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## HEAVY-ION-BEAM EMITTANCE MEASUREMENTS AT THE GSI UNILAC

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### Abstract

The GSI UNILAC, a linac for high current heavy ion beams, serves as an injector for the synchrotron SIS 18 and hence being a part of the future FAIR (International Facility for Antiproton and Ion Research) project. The UNILAC post stripper accelerator consists of five Alvarez tanks with a final energy of 11.4 MeV/u. In order to meet the requirements of the FAIR project (15emA  $^{238}\text{U}^{28+}$ , transverse normalised emittances of  $\beta\gamma\epsilon_x = 0.8\text{mmrad}$  and  $\beta\gamma\epsilon_y = 2.5\text{mmrad}$ ) a part of the UNILAC upgrade program is the increase of the beam brilliance. A detailed understanding of the correlation between space charge forces and focusing during acceleration of high intensity ion beams is necessary. For this purpose the study of the beam brilliance dependency on the phase advances in the Alvarez section is suited. The UNILAC with its various beam diagnostics devices offers excellent possibilities doing that. Measurements are planned in 2006 and coincide with the beam dynamics work package of the European JRA "High Intensity Pulsed Proton Injector" (HIPPI). Results of the measurements are presented as well as corresponding beam dynamics simulations.

Contribution to the LINAC2006, Knoxville, USA

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### INTRODUCTION

At GSI heavy ion beams are accelerated by the Universal Linear ACcelerator UNILAC (Figure 1) and the heavy ion synchrotron SIS 18. The UNILAC consists of two injectors, the High Current (HSI) and the High Charge Injector (HLI), and an Alvarez Drift Tube Linac (DTL). The HSI is delivered with ion beams from a low current (Penning type) and a high current ion source (MEVVA/ MUCIS type). The ions are transferred via a low energy beam transport line (LEBT) to the HSI where they are accelerated by an RFQ and two IH structures from 2.2 keV/u to 1.4 MeV/u. Afterwards the ions are stripped by a gas jet stripper and one charge state is selected in a magnetic charge separator system. Two bunchers, a quadrupole doublet and a triplet match the beam to the first tank of the Alvarez DTL. Passing the complete DTL the ions receive up to 11.4 MeV/u. In the transfer channel (TK) to the SIS 18 a stripper foil possibly provides for higher charge beams.

Presently the highest achieved number of  $^{238}\text{U}^{28+}$  ions at SIS injection amounts to  $1 \cdot 10^{11}$  per 100  $\mu\text{s}$  (4.5 emA). For the future accelerator complex of FAIR the UNILAC has to deliver up to  $3.3 \cdot 10^{11}$  particles of  $^{238}\text{U}^{28+}$  per 100  $\mu\text{s}$  (15 emA) to the SIS 18 with normalised transverse emittances of  $\beta\gamma\epsilon_x = 0.8$  mm mrad and  $\beta\gamma\epsilon_y = 2.5$  mm mrad [1]. As the Alvarez quadrupoles do not

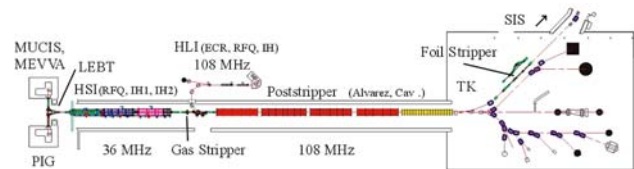


Figure 1: Schematic overview of the GSI UNILAC.

provide for adequate phase advances for highly space charge dominated beams [2], the corresponding normalised emittances can presently only be assumed to  $\beta\gamma\epsilon_x = 1.1$  mm mrad and  $\beta\gamma\epsilon_y = 3.6$  mm mrad based on calculations with the multiparticle simulation code DYNAMION [3].

To meet the FAIR requirements an appropriate upgrade program of the UNILAC is necessary [2]. One task is the increase of the high current beam brilliance. Machine experiments as well as corresponding calculations are mandatory to prepare the measures of the upgrade.

Within the beam dynamics work package of the European JRA "High Intensity Pulsed Proton Injector" (HIPPI) investigations of space charge forces during acceleration are funded. It is intended to benchmark different simulation codes [4] and to compare the results to experiments. For the first time exclusive beam time (96 shifts) for UNILAC machine experiments was requested and approved for 2006 by the scientific advisory committee.

### EXPERIMENTAL SETUP

A schematic overview of the beam diagnostics equipment mountings along the UNILAC are shown in Figure 2. The two transverse emittance measurement devices of slit/ grid type before and behind the Alvarez DTL are used to match the beam to the first accelerating periode of tank A1 [1, 5] and to determine the transverse emittance growth. The longitudinal emittance can also be measured in front of and behind the Alvarez section [6, 7]. Additionally the beam current, the transverse beam profiles and the longitudinal bunch spread can be observed with beam transformers, SEM-grids and capacitive phase probes arranged along UNILAC. These beam diagnostic tools are sufficient to study and optimise the settings of the UNILAC performance.

