OPERATING EXPERIENCE OF THE 20MV UPGRADE LINAC

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Abstract

The ISAC-II heavy ion linear accelerator has been in operation at TRIUMF since 2006. The Phase II section of the accelerator, consisting of twenty cavities with optimum β_0=0.11 is designed to double the total voltage of the ISAC-II linac to allow acceleration beyond the Coulomb barrier for all ISAC radioactive ion beams. The cavities are superconducting bulk niobium two-gap quarter-wave resonators with a frequency of 141 MHz, providing, as a design goal, a voltage gain of V_{eff}=1.08 MV at 7 W power dissipation. Production of the cavities is from a Canadian company, PAVAC Industries of Richmond, B.C.. Cavity and cryomodule production details as well as installation, commissioning and first operation results are presented and discussed.

INTRODUCTION

There is a significant interest world-wide in accelerator based research facilities for the study of radioactive ion beams. ISOL and gas catcher facilities utilize high intensity driver beams to create the radioactive products and powerful post-accelerators to boost the exotic beams from source potential to energies sufficient for a variety of physics research. TRIUMF with its 500MeV proton beam leads the world in terms of driver beam power at 50kW. The ISAC-II project at TRIUMF, proposed in 1999[1], aims to broaden the mass range above A=30 by adding an ECR charge state booster (CSB) in the low energy area and to increase the energy reach to above the Coulomb barrier with the addition of a 40MV superconducting linac. The goal specification for the ISAC-II post-accelerator is to reach 6.5MeV/u for particles with A/q=6. The ISAC-II project ensures that TRIUMF will remain among the leading ISOL based research centres as other facilities such as HIE-ISOLDE, SPIRAL-II and FRIB become operational realities.

The ISAC-II superconducting linac is divided into Phase I and Phase II segments each contributing 20MV. The Phase I segment (SCB section of Fig. 1) was commissioned in 2006[2]. The segment consists of twenty quarter wave cavities housed in five cryomodules with four cavities per cryomodule. The first eight cavities have a geometric beta of 5.7% and the remainder a geometric beta of 7.1%. The cavities operate at 106MHz and are specified to provide an effective acceleration of 1.1MV for a cavity power of 7W at 4.2K and corresponding peak surface fields of 30MV/m and 60mT. The Phase I linac has operated for the last four years above specification with an average operating gradient corresponding to a peak surface field of 33MV/m and with no discernable reduction in performance.

Development on the Phase II upgrade[3] began in 2006 with completion in March 2010.The upgrade consists of the addition of twenty QWR cavities at beta=11%. The cavities are housed in three cryomodules with six cavities in each of the first two modules and eight cavities in the third (SCC section in Fig. 1). Both Phase I and Phase II cryomodules have one 9T superconducting solenoid symmetrically placed in the cryomodule. This paper concentrates on the experiences gained in producing, commissioning and operating the Phase II addition.

CAVITIES

The phase II superconducting cavity is shown in Fig. 2. The cavities are quarter wave resonators (QWR). The cavities have a simple construction with a cylindrical shape, a rigid upper flange and an annular lower flange designed for mounting a removable tuning plate. The helium jacket is a cylinder of reactor grade niobium formed from two sheets and welded to the upper and lower flanges. A cavity of similar structure is used in the ISAC-II Phase I linac. The chief difference here besides the frequency is that in Phase II the inner conductor beam port region is outfitted with a donut style drift tube. The cavity specification is to operate at 141.44MHz (12th harmonic of the bunch frequency) at an effective voltage of 1.1MV corresponding to a peak surface field of 30MV/m and peak magnetic field of 60mT and with a cavity power ≤7W. Cavity prototyping studies began with PAVAC Industries Inc. in 2007. Two cavity prototypes were successfully developed and tested in 2008[4]. An order for twenty production cavities was given to PAVAC in March 2008.

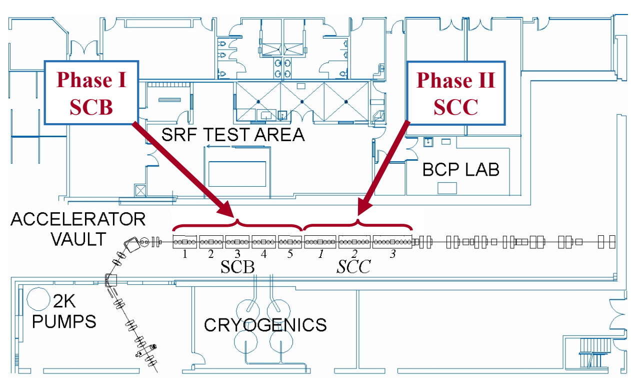

Figure 1: ISAC-II Phase II SC-linac upgrade.

