ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOPA16

UNILAC HEAVY ION BEAM OPERATION AT FAIR INTENSITIES

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Abstract

The GSI-UNILAC as well as the heavy ion synchrotron SIS18 will serve as a high current heavy ion injector for the FAIR synchrotron SIS100. In the context of an advanced machine investigation program acceleration and transport of space charge dominated argon beam inside entire UNILAC have been explored. The conducted high current argon beam measurements throughout the UNILAC-post-stripper and transferline to SIS18 show a transversal emittance growth of only 35% for the design current of 7 emA ($^{40}Ar^{10+}$). By horizontal collimation of the UNILAC beam emittance, the space charge limit could be reached at slightly lower pulse currents, but accordingly longer injection times. Further improvements in brilliance can be expected from the planned upgrade measures, in particular on the high-current injector linac.

INTRODUCTION

Besides two ion source terminals and a low energy beam transport system (LEBT) the High Current Injector (HSI) of the UNILAC (Fig. 1) comprises a 36 MHz IH-RFQ (2.2 keV/u up to 120 keV/u) and an IH-DTL with two separate tanks, accelerating the beam up to the final HSI-energy of 1.4 MeV/u. After stripping and charge state separation the Alvarez DTL provides for beam acceleration up to $\beta = 0.155$. In the transfer line (TK) to the synchrotron SIS18 a foil stripper and another charge state separator system can be used. In order to provide the highest heavy ion beam currents (15 emA, U^{28+}), as required for FAIR, the HSI must deliver up to $2.8{\cdot}10^{12}$ U^{4+} ions per pulse [1-12].

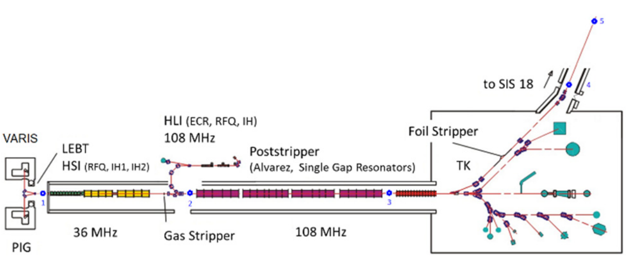

Figure 1: GSI-UNIversal Linear ACcelerator (UNILAC); the slit-grid-emittance measuring devices are shown in blue; 1: LEBT/UH1, 2: gas stripper section/US4, 3: post-stripper/UA4, 4: transfer line/TK5, 5: transfer line/TK8.

The positions of the emittance meters (slit-grid devices) used for the measurements presented in this paper are also shown in Fig. 1. With the AC beam transformers installed behind each accelerator cavity and along all transport routes, the beam transmission in all sections can be permanently monitored and measured with high precision.

Highly charged heavy ion beams with high average intensities (but low pulse intensities), from an ECR ion source of CAPRICE-type are accelerated in the High Charge State Injector (HLI) to 1.4 MeV/u. The HLI as well as the HSI serve in a time sharing mode for the Alvarez DTL. The FAIR proton linac has to provide the high intensity primary proton beam for the production of antiprotons. It will deliver a 70 MeV beam to the SIS18 with a repetition rate of 4 Hz. The proton linac will be located north of the existing UNILAC complex.

HEAVY ION BEAMS AT THE SPACE CHARGE LIMIT

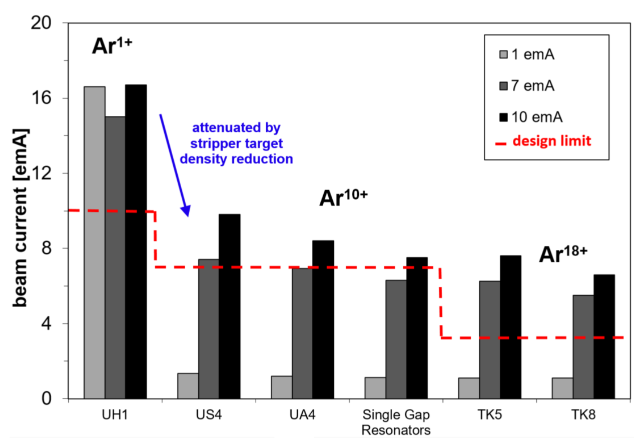

Figure 2: Argon beam variation beyond UNILAC design limitations.

