MEASUREMENTS AND SIMULATIONS ON THE BEAM BRILLIANCE IN THE UNIVERSAL LINEAR ACCELERATOR UNILAC AT GSI

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Abstract
In the framework of the GSI beam intensity upgrade program for the heavy ion synchrotron (SIS) the UNILAC was upgraded to deliver intense heavy ion beams up to uranium under space charge conditions. The SIS has to be filled up to its space charge limit. Measurements and simulations on the transverse beam emittance growth during acceleration in the Alvarez section of the UNILAC were performed. Transverse beam emittances were measured before and after the Alvarez section using a pepper pot and the slit-grid method. Results of measurements on the decrease of the beam brilliance of an intense Ar$^{10+}$ beam (10 emA) during acceleration are presented. The space charge forces correspond to an U$^{28+}$ beam with an intensity of 21 emA (design current 12.6 emA). Simulations on the dynamics of an high intense beam during acceleration were done using the code PARMILA. The experimental and theoretical results are discussed.

1 INTRODUCTION
The High Current Injector (HSI) section of the UNILAC (Fig.1) comprises a RFQ and two IH-structures providing a beam energy of 1.4 MeV/u. For high intensities the heavy ion beams are generated by MEVVA or MUCIS ion sources. After increasing the charge state in a gas stripper and subsequent charge state separation the beam is injected into the Alvarez section. The final energy of up to 11.4 MeV/u fits to the injection energy for the SIS. The UNILAC macro pulse (150 $\mu$s) is injected into the synchrotron filling its horizontal acceptance during 20 turns. This requires a horizontal UNILAC design emittance of 0.8 mm-mrad and a vertical emittance of 2.5 mm-mrad (normalized). In order to reach high beam intensities in the SIS the transverse emittance growth must be minimized in the UNILAC. Emittance growth is due to straggling during the stripping process and for high intensities also due to space charge forces. To first order this growth scales with the space charge parameter (SCP) [1]

$$SCP \sim I \cdot q \cdot \beta^{-1} \cdot (XYZ)^{-1},$$

where $I$ is the electrical beam current, $q$ is the charge state, $\beta$ is the normalized velocity, and $XYZ$ are the rms-widths of the bunch in the three dimensions. Figure 2 shows the SCP along the beam line from the exit of the HSI to the injection into the SIS. The impact of the space charge forces in the HSI is low resulting from a low charge state. The SCP has a first maximum after the stripping process before the charge state separation. Its second maximum results from the strong longitudinal bunch compression required by the increase of the acceleration frequency from 36 MHz in the HSI to 108 MHz in the Alvarez section. Additionally, the transverse bunch size must be reduced for proper transverse beam matching leading to a growth of the beam emittances during acceleration in the Alvarez section. The presented investigations aimed for the dependence of this growth on the beam intensity and on the transverse phase advance given by the focusing strength in the Alvarez section. In the following we refer to the phase advance $\sigma_0$ corresponding to a low intensity beam. The
maximum phase advance $\sigma_0$ for the heaviest ion $^{238}\text{U}^{28+}$ is limited by the quadrupole power supplies to 45°. To extend our investigations beyond this limit the measurements were performed with $^{40}\text{Ar}^{10+}$ using its lower mass to charge ratio. The high argon intensities achieved in the UNILAC impose (and exceed) the space charge conditions of the aimed uranium intensities.

2 EXPERIMENTAL SETUP

After the gas stripper the desired charge state is separated by slits in a dispersive section (Fig. 1). This chicane includes a setup to measure the horizontal phase space distribution using the slit-grid method. The central dipole can be switched off and the beam current and the longitudinal phase space distribution can be measured between this dipole and a beam dump [2]. A pepper pot device allows for the measurement of the transverse phase space distribution of a single pulse before and after the Alvarez section, respectively. Beam transformers before and after the section are used to measure the intensity and the transmission.

