ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL062

RECENT DEVELOPMENTS FOR CYCLOTRON EXTRACTION FOILS AT TRIUMF*

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Abstract

The TRIUMF 500 MeV H⁻ cyclotron employs stripping foils to extract multiple beams for different experimental programs. The upgrades in foil material and foil holders lead to significant improvements in beam quality and foil life time, as well as reduction of 7Be contamination originated in the foils. Thus, an accumulated beam charge extracted with a single foil increased from ~60 mA·hours to more than 500 mA·hours. A key role that lead to these advances was an understanding of the foil heating mechanism, major contribution to which is paid by the power deposition from electrons stripped by the foil. To further diminish this effect, we recently introduced a foil tilt from the vertical orientation that allows stripped electrons fast escape from the foil, well before losing their original momentum through the heat deposition. Other improvements were related to operational issues. Introduction of a "combo" foil consisting of wide portion and thin wire allowed both high and low intensity beam extraction without foils sacrifice. Deploying a wedge foil for extraction at 100 MeV helped reduction of beam intensity instabilities caused by beam vertical size and position fluctuations.

INTRODUCTION

The H⁻ cyclotron deploys stripping foils to extract multiple proton beams simultaneously. Two high energy (482 MeV) beams for the beam lines BL1A and BL2A 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 (see Fig. 1). Third high intensity beam (100 µA) is extracted at 100 MeV down BL2C4 for 82Sr isotope production.

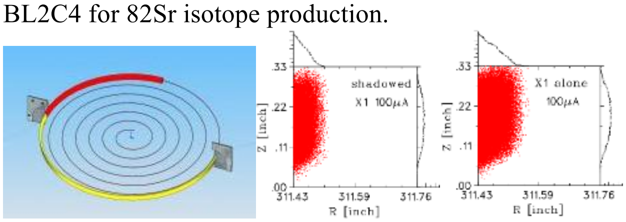

Figure 1: H⁻ radial shadow extraction scheme (left); simulated beam spots in the shadowed case (middle) and in single foil case (right). The spot size is ~ 2×8 mm.

In the early 2000-s, when the ISAC facility was ramping up beam power delivered by BL2A, a loose radioactive contamination near the 1A stripper was observed to become an order of magnitude higher than before. The activity was almost completely from 7Be. It was speculated to be due to dense beam spots on the 1A and 2A foils as a result of the shadowing extraction technique. A possible scenario was that the higher density spot produced a higher density stripped electrons which spiraled along the magnetic field B_z and passed though the foil repeatedly, dissipating their energy in the foil and the metallic foil holder and causing an overheat to the foil, thereby driving off 7Be that had been produced in the foil by nuclear reactions.

The foil frame did show evidence of excessive heating, as shown in Fig. 2 as an example. During those years, after an accumulation of ~60 mA-hrs, 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 2: Used foils showing the signs of overheated frame and cracked and warped foil.

These foils were made of pyrolytic graphite with thickness of 4.5±1 mg/cm^2 [1] unchanged over decades because thinner foils were not strong enough.

FOIL 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 [4] with the geometry and size of the original foil assembly (1st generation), which consisted pyrolytic graphite foil sandwiched between two stainless steel plates.

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 and scatter transversely. When the electron energy drops below the stop energy, it's fully deposited at next crossing.

In the simulation at each electron crossing the energy is decremented depending on the foil density (see Fig. 3). 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

* Funded under a contribution agreement with NRC (National Research Council Canada).

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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 the foil.

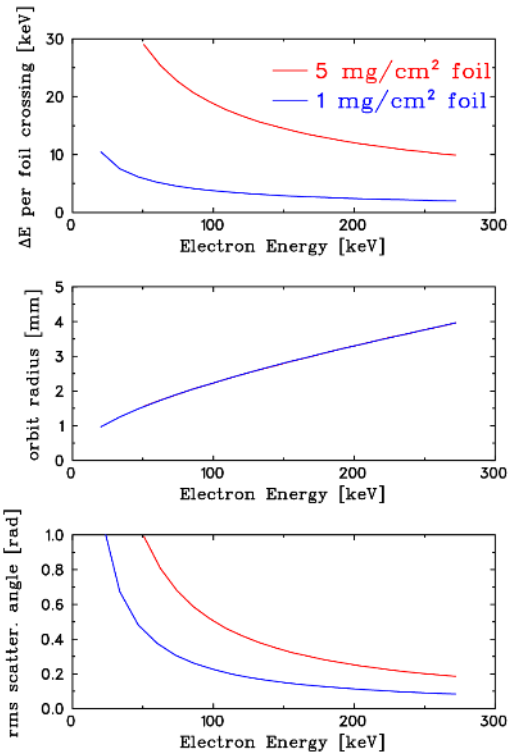

Figure 3: Top-to-bottom: Stripped electron energy drop per foil crossing, electron precession orbit radius in Bz, electron rms scatter angle vs electron energy for two typical foil densities: 1 & 5 mg/cm^2.

