THE TRIUMF 500 MeV CYCLOTRON: PRESENT OPERATION AND INTENSITY UPGRADE

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Abstract

A new series of experiments (mainly astrophysics) began at TRIUMF in July 2001 when the ISAC-I linear accelerator began delivering up to 1.5 MeV/u radioactive ion beams (RIB) to users. A superconducting linear accelerator extending the RIB energy to 6.5 MeV/u has recently been approved and is now being constructed (ISAC-II). Record RIB intensities are being achieved from different target ion sources with a primary incident proton beam of 500 MeV, up to 50 μA intensity. This will later be increased to 100 μA, compatibly with target acceptance. Furthermore, an additional 100 μA extracted proton beam is being considered for simultaneous (RIB) production from a second target-ion source system. This would significantly enhance the research potential of the laboratory. Four simultaneous high-intensity extracted beams would therefore be required for a total maximum cyclotron accelerated current of about 400 μA. Recently we have been able to deliver 300 μA to the existing three high intensity beam lines at 90% duty cycle. The cw delivery of beam was limited only by the presently available external beam dump capacity. In this paper we will review the present operational experience at 200/250 μA, the future plans for intensity upgrade to 350/400 μA, and the intrinsic factors limiting the total accelerated intensity beyond 400 μA.

INTRODUCTION

ISAC is an ISOL radioactive ion beam facility driven by a 500 MeV proton beam from one of the TRIUMF cyclotron's external beam lines[1]. A layout of the existing ISAC-I and the planned ISAC-II accelerator is shown in Fig. 1 [2, 3].

ISAC-I has been operating since 2001 and consists of a primary beam line (BL2A) capable of delivering up to 100 μA of protons to a target-ion-source mass-separator/LEBT system supplying radioactive beam to either a low-energy experimental area or to a room temperature linac consisting of an RFQ, a stripper, and a DTL in which ions with A $\leq$ 30 are accelerated up to 1.5 MeV/u.

ISAC-II, which is now under construction, will accelerate ions with A $\leq$150 to at least 6.5 MeV/u by 2009[2]. An ECR charge state-booster will produce higher charge-state ions with charge to mass ratios of A/q$\leq$30 for acceleration in the existing ISAC-I RFQ. A new room temperature IH-

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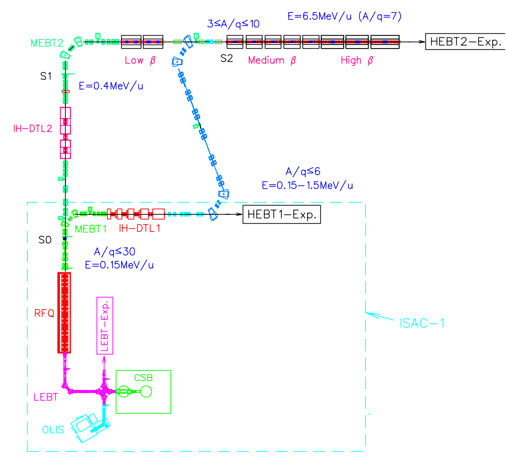

Figure 1: ISAC layout

DTL will accelerate the ions from the RFQ to 400 keV/u where they will be stripped and then injected into a heavy ion superconducting linac[4]. In 2005 the 20 medium β superconducting cavities will begin operating on line. A new beam line will also connect the exit of the ISAC-I DTL to the entrance of the medium β cavities so that the 1.5 MeV/u beam from ISAC-I can be accelerated up to 4.3 MeV/u, permitting higher-energy experiments to begin. In 2007 the high β cavities will be installed, increasing the available energy to at least 6.5 MeV/u. ISAC-II will be completed when the IH-DTL and the low β cavities are added to improve the stripping efficiency and to extend the mass range to A=150.

It is proposed that a new 100 μA extraction line (BL4N) and target station dedicated to target/RIB development be included in TRIUMF's next five year plan. This facility could eventually be reconfigured and used as an additional radioactive ion source for ISAC, allowing at least two experiments to run simultaneously using the proton beams from the TRIUMF cyclotron[3].

As shown in Table 1, using a surface ion source ISAC-I has already produced record intensity radioactive beams downstream of the mass separator. So far, the primary 500 MeV proton beam intensity has been limited to 50 μA. This will eventually increase to 100 μA[5]. An ECR source is now being commissioned in the recently completed east target station[5], and a laser ion source is being developed.

