TRIUMF EXTRACTION FOIL DEVELOPMENTS AND CONTAMINATION REDUCTION*

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Abstract

Progress has been made in understanding of failure modes and activation issues surrounding the extraction probes and stripping foils of the TRIUMF 500 MeV cyclotron. The radioisotope ^{7}Be has in the past decade been observed near the main extraction stripper, and relatedly, stripping foils warped or even broke during use. This is now understood to be due to over-heating in the foil and the frame, caused by the stripped 270 keV electrons migrating up the foil before dissipating their energy in the foil frame. As well, it is desirable to reduce beam spill along the high intensity primary beam lines. The spills are primarily caused by the large angle scattering from the stripping foil. It was thus suggested that thinner foils be used to minimize the scattering. In view of these 2 issues, improvements were made such that (1) highly-orientated pyrolytic graphite foils, of thickness around 2 mg/cm^2, are now used; (2) Tantalum frame is now used in place of the previous stainless steel. These changes, plus additional heat relief features introduced, have resulted in 4 times longer lifetime with the foil, and 5 to 10 times reduction to the tank contamination level around the extraction probe. Also, these improvements have led to significantly reduced amount of beam spill monitor trips.

INTRODUCTION

The 500 MeV H$^-$ cyclotron has been using stripping foils to extract multiple proton beams simultaneously. It has extracted increasingly intense proton beams during the past 40 years. Over the last 10 years, routine operation delivered peak currents up to 320 μA in total to the three primary beamlines, where the two high energy beams for the beamlines (1A and 2A) are extracted with the stripping foils operated in a radial shadow mode to obtain the desired beam split ratio. In such a shadow case, the beam density on the foils is 40% higher than in the single extraction case.

In the 2004 year-end shutdown it was observed that the ^{7}Be contamination near the 1A stripper was higher than in previous years by at least one order of magnitude. The activity was almost completely from ^{7}Be. It was speculated to be due to the dense beam spots on the 1A and 2A foils as a result of the shadowing technique used. A possible scenario was that the higher density spot produced a higher density electrons which spiraled around the magnetic field and passed though the foil repeatedly, ending up in the foil or the metallic holder and causing an overheat to the foil, thereby driving off ^{7}Be that had been produced there by nuclear reactions.

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The foil frame did show evidence of excessive heating, as shown in Fig. 1 as an example. During those years, after an accumulation of ~60 mA-hrs, which could take three to five weeks, the foil began to warp and even crack, producing beams with poorer quality and requiring frequent retuning and increasing spills along the beam line.

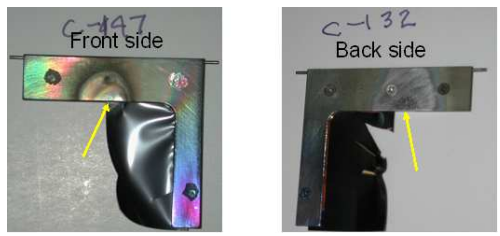

Figure 1: Used foils showing the signs of overheated frame and cracked and warped foil.

These foils were standard pyrolytic graphite, of thickness [1] 4.5±1 mg/cm^2, unchanged over decades because it was thought that thicker foils are stronger and therefore more durable. For a 5 mg/cm^2 carbon foil, Monte Carlo simulation result [2] shows that $> 6 \times 10^{-5}$ of particles are scattered beyond 3.3 mrad. These particles already run outside the 4″ beam pipe as the beam line transfer matrix element R_{34} or R_{12} reach 1.5 cm/mrad at maximum. This means that at 100 μA, there is >6 nA lost along the beamline. These losses are localized in a couple of spots and trigger beam trips by safety system, as only beam loss of <1 nA/m can be tolerated in order to retain access to the beamlines for service. Thus, it was suggested to use 2.5 to 5 times thinner foils to minimize the scattering.

ELECTRON HEATING SIMULATIONS

Simulations [2, 3] were performed to calculate the distribution of energy deposited by the electrons that are stripped from the H$^-$ ions of 500 MeV. Simulations began with the geometry and size of the original standard foil assembly (1st generation), which consisted of two plates (stainless steel, of thickness 0.031 inches) screwed together with a foil (pyrolytic graphite) and a pivoting pin clamped between them. A representative beam spot of H$^-$ used in the simulation was 2 mm wide and 8 mm tall, with a linear distribution in x (maximum at the edge) and a quartic distribution in y. The whole area was divided into grids of uniform size 0.1 mm in both directions.

