IN FLIGHT ION SEPARATION USING A LINAC CHAIN*

M. Marchetto†,F. Ames, P. Bender, B. Davids, N. Galinski, A. Garnsworthy, G. Hackman,
O. Kirsebom, R.E. Laxdal, D. Miller, A.C. Morton, A. Rojas,
C. Unsworth, TRIUMF, Vancouver, Canada
L. Evitts, C. Nobs, University of Surrey and TRIUMF

Abstract

The ISAC accelerator complex now can accelerate radioactive heavy ion beams to above the Coulomb Barrier. Recently an ECR type charge state booster has been added to allow the acceleration of radioactive beams with masses $A > 30$. A characteristic of the ECR source is the efficient ionization of background species that can overwhelm the low intensity RIB beam. The long linac chain at ISAC can be used to provide some in flight separation both in the time domain and in the spatial domain analogous to fragment separators at in-flight fragmentation facilities. The paper summarizes the work done at TRIUMF to develop tools for the filtration and diagnosis of beam purity in the post acceleration of charge bred beams.

INTRODUCTION

Radioactive ion beams (RIB) are produced and post accelerated at the TRIUMF ISAC facility, represented in Fig. 1, via the isotope separation on line (ISOL) method.

The ISAC RIB production uses protons from the TRIUMF cyclotron. The radioactive species released by the thick target are singly charged and extracted at source potential. The radioactive ions are magnetically separated and can be post accelerated to a variable final energy. The post-accelerator chain is composed of a radio frequency quadrupole (RFQ), a drift tube linac (DTL) and a superconducting (SC) linac.

In order to reach high energies and limit the cost of the post-accelerators the singly charged beam is stripped to a higher charge state. Light masses ($A \leq 30$) are stripped downstream of the RFQ by means of a thin carbon foil. Heavy masses ($A > 30$) are stripped before injection into the RFQ by means of an ECR type charge state booster (CSB).

The charge state booster ionizes both the RIB but also any other element present in its vacuum chamber and immediate surroundings. Such elements belong either to the background residual gas or to the materials that constitute the vacuum chamber itself. The ionization of these contaminants generates a background current of orders of magnitude higher than the radioactive species. This background makes identifying and selecting the RIB extremely challenging. In most of the cases the contaminants to RIB ratio can be improved in favor of radioactive species but the contaminants can not be completely suppressed. Also the necessary cleaning of the beam from contaminants has the side effect of losing part of the produced RIB.

In order to suppress the contaminants a toolkit of separation and filtration techniques as well as software and diagnostic aids to plan and streamline the beam tuning and delivery is in place.

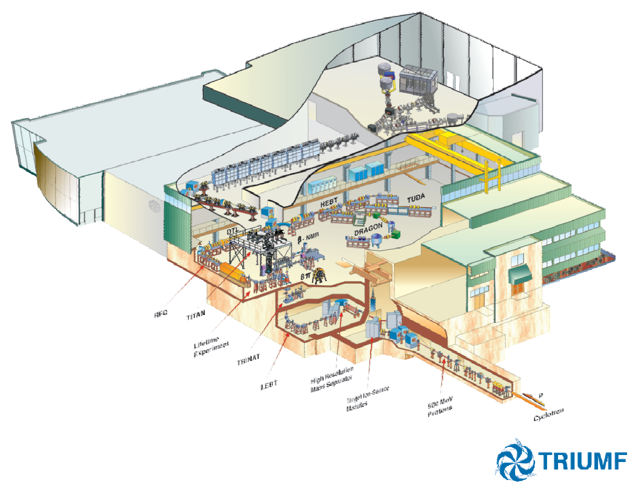

Figure 1: Artistic overview of the ISAC facility at TRIUMF.

THE ISAC FACILITY

The ISAC facility plan view is represented in Fig. 2. The detailed description of the facility can be found in previous proceedings [1].

The RIB production takes place in one of the two underground target stations (ITE and ITW see shaded area in Fig. 2) at a time using 500MeV up to 100μA of current (namely up to 50kW of beam power). Different target materials can be used to produce the neutral beams. Two types of production target containers are available, rated as low and high power relatively to the proton beam current. The production target material and type are chosen based on the experimental needs.

The produced neutral atoms diffuse into the ion source. Different sources are available (surface, LASER, FEBIAD) and others are under development (ECR). Each target is combined with the proper sources to optimized the overall

* TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada

† marco@triumf.ca

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RIB production. The beam is singly charged and extracted from the source at a potential up to 60kV.

