RECENT IMPROVEMENTS IN BEAM DELIVERY WITH THE TRIUMF'S 500 MeV CYCLOTRON.*

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Abstract

TRIUMF's 500 MeV H- Cyclotron, despite its 44 years age is under continuous development. Many aspects of beam delivery have been improved over the last few years. Regular 3-week cusp source filament exchange cycle has advanced to multi-months due to greatly improved filament life time. Fine source tuning allowed beam intensity rise in support of routine extraction of 300 µA of protons. The injection line model has been fully correlated with online measurements that enabled its tuning and matching to the emittance defining slits and the cyclotron entrance. Cyclotron routinely produces 3 simultaneous high intensity beams (~100 µA each). Multiple techniques have been developed to maintain extracted beams intensity stability within +/- 1%. Record extraction foil life times in excess of 500 mA-hours have been demonstrated with highly-oriented pyrolytic graphite foil material and improvements in foil holder. Beam rastering on ISOL target allowed higher yields. A single user extraction at 100 MeV was achieved by applying phase slip and deceleration inside the cyclotron.

ION SOURCE AND INJECTION LINE

A powerful test stand for H- ion source development has been built in 2012. An intense cusp source filament study carried on over a couple of years. Resulting choice of filament material and shape allowed a breakthrough in the filament life time. Regular filament change was based on a 3 weeks cycle. Recently deployed filament survived 9 weeks, when it failed prematurely for a reason unrelated to its deterioration. Presently projected filament life expectancy is about 4 months. Figure 1 shows filament current drop in time; each peak corresponds to a filament replacement.

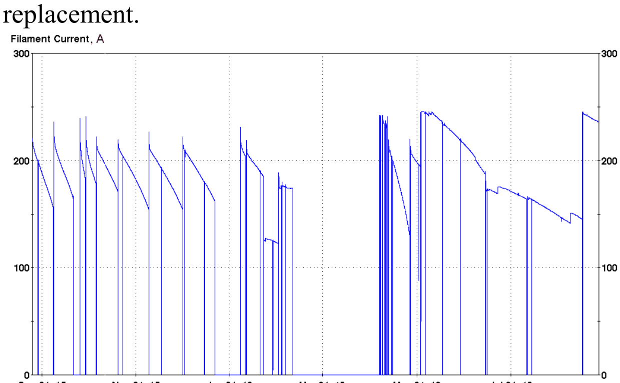

Figure 1: H- source filament current evolution.

In 2014 the ion source showed a very peculiar instability. It manifested itself as a strong dependence of beam steering at the output of the optics box on beam pulser setting (see Fig. 2). An assessment revealed an insulating coating layer on the electrostatic steering plate that was previously a grounded counterpart of the pulser deflecting plate. Electrical charge accumulated on the insulating layer was responsible for changing electrical field within steerer/deflector that caused uncontrollable beam steerinig. The problem was resolved by replacing aluminum plates with stainless steel ones.

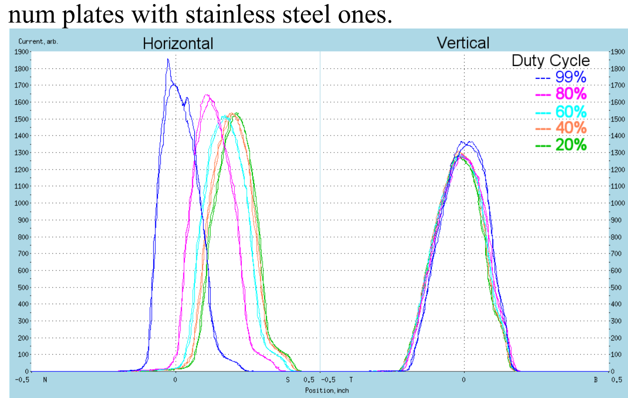

Figure 2: Beam horizontal steering vs duty cycle.

For a long time there was no clear understanding of the beam asymmetry at the exit of the source acceleration column. An OPERA model of an electrostatic steerer [1] offered an explanation to this issue: when circular apertures are used in conjunction with parallel plates and the plates have a net bias, the assembly acts partially as a quadrupole. There are two ways to avoid this effect: balancing the opposite polarity bias on the plates so the median plane becomes at ground potential or making a rectangular slot apertures of same orientation as the plates.

