COMPLETION OF THE ISAC-I ACCELERATOR FOR RADIOACTIVE IONS AND EXTENSION TO ISAC-II*

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Abstract

Since 1998 the TRIUMF H^- cyclotron has been equipped with a new 500 MeV proton extraction beam line dedicated to the new ISAC facility (Isotope Separator and ACcelerator). Up to 40 μA have so far been delivered to the ISAC target system for routine radioactive beam production. 100 μA (the ISAC primary beam design intensity) were also delivered for a specific target test. Initial ISAC experiments were performed with singly charged radioactive ions at target/ion-source energies ($E \leq 60$ keV/u). A cw linac based on a 35.4 MHz 8 m long RFQ ($A/q \leq 30$) followed by a 106 MHz post-stripper DTL ($3 \leq A/q \leq 6$) has recently been commissioned and now delivers radioactive ion beams to experiments at energies between 0.153 and 1.53 MeV/u ($A \leq 30$). Recently, TRIUMF was also funded to proceed with the construction of the ISAC-II expansion, which will accelerate beams of $A \leq 150$ up to energies of at least 6.5 MeV/u, above the Coulomb barrier. Recent milestones, initial operational experience with ISAC-I and first results from ISAC-II prototyping are reported.

1 INTRODUCTION

The TRIUMF laboratory and its major areas of activity were outlined at the first APAC conference in Tokyo [1]. Since then progress has been substantial in several areas including the Canadian contribution, through TRIUMF, to the LHC construction and the infrastructural support given to Canadian physicists involved in large experiments (mainly particle physics) at other international facilities. However, major achievements impacting the TRIUMF facility in Vancouver were (1) the first production, in November 1998, of an ISOL type radioactive beam at ion-source-target energies (≤ 60 keV/u) in the new ISAC-I building, (2) the first acceleration before year-end 2000, practically on schedule, of a $^4He^+$ beam to the design energy of 1.5 MeV/u, and (3) the delivery on July 26, 2001 of a first radioactive beam of $^8Li^{2+}$, at an energy of 750 keV/u, to an experiment in the high energy area. During year 2000, TRIUMF was also funded to proceed with the construction of the ISAC-II expansion, aiming at accelerating beams of $A \leq 150$ up to energies of 6.5 MeV/u (or above for light ions). These events are transforming TRIUMF into a major world laboratory for radioactive ion beam physics, and into the major ISOL type facility presently operating in North America.

2 THE ISAC PROJECT

The ISAC project has been previously described [2, 3]. Briefly, the 500 MeV primary proton beam is extracted from the H^- cyclotron with intensity up to 100 μA and directed through an underground tunnel to one of two ISAC target systems situated in a heavily shielded section of the experimental building. This section is equipped with a crane and hot cells for remote manipulation and maintenance of target modules. The target systems (East and West) (Fig. 1) are arranged in a configuration where radioactive ions are extracted toward a ± 60° "pre-separator" magnet with mass resolving power of $m/\Delta m \sim 300$. After momentum selecting slits, the remaining ions are transported to the "mass separator hall" where a 135° ($m/\Delta m \sim 10{,}000$) mass separator magnet, on a high voltage platform, is used to reject the fractional contamination remaining after the pre-separator. Downstream, the singly charged separated ion beam with transverse emittance around 10 π mm mrad and energy ≤ 60 keV is channeled through horizontal and vertical electrostatic LEBT transport sections from cyclotron level 264′, to a switchyard system at grade level 284′ in the ISAC-I experimental hall (Fig. 2). The switchyard directs the beam either to one of several low-energy experimental stations or to the entrance of the linear accelerator.

