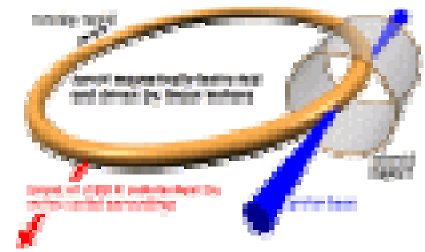

LS-DYNA Simulations of Thermal Shock in Solids

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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 50 Hz by a proton beam consisting of ~1ns long bunches in a pulse of a few micro-s length.
- The target material exposed to the beam will be ~ 20cm long and ~2cm 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)

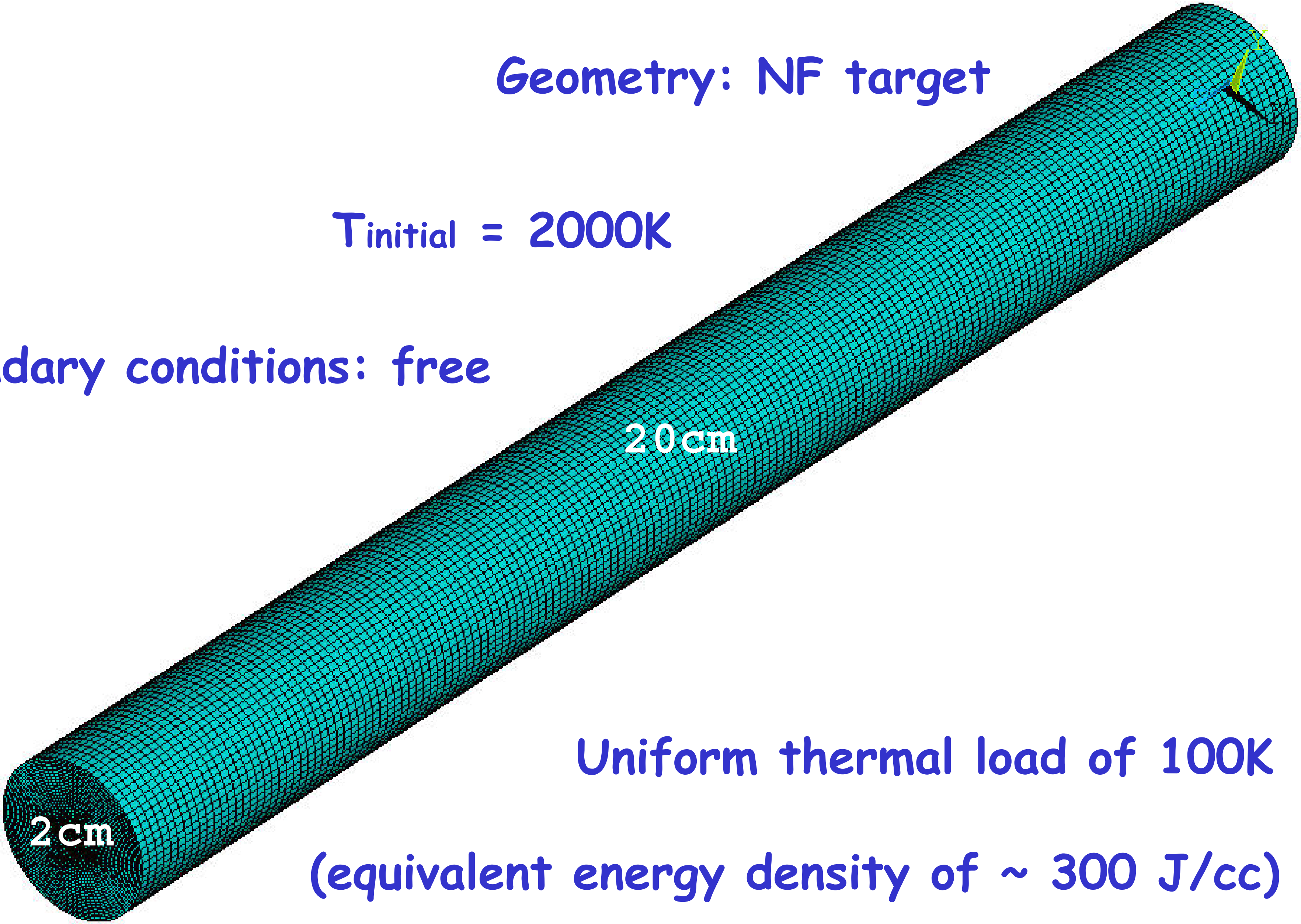
First studies (NuFact05 Proceedings)

- Because the target will be bombarded at up 50 Hz by a proton beam consisting of ~1ns 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

