Bunching and cooling of radioactive ions with REXTRAP

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The REX-ISOLDE Collaboration

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Abstract

The post-accelerator REX-ISOLDE at ISOLDE/CERN will deliver radioactive ion beams with energies up to 2.2 MeV/u. For this purpose a Penning trap and an electron beam ion source are combined with a linear accelerator. REXTRAP — a large gas-filled Penning trap — has started its commissioning phase. First tests have shown that REXTRAP is able to accumulate, cool and bunch stable ISOLDE ion beams covering a large mass range. Fulfilling the REX-ISOLDE demands, it can handle beam intensities from a few hundred up to $1 \cdot 10^6$ ions per pulse at repetition rates up to 50 Hz.

Key words: Penning trap, radioactive ion beams, ion beam cooling

1 Introduction

Radioactive ions accelerated to energies of several MeV/u will open up new fields in nuclear physics. The REX-ISOLDE (**R**adioactive beam **EX**periment at **ISOLDE**) post-accelerator [2,4] at the online mass separator ISOLDE is designed for a final energy of 2.2 MeV/u. This is well suited for nuclear structure studies via coulomb excitation and particle exchange reactions for nuclei with A < 40. Further experiments dealing with astrophysics, atomic physics, and solid state physics are planned [1].

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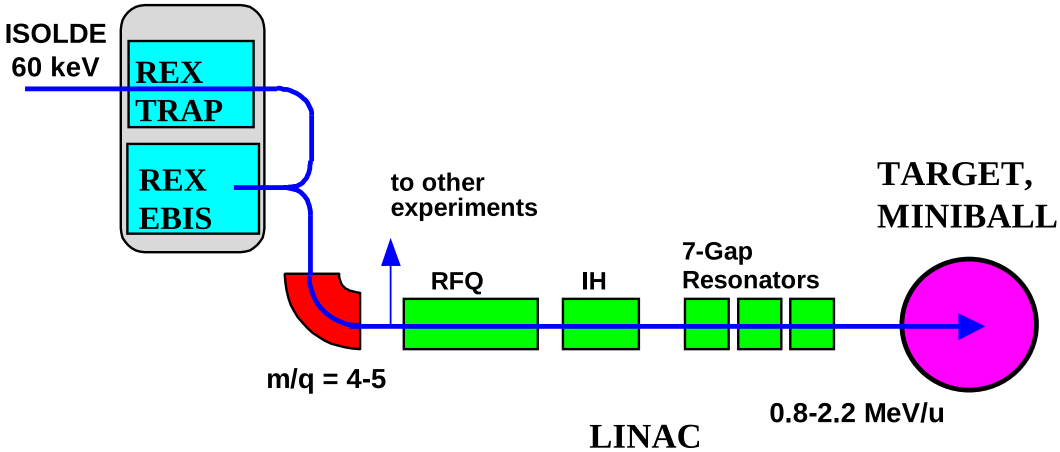

Fig. 1. Principal layout of the REX-ISOLDE post-accelerator.

In fig. 1 the layout of the post-accelerator is shown. The continuous beam of singly charged 60 keV ISOLDE ions is decelerated and accumulated in a gas-filled Penning trap (REXTRAP). The ions are cooled and released as bunches. After re-acceleration they are transferred to an electron beam ion source (REXEBIS). Here the charge state is increased to reach a charge-to-mass ratio of $q/m \approx 1/4.5$. With the magnetic q/m selector the desired charge state for the injection into the accelerator is chosen. The latter consists of an RFQ, an IH-structure and three 7-gap resonators. The final energy can be tuned from 0.8 to 2.2 MeV/u. It will run with a repetition rate of up to 50 Hz.

2 REXTRAP

For an efficient and cost effective operation of a radio frequency accelerator highly charged ions are required for injection. As a charge breeder for the REX-ISOLDE machine an EBIS will be used. High efficiency in an EBIS system is achieved by bunched injection. To form these bunches from the continuous ISOLDE ion beams and to match the acceptance of the EBIS ($5\,\pi$ mm·mrad at 60 keV) to the emittance of ISOLDE ($30\,\pi$ mm·mrad at 60 keV) REXTRAP has been developed. It uses the concept of bunching and cooling of an ion beam with a large gas filled Penning trap [6].

2.1 Principle

In a Penning trap ions are confined in radial direction by the action of a strong magnetic field and in longitudinal direction by a quadrupole electrical potential. This causes three eigen motions for the ions: oscillation parallel to the direction of the magnetic field and two radial oscillations perpendicular to it, the reduced cyclotron motion and the magnetron motion. The sum frequency of the latter two gives the cyclotron motion frequency of a charged particle in a pure magnetic field (ω_C = q/m·B).

