PROGRESS AND PLANS FOR HIGH MASS BEAM DELIVERY AT TRIUMF*

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Abstract

ISAC is a TRIUMF facility for the production and post-acceleration of radioactive ion beams (RIB). The RIBs are produced in two target stations using a 500 MeV proton of up to 100 μA of beam current. The produced radioactive species are then ionized and extracted up to 60 kV. The ions of interest are mass selected and transported to either the low energy experimental area or to the post-accelerators. The first stage of acceleration is accomplished via an RFQ followed by a DTL; at this medium stage the energy ranges between 0.15 MeV/u and 1.8 MeV/u for a mass to charge ratio range between $3 \leq A/q \leq 7$. The second stage of the acceleration is achieved with a 40 MV superconducting linac for a final energy up to 18 MeV/u. High mass (greater than 30) beams need multiple charges to be accepted by the RFQ. The single charge ions out of the target source are charge bred using an ECR charge state booster. The breeding process generates a significant amount of background contamination that masks the desired ions inside a mixed ‘cocktail beam. Such a cocktail needs to be cleaned of contaminants to be useful for the experiments. An unprecedented effort is going on at TRIUMF trying to clean the high mass cocktail beams using the accelerator chain as filter. The progress and future plans of the project will be presented in this paper.

INTRODUCTION

The ISAC facility at TRIUMF, represented in Fig. 1, produces, post-accelerates and delivers radioactive ion beams (RIB) using the isotope separation on line (ISOL) method.

A general scheme for this type of facility sees an accelerator, the driver, accelerates light projectiles, the primary beam, toward a thick target. The light projectiles, protons or light ions, break the target nuclei producing neutral radioactive isotopes. These neutral atoms diffuse into a source where they are ionized and extracted at source potential. In general the ISOL method produces high quality emittances but the complicated and relatively slow process reduces the possibility of extracting isotopes with few ms half-lives. The radioactive ions are magnetically separated and if necessary post accelerated to reach the final energy requested.

The singly charged RIB produced in the ISAC target ion source can be either used by the low energy experimental station with an energy up to 60 keV (extraction voltage) or post accelerated to the medium and high energy experiments. In order to inject ion beams with mass greater than 30 in the post accelerators we have to further strip the singly charged to reduce the mass to charge ratio to value ≤7. The charge state is boosted by means of an electron cyclotron resonance (ECR) source located downstream of the mass separator that select the RIB coming from the target.

The charge state booster ionized non only the RIB but also any other element present in its ionization chamber and immediate surrounding. Such elements belong either to the background residual gas or to the materials that constitute the vacuum chamber itself. These undesired element ionization generates a background current of orders of magnitude higher with respect to the radioactive species. This background makes extremely challenging identifying and selecting the RIB.

TRIUMF Accelerator division in collaboration with Science division (high mass task force) is engaged in an effort to develop a toolkit for such challenging charge bred beams. This toolkit includes separation and filtration techniques as well as software and diagnostic aids to plan and streamline the beam tuning and delivery.

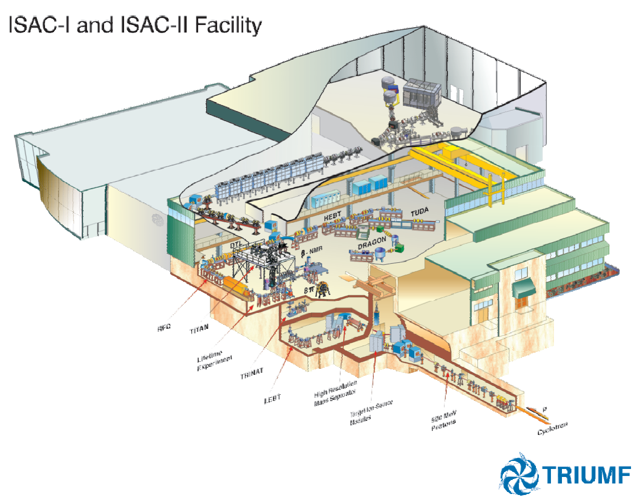

Figure 1: Overview of the ISAC facility at TRIUMF.