Processing Steps

Standard processing involves visual inspection, room temperature frequency measurement, degreasing and a Buffered Chemical Polish (BCP) etch of 60-120µm. An in-line chiller coil keeps the acid at 12^0C as it is pumped through the cavity during the etching procedure. The cavities are then assembled with a stainless steel top flange bolted to the niobium flange. The stainless steel

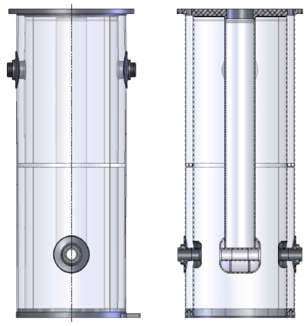

Figure 2: The 141.44MHz rf cavity for Phase II.

flange is outfitted with a mechanical damper assembly that is inserted into the inner conductor.

Pre-cool tubes of thin wall stainless steel pass through the neck of the stainless steel flange and inside the inner conductor and helium jacket to flow cold helium gas to the bottom of the cavities during cool-down.

After the cavity assembly is complete they are rinsed with high pressure ultra pure water for forty minutes and air dried in a clean room for 24 hours. For some cavities an alcohol rinse is used to aid in the drying. At this point the cavities are either assembled on the test cryostat for single cavity characterizations or mounted in the cryomodule for linac on-line operation. In either case the cavities are baked for 48 hours (85-90C in test cryostat, 70-75C in cryomodule) then the cryostat thermal shield is cooled with LN2. After 24 hours of pre-cool by radiation the cavity is cooled with LHe. Typical cooldown rates are 80-100K/hour between 150-50K.

Production

Cavity production started in 2008 at PAVAC Industries with a planned delivery of three separate batches (6+6+8=20 cavities) corresponding to the number of cavities to be assembled in the three cryomodules of the ISAC-II Phase II linac. Of the twenty production cavities four were rejected (#7, #8, #12, #13). In each case a vacuum leak opened in the beam tube region after an initial etching at TRIUMF of 100µm. The cavities were subsequently repaired but as a result the etch specification was reduced to 60µm as a precaution due to the tight schedule. The schedule also forced other anomalies. The twentieth cavity (cavity #12) was installed in the linac without a test. Three of the cavities were tested together in module SCC2 (Cavity#17, 18, 20).

The performance tests of nineteen cavities are shown in Fig. 3. Cavity #8 is a repaired cavity. The plot shows that only two cavities (Cavity #17 and Cavity #23) are significantly under the ISAC-II specification of Ep=30MV/m@7W cavity power. The average accelerating gradient corresponds to a peak surface field of 32MV/m at 7W. All cavities are within 30kHz of the goal frequency of 141.44MHz within the tuning range of the flexible tuning plate. In other measurements the He pressure sensitivity for the production cavities is -1 Hz/Torr with Lorentz detuning of -1 Hz/(MV/m)^2.

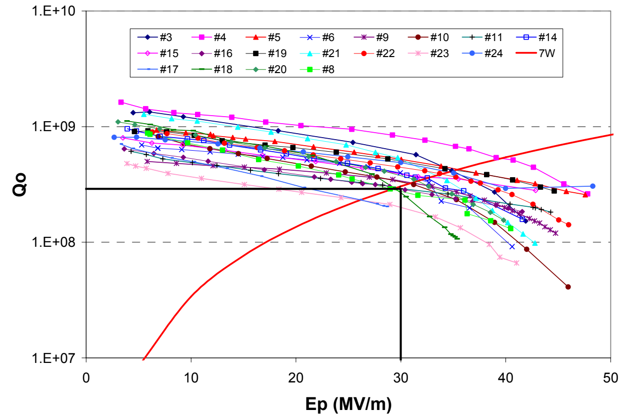

Figure 3: Performance curves for nineteen of the Phase II cavities.

Custom etching: According to analysis a uniform removal of material from the rf surface will result in a neutral frequency swing since the removal from the top half exactly compensates for the removal from the bottom half. However removal from either half exclusively will result in a 2kHz/µm frequency shift; a frequency reduction when removing at the root end and a frequency increase when removing from the drift tube end. During etching the cavity is positioned with the drift tube end up. For custom etching the cavity is filled only half full for a specific time to preferentially etch the root end and to drive the frequency down. After a prescribed time the cavity is filled the rest of the way to complete the required full cavity etch. With this technique we deliberately target a manufacturing frequency that is 20kHz higher than the post BCP goal in order to allow custom etching to bring the frequency into specification.

