# ISAC-II: STATUS OF THE 20MV UPGRADE

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*Abstract*

The ISAC-II heavy ion linear accelerator has been in operation at TRIUMF since 2006. The high beta section of the accelerator, consisting of twenty cavities with optimum $\beta_0$=0.11, is currently under production and is scheduled for completion in 2009. 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 with a Canadian company, PAVAC Industries of Richmond, B.C. after two prototype cavities were developed, produced and successfully tested. Cavity and cryomodule production details and test results will be presented and discussed.

## INTRODUCTION

The ISAC-II linac was first commissioned in 2006[1]. The existing linac (SCB section of Fig. 1) 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%. Each cryomodule is also equipped with a single superconducting solenoid of up to 9T in close proximity to the cavities. The cavities operate at 106MHz and produce an effective acceleration of >1.1MV for a cavity power of 7W at 4.2K. The average operating gradient corresponds to a peak surface field of 30-35MV/m and is significantly above the performance at other heavy ion linacs operating in cw mode.

TRIUMF is nearing completion of the ISAC-II Phase II upgrade[2] consisting of the addition of twenty more cavities at beta=11%. The cavities will be 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). Each cryomodule has one superconducting solenoid symmetrically placed in the cryomodule. The Phase II addition will double the voltage gain of the ISAC-II superconducting accelerator. The plan is to install the completed and tested cryomodules by the end of 2009.

SRF facilities at TRIUMF (Fig.1) include a preparation room for parts cleaning, a cavity test area with overhead crane, cryogenic services and test pit, a clean assembly area and high pressure water rinse area. A new lab for BCP etching has recently been added.

## CAVITIES

The phase II superconducting cavity is shown in Fig. 2. The cavities are quarter wave resonators (QWR) 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 cavity of similar structure is used in the ISAC-II Phase I linac. The chief difference here is that in Phase II the inner conductor beam port region is outfitted with a donut style drift tube. The drift tube is formed from machined end caps welded to an inner beam tube surrounded by an outer rolled and welded shroud. The whole donut drift tube assembly is then bored out and welded to the cylindrical inner conductor. The cavity specification is to operate at 141.44MHz (12th harmonic of the bunch frequency) at a gradient of 6 MV/m corresponding to a peak surface field of 30MV/m and peak magnetic field of 60mT with a cavity power ≤7W. Other cavity parameters are shown in Table 1. Two cavity prototypes were successfully developed and tested in 2008 [3, 4]. A further seventeen production cavities have been delivered thus far.

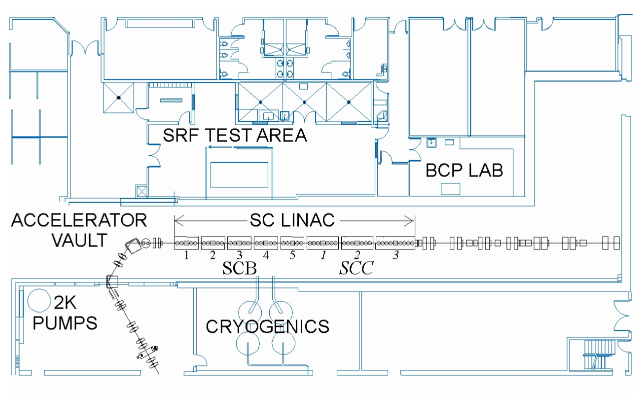


Figure 1: ISAC-II Phase II SC-linac upgrade.

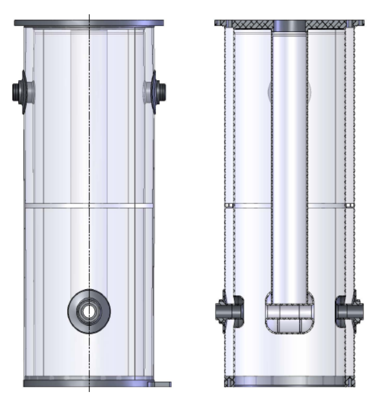

Figure 2: The 141.44MHz rf cavity for Phase II.

