Superconducting RF at TRIUMF/ISAC: Present Status and Future Plans

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Abstract

TRIUMF is presently operating an ISOL based radioactive beam facility, ISAC, supplying both low-energy ($\leq$60 kV, $A \leq 238$) and high energy (0.15-1.5 MeV/u, $A \leq 30$) experimental areas with exotic beams. We have recently been funded to proceed with a second stage, ISAC-II, to extend the final energy to at least 6.5 MeV/u and the mass range up to 150. The expansion includes the addition of a superconducting heavy ion linac supplying 42.7 MV of acceleration. The linac will be comprised of three cavity geometries, all quarter wave bulk niobium in design, with design velocities of 0.042, 0.072 and 0.105 and rf frequencies of 70.7, 106.1 and 141.4 MHz respectively. We have designed, fabricated and tested a medium beta prototype cavity in a collaboration with INFN-LNL with an achieved gradient of 6.7 MV/m @ 7W dissipated power at 4.5°K. An SCRF test lab is in construction at TRIUMF. A test cryostat has been fabricated and cryogenic tests with a dummy copper cavity are in progress. The present status of the SCRF work, future plans and project schedule will be presented.

1 INTRODUCTION

The first stage of a radioactive ion beam facility at TRIUMF, ISAC-I[1], is now in routine operation. In brief, the facility includes a 500 MeV proton beam (I $\leq 100\,\mu$A) from the TRIUMF cyclotron impinging on a thick target, an on-line source to ionize the radioactive products, a mass-separator, an accelerator complex and experimental areas. Present licensing permits continuous operation at 100 μA proton intensity for targets with $Z \leq 82$. Thus far 40 μA has been run on a Nb target and 20 μA on a Ta target. Beams of $E \leq 60$ keV and $A \leq 238$ are being delivered to the low energy experimental area. The ISAC-I accelerator chain (room temperature) 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 $3 \leq A/q \leq 6$ to a final energy between 0.153 MeV/u to 1.53 MeV/u. Both linacs are required to operate *cw* to preserve beam intensity. A first beam of ^{8}Li has been delivered to the TOJA experiment on July 25, 2001.

Recently funds have been allocated for an extension to the ISAC facility, ISAC-II[2], to permit acceleration of radioactive ion beams up to energies of at least 6.5 MeV/u for masses up to 150. The proposed acceleration scheme would use the existing RFQ with the addition of an ECR charge state booster to achieve the required mass to charge ratio ($A/q \leq 30$) for masses up to 150. A new room temperature IH-DTL or very-low-beta SC-DTL would accelerate the beam from the RFQ to a new stripping energy of 400 keV/u followed by a superconducting linac designed to accelerate ions of $3 \leq A/q \leq 10$ to a final energy of 6.5 MeV/u for $A/q \leq 7$. A first stage of ISAC-II installation will see a transfer line constructed from the ISAC-I DTL exit to join the medium-beta section of the ISAC-II SC linac for acceleration of lighter ions, $A \leq 60$, to energies above the Coulomb barrier. A schematic of the ISAC-I and ISAC-II linear accelerator complex is shown in Fig. 1. The first stage is expected to be completed in 2005.

2 SUPERCONDUCTING LINAC

The superconducting DTL is specified to deliver an effective accelerating voltage of 42.7 MV at the design synchronous phase of -30° or 49.3 MV at 0° in order to achieve the design energy of 6.5 MeV/u for $A/q = 7$. A two-gap quarter wave structure is chosen for ISAC-II because of its high velocity acceptance and inherent mechanical stability. The former is useful to accelerate a wide variety of ions ($3 \leq A/q \leq 10$) efficiently with a minimum of cavity types and the latter is essential to produce high accelerating gradients to minimize overall length/cost. Three cavity geometries corresponding to low, medium and high β_o (β_o=4.2%, 7.2%, 10.5%) values and rf frequencies of 70.7 MHz, 106.08 MHz and 141.4 MHz respectively are specified corresponding to the $6^{\rm th}$, $9^{\rm th}$, and $12^{\rm th}$ harmonics of the beam bunch frequency. The cavity design parameters are given in Table 1.

Table 1: Cavity design parameters for the three sections of the SC linac.

