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Recent achievements at TRIUMF

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Abstract A new series of experiments (mainly in astrophysics) began at TRIUMF in July 2001 when the ISAC-I linear accelerator started delivering radioactive ion beams (RIB) of energy up to 1.5 MeV/u. Since then the linac has operated reliably. Required improvements demand care during scheduled maintenance. More difficult was the smooth production of RIB with a 500 MeV proton beam on different target materials, where state-of-the-art techniques are being learned. Targets of CaO, Ta, SiC, Nb, and $CaZrO_3$ have been used in combination with a surface ion source and incident proton currents up to 40 μA. Record radioactive beam intensities were achieved. A second target station is now being commissioned and will become operational during the fall of 2002. A superconducting linear accelerator extending the RIB energy to 6.5 MeV/u has recently been approved and is now being constructed (ISAC-II). A new 3500 m^2 experimental building is being erected. A charge state booster, which will extend the mass range of the accelerated ions from $A \leq 30$ to $A \leq 150$, is also being commissioned. The 500 MeV cyclotron is being refurbished for reliability and upgraded to higher currents. A suitable operational beam tune for a total H^- accelerated beam current of 300 μA has been commissioned and is now available to supply beam to four separate extraction proton lines simultaneously.

Key words TRIUMF • ISAC • radioactive ion beams • ISOL • cyclotron • LINAC

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The ISAC project

The ISAC project has been previously described [5, 6]. It consists of 3 major systems: (1) the target ion-source/mass-separator/LEBT system serving the low energy experimental area or feeding the beam into the ISAC-I accelerator; (2) the linac, accelerating $A \leq 30$ ions up to 1.5 MeV/u; (3) the ISAC-II superconducting accelerator that will accelerate ions up to 6.5 MeV/u or higher (depending on mass). With a charge state booster (CSB) upstream of the RFQ, ions up to $A = 150$ may also be accelerated.

Target ion source & LEBT system

The target ion source system (Fig. 1) is situated at cyclotron level in a heavily shielded section of the ISAC-I experimental building [1]. Radioactive ions are extracted towards a pre-separator magnet with mass resolving power of $m/\Delta m \cong 300$. Downstream a 135° mass separator with mass resolving power up to $m/\Delta m \cong 10{,}000$ selects the ion beam of interest. The transverse emittance of the delivered beam is typically around 10π mm·mrad at energies ≤60 keV. The LEBT has been operating routinely at full transmission.

Different production targets were used. Typical ion yields downstream of the mass separator are given in Table 1 for different proton beam currents. The mass separator performed according to expectations. In most cases targets lasted through scheduled periods, typically a few weeks to several months. Interruptions of beam production occurred

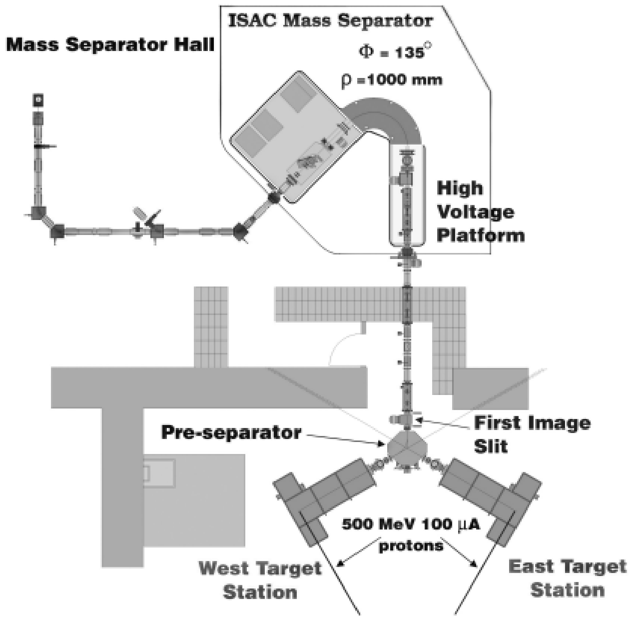

Fig. 1. The target mass separator area.

three times: once due to deposition of Ca on the extraction electrode, caused by rapid evaporation of CaO, once due to the overheating of a connection in the target electrical heating circuit, and once due to a vacuum leak at a high voltage feedthrough. To make beam scheduling more efficient, high priority was given to the completion of a backup (East) target system. The East target system is planned for commissioning during the fall of 2002.

Table 1. Radioactive ion yields achieved.

