DECELERATING HEAVY ION BEAMS USING THE ISAC DTL

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Abstract

At the ISAC facility in TRIUMF radioactive ion beams (RIB) are produced using the ISOL method and post accelerated. The post accelerator chain consists of a radio frequency quadrupole (RFQ) injector followed by a drift tube linac (DTL) that accelerates the ions from 150 keV/u up to 1.8 MeV/u. A further stage of acceleration is achieved using a superconducting linac where the beam is injected using the DTL and the energy boosted with 20 MV of acceleration voltage (increased to 40 MV by the end of 2009). The possibility of decelerating the beam maintaining good beam quality using the DTL is investigated based on experimenters request to reach energies lower than 150 keV/u. The beam dynamics simulation using the LANA code are compared with on line measurements. In this paper we will report the results of the investigation that aims to establish the lowest energy we can deliver in the post accelerator section of the ISAC facility.

INTRODUCTION

ISAC is the TRIUMF facility (Fig. 1) to produce, mass select and post accelerate radioactive ion beams (RIB). The radioactive species are produced using the ISOL method.

The driver of the facility is the TRIUMF cyclotron that accelerates H^- up to 500 MeV. The electrons are then stripped from the hydrogen ions by means of a stripping foil and the protons extracted. In the present configuration the cyclotron has three operating extraction beam lines (with the possibility of recommissioning a fourth existing one). Each beam line is characterized by different energies and beam intensities. In ISAC beam line they are extracted at the maximum energy up to 100 μA making the ISAC the highest power driver beam (50 kW).

The proton beam is then directed to one of the two underground target stations. The beam loses part of its energy through the target material while producing the radioactive isotopes in a neutral state. These isotopes migrate into the source where they are ionized and extracted up to 60 kV towards the mass separator. The selected isotope charged 1+ can be sent through a charge state booster (CSB) to increase the charge state.

The radioactive beam is eventually transported at ground level where it can be directed to a low energy area or to the post accelerators. In the low energy are the experiments use the beam at source potential up to 60 kV. In the medium and high energy area the energies range typically between 150 and 5 MeV/u (the upper limit being restricted at present by license).

The goal of this paper is to investigate the feasibility of delivering beam with energies lower than 150 keV/u, this
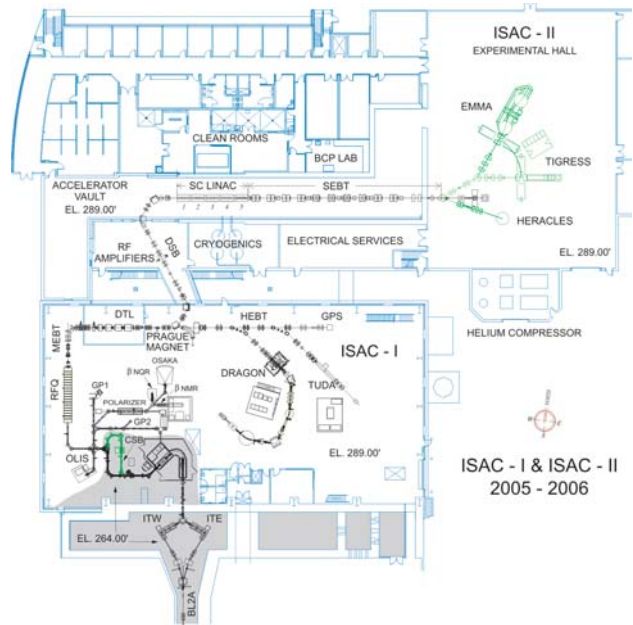

Figure 1: Overview of the ISAC facility at TRIUMF. The ISAC II linac is superconducting while in ISAC I they (RFQ and DTL) are normal conducting.

is mostly dictated by the request of TRIUMF experimentalists to have energies (in the post acceleration section) ideally as low as 100 keV/u. The result of this investigation sets the lowest limit for deliverable energies in the post acceleration section of ISAC facility.

THE POST ACCELERATORS

The post accelerator chain of the ISAC-I facility is composed of two room temperature linacs: a radio frequency quadrupole (RFQ) acting as injector for a drift tube linac (DTL). These two machines serve the medium energy experimental hall. In the ISAC-II facility the beam energy is boosted by a superconducting (SC) linac. This machine serve the high energy experimental hall.

