STATUS OF CONSTRUCTION AND COMMISSIONING OF THE GSI HITRAP DECELERATOR*

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Abstract

The GSI accelerator facility provides highly charged ion beams up to U^{92+} at the energy of 400 MeV/u. These are cooled and decelerated down to 4 MeV/u in the Experimental Storage Ring. Within the Heavy Ion Trap facility HITRAP the ions are decelerated further down. The linear decelerator comprises a 108/216 MHz double-drift-buncher, a 108 MHz-IH-structure, a spiral-type rebuncher, and an RFQ-decelerator with an integrated debuncher providing energy spread reduction. Finally the beam is injected with the energy of 6 keV/u into a Penning trap for final cooling. The decelerator is installed completely and first sections have been successfully commissioned. For commissioning of the individual sections different ion species, e.g. $^{64}Ni^{28+}$, $^{20}Ne^{10+}$, $^{197}Au^{79+}$ were used. Each section was studied with comprehensive beam diagnostics to measure energy, emittance, intensity, transverse profiles, and bunch structure of the beam. The report gives an overview of the beam dynamics, the decelerator structures, and some results of the different commissioning runs.

INTRODUCTION

There are two possible methods to generate very highly charged heavy ions. One method employs an intensive and dense beam of electrons in electron beam ion source/trap (EBIS/T). It has been proved, that highly charged ions up to bare uranium could be generated in an EBIT, but only in minor quantities [1]. The other method uses a heavy ion accelerator that accelerates uranium ions to relativistic energies, where the uranium ions can be fully stripped with significant efficiency. In order to reach an efficiency of about 40%, uranium ions have to be accelerated above 400 MeV/u and sent through a copper target. World wide only the accelerator facility of GSI does accelerate uranium to this energy and can store a significant quantity ($\sim 10^8$) of the produced fully stripped uranium ions in the experimental storage ring (ESR) [2]. Heavy, highly-charged ions at very low, well defined energy are ideal systems for a number of precision experiments in different fields of physics. In case of production with an EBIS/T the ions are already at low kinetic energies, whereas in case of the stripping method the ions have to be decelerated. The highly charged heavy ion trap facility (HITRAP) [3-5] issued in 2005, uses the storage ring in conjunction with an rf-linear accelerator for deceleration of the highly-charged ions down to the required energies in the keV/u range, where the ions can be caught in a special Penning trap. Deceleration in the storage ring allows for stochastic phase space cooling as well as cooling with electrons. This keeps the advantage of a small transverse emittance as well as a very small momentum distribution of the beam. Additionally, the linac can be extremely compact, using just an interdigital H-type drift tube structure for the main deceleration stage. The final deceleration and beam focusing is done by a 4-rod RFQ. The linac structures operate at the typical UNILAC rf-frequency of 108.408 MHz and run with a maximum duty cycle of 0.5%. The duty cycle is not defined by the beam structure, as the ESR provides a bunch of 1-3 µs length every 40 seconds, but by the need to keep the cavities on temperature level between the beam pulses.

STATUS OF THE HITRAP BEAM LINE

An overview of the HITRAP beam line system relevant for the beam commissioning is shown in Fig. 1. The transfer of ions from the ESR to the first structure of the linac, the double drift buncher (DDB), is done by using the beam optics elements available from the original re-injection line between ESR and SIS. A variety of diagnostics elements has been mounted in the beam diagnostics stations shown in Fig. 1. The diagnostics comprises Faraday cups (FC), grid-based beam profile monitors (BPM) and scintillation screens (SCS), where YAG crystals are used. Beam transport is provided by two bending magnets and two magnetic quadrupole singlets. Downstream the wall between the ESR and the HITRAP vault, a diaphragm is mounted, which has a length of 150 mm and an inner diameter of 12 mm. The diaphragm is required to decouple the ESR vacuum at a level of 10^{-11} mbar from the vacuum in the HITRAP linac of about 10^{-8} mbar. The transfer line is available since the first HITRAP beam time in 2007.