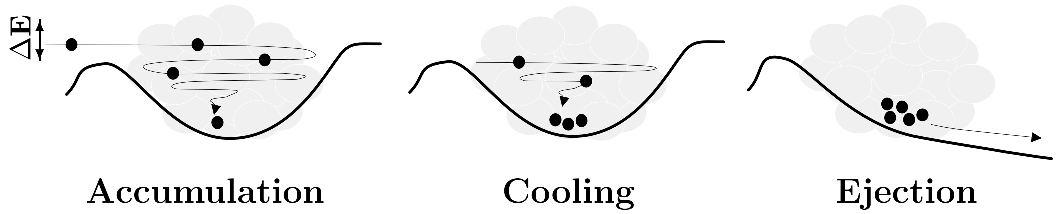

Fig. 2. Capturing, cooling, and bunching of a continuous ion beam in the potential of a gas-filled Penning trap.

In fig. 2 the principle of ion accumulation is illustrated. The injected ions are just allowed to pass the entrance potential well. During their passage through the system they will loose energy by collisions with the buffer gas and finally be trapped in the potential minimum. The dissipating force provided by the buffer gas leads to a further phase space reduction of the injected ion beam. Due to the energy dissipation the amplitudes of the axial and the reduced cyclotron motion decrease whereas the amplitude of the unstable magnetron motion increases. This can be circumvented by mass selective side band cooling [3,7,5]. An application of an azimuthal quadrupolar rf-field with frequency ω_C couples both magnetron and cyclotron motion. This leads to a simultaneous reduction of the amplitudes of both motions. Finally all ions are cooled and collected in the trap center. From there they can be extracted as short ion bunches by lowering the electrostatic potential well at the trap exit.

2.2 Experimental

The complete set-up of REXTRAP is placed on a 60 kV high voltage platform. The magnetic field of B = 3 T for the Penning trap is provided by a superconducting solenoid bore. Two differential pumping stages on both sides ensure good vacuum conditions in the beam lines going to and from the trap.

The injected ion beam is electrostatically decelerated in two stages. This part of the ion optical system is optimized for a minimum pick-up of radial energy when the ions enter the magnetic field region. This pick-up determines most of the energy spread ΔE the ions have when they reach the trap entrance. For an ISOLDE emittance of $\epsilon = 30\,\pi$ mm·mrad ΔE can be up to 70 eV. In order to achieve a high trapping efficiency a correspondingly high energy loss for the ions has to be ensured during one oscillation inside the trap.

The electrostatic trapping potential is provided by a stack of cylindrical electrodes. They are made from gold plated copper rings insulated by ceramic

