MATERIAL TESTING WITH ELECTRON BEAMS FOR NEUTRINO FACTORY TARGETS

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Abstract

Solid targets for a 4 MW neutrino factory are required to withstand the pulsed power deposition of up to 1 MW (time averaged), at repetition rates of 10 to 100 Hz. Instantaneous energy depositions of over 100 J per gram are possible and the consequent temperature jump experienced by the target induces high levels of stress. Somewhat limited experience is available for the behaviour of materials under these extreme conditions, and clearly the lifetime of target material in constant shock is an important issue. To address this, tests of target materials are planned which reproduce the order of the peak energy density and most significantly, will provide information on cycle lifetime. By using high power, swept beams of electrons from a CW welding machine the power densities and repetition rates expected in a neutrino factory can be reproduced at modest cost.

1 INTRODUCTION

Neutrino Factories have been proposed in Europe, Asia and North America, and designs based on proton linear accelerators and synchrotrons for the driver have been produced with beam powers in the 1-4 MW range and with energies of a few to 10s of GeV [1].

The target of a neutrino factory provides a source of pions which must be efficiently captured into the following accelerating structures. To maximise the capture and efficiency of production, the target is required to be as small as possible, and is surrounded by as little material as possible, thus avoiding re-absorption of the pions. These conditions remove the opportunity for the application of more traditional cooling techniques used on neutron spallation targets for example [2]. However, schemes involving liquid metal jet targets have been suggested, and are being evaluated. Alternatively, large amounts of average power can also be removed very efficiently by thermal radiation from a hot refractory metal target, such as tantalum [3].

2 TARGET ISSUES

The main issue with the target is due to the pulsed nature of the beam. The temperature rise generated by the driver beam interacting with the target depends on the average beam power, and on the pulse repetition rate of the driver. Neutrino factory drivers have been designed to operate at a few to 100 Hz. The most serious difficulties are encountered at the lower repetition rates, since the power is deposited in a few ns with each pulse. The resulting energy density can lead to temperature jumps of 1000 degrees. Moving the target to provide fresh material to the beam avoids the problem of the target melting, but the temperature rise itself generates immense stresses that can surpass the strength of the target material, and lead to a reduced lifetime through fatigue.

Candidate target materials can be tested on-line at accelerators (e.g. at CERN or BNL) but only at low average power, and so the effects of the stress cycling cannot be investigated.

3 PROPOSED TEST

To address the problem of simulating the large number of stress cycles that the target is expected to withstand, it has been proposed to use a low energy high current electron machine. High power electron beams are available at a number of laboratories. At the Welding Institute in Cambridge, UK, a number of high power (>100 kW) CW machines are available [4]. These normally provide large scale welding facilities, but are flexible enough to be adapted to the experiments described here.

The range of a 100 keV electron, for example, spans the range (approximately) 0.025-0.035 g/cm2 for Copper to Lead [5]. This corresponds to a range of 15 to 21 microns at the density of tantalum (16.6 g/cm^3). Using this as a guide to the nominal range, an electron beam of 100 keV energy has a range of nominally 20 microns in tantalum. The beam, focused to a diameter of 1 mm in diameter, is swept across the face of a thin foil strip at a speed of 4 mm per micro-second. If the beam power is ~100 kW, then the energy deposition is equivalent to ~75 J/g (average). By decreasing the beam energy and power, or by defocusing the electron beam, other levels of energy density can then be produced. After scanning, the beam is parked for 10 ms before repeating the process. During this interval the foil cools through (mainly) thermal radiation simulating the effect of the neutrino factory target. Since the proposed solid neutrino factor target is distributed [3] each piece of that target is subject to a beam pulse at a rate somewhat less than the full frequency of the driver beam, by, for example a factor of (e.g.) 10. For a 10/100 Hz driver, there are almost 1/10 million beam pulses per day, and some (e.g.) 0.1/1 million cycles per piece of the target. In this case, the repetition rate of the electron beam can simulate at least 10 days of operation of the neutrino factory in a single day.

The tests are made more efficient by subjecting more than one foil to each scan of the electron beam. The foils can also be subjected to additional static stresses which simulate some of the effects on the target (a moving conductor) in the environment of the strong magnetic field gradient of the pion capture system (20T Solenoid). During the tests we intend to measure the target temperature in real time using a fast spectrometer.

4 ELECTRON BEAM ENERGY DEPOSITION

The range of a low energy electron in matter is generally measured by passing a pencil beam through a set of thin foils and detecting the attenuation of the beam as a function of the number of foils [5]. In order to have a reasonable idea of the distribution of the energy deposition of the electron, we have constructed a simple Monte Carlo model: Assuming that the deposition is the result of a continuous, Bethe-Bloch slowing down of the particle:

$$\frac{dE}{dx} \propto -\frac{1}{E}$$

and also of elastic scattering of the electron by the nuclear atom at small radii (to allow for screening), a reasonable approximation can be made to experimental data by a Monte-Carlo technique, Figures 1 and 2.

