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ECRIS OPERATION AND DEVELOPMENTS AT TRIUMF

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Abstract

Rare isotope beams are used at the ISAC facility at TRIUMF for studies mainly in nuclear and astrophysics and applications ranging from material science to medicine. The isotopes are produced via the ISOL technique and ionized via a set of different ion sources depending on the application. In cases where highly charged ions are needed charge state breeding is done with a 14.5 GHz PHOENIX ECR ion source from PANTECHNIK. The source has been operational for over a decade, providing a wide range of ions from Na to U at A/Q < 7 for post-acceleration. A second ECR ion source, a SUPERNANOGAN, also from PANTECHNIK, is used to provide highly charged ions from stable isotopes either for set-up and calibration for the rare isotope beams or for nuclear reaction studies with stable ions. A summary of the results and the challenges and improvements to the original sources are presented. For the charge state breeding, this mainly optimizes the efficiency and purity of the delivered beams. In the case of the SUPERNANOGAN, special emphasis is put on operational aspects to cover a wide range of elements and ensure easy switchover. The latest in this series of improvements is the implementation of two-frequency plasma heating in both ion sources.

INTRODUCTION

At most rare isotope beams facilities, highly charged ions are not produced directly after the production target, but singly or low charged ions are injected into an ion source for charge state breeding like ECR ion sources or Electron Beam Ion Sources (EBIS) [1]. This allows the decoupling of the isotope production process in a highly radioactive environment and the production of the highly charged ions in a more accessible and controllable area. At TRIUMF, rare isotopes are produced by impinging up to 100 μA of 480 MeV protons on one of two solid targets. The targets are kept at high temperatures to allow the products to diffuse into an ion source for singly charged ions. Extracted ions are accelerated to up to 60 keV, mass separated and guided either directly to experiments or into a post accelerator, which consists of an RFQ, a room temperature drift tube linac (DTL) and a superconducting accelerator [2]. In the case of masses A > 30, higher charge states are needed for the post-acceleration, which is achieved by injecting the ions into the charge state breeder source and selecting the desired charge state with a Nier-type spectrometer before sending them to the accelerator [3]. The intensity of the rare isotopes can vary from up to several nA for isotopes close to stability to only a few per second for the most exotic ones. That means high efficiency for the charge state breeding is needed. In most cases the intensity of ions from the support gas of the ECRIS but also from residual gas and impurities of the source materials exceeds the intensity of the desired ions by many orders of magnitude. It is imperative to minimize the amount of residual gas and other impurities as much as possible by using high-purity gases and materials close to the ECR plasma and selecting a charge state of the radioactive ions with minimum overlap. Even with this, further purification by stripping at higher energy may be needed. Tools have been developed to guide this purification process and to choose the most optimal conditions for the experiments. Additionally, a SUPERNANOGAN ECR ion source from PANTECHNIK, part of the TRIUMF Off-line Ion Sources (OLIS) terminal, provides pilot beams for setting up the accelerators and stable ion beams for the experiments.

CHARGE STATE BREEDING

Several changes to the original design of the source have been implemented. Already shortly after taking it into operation in 2005 at a test set-up, it became clear that both the injection and extraction optics were not ideal for the requirement to operate at different voltages to match the energy acceptance of the RFQ (2.04 keV*A/Q). A two-step deceleration and acceleration scheme has been implemented on both sides, which gives the flexibility to operate at a source voltage between 10 and 15 kV. The next big change was the exchange of the stainless steel plasma chamber for aluminum and the application of an additional coating of pure aluminum to it in 2012. This reduced the background of ions from the stainless-steel components and slightly increased the efficiency. In 2014, the original Klystron RF amplifier was replaced by a TWT, which allowed some small-range frequency tuning. Most recently, two, two-frequency plasma heating has been implemented. It uses one waveguide to transport microwave power at two frequencies between 13 and 14.5 GHz into the source at up to 200 W each. Besides increasing the global charge breeding efficiency, it also shifts the charge state distribution to higher charges. More details and results are described in [4].

