THE ISAC-II LINAC PERFORMANCE*

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Abstract

The ISAC-II superconducting linac is operating for almost a decade. The linac first installation includes twenty cavities housed in five cryomodules. The Phase II linac upgrade consisted of the addition of twenty cavities housed in three cryomodules. The upgrade brings the linac to a nominal 40 MV of effective accelerating gradient according to the design specification. Moreover the upgrade was the first step to qualify a Canadian vendor (PAVAC) for the production of bulk niobium superconducting cavities. Each cryomodule includes bulk niobium quarter wave resonators and a 9 T superconducting solenoid for transverse focusing. The linac features a single vacuum space. Over the years the linac has experienced vacuum incidents and high power rf cable failures in vacuum that were addressed during maintenance. In a recent maintenance program cavities from a single cryomodule were removed and chemically etched to improve performance. Future cavity treatments are in the plan but they are restricted by the priority of the scientific program. The author will present the status of the linac performance and future development plans. Reliability and availability of the linac will be discussed, metrics that will be come even more important with the advent of ARIEL.

INTRODUCTION

The Isotope Separation and ACceleation (ISAC) facility at TRIUMF produces radioactive ion beams (RIB) (see Fig. 1).

The RIBs are produced using the isotope separation on line (ISOL) method [1] where an accelerator, the driver, produces light projectiles, the primary beam, that impinge on 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 ISOL method produces high quality emittances but the complicated and relatively slow process reduces the possibility of extracting isotopes with few ms half-lives.

The produced radioactive ions are magnetically separated and sent to an experimental station. ISAC counts fifteen experimental stations distributed in three experimental areas characterized by different energy ranges: low, medium and high. In the high energy experimental area the beam is boosted by the ISAC-II superconducting linac.

Presently only a single RIB is available and can be sent to one of the fifteen stations at the time. The future ARIEL facility is going to increment the RIB availability to three ion beams that can be sent simultaneously to three different experimental stations.

* Funded under a contribution agreement with NRC (National Research Council Canada)

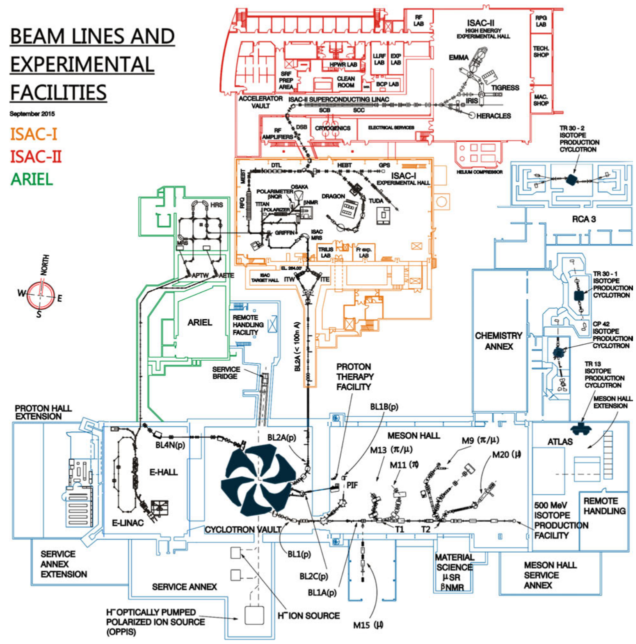

Figure 1: The TRIUMF site with the ISAC-I (red), ISAC-II (orange) and ARIEL (green) facilities.

ISAC OVERVIEW

ISAC uses the TRIUMF cyclotron as driver to accelerate protons at 500 MeV up to 100 μA of current. This is presently the highest power (up to 50 kW) driver beam for an ISOL facility. It allows to produce the most intense RIB of certain species like ^{11}Li for which yield of $2.2 \cdot 10^4\ s^{-1}$ has been achieved.

The overview of the ISAC facility is represented in Fig. 2 where the three experimental areas are highlighted.

Driver

The TRIUMF cyclotron accelerates H^- ions up to an intensity of 300 μA to a maximum energy of 500 MeV. The H^- are then stripped and protons are presently extracted in three different beam lines at different energies, one of which is dedicated for the ISAC radioactive beam production.

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. 3. This possibility together with an upgrade of the cyclotron [3] is key to the future ARIEL facility.