Before exiting the target hall, the extracted beam is pre-separated using a low resolution ($\Delta M/M \sim 1/500$) spectrometer (pre-separator). This spectrometer is in common between the two target stations. The pre-separation takes place in order to contain most of the radiation inside the target hall.

The beam is then further selected using the main separator that routinely operates with a resolution of $\Delta M/M = 1/3000$.

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, a 14.5GHz PHOENIX by Pantechnik [2], acts as charge state booster (CSB) to further strip 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 ≤ 7 for $A > 30$. This upper limit is dictated from the installed linacs (RFQ and DTL).

A Nier type spectrometer with a resolution of $\Delta M/M = 1/100$ is located downstream of the ECR to select the desired A/q.

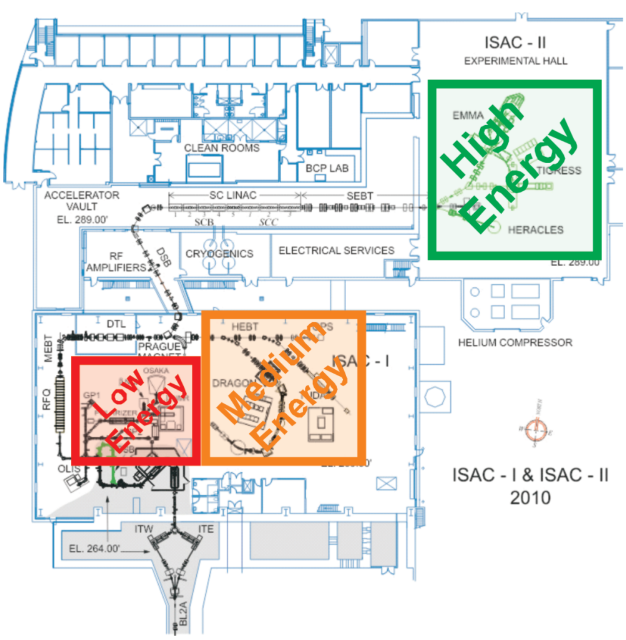

Figure 2: Plane view of the ISAC facility at TRIUMF. The acceleration chain is composed of room temperature RFQ and DTL in ISAC-I and a superconducting linac in ISAC-II.

The RIB can be directed to a low energy area at source potential (≤ 60keV).

In the post-accelerator chain the beam is injected at 2keV/u into the 35.36MHz CW RFQ and accelerated to 150keV/u. The RFQ accepts beam with $3 \leq A/q \leq 30$. The beam is pre-bunched at injection using a three harmonic (quasi saw-tooth) buncher located 5m upstream of the RFQ. The fundamental harmonic of the pre-buncher is 11.78MHz. Since the RFQ operates at the third harmonic, the time structure after acceleration consist of main peaks $\sim$ 86ns apart and smaller satellite peaks spaced $\sim$ 28ns apart. In order to remove the satellite peaks and clean the time structure an 11MHz chopper is located downstream of the RFQ.

The next stage of acceleration is accomplished with a DTL operating at 106.08MHz. The DTL acceptance in terms of mass to charge ratio is $2 \leq A/q \leq 7$. Any beam from the RFQ with $A/q > 7$ is further stripped upstream of the DTL using a 4μg/cm^2 carbon foil. The stripping efficiency to $A/q \leq 7$ is about 30% for ions with $A < 30$. The DTL can provide any energy between 150keV/u to 1.8MeV/u to a medium energy experimental area.

The last stage of acceleration utilizes a SC linac capable of 40MV of acceleration voltage. The SC linac is composed of two main sections (SCB and SCC) operating at 106.08MHz and 141.44MHz respectively. The beam is injected from the DTL at 1.5MeV/u. The final energy is A/q dependent with a peak velocity corresponding to 18MeV/u.

RIB DELIVERY

The ECR charge state booster is instrumental to accelerate high masses ($A > 30$) in ISAC. This type of breeder produces a background of stable species by ionization of residual gasses and vacuum chamber materials. Virtually any multi-charged bred radioactive isotope of interest is accompanied with a few stable isotopes (contaminants) with similar A/q ($(\Delta A/q)/(A/q) < 1/100$) forming a so called cocktail beam . Typical background currents are in the order of only a few pico-Amperes but they are still orders of magnitude higher with respect to the RIB intensity ranging between 10^3 to 10^6 particle/sec.

