HITRAP — HEAVY, HIGHLY-CHARGED IONS AND ANTIPROTONS AT REST*

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At the GSI Helmholtz-Center for Heavy-Ion Research, highly-charged ions up to bare uranium are produced by passing a 400 MeV/u beam through matter. Subsequently, the ions are decelerated, first in the experimental storage ring ESR from 400 to 4 MeV/u and in the HITRAP linear decelerator. It consists of an interdigital H-type (IH) structure and a radio-frequency quadrupole (RFQ) structure operated in inverse mode and decelerates the ions first from 4 MeV/u to 0.5 MeV/u and then to 6 keV/u. Deceleration down to 0.5 MeV/u has been demonstrated but its efficiency needs to be improved.

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1. Introduction

Heavy, highly-charged ions at very low but well defined energy are ideal systems for precision experiments [1]. In the following some examples are given.

If a single ion with just one electron left, as for instance hydrogen-like uranium, is stored in an ion trap, the g-factor of the bound electron in the extremely strong electro-magnetic field of the nucleus can be measured with

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unprecedented precision. Such a measurement would not only be a test of the most precise theory in physics, QED, but can be used to set new limits on fundamental constants like the electron mass.

The mass of a stored ion could be measured for different electron configurations with a very high precision of 1 ppt. This can be used to determine the electron binding energy with an uncertainty of a few electron Volt.

If many highly-charged ions are stored and cooled in a cryogenic environment, measurements of the hyperfine splitting can be performed with laser spectroscopy many orders of magnitude more precise than presently possible in a storage ring or electron beam ion trap. Stored clouds of ions also give access to X-ray spectroscopy with very high resolving power.

Processes like multiple-charge exchange can be studied with complete analysis of the kinematics in ion–atom collision experiments at very low, but well defined energies. For that, highly-charged ions are accumulated in the HITRAP cooler Penning trap and cooled by electron and resistive cooling to 4 K. After ejection a well defined ion beam will be targeted to a cold sample of neutral atoms and the products will be investigated by a reaction microscope.

If a highly-charged ion impinges on a surface a huge amount of energy is deposited on a very small spot. The nonlinear energy and particle distribution can, for instance, lead to self-ordering effects on the surface. To disentangle processes induced by the potential energy from irradiation damage due to high kinetic energy of the projectile, its kinetic energy has to be lower than the potential energy deposited per ion, hence, requires a beam of highly-charged ions below 100 keV total kinetic energy.

These experiments gain additional momentum and interest if conducted with antiprotons. Many successful investigations have been performed already at the antiproton facilities LEAR and AD at CERN/Geneva. HITRAP at the upcoming FAIR facility in Darmstadt and operated with antiprotons will offer new opportunities by the higher flux of antiprotons, the possible slow extraction out of the cooler trap and the very low emittance of the low energetic antiproton beam.

2. The HITRAP decelerator facility

At the GSI accelerator complex, using the universal linear accelerator UNILAC and the synchrotron SIS, highly-charged ions up to U^{92+} are produced by passing a 400 MeV/u beam through a gold foil (Fig. 1) stripping off all, or nearly all electrons. The HITRAP facility is built to decelerate those ions to almost rest and to provide them to the experiments. In a first step, the ions are decelerated in the experimental storage ring ESR [2] from 400 to 4 MeV/u accompanied with stochastic and electron cooling to keep the emittance small. Then, in the HITRAP linear decelerator the deceleration is performed in two additional steps. An interdigital H-type (IH) structure and a radio-frequency quadrupole (RFQ) structure are operated in inverse mode to decelerate first from 4 MeV$/u$ to 0.5 MeV$/u$ and then further to 6 keV$/u$. For final cooling below one meV the ions are captured in a Penning trap. The total kinetic-energy reduction amounts then to 13 orders of magnitudes from production to final storage in the Penning trap.