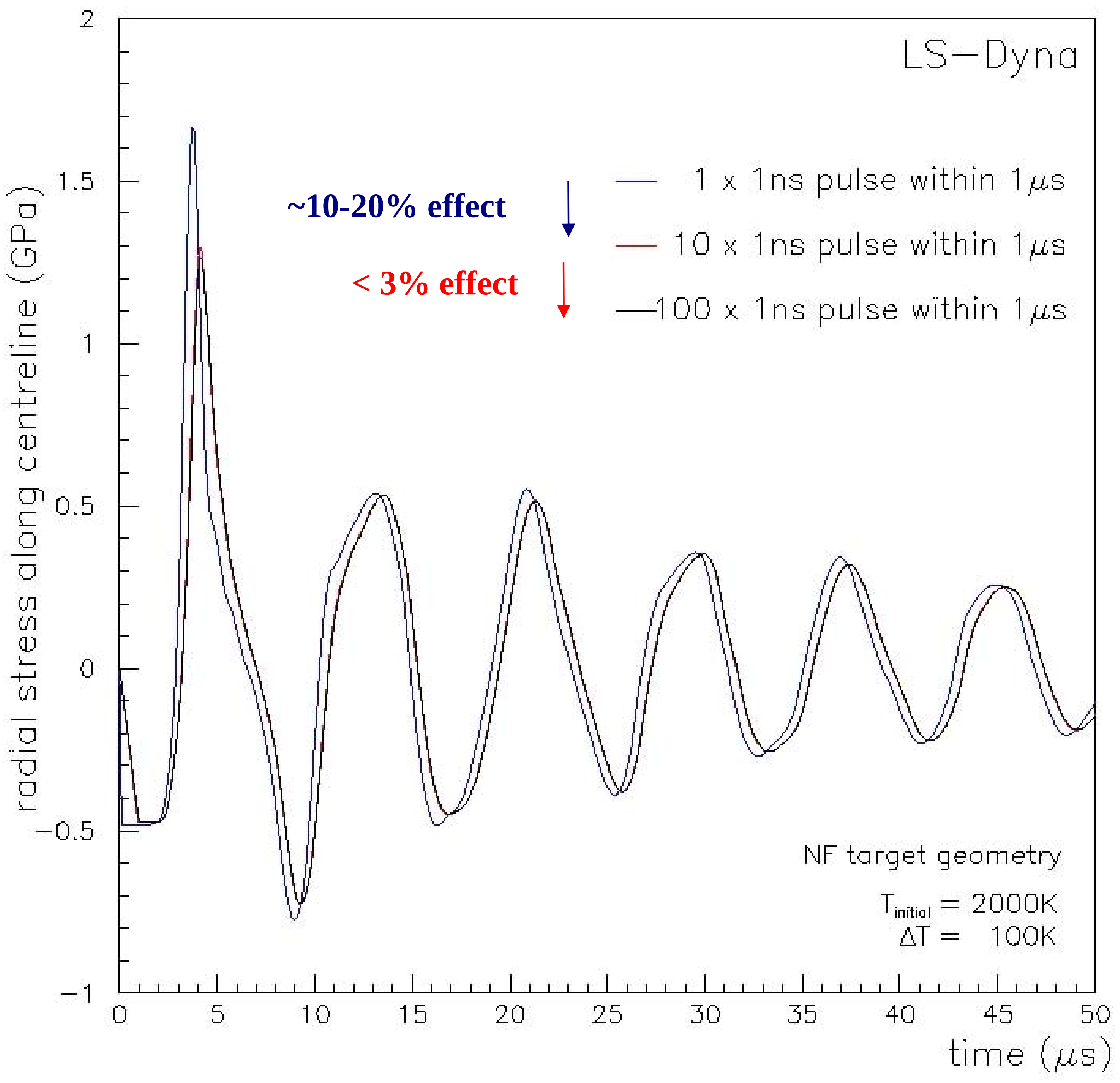
$T_{initial}$ = 2000K

Boundary conditions: free



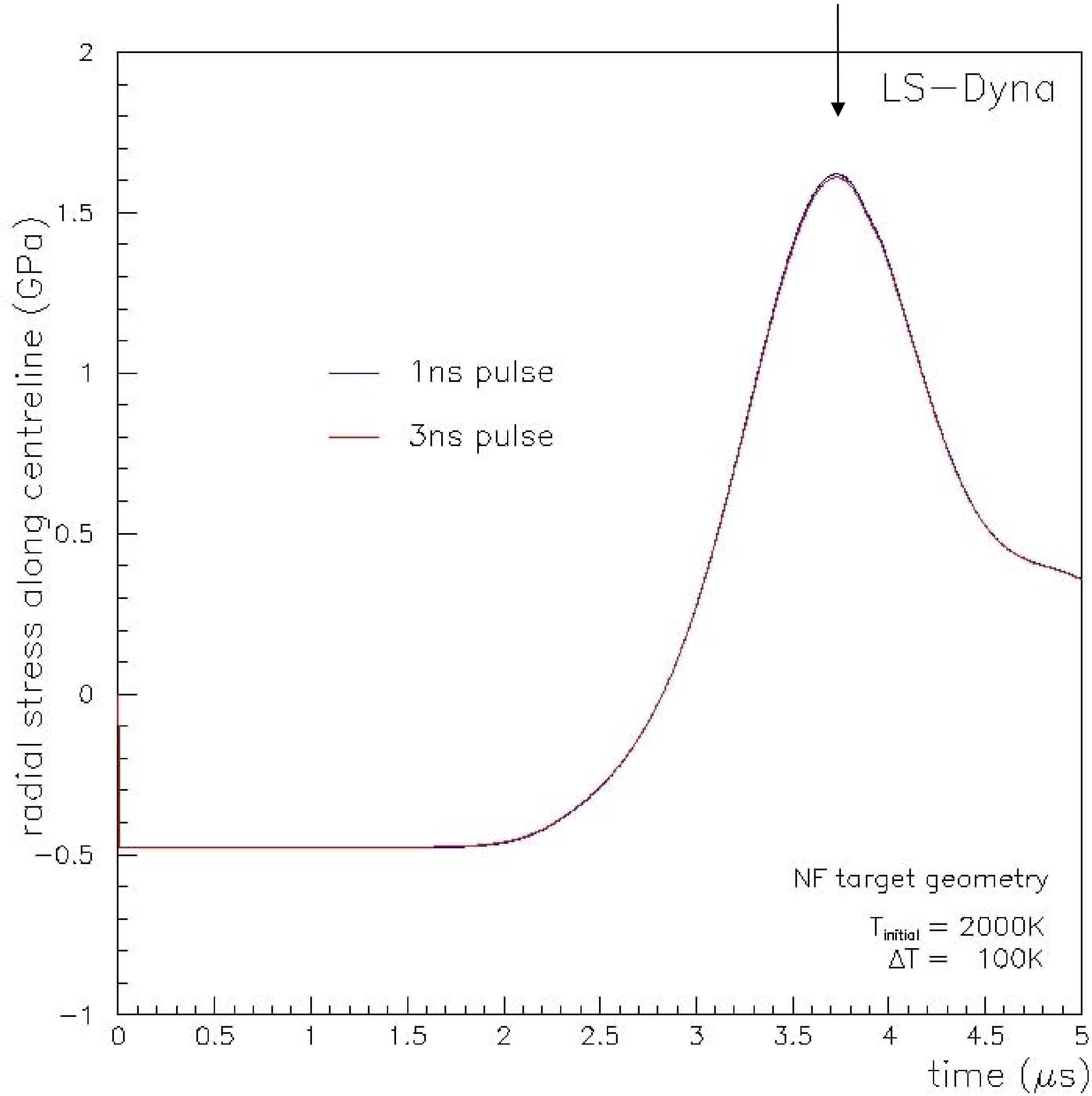
Uniform thermal load of 100K

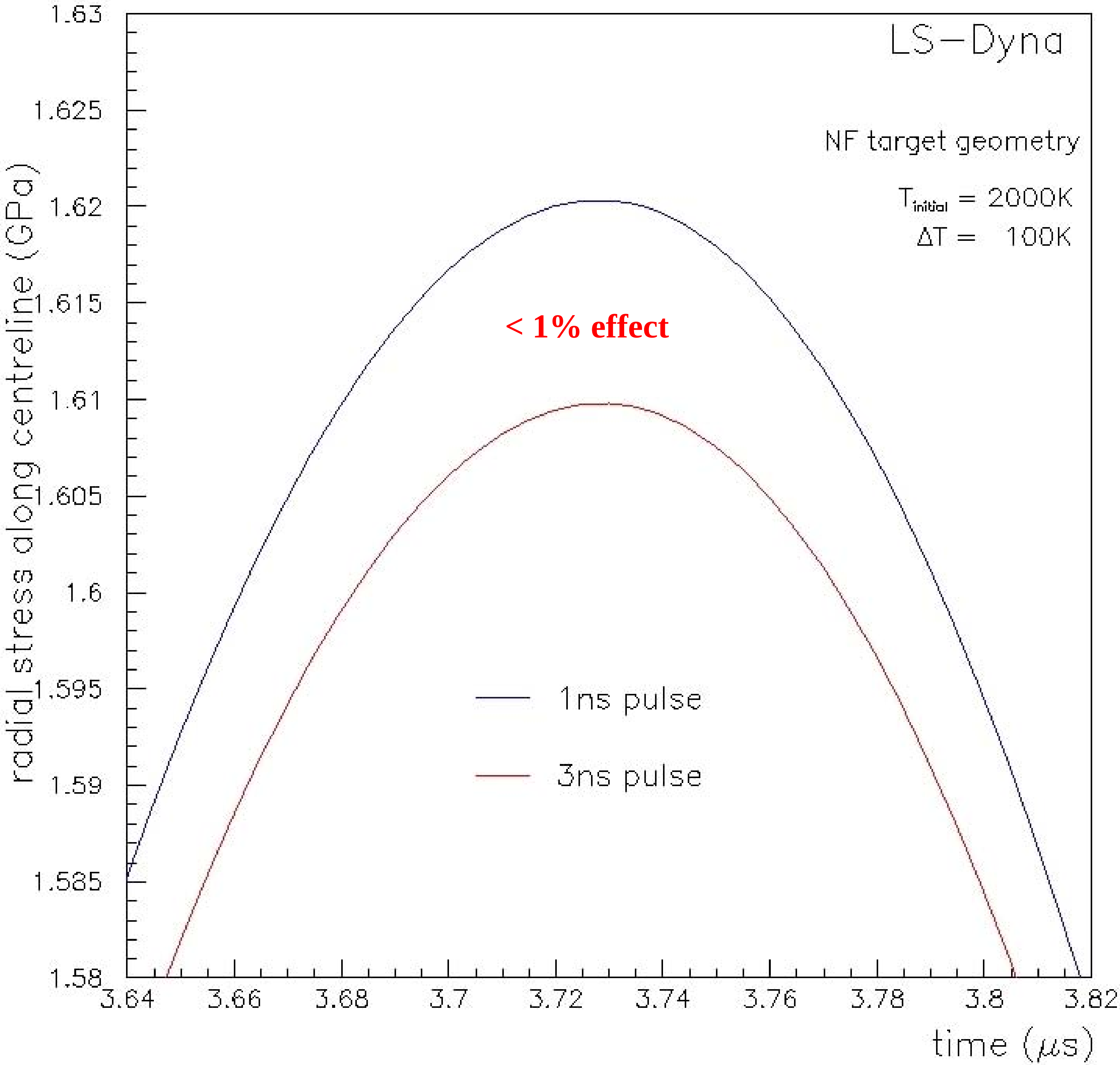
(equivalent energy density of ~ 300 J/cc)



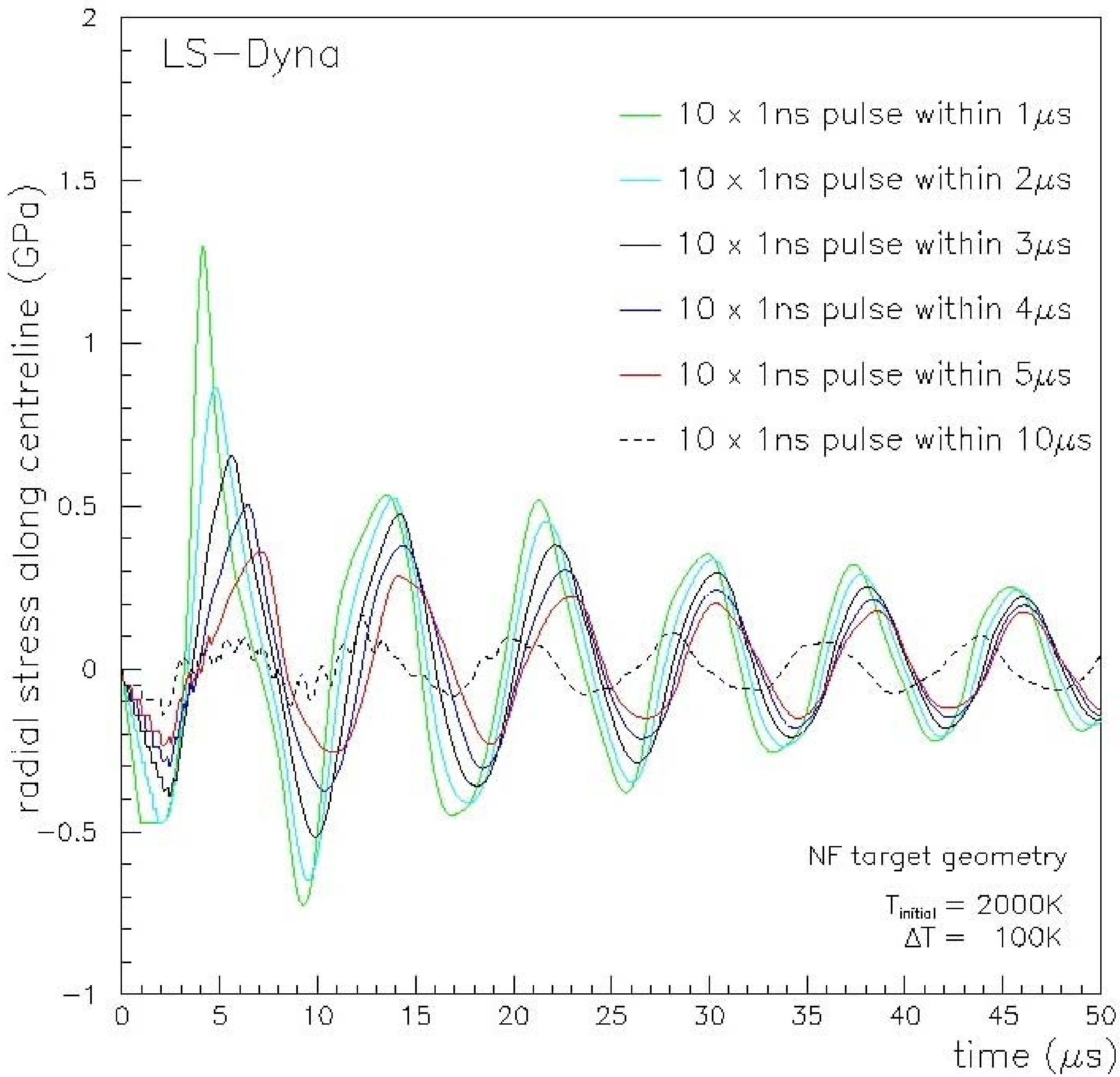
LS−Dyna
~10-20% effect
< 3% effect
1 x 1ns pulse within 1μs
10 x 1ns pulse within 1μs
100 x 1ns pulse within 1μs
NF target geometry
T initial = 2000K
ΔT = 100K
radial stress along centreline (GPa)
time (μs)
2
1.5
1
0.5
0
−0.5
−1
0
5
10
15
20
25
30
35
40
45
50

Characteristic time = radius / speed of sound in the tantalum





LS−Dyna
NF target geometry
T initial = 2000K
ΔT = 100K
< 1% effect
1ns pulse
3ns pulse
radial stress along centreline (GPa)
time (μs)
1.63
1.625
1.62
1.615
1.61
1.605
1.6
1.595
1.59
1.585
1.58
3.64
3.66
3.68
3.7
3.72
3.74
3.76
3.78
3.8
3.82



~ RAL proton driver

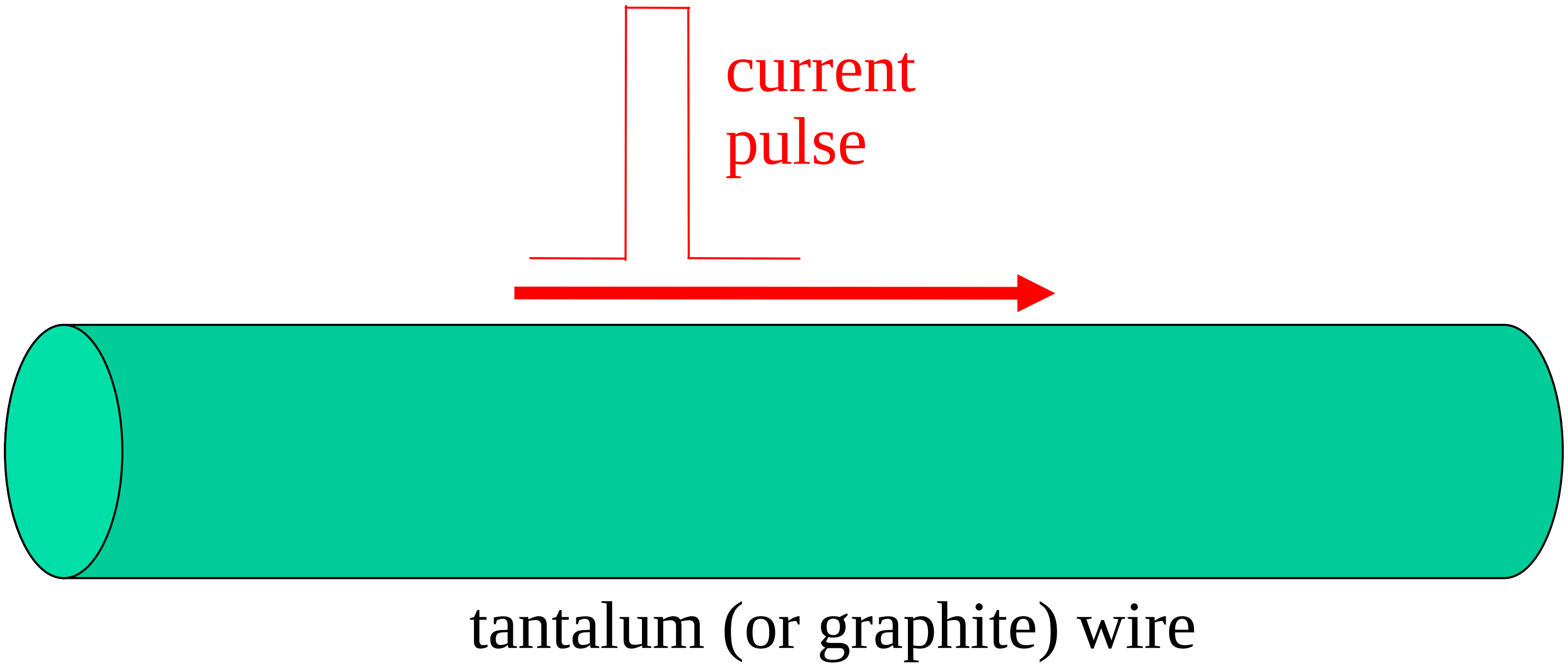
Important parameters: Energy deposition rate and shock transit time!