When all of TRIUMF's existing extraction lines are operating simultaneously at their maximum currents (BL1A at 150 μA for pion/muon production, BL2A at 100 μA for

Table 1: Radioactive Ion Yields

Ion	Target	$I_p(\mu A)$	Yield(P/s)
^{8}Li	Ta	40	8.3×10^{8}
^{9}Li	Ta	35	9.4×10^{7}
^{11}Li	Ta	30	1.2×10^{4}
^{20}Na	SiC	45	2.6×10^{8}
^{21}Na	SiC	45	9.9×10^{9}
^{37}K	TiC	40	6.4×10^{7}
^{38g}K	TiC	40	1.8×10^{10}
^{38m}K	TiC	40	7.4×10^{7}
^{74}Rb	Nb	30	1.3×10^{4}
^{74}Ga	ZrC	45	2.2×10^{6}
^{75}Ga	Ta	40	1.0×10^{6}
^{94}Y	Ta	11	6.0×10^{4}

ISAC, BL2C4 at 50 μA for isotope production), 300 μA will be required from the cyclotron. With the 100 μA BL4N operating, 400 μA will be needed. Because this total current exceeds those so far delivered, a high current development program was begun.

HIGH CURRENT DEVELOPMENT

Over the last 15-20 years TRIUMF has been responding to user demands by simultaneously extracting a total current of up to ≈220 μA down three or four external beam lines. Approximately 5,000 hours of beam time is scheduled each year, and typically 90% of this is successfully delivered. Recently a record total annual extracted beam charge of over 700 mAh was achieved. Our goal is to obtain 350-400 μA simultaneously extracted down the four beam lines shown in Fig. 2.

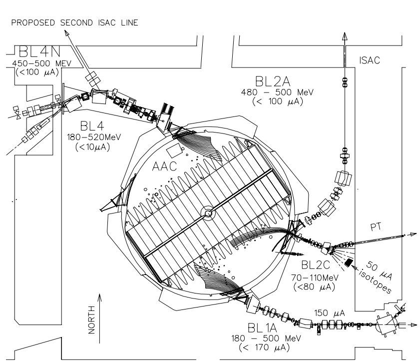

Figure 2: Layout of the TRIUMF cyclotron.

The beam injected into the cyclotron from the ion-source-injection system (ISIS) is normally bunched so that slightly over 70% of it is within the phase acceptance of the cyclotron. The remaining 30% is lost either radially or vertically in the centre region. Radial losses occur when ions that gain too little energy crossing the injection gap spiral into the vertical resonator walls surrounding the centre post. Vertical losses may occur over the first few turns when ions that cross the dee gaps when the rf phase is negative get defocused and hit beam scrapers attached to the dees. Space charge defocussing increases this vertical loss.

A portion of the radially lost beam was being deposited on poorly conducting stainless steel ribs used to reinforce the vertical resonator walls, producing temperature trips at currents higher than ≈220 μA.

In addition to the heating problem, by the end of 2001 it had been discovered while running pulsed beams that the cyclotron transmission dropped from over 60% with equivalent currents of 220 μA or less to approximately 50% with equivalent currents of 300 μA due to increased beam losses in the centre region.

Several improvements were made during the first half of 2002.

1. The correction plates shown in Fig. 3, used for vertical steering on the first few turns, were repaired and realigned after they were found to be beam damaged and misaligned.

2. As shown in Fig. 4, a water-cooled beam stopper was installed in the first quarter turn of the cyclotron to intercept that portion of the beam that previously was being lost radially.

3. The back edge of an r.f. contact was found to be protruding into the beam gap and was trimmed back.

4. Improved ISIS tunes were developed. Running the H^- cusp source at lower arc currents with higher gas flows seemed to improve the transmission through the cyclotron.

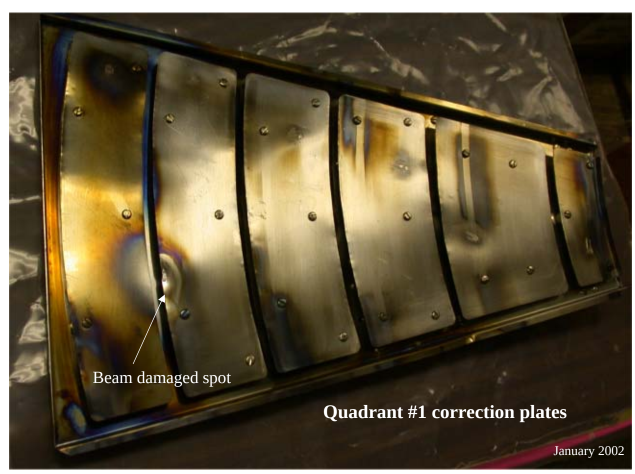

Figure 3: Centre region correction plates showing beam damage.

