COMPLETION AND OPERATIONS OF ISAC-I AND EXTENSION TO ISAC-II

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Abstract

The post-accelerator for ISAC includes a 35.4 MHz RF Quadrupole (RFQ) to accelerate beams of $A/q \leq 30$ from 2 keV/u to 153keV/u and a post-stripper, 106MHz variable energy drift tube linac (DTL) to accelerate ions of $3 \leq A/q \leq 6$ to a final energy from 0.153 to 1.53 MeV/u. Most recently the DTL has been installed with first acceleration to full energy achieved in Dec. 2000. The design concept, present status and early operating experience of the ISAC linear accelerator complex is summarized.

TRIUMF has also received funding through to 2005 to proceed with an extension to the ISAC facility, ISAC-II, to permit acceleration of radio-active ion beams up to energies of at least 6.5 MeV/u for masses up to 150. The accelerator design and present status of the project is presented.

1 INTRODUCTION

The first stage of a radioactive ion beam facility at TRIUMF, ISAC-I[1], is in a final beam commissioning phase. 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. Recent beams delivered to the yield station are 1.4×10^4pps ^{11}Li and 1.4×10^4pps ^{74}Rb.

A layout of the post-accelerator for ISAC is shown in Fig. 1. The accelerator chain includes a 35.4 MHz RFQ[2, 3], 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)[4] to accelerate ions of $3 \leq A/q \leq 6$ to a final energy between 0.153 MeV/u to 1.53 MeV/u. A low energy beam transport (LEBT) delivers stable beams from the off-line source (OLIS) or exotic beams from the mass-separator to the RFQ. The LEBT is completely electrostatic and houses an 11.8 MHz multi-harmonic pre-buncher 5.7 m upstream of the RFQ. The medium energy beam transport (MEBT) is composed of a matching section to the stripping foil, a charge selection section and a matching section to the DTL. A two frequency chopper provides separation between pulses of 85 and 170 ns and a 106 MHz bunch rotator produces a time focus on the stripper. The DTL matching section utilizes a 35.4 MHz spiral rebuncher. The high energy beam transport (HEBT) delivers the beam from the DTL to the experimental stations. A bunching station consisting of a low-β 11.8 MHz triple gap structure and a high-β 35.4 MHz spiral resonator are incorporated to maintain the good longitudinal emittance to the target. Both linacs are required to operate *cw* to preserve beam intensity.

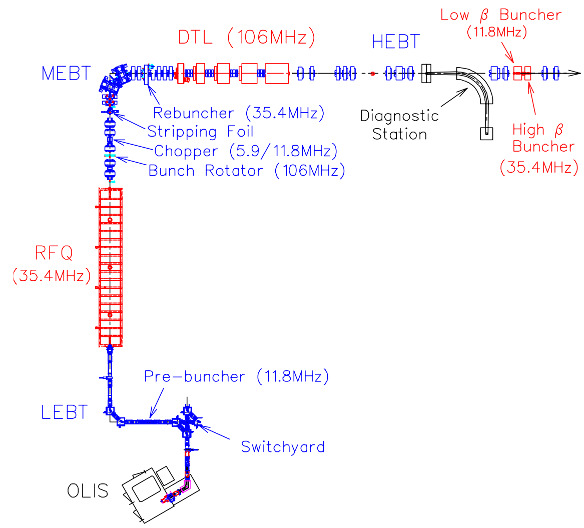

Figure 1: Schematic drawing of the ISAC-I experimental hall.

Recently funds have been allocated for an extension to the ISAC facility, ISAC-II[5], 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 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 $A/q \leq 7$ to the final energy. A schematic of the proposed ISAC-II linear accelerator complex is shown in Fig. 2.

2 ISAC-I STATUS

2.1 LEBT

OLIS and LEBT[6], including the multi-harmonic pre-buncher, have been operational since 1998. The pre-buncher operates at a fundamental frequency of 11.8 MHz, the third sub-harmonic of the RFQ. This introduces an 85 nsec bunch spacing that is useful for experiments. Presently three frequencies are utilized in the pre-buncher giving an over-all efficiency of up to 76% capture in the 11.8 MHz pulses with 5% of the beam in the two 35.4 MHz side-bands. The measured bunch structure upstream of the RFQ for one, two and three harmonic operation is shown in Fig. 3.

