COMMISSIONING AND EARLY EXPERIMENTS WITH ISAC-II

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Abstract

The first phase of the ISAC-II superconducting accelerator has recently been commissioned. The heavy ion linac adds 20MV to the 1.5MeV/u beam injected from the ISAC post accelerator. The linac is composed of five cryomodules; each cryomodule housing four 106 MHz quarter wave resonators and one 9T superconducting solenoid. On-line performance has confirmed cw operation at a peak surface field in excess of 35MV/m. The paper describes the successful commissioning and the early operation with both stable and radioactive beams.

INTRODUCTION

The ISAC facility [1] is now the leading facility for ISOL based radioactive ion beam production and acceleration. Beam production consists of a 500 MeV cyclotron producing a proton driver beam of up to 100μA onto one of two thick production targets, an on-line ion source and a mass-separator. The radioactive ions are accelerated in a chain of linacs consisting of a room temperature RFQ and DTL to an energy 1.5 MeV/u and a new superconducting linac that adds a further 20 MV to the beam for nuclear physics investigations near the Coulomb barrier. The experimental facilities are divided into low-energy areas (source potential), medium energies, variable from 150 keV/u to 1.8 MeV/u and the high energy hall after the superconducting linac. Presently we are limited by licensing restrictions to energies less than 5 MeV/u for experiment although commissioning studies restricted to the accelerator vault have produced beams up to 10.8 MeV/u.

Recent trends have shown a heightened interest in low beta (5-15%) cw superconducting light and heavy ion linacs including RIA, EURISOL, SPIRAL-II, SOREQ and REX-ISOLDE. All these facilities take advantage of the early developments, production and operation of QWR niobium cavities at ATLAS and later at INFN-LNL and JAERI. In the proposals the linacs are grouped into driver accelerator applications or RIB post-accelerator applications. Driver accelerators tend to be longer and cover a wider velocity range than post-accelerators with a larger number of cavity geometries. Consequently the operating gradients have to be chosen somewhat conservatively so that the beam can follow a prescribed velocity profile. In addition the driver beams are of higher intensity so halo control is important and gradient management particularly in the low velocity region overrides the actual capabilities of such cavities. In contrast when configured as a RIB post-accelerator the intensity of the beam is never an issue. The linac tends to be shorter, made up of only a few cavity types so gradients can be kept near the maximum possible with the number of cavities chosen as required by the experiment. Nonetheless maximum achievable gradient at a given cavity power is an important criteria since this will ultimately determine how much linac one requires to fit a prescribed set of experimental requirements.

A particular well-suited application for SC linacs is in the post-acceleration of ions in ISOL based radioactive beam facilities. The short independently phased cavities provide a flexible, large acceptance machine to support a varied nuclear physics program. Present cw operation is limited to peak surface fields of 20-25 MV/m. The new projects are attempting to take advantage of the lessons learned over the past twenty years and push the cw gradients to minimize project costs. The TRIUMF ISAC-II superconducting linac is the first realization of this new generation facility with a design goal to operate at a peak surface field of 30 MV/m.

ISAC-II SUPERCONDUCTING LINAC

The linac is grouped into low, medium and high beta sections. The initial five medium beta cryomodules represent a first stage (Stage 0) with a further 20 MV of high beta superconducting linac to be installed over the next three years (Stage 1). The ISAC-II accelerator final low beta Stage 2 is foreseen after 2010. A schematic representation of the expansion is given in Fig. 1. The present installation is

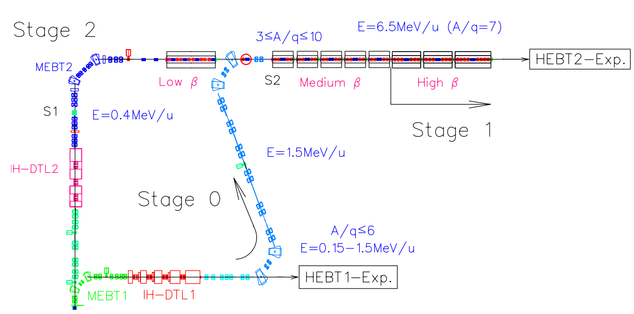

Figure 1: Stages 0, 1 and 2 for the ISAC-II upgrade.

composed of twenty 106 MHz bulk niobium, quarter wave, rf cavities housed four per cryomodule in five cryomodules. Each cryomodule contains one 9 T superconducting solenoid for periodic transverse focussing.