Table 1: Parameters of the Phase II Cavity

| | | |
|---|---|---|
| frequency | MHz | 141.44 |
| Aperture | mm | 20 |
| Gap | mm | 35 |
| Drift Tube | mm | 80 |
| Outer Diameter | mm | 180 |
| Inner Diameter | mm | 60 |
| Height | mm | 560 |
| beta | | 0.11 |
| TTF | | 0.936 |
| $U/E_a^2$ | $J/(MV/m)^2$ | 0.067 |
| $R_SQ_0$ | Ω | 26 |
| $E_P/E_a$ | | 4.9 |
| $B_P/E_a$ | mT/(MV/m) | 10 |
| $V_{eff}$ @7W (design) | MV | 1.08 |

### *Processing Steps*

Standard processing involves visual inspection, room temperature frequency measurement, degreasing and a 60-80 μm BCP etch. The etching facility houses a large fume hood sufficient in size to do the heavy ion quarter waves or multi-cell elliptical cavities. An in line chiller coil keeps the acid at 12C as it is pumped through the cavity during the etching procedure. A photo of the cavity after etching is shown in Fig. 3. The cavities are then assembled with a stainless steel top flange bolted to the niobium flange. The vacuum seal between the stainless steel and the niobium is formed with indium. The stainless steel flange is used to mate with the helium delivery system and is outfitted with a mechanical damper assembly that is inserted into the inner conductor. Pre-cool tubes of thin wall stainless 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.

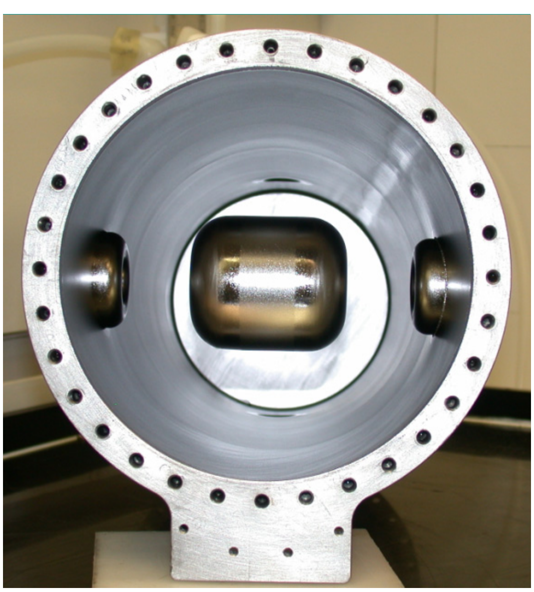

Figure 3: Phase II cavity after etching.

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. Next the cavities are assembled onto the cryostat top assembly flange, outfitted with sensors and inserted into the cryostat. The cavities are baked for 48 hours at 85C then the cryostat thermal shield is cooled with LN2. After 24 hours of pre-cool by radiation the cavity is cooled with LHe.

### *Prototyping*

Cavity prototyping studies began with PAVAC in 2007. Two copper full scale models were produced to establish the welding fixtures, manufacturing steps and frequency tuning. These were followed by the fabrication of two niobium cavities. The machining, forming and e-beam welding are done at PAVAC while the pre-weld etching and frequency tuning are done by TRIUMF. The final cavities after delivery to TRIUMF received a 100 micron chemical etch and HPWR before testing in the single cavity cryostat. The results of the cold test are shown in Fig. 4. Both cavities exceeded specification with an average gradient at 7W cavity power corresponding to a peak surface field of 38MV/m.

