Plans for Electron Beam Stress Testing of Target Materials
suitable for a Neutrino factory

Paul Drumm, Chris Densham

Introduction

The suggestion of a radiation cooled target for a neutrino factory was made shortly after the first NuFact workshop as a means of dissipating large amounts of average power and sustaining large temperature rises [1]. The suggestion was made as an alternative to the proposed water cooled rotating band and liquid metal jet targets which were believed to have significant practical difficulties. In the present case, the target, in the form of a toroid with the beam entering on a tangent is made to rotate and can be several metres in circumference providing a large volume with which to absorb the deposited beam power. At 2 GeV approximately 25% of the 4 MW beam power is deposited in the target volume (nominally 2 cm diameter and 20 cm long), which, depending on the repetition rate of the proton beam (in the limits of 15-100 Hz) leads to temperature increases per pulse of between 400 and 1000 degrees C. The target is allowed to maintain a high temperature in order to benefit from the $T^4$ radiation cooling law. Clearly, the higher the repetition rate of the beam, the lower the temperature rise experienced by the target, and the higher is the scope to increase the beam power. Fresh target material is presented to the beam at each pulse by virtue of the rotation and each piece of the target sees approximately 1% of the average beam power (~100kW).

Because of the high operating temperature refractory metals and alloys are seen as the most likely candidates of choice for such a target. These include the pure metals tantalum or tungsten, alloys of tungsten/rhenium, and low creep alloys e.g. Astar 811C (Ta-8W-1Re-0.7Hf-0.025C), Ta-10W or T-222 (Ta-9.6W-2.4Hf-0.01C). Since some experience has been gained at RAL with the use of tantalum as a target material, this has been used as the baseline material in studies so far.

The temperature rises in the target are of major concern from the point of view of the stresses induced and the consequent effect on the target lifetime. Since the energy from the beam is deposited in a short time (1 ns) much less than the relaxation time of the material (e.g. speed of sound in tantalum ~3.4 mm/µs, and the time to cross a 2 cm diameter is ~ 6 µs), the temperature jump causes the material to experience a pressure shock that can reach levels which would be expected to fracture the target. The situation of the target is somewhat different from a statically loaded sample in the laboratory, since the shock exists for a short time (providing some damping mechanism can dissipate the energy) and is at an elevated temperature (which may help). Information is rather poor concerning fatigue of metals at high temperature and under shock conditions. Some experience of high energy density targets is available at CERN and at FNAL for antiproton targets which is somewhat conflicting and gives cause for both pessimism and optimism. Beam tests for a neutrino target have been proposed both at CERN and at Brookhaven but will be at a very low repetition rate compared to that envisaged in the NF. The proposal expounded here aims to address the issue of yield strength under shock conditions and target lifetime.
Experience at ISOLDE

ISOLDE target containers are made from tantalum and heated to temperatures of the order of 2600 Kelvin. They are held in vacuum inside an aluminium can (target unit). The entrance window of the tantalum target container is a good approximation to a NF target. Experience is that the target units fail after about 2 weeks of running at 1 Hz operation. The mode of failure is usually associated with non-metallic seals used on the target units, however, the target containers themselves have shown signs of grain growth and fracture after such times. Since the circumstances of the operation of the target container are not well controlled (there is no direct temperature measurement for instance), it is not possible to ascribe a cause for this phenomena. On the other hand, the pessimistic view would be that the life time of the target is of the order of two weeks, which would imply that solid targets can be used but would need to be replaced frequently.

Experience at CERN and FNAL

At the FNAL Antiproton Source target discs are reported to have withstood pulsed power densities of 200, 600 and 600 J/g for tungsten, copper and nickel respectively, with a pulse length of 1.6 µs and beam size of σ = 0.1 - 0.2 mm, and at least the tungsten target in the range of $10^5 - 10^6$ pulses. Stress waves of magnitude 2800 MPa, 3400 MPa and 3600 MPa respectively for these cases would be expected, assuming linear elastic properties (although the material would be expected to be in the plastic region).