The HITRAP linac is installed in the vault of the re-injection line called the re-injection channel. Fig. 2 shows a view in beam direction into the re-injection channel with the DDB and IH-structure section. Since early 2009 the construction of all linac sections is completed. The first part of the HITRAP rf-linac the double drift buncher consists of two coaxial quarter wave resonators. The first

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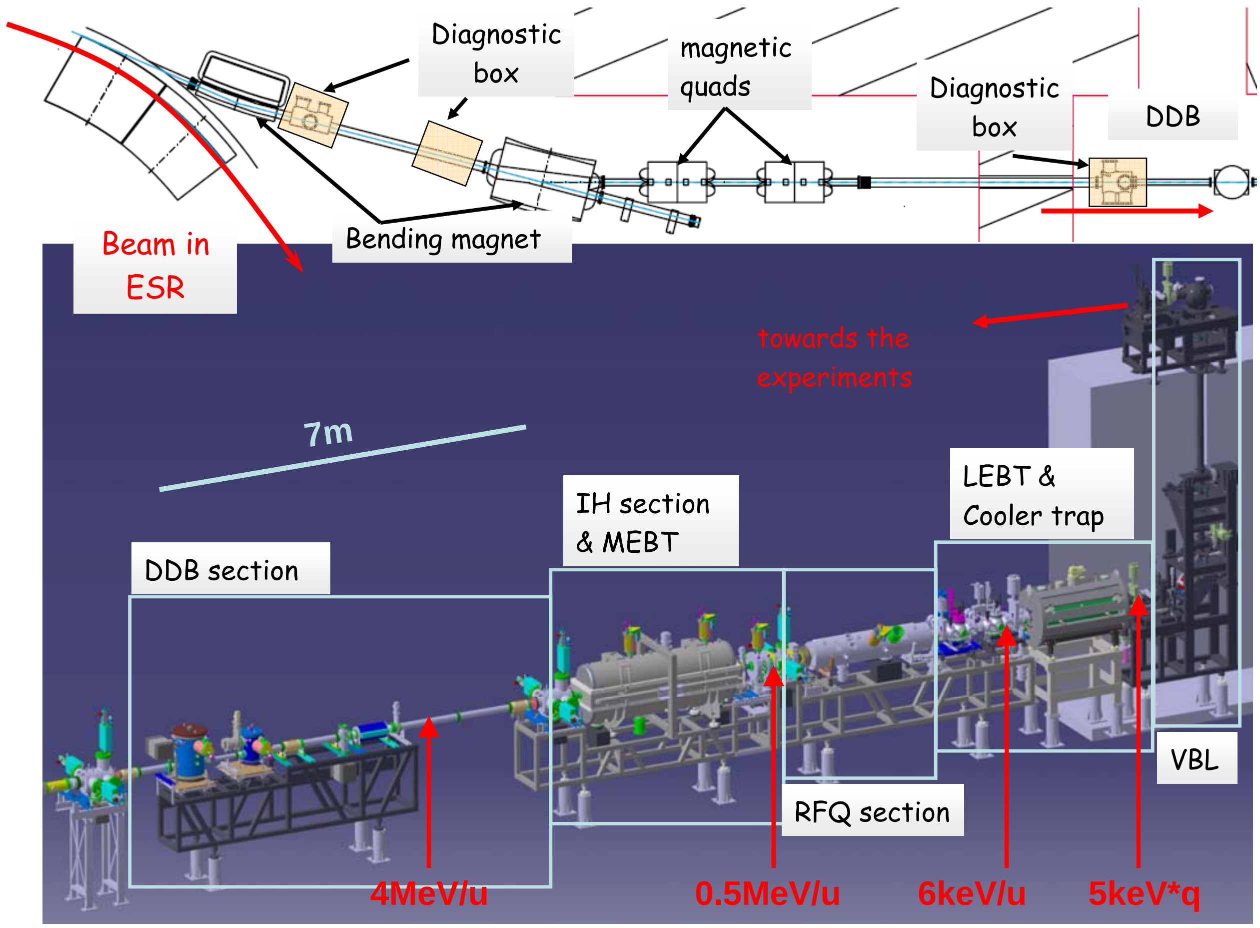

