HIGH BRILLIANCE URANIUM BEAMS FOR FAIR

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Abstract

The 40 years old GSI-UNILAC (Universal Linear Accelerator) 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. In the context of an advanced machine investigation program in combination with the ongoing UNILAC upgrade program, a new uranium beam intensity record (9.97 emA, U^{29+}) at very high beam brilliance was achieved recently in a machine experiment campaign. This is an important step paving the way to fulfill the FAIR heavy ion high intensity beam requirements. Results of high current uranium beam measurements applying a newly developed pulsed hydrogen gas stripper (at 1.4 MeV/u) will be presented in detail.

INTRODUCTION

High current uranium beam machine experiments at the GSI-High Current Injector (HSI) and the gas stripper section were conducted in November 2015. At this time, due to work on the rf-amplifier system of the UNILAC post stripper (Alvarez) only three of the five Alvarez tanks were available. The achievable high current beam brilliance at injection into the heavy ion synchrotron SIS18 is currently estimated only by using front-to-end high-current measurements with a proton beam performed in 2014. [1]

For uranium measurements at UNILAC, a novel multi-hole extraction system for extracting a high brilliant ion beam from the VARIS ion source [2] was used a second time. Moreover, the HSI RFQ is back in operation at nominal rf-voltage (for uranium operation) by applying a dedicated conditioning and development program. These measures facilitated the extensive beam optimizing program and thus the success of this measurement campaign. The already used pulsed hydrogen stripping target [3,4] has been further optimized in the meantime. The aim was to determine the maximum achievable average charge state. This was accomplished by installation of a second injection valve, which resulted in an increased target density. It was found, that (compared to the conventionally used nitrogen gas-jet) the average charge state can be increased by approximately three charge units. The high current measurements were therefore carried out in charge state 29+, but the same particle yield is also achievable at lower charge states (e.g., 28+). The measured maximum beam brilliance before the Alvarez-DTL is evaluated. In routine accelerator operation such peak values cannot be routinely achieved. They can be established only through a long-term and sustainable machine development program. Supplemented by extensive beam simulations [5], that were carried out recently for injection of a high-intensity uranium beam (from UNILAC) into the SIS18, the uranium beam intensity, achievable from the FAIR injector chain, could be estimated.

FRONT-TO-END HIGH CURRENT PROTON BEAM MEASUREMENTS

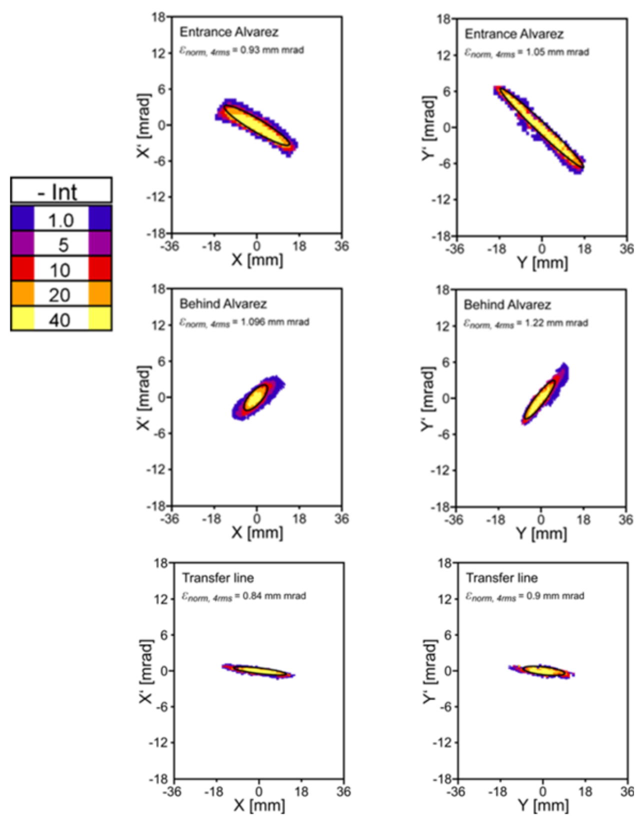

Figure 1: High-current proton beam measurements at GSI-UNILAC and transfer line to the SIS18 [1].

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. The high current proton beam emittance growth inside the Alvarez was measured to be 17% (rms) [1] (Fig. 1). Considering the overall beam transmission of 90%, the loss of beam

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

U-BEAM OPTIMIZATION AT HSI

The U^{4+}-beam current and brilliance was improved by applying a multi-aperture extraction system [6] 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 rf optimization by adjusting the plunger positions at the HSI RFQ tank and extensive rf-conditioning the forwarded rf-power was reduced to 790 kW, yielding 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 high current operation. After improved beam matching to the gas stripper by adapting the quadrupole channel a beam transmission of 90% in this section could be achieved. For the first time an U^{4+} beam current of 6.6 emA was available for heavy ion stripping. After upgrade of the stripper gas cell an optimal H_2 target thickness of ≈14 µg/cm^2 (for stripping into charge state 29+) was available. The charge separation procedure under high current conditions was re-optimized, resulting in an increased stripping efficiency of about 21%.