ISBN 978-3-95450-131-1

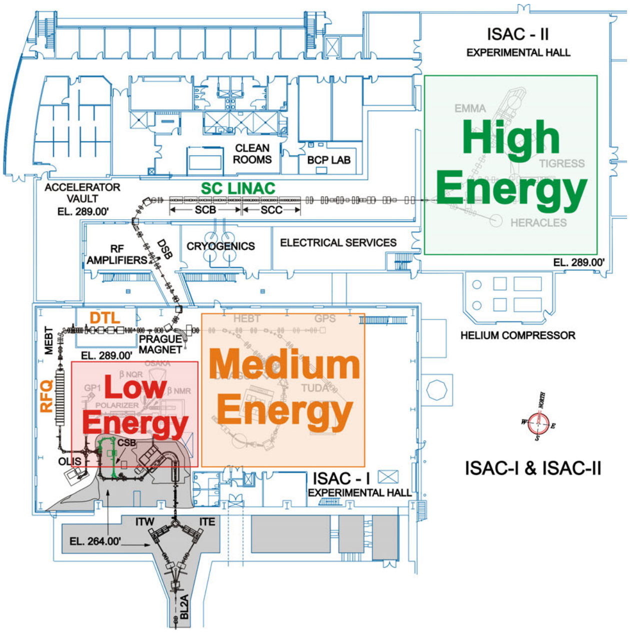

Figure 2: Overview of the ISAC facility at TRIUMF. The three experimental areas (low, medium and high) are highlighted. The grey shaded area is located two stories underground while the remaining is at ground level.

Target Station and Mass Separator

The ISAC facility has two independent target stations as represented in Fig. 4. 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 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.

Target materials include silicon carbide, tantalum and uranium carbide. Two target configurations are available: low and high power respectively for proton beam powers up to 20 kW and 50 kW.

A common pre-separator magnet is located inside the target hall to contain most of the produced radioactivity inside the shielded target hall.

A finer selection is accomplished downstream by the mass separator, typically operating at a resolving power of few thousands. 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 with $A > 30$.

The target stations and the separator area are located two stories underground. Once produced and selected the RIB is then transported to ground level where experimental stations are located.

ISAC-I Post Accelerators

The RIBs can be delivered to three experimental areas as represented in Fig. 2: a low energy area where the ions are accelerated at source potential (up to 60 kV), a medium energy area ($\beta = 1.8\% \rightarrow 6\%$) or a high energy area ($\beta = 6\% \rightarrow 18\%$) where the ions are post accelerated with linacs.

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 within $3 \leq A/q \leq 30$. The RFQ is a room

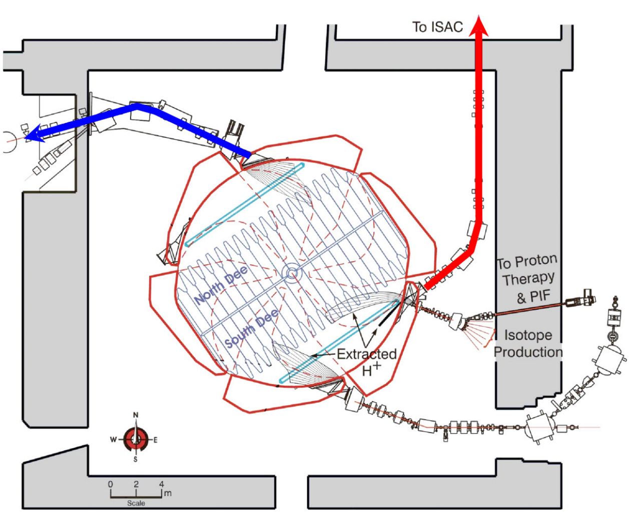

Figure 3: Schematic of the TRIUMF H$^-$ cyclotron. Multiple beams can be extracted simultaneously at different energies. The proton beam is extracted at 500 MeV and up to 100 µA for RIB production in ISAC (red line) and in ARIEL (blue line - future).

