COMMISSIONING OF THE 20MV SUPERCONDUCTING LINAC UPGRADE AT TRIUMF

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Abstract

The Phase II upgrade of the ISAC-II Superconducting Heavy Ion Linac involves the addition of twenty quarter-wave bulk niobium resonators housed in three cryomodules. This addition brings the total installed accelerating voltage from 20 MV to 40 MV. The cavities are produced in Canadian industry with cavity testing and cryomodule assembly at TRIUMF. The commissioning of, and operations with, this major upgrade, which commenced in April 2010 will be discussed in this paper.

INTRODUCTION

ISAC at TRIUMF is a facility for the production and post acceleration of radioactive ion beams (RIB).

The RIBs are produced using the isotope separation on line (ISOL) method [1]. An accelerator, the 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 diffuse 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 ISOL method produces high quality emittances but the complicated and relatively slow process reduces the possibility of extracting isotopes with few ms half-lives.

ISAC OVERVIEW

The ISAC facility uses the TRIUMF cyclotron as driver. The facility has the world highest power driver beam (50 kW). Table 1 compares ISAC with other present and future RIB facilities worldwide. 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 halo nucleus ^{11}Li.

The facility uses silicon carbide, tantalum or uranium carbide 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.

Driver

The TRIUMF H$^-$ cyclotron is the largest cyclotron in the world and has operated for almost 40 years. It accelerates H$^-$ ions up to an intensity of 300 μA to a maximum energy of 500 MeV. The H$^-$ are then stripped and protons

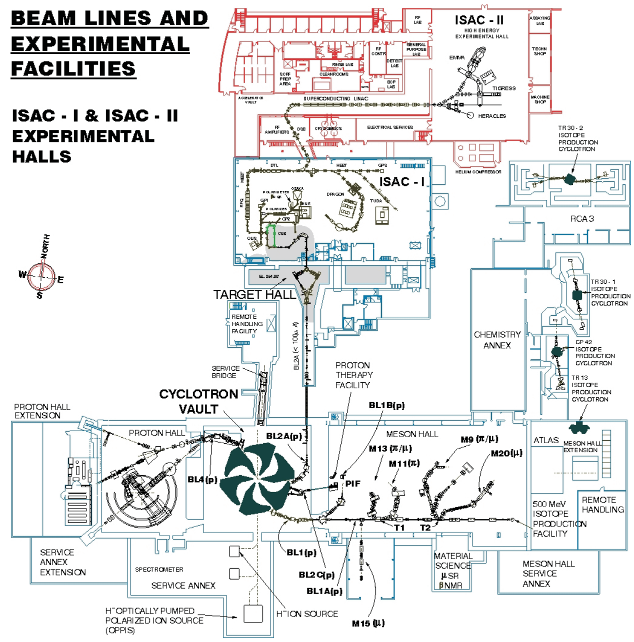

Figure 1: Overview of TRIUMF: the ISAC facility extends north of the main cyclotron.

are extracted in three different beam lines at different energies. One of these beam lines 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 key to the future ARIEL facility.

Target Station and Mass Separator

The ISAC facility has two independent target stations. The proton beam can be sent to one target station at a time.

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. The ionized species out of

Table 1: Present and Future RIB Facilities With Post-Accelerators

Laboratory	Facility	Method	Driver	Post-accelerator	V_{eff} (MV)	Energy (MeV/u)
Existing						
TRIUMF	ISAC	ISOL	500 MeV - 50 kW - p	RFQ - DTL - SCL	52.5	6.5-18
CERN	ISOLDE	ISOL	1.4 GeV - 2.8 kW - p	RFQ - DTL	13	3
GANIL	SPIRAL-I	ISOL	3 kW - HI	Cyclotron		5-25
ORNL	Holifield	ISOL	50 MeV - 500 W - p,d	Tandem	25	
ANL	CARIBU	Gas-catcher	RIB source	ATLAS SC linac	52	7-17
Future						
CERN	HIE-ISOLDE	ISOL	1.4 GeV - 2.8 kW - p	SCL	40	6.5-18
MSU/NSCL	FRIB	Gas-catcher	200 kW - HI	RFQ - SCL		12-20
GANIL	SPIRAL-II	ISOL	200 kW - d	Cyclotron		5-25

