DECELERATION OF HIGHLY CHARGED IONS FOR THE HITRAP PROJECT AT GSI*

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Abstract

The highly charged heavy ion trap (HITRAP) project at GSI is a funded mid term project and is planned to be operational end of 2007. Highly charged ions up to U^{92+} provided by the GSI accelerator facility will be decelerated from 4 MeV/u down to 6 keV/u and subsequently be injected into a large Penning trap for further deceleration and phase space cooling. The deceleration is done in a combination of the GSI experimental storage ring (ESR) and a linac based on an IH-structure and a RFQ. In front of the decelerator linac a double drift-buncher-system provides for phase focusing and a final de-buncher integrated in the RFQ-tank reduces the energy spread in order to improve the efficiency for beam capture in the cooler trap. The paper reports the beam dynamics design along the entire decelerator down to the trap injection point, as well as and the status of the cavities. Finally the time schedule and ESR and linac commissioning are discussed.

INTRODUCTION

The availability of highly charged ions from the GSI accelerator facility drives an extended experimental programme in atomic and nuclear physics. The GSI accelerator facility provides the highest intensities of highly charged ions worldwide for experiments at high beam energies. The demand of highly charged ions at low energies or even at rest can soon be satisfied by the highly charged heavy ion trap facility (HITRAP). The accelerator chain employed for the production of highly charged ions up to bare Uranium consists of the UNILAC, the heavy ion synchrotron SIS and the experimental storage ring ESR (fig.1). The ESR is equipped with stochastic and electron cooling devices, which are the tools to provide excellent beam quality of the extracted beams. In the ESR the highly charged ions will be decelerated down to 4 MeV/u. A deceleration down to 3 MeV/u in the ESR has been successfully demonstrated [1]. The deceleration is reached by the expense of a reduced number of $6*10^5$ ions, which can be stored at 4 MeV/u. Cooling of the beam is essential, in order to counteract the emittance growth due to deceleration.

The experiments at the HITRAP facility are grouped in Penning trap based experiments and collision experiments. A primary goal of the experiments is to explore the behavior of electrons in the strongest electromagnetic fields accessible to experimental, highly precise investigations. In addition precise investigations of the atomic structure of highly charged ions become possible at the HITRAP facility. The study of charge exchange processes in collisions between ions and molecules makes it possible to probe both, atomic structure, and the collision dynamics. Thus these studies are of particular interest for plasma physics, astrophysics and accelerator physics. Due to the low kinetic energy of the ions, the measurements are completely unaffected by Doppler corrections. The trapped and cooled HCIs can be used for high-precision determinations of fundamental properties of nuclei, like the nuclear binding energies, the nuclear g-factor and the distribution of the nuclear moment over the size of the nucleus. In addition to highly charged ions of stable nuclei, those of radioactive ones will also become available. These exotic species can be produced at GSI by the fragment separator FRS and can be injected into the ESR.

THE DECELERATOR LINAC

HITRAP employs an RF-linear accelerator for further deceleration of the ions extracted from the ESR down to 6 keV/u (fig.1). The main components are the double drift buncher (DDB) for phase matching, an IH-structure as booster and an RFQ. In addition a special Penning trap will be used for subsequent deceleration and cooling of the highly charged ions down to cryogenic temperatures. An end to end beam dynamics calculation has been done using the computer codes Cosy infinity, LORASR and PARMTEQ. The measured normalized transverse emittance of the beam from the ESR corresponds to 0.09 mm mrad. For all design calculations a factor of two larger emittance of beam from the ESR has been assumed. Table 1 shows the calculated emittances at the exit of the different cavities.

Table 1: Beam emittances downstream the ESR and downstream the cavities of the HITRAP-linac

Component	**normalized transverse emittance [mm mrad]**	**longitudinal emittance [keV/u*ns]**
ESR	0.19	$\Delta t=1\mu s$, $\Delta p/p=10^{-4}$
DDB	0.21	4 (220^o phase acceptance)
IH-structure	0.3	4.3
RFQ+De-buncher	0.5	13.8

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There is a transverse emittance growth induced by the phase gymnastic of the IH-structure and by the RFQ. For the longitudinal emittance, a capture range of the DDB in phase of 240^o has been assumed.

