OPERATING EXPERIENCE WITH MESON PRODUCTION TARGETS AT TRIUMF

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Abstract

High power targets are required for operation at beam powers in excess of 1 MW for spallation neutron sources and neutrino factories. TRIUMF has been operating beryllium and graphite meson production targets for many years. Although the proton beam power of 100 kW at 500 MeV is lower, the beam densities and fluences are higher than most operating solid targets. Other high power accelerators have used rotating targets or larger beam spots. The beam size on the TRIUMF targets is maintained at ~0.15 cm^2 and this beam density leads to proton fluences of 10^{23} protons/cm^2 per year. The beryllium targets are rectangular rods immersed in a water-cooled stainless steel jacket. The graphite targets consist of pie-shaped segments bonded to a water-cooled copper saddle. Operating experience shows that the graphite targets suffer thermal damage above beam currents of 120 µA but operate for long periods at 100 µA. The beryllium targets can operate to 200 µA and appear to survive radiation damage beyond 10 dpa. This paper will describe the operating experience with these targets and present some thermal and radiation calculations.

INTRODUCTION

The TRIUMF 500 MeV H$^-$ cyclotron routinely delivers 4000 hours per year of 500 MeV protons down BL1A at intensities from 100-150 µA for meson, isotope and neutron production. This operation is simultaneous with the delivery of 20-70 µA down BL2A for the production of radioactive beams at ISAC and with lower energy beams on BL2C for isotope production, proton therapy or proton irradiation studies. The extracted beam at 500 MeV has low emittance (~2 π mm mrad) and this can lead to very high power densities in the production targets unless steps are taken to control the beam size.

Meson production (pions or muons in secondary channels) takes place at two target locations on BL1A [1], a thin target T1 (<3 g/cm^2) 18 m upstream of a thick target T2 (<20 g/cm^2). To minimize multiple scattering in the targets and reduce beam loss downstream of the targets low Z materials are used. Most of the operating experience is with beryllium and graphite targets. At the other meson factories LAMPF [2] used some pyrolytic graphite targets but with a larger beam spot and PSI [3] uses rotating targets.

This paper summarizes the operating experience with these targets over more than 25 years and presents some thermal and radiation damage calculations in an attempt to understand the target behaviour.

TARGET DESIGN

Fig. 1 shows the two main types of target design that have evolved. The cassette target consists of an oval tube made from stainless steel bent to shape, with thin stainless steel windows e-beam welded at each end. A metal target, usually beryllium is held in the centre of the tube by a wire frame. Water enters the cassette near one end and leaves near the other end. Metal targets are completely immersed in water with flow paths at the entrance and exit faces and the sides. The standard beryllium target is 100 mm long at T2 and 12 mm long at T1.

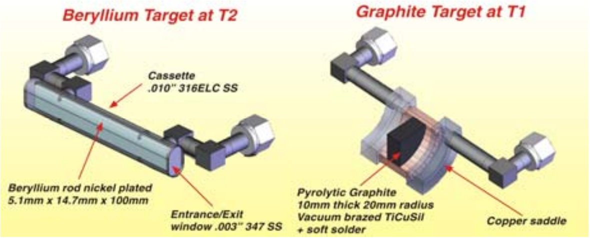

Figure 1: Target designs used at TRIUMF.

The edge-cooled graphite target design consists of a curved water-cooled copper saddle, which covers 90 degrees in azimuth, with a pie shaped graphite target bonded to the copper saddle. The bare edges of the target are aligned to the secondary channels, one to the left and one vertical. The graphite is vacuum brazed to a TiCuSil layer on the curved surface of the graphite. The metal layer is then soft-soldered to the copper saddle using a hot plate. Pyrolytic graphite has been the usual type of graphite used. It is a layered material with good but quite different thermal conductivity and thermal expansion coefficients in the two orthogonal planes. Targets of 7.5 cm and 10 cm length have been used at T2 and 10 mm length at T1.

The targets are located on a trombone ladder with five target locations. The trombone is designed so that most of the 22-litres/min water flow passes through the target that is in the beam position. Targets can be replaced in a nearby Hot Cell using a master/slave manipulator. Individual targets are connected to the target ladder using a Swagelock fitting.