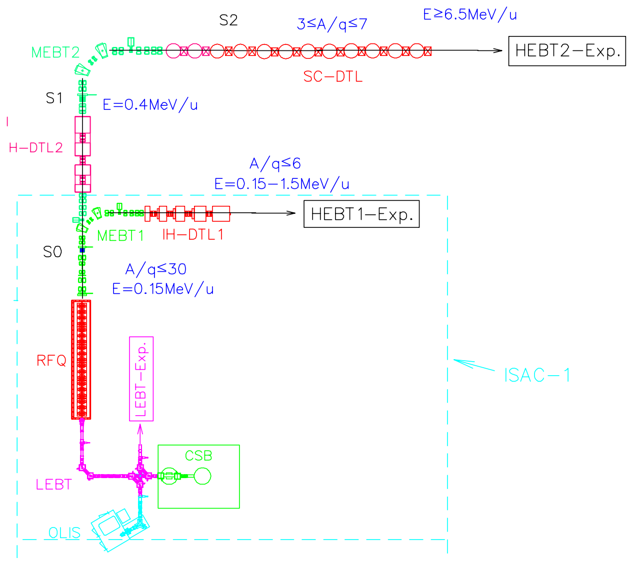

Figure 2: The proposed ISAC-II post-accelerator.

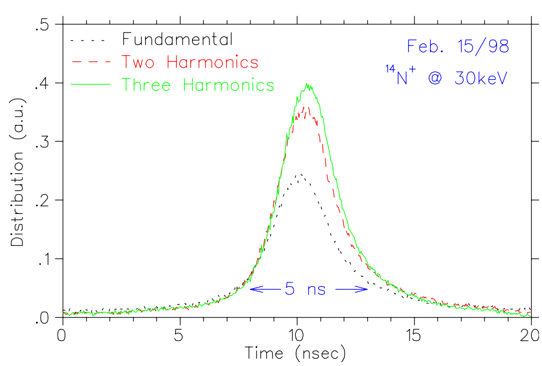

Figure 3: Time distribution of beam measured on a fast Faraday cup upstream of the RFQ for one, two and three harmonics on the LEBT prebuncher.

2.2 RFQ

The ISAC RFQ (Fig. 4) is a split ring 4-rod structure, 8 m in length with a bore radius of $r_0 = 7.4$ mm, operating up to an inter-vane voltage of 74 kV and power of 85 kW[2].

A unique feature of the design is the constant synchronous phase of $-25°$. Since in radioactive beam acceleration space-charge is not a concern we have eliminated the buncher and shaper sections in favour of the prebuncher.[7] This shortens the RFQ but in addition, injecting a pre-bunched beam yields a smaller longitudinal emittance at the expense of a slightly lower beam capture. In our case simulations show an improvement in the longitudinal emittance of a factor from $3 - 5$.

The RFQ has been commissioned in two stages. Initially the first 7 rings were installed and tested with beam.[3] During the 7-ring test the energy spread from the RFQ at 55 keV/u for the bunched and unbunched cases was measured at ±0.4% and ±0.7% respectively and compares well with PARMTEQ predictions.

Beam measurements on the final 19-ring installation in

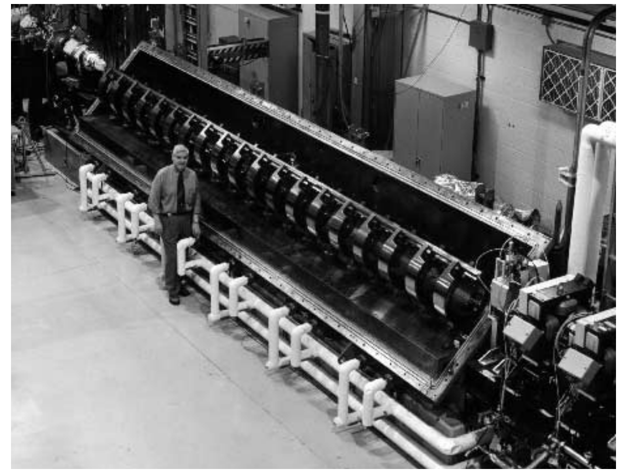

Figure 4: The ISAC 35 MHz RFQ.