The Double Drift Buncher

The first two cavities of the HITRAP linac belong to the double drift buncher, which matches the beam from the ESR longitudinally into the phase acceptance of the (IH) structure. The typical phase acceptance of the IH-decelerator averages to ±20^o. In order to match more than 60% of the beam into the acceptance of the IH-structure either a multi-harmonic re-buncher or a DDB is required. A DDB has the same bunching efficiency like a three harmonic driven single buncher. The HITRAP setup uses a 108.408 MHz cavity and a 216.816 MHz cavity separated by 0.9 m drift length. A magnetic quadrupole triplet lens matches the beam coming from the DDB to the entrance of the IH-structure in both transverse planes. The longitudinal phase space of the beam at the entrance of the IH-structure is shown in fig.2. The bunching efficiency is determined by the number of particles, which are within the phase acceptance of the IH-structure (fig.2). Thus about 75% of the particles from the ESR, which are in the main peak of the particle distribution, can be decelerated by the IH-structure and will not get lost.

The IH-structure

From the beam dynamics point of view, the HITRAP IH-structure has four synchronous particle sections. The synchronous particle structure starts with a bunching section of four gaps at 145^o. Then a deceleration section of 11 gaps at 180^o follows. After the inner tank lens a three-gap de-bunching section at -145^o starts and the structures is completed by a seven-gap 180^o part.

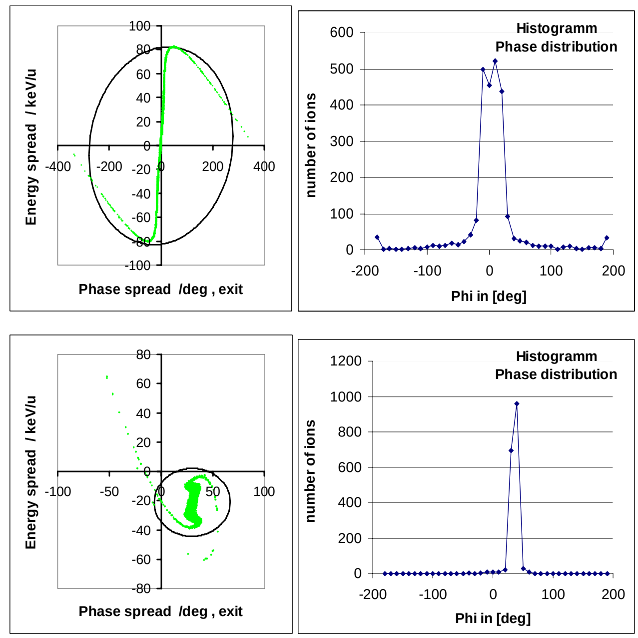

Figure 2: Longitudinal phase space of the beam bunched by the DDB at the entrance of the IH-structure (upper panels) and at the exit of the IH-structure.

The de-bunching section at -145^o counteracts the over focusing of the beam bunch in the longitudinal direction

