# TRIUMF HIGH INTENSITY CYCLOTRON DEVELOPMENT FOR ISAC

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*Abstract*

Over the last 15 years the 500 MeV $H^-$ cyclotron has been extracting routinely a total current of up to 220µA protons through three lines at different energies. For ISAC a new 500 MeV beamline which was recently commissioned to 100µA is now being operated up to 70µA. Work to increase the total cyclotron extracted current to 300µA was approved within the 2000-2005 plan. 300µA peak was successfully obtained at 95% duty cycle, limited only by the maximum beam current presently accepted by the beamlines. Measurements also confirmed the feasibility of 400µA total cw extracted beam, provided total beam dump capacity be increased. Total 400µA peak at 25% duty cycle was achieved with good transmission and reasonable percentage losses. Because of these results a new high intensity beam line with a 200µA beam dump and an additional RIB target ion-source was included in the next 2005-2010 plan submission. The new station will allow studies of target efficiency. Delivery of a second simultaneous RIB beam for experiments is also being considered. The paper will review recent results, and cyclotron refurbishing and primary beamline upgrade plans.

## INTRODUCTION

In December 2004 TRIUMF will celebrate the 30th anniversary of the first proton beam extraction from the 500 MeV cyclotron. A conceptual description of the machine was given by J. Warren in 1969 [1]. Here design limitations to the maximum intensity level beyond 450 MeV were highlighted, with the conclusion that because of electromagnetic stripping above 450 MeV, the routine intensity design goal was to be limited to 100µA at 500 MeV. Higher intensities (up to 400~500µA) would have been possible if extracted below 450 MeV. The easiness of partial extraction by stripping of simultaneous beams at different energies would have largely compensated for the above restriction. This was confirmed by thirty years of intense research activity around the cyclotron by several parallel groups of users in different fields of science. With the construction of ISAC the emphasis gradually shifted towards primary proton beams for the production of RIBs. A 100µA beam line is now routinely operating up to 70µA and another is planned for construction during the coming five-year period. The intensity of the cyclotron beam will also be increased to a total of 400µA for the four high intensity extracted proton beams. With the implementation of a fourth harmonic booster cavity [2] and improved remote handling routines, 250µA can now be operated at 500 MeV. This will set the stage for another successful 15 to 20 year period of intense multi-user research activity.

## INTENSITY DEVELOPMENTS

Over the last 15 years the cyclotron operated routinely up to 220µA total. Typically 150µA were transported at 500 MeV to the meson area (BL1A), 50 to 70µA at ~83 MeV were channeled to the isotope production target in the vault (BL2C4), and from a few nA to a few µA between 180 and 520 MeV were produced for proton and polarized proton experiments on BL4A or BL4B. Ocular melanoma treatment and proton irradiation of samples were also regularly carried out on BL2C1 and BL1B (see Fig.1). Availability was ~ 90% with ~5000 h/y of beam operation.

When ISAC was funded in 1995 a new large experimental building was constructed to the North of the facility. An additional beam extraction mechanism was installed in the cyclotron and BL2A was constructed to transport up to 100µA 500 MeV beam, to a heavily shielded portion of the new building (see Fig.1). A switching magnet at the end of the tunnel would allow to direct the proton beam to one of two adjacent target stations. The west target station started operation in 1998; the east target was commissioned recently. Target remote handling provisions were also installed. With the addition of BL2A the total 220µA previously available from the cyclotron would no longer be sufficient for the total new high intensity demands, now up to ~300µA (250µA at 500 MeV). However, currents in excess of 220µA had previously been consistently interrupted by arcing, vacuum deterioration or RF sparking and operation at these currents was not possible. An injection and centre region beam development program was therefore approved. Critical adjustments to specific center region electrodes were introduced during the 2002 spring shutdown. A cooled beam scraper was inserted on the inside of the first quarter turn to collect a significant portion of the particles not matching the RF acceptance. Improvements to the beam tune were also introduced at the ion source and along the injection line. In summer 2002 three simultaneous beams totaling an average of 285µA at 95% duty cycle, corresponding to 300µA space charge equivalent, could be extracted for several hours confirming the practical achievement of the 300µA goal [3]. A stringent requirement for the BL2A extracted beam was its stability, with tolerance set at ~2% of the 2A beam current, for stable maximum yield of RIB. In order to maintain optimal thermal equilibrium at the target brief interruptions caused by RF sparking or other reasons have also to be avoided. A tolerance goal was set to less then one interruption per 8 h shift.