Feb. 2000 and June 2000 further confirmed beam dynamics calculations. In particular the design choices taken to reduce the longitudinal emittance proved successful with a measured value of 0.5 πkeV/u-ns in agreement with calculations. The beam capture as a function of RFQ vane voltage measurements were completed for $^{14}N_{1,2}$ with both unbunched and bunched input beams. The results are given in Fig. 5 (squares N and circles N_2) along with predicted efficiencies based on PARMTEQ calculations (dashed lines). The RFQ capture efficiency (all rf buckets) at the nominal voltage is 80% in the bunched case (three harmonics) and 25% for the unbunched case in reasonable agreement with predictions.

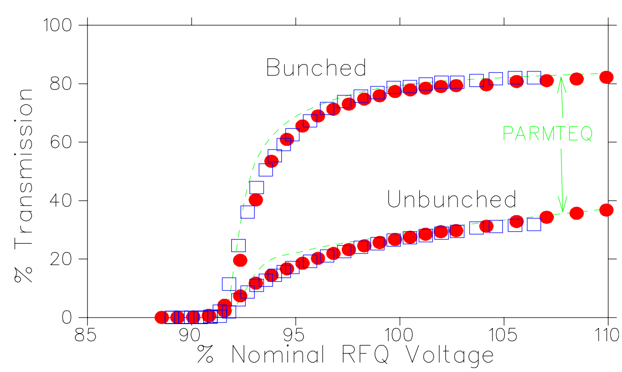

Figure 5: RFQ beam test results showing capture efficiency for beams of ^{14}N (squares) and $^{14}N_2$ as a function of relative vane voltage. The beam capture for both bunched and unbunched initial beams are recorded (squares) and are compared with PARMTEQ calculations (dashed lines).

2.3 MEBT

The MEBT optics and rf devices have been fully commissioned with beam. A bunch rotator and chopper are installed upstream of the stripping foil. The 106 MHz split ring bunch rotator is the slightly modified prototype buncher for the DTL. It provides a time-focus of the beam on the stripping foil to reduce the emittance growth due to energy straggling. The device results in improved capture by the DTL and reduced longitudinal emittance at the experiment.

The chopper has two modes of operation; one giving a bunch spacing of 85 ns removing 5% of the beam and the other a bunch spacing of 170 ns that removes 53% of the beam. The chopper consists of a series of two sets of plates located where horizontal divergence has been minimized followed by selecting slits near the stripping foil $\sim 90^\circ$ phase advance downstream. Each plate pair has one plate driven at rf voltage (11.8 MHz and 5.9 MHz respectively) and the other compensating plate is dc biased to produce zero deflecting field at the base of the rf waveform to reduce transverse emittance growth. In the first mode the two 35.4 MHz side-bands in the pulse structure (Fig. 6(d)) are deflected at 11.8 MHz (Fig. 6(a)) yielding the time structure shown in Fig. 6(e) . In the second mode the side-bands plus every second main pulse are deflected by adding the 5.9 MHz deflection (Fig. 6(b)) from the second set of plates to yield the combined deflecting field shown in Fig. 6(c) giving the time structure measured in Fig. 6(f).

Beam simulations show that such a chopper should not increase either the transverse or longitudinal emittance. Two lumped circuits drive the rf voltageon the plates up to $\sim$ 7 kV each. The chopper is now operational and proves very reliable and easy to tune. A profile monitor at the chopper slit is used to record beam deflection and to optimize the chopper phase and then the dc bias is set to optimize transmission through the chopper slit.

2.4 DTL

The variable energy DTL shown schematically in Fig. 7 is based on a separated function approach[8] with five independent interdigital H-mode (IH) structures, each with 0° synchronous phase, providing the acceleration and quadrupole triplets and three-gap bunching cavitiesbetween tanks providing transverse and longitudinal focussing 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 8.1 MV over the 5.6 m 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.