THE ISAC FACILITY

The ISAC facility has the highest power (50 kW) driver proton beam. The plain overview of the facility is represented in Fig. 2. The target stations, mass separator and charge breeder are located in the well shielded ISAC basement (see shaded area in Fig. 2). The target stations are inside a vault to contain radiation in a confined area. Different target materials are available for the production target including silicon carbide, tantalum, uranium carbide and niobium. Two target configurations are available: low and

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high power respectively for proton beam powers up to 20 kW and 50 kW respectively.

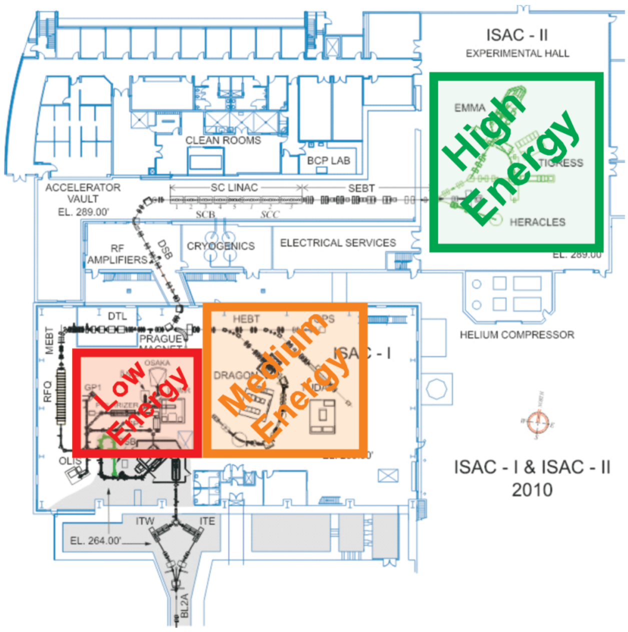

Figure 2: Overview of the ISAC facility at TRIUMF. The ISAC II linac is superconducting while in ISAC I the RFQ and the DTL are room temperature machines.

At ground level the facility has three different experimental areas characterized by the delivered energy range (see Fig. 2). The low energy experimental stations receive beam with energy up to 60 keV (source potential). The medium energy area in ISAC-I and the high energy area in ISAC-II receive post-accelerated beam with energy range respectively of 0.150 MeV/u$\leq$E$\leq$1.8 MeV/u (β=1.8%$\rightarrow$6%) and 1.5 MeV/u$\leq$E$\leq$18 MeV/u area (β=6%$\rightarrow$15%).

Driver

The TRIUMF H^- cyclotron [1] accelerates H^- ions up to an intensity of 250 μA to a maximum energy of 500 MeV. The H^- are then stripped and protons are extracted in three different beam lines at different energies the maximum being 500 MeV. One of these beam lines is dedicated for the ISAC radioactive beam production. In this case the beam is extracted at 500 MeV and up to 100 μA.

Target Station and Mass Separator

The two independent target stations [2] allow some services on one target station while producing and delivering radioactive beams with the other.

Each target station is composed of five modules. The entrance module houses the diagnostic and protection monitors for the proton beam. The target module contains the target and the source; this module is routinely removed to change both target and source. Four target modules are available. Different types of on-line ion sources are also available (surface, LASER, FEBIAD) while others are under development (ECR). The beam dump module is located downstream of the target module. The last two are the extraction modules housing the optics elements. They are oriented perpendicular to the proton beam direction.

Downstream of the targets there is a common pre-separator. The target modules and pre-separator are inside a concrete shielded area. The pre-separator reduces the radioactivity transported outside the shielded area in the downstream beam line.

After the pre-separator the RIBs are selected using the mass separator. The typical operational resolution of the separator magnet is ΔM/M=3000. The magnet is installed on a biased platform as an option to increase the resolution.

The Charge Breeder

After selection it is possible to divert the beam through an electron cyclotron resonance ion source (ECRIS) before sending it to ground level. The source is a 14.5 GHz PHOENIX by Pantechnik [6].

This source is a charge state booster (CSB) that further strips electrons from the singly charged beam. The selected charge state at the exit of the booster is such that the mass to charge ratio is $\leq$7 for A$>$30. This upper limit is dictated from the installed linacs.

A NIER type spectrometer with a resolution of ΔM/M=100 is located downstream of the ECR to select the desired charge state.

A small source face Cs ion source is placed upstream of the CSB to allow tuning it independently from the target station status.

