HITRAP – A DECELERATOR FOR HEAVY HIGHLY-CHARGED IONS

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Abstract

Heavy, highly-charged ions (HCI) with only one or few electrons are very interesting systems for precision experiments as for instance tests of the theory of quantum electrodynamics (QED). In order to match the production of HCI at 400 MeV/u with the requirements of the experiments – stored and cooled HCI at low energy - the linear decelerator facility HITRAP is being built at the experimental storage ring (ESR) at GSI in Darmstadt. The ions are decelerated in the ESR from 400 MeV/u to 4 MeV/u, cooled and extracted. The ion beam phase space is then matched to an IH-structure to decelerate from 4 MeV/u to 0.5 MeV/u before a 4-rod RFQ reduces the ions energy to 6 keV/u. Finally, the HCI are cooled in a Penning trap to 4 K. Up to one million highly-charged ions per deceleration cycle have been decelerated from 400 MeV/u to 0.5 MeV/u already and the commissioning of the remaining components is ongoing.

INTRODUCTION

Heavy, highly-charged ions like U^{91+} are very attractive systems for cutting edge experiments in atomic, nuclear and solid state physics [1]: They are simple and, hence, in combination with the very strong electric field of the heavy nucleus a perfect spectroscopic testing ground for the appropriate field theory, quantum electrodynamics (QED), at the strong-field limit. Measureable quantities for those tests are the g-factor of the bound electron, the electron binding energies or the hyperfine splitting. For those measurements, which require high precision to be decisive, the ions have to be stored, as single ion or in an ion cloud, in a well defined environment at very low energy as offered by a Penning trap. The observation of the stored particles will then allow for mass measurements at the ppt level and hence the binding energies of the components with eV precision, the determination of the bound state g-factor with a precision that even tests our knowledge of fundamental constants like the mass of the electron or, combined with laser excitation a several hundred times more precise investigation of the transition energies between hyperfine levels than feasible before.

Also new and unexplored reaction phenomena can be observed: Heavy, highly-charged ions are very instable systems when in close contact with electrons since a huge potential energy is concentrated in a very small volume. When those HCI at very low energy come close to neutral matter relaxation processes happen very fast and give snapshot-like insight into the dynamics and correlation of the electrons in the neutral collision partner. If energy and position are well defined the exchange of multiple charges can be studied by a complete analysis of the kinematics of all involved particles. For that, highly-charged ions are accumulated in a 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.

When the large potential energy that is concentrated on a small spot is released on the surface of a solid, self-ordered structures have been observed and need further investigation to clarify the role of impact energy and potential energy. This can be accomplished only if the impact energy, i.e. the kinetic energy of the particle, is well below the potential energy of a few 100 keV.

All those experiments require that kinetic energy and spatial position of the highly-charged ions can be well controlled. This is in contradiction to the most efficient production process that employs stripping of electrons at high energies by sending relativistic highly-charged ions with still many electrons through matter. The solution is a decelerator and storage facility for highly-charged ions produced by stripping all electrons of the ions from a 400 MeV/u beam – the HITRAP facility.

THE HITRAP FACILITY

The HITRAP facility is installed at the accelerator complex of the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany. It provides slow, heavy, highly-charged ions, produced by stripping of all

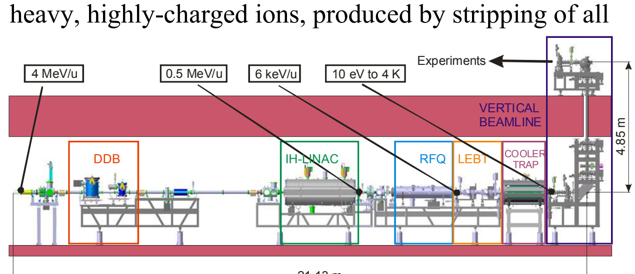

Figure 1: Overview of the HITRAP facility with the major components indicated. DDB: Double Drift Buncher for bunching the beam to adapt it to the longitudinal acceptance of the decelerator, IH–LINAC: Interdigital H-type structure for deceleration, RFQ: Radio-Frequency Quadrupole accelerator structure for deceleration, LEBT: Low-Energy Beam Transport line for efficient injection into the trap, COOLER TRAP: Penning trap for final deceleration and cooling.

electrons from medium charged ion, to various experiments applying a linear decelerator in connection with a Penning trap. The ions are decelerated and cooled such that the experiments can be supplied with up to 10^5 ions in highest charge states, as for instance bare uranium, with an energy spread below 1 eV and at low total energy of only a few keV.