The full DTL was installed in the latter half of 2000[9] (Fig. 8) with the first beam accelerated to full ISAC energy of 1.53 MeV/u on Dec. 21/2000.

First DTL commissioning was done with a $^{4}He^{1+}$ beam.[4] DTL rf parameters and beam optics settings were established for over twenty different energy set-points covering the whole specified operating range. The transmission through the DTL was over 95% for all cases. A summary plot of beam energies and transmissions is given in Fig. 9. Beam quality is consistently good over the whole energy range.

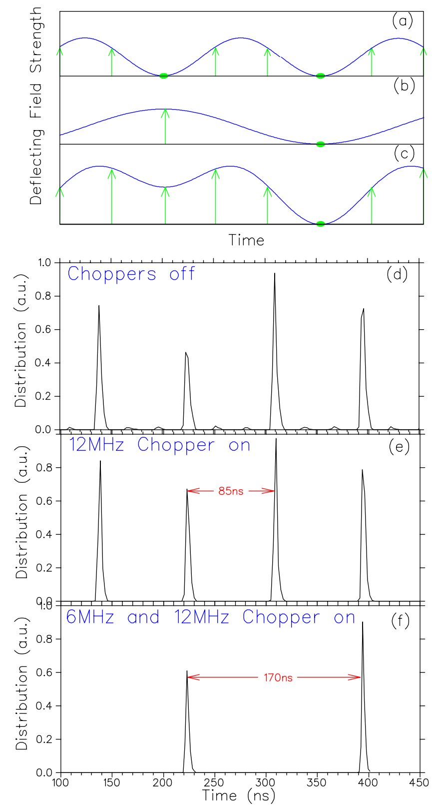

Figure 6: (a) Output time structure from the RFQ is shown in (d). The field produced by the 11.8 MHz chopper plate (a) produces a 85 ns time structure shown in (e). The field produced by the 5.9 MHz plate in (b) is combined with the 11.8 MHz deflection to produce the combined deflection shown in (c) and generates the time structure given in (f).

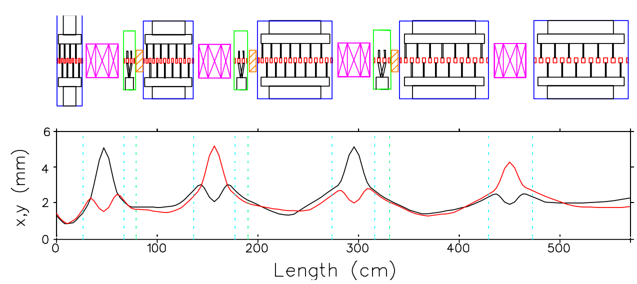

Figure 7: Schematic of the ISAC DTL showing five IH accelerating tanks, four quadrupole triplets and three triple gap bunchers. The transverse beam envelopes are also plotted.

Although the ISAC DTL is a variable energy device it still essentially operates as a fixed velocity linac (except for the last operating Tank) so that phase relationships between cavities are fixed regardless of particle mass and charge and only the voltage need be scaled, shortening beam tuning time.

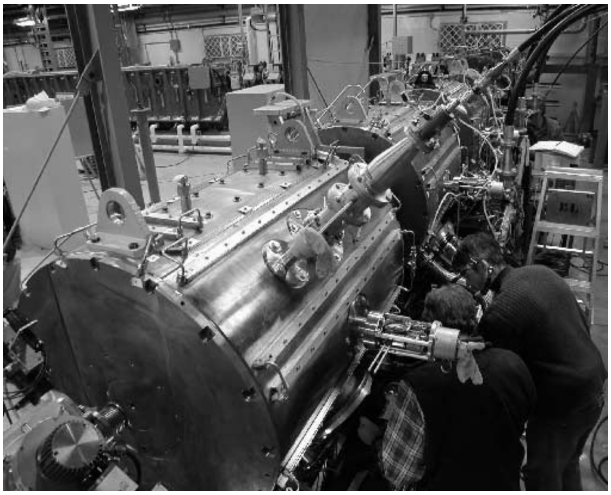

Figure 8: The ISAC 106 MHz DTL.