For medium heavy ions beams ($^{40}Ar^{10+}$) the HSI-intensity level behind gas stripper exceeds the space charge limit of 7 emA specified for SIS18. This enables to investigate acceleration and transport for space charge dominated beams inside entire UNILAC and transfer line to the SIS18. As depicted in Fig. 2, for further high intensity measurements the stripper gas density was chosen such that the desired Ar^{10+} current of 7 emA was achieved after optimization of the poststripper and TK. Also for highly charged ions (Ar^{18+}), stripping with a suitable carbon foil (400 $\mu g/cm^2$) allows to reach intensities that enable to fill the SIS18 up to the so-called space charge limit. The design current limit given in Fig. 2 (dashed line in red) is based on the FAIR requirements or the space charge limit achievable by multiturn injection of the high current beam from UNILAC into the SIS18.

Intensity variation at UNILAC is achieved by varying the gas stripper target density, which allows the particle

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ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOPA16

density in the desired charge state (Ar^{10+}) to be varied over a wide range [13-15]. However, since the defocusing space charge force also increases (quadratically) for high ion currents, undesirable emittance-growth effects already occur in UNILAC, which ultimately leads to measurable particle losses. This is shown in Fig. 3 for different A^{10+} input intensities (1 emA – 10 emA). For the highest current of 10 emA, the particle transmission drops by about 10% due to space charge.

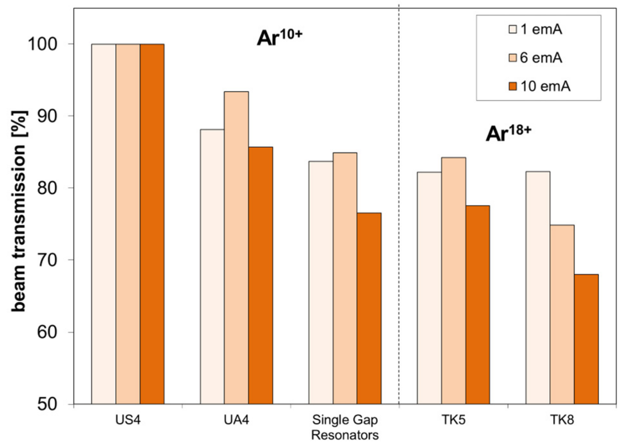

Figure 3: Beam transmission at poststripper and transfer line to SIS18 for different beam currents.

HIGH INTENSITY UNILAC MACHINE INVESTIGATIONS

In order to optimize the UNILAC poststripper for operation with the highest ion current, the particle transmission was first investigated by varying the transverse zero current phase advance. As Fig. 4 shows, the maximum achievable transmission is reached at a phase advance of 45 degrees. As known from previous investigations, the phase advance must be set to approx. 55 degrees to minimize the growth of emittance due to space charge; this was carried out for all subsequent investigations.

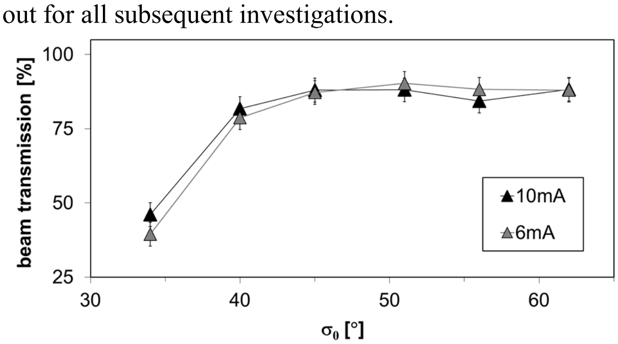

Figure 4: Ar^{10+}- beam transmission as function of the zero current phase advance for two different beam currents.