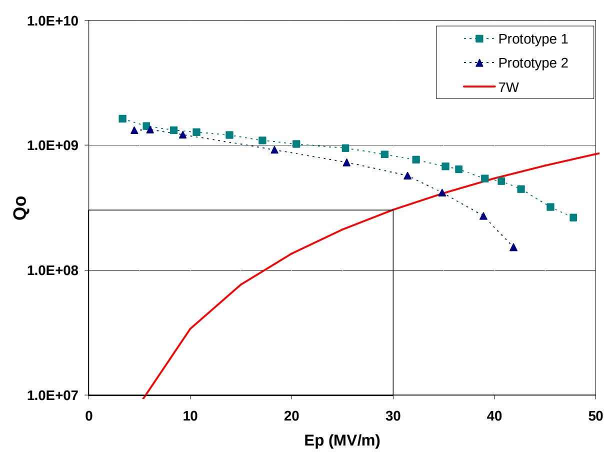


Figure 4: RF characterization Qo vs Ep of the two Phase II prototypes.

### *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. To date seventeen cavities have been delivered, with seven cavities cold tested, six cavities remaining to be tested and with four cavities rejected. The performance tests of the cavities for the first cryomodule are shown in Fig. 5. The plot shows that all six cavities meet or exceed the ISAC-II specification in single cavity tests of a peak surface field of 30MV/m at 7W cavity power. The average accelerating gradient corresponds to a peak surface field of 35MV/m at 7W. All cavities are within 15kHz of the goal frequency of 141.44MHz well within the tuning range of the flexible tuning plate.

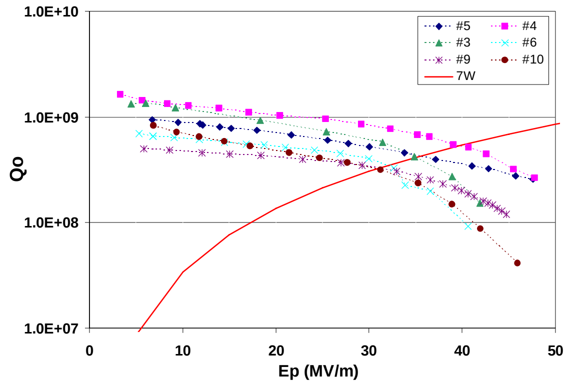


Figure 5: Performance curves for the six cavities for the first Phase II cryomodule.

**Frequency tuning:** According to our experience with the prototype cavities the frequency shift between 300K and 4K (including thermal contraction, air-vacuum change and pressure change) is 264 kHz and this provides the target frequency for the manufacture. Cavity production consists of steps for parts machining, tuning and welding. The cavity tuning during the production is based on a cavity RF model and measurements for frequency sensitivities and prototype production experience for shrinks after welds. There are three main tuning steps:

- Cavity length adjustment before flanges welding; with a sensitivity of -268 kHz/mm
- Acceleration gap adjustment before the beam ports welding; beam ports sensitivity 120 kHz/mm assuming movement at both gaps
- Final trim of bottom flange; with sensitivity ~8 kHz/mm
- A custom etching step to reduce the cavity frequency in a controlled way by 0-40kHz as required.

**Custom etching:** According to analysis of the cavity with a CST Microwave Studio Sensitivity model a uniform removal of material will result in a neutral frequency swing since the removal from the top half exactly compensates for the removal from the bottom half. However a removal from either half exclusively will result in a 2kHz/µm frequency shift with 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 to reach the desired frequency 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.

**Sludge build-up:** The acid is delivered to the bottom of the cavity and is removed from the top with an overflow tube. The first results from the new BCP chemical laboratory gave unpredictable resonant frequency shifts after initial etching. The problem was traced to a non uniform etching of the cavity due to:

- turbulent flow of acid inside of the cavity during the etching process as the acid is continuosly supplied to the cavity. This is now solved by supplying the acid with a ring with multiple ports pointed upward that reduce the turbulence towards the cavity wall
- "sludge" build-up – the contaminated acid drifts to the bottom of the cavity during etching and slows the removal rate at the root end. This is now mediated by removing the spent acid periodically from the cavity during etching with another pick-up ring close to the bottom

**Cavity repair:** The four rejected cavities are due to a common fault; a vacuum leak opening up in the saddle weld joining the drift tube assembly to the inner conductor. The joint in question is shown in Figure 6.