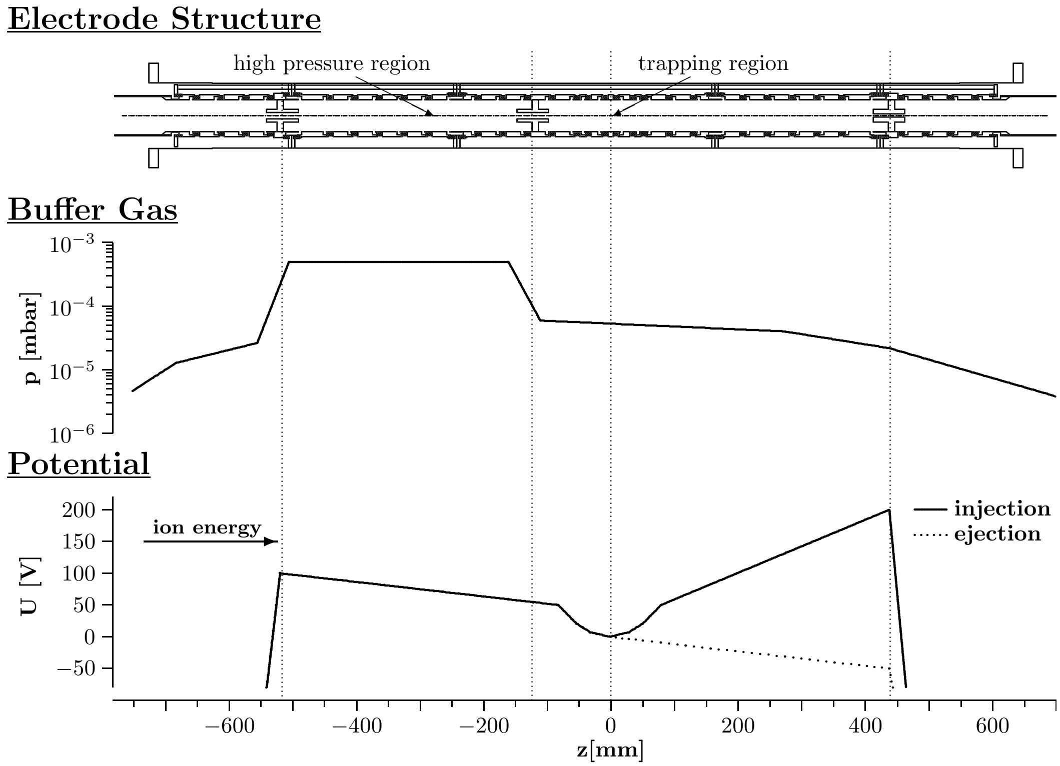

Fig. 3. Electrode structure, voltage and buffer gas pressure distribution inside the trap.

spacers. The trap is divided into two sections separated by diaphragms to achieve a voltage and pressure distribution as shown in fig. 3. A buffer gas pressure up to several 10^{-3} mbar argon in the first region provides enough energy loss for capturing the ions. Beads made from getter material installed in this region serve for buffer gas purification and a low residual gas pressure there. In the second part where the harmonic part of the trap potential is located the pressure is one order of magnitude lower. This gives a better cooling performance of the mass selective ion centering procedure and minimizes reheating during ejection.

After leaving the trap the ions are re-accelerated to 60 keV for their transfer to REXEBIS. The transverse emittance of the ejected ion pulses is expected to be in the order of $\epsilon_{trap} \leq 3\,\pi$ mm·mrad at 60 keV. It is determined by the final ion temperature (300 K) and their transverse spatial distribution. The longitudinal emittance depends mainly on the longitudinal dimensions of the ion cloud in the trap and the accelerating fields. Values of less than 10 eV·µs are expected.

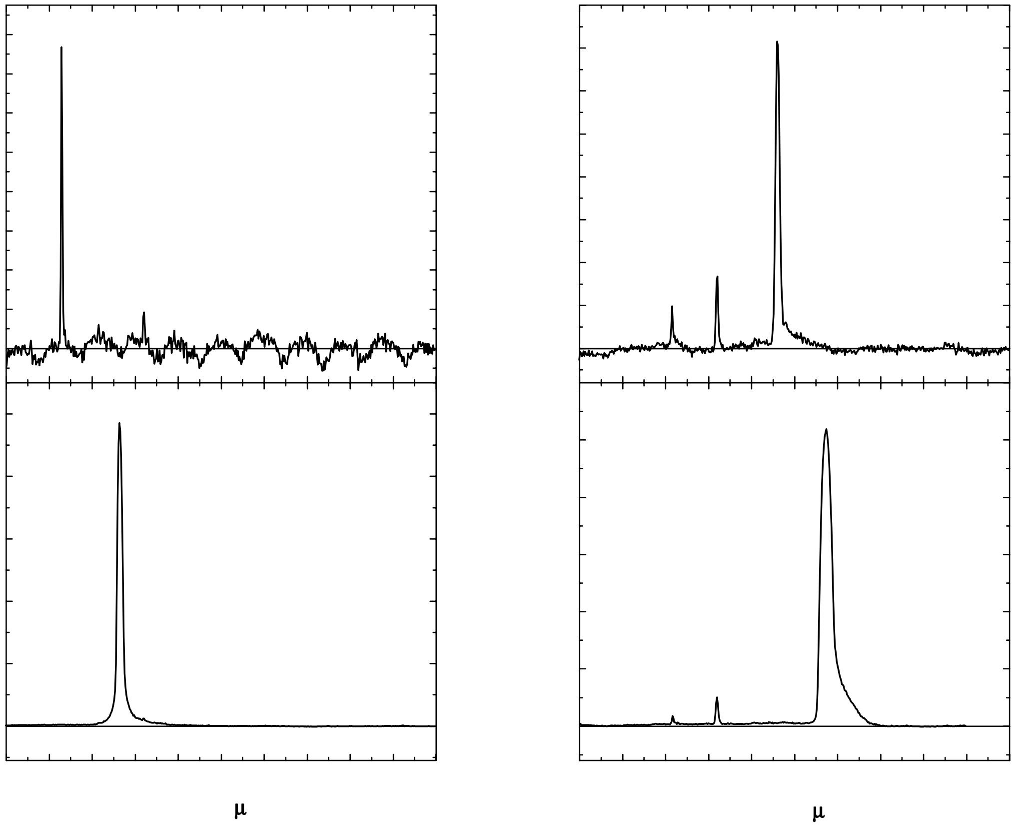

Fig. 4. Time-of-flight spectra of ions ejected from REXTRAP after accumulation of various ISOLDE ion beams.

