HIGH CURRENT URANIUM BEAM MEASUREMENTS AT GSI-UNILAC FOR FAIR

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Abstract

In the context of an advanced machine investigation program supporting the ongoing UNILAC (Universal Linear Accelerator) upgrade program, a new uranium beam intensity record (≈10 emA, U^{29+}) at very high beam brilliance was achieved last year in a machine experiment campaign at GSI. The UNILAC as well as the heavy ion synchrotron SIS18 will serve as a high current heavy ion injector for the new FAIR (Facility for Antiproton and Ion Research) synchrotron SIS100. Results of the accomplished high current uranium beam measurements applying a newly developed pulsed hydrogen gas stripper (at 1.4 MeV/u) will be presented. The paper will focus on the evaluation and analysis of the measured beam brilliance and further implications to fulfil the FAIR heavy ion high intensity beam requirements.

INTRODUCTION

Meeting the FAIR science requirements [1] higher beam intensities have to be achieved in the present GSI-accelerator complex, through faster cycling and, for heavy ions, lower charge state which enters quadratically into the space charge limit (SCL). The desired beam energy of up to 1.5 GeV/u for radioactive beam production will be delivered by the synchrotron SIS100. Recently GSI put effort into increasing the uranium beam intensity delivered to the SIS18. An advanced machine investigation program for the UNILAC is aimed at meeting the FAIR requirements. For uranium (FAIR reference ion) the UNILAC has to deliver at least 3.3×10^{11} U^{28+}-particles during 100 µs.

In the High Current Injector (HSI) comprising an IH-RFQ and an IH-DTL, the beam is accelerated up to 1.4 MeV/u. In the gas stripper section the initial charge state (4+) is increased; an uranium beam (28+ or higher charge state) is matched to the Alvarez DTL. After acceleration up to the final UNILAC-beam energy of 11.4 MeV/u the transfer line (TK) to the SIS18 provides optionally foil stripping and a charge state separator (Fig. 1).

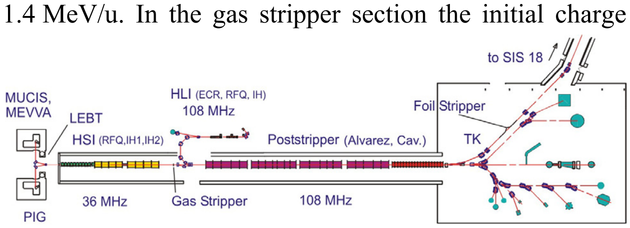

Figure 1: Schematic overview of the GSI UNILAC and experimental area. [1]

High current uranium beam machine experiments at HSI and the gas stripper section were conducted in November 2015. A multi-aperture extraction system for extracting a high brilliant ion beam from the VARIS ion source [2] was used. The RFQ-cavity underwent a dedicated conditioning and development program, providing for reliable rf-operation. These measures facilitated an extensive beam optimizing program and thus the success of this measurement campaign. The pulsed hydrogen stripping target [3,4] was further optimized aiming for operation at the maximum achievable average charge state. The high current measurements were therefore carried out for charge state 29+. The measured beam brilliance before the Alvarez-DTL was evaluated in detail. Due to an upgrade program, which renews the rf-amplifier system of the UNILAC post stripper (Alvarez) only three of the five Alvarez tanks were in operation. Thus, the achievable high current beam brilliance at injection into the SIS18 is currently estimated by using front-to-end high-current measurements [5] with a proton beam (with the same space charge capability as for the uranium beam) performed in 2014. Supplemented by extensive beam simulations [6] that were carried out recently for injection of a high-intensity uranium beam into the SIS18, the beam intensity, achievable from the FAIR injector chain, could be estimated.