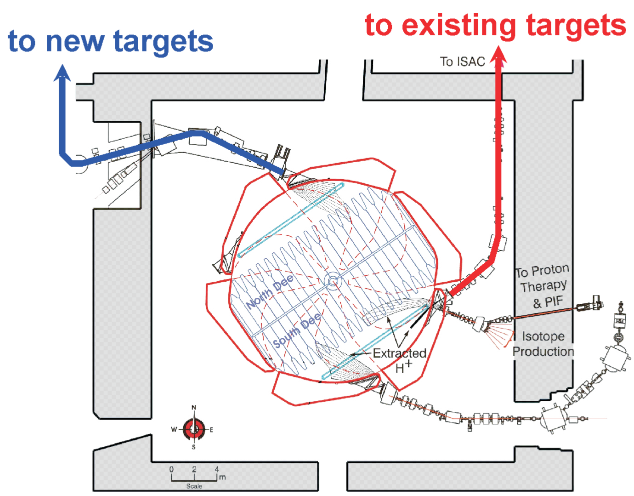

Figure 2: Schematic of the TRIUMF H^- cyclotron. Multiple beams can be extracted simultaneously at different energies.

the source are singly charged. 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 pre-separator. The target modules and pre-separator are inside a concrete shielded area. The pre-separator reduces the radioactivity transported outside the shielded area in the downstream beam line.

After the pre-separator 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 single 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.

ISAC-I 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$18%) where the ions are post accelerated with linacs.

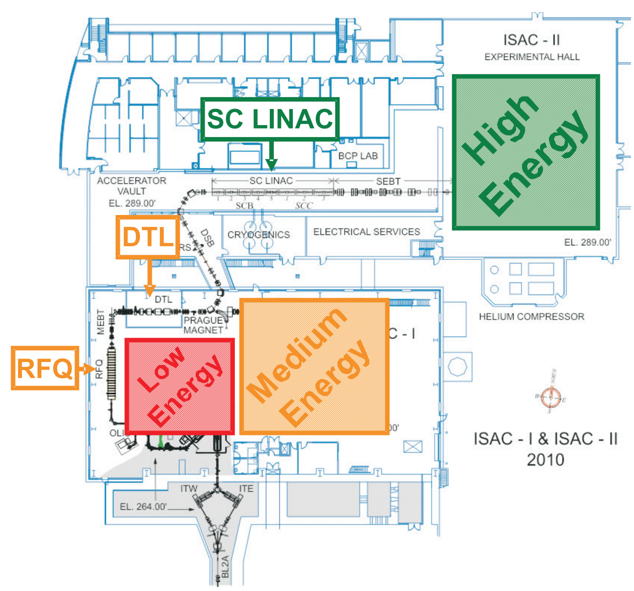

Figure 3: Overview of the ISAC facility at TRIUMF. The ISAC II linac is superconducting while in ISAC I the RFQ and the DTL are room temperature machines.

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 ratios within 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 pre-bunched 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 ion charge state is increased by means of stripping 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≤A/Q≤7. These are the acceptance limits 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% for A/q≤30.

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

ISAC-II PROJECT

The ISAC-II project is an expansion of the ISAC capabilities in terms of final energies. The project specification is to accelerate heavy ions to and above the Coulomb barrier (E≥6.5 MeV/u for A/q=6). It was decided to developed a 40 MV superconducting linac. The linac installation was staged in two phases as represented in Fig. 4 .

SC Linac Phase-I

The SC linac [7] phase-I (referred to as SCB section) installation was completed in 2006. At this stage the linac is 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 4K. All twenty cavities installed, fabricated in Italy by Zanon, meet or exceed the ISAC specification being 30 MV/m peak surface field at 7W of helium consumption.

The SC linac is usually operated at an average gradient of 35 MV/m peak surface field (7 MV/m of acceleration) at 7W. Each cavity is independently phased at -25° synchronous phase. The transmission through the SC linac is 100%.