Post Accelerators

The injector of the post-accelerator chain is a radio frequency quadrupole (RFQ) [3]. The RFQ boosts the energy from 2 keV/u to 150 keV/u. It can accelerate mass to charge ratio of 3$\leq$A/Q$\leq$30. The RFQ is a room temperature CW machine operating at 35.36 MHz. The eight meter long resonant structure is composed of nineteen split rings supporting the electrodes. The RFQ doesn't have a bunching section; the beam is pre-bunched at the entrance with a three harmonics (quasi sawtooth) RF buncher, the fundamental being 11.78 MHz. This configuration produces a high quality longitudinal emittance after the RFQ (0.22 π keV/u$\cdot$ns). Part of the beam transmitted but not accelerated is stopped into a fixed collimator downstream of the RFQ. The beam inside the longitudinal emittance after the slit is around 80% of the injected.

After the RFQ the charge state of ions with 7$<$A/Q$\leq$30 is increased by stripping them through a thin carbon foil (4 $\mu g/cm^2$). As a general rule the most populated charge state is selected using magnetic benders as long as the mass to charge ratio is within 2$\leq$A/Q$\leq$7 set by the following drift tube linac (DTL). The efficiency of the stripping foil depends on the mass of the stripped ions; in most of the cases it ranges between 30% to 50% for A$\leq$30 .

The DTL [4] is a variable energy machine covering the entire range of energies 150 keV/u≤E≤1.8 MeV/u. The beam is matched longitudinally into the DTL by means of a 35.36 MHz spiral buncher(MEBT buncher) located 1.5 m upstream in the medium energy beam transport (MEBT) line. The DTL is a separated function machine composed of five IH interdigital structure accelerating tanks and three split ring bunchers located between the first four tanks. This layout produces good beam quality for each energy. After the fourth tank the beam quality is already sufficient that no buncher is required. The resonance frequency of the tanks and bunchers is 106.08 MHz and they operate at room temperature in CW mode. Transverse focus through the linac is provided by quadrupoles triplets between each tank. The transmission of this linac is greater than 95%. The DTL is also used as an injector for the ISAC II superconducting (SC) linac.

The SClinac [5] is composed of eight cryomodules. The beam is matched longitudinally into the SC linac by means of a 35.36 MHz spiral buncher(DSB buncher) located 13.3 m upstream in the DTL to SC linac beam (DSB) transport line. This buncher differs from the MEBT one only for the design velocity β. Each of the first five cryomodules (identified as SCB) houses four superconducting cavities and one superconducting solenoid in the center position between cavity two and three. The last three cryomodule (identified as SCC) houses respectively 6-6-8 cavities. Each SCC module has also a superconducting solenoid in the center position similarly to the SCB's. The superconducting cavities are bulk niobium quarter wave resonators at 4K. The SCB cavities resonate at 106.08 MHz while the SCC resonant frequency is 141.36 MHz. The total accelerating voltage of the SC linac is 40 MV. Each cavity is independently phased at -25° synchronous phase. The transmission through the SC linac is 100%.

The Off-line IonSources

The post accelerator sections are tuned by means of the pilot beam technique. This technique consists in setting the beam lines and accelerators with a beam of stable ions with the same mass to charge ratio as the RIB. This is necessary because the intensity of the radioactive beam typically ranges between 10^3 and 10^6 particle per second. The pilot beam is produced by an off line ion source (OLIS) system that has multiple sources. A microwave cusp source is generally used to produced singly ch rage beam matching the production target. A surface source is also available for mono-charge beam. In order to match the radioactive beam coming from the CSB instead, an electron cyclotron resonance (ECR) source that can produce stable ions with higher charge states is installed. This source is a 14.5 GHz Supernanogan by Pantechnik [7].

HIGH MASS BEAM DELIVERY

The ISAC-II project characterized by the installation of the SC-linac has two goals with respect to ISAC-I: reaching higher energies (above the Coulomb barrier) and delivering high masses (beyond 30, ISAC-I limit). The Charge Breeder is instrumental to reach the second goal by reducing the M/q of high mass beams within the ISAC-I accelerators acceptance.

The fact is that the ECR type breeder produces a background of stable species (by ionizing residual gasses and vacuum chamber material) that can hide the RIB. Even few electrical pico-ampere of stable beam can overwhelm the radioactive beam that usually range between 10^3-10^6 particle/s in intensity.