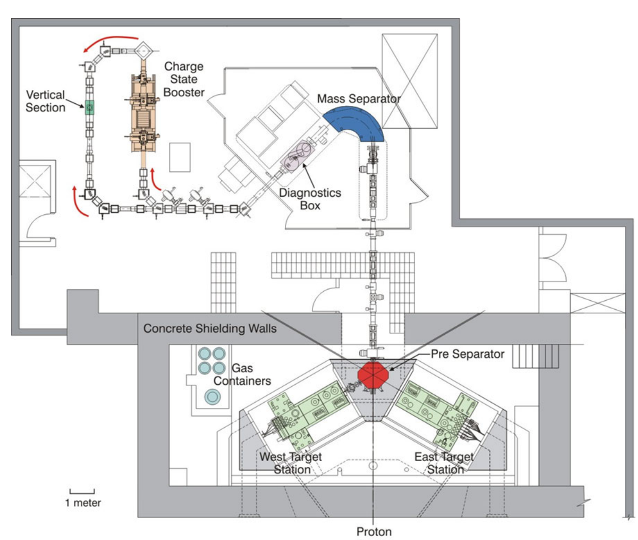

Figure 4: Representation of the two ISAC target stations and following separation stages.

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temperature CW machine operating at 35.36MHz. 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 $2 \le A/Q \le 7$. 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 $A/q \le 30$.

The DTL [6] is a variable energy machine covering the entire range of energies between 150 keV/u $\le E \le$ 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, specifically the goal is to reach an energy of $E \ge 6.5$ MeV/u for $A/q = 6$. This is equivalent to a minimum effective accelerating voltage of 30 MV. It was decided to develop a 40 MV superconducting linac. The linac installation was staged in two phases as represented in Fig. 5 . The total cost of the installed hardware is 15 M$ including cryogenics and power supplies.

Installation

The Phase-I installation (referred to as SCB section), completed in 2006 [7], is composed of five cryomodules.

The cryomodule design [8] consists of a top loading structure with a single vacuum as represented in Fig. 6. Each SCB cryomodule houses four superconducting cavities and one superconducting 9 T solenoid. All twenty cavities are fabricated in Italy by Zanon. The cavities and the solenoid hang from a strongback suspended by three posts. A helium reservoir keeps the the cavities and the solenoid in a helium

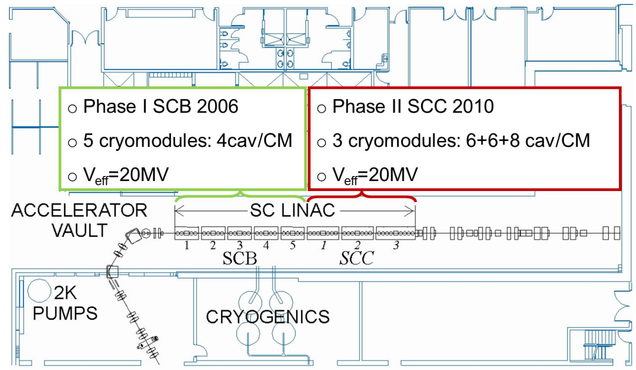

Figure 5: Final configuration of the ISAC-II superconducting linac. The first five cryomodules forms the SCB section, the last three forms the SCC section.

bath. The cryomodule has a heat shield cooled with liquid nitrogen to transition from 300 k to 4 k and a mu-metal shield to suppress external magnetic field.

Due to the single vacuum characteristic, each cryomodule is entirely assembled in a clean room.

The Phase-II installation (referred to as SCC section) is an upgrade consisting of twenty additional cavities to reach the total effective accelerating voltage of 40 MV. The twenty SCC cavities are housed in three cryomodules: six cavities in the first two cryomodules, eight in the third.

The cryomodule design is a duplicate of the phase-I module with some improvements based on the operational experience with the first installation. The strongback is suspended by four posts for added flexibility in the alignment stage. The

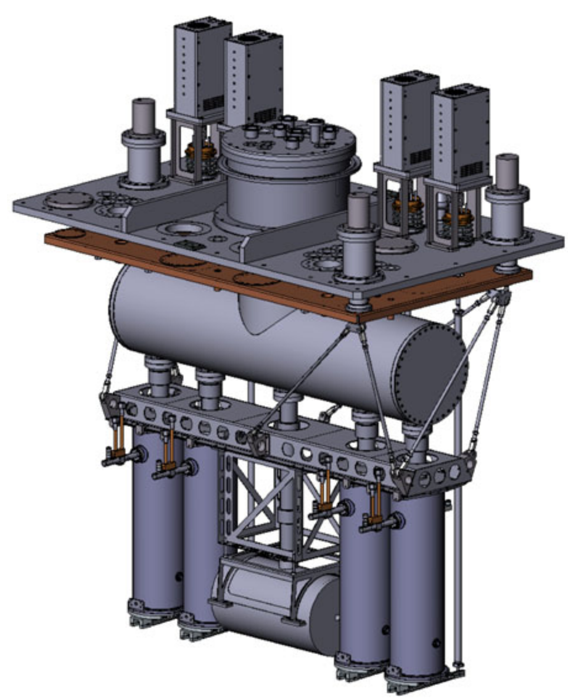

Figure 6: Superconducting linac cryomobule (SCB represented).

