RECENT PROGRESS AT TRIUMF

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Abstract

Recently, there has been a great deal of progress at ISAC I where experiments have been demanding new beams and facility upgrades, and at ISAC II which has moved from accelerator design phase to construction. A 500 MeV proton beam up to 50 μA intensity is now routinely extracted from the TRIUMF H^- cyclotron towards the ISAC target to produce exotic ions either for the "low energy experimental area"(E< 60 keV), or, for masses with A ≤ 30, for the "high energy area" (150 keV/u ≤ E ≤1.5 MeV/u). ISAC II, an extension of ISAC-I, will further accelerate the ions to 6.5 MeV/u and, with a charge state booster (CSB) upstream of ISAC-I, will extend the mass range of accelerated ions to A ≤ 150. This paper will give the most recent outline of the facility and report on recently achieved milestones, including the completion of the elegant ISAC-II building and the commissioning of the first cryomodule containing four quarter-wave SC cavities and one SC solenoid. Part of the next 2005-2010 five-year plan is a new facility to develop target/ion-source systems for RIB production, based on an additional 100 μA, 450 to 500 MeV proton beam extracted from the H^- cyclotron. Eventually this could lead to at least two simultaneous RIBs for ISAC. The total cyclotron H^- beam current will be increased to 400 μA to provide enough intensity for all four simultaneously extracted beams (existing programs plus ISAC).

INTRODUCTION

Renewed world wide interest in physics with Radioactive Ion Beams (RIB) has led to the recent construction or upgrade of a generation of facilities based on the ISOL & Acceleration method (e.g. REX-ISOLDE at CERN, SPIRAL at GANIL, ISAC at TRIUMF, etc.). In general ISOL facilities will deliver exotic ions at ion source energies for further acceleration, with useful intensity and good quality beams, limited however to isotopes with higher decay times (τ ≥~10 ms). These facilities are complementary to in-flight fragmentation facilities, where primary beams of heavy ions are impinging at high energy on thin targets to produce fast exotic ions with lower quality beam, but with decay times as low as a few μs. Isotopes of interest are then individually separated and focused by large acceptance spectrometers to compensate for the intensity reduction caused by the lower beam quality (e.g. RIKEN, GSI, MSU/NSCL, Dubna etc.).

In the ISOL facilities mentioned above the primary accelerator pre-existed the proposed RIB accelerator, prompting overall construction to proceed expeditiously, with the goal of exploring new physics in a time window of five to ten years, while the next generation of larger future facilities (of more general scope, like RIA, EURISOL and others), would go through funding, design, planning and construction phase. The experience gained with the recent facilities will provide technological advances that will be helpful for the realization of the larger machines.

ISAC is now the operating ISOL-type facility with the highest primary beam power: up to 40 to 50 μA of 500 MeV protons are delivered routinely on target; the 100 μA design goal has been demonstrated on a prototype target. An important issue continues to be the development of targets that can reliably withstand the high power of the driver beam. Target development has resulted in target lifetimes that now exceed an integrated proton dose of 5×10^{20}[1]. A thermal surface-ionization ion source has been the RIB production source up until now, but an ECR ionizer is being commissioned and a resonant laser ion source is being tested on a test stand. Higher beam power on target implies a higher degree of sophistication in remote handling equipment, radiation and contamination control, radiation hardening and simplification of instrumentation like exotic-ion sources or diagnostics in the active areas around the target. Table 1 lists measured yields for a selected list of isotopes for different targets and proton intensities. Radiation and contamination levels have been so far well under control.

CYCLOTRON, PRIMARY BEAM LINES AND ISAC TARGETS

The TRIUMF H- cyclotron has been delivering proton beam to users over the last 29 years. Over the last 15 years it has delivered routinely, with ~ 90% availability, up to three simultaneous beams with total current up to a maximum of 220 μA. The layout of the cyclotron vault with the extracted proton beam lines is shown in Fig. 1. Typically 150 μA were extracted at 500 MeV to the meson area (BL1A), 50 to 70 μA at ~85 MeV to an isotope production target in the vault (BL2C4), and, in BL4, from a few nA to a few μA, between 180 and 520 MeV, for proton and polarized proton experiments.