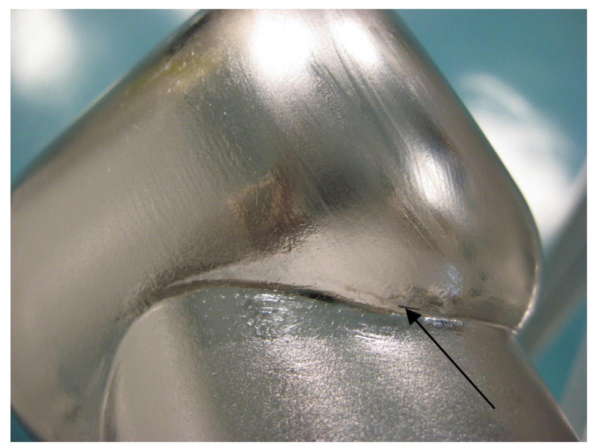

Figure 6: Saddle weld responsible for leaks in four cavities after BCP treatment. Arrow indicates crack.

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 opens after the final etching treatment. PAVAC led a corrective action with the goal to recover the leaking cavities. The weld is not accessible from the bottom flange so it is necessary to remove the inner conductor from the cavity assembly. The repair involves cutting out the inner conductor from the cavity at the top flange to gain full access to the saddle weld. The saddle weld is then repaired. Next the top flange and inner conductor flange material are cut back to prepare for a joining butt weld to secure the inner conductor back into the cavity. A niobium supporting ring is then welded into the top flange for mechanical strength. So far one cavity has been treated in this way as a proof of principle. The performance plot for Cavity 8 is shown in Fig. 7 indicating that the repair strategy is successful. The other cavities are now getting similar treatment over the coming weeks.

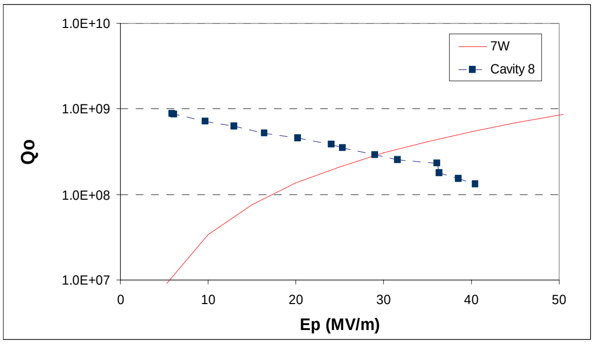


Figure 7: Cavity performance for Cavity #8 after repair of the vacuum leak in the drift tube to inner conductor weld.

## 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 very little evidence of degradation in cavity performance over the first two years of operation even after repeated thermal and venting cycles. Procedures are followed to help mitigate 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.

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*

There are some differences between the Phase I and Phase II cryomodules that either address small deficiencies in the Phase I design or are required due to the longer size of the Phase II cryomodules: 1. The vacuum tanks are essentially the same with dimensional differences to accommodate the internal components. The eight cavity SCC3 has an extra set of ribs on the lid and sides to reduce vacuum deformation on the larger areas. The mounting footprint is also elongated to give more stability. 2. The cavities and solenoid are supported from a rigid strongback that is in turn supported from the tank lid by support rods. In the SCB cryomodules a three point mounting system was used to suspend the strongback. The decision here is to adopt a four point system to reduce the freedom in the movement of the cold mass. The strongback assembly is considerably more robust than in the SCB due to the increased cold mass and length. 3. In the SCB the LN2 cooling for the side shields and the coupling loop is delivered in one series circuit. In the SCC the delivery to the coupling loops is achieved with parallel channels to reduce the size of the fittings on the coupling loop. 4. The solenoid mounting system is completely modified in SCC and is based on a linked strut system to aid in alignment. 5. The helium reservoir is redesigned with thicker wall material and a purchased "tee" section. Bulkheads are incorporated into the weld seams to make all welds external. The service stack for the helium space is now outfitted with a 12.5cm high spool piece that houses the feedthroughs and ports for all of the cryogenic and vacuum diagnostics. Provision for level sensor replacement has been added with ports on the top of the reservoir. Cables and He distribution lines are installed before final weld on each end of the reservoir. The welding is done in place of the SCB indium seals that were prone to early leaks. 6. The mu metal thickness has been increased from 1mm to 1.5mm. 7. 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. The vent gas can flow for any operation where there is a risk of contamination as in during loading of the top assembly into the cryomodule.

