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HIGH PERFORMANCE MEGAWATT URANIUM BEAMS AT GSI UNILAC

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Abstract

The 50 years operating GSI-UNILAC (Universal Linear Accelerator) as well as the heavy ion synchrotron SIS18 will serve as a high current short pulse heavy ion injector for the FAIR (Facility for Antiproton and Ion Research) synchrotron SIS100. This contribution presents the results of the full performance high current uranium beam machine experiment campaign at UNILAC, conducted in the last three years. In order to determine the behaviour of uranium beams, the transverse beam emittance at five selected measurement positions along the complete UNILAC have been measured for the first time in several machine investigation runs. A significant improvement in beam brilliance was achieved after several upgrade measures at the High Current Injector (HSI) by using the pulsed hydrogen stripper at 1.4 MeV/u. It could be shown that extremely low horizontal emittances, i.e. very high brilliances, are achieved along the complete UNILAC up to the SIS18 injection. Besides high intense uranium beams with charge state 28+ also 1.5 Megawatt-multi charge beams, comprising 27+, 28+, 29+ uranium ions, commonly recharged primarily to charge state 73+ using a carbon foil, were investigated and a record uranium beam current of 3.6 emA has been achieved.

INTRODUCTION

Besides the High Charge State Injector (HLI) accelerating highly charged ions from an ECR ion source of CAPRICE-type, the High Current Injector (HSI), fed by two ion source terminals and a low energy beam transport system (LEBT), serve as injector linac for the GSI-UNILAC (Fig. 1). The HSI 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 11.4 MeV/u. 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 [1-2]. With the AC beam transformers installed behind each accelerator cavity and along all transport sections, the beam transmission in all sections can be permanently monitored and measured with high precision. The positions of the emittance meters, used for the measurements presented in this paper, are shown in Fig.1.

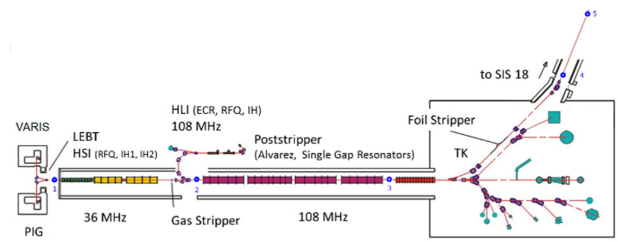

Figure 1: GSI-UNIversal Linear ACcelerator; emittance meters at LEBT (1), gas stripper section (2), poststripper (3), transfer line (4 and 5) are shown in blue marks.

UNILAC-UPGRADE MEASURES

For the recent uranium beam campaigns at UNILAC, a novel multi-hole extraction system for extracting a high brilliant ion beam from the VARIS ion source [3-4] was used. Moreover, the HSI RFQ has been equipped with new mini-vane electrodes so that it could be again operated at nominal RF-voltage for uranium operation by applying a dedicated conditioning and development program. The HSI-superlens also recently underwent an extensive upgrade programme. The electrodes were also replaced, so that uranium levels could be applied again without any problems. To prevent beam losses in the tank, the electrodes were protected by a suitable aperture diaphragm.

During preparation stage of the superlens upgrade, the beam emittances before and behind HSI-RFQ for high current argon-beam have been measured again after more than 12 years; the measured beam emittances are about 50% lower compared to the long past campaign. By measuring the RF-voltage influence on the beam emittance, it was possible to show that the RFQ-working point corresponds to minimum transversal emittance growth (see Fig. 2). Backtracking of measured beam emittance to RFQ-exit and subsequent forward tracking resulted in optimized superlens matching. A minimum beam spot at superlens entrance was confirmed by a profile measurement. Due to field strength limitations of the intermediate quadrupole duplet in front of the superlens, the optimum uranium beam matching (avoiding further beam losses) could be accomplished only by a new quadrupole duplet with increased field gradients.

The upgrade measures facilitated an extensive machine optimizing program and thus the success of this measurement campaign. The already used pulsed hydrogen stripping target [5] has been further optimized to enable for increased gas densities [6], as well as to determine the maximum achievable average charge state. It was found,

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that the average charge state can be increased by approximately three charge units (compared to the conventionally used nitrogen gas-jet). The high current measurements were carried out with charge state 28+, but the same particle yield is also achievable at charge state 29+.

