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 μs) 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]

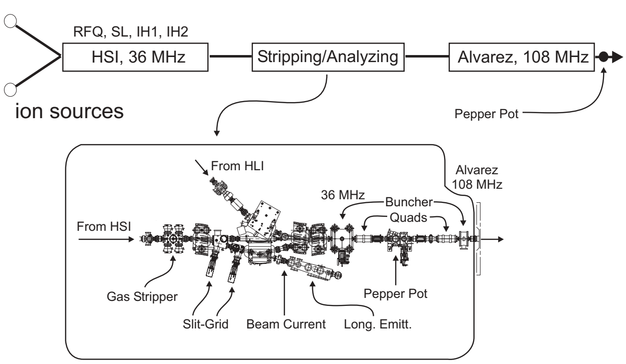

Figure 1: The Universal Linear Accelerator UNILAC.

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

where I is the electrical beam current, q is the charge state, β 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 σ_0 corresponding to a low intensity beam. The

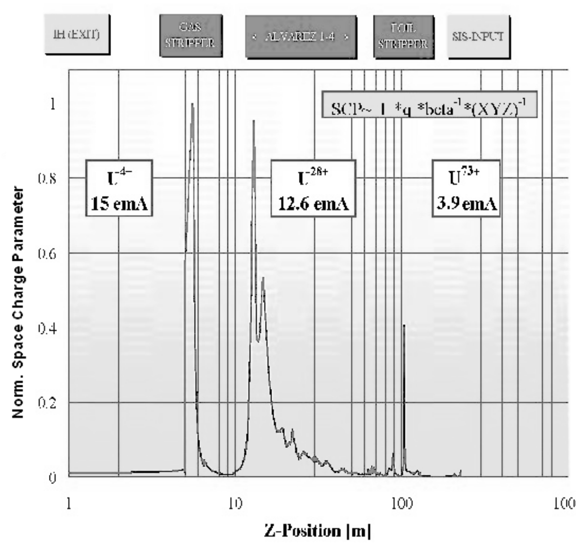

Figure 2: The space charge parameter SCP along the UNILAC for an intense uranium beam.

maximum phase advance σ_0 for the heaviest ion $^{238}U^{28+}$ is limited by the quadrupole power supplies to 45°. To extend our investigations beyond this limit the measurements were performed with $^{40}Ar^{10+}$ 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 σ_0 in the Alvarez (Tab. 1). The beam current after the stripper was

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

I(HSI)	σ_0 →	39°	45°	51°	59°
1 emA	T	86	86	89	85
	$\Delta\epsilon_x$	89±12	86±36	-17±9	–
	$\Delta\epsilon_y$	87±11	-32±21	-8.6±12	–
5 emA		85	93	94	90
		120±14	170±35	26±27	180±9
		-2.4±14	110±23	89±24	300±14
10 emA		78	88	92	86
		220±6	84±45	21±9	120±1
		57±17	105±35	48±5	162±1

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 σ_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

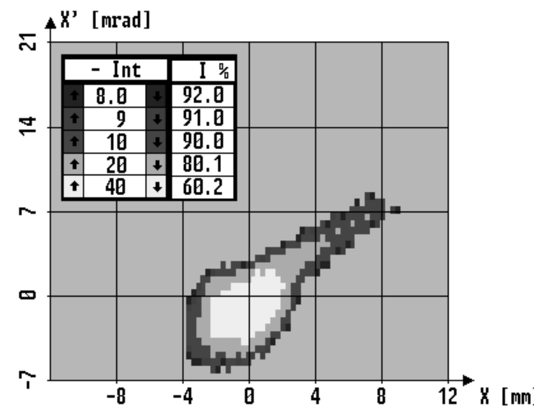

Figure 3: Measured horizontal phase space distribution using the slit-grid method in the chicane for an Ar^{10+} current of 1 emA. The distributions for 5 emA and 10 emA looked alike.