**Mechanical Tuner:** In the Phase I system 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 linear servo motor[6]. The system works well and provides high performance tuning for high gradient operation. The tuner motor is an expensive item and development work subsequent to the Phase I installation has resulted in a new design using a ball screw drive to replace the linear motor. The brush-less servomotor contains its own single turn absolute sine encoder. The power and encoder signals are connected through long cables to a matched digital servo-amplifier. The output shaft of the motor is connected directly to the anti-backlash internally preloaded precision ball screw nut, through a stiff bellows coupling. The anti-backlash nut is fixed rigidly to the anti-backlash liner guides that provide perfectly reproducible vertical straight-line motion resulting in a vertical position resolution of at least 0.03 microns (corresponding to an eigenfrequency shift of 0.2Hz) with a positioning bandwidth of at least 30 Hz. The interface connections are designed to retrofit the SCB low beta SRF tuner rod connector design.

**Coupling Loop:** The Phase I variable coupling loop[7] 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. However side loads from the LN2 cooling lines cause stiffness in some units in the mechanical motion at cold temperatures. A redesigned coupling loop with non-magnetic cross-roller bearings and symmetric loading has greatly improved the mechanical motion and the new design is being employed in SCC

### *Status*

The cryomodules are labelled from SCC1 to SCC3. The first two modules, SCC1 and 2 contain six cavities while SCC3 contains eight cavities. Because of space constraints in the clean room and available personnel only one cryomodule is assembled at a time. Each cryomodule will receive at least one cold test in the SRF facility before delivery to the linac vault. SCC1 is now fully assembled, cold tested and is ready for installation in the linac. SCC2 is now in clean assembly with the start of the cold test scheduled in ~1 month. Cryomodule SCC3 is fully fabricated and has been assembled in the dirty area (without cavities) in preparation for clean room assembly. All cryomodules are to be assembled and installed in the linac vault by year end.

### *SCC1 Test Results*

SCC1 is now completely tested. In all two full cold tests were completed. The first test was done with WPM installed (see below) and the second was done as a final installation without WPM. 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. 8 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 mu metal reduces the remnant magnetic field below 20mG in the cavity region as per specification.

**Alignment:** Due to the design changes between the Phase I and the Phase II cryomodules it was decided to repeat the use of the Wire Position Monitor (WPM) alignment system for SCC1. Here 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 the WPM axis. Monitors are placed on each cavity with two, one upstream and one downstream, on the solenoid. The specified alignment tolerance is the same as that for phase I: ±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

Figure 8: Cryomodule SCC1 assembly prior to the first cold test.