Good beam tunes were obtained at lower duty cycle for higher equivalent intensities [4]. In July 2003, a 400μA equivalent tune 25% pulsed was achieved with good transmission from injection to extraction, confirming that acceleration and extraction of 400μA total cw will be feasible once the overall beamline acceptance has been upgraded.

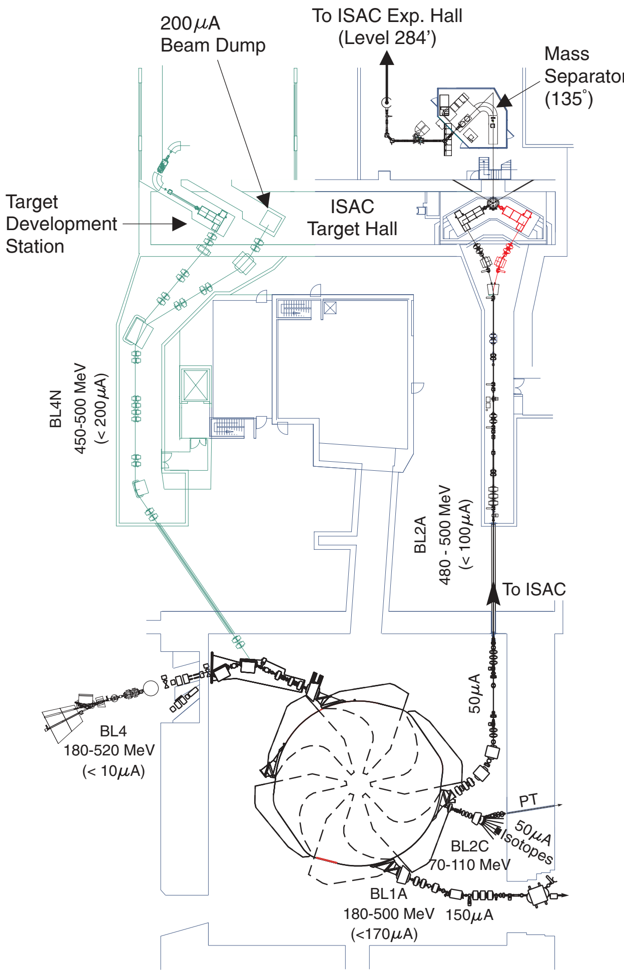


Figure 1: Cyclotron extraction lines and ISAC targets, level 264 (red is recent, green is future)

It should be stressed that whereas the 300μA equivalent demonstration (95% duty cycle) took place in rather normal and reproducible conditions, this was not the case for the 25% pulsed equivalent 400μA demonstration, in which some parameters had to be pushed to the limit, indicating the need for further study or upgrades in a few areas. Included are: (1) The ISIS system where CUSP ion source, injection line optics and buncher configuration can be upgraded for higher intensity; (2) the center region where critical geometry alignments and/or cooled collimators are being installed during scheduled maintenance shutdowns where required; (3) the beam phase history during the first few turns which is being adjusted with trim coils during beam development shifts for maximum and stable center region phase acceptance; and (4) the RF voltage where a five to ten percent increase would increase high intensity beam phase acceptance and transmission through the cyclotron. Not all improvements have to be implemented at the same time; however in order to satisfy the stringent stability requirements for ISAC it will be important to explore more than one way of approaching the 400μA goal.

It is proposed that the additional 100μA available from the cyclotron be channeled through a new beamline (BL4N) to a target station dedicated to ISAC target developments [4]. The new beam would be extracted from the BL4 extraction port and deflected in the cyclotron vault to a tunnel in the NW direction towards an area in the planned western extension of the heavily shielded portion in the ISAC target building (see Fig.1). In the same area a new beam dump will be installed capable of handling up to 200μA at 500 MeV. The new beam dump would solve the problem of insufficient extracted current acceptance for the optimization of the cyclotron. A fourth target station and corresponding analyzing system, fed by splitting one of the BL4N branches with a fast beam splitter, could allow simultaneous RIBs for ISAC. While priority will be given to the construction of the development station, provision will be made to keep the option of a second simultaneous RIB open.

