THE HITRAP DECELERATOR AND BEAM INSTRUMENTATION

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Abstract

A linear decelerator is being commissioned for heavy, highly-charged ions (HCI) at GSI in Darmstadt/Germany. HCI with only one or few electrons are interesting systems for many different experiments as for instance precision tests of the theory of quantum electrodynamics (QED). In order to transform heavy HCI produced at 400 MeV/u to stored and cooled HCI at low energy the linear decelerator facility HITRAP has been setup behind the experimental storage ring (ESR). The ions are decelerated in the ESR from 400 to 4 MeV/u, cooled and extracted. The ions are then matched to an interdigital H-type structure (IH) using a double drift buncher, decelerated from 4 to 0.5 MeV/u in the IH, and then down to 6 keV/u in a 4-rod radio frequency quadrupole (RFQ). To detect and analyze the weak and sparse ion bunches a new type of energy analyzing detector has been developed along with improvements of other standard beam instrumentation. One million highly charged ions have been decelerated with the IH from 400 MeV/u to about 0.5 MeV/u per cycle. The RFQ has shown in off-line tests to decelerate ions, however, the measured longitudinal acceptance does not fit the properties of the ion beam decelerated in the IH. This requires a refined design, which is underway.

INTRODUCTION

Heavy, highly-charged ions, as for instance U^{91+} or even the bare U^{92+}, are well suited for cutting edge experiments in atomic, nuclear and solid state physics [1]. They are simple but come along with a very strong electric field due to the heavy nucleus and hence the large amount of positive charge enclosed in the small nuclear volume. This suits perfectly well to test quantum electrodynamics (QED) theory at the strong-field limit. Quantities that can be calculated with high precision and which are at the same time sensitive to the investigated QED effects are the g-factor of the bound electron, the electron binding energies of the innermost electrons or the hyperfine splitting of the electronic levels. To be decisive, those measurements require the same high precision as the calculations. For this, the ions have to be stored and cooled in a well defined environment at very low energy. This is possible in a Penning trap by electron and resistive cooling to about 4K [2]. The observation of the stored particles will then allow for mass measurements at the ppt level, corresponding to a determination of the electron binding energies with eV precision. Similarily, the bound-state g-factor can be determined with a precision that even tests our knowledge of fundamental constants like the mass of the electron. Laser excitation of the transition energies between hyperfine levels will become feasible several hundred times more precise than presently [3].

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. 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 [4]. Two different target types will be applied for HITRAP experiments: a pulsed gas target [5] and a magneto optical trap [6].

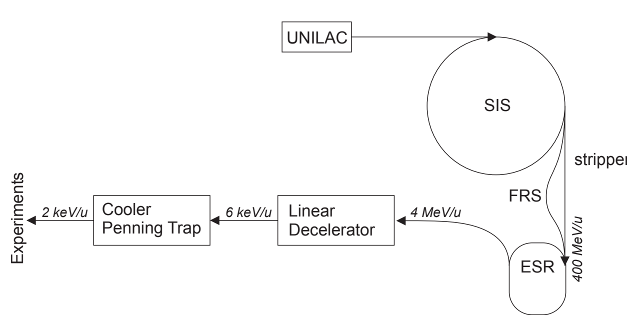

Figure 1: The HITRAP facility at the GSI accelerator complex. UNILAC stands for Universal Linear Accelerator, SIS is the heavy ion synchrotron and ESR is the Experimental Storage Ring. The beam from the SIS can be sent directly into the ESR of fragmented by nuclear reactions and then analyzed and separated in the Fragment Separator (FRS)

