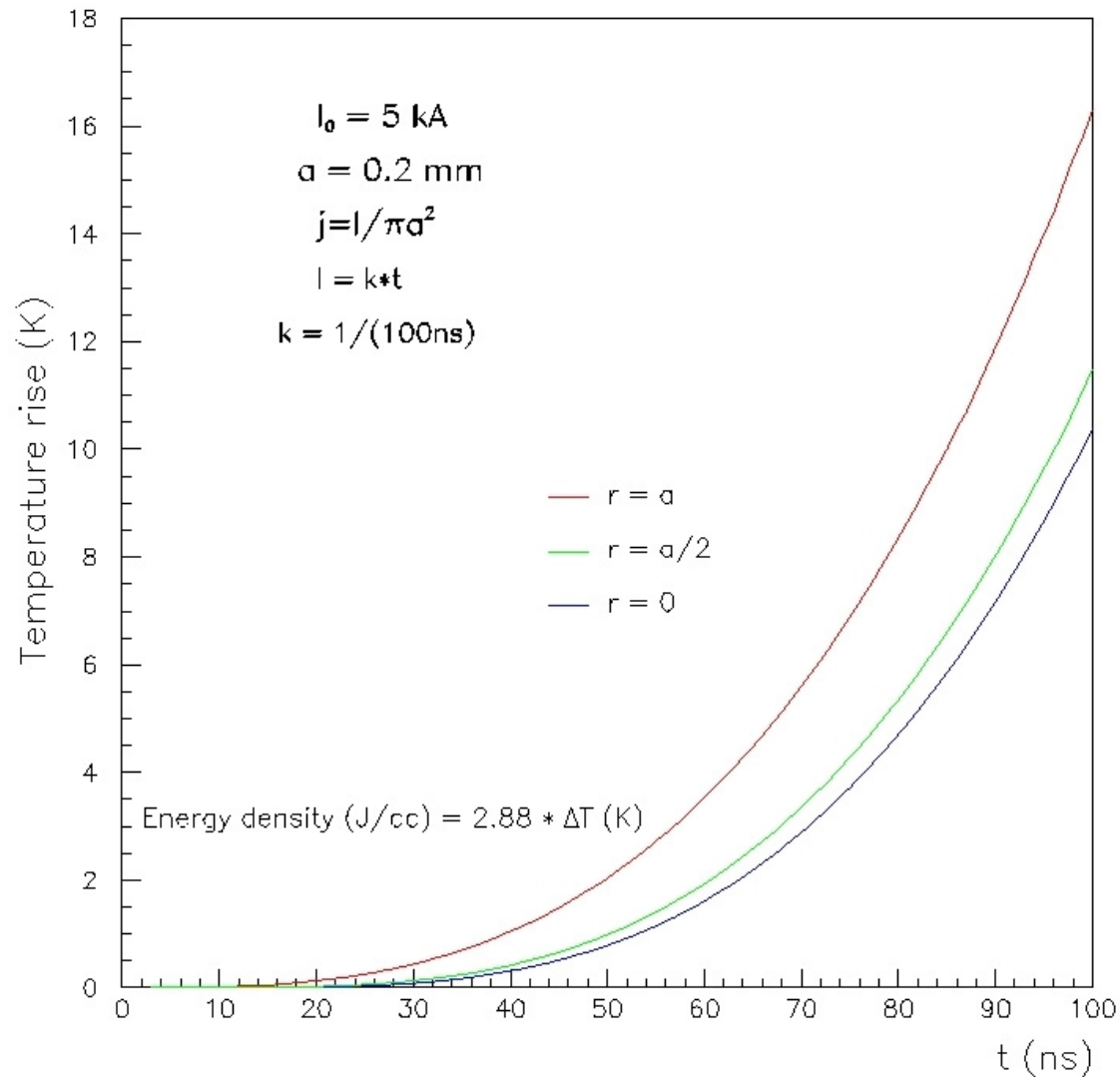
surface
velocity

'new' pulse time profile



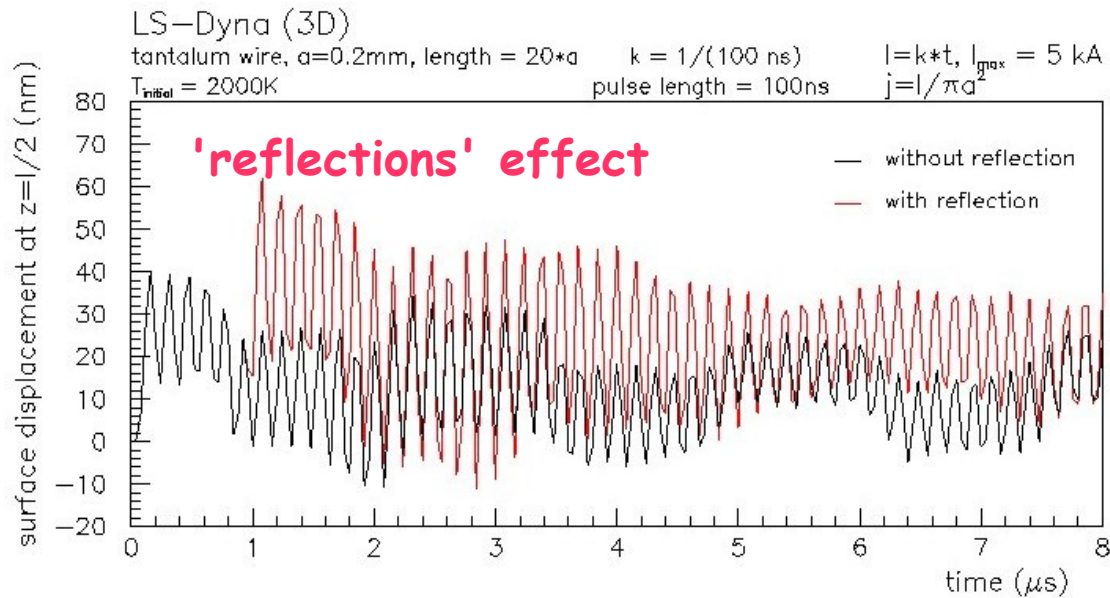
linear rise ($\sim 100\text{ns}$)
maximal current 5kA (8kA)

Pulse time profile - linear rise of the current

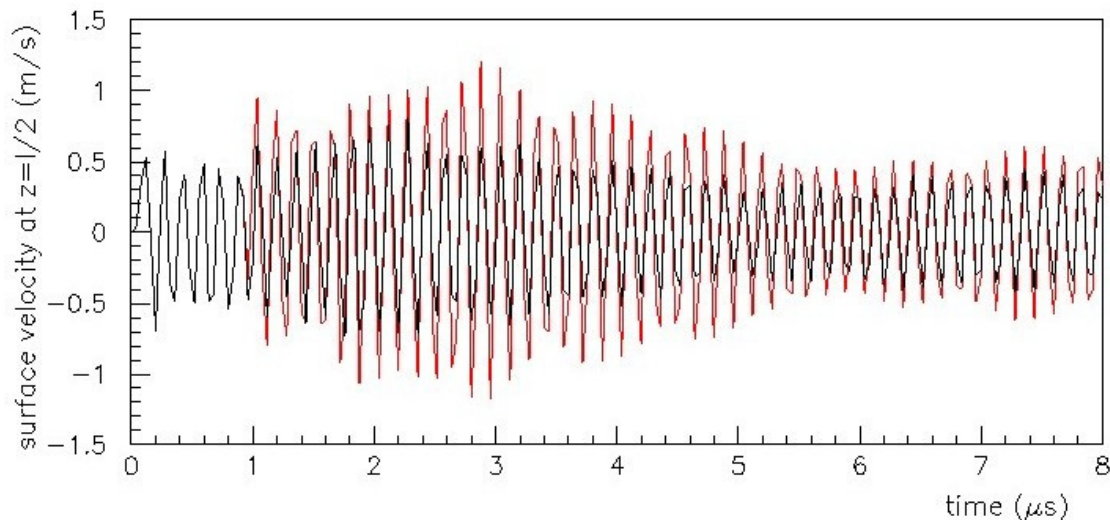


