OVERVIEW OF SOLID TARGET STUDIES FOR A NEUTRINO FACTORY*

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Abstract

The UK programme of high power target developments for a Neutrino Factory is centred on the study of high-Z materials (tungsten, tantalum). A description of lifetime shock tests on candidate materials is given as part of the research into a solid target solution. A fast high current pulse is applied to a thin wire of the sample material and the lifetime measured from the number of pulses before failure. These measurements are made at temperatures up to 2000 K. The stress on the wire is calculated using the LS-DYNA code and compared to the stress expected in the real Neutrino Factory target. It has been found that tantalum is too weak at these temperatures but a tungsten wire has reached over 26 million pulses (equivalent to more than ten years of operation at the Neutrino Factory). Measurements of the surface velocity of the wire using a single point Laser Doppler Vibrometer are in progress, which, combined with LS-DYNA modelling, will allow the evaluation of the constitutive equations of the material. An account is given of the optimisation of secondary pion production and capture in a Neutrino Factory and of the latest solid target engineering ideas.

INTRODUCTION

There are proposals [1] to build a Neutrino Factory in the US, Europe or Japan, in order to understand some of the basic properties of neutrinos. The Neutrino Factory will consist of a proton driver accelerator delivering short pulses of beam to a heavy metal target at GeV energies at up to ~ 50 Hz, with a mean power of ~ 4 MW. As a result of the beam interactions with the target, copious numbers of pions will be produced, as well as other secondary products. The pions decay to muons which are cooled and accelerated to tens of GeV. The muons then circulate in a large storage/decay ring with long straight sections where they decay to neutrinos. The neutrinos come off in a narrow cone along the axis of the muon beam and the arms of the decay ring are directed at suitable long baseline neutrino detectors thousands of kilometres away. Extensive Neutrino Factory R&D is underway around the world on a number of fronts. Target R&D is particularly important because it is a potential showstopper. The UK programme of high power target developments for a Neutrino Factory is centred on the study of high-Z solid materials (tungsten, tantalum).

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THE NEUTRINO FACTORY TARGET

The Neutrino Factory target is not a stopping target. It dissipates a mean power of about 700 kW in a $2-3$ cm diameter bar of tungsten about 20 cm long. The remaining 3.3 MW of beam is absorbed in a beam dump and surrounding shielding. The energy density averaged over the target volume is ~ 300 J/cm^3 per pulse (assuming a 2 cm diameter target). Tungsten and tantalum are candidate materials since they have high Z values, are refractory and are relatively strong. Also, these metals have been shown to be extremely resistant to radiation damage effects in the ISIS target [2] (up to 12 dpa), similar to the Neutrino Factory target after 10 years of operation.

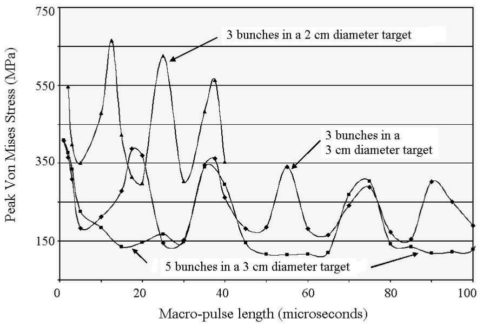

Figure 1: Variation of the peak stress versus macro-pulse length in 2 and 3 cm diameter targets, with 3 and 5 equally spaced bunches (each 2 ns long).

The magnitude of the thermal stress on the target, which is the main issue for solid targets, is governed by the magnitude and rate of change of the energy density (or temperature rise). With the Neutrino Factory there is a requirement for short micro-pulses of $1-2$ ns length within a macro-pulse of a few micro-seconds. MARS [3] calculations have been made of the beam hitting tantalum and tungsten targets to assess the distribution of energy deposition, and to calculate the corresponding temperature rise. The peak temperature rise is about 200 K, in which a parabolic transverse beam current distribution is assumed, where the beam radius and the target radius are equal.