In July 2002 a new high-current record was established for TRIUMF when 275 μA was accelerated at full duty cycle for 3 hours. As shown in Fig. 5 the stability of the extracted beam was acceptable (the four short beam-off periods were due to rf sparking and to external beam line problems). Extraction of average currents greater than 275 μA

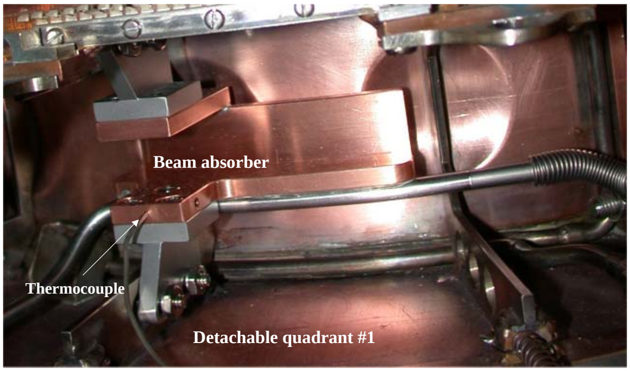

Figure 4: Centre region beam stopper.

was impossible because of external beam dump limitations, however we were able to extract 300 μA equivalent current at 90% duty cycle for two hours without encountering any problems. Cyclotron transmission was better than 60% in both cases while ISIS transmission was ≈90%. No temperature trips occurred during any of these runs. Just before the end of the development shift, 350 μA equivalent was accelerated at 40% duty cycle with 57% cyclotron transmission for half an hour.

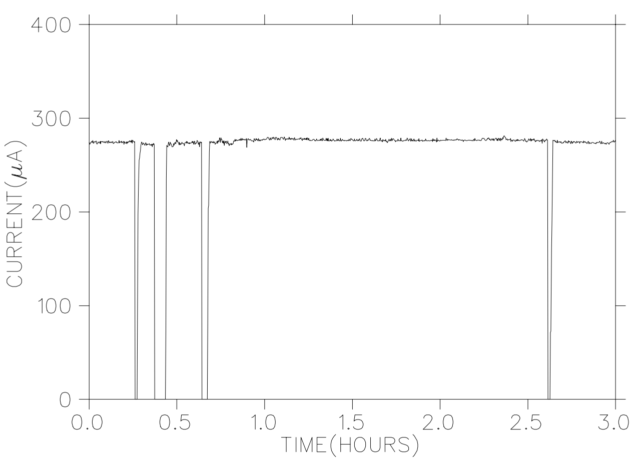

Figure 5: 275 μA extracted current versus time.

During subsequent development shifts we found that although the 300 μA results were easily reproduceable, it was difficult to increase the current much above 300 μA. Near the end of 2002 analysis of the rf power input to the dees and of the time-of-flight between injection and extraction indicated that the calibration of the rf voltage probes had been changing, and the actual rf voltage was ≈10% lower than indicated on the control console, thus limiting the cyclotron's phase acceptance. In December the rf voltage was increased, and equivalent currents of 350 and 380 μA were extracted at 10% duty cycle with over 60% transmission. Time limitations prevented us from trying to decrease the spills and raise the duty cycle or from trying to obtain 400 μA equivalent current. This work will resume in spring 2003 when high current operation resumes after the winter shut down (400 μA equivalent current was previously achieved with a lower transmission using a different ion source in 1988[6]).

Several improvements to facilitate high current development are being implemented or planned.

1. Adjustable emittance-limiting slits are being installed in ISIS to control the emittance of the injected beam.
2. Improved beam diagnostic devices are required in ISIS. An emittance measuring rig as well as additional wire scanners in the vertical section of ISIS are needed.
3. The ion source extraction voltage will be raised from 12 kV to 25 kV, and the source's extraction optics will to be redesigned so that higher currents can be extracted at lower arc currents.
4. The aging lower vertical section of ISIS needs replacing to enhance reliability. In addition, a third buncher may be installed in this section to improve bunching efficiency at higher currents[8].
5. For 400 μA tests and operations a new 200 μA beam dump is required to operate in parallel with the 200 μA acceptance of BL1A. It's proposed that this be installed on BL4N in the vicinity of the ISAC targets.

These projects are proposed for the next five year plan.

The high-current capability of TRIUMF is ultimately limited by space charge and by the spills produced by electromagnetic stripping of the H^- beam at higher energies. TRIUMF's space charge limit has been estimated to be ≈ 500 μA with 100 kV of dee voltage, which comfortably exceeds our 400 μA goal. Stripping losses have been reduced by installing an auxiliary rf booster cavity to increase the energy gain per turn above 450 MeV where most of the stripping loss occurs[7]. This allows us to increase the 500 MeV extracted beam from 170 to 250 μA. The rest of the beam would have to be extracted at 450 MeV or below.

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