ACCELERATION ABOVE THE COULOMB BARRIER – COMPLETION OF THE ISAC-II PROJECT AT TRIUMF*

R.E. Laxdal, TRIUMF, Vancouver, Canada

Abstract

The ISAC-II project at TRIUMF was proposed to boost the final energy of the radioactive ion beams of the TRIUMF ISAC facility above the Coulomb barrier. The nominal goal of 6.5MeV/u for ions with A/q=6 was recently achieved. The ISAC-II project consists of 40MV of installed heavy ion superconducting linac to broaden the energy reach and a charge state booster to broaden the mass reach. The project and commissioning is described.

INTRODUCTION

TRIUMF has operated a 500MeV H^- cyclotron since 1974. The TRIUMF facility (Fig. 1) was expanded in 1995 with the addition of a radioactive beam facility, ISAC. The radioactive species at ISAC [1] are produced by a 500MeV proton beam of up to 100μA bombarding a thick target. After production the species are ionized, mass separated and sent to either a low energy area or pass through a string of linear accelerators to feed experiments at higher energies. First beams from ISAC were available in 1998 while first accelerated beams were delivered in 2001. The initial accelerator consisted of a 4.5MV RF quadrupole and an 8.1MV Drift Tube Linac delivering beams with A/q≤30 to medium energy users at energies from 0.15-1.5MeV/u chiefly for experiments in nuclear astrophysics.

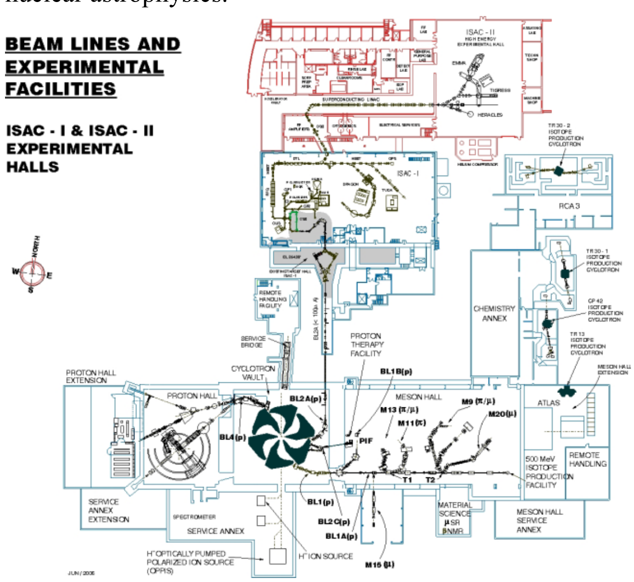

Fig. 1: The TRIUMF facility showing the 500MeV cyclotron and the ISAC-I and ISAC-II facilities.

The TRIUMF ISAC-II superconducting linac, proposed in 1999 [2], was designed to raise the radioactive ion beams above the Coulomb barrier to support nuclear physics at TRIUMF. The goal was to achieve E ≥ 6.5MeV/u for ions with mass to charge ratio of A/q ≤ 6. The first stage of this project, Phase I, commissioned in 2006, involved the addition of 20MV of superconducting linac. Phase II of the project consisting of an additional 20MV of superconducting linac has recently been installed and commissioned. In parallel an ECR ion source was installed to act as a charge state booster to raise the A/q ratio of low energy high mass beams to be compatible with acceleration through the ISAC accelerators. This paper will concentrate on the progress towards higher energies at ISAC and in particular on the recent Phase II upgrade.

