ISAC-II OPERATION AND FUTURE PLANS

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Abstract

The ISAC-II superconducting heavy ion linac now accelerates radioactive ion beams with the highest gradient of any operating SC ion facility in the world and provides a 20 MV boost to the ISAC accelerated beams. The addition of a further 20 MV of SC linac, with cavities made in Canada, will be installed by the end of 2009. The ISAC-III project scheduled to begin in 2010 will see the installation of an additional driver beam of 50 MeV electrons to produce RIBs by photofission, an expanded target area, and new front-end ion accelerators to expand the capability to three simultaneous radioactive beams for experiments.

INTRODUCTION

ISAC at TRIUMF is one of the major existing facilities for the production of radioactive ion beams (RIB). There are two commonly used methods for RIB production [1].

The first one is the in flight or fragmentation method. The facility using this method has a main accelerator that accelerates heavy ions toward a thin target. The heavy ion breaks apart going through the target producing a variety of radioactive ions. The ions, already at the final velocity, are selected through a fairly complex mass separator system and sent to the experiment.

The second method is the isotope separation on line or ISOL method. In this case an accelerator, called a driver, accelerates light projectiles, the primary beam, toward a thick target. The light projectiles, protons or light ions, break the target nuclei producing neutral radioactive isotopes. These neutral atoms are then transported into a source where they are ionized and extracted at source potential. The radioactive ions are magnetically separated and post accelerated to reach the final energy requested.

The two methods are complementary. The in flight is a fast production method that allows to deliver isotopes of very short half-lives (ms or less) but with a beam of relatively large emittance . The ISOL method on the contrary produces high quality emittances but the complicated and relatively slow process reduces the possibility of extracting isotopes with few ms half-lives. The in flight methods RIB has energy of several tens of MeV/u while the ISOL method can deliver beam of few keV/u.

ISAC OVERVIEW

The ISAC facility at TRIUMF is an ISOL facility. It has the highest power (50 kW) primary proton beam. The overview of the facility is represented in Fig. 1. The ISAC facility produces the most intense beam for certain species, an example being the exotic ^{11}Li.

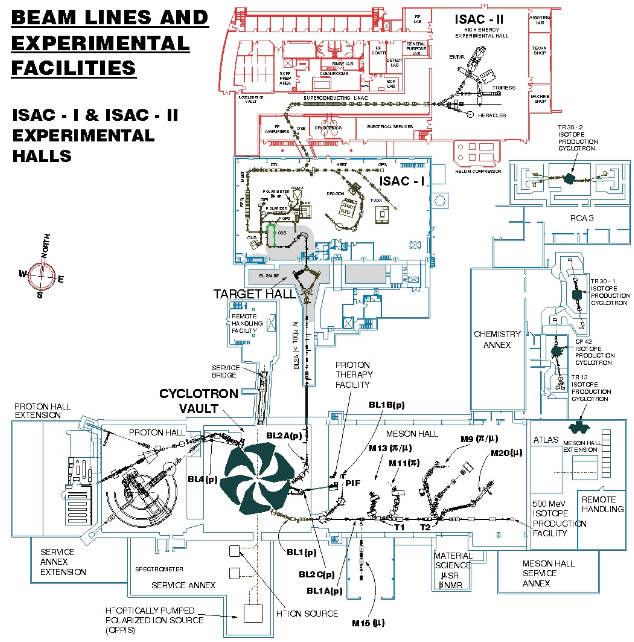

Figure 1: Overview of the TRIUMF site. The main machine is the H$^-$ 500 MeV cyclotron used also as driver of the ISAC facility.

The facility uses silicon carbide or tantalum targets for ion production. Two target configurations are available: low and high power respectively for proton beam powers up to 20 kW and 50 kW. Most recently beam production with a UOx target was successfully completed.

