Hyperfine Interactions **132:** 463–468, 2001.

Status of the SHIPTRAP Project: A Capture and Storage Facility for Heavy Radionuclides from SHIP

G. MARX[1,⋆], D. ACKERMANN[1], J. DILLING[1], F. P. HESSBERGER[1], S. HOFFMANN[1], H.-J. KLUGE[1], R. MANN[1], G. MÜNZENBERG[1], Z. QAMHIEH[1], W. QUINT[1], D. RODRIGUEZ[1], M. SCHÄDEL[1], J. SCHÖNFELDER[1], G. SIKLER[1], C. TOADER[1], C. WEBER[1], O. ENGELS[2], D. HABS[2], P. THIROLF[2], H. BACKE[3], A. DRETZKE[3], W. LAUTH[3], W. LUDOLPHS[3], M. SEWTZ[3] and the SHIPTRAP Collaboration[1]

[1] *GSI Darmstadt, Postfach 110552, D-64220 Darmstadt, Germany; e-mail: g.marx@gsi.de*
[2] *Sekt. Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany*
[3] *Institut für Kernphysik, Universität Mainz, J.-J. Becher Weg 45, D-55099 Mainz, Germany*

Abstract. The ion trap facility SHIPTRAP is being set up to deliver very clean and cool beams of singly-charged recoil ions produced at the SHIP 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 progress in testing the rf ion guide is reported. A transmission of about 93(5)% was achieved.

Key words: mass measurements, RFQ Buncher, buffer gas.

1. 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 [1]. It is optimized for the separation of heavy elements produced by complete fusion of projectiles from $A = 40$–80 with lead or bismuth nuclei. 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 at the end of SHIP 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. The noble gas in the stopping chamber, at pressures around one-tenth of an atmosphere, 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 short quadrupole rod structure that confines the ions to its

---

⋆ Corresponding author.

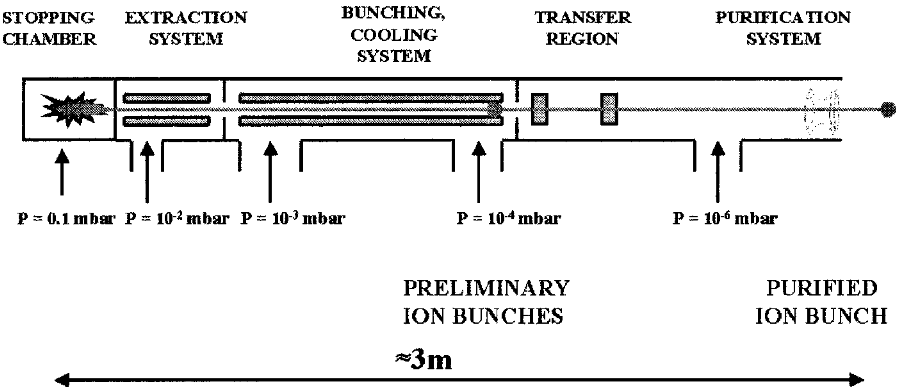

Figure 1. The overall SHIPTRAP configuration.

axis by an rf field while the noble gas is pumped away. An axial field within the structure 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 [2]. 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 axial dc and transverse rf fields and cooled in collisions with the buffer gas. The RFQ-buncher has been set up and is currently being 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.

2. The RFQ buncher

The classical Quadrupole Mass Analyzer (QMA) is operated by applying on its rods a dc bias voltage U and a radio-frequency of amplitude V and frequency ω_{rf}. An ion with mass m and charge e which enters the QMA performs an oscillation which is described by the Mathieu equations. In this equation one defines a pair of dimensionless parameters a, proportional to the dc bias voltage U ($a = 4eU/(m\omega_{\mathrm{rf}}^2 r_0^2)$) and q, proportional to the ac amplitude V ($q = 2eV/(m\omega_{\mathrm{rf}}^2 r_0^2)$). This pair of parameters characterizes the working point in a 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 QMA was tested in rf-only mode. The rf-only quadrupole is operated without dc bias, i.e., the operating region lies on the q axis. For a certain voltage applied to the rods, all ions whose operating points q are less than the stability limit 0.908 pass the filter. 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 about 93(5)% was achieved. Figure 2 shows a transmission plot