Developments planned for the upgrade of the cyclotron beam intensity, stability and reliability, and for the proposed beamline and target area expansion have been outlined in the 2005-2010 five-year-plan [5]. Highlights will be discussed below.

## ION SOURCE AND INJECTION SYSTEM

At reduced duty cycle, extracted currents in the range of 300 to 325 μA (space charge equivalent) have been frequently reproduced over the last two years. A number of possible developments are being explored to reach 400μA equivalent routinely. Among them are: 1) optimizing the 12 keV extraction system for higher currents; 2) improving the ion source brightness to provide more current for the same emittance; and 3) installing a 25 keV ion source and extraction system that would increase the current output by approximately 30% with no increase in emittance. A study is underway to improve the ion source brightness and characterize the differences between 12 keV and 25 keV ions sources. At the same time work to install a 25 keV ion source in an available high voltage terminal has commenced.

In order to provide variable dc beam currents as well as improved beam quality at cyclotron injection, two sets of x-y variable slits, $90^0$ apart in phase space, were installed in a periodic quadrupole section of the horizontal injection line. Typically these slits are set to a full width of 5 mm, thus defining an emittance of ~5π-mm-mrad (0.13π-mm-mrad normalized). A variable slit was placed in the dispersed vertical bend section to reduce energy tails.

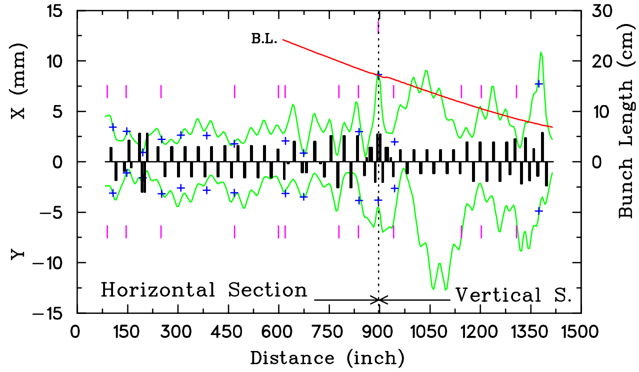


**Figure 2**: Calculated beam half envelopes (2 rms) in the injection line compared with the measured beam sizes (represented with + marks). The black vertical bars represent the quadrupoles. The pink vertical bars represent the collimators. The average beam current is 500µA cw. The red line represents the longitudinal bunch half-length (~1.7 rms).

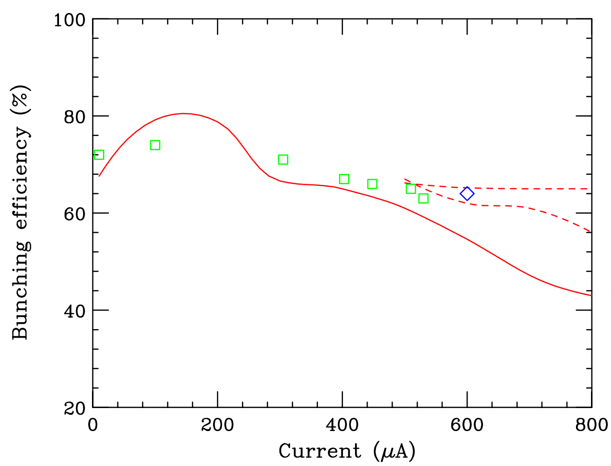


**Figure 3**: Bunching efficiency vs. beam current. The data points are operational results: the 'diamond' was achieved at 96 kV RF voltage and with the present buncher system. The solid line is the calculated result with 90 kV RF voltage and the present buncher system. The lower dashed line is the calculated result with 96 kV RF voltage and the present buncher system; the upper dashed line is the calculated performance with 90 kV RF voltage but with the third buncher added.