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

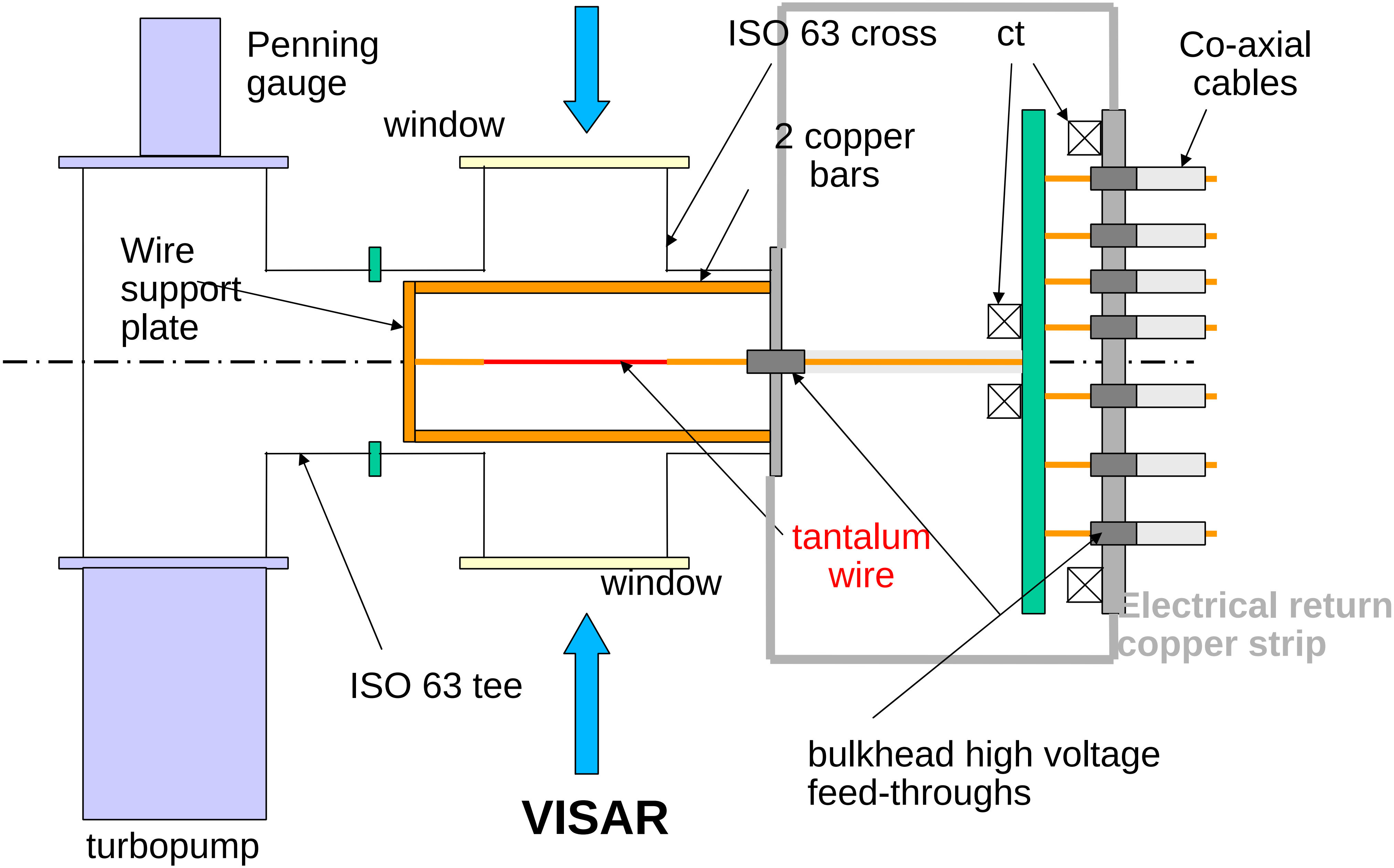
Pulsed ohmic-heating of wires may be able to replicate pulsed proton beam induced shock.



Energy density in the **Ta** wire needs to be ε_0 = 300 J cm^{-3} to correspond to 1 MW dissipated in a target of 1 cm radius and 20 cm in length at 50 Hz.

JRJ Bennett (NuFACT05)

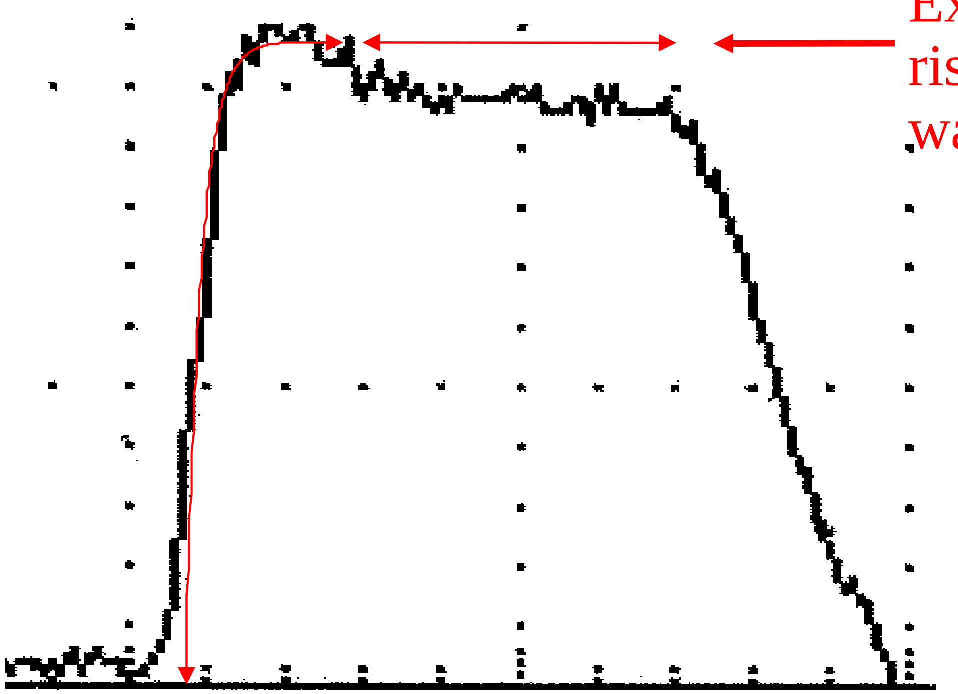
Schematic section of the wire shock-wave test assembly



JRJ Bennett (RAL)