downstream cavities and in the upstream and downsteam port of the solenoid to periodically chart the position of the cold mass in relation to the beam axis. The beam axis is defined by optical targets on the upstream and downstream beam port flange of the vacuum tank. Both the optical targets and the WPM give useful information. The optical targets give periodic information on the position of the cold mass line with respect to the beam axis while the WPM give continuous monitoring of the position of the whole cavity string. The WPM data is essential to know if there is any warping or twisting of the support structure that occurs during cooldown.
In the first cold test two complete thermal cycles were done from room temperature to 4K to test for the repeatability of the cold mass. The four point mounting system proved quite rigid and showed less swing than was found in the three point mount of the phase I cryomodule. The position of the cold mass from one cold condition to the next was unchanged within the measurement error ±50μm. The first test proved that the solenoid vertical beam position contracts by 4.25 mm while the cavity beam positions contract by 3.5 mm during the change from warm/atmosphere to cold/vacuum. To counter the effects of rf steering due to the asymmetric geometry of the QWR the cavity is required to be 1.25 mm below the beam axis. This is accomplished by aligning the cavities when warm 0.5mm below the solenoid. This warm off-set established in the first test was used to set the position of the cavities prior to the second test. The second test confirmed that the required alignment tolerance was met with the solenoid within ±100μm and the cavities within ±250μm of the goal position.

**Cavity performance**: The first test confirmed that all cavities were functional and that the rf ancillaries were performing as expected. Three amplifiers were available for the test. Various cavities in sets of three were locked at the design frequency to prove the performance of the tuners and to explore any cross-talk between tuners. The individual cavities were also tested. In this case all cavities reached a reasonable gradient but there was heavy field emission; clear signs of cavity pollution. Before the second test several steps were taken to reduce the chances of particulate contamination including: cleaning of the clean room, rinsing of the cavities and thorough cleaning of the vacuum vessel and LN2 liner. The results of the second rf tests are shown in Fig. 9.

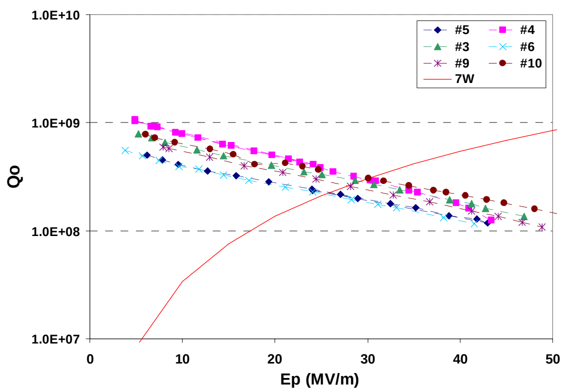


Figure 9: Rf performance of the cavities in SCC1 during the second cold test.

The test results indicate that the cavities are clean with very little field emission even at high field. However the average gradient in the test corresponded to a peak surface field of 28MV/m down from 35MV/m in the single cavity tests. Comparing to Fig. 4 the shape of the curves is quite different leading us to believe that the cavities are contaminated with Q-disease. The cooldown to the cavities was not particulary slow with the transition from 200K to below 50K taking ~2 hours. Nonetheless in a severely polluted cavity this could be enough to cause the observed performance degradation. Future tests will involve trying to diagnose the severity of the hydrogen contamination in single cavity tests. We have seen the presence of hydrogen contamination in one dedicated study of a Phase II cavity but no systematic study of Q-disease of these cavities has been done. We are also looking for a hydrogen degassing furnace in the Vancouver area to reduce the hydrogen concentration in the niobium. There is some speculation that the hydrogen may be absorbed by the niobium during contact with water during the various rinsing stages. The temperature of the BCP stage is monitored closely and so we do not suspect improper etching procedures.

In other measurements the He pressure sensitivity for the production cavities is -1 Hz/Torr which is ~3 time less than for the prototype due to better stiffening during cavity assembly. Lorentz force detuning measured at these tests was -1 Hz/(MV/m)$^2$ which is the same as for prototypes.

**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 supply valve and diverting the return exhaust helium through a gas meter. It is found that the static load is 24.5W. This is somehat higher than expected considering that the static load for the Phase I cryomodules is only 13W. There is an extra support strut and increased length and component size in the Phase II cryomodule so this explains some of the increase but the large difference is not easily explained. The LN2 usage while thermalized is about 5-6 liters/hour the same as for the Phase I modules.

