

# BEAM DYNAMICS STUDIES ON THE ISAC II SUPERCONDUCTING LINAC

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## Abstract

The ISAC II superconducting linac is presently in the beam commissioning phase. The linac lattice consists of modules of four quarter wave cavities and one superconducting solenoid. At the moment five cryomodules (indicated as medium beta section) are installed. Beam steerers between cryomodules compensate for steering effects due to misalignments in the solenoids. Beam dynamics aspects of linac commissioning are highlighted.

## INTRODUCTION

ISAC at TRIUMF is a facility for the production and post acceleration of radioactive beams, operational since 1999. Presently a normal conducting LINAC (RFQ followed by a DTL) post accelerates stable and radioactive beams up to 1.8 MeV/u [1]. ISAC II is an upgrade of the ISAC facility that will be completed in two phases. A new superconducting LINAC fed with beams of  $2 \leq A/Q \leq 6$  from ISAC I adds 20MV in the first phase and 20 MV more in the second. The complete accelerating structure of the LINAC will be composed of forty quarter wave bulk niobium resonant cavities operating at 4K installed in eight cryomodules. Transverse focusing is provided by superconducting solenoids [2]. Presently the medium beta section (Phase I) is installed consisting of five cryomodules each containing four resonant cavities and a superconducting solenoid. The remaining twenty cavities forming the high beta section will be installed by 2008.

The commissioning of the medium beta section of the ISAC II superconducting LINAC started in April of this year. At present we have accelerated beams at three different  $A/Q$  values: 2 ( $^4\text{He}2+$ ), 4 ( $^4\text{He}1+$ ,  $^{12}\text{C}3+$ ,  $^{20}\text{Ne}5+$ ,  $^{40}\text{Ca}10+$ ), 5.5 ( $^{22}\text{Ne}4+$ ). Data are collected to establish the performance of the LINAC as well as to study the quality of the beam produced. The main aim of the runs to date was to gather information in support of the operating license application. These involved, for the most part, accelerating beams and measuring radiation levels at various intensities. In addition some beam time was spent developing application software required to operate the machine. The commissioning runs, however, did include some investigations on beam quality and these are presented here. More beam time is scheduled in the following months where we want to investigate more deeply issues that come out from the previous runs.

## DIAGNOSTIC

In ISAC II we use for most part the same diagnostics we have in ISAC I. A compact diagnostic box is positioned

upstream of each cryomodule containing a linear profile monitor (LPM) and faraday cup (FC). The LPM consists of a metal plate with a vertical and a horizontal slot that is driven across the beam axis at  $45^\circ$  by a stepper motor. The two slots scan the beam while the beam intensity is measured in the FC behind the LPM. The slot can be stopped in correspondence of the beam axis thus acting like a collimator.

In the transfer line from ISAC to ISAC II (S-BEND) and in the high energy transport line from the LINAC to the ISAC II experimental hall (SEBT) we have rotating profile monitors (RPM) and Faraday cups at each focal point. The RPM consists of a pair of wires  $90^\circ$  apart rotating in the transverse plane across the beam axis. The wires intercept the beam measuring the beam intensity itself.

In order to phase the cavity we have a silicon detector 4 m downstream of the last cryomodule. The beam particles are scattered toward the silicon detector from a gold foil inserted into the beam with an actuator. The silicon detector is calibrated using the beam from ISAC-I at two known energies.

For a more precise energy measurement we have a flight time monitor (FTM) system. This system consists of two grounded cans placed 9.2m apart mounted on actuators. Each can has two beam ports and a biased wire placed in the center (see schematic in Fig. 1). When the two cans are inserted the beam passing through them intercepts the biased wires. Secondary electrons emitted from the wire pass through a hole in the can and are collected by a microchannel plate [3]. The FTM system is tested against the  $90^\circ$  analysing magnet used to measure the energy in ISAC I. The discrepancy between the two measurements is less than 0.5%.

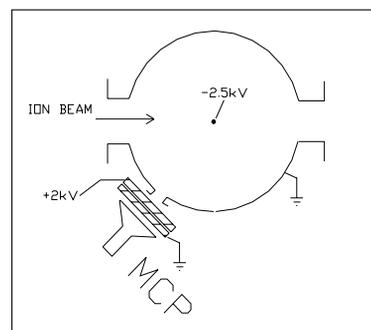


Figure 1: Schematic of the TOF system.

A DANFYSIK emittance rig is installed in the SEBT line. This device consists of two slits placed 1.6 m upstream of a wire harp. The beam scanned horizontally and

vertically by the slits is intercepted by the harp. The correlation between the slit position and the harp area hit by the beam allows to reconstruct the transverse emittance of the beam itself in both horizontal and vertical planes.

### ACCELERATION

The beam coming from ISAC I is injected into the ISAC II linac at 1.5 MeV/u. A normal conducting 35 MHz buncher is present in the S-BEND to provide a longitudinal match of the beam entering the superconducting LINAC. The silicon detector at the end of the LINAC is used to set the buncher phase. The amplitude of the buncher is then rescaled according to the distances to provide the correctly matched beam. The estimated longitudinal emittance, by phase space reconstruction, of the non accelerated beam at the entrance is 1.5  $\pi$  keV/u·ns.