Temperature rise

Pulse time profile - linear rise of the current



surface
displacement

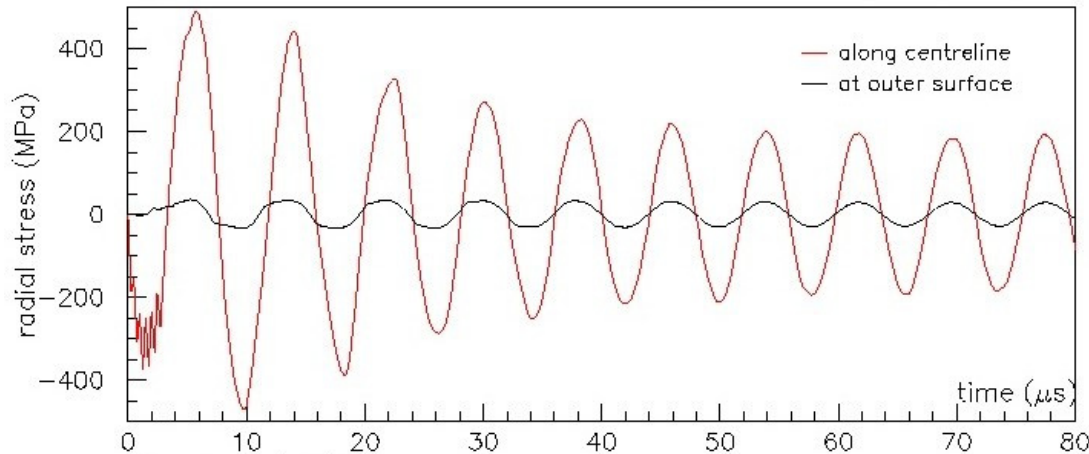


surface
velocity

Neutrino Factory vs. 'current pulse - wire' test

LS-Dyna (3D)
tantalum, $a = 1\text{cm}$, length = 20cm
 $T_{\text{initial}} = 2000\text{K}$