When H$^-$ enters the foil, the electrons are stripped. The stripped electrons pass through the foil, and then spiral around the magnetic field and cross the foil multiple times. At every crossing, the electrons lose energy longitudinally

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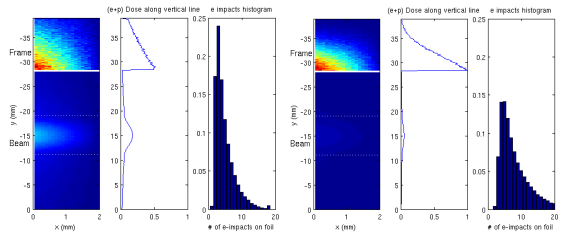

Figure 2: Results of simulation made with 5 (Left) and 1 mg/cm^2 (Right) foils, showing contours of energy deposit, distribution of energy deposit along y, and a histogram of number of electron impacts.

and scatter transversely. When the electron energy becomes lower than the foil's stop energy, it's fully deposited in the foil at next crossing.

In the simulation at each electron crossing the energy is decremented according to standard tables of energy-dependent loss in graphite. The vertical scattering angle is chosen as a normally distributed random variable, and the horizontal scattering is neglected as it has hardly any effect on the next impact position of the electrons. An electron whose accumulated scattering reaches the bottom of the foil is tracked no longer and its remaining energy not deposited. But electrons that migrate upward sufficiently to reach the foil frame are stopped there, losing all remaining energy. Also the electrons can skip over the frame and be lost. Protons pass only once through foil or frame.

The simulation produces a table of energy dose in each grid point. As an example, Fig. 2 shows the results obtained with 5 and 1 mg/cm^2 foils. Remarkably, the dose maximum is not in the foil but in the frame. This is because at this energy, scattering dominates over straggling; roughly half of the electrons reach the frame before they have lost any significant amount of energy, especially for thin foils; the other half are lost off the bottom. This explains why a hot spot is seen on the top frame just above the foil edge, as shown in the Fig. 1. The histogram shows that the electrons mostly impact the foil 3 times before lost or stopped in the frame. This is because the energy loss is only around 10 keV for the first couple of impacts even for the 5 mg/cm^2 foil, the electrons remain on a spiral radius large enough to swing around the foil, and then the large scattering angle of -150 to +150 mrad drives them vertically.

The thinner the foil, the fewer electrons stop at the proton spot where ^{7}Be isotopes are created.

TEMPERATURE CALCULATIONS

Thermal calculations began with the first generation foil assembly and the above stated heat load distribution, where the foil was pyrolytic graphite and the frame was stainless steel. The temperature dependencies of thermal conductivity and heat capacity of these materials were taken into account. Figure 3 shows the equilibrium temperatures, calculated with 100 μA beam current and 5 and 1 mg/cm^2 thicknesses respectively. Notice that thicker foil results in higher temperature on the foil at the location of beam spot

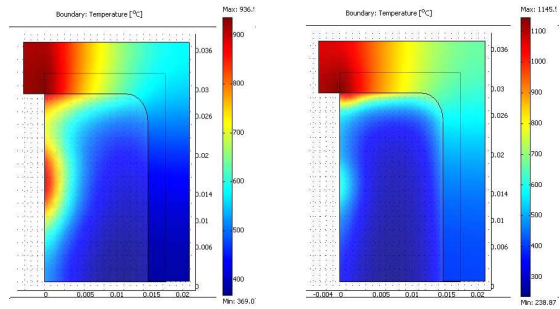

Figure 3: The foil (PG) and frame (SS) temperature distribution, calculated with 5 (Left) and 1 mg/cm^2 (Right) thicknesses. The darkest red is 1100°C.

Table 1: Maximum temperature (in °C) on the foil at the beam spot location and frame vs. the foil and frame materials, for foil thickness of 2 mg/cm^2.

	PG		HOPG	
	Foil	Frame	Foil	Frame
SS304	780	1092	630	1045
Tantalum	780	940	640	900
Molybdenum	780	850	640	810
Tungsten	780	840	640	800

where the protons create ^{7}Be. Since lower foil temperature reduces the amount of ^{7}Be released, it was decided to reduce the foil thickness to $\leq$2 mg/cm^2.

Calculations were also made to determine temperature dependence upon frame material and whether the foil is pyrolytic graphite (PG) or highly oriented pyrolytic graphite (HOPG). Some results are shown in Table 1. It's seen that the foil maximum temperature at the beam spot location is almost frame material independent, but with HOPG, the foil temperature is lower by 140°C than with PG. With Tantalum frame, the frame maximum temperature is lower by 150°C than with SS304; for Molybdenum or Tungsten, the frame temperature is even lower. This is because HOPG and Ta, Mo, W conduct heat better than PG and SS304 respectively. These results contributed to the decision to employ HOPG for the foil and Tantalum for the frame.

FOIL AND FRAME DEVELOPMENTS

A number of changes were made over the years to reduce the temperature rise on the foil and frame.