^{A}X	Target	Experiment	I(p) μA	Yield (P/s)
^{37}K	CaO	TRINAT	1	3.0×10^{6}
^{38}K	CaO	TRINAT	1	3.0×10^{8}
^{37}K	CaO	lifetime	1	6.0×10^{6}
^{38}K	CaO	lifetime	1	3.0×10^{8}
^{74}Rb	Nb	lifetime	10	5.0×10^{3}
^{75}Rb	Nb	LTNO	10	2.4×10^{5}
^{8}Li	Nb	β-NMR	10	2.0×10^{8}
^{74}Rb	Nb	lifetime	10	4.0×10^{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}
^{8}Li	Ta	β-NMR	40	8.3×10^{8}
^{9}Li	Ta	yield meas.	35	9.4×10^{7}
^{11}Li	Ta	yield meas.	30	1.2×10^{4}
^{20}Na	SiC	yield meas.	15	3.4×10^{7}
^{21}Na	SiC	DRAGON	15	9.8×10^{8}
^{74}Ga	Nb	yield meas.	20	6.1×10^{4}
^{75}Ga	Ta	LTNO	30	4.2×10^{5}
^{94}Y	Ta	yield meas.	11	6.0×10^{4}

ISAC-I linac

The ISAC-I linac (Fig. 2) consists of a split ring 4 rod RFQ, an MEBT ion-stripping section and a separated function DTL accelerator system. A stable $^{4}H^{+}$ beam was accelerated to full energy (1.53 MeV/u), on schedule on December

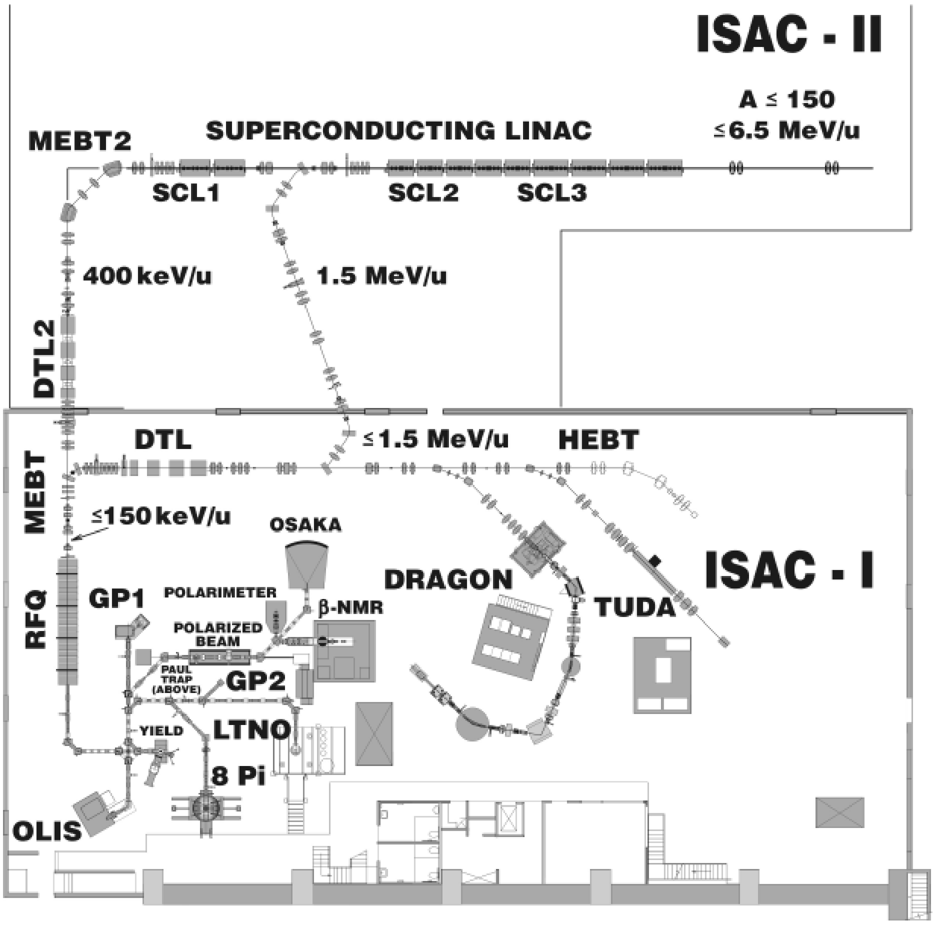

Fig. 2. Layout of the ISAC-I experimental hall and the ISAC-II accelerator.