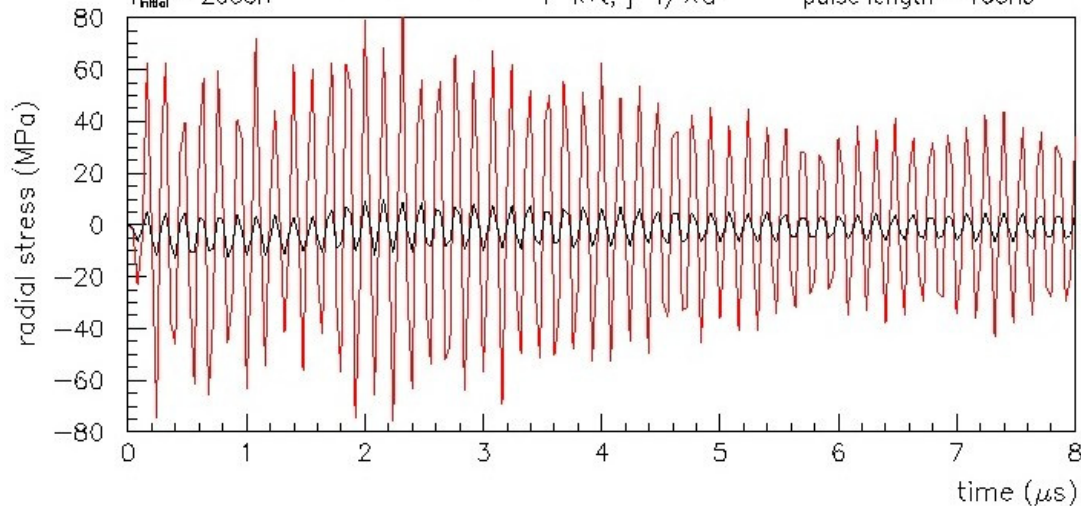
Neutrino Factory
300J/cc (average), in 6 pulses (each 2ns long) within $3\mu\text{s}$
gaussian beam profile, $\sigma = a/3$



LS-Dyna (3D)
tantalum wire, $a = 0.2\text{mm}$, $l = 20 \times a$
 $T_{\text{initial}} = 2000\text{K}$

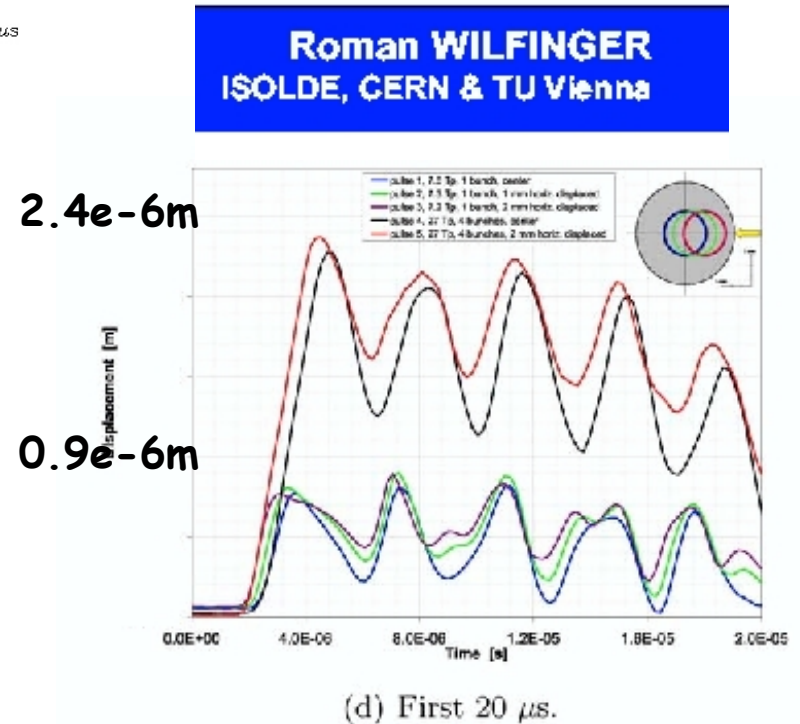
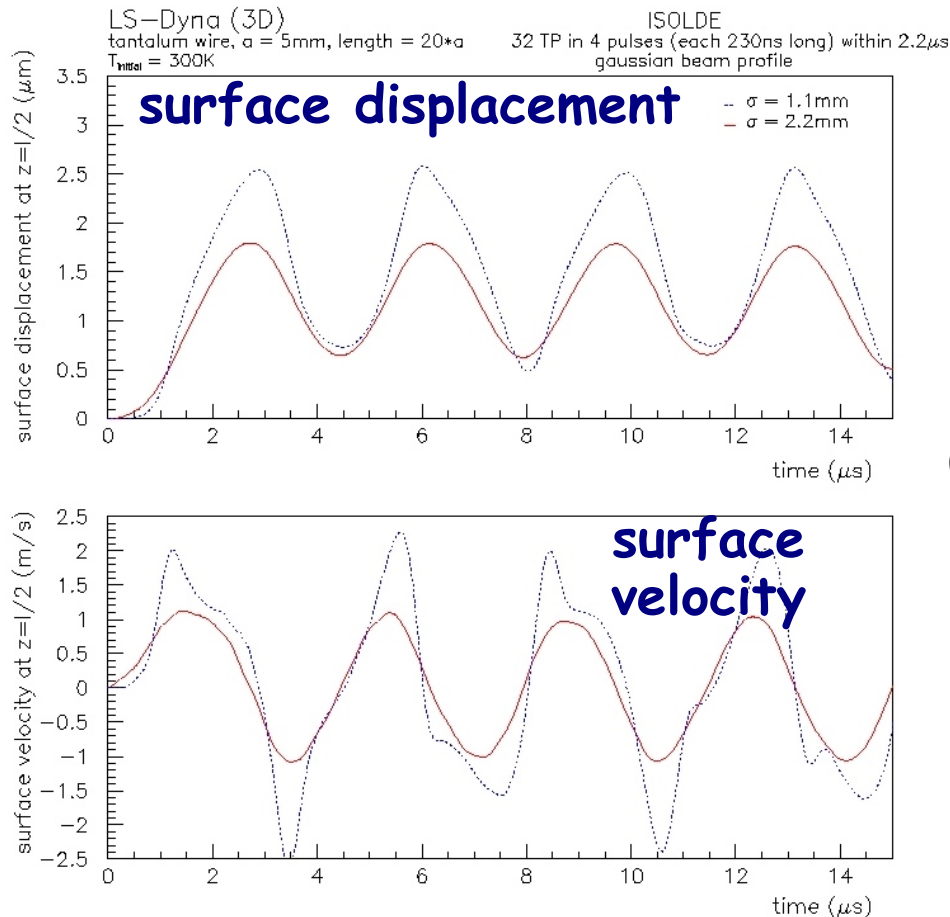
$I_{\text{max}} = 5\text{kA}$
 $I = k \cdot t$, $j = I / \pi a^2$