LINEAR ACCELERATORS - GENERAL

Since this is a cyclotron conference a talk on a linear accelerator installation may seem somewhat out of place. TRIUMF is at its roots a cyclotron lab with a pedigree not only based on the main 500MeV cyclotron but also on the design, commissioning and operation of the commercial cyclotrons TR30 and TR13. As cyclotron builders we also have to be cognizant of other particle accelerators and their capabilities. These other machines can be used in combinations with cyclotrons either for injection or post-acceleration. The strong advantage of a cyclotron is the improved efficiency of rf utilization in cw application with the same rf system used on multiple turns. This does require a precise magnet to maintain isochronism so that the beam remains in phase with the accelerating field. Injection and extraction are complicated and beam emittance can be broadened due to the dependence of energy and radial position and particularly in cases where a variety of ions require acceleration. Cyclotron builders have imaginative ways of reducing the impact of these complications. Linear accelerators hold some advantage in certain applications. In general injection and extraction from linear accelerators is relatively straightforward and transmission high due to simplified acceleration. In particular RF quadrupoles with their strong transverse focussing and high acceptance have been used successfully in injection beamlines to take the place of large and complicated high voltage platforms that were historically used to reach the required injection energy. Drift tube linac tanks can be made with relatively few gaps (at the expense of rf efficiency) to allow some phase slip of the accelerating beam yielding straightforward ways of achieving variable energy acceleration. Superconducting hadron linacs can achieve, for very short versatile structures, significantly improved rf efficiency (~100 times) over cw room temperature linacs due to the very low resistive losses. It is relatively straightforward to accelerate beams with a normalized transverse emittance

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defined by the source, longitudinal emittances of 1keV/u-ns with fully variable energy and with high transmission.

ISAC-I ACCELERATORS

The accelerator chain includes a 35.4 MHz RFQ, to accelerate beams of $A/q \leq 30$ from 2 keV/u to 153 keV/u and a post stripper, 106 MHz variable energy drift tube linac (DTL) to accelerate ions of $2 \leq A/q \leq 6$ to a final energy between 0.153 MeV/u to 1.53 MeV/u. Typically 1+ beams are produced in the on-line source but recently the Charge State Booster ECR source has been commissioned to raise the charge state of the 1+ ions to produce high mass beams with charge to mass ratios compatible with acceleration.

The RFQ[3], a four vane split-ring structure, has no bunching section; instead the beam is pre-bunched at 11.8 MHz. This not only shortens the linac but reduces the longitudinal emittance at a small expense in the beam capture. The variable energy DTL[4] is based on a unique separated function approach with five independent interdigital H-mode (IH) structures, each with 0^o synchronous phase, providing the acceleration with quadrupole triplets between tanks and three-gap bunching cavities before Tanks 2,3,4 providing transverse and longitudinal focusing respectively. The DTL is designed to efficiently accelerate low-β heavy ions over a large operating range while maintaining high beam quality. The IH tanks consume only 63 kW of rf power to produce a total accelerating voltage of 8.1MV over the 5.6m length. To achieve a reduced final energy the higher energy IH tanks are turned off and the voltage and phase in the last operating tank are varied. Both the RFQ and DTL have been used to reliably provide a variety of radioactive and stable ions since 2001.

THE ISAC-II LINAC

The ISAC-II linac was commissioned in 2006[5] and the Phase II upgrade[6] was commissioned Apr.-Aug., 2010. The superconducting linac is composed of bulk niobium, quarter wave resonator (QWR) for acceleration, and superconducting solenoids, for periodic transverse focusing, housed in several cryomodules. The Phase-I linac consists of twenty QWRs housed in five cryomodules (SCB1-5) 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. The Phase-II upgrade also consists of twenty QWRs housed this time in three cryomodules (SCC1-3), six cavities in each module for SCC1-SCC2 and eight cavities in SCC3. These bulk niobium cavities have a geometric beta of 11% and are resonating at 141.44MHz. One 9T superconducting solenoid is installed in the middle of each of the eight cryomodules in close proximity to the cavities. The ISAC-II building is shown in Fig. 1; the SCB and SCC sections of the linac are identified.

SRF facilities at TRIUMF (Fig. 2) include a preparation room for parts cleaning, a cavity test area with overhead crane, cryogenic services and test pit, a clean assembly area, a BCP etching lab and high pressure water rinse area. The cryogenic facilities that deliver both LHe and LN2 to the linac vault are adjacent to the linac tunnel.