The simulation produces an energy dose deposition across the foil and the frame. As an example, Fig. 4 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 electrons reach the frame before they have lost any significant amount of energy, especially for thin foils; the other half are lost off the foil bottom. This explains why a hot spot is seen on the top frame just above the foil edge, as shown in the Fig. 2. 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/cm2 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 they are created.

Thermal calculations began with the first generation foil assembly and the above stated heat load distribution. Heat removal is assumed through thermal radiation only. The temperature dependencies of thermal conductivity and heat capacity of all materials were taken into account.

Figure 5 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 where the protons create 7Be. Since lower foil temperature reduces the amount of 7Be released, it was decided to reduce the foil thickness to $\leq$2 mg/cm^2. This, in combination with Tantalum frame of improved geometry, allowed foil life time improvement to over 500 mA·hours.

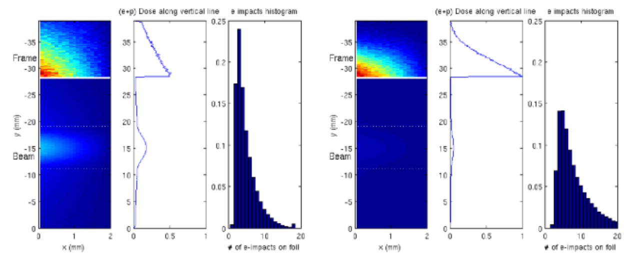

Figure 4: Results of simulation made with 5 (Left) and 1 mg/cm^2 (Right) foils, showing contours of energy deposit, distribution of energy deposit along y, and a histogram of number of electron impacts.

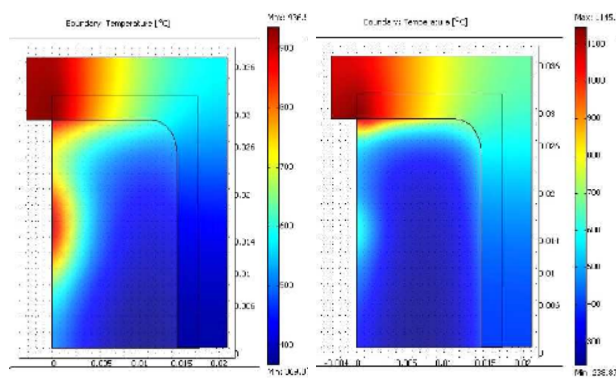

Figure 5: The foil (PG) and frame (SS) temperature distribution, calculated with 5 (Left) and 1 mg/cm2 (Right) thicknesses. The darkest red is 1100C.

TANK CONTAMINATION REDUCTION

With the use of the thin, higher quality Highly Oriented Pyrolytic Graphite material the foil heating is reduced and this allows retaining the 7Be 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 in 2012 (See Fig. 6). Further contamination reduction has been achieved by lowering the beam spot on 1A foil by roughly 6 mm.

TILTED FOIL

Further development towards reduction of foil temperature lead to a proposal of new configuration of foil interaction with stripped electrons. Instead of straight vertical position, foil was tilted at 20 degrees along the beam path (see Fig. 7). This allows stripped electrons promptly escape from the foil in both vertical directions before losing their energy and miss the upper portion of the foil frame. These electrons are eventually stopped at the bottom of the cyclotron vacuum chamber and at the heat shield plate

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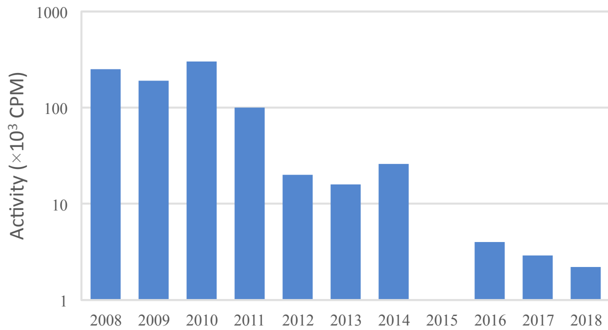

Figure 6: Cyclotron tank contamination level (7Be) under 1A foil (year 2015 data missing).

installed on the extraction probe arm above the foil. Normalized combination of the signals read from the foil and the shield plate represents the extracted beam current.

