INITIAL COMMISSIONING RESULTS FROM THE ISAC-II SC LINAC

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Abstract

TRIUMF has installed 20 MV of superconducting heavy ion linac as part of the first phase of the ISAC-II project. The linac consists of five cryomodules each with four 106 MHz quarter wave cavities and one superconducting solenoid. The full linac was installed by early 2006 with full linac beam commissioning tests starting in April 2006. A highlight was full beam acceleration with accelerating gradients exceeding specification by 20%. The linac hardware is described and the commissioning tests and results are summarized.

INTRODUCTION

Many new projects are now being discussed involving a new generation of low beta (5-15%) 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. 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.

The TRIUMF heavy ion superconducting linac is an extension to the ISAC facility [1], and adds ∼20 MV of accelerating voltage to the existing room temperature linac capability of 1.5 MeV/u for ions with $A/q \leq 6$. The superconducting linac is composed of bulk niobium, quarter wave, rf cavities, for acceleration, and superconducting solenoids, for periodic transverse focussing, housed in several cryomodules. 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.

CAVITIES

The present installation consists of twenty 106 MHz quarter wave cavities. The cavities, originally developed at INFN-LNL [2], 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). The initial four were chemically polished at CERN and the remaining sixteen were chemically polished at JLab. Two cavities received additional electro-polishing in a collaboration with Argonne. The cavities are equiped with a mechanical damper which limits microphonics to less than a few Hz rms. A demountable flange on the high field end supports the tuning plate. Rf coupling is done inductively through a side port near the upper end of the cavity.

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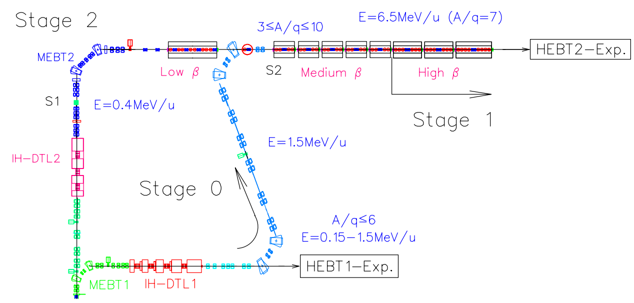
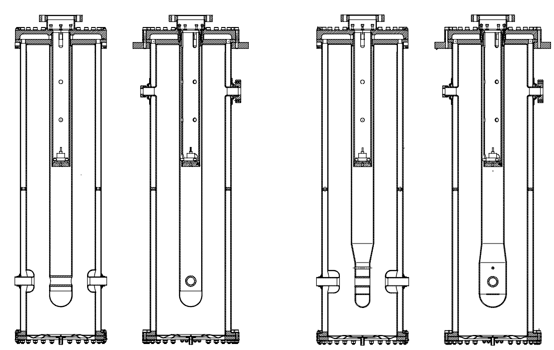


Figure 1: Stages 0, 1 and 2 for the ISAC-II upgrade.



(a) Nominal (β=7.1%) (b) Flat (β=5.7%)

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 gradient corresponds to an acceleration voltage of 1.1 MV, a challenging peak surface field of $E_p = 30$ MV/m and a stored energy of $U_o = 3.2$ J and is a significant increase over other operating heavy ion facilities.

TOWARDS HIGHER GRADIENT

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. The large stored energy requires an rf system capable of achieving stable performance. To achieve stable phase and amplitude control the cavity natural bandwidth of ± 0.1 Hz is broadened by overcoupling to accomodate detuning by microphonic noise. The required forward power on resonance is given by $P_f(W) \simeq \pi U_o \Delta f_{\frac{1}{2}}$ for overcoupled systems. The chosen tuning bandwidth of ± 20 Hz demands a cw forward power of $\sim$200 W and peak power capability of $\sim$400 W to be delivered to the coupling loop. An LN2 cooled coupling loop [3] was developed to handle the higher forward power while releasing less than 0.5 W to the LHe. To minimize detuning from slower perturbations such as helium pressure fluctuations ($\sim$ 2 Hz/Torr) a fast zero backlash tuner was developed[4] with a demonstrated mechanical response bandwidth of 30 Hz. Amplitude and phase regulation can be maintained for eigenfrequency changes of up to 60 Hz/sec. 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. The lattice is compatible with acceleration of multi-charge beams of $\Delta Q/Q \leq 7\%$. Also unique is the use of unshielded high field solenoids with added cancelling coils operating in close proximity to the cavities[5].

LINAC PREPARATION

All cavities are characterized via cold test in a single cavity test cryostat prior to mounting in the cryomodule[7]. Some cavities received repeated tests depending on the initial performance. Prior to installation all twenty cavities met or exceeded ISAC-II specifications for frequency and performance. At 7 W rf power the average peak surface field for the cavities is 38 MV/m and corresponds to a gradient of 7.6 MV/m and a voltage gain per cavity of 1.4 MV. Conversely the cavities would consume an average of 3.3W to each produce the design peak surface field of 30 MV/m.

