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SHIPTRAP is Trapping: A Capture and Storage Device on Its Way towards a RIB-Facility

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Abstract. First off-line tests at the ion trap facility SHIPTRAP took place. The facility is being set up to deliver very clean and cooled beams of singly-charged recoil ions (Rare Isotope Beam) produced at the SHIP (Separator for Heavy Ion Production) velocity filter at GSI, Darmstadt. SHIPTRAP consists of a gas cell for stopping and thermalizing high-energy recoil ions from SHIP, an rf ion guide for extraction of the ions from the gas cell, a linear rf trap for accumulation and bunching of the ions, and a Penning trap for isobaric purification. The physics programme of the SHIPTRAP facility comprises mass spectrometry, nuclear spectroscopy, laser spectroscopy and chemistry of transeinsteinium elements. The progress in testing the sub-systems separately and in combinations is reported.

Key words: ion traps, RFQ buncher, Penning traps, buffer gas.

1. Introduction

Important pre-requisites for high-accuracy experiments are the extremely small phase space in which ions reside in a trap, the possible long storage time and the extremely high purity that can be obtained. From this the interest in coupling ion traps to sources of radionuclides arises. The purification is very important since contaminants always plagued the investigation of exotic radioactive species. This separation not only allows for very sensitive and accurate experiments to be performed within the ion trap itself but also allows the collected radionuclides to be extracted from the trap and studied in a well-defined low-emittance ion beam. Together, these possibilities open a wide range of physics applications.

SHIPTRAP will enable very sensitive and accurate experiments, performed within the ion trap itself or with an extracted beam [1]. The half-lives of the most neutron-rich isotopes of the elements up to hassium ($Z = 108$) are longer than one second, which is also predicted by theory for a large number of ions in this region of the chart of nuclei. This is long enough to prepare the ions and to perform precision experiments. The advantage of such facilities is that they enable the rich variety of physics experiments currently performed at ISOL facilities to be extended to isotopes for which target/ion source systems do not exist at ISOL facilities. The particular advantage that SHIPTRAP will have is the ability to ex-

tend these experiments to transuranic nuclides. Thus, SHIPTRAP will enable the application of refined trapping techniques for the first time to nuclides with nuclear charge $Z > 92$, extending even to the superheavy elements of which many have a sufficiently long half-life for trap technology.

2. The SHIPTRAP facility

SHIP is a kinematic separator for reaction recoils from thin targets irradiated by beams from the heavy-ion linear accelerator UNILAC at GSI [2]. It is optimized for the separation of heavy elements produced by fusion of projectiles from $A = 40$ to 80 with heavy target nuclei such as lead or bismuth. The primary beam has an energy close to 5 MeV/u and time-averaged intensities of typically $2 \cdot 10^{12}$–$5 \cdot 10^{12}$ ions/s.

The SHIPTRAP facility is set-up at the exit of SHIP. It stops and thermalizes the produced recoil ions in a noble gas from which they are then extracted and collected in a trap. The system is outlined in Figure 1. It consists of a stopping chamber containing the noble gas, an extraction system to bring the stopped ions into a vacuum region, a radiofrequency trapping system to collect the ions in this vacuum region and to cool them into well-defined bunches which are then extracted and injected into a Penning trap for isobaric purification. The Penning trap accumulates the ion bunches, filters out possible contaminants and further cools the ion ensemble to room temperature. This ensemble is then extracted on the demand of downstream experiments.

The noble gas in the stopping chamber, at pressures around 100 mbar, will thermalize recoil ions preferentially in the singly ionized state. An electric field, together with the gas flow, then guides the ions out of the chamber into the extraction system where they are separated from the gas. This system is a quadrupole rod structure with a length of 18 cm that confines the ions to its axis by an rf field while the noble gas is pumped away. An axial electric dc field applied to the

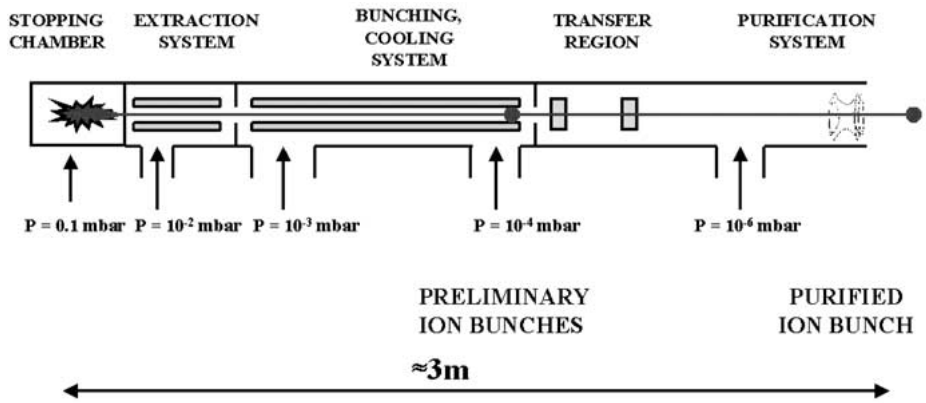

Figure 1. The overall SHIPTRAP configuration.

