

SIMULTANEOUS EXTRACTION OF TWO STABLE BEAMS FOR ISAC

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Abstract

The TRIUMF cyclotron was originally conceived for several proton beams extracted simultaneously at different energies. Recent operation includes a 500 MeV beam up to 150 μA for meson users, a 500 MeV beam up to 80 μA for rare isotope production, and a 100 MeV beam up to 70 μA for medical isotopes. Extraction of a second primary beam for ISAC has now been given priority. A necessary characteristic for the primary beams for ISAC is intensity stability better than 1% to allow the highest target temperature (and therefore the most efficient yield of rare ions) to be maintained. An operational solution for stabilization of the existing beam has been shown to be applicable to both beams because of the particular angular separation between the two stripping foils in the cyclotron. Stability dependence from the angular foil separation in the cyclotron is illustrated.

INTRODUCTION

For the last 30 years the 500 MeV TRIUMF cyclotron [1] has been operating at high intensity, extracting simultaneous proton beams for multi-user operation. Over the last two decades beam availability was maintained around or above 90%. In recent years up to 250 μA total current was delivered routinely to users through three separate extraction lines. Up to 290 μA in cw mode and 400 μA (peak) at 25% duty cycle were also demonstrated during development shifts [2]. During typical routine operation $\sim 125 \mu\text{A}$ were extracted to BL1A for mesons, $\sim 75 \mu\text{A}$ to BL2A for ISAC, both at 500 MeV, and $\sim 50 \mu\text{A}$ at 100 MeV to BL2C4 for isotopes (Fig. 1).

The two 500 MeV beams are extracted by inserting extraction foils to intersect the cyclotron beam at the appropriate radius and bite as much as needed to deliver the desired beam split ratio. However, it was observed that this “double stripping shadowing” mode would introduce irregular slow drifts in the extracted intensities, of amplitude significantly larger than had been previously experienced during high intensity single-beam extraction on BL1A. Tighter intensity tolerances of $\pm 1\%$ were imposed by ISAC to keep the temperature of the ISAC production target as high as possible for its maximum yield (but just below the limit preventing thermal damage to the target material). Interlock trips that stop the beam and cause loss of thermal equilibrium for several minutes had to be minimized. To ease this situation in a simple and ad hoc manner

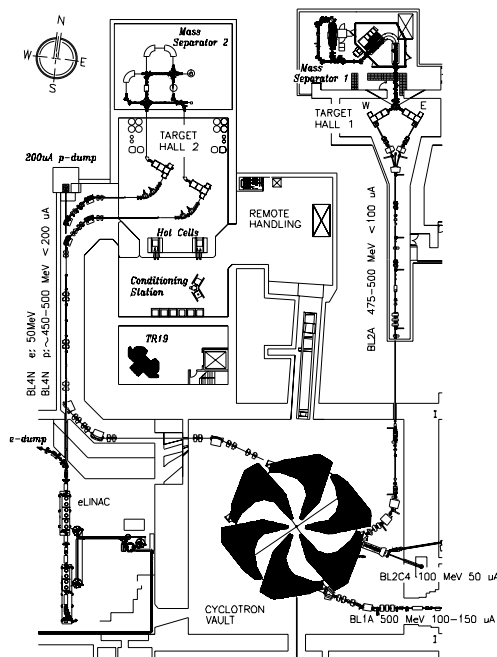


Figure 1: Existing and proposed primary beam lines for ISAC.

the instability in BL2A was corrected by adjusting the intensity of the cyclotron current at injection. Feedback from the BL2A stripper current to the variable duty cycle (VDC) pulser at injection was used. The TRIUMF pulser is ideal because the average beam current can be varied without detectable changes in beam structure in the cyclotron and along the beamlines [3]. Slow control software routines were used for the feedback because of the slow nature of the perturbations. Although this resulted in increased instability in BL1A, it is acceptable because beam stability is less critical for the meson targets. A reduction by a factor of ~ 5 of the original instability in BL2A has been achieved (see Fig. 2).

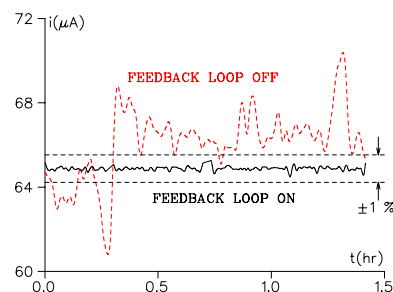


Figure 2: BL2A stability with feedback off and on.

As projected in the 2010-15 and 2015-20 five-year-plans, stability of primary beams, developments toward higher intensity, two beams for ISAC, and key machine refurbishments for reliability will be driving priorities for the cyclotron. High intensity aspects were discussed previously [2]. This paper will focus on achieving adequate stability for multiple simultaneous beams. For ISAC, primary beam stability is at least as important as intensity.

