A NOVEL METHOD FOR THE PREPARATION OF COOLED RARE ISOTOPE BEAMS

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Abstract

A storage ring can be used for magnetic separation of the different beam components which are produced by projectile fragmentation of a primary heavy ion beam in a production target. In addition to the separation by the magnetic field, the application of electron cooling allows the separation by forcing the ions to a certain velocity. As a result the different isotopes initially stored on the same orbit are separated and a certain component of the injected cocktail beam from the target can be prepared with high selectivity. A first demonstration of this method at the heavy ion storage ring ESR has been performed.

INTRODUCTION

The production of isotopes by projectile fragmentation of a heavy ion beam is commonly achieved by the use of magnetic separators. The selection of an isotope is based on magnetic separation of a certain species which is created within a multi-component cocktail of isotopes emerging from the production target. Further refinement of the separation employs the combined $B\rho - \Delta E - B\rho$ separation which allows the preparation of isotopically pure beams of secondary rare isotopes [1].

In combination with beam cooling a storage ring can be very powerful in the identification and separation of isotopes as demonstrated in the measurement of masses of rare isotopes by Schottky Mass Spectrometry [2], but also in an isochronous mode of the storage ring optical lattice [3] the masses of short-lived isotopes can be determined with high resolution by measurement of their revolution time by a time-of-flight method.

The storage ring can also be employed in the selective preparation of rare isotope beams. For an incoming ensemble of rare isotopes the storage ring acts as a filter selecting particles which match a magnetic rigidity $B\rho$ window defined by the acceptance of the injection orbit. For a given value of the magnetic rigidity particles with different mass over charge ratio have also different velocities. All injected particles have the same ratio $Am_o\beta\gamma c/qe = B\rho$, with the mass Am_0 and charge qe of the ion and the relativistic Lorentz factors β and γ. Therefore these particles, although they can have different velocity or specific energy, will circulate within a certain band defined by the momentum acceptance of the injection orbit.

If the storage ring is equipped with electron cooling, it can also be used to selectively separate certain isotopes from a cocktail of rare isotopes. The selectivity originates from the fact, that the storage ring acts a $B\rho$-separator, whereas the application of electron cooling drags all rare isotopes after storage in the ring to the same velocity, corresponding to an identical specific kinetic energy of the stored rare isotopes. As a result the cooled rare isotopes circulate on different orbits determined by their mass and charge and the velocity of the electrons. The different isotopes will be horizontally separated in a dispersive section of the ring. There the required isotope can be selected by the use of mechanical scrapers to remove all other species.

COOLED BEAM PROPERTIES

The possibility to separate and prepare cooled beams of isotopically pure rare isotopes is strongly linked to the power of the cooling process and the achievable phase space density of the cooled beam. In general, cooling can increase the phase space density by many orders of magnitude. On the other hand, the phase space density of heavy ion beams under electron cooling is limited by intrabeam scattering, as is known from theoretical and experimental investigations [4]. The emittance and the momentum spread grow with the number of particles [5]. Even for intensities of up to 10^7 stored ions the 3σ-value of the emittance is below 0.1 mm mrad and of the momentum spread below 1×10^{-4}. The 3σ- value of the transverse distribution is relevant, if a scraper is moved into the tail of the distribution, the surviving intensity of the stored beam is, for a certain scraper position, approximately equal to the fraction within the 3σ-value of the transverse distribution [6]. For low intensity beams of 10^3 stored ions or less, which is not unusual for exotic rare isotopes, even much lower emittance and momentum spread can be achieved. A momentum spread below 10^{-6} and emittances below 10^{-5} mm mrad (3σ-values) were demonstrated experimentally [5].

The possibility to separate cooled beams by collimators or scrapers is also linked to the ion optical functions at the location of the intercepting device. Best separation is achieved at a location with large dispersion and small horizontal beta function. As values which are well suited for good separation and also realistic in a typical storage ring, a dispersion $D = 10$ m and a horizontal beta function $\beta_x = 10$ m at the location of the scraper is assumed. For these values the contributions to the beam size by dispersion and emittance are both less than 1 mm, if the typical momentum spread of less than 10^{-4} and an emittance below 0.1 mm mrad is achieved. For this beam quality beam

components with different mass to charge ratio and a corresponding difference in momentum of order 10^{-4} can be separated by destructive scrapers. For the ultracold low intensity beams, which were observed at the ESR for intensities below 10^3 stored particles [5], with much smaller emittance and momentum spread, the separation power is another two orders of magnitude better. As a consequence, it is clear that the use of scrapers to electron cooled ions is a powerful tool to prepare single or few component beams from a many component cocktail of secondary particles.