Deceleration in the ESR

The heavy, highly charged ions produced at 400 MeV/u are at first decelerated in the Experimental Storage Ring (ESR) [2] before injection into the linear decelerator. In the ESR the energy is reduced from 400 MeV/u to 4 MeV/u accompanied by stochastic and electron cooling. After injection at 400 MeV/u the ions are immediately cooled stochastically for a few seconds. Then a first deceleration step from 400 MeV/u to an intermediate energy of 30 MeV/u is performed. The stored particle beam is cooled with electrons for about five seconds before it is again bunched to prepare for the final deceleration step from 30 MeV/u to 4 MeV/u. To allow for reproducible and stable ejection of a well defined beam, electron cooling is applied again. The beam, which is coasting after electron cooling, is then rebunched to a single, one-microsecond bunch as required for capture in the cooler Penning trap further downstream.

Linear Decelerator

The linear decelerator consists of three main components (Fig. 1): the double drift buncher (DDB), the interdigital H-type structure, and the radio-frequency quadrupole structure with an integrated debuncher.

The double drift buncher is needed to restructure the 1 µs macro bunch into 0.5 ns bunches that match the radio-frequency buckets of the decelerating structures. At the linac frequency of 108 MHz, the double drift buncher cavities run at 108 and 216 MHz, respectively. It has been tested with ion beam from the ESR and operates according to specifications [3].

The ions then enter the interdigital H-type structure for deceleration from 4 MeV/u to 500 keV/u. The IH structure has 25 accelerating gaps and is completed with a magnetic quadrupole triplet still inside the resonator tank. The total deceleration voltage of 10.5 MV is reached by driving the resonator with a 200 kW amplifier running at 108 MHz. After the IH the decelerated particles are rebunched in a two-gap spiral buncher to meet the requirements for injection into the RFQ.

For further deceleration from 0.5 MeV/u to 6 keV/u a four-rod radio-frequency quadrupole (RFQ) structure has been designed and built. This two-meter long RFQ, with a maximum vane-vane voltage of 77 kV, is completed with an integrated debuncher to reduce the energy spread from about 7% to 4% for optimal injection into the cooler Penning trap.

Cooler Penning Trap

After deceleration to 6 keV/u the ion bunch has a large divergence as well as energy spread. An emittance of 100 π mm mrad and an energy spread of up to 4% require substantial cooling before the ions meet the requirements of the experiments. This is accomplished in the cooler Penning trap, where the ions are captured in-flight and then stored in a combination of a weak electric quadrupole field and a 6 T magnetic field. The interaction with simultaneously stored electrons and, in a second step, a cooled resistive circuit reduces the energy of the stored ions to well below 1 eV. The ions are then ejected either in 1 µs bunches or quasi-continuously and separated with respect to charge state by a magnetic dipole. Then a beam line with electrostatic quadrupole lenses takes over the transfer to the experiments. At the end about 10^5 heavy, highly-charged ions up to bare uranium will be delivered with an energy spread below 1 eV every 10 to 30 seconds. The complete decelerator is designed for mass-to-charge ratios below three which makes it possible to decelerate also antiprotons once available at the future FAIR facility.

COMMISSIONING

Until now eight commissioning beam times of about six days each have been carried out for HITRAP. The major challenges for commissioning of the HITRAP linear decelerator are the low repetition rate and the small beam intensity. While the low repetition rate causes very time consuming, tuning and optimization efforts the low intensity requires adapted and newly developed diagnostic tools.

For the two recent commissioning runs a new mode of operation has been developed and used. The heavy-ion synchrotron SIS accelerates to 30 MeV/u only before the ion bunch is transferred to the ESR. This removes the first deceleration and cooling steps in the ESR and reduces the cycle time from about 50 to below 30 seconds.

The beam diagnostics systems at HITRAP are a combination of Faraday cups, single crystal YAG scintillators and wire grids for transversal beam analysis. The scintillation crystals proved to be very useful since even bunches with considerably less than 10^6 ions are easily detectable.

For longitudinal beam analysis capacitive pickups were

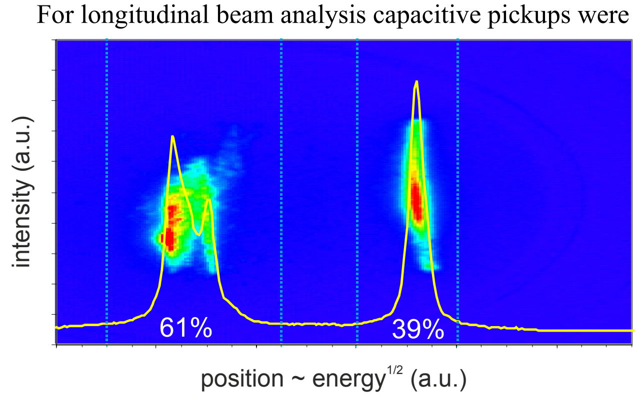

Figure 2: Energy spectrum of ions after the IH. The dashed lines indicate the areas used for integration. The rightmost peak corresponds to 0.5 MeV/u and the leftmost one to 4 MeV/u.