The cryomodule assembly and commissioning off-line tests are conducted in the clean laboratory area in the ISAC-II building. In total ten cold tests were completed in order to characterize and prove the performance of the five cryomodules and establish alignment of the cold mass. 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. The top assembly is assembled in the Class III cleanest area. The tank is installed in the test pit in the Class II area that is serviced with an overhead crane. After completion the top assembly is moved to the Class II area and inserted in the tank assembly for cooldown and rf testing.

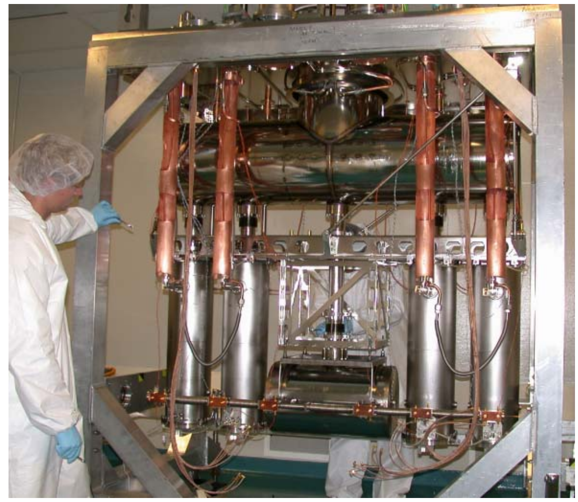


Figure 3: Cryomodule top assembly in the assembly frame prior to the cold test.

The cold mass elements are pre-aligned warm to offsets determined in the initial cooldowns. A Wire Position Monitor[8] system was used during initial studies to characterize the motion of the cold mass during cooldown. Optical targets inserted in the solenoid are used to align the cold mass with respect to the tank beam ports once thermalization is reached. After the final cold test the top assembly is opened to remove the targets then re-installed, pumped down and moved to the vault. Alignment in the vault is done with optical targets in the tank beam ports. A view of the final vault installation is shown in Fig. 4.

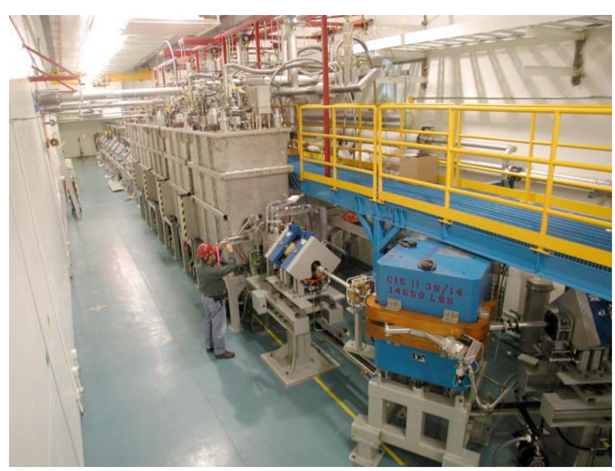


Figure 4: The ISAC-II accelerator vault.

CRYOGENICS

The linac cryomodules are cooled by 4K LHe at 1.1 Bar. The measured static heat load for a single cryomodule is ∼13 W with a LN2 feed of 5 ltr/hr. Together with estimated thermal losses from the cold distribution of 85 W this gives a total static load of 150 W. The budget for active load component is 8 W per cavity giving 160 W for the twenty medium beta cavities for a total estimated heat load of 310 W. A TC50 Linde cold box complete with oil removal and gas management system, main and recovery compressors is installed and commissioned. The measured refrigeration power with LN2 precooling is 610 W at 0.7gm/sec liquifaction. In addition three turn down modes are possible by utilizing the variable frequency drive on the main compressor corresponding to peak refrigeration power of 375 W, 280 W and 190W and fractional wall power of 0.7, 0.59 and 0.53 respectively compared to the full output. The demonstrated liquifaction rate based on a rising dewar level is 225 ltr/hr. There is a periodic slow oscillation (T=12 min.) of the suction pressure of $\sim$ 10 Torr peak to peak that is easily accomodated by the ISAC-II tuners.

The refrigerator supplies liquid helium to a dewar. The cold helium piping was supplied by Demaco to TRIUMF's specification. The main linac manifold supply line is fed LHe from the dewar via an overpressure of 1.2 bara. The cryomodules are fed in parallel from this helium supply 'trunk' line through variable supply valves and field joints. The cold return from the cryomodules comes back to the trunk cold return line through open/close valves and field joints. During cooldown, when warmer than 30°K, the returning gas is sent back to the suction side of the compressor through the warm return piping and in-line vaporizers. Keep cold sections with proportional valves join the trunk supply and the trunk cold return at each end. All supply and cold return piping is vacuum jacketed and except for the short feed line from supply valve to cryomodule is cooled with LN2.