Driver

The TRIUMF H$^-$ cyclotron is the largest cyclotron in the world and has operated for almost 35 years. It accelerates H$^-$ ions up to an intensity of 250 μA to a maximum energy of 500 MeV. The H$^-$ are then stripped and protons are extracted in three different beam lines at different energies the maximum being 500 MeV. One of these beam line is dedicated for the ISAC radioactive beam production. In this case the beam is extracted at 500 MeV and up to 100 μA.

The simultaneous extraction of multiple beams with stable delivery is challenging. Nevertheless a 90% availability of the proton beam for the ISAC facility is regularly achieved.

The capability of multiple extractions can be expanded by refurbishing a fourth existing extraction beam line giving two simultaneous proton beams for RIB production [2] as represented in Fig. 2. This possibility together with an upgrade of the cyclotron [3] is one of the goals for the next

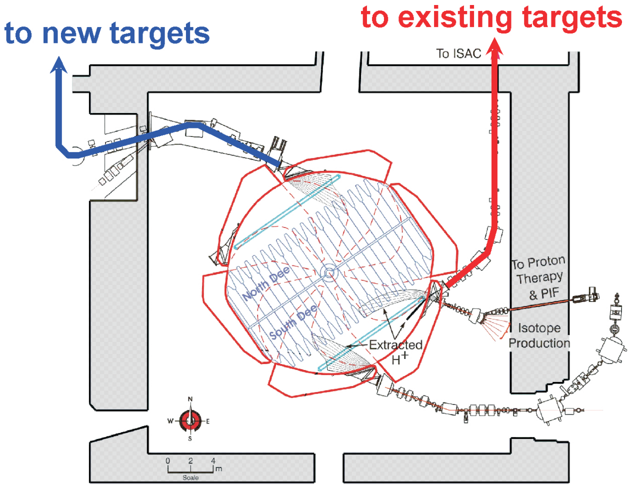

Figure 2: Schematic of the TRIUMF cyclotron. Three operating extraction beam lines in the SE side. One existing extraction beam line in the NW side.

five year plan as explained in the last section of this paper.

Target Station and Mass Separator

The ISAC facility has two independent target stations. This allows service on one target station while producing and delivering radioactive beams with the other.

Each target station is composed of five modules. The entrance module houses the diagnostic and protection monitors for the proton beam. The target module contains the target and the source; this module is routinely removed to change both target and source. Four target modules are available. The beam dump module is located downstream of the target module. The last two are the extraction modules housing the optics elements. They are oriented perpendicular to the proton beam direction.

Downstream of the targets there is a common preseparator. The target modules and preseparator are inside a concrete shielded area. The preseparator reduces the radioactivity transported outside the shielded area in the downstream beam line.

After the preseparator the RIBs are selected using the mass separator. This device is installed on a biased platform to increase the resolution.

After selection it is possible to boost the charge state of the radioactive ion by diverting them through an electron cyclotron resonance ion source (ECRIS). This charge breeder allows post acceleration of masses A>30.

The target stations and the separator area are located underground. Once produced and selected the RIB is then transported to ground level where the post accelerator and experiments are located.

Post Accelerators

The RIBs can be delivered to three experimental areas as represented in Fig. 3: a low energy area where the ions are accelerated at source potential (up to 60 kV),a medium energy area (β=1.8%$\rightarrow$6%) or a high energy area (β=6%$\rightarrow$15%) where the ions are post accelerated with linacs.

