COLD TEST RESULTS OF THE ISAC-II MEDIUM BETA HIGH GRADIENT CRYOMODULE

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Abstract

Many proposals (RIA, Eurisol, ISAC-II) are emerging for a new generation of high gradient heavy ion accelerators. The ISAC-II medium beta cryomodule represents the first realized application that encorporates many new techniques to improve the performance over machines presently being used for beam delivery. Developments include upgraded tuner and coupling loop designs, electronic alignment monitoring systems and a high density lattice using superconducting solenoids. The new developments are described and the results of the first cold tests are presented.

INTRODUCTION

TRIUMF is now preparing a new heavy ion superconducting linac as an extension to the ISAC facility [1], to permit acceleration of radioactive ion beams up to energies of at least 6.5 MeV/u. The superconducting linac is composed of two-gap, 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. An initial installation of 18 MV of medium beta cavities ($\beta = 5.8\%$, 7.1%) is due for commissioning in 2005. The first major milestone, reported here and achieved in June 2004, is the first rf cold test of the completed cryomodule.

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. 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. This goal not only demands clean rf surfaces but an rf system capable of achieving stable performance. To achieve stable phase and amplitude control the cavity natural bandwidth of $\pm$0.1 Hz is broadened by overcoupling to accomodate detuning by microphonic noise and helium pressure fluctuation. The chosen tuning bandwidth of $\pm$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.

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 $\Delta Q/Q \leq 7\%$.

MEDIUM BETA CRYOMODULE

The engineering description and cryogenic tests are reported in a separate article.[6] The vacuum tank consists of a stainless steel rectangular box and lid. All services and feedthroughs are located on the lid. A serial LN2 piping circuit cools both the copper panels formed into a thermal shielding box and the rf coupling loops. Magnetic shielding in the form of high μ sheet is suspended between the warm wall and the cold shield. Cavities and solenoids are suspended from a common support frame itself suspended from the tank lid (Fig. 1). Each cryomodule has a single vacuum system for thermo-isolation and beam acceleration. This demands extreme cleanliness of internal components and precludes the use of volatile lubricants and flux, as well as particulate generators, to avoid superconducting surface contamination. Assembly is done in the new ISAC-II clean room.

Figure 1: Cryomodule top assembly in the assembly frame prior to the cold test.

Alignment

The cavities must be aligned to within 0.4 mm and the solenoid to 0.2 mm. A wire position monitor (WPM)[7] system has been developed to monitor the position of the cold mass during thermal cycling. The monitors each consisting of four striplines are attached to the cavities and solenoid by off-center 'L' brackets. A wire running parallel to the beam axis and through the monitors carries an rf signal that is measured by the striplines and is converted to an x-y position. In addition optical targets are placed in

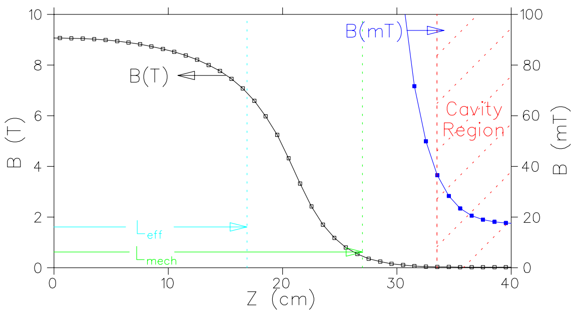

Figure 2: ISAC-II solenoid axial field map showing fringe field in the cavity region.

each cavity and in the entrance and exit bore tube of the solenoid.

Solenoid

The 9 T solenoids, fabricated by Accel, have a bore of 26 mm, an effective length of 340 mm and a mechanical length of 540 mm. The magnets are mounted in a liquid Helium vessel fed from the common Helium header. The power leads are vapor cooled. Due to the close packing of the lattice the solenoids are equiped with bucking coils to actively limit the fringe field in the adjacent cavity to less than 100 mT to prevent reduction in cavity performance. The axial field map of the Accel solenoid is shown in Fig. 2 with the fringe field strength highlighted. The map indicates that the fringe field in the cavity region is less than 40 mT.

