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Status of deceleration and laser spectroscopy of highly charged ions at HITRAP

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Abstract Heavy few-electron ions are relatively simple systems in terms of electron structure and offer unique opportunities to conduct experiments under extremely large electromagnetic fields that exist around their nuclei. However, the preparation of highly charged ions (HCI) has remained the major challenge for experiments. As an extension of the existing GSI accelerator facility, the HITRAP facility was conceived as a multi-stage decelerator for HCI produced at high velocity. It is designed to prepare bunches of around 10^5 HCI and to deliver them at low energies to various experiments. One of these experiments is SpecTrap, aiming for laser spectroscopy of trapped, cold HCI. We present the latest results on deceleration of ions in a radio-frequency quadrupole, synchrotron cooling of electrons in a trap as a preparation step for the prospective electron cooling of the HCI decelerated in HITRAP, as well as laser cooling of singly charged Mg ions for sympathetic cooling of HCI in SpecTrap.

Keywords Highly charged ions · Deceleration · Penning trap · Sympathetic cooling · Laser spectroscopy

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1 Introduction

Heavy, highly charged ions (HCI) like the hydrogen-like U^{91+} or Bi^{82+} represent simple systems in terms of electron structure which offer opportunities for cutting edge tests of quantum electrodynamics (QED) in the extreme fields that exist around their nuclei [1, 2]. The HITRAP project [3] at the GSI Helmholtz Centre for Heavy Ion Research and the Facility for Antiproton and Ion Research (FAIR) was started several years ago with the goal of preparing large bunches of such ions at very low energies and distributing them to different associated experiments. The experiments include, but are not limited to, laser spectroscopy with trapped HCI [4], measurements of the bound-electron *g*-factor [5], study of multiple electron transfer in cold atom-HCI collisions [6] and investigation of interaction between HCI and highly intense laser light [7]. Such experiments with heavy HCI at GSI were so far hampered by the relatively large energy uncertainty of the HCI produced by the accelerator facility, resulting in e.g. large Doppler width of the transition and uncertainty of the ion velocity for laser spectroscopy experiments [8]. In experiments with HCI produced by an EBIT [9] the ion energy is significantly lower, but the experimental precision is still limited by the ion temperature or simply by the low yield of the high charge states.

At GSI/FAIR, HCI are produced by acceleration and in-flight stripping of electrons in several steps. The ions can then be stored in the experimental storage ring (ESR) for experiments at energies between 400 MeV/u and 4 MeV/u. The latter is the lowest energy at which ions can still be efficiently stored in the ESR. By taking ion bunches of some 10^6 ions from the ESR, pre-decelerated to 4 MeV/u, the HITRAP facility is designed to reduce their energy further in two linear decelerators and finally in a Penning trap all the way into the sub-eV range. The cold HCI can then be forwarded at a chosen transport energy towards different experimental setups along the beamline.

2 The HITRAP linear decelerator

The first stage of the linear decelerator consists of a double-drift buncher (DDB) and an interdigital H-type structure (IH). The DDB preconditions the beam to the longitudinal acceptance of the IH structure, which decelerates the ions from 4 MeV/u down to 500 keV/u. The second stage comprises an intermediate rebuncher (RB) and a four-rod radio frequency quadrupole (RFQ) decelerator. The RB ensures maximum efficiency when the beam is injected into the RFQ decelerator, which slows down ions from 500 keV/u to 6 keV/u. Both deceleration stages run at about 108 MHz and require a peak power of up to 200 kW and 80 kW, respectively (Fig. 1).

The IH-decelerator was successfully commissioned several years ago with deceleration efficiencies close to the theoretical maximum [10] of some 60 %. The major breakthroughs were the installation of an energy-sensitive detector and the energy reduction of the ions injected into the ESR down to 30 MeV/u for purposes of commissioning, which eliminated one deceleration step in the ring and enabled up to two ejections towards HITRAP per minute, speeding up setup and optimization.