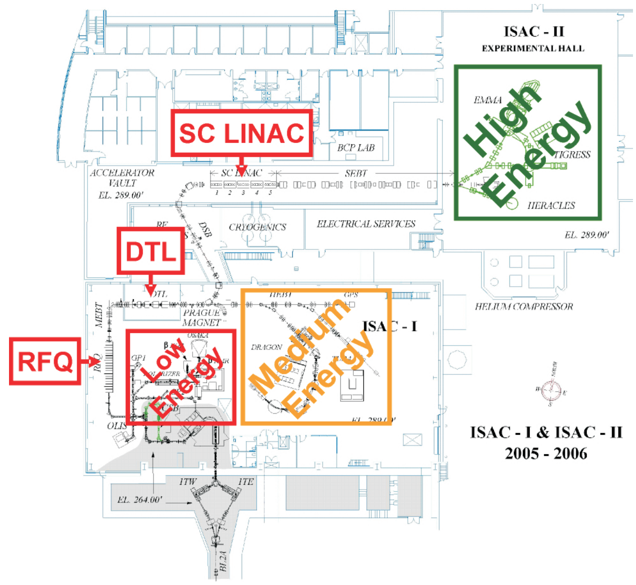

Figure 3: Overview of the ISAC facility at TRIUMF. The ISAC-II linac is superconducting while in ISAC-I the RFQ and the DTL are room temperature machines.

The first stage of acceleration uses a radio frequency quadrupole (RFQ) acting as an injector [4]. The RFQ boosts the energy from 2 keV/u to 150 keV/u. It can accelerate mass to charge ratio of 3$\leq$A/Q$\leq$30. The RFQ is a room temperature CW machine operating at 35.36 MHz. The eight meter long resonant structure is composed of nineteen split rings supporting the electrodes. The RFQ doesn't have a bunching section; the beam is prebunched at the entrance with a three harmonics RF buncher, the fundamental being 11.78 MHz. This configuration produces a high quality longitudinal emittance after the RFQ (0.22 π keV/u·ns). Part of the beam transmitted but not accelerated is stopped into a fixed collimator downstream of the RFQ [5]. The beam inside the longitudinal emittance after the slit is around 80% of the injected.

After the RFQ the charge state of the ions is increased by stripping the ions through a thin carbon foil (4 μg/cm^2). As a general rule the most populated charge state is selected using magnetic benders as long as the mass to charge ratio is within 2$\leq$A/Q$\leq$6 set by the following drift tube linac (DTL). The efficiency of the stripping foil depends on the mass of the stripped ions; in most of the cases it ranges between 30% to 50%.

The DTL [6] is a variable energy machine covering the entire range of energies 150 keV/u$\leq$E$\leq$1.8 MeV/u. The DTL is a separated function machine composed of five IH interdigital structure accelerating tanks and three split ring bunchers located between the first four tanks. This layout produces good beam quality for each energy. After the fourth tank the beam quality is already sufficient that no buncher is required. The resonance frequency of the tanks and bunchers is 106.08 MHz and they operate at room temperature in CW mode. Transverse focus through the linac is provided by quadrupoles triplets between each tank. The transmission of this linac is greater than 95%. The DTL is also used as an injector for the ISAC-II superconducting (SC) linac.

The SC linac [7] is at present composed of five cryomodules. Each cryomodule houses four superconducting cavities and one superconducting solenoid. The superconducting cavities are bulk niobium quarter wave resonators at 106.08 MHz operating at 4 K. All twenty cavities installed, fabricated in Italy by Zanon, meet or exceed the ISAC specification being 30 MV/m peak surface field at 7 W of helium consumption. In fact the SC linac is now operating for two years at an average gradient of 35 MV/m peak surface field (7 MV/m of acceleration) at 7 W. During this period there is on average no significant degradation in the cavities performance. Each cavity is independently phased at -25° synchronous phase. The transmission through the SC linac is 100%.

Beam Delivery

The post accelerator sections are tuned by means of the pilot beam technique. This technique consists in setting the beam lines and accelerators with a beam of stable ions with the same mass to charge ratio as the RIB. This is necessary because the intensity of the radioactive beam typically ranges between 10^3 and 10^6 particle per second. In order to match the radioactive beam coming from the charge breeder an electron cyclotron resonance (ECR) source that can produce stable ions with higher charge states is now installed. The switchover procedure from the pilot beam to the radioactive is straightforward. The transmission of the RIB is checked using several low intensity detectors (like silicon detector, photodiode or channeltron) distributed along the beam line.