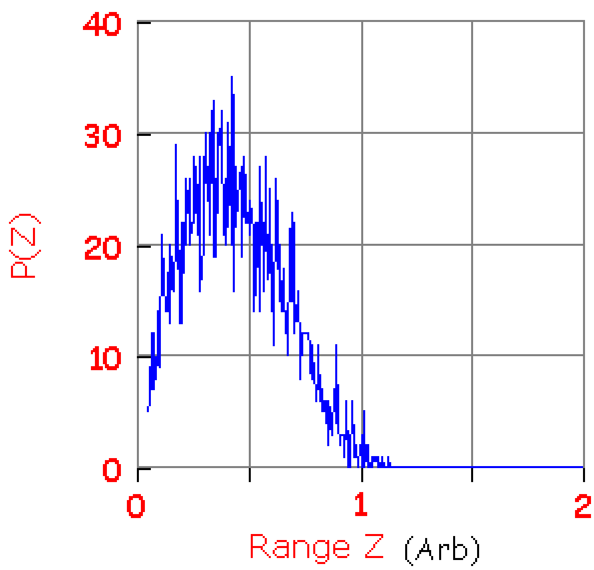

Figure1. Monte Carlo modelling of the Energy Deposition of a beam of 100 keV electrons in Tantalum.

Our conclusion is that the electrons will deposit their energy over their range (nominally 20 microns) predominantly at half that distance because of scattering. Such calculations give a reasonable agreement with the shape of transmission measurements in the literature [6].

5 PREDICTED STRESS LEVELS

Finite element calculations of the shock waves generated in a neutrino factory target and in foils subject to electron beams have been performed using the general purpose FEA code ANSYS.

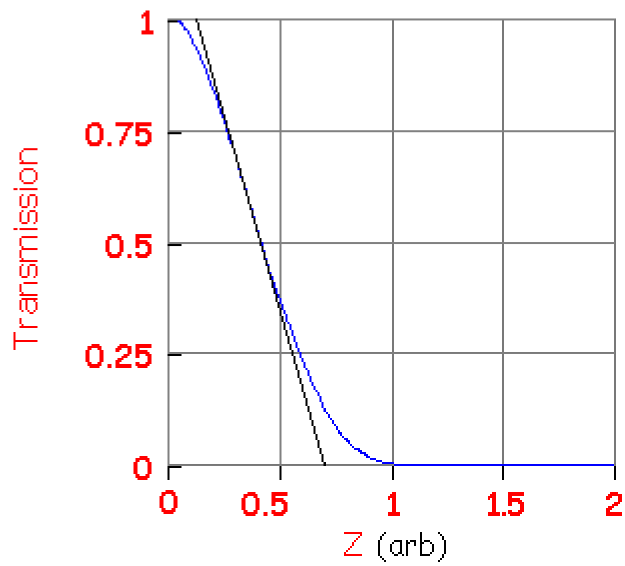

Figure 2. As Fig. 1, the resulting transmission of electrons through a thickness of material (curve). The straight line is an extrapolation of the linear part of the curve.

For a proton driver frequency of 10 Hz depositing a mean power of 1 MW over a 20 cm length of 2 cm diameter tantalum cylinder, the power input per pulse is 96 J/g and the expected stress magnitude is 3500 MPa assuming linear elastic properties although clearly the material would be plastic at these pressures. Like all metals, the strength of tantalum reduces considerably with increasing temperature, and a tensile strength at 2000^{o}C of 12 MPa is expected (dropping from ~400 MPa at room temperature). At a temperature of over 2/3 of the melting point, it is probable that creep will be the main concern rather than outright failure. Such considerations indicate a maximum permissible stress of around 0.6 MPa at a temperature of 2000^{o}C This criterion is a twentieth of that given above for the tensile strength.

In this case, one would expect the proposed target to be severely damaged by such a strong shock wave as would be developed in a neutrino factory target. However, modelling of other targets subject to intense pulsed powers (e.g. the FNAL Antiproton Source) von Mises stresses oscillating around 1600 MPa for tungsten and 2700 MPa for nickel were calculated. From the fact that the FNAL target has survived for a significant time, it would appear possible for solid targets to have a useful lifetime at such high proton beam intensities, notwithstanding the extremely high pressures generated within them. However, it is difficult to calculate the expected lifetime for such a neutrino factory target based on the very limited relevant experience reported world wide.