Cavity	Low	Medium	High
No. of Cells	2	2	2
β_o(%)	4.2	7.2	10.5
f (MHz)	70.72	106.08	141.44
$\beta_o\lambda(cm)/2$	8.9	10.2	11.1
$\lambda/4$ (cm)	106	70.7	53.0
$\Sigma V_{\rm eff}$ @ 0° (MV)	7.2	21.6	21.6

The cavity parameters are set to optimize acceleration efficiency and to provide an initial installation stage sufficient to reach a final energy above the Coulomb barrier for light ions ($A \leq 60$) using only the medium beta section. The expected equilibrium charge states after the stripping foil produce ions with $3 \leq A/q \leq 7$. In addition it was thought useful to extend the linac acceptance range to include ions from the Charge State Booster that could be accelerated without stripping. Mass to charge ratios from $3 - 10$ are considered in the optimization. The short independently phased cavities give a wide velocity acceptance and so the

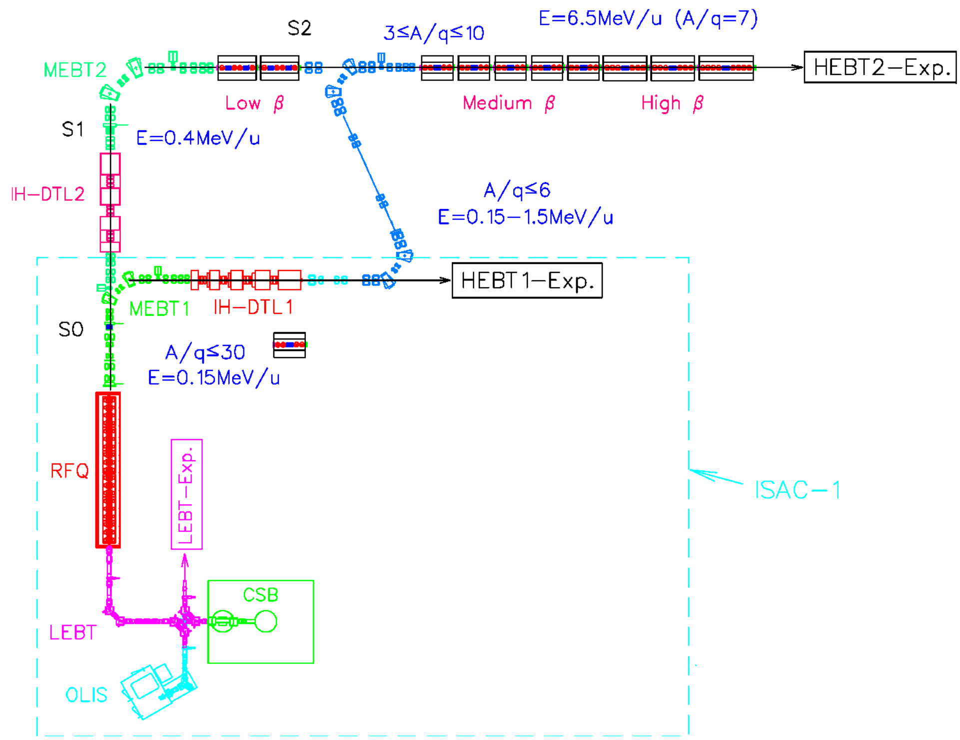

Figure 1: The ISAC-I and ISAC-II accelerator complex.

final energy for each ion can be optimized. The design parameters give an integrated transit time factor that is no worse than 90% of the optimum transit time factor over the complete mass to charge range. The final energy/nucleon for the full range of A/q values is shown in Fig. 2.

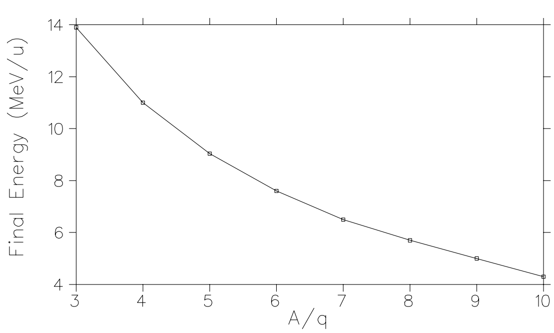

Figure 2: Final ion energy as a function of particle mass to charge ratios.

2.1 Cavity Dimensions

Cavity dimensions are set by the choice of design velocity and rf frequency. TRIUMF has benefited enormously from a close collaboration with INFN-LNL. The present ISAC-II design utilizes the principles developed for the low beta bulk niobium cavities on the ALPI and PIAVE linacs at Legnaro; their unifying characteristic is that different design velocities can be reached by varying the resonator length and altering slightly the geometry of the grounded beam tubes and central conductor while maintaining a constant cavity diameter. In this way Legnaro reduces design time by maintaining a consistent cryostat geometry with four cavities per cryostat. Other important features of these cavities are the mechanical damper installed in the inner conductor, the complete Niobium construction, and the simplified construction suitable for mass production in industry. A final and important point, the cavities yield wonderful performance with gradients typically above $6-7$ MV/m for 7 W @ 4°K.