The Radio Frequency Quadrupole

The RFQ has a nineteen split rings structure that support the four 7.6 m long electrodes [1]. It operates in continuous wave (CW) mode at a resonance frequency of 35.36 MHz. The beam is accelerated from 2 keV/u to 150 keV/u. Based on the available voltage (up to 74 kV) the RFQ is capable of accelerating isotopes with mass to charge ratio $3 \leq A/Q \leq 30$.

In order to obtain good longitudinal emittance after the

RFQ [2] the beam is prebunched at the entrance by means of an electric three harmonics buncher (Prebuncher) located ∼5.5 m upstream of the RFQ entrance port. The fundamental harmonic of the prebuncher is 11.78 MHz. For the same purpose a percentage between 75-80% of the accelerated beam is transported downstream of the RFQ while the rest (tails of the longitudinal phase space) is dumped into fixed slits at the exit port of the machine.

The Drift Tube Linac

The DTL (see Figure 2) represents the second stage of acceleration in ISAC-I. This linac is composed of five accelerating modules (tanks); downstream of each one of the first three tanks there is a buncher. This layout [3] allows to accelerate all the energy between 150 keV/u and 1.8 MeV/u with a good beam quality.
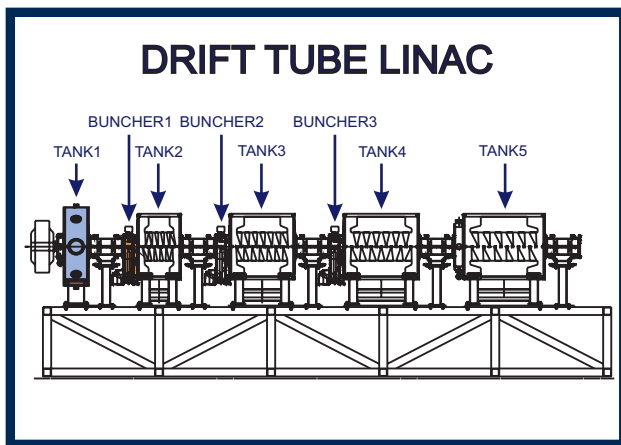

Figure 2: Side view of the ISAC DTL.

The DTL has an IH iterdigital RF structure that resonates at 106.08 MHz. A triplet of quadrupoles is situated between tanks; these are necessary to maintain the transverse profile of the beam inside the 1.8 cm aperture of the drift tube.

The DTL design is optimized for mass to charge ratio 2≤A/Q≤6. A stripping foil is present in the medium energy beam transport (MEBT) line that connects the RFQ to the DTL. The foil increases the charge state of the beam reducing the mass to charge ratio to a value inside the acceptance of the DTL. In order to minimize the transverse and longitudinal emittance growth during the stripping we focus transversally and bunch the beam in time at the foil location. The beam is also rebunched at the entrance of the DTL using a 35.36 MHz buncher (Rebuncher). Usually transmissions higher than 95% are achievable through the machine.

The DTL also inject the beam in the ISAC-II superconducting linac; in this case the beam is accelerated at 1.5 MeV/u.

The Superconducting Linac

The third stage of acceleration is achieved with the ISAC-II superconducting (SC) linac [4]. The present installation of the SC linac is composed of five cryomodules each housing four superconducting bulk niobium quarter wave resonators (cavities) and one superconducting solenoid. These cavities resonate at 106.08 MHz. The cavity voltages are set to operate each at a fixed cryogenic power of 7 W, for a total of ∼20 MV of acceleration. The twenty cavities are independently phased at -25 ° synchronous phase. The number of cavities turned on determines the final energy.

The ISAC II linac is going to be upgraded by the end of 2009 adding twenty more cavities housed in three cryomodules [5]. The new cavities have a resonant frequency of 141.44 MHz.