New foil was installed in BL2A extractor in spring 2017 and operated well throughout the year. Expected outcome will be reduced temperatures of the foil and its frame leading to extended foil life time (to be confirmed). Observed improvement was manifested by 7Be release reduction by factor of 2.

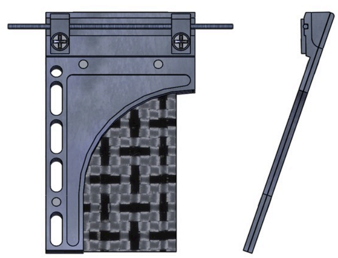

Figure 7: BL2A foil tilted at 20 deg. from vertical orientation by offsetting the frame's centre of gravity.

BEAM INTENSITY STABILIZATION

Stable beams delivery is an important requirement for the operations. High order magnetic field components generate coupling resonances in the beam dynamics inside the cyclotron, that cause beam density oscillation and high sensitivity to many instabilities like beam position at injection, RF amplitude and phase, magnetic field. With the shadow extraction technique all this can translate into intensity instability of the extracted beams. These problems have been successfully solved for extraction to BL1A and BL2A [5].

Since 2013 the BL2C4 has been the only high current beam line facing intensity instability in excess of ±5%. Observations suggest that with a beam vertical missteering at injection the vertical size/position fluctuation is generated and thus it affects the fraction of the circulating beam being extracted with partially dipped 2C wide foil. An ad hoc fix of this problem was suggested with employing an extraction by a narrower foil fully dipped through the beam (see Fig. 8a). In this configuration a small vertical oscillation has negligible effect on the split ratio in question. Implementation of this approach yielded 5 times gain in reduction of fast instabilities (down to +/- 1%). As a side effect, a fully dipped foil generates vertically symmetric beam compared to a one side truncated beam produced by partial dipping. That allows better control of beam centering at the isotope production target. Also, a narrow foil generates smaller horizontal beam size (and halo) that leads to lower collimator temperature at the target entrance. Shown in Fig. 8b foil is wedged for minor intensity adjustment.

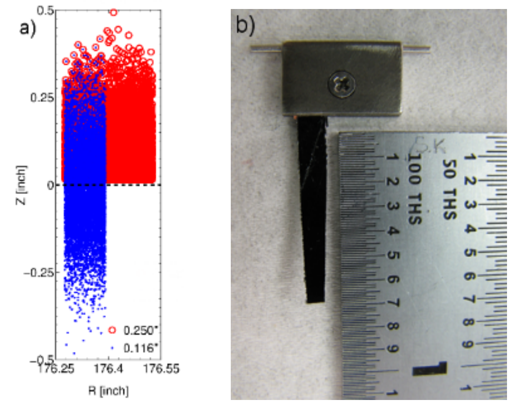

Figure 8: a) Particle distribution on fully (blue) and partially (red) dipped foils with the same split ratio 0.4; foils widths are 0.116" and 0.250" respectfully. b) BL2C4 extraction "wedged" foil.

COMBO FOIL

Every time BL1 is switched between high current (BL1A) and low current (BL1B) users, the foil has to be changed from wide one to a wire and back (~10 times a year). Present extractor design does not allow re-use of foils; with every exchange the old foil has to be discarded. Associated overhead: downtime during transition; wear of extractor mechanics; loss of good, healthy foils. A new proposed solution of "combo" foil assembly (see Fig. 9) comprises a wide foil and a wire. Required section intercepts the beam by adjusting its vertical position. It was installed in 2017 and operated well in all configurations without changing and degradation throughout the year.

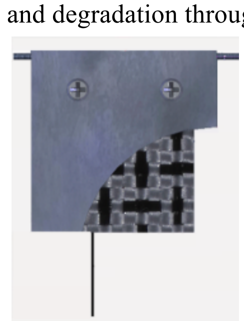

Figure 9: BL1 Combo foil comprising a wide section and a wire.

CONCLUSIONS

Electron heating simulations and temperature calculations provided us a better understanding of the problems with extraction foils. With this knowledge we implemented modifications that allowed mitigation of 7Be contamination problem and drastically extended foil lifetime, far

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beyond regular annual maintenance cycle. Other foil configuration improvements provided operational flexibility and gained beam stability at 100 MeV in support of isotope production program.

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