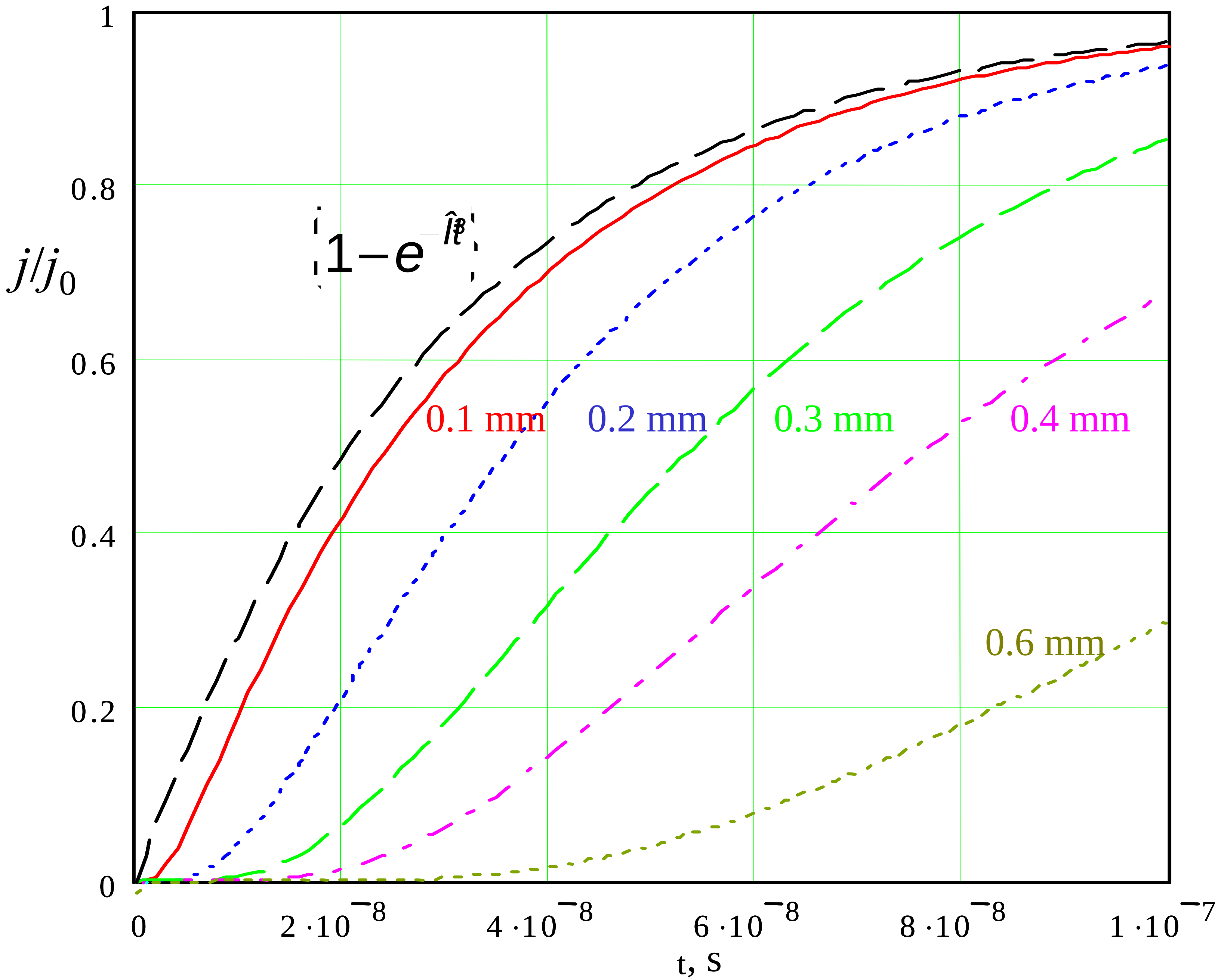
Doing the Test

The ISIS Extraction Kicker Pulsed Power Supply



Rise time: ~100 ns

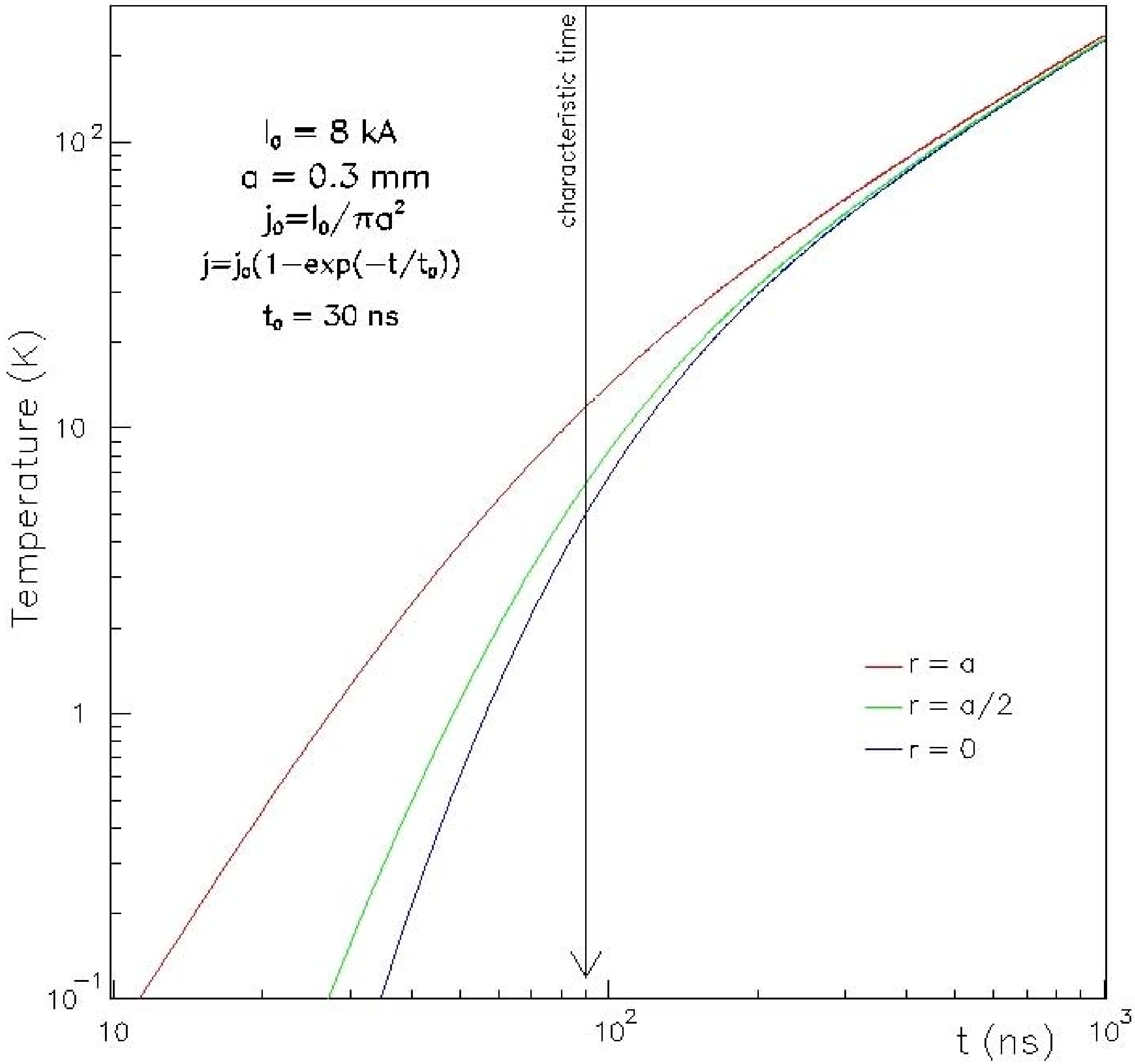
Flat Top: ~500 ns



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

JRJ Bennett (NuFACT05)

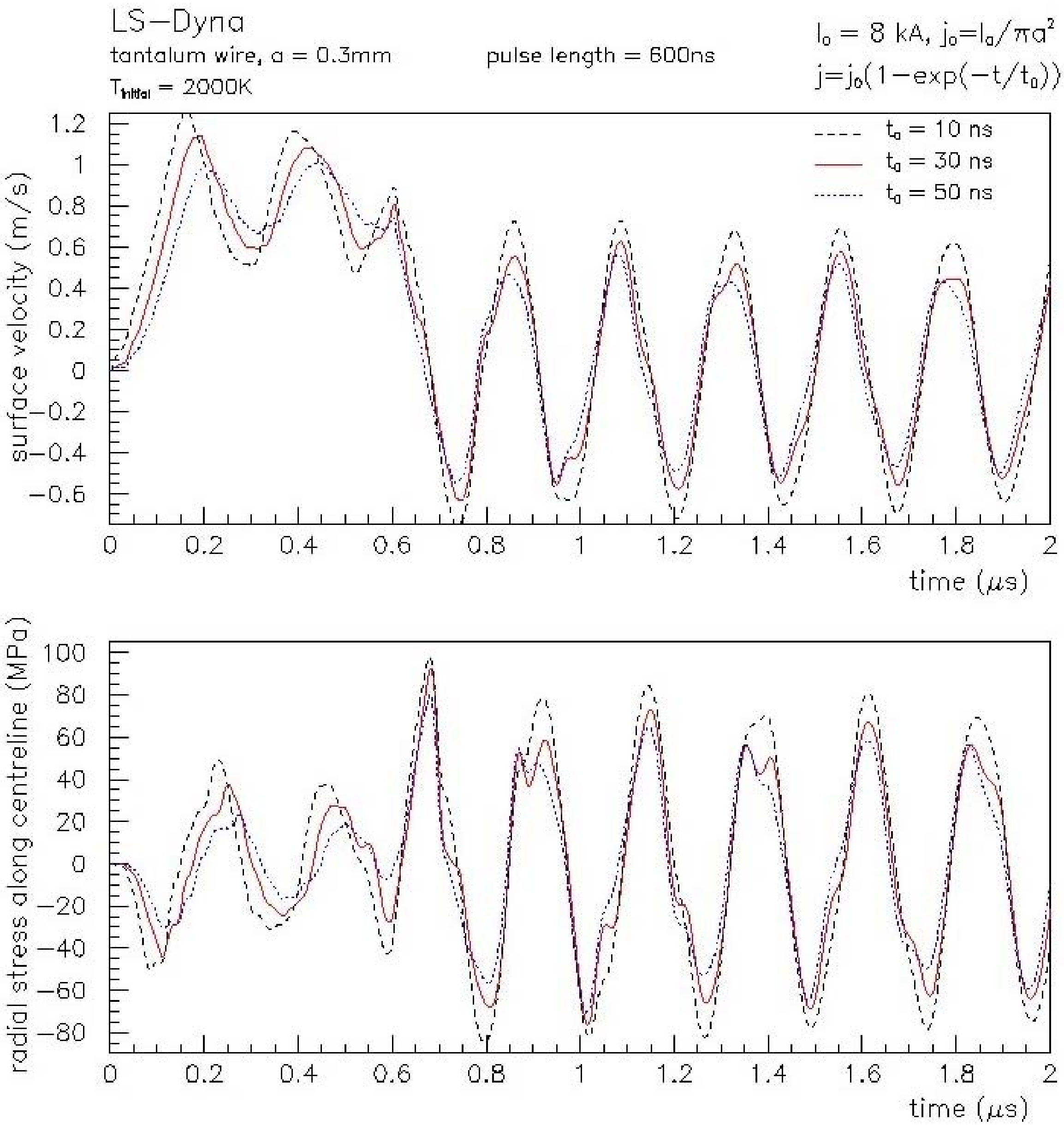
Pulse time profile - exponential rise of the current



Temperature rise

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

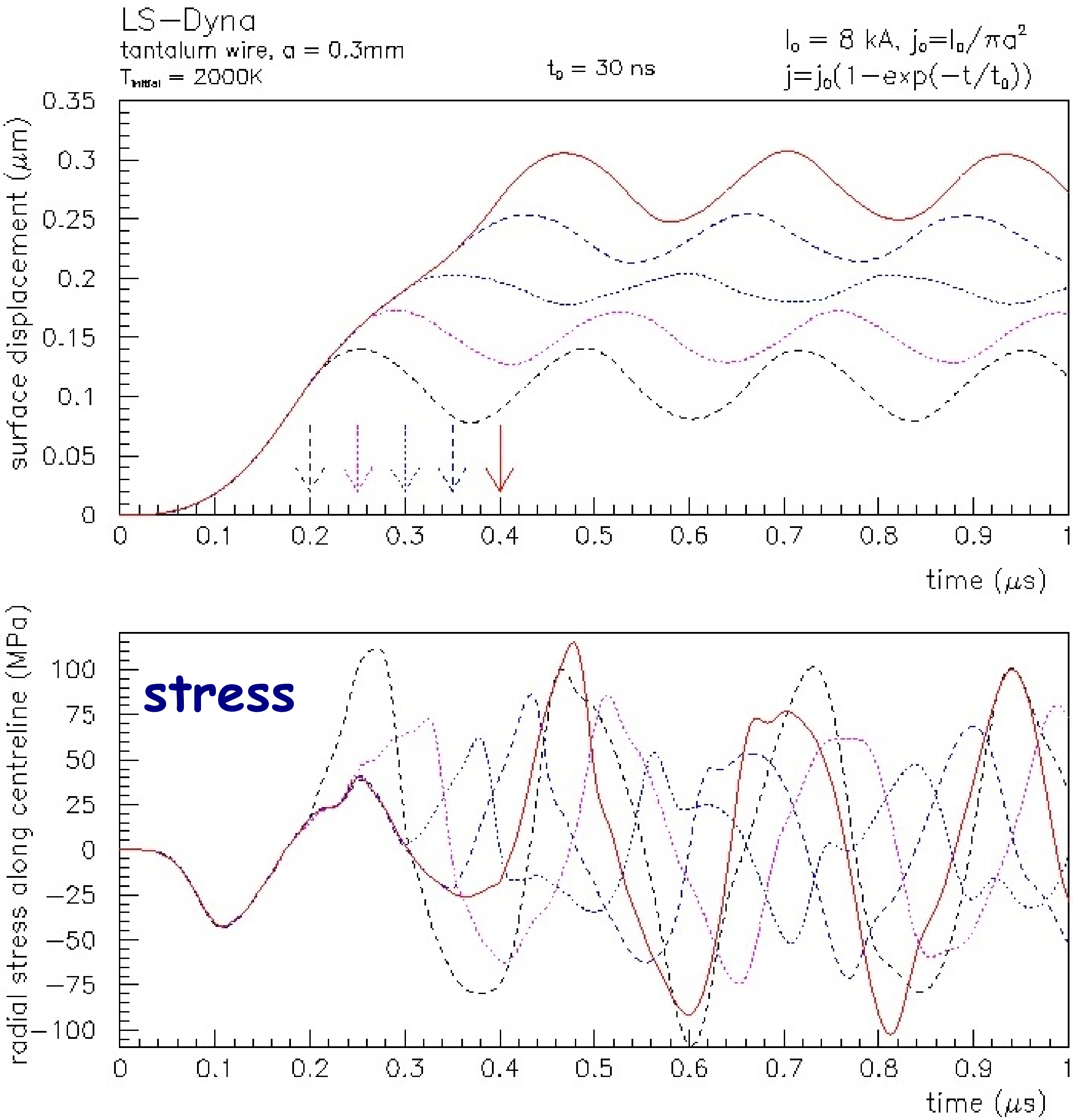
Pulse time profile - exponential rise of the current



