TRIUMF CYCLOTRON BEAM QUALITY IMPROVEMENT

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Abstract

TRIUMF cyclotron for decades operated at 500 MeV. Recently, the two primary beamlines 1A and 2A, have been reconfigured for running at 480 MeV. The objective was to reduce beam losses caused by the electromagnetic stripping by 30%. The radiation losses reduction was confirmed with both online measurements and residual activation field mapping after 8 month of beam production. In order to improve stability of both primary beams, one of the harmonic coils was configured in Bz-mode to compensate for the beam split ratio fluctuations. Br-mode of this coil and two outer radius trim coils was utilized to correct the beam vertical position at extraction. Moreover, to make the beam spot position on the target stable and insensitive to any uncontrolled movement of the stripper foil due to heat distortion, the beamline front end optics was tuned to compensate the cyclotron's inherent dispersion. Details of these developments and improvements are discussed in the paper.

INTRODUCTION

Over past decade TRIUMF cyclotron has been demonstrating steady performance with availability of ~90%. At the same time the beam development team has made a significant effort to quantify the operational ISIS and cyclotron tunes, to better understand apparent discrepancies in the beam optics, to reduce tuning time, to decrease beam losses, to improve beam intensity and position stability and to increase the extracted current. This resulted in continuous increase of beam peak intensity as well as charge delivered to three major beam lines: BL1A (μSR program), BL2A (ISAC radioactive beams) and BL2C4 (medical radioisotopes) (see Fig.1 and 2). Last year a record beam charge has been produced for BL2C4 and BL2A, and a maximum extracted intensity of 310 μA has been achieved in routine operation. Future programs, for example an additional proton beamline for ISAC, will call for even higher intensities (~400 μA) and enhanced beam quality.

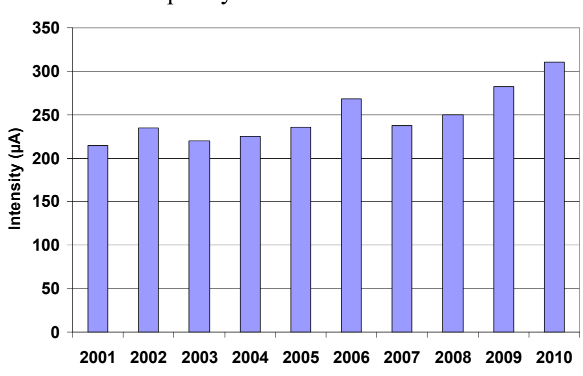

Figure 1: Total peak beam extracted.

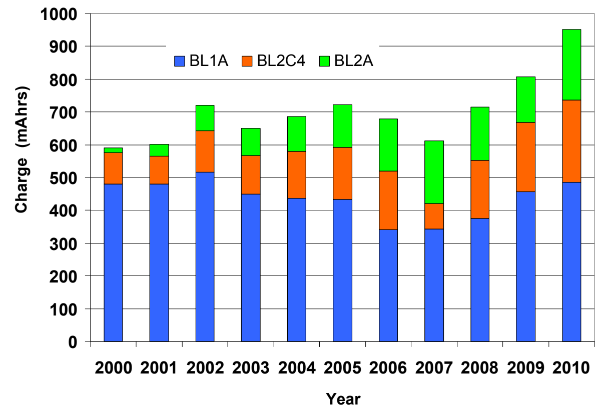

Figure 2: Annual beam charge delivered to 3 beam lines.

CYCLOTRON INJECTION TUNING

The injection line now operates routinely at ~450 uA cw at 300 keV. This enables an extraction of ~300 uA with less than 1.0% of internal beam losses.

Operational experience and calculations including space charge demonstrated that the high current ISIS tune also works well for lower currents. Studies comparing the measured and calculated beam envelopes show that ISIS tune in the horizontal section is well matched. The tune in the vertical section is mis-matched, but the beam still stays within the limiting apertures [1].