6 CONCLUSION

The important issue of target lifetime can be tested in a significant manner using high power, fast switched electron beams. Stress levels equivalent to those expected at the neutrino factory can be generated, albeit in small volumes. Significantly, large numbers of stress cycles can be generated in a cost effective manner. The effects of radiation damage on the material structure will not be present in these tests, but nevertheless, the proposed measurements will provide an optimistic limit into the behaviour of materials under these cyclic stress conditions.

7 REFERENCES

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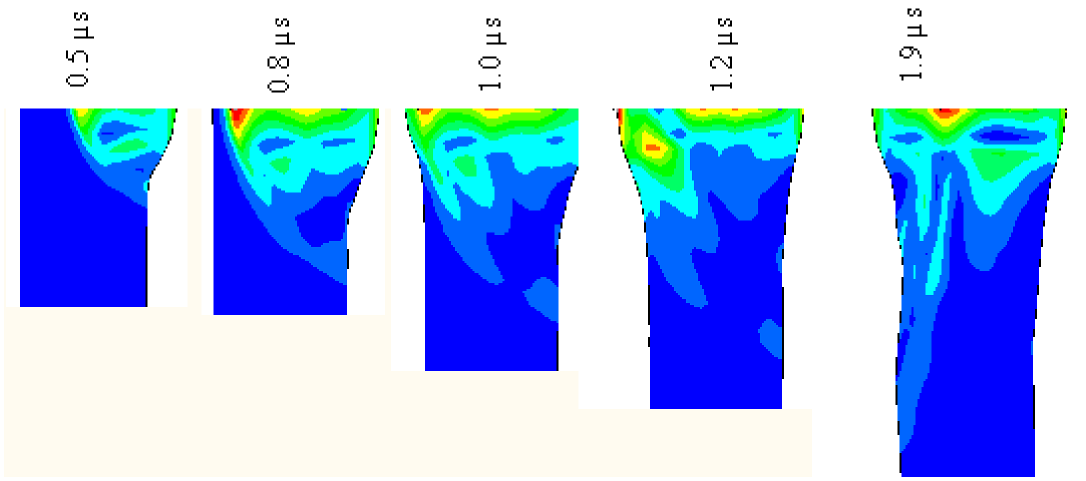

Figure 3. Stress pattern sequence produced in thin tantalum foil due to the passage of a swept electron beam over the width (travelling from the bottom of the foil to the top).

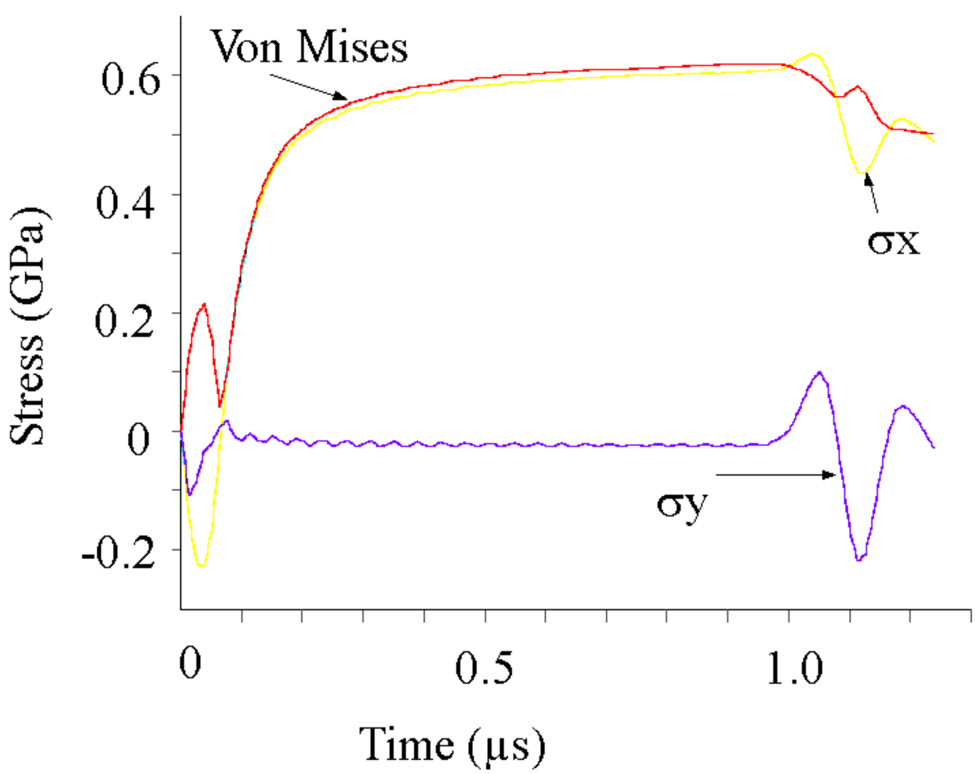

Figure 4. Surface stress levels in the foils as a function of time.

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