HIGH CURRENT PROTON BEAM EMITTANCE MEASUREMENTS

The horizontal beam emittance is one of the crucial quantities at a fixed beam intensity to characterize the high-current capability of a synchrotron injector. The high current proton beam emittance growth inside the Alvarez was measured to be 17% (rms) [5] (Fig. 2). Considering the overall beam transmission of 90%, the loss of beam brilliance inside the Alvarez is 23%; the subsequent transport into the transfer line was accomplished without particle loss. However, due to a vertical bottle neck in the transfer line an additional loss of 15% was measured. The

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transversal emittance remains the same until injection into the SIS18. The overall horizontal proton beam brilliance is diminished by 25% under high current conditions.

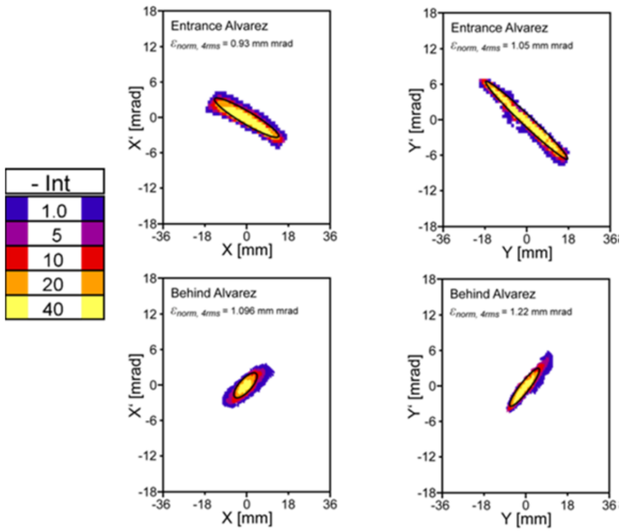

Figure 2: High-current proton beam emittance measurements at GSI-UNILAC poststripper accelerator. [5]

As shown in Fig. 3, the core of the high current phase space distribution remains constant during acceleration up to the final beam energy of 11.4 MeV/u and the adjacent beam transport in the transfer line to the SIS18. The fringe area blows up, while the beam envelope increases until particles get lost at the limiting beam aperture.

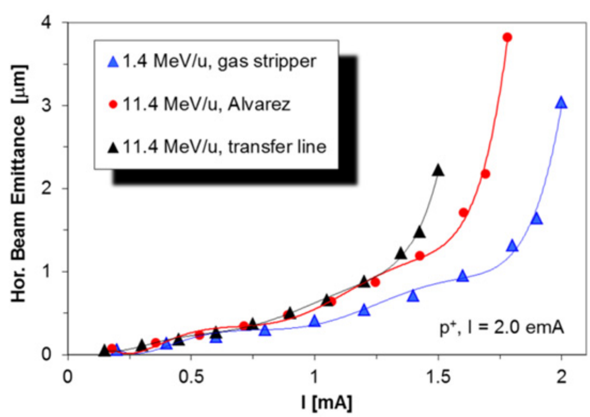

Figure 3: Analysis of high-current proton beam emittance measurements at Alvarez DTL (see Fig. 2) and transfer line to the SIS18; the beam transmission is 75%.

HIGH CURRENT ELECTRON STRIPPING IN A PULSED H_2-GAS CELL

Characterizing the stripping performance, the absolute stripping efficiency into the desired charge state is a key indicator. A sufficient charge state resolution is required to enable highest intensities in the desired charge state. As shown in Fig. 4, the stripping efficiency into the desired charge state could be improved (with the H_2 gas stripper cell). Applying a high density H_2-target (instead of a N_2-target) the yield is 50% higher, the maximum of the charge state distribution increases by 3 units.

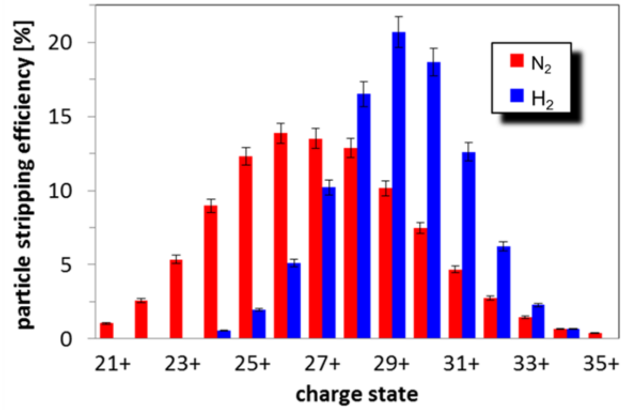

Figure 4: Charge state distribution after stripping of uranium projectiles in a H_2 gas target and a N_2 gas target.