segmented rods guides the ions along the axis towards the bunching system. The recent development for the SHIPTRAP stopping chamber and the extraction RFQ is described elsewhere [3].

In the ion bunching system, a 1 m quadrupole rod structure immersed in a low-pressure buffer gas, the ions are trapped by a proper choice of longitudinal dc and transverse rf fields and cooled in collisions with the buffer gas. The RFQ-buncher was set up and tested. The purification system into which these preliminary bunches are collected is based on a Penning trap similar to the one used for this purpose at the ISOLTRAP facility at ISOLDE. In such a system the contaminating isotopes are very effectively suppressed due to the high mass resolving power of the cooling process. Depending on the trapping time it can reach M/δ M(FWHM) = 10^5.

The ion bunches delivered by this Penning trap system will have extremely low emittances, thermal energy spreads and pulse durations of typically less than a microsecond, although bunches of longer duration could be extracted if desired. These bunches could be delivered at any energy desired up to about 60 keV. In some cases it may be advantageous to use specifically those ions from SHIP that become neutral atoms in the stopping gas. These can then be re-ionized by a laser beam (resonance ionization spectroscopy, RIS) for delivery to the vacuum system. Such a scheme provides element selectivity, and for heavy elements isotopic selectivity as well, in the stopping chamber itself.

3. The RFQ buncher

The radiofrequency quadrupole is operated by applying to its rods a radiofrequency of amplitude V and frequency ω_{rf} and a dc bias voltage U. An ion with mass m and charge e, which enters the RFQ, performs an oscillation which is described by the solution of the Mathieu equations. In this equation one defines a pair of dimensionless parameters $a = 4eU/(m\omega_{rf}^2 r_0^2)$, and $q = 2eV/(m\omega_{rf}^2 r_0^2)$. This pair of parameters characterizes the working point in the a, q-stability diagram. The motion of the ion is stable if the amplitude of the oscillation remains finite, and unstable if its amplitude rises exponentially. In our case the RFQ was tested in rf-only mode, i.e. without a dc voltage U. Then the operating region lies on the q axis. For a certain rf voltage applied to the rods, all ions pass the filter for which q is less than the stability limit 0.908. The rods of the SHIPTRAP RFQ have a diameter of 9 mm. The distance between two opposite rods is 7.86 mm.

In first tests in the rf-only mode with a calibrated ion source a transmission of 93(5)% was achieved. Figure 2 shows a transmission plot for Ar^+ ions. The driving field frequency was set to $v_{rf} = 600$ kHz. The asymmetry in this transmission curve is well understood and explained by theory [4]. Trapping times of up to 30 s without significant ion loss have been achieved. Accumulation of ions with a dc-injection as well as a pulsed injection was demonstrated. The ions can be extracted in a pulsed mode in bunches with high phase-space density and can be delivered

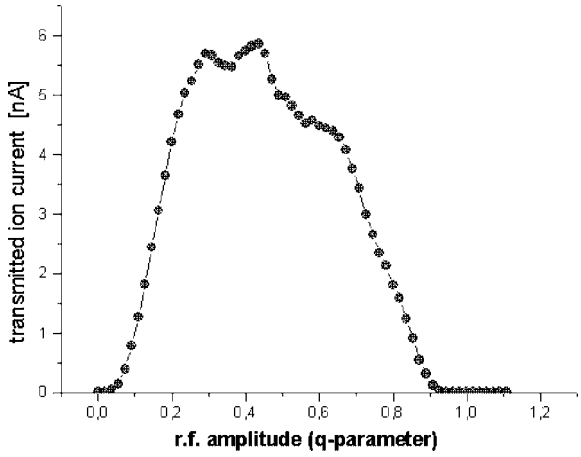

Figure 2. Transmission plot in rf-only mode for Ar^+ ions.