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[9]. This requires a LHe 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. After each module is filled it remains at level even as the warm modules are cooled. A level probe in the cryomodule helium reservoir is used to regulate the variable supply valve during operation. An immersion heater in the main dewar is used to regulate the dewar level. With these two regulation systems the helium levels are maintained independent of the rf active load. Before linac tuning commences a refrigerator mode is selected to allow enough headroom in the dewar heater to accept the planned active load. As the cavities are turned on the dewar heater value decreases to maintain the dewar level.

BEAMLINES

The S-bend transport line from the ISAC-I hall to the superconducting linac consists of two achromatic bend sections of $\sim 120^\circ$ with two 4Q straight segments between. A 35 MHz buncher between straight segments matches the beam from the ISAC-I DTL to injection into the SC linac.

The high energy beamline is designed with a removeable section to be compatible with the installation of the high beta cryomodules. This represents a full length of 8.84 m so two 4.42 m long 4Q sections are used. This periodicity is maintained to the end of the vault with five 4Q sections. The sections can be tuned to unit cells with double focus points at the end of each section or to periodic doublet sections with a phase advance of $\sim 90^\circ$ for multicharge transport. Previous studies have shown that the accelerator can accomodate multicharge beams up to $\Delta Q/Q = \pm 10\%$. The present beamline design will accomodate such beams with a small emittance growth due to the mismatch at the first cell after the linac.

At present the plan is to use existing dipoles from Chalk River to deliver beam to up to three experimental stations. The installation of these beamlines will be staged over the next several years. The first experimental station will be on the straight section just downstream of the vault wall.

ACCELERATION TESTS

Acceleration commissioning is done using stable beams from the ISAC off-line ion source. The beams are accelerated to 1.5 MeV/u and transported to ISAC-II via a 25 m S-bend transport line complete with a 35 MHz two gap spiral buncher for longitudinal matching to the new linac. Acceleration commissioning runs are scheduled between experimental physics beam delivery periods with a frequency of about once per month.

Diagnostics

A silicon detector 4 m downstream from the linac monitors ions back scattered from a thin gold foil. The monitor is used for cavity phasing and energy measurement. A time of flight monitor also in the downstream beamline is used for more precise energy measurement. The monitor consists of two identical units spaced 9.2 m apart. 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.

Measurements

The rf cavities are initially pulsed conditioned to optimize performance where required. An initial beam acceleration was done with cavities averaging 6 MV/m with about 4 W/cavity. For the next and all subsequent runs the cavities are set to the power limit of 7 W per cavity at critical coupling. The coupler is then moved to a position requiring a forward power of ~160 W for a coupling β ~100 that has been determined to provide sufficient rf bandwidth to maintain lock. The cavities are initially locked and left for twenty-four hours to test the operational stability and tuner perfomance.

Six different beams have been accelerated to date corresponding to three different mass to charge ratios; 40Ca10+, 22Ne4+, 20Ne5+, 12C3+, 4He1+ and 4He2+ with A/q ratios of 5.5, 4 and 2. Beams from ISAC at two different reference energies are delivered and coasted through the linac to calibrate the silicon detector and cross-check the time of flight monitor. The S-bend buncher is tuned using the silicon detector downstream of the linac and a fast faraday cup in a box immediately upstream of the first module.

Each cavity is turned on starting at the upstream end. The cavities are phased by measuring the beam energy for four different phases and fitting the data to a cosine profile to find 0°. All cavities are set to a sychronous phase of $-25°$ for acceleration. The focussing solenoids and beamline optics are set to their theoretical settings as the acceleration progresses.

Beam Energy and Cavity Gradient Final achieved energies are shown in Fig. 5(b) 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. Single cavity rf test results for each cavity are plotted for comparison. The gradients in general match well the gradients from initial single cavity tests[7]. A few cavities have obviously been contaminated during assembly and others have improved perhaps during the final assembly rinse.

The average operating gradient is down by only 5% from the single cavity result. Furthermore over the first three months of commissioning the average gradient has not deteriorated. On one occasion cryogenic procedures forced a warm-up of the cavities above transition. Since the solenoids have a larger thermal mass they stayed below transition and even though driven to zero still retained frozen flux that upon subsequent cooldown contaminated the adjacent cavities and reduced the Q. This is a well documented phenomenon [5] observed during cryomodule testing. The solution is to warm both the solenoid and cavities above transition to quench the frozen flux before recooling. After this procedure cavity performance returned to previous levels.