There are two major challenges in dealing with these cocktail beams. The first is the identification of the RIB component and the consequent optimization of the transport beam lines, including the accelerators, for this component. The second is the filtration of the contaminants. This last one is related to the issue that the RIB's need to be delivered relatively pure (free of contaminants) to the experimental stations.

Both hardware and software diagnostic tools are required to identify the radioactive species. In-flight separation is necessary to reduce the stable component.

THE TOOLKIT

The toolkit is an ensemble of diagnostic tools, stripping/energy degrading carbon foils and filtration techniques that act both in the longitudinal and transverse phase space.

Diagnostic tools

The standard ISAC diagnostics include Faraday cups (FC), rotating (RPM) and linear (LPM) profile monitors, and low intensity monitors (mostly Si detectors) that provide information on the intensity (counts/s), energy, and

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time profile of the beam. Additional dedicated diagnostics are installed to analyze the cocktail beam and optimize the accelerator tune.

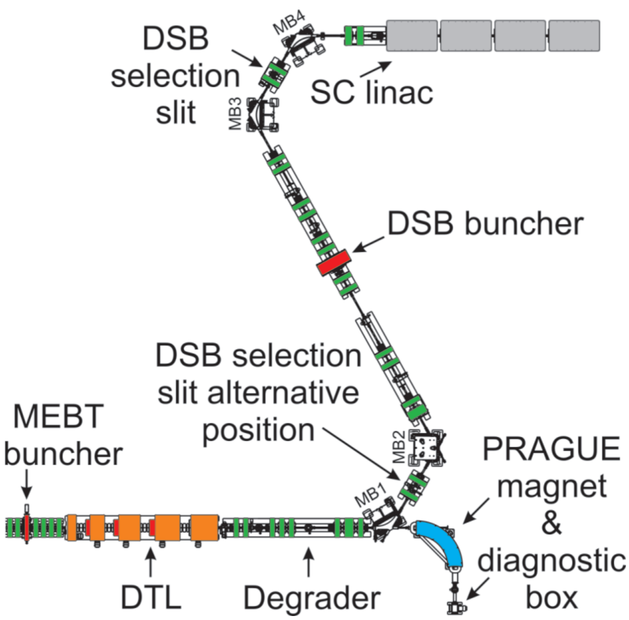

Figure 3: The DTL to SC linac beam (DSB) transport line has an S-shape with two achromatic bending sections. The DSB buncher is needed to match the beam into the SC linac. A stripper-degrader (thick carbon foil) is used to generate velocity differences and therefore selection along the beam line.

A diagnostic station is positioned downstream of the analyzing magnet (PRAGUE) serving the medium energy section after the DTL. The diagnostic station is comprised of a silicon detector to detect total counts and identify total energy (mass of the cocktail constituents), a beta counter to detect activation and a gamma counter to identify the activation. A stripping foil (degrader) upstream of the magnet (see Fig. 3) can be used to strip the ions into a variety of charge states that further enable particle identification after an A/q magnet scan.

Two different detectors located downstream of the SC linac can be used to determine the beam composition before the final delivery (see Fig. 2). A $\Delta E - E$ silicon detector telescope is capable of identifying beam A and Z for total intensities limited to a few 10^3. This detector is extremely valuable but we are limited in the amount of current we can send through it. The second is a $\Delta E - E$ gas Bragg detector capable of handling higher current up to 10^5.

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

The first is a web based application [3] (the so called $CSBAssistant$) that predicts all the possible contaminants based on measured atomic masses (M) for given A/q ranges as defined by the separation techniques including an in-flight charge stripping stage. The tool highlights expected contaminants based on the CSB background scan. The tool is useful in determining the best M/q value and filtering strategy to minimize the level of contamination while optimizing the transport efficiency.

The second application is the scaling routine. This is an EPICS application that scales all optics elements and RF amplitudes base on M/q and beam energy.

Electrostatic elements are scaled by voltage while magnetic components are either scaled by current (steerers and quadrupoles) or by magnetic field (hall probe in dipoles). Studies show that cycling the quadrupole current to a set point gives a field reproducibility of 2.26G over 1240.26G while approaching the field from the same side of the hysteresis curve gives a field reproducibility of < 0.05G over 1240.8G. In order to provide the best reproducibility, the scaling routine has the option of invoking a current set-point ramped from zero to the set-point. The routine also scales the amplitudes of all the RF cavities (RFQ, DTL, SC linac, etc.).