BL4N, planned to become available later in the 2010-2015 period, is shown on the left of Fig. 1. It is designed to operate simultaneously with BL2A, BL2C4 and BL1A. It will be equipped with a dedicated $200\ \mu\text{A}$ beam dump to be available to operations for routine reproduction and optimization of a $400\ \mu\text{A}$ peak, 50% duty cycle, 500 MeV beam in the cyclotron. At this duty cycle important thermal effects caused by halo losses can be detected and tuned out. BL4N will eventually operate up to a proton intensity of $100\ \mu\text{A}$ for the production of radioactive ion beams (RIBs) for ISAC. Currents up to $200\ \mu\text{A}$ may occasionally be used for target studies.

There are two major differences between BL4N and BL2A. First, BL4N will be an achromatic beam line; consequently, beam size along the line will be smaller and more stable than in BL2A. Second, once two targets have been installed after 2015, the two primary proton beams and the mass separator downstream in BL4N will have the capability of simultaneously producing different RIBs in two of the three different ISAC experimental areas.

Also indicated in Fig. 1 is the location of a high-intensity cw electron linac with an extraction line that will transport a 50 MeV electron beam to the BL4N tunnel and the same target stations for the production of RIBs through photofission. The electron line will lie above the proton line in the tunnel. With two targets completed, electron-generated and proton-generated RIBs would be available simultaneously on the experimental floor. A description of the e^- facility is presented elsewhere at this conference [4].

Finally, for the 2015-20 period the ISAC linac expansion is proposed that would allow simultaneous delivery of three RIBs, to the existing ground-floor experimental areas: low energy (E up to 60 keV), medium energy (E/u up to 1.8 MeV), and high energy (E/u up to 6.5 MeV for $A=150$). This will allow efficient utilization of the existing facilities. This upgrade is described elsewhere at this conference [5].

STABILITY OF SIMULTANEOUSLY EXTRACTED INTENSE BEAMS

The method presently used to stabilize the ISAC beam in BL2A with a feedback to the current injected into the cyclotron is a method that cures symptoms (creating side effects) but not the cause. A primary cause is the $\nu_r = 3/2$ resonance at 428 MeV triggered by a 3rd harmonic gradient imperfection in the magnetic field [6]. The effect of the resonance on an initially well-centered and matched radial phase-space ellipse is shown in Fig. 3. Stretching occurs approaching the resonance. Downstream the ellipse,

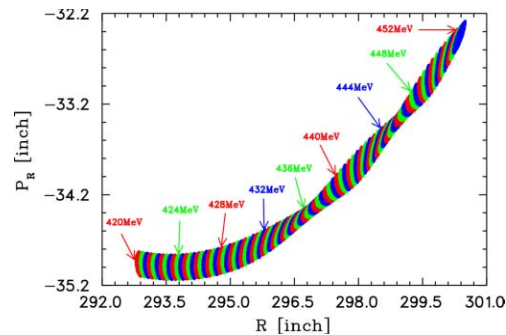


Figure 3: Phase ellipse simulation through a $\nu_r = 3/2$ resonance at 428 MeV.

now mismatched with respect to the cyclotron acceptance, starts precessing. The precession will generate radial density modulations (Fig. 4a). Precession and modulations can lead to significant beam instabilities. Examples are instabilities generated by rf voltage variations. Because the radial position of the density modulations in Fig. 4a is rf voltage dependent, the density at a given radius will vary according to the rf voltage. Fig. 4b shows the measured

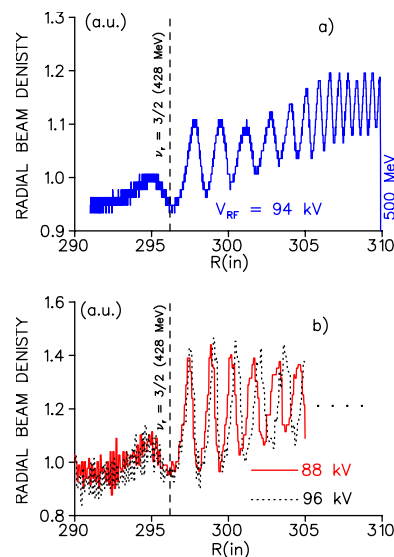


Figure 4: Fig. 4a (above) Radial density modulation simulated for 94 kV rf and Fig. 4b (below) Modulation measured with a radial density probe for 88 and 96 kV rf.

effect of a large voltage variation on the the radial profile of a density-probe scan during the first six periods of the modulation. Measured and simulated profiles are in good agreement. A density electrode parked at the extraction radius would detect a significant rf voltage-dependent instability. Note that had a total current probe been used this instability would not appear.