The cavities consist of only two accelerating gaps giving a broad velocity acceptance. The first eight have a design velocity of $\beta_o = 5.7\%$ while the remaining twelve have a design velocity of $\beta_o = 7.1\%$(Fig. 2). A demountable flange on the high field end supports the tuning plate. Rf

* TRIUMF receives funding via a contribution agreement through the National Research Council of Canada

coupling is done inductively through a side port near the upper end of the cavity.

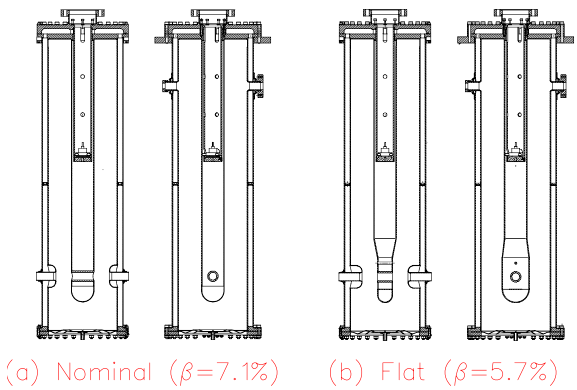

Figure 2: The two medium beta quarter wave cavities for the ISAC-II linac.

The ISAC-II medium beta cavity design goal is to operate up to 6 MV/m across an 18 cm effective length with $P_{cav} \leq 7$ W. Note that there is no agreed upon definition of cavity length within the heavy ion community so accelerating gradient is not the best indication of performance. The ISAC-II design gradient corresponds to an acceleration voltage of 1.1 MV, a peak surface field of $E_p = 30$ MV/m and a stored energy of $U_o = 3.2$ J. This is a significant increase over other operating heavy ion facilities. The gradient may seem low compared to the present state of R+D in elliptical cavities where single cavity tests are pushing peak surface fields of 100 MV/m and gradients of 50 MV/m. There are two important points to keep in mind. Firstly ILC cavities will operate pulsed at or near the highest attainable peak surface field whereas cw cavities are restricted by the cryogenic system to a given cavity power. In this case the cavity Q at the operating point is the critical parameter. The second point is that because of the difference in the velocity regimes, frequency and hence cavity geometry the E_p/E_a ratio differs markedly between a $\beta = 1$ cavity (E_p/E_a=2) and a heavy ion cavity ($E_p/E_a \sim 4-5$)). Future cw projects for relativistic electrons such as the Cornell ERL are specifying cavities with a $E_a = 15-20$ MV/m corresponding to peak surface fields from $30-40$ MV/m in line with the ISAC-II aims.

Several design and hardware choices were made in an effort to reach the gradient goal. The high peak surface field demands clean rf surfaces. For simplicity of mechanical assembly a single vacuum space for cavity and thermal isolation is used but clean assembly methods and cavity rinsing are adopted. (It is important to note that many of the present heavy ion initiatives in the last few years are being designed with separate vacuum systems for the thermal vacuum and the beam/rf vacuum.) The large stored energy requires an rf system capable of achieving stable performance. The chosen tuning bandwidth of ±20 Hz demands a cw forward power of ~200 W and peak power capability of ~400 W to be delivered to the coupling loop. An LN2 cooled coupling loop [2] was developed to handle the higher forward power while releasing less than 0.5 W to the LHe. To minimize detuning from slower perturbations such as helium pressure fluctuations (~ 2 Hz/Torr) a fast zero backlash tuner was developed[3] with a demonstrated mechanical response bandwidth of 30 Hz. The large accelerating gradients produce a large rf defocussing. A linac lattice consisting of modules of four cavities with a single high field (9 T) superconducting solenoid in the center is adopted. Beam diagnostics are positioned between modules at a waist in the beam envelope. Also unique is the use of unshielded high field solenoids with added canceling coils operating in close proximity to the cavities[4].