The first attempt made was using a narrower frame while the material remained stainless steel (the 2nd generation). Still, the frame became thermally damaged and the foil was broken. For generation 3, a larger radius was used for the frame inside corner to try to reduce the stresses on the foil material (HOPG). This was marginally successful, but the frame still suffered some damage. See Fig. 4. Also, a copper frame assembly was experimented with the same shape as the 3rd generation frame, but it yielded disastrous outcome: the frame was partially melted and copper was deposited on the probe arm and surrounding parts [2].

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Figure 4: Left: The 3rd generation assembly, where the frame remained SS but had a larger radius. This was marginally successful but the frame still suffered some damage. Right: A used 4th generation foil/frame assembly which had accumulated about 176 mA-hr when it was removed in February, 2012. There was no visible damage to the foil or the Tantalum frame.

Pyrolytic graphite of 5 mg/cm^2 was used until 2006. Thinner PG foil of 2.5 mg/cm^2 was used in the years 2007 and 2008, and did increase the foil life, but only marginally. Finally from 2009 to the present, highly oriented pyrolytic graphite (HOPG) was used. The thickness was in the range of 1.5 to 2.5 mg/cm^2. This foil material has been extremely reliable, and is now used for high current extraction on all extraction probes. The frame material was changed to Tantalum in 2009, with a thin copper cushion sandwiched between the frame plates and the foil to relive the stress of the foil. The larger corner radius was kept to better support the foil and reduce any stresses on it. The frame damage issue has disappeared. Moreover, in order to minimize heating to the Molybdenum tape which drives the trolley along the probe arm, a Tantalum shield [2], mounted on ceramic blocks, was installed to absorb and spread out the heat from the electrons that skip above the foil frame.

With the employment of HOPG foil and Tantalum frame plus the Tantalum heat shield etc, the foil life increased dramatically, with a TRIUMF record being set in August 2010 of 253 mA-hr accumulated over 17 weeks. This was 4 times longer than the typical foil life using the 5 mg/cm^2 PG foil and a stainless steel frame. Also, all indications were that it was still in good operational condition, and swiping did not show any ^{7}Be contamination at the probe arm. Fig. 4 shows a photo of a 4th generation foil assembly which had accumulated about 176 mA-hr when it was removed in February, 2012. There is no visible damage on the foil or the Tantalum frame.

TANK CONTAMINATION REDUCTION

Since the 2004 year-end shutdown, ^{7}Be contamination has been discovered in the vicinity of the main extraction foil (1A). With the use of the thin, higher quality HOPG foil and Tantalum frame of improved geometry, the foil heating is reduced and this retains the ^{7}Be inside the foil material instead of contaminating the surrounding environment. The tank contamination level surveyed around the 1A foil has been reduced by a factor of 5 to 10 in 2012. See Fig. 5. Should be mentioned that in 2012 the beam spot on 1A foil was lowered by roughly 6 mm.

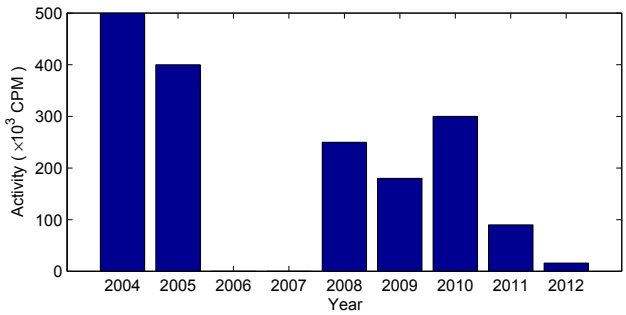

Figure 5: The cyclotron tank contamination level surveyed near the 1A foil position over the last several years (where the year 2006 and 2007's data were missing). It has been reduced by a factor of 5 to 10 in 2012.

CONCLUSIONS

Through the electron heating simulations and the temperature calculations, we gained a better understanding of the problems that we had in the past with the extraction probes and foils and frames. We became aware that it was the over-heating of the frame due to the stripped electrons scattering vertically upwards along the magnetic field lines. The high temperature caused problems such as the ^{7}Be contamination, foils cracking and warping, and occasional mechanical malfunction of the probe. For mitigation, highly-orientated pyrolytic graphite is now used as stripping material, mounted in a tantalum frame with a thin copper cushion. Additional heat relief features were introduced in the mechanism of the extraction probe. These changes have resulted in foil lifetimes extended from the typical ∼60 mA-hr to 250 mA-hr for the 1A foil, operating at 140 μA and 480 MeV with negligible release of ^{7}Be contamination. Also, these improvements have resulted in improved beam quality and stability; the amount of beam spill monitor trips has been significantly reduced.

ACKNOWLEDGMENTS

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