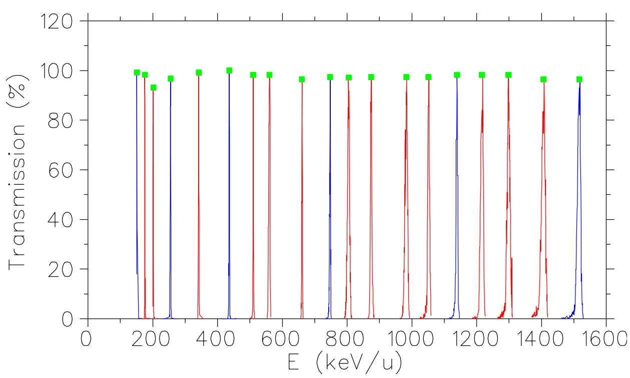

Figure 9: We plot the measured transmission for the various beams that have been accelerated through the DTL during commissioning studies with ^{4}He.

2.5 HEBT

The high energy beam transport (HEBT) feeds two target stations 23 m and 30 m downstream of the DTL; the DRAGON windowless gas target and recoil mass spectrometer and the TUDA multi-purpose detector array. The HEBT is composed of four basic sections; a section to match the beam from the DTL to the HEBT, a diagnostic section and bunching section, achromatic bend sections to deliver beams to the experiments and matching sections to focus the beam to the experimental targets.

The diagnostic section is used by accelerator personnel for beam commissioning and pre-tuning before experiments. Included in the section are a high dispersion 90° analyzing magnet for beam energy and energy spread analysis and a transverse emittance rig. A low-β ($\beta_o = 0.022$) 11.8 MHz rebuncher and a high-β ($\beta_o = 0.032$) 35.4 MHz rebuncher are positioned on either side of a double focus positioned 12 m downstream of the DTL. The 11.8 MHz rebuncher is a three gap structure driven by two lumped element circuits with up to 30 kV required on each drift tube. The 35.4 MHz buncher is a two-gap spiral device similar to the MEBT rebuncher with up to 170 kV required on the drift tube.

The HEBT line including the high β buncher has been commissioned in April 2001. Fig. 10 shows the beam time distribution close to the DRAGON target for the buncher off and on. The low-β buncher is scheduled for installation in Sept. 2001.

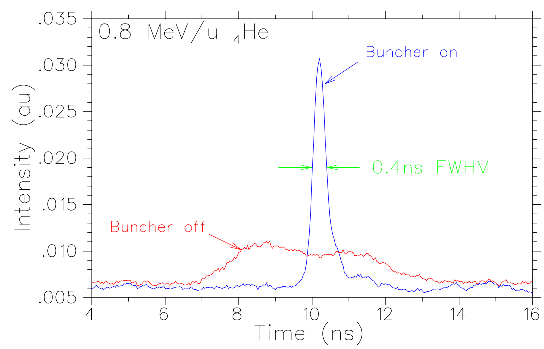

Figure 10: Beam time distributions measured on a fast Faraday cup near the DRAGON target for high β buncher off and on.

3 BEAM DELIVERY

Stable beams of $^{4}He^{1+}$, $^{14,15}N^{4+}$, $^{16}O^{4+}$, $^{21}Ne^{5+}$,and $^{24}Mg^{6+}$ have been delivered to the two experimental facilities at various beam energies. These delivery periods have proved essential both in training the operators and in determining hardware improvements and required developments prior to first scheduled radioactive beam delivery of ^{8}Li in mid July. Beam tunes are established by a beam physicist with round the clock delivery by ISAC operations staff. Operators now handle routine procedures such as foil changes, small energy changes and recovering beam delivery after hardware trips.

Several early improvements have been added that greatly reduce linac tuning time. Foil changes are facilitated by a global phase shifter between the pre-stripper and post stripper accelerator sections to account for slight difference in foil thickness. A cold trap surrounding the stripper foil has now minimized foil thickness changes due to carbon buildup. A procedure has been implimented to enable operators to provide small energy steps down to 0.1% to allow resonance searches at the experiment.