ISBN 978-3-95450-131-1

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 lowering the likelihood of contaminating the superconducting RF surface with impurities that may reduce the performance. The variable coupler is now guided by two linear bearings reducing the likelihood of a stuck coupler. The motor driving the mechanical tuner is changed in favour of a brushless servo and ball screw a cheaper unit that maintains the mechanical stability and rigidity required.

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 phase-II installation was completed in March 2010 [9].

Rf Cavities

The basic accelerating cavity for both phases is a quarter wave bulk niobium resonator operating at 4 K.

Phase-I and Phase-II cavities resonate respectively at 106.08 MHz and 141.44 MHz. Two types of Phase-I cavities are installed with design β of 5.7% (cavity 1–8) and 7.1% (cavity 9-20). Phase-II cavities are of just one type with $\beta = 11\%$. All types of cavities are represented in Fig. 7. The cavity specification requires an effective voltage of 1.1 MV at 7 W of helium power consumption.

Each cavity has an rf inductive coupler [10] and an electrical pickup. The rf coupler has liquid nitrogen cooling. A corrugated slotted niobium tuning plate provides compensation of frequency variation due to helium pressure fluctuations.

Each cavity is individually tested before being assembled in the cryomodule. All Phase-I meet or exceed the ISAC specification of 30 MV/m peak surface field at 7W of helium consumption when installed. The original average performance of the PAVAC cavities is 32 MV/m at 7 W; this significant result exceeds the ISAC specification.

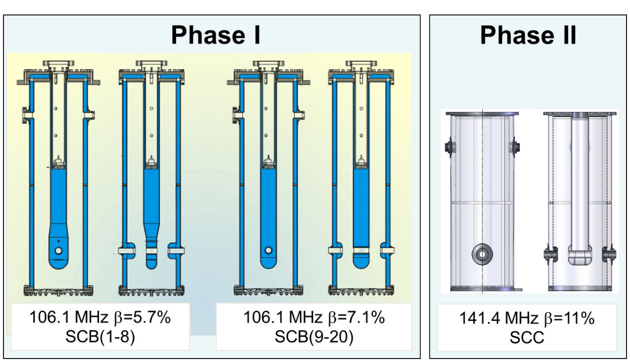

Figure 7: Superconducting linac cavities of the SCB (phase-I) and SCC (phase-II) section.

Cryogenic Distribution

The cryogenic plant [11] comprises two Linde TC50 (600 W at 4 K) refrigerator systems connected to a 1000 l dewar. Each refrigerator is supplied with high pressure helium gas from a dedicated Keiser compressor.

The liquid helium at 4 K is transferred from the dewar to the cryomodules by differential pressure through the supply line. The helium gas can be sent back to the compressor via the cold return or the warm return line depending if the gas temperature is below or above 20 K.

When returned through the cold line the gas travels though the refrigerator before reaching the compressor. This return path increases the efficiency of the refrigerator itself.

An additional recovery compressor is installed to load the warm return gas into a buffer tank in case the main compressor is down.

The cryogenic system also supplies liquid nitrogen to the module for the heat shield and the rf coupling loops.

OPERATIONAL EXPERIENCE

In first decade of operation we experienced a few technical issues.

Some cavities require extensive multipacting conditioning that needs to be accounted for in the set-up time and in some cases causes down-time during operation. The choice of a variable coupler greatly reduces the amount of time required to recover from a cavity trip in the case where multipacting interferes with cavity turn-on.

In order to reduce the conditioning time, a technique is in place where all the twenty cavities in each phase are conditioned simultaneously using a single external signal generator to drive all the amplifiers of each cavity bypassing the low level rf system. The generator frequency is swept with a bandwidth that covers all the natural resonant frequencies of all the cavities. This technique reduces the conditioning time from days to hours.