EXPERIMENTAL DEMONSTRATION

An experiment demonstrating the feasibility of isotope separation was performed in the ESR storage ring [7]. A 10 mm thick beryllium target was installed in the beamline from the synchrotron SIS [8], which provides the high energy heavy ion beams, to the ESR. It was bombarded with a single intense bunch of up to 2×10^9 $^{238}U^{72+}$ ions which were accelerated in the SIS to 381 MeV/u. Accounting for the mean energy loss in the target, the beamline after the target and the ESR ring magnets were tuned to accept 186 MeV/u $^{237}U^{90+}$ ions.

The partial aperture injection kicker of the ESR can accept ions with a maximum transverse emittance of 20 mm mrad within a momentum window of $\Delta p/p = \pm 0.35$ % . All fragments produced in the target with a magnetic rigidity corresponding to the injection orbit of the ESR, which fell into this acceptance window, were stored. However, these ions differed in mass, charge and velocity, as the target produces secondary particles with a broad distribution of these quantities.

After storage in the ESR, electron cooling was applied, forcing all ions to the velocity of the merged electron beam. As a consequence, the revolution frequency and the orbit of the different beam components were changing to new values. For the ESR storage ring with a momentum acceptance $\Delta p/p = \pm 1.3$ % and an injection orbit with a momentum offset $\Delta p/p = +1.0$ %, particles with an initial velocity about more than 0.3 % below the electron velocity and about less than 2.3% above the electron velocity will be lost at the acceptance of the ring. The electron cooling force was utilized to drag a selected species to the required orbit by choice of the electron velocity. As the electron cooling force is weak, if the velocity difference between ions and electrons v_{rel} is large ($F \propto v_{rel}^{-2}$), it will take long to drag the ions to the new orbit. For fast cooling, e.g. important for short-lived isotopes, the electron velocity should be chosen close to the velocity at which the selected species is injected. At the end of the cooling process the ions which originally circulated on the injection orbit filled the full momentum acceptance of $\Delta p/p = \pm 1.3$ % of the ESR.

The ESR is equipped with a pair of scrapers installed in a section with large dispersion ($D \simeq 6$ m) and a moderate horizontal beta function ($\beta_x = 23$ m). The scrapers can be moved radially from the inside and outside towards the central orbit, they are pneumatically actuated and can be positioned to a programmable position with an accuracy of better than 0.1 mm. As both scrapers are designed to stop at the central orbit and cannot cross it, the selected beam component must preferentially circulate on the central orbit.

Various methods to bring the selected species to the central orbit are available. Dragging the ions with the cooling force of the electrons to the central orbit can be time consuming due to the reduced cooling force for ions with large relative velocity. The use of the rf system is not very selective, as also other isotopes can be captured by the bucket of the rf voltage. As the ESR is designed for ramping of the magnetic system, it is a well established technique to vary the magnetic field in a controlled manner that brings the selected beam component from its orbit after electron cooling to the central orbit.

Ramping of the magnetic field affects the orbits of all stored species, but keeps their separation to first order constant. Some components can be lost at the inner or outer acceptance limit, depending on the sign of the field variation. The end value of the magnetic field is chosen to bring the selected species to the central orbit. In order to profit from the precision of the scraper positioning of 0.1 mm the orbit with respect to the scraper should be defined with adequate precision. This is mainly achieved by precise control of the main dipole field, but additional local corrections can be added if necessary. The advantage of magnetic field variation is that the manipulation of the continuously cooled beam is very forgiving and not subject to unintended beam loss. The time for cooling can be minimized by cooling the selected species at a velocity which is close to the velocity after injection.

In the demonstration experiment an additional complication resulted from a requirement of the users. For the experiment the lithium-like charge state $^{237}U^{89+}$ was needed which could not be produced in large abundance at the relatively high primary energy of 381 MeV/u needed for fragmentation [9]. The lithium-like charge state was consecutively produced in the ring by recombination of $^{237}U^{90+}$ with electrons in the cooling section. With an electron current of 0.45 A in the electron cooler after 5 min. of storage nearly half of the stored ions ($1 - 2 \times 10^5$) had captured an electron and were converted to the lithium-like charge state. Then this charge state was selected for the preparation of the purified beam by increasing the magnetic field by about 1.1 % in order to bring this beam component to the central orbit.

In the final step the pair of scrapers was moved from the inside and the outside radially to the central orbit removing all species which were not circulating on the central orbit. The selected species and, depending on the distance of the scraper end position to the central orbit, a few species with very similar mass to charge ratio, i.e. species circulating very close to the central orbit, survived the final cleaning. This complex manipulation is illustrated in Fig. 1.