The issue is that the RIB need to be delivered relatively pure (free of contaminants).

THE TOOLKIT

The ongoing effort has the main goal of producing an ensemble of filtering techniques (we call it the toolkit) to choose from when planning the delivery of an RIB. This is of particular interest when the beam is composed of charge bred high mass (A>30) ions and the background level is significantly higher than the desired species.

The toolkit includes new diagnostic instrumentation, stripping and energy degrading carbon foils, software applications as well as it takes advantage of existing beam line and accelerator characteristics to filter out the beam.

Pre-buncher and RFQ Filter

It is possible to achieve a longitudinal selection of (M/q)/Δ(M/q)∼1000 by exploiting the time of flight separation between the pre-buncher and the RFQ.

The pre-buncher is 5 m upstream of the RFQ as represented in Fig. 3. The source extraction voltage is fixed; this means that different M/q's are extracted with different velocities $v=(2 \cdot q \cdot V_{ext}/M)^{1/2}$. Different velocities generated different time of flights between the pre-buncher and the RFQ. The RFQ phase acceptance is 40 or $\delta t = 3 \cdot 10^{-9}$ s. So M/qs that are spaced in time more than $\delta t = 3 \cdot 10^{-9}$ s at the RFQ injection can be filtered by adjusting the pre-buncher phase (namely synchronizing the desired M/q with the RFQ accelerating bucket).

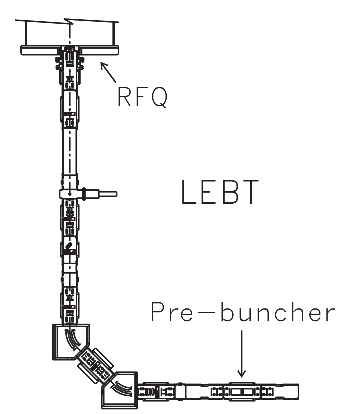

Figure 3: The three harmonics pre-buncher is located in the low energy beam transport (LEBT) line 5 meters upstream of the RFQ.

In numbers we have the following. At 2 keV/u (the injection energy for the RFQ) the beam velocity is v=$6\cdot10^5$ m/s (β=0.002). This produces a time of flight t=$8.3\cdot10^{-6}$ s. The RFQ relative phase acceptance is then δt/t=$3.6\cdot10^{-4}$.

The velocity δv due to the source fixed extraction voltage is such that δ(M/q)/(M/q)=-2$\cdot\delta$v/v. We also have that the relative velocity δv/v is equal to δt/t. The relative phase acceptance at the entrance of the RFQ becomes then a relative M/q acceptance equal (in absolute value) to δ(M/q)/(M/q)=$7.2\cdot10^{-4}$ or (M/q)/Δ(M/q)=1389.

Such a resolution is demonstrated using stable beam with multiple components (cocktail beam) from the OLIS ECR source. A first cocktail beam have $^{116}Sn^{18+}$ with M/q=6.439 and $^{84}Kr^{13+}$ with M/q=6.455 wit a resolution of (M/q)/Δ(M/q)=408. By changing the relative phase of the pre-buncher with respect to the RFQ we preferentially select either Sn or Kr namely we synchronized the RFQ bucket with either one of the two elements that arrive at the RFQ at different time (as explained above). By preferentially selecting the Kr we increase its purity with respect to Sn of two order of magnitude.

A second cocktail beam used is composed by $^{19}F^{3+}$ with M/q=6.333 and $^{38}Ar^{6+}$ with M/q=6.327. The two has a resolution of (M/q)/Δ(M/q)=1115. The calculated separation is between F and Ar at the RFQ entrance is 49 degree. By changing the relative phase of 30 degree the ^{38}Ar purity increases of one order of magnitude (see Fig. 4).