LANA SIMULATIONS

The ISAC DTL beam dynamics is designed using the LANA code [6]. In all DTL development studies this code is demonstrated to model quite accurately the machine [7]. In Figure 3 both the simulated and measured energy gain versus RF phase curve for DTL tank 1 are plotted.
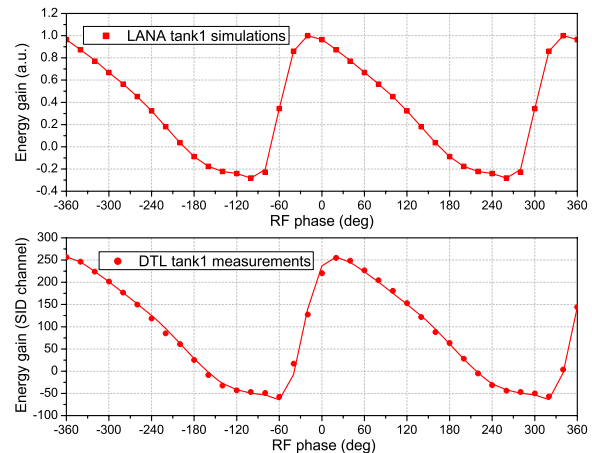

Figure 3: Simulated (top) and measured (bottom) energy gain versus RF phase curve.

Preliminary simulations show that a reasonable deceleration is possible using the first three tanks and two bunchers. In this simulation we use a longitudinal emittance of 1 π keV/u·ns. This value differs from the design emittance being 1.5 π keV/u·ns. The new value comes from an estimate done during a previous development run. The particle used in the simulation has an A/Q=6. The initial beam distribution, both transverse and longitudinal, is the same used in acceleration run.

The goal of the simulations is to check quality of the beam after deceleration. The operating voltage as well as the synchronous phase are used as free parameters to find

the optimum solution in term of maximum deceleration and minimum disruption of the longitudinal phase space (tails formation).

Since the DTL drifts are designed for an increasing beta it is necessary to verify which voltage gives more deceleration. Simulations show that the maximum deceleration happens at the maximum voltage. The acceleration rate is indeed very modest (see Table 1). In Figure 3 are plotted the Tank1 energy gain curves for different amplitude of the accelerating voltage. The amplitudes are given in term of the nominal voltage; the value 1 being the operational voltage that is used normally to accelerate a certain A/Q. This voltage scaled with the A/Q in order to reach always the final energy in term of keV/u. For reference the final maximum energy of Tank1 is 237 keV/u.
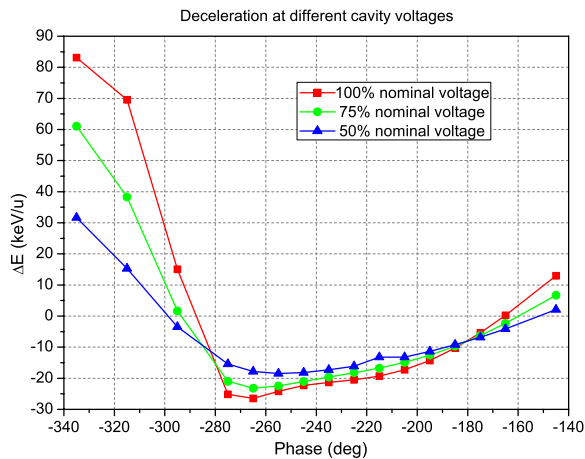

Figure 4: Energy gain versus RF phase curves for different nominal voltage amplitudes of DTL Tank1. The maximum deceleration happens using the maximum voltage.

The RF phases are set close (20° to 40°) to the decelerating peak for the tanks while the bunchers (1 and 2) are phased at -90° (bunching phase). It's evident from the Tank1 curves (Figure 3) that in the DTL case the fitting is more complex than a simple cosine function and the crest to valley distance is greater than 180°. As consequence even at 40° far from the peak the energy gain is still more the 90% with respect to the peak.

The simulations also show that at low energy some beam losses of the order of 10% are expected in the transverse plane. The possibility of reducing or minimizing such losses requires further studies varying the initial matching into the DTL. These studies are not object of this paper.

ON LINE MEASUREMENT

The on line deceleration measurements are done using $^{18}O^{4+}$ beam (A/Q=4.5). The beam energy profile and centroid (beam energy) are measured using a 90° analyzing magnet (PRAGUE magnet) located downstream of the

DTL. This magnet is also used to phase this linac [7]. A second diagnostic consisting of a silicon detector (SID) is present downstream of the DTL; this gives information about energy and time structure of the accelerated beam. This can also be used to phase the linac.

