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 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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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...
10^{-13} \text{ mbar} \) from the typical RFQ vacuum of \( 10^{-8} \text{ mbar} \). In addition, the electrostatic beam focusing of the LEBT must cover a beam emittance of approximately \( 200 \text{ mm mrad} \), expected at the exit of the RFQ. The components of the LEBT have been baked and reached the specified pressure of \( 10^{-10} \text{ mbar} \). 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 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 \( \mu \text{s} \) 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>
<thead>
<tr>
<th>Component (resonator type)</th>
<th>( Z_{\text{eff}} ) [( \text{M}[\Omega/\text{m}] ) or [( \text{k}[\Omega\cdot\text{m}] )] (RFQ)</th>
<th>( Q ) value</th>
<th>( U_{\text{eff}} ) for ( A/q = 3 ) [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDB1 (4-gap QWR)</td>
<td>51.7</td>
<td>10950</td>
<td>220</td>
</tr>
<tr>
<td>DDB2 (2-gap QWR)</td>
<td>43</td>
<td>11100</td>
<td>70</td>
</tr>
<tr>
<td>IH-structure (25 gaps)</td>
<td>270</td>
<td>25800</td>
<td>11060</td>
</tr>
<tr>
<td>Re-buncher (spiral)</td>
<td>28.6</td>
<td>5300</td>
<td>105</td>
</tr>
<tr>
<td>RFQ (4-rod)</td>
<td>138</td>
<td>3700</td>
<td>77.5</td>
</tr>
<tr>
<td>De-buncher (2-gap spiral)</td>
<td>15.5</td>
<td>2700</td>
<td>0.4</td>
</tr>
</tbody>
</table>

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 \( \omega \) with its various higher
harmonics $2\omega$, $3\omega$, $4\omega$ 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.

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 5: Bunching of the ion beam from the ESR.](image)

![Figure 6: Bunching of the ion beam from the ESR for different buncher systems in comparison.](image)

![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.](image)
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.

REFERENCES