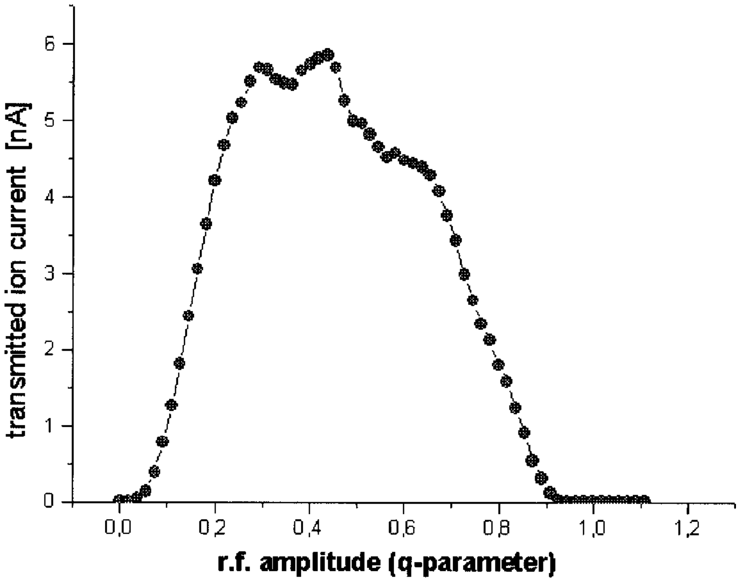

Figure 2. Transmission plot in rf-only mode for Ar^+ ions.

for Ar^+ions. The driving field frequency was set to $\omega_{\rm rf} = 600$ kHz. In simulations it was shown that the left edge of the transmission curve is affected by beam divergence, whereas the right edge is rather unaffected [3]. A lower transmission for low q values as beam divergence grows can be explained by the fact that ion entry angle grows; hence the probability of hitting the rods increases. The right edge is affected by beam width effects, becoming less abrupt as beam width grows. In simulations it was shown that this effect is more pronounced when the ion beam is not centered or annular. As a conclusion our transmission curves are indicating an off-axis ion source with low emittance.

Another interesting point becomes evident when we zoom into the center region of the stability diagram. In Figure 3 we benefit from a segmented Faraday Cup that gives us a closer insight in the shape of the extracted ion beam of Figure 2. The Faraday cup is divided into three segments, a 3 mm diameter inner section, a 3–8 mm diameter second ring, and an outer ring from 8 to 12 mm diameter. In Figure 3 one can see the detected ion currents. The sequence of maxima and minima on the central plate and the second ring shows how the beam emittance is affected by the operating point. The current on the third plate is low and not shown. The fundamental task of the RFQ buncher at SHIPTRAP is to cool the ions from the stopping chamber and to collect them. Since the RFQ buncher will therefore be operated under buffer gas it is necessary to investigate the influence of gas on the ion motion. The average effect of ion collisions with buffer gas molecules can be approximated by a frictional drag force. This leads to the usual form of the Matheu equation but with an added velocity dependent term. Figure 4 shows three measured transmission curves at different pressures. One can see a tendency that

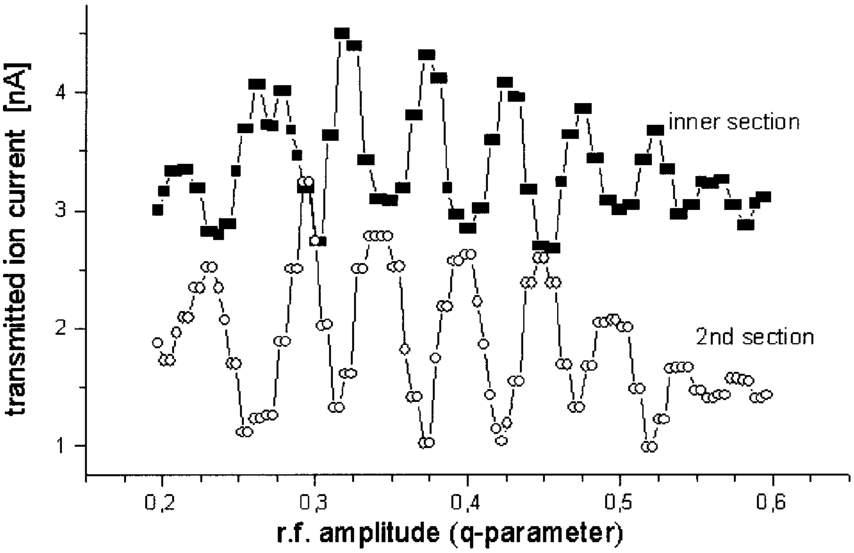

Figure 3. Transmission plot in rf-only mode for Ar$^+$ ions. Various maxima and minima on a segmented Faraday cup behind the RFQ showing a dependence of the emittance on the rf amplitude.