Table 1: A selected list of measured ISAC yields from specified targets with a thermal ion source.

Isotope	Target	Target Thickness (g/cm^2)	Proton Current (μA)	Yield (/s)
Li-8	Ta	43.6	10	2.0E+07
Li-8	Ta	43.6	40	8.3E+08
Li-8	ZrC	37.6	45	1.9E+08
Li-8	SiC	20.4	45	8.1E+07
Li-8	Nb	22	40	8.1E+07
Li-8	Ta	21.8	40	4.8E+07
Li-11	Ta	21.8	39	1.6E+04
Li-11	Ta	43.6	40	2.2E+04
Na-20	SiC	20.4	45	1.1E+08
Na-21	SiC	20.4	45	9.1E+09
Na-26	ZrC	37.6	45	4.3E+06
Na-26	SiC	20.4	45	3.2E+07
Na-26	Ta	21.8	40	9.0E+06
Na-29	TiC	37.1	40	1.6E+03
Al-32	TiC	37.1	40	5.6E+01
K-35	TiC	37.1	40	3.5E+03
K-37	TiC	37.1	10	6.1E+05
K-37	TiC	37.1	41	6.4E+07
K-38m	CaZrO	42.3	2.6	2.9E+08
K-38g	CaZrO	42.3	2.6	2.9E+08
Ga-62	ZrC	37.6	45	2.9E+02
Ga-63	Nb	22	40	3.8E+03
Ga-63	Nb	11.5	20	1.3E+04
Ga-75	Ta	43.6	40	1.0E+06
Rb-74	Ta	22	25	9.2E+03
Rb-74	Ta	11.5	20	6.1E+03
Sr-94	ZrC	37.6	45	5.9E+06
Sr-94	Ta	21.8	21	2.1E+04

In 1995 ISAC-I was funded. A dedicated large green field experimental building was constructed to the North of the cyclotron building. A proton beam line, BL2A, was installed in an underground tunnel to transport up to 100 μA of ~500 MeV protons to the heavily shielded portion of the ISAC-I building. A switching magnet at the end of the tunnel would allow to direct the proton beam to one of two target stations: the west target station in operation since 1998, when ISAC was first commissioned at low energies, or the east target station commissioned recently as a back-up target. Either target station is designed to feed the RIB to the mass-separator & LEBT system (Fig. 1), so either station can become the primary operating station. The alternate station will allow the next scheduled target/ion-source to be installed, commissioned and tested, while the other station is used for production, thus avoiding two to three weeks interruption for anticipated target changes. It is clear that this operational function is hardly compatible with the essential requirement of having a target station and its analyzing system dedicated to new target/ion-source developments.