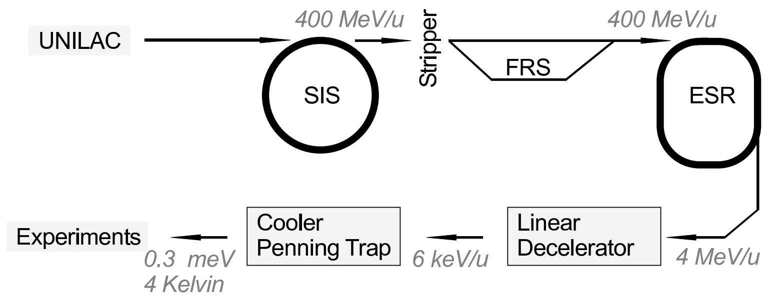

Fig. 1. The HITRAP facility at the GSI accelerator complex.

The highly-charged ions of unstable nuclei can also be investigated. Those are produced and mass separated by the fragment separator (FRS) and injected in the experimental storage ring (ESR).

3. Status of installation

All components from the ESR to the IH structure, the RFQ and most parts of the low energy beam line are installed and taken into operation. In detail, these are the beam transfer line between ESR and HITRAP, which includes several new diagnostics and a tubular diaphragm to decouple the ESR vacuum from the HITRAP vacuum. Downstream, the double-drift buncher has been installed and tested including two capacitive pickups, with which the time structure of the beam could be diagnosed. In 2008 the first accelerator structure, the IH, has been installed. Also the high-frequency amplifiers, plunger drivers, electronics and all necessary diagnostics have been tested and perform as expected. The intermediate section between IH an RFQ is in place and being tested including the spiral rebuncher. The RFQ structure itself has been mounted in 2009.

The cooler Penning trap has been assembled to be installed in the immediate future after the ongoing magnet tests. An electron source to feed the trap with electrons needed for cooling has been designed and built. It uses a photo cathode covered with caesium from which electrons are emitted in the light of an ultraviolet flash lamp.

To test the cooler Penning trap two different ion sources are available. Either protons and deuterium from a gas discharge source or light, highly-charged ions can be used to investigate the properties of the electron and resistive cooling with different species. The light, highly-charged ions are produced in a small room-temperature electron beam ion trap (SPARC-EBIT) based on permanent magnets [3]. This is located on the second floor and can hence produce ions for the cooler Penning trap tests as well as for the testing phase of the experiments.

All components for the transfer line to the second floor arrived meanwhile at GSI and are ready for installation. The beam line to the second floor, which connects to the SPARC-EBIT [3] and the experiment beam line, can be installed and tested off-line beginning of next year.

4. Results of commissioning

Six beam times of about one week each have been used until now for the commissioning of HITRAP. For that the only relevant parameters for the ion beam used are energy, which should be 4 MeV/u, and mass-to-charge ratio that needs to be below three.

In the first beam times, the cooling process in the ESR was optimized with stochastic cooling at injection energy. A reliable and stable extraction has been achieved, the double-drift buncher was operated successfully, and the first tests of the IH structure were performed. Beam bunches have been detected with capacitive pick ups and by a diamond detector [4, 5]. The emittance of the incoming beam at 4 MeV/u was measured as reported in [6] and again in a recent run by investigating the beam profiles with changing focal length of a lens. It turned out to be slightly bigger than the 2.2 πmm mrad assumed in transverse beam dynamics calculations.

In October 2008 a $^{64}Ni^{28+}$ beam was injected into the HITRAP decelerator, which was detected on a movable array of diamond detectors. In Fig. 2 the measurement on the diamond detector is shown. A diamond detector has single ion sensitivity and the signal created by the ion impinging on the detector is proportional to the ion's energy. Our detector was apparently already damaged by earlier irradiations which degraded its resolution. However, beam components with different energies are visible. To calibrate the energy scale, a spectrum without radio frequency supplied to the IH structure was taken first (dashed line). As soon as the IH was then switched on the second spectrum (solid line) was taken. As also seen in simulations the decelerated beam has at least two components and this indicates that the settings of the double drift buncher are not yet optimal. Only a fraction of the detected beam is decelerated to low energies: With the present set of parameters, at least 10% of the detected beam was decelerated to 0.5 MeV/u.