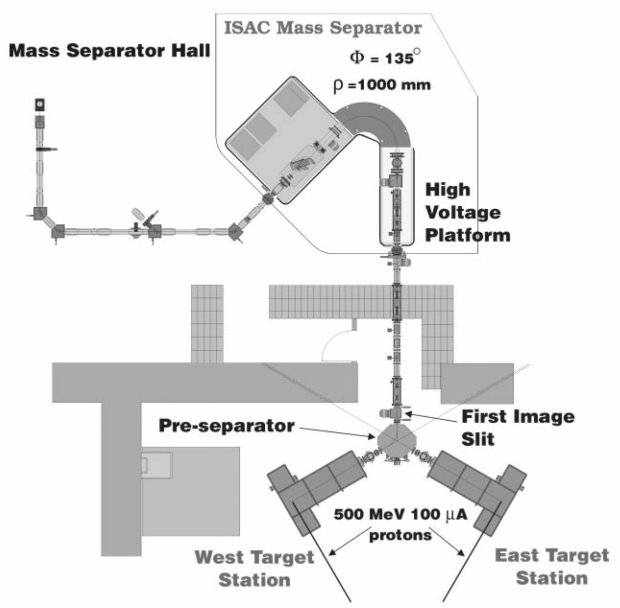


Figure 1: The target mass separator area.

The accelerator complex consists of an RFQ linear accelerator, a stripping section, and a DTL system. The RFQ consists of an 8 m long, 35.4 MHz, 4 rod split ring rf quadrupole accepting ions with $A/q \le 30$ and operating at an rf power level of ~80 kW cw. The beam is accelerated to 150 keV/u. The 90° stripping/bender section selects the A/q ratio of the ion beam to be injected into the DTL, which comprises five IH DTL structures in separate tanks for acceleration, intercalated with four magnetic triplets and three rf bunchers for transverse and longitudinal focusing. Acceleration to energies between 0.150 and 1.5 MeV/u is provided for ions with $3 < A/q < 6$. Five additional bunchers and two choppers are inserted elsewhere along the linac to allow the final beam to be distributed longitudinally in bunches at 86 or 172 ns intervals. The final beam energy can be varied by shutting off the power on one or more tanks at the end of the accelerator and/or by varying the phase of the last powered DTL tank.

The ISAC-II expansion will include a DTL2 section extending the present 150 keV/u line to the North and accelerating the beam to an energy of 400 keV/u for stripping, so that heavier ions can be efficiently stripped for acceleration through the downstream superconducting linac. This linac will consist of low, medium, and high β sections with $\lambda/4$ cavities resonating at 70.8, 106.2, and 141.6 MHz for β of 4.2%, 7.2%, and 10.5%, respectively. In order to be accepted by the RFQ, singly charged ions from the ion source, with $30 \le A/q \le 150$, will have to be ionized to a higher multicharge state at injection. An ECR charge state booster is presently being evaluated in collaboration with ISN Grenoble .

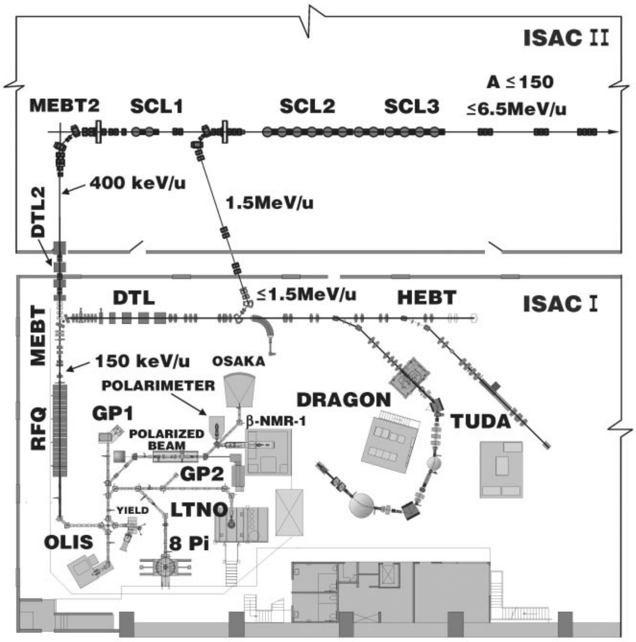


Figure 2: Layout of the ISAC-I experimental hall and the ISAC-II accelerator.