The DTL is phased for deceleration following the LANA simulations using the PRAGUE magnet. The tank amplitudes are set to the same maximum value (nominal voltage) used for full acceleration of the same species (A/Q=4.5). The tanks are phase closed to the negative peak to maximize deceleration and minimize energy spread. The buncher amplitudes are set to 50% of the nominal voltage while they are phased in pure bunching mode (-90° synchronous phase).

The main result is that the deceleration is possible in the amount predicted by the simulations. In Table 1 the final simulated and measured (at the PRAGUE magnet) energies after each DTL RF device are listed.

Table 1: Final energies after each DTL RF device; the injection energy into the DTL is 150 keV/u.

DTL RF device	Simulated energy (keV/u)	Measured energy (keV/u)
Tank1	129	127.7±1
Buncher1	129	127.7±1
tank2	121	124±1
Buncher2	121	124±1
Tank3	115	117±1

Fig. 3 represents the final energy as measured at the PRAGUE magnet; the energy spread is in line with respect to what we typically deliver at such low energy.
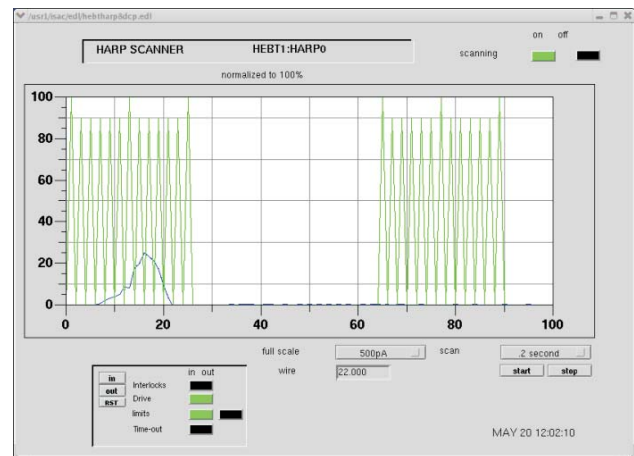

Figure 5: Simulated (top) and measured (bottom) energy gain versus RF phase curves for DTL Tank1.

Fig. 6 represents the time structure after DTL tank1 at the SID location (9.1 m downstream of tank1). The ISAC-I facility has two bunchers in the high energy beam transport (HEBT) line between the DTL and the ISAC-I experimen-

tal stations. One buncher operates at 11.78 MHz, the other at 35.36 MHz. These two bunchers (operating inside different velocity range) are normally used to compress the time (or the energy) down to 1 ns at the experiment. In the deceleration case, though, the beam is debunched so much that the phase spread at these buncher location is (in the best case) more than 100° for the lower frequency buncher. The HEBT bunchers can not be used with such a phase spread without forming tails in the longitudinal phase space. In term of time spread the beam is ∼30 ns wide at the HEBT bunchers location; this time spread more or less doubles at any ISAC-I experimental station. Considering the beam bunches are spaced ∼86 ns, it means that the beam is almost continuous at any ISAC-I experiment.
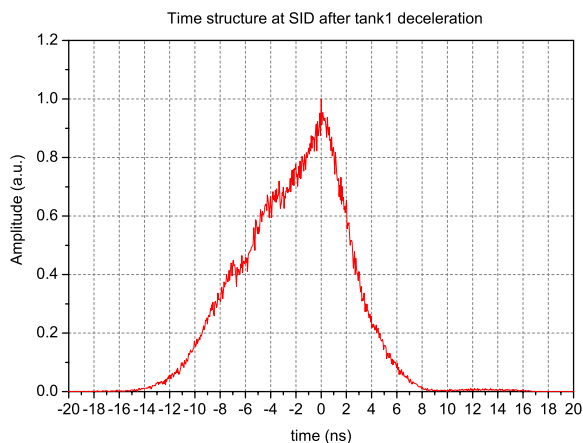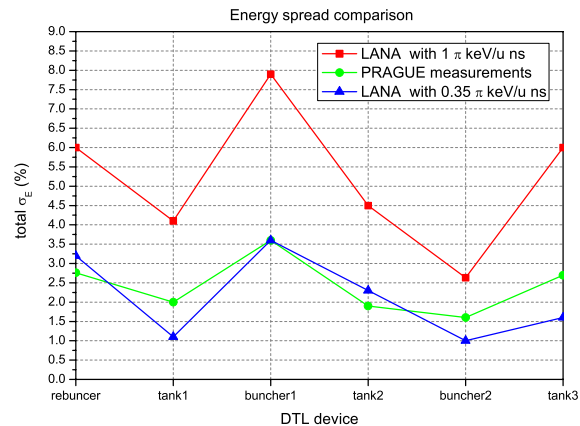