Figure 1: Overview of the ESR-HITRAP transfer line and of the HITRAP linac.

cavity has four gaps and operates at the first harmonic, whereas the second buncher resonator operates at the second harmonic and comprises two gaps. The main decelerating structure is the 25 gap interdigital H-type (IH) structure, shown in Fig. 3. The resonator is the main booster cavity, employing up to 10.5 MV effective voltage over 2.6 m inner tank length. The structure comprises one magnetic inner tank triplet lens and has been installed in 2008. Transverse matching of the beam from the DDB into the acceptance of the IH-structure is done with a magnetic quadrupole triplet lens as well. The intermediate section between IH-structure and the 4-rod radio frequency quadrupole structure (RFQ) has been installed in 2008, too. This section comprises two magnetic quadrupole doublet lenses and a two gap spiral re-buncher cavity. This inner tank section is required for the transverse and longitudinal matching of the beam coming from the IH-structure to the acceptance of the RFQ. The next section of the linear decelerator, the RFQ structure, was tested for vacuum leaks and conditioned at low rf power level in 2008. The space of the RFQ structure in the beam line has been used for beam diagnostic systems before [6]. The RFQ structure has finally been installed in early 2009.

Integrated in the RFQ tank is a short spiral buncher cavity [7]. Both are shown in Fig. 4. The spiral structure de-bunches the beam and reduces the energy spread of the ions decelerated by the RFQ structure. This reduction of the energy spread is mandatory for an efficient injection of the ions into the strong magnetic field of the HITRAP cooler Penning trap. The low energy beam transport line (LEBT) that connects the RFQ to the cooler trap is installed since 2008. The beam line houses six Einzel lenses, two diagnostic boxes and two diaphragms for differential pumping purposes. The LEBT has to decouple the cooler trap vacuum in the order of

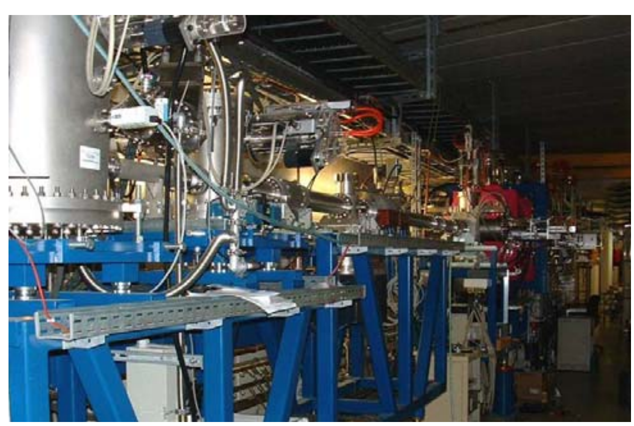

Figure 2: The re-injection channel in beam direction. The DDB structures appear on the left hand side and the IH-structure in pink are visible.

Figure 3: View into the HITRAP IH-structure from the low energy end of the resonator.

10^{-13} mbar from the typical RFQ vacuum of 10^{-8} mbar. In addition, the electrostatic beam focusing of the LEBT must cover a beam emittance of approximately 200 mm mrad, expected at the exit of the RFQ. The components of the LEBT have been baked and reached the specified pressure of 10^{-10} mbar. The LEBT beam line elements are operational and beam can be transported towards the HITRAP cooler trap.

