ISAC-I AND ISAC-II AT TRIUMF: ACHIEVED PERFORMANCE AND NEW CONSTRUCTION

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Abstract

ISAC-I at TRIUMF is now delivering intense beams of both low energy and accelerated radioactive ion beams (RIBs) for experiments. The post-accelerator for ISAC-I includes a room temperature RFQ and DTL operating cw to accelerate ions of $A \leq 30$ to a final energy fully variable from 0.153 to 1.53MeV/u. The design concept, machine status and early operating experience of the ISAC-I linear accelerator complex will be summarized.

TRIUMF has received funding through to 2005 to proceed with an extension to the ISAC facility, ISAC-II, to permit acceleration of radio-active ion beams above the Coulomb Barrier for masses up to 150. Central to the addition are a ECR charge state booster before the ISAC RFQ and a superconducting heavy ion linac. The accelerator design and present status of the project including superconducting rf developments will be presented.

1 INTRODUCTION

There is an intense interest world-wide in the use of Radioactive Ion Beams (RIBS) for experiment. Within the past year three new ISOL based facilities have added dedicated post accelerators to deliver accelerated RIBs to experiment. By virtue of a strong driver beam and with the completion of the ISAC-I post-accelerator, TRIUMF is now poised to become the leading facility for ISOL based systems, delivering intense beams of both low energy and accelerated RIBs for experiments. In brief, the facility includes a 500 MeV proton beam (I $\leq$ 100 μA) from the TRIUMF cyclotron impinging on a thick target, an on-line source to ionize the radioactive products, a mass-separator, an accelerator complex and experimental areas.

The accelerator chain includes a 35.4 MHz RFQ[1], to accelerate beams of $A/q \leq 30$ from 2 keV/u to 153 keV/u and a post stripper, 106 MHz variable energy drift tube linac (DTL)[2] to accelerate ions of $3 \leq A/q \leq 6$ to a final energy between 0.153 MeV/u to 1.53 MeV/u.

TRIUMF is now constructing an extension to the ISAC facility, ISAC-II, to permit acceleration of radioactive ion beams up to energies of at least 6.5 MeV/u for masses up to 150. In brief the proposed acceleration scheme would use the existing RFQ with the addition of an ECR charge state booster to achieve the required mass to charge ratio ($A/q \leq 30$) for masses up to 150. A new room temperature IH-DTL would accelerate the beam from the RFQ to 400 keV/u followed by a post-stripper heavy ion superconducting linac designed to accelerate ions of $A/q \leq 7$ to the final energy. A new building will be ready for occupancy in Jan. 2003. An initial installation of 25 MV of superconducting linac will be completed in 2005 with a further 18 MV added two to three years later. Present studies are concentrating on design and development for the first stage installation.

2 BEAM PRODUCTION

Present licensing permits continuous operation at 100 μA proton intensity for targets with $Z \leq 82$. Thus far 40 μA has been run onto Nb and SiC targets and 20 μA onto a Ta target. Beams of $E \leq 60$ keV and $A \leq 238$ have been delivered to the low energy experimental area since 1998. Sample yields are 2.2×10^4pps ^{11}Li from a Ta target, 1.4×10^4pps ^{74}Rb from a Nb target and 3×10^9pps ^{21}Na from a SiC target. Presently beams are run to six experimental stations in the low energy area and two experimental stations in the high energy area.

Present production is restricted to a single 'West' target station. Completion of a second 'East' target station is imminent with commissioning from a stable surface source scheduled for Sept. 2002. A 2.45 GHz ECR source for the production of singly charged gaseous species is operational on an off-line test stand and is scheduled for installation in the 'East' target station for commissioning with stable beams in Oct. 2002. First radioactive beams are expected from the ECR in Nov. 2002. Operation of the 'West' target continues in the fall with the installation of a TaC target for potassium beams.

3 ISAC-I ACCELERATOR

3.1 Description

A low energy beam transport (LEBT) delivers stable beams from the off-line source (OLIS) or exotic beams from the mass-separator to the RFQ. A switchyard can send the stable beams to the low energy area while simultaneously delivering RIBs to the high energy area, or *vice versa*. The LEBT is completely electrostatic and houses an 11.8 MHz multi-harmonic pre-buncher 5.7 m upstream of the RFQ. A layout of the post-accelerator for ISAC is shown in Fig. 1.