Cavities

The cavities, originally developed at INFN-LNL[2], are two-gap bulk niobium quarter wave cavities of design velocity $\beta_o \sim 7\%$. 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 through a side port. After fabrication the cavities are chemically polished and rinsed with high pressure water before rf characterization in the single cavity cryostat. Results of these tests are presented in Fig. 3. All cavities reach the ISAC-II specified performance although Q degradation at high fields due to field emission is apparent.

RF Systems

RF Controls: The RF Control system [3] is a hybrid analogue/digital system. Each system consists of a self-excited feedback loop with phase-locked loops for phase and frequency stabilization. Amplitude and phase regulations, as well as tuning control, are performed using digital signal processors.

LN2 Cooled Coupling Loop: Initial cavity studies at TRIUMF were done with an adjustable coupling loop designed at INFN-Legnaro suitable for operation with lower gradients and lower forward power. A new coupler has been developed[4] that reduces the helium load to less than 0.5 W at the design gradient of 6 MV/m and $P_f = 200$ W.

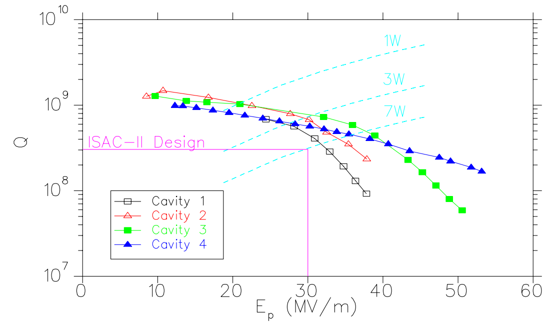

Figure 3: Characterization curves for the four cavities of the test cryomodule as measured in the single cavity cryostat.

The coupler has a stainless steel body for thermal isolation and a copper outer conductor cooled with LN2. Cooling of the inner conductor is achieved by adopting a thermally conducting Aluminum Nitride dielectric localized in the coupling loop. The rf drive cable is uncooled but thermal radiation to 4K surfaces are intercepted by an LN2 cooled copper tube surrounding each cable.

Mechanical Tuner: A new high resolution mechanical tuner[5] has been developed. The tuning plate is actuated by a vertically mounted permanent magnet linear servo motor, at the top of the cryostat, using a 'zero backlash' lever and push rod configuration through a bellows feedthrough. The system resolution at the tuner plate center is $\sim 0.055 \mu$m (0.3 Hz). The tuning plate is radially slotted and formed with an 'oil can' undulation to increase the flexibility. The demonstrated dynamic and coarse range of the tuner are ± 4 kHz and 33 kHz respectively. The demonstrated mechanical response bandwidth is 30 Hz. The tuner on-line performance is measured by altering the cavity frequency by forced variations of the helium pressure that induces an eigenfrequency change of 2 Hz/Torr. Fig. 4 shows the pressure change, the associated position signal from the tuner and the corresponding control loop error parameters while operating in ISAC-II conditions; $E_a = 6$ MV/m and $P_{for} = 200$ W. The cavity remains locked throughout but the amplitude regulation goes out of range when the rate of eigenfrequency change exceeds 60 Hz/sec.

CRYOMODULE TESTING

The cryomodule assembly and commissioning tests are conducted in the clean laboratory area in the new ISAC-II building. Thus far two cold tests have been completed. An initial cold test in April 2004, without rf ancillaries installed, characterized cryogenic performance and determined the warm off-set required to achieve cold alignment[6]. Briefly, the static helium load without rf ancillaries is 11 W and the required LN2 flow is 5ℓ/hr in line with predictions.

Preparation

Following the initial test the four rf sub-systems consisting of tuner, coupling loop and rf pick-ups are installed.