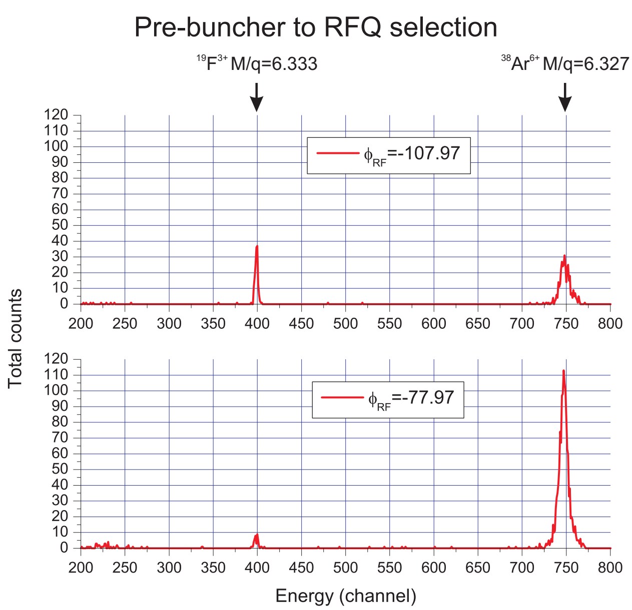

Figure 4: The pre-buncher to RFQ time of flight difference is used increase the purity of $^{38}Ar^{6+}$ with respect to $^{19}F^{3+}$ of one order of magnitude.

Beam dynamics simulation are underway to support the experimental results.

Carbon Foil Stripper-degraders

Beam with different mass but same M/q ratio are accelerated at the same final velocity by the DTL corresponding to 1.5 MeV/u. A stripper-degrader is installed between the DTL and the SC linac. This is a relatively thick carbon foil with two functions: stripping the beam and creating velocity difference depending on the particle Z by mean of energy loss (according to the non-relativistic Bethe formula). A mechanism drives the foil in and out by means of a stepper motor (by default we run with the foil in the out position); it can hold up to four foils. The standard foil thickness is 44 μg/cm^2 in order to reach charge state equilibrium. It is possible to load different thickness according the need.

The stripping aim to shifting the M/q of the contaminant further enough to be resolved downstream.

The velocity difference allows magnetic selection around the bending section of the beam line (DSB) that connects the two linacs (see next paragraph). It also induces transverse beam loss since the optics is optimized for a reference beam with certain M/q and velocity.

There are two identified locations for the degrader along the DSB beam line as represented in Fig. 5.

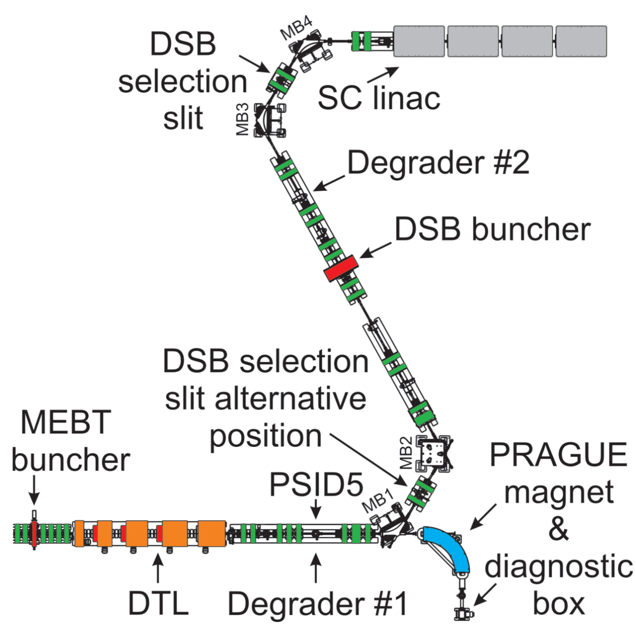

Figure 5: The DTL to SC linac beam (DSB) transport line has an S-shape with two achromatic bending section. The DSB buncher is needed to match the beam into the SC linac. A stripper-degrader (thick carbon foil) is used to generate velocity difference and therefore selection along the beam line.

The first one is 3.6 m downstream of the DTL. In this case the degraded beam travels 14.6 m before entering the DSB buncher (that match the beam into the SClinac) and 13.3 m from the buncher to the SC linac. Considering the distance from the foil to the SC linac equal to 27.9 m and that the beam velocity after the DTL is v=$1.71\cdot10^7$ m/s (β=0.057), the time of flight is t=$1.63\cdot10^{-6}$ s. Assuming again a 40 degree phase acceptance for the 106.08 MHz SCB cavities we then have a selection δv/v=$6.4\cdot10^{-4}$. The velocity difference at this location though is going to be partially compensated by the function of the DSB buncher.