The medium energy beam transport (MEBT) is composed of a matching section to the stripping foil, a charge selection section and a matching section to the DTL. A two frequency chopper[3] provides a clean separation between pulses selectable between 85 and 170 ns and a 106 MHz bunch rotator produces a time focus on the stripper foil. The DTL matching section utilizes a 35.4 MHz spiral rebuncher. The high energy beam transport (HEBT) delivers the beam from the DTL to the experimental stations. A bunching station consisting of a low-β 11.8 MHz triple gap structure and a high-β 35.4 MHz spiral resonator are incorporated to maintain the good longitudinal emittance to the

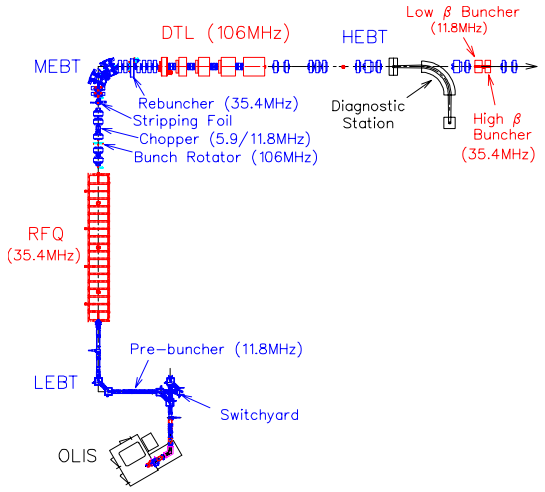


Figure 1: The ISAC-I accelerator.

target.

The RFQ [1], a four vane split-ring structure (Fig. 2), has no bunching section; instead the beam is pre-bunched at 11.8 MHz.This not only shortens the linac but reduces the longitudinal emittance at a small expense in the beam capture. The variable energy DTL (Fig. 3) is based

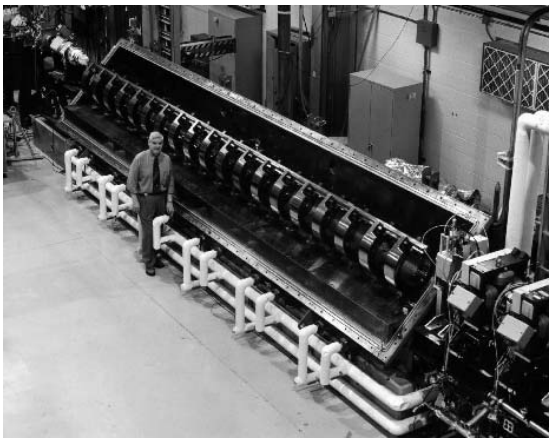


Figure 2: The ISAC 35.4 MHz RFQ.

on a unique separated function approach with five independent interdigital H-mode (IH) structures, each with 0° synchronous phase, providing the acceleration with quadrupole triplets between tanks and three-gap bunching cavities before Tanks 2,3,4 providing transverse and longitudinal focussing respectively. The DTL is designed to efficiently accelerate low-β heavy ions over a large operating range while maintaining high beam quality. The IH tanks consume only 63 kW of rf power to produce a total accelerating voltage of 8.1 MV over the 5.6 m length. To achieve a reduced final energy the higher energy IH tanks are turned off and the voltage and phase in the last operating tank are varied.

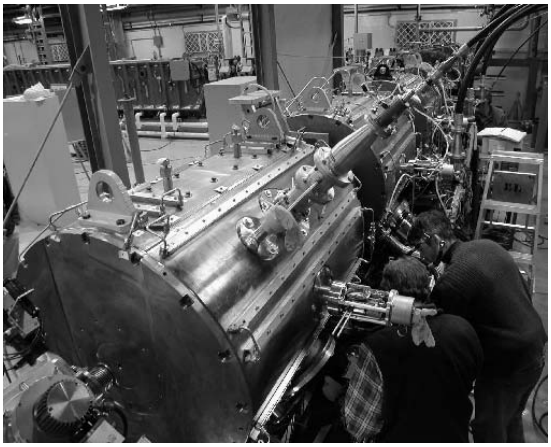


Figure 3: The ISAC 106.1 MHz DTL.