Table 1: Radioactive ion yields achieved.

^{A}X	Target	Experiment	I (p) μA	Yield P/s
^{37}K	CaO	TRINAT	1	3×10^{6}
^{38}K	CaO	TRINAT	1	3×10^{8}
^{37}K	Cao	Lifetime	1	6×10^{6}
^{37}K	CaO	Lifetime	1	3×10^{8}
^{74}Rb	Nb	Lifetime	10	5×10^{3}
^{75}Rb	Nb	LTNO	10	2.4×10^{5}
^{8}Li	Nb	β-NMR	10	2×10^{8}
^{74}Rb	Nb	Lifetime	10	4×10^{4}
^{8}Li	Ta	β-NMR	20	5.6×10^{8}
^{11}Li	Ta	Yield meas.	20	1.4×10^{4}
^{38m}K	$CaZrO_3$	Lifetime	1	5.5×10^{6}
^{38m}K	$CaZrO_3$	TRINAT	1.5	1.5×10^{7}
^{21}Na	SiC	Yield meas.	10	3.3×10^{8}
^{74}Rb	Nb	Lifetime	30	8.5×10^{4}

Low-energy beam facilities like TRINAT, GPS and β-NMR are used in a broad program covering fundamental symmetry tests, nuclear structure studies in exotic nuclei and condensed matter studies with light polarized ions. A low temperature nuclear orientation refrigerator (LTNO) is used for on-line nuclear magnetic resonance and perturbed angular correlation studies. An 8π germanium gamma-ray detector array will be used in studies of nuclear deformation in transitional regions. The facilities served by the ISAC-I accelerator reflect emphasis on nuclear astrophysics. A large-acceptance recoil spectrometer system (DRAGON), with a rejection factor of $1/10^{15}$, is being commissioned to study radiative capture reactions involved in explosive events like novae, supernovae, and X- and γ-ray bursts. To complement it, a large-acceptance scattering facility (TUDA) has been developed to locate resonances of interest in the corresponding compound nuclei. ISAC-II is designed mainly to enable a range of nuclear structure studies to take place with proton- or neutron-rich projectiles near the limits of stability, but a strong focus on nuclear astrophysics will remain.

3 COMMISSIONING AND INITIAL OPERATION OF ISAC-I

3.1 Target Ion Source & LEBT System

Different production targets were operated. Typical ion yields downstream of the mass separator are given in Table 1 for different primary proton currents. The transmission through the LEBT system was routinely above 80 or 90%. The mass separator system performed according to expectations. In most cases targets lasted through the scheduled periods, typically of a few weeks to several months. Interruptions of beam production occurred once because of the deposition of Ca on the extraction electrode, caused by rapid evaporation of CaO, in another case because of overheating of a connection in the electrical target heating circuit. This caused metallization on insulators and related high voltage holding problems. To make beam scheduling more efficient, high priority was given to the completion of a second (East) target system so that the second system could be ready at the end of the production period from the first target, thereby avoiding lengthy interruptions because of target maintenance. The East target system is planned for installation during the Spring 2002 shutdown. An LEBT system highlight was the on-line laser polarization of the ^{8}Li beam neutralized with a Na vapour jet and ionized 1.9 m downstream in a He gas cell [4]. A beam of ~10^{7} ions/s with maximum polarization of 75% was delivered to the β-NMR facility. This unique facility allows the implantation of radioactive ions at different depths in thin film structures.

3.2 The ISAC-I Linac

The commissioning of the ISAC-I accelerator proceeded in various phases. Initially, high priority was given to RFQ design, construction and testing. Because of the low intensity beam, the gentle shaper buncher section could be omitted. An 11.8 MHz pseudo-sawtooth pre-buncher was instead installed 5 m upstream. After testing the first 7 ring low-β entrance section at full rf power with beam, the whole RFQ with 19 rings was successfully commissioned during summer 1999 [5]. The alignment tolerance of ±0.08 mm had been achieved. An unexpected difficulty was the appearance of substantial dark currents associated with field emission. Careful cleaning procedures and high power pulsing drastically reduced this phenomenon and allowed routine beam acceleration at the nominal maximum voltage of 74 kV. The beam injected from the pre-buncher was found to be accepted for acceleration with 75% transmission in buckets 86 ns apart. Typical transverse and longitudinal emittances of the accelerated beam were 0.1 π mm mrad and 0.7 π keV/u ns.