The second location is 3.2 m downstream of the DSB buncher (or 10.1 m upstream of the SC linac). The reduced distance from the degrading point to the SC linac reduce the velocity selection to $\delta v/v=1.8 \cdot 10^{-3}$ but in this case there is no compensation by the buncher.

The effectiveness of the longitudinal selection after the degrader depends on the species entering the carbon foil (Z dependence) and their final $\delta v/v$.

Presently the stripper-degrader is installed in the second location.

The DSB Selection

It is possible to exploit the dispersion of the DSB bending magnets by installing a downstream selection slit.

The first dipole of the first achromatic bending section (MB1 see Fig. 5) of the DSB line creates a dispersion of ∼1.5 m in the center of the same section. The beam spot at this location is ∼4 mm wide including 90% of the beam. This makes possible to achieve a resolution of (M/q)/Δ(M/q)=375 where peaks are fully separated.

The first dipole of the second achromatic bending section (MB3 see Fig. 5) of the DSB line creates a dispersion of ∼1.6 m in the center of the same section. The beam spot at this location is ∼5 mm wide including 90% of the beam. This makes possible to achieve a resolution of (M/q)/Δ(M/q)=320 where peaks are fully separated. Such a resolution is confirmed by simulation.

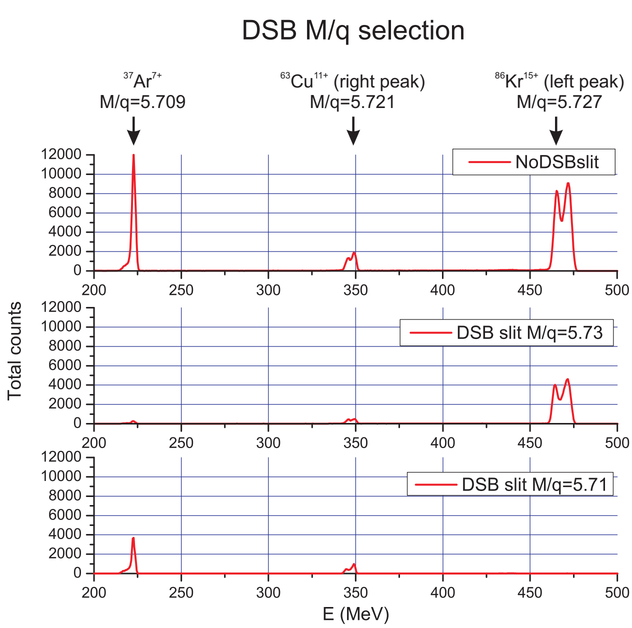

Figure 6: The three different spectra show the effectiveness of the DSB selection.

A selection slit 2 mm wide is installed in the center of the second bending section downstream of MB3. The calculated resolution is demonstrated by selecting $^{40}Ar^{7+}$ with M/q=5.709 over $^{86}Kr^{15+}$ with M/q=5.727, as represented in Fig. 6. The two elements are separated by (M/q)/Δ(M/q)=309 therefore the can be fully separated. The measurement show that by setting the bending magnet for M/q=5.709 the Kr peak after the slit disappear and vice-versa.

The same measurement show also that we can change the aspect ratio of $^{40}Ar^{7+}$ with respect to $^{63}Cu^{11+}$ that has M/q=5.722. These two has a resolution of (M/q)/Δ(M/q)=477 therefore they can not be fully separated.

Software Tools and Diagnostics

There are two software applications in support of the high mass beam delivery.

The first is a web based application [8] (called CSBassistant) that predicts all the possible contaminants for a given accelerated species. This application can be used as a general tool but it has some specific characteristics based on the ISAC beam lines. It includes possible contaminants coming from the ISAC CSB based on the measured background. It also include filtration based on the ISAC accelerator chain and the above reported resolution in the different sections. It uses real atomic mass. In general we use this tool to decide the M/q that provide the best compromise between transport efficiency and beam purity.

The second application is the scaling routine. This as an EPICS application that is custom built around ISAC beam lines. It scales all the optics element (both electrostatic and magnetic): quadrupole, bender, correction steerers and dipole.

The voltage is the quantity scaled in the electrostatic elements. The current is scaled in the magnetic quadrupole and steerers.