$k = 1 / (100\text{ ns})$
pulse length = 100ns



similar
stress
patterns

Test at the ISOLDE



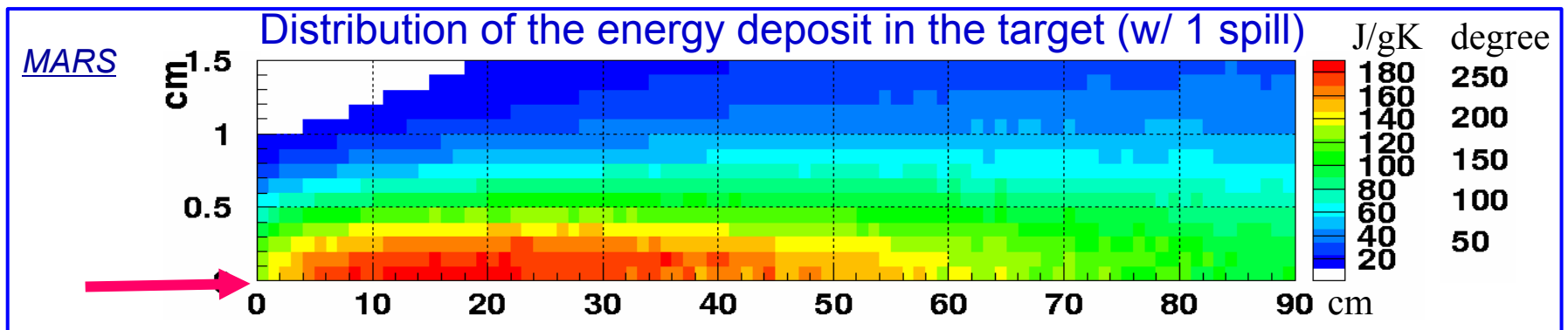
**Proton Induced Thermal
Stress Wave Measurements**