Commissioning of the 90° MEBT stripper/bender section, which includes several magnetic quadrupoles, a 6 kW split-ring triple-gap buncher and a 2 kW spiral double-gap buncher [6] for transverse and longitudinal beam focusing, did not involve unexpected problems. The beam was tested to the end of the first DTL section. Worth mentioning is the occurrence of foil thickness alterations due to carbon build-up because of local vacuum contamination. A cold trap was installed around the stripping foil to minimize this effect. Also, a global phase shifter to correct for small thickness variations during foil changes was found to be very useful.

Beam commissioning through the DTL linac, its three bunchers, and four triplets was also reasonably smooth after a few problems had been corrected. One problem was the disagreement between the rf power found to be dissipated on the DTL tank walls during power tests and the one predicted from our MAFIA calculations. In order to avoid drilling cooling lines in the tank walls after they had already been assembled and aligned with their drift tubes, it was decided to attach external water cooling lines to tanks 2, 3, 4, and 5 using a special hardening cement in a configuration that would maintain the tank temperatures below 45° C at full power [7].

Another rf problem appeared on tank 3 where some residual flux, remaining after soldering the entrance nose cone to the tank lid, diffused towards the rf gap. The flux caused poor local vacuum, unstable voltage regulation and three coupling loop failures. After cleaning the solder joint and installing an rf shielding cup over it, the tank was reliably powered.

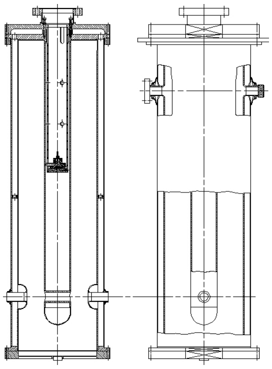
A ^{4}He^{+} beam was accelerated to full energy (1.53 MeV/u) on December 21, 2000 practically on schedule. Thereafter, the tunes were established for 20 different final energies to cover the whole operating range. The transmission through the DTL was over 95% in all cases. Tunes for other stable ions from the OLIS ion source (^{14,15}N^{4+}, ^{16}O^{4+}, ^{21}Ne^{5+}, and ^{24}Mg^{6+}) were also established. Transverse emittances (normalized) were typically of the order of 0.1 π mm mrad for stripped ions, or smaller for unstripped ions (^{4}He^{+}). Longitudinal emittances were found to be ~0.8 π keV/u ns for the unstripped beam and about three to five times larger for the stripped beam. Transmissions through the DTL were in all cases well above 95%. Overall transmission for the ISAC-I accelerator was therefore ~20% (70–75% through RFQ, ~30% through stripper, ~95–100% through the DTL) when using the 11.8 MHz 86 ns chopper. With the 5.9 MHz 172 ns chopper the transmission was reduced by a factor of two (to ~10%).