Commissioning and Beam Delivery Beam commissioning with stable beams confirm the design aims of the accelerators. The steps taken to reduce the longitudinal emittance proved successful with a measured value of 0.5 πkeV/u-ns in agreement with calculations. The RFQ capture efficiency at the nominal voltage is 75-80% in the bunched case (three harmonics) and 25% for the unbunched case in reasonable agreement with predictions. DTL rf parameters and beam optics settings were established for over twenty different energy set-points covering the whole specified operating range. The transmission through the DTL was over 95% with good beam quality over the whole energy range. Energy spread and pulse width measurements after the DTL are consistent with an emittance of 1πkeV/u-ns. Measured time width and energy spread results for a sample of energies are given in Fig. 4. The HEBT line including the high and low β buncher has been commissioned in 2001. Fig. 5 shows the beam time distribution close to the DRAGON target during operation of the high β buncher.

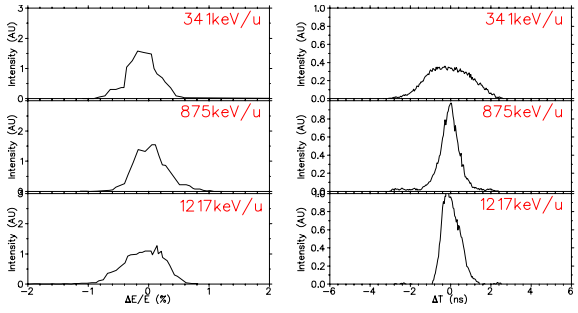


Figure 4: Time width and energy spread measurements for a few sample beam energies.

Stable accelerated beams have been delivered to two experimental stations, the DRAGON recoil mass spectrometer and the TUDA general purpose scattering chamber, since April 1, 2001. They include $^{4}He^{1+}$, $^{13}C^{3+}$, $^{14,15}N^{4+}$, $^{16}O^{4+}$, $^{20,21}Ne^{4,5+}$ and $^{24}Mg^{6+}$. These delivery

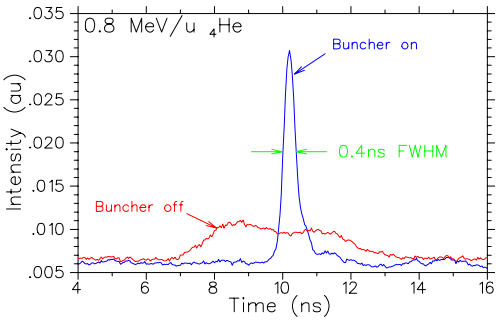


Figure 5: Bunch time spread measurement just upstream of DRAGON for the high β buncher off and on.

periods have proved essential both in training the operators and in determining hardware improvements and required developments prior to first scheduled radioactive beam delivery. Several early improvements have been added that greatly reduce linac tuning time. Foil changes are facilitated by a global phase shifter between the pre-stripper and post stripper accelerator sections to account for slight differences in foil thickness. In addition a cold trap surrounding the stripper foil has now minimized foil thickness growth due to carbon build-up. A phase and amplitude monitoring utility, independent from the rf control system, is nearing completion to enable reliable restoration of rf settings.

RIB beams have been accelerated since July 2001 with 2×10^7 pps $^8Li^{2+}$ delivered to the TOJA experiment. Since then $^{21}Na^{5+}$ has been delivered to both DRAGON and TUDA with intensities up to 6×10^8 pps. Pilot beams of $^{16}O^{4+}$ and $^{21}Ne^{5+}$ respectively were used for pre-tuning the accelerator. The switch from pilot beam to RIB is straightforward. In general beam tunes are established by a physicist with delivery monitored and optimized by operations staff 24 hours/day seven days a week. A plot of various beams and energies accelerated to experiment are given in Fig. 6.