2.3 Results

A test of the basic trap functions has been successfully performed with ion beams from ISOLDE and a test ion source. Systematic investigation and optimization of the most important trap parameters have been carried out.

For the measurements the following cycle was continuously repeated. The beam gate in front of the trap is opened for trap loading. Simultaneously the rf-field for ion centering is applied. After closing the beam gate an additional cooling time is needed in order to allow all ions to be centered. With a buffer gas pressure of about $1 \cdot 10^{-3}$ mbar argon in the high pressure region of the trap cooling time constants of a few milliseconds were reached which is close to theoretical predictions deduced from ion mobility data [8]. This allows REXTRAP repetition rates of up to 50 Hz. By pulsing the potential at the trap exit short ion pulses are extracted.

Trapping tests with stable isotopes ranging from ^{7}Li up to ^{181}Ta have been successfully carried out in order to verify the applicability of REXTRAP to a large mass range. Typical time-of-flight (TOF) spectra of accumulated and cooled ISOLDE ion beams after ejection out of REXTRAP are shown in fig. 4.

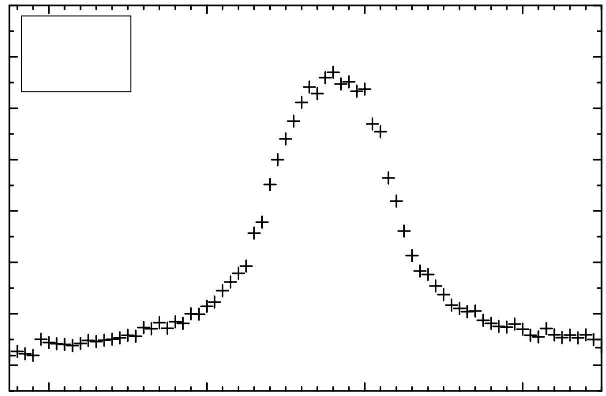

Fig. 5. Number of ions ejected from REXTRAP as a function of the applied radio frequency for the ion centering in the case of ^{133}Cs ($\nu_C = 343800\,$Hz).

These spectra have been obtained using a microchannel plate detector located around 1 m behind the trap exit at ground potential. They demonstrate the possibility of handling beam intensities ranging from the present detection limit of a few hundred ions per second up to 10^6 ions per cycle. With the trap repetition rate of 50 Hz this corresponds to more than $5 \cdot 10^7$ ions per second. In most TOF spectra peaks of trapped residual gas (mainly H_2O) and buffer gas ions can be seen in addition to those of the injected ions. These species are caused by impact with trapped secondary electrons produced near the trap entrance. In additional measurements it was possible to remove these unwanted ions by the application of a dipole excitation field at the magnetron motion frequency during the cooling process.

In principle the mass selectivity of the cooling technique could be used for a further purification of the ISOLDE beam. This is illustrated in fig. 5 which shows the number of extracted ions as a function of the frequency of the applied quadrupole field. However at a buffer gas pressure of about $1 \cdot 10^{-3}$ mbar the width of the resonance is completely determined by the correspondingly strong damping and a mass resolving power of only R $\approx 300 \ldots 500$ is achieved. A higher value of R can be reached if lower gas pressure in the trap region and longer cooling times are used.

Already during the first measurements reported here efficiencies of up to 30% for ISOLDE and 50% for the test ion source have been achieved. The lower value for the ISOLDE beam may find its explanation in a misalignment of a kicker bender system in the injection beam line, discovered recently.

REXTRAP has proved its ability to serve as a highly efficient accumulation, cooling and bunching system for ISOLDE ion beams. Emittance measurements of the ejected ion bunches will complete the characterization of the REXTRAP parameters.

Technical modifications to circumvent the contamination of the ejected ion bunches are already on the way. An electron barrier at the trap entrance will reduce the trapping of secondary electrons significantly. Additional getter material for cleaning the buffer gas and lowering the residual gas pressure in the trap will help to solve the problem.

For an increase of the capture efficiency to a value close to 100% an increase of the buffer gas pressure is planned. This was not possible during the measurements reported here in order to avoid damage of the used ion detector.

Above 10^6 trapped ions space charge effects were observed. The planned emittance measurements will show to which extent such effects can be tolerated in the transfer of the ions into REXEBIS.

Acknowledgements

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