4 ISAC-II STATUS

The present design (Fig. 2) calls for a $\sim$5 m room-temperature IH linac on an extension of the present RFQ-MEBT line to accelerate the ions of $A \leq 30$ from the 0.153 MeV/u RFQ energy to the new stripping energy of 0.4 MeV/u. After stripping the ions ($3 \leq A/q \leq 7$) are charge selected and matched into the superconducting DTL, accelerated to at least 6.5 MeV/u and then transported to the experimental stations. The short independently phased cavities that make up the post-stripper linac give a wide velocity acceptance and so the final energy for each ion can be optimized. In this case the final energy/nucleon for light ions could be more than double that for the high mass particles.

The specification of the superconducting linac calls for three cavity types of frequency (β_o) 70.7 MHz (4.2%), 106.08 MHz (7.2%) and 141.4 MHz (10.5%) respectively. A medium β quarter wave bulk niobium cavity[10] has been designed in collaboration with INFN-Legnaro, fabricated in Italy, received chemical polishing in CERN, and rf tested in Legnaro. The cavity is shown in Fig. 11 along with some design parameters. Results of the first rf test are shown in Fig. 12. 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. A superconducting rf test lab is now being planned at TRIUMF. The design of the building extension to house the ISAC-II facility is nearing completion with building occupancy scheduled for Jan. 2003. A first stage of the superconducting linac consisting of twenty mid-β cavities is planned for 2004. A collaboration on the ECR charge state booster has just been initiated with ISN Grenoble.

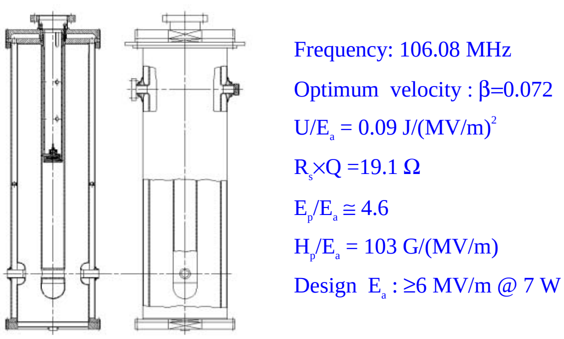

Figure 11: The prototype 106.1 MHz medium-β cavity for the ISAC-II project at TRIUMF.

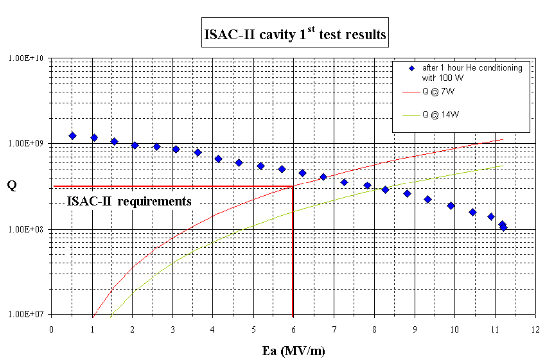

Figure 12: First rf test results for the prototype 106.1 MHz medium-β cavity for ISAC-II.

We are considering the possibility of utilizing multi-charge acceleration in the ISAC-II superconducting linac to preserve beam intensity[11]. Although the principles of multi-charge acceleration apply equally to the driver[12] and RIB post-accelerator there are considerations unique to each case. For example final beam quality is not a strong criterion in a driver linac but may be crucial to a RIB experimentalist. Conversely the need for installation of expensive matching sections to clean multi-charge beams in a high intensity driver may not be required in the post-accelerators designed to accelerate, in general, low intensity short lived radioactive species. Simulations show that the ISAC-II superconducting linac lattice can accept $\Delta Q/Q \leq \pm 5\%$ in the low-β section and $\Delta Q/Q \leq \pm 7\%$ in the mid and high-β sections.

5 ACKNOWLEDGEMENTS

The ISAC accelerator installation and commissioning represents a huge effort by a talented and dedicated team. We look forward to the next five years, superconducting rf and life beyond the Coulomb barrier.

6 REFERENCES

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