With a pulse particle current of . 0 345 pmA a new intensity record at 1.4 MeV/u was achieved. With further increase of the loading gas inside the H_2-gas cell an equilibrated regime was reached. For this equilibrium charge state (29+) the transversal beam emittance at 1.4 MeV/u (Fig. 5 at the top) was measured at the maximum electrical beam pulse intensity of 9.97 emA. Due to the lower efficiency for stripping at a N_2-target, the pulse intensity is reduced as well. The related beam emittance measured at 4.5 emA corresponding to charge state 28+, where the stripping efficiency is almost the highest, is shown in Figure 5 at the bottom.

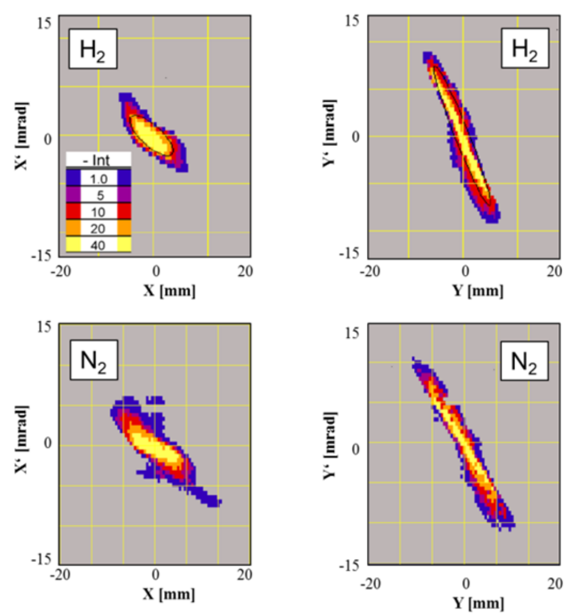

Figure 5: Measured horizontal (left) and vertical (right) high current uranium beam emittance after stripping to the equilibrium and charge separation at 1.4 MeV/u; at H_2- (top) [7] and at N_2-target (bottom) [8].

The main beam parameters achieved with H_2 and N_2 stripping targets are summarized in Tab. 1.

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Table 1: Measured Beam Parameters [7]

	N_2-gas jet [8]	H_2- gas cell (pulsed)
Back-pressure	0.4 MPa	5.5 MPa
U^{4+}-current (HSI)	6.0 emA	6.6 emA
Stripping charge state	28+	29+
Stripping efficiency	12.7±0.5%	21.0±0.8%
Energy loss	14±5 keV/u	27±5 keV/u
Max. current	4.5 emA	9.97 emA
ε_x (90%, tot.) norm.	0.76 µm	0.66 µm
ε_y (90%, tot.) norm.	0.84 µm	1.15 µm
Hor. brilliance (90%)	5.32 mA/µm	13.60 mA/µm
FAIR requirements:		
ε_x (tot.) norm.	1 µm	
U^{28+}-Intensity	15 mA	
Hor. beam brilliance	15 mA/µm	

URANIUM BEAM OPTIMIZATION

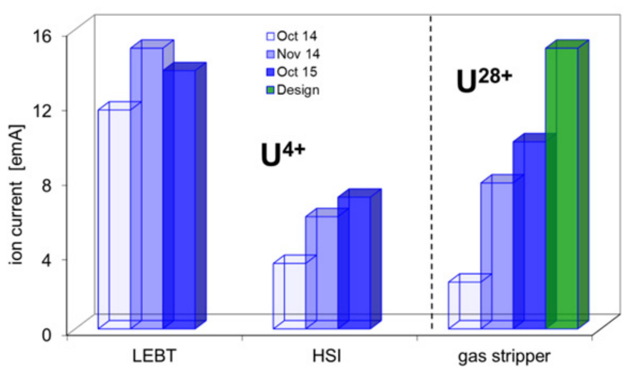

Figure 6: Measured uranium beam transmission at GSI-HSI and stripper section.

