SINGLE-SHOT MEASUREMENTS OF THE 4-DIMENSIONAL TRANSVERSE PHASE SPACE DISTRIBUTION AT THE UNILAC AT GSI

W. Barth and L. Groening, GSI, Darmstadt, Germany

D. Liakin, ITEP, Moscow, Russia

Abstract

The UNILAC is used as an injector for the synchrotron SIS. It is designed to fill the synchrotron up to its space charge limit. The upper limit for the useful beam emittance of the UNILAC is given by the finite acceptance of the SIS during the injection process. In order to remain within this acceptance the emittance growth during beam acceleration and transportation due to space charge effects must be minimized by applying an appropriate beam focusing. Therefore, the influence of the magnetic focusing strength on the beam emittance growth was investigated experimentally for different beam currents. Measurements of transverse phase space distributions were performed before and after the Alvarez accelerator with a periodic focusing channel, respectively. In order to perform such a wide parameter scan within a reasonable time with respect to machine stability, the pepper pot technique was applied. The pepper pot method allows for single-pulse measurements. For comparison several measurements using the slit-grid technique, which averages over many pulses, were performed. Both transverse planes were measured simultaneously. Using two pepper pot devices more than 60 single shot measurements of the full 4-dimensional transverse phase space distribution were performed within 8 hours. In this paper we report on the results of the measurements and we compare them to beam dynamic simulations and we give an outlook on further developments on pepper pot devices.

INTRODUCTION

The High Current Injector (HSI) of the UNILAC (Fig.1) comprises a RFQ and two IH-structures operated at 36 MHz. It accelerates intense ion beams generated by a MUCIS- or MEVVA- ion source to an energy of

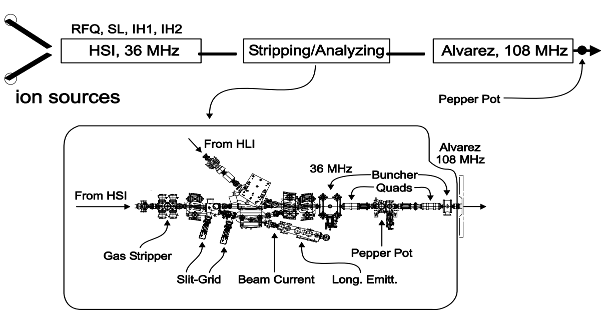

Fig. 1: Schematic overview of the Universal Linear Accelerator UNILAC at GSI.

1.4 MeV/u. After the HSI the ion charge state is increased by passing the beam through a gas jet stripper. A subsequent charge state separator selects the charge state for further acceleration in the Alvarez DTL (108 MHz) to 11.4 MeV/u. To match the periodic transverse focusing in this section, the beam size must be reduced significantly in all three dimensions. This leads to a strong increase of the space charge forces, which scale with the space charge parameter SCP [1]

$$SCP \sim I_p \cdot q^2 \cdot \beta^{-1} \cdot (XYZ)^{-1} ,$$

where I_p is the particle beam current, q is the ion charge state, β is the relative velocity, and (XYZ) is the bunch volume. As shown in Fig.2 the SCP has two maxima

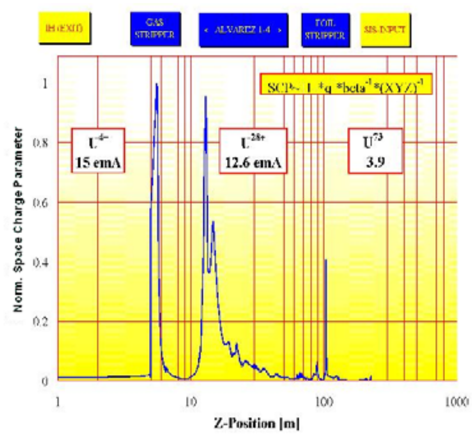

Fig. 2: The space charge parameter SCP along the UNILAC.

during the stripping process and at the entry to the Alvarez section, respectively. During acceleration it decreases due to the increase of β. For a given beam current the emittance growth along the section depends on the transverse focusing strength. According to theory the growth should be reduced by a stronger focusing. We aimed on the experimental investigation of this dependence for three different beam intensities.

EXPERIMENTAL SET-UP

Figure 1 shows the set-up of the experiment. Beam currents were measured before and after the Alvarez section. The 4-dimensional transverse phase distributions were measured during single-shots using a pepper pot device before and after the DTL, respectively. Additionally, a horizontal slit/grid set-up was employed, which serves normally to optimize the charge state separation. A detailed description of the diagnostics at the UNILAC can be found in [2].