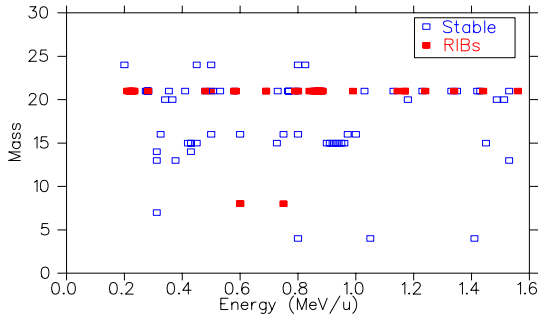


Figure 6: Stable and radioactive beams accelerated to experiment.

4 ISAC-II

4.1 ECR Charge Breeder

TRIUMF is collaborating with ISN Grenoble on the development of an ECR based charge state booster. A 14 GHz Phoenix source has been ordered and will be assembled on a test stand at TRIUMF. Results of initial studies measuring 1+/n+ conversion efficiency performed on the ISN test stand are given in Table 1[4]. These 'fasting tuning' results can be improved by a factor of two by careful optimization of the particular charge state.

Table 1: Experimental results from ISN/TRIUMF collaboration on ECR Charge Breeder at Grenoble.

Isotope	Q	Eff.(%)	I (pnA)	A/q
^{115}In	18+	3.3	130	5.8
^{109}Ag	17+	3.0	175	6.4
^{64}Zn	10+	2.8	42	6.4
^{120}Sn	19+	4.1	167	6.3
^{88}Sr	14+	3.7	470	6.3
^{69}Ga	11+	2.0	460	6.3
^{90}Y	14+	3.3	178	6.4
^{208}Pb	25+	2.0	700(2+)	8.3

4.2 Superconducting Linac

The two stages of the ISAC-II installation are shown in Fig. 7. A comprehensive first order design study[5], now

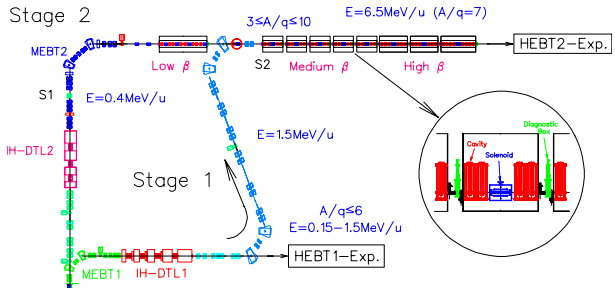


Figure 7: Stage 1 and Stage 2 of the ISAC-II expansion.

complete, set the parameters of the floor layout prior to building construction. The solution includes all transport beamlines, including the first stage transfer line and second stage 90° isopath bend section as well as the first order dynamics of the superconducting linac. Designs are compatible with multi-charge acceleration to $\Delta Q/Q \leq \pm 8$ to preserve beam intensity and/or allow the possibility of a second optional stripping stage to boost the final ion energy. The superconducting linac is composed of two-gap, bulk niobium, quarter wave rf cavities, for acceleration, and superconducting solenoids, for periodic transverse focussing, housed in several vacuum insulated cryomodules. The linac has been grouped into low, medium and high beta sections corresponding to cavities with design velocities of $\beta_o = 4.2\%$, $\beta_o = 5.7, 7.1\%$ and $\beta_o = 10.4\%$ respectively.

The two cavity types in the mid beta section (Fig. 8), composed of eight $\beta_o = 5.7\%$ and twelve $\beta_o = 7.1\%$ cavities, are now being fabricated in industry. A prototype of the $\beta_o = 7.1\%$ cavity[6] has been designed in a collaboration with INFN-LNL, and fabricated in Italy. The *flat* cavity, recently added to the design for improved beam dynamics (see below), borrows from the geometry of the low β cavities on the Piave accelerator at INFN-LNL[7].

The linac has been designed assuming design gradients of 5 MV/m in the low beta section and 6 MV/m in the medium and high beta sections respectively. These correspond to rather aggressive peak surface fields of 25 and 30 MV/m respectively. The prototype cavity performance exceeds the ISAC-II requirements with an accelerating gradient of 6.7 MV/m for 7 W dissipated at 4°K. A peak gradient of 11 MV/m ($E_p = 55$ MV/m) was achieved.

