U^{28+}-intensity record applying a H_2-gas stripper cell

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To meet the Facility for Antiproton and Ion Research science requirements higher beam intensity has to be achieved in the present GSI-accelerator complex. For this an advanced upgrade program for the UNILAC is ongoing. Stripping is a key technology for all heavy ion accelerators. For this an extensive research and development program was carried out to optimize for high brilliance heavy ion operation. After upgrade of the supersonic N_2-gas jet (2007), implementation of high current foil stripping (2011) and preliminary investigation of H_2-gas jet operation (2012), recently (2014) a new H_2-gas cell using a pulsed gas regime synchronized with arrival of the beam pulse has been developed. An obviously enhanced stripper gas density as well as a simultaneously reduced gas load for the pumping system result in an increased stripping efficiency, while the beam emittance remains the same. A new record intensity (7.8 emA) for $^{238}U^{28+}$ beams at 1.4 MeV/u has been achieved applying the pulsed high density H_2 stripper target to a high intensity $^{238}U^{4+}$ beam from the VARIS ion source with a newly developed extraction system. The experimental results are presented in detail.

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I. INTRODUCTION

Meeting the science requirements of the Facility for Antiproton and Ion Research (FAIR) [1] higher beam intensities has 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 energy of up to 1.5 GeV/u for radioactive beam production will be delivered by the synchrotron SIS100. In past years, GSI put effort in increasing the uranium beam intensities delivered to the SIS18. An advanced upgrade program for the UNILAC aimed to meet the FAIR requirements. For uranium (FAIR reference ion) the UNILAC has to deliver 3.3×10^{11} U^{28+} particles per 100 μs (see Table I) [2].

In the high current injector (HSI) [3] comprising an Combination of Interdigital H-Structure and Radio Frequency Quadrupole and an Interdigital H-Structure Drift Tube Linac, the beam is accelerated up to 1.4 MeV/u. The gas stripper section [4] provides for a higher charge state; during standard operation an U^{28+} beam 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 for foil stripping and another charge separating system.

II. STRIPPING OF HEAVY IONS

Suitable charge stripper technologies [5] are crucial to meet the challenging demands of state of the art heavy ion accelerator facilities like RIBF at RIKEN, FRIB at MSU, and FAIR [2,6–9]. At FAIR presently under construction at GSI, the existing linear accelerator UNILAC and the synchrotron SIS18 will serve as an injector chain for the FAIR SIS100 synchrotron. Within an advanced UNILAC upgrade program, aimed to meet the FAIR demands, different approaches are investigated to increase the stripping efficiency of the heavy ion beam at 1.4 MeV/u and to generate higher charge states [2,9–11]. This includes extensive studies with carbon foil strippers, the development of a plasma stripper setup at the Institute for Applied Physics (IAP) at Frankfurt University [12], and the application of alternative stripper gases [13]. For FAIR design beam currents, the stripper target at 1.4 MeV/u has to cope with a very high ion beam power of up to 1.5 MW for 18 emA U^{4+} beams during short beam pulses (100 μs) at low duty cycle (2.7 Hz repetition rate). Though for high beam powers gas or liquid strippers have clear advantages compared to foil strippers concerning durability and operational reliability, gas strippers lead to much lower equilibrium charge states due to the strongly reduced influence of the density effect [6,7,14] compared to solid strippers. Since electron capture cross sections of the heavy ions in the low-Z gases are considerably

TABLE I. FAIR-design uranium beam parameters at the UNILAC [2].

	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection	
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{28+}$	$^{238}U^{39+}$ (future option)
Electrical current [mA]	25.0	18.0	15.0	15.0	10.8
Particles/100 μs pulse	3.9×10^{12}	2.8×10^{12}	3.3×10^{11}	3.3×10^{11}	2.4×10^{11}
Energy [MeV/u]	0.0022	1.4	1.4	11.4	11.4
Δ W/W	...	4×10^{-3}	$\pm 1 \times 10^{-2}$	$\pm 2 \times 10^{-3}$	$\pm 2 \times 10^{-3}$
$\varepsilon_{\mathrm{norm},x}$ [mm mrad]	0.3	0.5	0.75	1.0	1.0
$\varepsilon_{\mathrm{norm},y}$ [mm mrad]	0.3	0.5	0.75	2.5	2.5

suppressed [14,15], in particular hydrogen promises higher equilibrium charge states as compared to nitrogen which is routinely used at the UNILAC gas stripper [16].