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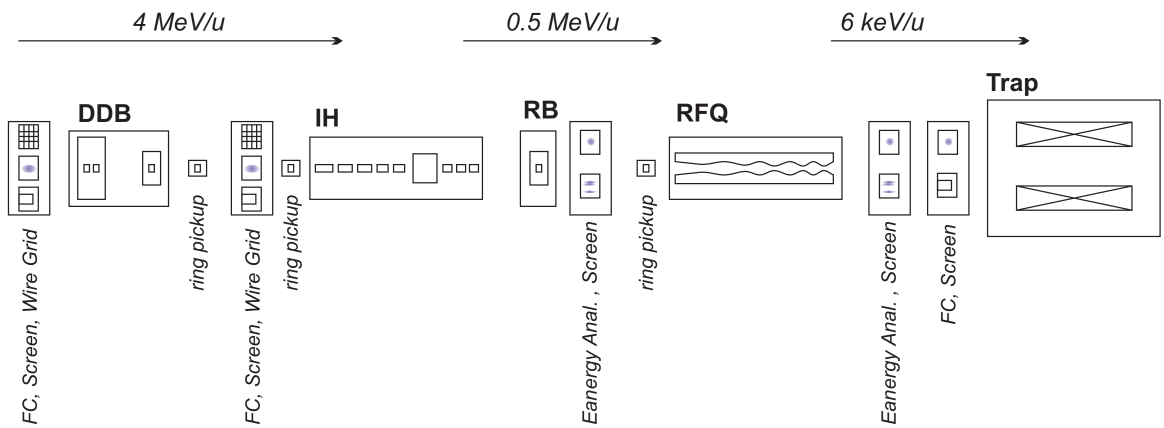

Figure 2: The functional units of the HITRAP linear decelerator: the double drift buncher (DDB), the interdigital H-type structure (IH), a spiral re-buncher (RB), the four-rod radio frequency quadrupole structure (RFQ) and the cooler Penning trap (Trap). Additionally indicated are the major diagnostic units. For description see text.

When the large potential energy is concentrated and released on a small surface spot of solid matter, self-ordering has been observed. This phenomenon needs 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 [7].

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

HITRAP is setup at the accelerator facility of the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt/Germany (fig. 1). The universal linear accelerator UNILAC is used to deliver intermediate charged ions with 11 MeV/u to the heavy ion synchrotron SIS. After acceleration to 400 MeV/u the ions are sent through a thin foil such that all electrons are stripped of the nucleus. The experimental storage ring ESR is then used to cool the ion beam produced that way and decelerate it to 4 MeV/u in two steps. After initial stochastic cooling the beam is decelerated to 30 MeV/u and then cooled with electrons. The next deceleration step from 30 MeV/u to 4 MeV/u is followed by another electron cooling period before the coasting beam is bunched in 1 μs bunches and ejected towards the HITRAP linear decelerator facility.

The linear decelerator (fig. 2) consist of a double drift buncher at 108 and 216 MHz for preparation of the beam to the longitudinal acceptance of the first decelerating structure, the interdigital H-type structure (IH). There, the ions are decelerated from 4 MeV/u down to 500 keV/u. An intermediate rebuncher will ensure maximum efficiency when the beam is injected into the second decelerating structure, a four-rod radio frequency quadrupole decelerator (RFQ). Both decelerating structures run at 108 MHz and require a power of 200 and 80 kW, respectively. In the RFQ the ion beam is decelerated from 500 keV/u to 6 keV/u and then dynamically captured in a Penning trap for final cooling.

BEAM INSTRUMENTATION

In fig. 2 the main instrumentation to detect the ion beam along the linear decelerator is indicated. To tune the beam transport from the ESR through the beam line into the IH structure, two kind of position sensitive detectors and standard Faraday cups are used. They are typically grouped in a common diagnostic chamber. Additionally, to monitor the functioning of the double drift buncher (DDB), ring shaped, capacitive pick-ups are installed. They also deliver additional energy information by time-of-flight measurements if there is sufficient beam intensity of at least 1 μA. An overview of those diagnostic installations can be found in [8].

During commissioning it turned out that it is not sufficient to detect the beam intensity and position alone. It is indispensable to have an energy dispersive detector behind the decelerating structures since the beam behind the IH and RFQ is a mixture of decelerated and non decelerated components. Therefore, after attempts with a large magnetic dipole and a diamond detector, a one-shot energy sensitive detector has been developed [9, 10].