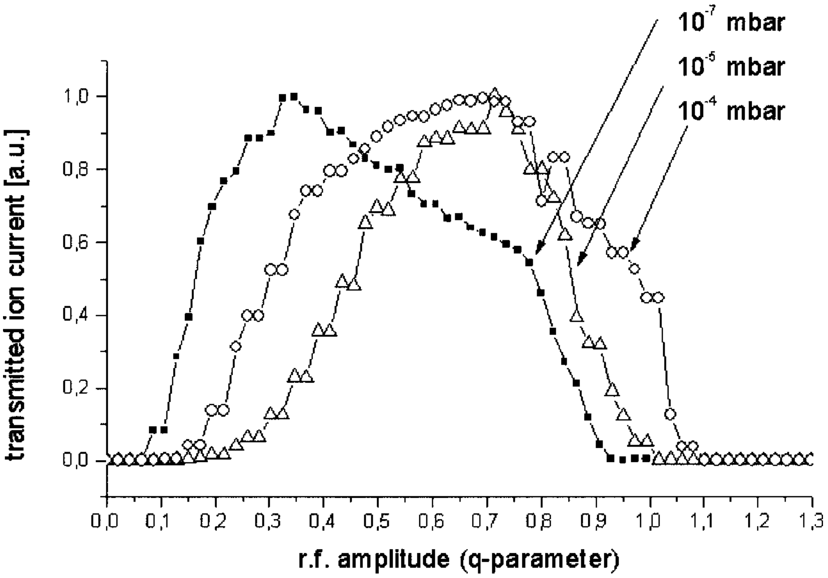

Figure 4. Influence of buffer gas on the transmission curve.

the right edge of the stability diagram is shifted to higher q-values. Due to the damping of the ion motion one can apply higher quadrupole field strength until the ion motion is unstable. On the other hand it should be noted that the pressure at which the stability region starts to broaden is typically near the minimum in the Paschen curve for voltage breakdown of the gas being used. In fact the range of investigation shown in Figure 4 did not reach the minimum in the Paschen curve since the used gas fed cross beam ion source is affected by an increase of the buffer gas pressure. We will repeat this investigations with a slightly changed setup that will provide us with better differential pumping between ion source and buncher. The information how much the stability region is increased under buffer gas operation is important since one tries to use the limited mass resolution of the RFQ in rf only mode to suppress contamination of a lighter ion species. The qualitative overall effect of space charge on an ion beam in an RFQ rod structure, neglecting the size of an ion beam due to thermal motion of the ions, will push out the ions until those at the periphery of the beam experience an effective radial electric force from the confining field that balances the radial expansion force of the space charge. Assuming a uniform charge distribution along the beam axis, the space charge electric field at the edge of a beam of radius r is balanced by the effective trapping field electric field. This results in a charge density

$$\rho_z = \frac{\pi \varepsilon_0}{4} \frac{m}{e} q^2 \omega_{\mathrm{rf}} r^2.$$

For a typical set of operating conditions ($q = 0.45$; $\omega_{\mathrm{rf}}/2\pi = 1$ MHz; $r = 2$ mm; $m = 100$ amu) the linear charge density will be about 0.2 nC/m. For the SHIPTRAP RFQ buncher of 1 m length assuming a drift field to give the ions an axial velocity of 1000 m/s, the ion density along the device result in a maximum beam current of about 200 nA. Our tests have been done well below this space charge limit.

3. Nuclear mass measurements of transuranium isotopes

A high-resolution Penning trap mass spectrometer coupled to the SHIPTRAP facility will allow for direct mass spectrometry of heavy actinide and transactinide isotopes, provided the background of transfer products can be sufficiently suppressed. In such measurements nuclear binding energies can be determined with high precision. Investigations of the heaviest elements at SHIP has led to the discovery of a shell-stabilized deformed region centered at $Z = 108$ and $N = 162$. This region of enhanced stability against fission interconnects the transuranium elements and the predicted superheavy shell located at $Z = 114$ and $N = 184$ [4]. For the most neutron-rich isotopes of the elements up to hassium ($Z = 108$) half-lives longer than 1 s were observed. These long half-lives open the possibility of high-accuracy mass measurements on heavy elements with ion traps [5].

4. 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 different physics experiments. After an intense simulating and construction phase first components are set up and under test. SHIPTRAP will start operation in Summer 2001. The experimental programme which is envisaged by the SHIPTRAP user community promises to give new insights into the nuclear, atomic and chemical properties of the transeinsteinium elements.

Acknowledgement

We acknowledge financial support by the European Union (Network EXO-TRAPS).

References

1. Münzenberg, G. *et al.*, *Nucl. Instrum. Methods* **161** (1979), 65.
2. Engels, O. *et al.*, this issue, 505.
3. Muntean, F., *Internat. J. Mass Spectrom. Ion Processes* **151** (1995), 197–206.
4. Möller, P. *et al.*, *At. Data Nucl. Data Tables* **59** (1995), 185.
5. Dilling, J. *et al.*, this issue, p. 331, p. 495.