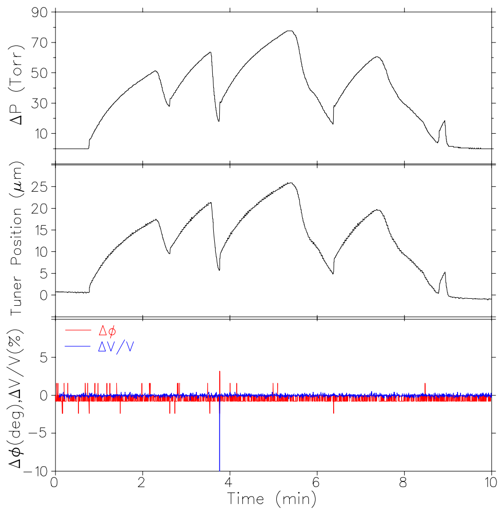

Figure 4: Tuner position response for forced pressure fluctuations in the helium space. The cavity maintained phase lock during the test. The bottom plot shows the phase and amplitude error. The cavity gradient is 6 MV/m with a bandwidth of $\pm$20 Hz.

Cables for the rf and tuners systems are run from a multi-cavity controller cabinet and rf amplifier unit located outside the clean room. A single cavity cold test confirmed the integrity of each of the controller and cabling systems. Information collected during the first cold test is used to establish the warm alignment positions of the cavities and solenoid. Optical targets are installed in each element to check the alignment during the second cold test.

Exhaust gases from the cryomodule are passed through vaporizers and the flow is monitored by gas meters. A local computer records WPM information. Control and data acquisition are done with an EPICS control system.

Test Results

Cavities The cavities are first baked at ~80°C for 24 hours. The cold mass is pre-cooled with LN2 to about 200°K before helium transfer. The quality factor of each cavity is determined by measuring the time constant of the field decay in pulsed mode at critical coupling. The Q values, presented in Table 1 are similar to those measured in the single cavity cryostat (Fig. 3) indicating that the μ-metal reduces the remnant magnetic field to a sufficient level. Also shown are the field values reached for a cavity power of 7 W. Cavity 2 high field results are not available due to a problem with the coupling loop. The results are below the design specification. The cavities were not rinsed prior to the test since system integrity and not high gradient are the immediate goal. As well there was insufficient helium to adequately condition the cavities.

Solenoid: The solenoid tests were done to determine the effect, if any, on cavity performance due to the high operating field or induced remnant fields. The solenoid was ramped up to 9 T with cavity 2 and 3 on. The cavities remained on and the measured Q values did not change. The solenoid and cavities were then allowed to warm above transition. After subsequent cooldown the cavity Q values were again measured. There was no change in the values showing that fields induced by the solenoid in the region of the cavities are tolerably small.

Table 1: Cavity performance during cold test

Cavity	Q_o	E_a@7 W (MV/m)	E_p@7 W (MV/m)
1	1.5×10^9	4.3	22
2	1.4×10^9	-	-
3	1.5×10^9	5.4	27
4	1.3×10^9	5.4	27

RF Control and Tuning One of the cavity control boards was shown to have a hardware fault so not all cavities could be locked simultaneously. However cavities 1,3,4 and cavities 2,3,4 were simultaneously locked to a common external frequency. In a final system test cavities 1,3,4 were each set to ISAC-II control conditions, $P_{cav} =\sim 4$ W and $P_{for} = 200$ W, and the solenoid was turned on to 9 T. The cavities remained locked to an external frequency while undergoing forced helium pressure fluctuations of 60 Torr.

CONCLUSIONS

Given the complexity of the undertaking the test was very successful. Cryogenically the cryomodule performed well with helium and LN2 consumption near expected values. Simultaneous locking of multiple cavities to an external frequency was demonstrated. The operation of the high field solenoid did not negatively impact the cavity performance. Future tests will involve a high pressure rinse and final clean assembly to reach for the design gradients.

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