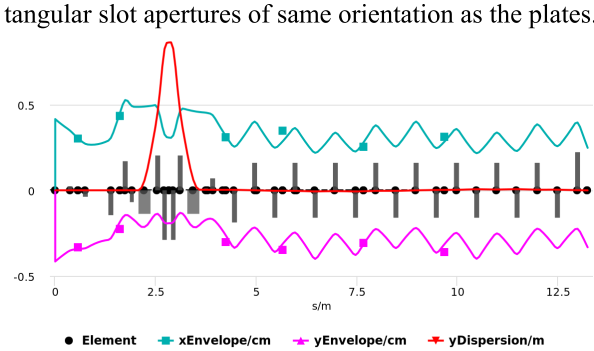

Figure 3: Beam envelope trough 1/3 of injection line; squares represent beam size at profile monitors.

Removing the quadrupole effect from the otherwise symmetrical section of beam optics allowed development of the accurate model of beam optics from the source down to the cyclotron entrance. This effort culminated by introduction of a High Level Application (HLA) that models the whole injection line. It uses online data from 5 profile monitors and live settings of the optics to reconstruct beam parameters and produces a new optics setting

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aiming at beam matching into emittance defining slits which are situated at the start of the first long periodic section. A typical plot of beam envelopes after matching is shown in Fig. 3. Straightforward beam tuning validated the high accuracy of the optics model. Also, a user-friendly interface has allowed smooth implementation of this first live HLA into operations.

INTENSITY STABILIZATION

Three high intensity beams are routinely extracted from the cyclotron: 100-130 μA at 480 MeV to the Meson Hall users (BL1A), up to 100 μA at 480 MeV to the ISAC facility (BL2A), and 100 μA at 100 MeV for the medical isotopes (Sr-82) production (BL2C4). Stable beams delivery is an important requirement for the operations. It is the most critical for the ISOL target where rare isotope yields are highly non-linear with respect to primary beam. This was recognized at inception of ISAC beam delivery and a palliative solution has been applied by regulating extracted beam down 2A beam line with a total intensity variation at injection using pulser which varies the duty cycle at 1 kHz at the source [2]. But, while solving the BL2A instability issue, this approach introduced magnified intensity changes in the remaining beamlines. The origin of the beam split ratio instability between BL1A and BL2A is the radial beam density oscillation induced by the $\nu_r = 3/2$ resonance at the energy 428 MeV [3, 4] due to residual third harmonic of the cyclotron magnetic field. We were able to compensate this component with available harmonic coils 12 and 13 [3, 4]; and then compensate remaining slow drifts in extracted beam split ratio by active feedback that adjusts radial beam position by regulating first harmonic component of the harmonic coil 12 [5, 6]. Since 2013 BL2C4 has been the only high current beamline facing intensity instability and its source is not fully understood yet. We could only see that with a beam vertical mis-steering at injection it generates vertical size/position fluctuation and thus affects the fraction of the circulating beam being extracted with partially dipped 2C wide foil.

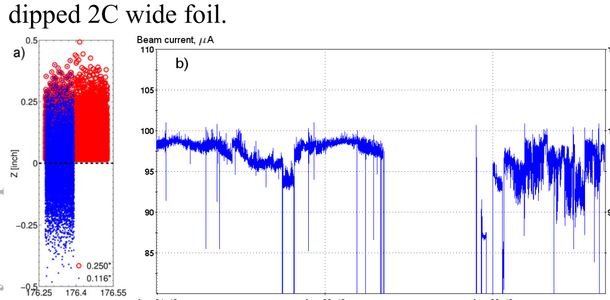

Figure 4: a) Particle distribution on fully (blue) and partially (red) dipped foils with the same split ratio 0.4.
b) BL2C4 extracted current: left part - extraction with fully dipped foil; right part - with partially dipped foil.