Charge State Distributions and Efficiencies

Figure 1 shows the charge state Q with the maximum intensity, or the one used for the experiment as a function of the atomic number Z, for all stable or radioactive isotopes used so far. The solid line indicates the minimum charge state, which is needed to satisfy the acceptance of the accelerator chain of A/Q < 7. It shows that up to about Z = 65, the charge state with the highest efficiency for the charge state breeding can be chosen. For neutron deficient isotopes the required charge state is lower, whereas for neutron rich isotopes a higher charge state is needed. For higher atomic

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numbers, a higher charge state may be used with some losses. The different values for the same atomic number reflect the need for different charge states for different numbers of neutrons or for improvements over the years of operation. The heaviest radioactive isotope delivered to an experiment so far is the neutron-deficient isotope $^{158}_{68}$Er with a charge state of 23+. Figure 2 shows the efficiency of the charge state

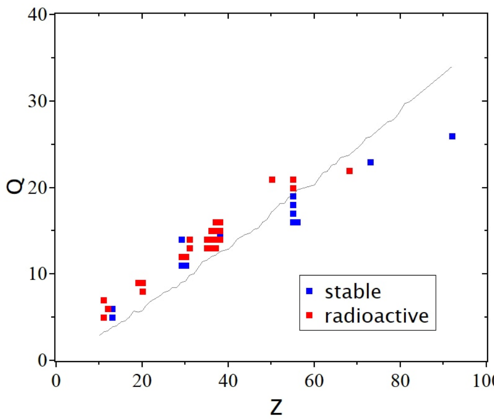

Figure 1: Charge state with the maximum intensity as a function of the atomic number Z red radioactive (see text for details).

breeding to the charge state of radioactive ions used for the experiment again as a function of the mass. It can be up to about 7 % for ideal cases, but in general it is around 3 %. The efficiency for radioactive ions, as used by the experiment in many cases, is slightly lower than for stable ions. Using the two-frequency plasma heating up to 9 % have been achieved for $^{133}Cs^{26+}$ [4]. The most abundant charge state cannot be used in many cases due to the background at this A/Q value. Additionally, losses due to the decay reduce the efficiency of short-lived isotopes. Again, different values for the same mass reflect changes over time.

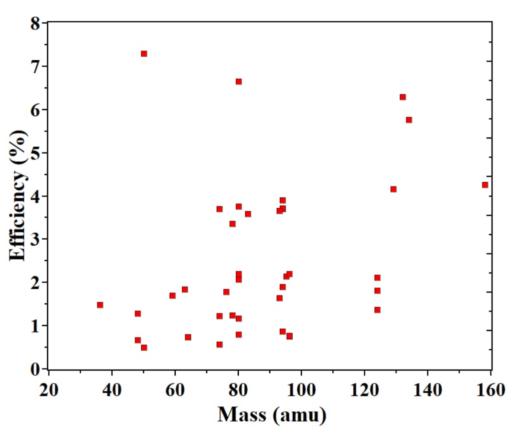

Figure 2: Efficiency for the charge breeding of radioactive ions as a function of mass as used for experiments.

Purification

Figure 3 shows a typical ion current as a function of A/Q in the interesting region between 5 and 7 from the charge breeder source. Although the source was operated with pure He gas, charge states of isotopes of C, O, N, and Ar can be clearly identified, besides some other less abundant elements. Some of the peaks can go up to the μA level. The figure shows the change in the spectrum after exchanging the stainless steel plasma chamber for aluminum. Ion intensities from Fe, Ni, Mo, and other common components of steel are significantly reduced or missing. Even with this, the background intensity at an A/Q value can be orders of magnitude higher than that of the desired radioactive isotope. A

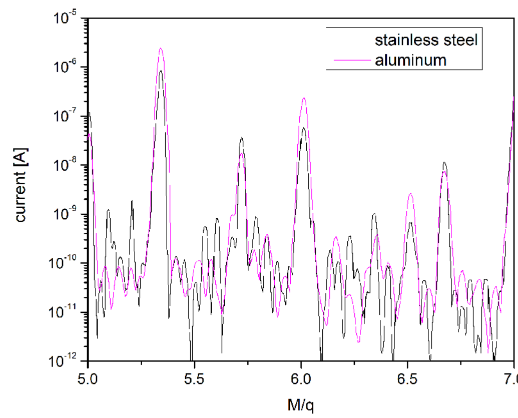

Figure 3: Ion current as a function of mass to charge ratio from the charge state breeder [3].