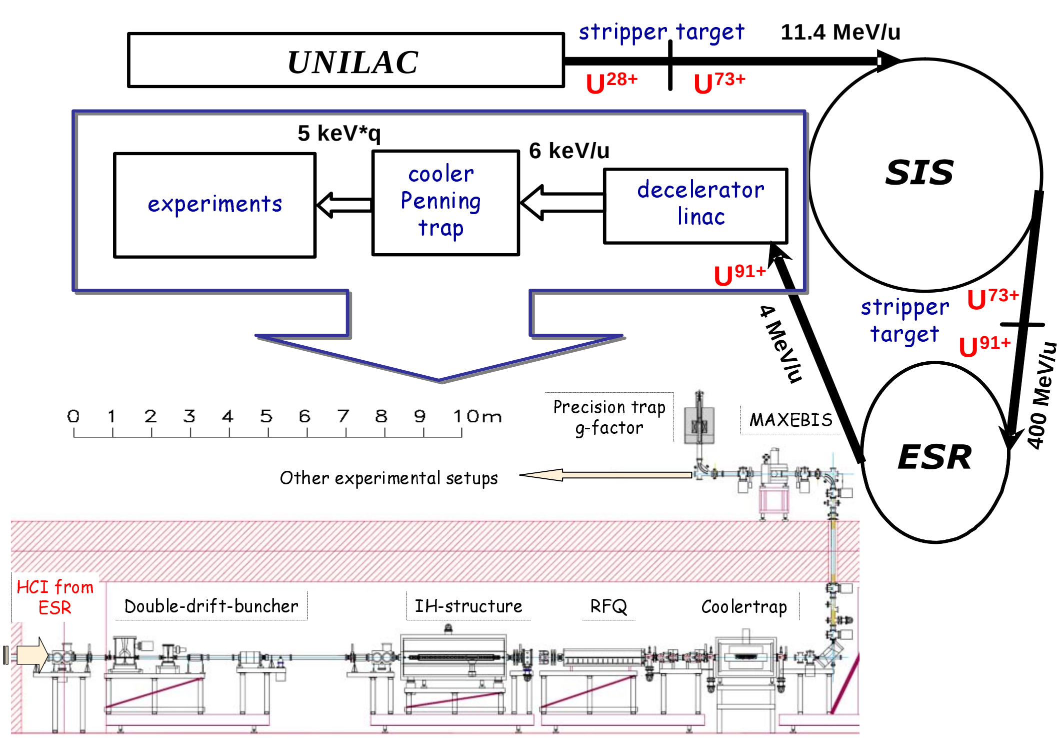

Figure 1: Schematic of the GSI accelerator chain and the HITRAP LINAC

after the first deceleration section. One inner-tank quadrupole triplet lens keeps the beam small. 76% of the beam coming from the ESR can be decelerated and fit into a bunch of 20^o phase spread and 7% energy spread (see fig.2). A new matching section between the IH-structure and the RFQ has been designed, using a two gap spiral re-buncher and two quadrupole doublet lenses. The 20^o phase spread of the ion bunches extracted from the IH-structure needs to be matched to the RFQ acceptance of 20^o. This is done with the re-buncher cavity in the MEBT section.

The RFQ and Cooler Trap

Due to the low $A/q < 3$ of the highly charged ions the HITRAP RFQ is as short as 1.9 m with 143 cells. The maximum require rod voltage is 77.5 kV. For sufficient transport and injection efficiency into the cooler trap a minimal energy spread of the ions is required. To reduce the 14% energy spread of the beam leaving the RFQ, a low energy de-buncher will be installed at the RFQ's exit [2]. Simulations have shown that the energy spread of the ions can be reduced to 8% using a single harmonic two gap spiral buncher.

HITRAP COMMISSIONING

The beam development and commissioning of HITRAP until March 2008 focus on the following issues:

- To shorten the ESR cooling and ramping time to about 10 s per cycle.
- To merge the ion bunches in the ESR and to compress the bunch longitudinal in a bunch of approximately 1 µs length.
- To optimize the beam transfer from the ESR towards the linac entrance.
- To measure and optimize the beam quality behind each cavity section of the HITRAP decelerator linac via emittance and energy analysis.
- To optimize the beam transmission through the linac according to the design calculations.
- To optimize the injection efficiency into the HITRAP cooler trap.

At present the complete deceleration and cooling cycle takes 37 s. The final goal is to reduce the total deceleration time in the ESR to about 10 seconds. Improvements of the efficiency of deceleration can be expected after implementation of online measurements of beam position and tune during the ramp and development of an algorithm to correct the magnet values according to the measured beam behaviour. Electron cooling after deceleration with higher electron currents allows faster cooling and has to be verified. Faster cooling at injection energy can be achieved if stochastic cooling is used. It is not clear yet whether the stochastically cooled beam can be decelerated with the same efficiency as the electron cooled beam. By RF-techniques like barrier bucket for instance the decelerated beam bunches could be merged and compressed longitudinally in one bunch.

For a proper tuning of the linac cavities, which comprises the right power level and the phase delay between the cavities, measurements of beam quality at the exit of the different cavities are required. The measurement of the transverse beam quality will be done via emittance measurements using the GSI emittance meter based on the “single shot pepper pot system” [3]. Due to the low repetition rate of pulses from the ESR, measurements with a slit-grid system are not practicable in a reasonable time. The pepper pot system has to be modified in order to be sensitive to low-intensity beams of highly charged particles. For this purpose the used fluorescence target will be exchange by YAG crystals or channel plate detectors. Test of the pepper pot system with highly charged ions from the MAXEBIS [5] are in preparation. With pairs of identical phase probes the beam energy can be determined by a time-of-flight measurement. In the HITRAP decelerator beam line phase probes will be permanently installed upstream to the IH-structure and in the inter tank section between IH-structure and RFQ. The micro-bunch length will be measured with a set-up based on diamond detectors [4]. Thus the right phase and amplitude setting can be determined.

Three beam times have been approved for commissioning of the three linac sections. The first section comprises the DDB and the beam transport towards the IH-structure, the second section is the IH-structure and the inter tank section between IH-structure and RFQ and the third linac section is the RFQ and the low energy re-buncher. The low energy section of HITRAP including the cooler trap can be tested in parallel to the linac commissioning offline using the Frankfurt MAXEBIS, now installed at GSI. However, the injection of decelerated beams from the ESR and test of the timing must be performed. The challenge is the much larger beam emittance of the beam from the RFQ in comparison to the MAXEBIS, which is about a factor of four to five.

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