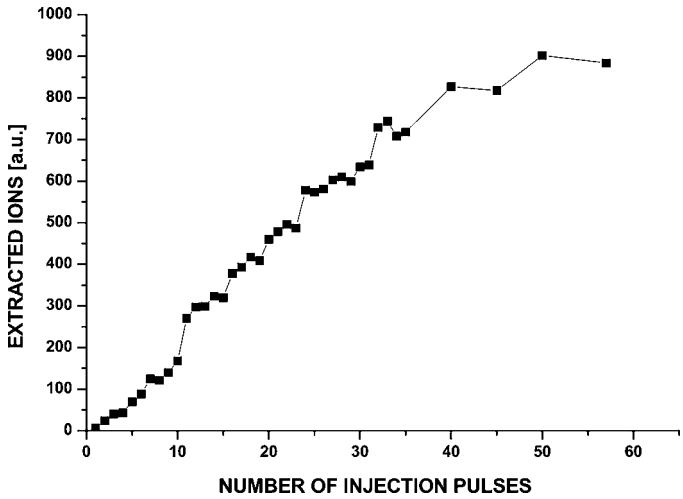

Figure 3. Accumulation of ions in the RFQ. The number of ions, which are extracted from the RFQ buncher and detected by a microchannel plate, is plotted as a function of the number of injection cycles.

to the high-vacuum region. Figure 3 shows an example for accumulation of ions in the RFQ. For this measurement the extraction electrode of the off-line ion source was pulsed, delivering about 10^3 ions per bunch.

4. The Penning traps

A double-trap system is installed within one superconducting magnet at SHIPTRAP. Both traps have cylindrical electrodes with an inner diameter of 30 mm. The purpose of the first trap is to catch ion bunches from the RFQ buncher and to purify the ion bunches. The second trap is for, e.g., mass measurements. The traps

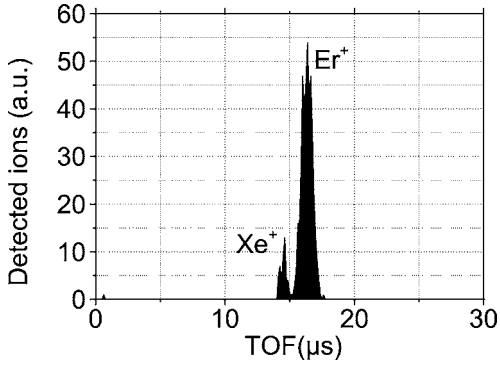

Figure 4. Ion bunch injected from the RFQ buncher, trapped for 200 ms in the purification trap and extracted through the diaphragm and the measurement trap.

(distance between the centers of traps: 20 cm) are separated by a diaphragm for differential pumping.

In a first test the injection into the magnetic field, the transmission between both Penning traps, and the extraction out of the magnet have been studied. Figure 4 shows an ion bunch injected from the RFQ buncher, trapped for 200 ms in the purification trap and extracted through the diaphragm and the measurement trap. The pure transmission efficiency through the Penning traps has been determined to be about 80%. The trapping efficiency, i.e. the ratio of the number of ions captured in the Penning trap compared to the number of ions delivered from the RFQ buncher is about 80%. The tests have been done under UHV conditions at 10^{-8} mbar.

In a second step the motion of stored ions in the Penning trap was excited by an electric rf field. The driving rf field was coupled to a split electrode of the trap for a dipole excitation of the cyclotron motion of the trapped ions. The excitation frequency was scanned and the number of extracted ions was measured. At each frequency step, ions were loaded into the trap, the excitation field was switched on, then the ions were detected on a microsphere plate (MSP). An example of such a cyclotron-frequency measurement with trapped Ar^+ ions is shown in Figure 5. When the driving rf frequency is in resonance with the cyclotron frequency ν_+ (at about 2.7 MHz) of the trapped Ar^+ ions, the size of their cyclotron orbits is increased such that the extracted ions cannot reach the detector, resulting in a pronounced minimum in the number of detected ions. Axial sidebands at the frequencies $\nu_+ \pm \nu_z$ (at 2.6 and 2.8 MHz) are clearly visible in Figure 5, which are due to anharmonic components of the electrostatic trapping potential.