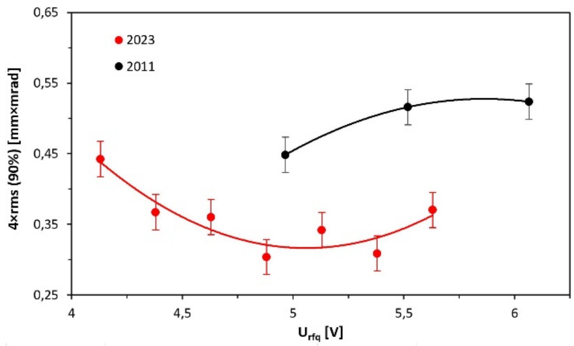

Figure 2: Transverse argon emittance (4×rms) as function of the RFQ voltage (in control units); the emittance growth has minimum at the RFQ-working point (4.8 V).

The maximum beam brilliance before the Alvarez-DTL has been measured. In routine accelerator operation such peak values can be achieved only through a long-term and sustainable machine development program (see Fig. 3). This program was launched in 2014, and a peak intensity of 11.5 mA was achieved after just two years, thanks in particular to the use of the pulsed hydrogen stripper. In 2017 and 2018, the RFQ was not available for uranium operation due to significant surface contamination, so the programme had to be completely restarted after installing new RFQ electrodes. The strongly limited possibilities for the facility maintenance in 2021-2022 and, in particular, the poor RF performance of the superlens delayed further the ramping up of uranium intensities. Since 2023 very high U^{28+} currents have been available again.

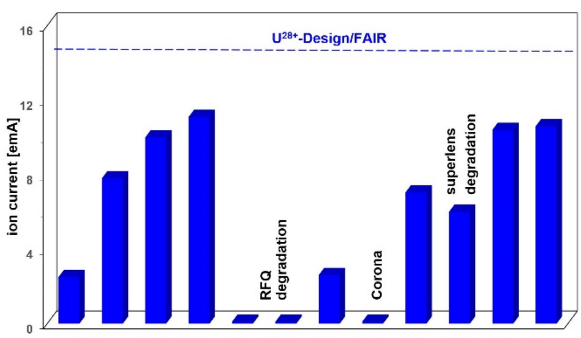

Figure 3: U^{28+}- beam intensity development.

HEAVY ION BEAMS BEYONED SPACE CHARGE LIMIT

For medium heavy ion beams ($^{40}Ar^{10+}$) the HSI-intensity level behind gas stripper potentially exceeds the space charge limit basically specified for SIS18. This enables to investigate acceleration and transport for space charge dominated beams inside entire UNILAC and transfer line to the SIS18 [7]. Bearing in mind the high ion current of 7 emA in UNILAC main linac (Alvarez section), the average transverse rms-emittance growth was measured as relatively low at 35% and the beam emittance fits perfectly into the transversal acceptance of the synchrotron. The evolution of the transverse beam emittance along the UNILAC and transfer channel TK under high current conditions as well as corresponding high current front to end simulations were published in [8]. It was shown, that the simulated emittance growth depends strongly on the starting conditions. For high current operation emittance grows under ideal conditions inside poststripper and TK increases by almost a factor of 2 at a beam transmission of 70%. In view of the upgrade measures described above [9] and the subsequent beam optimisation campaign, the entire high-current injector was optimised for a record argon intensity of over 7 emA (Ar^{1+}) [10]. The efficiency of the stripping process in the charge state 11+ (at 1.4 MeV/u) was also optimised to more than 35% under high-current conditions, so that a measured record intensity of 28 emA was achieved for the separated charge state Ar^{11+}. This corresponds to four times the UNILAC design current and a pulse beam power of 140 kW.

URANIUM (28+) HIGH INTENSITY UNILAC MACHINE INVESTIGATIONS

In order to optimize the UNILAC poststripper for operation with the high uranium beam current, the particle transmission was as a first step investigated by varying the transverse zero current phase advance. 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 higher values in order to minimize the growth of emittance due to space charge; a phase advance of 50 degree was carried out for all subsequent investigations.

One of the crucial quantities at a fixed beam intensity to characterize the high-current capability of a synchrotron injector is the horizontal beam emittance. To determine and to optimize the behavior of the UNILAC for heavy ion beams, high intensity Uranium beams were used in several machine investigation runs (2019-2024) for the first time to measure the transverse beam emittance at five selected measurement positions along the complete UNILAC. By using the pulsed hydrogen stripper, a very high U^{28+} intensity of 10 emA (behind charge separator) was available for the recent measurement campaign. After an extensive optimization procedure, a beam current of more than 8 emA (at a beam power of 780 kW) with a transmission of 81% was achieved in the entire Alvarez poststripper; a transmission of 80% was obtained in the transfer channel to the SIS18. The measured uranium beam current of 6.5 emA represents a record intensity achieved for the first time at full UNILAC energy at the SIS18 injection point. At this machine performance the mean transverse rms-emittance increased by about 30%. A small horizontal emittance, with a value of 0.62 mm (90%, 4×rms, norm.), approx. 20% smaller than the vertical emittance, is decisive for optimal SIS18 injection by

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horizontal stacking. Smaller horizontal emittance values have also been measured several times in the past.