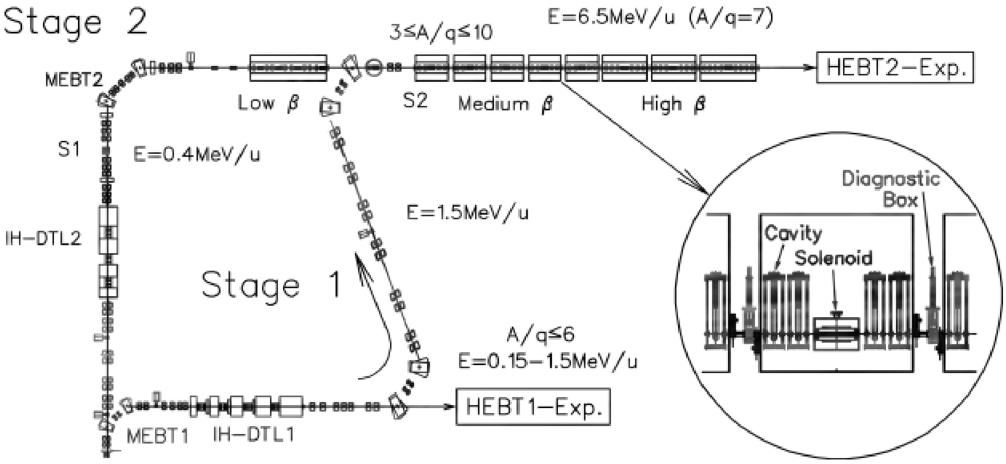

Fig. 3. Stage 1 and stage 2 of the planned ISAC-II installation.

21, 2000. Thereafter, tunes were established to cover the whole operating range of energies and other stable ions from the "Off Line Ion Source" (OLIS) including $^{14,15}N^{4+}$, $^{16}O^{4+}$, $^{21}N^{5+}$, and $^{24}Mg^{6+}$. Transverse emittances (normalized) were typically of the order of 0.1π mm·mrad for stripped ions or smaller for unstripped ions (like $^{4}He^{+}$). Longitudinal emittances were found to be ~0.5π keV/u ns for the unstripped beam and about twice larger for the stripped beam. Transmission through the DTL was in all cases well above 95%. Taking into account the reduction due to stripper charge selection, overall transmission for the ISAC-I accelerator was about 20% when using the 11.8 MHz 85 ns chopper. With the 5.9 MHz 170 ns chopper the transmission was reduced by a factor of two (to ~10%), in accordance with expectations.

On July 26, 2001 we accelerated the first radioactive beam of $^{8}Li^{2+}$ to an experiment in the high energy area. The flux after 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. The tuning was aided by pilot beams of stable ^{7}Li produced at the RIB target and by $^{16}O^{2+}$ ions from the stable off-line ion source. Once the pilot beams had been optimized, the acceleration of ^{8}Li ions was easy and only minor adjustments were necessary to reduce losses and maximize transmission. Intensities were sufficient to tune with Faraday cups and wire scanners. ^{8}Li losses on slits or collimators could be detected via a hand-held X-ray/γ-ray detector. They were minimized and practically eliminated in a short time. The technique of using pilot beams with stable ions for initial tuning minimizes the tuning time with unstable ions. This, therefore, avoids substantial losses and background contamination introduced by lengthy RIB tuning. Initial diagnostics were also commissioned. Silicon detectors were 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}. Other diagnostic monitors are being ready for routine RIB detection at low intensities.

ISAC-II

During the year 2000, TRIUMF was funded to proceed with the construction of ISAC-II. In order to be accepted by the RFQ, singly charged ions from the ion source, with $30 < A \leq 150$, will have to be ionized to a higher multicharge state with $A/q \leq 30$. An ECR charge state booster (CSB) is being constructed by PANTECHNIK in collaboration with ISN Grenoble and TRIUMF and will be installed at TRIUMF for final commissioning in the fall of 2002.

The ISAC-II accelerator (Figs. 2 and 3) will include a DTL2 section extending the present 150 keV/u MEBT line to the North and accelerating the beam to energy of 400 keV/u before 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 λ/4 cavities resonating at 70.8, 106.2, and 141.6 MHz for β_0 of 4.2%, 5.7% and 7.1%, and 10.5%, respectively. The design includes a transfer line between the ISAC-I DTL exit and the ISAC-II medium-β section entrance for initial commissioning and operation of the medium-β section. A comprehensive design study has been completed. The design is 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 consists of two-gap, bulk niobium, quarter wave RF cavities for acceleration and superconducting solenoids for periodic transverse focusing, housed in several cryomodules. The mid-β section is composed of eight $\beta_0 = 5.7\%$ and twelve $\beta_0 = 7.1\%$ cavities, now being fabricated in industry. A prototype of the $\beta_0 = 7.1\%$ cavity was designed and was fabricated and tested at Legnaro, Italy in collaboration with INFN-LNL. A modified cavity, flattened in the accelerator gap region, was recently introduced at lower β_0 (5.7%) to reduce the effects of a focusing asymmetry in the transverse RF electric fields due to the cylindrical stem geometry. The linac has been designed assuming design gradients of 5 MV/m in the low-β section and 6 MV/m in the medium and high-β sections, respectively. The prototype cavity exceeded the ISAC-II requirements with an accelerating gradient of 6.7 MV/m for 7 W dissipated at 4 K. A maximum peak gradient of 11 MV/m has been achieved for higher power dissipation. A superconducting RF test lab has now been set-up at TRIUMF and prototype testing is in progress.