For the results of the Argon emittance measurements shown in Figs. 5 and 6, the stripper gas density was adjusted so that the FAIR design current of 7 emA (Ar^{10+}) was available at the end of the transfer line to the SIS18 [16,17].

For argon high-current operation the effect of emittance asymmetry described in, turns out to be much smaller, because the horizontal beam spot can be set much larger due to the extremely high space charge forces, since the requirements on the beam spot size for the separation of the neighboring argon charge states are much smaller compared to the operation with heavy ions (e.g. Bi, U). For the argon high-current campaign, the RF-supply of Alvarez tank 4 was not available, so the UNILAC energy was 8.6 MeV/u. However, the emittance values given in the following are all normalized for better comparability. An Ar^{10+}-transmission of about 65% for poststripper and transfer line could be achieved for this high intensity.

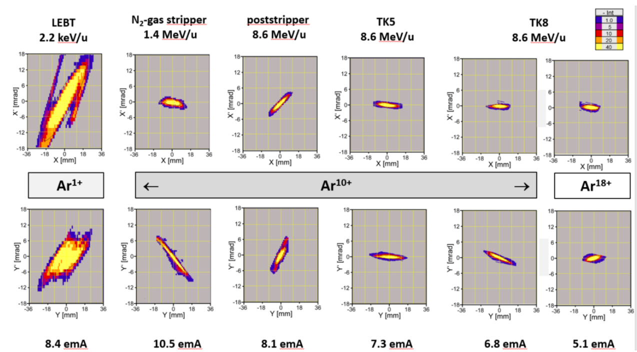

Figure 5: High intensity ^{40}Ar-beam emittance and current measurements along UNILAC and TK.

Bearing in mind the very high ion current in this section of UNILAC, the average transverse rms-emittance growth is relatively low at 35% and fits perfectly into the transversal acceptance of the synchrotron. The evolution of the transverse beam emittance along the UNILAC and transfer channel under high current conditions is displayed in Fig. 6. High current front to end-simulations at GSI-UNILAC were published in [18]. The simulated emittance growth depends strongly on the starting conditions. For high current operation emittance grows under ideal conditions inside poststripper and TK by almost a factor of 2 at a beam transmission of 70%.

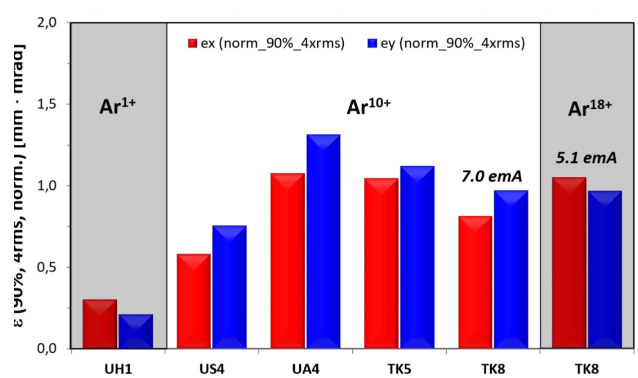

Figure 6: Evaluation of high intensity ^{40}Ar-beam emittance measurements corresponding to fig. 10.