An ad hoc fix of this problem was suggested with employing an extraction by a narrower foil fully dipped through the beam (see Fig. 4a). In this configuration a small vertical oscillation has negligible effect on the split ratio in question. Figure 4b depicts BL2C4 intensity instability throughout the extraction foil change: from a 0.116” wide foil fully dipped in the beam to a 0.250” wide foil partially immersed in the beam. Fast instability rise is clearly visible. As a side effect, a fully dipped foil generates a 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 that leads to lower collimator temperature at the target entrance. Beam studies aiming at identifying the source of this instability will continue.

SR-82 PRODUCTION

Since about 2 decades TRIUMF has been producing Sr-82 isotopes for medical imaging at its Solid Target Facility (STF). In 2007 the STF was upgraded to 80 μA and in 2013 with beefed-up shielding it reached its maximum capacity at 100 μA of protons. Production target is surrounded by cooling water. With 10 kW of beam power we observe water dissociation with release of O-15 isotopes into nuclear ventilation. The mitigation measure is to run radioactive exhaust through a delay line to allow substantial decay of radioactive species before releasing it to the atmosphere.

TRIUMF cyclotron is equipped with 56 pairs of co-axial trim coils, covering the entire energy range of the machine. With a proper combination of 3 of these coils, one can always create a localized field bump in B_z with tails zeroed off at both inner and outer radii, while remaining the B_r component unchanged. This allows to make a phase slip to the beam over certain radial range while minimizing any unwanted perturbations outside. We chose to create such a field bump after ~190" i.e. after BL2C4 100 MeV extraction radius, with an amplitude of ~1.0 G. This amplitude was large enough to make a 180 degree phase slip to the beam, so that the whole beam of ~50 degree phase band turns round and gets decelerated back (see Fig. 5) and passes through the 2C4 extraction foil again. This scheme is useful for the BL2C single user operation mode with a <0.4" foil taking large fraction (~100μA) of the circulating beam while still leaving small amount running to high energy where it was dumped on the diagnostic probe at ~500 MeV. The new configuration helps reducing cyclotron activation. Figure 6 shows a signal from BL2C4 capacitive probe for the beam injected at ~10% duty factor. Small decelerated fraction of the beam pulse (in red) is delayed at extraction.

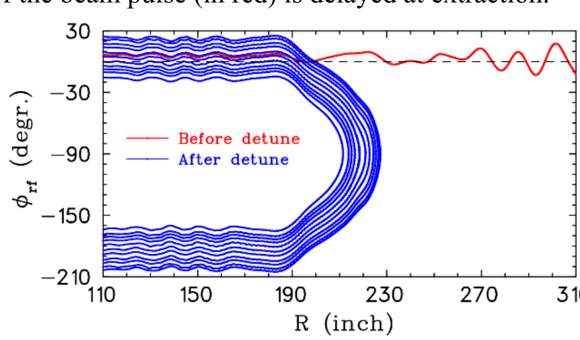

Figure 5: Phase space diagram of beam deceleration.

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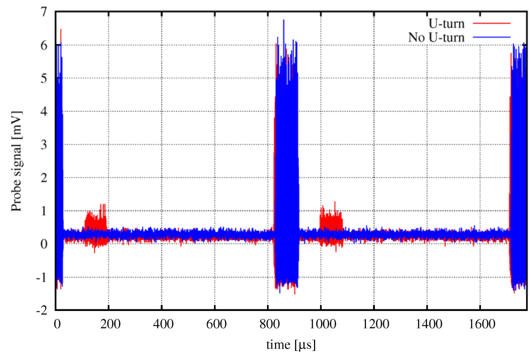

Figure 6: BL2C4 extracted beam: blue – no deceleration, red – with deceleration.

TRIUMF has further plans of Sr-82 isotope production increase. It can be achieved with elongated Rb target. Simulations suggest that with a doubled target thickness (63 mm) one can yield 50% more Sr-82. The validation test will take place this fall. In the longer term we want to redesign the whole beam transport to the STF (~5 m) and introduce beam rastering capability that will allow target temperature reduction and higher yields.