CRYOMODULES

The Phase-II cryomodules are identical in many respects compared to the Phase I cryomodules[5]. A key design choice was to maintain the philosophy of incorporating a single vacuum space for thermal isolation and beam/rf volumes. This has been the historic choice in the low-beta community (ATLAS, INFN-Legnaro, JAERI) but recent proposed facilities in development or assembly have chosen separated vacuum systems (SARAF, SPIRAL-II, FRIB). The decision to maintain a single vacuum comes from our experience with Phase I operation of the SC-linac. We have seen no evidence of degradation in cavity performance over the first four years of operation even after repeated thermal and venting cycles[6]. Procedures are followed to help mitigate cavity degradation: 1. Initial cavity treatment and overall assembly with HPWR and clean conditions 2. in vacuum materials and components are free from particulate, grease, flux and other volatiles 3. installation of LN2 cold traps upstream and downstream of the linac to prevent volatiles migrating from the beamline into the cryomodule 4. Cryomodule venting with filtered nitrogen 5. Pumping and venting of modules at slow rates to avoid turbulences. All cryomodules are assembled in a `dirty' assembly area to check the fitting of all components. Next the assembly is completely dismantled, all parts are cleaned in an ultrasound bath, rinsed with 18MΩ water at high pressure and dried in a clean room before assembly.

Design Features

The cryomodules have the following features: 1. Stainless steel vacuum tank 2. The cavities and solenoid are supported from a rigid strongback that is in turn supported from the tank lid by support rods. 3. LN2 thermal shield formed by copper panels with soldered copper cooling tubes and panels formed into a box. 4. Helium reservoir acts as phase separator and delivers gravity fed liquid helium at 4K to the cavities. 6. Warm μ-metal sheets 1.5mm thick attached to the inside of the cryo-vessel.

Direct venting: The cleanliness of the cavities is now protected by a direct venting system to the rf pick-up ports. This allows direct venting of the cavities using filtered nitrogen instead of venting from the thermal isolation vacuum and avoids particulates drifting into the cavity. Vent gas can also flow for any operation where there is a risk of contamination; for example during loading of the top assembly into the cryomodule.

Mechanical Tuner: In both Phase I and II the cavities are tuned by a lever arm that pushes against a tuner plate on the bottom end of the cavity. The lever arm is actuated by a long push rod that extends to the top of the cryomodule through a bellows to a servo motor. The system provides high performance tuning for high gradient operation to maintain the cavity frequency within the ±15Hz bandwidth. The linear servo motor used in Phase I has been replaced by a brushless rotary servo motor in Phase II as a less expensive alternative. The output shaft of the motor is connected directly to an anti-backlash preloaded precision ball screw nut, through a stiff bellows coupling. Anti-backlash liner guides achieve reproducible motion resulting in a vertical position resolution of less than 0.03 microns (corresponding to an eigenfrequency shift of 0.2Hz).

Coupling Loop: The Phase I variable coupling loop uses a rack and pinion mechanical arrangement and Teflon guide bearing. An Aluminum nitride ceramic washer provides a thermal path between the inner and outer conductor. The outer conductor is directly cooled through a LN2 cooled heat exchange block. A redesigned coupling loop for Phase II with non-magnetic cross-roller bearings and symmetric loading has improved the mechanical motion.

Alignment: A Wire Position Monitor (WPM) alignment system is used to check the stability and repeatability of the alignment during thermal cycles. Stripline monitors are attached to the cold mass using off axis alignment posts and a wire is passed along the axis of the monitors that carries a driving rf signal. The monitors pick up the signal from the wire and record the position of the wire with respect to each WPM axis. The specified alignment tolerance is ±200microns for the solenoid and ±400microns for the cavities. In addition to the WPM system optical targets are placed in the beam ports of the upstream and downstream cavities and in the upstream and downstream port of the solenoid to periodically chart the position of the cold mass in relation to the beam axis. The alignment tests confirmed that the required alignment tolerance are met with the solenoid within ±100μm and the cavities within ±250μm of the goal position.