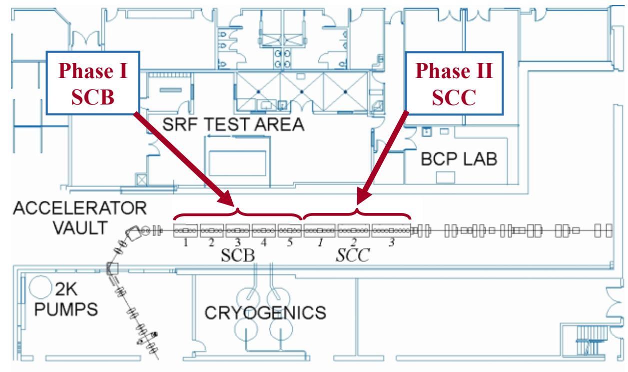

Fig. 2: The ISAC-II superconducting linac.

CAVITIES

The ISAC-II superconducting cavities are shown in Fig.3. The rf cavities are patterned after structures built for the low beta section of the INFN-Legnaro heavy ion linac. 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 common outer conductor diameter of 180 mm is used for all cavities. The chief difference between the Phase I and II cavities besides the frequency (and therefore the height) is that in Phase II the inner conductor beam port region is outfitted with a drift tube. The ISAC-II performance goal is to operate cw at a gradient of 6 MV/m, as defined by the inner diameter of the outer conductor, corresponding to a peak surface field of 30MV/m and peak magnetic field of 60mT with a cavity power ≤7W.

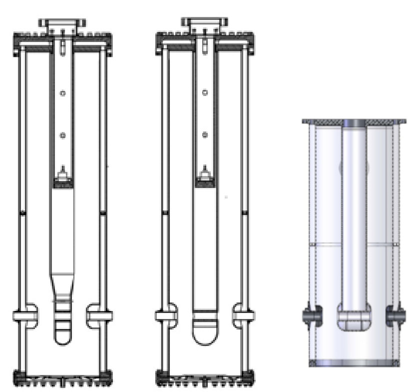

Fig. 3: From left to right: the 106 MHz β=5.7% and 7.1% QWRs for phase-I and 141.44MHz β=11% QWR for Phase-II.

The Phase I cavities were produced by Zanon in Italy and the Phase II cavities by PAVAC Industries in Canada. Cavity prototyping studies began with PAVAC Industries in 2007. Two cavity prototypes were successfully developed and tested in 2008 [7]. Both cavities exceeded specification with an average gradient at 7W cavity power corresponding to a peak surface field of 38MV/m.

Processing and Preparation

Standard cavity processing involves visual inspection, room temperature frequency measurement, degreasing and a Buffered Chemical Polish (BCP) surface etching; 120µm in Phase I and 60-100µm in Phase II. In Phase II a number of cavities receive a custom etch where the root end (top of the cavity in Fig. 2) receives more etching to tune the frequency. An in-line chiller coil keeps the acid at 12^0C during the etching procedure. A photo of the Phase II cavity after etching is shown in Fig. 4.

The cavities are then assembled with a stainless steel top flange bolted to the niobium flange. The stainless steel flange is outfitted with a mechanical damper assembly that is inserted into the inner conductor to reduce detuning vibrations from microphonics. 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 assembly is complete the cavities are rinsed with high pressure ultra pure water for forty minutes and air dried in a clean room for 24 hours. Some Phase II cavities have received an additional alcohol rinse after HPWR to aid in 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.

Both the single cavity cryostat and cryomodule assembly take place in a clean room. In both cases there is no isolation between the thermal isolation vacuum and the rf space vacuum; cryostat and cryomodule design avoid particulate generators (MLI) and volatile lubricants, solvents, flux that could reduce cavity performance [8]. A single cold Cryoperm magnetic shield is clamped around the cavity for single cavity tests while in the cryomodule a warm µ-metal layer is fastened inside the vacuum vessel wall (1mm in SCB's and 1.5mm in SCC's). The goal is to achieve a background magnetic field of <20mG to avoid trapped flux in the superconductor that can increase surface resistance.