3 MEASUREMENTS AND RESULTS

The beam transmission and the transverse emittance were measured for three different ion currents and for four different transverse phase advances $\sigma_0$ in the Alvarez (Tab. 1). The beam current after the stripper was changed by varying the stripping gas density. This method preserves the shape of the phase space region occupied by the beam allowing to vary its brilliance exclusively. The horizontal phase space distribution was measured for currents of 1 emA, 5 emA, and 10 emA using the slit-grid method in the charge state separator (Fig. 3). No dependence on the beam current was observed. The quadrupole strength along the Alvarez section was set for a constant transverse phase advance $\sigma_0$ of 45°. The transmission through the Alvarez section was optimized for 10 emA using two quadrupole multiplets in front of it. Applying these quadrupole settings the beam transmission and the transverse emittances before and after the Alvarez section were measured for the different currents. The scans were performed for transverse phase advances of 39°, 45°, 51°, and 59°. The beam optics was changed exclusively downstream of the stripper in order to keep the shape of the occupied phase space region constant at the position of the slit-grid setup.

For 10 emA transmissions from 92% at a phase advance of 51° to 78% at 39° were obtained (Tab. 1). Figure 4 shows the horizontal phase space distributions measured after the Alvarez section for 10 emA using phase advances of 39° and 51°, respectively. The smallest beam emittances ac-

Table 1: Measured transmissions, horizontal, and vertical norm. total 90%-emittance growths in percent for different $\text{Ar}^{10+}$-currents and phase advances.

<table>
<thead>
<tr>
<th>I(HSI)</th>
<th>$\sigma_0 \rightarrow$</th>
<th>39°</th>
<th>45°</th>
<th>51°</th>
<th>59°</th>
</tr>
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<tbody>
<tr>
<td>1 emA</td>
<td>$\Delta \epsilon_x$</td>
<td>86</td>
<td>86</td>
<td>89</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>$\Delta \epsilon_y$</td>
<td>87±11</td>
<td>-32±21</td>
<td>-8.6±12</td>
<td>-</td>
</tr>
<tr>
<td>5 emA</td>
<td></td>
<td>85</td>
<td>93</td>
<td>94</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>120±14</td>
<td>170±35</td>
<td>26±27</td>
<td>180±9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-2.4±14</td>
<td>110±23</td>
<td>89±24</td>
<td>300±14</td>
</tr>
<tr>
<td>10 emA</td>
<td></td>
<td>78</td>
<td>88</td>
<td>92</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>220±6</td>
<td>84±45</td>
<td>21±9</td>
<td>120±1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>57±17</td>
<td>105±35</td>
<td>48±5</td>
<td>162±1</td>
</tr>
</tbody>
</table>

Figure 3: Measured horizontal phase space distribution using the slit-grid method in the chicane for an $\text{Ar}^{10+}$-current of 1 emA. The distributions for 5 emA and 10 emA looked alike.

Figure 4: The horizontal phase space distributions measured with the pepper pot after the Alvarez section for an $\text{Ar}^{10+}$-current of 10 emA and a transverse phase advance of 39° (upper part) and 51° (lower part). The measured transmissions were 78% and 92%, respectively.
The measured emittances for 10 emA, the highest brilliance for low currents, is due to the finite accuracy of the experimental estimation. The measured brilliance is caused by the measured final beam brilliance. A further increase of the focusing strength seemed to decrease the final brilliance. For a low initial current of 1 emA the measured final beam brilliance did not depend significantly on the focusing strength.

5 CONCLUSION AND OUTLOOK

The beam brilliance after acceleration in the Alvarez section was measured and calculated for different initial beam currents and for different transverse betatron phase advances in the section. The experimental data indicate the highest transmissions in connection with the lowest emittance for phase advances between 45° and 51° and revealed a decreased brilliance for even higher phase advances. Accordingly, an increase of the current limitation of the 238U28+ phase advance (45°) in the Alvarez section should result in higher intensities and smaller emittances also for uranium beams. The authors like to thank D. Likan for the support during the measurements with the pepper pot devices.

6 REFERENCES