Two sets of emittance limiting slits, separated by a 90 degree phase advance were installed in a horizontal periodic section of ISIS. These slits effectively reduce the emittance tails that would otherwise contribute to the downstream spills. A third set of slits in the vertical bend clean up the energy dispersion produced by the upstream bunchers.

The allowable source adjustments were chosen so that it would be possible to centre the beam on the first two sets of ion source slits. The third ion source slit aperture, although adjustable, was set to 12 mm. The amount of current injected into the cyclotron was adjusted by changing the setting of the ISIS emittance limiting slits rather than by changing the source current.

The injection line beam matching was accomplished by measuring the beam profiles on a number of scanning wire monitors along the beam line and then fitting the optics to find the beam's initial size, divergence and emittance. A tune for the matching section was developed [2]. An Allison-type emittance scanner was recently installed to measure the beam's emittance downstream the source. This has simplified the matching exercise.

At the cyclotron injection an adjustment of the centre region tune is required to reduce beam spills and to keep the temperatures of the scraping apertures inside the cyclotron within acceptable limits. Although this was initially difficult, it became fairly routine after learning the correlations between centre region parameters and spills and temperature increases.

Two hardware modifications were done to decrease centre region heating caused by beam losses. A water cooled beam absorber was installed after the injection gap on the first quarter turn to intercept the lower radius beam that would otherwise hit the inner resonator wall surrounding the center post. In addition, the beam scrapers protecting the centre region vertical deflection plates were re-aligned so that they wouldn't intercept any non-stray beam.

EXTRACTION AT 480 MEV

TRIUMF cyclotron, being an H- machine, has an energy limitation around 500 MeV caused by electromagnetic stripping losses (see Fig. 3) that constitute a major component of the total beam loss.

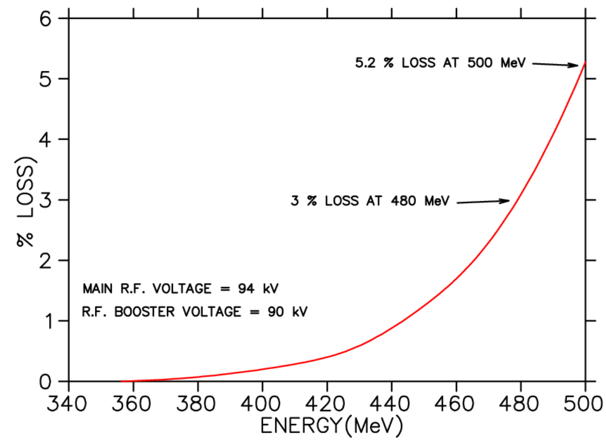

Figure 3: Electromagnetic stripping losses.

Last year the extraction energy was reduced from 500 to 480 MeV to reduce this effect. Prior to this the yield reduction impact was measured for every user. ISAC radioactive beams and surface muons production impact was negligible, while in-flight muons and 500 MeV isotope production reduced by 15-20%. The later was compensated by the intensity increase down BL1A.

Energy reduction impact on the beam losses and consequently machine activation was monitored online and at the end of the production run. Table 1 represents a relative activation reduction for 480 MeV extraction compared to 500 MeV. All data normalized to the beam annual charge (except for neutral beam).

Table 1: Activity Reduction Due to 480MeV Extraction

Neutral Beam Production Rate	0.68
Air Activation During Beam Production	0.65
Residual Activation	
Cyclotron Lid	0.72
Cyclotron Upper Vault	0.74
Cyclotron Basement	0.66
Beamline 1A	0.83
Cyclotron Tank (inside)	0.60

Correction of Vertical Error

The cyclotron is equipped with a series of trim and harmonic coils (TC and HC) to make magnetic field corrections as a function of radius R. The TC are used to adjust the isochronism (in "BZ mode", meaning the upper and lower coils are powered in the same direction) and the median plane vertical position (in "BR mode", meaning that the upper and lower coils are in opposition). The HC are used to correct orbit centering (in "BZ mode") and median plane tilt (in "BR mode"). There are 54 TC and 13 HC (see Fig. 4). Though there are orbit excursions of typically up to 20 mm, these are left uncorrected as the beam gap is far larger at 100mm. Thus the HC are rarely used.