In several aspects, the case of fractions of the total cyclotron beam being detected by density electrodes in a radial probe is analogous to the case of double-shadowing strippers or triple-shadowing extraction modes generating partially extracted beams. Here too the beams are extracted in separate portions of the total beam emittance and will normally be unstable with varying rf voltages, although in

general the total beam intensity extracted by the shadowing strippers combined will appear stable (like the total current in the cyclotron).

It is important to point out that parallel efforts are being pursued in at least three directions. (1) The $\nu_r = 3/2$ resonance should be corrected using 3rd harmonic coils. Use of the existing harmonic coils was predicted to reduce the amplitude of density modulations by $\sim 50\%$; during a recent first test with probe HE2 in the cyclotron a reduction of 30-40% was observed. (2) To reduce the rf voltage instabilities new voltage probes will be installed that will measure the voltage between dees rather than between cantilevered hot and cold arm, which are more subject to error. (3) The possibility of using a feedback to the variable duty cycle pulser for an ad hoc stabilization of both simultaneous beams for ISAC will be also explored. This method is discussed in more detail below.

In Fig. 5 the azimuthal positions of the extraction strippers for BL1A (X1), BL2A (X2) and BL4N (X4) at the 500 MeV equilibrium orbit are shown schematically. X1 and X2 are 60° apart and X2 and X4 are 120° apart. We assume that, for all energies between 428 MeV where $\nu_r = 1.5$ and 500 MeV where $\nu_r = 1.56$, in first approximation we can treat phase advances between strippers as 90° between X1 and X2 and 180° between X2 and X4. Simulations of effects at energies of 475 MeV and

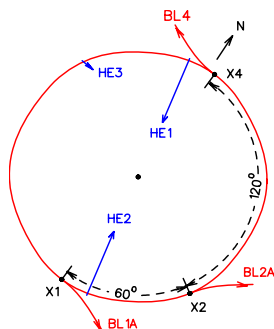


Figure 5: Locations of high energy probes HE1, HE2 and HE3 and extraction probes X1, X2 and X4.

500 MeV have confirmed that this assumption is valid.

Conclusions from several simulation studies are as follows. (1) For double-shadowing extraction the 60° angular separation or 90° phase advance (such as that between BL1A and BL2A) is the worst possible. Here the split ratio between the intensities of the two extracted beams, set at unity (50% on each foil) at a nominal voltage of 94 kV, will vary by more than $\pm 10\%$ for a voltage variation of ± 1 kV. (2) For a 120° angular separation or 180° phase advance, as between BL2A and BL4N, double-shadowing extraction is at its best because once the split ratio is set around unity at 94 kV it will stay within 2% of unity between 93.5 and 95 kV. (3) For a triple-shadowing extraction of three beams initially set at 50% for X1 and 25% for each of X2 and X4, the X1/X2 and X1/X4 split ratios will both vary with the rf voltage in about the same way. This is the only possible manner that a single feedback to the pulser could stabilize

both primary beams for ISAC. The result of this simulation is shown in Fig. 6 and confirms that the feedback to pulser

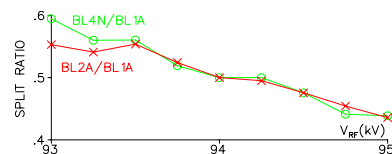


Figure 6: Simulation of the X2/X1 and X4/X1 split ratios as a function of rf voltage.

variation will be a useful tool to mitigate the instability in both ISAC beams simultaneously.

Because the X4 extraction probe was not available recently, direct experimental verification could not be made at this time with X1, X2 and X4. However, noting in Fig. 5 that the angle between the high energy probe HE3 and X1 is 120° and the one between HE2 and HE1 is 180° (or 270° phase advance) corresponding to the angular distance between X1 and X4, we were able to verify experimentally the split ratio versus voltage for these two cases (Fig. 7). This preliminary measurement shows a strong dependence on the rf voltage for the HE1/HE2 case (180°) and a much weaker dependence for the HE3/X1 case (120°). This is a first confirmation of agreement between predictions and measurements. Further measurements are planned when the X4 extraction probe becomes available.

The above measurements were done for 500 MeV extraction. Measurements will be performed also at 475 MeV. The triple radial shadowing option at a reduced extraction energy of 475 MeV instead of 500 MeV will allow a reduction of $\sim 50\%$ of the cyclotron electro-magnetic stripping losses at higher energies, with reasonable reduction of yields for RIB (5%) and mesons ($\sim 10\%$ to 15%). Other options based on partial extraction with vertically inserted strippers are also being considered.

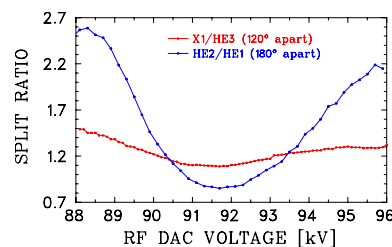


Figure 7: Split ratios as a function of rf voltage.

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