BEAM ALIGNMENT AND CONTROL

The most important factors in reliable target performance are to ensure that the proton beam is centred on the target and the beam density is not too high. A 16 x 16 SEM grid profile monitor is attached to the target ladder and it can be moved into the beam position for measuring the beam size and position at low intensities (<10 µA). This is useful for beam set up but not for continuous monitoring. The nominal beam size

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(containing 90% of the beam) is 2-3 mm horizontal and 6-7 mm vertical.

Target protect monitors are located just upstream of the target ladder and used to maintain beam centring and the required beam density. The target protect monitor consists of a number of layers of 0.001” aluminum foils separated by high voltage planes.

Two pairs of foils define a 5 mm by 5 mm aperture with left-right and up-down readout. The foils read the secondary electron current that is a few % of the proton current at 500 MeV. Originally a full foil was used to measure the total beam current but did not survive a 200 µA beam test. A hard-wired interlock system ensures that the beam is centred and that sufficient beam is present on the up/down monitor foils to ensure a tall beam. The so-called density trip is U+D/Total <5%.

The alignment of the target to the target protect monitor is critical to ensure that the beam is positioned correctly. When a new target is installed a series of beam scans are taken by steering a low intensity beam (<3 µA) across the protect monitor foils and recording the current readings along with the pion or muon production rate in the secondary channels. This ensures the relative centring of the target and protect monitor. Fig. 2 shows the results of a typical scan. When target ladders are serviced it is possible to see the imprint of the beam spot size and location on the entrance windows of the cassette targets for confirmation of the position.

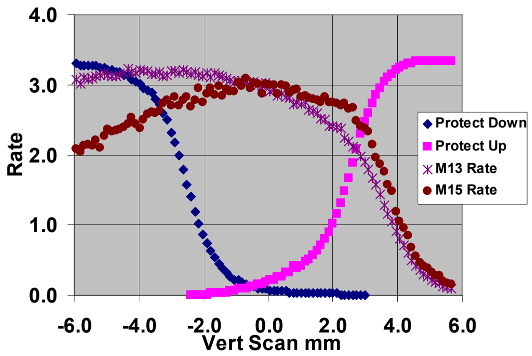

Figure 2: Target scan to check alignment of protect monitor to target.

The proton beam is continuous with a 23 MHz microstructure. To minimize thermal shock from turning the beam on after a trip there is a programmed ramp of the intensity from 30 µA to the operating current over 20 s.

OPERATING EXPERIENCE

Three types of target failures have been observed over the years:

- Beam misaligned on the target so that it hits the welds causing a water leak
- Beam centred but the entrance or exit window develops a pinhole leak.
- The secondary pion or muon intensity drops and the target integrity is suspect

Cassette Targets

Most of the operating experience is with the beryllium targets as they are most reliable.

Type 1 failures occurred in 1988, 1989 and again in 2003. In the latter case a vertical misalignment of 4 mm was found between the target and the target protect monitor due to a fault in the target positioning readout.

Type 2 failures occurred in 1982, 1986, 1988, 1994, 1995, 1996. Most of these were in the short targets at T1 where the beam density is highest. Improved e-beam welding of the windows solved this problem.

Type 3 failures were reported in 1983 and 1997 on T2. The most likely failure was in 1997 on a target that had survived over 500 mA-hours of beam. The evidence was a 10% drop in muon flux and an increase in the conductivity and activity of the cooling water. This target had been operated for extended periods at currents of 170 µA. It is extremely difficult to open the cassettes for study after irradiation, so direct observation of the integrity of the beryllium was not made.

Edge-Cooled Targets

A bare graphite target is preferred for surface muon production (30 MeV/c μ^+ produced from the decay of π^+ stopping just at the surface of the production target) as this geometry can enhance the μ^+ flux by a factor of ~1.5 over a water-cooled beryllium target.

This target design using pyrolytic graphite has operated successfully at currents below 100 µA but was never able to survive for extended periods above 120 µA. Typically after 1-3 weeks of operation above 120 µA the target delaminated, i.e. the layers of the target opened as shown in Fig. 3, and/or sections would fall off. The targets were segmented into shorter sections, as shown in the photo. Most of the experience was with a 10 mm graphite target at T1 but 7.5-10 cm graphite targets were tried at T2. Operation with radiation-cooled targets and tests with diamond and ordinary graphite targets have also been carried out.