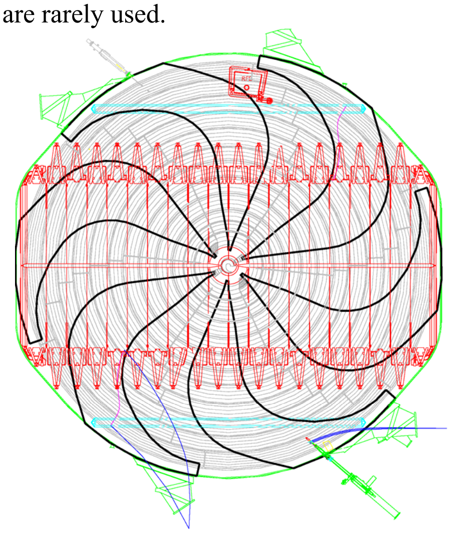

Figure 4: Cyclotron schematic layout. RF resonators are in red; trim and harmonic coils in grey.

An unanticipated consequence of lowering the extraction energy was that the extracted beams were poorly centred vertically in the BL1A at its entrance. Steering elements are too far downstream to correct. The reason for the effect is that the median plane has a strong radial modulation in this energy region, resulting in a strongly downward-directed beam at 480 MeV.

Attempts to center the beam with TC #46 and TC #49 BR to change both the position and angle of the beam at the stripper for BL1 (at 480 MeV) were successful, but resulted in considerable spill on the cyclotron scraper monitors indicating that centring out one point was causing mis-centring at another azimuth. The corrective is therefore to use TC's in combination with a HC in BR mode. HC12 was chosen; by varying its amplitude and phase, a setting was found that centred the beam at BL1 entrance while keeping spills low.

STABILIZATION OF SHARED BEAM

The two high energy beams extracted from the cyclotron are 60º apart in azimuth. By placing stripping foils completely through the median plane, the one foil "shadows" the other. This is a mode of sharing that is insensitive to vertical beam fluctuations, but sensitive to radial ones if the radial beam density is not radially uniform. Unfortunately, the beam is not uniform radially because of the uncorrected effect of the η_r=3/2 resonance. RF voltage fluctuations cause disproportionately large fluctuations in the extracted current, and these fluctuations are dangerous for the radioactive beam facility whose target operates at temperatures near the meting point.

For stabilization of BL2A intensity we have been varying the duty cycle in a feedback loop that uses the measured extracted current as signal. This has the obvious disadvantage that BL1A's current fluctuations are not stabilized but are on the contrary doubled.

A preferred approach is to stabilize the sharing rather than stabilizing only one of the two extracted beams. This can be done by:

- correcting the η_r=3/2 resonance,
- stabilizing the rf voltage,
- feeding back the ratio of extracted currents to move the orbits radially on the stripper foils.

Initial studies have been made of the third option. Moving the beam radially in a manner that changes the split ratio requires simply moving the orbit centre. This is accomplished with an HC in BZ mode.

In summer 2010, an experiment was performed to test the viability of this technique. HC12 BZ phase and amplitude were adjusted manually. This resulted in a significant change in the BL1/BL2A split ratio. Similar effect can be observed using high energy (HE) probes (see Fig. 5). Further work is planned for this year. The implementation is not straightforward: automatic control of the 6 HC power supplies has never been attempted; it is complicated when they must switch polarity. As well, the feedback loop must be made independent of the existing loop which stabilizes the main cyclotron field.