The temperature rises are then used in the commercial package LS-DYNA [4] to calculate the dynamic stresses in the target. As can be seen in Fig. 1, the equivalent Von Mises stress can reach several hundred MPa, depending on the target diameter, the number of bunches (an odd number of bunches is preferred for the muon accelerator) and the pulse length. Also, we can see that by a clever choice of pulse length (assuming equally spaced bunches) we will be able to reduce the stress on the target by a factor of two or more. When discussing a solid tungsten (or tantalum) bar as a choice for a Neutrino Factory target we do not mean to have a single bar; this would be impossible if we keep in mind the energy density, repetition rate and temperature rise per pulse. In our case, the individual bar concept assumes that we have hundreds of bars, and that a 'new' bar would be presented for each beam pulse and then cooled by radiation until the next turn. We have studied different possible designs [5] but the most interesting one is a spokeless wheel concept [6] in which targets are mounted on a wheel which will rotate perpendicularly to the beam direction. In this case, around 150 bars (spaced apart by 100 mm) will form an outer rim that is connected to an inner 'guide/driver' rim of the wheel. The outer diameter will be 5 m, giving a rim speed of 5 m/s. In this concept, the magnetic solenoid magnet used for pion capture has to be split into two halves (Helmholtz coil). This could affect the captured pion yield, but calculations [7] have shown that the capture rate is very similar to the corresponding results for an alternative mercury jet target. These simulations have been done by calculating the pion production rate in the target using MARS and then transporting the captured pions and muons to the end of the front-end using ICOOL code [8]. A lot of work is still required to develop this new engineering idea into a full concept, for example to examine the effect of eddy currents on the wheel, to estimate the forces that the support structure will need to withstand, etc. However, the first step in this direction is to determine the lifetime of tungsten and tantalum as potential Neutrino Factory targets.

LIFETIME SHOCK TESTS

In order to make thermal shock measurements on tantalum and tungsten samples it would be best to do a lifetime test on a real size target in a proton beam over several years. However, beams of this power are not readily available for any length of time. Hence, it was decided to pass a fast, high current pulse through a thin wire made of the candidate materials. Coupled with the use of codes (such as LS-DYNA) to model the thermal shock in the wire it will be possible to find the constitutive equations of state of the material under dynamic conditions. Using the correct constitutive equations for tungsten at high temperatures will allow a better computation of the thermal stresses in a real target of various geometries.

A thin wire is necessary to allow the current to diffuse into the centre of the wire in a sufficiently short time for the shock to be effective. For tantalum and tungsten, the wire cannot be greater than ~ 0.75 mm in diameter. A power supply for the ISIS [9] kicker magnets is being used, supplying a maximum of 60 kV and 9200 A at up to 50 Hz in a pulse which rises in 100 ns and is ~ 800 ns long. The wires, of $3-5$ cm length, are supported in a vacuum chamber to avoid oxidation. One end of the wire is firmly clamped, while the other end is allowed to expand freely through a pair of graphite conductors that lightly clamp the wire (see Fig. 2). The wire is operated at temperatures from 300 to 2500 K by adjusting the pulse repetition rate . The wire temperature is measured by a manually operated optical pyrometer.

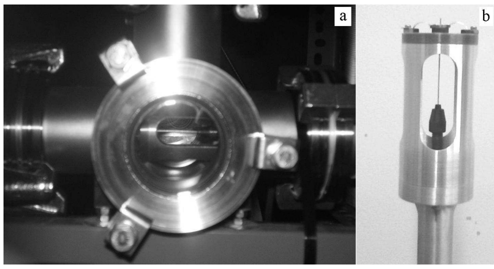

Figure 2: Photograph of a 0.75 mm diameter tungsten wire during current pulse tests (a) and illustration of wire clamping (b)

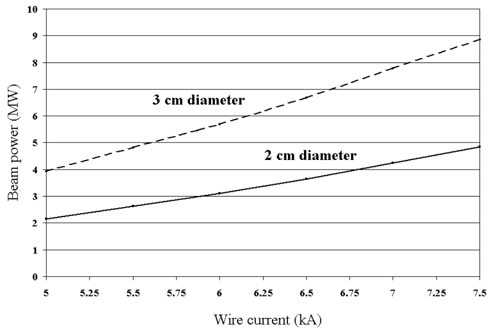

Figure 3: Beam power into a target of 2 and 3 cm diameter versus wire current for the same peak stress (at the initial temperature of 2000 K). Using a proton beam requires that we have 3 bunches at optimum spacing to minimise the stress in the target.