All the twenty medium beta section cavities are phased independently starting from the upstream end. The beam energy (or alternatively beam time of arrival) are recorded with the Silicon detector for different RF cavity phases Fig. 2. The recorded points are fit with a sinusoid to calculate the 0° phase. Acceleration is done at a synchronous phase of -25°. Application software to automatically phase the cavities is now being implemented. The energy reached for different A/Q values as a function of cryomodule is shown in Table 1.

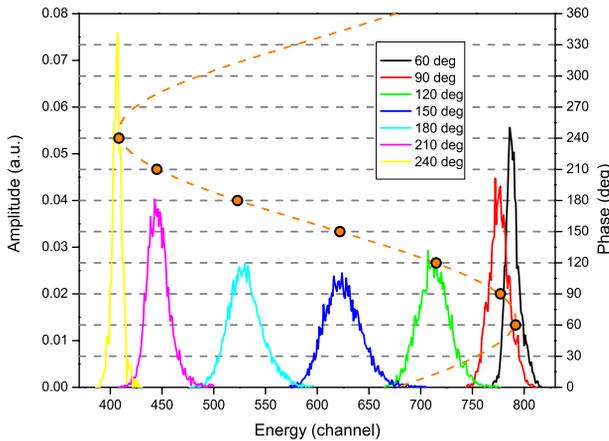


Figure 2: Energy peak for different RF cavity phases.

Table 1: Energies reached with different A/Q. The injection energy is E=1.5 MeV/u.

Specie	A/Q	Energy after cryomodule (MeV/u)				
		1	2	3	4	5
<sup>4</sup> He 2+	2	3.83	5.67	7.42	9.21	10.86
<sup>4</sup> He 1+	4	2.66	3.74	4.74	5.85	6.8
<sup>22</sup> Ne 4+	5.5	2.38	3.16	3.91	4.75	5.47

## BEAM QUALITY

### Transverse Emittance

The <sup>4</sup>He1+ beam is used for a transverse emittance study of the accelerated beam. Emittance data is taken after complete acceleration through each cryomodule. Data after acceleration with Cryomodule 1 and after full acceleration using Cryomodules 1-5 are presented in Fig. 3). The measured emittances at 2.7 MeV/u of  $\epsilon_{x,y} = 2.3\pi\mu\text{m}$  correspond to normalized emittances of  $\beta\epsilon_{x,y} = 0.17\pi\mu\text{m}$ . The measured emittances at 6.8 MeV/u of  $\epsilon_x = 1.6\pi\mu\text{m}$  and  $\epsilon_y = 1.0\pi\mu\text{m}$  correspond to normalized emittances of  $\beta\epsilon_x = 0.11\pi\mu\text{m}$  and  $\beta\epsilon_y = 0.19\pi\mu\text{m}$ .

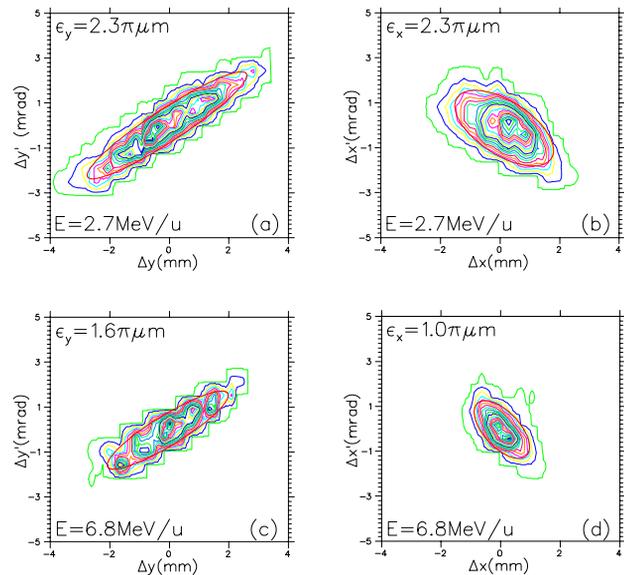


Figure 3: Measured transverse emittance for a <sup>4</sup>He1+ beam at two different energies: after the first cryomodule (top) and the fifth (bottom).

Other normalized transverse emittance measurements for different beam energies are summarized in Fig. 4. The results are consistent with little or no growth through the acceleration process. In addition there does seem to be a transfer of emittance between planes as the solenoid rotates the reference frame. The linac and beamlines are designed with a normalized emittance of 0.3 $\pi\mu\text{m}$ .