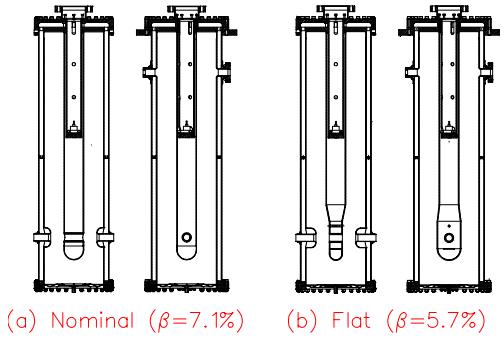


Figure 8: The two medium beta cavities.

The eight low beta cavities are housed in one long cryomodule with three solenoids interspersed between cavities. The twenty medium beta cavities are installed four per cryomodule in a total of five modules. Twenty high beta cavities are divided into two modules of six cavities and one module of eight cavities. Each of the medium and high beta cryomodules are equiped with one solenoid. Thin diagnostic boxes are positioned at waists in the transverse envelopes between cryomodules.

Beam Dynamics Studies Detailed beam dynamics studies have concentrated on the first stage SC linac installation, and in particular on the medium beta section. Two main asymmetries in the medium beta cavity fields are responsible for differences between a 'simple cavity model' and 'realistic field' simulations. Inherent in quarter wave cavities are both a vertical electric dipole field and a radial magnetic field that give velocity and phase dependent vertical kicks to the beam[8]. The vertical steering can lead to loss of dynamic aperture and transverse emittance growth especially for multi-charge beams. The steering can be largely cancelled by displacing the cavity vertically so the electric focussing field compensates for the magnetic kick[9].

The cylindrical stem while simplifying construction produces an asymmetry in the transverse rf electric fields. The asymmetry leads to a mismatch between horizontal and vertical motion. In a solenoidal lattice the beam is rotated periodically and a mismatch between transverse planes can lead to transverse emittance growth once the beam is delivered to a quadrupole transport system.

To reduce the effects of the focussing asymmetry we alter the original design by adding a new cavity geometry. In the 'flat' cavity (Fig. 8(b)) the inner conductor is squeezed to 40 mm from 60 mm in the beam direction and the grounded beam ports are extended to maintain the original gap. The transverse deflections from the two cavity types are summarized in Fig. 9 over the operating velocity range required of the cavity for an accelerating gradient of 6 MV/m, an ion of $A/q = 3$, and a phase of $\phi_s = -30°$. The solid lines show the vertical and horizontal defocussing perturbations for a 1 mm displacement from the electrical axis. The dashed lines show the uncorrected, on-axis dipole steering components and the corrected components for cavities shifted down by 0.8 mm in the *nominal* case and 0.5 mm in the *flat* case with respect to the beam and solenoid axis.

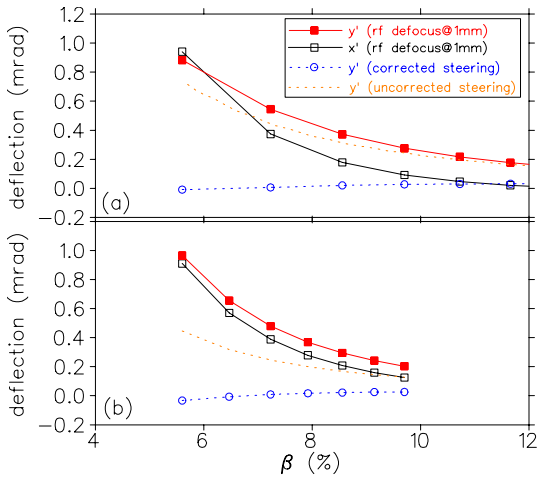


Figure 9: Focussing and steering perturbations for the two medium beta cavities (a) *nominal* (b) *flat* as calculated in HFSS for $E_a = 6$ MV/m, $A/q = 3$, and $\phi_s = -30°$. The dashed lines are the uncorrected (on-axis) and corrected (displaced axis - (a) $\Delta y = 0.8$ mm, (b) $\Delta y = 0.5\ mm$) vertical dipole perturbations. The solid lines are the vertical and horizontal defocussing perturbations for a 1 mm displacement from the electrical axis.

Studies show that a small but worthwhile improvement in dynamic aperture is gained for light beams by replacing the first eight 'nominal' cavities in the medium beta section with the 'flat' cavities[10]. Adding more than eight 'flat' cavities reduces linac performance because of the reduced β_o.