Based on the developments at LNL the design gradients were set at 5 MV/m for the low beta cavities and 6 MV/m for the medium and high beta sections. The cavity geometries are chosen to match the transverse dimensions of the LNL bulk niobium resonators. The medium β quarter wave bulk Niobium cavity[3] is shown in Fig. 3 along with some design parameters. A summary of cavity specifications for the three ISAC-II superconducting cavity types are given in Table 2. The cavities will typically be operated at a negative synchronous phase for stable longitudinal motion and this gives rise to a net transverse defocussing force and vertical steering due to the vertical asymmetry. A summary plot of the cavity transverse perturbations for the three geometries are shown in Fig. 4 assuming a phase of $-30°$, a field gradient of 6 MV/m and A/q of 3.

These calculations point out the strong defocussing and steering produced in the low β section. The latter is especially troublesome for multi-charge acceleration since the transverse phase advance per cell varies with charge so that vertical deflections on the ensemble will eventually become

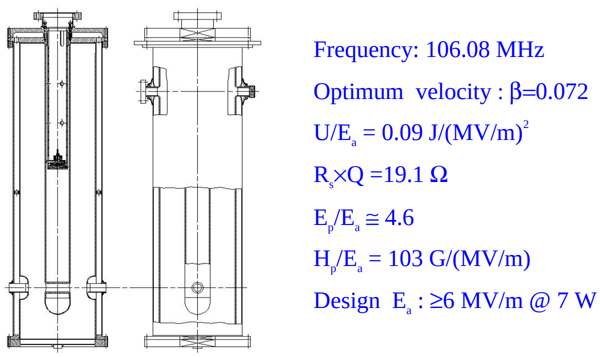

Figure 3: The prototype 106.1 MHz medium-β cavity.

Table 2: Present geometrical parameters of ISAC-II superconducting cavities. Lengths in the beam direction are given for entrance and exit grounded tubes, the acceleration gaps and the inner conductor tube.

Cavity	Low	Medium	High
β(%)	4.2	7.2	10.6
Number required	8	20	20
Design gradient (MV/m)	5	6	6
$V_{\rm eff}@0°$ (MV)	0.9	1.08	1.08
ID (mm)	180	180	180
Inner Tube L (mm)	40	60	60
Gap L (mm)	46	40	50
Grounded Tube L (mm)	24	20	10
Full Bore (mm)	20	20	20

incoherent and lead to emittance growth. We may, as a result, alter the cavity geometry to lower the design velocity of the low β cavity.

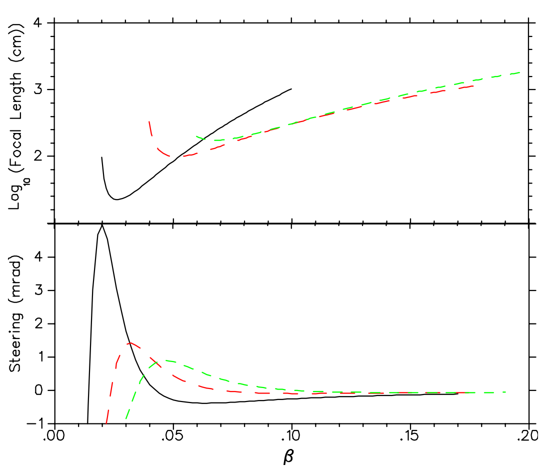

Figure 4: (a) Integrated defocussing effect and (b) steering effect from single cavities and three geometries assuming 6 MV/m, $A/q = 3$, and $\phi_s = -30°$.

2.2 Linac Lattice

We are considering the possibility of utilizing multi-charge acceleration in the ISAC-II superconducting linac to preserve beam intensity and/or allow the possibility of a second optional stripping stage to boost the final ion energy. In initial lattice studies Legnaro/JAERI-style four cavity cryomodules were assumed separated by focussing magnets at room temperature. The studies show that superconducting solenoids are the optimum focussing element for transporting beams with multiple-charge states[5]. Simulations show that the four cavity linac lattice can accept $\Delta Q/Q \leq \pm5\%$ in the low-β section and $\Delta Q/Q \leq \pm7\%$ in the mid and high-β sections.