Effect of rise time

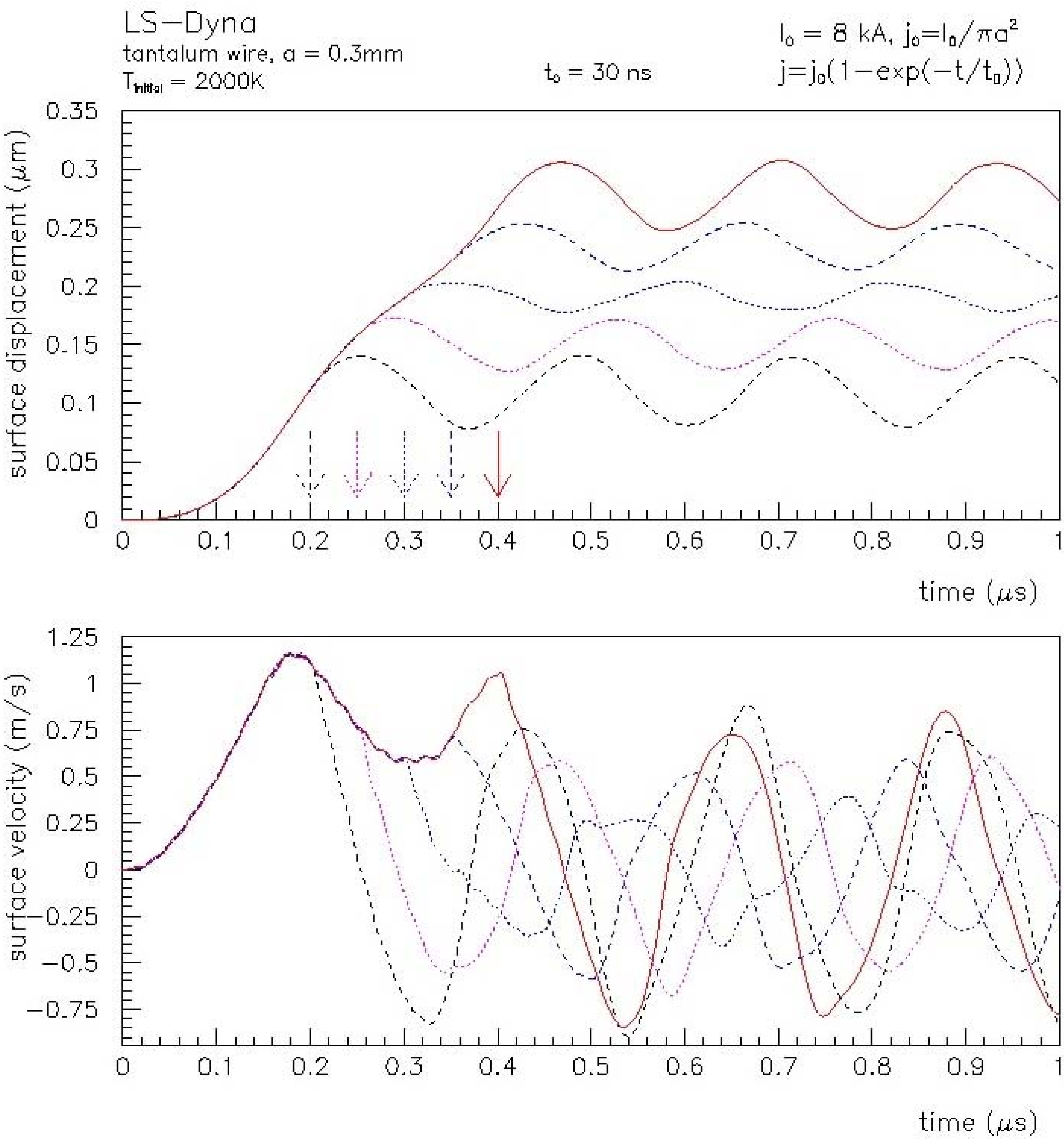
wire diameter = 0.6 mm

Pulse time profile - exponential rise of the current



Effect of pulse length (arrows - end of pulse)

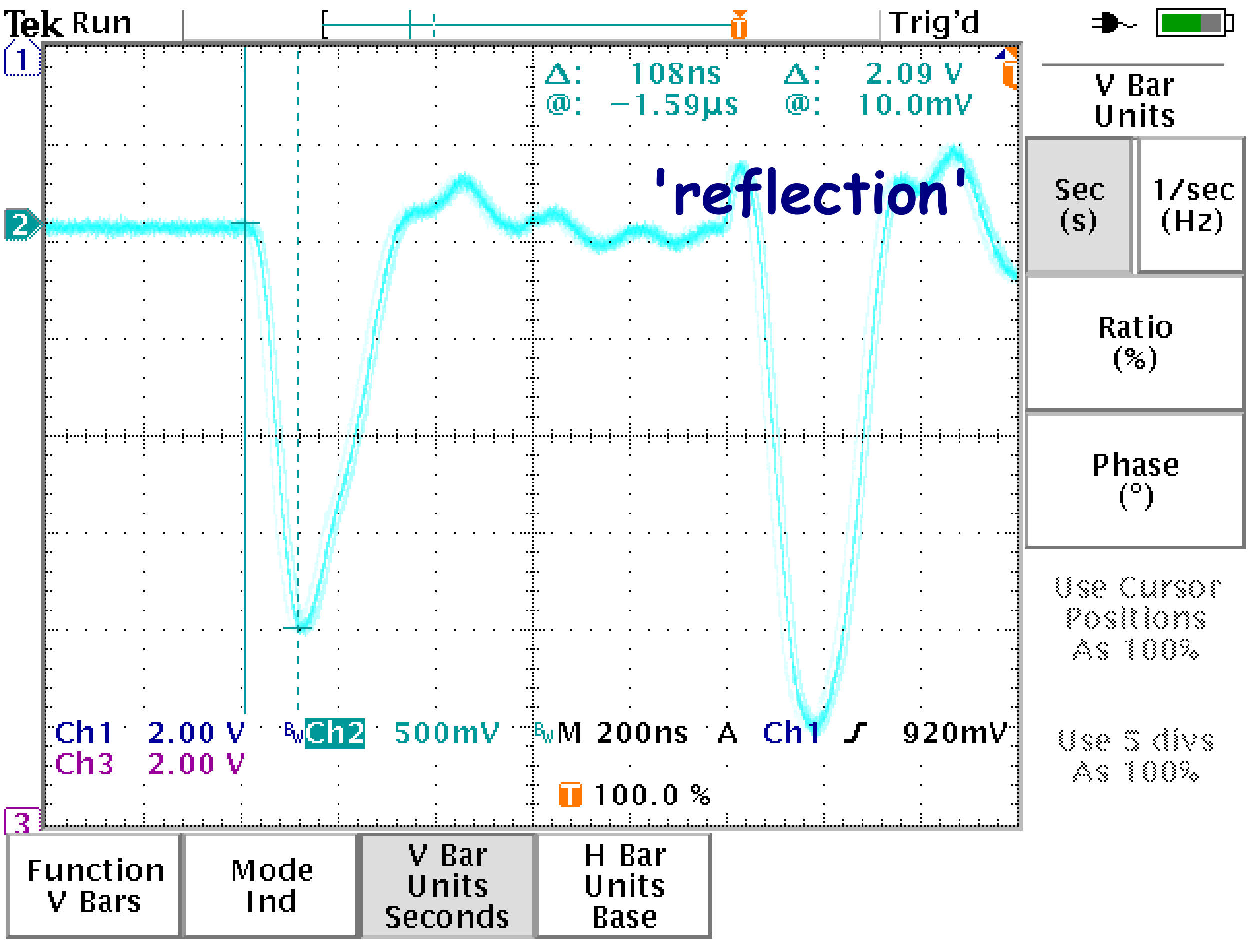
Pulse time profile - exponential rise of the current



Effect of pulse length (arrows - end of pulse)