## INSTALLATION

### *Amplifiers*

As part of the upgrade of the ISAC-II superconducting linac, twenty solid state amplifiers are on order from QEI Corporation, NJ, USA. We have now received 12 amplifiers. A prototype amplifier has been tested thoroughly prior to series production. The gain of the amplifier, the 3 dB bandwidth and output power were measured and are within the specification. Gain linearity is within ± 0.5 dB and phase linearity is within ± 2.0 dB for the output power range from 1 to 250 watts. The amplifier gain is measured to be 65 ± 0.75 dB, which is 10 dB higher than specified. The phase noise of the prototype amplifier is estimated by tests into both a dummy load and one of the prototype cavities. These measurements are compared to the same values using a tube amplifier. The solid state amplifier is significantly less noisy than the tube amplifier. For the solid state amplifier the average noise value is 0.0044° rms in the frequency range of 2-200 Hz. The average noise for the tube amplifier in the same frequency range is 0.098° rms. The integrated value of phase noise in the bandwidth of 2 – 200 Hz was specified to be less 0.3° rms. These amplifiers are being installed in the power supply room adjacent to the accelerator vault with a remote interface through the EPICS protocol.

## CRYOGENIC SYSTEM

The Phase I cryogenic system consists of a Linde TC50 cold box configured with a 79gm/sec KAESER compressor. Helium produced in the cold box is fed 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 Phase II addition ot the cryogenic system (shown with Phase I in Fig. 10) essentially duplicates the Phase I system. A second Linde plant has been installed identical in every respect to Phase I except that a second recovery compressor was not ordered. The system has been installed by TRIUMF and commissioned. 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.

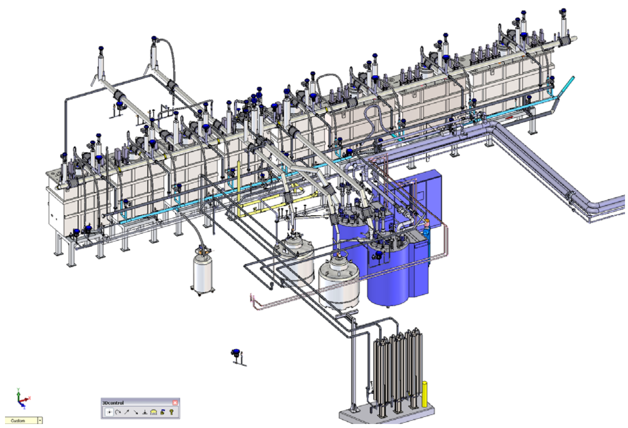

Figure 10: The cryogenics system for ISAC-II Phase I and II.

### *Cryomodules*

The first cryomodule will be installed in the vault starting Oct. 15 followed each month by another module. The inistallation will include final alignment, cable and hardware connections and vacuum pumpdown. After each installation the cryomodule will undergo a complete in situ cold test to establish the functioning of all on-line systems. Full beam commissioning will commence in January of 2010.

## SUMMARY

Seventeen of the twenty production cavities for the ISAC-II Phase II linac are delivered to TRIUMF. Six of the cavities have met specification and been installed in the first cryomodule. Cold tests confirm the operation of all sub-systems. Cavity test results from the cold test give an indication of some reduced Q that may be related to hydrogen contamination. Six cavities are still to be tested. Four cavities experienced a vacuum leak after the final cavity etching. The manufacturer has devised a plan to recover the leaking cavities. The first repaired cavity has been tested successfully at TRIUMF. The rest of the repaired cavities and the remaining production cavities are expected in the next six weeks.

A new BCP chemical laboratory is now operational at TRIUMF. A sensitivity model of the cavity was successfully used for tuning of the cavity frequency with BCP.

The installation in the accelerator vault has now begun. The first eight quadrupoles of the high energy beam line have been removed in preparation for the installation of the stands and supporting infrastructure for the SC-linac addition. We expect to begin beam delivery in April 2010.

## ACKNOWLEDGEMENTS

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