Good agreement was achieved, at reduced duty cycle, between the measured and calculated transverse sizes (2rms) of the 300 keV beam in the injection line at 500 µA (320µA cyclotron extracted). Matching to the periodic sections appears good in the horizontal section (see Fig.2), but not good in the vertical section where there are fewer diagnostics and beam-size restraining collimators. With bunching, the local current reaches > 3 mA at cyclotron injection. This causes the space charge effect to become increasingly dominant as the beam travels along the injection line. For injection line currents above 500µA, the fraction of beam that can be accepted by the cyclotron centre region begins to fall despite adjustments to the existing bunchers [6] (see Fig.3) This could be corrected by introducing an additional first harmonic buncher in the vertical section ~2.5 m upstream of the inflector. Alternatively, this effect could be partially compensated by increasing the RF dee voltage, thereby increasing the longitudinal cyclotron phase acceptance.

The choice of the final system configuration for 400µA extracted will largely depend on reliability, reproducibility and stability issues including filament lifetime.

## CENTRE REGION

Originally the centre region design was tested in a 1:1 scale model, capable of accelerating 100µA to a radius of 32 in at 3MeV [7]. At these currents the only collimators required were watercooled beam scrapers designed to vertically limit the beam at the dee gaps. The beam outside the rf acceptance was mostly dumped on a vertical water cooled copper wall joining the upper and lower hot arms and partially surrounding the centre post. In the 500 MeV cyclotron, cooled scrapers were installed at the dee gaps, and uncooled scrapers with thermal sensors were added above and below the median plane upstream of the quadrant 2 and 4 correction plates in the 3 to 5 MeV region. The 220µA overheating problem was solved during the 2002 shutdown by installing a water cooled beam absorber tangentially to the beam inside the first quarter turn, to remove a significant fraction of the ions injected outside the RF acceptance which were impinging on a small non cooled SS support bracket. Consequently average currents could be raised and 285µA average 95% pulsed (300µA space charge equivalent) could be extracted. Recently heating and burn marks were observed on the beam scrapers protecting the correction plates in upper quadrant 2 (UQ2) and lower quadrant 4 (LQ4). The thermal sensors indicated that overheating trips would likely occur between 300 and 400µA. Adjusting the correction plates and trim coils to deflect the beam plane failed to solve the problem.

In 2004 the LQ4 plates were surveyed and found to be 6 mm too close to the median plane. After re-alignment LQ4 heating was substantially reduced. The UQ2 plates will be surveyed and re-aligned during the next winter shutdown hopefully leading to 400µA cw acceleration capability. If necessary these scrapers will be watercooled. In Fig. 4 beam transmission scans from the ISIS beam stop above the inflector to the LE centre region probe are plotted for two different situations: one (Dec 01) before the beam absorber was installed and LQ4 realigned and the other one (June 04) after. The two curves are both normalized to 70% at 40 in, consistently with the 62% transmission to 500 MeV achieved in both tests combined with the well established 8% outer region (R>40 in) losses [8]. It is evident that most of the unwanted centre region beam has been taken care of.

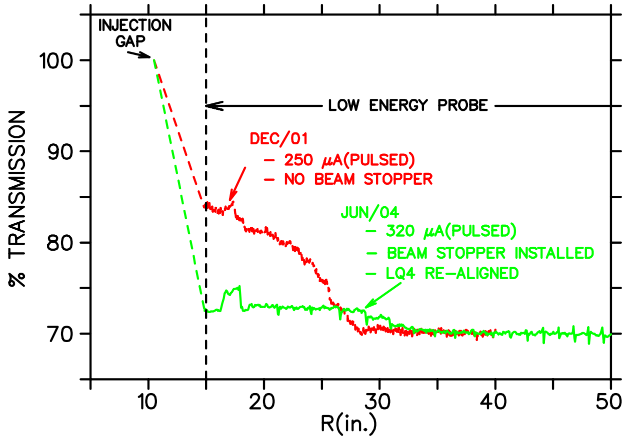


Figure 4: Centre region transmission measured on the low energy probe.