The SCB section uses tube amplifiers while the SCC section uses solid state. The latter are proven to be more stable for operation. The tube amplifier needs to be phase tuned as the tube ages and their performance can degrade during the experimental run leading to downtime.

Some of the SCB cavities are affected by stuck variable couplers. This issue can result in the difficulty of conditioning the cavity or in achieving stable operation and therefore losing accelerating voltage. This issue is not present in the SCC section thanks to the improved design with linear bearings.

In 2009 the fourth cryomodule of the SCB section (SCB4) experienced a catastrophic failure of one of the turbo pumps. Debris from the exploded blades landed inside the cryomodule. An in situ cleaning and replacement of the pump occurred with no immediate degradation of the cryomodule performance.

Some rf cables developed in vacuum rf shorts rendering the relative cavity inoperable. This issue has been identified and corrected. The adopted solution consists in replacing the ANDREW 3/8″ FSJ2-50 cable with an ANDREW 1/2″ FSJ2-50 cable instead.

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Linac Performance

The average effective gradients as measured after the initial installation is 6.98 MV/m and 5.02 MV/m respectively for the SCB and SCC section. After almost a decade of operation (as measured on August 2015) we experience a performance degradation of 19% and 14% respectively for SCB and SCC as shown in Fig. 8.

The SCB4 cryomodule shows more degradation in performance with respect to other cryomodules. This is attributed mainly to the vacuum accident and the single vacuum configuration. Since the SC linac is thermally cycled every year during the main shutdown, the fine particulate generated during the pump explosion eventually can migrate and contaminate the rf surface.

Two cavities, located in two different cryomodules (SCB1 and SCC2), still suffer from rf glow discharge in rf cables. These cables will be replaced in future shutdowns.

In general reduced maintenance activities due to other priority on site is one of the factor for the loss of performance. Nevertheless the linac is still capable of meeting the original ISAC-II specification of delivering effective accelerating voltage of 30 MV.

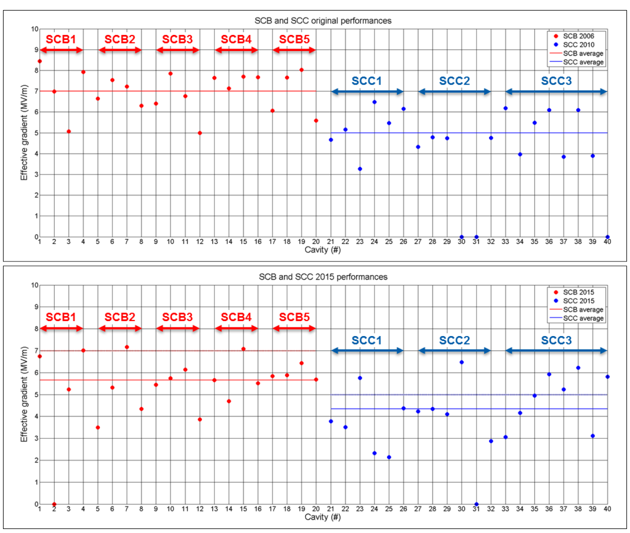

Figure 8: Linac performance in the original installation (top) and as of August 2015 (bottom). Two cavities (SCB1:CAV2 and SCC2:CAV5) are not operable due to damaged rf cables.

Future Plan

Presently the SC linac is capable of providing the effective accelerating voltage according to specifications, and hence accommodating energy requests from the user, as well it can maintained stable operation defined as > 90% of the scheduled beam time. In order to maintain this capability though it is necessary to invest in maintenance that requires long period of shutdown.

Treatment of the cavities such as degassing and additional buffer chemical polishing (BCP) followed by high pressure water rinsing (HPWR) can restore the rf surface and recover the original gradients.

Retrofitting of rf cables and couplers with linear bearings is also in the plan, as well as the upgrade to solid state amplifier for the SCB section.

All this planned maintenance aims at recovering effective accelerating voltage and stability during operation. This is critical in view of the ARIEL project [12] completion that is going to increase, an estimate four fold, the amount of RIB available for post-acceleration with the SC linac.

CONCLUSION

After a decade of operation the SC linac has experienced some degradation in performance. Nevertheless the accelerator is still capable of delivering the effective accelerating voltage of 30 MV as requested in the original specification of the ISAC-II project. A plan is conceived to restore the linac performance to the original installation and maintain stable operation. This is important for the future when the new ARIEL facility will increase the beam availability.

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