possible solution to this would be operating at an ultra-high vacuum. The TRIUMF source operates in the mid 10^{-8} Torr range. That means even an improvement of 2 or 3 orders of magnitude, which might be possible, will not completely solve this problem. Another option is an increase in mass resolving power for selecting the desired A/Q value. With a 4 rms emittance of about 20 μA from the source, this would be very costly if no major beam losses can be accepted. TRIUMF has chosen a more pragmatic way of dealing with this problem [5]. First, a software tool has been developed which lets the operator select the charge state, which is still close to the maximum in the charge state distribution but with a minimum in the background. It identifies possible background ions from stable elements within an A/Q window of 1/200, the resolving power of the charge state selector. The total intensity is based on previous measurements and identifications of the components. After this, the mass dependencies of the linear accelerator components, like the RF phases, are used to add further resolving power. Finally, if more background reduction is needed, a stripper foil can be introduced after the DTL at an energy of 1.5 MeV/u. Although the stripping will introduce some losses, it will eliminate nearly all ions with a different mass, as they will end up in different A/Q values. Only direct isobars can remain, but depending on the Z dependence of the stripping efficiency, they can be reduced as well.

OFF-LINE ION SOURCE

The TRIUMF off-line ion source (OLIS) provides beams of stable isotopes as pilot beams for beamline and accelerator setup and for experiments with accelerated stable beams. For setup and tuning, currents around 1 nA are usually sufficient. Intensities for accelerated stable isotopes for experiments may be up to the space charge limit of the accelerator around a few μA. Three ion sources are available to cover the entire mass range. A surface source is mainly used for alkali elements. A 2.45 GHz microwave-driven plasma ion source can deliver singly to low-charge ions. This source is operated mainly with gaseous elements, but it can also deliver other elements evaporated from an oven or from sputter samples. The third one is an ECR ion source (a 14.5 GHz SUPERNANOGAN from PANTECHNIK) for highly charged ions. Similar to the plasma ion source, it can deliver beams of gaseous elements and of condensable elements from ovens or via sputtering [6, 7].

Recent Results

The OLIS ECR ion source has been equipped with two-frequency heating. A TWT RF amplifier operating between 12.75 GHz and 14.5 GHz with an output power of up to 200 W and a solid-state amplifier with the same frequency range and maximum power of 50 W. Contrary to the charge breeder source, the two different RF frequencies can be coupled via two waveguides. Most recent results have been published in [8]. In most cases, a total power below 100 W is sufficient to deliver the desired intensities and charge states. For optimization, the frequencies and power can be scanned independently by observing the output current at the desired A/Q value to find the best conditions. Typically, the difference is around 0.8 GHz. As an example, 12.98 GHz and 13.78 GHz in the case of Kr ions. With dual-frequency heating, the current has increased by a factor of 2 compared to single-frequency heating at the same total power. As this source is very efficient compared to the microwave plasma source, it can also be used to deliver low-charged ions. This is important in cases where expensive materials are used or yields from evaporation or sputtering are low. An example of this is Cerium. It was used for an experiment to produce CeF molecules by sending a beam of Ce^{+} or Ce^{2+} through a gas reaction cell. Ce was produced by sputtering, and the support gas pressure in the ECR ion source was adjusted so that highly charged ions were suppressed, and only the low charges remained [9].

FUTURE DEVELOPMENTS

Charge State Breeder Improvements

Although the efficiency of the charge state breeding has improved over the past years, it is still lower than reported in other places [1]. Detailed ion optical simulations have shown that the reason for this is mainly the ion injection into the source. The present design uses an opening in the iron joke for the solenoid field, which has an asymmetric cutout. This is used for connecting the waveguide for the RF and the gas inlet. It introduces steering to the injected beam, which is difficult to compensate, and ions can be lost. A new design has been developed which uses a cylindrical symmetric yoke. It will also require some changes to the plasma chamber, which then allows the connection of two waveguides. Details of the new design are presented in [10].

Off-line Ion Source

Constant developments are underway to improve reliability and stability and meet the experimenters' requests for specific beams from the off-line ECR ion source. This mainly involves changes to the gas inlet system to optimize for specific gas compositions and testing and optimizing materials to be used in the oven or as sputtering targets. With its present configuration, the ion source is not optimized for the operation at a wide range of ion energies as required for the experiments. This causes beam losses in the transport, especially in the section close to the source. Although this is usually not a big problem for stable ions, it can cause instabilities in the beam. Beam losses that cause sputtering and material deposition make frequent cleaning and maintenance of this beamline section necessary. Therefore, a two-step acceleration at the extraction is being developed in a manner similar to that of the charge breeder source. It will be accompanied by changes in the ion optical components directly after the extraction to match the new design to the beam transport.

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