installed initially. Given enough intensity, i.e. at least 10^7 charges per 1 µs bunch, those pickups deliver enough signal to tune and monitor the operation of the double-drift buncher (DDB). However, it was not possible to measure or tune the beam energy after deceleration due to the present mixture of ions with different energies (compare also Fig. 2). After first successful tests with a semi-conductor detector based on poly and single crystalline diamond in combination with magnetic separation of the different energies present in the beam [4], a special diagnostic scheme for a one-shot energy analysis has been developed based on a permanent magnet and a micro-channel plate detector – phosphor screen combination [5].

Optimization of DDB and IH

After installation of the one-shot energy analyzer the optimal settings of DDB and IH for deceleration have been found. Especially the second buncher of the DDB is very important when it comes to adjusting the beam energy to fit the acceptance of the IH. It turned out that only slight changes (0.5%) in beam energy as delivered by the ESR require a noticeable retuning of the phase difference between DDB and IH.

The result of an optimized setting is shown in Fig. 2. About 40% of the overall beam that is detected after the IH is decelerated to 0.5 MeV/u. This is to be compared to about 55% deceleration efficiency as deduced from recent calculations that include the measured gap voltage distribution in the IH structure. The measured distribution deviates less than 2% from the expected distribution, a value reached after retuning the IH resonator installing additional material in the low-energy section.

Beam Dynamics Calculations

The commissioning runs have always been accompanied with detailed ion optical calculations of transversal and longitudinal beam parameters. This way it has been understood that the IH also creates and transports ions of intermediate and full energy. Those ions disturb noticeably the detection and optimization of the wanted low-energy ions on the scintillating screens [5].

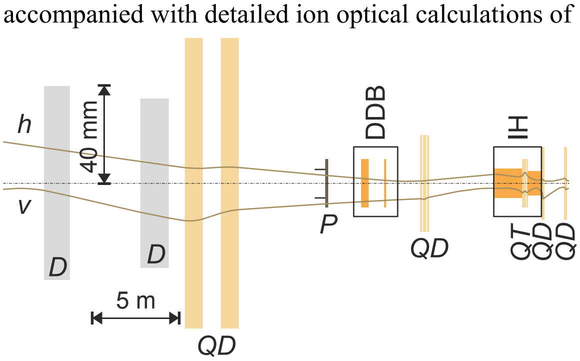

Figure 3: Ion optical system of HITRAP from the ESR to the RFQ. Transversally the beam is controlled by magnetic dipoles (*D*), magnetic quadrupole doublets (*QD*), and triplets (*QT*). The diaphragm (*P*) separates ESR and HITRAP vacuum and the black lines show the old aperture in scale. The lines are the beam envelopes in horizontal (*h*) and vertical (*v*) direction and the vertical size of the optical components is proportional to the available aperture. Note that horizontal and vertical scales differ.

New tools to describe the accelerating gaps correctly have been added to COSY INFINITY [6] and now the complete beam from ejection out of the ESR to injection into the RFQ can be calculated including the action of the decelerating structures. The result is shown in Fig. 3.

The beam properties have been measured in several commissioning experiments and are the basis for the detailed transport calculations. With an emittance of 0.6 π mm mrad and 3.2 π mm mrad in horizontal and vertical direction, respectively, the beam is described best; benchmarked with profiles measured during the recent commissioning runs along the beam line. One of the many challenges is to fit the beam through the narrow pumping barrier, a 150 mm long tube with originally 12 mm diameter. This barrier was introduced to decouple the vacuum of the ESR and the linear decelerator. New calculations, as presented in Fig. 2, show that only an increased diameter of 20 mm allows decelerating the beam in the IH such that it can be efficiently injected into the next decelerating structure, the RFQ. The beam envelopes shown in Fig. 3 demonstrate that a low divergence is essential for entering the IH, only possible with the bigger diameter of the pumping barrier.

CONCLUSION

Three major steps for decelerating heavy, highly-charged ions have been accomplished. The ESR, the DDB and the IH operate according to their specifications. The remaining tasks are to take the last decelerating structure of the linac, the RFQ, into operation and to inject, store and cool ions in the cooler Penning trap. The next commissioning run in November this year is hence dedicated to the RFQ and meanwhile the cooler Penning trap is tested offline.

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