Production

Including the initial prototype, 21 Phase I cavities were received from Zanon. Of these one did not meet specification due to a low field quench. The others were assembled into the working linac. Single cavity characterizations gave an average single cavity performance corresponding to a peak surface field of 37 MV/m at 7W cavity power and an effective voltage of 1.3MV.

Fig. 4: Phase II cavity after etching.

Two prototypes were tested frm PAVAC Industries in 2007. Twenty production cavities were ordered from PAVAC in 2008. The planned delivery sequence of three separate batches (6+6+8 cavities) corresponded to the number of cavities to be assembled in the three cryomodules of the Phase II linac. Four cavities were rejected (#7, 8, 12, 13) due to a common fault; a vacuum leak opening up in the saddle weld joining the drift tube assembly to the inner conductor. After the weld the joint is surface polished to make a smooth transition but this step causes a thinning in the melt zone. In each case the cavity leak opened after the final etching treatment at TRIUMF of 100µm. The cavities were subsequently repaired but as a result the etch specification was reduced from 100µm to 60µm as a precaution. The rationale was as follows: all inner conductor assemblies had been completed with similar fabrication technique and due to the tight project schedule further cavity failures were deemed a high risk.

The performance tests of nineteen cavities are shown in Fig. 5. 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. We believe that the reduced performance with respect to Phase I is related to the reduced etching. This is under study. All cavities are within ~30kHz of the goal frequency of 141.44MHz within the tuning range of the flexible tuning plate.

CRYOMODULES

The Phase-II cryomodules are identical in many respects compared to the Phase I cryomodules [8]. 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). We have seen very little evidence of degradation in cavity performance over the first four years of operation even after repeated thermal and venting cycles. Procedures are followed to help reduce cavity degradation: 1. Initial cavity treatment and overall assembly using HPWR and clean conditions 2. Vacuum materials and components to be free from particulate, grease, flux and other volatiles 3. Maintain a LN2 cooled cold trap 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.

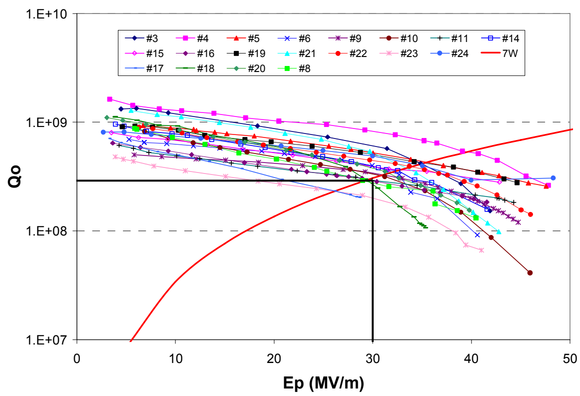

Fig. 5: Performance curves for nineteen of the Phase II cavities.

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.

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.

Because of space constraints in the clean room and available personnel 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 and the rf ancillaries, 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. 6 as the cold mass is lowered into the vacuum chamber prior to the first cold test. 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.

Fig. 6: Cryomodule SCC1 assembly prior to the first cold test

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 gas meter. It is found that the static load is ~12-13 W for the phase I cryomodules and ~15-19 W for the Phase II cryomodules. The LN2 usage while thermalized is about 5 liters/hour for Phase I and 6 liters/hour for Phase II. These values match design estimations.

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.

RF ANCILLARIES

Mechanical Tuner: Due the high cavity Q an accurate responsive tuner is required for stable cavity performance. The natural cavity bandwidth of <1Hz is broadened by overcoupling to ±15Hz. This corresponds to a motion of the lower tuning plate of ±2 microns. In both Phase I and Phase II sections the cavities are tuned by a zero back-lash 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 motor. In Phase I a linear servo motor is used. In the phase II system the linear servo motor has been replaced with a harmonic drive, brushless rotary servo motor driving a pre-loaded ball screw.

Coupling Loop: An adjustable loop coupler is used with a typical coupling β during acceleration of ~100 for a forward power of ~150W. The outer conductor is directly cooled through a LN2 cooled heat exchange block..