The U^{4+}-beam current and brilliance was improved by applying a 7 hole-aperture extraction system [8] at the VARIS ion source [2]. By optimization of the low energy beam transport and improved RFQ matching an RFQ transmission of 70% (9.70 emA) was achieved. After advanced rf optimization and rf conditioning the HSI RFQ tank yields for reliable high-current uranium beam operation. Optimizing the MEBT (Medium Energy Beam Transport) between RFQ and IH DTL by increasing the transverse and longitudinal focusing the previously disturbing beam losses could be minimized significantly, resulting in a stable overall high current operation. Beam matching to the gas stripper by adapting the quadrupole channel resulted in a beam transmission of 90% in this section. For the first time an U^{4+} beam current of 6.6 emA was available for heavy ion stripping. Applying the stripper gas cell at an optimal H_2 target thickness (≈14 µg/cm^2) and after re-optimization of the charge separation procedure under high current conditions, an increased stripping efficiency of about 21% was achieved.

Finally the uranium beam intensity at injection into the poststripper accelerator was increased by almost a factor of 4 accomplished in a 12 months lasting machine optimizing program (see Fig. 6).

BEAM BRILLIANCE ANALYSIS

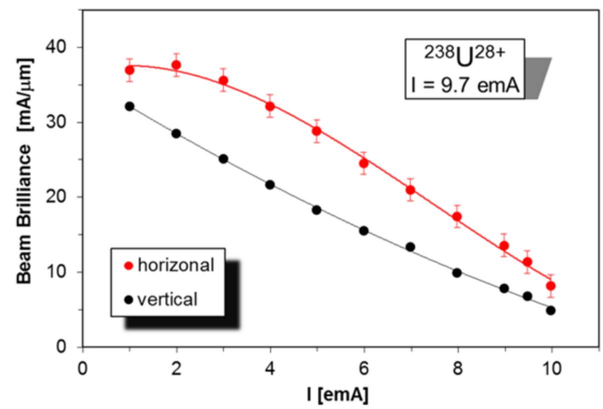

Figure 7: Horizontal and vertical brilliance (at 1.4 MeV/u) for uranium beam on H_2-target (9.7 emA, U^{28+}). [7]

For a wide range of different current densities and for the H_2 as well as for the N_2 target the fractional horizontal phase space distributions differ slightly in the peripheral region. The vertical beam emittance for uranium beam on a H_2-target (9.97 mA, U^{29+}) is significantly increased, while the horizontal emittance remains the same at higher beam current.

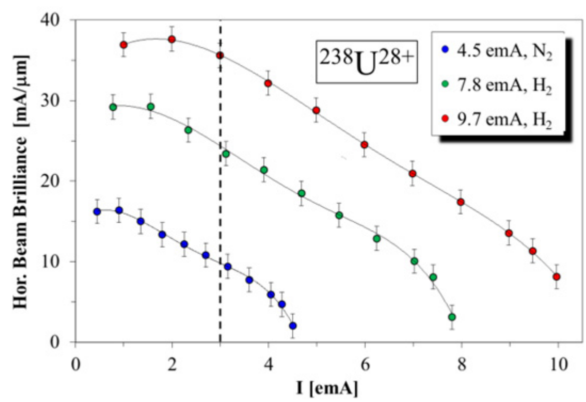

Figure 8: Beam brilliance for different beam intensities applying two different H_2 target thickness and equilibrium at the N_2 target.