The design of the building extension to house the ISAC-II facility is nearing completion and building occupancy is scheduled for February 2003. The first stage of the superconducting linac, consisting of twenty mid-β cavities and a number of high-β cavities, is planned for installation and commissioning in 2004 with first beam to users in 2005.

The 500 MeV cyclotron

The vault layout of the H^- cyclotron and of the four extraction beam lines is given in Fig. 4. During the 2001 cyclotron conference at MSU the following proton beam intensities were reported [4]: 150 μA at 500 MeV down BL1A, up to 20 μA at $\sim$495 MeV down BL2A, 50 μA at 85 MeV down BL2C4 for isotope production and up to 1 or 2 μA down BL4A/4B. This corresponded to a total accelerated H^- beam current of $\sim$220 μA cw, a value that had been the limit of high current operation for several years. The reason for this limitation has been traced to electrode heating problems in the centre region. A 500 MeV, 400 μA equivalent beam, 200 μA average, pulsed in a 50% duty cycle mode, had been previously demonstrated [3], confirming that the intrinsic space charge limit was well above the 220 μA limit. With ISAC planned for 100 μA, a higher total accelerated H^- current was required. A goal of 300 μA total cyclotron current was set, which will allow 100 μA for ISAC while other extracted beams are kept at traditional intensity levels.

Several development shifts were scheduled for high intensity studies. Before year-end it was determined that most overtemperature trips were caused by radial beam losses along the first quarter turn in the cyclotron. Although these losses corresponded to only 50 W dumped on a water cooled structure, a fraction of the beam was hitting structural stainless steel reinforcing ribs, causing high temperatures in some of the stainless steel elements. It was also found that, whereas tunes up to 220 μA could be transmitted from injection to extraction with better than 60% transmission, the transmission would drop to values around 50% when the H^- ion source was set to higher values of arc voltage and arc current, required for 300 μA acceleration. The reason for lower transmission at higher currents was attributed to vertical losses at the 2nd or 3rd turn, where axial magnetic focussing is known to be very weak and focussing is mainly electric and therefore phase dependent. A breakthrough came when it was discovered, for a 250 μA tune, that 60% transmission could be achieved by using the lowest possible source arc power compatible with the required extraction current. Increasing the hydrogen flow helped to maintain this low arc power source setting. A lower injected beam emittance is implied, but systematic emittance measurements have not yet been performed.

During the winter 2002 shutdown, several improvements were introduced in to the centre region: (1) a water-cooled copper absorber was installed inside the first quarter turn beam orbit to absorb radial beam losses caused by ions not matching the cyclotron RF phase acceptance. As a result overtemperature problems at the first turn electrodes disappeared; (2) first quadrant correction plates [2], showing evidence of beam damage, were found to be misaligned, and protruding into the vertical beam acceptance gap, as defined by protecting lower and upper horizontal copper bars upstream of the plate system. The correction plates were carefully realigned so that they would no longer protrude; (3) the back edge of an RF contact was also found to protrude into the vertical beam gap. The contact was tailored to avoid the protrusion.

After the shutdown, the following results were achieved:

(1) A 275 μA total internal beam current was accelerated at full duty cycle during 3 hours and beam fractions were extracted down BL1A (165 μA), BL2C4 (70 μA), and BL2A (40 μA). The beams were stable and could be used for experiments. The overall transmission was better than 60%.