LINAC PREPARATION

Cryomodules

Each module has two main assemblies, the top assembly and the tank assembly. The top assembly shown in Fig. 3 includes the vacuum tank lid, the lid mu-metal and LN2 shield, the cold mass and the cold mass support. The tank consists of the vacuum tank, the mu-metal liner and the LN2 box insert. Both the top and bottom sub-components were assembled separately in a 'dirty assembly' area as a pre-assembly step. The sub-components were then disassembled, cleaned and delivered to the ISAC-II clean room for final assembly, alignment and testing.

Figure 3: Cryomodule top assembly in the assembly frame prior to the cold test.

A view of the final vault installation is shown in Fig. 4.

Cooldown

The cavities are first baked at ~90°C for 48 hours. LN2 is then fed through the side-shields and the cold mass is cooled by radiation for at least 48 hours to bring the average temperature to about 200K before helium transfer. Linac cooldown is done sequentially, one cryomodule at a time, to achieve a cavity cooling rate of ~100K/hour to mitigate the effects of Q-disease[5]. This requires a LHe

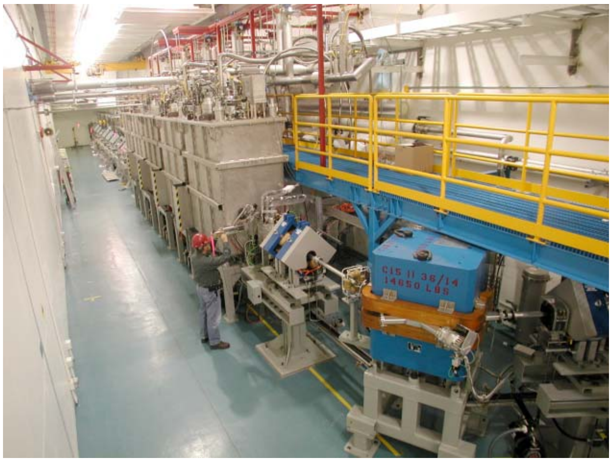

Figure 4: The ISAC-II accelerator vault.

flow of ∼100-150 ltr/hr. It takes about five hours to establish a 120 ltr inventory in the cryomodule and roughly 24 hours to complete the bulk of the thermalization. A full cooldown takes a minimum of seven days with two days for the cold box, dewar and trunk line and one day each for the cryomodules.

LINAC OPERATION AND COMMISSIONING

First beam from the linac came in April 2006 followed by a full set of commissioning studies. The first radioactive beam was accelerated in January 2007 followed by a shutdown with a full warm-up and maintenance activities. Beam production was resumed in May 2007.

Linac Tuning

The superconducting linac is tuned using stable beams from the ISAC off-line ion source. The beams are accelerated to 1.5 MeV/u and transported to the ISAC-II linac via a 25 m S-bend transport line complete with a 35 MHz two gap spiral buncher for longitudinal matching to the new linac. To accelerate each cavity is turned on and phased sequentially starting at the upstream end until the desired energy is reached. The last operating cavity is then fine tuned in voltage or phase to achieve the requested energy. The cavities are phased by measuring the beam energy (see below) for five different phases then fitting the data to a cosine profile to find 0°. All cavities are set to a synchronous phase of -25° for acceleration. The focusing solenoids and beamline optics are set to their theoretical settings as the acceleration progresses. The short independently phased cavities provide a useful flexibility. For example we have demonstrated that if a cavity becomes inoperable the linac can be retuned starting from the downstream cavity without a reduction in performance. The full linac can be tuned in about four hours. In most cases we have kept the gradients at the maximum cavity power level of 7 W and tuned the phases for each new beam; however we have also demonstrated that a 20% change in ion mass can be quickly tuned by rescaling of the rf voltages while keeping the rf phases fixed.

To tune a low intensity radioactive ion beam (RIB) a stable pilot beam from an off-line source with the same A/q is tuned to the experiment. The low energy beam line is then switched to accept the radioactive beam from the on-line source. Low-intensity diagnostics are distributed at key locations in the delivery chain to check that the RIB transmission matches the pilot beam.