ENG / BENE Meeting,
March 16th, 2005, page 7

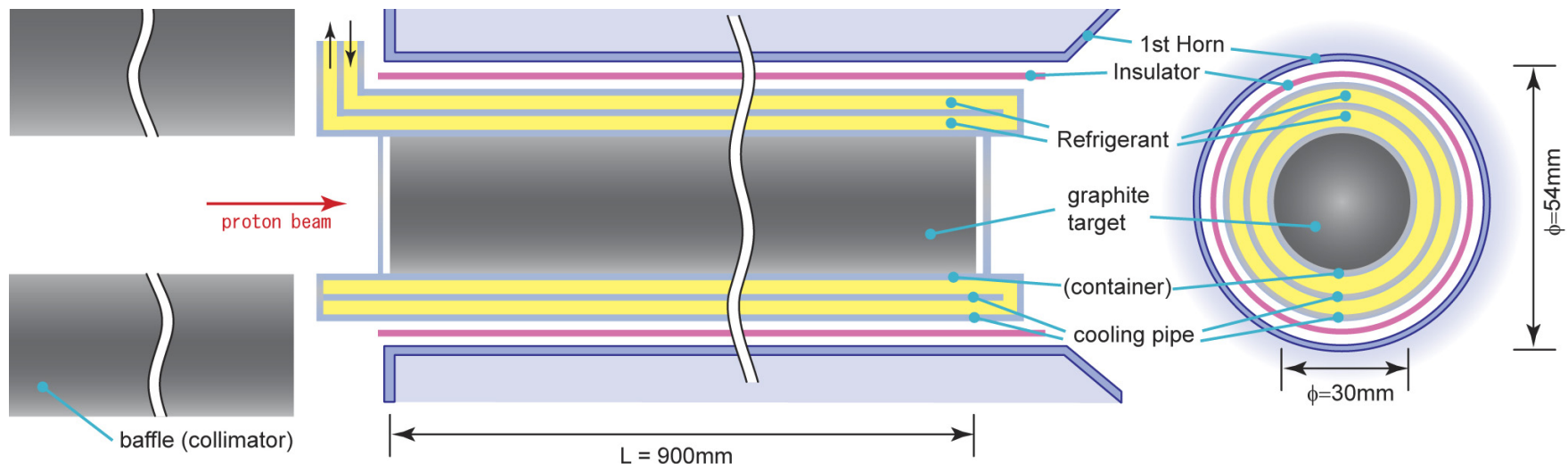
nice (initial) agreement with previous experiment!

T2K target conceptual design

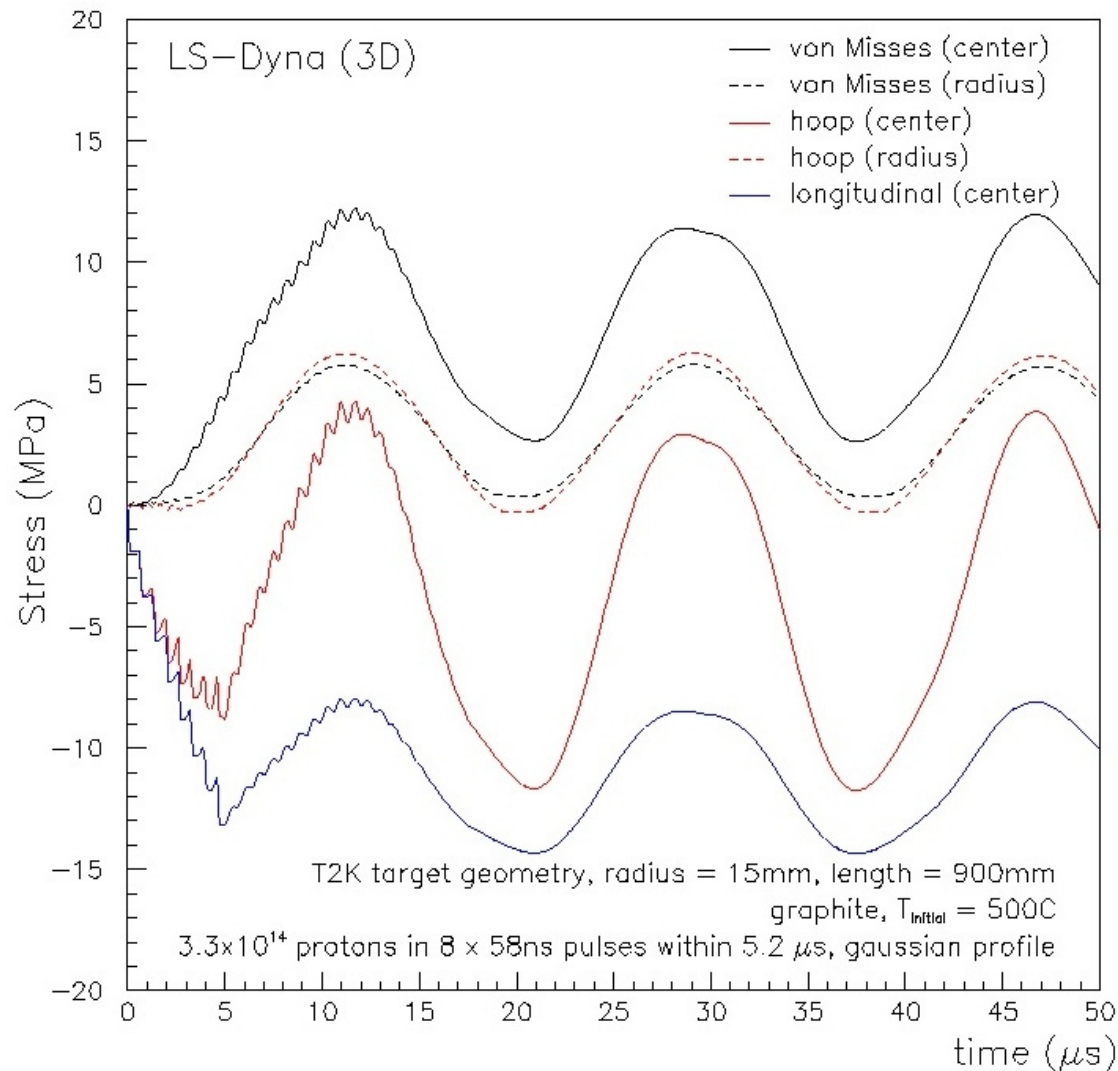
- Graphite Bar Target : $r=15\text{mm}$, $L=900\text{mm}$ (2 interaction length)
 - Energy deposit ... Total: 58kJ/spill , Max: $186\text{J/g} \rightarrow \Delta T \approx 200\text{K}$