(2) A 300 μA tune at 90% duty cycle and better than 60% transmission was also demonstrated. The duty cycle limitation was caused by insufficient total beam dump

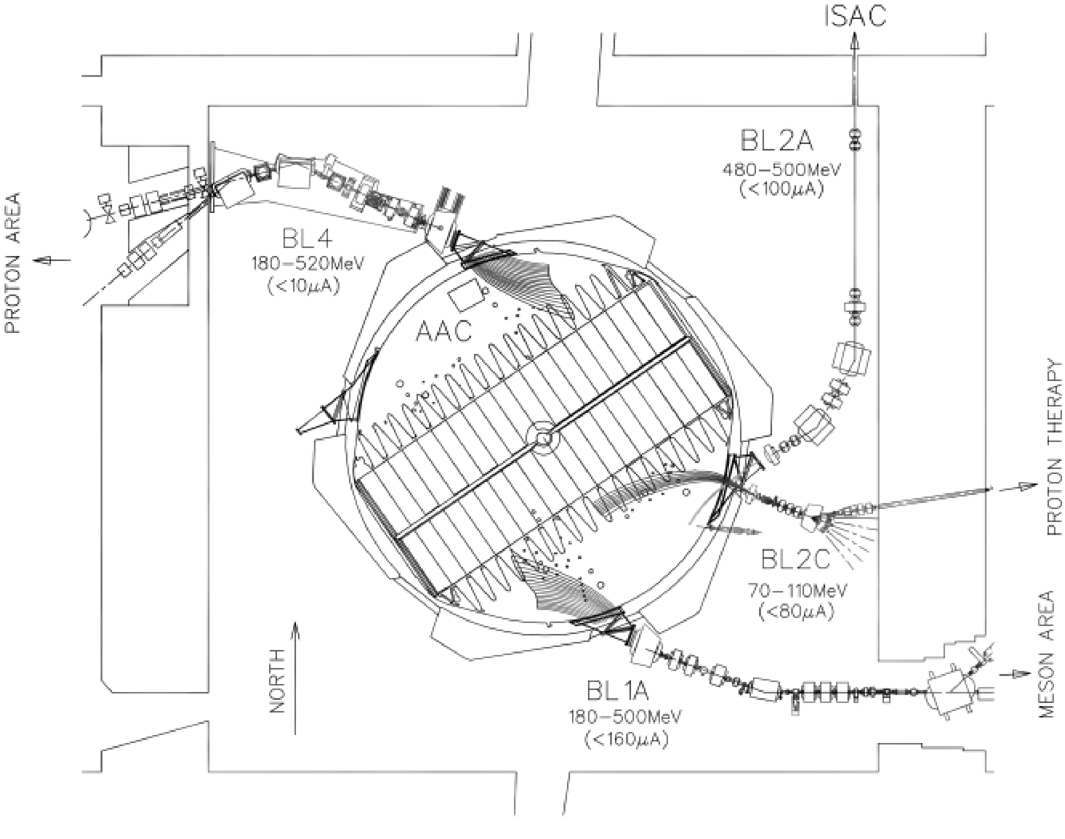

Fig. 4. Layout of cyclotron vault and of four systems for simultaneous extraction.

capacity. The beam was maintained for a period of 2 hours and did not create thermal or other problems. Experimenters used extracted beams.

(3) A 350 μA equivalent tune was also obtained at 40% duty cycle and 57% transmission. The duty cycle was limited because of using only one extraction line, beam line 1A, for easier tune convergence. The transmission could not be brought up to the 60% level, indicating that a fraction of the transmitted beam in excess of 5 μA was lost, probably vertically at the 2nd/3rd turn radial region. A short attempt at raising the duty cycle showed rising temperatures on non-cooled electrodes.

Additional electrode cooling may be required for the 350 μA current, but we believe that this intensity is a realistic goal. Probe scans to verify the above behaviour and further measurements and studies are planned before year-end at low duty cycle at intensities equivalent to 300 μA and above. Measurements of the ion source beam emittance *vs*. ion source parameters are also being planned.

In conclusion, the 300 μA goal has practically been achieved. 300 μA will be delivered during normal operation as soon as ISAC demands proton beams of 80 μA. Interest has now shifted towards total currents higher than 300 μA, and the possibility of transforming the 4A extraction line into a second (BL4 North) high intensity (100 μA) line to new ISAC target ion source stations situated west of the present target system. A total cyclotron accelerated current of 400 μA cw is being considered. The second 100 μA ISAC line, with energy of 450 MeV, to 500 MeV will overcome a most serious limitation to the present ISAC experimental program caused by the fact that RIB experiments are now being scheduled sequentially. Experiments include low energy RIB experiments ($E \leq 60$ keV), ISAC-I accelerated RIB experiments (0.150 MeV/u $\leq E \leq$ 1.5 MeV/u), and will soon include ISAC-II experiments at higher energies (1.5 MeV/u $\leq E <$ 6.5 MeV/u) for a wider mass range. The additional ISAC high intensity proton beam line coupled to two new target systems or another alternative RIB production system will be a key feature in our imminent 2005–2010 five-year plan proposal.

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