BEAM BRILLIANCE ANALYSIS

The measured beam brilliance is defined as the measured beam current divided by the accordingly measured beam emittance. The fractional brilliance is obtained when the measured beam emittance is cut in the post analysis so that

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particles (with highest momentum) are removed from the limiting edge. The remaining phase space area is again divided by the remaining current and results in the corresponding fractional brilliance. For the determination of the beam brilliance at the end of the transfer line (TK8), the beam emittance was evaluated again in more detail and linked to the corresponding beam current measurement. For brilliance analysis, the fractional emittance values were determined in the horizontal and vertical directions, resulting in corresponding fractional brilliance quantities which can be obtained by cutting the phase space in the dedicated collimation channel directly in front of the installed emittance measuring device. Fig. 7 shows the normalized Ar^{10+} and U^{28+}(fractional) beam brilliance analysis based on beam emittance and corresponding beam intensity measurements at the end of the transfer line (TK8) to the SIS18. The data refers to the norm. high current FAIR requirement of 1mA/µm defined for U^{28+} as reference ion (A/Z = 8.5; I = 15 emA, hor. emittance = 1 µm).This FAIR demand is also plotted as the horizontal brilliance of the injected UNILAC beam required to reach the SIS 18 space charge limit by multi turn injection into the ring accelerator (dashed line). One can easily see that the brilliance increases from the edge to the core of the phase space distribution. By suitable collimation of the phase space distribution in such a way that about 5 emA Ar^{10+} remains, the SIS18 space charge limit can be reached. By this method the FAIR design condition in particular for medium heavy ions could be fulfilled.

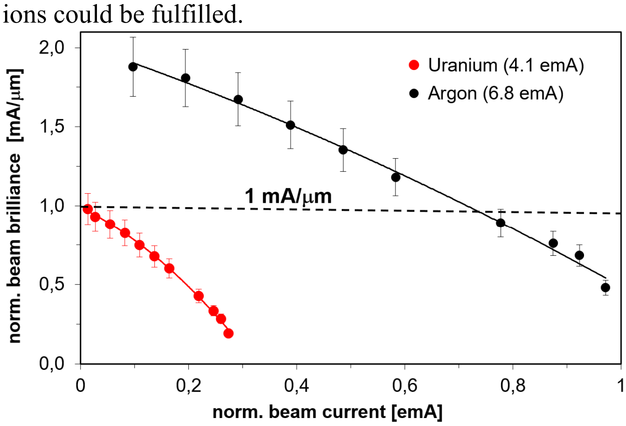

Figure 7: Normalized Ar^{10+} and U^{28+}(fractional) beam brilliance analysis based on beam emittance and corresponding beam intensity measurements at the end of the transfer line (TK8) to the SIS18; The data refers to the normalized high current FAIR requirement of 1mA/µm defined for U^{28+} as reference ion (A/Z = 8.5; I = 15 emA, hor. emittance = 1 µm).

At present, the available uranium intensities are not yet sufficient to reach the SIS18 space charge limit with an adequately small number of multiturn injections. As depicted in Fig. 7, the Uranium intensity in the given phase space area must be increased again by a factor of 3.

SUMMARY AND OUTLOOK

In preparation for successful high current operation with medium and heavy ions, the full spectrum of ions at high intensity is available for the first time in 5 years. For medium-heavy ions, the UNILAC is now easily capable of delivering the intensities required to achieve the SIS18 space charge limit. However, the decisive parameter for this is the beam brilliance, i.e. the current in a given phase space area. By horizontal collimation of the UNILAC beam emittance at the end of transfer line, the space charge limit could be reached at slightly lower pulse currents, but accordingly longer injection times [19, 20]. The conducted high current Argon beam measurements throughout the UNILAC-poststripper and TK show a transversal emittance growth of only 35% for the design current of 7 emA ($^{40}Ar^{10+}$) at the end of TK. The measured high current Uranium beam emittance grows with 40% until SIS18 injection accordingly. Through horizontal collimation (≤ 2.5 mm·mrad), the number of Uranium particles in this phase space area is sufficient to fill the SIS18 up to 30% of the space charge limit. Further improvements in brilliance can be expected from the planned upgrade measures, in particular on the high-current injector linac.

ACKNOWLEDGEMENTS

Successful beam testing could not be accomplished without strong support of highly committed people from different GSI-departments.

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