The functional principle is shown in fig. 3. When the beam enters from the left, it is first made sure with at least one, and after the IH with two slit systems that it is narrow enough for the required resolution. The slits are typically 0.1 mm wide. The beam is then deflected in a magnetic dipole field of $B = 0.5\,\mathrm{T}$ (for the RFQ it is only 0.1 T) with

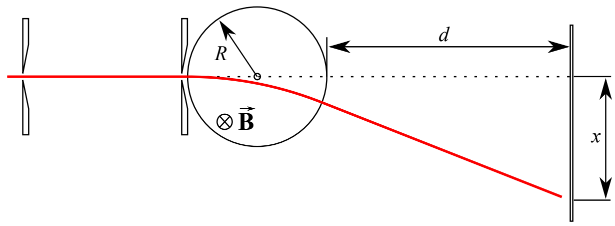

Figure 3: Principle setup of the energy analyzing detector installed behind the IH and the RFQ. The beam enters from the left through one or two slits before it is deflected in a permanent magnet and finally hits a screen with a deviation x. The complete setup is retractable remote controlled from the beam line.

an effective radius $R \approx 30\,mm$. At a distance $d \approx 100$ mm an MCP detector in combination with a phosphorous screen is used to read the deviation x.

The first slit is only available at the setup after the IH and makes sure that geometrical beam deviations from axis do not dominate the measurement of the deviation x and hence the beam energy. The slit, as well as all other components of the system can be retracted from the beam line.

For the very low energy after the RFQ of about 6 keV/nucleon we used an electrostatic 180° analyzer with spherical electrodes developed at the University of Frankfurt. With this device it is possible to measure also the energy spread of the decelerated beam.

Special instrumentation has also been developed to determine the emittance of the incoming, i.e. 4 MeV/nucleon beam, and the decelerated beam after the IH, i.e. at about 500 keV/nucleon [11]. Requirements were a compact device that can handle low intensities of only 1 μA peak current for 3 μs once a minute.

STATUS OF COMMISSIONING

Funding for the construction of HITRAP has started in 2005 and commissioning of first components started 2007. About two commissioning beam times have been granted per year with an average duration of 6 days. An overview of those beam times and the achieved or planned steps is displayed in table 1.

Presently, the deceleration to 500 keV/u has been shown and is working efficiently [14]. The major breakthrough was the successful installation of an energy sensitive detector, which gives shot by shot the complete energy spectrum of the ions after the IH structure [10]. However, the optimization of the combination of two bunchers (combined in the double drift buncher) and the IH is still difficult and not completely understood. The large parameter space given by three RF amplitudes and two phases requires the investigation of many different settings. This takes a lot of time and is virtually impossible due to the low repetition rate of at most one shot every 30 seconds. Two improvements have been implemented: the energy of the particles entering the ESR was limited to 30 MeV/u for commissioning of the linear decelerator which saves one deceleration step and hence time; the longitudinal analysis of the bunches created by the double drift buncher has been enhanced by a dedicated analysis procedure [15] (see also above).

The focus of recent beam times was on the detailed investigation of the IH structure output. Supported by detailed simulations [16] the deceleration efficiency was increased and reached about 50%, very close to the theoretical limit.

In the most recent beam time the third buncher, the rebuncher between the IH and RFQ structures, was taken into operation. With a measured loaded Q-value of about 5000 and an effective impedance of 29 MΩ/m it yields a designed gap voltage of 100 kV for $A/q = 3$. For the ^{50}Ti^{22+} ions used in the recent beam time this corresponds to about 80 kV gap voltage and hence a maximal theoretical energy change of about 35 keV/nucleon.

The action of the rebuncher was tested by measuring the beam on the energy sensitive detector after the buncher and changing the phase relative to the master oscillator driving the IH radio frequency and the radio frequency of the rebuncher. The result is shown in fig. 4. The maximal position change of about 0.8 mm corresponds to about 50 keV/nucleon energy variation which is pretty close to the expected value.

Two more conclusions can be drawn from fig. 4. The relative energy shift can be measured to a precision of less than 1 keV, which means that the energy measurement is dominated by systematic uncertainties. The full-width-half-maximum of the peak on the detector corresponds to 45 keV/nucleon. This is a convolution of the geometrical spread due to the imaging, the slit sizes and camera issues with the actual energy spread of the ion beam. This has not yet been disentangled, but first rough estimated show that at least half of that spread is due to real energy spread.

