# THE HITRAP DECELERATOR LINAC AT GSI*

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*Abstract*

Highly-charged, heavy ions at rest are the perfect tools for cutting edge experiments in atomic and nuclear physics. The HITRAP facility at the GSI accelerator complex decelerates highly-charged ions as heavy as $U^{92+}$ produced by stripping of all electrons passing a 400 MeV/u beam through matter. In the experimental storage ring ESR the ions are decelerated from 400 to 4 MeV/u. An interdigital H-type (IH) structure and a radio-frequency quadrupole (RFQ) structure are operated in inverse to decelerate from 4 MeV/u to 0.5 MeV/u and to 6 keV/u, respectively. First deceleration down to 0.5 MeV/u has been demonstrated and the remaining parts of the linear decelerator for HITRAP are mostly installed and being tested.

## INTRODUCTION

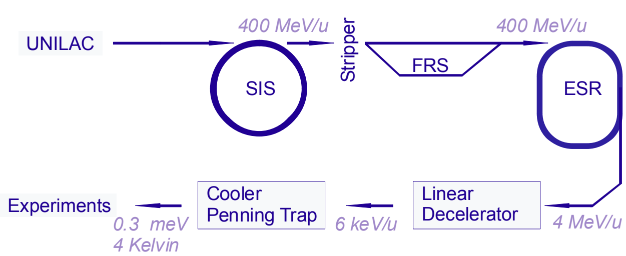


Figure 1: Schematic view on the production of slow, highly-charged ions with HITRAP.

Heavy, highly-charged ions at very low, well defined energy are ideal systems for a number of precision experiments in different fields of physics. Using a single ion with just one electron left stored in an ion trap, the g-factor of the bound electron in extreme systems as for instance hydrogen-like uranium will be possible. This is not only 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. To measure the electron binding energy in an independent manner the stored ions mass will be measured for different electron configurations with a very high precision of 1 ppt.

If many highly-charged ions are stored in a cryogenic environment and cooled accordingly, measurements of the hyperfine splitting can be performed with laser spectroscopy one thousand times more precise than presently possible based on the reduced Doppler broadening. Stored clouds of ions also give access to precision X-ray spectroscopy.

Precise studies of processes like multiple charge exchange can be performed with complete kinematical analysis in ion – atom collision experiments. For that a well defined ion beam will be targeted to a cold sample of neutral atoms and the products are then investigated in a reaction microscope. If a highly-charged ion approaches a surface a huge amount of energy is deposited on a very small spot.

This leads to nonlinear effects within the atomic structure of the surface. To disentangle those processes from the typical irradiation damage the kinetic energy of the projectile has to be lower than the potential energy deposited per ion and requires a beam of highly-charged ions below 100 keV total kinetic energy.

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 stripping off all electrons passing a 400 MeV/u beam through a gold foil. The HITRAP facility is built to decelerate those ions to almost rest and to provide them to the experiments (see Fig. 1) [1]. 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 more steps. An interdigital H-type (IH) structure and a radio-frequency quadrupole (RFQ) structure are operated in inverse to decelerate first from 4 MeV/u to 0.5 MeV/u and then further to 6 keV/u. The major components have been installed and are taken into operation. A number of tests and simulations have been performed and decelerated ions at 0.5 MeV/u have been produced.

## THE LINEAR DECELERATOR

After deceleration and cooling in the ESR the ion beam is extracted about every 30 to 40 seconds. To keep the cavities on constant temperature, the decelerator structures are still operated with a duty cycle of 0.5%. Due to the final electron cooling in the ring there is no internal time structure in the extracted ion pulse of about 1 µs length, which contains up to $10^5$ uranium ions.