MULTI CHARGE STATE OPERATION AT THE SPACE CHARGE LIMIT

In 2023 and 2024 an uranium high current measurement program was carried out with the aim of providing the highest possible U^{73+} intensities for SIS18 injection. For this several uranium charges were accelerated under high-current conditions in the poststripper. In order to compensate the different velocities of the ions with different charges, single gap resonators were used in rebunching mode. Figure 4 shows the beam spots measured for a triple charge mode behind charge separation. Uranium currents of 16 emA (dual charge mode) and 24 emA (triple charge mode) were achieved for poststripper injection.

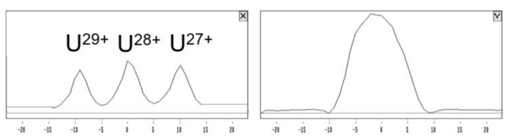

Figure 4: Measured beam spot behind charge separation for triple charge operation.

Figure 5 shows the transverse poststripper emittances measured for single, dual and triple charge mode after acceleration to 11.4 MeV/u. A deformation of the phase space distribution caused by mismatch are clearly visible. Nevertheless, a record current of 16 emA was achieved, which corresponds to a beam pulse power of 1.55 MW. The beam load in the five Alvarez tanks have been sufficiently provided by the high-power amplifiers. Table 1 summarizes the applied forward power and the measured additional beam load for all poststripper tanks.

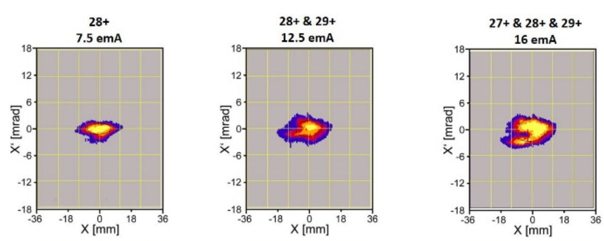

Figure 5: Horizontal emittance for single (left), dual (middle) and triple (right) charge beam after acceleration.

Table 1: Measured RF-power and Additional Beam Load

Energy gain [MeV/u]	RF power [kW]	Beamload [kW]
2.20 (A1)	1030	390
1.20 (A2A)	695	325
1.10 (A2B)	535	196
2.70 (A3)	1525	615
2.80 (A4)	1430	390
10.00 (tot.)	**5215**	**1916**

In the multi-charge mode an uranium beam with an intensity of approx. 10emA was stripped applying a 600µg/cm^2 carbon foil; for charge state 73+ a beam current of 4.0 emA has been measured. The foil could be used for 24 hours at a pulse power of approx. 1MW.

U73+-BEAM BRILLIANCE ANALYSIS

The beam brilliance is defined as the measured beam current divided by the according beam emittance. The fractional brilliance is obtained when the measured beam emittance is cut in the post analysis so that outer particles (with highest coordinate-momentum combination) are removed from the consideration. The remaining phase space area is again divided by the remaining current and results in the fractional brilliance. For the determination of the U^{73+}-beam brilliance, generated from a triple charge beam accelerated in the poststripper, the measured beam emittance was evaluated in 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 emittance measuring device. Figure 6 shows the normalized brilliance analysis based on beam emittance and corresponding intensity measurements. The data refer to a high current requirement of 3mA/µm defined for U^{73+} as reference ion, plotted as the horizontal UNILAC-brilliance required to reach a certain space charge limit by multi turn injection [11] into the SIS18 (dashed line).

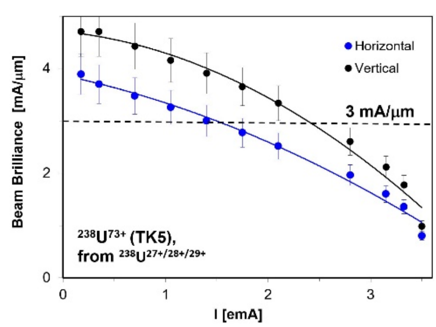

Figure 6: U^{73+}-beam brilliance analysis.

SUMMARY AND OUTLOOK

The HSI-high current performance was recently significantly improved. High current measurement campaigns have been conducted successfully, while the UNILAC accelerated more than 8 emA of U^{28+} beam, resulting in a record beam current of 6.5 emA achieved at the end of the transfer line. At the poststripper up to 16 emA of uranium beam could be accelerated in triple charge mode with an observed beam load of 1.9 MW. A world record U^{73+} beam intensity of 3.5 emA at full UNILAC-energy was accomplished. The next step is to test high intensity Uranium SIS18 beam operation.

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