Penning-trap mass spectrometers at ISOLDE/CERN [5], Stockholm [6], and Argonne [7] use a time-of-flight method [8] to measure eigen-frequencies of trapped ions. The ions are ejected out of the trap and their time-of-flight to a detector is recorded. Typically this requires the detection of a total number of 100–1000 ions. Assuming a production rate in the order of 10^{-3} ions/s, e.g., for Sg ($Z = 106$),

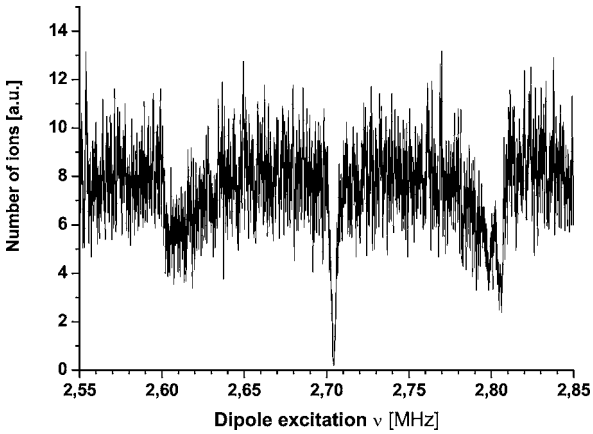

Figure 5. Dipole excitation of the cyclotron motion of stored Ar^+ ions in the Penning trap. When the cyclotron motion (at about 2.7 MHz) is excited, the number of extracted ions is strongly reduced.

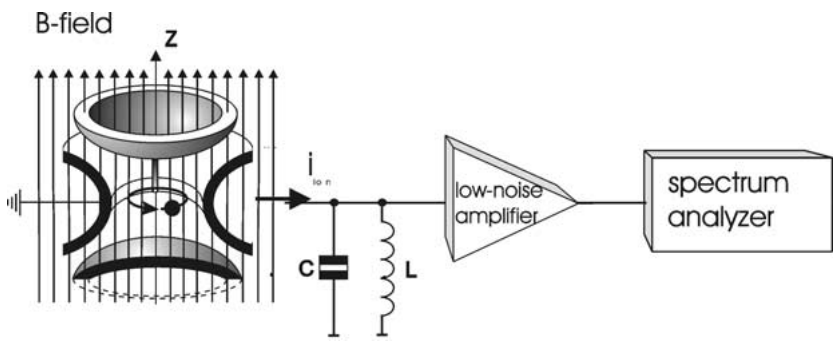

Figure 6. Principle of non-destructive FT-ICR technique. The image current of trapped ions is picked up on a split electrode, amplified and frequency-analyzed.

this corresponds to a required beam time of about 1–10 days. The measurement sensitivity can be enhanced by a non-destructive (Schottky) detection method via the image currents which are induced in the trap electrodes by the ion motion (Figure 6). This method is employed, e.g., at the University of Washington [9] and at MIT [10]. It allows for the non-destructive identification of one single ion. The required beam time for mass measurements on heavy elements would be strongly reduced. The image current of a single trapped ion is given by

$$I_{\text{ion}} = \frac{1}{\sqrt{2}} \frac{r_{\text{ion}}}{D} \cdot q \cdot \omega_{\text{ion}}. \tag{1}$$

This signal can be detected via a LC-resonance circuit of quality factor Q. With inclusion of the thermal noise of the circuit, the signal-to-noise ratio (S/N) is

$$\frac{S}{N} = \frac{\sqrt{\pi}}{2} \cdot \frac{r_{\text{ion}}}{D} \cdot q \cdot \sqrt{\frac{\nu}{\Delta\nu}} \sqrt{\frac{Q}{kT \cdot C}}, \tag{2}$$

where r_{ion} is the radius of the ion orbit in the trap, D characterizes the trap size, T is the temperature, and C is the stray capacitance of the system. The signal-to-noise ratio can be optimized by a large quality factor Q, a low temperature T, and by minimizing the capacitance C. The set-up, which is under development at SHIPTRAP, will consist of a cryogenic system with the trap environment at liquid nitrogen temperature and with an external superconducting resonance circuit at 4 K. With this set-up, single-particle detection sensitivity can be reached.

5. Summary

The SHIPTRAP facility at GSI Darmstadt is designed to slow down heavy-ion projectiles from the velocity filter SHIP to thermal energies, to accumulate and cool them in an ion-trap system and to deliver these ions as isobarically pure ion bunches with low emittance to physics experiments. After an intense simulation and construction phase all components are presently under test. SHIPTRAP will undergo a test beam time in winter 2001 and in summer 2002. The experimental programme which is envisaged by the SHIPTRAP user community promises to give new insights into the nuclear, atomic and chemical properties of elements beyond uranium.

Acknowledgement

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