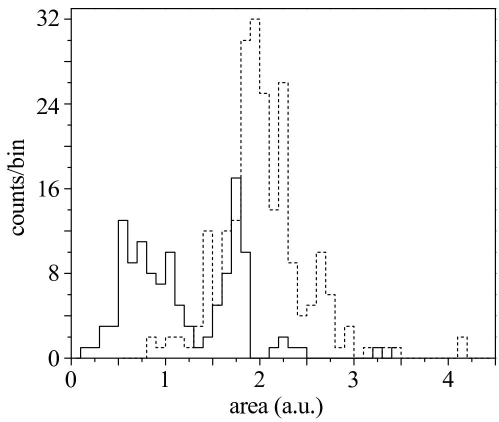

Fig. 2. Signal on the diamond detector binned by peak area, which is proportional to the impinging ion's energy, with the radio frequency of the IH structure switched on (solid line) and off (dashed line).

The main result from the first tests is that the IH structure transmits a large part of the beam independent of its energy. This has been investigated meanwhile in extensive calculations. Those calculations reproduce that behavior and showed that the amplitude of the radio frequency driving the cavity is more sensitive than for accelerating structures. Additionally, it was found that the input energy is a significant parameter for the deceleration efficiency and has to be controlled precisely by tuning the second buncher to the right phase and amplitude.

5. Outlook

For the further commissioning the repetition rate will be increased and the diagnostics improved. The repetition rate is given by the time the ions need in the GSI accelerator complex until they are delivered to HITRAP. Most of the time is spend to decelerate and cool the ions in the ESR. For commissioning the two step deceleration cycle will be reduced by one step. Intermediately charged ions will be injected at 30 MeV/u, hence, only decelerated from 30 MeV/u to 4 MeV. This will yield twice as many ion bunches per time and will speed up commissioning and optimization.

In order to ease the tuning of the IH structure in combination with the double-drift buncher a "one-shot" energy analyzer is being developed. This device will yield the energy spectrum of the beam from the IH after each shot. From simulations it was found that this spectrum shows characteristic patterns dependent on the particular tune of the components along the beam line.

The principle layout of the one-shot energy analyzer is shown in Fig. 3. A small permanent magnet bends the beam according to its energy. The magnetic field of 0.5 T over 45 mm creates a displacement of about 10 and 4 mm in the detection plane for a $^{136}Xe^{54+}$ beam at 0.5 and 4 MeV/u, respectively. If sent first through a slit 0.2 mm wide and having the detection plane at a distance of 135 mm from the magnet's center we will reach an energy resolution of about $\Delta E/E = 0.2$ at 0.5 MeV/u, equivalent to 100 keV. The detection on a multi-channel plate in combination with a phosphorous screen ensures highest sensitivity.

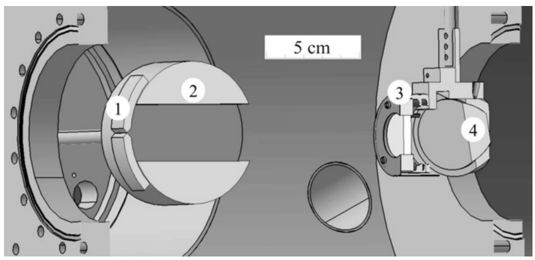

Fig. 3. Layout of the one-shot energy analyzer. The beam is send through a narrow slit (1) before it is dispersed by a permanent magnet (2). The energy dependent displacement is detected and converted into light on a single-ion sensitive multi-channel plate and phosphor-screen arrangement (3). The light is deflected with a mirror (4) to a CCD camera behind a glass viewport.

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