The choice for superconducting solenoids allowed us to re-think the cryomodule specification with a goal to rationalize the transverse optics. Three different cryomodule layouts are now specified one for each linac section (see Fig. 5). The number of focussing elements are varied along the accelerator length for a reduced transverse envelope and the diagnostic boxes are positioned at waists in the transverse envelopes. The new cryomodule concept also allows the possibility of optimizing the transverse dimensions of each cavity type. This will receive further study.

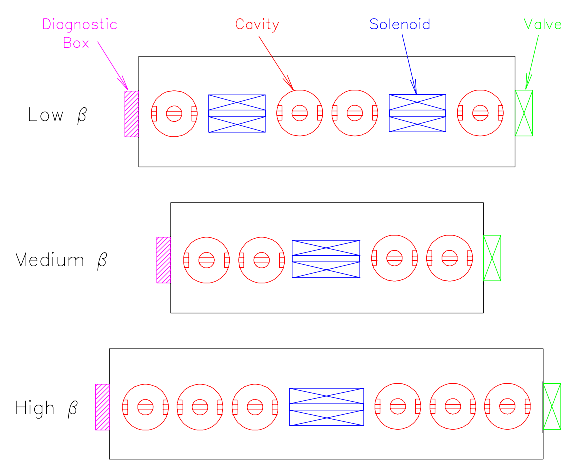

Figure 5: Proposed cryomodule layout for the three sections of the ISAC-II SC linac.

The cryomodules have lengths of 2.1, 1.8 and 2.4 m respectively for low, medium and high beta sections with two low beta and five medium beta cryomodules required. In order to encorporate twenty high beta cavites it is considered to use two, six cavity cryomodules and one, eight cavity cryomodule.

3 SCRF DEVELOPMENTS

Although the program at TRIUMF is still in it's infancy a number of developments are underway including the fabrication and test of a medium beta cavity prototype, the fabrication and cryogenic test of a test cryotest and the design of an SCRF laboratory.

3.1 Medium Beta Cavity

A medium β quarter wave bulk niobium cavity[3] has been designed in collaboration with INFN-Legnaro, fabricated in Italy[4], received chemical polishing in CERN, and was rf tested in Legnaro. The cavity is shown in Fig. 6 prior to the first cold test. This cavity differs slightly from the Legnaro resonators in that the bottom tuning plate is now made from Niobium sheet rather than sputtered Niobium on a copper substrate and additional rigidity has been added at the top plate to reduce the cavity detuning due to flucuations in the pressure of the cryogenic system. Multipacting conditioning, started at room temperature, was completed during resonator pre-cooling with an elapsed time of about four hours. After cool-down to 4.2°K the cavity was pulse conditioned for 1 hour in a 3×10^{-5}mbar Helium. Results of the first rf test are shown in Fig. 7. The cavity performance exceeds the ISAC-II requirements with an accelerating gradient of 6.7 MV/m for 7 W dissipated at 4°K. A peak gradient of 11 MV/m was achieved. The cavity is now being prepared for further rf tests at TRIUMF.

Figure 6: TRIUMF medium beta prototype cavity before cold test at INFN-LNL.

3.2 Test Cryostat

A test cryostat has been designed and built in a collaboration between TRIUMF and Quantum Technologies of Whistler, Canada. The cryostat is shown in Fig. 8. The cryostat vacuum vessel is 2.4 m high by 0.8 m in diameter. A LN_2 side shield holds a volume of 200 litres and is directly connected to a copper bottom shield baffled to allow adequate conductance for pumping. A top shield of copper is bolted to a copper flange at the top of the LN_2 vessel with bolt access available through six KF-50 flanges on the top plate. This copper flange is cooled by a copper cylinder inserted in the LN2 vessel to a depth of 65 cm. The top plate assembly consists of two large flanges that allow separate removal of either the helium dewar/cavity assembly or the LN2 vessel. The LHe vessel holds a volume of 48 litres.

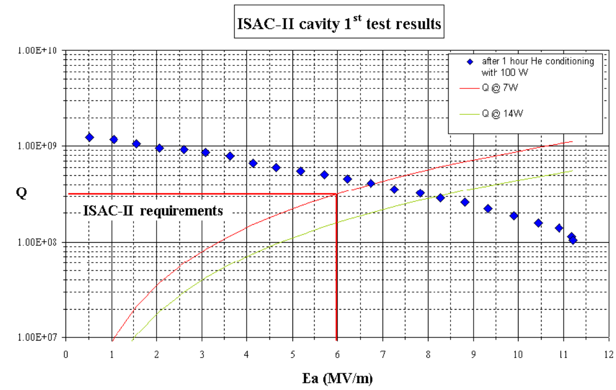

Figure 7: Results of the first rf test on the medium beta cavity at INFN-LNL.