All efforts to decelerate the beam further with the RFQ structure failed so far. The most probable reason is a slight mismatch of the IH output energy distribution and the energy range accepted by the RFQ. This was found in recently updated simulations of the RFQ structure using the code DYNAMION [17] accompanied by a detailed 3D measurements of the electrodes. To verify those findings and work towards a solution the RFQ was installed at a Pelletron accelerator at the Max-Planck Institute for Nuclear Physics in Heidelberg/Germany.

RFQ off line tests

The RFQ was installed at the Pelletron accelerator in Heidelberg and tested with $H_2{}^+$ ions with total kinetic energy around 1 MeV. This corresponds to the necessary energy of about 500 keV/nucleon. About 500 nA where available at the entrance of the RFQ.

It has been shown that the HITRAP RFQ can decelerate ions from 517 keV/nucleon to 6.7 keV/nucleon. The energy spectrum measured behind the RFQ with an electrostatic energy analyzer is shown in fig. 5. The measured energy

Table 1: Overview of conducted commissioning beam times.

Date	Ion	Comment
5-2007	$^{64}Ni^{28+}$	Vacuum separation ESR/HITRAP installed - acceptance test
8-2007	$^{20}Ne^{10+}$	Double Drift Buncher test using diamond detector in front of IH
8-2008	$^{197}Au^{79+}$	Bunches transported through IH, analyzed on diamond det. [12]
10-2008	$^{64}Ni^{28+}$	First decelerated particles at 500 keV/u with energy spectrometer
2-2009	$^{58}Ni^{28+}$	First run after IH retuning. 4 MeV/u transport-mode test
6-2009	$^{132}Xe^{54+}$	Beam measured with pepper-pot emittance meter [11, 13, 9]
3-2010	$^{86}Kr^{33+}$	Improved IH energy analyzer [10]
4-2010	$^{86}Kr^{35+}$	Beam to RFQ, energy analysis sensitive only to 6 keV/u [14]
11-2010	$^{86}Kr^{35+}$	RFQ Energy analyzer also to 500 keV/u sensitive
5-2011	$^{54}Cr^{24+}$	IH Energy measurements
6-2011	$^{14}N^{7+}$	IH Energy measurements, RFQ parameters scanned
9-2011	$^{136}Xe^{50+}$	IH and DDB combined optimisation, ESR energy scan
5-2012	$^{50}Ti^{22+}$	IH and DDB combined optimisation, RB test, RFQ scan

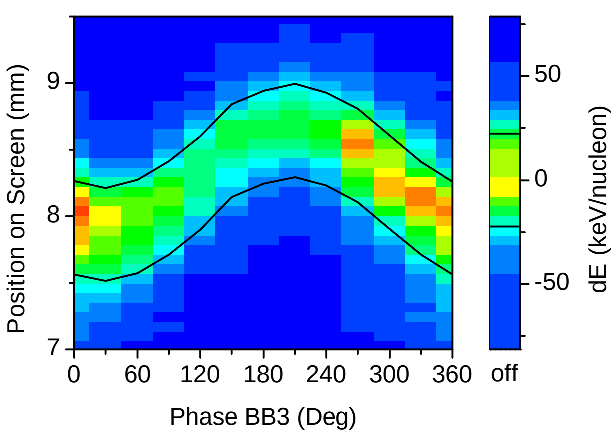

Figure 4: Results of the commissioning of the spiral rebuncher between IH and RFQ. Shown are position on the screen, corresponding energy shift, and intensity (in arbitrary units) of the beam on the energy analyzing detector versus the phase of the radio frequency driving the buncher cavity. A power of 1.1 kW was used for all phases. The lines are the FWHM limits of a gaussian fit of the beam profile at each phase.

spread of about 6% is somewhat lower than expected without the intertank debuncher installed at the end of the RFQ but not used for the presented measurement. This is probably due to the very low energy spread of the incoming beam from the Pelletron. The energy of the beam itself is more than 10% higher than the design value, which complicates the injection into the cooler Penning trap especially for ions with mass to charge ratio close to three.