The cooler Penning trap superconducting magnet has been tested and is being operational. The trap electrode structure is being assembled and ready to be installed in the SC-magnet. Most components for the transfer line to the experiments are available and ready for assembly in the re-injection channel, too. The SPARC-EBIT is being installed on top of the concrete shield of the re-injection channel. It will deliver highly-charged ions for offline commissioning of the cooler trap.

The status of the commissioning in the past two years has been described elsewhere [6, 8] in details. However, main purpose of the diagnostics used in the linac beam line is devoted to the determination of the transverse beam quality and of the beam energy of the ions. Measurements of the transverse beam emittance are done with a magnetic quadrupole lens scan and by using pepper pot emittance meter systems [9]. The beam energy is determined by deflecting the ions with a steerer magnet and by energy analysis using diamond detectors [10]. From the beam commissioning experiments done so far an urgent need of the ion beam energy analysis downstream the IH-structure has been concluded. A significant fraction of the ion beam which is transmitted by the IH-structure has higher kinetic energies than the expected 500 keV/u.

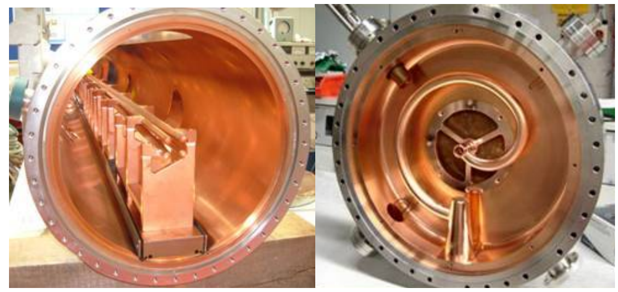

Figure 4: View into the HITRAP 4-rod RFQ and inside the de-buncher integrated into the RFQ tank.

HITRAP BEAM DYNAMICS

The beam dynamics of the HITRAP linac face several challenges due to the use of existing beam optics equipment and the reverse operation of the rf-accelerator structures. The rf-properties of the cavities determine essentially the overall beam dynamics from 4 MeV/u down to 6 keV/u. The main rf-parameters, such as effective shunt impedance, Q-value and the required effective acceleration voltage of the HITRAP linac structures are summarized in Table 1. The corresponding data have been taken into account for the beam optics simulations done for HITRAP.

The beam provided by the ESR is a bunch of 1-3 μs length. No microstructure, which is matched to the rf-frequency of the linac structures, is available from the storage ring. Therefore the DDB does the longitudinal matching of the beam into the phase acceptance of the IH-structure. The principle is explained in Fig. 5. The phase or time window for deceleration of an ion down to 0.5 MeV/u is about 15° or 0.4 ns.

Table 1: Rf-Parameter of the HITRAP Linac Structures (QWR = quarter wave resonator)

Component (resonator type)	Z_{eff} [MΩ/m] or [kΩ·m] (RFQ)	Q value	U_{eff} for A/q = 3 [kV]
DDB1 (4-gap QWR)	51.7	10950	220
DDB2 (2-gap QWR)	43	11100	70
IH-structure (25 gaps)	270	25800	11060
Re-buncher (spiral)	28.6	5300	105
RFQ (4-rod)	138	3700	77.5
De-buncher (2-gap spiral)	15.5	2700	0.4

A saw tooth like waveform of the buncher voltage is ideal for efficient bunching of a quasi continuous beam. However, it is difficult to generate it at the required rf-frequency and power level. In a harmonic buncher a saw tooth like voltage waveform is obtained by superposition of fundamental frequency ω with its various higher

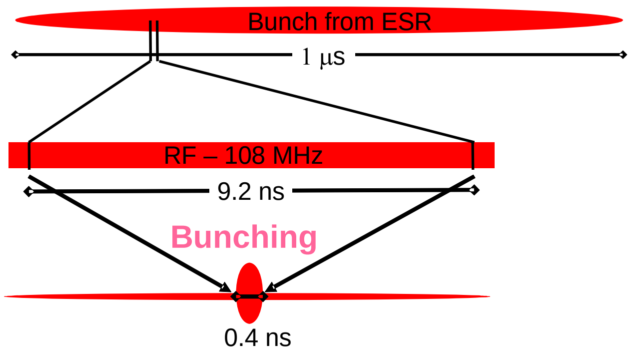

Figure 5: Bunching of the ion beam from the ESR.