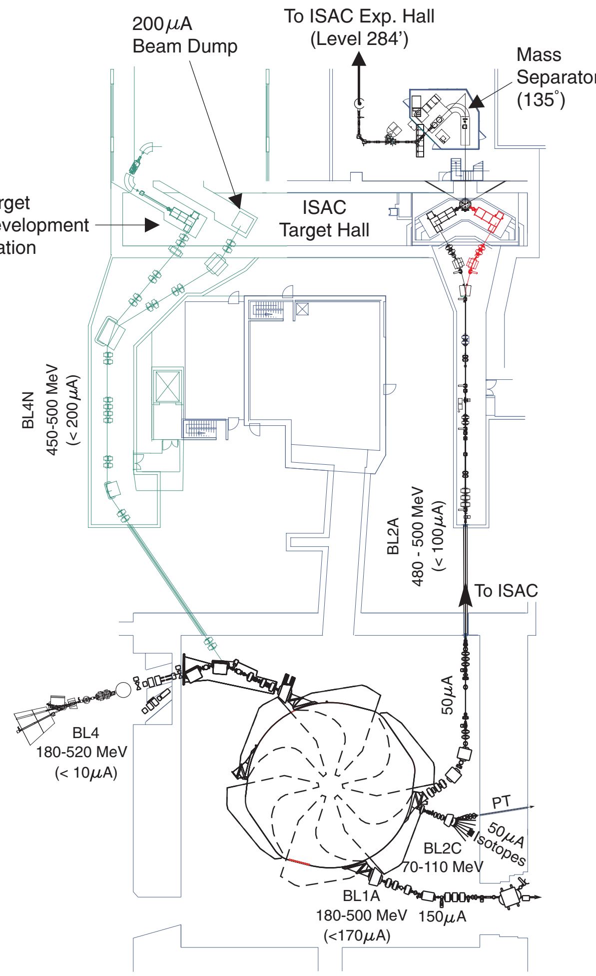

Figure 1: Cyclotron extraction lines and ISAC targets, level 264 (red is recent, green is future).

With the addition of 2A and its 100 μA requirement, the total 220 μA so far available from the cyclotron will not be sufficient to cover previous and new intensity demands, totaling ~300 μA. Since we had never been able to exceed the 220 μA limit because of heating and arcing problems in the cyclotron centre region, a development program for higher H^- intensities was undertaken. Critical adjustments to a few specific centre region electrodes were introduced, as well as improvements to the beam tune at the ion source and along the injection line. In summer 2002 we achieved three simultaneously extracted beams totaling an average of 285 μA, at 95% duty cycle, corresponding to 300 μA equivalent (300 μA cw could not be extracted because of present current acceptance limitations from the various beam lines). At lower duty cycle, we also optimized beam tunes at higher equivalent intensities [2]. In July 2003, we achieved a 400 μA equivalent tune, at 25% duty cycle, with good beam transmission from injection to extraction, implying that the acceleration and extraction of 400 μA total in cw mode would be practically feasible once the total acceptance from the beam lines will have been upgraded to 400 μA cw. A few centre region adjustments in terms of electrode alignment or cooling may still be required and will be introduced gradually during a few regular shutdowns.

It has been proposed [3] that the additional current available from the cyclotron be channeled through a new independent beam line to a specific target station dedicated to ISAC target developments. The new beam would be extracted from the BL4 extraction port and, using a switching magnet in the vault section of BL4, redirected in the NW direction to a new NS tunnel connecting the cyclotron building to the western extension of the heavily shielded ISAC-I target building (see Fig. 1). In the tunnel the new beam line (BL4N) would split into two separate branches, one directed to the development target station, the other to a new beam dump, capable of handling up to 200 μA at 500 MeV. The new beam dump would solve the problem of insufficient extracted current acceptance for the high intensity optimization of the cyclotron. A fourth target station and corresponding analyzing system, fed by splitting the BL4N beam with a fast beam splitter, has also been considered as an important future option which would allow simultaneous RIBs for ISAC. While priority will be given to the target development station, provision will be made in the building upgrade design to keep the option of the second simultaneous RIB open.

ISAC LINACS AND FACILITIES

ISAC-I and ISAC-II have been described before [4], [5] and the recent layout of accelerators and facilities is shown in Fig. 2. Briefly, once the radioactive ion beam has been mass analyzed at level 264′ (cyclotron level), in the underground section of the ISAC-I building, it is raised to grade level (284′) in the ISAC-I experimental hall by a vertical LEBT line. Here a switchyard directs the ≤ 60 keV beam to either one of several LE experimental stations or to the entrance of the 8 m long, 35.4 MHz, four rod split ring cw RFQ, designed to accept 2 keV/u ions with A/q ≤ 30 and to accelerate them to 150 keV/u. Downstream a stripper and 90º bending section selects the A/q ratio of the ion beam to be injected into the DTL1 which accelerates ions to energies between 0.150 and 1.5 MeV/u with 3 < A/q < 6.