RF Amplifiers: Phase I utilizes 800W 106MHz tube amplifiers while Phase II utilizes 600W 141MHz solid state amplifiers. Both amplifier types provide good performance. Comparative measurements have shown that the solid state amplifier is less noisy than the tube amplifier by a factor of ~20. Both amplifiers meet specifications.

CRYOGENIC SYSTEM

The Phase II cryogenic system mirrors the Phase I system except that they share a recovery compressor. A 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 with a slight overpressure in the dewar. The cryomodules are fed in parallel from a main supply manifold (trunk) through variable supply valves. The level in the cryomodules is used to control the opening of the supply valves. 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 for Phase II 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.

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: 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

Beam Commissioning

The complete linac from the downstream end is shown in Fig. 7. The final cryomodule was installed March 21. A 16O5+ beam (A/q=3.2) from the ISAC off-line (stable) 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. 8(a). The final energy is equivalent to acceleration of a beam with A/q=6 to 6.5MeV/u and as such demonstrated the ISAC-II goals on the first acceleration. This was achieved despite the fact that five cavities were not available for acceleration. Fig. 8(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.

Fig. 7: The ISAC-II Superconducting linac.

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+ (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.

Phase I Performance: The performance of the Phase I SCB cavities is monitored periodically typically during start-up after shutdown. The linac is warmed up once per year for three months as part of the site maintenance shutdown. In addition several of the cryomodules have been vented (pump replacement) and some have been taken off line for disassembly to repair internal faults (rf cable, coupling loop faults). Despite this the Phase I performance is very stable. There is some fluctuation in individual cavity performance over time but the average accelerating gradients at 7W cavity power correspond to a peak surface field of 33±1 MV/m over the first four years of operation.

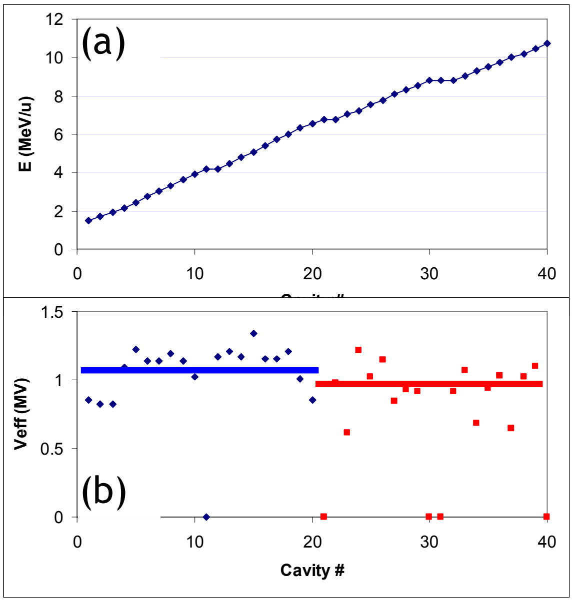

Fig. 8: Results from first acceleration of a 16O5+ beam. (a) A plot of beam energy after each cavity and (b) a plot of the effective voltage of each cavity; blue and red lines indicate the average values for Phase I and Phase II respectively.

Phase II Performance: In comparison the Phase II performance has averaged accelerating gradients corresponding to peak surface field of Ep=26MV/m at 7W in the first six months of operation. In particular the performance of cavities in SCC2 and 3 are reduced compared to single cavity test values. This is under investigation. 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.

Table 2: Given are the summary cavity performance values for the Phase I and Phase II linacs.

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

Operating experience: Multipacting conditioning is required for extended periods after start-up and does cause delays in initial beam tuning. 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 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.

SUMMARY

The ISAC-II linear accelerator represents a ten year activity of research, development, prototyping, production and installation. 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 an ISOL facility to energies above the Coulomb barrier.

ACKNOWLEDGMENT

The work reported here chronicles the efforts of the TRIUMF engineering and technical teams who embraced the new technical challenge and succeeded through dedication, hard work and talent.

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