3.3 First Acceleration/Operation of the RI Beam

The first radioactive beam accelerated through ISAC-I was a ^{8}Li beam extracted from a Ta target. The flux at the mass separator was a few 10^{8} ions/s, whereas at the experiment, with the 172 ns chopper, we obtained a few 10^{7} ions/s. Results were in reasonable agreement with the 10% transmission expected. The tuning of the radioactive beam was aided by pilot beams. First a ^{7}Li stable beam was produced at the RIB target. The intensity of this beam, ~1 nA, was sufficient for the normal diagnostics (scanning wires and Faraday cups) to be used. At the OLIS ion source, upstream of the RFQ, a stable beam of ^{14}N^{2+} was produced, tuned through the RFQ, stripped to ^{14}N^{4+}, and then accelerated through the DTL. The ^{7}Li^{+} beam was then easily injected in the tuned accelerator, stripped to ^{7}Li^{2+}, and then accelerated through the DTL. For the ^{8}Li^{+} beam, calculated variations of the optical parameters expedited the LEBT tuning to the RFQ. From here on stable OLIS ^{16}O^{2+} ions (^{16}O^{4+} after stripping) had been used to set the tune parameters for the acceleration of the ^{8}Li ions. Only minor adjustments were necessary to maximize the transmission. ^{8}Li losses at slits or collimators could be detected via a hand-held X-ray /γ-ray detector, minimized and most often eliminated. The technique of pilot beams avoids substantial RIB losses introduced by a lengthy tuning process and therefore avoids the build-up of background contamination. Several diagnostic monitors are being readied for RIB detection at low intensities. Silicon detectors have been used for correlated measurements of energy and time (phase) and ion flux. Conventional scintillator screens have been used at a few $\times 10^4$ stable ions per mm^2. They may be useable at lower fluxes, especially when decay products provide additional light. γ- and X-ray detectors will monitor loss near slits or collimators.

4 ISAC-II PROTOTYPING

A medium-β λ/4 bulk niobium superconducting cavity has been designed in collaboration with INFN-LNL (Legnaro). This was fabricated in Italy, received chemical polishing at CERN, and was rf tested at LNL. The cavity is shown in Fig. 3 along with design parameters. Results of the first rf tests are shown in Fig. 4. The cavity performance exceeded the ISAC-II requirements of 6 MV/m. An accelerating gradient of 6.7 MV/m for 7 W dissipated at 4 K was achieved [8]. A peak gradient of 11 MV/m was also achieved before quenching. A superconducting rf test lab is now being set up at TRIUMF. The design of the building extension to house the ISAC-II facility is nearing completion and construction is imminent with building occupancy scheduled for January 1, 2003. The first stage of the superconducting linac consisting of twenty medium-β cavities is planned for installation and testing in 2004.



Frequency: 106.08 MHz

Optimum velocity : β=0.072

U/E_a = 0.09 J/(MV/m)^2

$R_s \times Q$ =19.1 Ω

$E_p/E_a \cong 4.6$

H_p/E_a = 103 G/(MV/m)

Design E_a : ≥6 MV/m @ 7 W

Figure 3: The prototype 106 MHz medium-β cavity for the ISAC-II project at TRIUMF.

The number of high-β cavities which will be installed within this five year plan (before March 31, 2005) may be affected by budget limitations. However, we expect to reach the energy of 6.5 MeV/u for at least the lighter ions (A < 60). The ECR charge state booster unit upstream of the RFQ will be used. Stripping will take place at 150 keV/u, before DTL injection. A transfer line connecting the ISAC-I HEBT line to the front end of SCL2 in ISAC-II (Fig. 2) will allow the ISAC-II experimental work to start in 2005 or sooner. The DTL2 linac and the low-β SCL1 linac will be added later to accelerate all ions in the A < 150 range.

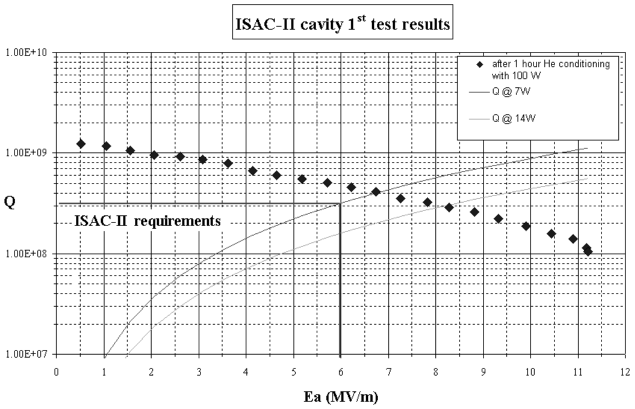


Figure 4: First rf test results for the prototype 106 MHz medium-β cavity for ISAC-II.

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* TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada.

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