ISAC-II will permit acceleration of radioactive ion beams to energies of at least 6.5 MeV/u for masses up to 150. Ions are accelerated to 150 keV using the same RFQ, but a charge state booster inserted on line at injection will convert the singly charged ions to multiple charged ions in order to satisfy the A/q ≤ 30 requirement set by the RFQ acceptance. Two different schemes for further acceleration are considered (Fig. 3): (1) An additional room temperature IH-DTL2 would accelerate the beam to a 400 keV/u stripping section (for higher masses), followed by a 90º bend and a superconducting linac (grouped into low, medium and high beta sections) designed to accelerate ions of A/q ≤ 7 to the final energy; (2) A transfer line would channel the 1.5 MeV beam between the exit of the IH-DTL1 and the entrance of the medium β section of the SC-linac for further acceleration to the final energy. The second scheme will be of lower cost and more rapid implementation; it will however limit the maximum energy, intensity and type of exotic ions achievable, since it is based on 150 keV stripping (inadequate for higher masses). To maximize scientific output, it is planned to install the transfer line scheme first and add the DTL2 option later.

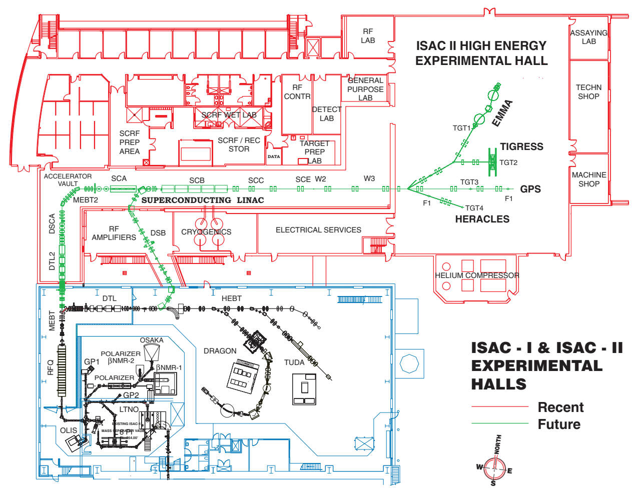

Figure 2: Linacs and facilities for ISAC (I and II).

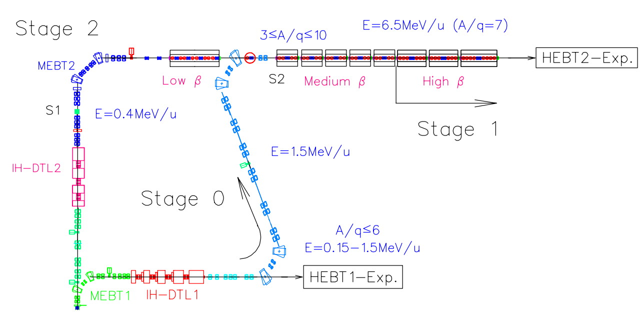

Figure 3: Stages 0, 1 and 2 for the ISAC-II upgrade.

ISAC-I has been delivering ions to low energy experiments since 1998. Since 2001 it has delivered ions with A ≤ 30 at 150 keV/u < E < 1.5 MeV/u mainly for astrophysics research with Dragon and Tuda [5]. ISAC-II is scheduled to provide a first useful beam in 2005 at 4.3 MeV/u (stage 0 in Fig. 3). This will be followed two years later by beam at energy of 6.5 MeV/u (stage 1 of Fig. 3). With the installation of stage 2 by 2009, stripping at 400 keV will become possible and the acceleration of exotic beams will be optimized over the whole A ≤ 150 mass range. Staging was mainly dictated by cash flow and resource limitations. It will however allow an early start of experimental data taking.