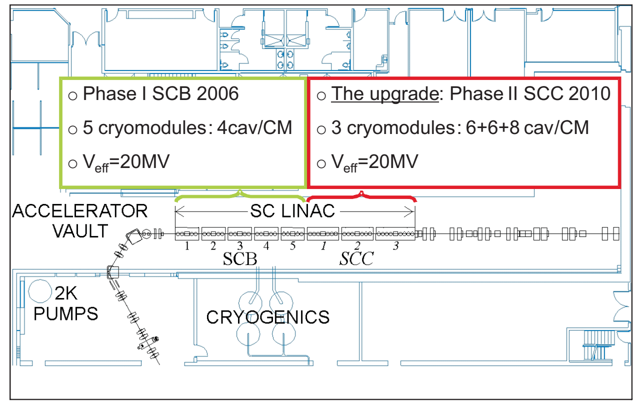

Figure 4: Final configuration of the ISAC-II superconducting linac. The first five cryomodules forms the SCB section, the last three forms the SCC section (the upgrade).

SC Linac Phase-II - The Upgrade

The SC linac upgrade (referred to as SCC section) consists of the addition of twenty more cavities to reach the total effective accelerating voltage of 40 MV.

The upgrade is a 7.5 million Canadian dollars project completed on time and on budget. The total amount for the accelerating structure is 3.8 M$: 1.4 M$ for the cavities and 2.4 M$ for the cryomodules. A new cryogenic plant (a twin system of the existing one) and helium distribution line account for 2.7 M$. The remaining 1 M$ includes RF amplifiers, power supplies and other installation costs.

A key element of the upgrade is the development and fabrication of the cavities by PAVAC industries, a Canadian company located in the Vancouver area, in collaboration with TRIUMF. The cavity development started in 2007. The production cavities were ordered in March 2008. The project was completed in March 2010.

Accelerating Structure

The twenty cavities are housed in three cryomodules: six cavities in the first two cryomodules, eight in the third. Each module houses also a superconducting solenoid for transverse focusing.

The cryomodules design is a duplicate of the already existing phase-I module with some improvements based on the Phase-I operational experience. The new module has a venting system through the RF pick-up ports of each cavity. The single vacuum inner space of the module is vented using dry filtered nitrogen from inside each cavity. This reduce the possibility of contaminating the superconducting RF surface with impurities that may reduce the performance. The variable coupler is now guided by two linear bearings. This reduces the likelihood of a stuck coupler. The motor driving the mechanical tuner is changed in favor of a brushless servo and ball screw and cheaper unit maintaining though the mechanical stability and rigidity required.

The phase-II cavities are bulk niobium quarter wave resonators similar to the phase-I cavities but operating at 141.44 MHz (Fig. 5). The cavity specifications are similar to the previous one, namely an effective voltage of 1.1 MV at 7W of helium power consumption. The transverse geometry of the cavities is maintained while the height is shorter to achieve the higher frequency. The drift tube geometry is optimized for acceleration efficiency with a design beta of 11%. Each cavity is individually tested before being assembled in the cryomodule. The average performance [8] of the PAVAC cavities is 32 MV/m at 7W. This significant result exceeds the ISAC specification.

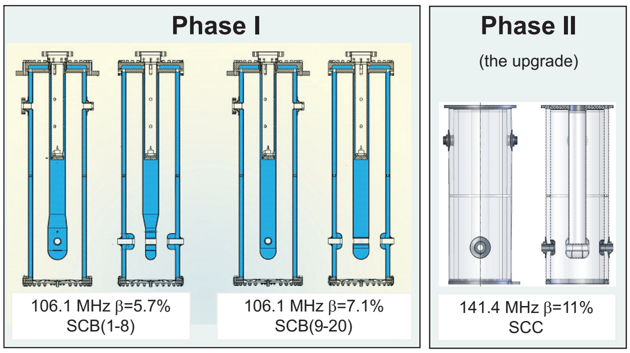

Figure 5: Superconducting linac cavities of the SCB (phase-I) and SCC (phase-II) section.

Beam Commissioning Results

The commissioning follows a detailed plan. This ensures quality and it streamlines troubleshooting. The beam commissioning is preceded by hardware checks including optics, vacuum and diagnostics.

The first step of beam commissioning is coasting the beam at 1.5 MeV/u through the linac. This checks that the solenoids are working properly. The theoretical settings produce the expected beam profile downstream of the linac. Also the transmission through the linac is 100% with no steering correction required. The solenoids don't steer the beam as the magnetic field increases. This suggest they are well aligned.