It is not possible to hysteresis cycle the magnetic quadrupole since we don't have the possibility to reverse the polarity. Studies show that cycling the quadrupole current to a set point give a field reproducibility of 2.26 G over 1240.26 G. The same studies also show that only approaching the field from the same side of the hysteresis curve give a filed reproducibility of <0.05 G over 1240.8. In order to provide the best reproducibility, the scaling routine as the option to drive each quadrupole to the maximum current, back down to zero and finally back up to the final set-point.

Each magnetic dipole has a an hall probe. The magnetic field read by the probe is scaled.

The routine also scaled the amplitudes of all the RF cavities (RFQ, DTL, SC linac, etc.).

The scaling factors are calculated in each section defined in term of M/q ratio (either from the source or after a stripper-degrader foil) and energy (form the ion source or after a linac). It is demonstrated that the scaling routine can precisely step to the desired M/q starting from a reference one. It is crucial to know exactly the species we tune the accelerator with and their M/q to select a reference starting point for the scaling.

It's also fundamental to have a dedicated diagnostic in order to identify the RIB.

The available diagnostic (beyond the standard ISAC diagnostic [9]) is a purity monitor (PSID5) downstream of the DTL (see Fig. 5). This is silicon detector positioned at 30° with respect to the beam direction that intercepts the beam scattered from a gold foil. The beam components are identified in terms of total energy; this means that two species with the same mass but different Z can not be distinguished.

Two new detectors located downstream of the SC linac serve the same purpose, they are used to determine the beam composition before delivering to the high energy experimental area (see Fig. 2). The new diagnostic already in place is a ΔE-E silicon detector telescope that provides information and it's capable of identifying beam with same M/q but different mass and Z. This detector is extremely valuable but we are limited in the amount of current we can send through it. A second ΔE-E detector capable of handling much higher current (gas Bragg detector) is in the final assembly stage.

RIB BEAM DEVELOPMENT RUN

The main goal of the high mass task force is to prove that is possible to deliver a relatively pure charge bred high mass radioactive beam to an ISAC-II experiment.

Results from a recent dedicated development run show that it's possible but extremely challenging. The RIB chosen for the run is $^{76}Rb^{1+}$ from the ISAC target charge bred to $^{76}Rb^{15+}$. The choice of $^{76}Rb^{15+}$ is based on the ISAC-I accelerator acceptance and the purity calculated by the CSBassistant.

Since a exact match for the $^{76}Rb^{15+}$ was not available, the accelerator was set up with $^{12}C^{2+}$ from the off line ion source. The C was further stripped to $^{12}C^{5+}$ in the DSB stripper degrader.

The measurements consist in stepping through the M/q from 2.581 to 2.896 using the scaling routine and characterizing the charge state distribution of each component of the cocktail beam. Each M/q is associated with an accelerator and beam lines scaled tune. The abundance of each component is measured downstream of the SClinac at the silicon detector telescope. The silicon telescope is calibrated based on known beam components and their energies. Once a single element (ideally the RIB of interest, in this case ^{76}Rb) and its charge state are identified, we select them as reference M/q to scale the linac.

In Fig. 7 it is represented the charge state distribution of the cocktail beam downstream of the DSB stripper-degrader. Two components are preliminary identified with ^{61}Ni and ^{56}Fe. A third component ^{A}X is not clearly identified. The ^{76}Rb is not one of the component since it was blocked at the source during the charge state distribution measurements. The higher peak of the ^{61}Ni distribution that shows at M/q=2.821 is identified as charge state 21+. The real M/q of $^{61}Ni^{21+}$ is 2.902.

This $^{61}Ni^{21+}$ scaled tune is the reference point to rescale the linac for $^{76}Rb^{26+}$. This last choice take into consideration purity and relative abundance of the ^{76}Rb charge state distribution. With the linac scaled on the right M/q the ^{76}Rb was released form the source. Fig. 8 shows the different spectra at the telescope with and without the Rb injected into the system. The Rb is expected to grow in the red square marked on the graph. As expected the Rb counts are extremely low but identifiable.