The commissioning of the RFQ decelerator has proven to be more challenging because of the very large parameter space combined with a relatively low acceptance of the device. The sampling of the full parameter space is very time consuming and, with the repetition rate of at best one shot per 30 seconds, virtually impossible. In an attempt to improve on this, the electrodes of the RFQ were redesigned [11] and offline tests were carried out at MPIK in Heidelberg [12]. The modified RFQ was designed to have a bigger acceptance at the

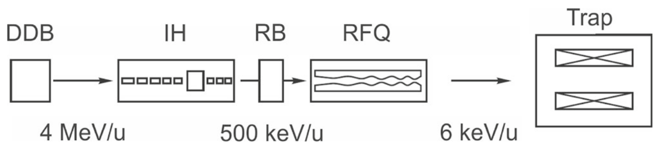

Fig. 1 Ion deceleration stages of the HITRAP facility. DDB - double drift buncher; IH - interdigital H-structure; RB - rebuncher; RFQ - radio frequency quadrupole; Trap - Penning trap

price of a larger energy dispersion of the decelerated particles. It was reinstalled at GSI and successfully commissioned in 2014. Figure 2 shows the signal of the HCI decelerated from 500 keV/u to around 6 keV/u by the RFQ, obtained after systematic scans and optimization of the system parameters. The ions leaving the RFQ were sent through the magnetic field of a permanent magnet with integrated slits. As a result, the ions with smaller energy get a larger deflection angle (the left peak in Fig. 2) and can be distinguished from the non-decelerated ions (the right peak), given with a mixture of 4 MeV/u and 500 keV/u ions. A more detailed description can be found in [13].

The future commissioning beamtimes at GSI will bring detailed analysis of the energy spectrum of the decelerated ions and their transport towards the cooling trap. Finally, the ions should be stored in the trap, where the combination of different cooling techniques brings their energy to the sub-eV range.

3 The HITRAP cooling trap

The ions leave the RFQ delecerator with a wide energy spread centred around 6 keV/u and with a very large beam emittance, making further transport very difficult. However, this energy is in principle low enough for a dynamic capture of the ions in the HITRAP cooling trap, where the ions can undergo further cooling. The trap consists of 23 gold-plated cylindrical electrodes, aligned in a row to form a 40 cm long trap. Each electrode can be supplied with high voltage individually, which can be used to create multiple regions with a quadrupole electric potential inside the electrode structure. The complete setup is situated inside the cold bore of a superconducting magnet, providing a magnetic field of up to 6 T.

The goal the cooling trap is to cool the HCI down to the temperature of the trap (4 K) or lower. Additionally, a rapid cooling mechanism is needed in order to avoid ion loss in collisions with the residual gas particles. Different cooling techniques can be used to that end; in this case a combination of electron cooling [14] and resistive cooling [15] was chosen. Evaporative cooling was not an option because it is directly connected to ion loss, possibly not fast enough and the final energy is comparably large. Sympathetic cooling with a laser-cooled ion cloud could be another option, but it was abandoned because it required laser maintenance and optical detection, which are technically demanding for an online facility with a repetition rate of one to two shots per minute. Only a limited number of experiments with resistive cooling of large clouds of HCI is available so far, indicating that the ions are slowly (of the order of a few seconds) cooled to the temperature of the electronic circuit, which can be the same or higher than the environment temperature of 4 K [16, 17]. For the current design of the cooling trap, the ion cloud will be cooled by the electrons down to some 10 eV/q, at which point the electrons should be ejected to avoid recombination, and resistive cooling should take over, cooling the ions down to the cryogenic temperatures.

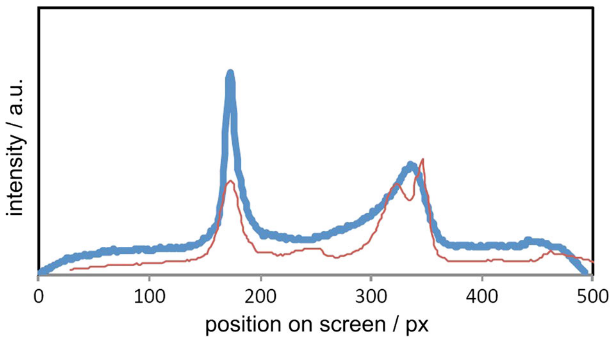

Fig. 2 Ion deceleration in the RFQ as seen by the energy analyser. The thin, red line is the reference signal from the offline tests and the thick, blue line is the online signal achieved at HITRAP. The low energy part, i.e. the decelerated ions' signal is the peak to the left. The peak to the right is the undecelerated part of the beam

First trapping tests showed the capability of electron storage, and their self-cooling through emission of synchrotron radiation. In the strong magnetic field of the trap the electrons undergo a fast cyclotron motion and experience a loss in energy via emittance of synchrotron radiation due to the high Lorentz acceleration. The time constant of this self-cooling process is of the order of a few seconds. It strongly depends on the electrons' cyclotron frequency and thereby on the magnetic field.