Thus a new setup, suitable for H_2 operation has been constructed. To avoid explosive gas mixtures, nitrogen was injected as inert gas into the vacuum exhaust pipe of the stripper and of the neighboring vacuum sections to provide for a hydrogen concentration in the exhaust air below 2.0%, a factor of 2 below the lower explosion limit. After injection of the inert gas, the exhaust air was extracted by a blower and was discharged to the atmosphere. The stripper gas flow rate and thus the resulting gas pressure at the gas inlet upstream of the Laval nozzle is controlled by a calibrated mass flow controller. For hydrogen gas jet operation, merely a maximum mass flow rate of about 1.4 g/min could be reached due to the low mass density of hydrogen gas and because of steeply rising vacuum pressures in the stripper box and in the neighboring vacuum sections, since hydrogen is only very poorly pumped by the vacuum pumps.

Due to the low mass density of the hydrogen gas jet, the highest charge state which could be measured in this first experiment was about U^{21+}. The maximum of the charge state spectrum could not be measured due to the limited field strength of the bending magnet. Analyzed beam currents for U^{20+} and U^{21+} were steeply rising with increasing gas pressure. Thus, the obtained hydrogen target thickness was far too low to reach an equilibrium charge state distribution [5].

To enhance the gas density a different approach was chosen, exploiting the fact that FAIR will use pulsed ion beams with low duty cycle ($\leq 100\,\mu$s, 1–3 Hz). Accordingly, a pulsed gas injection [17] was implemented instead of a continuous gas inlet as in the existing setup. This allows an increase of the maximum gas pressure. The time between two pulses is used to remove most of the gaseous particles from the system before injection of the next pulse. For further investigations, the flange with the Laval nozzle was replaced by a new flange, which features a pulsed gas valve designed for back pressures up to 12 MPa and features opening times down to a few hundred microseconds. To prevent the gas from instantaneous removal through the roots vacuum pump, it is forced through a transverse tube, installed along the beam trajectory. This creates a high-pressure interaction zone for the stripping process. To estimate the optimum opening time of the valve, the pressure during an opening process is measured on top of the main chamber. The measurements showed a saturation of the gas pressure up to higher opening times. For nitrogen (as well as for hydrogen) an ideal opening time of 0.5 ms was determined by measuring the saturation of the total current signal. For this opening time the pressure in the neighboring beam line was still tolerable.

The gas injection is triggered by a timing signal of the central accelerator control unit, allowing synchronized operation of all components installed along the beam line. The gas injection is stopped at the end of the beam pulse. This associated decrease of the total gas volume allowed an increase of the gas pressure inside the gas pulse and therefore a maximum stripper target density [17].

III. SETUP OF THE STRIPPER SECTION

For the UNILAC a stripper section [4,18] was redesigned and installed in 1999 (shown in Fig. 1). Some additional design features were considered: charge state separation and beam transport under highest space charge conditions and multibeam operation with pulsed magnets. By two quadrupole doublets the beam is matched to the gas stripper. A supersonic N_2-gas jet produced by a Laval nozzle crosses the ion beam in the central interaction region of the gas stripper chamber. More than 99% of the gas load is dumped by a large roots booster pumping station installed in the basement below the gas stripper for pumping of the central stripper box region. Two sections of differential pumping upstream and downstream of the central region are pumped by four powerful turbo pumps (pumping speed 1200 l/s) to ensure a suitable vacuum in the adjacent beam lines. Compared to the original stripper [19], the free aperture is approximately 40% larger, ensuring a small beam size at the analyzing slit without any additional focusing elements. The charge state separator comprises three bending magnets, operating in pulsed mode. With a 15 degree fast kicker magnet (inflecting the beam from the high charge state Injector to the UNILAC axis) a multipulse mode from the different injectors is possible. In the following transport line the longitudinal matching (with two rebunchers at 36 and 108 MHz) and the transversal matching (with a quadrupole