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



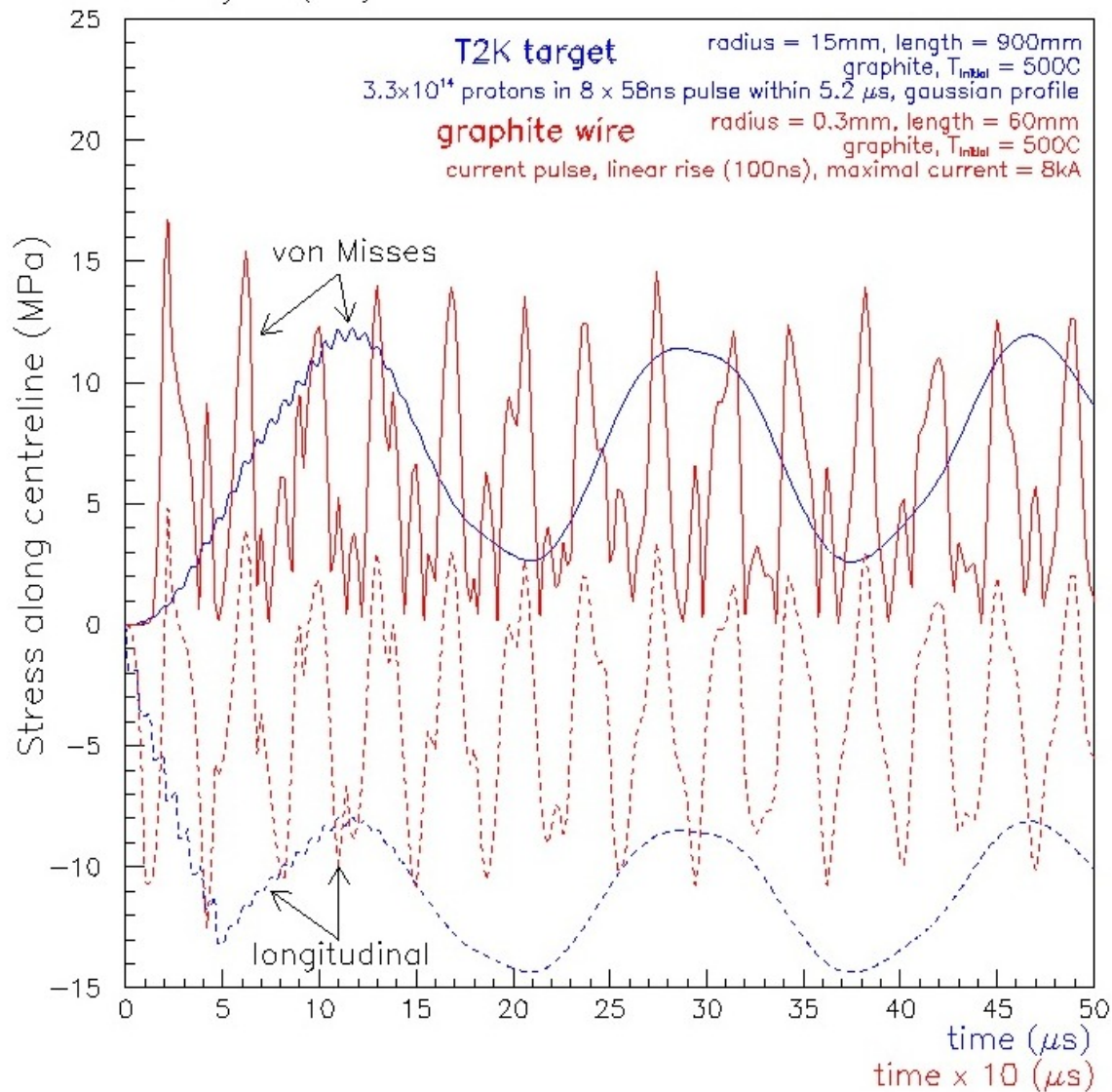
Stresses in T2K target



at the level of 10
MPa

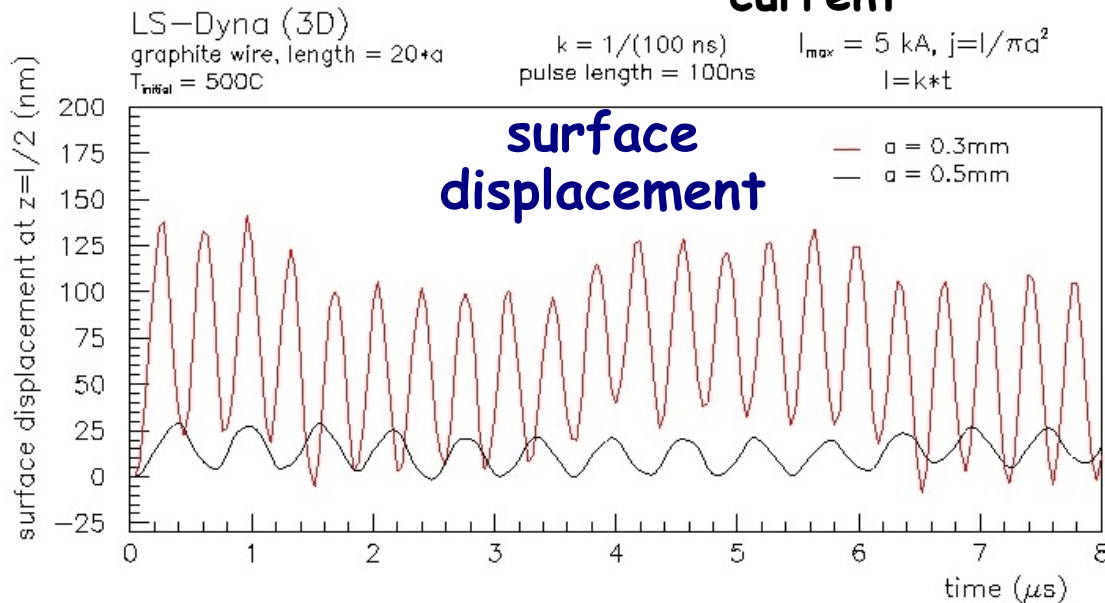
T2K target vs. 'current pulse - wire' test

LS-Dyna (3D)

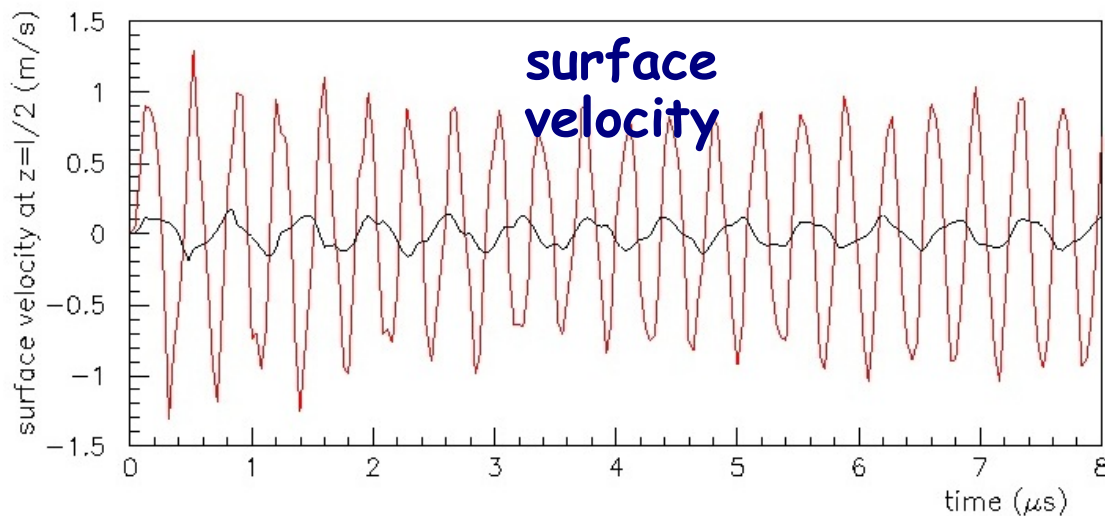


'similar'
stress
patterns

Pulse time profile - linear rise of the current



GRAPHITE WIRE



velocities (in all the cases) at the level of $\sim 1\text{m/s}$
→ accessible to modern VISAR's

Extraction of material data (first steps)

1. VISAR time resolution = 10ns, velocity resolution = 0.1m/s;
2. VISAR time resolution = 40ns, velocity resolution = 0.025m/s.

Table 1. Tantalum property values used as an input for LS-Dyna and obtained as a result of the fitting procedure (MINUIT) in the case of 5kA maximal current. Numbers in parantheses are estimated errors of the parameters (in the last digits).