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-

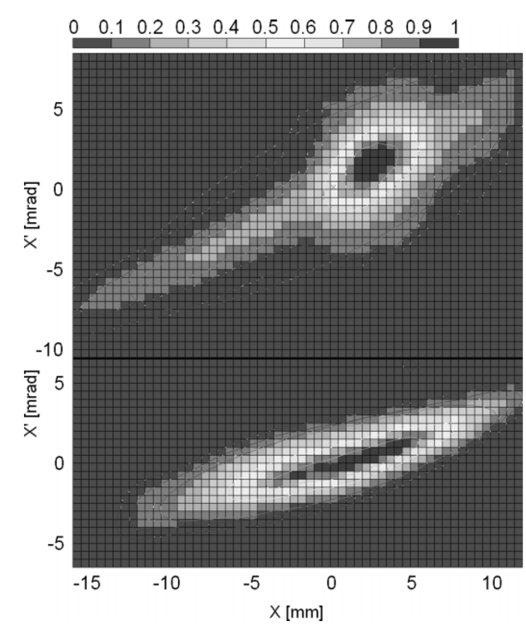

Figure 4: The horizontal phase space distributions measured with the pepper pot after the Alvarez section for an Ar^{10+} current of 10 emA and a transverse phase advance of 39° (upper part) and 51° (lower part). The measured transmissions were 78% and 92%, respectively.

companied by the highest transmissions were found for an Alvarez phase advance of 51°. A further increase to 59° resulted in larger final emittances and a decrease of transmission. It must be mentioned that the angular resolution of the pepper pot devices proved to be not sufficient for quantitative measurements of the phase space distribution. However, the data were used to estimate a lower limit of the beam current which is contained in the transverse UNILAC design emittance. These values are shown in Fig. 5 as function of the phase advance for the different beam currents. As already indicated by the measured transmissions and by

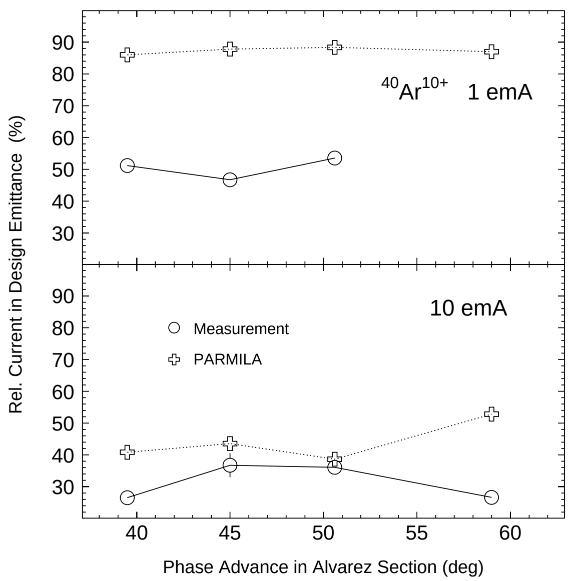

Figure 5: Current of Ar^{10+} (normalized to current at the slit-grid setup) in the transverse UNILAC design emittance after the Alvarez section as function of the transverse phase advance in the section for 1 emA (upper part) and 10 emA (lower part) after the stripper. The measured values are a lower limit of the brilliance.

the measured emittances for 10 emA, the highest brilliance after the Alvarez is observed for transverse phase advances between 45° and 51°. 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.

4 SIMULATIONS

The horizontal phase space distribution measured after the gas stripper (Fig. 3) was used in connection with previous measurements of longitudinal distributions [2] to reconstruct the initial conditions after the stripper. Additionally, the pepper pot measurements and beam profiles recorded before the Alvarez section were used. The obtained six dimensional distribution and the beam focusing settings were used as input to simulate the experiment with the PARMILA code. In the simulations the measured beam parameters before the Alvarez section were reproduced. However, this just means that the corresponding projections of the initial phase space distribution agree with the experiment. Especially the assumed correlations between the longitudinal and transverse distributions were not measured, but they have a significant impact on the beam dynamics for high intensities. The incomplete knowledge of the initial six dimensional phase space distribution must be kept in mind for the discussion of the results. Figure 5 shows the calculated currents in the UNILAC design emittance.

The measured values give lower limits for the brilliance. Correspondingly, the simulations and the experiment must be compared qualitatively. The systematic difference between calculated and measured values, observed especially for low currents, is due to the finite accuracy of the experimental estimation. The observed decrease of the brilliance at the highest phase advance of 59° with respect to its maximum was not reproduced by the simulations. The calculations revealed a strong emittance increase during the matching of the beam into the Alvarez section as indicated by the space charge parameter (Fig. 2). The growth of the emittance is caused by the longitudinal bunch compression and transverse focusing before the Alvarez section. Due to acceleration the growth decreases along the section and the beam emittances saturate after the second Alvarez tank. The beam brilliance in the UNILAC design emittance shows a similar behavior. It strongly decreases during beam compression and remains constant after the second Alvarez tank. The calculated transmissions were between 90% and 92% and did not depend on the transverse 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 growths 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 $^{238}U^{28+}$ 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. Liakin for the support during the measurements with the pepper pot devices.

6 REFERENCES

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