Diagnostics

A silicon detector 4 m downstream from the linac records ions back scattered from a thin gold foil producing energy and timing distributions of the beam. The monitor is used for cavity phasing and rough energy measurement.

A time of flight (TOF) monitor also in the downstream beamline is used for more precise energy measurement. The monitor consists of three identical units spaced 2.19 and 9.07 m apart respectively. The three monitors provide three TOF values that are combined in a weighted average to produce the calculated energy[6]. Each unit consists of a biased wire inside a grounded can. A hole in the can allows the beam to pass. Electrons driven off the wire are accelerated through an aperture in the can to a micro-channel plate for timing information. The response and delay times of the monitors are pre-set by a laser calibration on a test bench. The distance between the monitors is measured by an alignment laser. Beams of known energy from ISAC are used to cross check the accuracy of the TOF monitor.

Each linac cryomodule has a diagnostic box upstream containing a Faraday cup (FC) and profile monitor (LPM). The LPM consists of a plate machined with 'x' and 'y' slits that is driven by a stepper motor. During a scan the transmitted beam is recorded by the downstream FC to produce transverse profiles. For low intensity measurements the LPMs are paired with Secondary emission monitors (channeltron) and Silicon detectors (SiD) to give both profile and intensity information. A non-intercepting monitor with sensitivity less than 1 enA has been developed personnel protection during beam delivery.[7]

Commissioning results

Initial commissioning beams were chosen to span the range of anticipated mass to charge ratios. The beams included 40Ca10+, 22Ne4+, 20Ne5+, 12C3+, 4He1+ and 4He2+ with A/q ratios of 5.5, 4 and 2. Prior to acceleration the cavity voltage for each is set to a cavity power of 7 W to benchmark the cavity performance.

Final achieved energies are shown in Fig. 5(c) compared to expected final energies assuming the design gradient of 6 MV/m. Final energies of 10.8, 6.8 and 5.5 MeV/u are reached for beams with A/q values of 2, 4 and 5.5 respectively. The average cavity gradients for the three cases as calculated from the acceleration rate are shown in Fig. 5(a). The average gradient in each case is 7.2 MV/m corresponding to an average peak surface field of 36 MV/m and an average voltage gain of 1.3 MV/cavity.

1-4244-0917-9/07/$25.00

Initial rf test results from the single cavity cryostat are plotted for comparison. In this case the average peak surface field for the cavities is 38 MV/m at a cavity power of 7 W. This corresponds to a gradient of 7.6 MV/m and a voltage gain per cavity of 1.4 MV. The *in situ* gradients in general match well the gradients from initial single cavity tests. A few cavities have obviously been contaminated during assembly while others have improved perhaps during the final assembly rinse. A significant point is that the average operating gradient during the initial commissioning period is down by only 5% from the single cavity result.

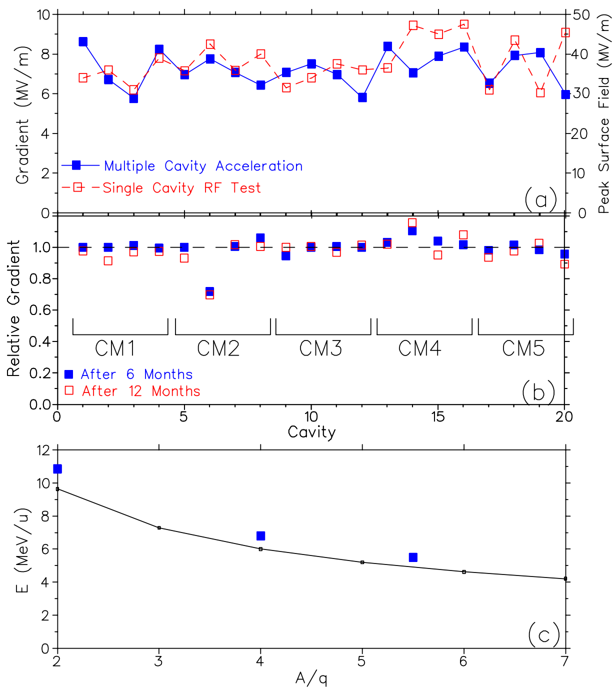

Figure 5: (a) Average cavity gradients for the three A/q values and for 7 W cavity power. Results are inferred from the step energy gain per cavity during acceleration. Also shown are gradients from initial single cavity characterizations. (b) Relative cavity gradients at 7 W comparing the initial *in situ* results to results at both six months and twelve months after the initial tests. (c) Final energies for the three cases compared to expected final energies assuming the design gradient of 6 MV/m.