Par.	Property	LS-Dyna input	Case 1	Case 2
1	El. modulus, E [GPa]	144	164 (3)	138 (2)
2	CTE, α [10^{-6} m/m/K]	7.4	8.4 (17)	7.6 (4)
3	Temp. rise, ΔT	12-18	20 (12)	19 (1)
4	Poisson's ratio, ν	0.33	0.325 (3)	0.36 (1)
5	Density, ρ [g/cm ³]	16	16.13 (4)	15.77 (1)
6			0.768 (1)	0.817 (3)
7			0.48 (1)	0.48 (1)

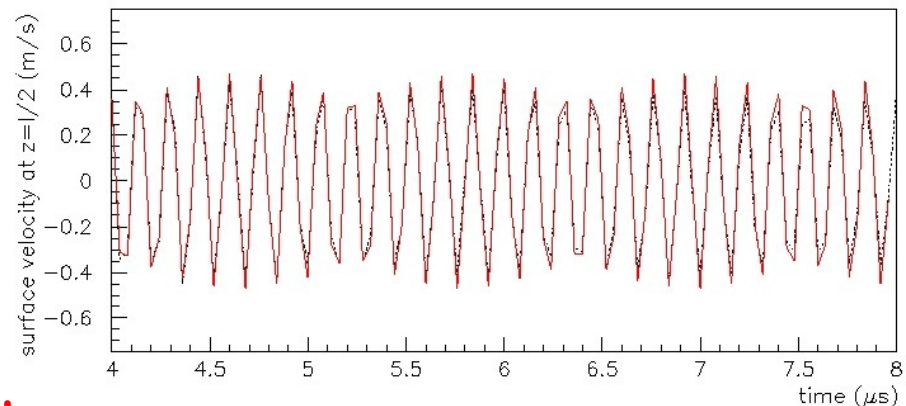
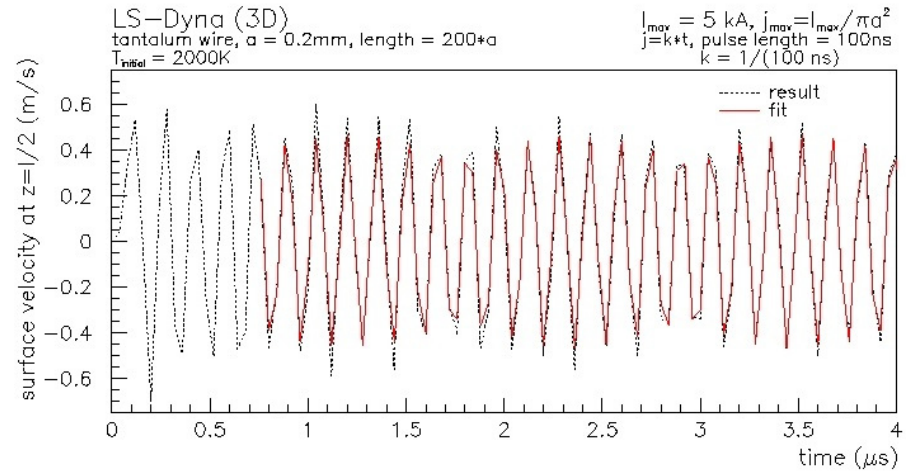
Table 2. Tantalum property values used as an input for LS-Dyna and obtained as a result of the fitting procedure (MINUIT) in the case of 8kA maximal current. Numbers in parantheses are estimated errors of the parameters (in the last digits).

Par.	Property	LS-Dyna input	Case 1	Case 2
1	El. modulus, E [GPa]	144	136 (2)	155 (2)
2	CTE, α [10^{-6} m/m/K]	7.4	8.1 (5)	7.5 (2)
3	Temp. rise, ΔT	26-40	43 (3)	43 (1)
4	Poisson's ratio, ν	0.33	0.284 (3)	0.30 (1)
5	Density, ρ [g/cm ³]	16	16.05 (2)	16.18 (1)
6			0.852 (1)	0.800 (2)
7			0.42 (1)	0.42 (1)

fitting formula:

$$v = \frac{P_2 \cdot P_3}{(1 - P_4)} \cdot \frac{a}{t_0} \cdot \cos[P_6 \cdot \pi \cdot \Theta + P_7 \cdot \pi],$$

$$c = \sqrt{\frac{P_1}{P_5(1 - P_4^2)}}.$$



Details, progress, etc... see URL:

[http://hepunx.rl.ac.uk/
Shock Simulations](http://hepunx.rl.ac.uk/Shock Simulations)



Target Studies



Thermal

Summary of results so far:

- **Neutrino Factory:**

- Shock waves in Ta characterised within limitations of material knowledge
- Effects of beam pulse length and multiple bunches/pulse understood

- **Test of wire:**

- Power supply available which can supply necessary current (8kA) within short enough time to generate shocks of similar magnitude to those in NF
- VISAR to be purchased with sufficient time resolution and velocity sensitivity to measure surface velocity of wire and compare results with LS-DYNA calculations

Still to do:

- **Shock test of Ta wire:**
 - Perform experiment
 - Work out how to extract material data from experiment
 - From lifetime test predict lifetime of tantalum NF target
- **Repeat experiment with graphite:**
 - Graphite is target material of choice for CNGS and T2K(JPARC facility)
 - Serious candidate material for a NF