The scaling factors are calculated in each section from the M/q ratio (either from the source or after a stripper-degrader foil) and energy (from the ion source or after a linac). The scaling routine performs precise steps in M/q of the entire acceleration chain starting from a reference tune. The accelerator is tuned with a known stable beam (example $^{12}C^{2+}$) of convenient intensity. This beam is also used to calibrate the various energy detectors.

Pre-buncher and RFQ filtration

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

At fixed source extraction voltage, different M/q's are extracted with different velocities $v = (2 \cdot q \cdot V_{ext}/M)^{1/2}$. Different velocities generate different times of flight in the 5m between the pre-buncher and the RFQ. The RFQ phase acceptance is $75°$ (being $-25°$ the synchronous phase of the RFQ [4]) or $\delta t = 5.9$ns. M/q's that are spaced in time by more than $\delta t = 5.9$ns at the RFQ injection can be filtered by adjusting the pre-buncher phase (namely synchronizing the desired M/q with the RFQ accelerating bucket). At 2keV/u (injection energy for the RFQ) the beam velocity is $v = 6 \cdot 10^5$m/s ($\beta = 0.002$) that produces a time of flight $t = 8.3\mu$s. The RFQ relative phase acceptance is then $\delta t/t = 7.1 \cdot 10^{-4}$.

At fixed extraction voltage the following relation holds:

$$\frac{\delta(M/q)}{(M/q)} = -2 \cdot \frac{\delta v}{v} = -2 \cdot \frac{\delta t}{t} \tag{1}$$

The relative phase acceptance at the entrance of the RFQ becomes then a relative M/q acceptance equal (in absolute value) to $\delta(M/q)/(M/q) = 1.42 \cdot 10^{-3}$ or $(M/q)/\Delta(M/q) \sim 700$.

This resolution was demonstrated [1] using two cocktail beams: $^{116}Sn^{18+}$ and $^{84}Kr^{13+}$ with M/q respectively of 6.439 and 6.455 ($(M/q)/\Delta(M/q) = 408$), and $^{19}F^{3+}$ and $^{38}Ar^{6+}$ with M/q respectively 6.333 and 6.327

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$((M/q)/\Delta(M/q) = 1115)$. Suppression factors of 100 and 15 respectively were achieved in each case.

Carbon foil stripper-degraders

Beams with different mass but the same M/q ratio are accelerated to the same final velocity by the DTL. A stripper-degrader (thick carbon foil) is installed 3.6m downstream of the DTL (see Fig. 3) to strip the beam to a new charge state and M/q range as well as create a velocity difference depending on the particle Z. Different foil thickness can be selected, the standard one being 44μg/cm^2 in order to reach charge state equilibrium.

The goal is to shift the M/q of the contaminant outside the acceptance of the downstream linac chain that is tuned to the M/q of the RIB.

In order to accelerate the beam through the SClinac it is necessary to compensate the energy loss of the beam going through the degrader. This energy loss is accurately measured at the the PRAGUE magnet. The compensation is done by increasing the beam energy out of the DTL enough to enough to match the velocity of the ion to the unstripped velocity. Such increase in energy, though, leads to a time of flight difference over the 3.6m that separate the DTL from the foil. This difference is compensated by adjusting the downstream RF devices (DSB buncher and SC linac sections) phases by a calculated amount.

Given that the distance from the degrader to the SC linac is equal to 27.9m and that the beam velocity at 1.5MeV/u is $v = 1.71 \cdot 10^7$m/s ($\beta = 0.057$), the time of flight is $t = 1.63\mu$s. Given a 40° phase acceptance for the 106.08MHz SCB cavities we then have a selection $\delta v/v = 6.4 \cdot 10^{-4}$ or $(M/q)/\Delta(M/q) \sim 800$. The velocity difference at this location though is going to be partially compensated by DSB buncher (see Fig. 3) that has the function to match the beam at the entrance of the SC linac by minimizing the time spread.

The DSB filtration

The two achromatic bending section in the DSB beam line (see Fig. 3) have a dispersed focus between dipoles of 1.5m and 1.6m respectively giving resolving power of $(M/q)/\Delta(M/q) \sim 375$ and $(M/q)/\Delta(M/q) \sim 320$ respectively.