For the high current beam dynamics layout of the gas stripper section, an enlarged vertical beam envelope in the interaction zone is foreseen, resulting also in an enhanced beam emittance growth due to strong particle straggling. Regardless of the ion current, the horizontal phase space distribution is nearly identical. Thus horizontal beam brilliance (Fig. 7) at 1.4 MeV/u is significantly higher. As shown in Fig. 8 the horizontal beam brilliance simply scales with the pulse current, independently on the used

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target and/or the applied target thickness. For instance, the increase of the beam intensity by 1 emA leads to a four times higher horizontal beam brilliance (for a fractional current of 3 emA as indicated with a dashed line in Fig. 8). For the determination of the U^{28+}-beam brilliance, achievable at SIS18 injection, the front-to-end high-current proton beam measurements were used. Basically the UNILAC parameters scale with the mass-to-charge ratio m/q:

$$\frac{m}{q}(scal) = \frac{m/q\,(U^{28+})}{m/q\,(p^{+})} = \frac{8.5}{1}$$

Proton beam transmission TM_{fin} until SIS18-injection was measured as: $TM_{fin}(p^{+}) = 75\%$, while the measured proton rms emittance growth $EW_{fin}(p^{+})$ is negative: $EW_{fin}(p^{+}) = -3\%$. The resulting proton beam brilliance loss $BL(p^{+})$ could be evaluated for:

$$BL(p^{+}) = 100\% - \frac{TM_{fin}(p^{+})}{100\% + EW_{fin}(p^{+})} \cdot 100\% \approx 23\% \cdot$$

Assuming the brilliance loss scales with ion current density, the expected brilliance loss $BL(U^{28+})$ for the measured maximum uranium beam current (for charge state 28+) of 9.70 emA is:

$$BL(U^{28+}) = \frac{9.70emA}{2emA \cdot \frac{m}{q}(scal)} \cdot BL(p^{+}) \approx 0.6 \cdot 23\% \approx 15\%.$$

SUMMARY AND OUTLOOK

For operation with high intensity intermediate charge state heavy ion beams loss-free injection into the SIS18 is an essential condition. By horizontal collimation of the uranium beam emittance in the transfer line, the SIS18 space charge limit could be reached at significantly lower pulse currents, but accordingly longer injection times. The conducted high current proton beam emittance measurement throughout the UNILAC shows a loss of horizontal beam brilliance of 23%. The high current uranium beam brilliance (measured at 1.4 MeV/u) decreases accordingly until SIS18 injection. Besides the measured proton beam brilliance of the core stays constant during acceleration and transport to the SIS18. Through horizontal beam collimation (≤ 2 mm·mrad), the number of uranium particles in this phase space area is sufficient to fill the SIS18 up to the space charge limit (Fig. 9). Within a normalized emittance of 0.31 mm·mrad (tot. emittance = 2 mm·mrad) an available uranium beam current of 6 emA from the UNILAC corresponds to a normalized beam brilliance of 19.35 mA/mm·mrad, while 30 turns have to be injected in the SIS 18 [6,9]. The necessary pulse length is approximately 140 µs, available at UNILAC without any performance limitations. For further confirmation, it is evident to perform high intensity uranium beam measurements at full UNILAC energy.

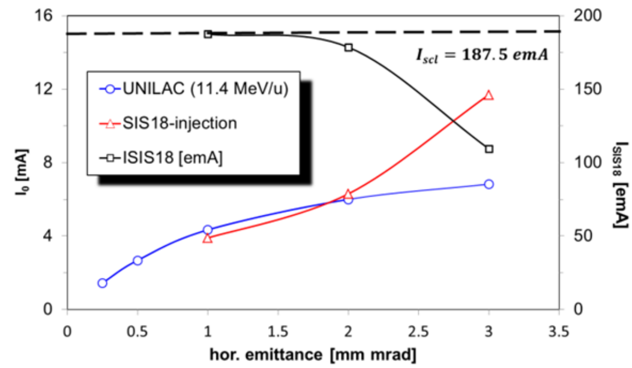

Figure 9: Injection current to reach SIS18-space charge limit (red), UNILAC-beam current (blue) and total current (black) as a function of U^{28+} horizontal input emittance at SIS18-injection.

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