The delivery of RIBs is challenging considering the long chain of production, selection and post acceleration. In order to transport the radioactive ions to the experiment every single component has to function properly. The availability of the ISAC linacs is 98%.

ISAC-II UPGRADE

A linac upgrade is underway [8]. The upgrade consists of twenty more cavities housed in three cryomodules installed downstream of the existing section. The first two cryomodules house six superconducting cavities and one superconducting solenoid while the last one has eight superconducting cavities and a superconducting solenoid.

This upgrade increases the ISAC-II linac voltage capability to 40 MV. This voltage will boost the beam energy above the Coulomb barrier for all masses. Since the SC linac always operates at the maximum possible voltage for stable operation, the final energy depends on the mass to charge ratio of the accelerated species. We anticipate an energy of 22 MeV/u for A/Q=2 and 8 MeV/u for A/Q=6 as represented in Fig. 4 (lower graph).

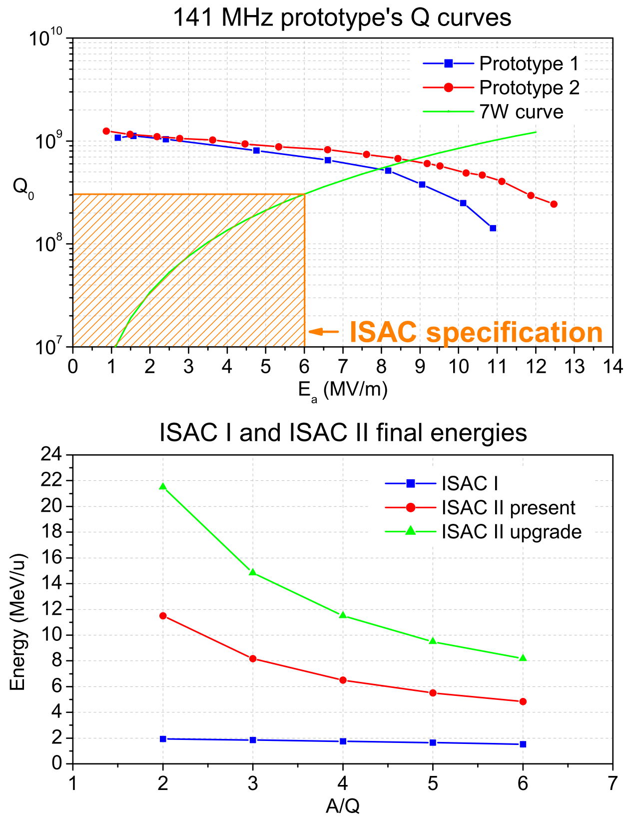

Figure 4: (Upper) Characteristic Q curves of the two new 141 MHz bulk niobium quarter wave resonator fabricated by PAVAC. (Lower) Expected final energies for the ISAC-II SC linac.

Figure 5: The first superconducting cavity produced by PAVAC Industries: the 141MHz quarter wave bulk niobium resonator for the ISAC-II linac upgrade.

The new superconducting cavities are quarter wave bulk niobium resonators operating at the higher frequency of

141.44 MHz.

The fabrication of the new cavities is done through a collaboration between TRIUMF and a local Canadian company, PAVAC Industries. PAVAC machines and electron beam welds the niobium material provided by TRIUMF (see Fig. 5). The pre welding chemical etch, as well as the final etch, is done by TRIUMF. All fabrication steps are followed by TRIUMF experts.

The first two niobium prototypes fabricated by PAVAC are already tested. They both exceed the design specifications of 30 MV peak surface field at 7W of helium consumption. The characteristic Q curves of these two cavities (Fig. 4, upper graph) show that at 7 W the accelerating fields are around 8 MV/m. This result is a significant achievement being the first cavities produced by PAVAC Industries.

The cryomodules are scheduled for installation and commissioning by the end of 2009.