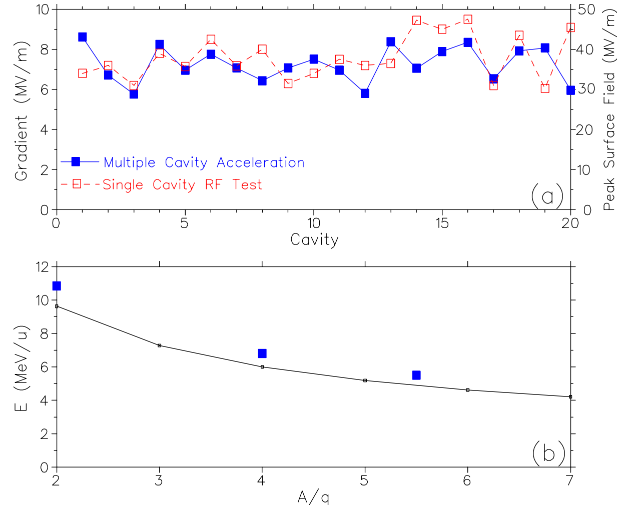


Figure 5: (a) Average cavity gradients for the three A/q values and for 7 W cavity power. Results are inferred from the step energy gain per cavity during acceleration. Also shown are gradients from initial single cavity characterizations. (b) Final energies for the three cases compared to expected final energies assuming the design gradient of 6 MV/m.

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 if we consider that the solenoid mixes the two planes and emittances of different size entering the linac will appear as alternating in emittance during acceleration as the reference frame rotates.

During the first year of operation there will be 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[10]. 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.

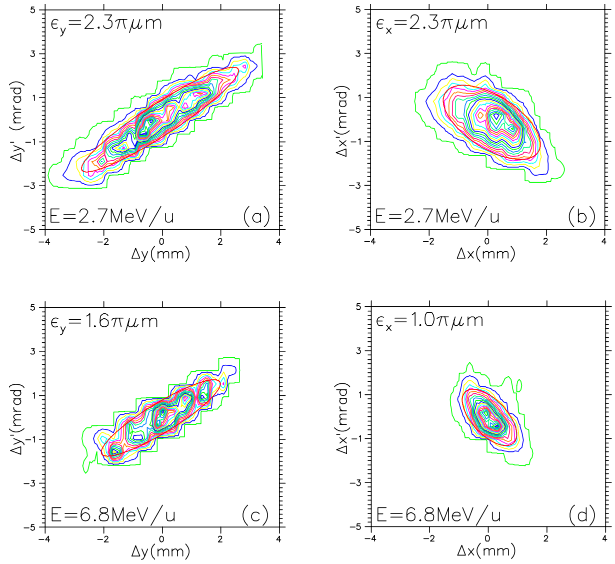


Figure 6: Shown are the vertical (left) and horizontal (right) transverse emittances measured downstream of the linac for 4He1+ at two different energies, 2.7 MeV/u and 6.8 MeV/u.

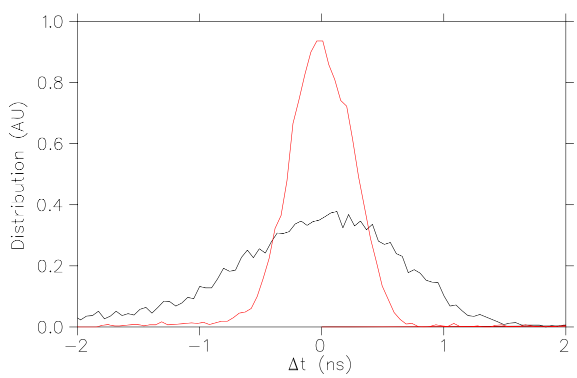


Figure 7: Time spectra recorded at a silicon detector with and without cavity 19 used as a buncher. Cavity 1-8 are 'on' producing a beam energy of 3.7 MeV/u.

The transmission is >90% and the tuning is straightforward. In general the required steering strengths are higher than expected, evidence that the solenoid alignment is not within specification in some cases. This is presently under investigation. A development to improve beam stability is also underway. There are several cavities exhibiting phase noise outside the specification of $\pm 1^\circ$[7]. We believe that the switching power supply in the driver amplifier is susceptible to RF interference. Future steps will involve stabilizing the power supplies.

CONCLUSION

The performance represents the highest accelerating gradient for any operating cw heavy ion linac. There is strong interest to see whether the initial very positive results can be maintained through long term running or degrade as has been observed at other labs[11]. Initial commissioning runs have concentrated on completing measurements in support of our operating license. Further runs will be devoted to reducing rf phase error, measuring beam quality and improving application programs in support of beam delivery. First experiments with radioactive beams are scheduled for Nov. 2006.

ACKNOWLEDGEMENTS

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