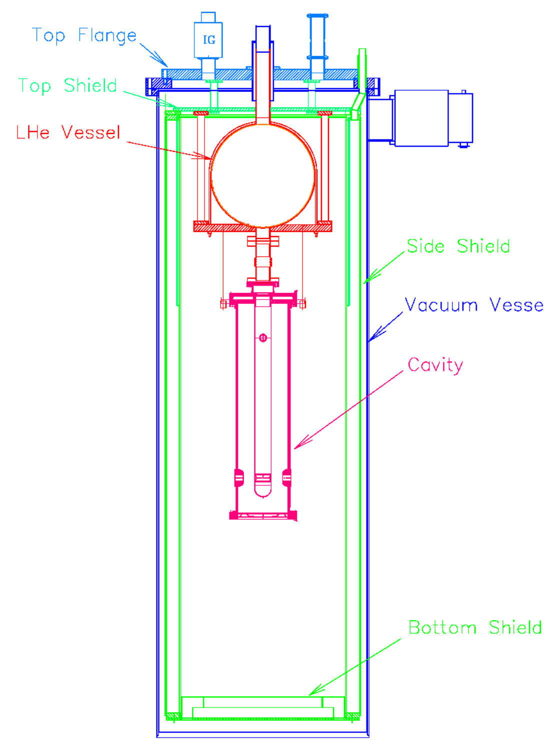

Figure 8: ISAC-II test cryostat with 'dummy' copper cavity.

A 'dummy' full scale medium beta cavity has been fabricated in copper for cryostat tests and to establish test procedures. Initial cryostat tests have been completed. The top plate, top shield, LHe reservoir and dummy cavity are shown in Fig. 9 prior to assembly in the cryostat. The LHe boil off rate has been established by both measuring the flow of the escaping gas and by charting cavity temperature with time after a fill. A static heat load of 1.2 W was found corresponding to a boil off of 1.4 litres/hr. The loss rate for LN_2 is 1.5 litres/hr. The vacuum pressure in the cryostat was 5×10^{-7} while warm and 8×10^{-10} torr while cold.

Figure 9: ISAC-II test cryostat inner assembly with 'dummy' copper cavity.

3.3 *SCRF Test Laboratory*

A temporary superconducting rf test lab is now being installed in a space rented by TRIUMF in a neighbouring laboratory complex. It is intended that the space will be occupied for at least two years until the SCRF area in the new ISAC-II building is available for occupancy. We expect completion of the temporary lab space in two months. The laboratory includes a test area with a sunken cryostat pit for high field rf testing, and clean areas for cavity assembling and high pressure water rinsing (Fig. 10). The total space comes to $\sim 100\,\mathrm{m}^2$.

4 SCHEDULE

An order for 20 medium beta cavities will be placed in industry before year end. The design of the building extension to house the ISAC-II facility is nearing completion with building occupancy scheduled for Jan. 2003. A collaboration on the ECR charge state booster is underway with ISN Grenoble. A first stage of the superconducting linac consisting of twenty mid-β cavities is planned for installation in 2004 with first beam expected in 2005.

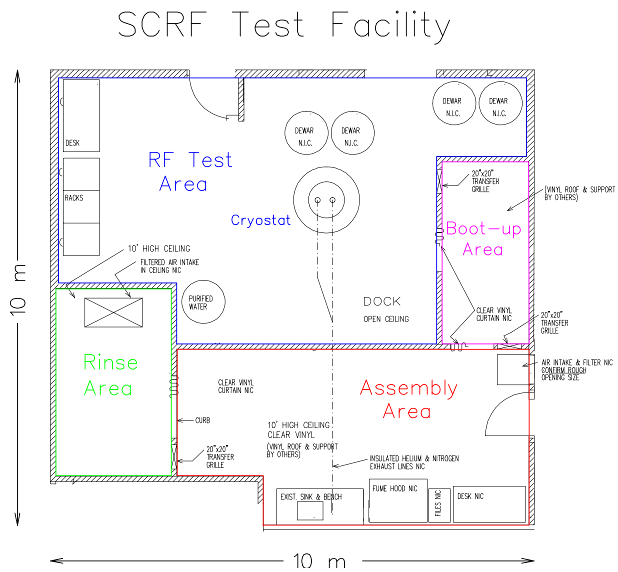

Figure 10: The SCRF test facility being installed by TRIUMF.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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