The beam focusing along the DTL was set to a transverse zero current phase advance σ_o of 39°. By variation of the stripping gas pressure the current of the $^{40}Ar^{10+}$ beam was set to 10 emA for the first measurement of the parameter scan. The five quadrupole lenses before the DTL were set in order to maximize the beam transmission. Beam emittances and currents were measured before and after the DTL using the pepper pot devices. Beam intensity reduction (1 emA, 5 emA) was done by varying the stripping gas density. This method preserves the shape of the phase space region occupied by the beam. These three measurements were repeated for phase advances σ_o of 45°, 51°, and 59°, respectively. In total 12 measurements on emittance growth were performed including more than 60 measurements of the full transverse 4-dimensional phase space distribution. This scan could not have been accomplished using slit/grid set-ups within a reasonable time with respect to machine stability. Additionally, for each current one measurement of the horizontal phase space distribution was performed with the slit/grid set-up (Fig.3). The results confirm that the shape of the distribution did not change significantly with the beam intensity.

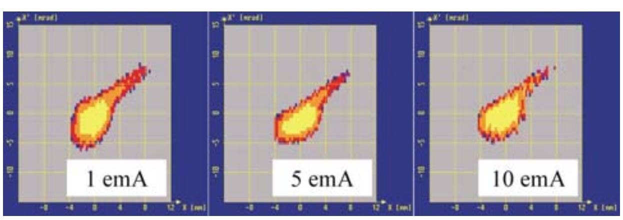

Fig. 3: Measured horizontal phase space distribution for three different ion currents using a slit/grid set-up before the Alvarez section.

EXPERIMENTAL RESULTS

Figure 4 shows the horizontal phase space distributions after the DTL measured with a pepper pot device for different currents and phase advances. For a σ_o of 45° and 51° compact distributions were observed. In case of 39° and 55° large tails of lower density occur, which increase the emittance. The measurements were used to extract the normalized beam emittances for both transverse planes. Figure 5 summarizes the obtained emittances after the Alvarez DTL together with the beam transmission through the section. As already seen qualitatively on the pepper pot images, the extracted horizontal emittance is lowest for σ_o=51°, which is 10% higher than the phase advance of 45° used so far in routine operation of the UNILAC for intense beams. This behaviour of the horizontal emittance fits to the measured transmissions, which were highest at 51° as well. The vertical emittance

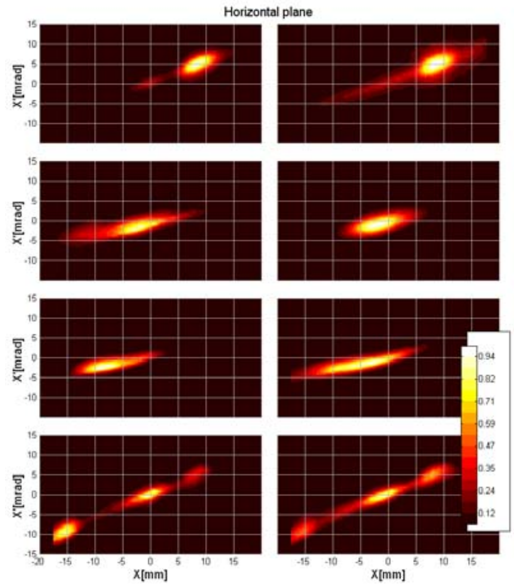

Fig. 4: Horizontal projections of single-shot measurements of the phase space distributions after the Alvarez section using a pepper pot device. Shown are the results for currents of 1 emA (left) and 10 emA (right) for transverse phase advances σ_o of 39°, 45°, 51°, and 59° (top to bottom).

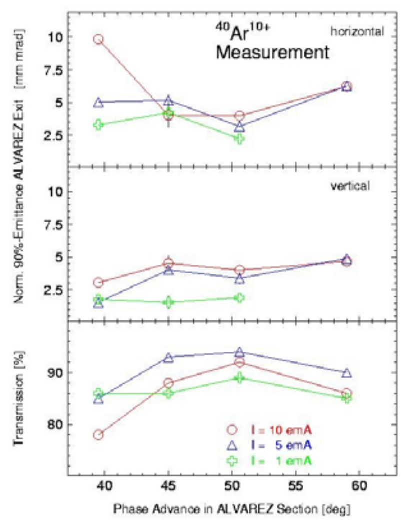

Fig. 5: The measured normalized horizontal and vertical emittances after the Alvarez section. The values refer to 90% of the particles. The bottom part shows the transmission through the Alvarez DTL.