Cryogenic System

The Phase II cryogenic system mirrors the Phase I system except that they share a recovery compressor. A second Linde TC50 cold box feeds LHe to a 1000 liter dewar. The LHe is delivered to the cryomodules at 4K through vacuum jacketed LN2 cooled helium transfer lines. The cryomodules are fed in parallel from a main supply manifold (trunk) through variable supply valves regulated by LHe level in the cryomodules. The vapour from the cryomodules is returned either in a warm return line direct to the compressor during cooldown or through a cold return line back to the cold box during normal operation. The measured liquefaction with LN2 pre-cool is 240ltr/hour and the refrigeration power is 600W. The stability of the helium pressure is within ±7mBar well within the capability of the tuner.

The helium in the Phase I and Phase II systems is typically isolated. The Phase I system feeds LHe to SCB1-3 and the SRF test facility while Phase II supplies LHe to SCB4-5 and SCC1-3. Valves in the distribution system allow the cooling of the whole linac from either of the plants during maintenance periods.

INSTALLATION AND COMMISSIONING

Cryomodules

Because of space constraints in the clean room only one cryomodule is assembled at a time. Each cryomodule receives at least one cold test in the SRF facility before delivery to the linac vault. The cold tests: 1. establish the repeatability of the alignment under thermal cycling, 2. provide the warm offsets required in the cold mass to achieve the prescribed alignment tolerance when cold, 3. check the performance of the cavities, the rf ancillaries and the solenoid, 4. determine the cryogenic performance given by the static load at 4K and the LN2 consumption and 5. confirm the integrity of the vacuum. The completed SCC1 top assembly is shown in Fig. 4 as the cold mass is lowered into the vacuum chamber. Measurements prior to the cold test confirm that the μ-metal reduces the remnant magnetic field below 20mG in the cavity region as per specification.

Cryogenic Performance: The cryogenic performance is established by measuring the static helium load after full thermalization. Full thermalization occurs within ~2-3 days of achieving a liquid level in the helium reservoir. The static load is measured by closing the helium supply valve and diverting the return exhaust helium through a

Figure 4: Cryomodule SCC1 assembly prior to the first cold test.

gas meter. It is found that the static load is ~13 W for the phase I cryomodules and ~15-19W for the Phase II cryomodules. The LN2 usage while thermalized is about 5 liters/hour for Phase I and 6 ltr/hr for Phase II.

Installation: The cryomodules are installed one at a time in the vault as they are prepared. The installation includes final alignment, cable and hardware connections and vacuum pumpdown. All cables and controls are prepared in advance for each cryomodule to allow full cold testing in situ immediately after installation.

PHASE II COMMISSIONING

.Phase II Schedule

The Phase II project had a very well defined time-line. TRIUMF funding for the project was scheduled to end April 1, 2010 to coincide with the start of the next five year budget cycle. In addition major initiatives proposed for the new five year cycle were politically linked to a successful conclusion of the previous five year cycle. The installation was scheduled for an extended shutdown from Sept. 2009 to March 31, 2010. Table 1 gives a breakdown of the various installation and testing dates.

Beam Commissioning

The complete linac from the downstream end is shown in Fig. 5. The final cryomodule was installed March 21. A16O5+ beam (A/q=3.2) from the ISAC off-line (stable)

Table 1: Installation and Testing Schedule for Phase II Linac

Milestone	**SCC1**	**SCC2**	**SCC3**
Assembled	June 09	Nov 09	Mar 7/10
Test off-line	July-Sep 09	Dec 09	Mar 15/10
Install	Oct 09	Jan 10	Mar 21/10
Test on-line	Nov 09	Feb 10	Apr 7/10

Figure 5: The ISAC-II superconducting linac.

source was accelerated to 10.8MeV/u just one month later on April 24. A plot of beam energy as a function of cavity number is shown in Fig. 6(a). The final energy is equivalent to acceleration of a beam with A/q=6 to 6.5MeV/u and as such demonstrates the ISAC-II goals on the first acceleration. This was achieved despite the fact that five cavities were not available for acceleration. Fig. 6(b) shows the effective voltage of each cavity during the first acceleration. Of the working cavities the average effective voltage for the Phase I linac is 1.09MV while the average effective voltage for the Phase II linac is 0.97 close to the design goal of 1.08MV. These correspond to peak surface field values of 30MV/m and 27MV/m respectively. RF measurements of the installed cavity gradients corresponding to a cavity power of 7W yield a peak surface field of Ep=26MV/m compared to single cavity results of 32MV/m. In particular the performance of cavities in SCC2 and 3 are reduced compared to single cavity test values. A summary of Phase I and Phase II performance is shown in Table 2 as given by the average peak surface field for single cavity tests and on-line tests at 7W cavity power, and values for stable operation during acceleration. In general the performance of Phase II is ~15% lower than Phase I. A possible explanation is insufficient etching during initial processing. In addition environmental effects in the cryomodule including trapped flux or Q-disease could be responsible for the reduced Q's. Development is on-going and mitigation steps will be taken during shutdowns to improve the performance when causes are known. In any case the installed cavities on average meet the ISAC-II specification of 30MV/m for 7W/cavity cryogenic load. values for the Phase I and Phase II linacs.