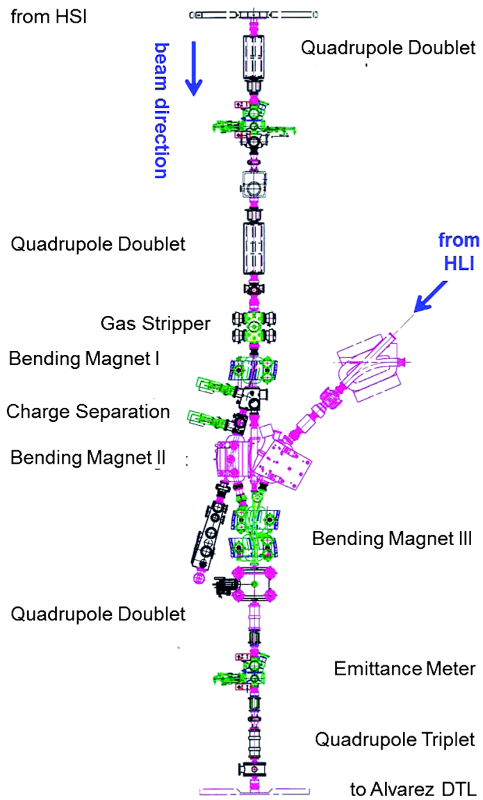

FIG. 1. Layout of the 1.4 MeV/u stripper section; 14.0 m total length.

doublet and a triplet) to the poststripper accelerator is accomplished. All sensitive elements are protected by diaphragms to handle with the highest beam pulse power along the UNILAC (up to 1.4 MW).

A. Stripper upgrade program

With the small beam apertures in the original stripper box, it was possible to increase the stripper gas density significantly. For medium intense uranium beams a stripping efficiency of 12.8% for U^{28+} was reached at a 70% higher gas density. During long term operation the pumping speed of the old vacuum pumps was not sufficient to compensate the additional gas load. For high current operation, as required for FAIR, the defocusing effect of the space charge forces leads to particle loss in the transport section after the stripping area. In the gas stripper box (as shown in Fig. 2), installed in 2007, the high stripper gas density for the necessarily enlarged apertures of 22 mm (at the interaction zone) is provided by enhanced vacuum pumping speed.

In Fig. 3 the stripping efficiency is shown as a function of the stripper target density for different charge states of a high current uranium beam. In standard mode a stripper target prepressure of up to 0.45 MPa (55% more compared to the original maximum) can be used. The efficiency for charge state 28+ remains the same as for the original setup, but for the low current case. For high current uranium beam operation charge state 27+ with an efficiency of

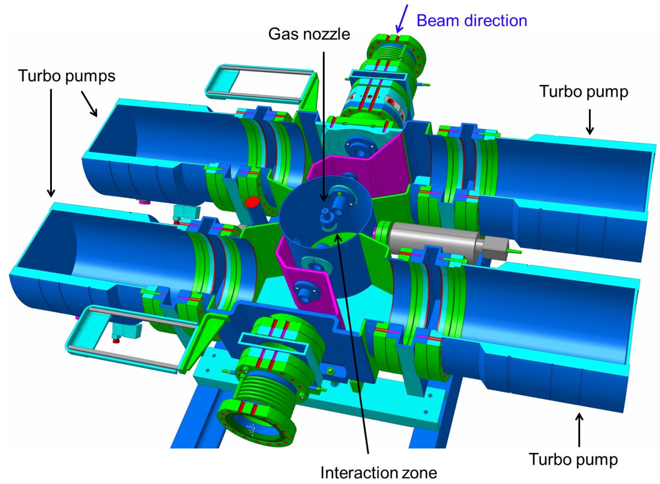

FIG. 2. Gas stripper box with enlarged beam aperture and two times higher pumping speed [20].