To adapt this ion bunch to the limited longitudinal acceptance of the decelerator, a double drift buncher (DDB) operated at 108 and 216 MHz is used. The two coaxial-quarter wave resonators are separated by a 0.9 m

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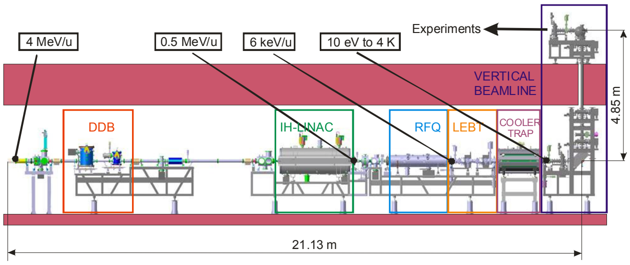


Figure 2: Overview of the HITRAP facility with the major components indicated. DDB – Double Drift Buncher for bunching the beam to adapt it to the longitudinal acceptance of the decelerator, IH – LINAC – interdigital H-type structure for deceleration, RFQ – radio-frequency quadrupole accelerator structure for deceleration, LEBT – Low energy beam transport line for efficient injection into the trap, COOLER TRAP – Penning trap for final deceleration and cooling.

drift. With this DDB, about 67% of the incoming beam should be accepted by the IH, which has an acceptance of about 10 to 15° phase spread relative to the 108 MHz.

The interdigital H-type structure with an overall length of about 2.7 m and 25 gaps of 12 and 10 mm diameter has one innertank triplet lens with attached steerer magnets. With an effective deceleration voltage of 10.5 MV the ions are decelerated from 4 to 0.5 MeV/u. With a measured Q value of 23000 and a measured shunt impedance of about 270 MΩ/m the structure can be driven by a 200 kW power amplifier as designed. After tuning with a static 1:1 tuner body to rise the low energy part of the voltage distribution the deviation from the designed voltage distribution is in both sections smaller than 2%.

Downstream of the IH-structure the 0.5 MeV/u beam is then fit with a spiral re-buncher to the RFQ, which finally decelerates the ions to 6 keV/u. The RFQ, operated also at 108 MHz,, has 143 cells, is 1.9 m long and has a mean aperture radius of 4 mm. With a maximum rod voltage of 75 kV the incoming ion beams with $m/q < 3$ can be decelerated to the final 6 keV/u. In the following low-energy beam line (LEBT) the beam is focussed with electrostatic Einzel lenses through two diaphragms for vacuum separation. Then it is injected into the cooler Penning trap for final cooling and bunched or continuously extracted at 5 keV/q. For high acceptance and efficient transport into the trap the ion beams energy spread is reduced by a single harmonic buncher from about 14% to 8%.

## 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 including two capacitive pickups for diagnosing the time structure of the beam, have been installed and tested. 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 installed including another pair of capacitive pickups and the spiral rebuncher.

The next section of the linear decelerator, the RFQ structure, was machined, tested for vacuum leaks and conditioned at low rf power level in 2008. The structure has been installed in February and March 2009.

The low energy beam line that connects the RFQ and the cooler Penning trap is already installed in its final position. The components have been baked and reached the specified pressure of $10^{-10}$ mbar. All electrical connections for the Einzel lenses are prepared as well as their power supplies.

The cooler Penning trap is assembled in the moment to be installed in the immediate future. An electron source to feed the trap with electrons needed for cooling has been designed and built based on a photo cathode covered with Caesium driven by an ultraviolet flash lamp.

Most components for the transfer line to the experiments arrived meanwhile at GSI and are ready for installation. The missing diagnostics and the kicker bender are predicted to arrive in late spring 2009 so that the beam line to the second floor, which connects to the SPARC-EBIT and the experiment beam line, can be installed and tested off-line with the EBIT within this year.

## RESULTS OF COMMISSIONING

Six beam times of about one week each have been used for the commissioning program of HITRAP until now. Even though the experiments are interested mostly in the heaviest ions, the commissioning was performed with varying ion species, because the only relevant limit for the decelerator is the mass to charge ratio, which should be below three.

In the first beam times, the cooling process in the ESR was optimized with stochastic cooling at injection energy, reliable and stable extraction has been reached, the double-drift buncher was operated and the first tests of the IH structure operation performed. A bunched beam has been detected with capacitive pick ups and on a diamond detector [3,4] and the emittance of the incoming beam was measured [5]. This was measured again in a recent run changing the focal length of a lens and yields 2.5 and 3.7 π mm mrad for 90% of the beam. This is slightly higher than the 2.2 π mm mrad assumed in transverse beam dynamics calculations and requires refined calculations of the transverse optics.