The investigation of the post stripper brilliance for high current beams were performed with 7 emA  $^{40}\text{Ar}^{10+}$  which is adequate to 15 emA  $^{238}\text{U}^{28+}$ . Due to the more than two times lower mass over charge ratio ( $m/\zeta$ ) of  $^{40}\text{Ar}^{10+}$  the required focusing strength of the Alvarez quadrupoles for a high phase advance can be provided, even more.

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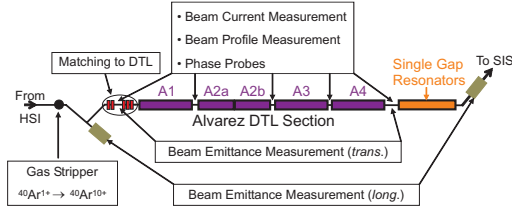


Figure 2: Experimental overview.

## OPTIMISATION OF UNILAC SETUP

In former UNILAC machine experiments the transverse emittances were measured as a function of beam energy for a 1 emA  $^{40}\text{Ar}^{10+}$  beam by switching off the Alvarez tanks starting with the last one. The results are shown in Figure 3 as well as results achieved by simulations with the code DYNAMION. Due to the simulations no transverse emittance growth is expected while in the measurements a remaining emittance growth was detected.

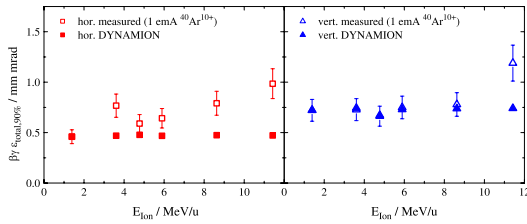


Figure 3: Measured and calculated (DYNAMION) transverse beam emittances for different Alvarez energies (3.6, 4.8, 5.9, 8.6 and 11.4 MeV/u). The emittance at injection is measured ahead the Alvarez at 1.4 MeV/u.

Therefore the UNILAC was at first optimised for a low intensity  $^{40}\text{Ar}^{1+}/^{10+}$  beam at an energy of 11.4 MeV/u by improving the beam transmission of the Alvarez DTL ( $\geq 95\%$ ) and by minimising the emittance growth.

### Energy Parasites

The energy dispersive bending into the TK is suited to analyse the energy spectrum. Energy parasites can emerge e. g. if the rf phase of the Alvarez DTL is not well adapted to that of the HSI, if the energy spread or the phase width of the beam at Alvarez entrance exceed the design values or if the beam is not well matched to the first Alvarez tank. Parasitic beam fractions reduce the transmission to the TK and lead to transverse emittance growth in the Alvarez. To minimise them rf parameters of the HSI and the Alvarez were synchronised and the beam was matched to the first Alvarez tank.

### Gas stripper optimisation

Also the gas stripper performance [8] can influence the quota of energy parasites. An inhomogeneous density profile increases the energy spread of the ions and thus the occurrence of energy parasites is possible. Such an inhomogeneous profile can result from an insufficient high pressure

of the gas jet or an unsuited distance of the gas nozzle to the beam axis. Both parameters were optimised.

### Influence of Alvarez Bunchers

As shown with beam dynamics calculations, the beam is longitudinally matched only to the first Alvarez tank [2]. The bunchers between tank A2a and A2b and between tank A3 and A4 usually used for rebunching low energy beams were in use to improve the longitudinal emittance.

### Alvarez RF Phases

The first three Alvarez tanks were designed to accelerate heavy ion beams at a reference rf phase of  $\phi_0 = -30^\circ$  and the last two at  $\phi_0 = -25^\circ$ . As shown exemplarily in Figure 4,  $\phi_0$  can be varied in a wide range without significant transmission losses or emittance growth. A variation of the rf phases was performed measuring the transmission and the emittance behind the Alvarez DTL in order to optimise the rf phase settings.

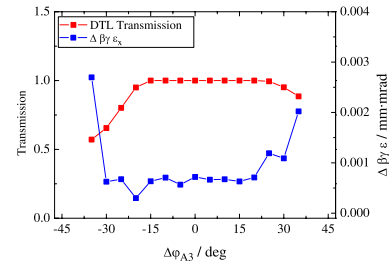


Figure 4: DYNAMION simulation of the transmission and emittance growth for different rf phases of tank A3.