OPERATION

First stable beam was delivered to users on April 25 just one day after commissioning and first radioactive beam was delivered one week later on May 3. Since then the linac has supported a full physics program with both stable and radioactive beams being delivered. To date stable beams of 16O5+, 15N4+, 20Ne5+ and radioactive beams (and their stable pilot beams) of 26Na, 26Al6+ (26Mg6+), 6He1+, (12C2+), 24Na5+ (24Mg5+), 11Li2+

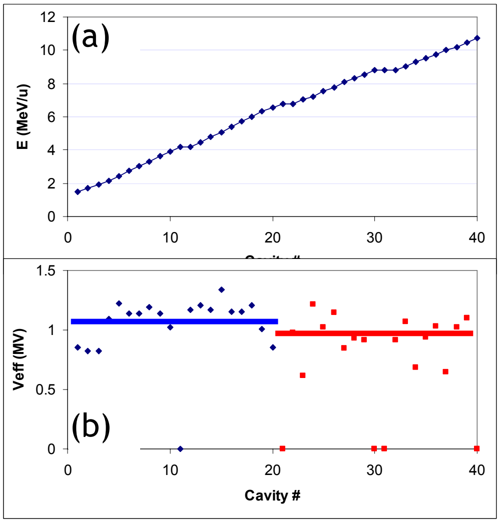

Figure 6: Results from first acceleration of a 16O5+ beam. (a) A plot of beam energy after each cavity and (b) a plot of the effective voltage of each cavity; blue and red lines indicate the average values for Phase I and Phase II respectively.

Table 2: A Summary Comparing Phase I and Phase II Cavity Performance Values for Different Metrics

Test	Metric	SCB MV/m	SCC MV/m
Single cavity	Ep average at 7W	37	32
Acceleration	Operating Ep	30-32	27
Installed	Ep average at 7W	33	26

(22Ne4+) including 74Br14+ from the charge state booster have been delivered. In addition short commissioning periods between beam delivery runs are used to characterize the machine and to satisfy licensing requirements.

Multipacting conditioning is required for extended periods after start-up. Extended periods of conditioning (short pulse, low voltage) are required for 1-2 weeks after cool-down to reach a reasonable operating regime. Some degradation has been seen in cavities due to trapped flux from the solenoids. Most typically this is caused when a small interruption in helium delivery causes the cavities to warm above transition and then cool in the magnetized environment caused by the solenoid. A degaussing procedure has been developed that takes ~2 hours. The solid state rf amplifiers installed in Phase II have proven more stable than the tube amplifiers of Phase I. The tube amplifiers have been a source of downtime due to tube aging issues causing phase drift and non-linear output affecting LLRF operation. Four cavities in Phase II remain unavailable until the next warm-up due to shorts in the rf drive lines. There is one open circuit cable in Phase I. Impurities in the Phase I cold box have caused reduction in the Phase I cryogenic performance. A compressor motor failure in Phase I caused a 1 week loss of beam time.

CONCLUSIONS

The ISAC-II linear accelerator represents a ten year activity of research, development, prototyping, production and installation and was completed on time and on budget. Along the way TRIUMF has gained a core competence in superconducting rf cavity production, processing and testing. This initiative is interesting in its own right as a source of study for students and young researchers but also allows TRIUMF to consider other cutting edge accelerators such as the e-Linac project for radioactive beam production now in development. In addition we have mentored a local company, PAVAC Industries, in the fabrication of niobium resonators. Finally we have provided for our nuclear physics users an important new capability unique in the world; the ability to accelerate exotic ions from a high power ISOL target to energies above the Coulomb barrier. A small reduction in Phase II operating gradient may be the result of the aggressive schedule but it is important as machine builders that we deliver our projects on time. Developments are underway to develop the Phase II cavity performance to Phase I levels and meanwhile the ISAC nuclear physicists are happily receiving beam.

ACKNOWLEDGMENTS

The success of the Phase II upgrade is due to the strong support of TRIUMF management. We would also like to acknowledge Pavac Industries; a committed and inventive industrial partner. Finally special thanks to the TRIUMF technical team who embraced the challenge and succeeded in spite of the tight time pressure.

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