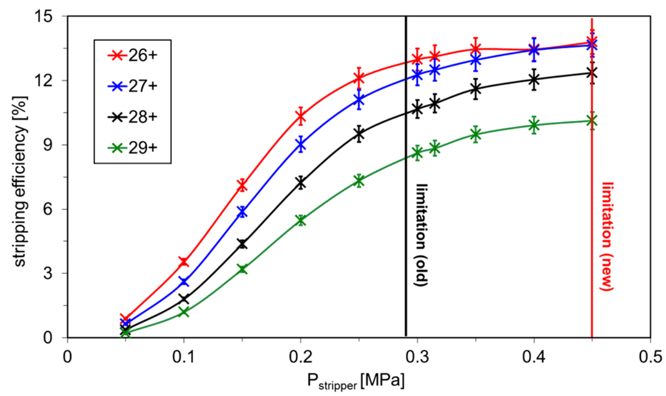

FIG. 3. Measured high current uranium beam stripping efficiency as a function of the stripper target density (prepressure); N_2-supersonic gas jet with enlarged beam apertures (22 mm) [21].

13.7 ± 0.2% was achieved, delivering up to 5.5 emA to the GSI synchrotron SIS18 for high current uranium operation.

B. Foil stripping

Carbon stripper foils (20, 40 and 50 $\mu g/cm^2$) were used at 1.4 MeV/u to provide for highly charged uranium ions (39+) to be delivered to the SIS18 for machine experiments (beam lifetime measurements) as well as for routine experiment operation [2]. In preparation high current tests were performed to check the durability of the carbon foils.

After careful optimization for maximum beam transmission with a low intensity beam from a Penning Ionization Gauge (PIG) type ion source, a high current uranium beam from a VARIS was in operation to accelerate a 0.5 MW-beam pulse (1 Hz, 100 μs) up to 1.4 MeV/u to a maximum U^{39+} beam intensity. The poststripper transmission was optimized for 95%, while up to 6 emA could be delivered to the SIS18. In a high current beam test with a 20 $\mu g/cm^2$ foil no significant change of the beam emittance as well as the energy loss (typical values range between 17 keV/u and 22 keV/u) and the beam transmission could be observed during 6 hours of operation. An U^{39+}-beam intensity of up to 10^{11} particles per 100 μs was obtained in the transfer line to the SIS18. Investigations of stripper foils with different thicknesses are published in [2]. Long time observation of all relevant beam parameters (transverse emittance, energy spread and energy loss, bunch shape and beam transmission up to the SIS injection) are also presented.

Nevertheless, in the target center the amorphous carbon was transformed to polycrystalline graphite at high temperature. Generally, the lifetime of the 20 $\mu g/cm^2$ foils is approximately 3 times higher compared to the thicker foils. An average operating time for the thin foils of 11 ± 4 hours was obtained for average current (up to 6 emA, U^{4+}) uranium beams from the high current injector. A significant dependence of the foil lifetime on the ion beam pulse length was observed. Foils irradiated with beam pulses of 50–100 μs length showed significantly longer lifetimes than foils irradiated with 50% longer beam pulses.

Simulations have been carried out by Tahir [22] using a sophisticated 3D computer code that is equipped with ion energy deposition, heat conduction and thermal radiation losses from the target surface. Different phases of the target material are handled by using an advanced multiphase, multicomponent equation of state package [23]. A wide range of beam and target parameters has been considered. A uranium beam current of 6 emA (as available in machine experiments) and 18 emA (FAIR requirement) have been considered (pulse length is taken to be 100 μs, pulse repetition rate is assumed to be 2 Hz). The transverse ion intensity distribution in the focal spot is Gaussian with $\sigma = 3.67$ mm. The results have shown that in the case of the higher beam current of 18 emA, at the foil center where the maximum of the Gaussian is located, the temperature at the end of the ion pulse exceeds the sublimation temperature of carbon in vacuum even in a single irradiation. This means that the foil will be severely damaged due to the creation of a hole in that region. In case of the lower beam current of 6 emA, simulations show that the maximum temperature is close to the sublimation temperature of carbon in vacuum. Nevertheless the induced thermal stresses and the material fatigue will finally result in damage after a certain number of irradiations as observed in the experiments (see Fig. 4). It is therefore concluded that the use of a solid stripper foil is not feasible at highest intensities in combination with pulse lengths of 100 μs desired during FAIR operation at the GSI-UNILAC.