To prove this self-cooling behaviour, bunches of about 10^8 electrons, emitted from a GaAs surface after irradiation with UV light [18], were injected into the trap and captured between two electrodes with fast voltage switching. The electrons were ejected from the trap after different time intervals and guided to a multi channel plate (MCP) detector. The energy of the ejected electrons was measured by applying a repelling voltage to an electrode between the trap and the detector and by measuring at which field strength the electrons were fully repelled. This measurement showed an exponential decay of the electron energy as a function of the storage time. The measurement was repeated for different magnetic fields, as shown in Fig. 3, confirming the expected decrease of the electrons' synchrotron cooling time for increasing magnetic fields.

The electrode structure of the trap allows a simultaneous storage of ions and electrons in the same area. To that end, locally produced highly charged oxygen ions were injected into the trap and stored for extended amounts of time before ejecting them towards the detector. Such offline tests of the cooling trap's ion storage capability have already yielded storage times of several seconds [20]. By superimposing the ion cloud with a previously injected, self-cooled electron plasma, the ions will be able to transfer a large portion of their kinetic energy to the electrons via elastic scattering. Because of this rapid energy reduction, the storage time is expected to increase enough so that resistive cooling can take over after ejecting the electrons. Thus, the detection of electron cooling of ions is one of the main short-term objectives to be achieved with the HITRAP cooling trap. Further goals include improved vacuum conditions, the optimization of the ion and electron capture process as well as ion cooling with the resistive cooling technique down to the environment temperature of a few K.

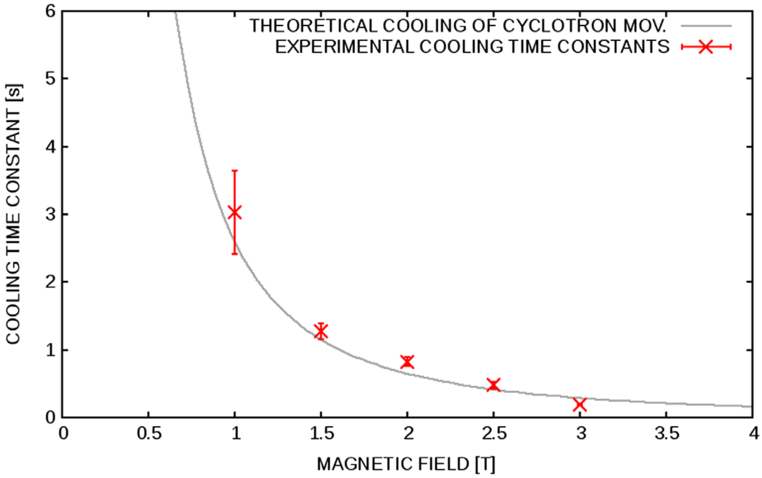

Fig. 3 The measured cooling time constants (red) in comparison with the theoretical prediction for different magnetic fields (grey). One should note that, aside from the good general agreement, the remaining deviations between experiment and theory arise from experimental parameters like field inhomogeneities and particle-particle interactions, and are not expected to vanish in the experiment [19]

4 Laser spectroscopy of highly charged ions

The HCI from the HITRAP cooling trap will be transported with an energy of around 5 keV/q towards the associated experiments. The beamline for low-energy transport of HCI was finished and commissioned in 2013. It makes a direct connection between the cooling trap, a local EBIT [21] and the HITRAP experiments, with the possibility to guide the ions in both directions. In that way, both the cooling trap (for testing purposes) and the experiments can be supplied with medium heavy HCI from an ion source independent of the GSI accelerator infrastructure. Depending on the number of ions in a bunch and their energy per charge, transport efficiencies close to 100 % were achieved [22].

As one of the experiments associated with HITRAP, the SpecTrap setup [4] is preparing to accept heavy HCI from the facility and re-trapping them in a Penning trap. With a dedicated Helmholtz-type superconducting magnet, the SpecTrap open-endcap Penning trap enables direct optical access both in the axial and radial directions. As such, it is an ideal tool for laser spectroscopy experiments with few-electron ions and the direct observation of their fluorescence.

Highly charged ions from the EBIT are transported towards SpecTrap with an energy of a few keV/q. Before trapping, this energy is reduced by a pulsed drift tube down to 500 eV/q. The ions with this energy can be trapped in the SpecTrap Penning trap, but a rapid cooling mechanism is still needed to reduce the number of charge-exchanging collisions with the residual gas particles. Cooling the ions to low temperatures also reduces the Doppler broadening of the transition frequencies, bringing a high relative accuracy of the measurement as compared to e.g. similar measurements in the GSI storage ring. Similar as in the case of the HITRAP cooling trap, both resistive cooling and sympathetic cooling are foreseen to that end. Here, laser-cooled singly charged Mg ions will be used instead of electrons. Figure 4 shows the line profile of a laser cooled Mg^+ cloud with several hundred ions.