Also of note is that the transmission is >90% and the tuning is straightforward. However the required steering strengths are higher than expected, evidence that the solenoid alignment is not within specification in some cases. We have utilized the adjustable support posts on the cryomodule top plate to move the cold mass with respect to the beam line to reduce the solenoid steering. The first few cryomodules have been done with reasonable success. This work will continue.

Beam Quality Beam emittance measurements are taken with a standard slit and harp device. A sample measure is shown in Fig. 6. Here the vertical and horizontal emittance of a 4He1+ beam is displayed for energies of 2.7 MeV/u and 6.8 MeV/u. The energies correspond to acceleration with the first cryomodule and with all five cryomodules respectively. The measured vertical emittances of 2.3$\pi\mu$m and 1.6$\pi\mu$m correspond to normalized emittances of 0.17$\pi\mu$m and 0.19$\pi\mu$m respectively while the measured horizontal emittances of 2.3$\pi\mu$m and 1.0$\pi\mu$m correspond to normalized emittances of 0.17$\pi\mu$m and 0.12$\pi\mu$m respectively. The result is consistent with no emittance growth within the experimental uncertainty.

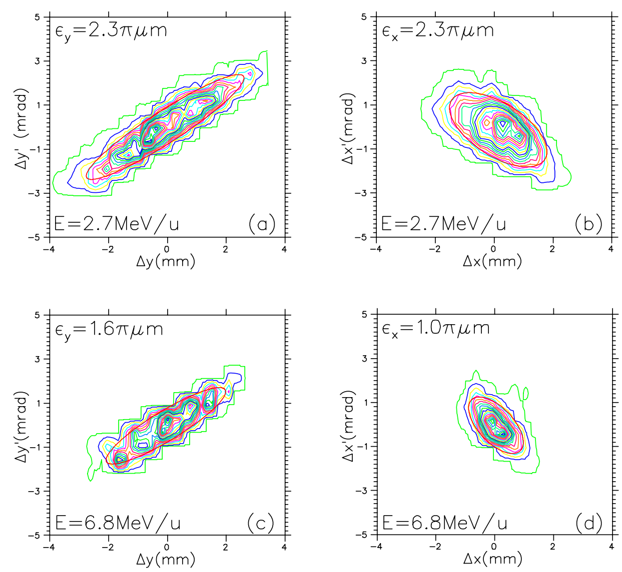

Figure 6: Shown are the vertical (left) and horizontal (right) transverse emittances measured downstream of the linac for 4He1+ at two different energies, 2.7 MeV/u and 6.8 MeV/u.

Presently there is no buncher in the downstream beam transport. However we have successfully demonstrated that for experiments that do not require the full energy, and hence have only a limited number of cavities 'on' starting from the linac's upstream end, a downstream cavity, normally 'off', can be tuned to manipulate the longitudinal phase space to provide either time focussed or energy focussed beams at the experiment. Fig. 7 shows the case with cavities 1-8 'on' and cavity 19 used as a buncher to provide a time focus at the downstream silicon detector.

Longitudinal emittance measurements are estimated by reconstructing the phase space based on beam time widths. The time widths are measured at three timing monitors in the downstream beamline each separated by $\sim$9 m. A downstream cavity is used to arrange a timing minimum in the middle monitor. The method gives a longitudinal emittance of $\sim$1 keV/u-ns and the results are consistent with little or no emittance growth. Measured beam time widths at 1σ are of the order of $\pm$250 ps.

