UK Studies of Solid Targets for Neutrino Factories

J. R. J. Bennett
CCLRC, Rutherford Appleton Laboratory, Chilton Didcot, Oxon, OX11 0QX, UK

An account is given of the research programme in the UK into targets for a neutrino factory. The studies will concentrate on the thermal shock induced in the target by the intense pulsed beam.

1. INTRODUCTION

There is a growing demand to develop reliable high power density targets [1] to produce intense beams of neutrinos and neutrons by impacting high energy (2-30 GeV) pulsed proton beams of several MW mean power. The high energy dissipation in the target creates a number of severe problems. Not only has the target to dissipate the power but it must withstand the thermal shock loading from the pulsed beam. No proven solution yet exists for a pulsed beam of power greater than ~1 MW.

Two technologies are currently being studied in Europe for neutrino factory targets: flowing liquid mercury jets and solid materials [2-4]. There is a world wide collaboration into a free mercury jet for a neutrino factory target led by groups from the USA. This has culminated in a proposal [5] to test the jet in a magnetic solenoidal field of 15 T with an intense pulsed beam at CERN. This technology looks very promising.

The target for the pulsed spallation neutron source, the SNS [6] (60 Hz pulse, 1-2 MW mean), being built in the USA is a contained flowing mercury system. Currently tests indicate damage to the container due to the pulsed nature of the beam after a relatively small number of pulses [7,8]. This technology is unlikely to be suitable for a neutrino factory since the target must be considerably smaller and would exacerbate the problem still further.

The use of small solid spheres cooled by flowing helium has been considered by Sievers [9] and mainly avoids the problem of thermal shock. The research effort in the UK is involved with the jet studies at CERN and in solid target technology, particularly on the problem of thermal shock. This paper concentrates on the solid target studies for a European neutrino factory.

2. TARGET REQUIREMENTS

The neutrino factory target will dissipate ~1 MW (mean) from the high energy (2-30 GeV) proton beam of ~4 MW mean power. The beam pulse, ~1 µs long at a repetition rate of ~50 Hz, will consist of one or more 1ns long pulses. The energy density dissipated in a single pulse in a typical heavy metal target, 2 cm diameter, 20 cm long, will be ~300 J cm⁻³.

The target is enclosed by a pion collector – either a ~20 T solenoid or a magnetic horn. This severely restricts access to the target. Since the target does not stop the beam, there is ~3 MW to be dissipated in a dump target located further downstream. The whole area will become extremely radioactive and must be surrounded by considerable shielding. Remote handling of components for maintenance or replacement will be necessary. Hence the design of the target station and components will present a difficult challenge.

3. THE ROTATING TOROIDAL TARGET

The UK is currently investigating the feasibility of a solid refractory metal target [10-12] in the shape of a rotating toroid, or individual bars passing through the beam at every beam pulse. Cooling is by thermal radiation to the water-cooled walls of the surrounding vacuum chamber. It is proposed to levitate and rotate the toroid-cooled walls of the surrounding vacuum chamber. It is proposed to levitate and rotate the toroid-electromagnetically. Tantalum and tungsten have been chosen as candidate materials because they are refractory and are resistant to radiation damage [13]. Also, it is proposed to study graphite as part of the UK involvement in the T2K experiment [14] in Japan.
Figure 1 shows schematically the toroid rotating in a vacuum. The proton beam passes tangentially through ~20 cm length of the toroid at a small angle to its plane. To avoid overlapping of successive 20 cm lengths of the toroid that are irradiated by beam pulses, the circumferential velocity, \( V \), must be at least 10 m s\(^{-1}\) at 50 Hz repetition rate. To dissipate 1 MW by thermal radiation, the toroid would be ~6 m in radius (\( R \)) with a section diameter (\( d \)) of 2 cm. This assumes a peak temperature of 2300 K, falling to ~2200 K before the next beam pulse and a thermal emissivity of 0.8. The target can dissipate powers of several megawatts at larger radii (\( R \)).

\[ \text{Figure 1. Schematic diagram of the rotating toroid.} \]

However, there is a possible problem of destruction or weakening of the target by thermal shock. It is essential to show conclusively that such a target can withstand repeated pulses from a 4 MW proton beam for at least one year of operation. Investigations of these shock effects are just commencing.

### 3. THERMAL SHOCK IN TARGETS

Simple classical elastic calculations of the thermal effects of the pulsed beam would lead one to conclude that the toroid would suffer forces that exceeded the yield strength of the material. However, some high power targets already in operation demonstrate a useful life under these loadings. Table 1 shows a number of existing high-energy density targets.