Foil stripping at the full UNILAC energy (11.4 MeV/u) is the favored option to gain for beam energy of up to 1 GeV/u in the GSI-SIS18 for more moderate particle currents. A 1.4 MeV/u foil stripping approach is a notable option (U^{39+} operation) for short and medium term and offers the opportunity to investigate FAIR relevant space charge effects for heavy ion beams in the GSI-accelerator complex. As a long term option foil stripping at 1.4 MeV/u could be considered only, if the pulse length at maximum intensity is reduced to maximum 30 μs, feasible for synchrotron injectors at higher beam energy ($\geq$100 MeV/u).

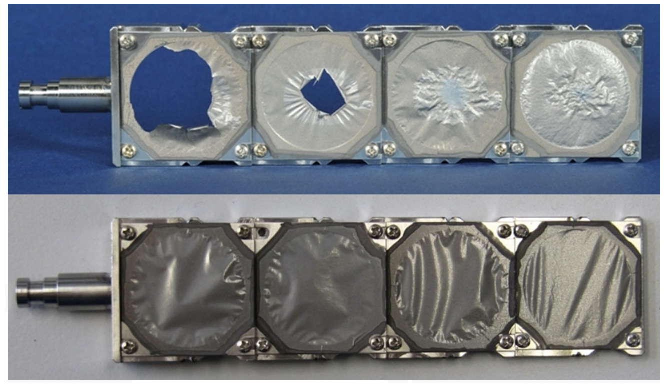

FIG. 4. Foil stripper before (bottom) and after (top) high current operation. For the second foil (top, from the right) 11 kJ of beam energy were deposited without any observed influence on the beam parameters [2].

IV. HIGH INTENSITY BEAM EXPERIMENTS WITH A PULSED GAS STRIPPER

Characterizing the stripping performance, the absolute stripping efficiency into the desired charge state is a key indicator. The absolute stripping efficiency into a specific charge state denotes which fraction of the ions entering the gas stripper is stripped into the corresponding charge state. The stripping efficiency into a dedicated charge state (28+) can be calculated from current measurements of $^{238}U^{4+}$, measured in front of the gas stripper, and $^{238}U^{(28+)}$, measured after the gas stripper. For the current measurement after the gas stripper, the width of the slit is adjusted to match the width of the corresponding charge state peak. A sufficient charge state resolution is required to enable highest intensities into the desired charge state.

To compare the performance of the modified stripper setup with that of the existing gas-jet stripper setup, measurements with both setups were conducted with uranium beam from the injector applying a N_2 target in both cases. As shown in [17] the measured relative charge state spectrum for jet operation as well as for pulsed gas cell with Bi beam from the HSI remains the same inside the error limits, if the applied pressure inside gas jet and gas cell is high enough to reach the maximum equilibrium charge state. A comparable absolute spectrum could be potentially reached, when the beam is matched to gas jet-/gas cell-stripper target and adjacent charge separating system.

In the following results of uranium beam measurements using a high density H_2-pulsed gas cell target are

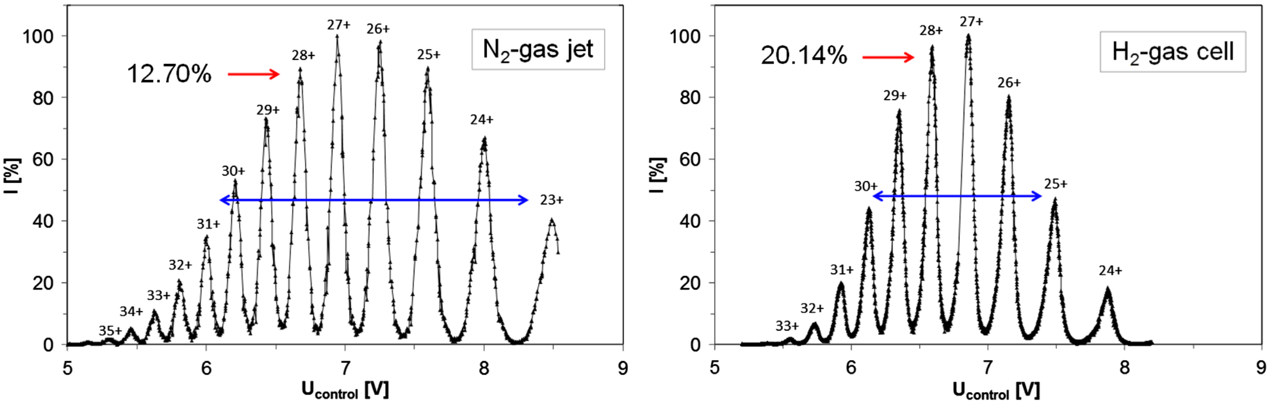

FIG. 5. N_2-gas jet (left) and H_2-pulsed gas cell charge spectra for maximum available target density.