The second step is proving acceleration up to the specifications. The first measurement shows the linac is capable of accelerating $^{16}O^{5+}$ to 10.8 MeV/u as represented in Fig. 6. This is equivalent to an effective voltage of 30 MV. This also means the linac can accelerate A/q=6 to 6.5 MeV/u namely it meets the ISAC-II project specification. In this first acceleration four cavities could not be operated due to RF cable problems.

We characterized the beam quality after acceleration with each cavity in term of transverse and longitudinal emittances.

The transverse emittance measurements are done using a DANFYSIK emittance rig composed of a slit synchronized with a harp 1.6 m downstream. The slit slices the beam transversely while the divergence of each single slice

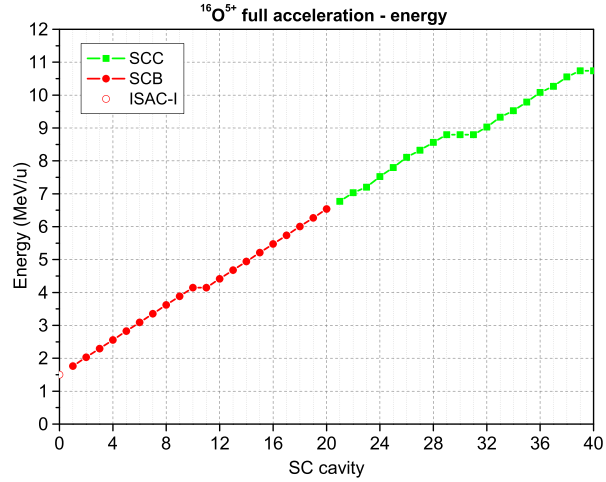

Figure 6: Final energy as a function of the cavity. $^{16}O^{5+}$ is accelerated to 10.8 MeV/u meaning an effecting accelerating gradient of 30 MV (equivalent to 6.5 MeV/u for A/q=6).

is measured at the harp. The figure 7 represent a transverse emittance scan of a $^{12}C^{2+}$ beam. The represented data are already cleaned from the background. These measurements are taken with a current of 3 enA. The final results for the transverse emittance are summarized in figure 8. On average the transverse normalized 2rms emittance is around 0.2 π·mm·mrad. This value is expected and it matches with the one used in the beam lines transport simulation. It is also in line with the measurements done after the SCB cavities [9] in 2007. Moreover this value is confirmed by looking at the beam spot at the ISAC-II experimental stations. Overall there is no emittance growth. The fact that the horizontal emittance is half the vertical one is still object of investigation.

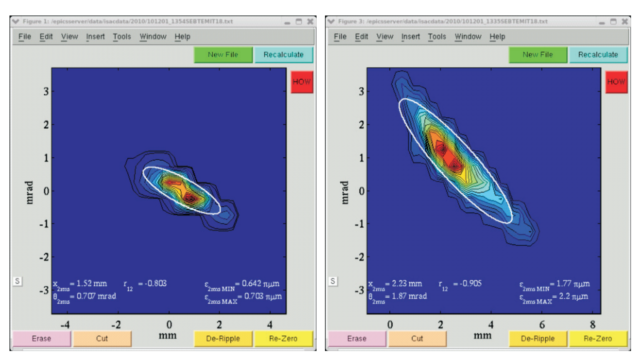

Figure 7: Horizontal (right) and Vertical (left) transverse emittance.

The longitudinal emittance is estimated using three time of flight monitors located downstream of the linac. This technique measures the time spread of the drifting beam at the three different locations. Due to the marginal separa-

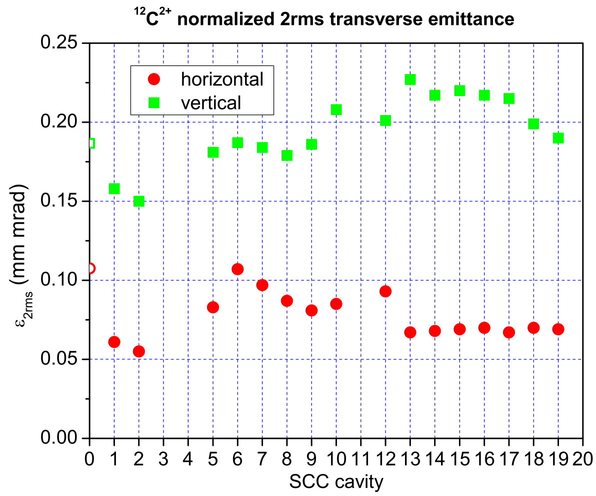

Figure 8: Horizontal (red dot) and Vertical (green square) transverse emittance after each cavity of the new accelerating section.

tion between the monitors our measurements are not very precise. Nevertheless they give us an indication of the longitudinal emittance of the beam that is around 1 keV/u·ns. This value is also in line with previous measurements [9].