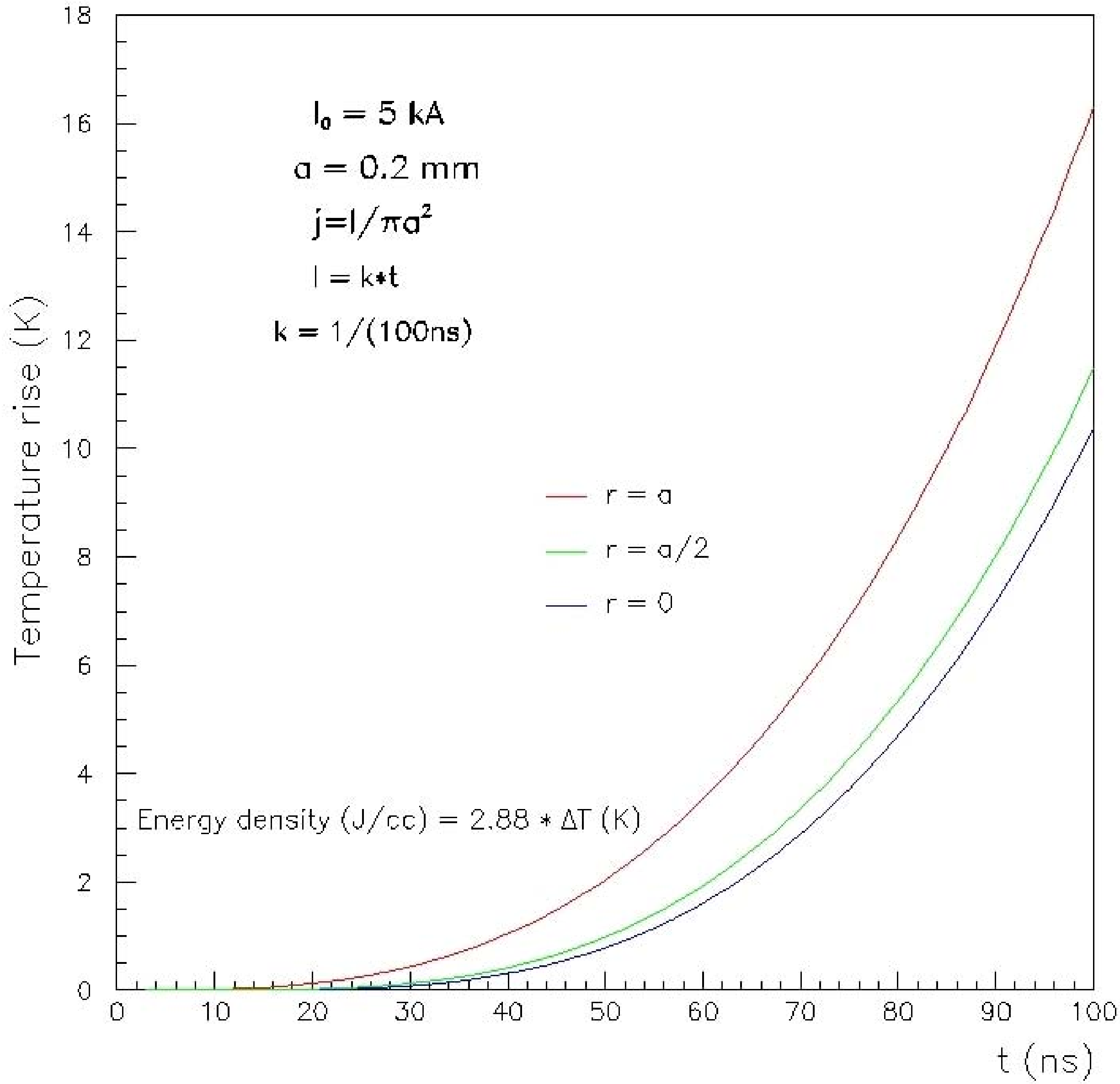
surface velocity

'new' pulse time profile



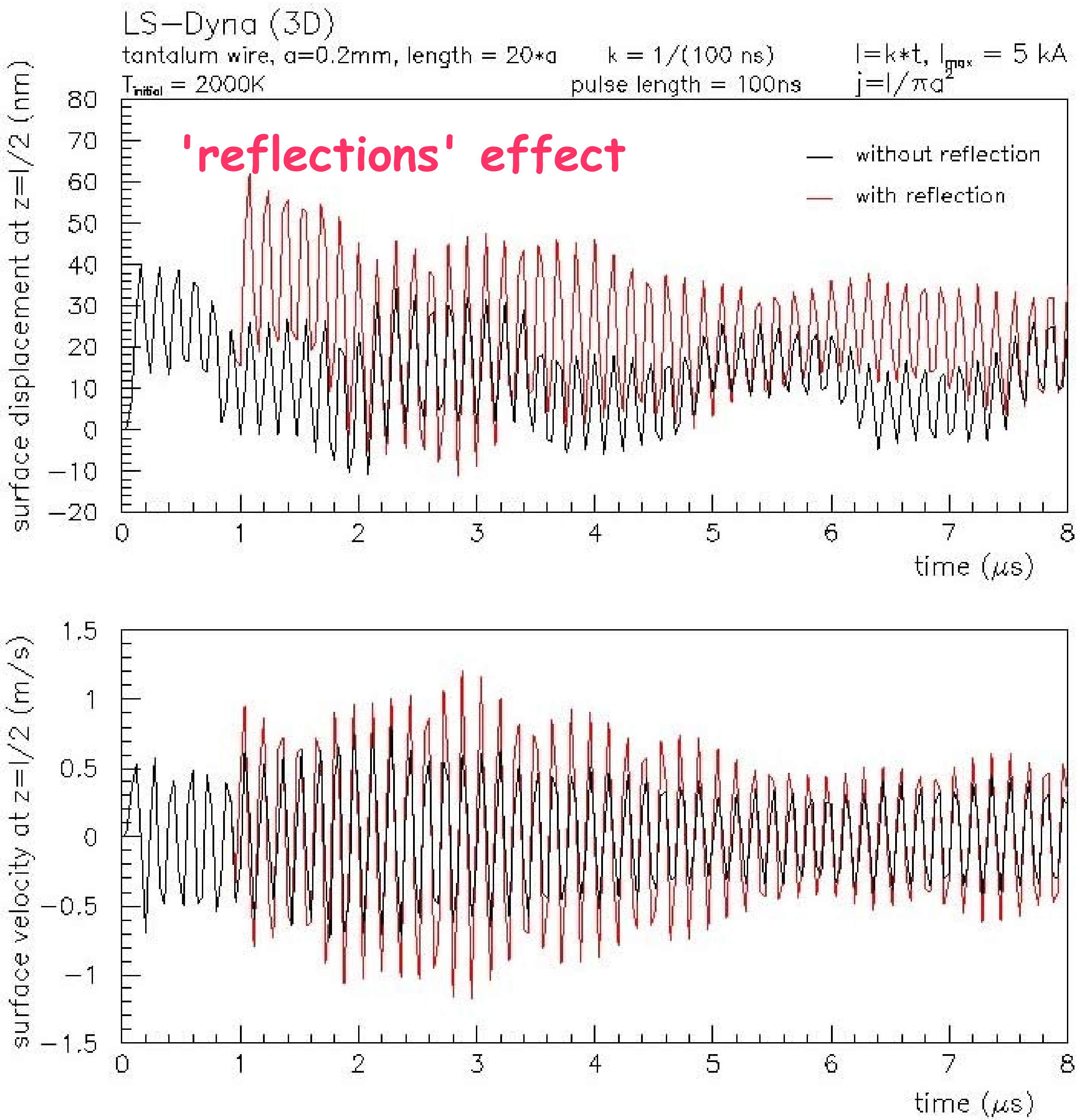
linear rise (~100ns)
maximal current 5kA (8kA)

Pulse time profile - linear rise of the current



Temperature rise

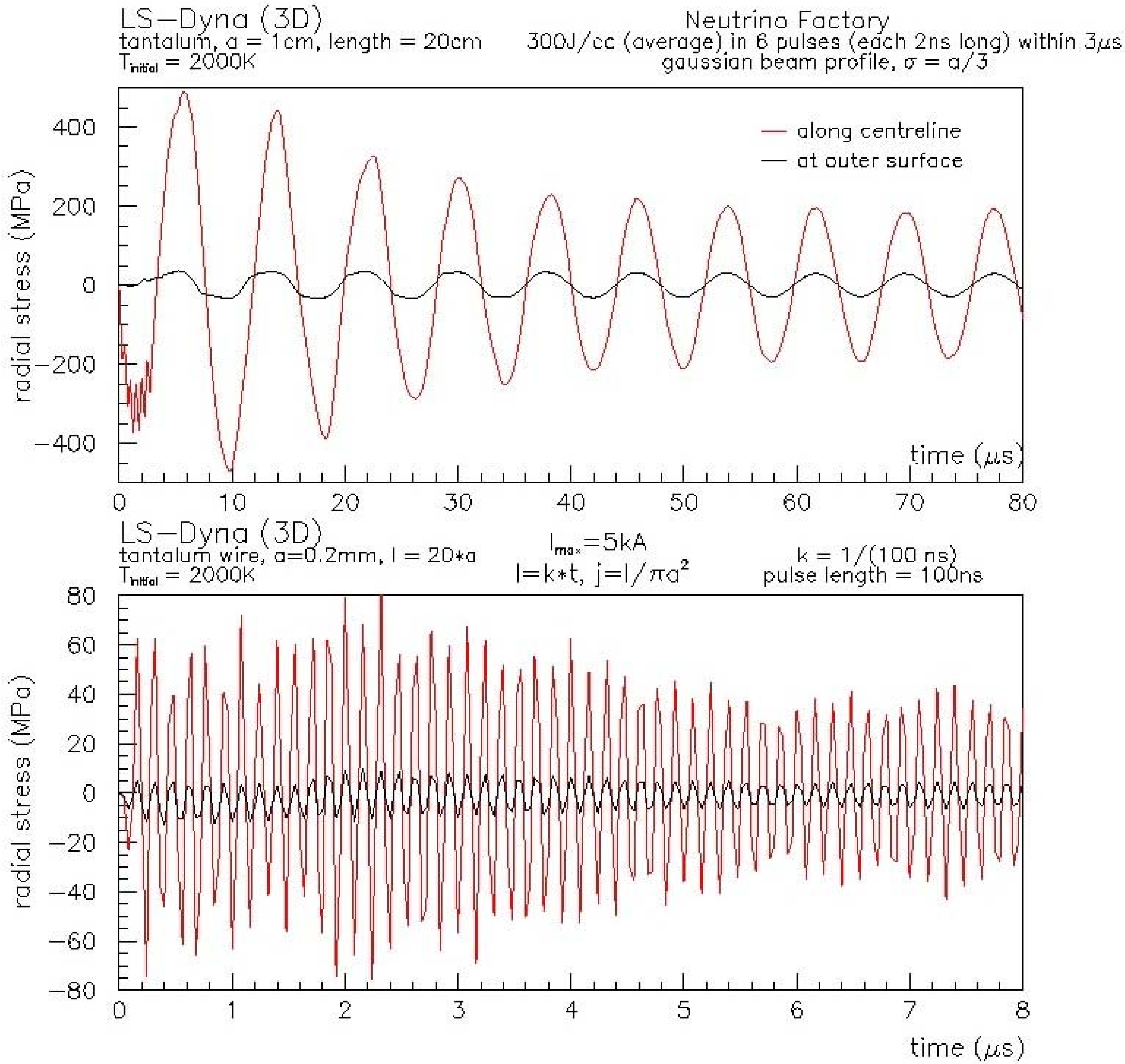
Pulse time profile - linear rise of the current



surface displacement

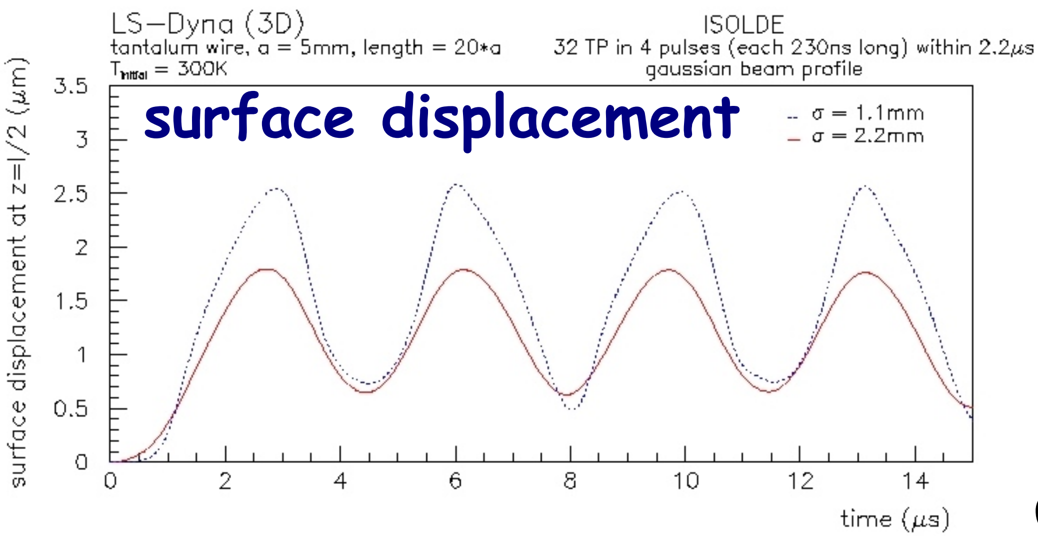
surface velocity

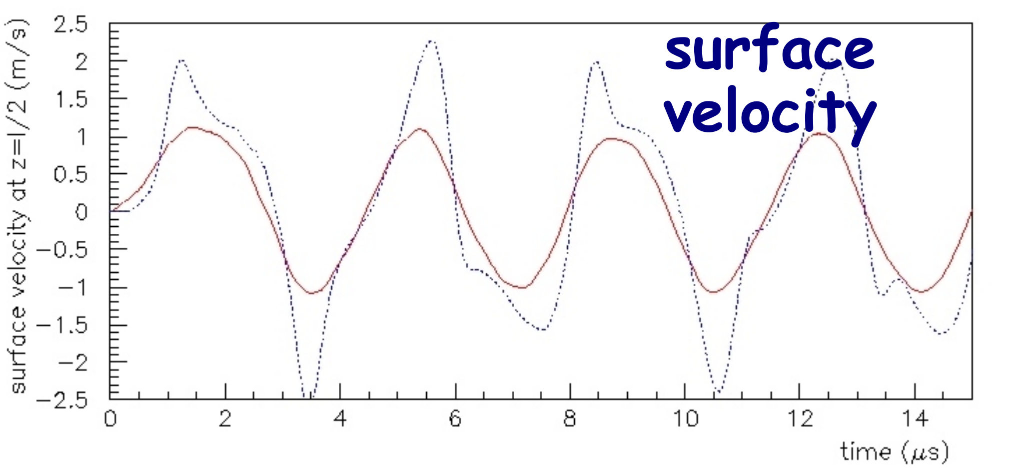
Neutrino Factory vs. 'current pulse – wire' test