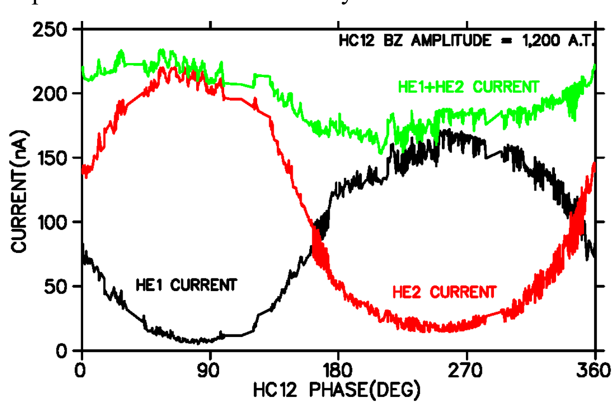

Figure 5: HE1 and HE2 currents vs HC12 Bz phase.

NON-SHADOW EXTRACTION MODE

Besides the radial shadow mode extraction which we have been using routinely for many years, we developed a non-shadow mode extraction procedure for BL1A and BL2A by placing a wide fully intercepting foil in BL1A stripper (X1) and a narrow 0.03 inch wide partially intercepting foil in BL2A stripper (X2). Non-shadow extraction was done by placing X2 inside of X1 so that the current on X2 was unaffected by small changes in the radial position of X1. The object of this experiment was to determine if non-shadow mode extraction improves the current stability in BL2A and to determine the feasibility of using a narrow foil as an extractor.

In non-shadow mode the X2 stripper has to be moved vertically rather than radially to adjust the 2A/1A current split ratio. The original tune didn't work for non-shadow mode because it produced an unacceptable asymmetric vertical spot on the ISAC target (see Fig. 6a). Further, a new BL2A tune was devised so that the asymmetry could be corrected by adjusting a single quadrupole.

The non-shadow mode tune was run for several weeks with 2A currents as high as 50 uA. The narrow foil behaved well during this run, but the 2A current stability seemed to be worse than that in shadow mode.

As a result, the non-shadow mode didn't look appealing for operation.

(a) (b)

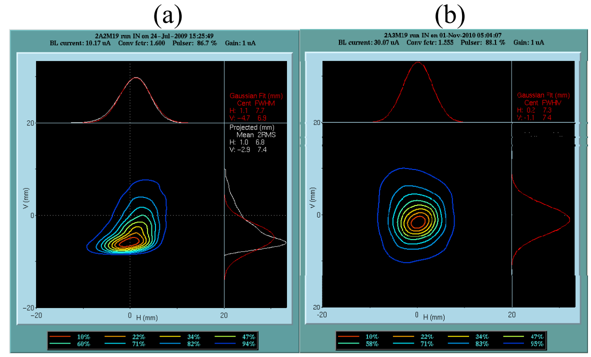

Figure 6: Non-shadow extraction beam profiles before (a) and after (b) tune correction.

DISPERSION-COMPENSATION

Cyclotrons have inherent dispersion; there is a correlation between a particle's radial position and its energy. In separated-turn cyclotrons, this applies from turn to turn and not within a turn. Thus for single turn extraction this is not a consideration. However, in an H- cyclotron, there is no turn separation. Thus if the stripper foil moves, both the radial position and the energy of the extracted beam change together with a dispersion of $\Delta x/\Delta p/p \sim R/\gamma^2$. Often this effect is ignored and the beamline for the extracted beam is designed to be achromatic. A better approach would be to design the beamline to compensate for the cyclotron's periodic dispersion as this would make the extracted beam insensitive to small movements of the stripper foil.

This idea was tested this past summer. A new tune was devised for BL1A and implemented. This tune indeed showed reduced sensitivity to stripper motion. Further investigations are planned for the coming year.

REFERENCES

[1] R. A. Baartman and Y.-N. Rao, Determination of initial beam parameters in ISIS, TRI-DN-04-02, TRIUMF Design note, 2004.

[2] R. A. Baartman et. al., Reliable Production of Multiple High Intensity Beams with the 500 MeV TRIUMF Cyclotron, Cyclotrons-2010, China, 2010.