Operational Experience

The upgraded linac operates since April 2010. During this running period two more cavities with respect to the initial acceleration developed RF cable problems. Some cavities experienced low level multipacting making them difficult to be turned on. The cavities of the third SCC cryomodule significantly underperformed with respect to the single cavity test. Few cryogenics problem, included a compressor motor failure and impurities present in the helium caused substantial downtime. The majority of these problems have been resolved during the winter shutdown. Most of the cavities are expected to be available with only two out of forty not operational.

The new cavities are powered by solid state instead if tube amplifier (as for the SCB cavities). This type of amplifier has a longer lifetime and don't degrade in performance over a one year running period.

The SC linac operates always at the maximum voltage. The final energy depends on the A/q ratio of the accelerated species; the lower the ratio the higher the final energy. In order to exploit this characteristic we installed a stripping foil in front of the linac to boost the charge state of the injected beam. The stripping occurs at 1.5 MeV/u. At such energy we manage to fully strip the lighter ions with good efficiency (around 30%). Using this stripping foil we accelerated $^{16}O^{8+}$ to 15 MeV/u.

We also accelerated high charge state beams from the ECRIS charge state booster (CSB). Beams from such a source come with a significant content of contaminants. In many cases the undesired species have intensities orders of magnitude higher than the desired RIB. Such cocktail beams are useless to the experiments that usually require 90% pure beams. A task force is in place to study and solve the contamination problem. Different techniques are considered in order to clean the beam: mass resolution in transport lines, time of flight separation after energy degradation and new particle identification diagnostic.

Solving this problem is crucial since ISAC demonstrated the capability of producing heavier masses using uranium carbide targets. The produced masses are higher than 30 (the RFQ acceptance in term of A/q) and therefore their charge state need to be boosted.

The completion of the SC linac is also important for the future ARIEL facility at TRIUMF. ISAC and ARIEL will form a multi-users facility with three simultaneously delivered RIB beams.

CONCLUSION

The ISAC-II superconducting linac upgrade has been completed on time and on budget. The SC linac in its final configuration meets the ISAC project specification at the first acceleration. ISAC-II is now capable of accelerating high quality beams to and above the Coulomb barrier. ISAC is a main reference for RIB facilities world-wide.

REFERENCES

[1] M. Marchetto, "ISAC-II operation and future plans", LINAC08, Victoria, British Columbia, CANADA, September 2008.

[2] G. Dutto et al., "Simultaneous Extraction of Two Stable Beams for ISAC", EPAC08, Genova, ITALY, June 2008 , p. 3505.

[3] I. Bylinskii et al., "TRIUMF 500 MeV Cyclotron Refurbishment", Cyclotrons and Their Application, Giardini Naxos, ITALY, September 2007 , p. 143.

[4] R.L. Poirier et al., "CW Performance of the TRIUMF 8 Meter Long RFQ for Exotic Ions", LINAC2000, Monterey, California, USA, August 2000 , p. 1023.

[5] S. Koscielniak et al., "Beam Dynamics Studies on the ISAC RFQ at TRIUMF", PAC'97, Vancouver, British Columbia, CANADA, May 1997, p. 1102.

[6] R.E. Laxdal et al., "Beam Commissioning and First Operation of the ISAC DTL at TRIUMF", PAC2001, Chicago, Illinoois, USA, June 2001, p. 3942.

[7] R.E. Laxdal, "Commissioning and Early Experiments with ISACII", PAC07, Albuquerque, New Mexico, USA, June 2007, p. 2593.

[8] D. Longuevergne et al.l, "RF Cavity Performance in the ISAC-II Superconducting Heavy Ion Linac", LINAC10, Tsukuba, Japan, September 2010.

[9] M. Marchetto et al.l, "Beam Quality and Operational Experience with the Superconducting Linac at the ISAC-II RIB Facility", PAC07, Albuquerque, New Mexico, USA, June 2007, p. 1392.