With the available flexibility and control of the beam at the test facility it was also possible to map in detail the acceptance of the RFQ concerning the energy of the incoming ions. For deceleration to the designed energy and the optimal RF setting the accepted energy ranges from about 512 to about 522 keV/nucleon FWHM. The range is hence as expected but in comparison to the observed spread for the ion beam coming from the IH (compare fig. 4 and its explanation) to narrow.

The major result from the off-line test is that the central value of the accepted energy is not the designed and required 500 keV/nucleon but about 17 keV/nucleon to high. This has been anticipated in refined calculations before the off-line test and could be verified by those.

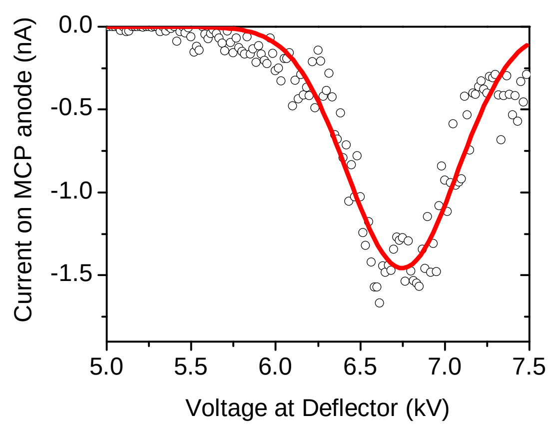

Figure 5: Energy spectrum of decelerated beam as measured behind the RFQ during off-line tests. The voltage at the deflector is equivalent to the ions energy per nucleon. The line is a gaussian fit to the data that yields a central energy of 6.75 keV/nucleon and a FWHM of 0.76 keV/nucleon.

Cooler Penning trap and EBIT

The cooler Penning trap is tested offline with deuterium ions from a cross beam ion source. An electron source has been installed already to provide the electrons for the electron cooling scheme [18]. It is based on UV-light-released electrons from a GaAs surface and is fully compatible with the required ultra-high vacuum. Electrons have been captured already in the cooler Penning trap and the ion capture process is being tested in the moment.

In order to test the low energy beam lines that connect to the experiments as well as the trap operation, a compact, room temperature electron beam ion trap (EBIT) of the Dresden type has been installed. It's beam has been used to commission the vertical beam line between the trap and the experimental platform. It has also been used for charge breeding and can to provide ions for experiments when they are not available as gaseous elements [19].

SUMMARY AND OUTLOOK

The HITRAP facility has been conceived to the decelerate and cool beams of heavy, highly charged ions produced at 400 MeV/nucleon at the GSI accelerator complex in Darmstadt, Germany. It's setup has been started in 2006 and commissioning is still ongoing. The cooling, deceleration and extraction of heavy, highly charged ion beams in the experimental storage ring (ESR) is meanwhile a routine operation. Up to ten million ions can be extracted from the ESR at 4 MeV/nucleon and sent to HITRAP.

The HITRAP linear decelerator has three major components, a double drift buncher (DDB), an IH and an RFQ structure. Commissioning of the DDB and the IH has reached reproducible operation conditions. Ions are decelerated to 500 keV/nucleon and investigations towards higher stability of operation and higher efficiency are ongoing. Major efforts went into the characterization of the energy spectrum of the decelerated ion beam, which showed a larger energy spread than anticipated. In the section between the IH and the RFQ a rebuncher is installed to refocus the transversal phase space. The rebuncher has been commissioned recently and shows the expected behavior.

The last step of deceleration, the RFQ, has been commissioned off-line. It has been shown that the structure decelerates ions from about 500 keV/nucleon to about 6 keV/nucleon but does not reach the exact design specifications. This made it impossible to achieve deceleration in the dedicated on-line commissioning runs.

For final deceleration the existing RFQ resonator will be equipped with new electrodes. After detailed simulations of the present electrodes explain most of the experimentally observed features, calculations for a new set of electrodes have been started with the aim to have a new set of electrodes available end of this year. Furthermore, a completely new and different structure based on the IH concept is discussed. Major parameters to be optimized are the energy acceptance, the transversal acceptance and the energy spread of the decelerated ion beam.

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