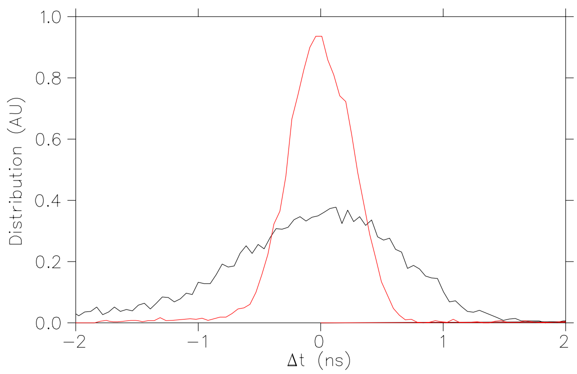

Figure 7: Time spectra recorded at a silicon detector with and without cavity 19 used as a buncher. Cavity 1-8 are 'on' producing a beam energy of 3.7 MeV/u.

Shutdown Activities and Start-up

RIB production at the ISAC facility is dependent on the availability of the TRIUMF cyclotron drive beam. The cyclotron typically is shut down for three months of the year and the ISAC-II linac is warmed during these shutdown periods. During the shutdown significant work was done. One cryomodule (CM1) was taken out of the line, removed to the cleanroom and the cold mass opened for repair of a coupling loop drive. The removal, repair and reinstallation of the cryomodule takes about two weeks. As well four turbo-pumps, two Leybold Maglevs and two Varian pumps with ceramic bearings had failed during the previous running period. (The reason for the high rate of failure (four out of ten) is still not clear.) One of the pumps was replaced in the clean room during the coupling loop drive repair. The other three were replaced *in situ*. Due to the single vacuum space for rf and thermal isolation the risk of particulate contamination is a serious concern. The replacements were done by venting slowly with filtered nitrogen and removing the pump while providing a slight overpressure of filtered nitrogen for control of particulate contamination. During repair it was discovered that one Varian pump on CM4 had completely failed with turbine blade shards scattered on the LN2 thermal liner. The shards were removed from the turbo-pump port, the LN2 shield vacuumed as access would allow and the pump was replaced. No attempt was made to remove the cryomodule for particulate decontamination in the clean room due to the lack of time.

These activities proved a good test of procedures and give some indication of the sensitivity of cavity performance to contamination and to warming cycles. A comparison of the relative cavity gradients after the initial operating period (six months) and after the shutdown (twelve months) compared to the gradients recorded in initial measurements are shown in Fig. 5(b). The cavity performance shows only minimal deterioration with an average of 99% of performance after six months and 98% after twelve months. In particular despite the work done in the shutdown the cavity performance in CM1 and CM4 are unaffected. The one significant change is to CM2:Cavity2 that suffered a modest performance reduction that we think is related to Q disease.

First RIB Delivery

The first RIB experiment at ISAC was a collaboration between TRIUMF, Ganil and Argonne studying the halo nucleus of 11Li. The experiment involved delivery of 11Li at two energies, 3.6 MeV/u and 5 MeV/u, with 9Li also delivered toward the end of the run for calibration. 22Ne2+ and 18O2+ were used for pilot beams. The experiment ran for two weeks before the shutdown and five weeks after the shutdown. The SC-linac ran well with an integrated downtime of only 32 hours split roughly 50/50 between the cryogenic system and the cavities. The cavity downtime was due to aging of the tubes in five of the rf amplifiers. The overall availability of the RIB beam including tuning procedures and downtime of the driver accelerator, target and post-accelerator was 75%.

CONCLUSION

The performance represents the highest accelerating gradient for any operating cw heavy ion linac. The experience from the first full year of operation including full thermal cycling and significant maintenance and repair involving venting of the primary vacuum of sixteen of the cavities indicates stable cavity performance with little or no cavity degradation. This is extremely encouraging and suggests that for cw applications a single vacuum system does not preclude high performance operation.

ACKNOWLEDGMENTS

The first RIB delivery above the Coulomb Barrier was an important milestone at TRIUMF. This report represents the combined efforts of the commissioning, beam delivery and engineering teams that have come together for this very successful first year of operation.

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