Shock Wave Analysis

Finite element calculations of the shock waves generated in the proposed target ring have been performed using the general purpose FEA code ANSYS version 5.5.

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°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°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, for the FNAL conditions noted above a 2D axially-symmetric model was generated for a section through one Antiproton Source target disc, with the beam traversing a chord. ANSYS calculated von Mises stresses were somewhat less than those expected, oscillating around 1600 MPa for tungsten and 2700 MPa for nickel with the above heat inputs. The peak
stress was located on the beam axis, dropping off by a factor of 5-10 at 3 mm from the beam axis. 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.

Proposed Experiment and the Aims

The opportunity is presented to make use of high power electron beam welding equipment at The Welding Institute (TWI) in Cambridge. A number of machines are available, characterised by beam energies of 150 keV and power levels of 100 kW. At this beam energy the penetration depth of the electrons is quite small (~100 µm) in contrast to the actual NF target (20 cm). However, in a small volume, the energy density can be comparable (~38 J/g). The electron beams are operated in continuous mode (due to cathode heating times), but are capable of being rapidly deflected across a sample, providing us with the means of depositing energy in a short time (using sweep speeds of up to 4 mm/µs) compared to the propagation of sound (~3.4 mm/µs). Hence shock waves can be generated. The effect of such a beam scanned across a strip of tantalum has been modelled using ANSYS, and has been calculated to generate a stress of 522 MPa with a temperature jump of 342°C.

A further advantage comes from the high rate at which samples can be repeatedly subject to a shock which is of the order of 100 Hz, approximately 100 times faster than for the NF.

Initial Test

An initial feasibility test consisting of up to 24 hours of beam time is foreseen to demonstrate the behaviour of tantalum under shock heating by the electron beam. Visual observation and simple diagnostics would be envisaged for these first tests (Simple diagnostics would involve the use of an optical pyrometer and streak video camera to record temperature and state of the samples).

The first test would consider a few thin foil held in a static frame over which the beam is scanned. The foils would be held vertically and would be of different lengths to simulate various static loads. The electron beam would be repeatedly scanned across the faces of the foils at a frequency of 100 Hz. The beam profile would also be monitored periodically to establish consistent conditions applied.

The test would consist of monitoring the temperature and state of the foils for various numbers of beam strikes prior to microscopic analysis. At least one set of samples would be tested to destruction within the limits of the available beam time. Analysis of the samples post irradiation would be used to determine the need for subsequent tests. In such a case, some mechanical arrangement would be constructed where by many samples could be tested at once (Figure 2).
Initial Experiment:

Beam Sensors

Beam Dump

Electron Beam
Figure 2. Many Sample experimental arrangement.

Rotating Sample Wheel

Electron Gun (150 keV)

X-Y Deflection System

Ebeam spot ~ 0.5mm Ø

Tantalum Strip Samples

30 mm/ms

R=50 mm

σ=½ρω².(l²+2lR)

Centrifugal Stress
Project Plan

Project Costs

An indication of cost has been provided by TWI, and consists of a fixed initial cost covering the construction of a high power beam stop, three periods of 8 hours of beam time and subsequent optical and electron microscope analysis of the samples. Subsequent tests would be charged per 8 hour day, and consultancy would be extra.

Phase I
Costs to TWI
Set-up costs
3x8 Hour running periods
TWI Total: £11,700+VAT
Cost of foil: £200+VAT
Hire of RAL equipment: free

Phase II - estimate - assumes 3 day machine time
Beam costs: 3x£2,100/7.25 hour day
Consultancy: 0.5x£1,070/7.25 hour day
Construction Costs: £10,000
Total: £16,835

Time Scales

The lead in time for preparatory work before the first beam is likely to be of the order of 3 months. The first test would then take little time to complete (1 month).

Following consideration of the results, a decision would be made to embark on a second phase of measurements increasing the number of samples under investigation.