EXTRACTION FOILS

Over the last decade there was an effort to improve extraction foils [7]. Since last modification in 2011 we have collected an impressive statistic on foil life time. There was not a single foil failure in the beam. The highest charge accumulated over 4 years on 100 MeV extraction foil is 560 mA-hours, and on 480 MeV foil, 420 mA-hours. Also, earlier observed loose contamination from Be-7 released from the foils is no longer an issue. All these achievements can be attributed mostly to the choice of highly-oriented pyrolytic graphite foil material and tantalum material of the foil holder.

BEAM LOSSES

Recent achievements in ramping of machine intensity to 300 µA motivated intensive effort aiming at beam loss reduction. There are three mechanisms leading to beam losses: 1) vertical effective emittance growth; 2) electromagnetic (Lorentz) stripping; 3) stripping on residual gas.

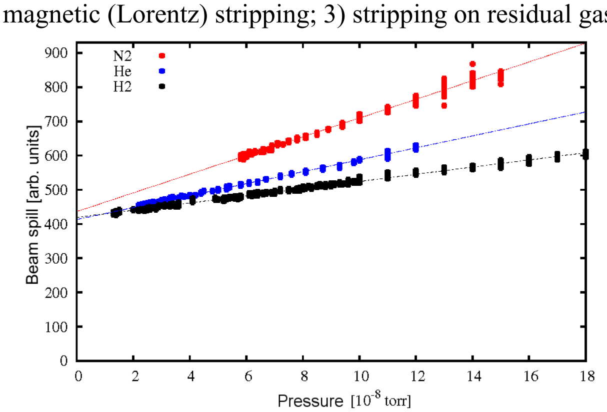

Figure 7: Beam spill vs partial pressure of some gases

The most significant high energy loss reduction from 5% to 3% was achieved by reducing extraction energy from 500 MeV to 480 MeV due to a drop in Lorentz stripping [8]. Then, after the cryo-pumping system upgrade the pressure in the tank dropped from $8\cdot10^{-8}$ to $2\cdot10^{-8}$ Torr. We evaluated the impact of partial pressure of basic gases on the beam losses and concluded that this factor adds negligible contribution to the effect and no more vacuum improvements are warranted. Figure 7 shows beam loss dependence on residual pressure of different gases. Studies of beam vertical halo will continue.

RASTERING

With beam rastering, it's expected to reduce the radial temperature gradient across the ISAC target and thus allow higher beam intensities to be accepted for the same maximum temperature. The raster magnets are located midway between the E-W splitter dipole and the final dipole. From there to the target there is a drift, a doublet quadrupole, and a drift. Theoretically, it's best to make the section from raster magnets to target point-to-parallel as needed for steering, and at the same time parallel-to-point, as needed for focusing. But in practice, it is more important to know the beam size, position and angle at the target. Given that we do not have diagnostics on board the target but upstream of the target (~1.1 m), it's critical that we have a tune where the spot size at the target better reflects the beam sampled at the upstream monitor. We developed such a tune by having polarities of the last doublet reversed from the previous. This tune is plotted in Fig. 8 (solid line), as opposed to the previous tune (dashed line) where the beam envelope gets sharply focused on the target in the vertical plane. This tune has been demonstrated to be working properly in terms of rastering with a beam spot of ~4mm, though it has little flexibility to change the spot size. Also, with a new Beam Position Monitor added into the final section of the beamline, the beam centering corrections in both position and angle is considerably facilitated.

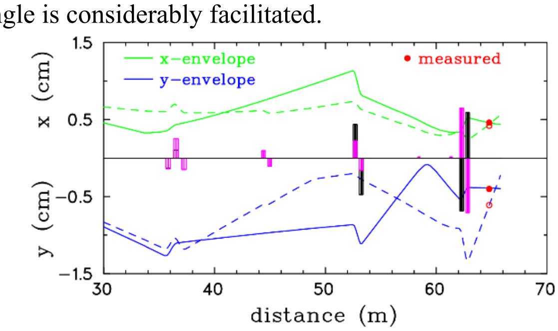

Figure 8: BL2A beam envelope: dashed lines – old tune; solid lines – new tune.

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