## RF

A comprehensive refurbishing program [ref. 9] has been established and is in progress to improve the overall reliability of the rf system. Although this includes major activities such as the installation of a new output combiner system and the installation of a more reliable crowbar protect system for the anode power supply, the major contribution to the high intensity program was the tuning of the amplifiers for better efficiency to produce an output power of 1 MW to comfortably allow for the added beam power and reliable regulation of pulsed mode operation. Recently a significant reduction of cyclotron downtime due to rf sparking was accomplished by upgrading the resonator tip tuning controls (used to minimize rf leakage in the beam gap) for reliable and easy adjustment. The recovery time permitted by the after-spark restart procedure was also reduced by a factor of 5 to 10. Finally we have started a new program of numerical simulations of the leakage field using HFSS [ref. 10] to further understand and control the rf leakage distribution.

With the above improvements it was possible to raise the rf voltage from the nominal 90 kV to 94 kV, in rather stable conditions. Higher voltage increases the phase acceptance of the cyclotron, and reduces the EM and vacuum stripping losses. The 400 µA, 25% duty cycle demonstration in 2003 was achieved with 96 kV but without the desired stability. Recently we have demonstrated a very stable performance at 94 kV with 200 µA beam extracted, running for 45 hours without sparks. Further rf tests at higher voltages are scheduled.

## EXTRACTION

During the last few years beam was mostly extracted down BL1A, BL2A and BL2C with currents up to 150, 70, and 70µA respectively, at energies of 500, 500 and 83 MeV. Total 250µA were produced in a routine mode. It was found that extracting the BL1A and BL2A beams at the same energy of 500 MeV, through shadowing, and using fully extracting L foils (see Fig.5) was preferable for BL2A beam stability. Partially extracting foils at lower energy may have caused portions of beam to be accelerated past the foil and then reflected backwards and, because of marginal isochronous conditions in the outer magnetic field, to be finally extracted with different emittance. We believe this can be cured by improvement of the overall cyclotron stability in the cyclotron extraction region.

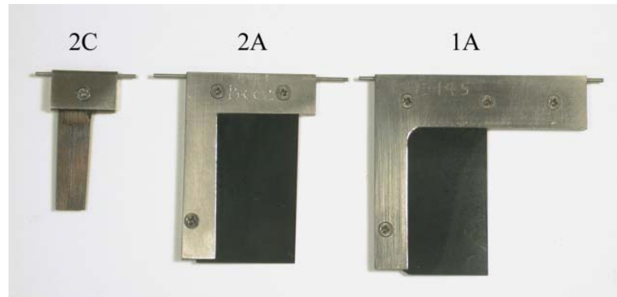


Figure 5. Set of foils installed for the extraction of three high intensity beams totalling 300µA total. The BL2C foil is for partial extraction at lower energies.

Beam line 2C uses a partial stripping 6.4 mm wide brush of 0.032 mm diameter monofilaments of carbon, whereas beam lines BL1A and BL2A use 16 mm wide foils of 5 $mg/cm^2$ pyrolytic graphite. The carbon brush has been found to last longer than other types of foil in the low energy region (<100 MeV) where the $\int dE/dx$ deposited by the $H^-$ nucleus is larger then the contribution of the stripped electrons energy. Foil aging is indicated by increased beam spills in the transport beam lines due to poor beam quality caused by cracks and/or deformations arising from a combination of radiation and thermal effects. Improved foil mounting designs have lead to lifetimes of about 1.35e21 p+ (60mAh) and an improvement of a factor of 2 over earlier results. It should be pointed out that extraction mechanisms allow for the substitution of foils and that with the exception of BL2C, new cartridges of foils can be inserted without interrupting the cyclotron vacuum. A special carousel in BL2C normally allows approximately one-year operation without having to recharge the carousel.

Beam line 4N will require an extraction system capable of delivering ≤200 µA at 500 MeV. This will be the best energy (with a three foil shadow arrangement) for initial commissioning and for the initial target development work. The existing BL4A extraction probe has been previously tested up to 10µA, and may work at higher currents. However a new dedicated mechanism will be designed, similar to the one being used for BL2A and will allow full 200µA extraction at 500MeV (previously tested on BL1A) and partial extraction, up to 100µA, between 450 and 500 MeV. Partial extraction below 500 MeV will be challenging, but a lot of experience was accumulated on this at lower intensities. We do not expect insurmountable problems due to the possible x2 beam density increase when the cyclotron current is gradually raised from ~220 to ~ 400µA.