FUTURE PLANS

TRIUMF is funded in a five year cycle, the next being 2010-15. A proposed upgrade of the ISAC facility, commonly called ISAC-III [9], is contained in the published five year plan.

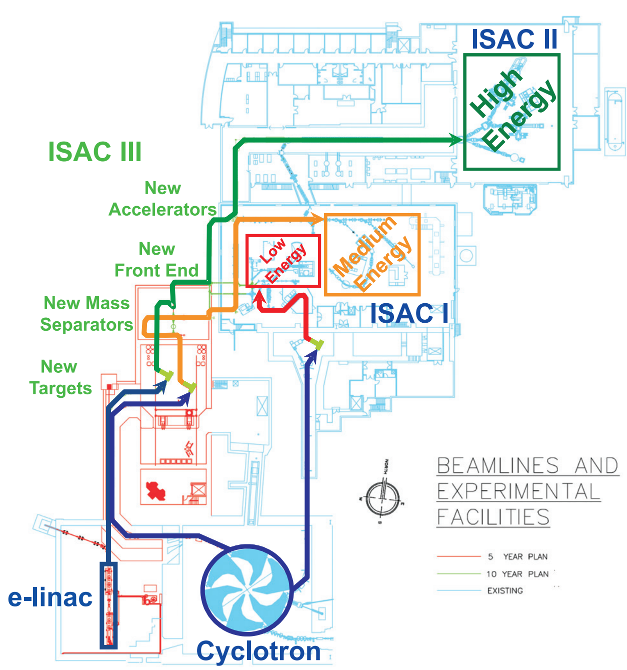

Figure 6: Layout of the proposed ISAC-III upgrade. In the picture a possible delivery schematic of three simultaneous RIBs is outlined.

At present the ISAC facility is limited by the possibility of delivering only one RIB at any given time to one of the twelve experimental stations distributed in the three experimental areas. This limits the development of new radioactive beams since this takes beam time from experiments.

It is then proposed to expand the ISAC facility with two new target stations for RIB production, two new mass separators, and a second post acceleration path (new RFQ and DTL similar to the existing ones) that can inject the beam directly into the SC linac without going through the ISAC-I accelerators.

The expansion foresees also the installation of a new electron driver (e-linac). In this way the new target stations can use as primary beam either the electrons from the new driver (e-linac) or the protons from the fourth extraction beam line (see Fig. 2) of the cyclotron.

Each one of the two new target stations will have a dedicated preseparator inside a shielded area. Two mass separators, one low resolution the other high resolution, are going to be available. The new targets and mass separators are planned to be connected via an electrostatic switchyard that gives the possibility of sending the beam from either target to either mass separator or bypass them.

Another flexible switchyard after the new separators allows to send each of the RIBs to either of the experimental areas.

The layout of the future expanded facility is represented in Fig. 6; in this picture a possible delivery schematic of three simultaneous RIBs is outlined.

The primary goal is to produce three simultaneous radioactive beams making TRIUMF the future leading ISOL facility. Figure 7 show the expected ISAC RIB production in the next decade based on the proposed upgrade.

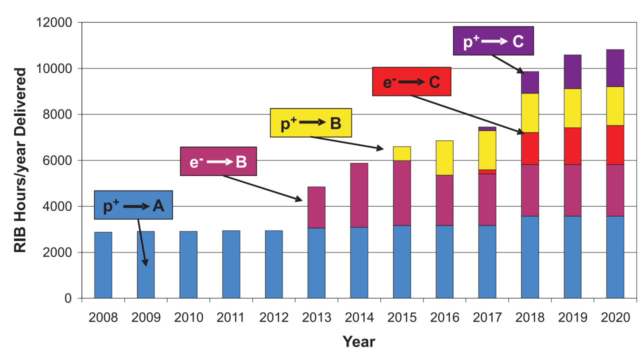

Figure 7: Expected RIB delivery in the next decade for the proposed ISAC-III upgrade. A is one of the two existing target stations, B and C are the new target stations.

e-linac

It is possible to produce radioactive ion beams through photofission [10]. The photons (Bremsstrahlung radiation) are produced by an electron beam. This method produces a higher yield of certain isotopes with respect to proton production, but it doesn't cover the entire nuclide chart as represented in Fig. 8. The two production methods then, photofission and proton induced, are complementary.