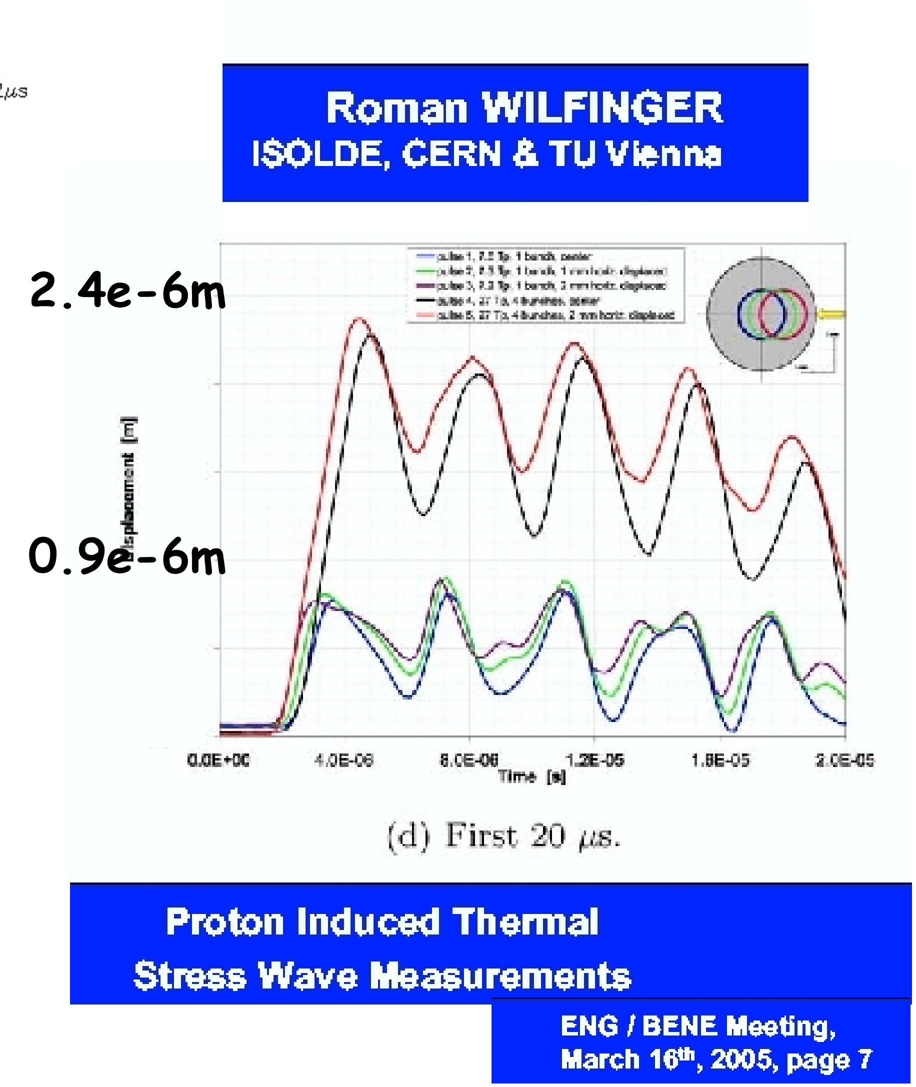


similar stress patterns

Test at the ISOLDE





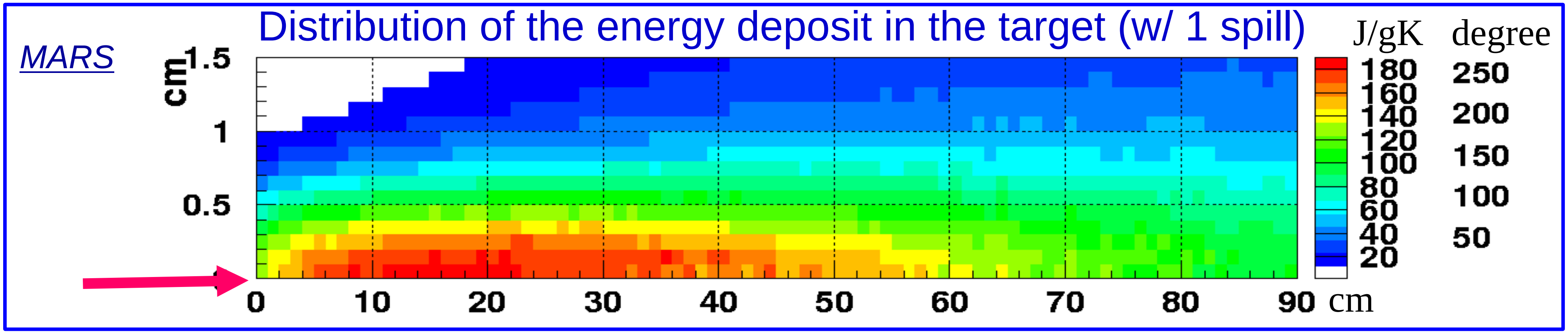


nice (initial) agreement with previous experiment!

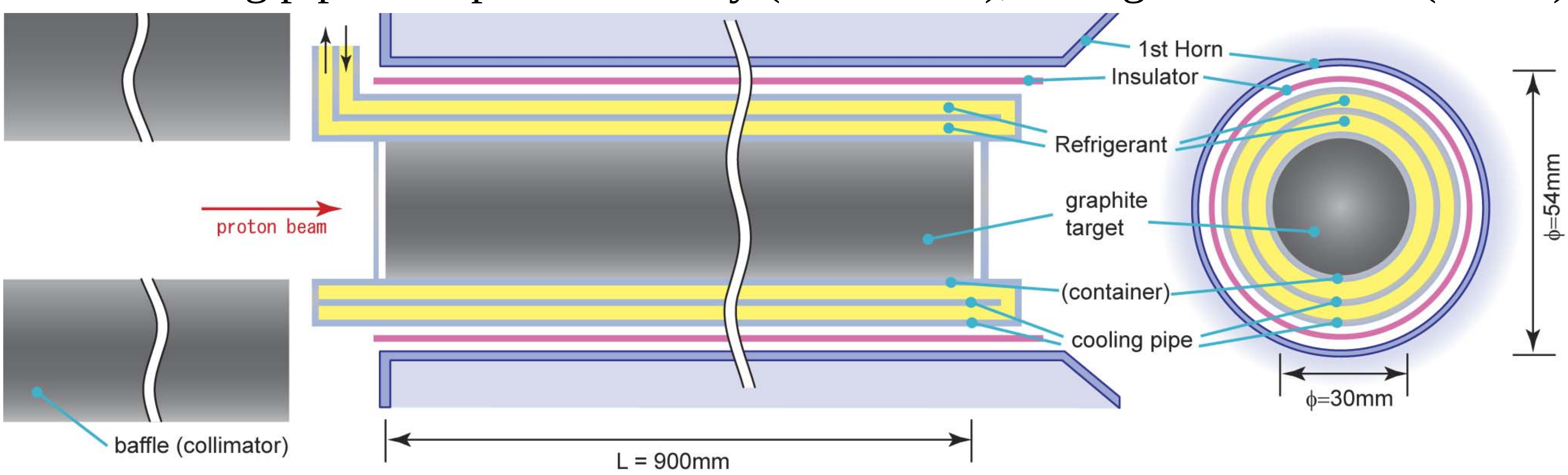
Chris Densham
UK NF Meeting
September 2005.

T2K target conceptual design

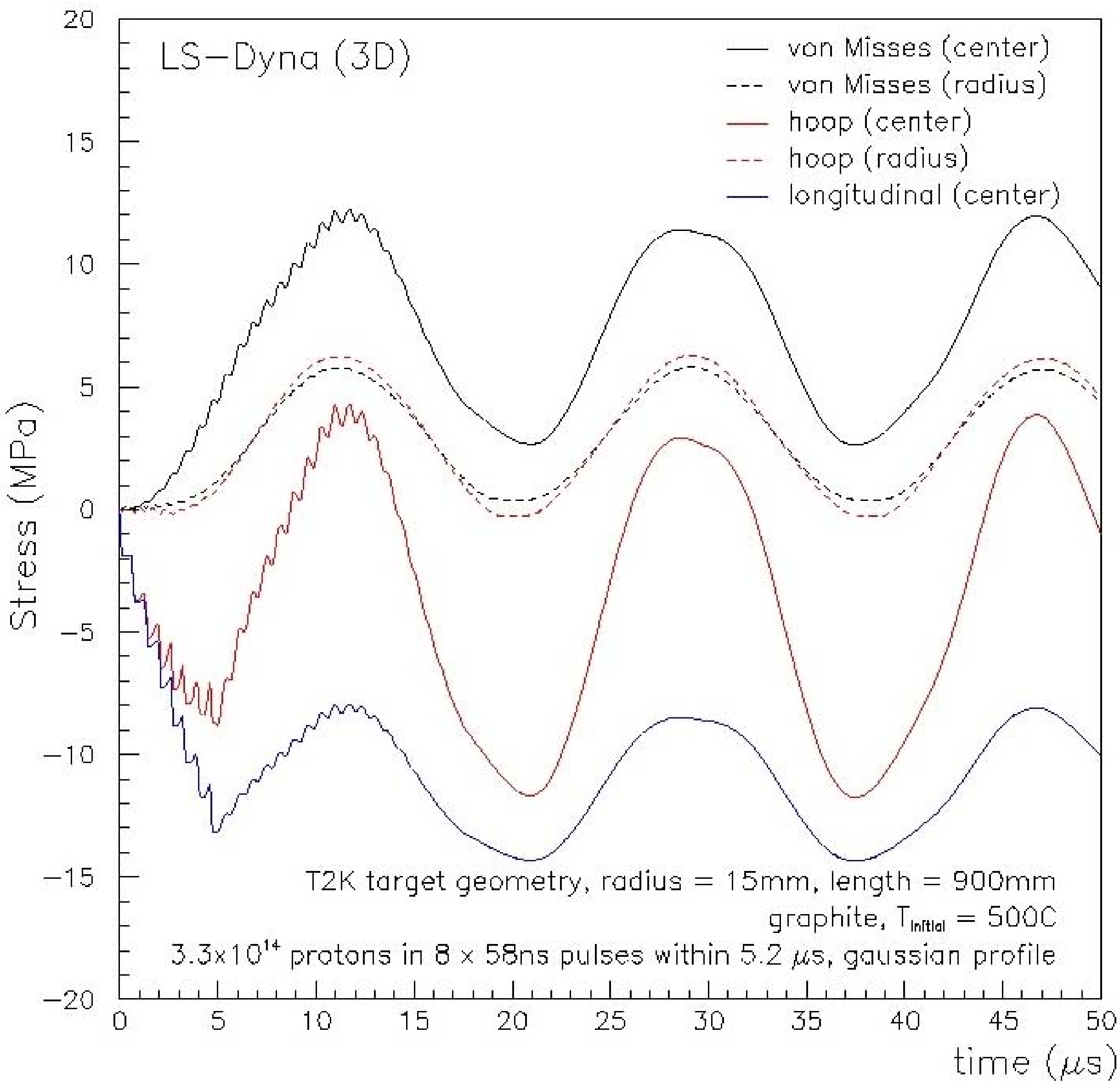
- Graphite Bar Target : r=15mm, L=900mm (2 interaction length)
  - Energy deposit … Total: 58kJ/spill, Max:186J/g → ΔT ≈ 200K