## PRIMARY BEAMLINES AND ISAC TARGETS

TRIUMF delivers at present some of highest yields of exotic ions. We have been routinely delivering 40μA of 500 MeV protons to metallic foil targets (Ta,Nb) with normal cooling, and we have started delivering 70μA to high power targets. Carbide targets (SiC,TiC,ZrC) are operated between 30 and 40μA. Because of Radiation Enhanced Diffusion (RED), yields normally vary non-linearly with proton fluxes depending on the prevailing annihilation mechanism of the Frenkel defects (vacancies and interstitials) in the target material lattice [11]. We have observed yield enhancements as a function of proton beam current for many short-lived products from a variety of ISAC targets. Generally enhancements are well above expectations and lie within the bounds of the $\Phi_p^{3/2}$ and $\Phi_p^2$ extrapolations. Fig. 6 displays the $^{11}$Li yield as a function of $p^+$ beam current, (lying above the $\Phi_p^2$ extrapolation).

This type of investigation is only one example of the study or development work that is required to design targets and maximize their yields. Other essential work concerns the design and optimization of RIB ion sources. Both activities require a real proton beam with the same characteristics of the beam used for RIB production and real target conditions. The importance of this work for the success of the experiments is overwhelming. On the other hand it is immediately obvious that this activity could not be performed in parallel with RIB production using the system of two target stations at the end of BL2A. The second recently installed station is required as a backup and to avoid long program interruptions because of target changes. Both targets share the same mass separator [12] making it impossible to perform efficient target development work. The availability of an additional 100μA beam extracted from the cyclotron was seen as a unique opportunity to create a real beam test stand for ISAC targets. This led to the proposal of BL4N [13] (see Fig. 1 in the introduction).

Beamline 4N is similar to beam line BL2A in that there is a long (16m) drift through the shielding berm. The beam is then directed north to a target assembly (similar to that that exists on beamline 2A) or to a beam dump. The beam dump will be capable of handling the 200μA proton beam dump requirement during tuning of the cyclotron for 400μA operation. The optics of beamline 4N utilizes three existing quadrupoles in the cyclotron vault, an existing dipole, and an added quadrupole doublet to control the beam size through the dipole and to produce a dispersed double waist at the midpoint of the long drift. In the external tunnel quadrupole doublets on either side of a second dipole produce an achromatic double waist. A four-quadrupole matching section follows to produce another double waist, nominally 4mm in diameter. Beam transport elements downstream of the matching section deliver beam to either the beam dump, where a beam ~8cm in diameter is required, or to the target assembly, where a singly achromatic double waist, is produced. Because beam spots on existing ISAC targets are a function of the stripper foil dimensions, uneven heating of the target material may occur. Furthermore, in order to provide the desired flexibility for the target development station, simple ways of reproducing and manipulating incident beam spot sizes are being investigated. A telescopic section is being considered.

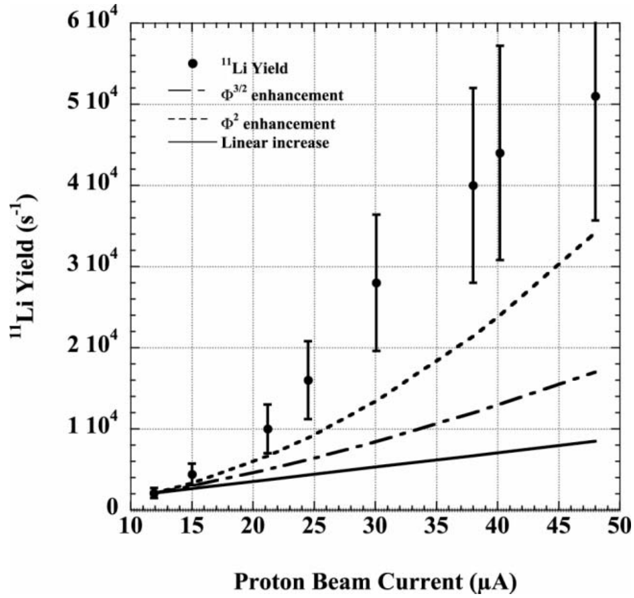


Figure 6: $^{11}$Li yield as a function of the proton beam intensity.

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