Studies of solid high-power targets

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The target material exposed to the beam will be ~ 20 cm long and ~2 (or 1 or 3) cm in diameter.

- Rotating toroidal ring (operating at ~2000 K);
- Individual bars...
- Cooling: radiation
- The target is bombarded at up 50 Hz by a proton beam consisting of ~1 ns long bunches in a pulse of a few micro-s length.

- Energy density per pulse ~ 300 J/cc.

Beam: protons, 3 – 30 GeV

ISS baseline (April 2006): 4 MW, 10 GeV, 50 Hz, 3 bunches per pulse, 2 ns rms.
One of the main problems: Thermal Shock (Stress)

- In-beam lifetime/fatigue tests hardly possible
- Shock can be modelled: Finite Element Software (FES)
- Target surface motion can be measured for (every) beam pulse and used as an indication what’s happening inside the target (evaluation of the constitutive equations with the help of FES)
- Simulate the level of shock in the real target by passing a pulsed current through a very thin wire
- Lifetime/fatigue tests
- Measurements of the wire surface motion

FE simulations: prediction and interpretation of tests results
Simulations... as realistic as possible

High energy particle cascade calculations (MARS)

Energy deposition in solid target

Temperature rise in solid target

Input for thermal stress calculations (LS-DYNA)

MARS vs. HARP

Comparison between experimental data from HARP experiment and Monte Carlo calculations (MARS15) on pion production in proton-tantalum interactions will help to tune all the Neutrino Factory related calculations.

We are most interested in the HARP results for beam momentum of 12 GeV/c because this is closest value to the 'standard' beam energy (10 GeV) we use in UKNF simulations.

The agreement between MARS and HARP is relatively good.

Status of simulations of the current pulse - wire tests at RAL

Geometry

- 0.5mm diameter; 3cm long wire; supported at bottom, free at top

- Rise time: ~100 ns

- Flat Top: ~500-700 ns

Loads

- Current pulse: ~5-10 kA, exponential rise

The power supply planned for the test program can deliver up to 50kA and the pulse waveform has a rise time of about 200ns and a flat top of about 500ns. The shape of the pulse waveform is exponential \( I(t) = I_0 (1 - e^{-t/T}) \) with rise constant \( T_0 = 200 \text{ ns} \). Assuming that an electric field is instantaneously applied across the conductor of radius \( a \), and that current density \( J \) is radially symmetric about the axis of the conductor the corresponding diffusion equation can be obtained by using Maxwell’s equations. The solution of the diffusion equation for the case of an exponential rise in current density at \( t = 0 \) has the form:

\[
\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial t} \left( \frac{\rho}{\mu} \right) + \frac{\partial}{\partial r} \left( \frac{\rho}{\mu} \right)
\]

where \( \rho \) is the current density at \( r = a \), \( \mu \) is the electric field, and the corresponding Bessel functions of the first kind, \( J_0(x) \) and \( J_1(x) \) are the corresponding Bessel functions, \( r = 1/\mu \) with \( \mu \) being the permittivity of free space and \( n \) is the electrical conductivity.

- Energy density; temperature rise across the wire

- Lorentz force induced pressure wave

LS-DYNA simulations

Material model used in the analysis

- Temperature Dependent Bilinear Isotropic Model

- Uses 2 slopes (elastic, plastic) to represent the stress-strain curve

- Inputs: density, Young’s modulus, CTE, Poisson’s ratio, yield stress, ...

LS-DYNA input (estimate; especially for T > 1000K)

Problems with material data:

- Reliable data can be found for temperatures up to 1000K (but inconclusive);
- No data (practically) at high temperatures.
Comparison with existing experimental results

Tests at the ISOLDE
Tantalum Cylinder, 1x10 cm

LS-DYNA simulations

Violin modes (target bending,...)

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Roman WILFINGER
ISOLDE, CERN & TU Vienna

ENG / BENE Meeting, March 16th, 2005, page 7
**NuFact target**

Power = 4 MW, repetition rate = 50 Hz,
Beam energy = 6 GeV (parabolic distribution)
2 ns long bunches

Energy deposition from MARS

characteristic time (shock transit time) = characteristic length / speed of sound in material

**TUNGSTEN target**

operating at 2000 K

3 cm x 20 cm

Beam radius = Rod radius

Beams are equidistant.

Characterization time = characteristic length / speed of sound in material

**Stress reduction by choosing optimal pulse length**

Time between successive bunches [μs]
Comparison of the simulations results:
Stress in real target vs. stress in tungsten wire

Stress in 2 x 17 cm tungsten target (4 MW, 50 Hz, 6 GeV)

Stress in tungsten wire (7.5 kA, 800 ns long pulse)
**Stress in real target vs. stress in tungsten wire**

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

**Target:**
- repetition rate = 50 Hz;
- beam energy = 6 GeV;
- beam radius = target radius;
- beam offset = 0.5*target radius;
- 3 x 2 ns long bunches;
- pulse length = 15 μs (1 cm x 17 cm), 20 μs (2 cm x 17 cm), 25 μs (3 cm x 20 cm);
- energy deposition = MARS

** ls-dyna **

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

* - Von Mises stress
Stress in real target vs. stress in tungsten wire

Wire test results: Number of pulses to failure \([x10^6]\)

- new \(\rightarrow 10.0\) (nb) \([\text{Max temp} = 1900K]\) + 2.0 (nb) \([\text{Max temp} = 1300K]\)

The aim to observe any surface damage which might indicate the presence of thermal fatigue.

Results: inconclusive

SEM imaging

BegbrokeNano, Oxford Materials Characterisation Services

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Energy dispersive analysis

Spectrum 1

Full Scale 349 cts Cursor: 10.571 (3 cts)
VISAR wire tests

Velocity Interferometry System for Any Reflector
Surface displacements \( \sim 100 \) nm; velocity \( \sim 1 \) m/s

If we measure this...
... we will know this.
In-beam VISAR tests (ISIS, for example)

'optimal target dimensions'

Peak Stress (ISIS, 100% beam) = 287 MPa

Peak Stress (Neutrino Factory, 4 MW, 2 cm diameter, optimised pulse length) ≈ 300 MPa

FLUKA results on target activation for full ISIS beam power (maybe we will have only 10% of this value in so-called 10% beam dump area)

Additional focusing will be needed to achieve the required energy density
Summary

Solid target for the Neutrino Factory:

- Shock waves in candidate materials (Ta, W, C) characterised within limitations of material knowledge
- Effects of beam pulse length and multiple bunches/pulse understood (stress reduction by choosing optimal macro-pulse length)

Test of wire:

- First estimate of the lifetime of tungsten NuFact target
- VISAR is purchased to measure surface velocity of wire and compare results with LS-DYNA calculations (this will help to extract high temperature material data from experiment)

MERIT:

- We started taking part in the analysis of the data

Important:

- Whichever the final choice of the NuFact target (liquid/solid) we will have the solids exposed to the high power beam