In an investigation of misalignment tolerances the realistic fields are used to generate velocity dependent linear matrix elements to speed the calculations. The beam centroid is tracked through the linac for multiple seeds of linac misalignments. For each seed linac element positions are

displaced randomly within a Gaussian distribution. Results for 50 seeds and for a misalignment distribution width of $2\sigma = 250\mu$m are shown in Fig. 10. The dots represent the individual seed displacements and the solid line shows the rms displacement of the beam centroid. In the bottom plot steerers after each cryomodule are used to reduce the centroid position error to within $\sim \pm 0.5$ mm.

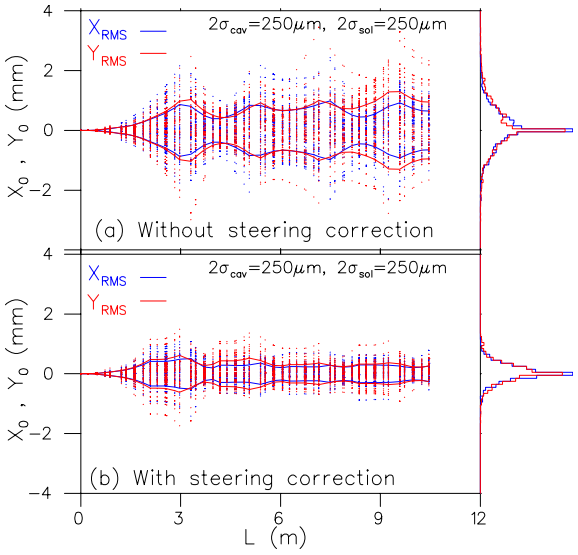


Figure 10: Results for 50 seeds and for a misalignment distribution width of $2\sigma = 250\mu$m; the dots represent the individual seed displacements and the solid line shows the rms displacement of the beam centroid (a) without and (b) with steering compensation.

Hardware Work is ongoing on several fronts with the goal of realizing beam delivery in 2005[11]. The first major milestone is the fabrication and cold test of a completed medium beta cryomodule in mid 2003. A summary of the present developments are given below.

Cryomodule Design A prototype of the medium beta cryomodule is now in the design phase. The vacuum tank consists of a stainless steel rectangular box and lid. All services and feedthroughs are located on the lid. Copper sheet cooled with LN2 piping serve as heat shields. Cavities and solenoids are suspended from a common support frame hung from a 200ltr LHe reservoir. Pre-cool of components is done by delivering cold helium vapour to the bottom of each major component.

Solenoids Focusing in the SC LINAC is provided by 9 Tesla 26 mm diameter bore SC solenoids of lengths 16, 34 and 45 cm corresponding to the low, medium and high beta cryomodules respectively. An order for five medium beta and two high beta solenoids is soon to be placed in industry.

SCRF Developments A temporary superconducting rf test lab of $\sim$ 100 m^2 is set-up in a space rented by TRIUMF in a neighbouring laboratory complex. The laboratory includes a test area with a sunken cryostat pit for high field rf testing, and clean areas for cavity assembly (Class 1000) and high pressure water rinsing (Class 100). In the high pressure rinse area an on-line treatment system delivers 20 ltr/min of 18 MΩ water at 2000 psi to a manual rinse unit. A prototype rf controls system using a self-excited loop architecture with digital signal processors is in development and has been used to successfully lock a cold cavity in both self-excited and fixed frequency operation. A prototype mechanical tuner is now being tested. It consists of a lever mechanism acting directly on the center of the cavity tuner plate through a zero backlash hinge and stiff rod connected through a bellows to a precision linear stepper motor located on the top of the cryostat. Cold tests of the prototype cavity are ongoing at the rate of one a month.

Refrigerator An order for the Stage 1 LHe refrigerator with a 500 W capacity at 4.2°K is soon out for tender.

5 ACKNOWLEDGEMENTS

The author is representing a strong and talented accelerator group at TRIUMF/ISAC whose many accomplishments are summarized here. Further, the ISAC-I/ISAC-II project has benefited over the years from many outside collaborations. In our most recent adventures in superconducting rf we are guided by our collegues and friends at Argonne and Legnaro.

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