HIGH CURRENT U-STRIPPING AT A PULSED H_2-GAS CELL

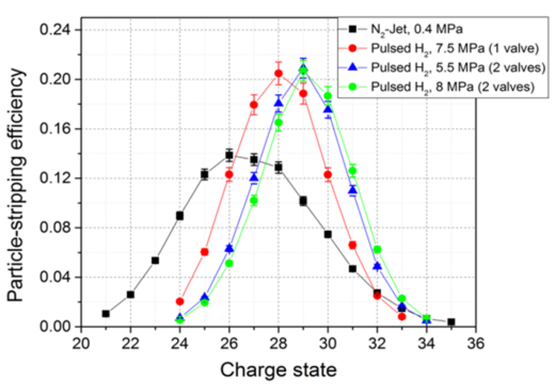

Figure 2: Charge distribution after stripping of uranium projectiles in a H_2 gas target for different target thickness (max. average charge distribution is depicted in green color); uranium beam on a N_2–target is shown as well.

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. 2 (with the H_2 gas stripper cell) the stripping efficiency (into 28+) could be improved. Applying a high density H_2-target (instead of a N_2-target) the yield is 65% higher, the maximum average charge distribution shifts by 3 charge units.

With a pulse particle current of 0.345 mA, a new intensity record at 1.4 MeV/u was achieved. For the equilibrium charge state (29+) the transversal beam emittance (Fig. 3) was measured at an electrical beam pulse intensity of 9.97 emA. The main beam parameters achieved with H_2 and N_2 stripping targets are summarized in Table 1.

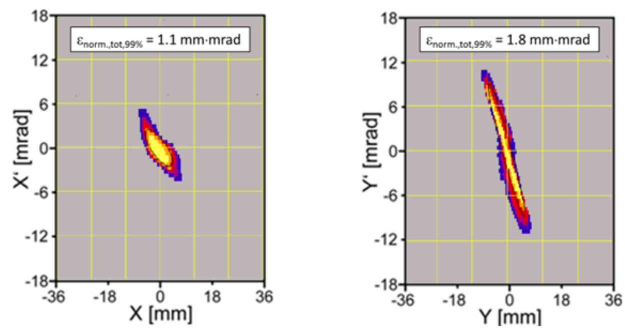

Figure 3: Measured horizontal and vertical high current (9.97 emA) U^{29+}-beam emittance (at 1.4 MeV/u).

Table 1: Measured Beam Parameters

	N_2-gas jet [6]	H_2- gas cell
Stripper-back-pressure	0.4 MPa	5.5 MPa (pulsed)
U^{4+}-current (HSI)	6.0 emA	6.6 emA
Stripping charge state	28+	29+
Max.uranium-current	4.5 emA	9.97 emA
Stripping efficiency	12.7±0.5%	21.0±0.8%
Energy loss	14±5 keV/u	27±5 keV/u
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 requirement:		
ε_x (tot.) norm.	1 µm	
U^{28+}-Intensity	15 mA	
Hor. beam brilliance	15 mA/µm	

BEAM BRILLIANCE ANALYSIS

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. For the high current beam dynamics layout of the gas stripper section, an enlarged vertical beam

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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. 4) at 1.4 MeV/u simply scales with the pulse current.

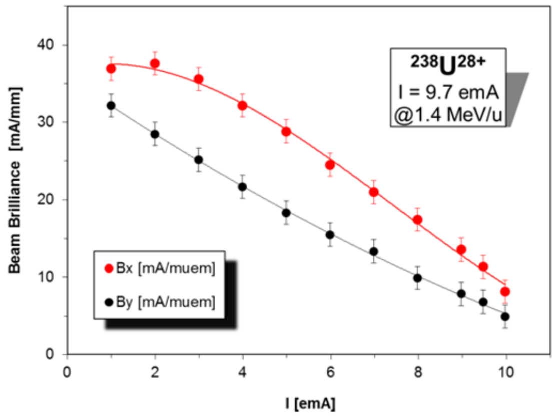

Figure 4: Horizontal and vertical brilliance (at 1.4 MeV/u) for uranium beam on H_2-target (9.97 emA, U^{29+}).

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: $EW_{fin}(p^{+})=-3\%$. 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 brilliance loss $BL(U^{28+})$ for the measured maximum uranium beam current (for charge state 28+) of 9.70 emA is:

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

SUMMARY AND OUTLOOK

Loss-free injection into the SIS18 is a necessary condition, especially for operation with high intensity intermediate charge heavy ion beams. By horizontal collimation of the UNILAC 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) grows until SIS18 injection accordingly. Through horizontal 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 (see Fig. 5). 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 [5,7]. The necessary UNILAC pulse length is approximately 140 µs. For further confirmation, it is evident to perform uranium measurements at full UNILAC energy.

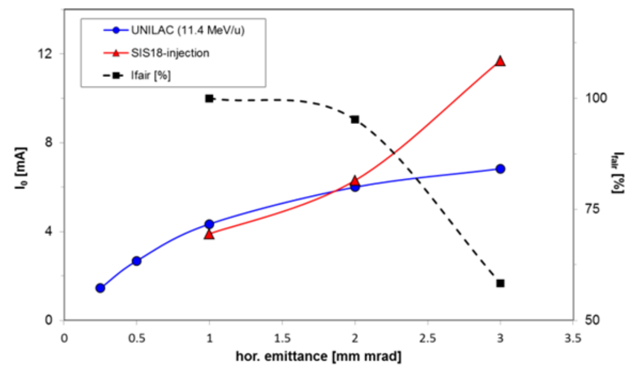

Figure 5: Necessary injection current to reach SIS18-space charge limit (red), UNILAC-beam current (blue) and total current (black) as a function of U^{28+} horizontal input emittance at SIS18-injection.

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