## RESULTS OF LOW CURRENT EMITTANCE MEASUREMENTS

For the initial setup a 17 emA  $^{40}\text{Ar}^{1+}$  beam was injected into the HSI and a stripper pressure of 480 mbar was chosen to reduce the  $^{40}\text{Ar}^{10+}$  beam intensity at Alvarez entrance to 1 emA. For appropriate rf settings of the HSI RFQ, IH2 and Alvarez DTL and for a suited matching to the first Alvarez tank an Alvarez transmission of 96% was achieved. Nevertheless the transverse emittance growth along the Alvarez DTL amounted to a factor of 2.5 and energy parasites were detected. Choosing a stripper pressure of 2000 mbar and deminishing the beam current in front of the HSI reduced the 90% total longitudinal emittance behind the stripper from  $\epsilon_{z,\text{tot},90} = 635$  mm mrad to  $\epsilon_{z,\text{tot},90} = 250$  mm mrad. Re-adjusting the rf settings and matching the beam again to the first Alvarez tank resulted in a transmission to the transfer channel of 99% and an emittance growth along the DTL of only 1.28 horizontally and 1.09 vertically. The absolute values of the emittances were determined to  $\beta\gamma\epsilon_{x,\text{tot},90} = 0.9$  mm mrad and  $\beta\gamma\epsilon_{y,\text{tot},90} = 0.7$  mm mrad (cf. Figure 5).

The influence of the two bunchers in the Alvarez section was investigated measuring the longitudinal phase space distribution with the luminescent screen in the transfer channel to the SIS 18 (cf. Figure 2). As shown in Figure 6, the usage of these bunchers significantly improves

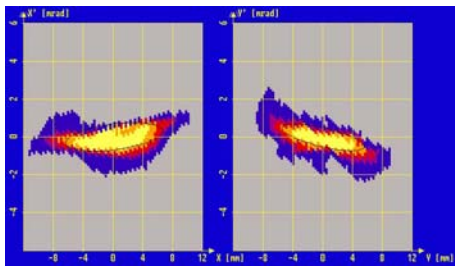


Figure 5: Measured transverse beam emittances for optimised UNILAC settings at 11.4 MeV/u and  $p_{\text{stripper}} = 2000$  mbar.

the longitudinal emittance. The transverse emittance values are not effected only the twiss parameters  $\alpha$  and  $\beta$  are changed.

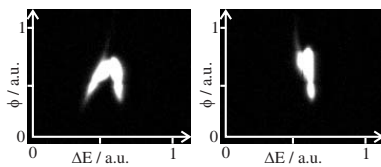


Figure 6: Longitudinal phase space distribution with Alvarez bunchers off (left) and on (right); the 1<sup>st</sup> buncher is longitudinally focusing while the 2<sup>nd</sup> is defocusing.

The variation of the rf phase of each Alvarez tank, starting with the first while the following were not powered, showed that for low current all rf phases are well adjusted resulting in a minimum contribution to the transverse emittance growth. In Figure 7 the 90% total emittance after this optimisation is shown as a function of beam energy. The emittance growth along the Alvarez DTL amounts about a factor 1.27 horizontally and 1.21 vertically. This is an improvement compared to the results of Figure 3 of about a factor 1.7 and 1.4 respectively. As shown in Figure 7 the transverse emittance growth mainly took place in the first tank. A significant growth due to acceleration in the following tanks did not exist as it is represented by the lines (mean values). A possible reason for that might be a still remaining mismatch of the first Alvarez tank despite the performed matching procedures.

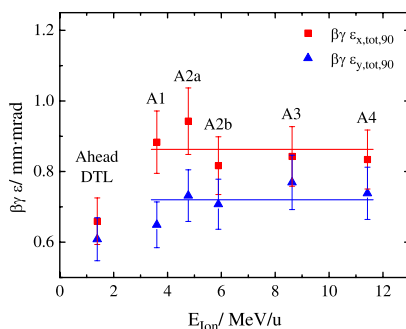


Figure 7: Normalised transverse emittances at different beam energies.

## SUMMARY AND OUTLOOK

In simulations with the particle tracking code DYNAMION as well as in machine experiments it was shown that an ion beam with neglectable space charge forces can be accelerated without any significant particle losses and without a significant transverse emittance growth. During the first part of the HIPPI machine experiments it was verified that for a low intensity beam energy parasites lead to significant transmission losses and emittance growth. Optimising rf parameters especially of the HSI RFQ and the second HSI IH structure, the phase correlation between HSI and Alvarez DTL, the settings of the gas stripper, and the matching of the beam to the first Alvarez tank a transmission of 99% and a minimum transverse emittance growth of about 1.2 was achieved.

Further multiparticle simulations are needed to understand the results of these experiments in more detail. The results of different simulation codes have to be compared. Further experimental investigations should lead to a complete suppression of transverse emittance growth for low beam intensities. In the second part of the HIPPI machine experiments in November 2006 similar optimisation procedures will be applied for high current heavy ion beams.

## ACKNOWLEDGEMENT

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