### Demonstration of Bunching

For cases where the full linac energy is not required it is possible to use a downstream cavity, normally off, in bunching or debunching mode to reduce the phase spread or the energy spread of the delivered beam. In the case reported here the first eight cavities are ‘on’ producing a beam of <sup>4</sup>He1+ at 3.7 MeV/u. Cavity 19 is phased to bunch the beam. Fig. 5 shows the energy spread and time spread of the beam with the bunching cavity ‘off’ and ‘on’. To minimize the energy spread (debunch mode) the buncher amplitude is about half the value used in the bunching

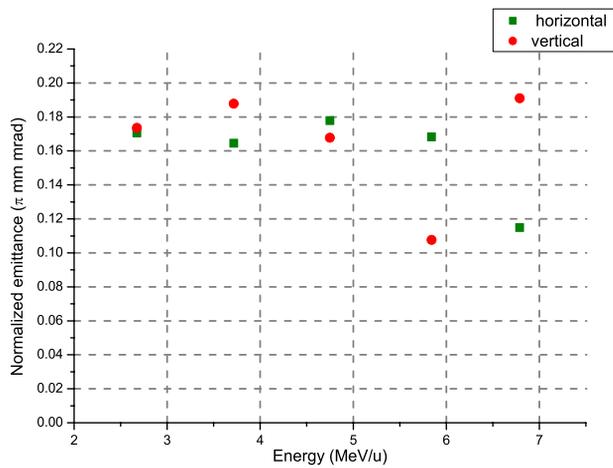


Figure 4: Measured normalized emittance of the  $4\text{He}^{1+}$  beam for different energies.

case. A superconducting buncher cavity will eventually be placed in the SEBT beamline but the method reported here can provide some improvement in longitudinal beam characteristics until that time.

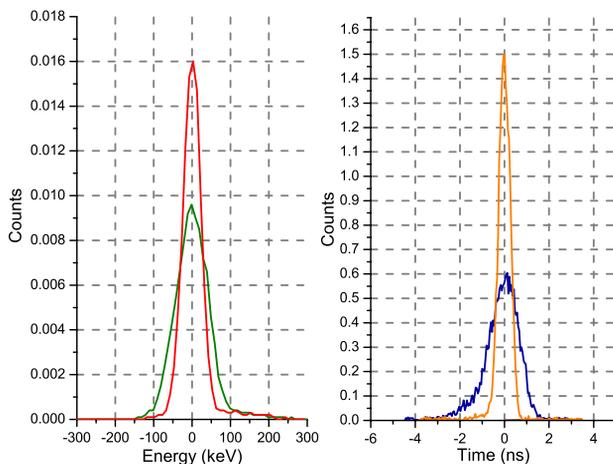


Figure 5: Resulting longitudinal profiles after using cavity 19 to bunch in energy (left) and time (right).

### Solenoid steering

Beam transmission during acceleration is well over 90%. However the setting of beam steerers is higher than expected indicating that one or more solenoids is outside the alignment specification. Previous studies indicate that a misalignment of  $250\mu\text{m}$  displaces the centroid of the beam within 2 mm if not corrected by the steerers and within 1 mm if corrected [1]. A study using the beam to investigate solenoid misalignment has been undertaken. With the solenoid off steerers upstream of the cryomodule are used to center the beam on both the upstream and downstream LPM monitors that define the true ideal beam axis. Next the solenoid is powered at various settings to check for

solenoid steering. Fig. 6 demonstrates that the solenoid in Cryomodule 1 is not centered with respect to the ideal beam axis. Similar measurements with other solenoids show that they all steer the beam to varying degrees.

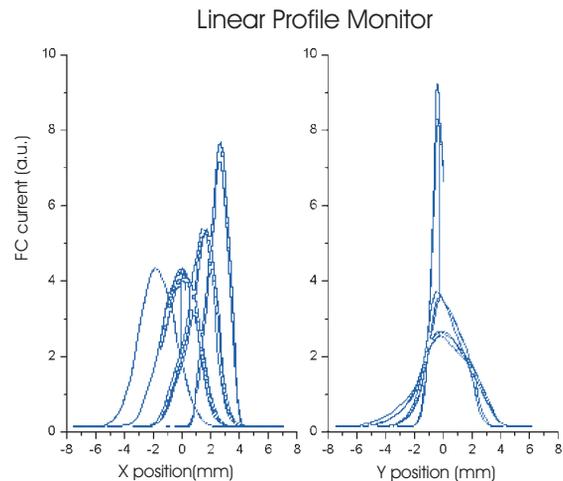


Figure 6: Beam profiles downstream of the solenoid for various solenoid strengths.

Since it is possible to move the solenoid within the cryomodule a program is underway to measure the centered beam position for various solenoid currents and to predict the solenoid translation and rotation that produces the measured steering. The transfer matrix of a skewed and translated solenoid will be used in MATHEMATICA to make the analysis.

### SUMMARY

The commissioning of the new ISAC II superconducting LINAC at TRIUMF is on going. We have fulfilled all the requests necessary to obtain the operating license. We have good indications about cavity performance and transverse beam quality coming from the first commissioning runs. More beam time is scheduled for the next months. The major issue we want to address is the solenoid misalignment. We are also interested in more transverse and longitudinal emittance measurements.

### REFERENCES

- [1] R. E. Laxdal, "ISAC I and ISAC II at TRIUMF: Achieved Performance and New Construction" Linac2002, Gyeongju, Korea, August 2002.
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- [3] R. E. Laxdal, "Initial Commissioning Results from the ISAC II SC LINAC" this conference.