harmonics 2ω, 3ω, 4ω etc. on a single gap. A double drift bunching system consists of two bunchers that are separated in space and are driven independently and phase locked together. The second buncher is driven at twice the frequency of the first. The phase adjustment is more flexible due to the long drift and the pre-bunching of the ions in the first cavity. A double drift buncher reveals the same bunching efficiency like a triple harmonic buncher of about 70% [11].

A comparison of the different systems is shown in Fig. 6. In this graphic the final phase distribution of the particles at the entrance of the IH-structure is plotted versus their initial phase at the entrance of the corresponding buncher. For the single harmonic buncher (red curve) about 40% of the ions can be bunched into the 15° phase interval, whereas the triple harmonic buncher and the DDB systems allow for about 70% of the particles focused into the phase acceptance. Note that the DDB has an even better bunching efficiency than the triple harmonic buncher.

The transverse focusing of the beam along the beam transport lines and in the linac is quite delicate, because the transverse emittance of the ions is very sensitive on the deceleration in the IH-structure. The beam dynamics design of the IH-structure has been done with the LORASR code [12]. This code has no fitting routines for the transverse beam matching with magnetic quadrupoles. Therefore an rf-gap routine has been developed for the COSY Infinity code [13], which incorporates the rf-defocusing in an acceleration gap. The COSY Infinity code has a couple of fit routines available, which can be used to match the beam in transverse direction to the IH-structure and to the RFQ further downstream. The results are shown in Fig. 7. Two panels show the two cases of beam dynamic with optimized settings. One covers the case that the beam is not decelerated (upper panel) and the other lower panel shows a perfectly decelerated beam down to 0.5 MeV/u. The brown box determines the location of the RFQ and of the beam measurement equipment in the commissioning runs. The 0.5 MeV/u beam is matched to the RFQ entrance conditions, whereas the 4 MeV/u beam is mismatched at the entrance of the RFQ and divergent. The goal is the reduction of particles with higher energies than 0.5 MeV/u at the entrance of the RFQ and to improve the signal to noise ratio of the decelerated ions.

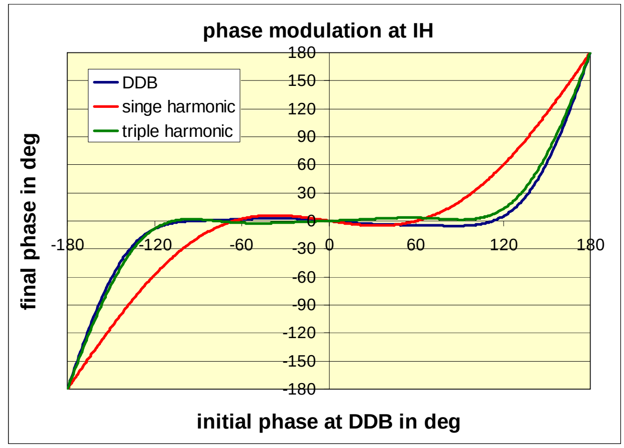

Figure 6: Bunching of the ion beam from the ESR for different buncher systems in comparison.

In addition to the transverse matching, the deceleration performance of the IH-structure is sensitive to the right phase setting and the injection energy [14]. Therefore the energy distribution of the ions at the exit of the IH-structure has been investigated with the LORASR code.