THERMAL & RADIATION CALCULATIONS

Calculations of the thermal behaviour of the beryllium and graphite targets have been carried out using the FEA codes ALGOR and COSMOS. A beam power corresponding to 150 µA proton current and two beam sizes were studied. For 500 MeV protons more than 90% of the beam power is lost through ionization with only a small fraction from nuclear reactions. Fig. 4 shows a typical FEA result for the temperatures and stresses in the edge-cooled graphite target and Table 1 summarizes the results for both targets.

Radiation damage calculations have been carried out using SRIM [4] and checked against analytic calculations.

100 mA-hrs of beam in an area of 0.15 cm^2 corresponds to about 5 dpa in graphite or beryllium.

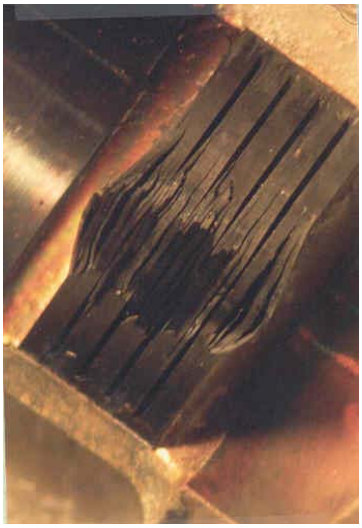

Figure 3: Beam damage to graphite target.

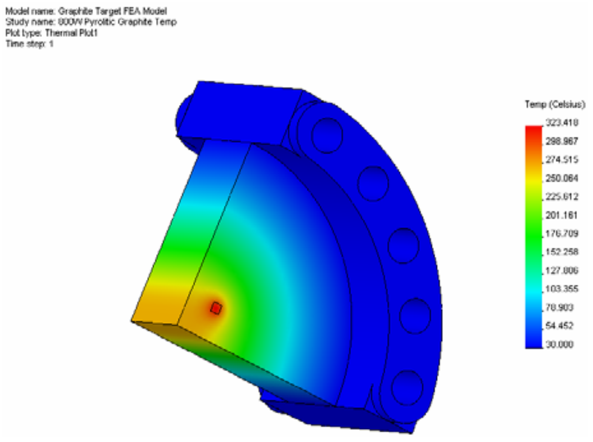

Figure 4: Temperature profile in the edge-cooled pyrolytic graphite target.

SUMMARY

The thermal calculations indicate that both targets should survive proton beam currents of 150 µA with the normal beam spot. For the beryllium target a small beam spot of 1 mm^2 leads to thermal stresses that are close to the yield strength of the material and should be avoided. However beryllium targets have survived up to 1300 mA-hr (2 x 10^{23} protons/cm^2). At this level there is likely serious radiation damage to the cross section of the target exposed to the beam but the surrounding material seems to keep the target intact.

The pyrolytic graphite target does not survive at beam densities where the calculated temperatures and thermal stresses indicate that it should. The shear stresses at the beam spot are significant but the maximum stresses are between the graphite and the copper saddle. Possibly the thermal contact at this bond becomes damaged, leading to higher stresses and temperatures in the graphite at the beam location. The problem does not appear to be caused by changes in the thermal conductivity due to radiation damage as these targets have not lasted beyond 1 dpa and the damage rate is directly related to beam intensity.

As the graphite targets have advantages for surface muon production, continued development of edge-cooled targets is envisaged.

Table 1: FEA Calculations of Temperature and Stresses

	Beryllium	**Pyrolytic Graphite**
BEAM SIZE 1 MM X 1MM		
Peak Temp °C	260	335
Von Mises stress		
MPa	345	19.3
Psi	50,000	2,800
BEAM SIZE 2 MM X 6MM		
Peak Temp °C	208	320
Von Mises stress		
MPa	262	13.8
Psi	38,000	2,000
YIELD STRENGTH		
MPa	345	a 82
Psi	50,000	a 12,000
Shear Strength (Psi)		a 500

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