The proposed neutrino factory target is shown first for comparison. It must dissipate an energy density of ~300 J cm\(^{-3}\) at 2300 K. The ISOLDE targets also operate at these high temperatures. Some have exhibited damage which has been ascribed to thermal shock [2,15]. The Pbar targets [16,17] operate at room temperature and at much higher energy densities than required for the neutrino factory. Some damage has been seen although it may, at least partially, be caused by overheating (melting).

It is claimed that shock is not a problem for the NuMI graphite target [18]. The SLC electron target [19,20] does show some signs of damage after 1x10\(^{10}\) pulses. Since the SLC target rotates, the number of pulses on any one spot, assuming uniform scanning of the circumference, is ~5x10\(^{7}\). It is not clear that the damage is caused by thermal shock.

The last case is a life test of thin tantalum foils with a pulsed electron beam [21]. These tests indicated that they would survive at least 10\(^{9}\) pulses although the conditions were not ideal and oxidation of the samples occurred in the poor vacuum [22]. However, thin foils may have a more favourable geometry to withstand thermal shock than solid bars.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Particle</th>
<th>Target material</th>
<th>Energy density per pulse J cm(^{-3})</th>
<th>Life, number of pulses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino Factory</td>
<td>p</td>
<td>Ta</td>
<td>318</td>
<td>10(^9)</td>
</tr>
<tr>
<td>ISOLDE (CERN)</td>
<td>p</td>
<td>Ta</td>
<td>279</td>
<td>2x10(^6)</td>
</tr>
<tr>
<td>Pbar (FNAL)</td>
<td>p</td>
<td>Ni</td>
<td>10000</td>
<td>5x10(^6) Damage</td>
</tr>
<tr>
<td>NuMI</td>
<td>p</td>
<td>C</td>
<td>600</td>
<td>Shock not a problem</td>
</tr>
<tr>
<td>SLC (SLAC)</td>
<td>e</td>
<td>W26Re</td>
<td>591</td>
<td>5x10(^3)</td>
</tr>
<tr>
<td>RAL/TWI</td>
<td>e</td>
<td>Ta thin foil</td>
<td>500</td>
<td>10(^6)</td>
</tr>
</tbody>
</table>

Table 1. Comparison of some existing pulsed high-energy density targets with the proposed neutrino factory target.

### 4. THERMAL SHOCK EXPERIMENTS

It is proposed to make measurements on tantalum and tungsten at high temperatures under thermal shock conditions to characterize the materials and to construct material yield models (constitutive
equations). These can then be used in existing advanced computer hydrocodes [23] to model the behaviour of the materials in various geometries under thermal shock with realistic beam profiles that are expected in the neutrino factory targets.

Experiments can be carried out in the laboratory by impacting a projectile on to the sample material at high temperature. However it is preferable to measure the sample in a proton beam to accurately reproduce both the thermal shock and the radiation damage. Both these techniques are being examined.

Whilst single pulse thermal shock analysis is useful, ultimately the effects of many pulses must be taken into account. It is unrealistic to carry out a life test, even of 1 year (10^9 pulses for 200 days at 50 Hz), in a beam. It is hoped that up to 10^9 pulses can be delivered to a target in a test in ISOLDE. Since any one part of the toroid only receives 10^7 pulses, this will give some indication of the likely life of the target.

Tests on a tantalum disc in the Pbar target at FNAL are underway. Material loss, indicating damage, of greater than ~1% from the volume exposed to the beam can be detected. Present indications are that the target is withstanding energy densities higher than required for the neutrino target without measurable damage [24].

5. CALCULATIONS

Calculations [23] have been carried out on the advanced computer codes using existing data for tantalum extrapolated to high temperatures. These indicate that damage is occurring. However, it must be stressed that the material data has been obtained by extrapolating beyond its range of validity. Until correct data is obtained by measurements, as specified in section 4, it will not be possible to confidently assess the likely damage to the target by thermal shock.

ACKNOWLEDGEMENTS

The author would like to acknowledge the contributions of everyone working on the high-power target research programme both in the UK and abroad.

REFERENCES

2. H. Ravn in [1].
3. K. McDonald in [1].
4. J. R. J. Bennett in [1].
7. J. R Haines in [1].
8. B. W. Reimer in [1].
9. P. Sievers in [1].
16. J. Morgan in [1].
17. P. Hurh in [1].
18. N. Mokhov in [1].
19. V. Bhardwaj in [1].
22. P. V. Drumm and C. J. Densham, private communication.