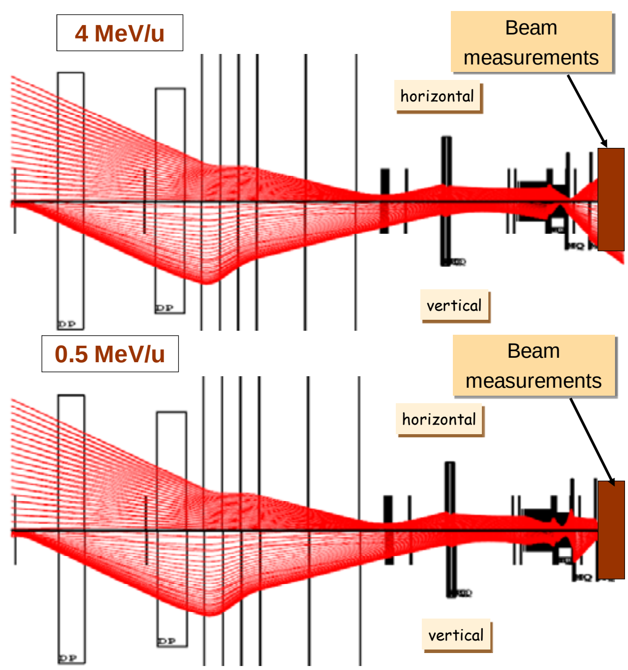

Figure 7: Transverse beam optics in the HITRAP beam line from ESR towards the RFQ for a matched beam tune calculated with COSY9. The upper panel shows the beam transport for a 4 MeV/u beam, the lower a decelerated beam that has 0.5 MeV/u downstream the IH-structure.

Fig. 8 demonstrates the dependence of the ion energy distribution on the phase setting of the IH-structure. For theses simulation the assumption was made that all ions were bunched into a 20° phase interval at the entrance of the IH-structure. Even in this case, the ion energy distribution varies significantly with the phase setting of the IH-structure when it differs from the nominal phase setting of about 10°. At 40° the ion energy distribution

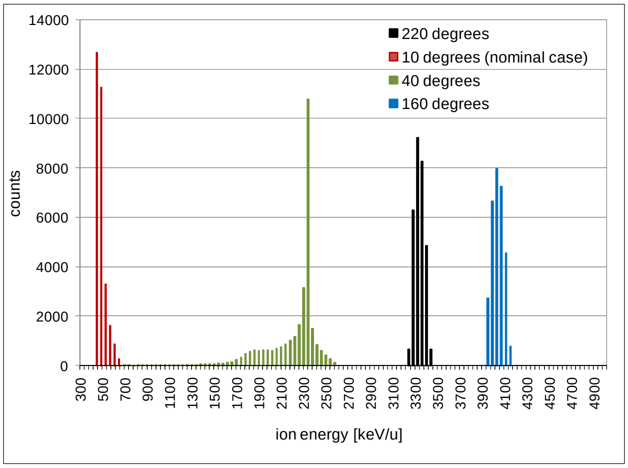

Figure 8: Energy distribution of the ions for different settings of the IH-resonators, assuming that all ions are pushed into a bunch of 20° phase length by the DDB.

reveals a maximum at an intermediate energy of about 2.3 MeV/u, which has been seen in the first commissioning run of the IH-structure in 2008. At 160° the ion energy distribution is peaked around 4 MeV/u, where the IH-structure has considerably high transport efficiency. In real life the situation is even worse, because the bunching efficiency of the DDB into the 20° phase interval is only about 75% and therefore 25% of the particles are distributed over the remaining 340°. Hence, these ions will populate the energy range between 1 MeV/u and 4.1 MeV/u.

Therefore we conclude that a single shot online analysis of the energy distribution of the ions is an important issue and a corresponding diagnostic has to be included in the HITRAP setup. However, decelerated ions with kinetic energy of 0.5 MeV/u could be detected and ions could be injected into the RFQ. The final energy of the ions downstream the RFQ requires a single shot energy analysis as well to find the right working points of the decelerator structures.

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