The 43 MV superconducting linac is composed of 48 two gap, bulk niobium, quarter wave RF cavities and superconducting solenoids arranged into nine cryomodules for the low, medium and high beta sections corresponding to β=4.2%, β=5.7 & 7.1%, and β=10.4% respectively. Each of the cryomodules is equipped with at least one SC solenoid. The design gradient is ≥ 6 MV/m, (corresponding to a stored energy of ~3J for a medium β cavity). The first prototype was constructed and successfully tested at Legnaro in collaboration with INFN-LNL. Tests were successfully reproduced at TRIUMF in our new SCRF facility. 20 medium β cavities have been received from industry. A prototype medium beta cryomodule has been constructed and is being commissioned. RF cold tests of the cryomodule assembly are imminent.

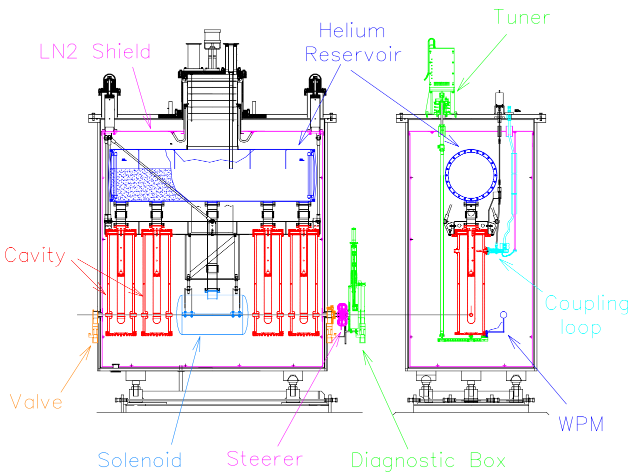

Figure 4: The ISAC-II prototype medium β cryomodule.

Figure 5: View of the SC structure before installation.

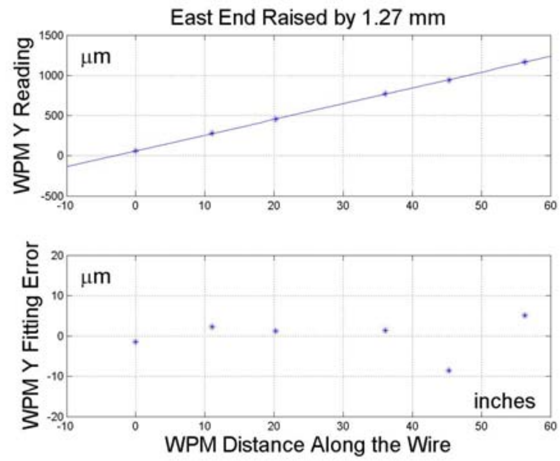

Figure 6: WPM response to a vertical tilt of the structure (top) compared to dial gauge readings (bottom).

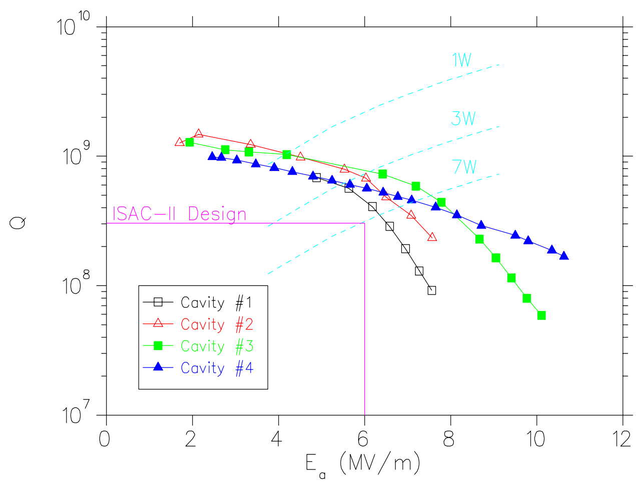

Figure 7: Cold test results for the cavities of the first medium β cryomodule.