In this context an electron driver for RIB production makes ISAC a facility capable of delivery a complete spectrum of radioactive species. The electron driver (e-linac) is

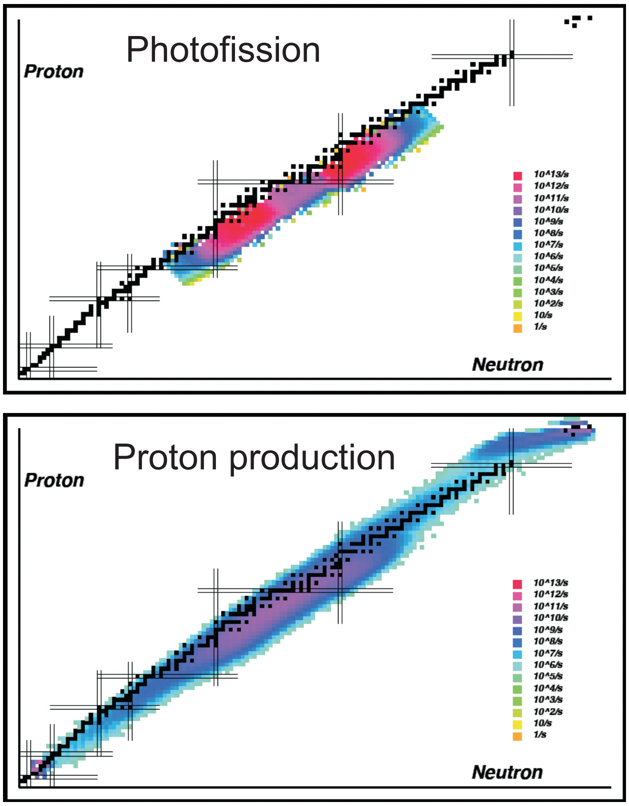

Figure 8: Simulated yield for photofission (upper) and proton (lower).

going to play a fundamental role in making ISAC the future leading ISOL facility.

The e-linac is envisaged as a 0.5 MW machine with a final energy of 50 MeV and an average current of 10 mA [11]. The linac operates in CW mode using superconducting elliptical cavities at 1.3 GHz and operating at 2 K. The layout of the machine foresees an electron gun followed by a buncher, an injector module and an accelerator composed of four nine cells cavities hosted in two cryomodules.

At present the cyclotron is shutdown for four months each year for maintenance. The e-linac is going to be independent from the cyclotron meaning the RIB production can cover the entire year.

New SCRF Activities

TRIUMF has a world class expertise in low β superconducting RF (SCRF) gained through the ISAC-II SC linac. This expertise is going to be extended to the β=1 region with the design and construction of the e-linac.

A new series of SCRF activities are being initiated at TRIUMF [12]: a new vertical cryostat is tested for 2 K operation and being readied for single cavity test. A single cell elliptical cavity test is scheduled this Fall. A RRR measurement apparatus is used to test the electron beam welding quality of niobium material. PAVAC Industries, in collaboration with TRIUMF, is testing fabrication procedures to produce elliptical cavities. All these activities are supported also by external collaborators like the University of Toronto, VECC laboratory in Calcutta and Fermilab.

CONCLUSION

The ISAC facility at TRIUMF is one of the major ISOL facilities for radioactive ion beam production. It can provide the most intense beams for certain species. Through the next five year plan TRIUMF wants to overcome some existing limitations and become the leading ISOL facility for RIBs. Furthermore TRIUMF has planned to be an R&D center for SCRF activities covering the entire range of β.

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