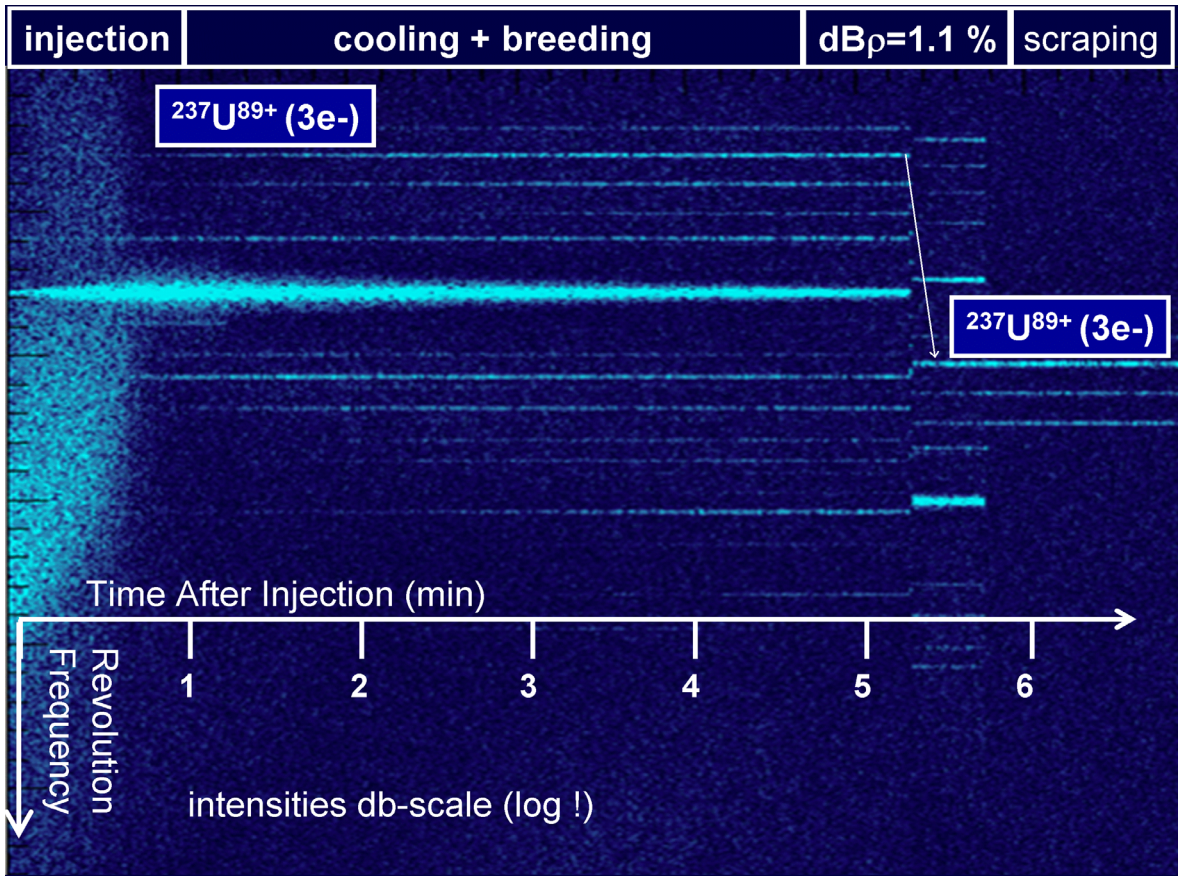

Figure 1: Longitudinal Schottky signal as a function of storage time. Initially a cocktail beam with a broad distribution is injected. After about 40 s the components are well separated due to electron cooling. The main component $^{237}U^{90+}$ is converted over 5 min. to $^{237}U^{89+}$ by electron capture in the electron cooler. After 5.3 min. the $^{237}U^{89+}$ component is moved to the central orbit by a 1.1 % increase of the magnetic field elements. After 5.8 min. scrapers are moved into the beam with only $^{237}U^{89+}$ and two other weak components ($^{234}Pa^{88+}$, $^{231}Th^{87+}$) surviving.

OUTLOOK

The demonstration of the method was applied to the regime of intermediate intensities where the different beam components have a horizontal size of around one millimeter and the control of the scrapers has to be performed with comparable precision. This way a rather intense rare isotope beam with more than 10^5 stored ions was prepared. For a low intensity beam with a beam size one to two orders of magnitude smaller the purification of the cocktail beam will be even more powerful. Scraper motion with a resolution better than 0.01 mm is available in the ESR by use of stepping motors [6]. This will allow to clean a certain isotope from others which have a charge to mass ratio difference of about 10^{-5}. Even better precision can be achieved by active control of the electron velocity or magnetic orbit correction at the scraper. This could result in the separation of species with differences in the charge to mass ration down to 10^{-6}. This will finally allow the preparation of isotopically pure beams of up to 10^3 stored rare isotope ions with the typical small emittance and momentum spread of the ultracold state achieved by electron cooling.

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