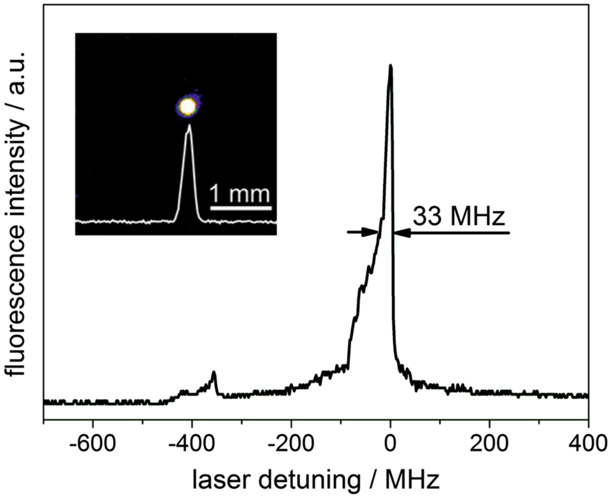

Fig. 4 Line profile of the laser cooled Mg^+ ions at SpecTrap. After the laser frequency is scanned over the transition, laser cooling turns into heating and the signal drops almost to zero. Therefore, the FWHM of the observed signal (33 MHz) represents only one half of the full profile. The comparison of the observed signal to the natural linewidth (42 MHz) can be used to give the upper limit for the ion temperature (60 mK). An image from a CCD camera is shown as inset, indicating the actual size of the cooled ion cloud

The laser wavelength was scanned across the resonance. The signal dropped rapidly to zero after crossing the central transition frequency. A comparison of the observed linewidth to the natural linewidth of the transition gives a conservative upper limit to the ion temperature of $T \leq 60$ mK [4]. The inset shows the cooled ion cloud recorded with a CCD camera, indicating its size of less than a millimeter.

Using the ions produced locally by the EBIT, the laser cooled ions in SpecTrap were mixed with HCI and the investigation of the ion dynamics in ongoing. Due to the low temperature achievable through sympathetic cooling, the expected relative accuracy of laser spectroscopy of forbidden transitions in HCI is of the order of $10^{-7} - 10^{-8}$. The limiting factors are the ion lifetime in the trap and the availability of the suitable laser systems and fluorescence detectors. Taking that into account, the measurement candidates include fine structure transitions in medium-heavy systems like Ar^{13+} and Ca^{14+} produced locally, as well as hyperfine structure transitions in $Bi^{80+,82+}$ produced by the GSI accelerator complex and decelerated by the HITRAP facility [23]. Alternatively, highly charged heavy ions can be extracted from the so-called S-EBIT [24], on loan from Helmholtz Institute Jena and currently under construction at HITRAP. It will be connected directly to the existing HITRAP infrastructure and together with the existing EBIT, it will provide medium heavy and heavy highly charged ions, independent of the accelerator beamtime at GSI, thus helping to bridge the shutdown period necessary for the construction of FAIR [25].

5 Conclusions

As the first facility of its kind in the world, HITRAP has had to overcome many difficulties on the road towards large clouds of heavy highly charged ions decelerated all the way from the their production energy of 400 MeV/u down to the sub-eV range. The first promising results have shown that the desired multi-stage deceleration can work as a concept, but requires fine tuning specific to the application. The ions were nevertheless successfully decelerated down to about 6 keV/u which makes dynamic capture in a Penning trap possible. The combination of high vacuum, high voltage, strong magnetic field and cryogenic environment makes also this step very demanding and it will require more work in the coming years. However, the trap itself has been tested with locally produced ions and electrons, including the demonstration of the synchrotron cooling necessary for sympathetic electron cooling of HCI.

The experiments around HITRAP are developed in parallel to the facility and have also seen first tests with locally produced ions. One of them is SpecTrap, where singly charged Mg ions were loaded into the trap and laser cooled to a temperature significantly under 1 K. As such, they will enable sympathetic cooling of HCI which may come from a local EBIT or the HITRAP facility. The first test with Ar^{13+} have already been carried out and further optimization of the process is ongoing. The long term goal of the experiment is trapping and laser spectroscopy with $Bi^{80+,82+}$. The energies of the hyperfine splitting in these two ion species have been recently measured in the ESR [8] and an increase in relative accuracy of several orders of magnitude is expected in the trap.

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