The stress in the wire is calculated including both temperature and the Lorenz force from the magnetic field produced by the current passing through it. It was shown that Von Mises stress in the wire reaches similar values to the beam-target case, hence it is possible to relate the current in the wire that produces the same peak stress as the beam in the full sized target (see Fig. 3). The illustration of the results of a number of tests with 0.5 mm diameter tungsten wires is shown in Table 1. The tantalum was too weak at temperatures of 1400 K or more. The tungsten was much more robust and the wire only failed when operated at temperatures well over 2000 K. As can be seen in Table 1, in some cases the wire(s) survived tens of millions of pulses, for example 26.4 million pulses in the high temperature regime at the equivalent beam power of 4 MW in a 2 cm diameter target. This corresponds to the target lifetime at the Neutrino Factory of more than 10 years (more than 20 years for a 3 cm diameter target). The situation is even better at lower temperature (see the last row in Table 1).

Table 1: Results of tungsten wire tests. The 'Beam Power' column shows the equivalent beam power for a full size target of 2(3) cm diameter for the same stress in the test wire. These results assume a parabolic beam distribution, 3 bunches per macro-pulse of $20\mu s$, and a beam diameter equal to the target diameter.

Current (A)	**Temperature (K)**	**No. of pulses (*10^6)**	**Beam Power (MW)**	**Target Diameter (cm)**
5560	1900	4.2	2.7 (5.0)	2 (3)
5840	2050	9.0	3.0 (5.4)	2 (3)
6200	2000	10.1	3.3 (6.1)	2 (3)
6520	1940	26.4	4.1 (8.7)	2 (3)
4720	1840	54.4	2.1 (4.5)	2 (3)
6480	600	80.8	4.0 (8.6)	2 (3)

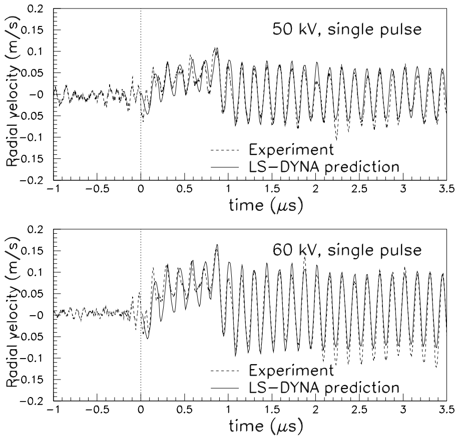

Figure 4: (Top) Radial velocity of the 0.5 mm diameter tungsten wire as a function of time for 50 kV peak voltage; (Bottom) Radial velocity of the 0.5 mm diameter tungsten wire as a function of time for 60 kV peak voltage. The full lines represent the results of LS-DYNA simulations.

LDV MEASUREMENTS

A single point Laser Doppler Vibrometer (LDV) from Polytec [10] has been used for measurements of the wire's longitudinal and radial surface oscillations. The main goal of these measurements is to measure tungsten properties as a function of applied stress and temperature, as well as to check the modelling results and, hopefully, confirm the results of lifetime tests. The measurement system consists of the optical sensor head OFV-534 which is connected to the OFV-5000 vibrometer controller. The sensor head consists of a laser source, an interferometer and a photo-detector.

We have performed an extensive set of measurements of the surface displacement and velocity of tungsten wires at high temperature and high stress [11]. A characteristic set of the results is shown in Fig. 4. The top plot in Fig. 4 shows the radial velocity of the 0.5 mm diameter tungsten wire as a function of time for 50 kV peak voltage while the bottom plot shows the same but for 60 kV peak voltage. The full lines represent the results of LS-DYNA simulations. The time scale starts at $t < 0$ in order to illustrate the signal to noise ratio. At $t = 0$ the current pulse arrives and the wire starts first to contract (because the magnetic pressure effect is dominant at the beginning of the pulse) and then to expand. As can be seen, the LS-DYNA result (full line) nicely follows the experimental data. All the other experimental data agree very well with modelling results [11] which means that the results of the lifetime tests have been confirmed.

CONCLUSIONS

Our lifetime shock tests demonstrated that our original material candidate, tantalum, is not strong enough at high temperatures, but a tungsten wire has reached over 26 million pulses, equivalent to more than ten years of operation at the Neutrino Factory. Measurements of the surface oscillations of the wire using a single point Laser Doppler Vibrometer are in progress, and the first results fully confirm our modelling results. These measurements, combined with additional LS-DYNA modelling, will allow the evaluation of the constitutive equations of the material under conditions expected at the Neutrino Factory.

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