In October 2008 a $^{64}Ni^{28+}$ beam was investigated with an additional energy measurement setup downstream of the IH. A magnetic steerer and a movable array of diamond detectors allowed one to separate the beam

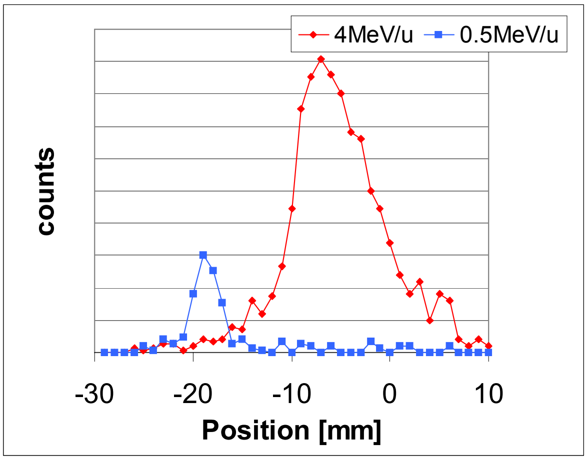


Figure 3: Signal on the diamond detector. The beam components with 0.5 MeV/u und 4 MeV/u are displayed in blue and read. The spatial separation is due to a magnetic dipole field in front of the detector.

according to energy and to measure with single ion sensitivity. This has been used to find and optimise the first branch of slowed down ions. For the first time, decelerated ions have been seen in the linear decelerator of HITRAP.

In Figure 3 the measurement on the diamond detector is shown. The signal amplitude at the diamond detector is proportional to the energy deposited in the detector. This way the beam components with different energies have been separated. Only a fraction of the detected beam is decelerated to 0.5 MeV/u while the majority ends up at higher energies. This presents a challenge for typical beam diagnostics as for instance the phase probes or the scintillation screens due to the mixture of energies. The phase probe will not show an easy to interpret bunched spectrum any more and since the energy deposition of the 0.5 MeV/u ions is about eight times lower, the light from their impact on the scintillation screen will disappear in the scintillation light from the 4 MeV/u ions. With the present set of parameters, which are not optimal yet, about 10% of the detected beam is decelerated to 0.5 MeV/u.

The IH structure obviously transports also beam that was not decelerated efficiently. This has been investigated meanwhile in extensive calculations that showed also the importance of the input energy. Even a deviation by only 10 keV/u from the design energy of 4 MeV/u creates a considerable amount of ions with other energies than 0.5 MeV/u at the end of the IH structure. Furthermore, the amplitude of the radio frequency driving the cavity is more sensitive than anticipated as shown in fig. 4.

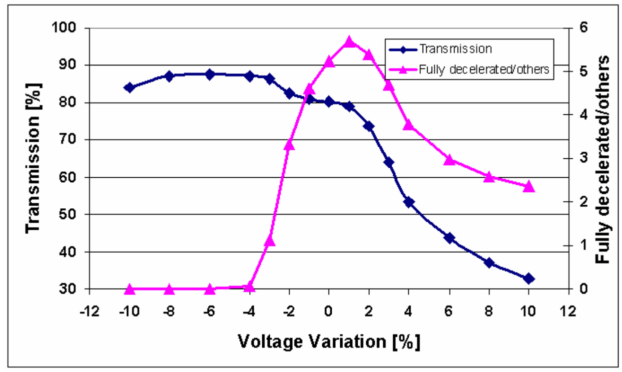


Figure 4: Calculations on the deceleration and transmission of the IH structure using LORASR. Shown is the transmission in blue and the ratio of transmitted particles to decelerated particles in pink versus the variation of the RF amplitude change in percent in the IH tank.

In the most recent commissioning beam time the installed RFQ structure was operated the first time. Here again, up to 10% of the initial 4 MeV/u beam is transported which disturbs the detection of the ion decelerated to 6 keV/u. Hence, no particles declerated to 6 keV/u could be identified until now.

Summarizing, the first part of the HITRAP linear decelerator has been taken into operation and decelerated highly-charged ions from 4 MeV/u to 0.5 MeV/u. The remaining parts are mostly installed and being tested. The next step is the development of a "one-shot" energy analyzer to improve on the fine tuning of the IH and the RFQ and hence increase the amount of decelerated ions. The final installation and test of the cooler Penning trap is also ongoing.

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