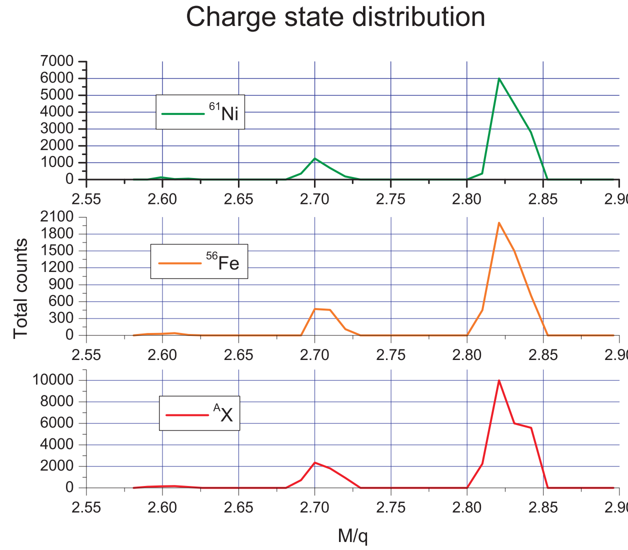

Figure 7: Charge state distribution of the cocktail beam downstream of the DSB stripper-degrader. Two components are preliminary identified with ^{61}Ni and ^{56}Fe. A third component ^{A}X is not clearly identified. The ^{76}Rb is not one of the component since it was blocked at the source during the charge state distribution measurements.

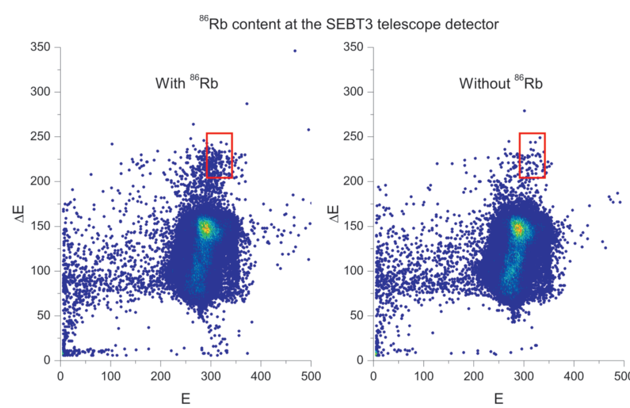

Figure 8: ^{76}Rb trace at the silicon telescope installed downstream of the SClinac. The total counts in the red square are three time higher when the ^{76}Rb is injected into the CSB.

FUTURE DEVELOPMENT

The stripper-degrader second location is not ideal. The DSB buncher is used to compensate the energy loss through the carbon foil moving the RF phase beyond the linear region and as consequence we lose the proper match into the SClinac.

The stripper-degrader is going to be moved in the first location (see Fig. 5). The energy loss for the desired M/q through the carbon foil can be properly compensated by increasing the output energy of the DTL (and so restoring the nominal 1.5 MeV/u after the foil) . In this case the DSB buncher has only to match the beam into the SC linac. Also the time of flight between these two is not changed so there is no need to re-phase the buncher with respect to the linac. The time of flight from the DTL to the carbon foil (covering the 3.6 m distance) is instead going to change by increasing the final energy of the DTL. This change the beam time of arrival at the DSB buncher location. Such a time shift can be easily compensated with an already present phase shifter that moves the DSB buncher and SC linac cavity phases with respect to the DTL.

The carbon foil in this first location allow also to use the DTL analyzing (PRAGUE) magnet as a spectrometer. The PRAGUE diagnostic box (see Fig. 5) has an harp profile monitor that gives information about total energy, energy spread. The diagnostic box has also a Faraday cup (FC) that provide the intensity of the beam so it's possible to reconstruct the charge distribution of the different beams. As an upgrade we are going to instrument the box with a beta counter in order to detect radioactivity from the weak RIB.

CONCLUSION

We demonstrated that phase selection in the accelerator chain can be use as M/q resolution. Dedicated diagnostics is fundamental to tune RIB above all when stable background is present. The scaling routine is crucial to set the beam lines on the right M/q. A CSBassistant type of calculator is important to predict the purity of the beam and therefore tune on the most favourable M/q region.

An unprecedented effort to the issue of delivering high mass charge bred beam at ISAC is showing the first encouraging result. It remains clear that the delivery of such beam is not going to be effortless. Every new RIB delivery has to be planned in advance and required development time.

TRIUMF is gaining valuable knowledge to understand and exploit the full potential of ISAC as well as to design future facilities.

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