HIGHLIGHTS

ISAC-II Building

Shown in Fig. 2 is the topography of the first floor of the new ISAC-II building which was built during 2002 and occupied in mid 2003. One can see offices, meeting rooms, laboratory spaces and an area dedicated to SCRF preparations and a clean room close to the SC linac vault. The addition of office and lab space was welcome since it partially relieved the congestion in some old trailers now removed. In the high-energy experimental hall one can see a possible layout of the ISAC-II experimental facilities that are being designed. These include a recoil spectrometer (EMMA), a high efficiency segmented γ ray detector (TIGRESS), a 4π multidetector array for the study of heavy reactions (HERACLES), a large array of strip detectors to study resonant and transfer nuclear reactions (TUDA), and a general purpose station.

Cryomodule

The medium beta prototype cryomodule is shown schematically in Fig. 4. The vacuum tank consists of a stainless steel rectangular box. All services and feedthroughs are located on the rectangular lid. Cavities and solenoids are suspended from a common support frame supported from the tank lid. The assembled support frame, lid and SC elements are shown in Fig. 5 before installation in the tank.

Alignment

SC cavities and solenoid must be aligned within 0.4 mm and 0.2mm respectively. Since relative displacements in the cryomodule during cool down are of a few mm, we adopted a stretched wire alignment system based on a TESLA design concept [6]. The six wire position monitors assembled on a straight line and firmly referenced with respect to the cold mass, and the conducting enclosure ensuring a noise free environment for the rf loaded copper bronze wire can be noticed in Fig. 5. RF processing electronics uses commercial modules and a software code to handle calibration and measurement phases. The system is able to measure in real time displacements up to ±4 mm with a resolution of the order of ±20 μm. Fig. 6 shows the response of the six detectors to a vertical tilt of the optically aligned cold mass elements induced on the support frame before installation. The electronic readings are compared to the ones from reference dial gauges and the differences are plotted on the bottom figure.

SC Cavities

The first four medium beta cavities received by industry and chemically polished at CERN where tested one by one in the cryostat of our SCRF facility. The measured behaviour of the four cavities now installed in the cryomodule is shown in Fig. 7. Better than 6 MeV/m for 7 W is obtained for all cavities but field emission at higher gradients should be reduced through high pressure rinsing and rf conditioning for the most recent cavities.

Mechanical Tuner and RF Coupler

Stable operation of the quarter wave cavities at gradients above 6 MV/m implies a high level of regulation to reduce the required tuning bandwith and the development of a power coupler capable of operating at high forward power with minimal contribution to the static helium load [7]. A mechanical tuner was developed capable of both coarse (kHz) and fine (Hz) frequency adjustments of the cavity. The adjustment was obtained by acting on a 1 mm thick Niobium end plate, therefore affecting the capacitive load on the cavity, with a system of a vertically mounted permanent magnet linear servo motor, using a "zero backlash" lever and push rod configuration through a bellows feed-through. A tuner resolution better than 0.1 μm was demonstrated, with a dynamic range of 8 kHz, for a bandwidth of 40 Hz. The power being added by the 200 W forward power operating coupling loop to the helium load was reduced from about 5 W in the initial prototype configuration to less than 1 W in the latest development This was achieved by minimizing the radiated heat distribution at the loop with adequate heat radiation shielding, installing good heat conducting dielectric material between the inner and outer conductor of the loop assembly, and cooling the outer conductor with an LN_2 cooling loop.

Charge State Booster

The CSB was developed in collaboration with ISN in Grenoble, manufactured by Pantechnic and recently delivered to TRIUMF. It has now been installed on a teststand LEBT including magnetic and electrostatic analyzing systems. The ECR source has now been commissioned with a buffer gas and commissioning and development of the $1^+/N^+$ operation is about to start. The first results obtained in Grenoble were encouraging: efficiencies of 2% to 8% and charge multiplication factors between 6 and 19 were achieved for various elements [8]. Developments will now aim at improving efficiencies and charge multiplication factors, which is essential for RIB beams.

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