Figure 7: Simulated and measured energy spread after each DTL RF devices: the simulated data are for two different longitudinal emittances. The measured energy spread is as measured at the PRAGUE magnet.

Figure 6: Time structure after DTL tank1.

SIMULATIONS VERSUS ON LINE MEASUREMENTS

Besides the final energy it is interesting to look at the energy and time spread after each DTL element and to compare them with the simulated value.

Table 2: Injection parameters used in the LANA simulations for different initial longitudinal emittances. The lower emittance simulation matches the measured values for time and energy spread.

$\varepsilon_{\mathbf{z}}$ (keV/u·ns)	$\alpha_{\mathbf{z}}$	$\beta_{\mathbf{z}}$ (ns/(keV/u))	$\Delta\mathbf{E}$ (%)	$\Delta\mathbf{T}$ (ns)
1	-0.2	0.053	±3	±0.23
0.35	-0.2	0.085	±1.38	±0.17

Fig. 7 and Figure 8 represent respectively the plot of the energy and the time spread versus each RF device. The measured energy spread is on average 45% of the simulated when using a longitudinal emittance of 1 π keV/u·ns. The
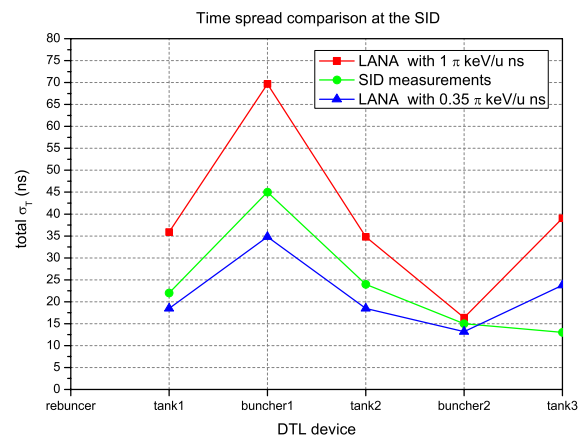

Figure 8: Simulated and measured time spread: in all cases the reported time spread is at the SID location.

measured time spread is on average 75% of the simulated when using the longitudinal emittance as above.

These lower values suggest the emittance of the real beam is smaller than 1 π keV/u·ns. The asymmetry of the percentages can be interpreted as a different match in the longitudinal plane with respect to the simulations.

The results from a new set of simulations with a lower emittance match in a better way the measured energy and time spread (see Fig. 7 and Fig. 8). In this new simulations the longitudinal emittance and the Courant-Snyder parameter β are changed in order to reduce the energy and time spread respectively to ∼45% and ∼75% of the original value. In Table 2 the injection parameters for the two longitudinal emittances are listed.

The quality of the longitudinal emittance is determined

by the Prebuncher setting, the focusing of the beam at the stripping foil location and the stripping foil itself. Different longitudinal emittances inside some range are possible based on the different tuning configuration. This aspect requires further investigation.

CONCLUSION

The deceleration of the beam using the ISAC DTL is possible from 150 keV/u to 117 keV/u. The energy spread after deceleration is in line with the one reached for low energy accelerated beam. The time spread after deceleration is such that the beam has practically no time structure (continuous beam) at any ISAC-I experimental stations. The development leaves two open questions that need further investigation. The first issue is regarding the transmission through the DTL at such low energy. A better matching at injection can minimize the beam loss. The second issue is related to the size of the longitudinal emittance that seems to vary based on the quality of acceleration thought the RFQ and the interaction with the stripping foil.

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