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

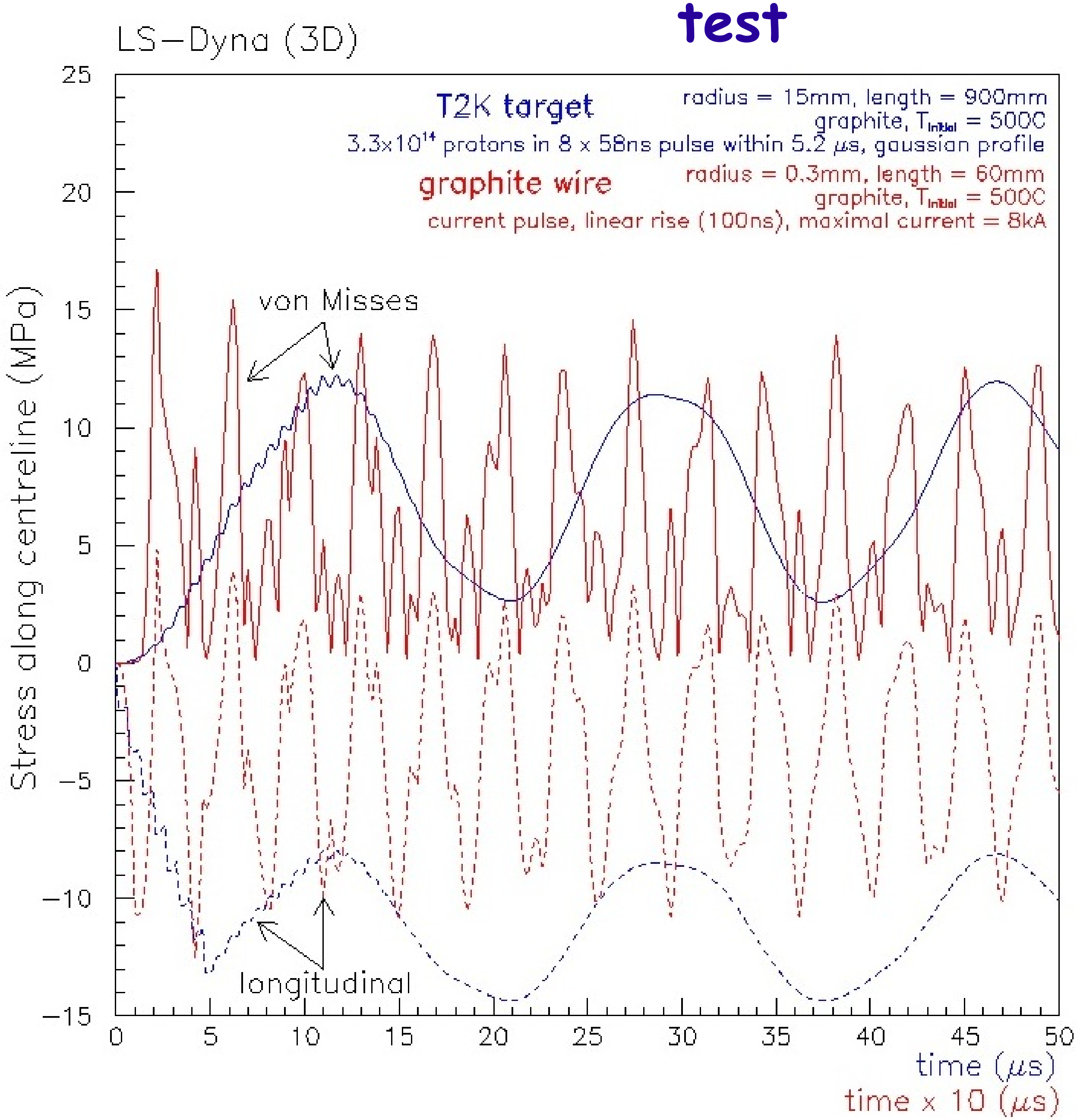


Stresses in T2K target



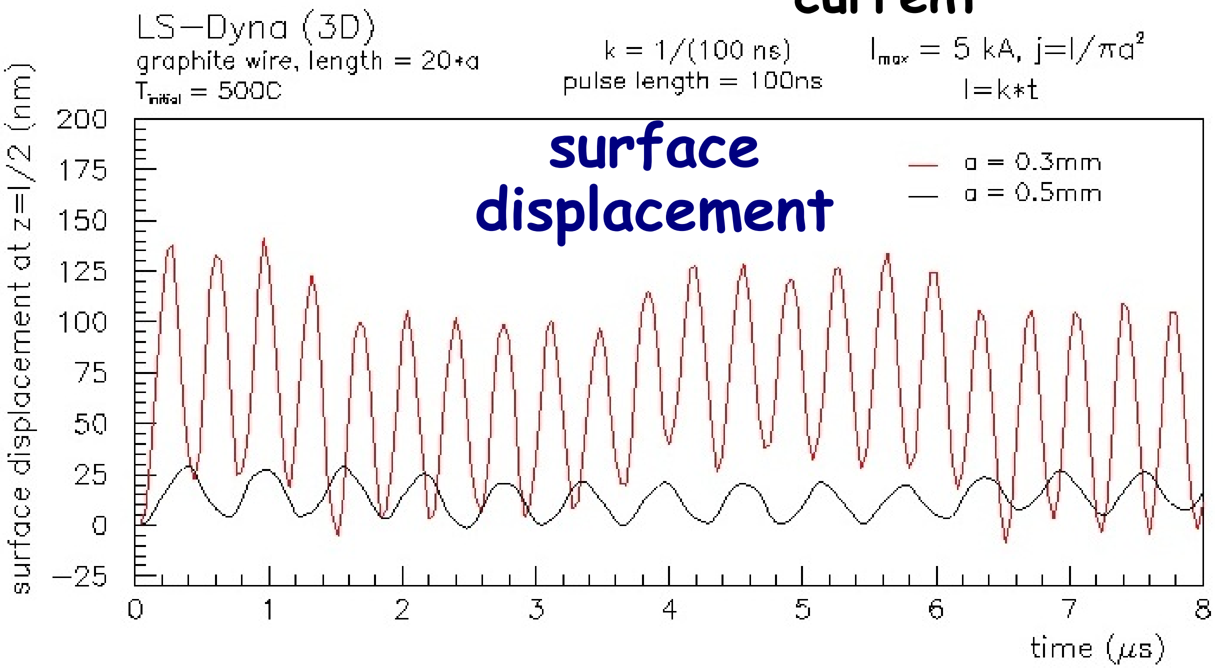
at the level of 10 MPa

T2K target vs. 'current pulse – wire' test

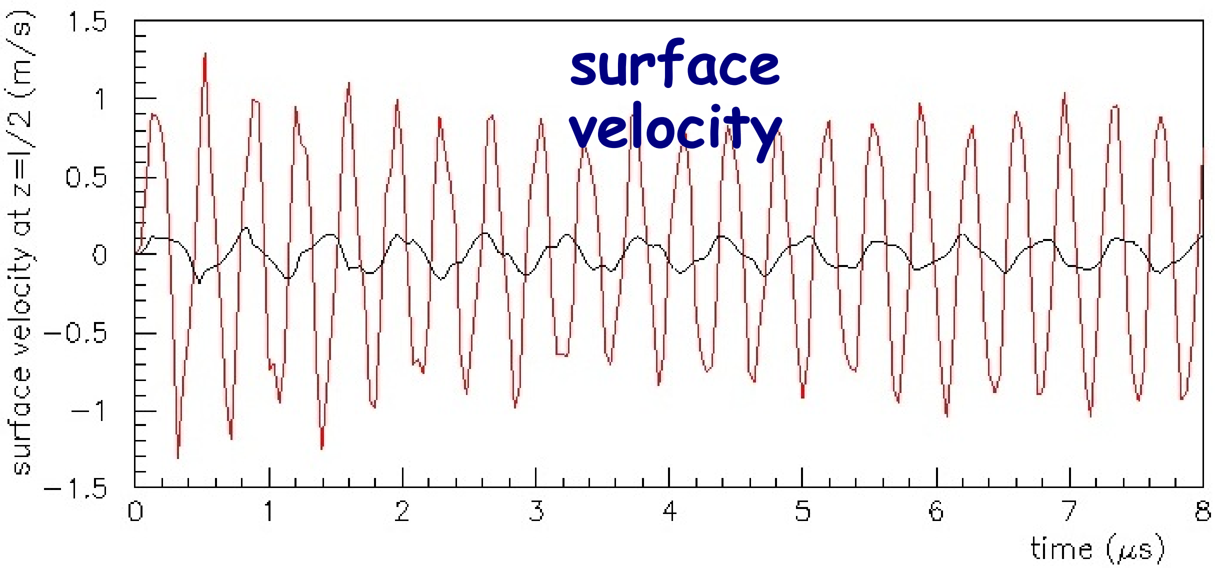


'similar' stress patterns

Pulse time profile - linear rise of the current



GRAPHITE WIRE



velocities (in all the cases) at the level of ~ 1m/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)

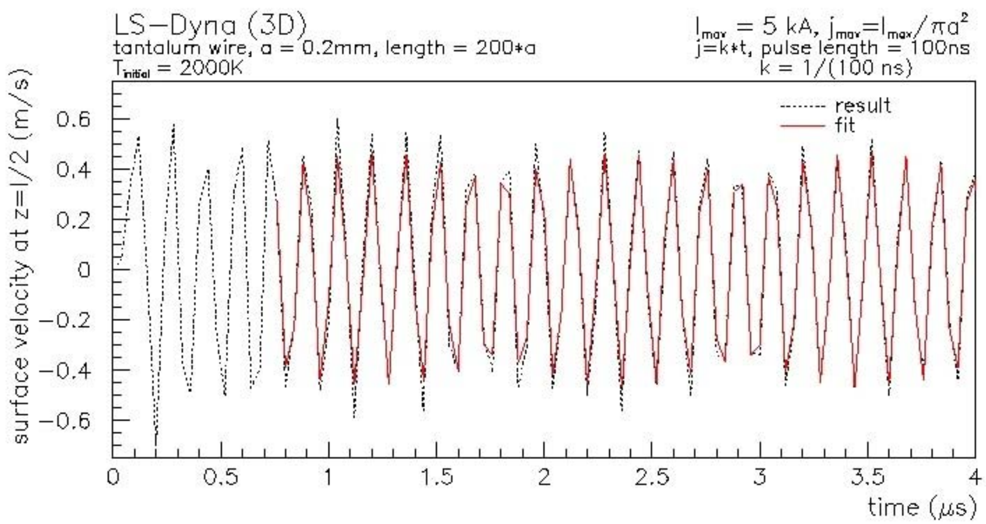
Table 2. Tantalum property values used as an input for LS-Dyna and obtained as a result of the fitting procedure (MINUIT) in the case of 8kA maximal current. Numbers in parantheses are estimated errors of the parameters (in the last digits).

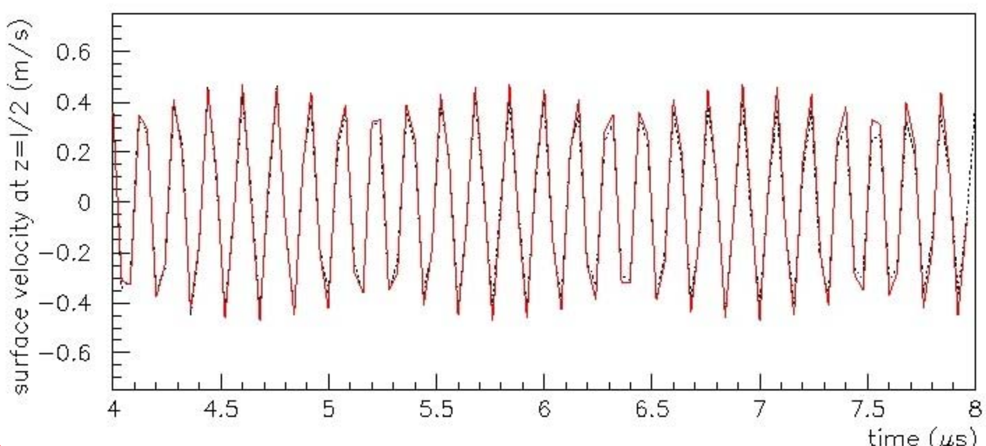
Par.	Property	LS-Dyna input	Case 1	Case 2
1	El. modulus, E [GPa]	144	136 (2)	155 (2)
2	CTE, α [10^{-6} m/m/K]	7.4	8.1 (5)	7.5 (2)
3	Temp. rise, ΔT	26-40	43 (3)	43 (1)
4	Poisson's ratio, ν	0.33	0.284 (3)	0.30 (1)
5	Density, ρ [g/cm^3]	16	16.05 (2)	16.18 (1)
6			0.852 (1)	0.800 (2)
7			0.42 (1)	0.42 (1)

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/ → Target Studies → Thermal Shock Simulations

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