after the DTL as function of σ_o did not show a conclusive behaviour. It was observed to be constant within the accuracy of the data reduction. Additionally, the measured emittances before the Alvarez DTL showed a strong dependence on the beam size at the pepper pot for all beam currents as shown in Fig.6. The emittance before the DTL should not depend on the beam focusing especially for very low currents of 1 emA. The measured rms emittance shows a linear dependence on the beam size. The slope is about 2.7 mrad. Besides the beam size the rms beam divergence was evaluated and found to be larger than 2 mrad for all beam sizes being comparable to

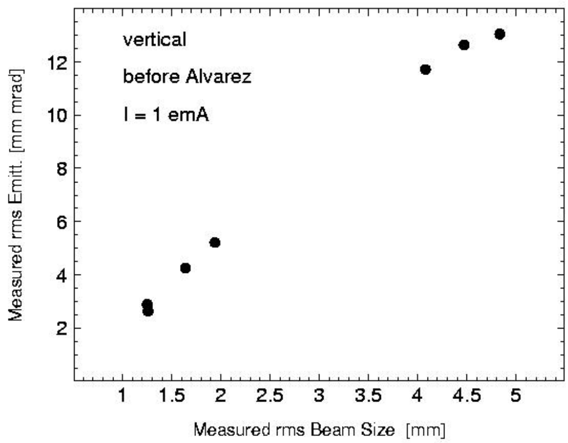

Fig. 6: The measured horizontal rms emittance for different horizontal beam spot sizes on the pepper pot. The ion beam parameters are identical for all measurements.

the slope of 2.7 mrad mentioned before. This observation can be understood, if the angular resolution of the pepper pot devices before the DTL, i.e. at 1.4 MeV/u, is about 2 mrad. These linear dependences at low currents were observed for both planes before and after the DTL. At higher ion energies of 11.4 MeV/u the angular resolution seemed to be about 1 mrad. Starting from the phase space distributions measured with the slit/grid set-up we expect rms beam divergences, which are about half of the angular resolution estimated from the measurements with the pepper pot devices. However, the quantitative results of the pepper pot measurements clearly showed that most compact phase space distributions could be obtained if the DTL phase advance σ_o for high intensities is set close to 50^o.

SIMULATIONS

In order to model the initial 6-dimensional distribution, the measurements with the slit/grid set-up, with the pepper pot devices, and with various beam profile monitors before the Alvarez DTL were used. Additionally, previous measurements of the longitudinal phase space distribution were taken into account [3]. Using the obtained distribution as an input for PARMILA the simulations showed consistency with all measurements before the DTL. However, the correlations between the longitudinal and transverse distributions were not accessible by measurements but they influence considerably the beam dynamics in the subsequent DTL. This must be kept in mind for the interpretation of the simulations.

Using the reconstructed initial 6-dimensional distribution before the DTL, the experimental scan was simulated. The results showed a decrease of the emittances after the DTL as function of σ_o for all beam currents. The smallest emittances were calculated for the strongest focusing. For σ_o up to 51^o this is in agreement with the experimental observations. But the experimentally observed increased emittance growth for the strongest focusing of $\sigma_o = 59^o$ with respect to the minimum at 51^o was not reproduced in the simulations. The calculated beam transmission was 90% and did not depend on the beam current and on the focusing strength. However, this value fits within the measured transmissions ranging from 80% to 93%.

SUMMARY AND OUTLOOK

Using two pepper pot devices before and after the Alvarez DTL the emittance growth in the DTL was measured qualitatively as function of the beam intensity and of the beam focusing strength. The results showed that the emittance growth is smallest for a zero current phase advance between 45^o and 55^o. Due to the limited angular resolution of the devices no quantitative measurements could be done so far. The resolutions were found to be about 2 mrad at an ion energy of 1.4 MeV/u (before DTL) and about half of this value at 11.4 MeV/u (after DTL). In order to scope with the typical beam parameters at the UNILAC the angular resolutions should be increases by a factor of five. However, the experimental results strongly suggest an increase of the currently used zero current phase advance of 45^o to 50^o for routine operation of high intensity beams. For the heaviest ion species $^{238}U^{28+}$ this requires an update of the power supplies of all quadrupoles along our Alvarez DTL. The implementation of horizontal and vertical slit/grid set-ups before and after the DTL is foreseen for this year. Future experiments will thus allow for comparing measurements using pepper pot devices and slit/grid set-ups.

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