A selection slit 2 mm wide is conveniently installed in the center of the second bending section downstream of MB3. The resolution of this magnet is confirmed with simulation and measurement [1] using a cocktail beam composed of ${}^{40}Ar^{7+}$,${}^{63}Cu^{11+}$ and ${}^{86}K^{15+}$ with M/q values of 5.709, 5.722 and 5.727 respectively.

HIGH MASS DEVELOPMENT RUN

The goal of the development run (August 2012) was to demonstrate the capability of purifying the radioactive isotope ${}^{94}Rb$ to an acceptable level for a real experiment. This run takes advantage of previous developments (May 2012 [1]) in particular in terms of the new diagnostic installed in the PRAGUE box, the location of the degrader

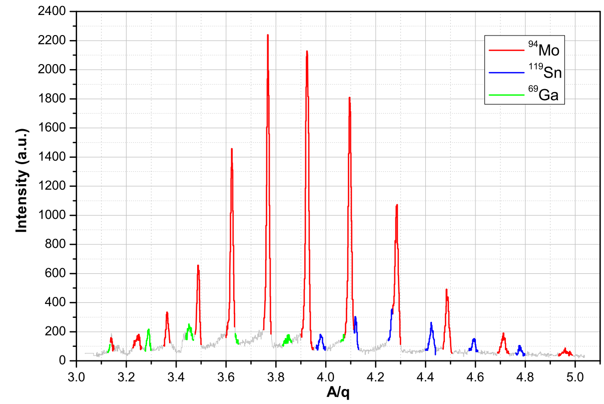

Figure 4: Charge state distribution at the PRAGUE magnets. Three isotopes are identified: ${}^{69}Ga$, ${}^{94}Mo$, ${}^{119}Sn$.

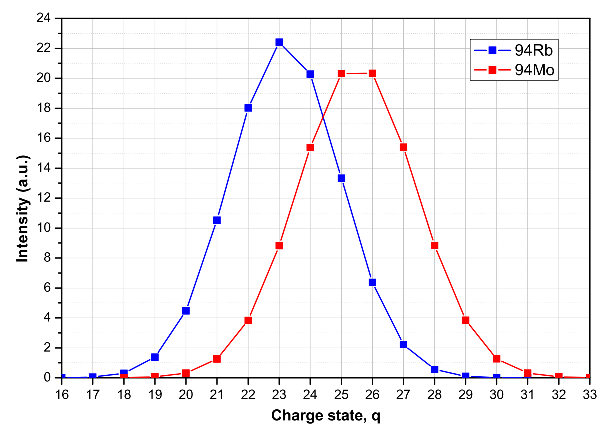

Figure 5: Theoretical charge state distribution of ${}^{94}Rb$ and ${}^{94}Mo$. The two isobars are separated by a relative mass difference of $\Delta M/M = 1/4405$.

downstream of the DTL and the installation of the new Bragg detector downstream of the SC linac.

The entire linac chain is initially tuned with ${}^{12}C^{2+}$ with no stripping foil in place. Once the tune is established the accelerator is scaled from ${}^{12}C^{2+}$ to the M/q containing the RIB using the scaling routine.

A ${}^{94}Rb$ charge state of 15+ ($M/q = 6.260$) is selected in the Neir spectrometer. The selection is based on the prediction from the $CSBAssistant$ where only three low intensity contaminants ${}^{69}Ga^{11+}$, ${}^{94}Mo^{15+}$ and ${}^{119}Sn^{19+}$ are expected after the pre-buncher and RFQ time of flight filtration. The M/q's of these isotopes are respectively 6.265, 6.260 and 6.258.

The stripping foil produces characteristic charge state distributions at the Prague magnet diagnostic station. The charge state distribution measured downstream of the PRAGUE magnet confirms the predicted cocktail compo-

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sition as represented in Fig. 4.

In this case the DSB is tuned to $^{94}Mo^{22+}$ ($M/q = 4.268$) in order to filter out the contaminants with $A = 69$ and $A = 119$. The charge state choice is a compromise between purity and efficiency of the RIB beam. Figure 5 is the expected charge state distribution of ^{94}Rb and ^{94}Mo ($(M)/\Delta(M) = 4405$). The stripping efficiency ratio between ^{94}Rb and ^{94}Mo at charge state 23+ and 22+ is respectively 2.5 and 4.5.

The DSB buncher and the SC linac sections RF phases were shifted respectively of 26°, 77° (for SCB) and 103° (for SCC) after energy compensation at the stripping foil.

The beam accelerated with the SC linac is analyzed at the Bragg detector. The result is shown in Fig. 6, left picture. The cocktail is dominated by $^{94}Mo^{22+}$ with still a minor component of ^{69}Ga and ^{119}Sn plus other contaminants that are in the noise of the charge state distribution. The ^{119}Sn is in the tail of the charge state distribution of $^{94}Mo^{22+}$ (see Fig. 4). The result is also compatible with the $CSBAssistant$ calculation as shown in Fig. 7. Even though nuclides like ^{107}Ag, ^{113}In or ^{132}Xe are theoretically cut out by the pre-buncher and RFQ filtration (represented in Fig. 7 by the cyan vertical band), it's possible that these ions have extended distribution tails that are eventually accelerated.

In fact the accelerator can be optimized on these extra elements (with respect to ^{94}Mo) by changing the pre-buncher phase. For example a shift of $-12°$ highlights ^{69}Ga, while 20° phase shift increases the ^{119}Sn and 71° shift increases ^{100}Mo.

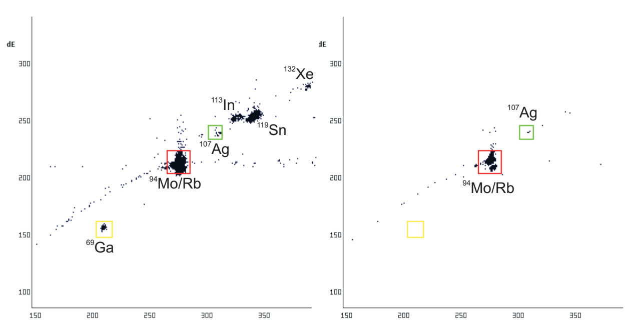

Figure 6: Effect of the DSB filtration measured at the Bragg detector: the left picture correspond to the unfiltered cocktail beam from the DTL

Virtually all contaminants are finally suppressed using the DSB slit filtration as represented in Fig. 6 right picture. This result is also in agreement with the $CSBAssistant$ calculation. The final filtered cocktail beam is optimized on the radioactive beam $^{94}Rb^{22+}$, noting that the final distribution is still dominated by the $^{94}Mo^{22+}$ contaminant.

CONCLUSION

ISAC is now in a position to deliver its first high mass charge bred radioactive beam to an experiment. A set of

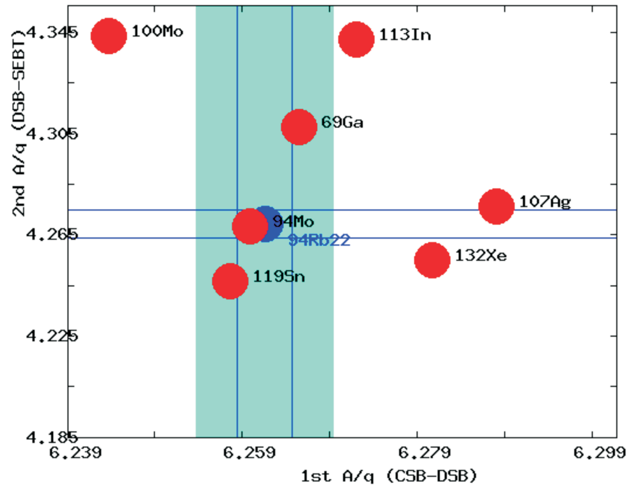

Figure 7: Filtration prediction of the$CSBAssistant$. The cyan vertical band represent the pre-buncher and RFQ filtration while the horizontal band represent the DSB filtration.

tools is available to address the contamination of the delivered beam. It remains clear that the delivery of such beams is not going to be effortless. Every new RIB delivery has to be planned in advance and will require development time.

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REFERENCES

[1] M. Marchetto,"Progress and Plans for the High Mass Beam Delivery at TRIUMF", HIAT 2012, Chicago, Illinois, USA, June 2012.

[2] F. Ames et Al.,"Commissioning of the ECRIS Charge State Breeder at TRIUMF", ECRIS2010, Grenoble, France, August 2010, p. 178

[3] A. Garnsworthy, http://trshare.triumf.ca/ garns/CSB

[4] S. Koscielniak et al., "Beam Dynamics Studies on the ISAC RFQ at TRIUMF", PAC'97, Vancouver, British Columbia, CANADA, May 1997, p. 1102.

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