presented and compared with results from measurements applying the N_2-gas jet as its maximum during the same beam time.

As shown in Fig. 5 the measured charge stripping distribution using the maximum target thickness available for N_2-jet operation shows a relatively broad distribution (FHWM $\approx$ 7 charge states), but well separated peaks. The same level of separation purity was observed for H_2-gas cell operation at 8 MPa. But the width of distribution is much narrower (FHWM $\approx$ 4.5 charge states) and the shape of distribution is obviously more symmetric. As a result the relative maximum is significantly increased, while the peripheral areas are diminished. Besides, the maximum of the distribution is shifted by one charge state; the mean charge state for N_2-gas jet operation is designated between 26+ and 27+, while for the H_2-gas cell a mean charge state between 27+ and 28+ is observed. The evaluation of charge spectra resulted in a 59% higher stripping efficiency for U^{28+} as the most interesting uranium charge state for FAIR injector operation.

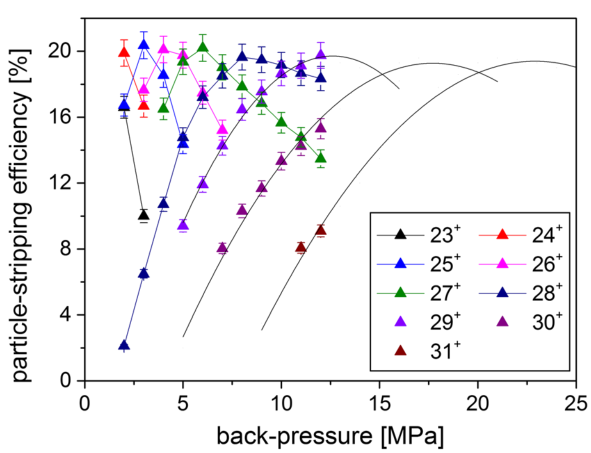

FIG. 6. Stripping efficiency for different uranium charge states in a H_2-gas cell; the maximum available back pressure was limited for 12 MPa. An optimistic trend approximation is included for higher back pressure values.

In particular the stripping efficiency for a dedicated charge state depends strongly on the target thickness. As shown in Fig. 6 for H_2-gas cell operation the maximum of distribution could be shifted from charge state 25+ (at 2 MPa) to 28+ (at 8 MPa). The extrapolation of stripping efficiency progress per charge state above the measured data at 12 MPa shows very high stripping efficiencies for charge state 29+, 30+ and 31+. Assuming a similar behavior of stripping efficiency as a function of target thickness, high current uranium operation for poststripper acceleration with higher charge states is a realistic option for the near future.

For further acceleration of the desired charge state (28+), it is important to characterize the beam quality before injection into the following accelerator section. As a first step it was confirmed by current measurement using the faraday cup behind the first 15 degree kicker magnet with the switched off gas target and kicker magnet, that the beam transmission of the high intensity U^{4+} beam (6 emA) through the gas stripper box is 100%. The high current uranium beam passing the charge separating system after stripping inside the H_2 gas cell has to be matched under space charge conditions; the electric beam current is increased inside target to 42 emA (total uranium current), while space forces are multiplied by a factor of 49 due to the additional charge enhancement from 4+ to 28+ (in average). In Fig. 7 it is presented, how the quadrupole beam line to the gas stripper and the charge separating system was adapted for ideal matching under full space charge conditions. The horizontal beam profile shows a good separation of the neighboring charge states. The position of the separation slits was set for full transmission of the desired charge state (28+) and complete annihilation of all other charge states, confirmed by a profile grid 150 cm behind the separating system.

The beam emittances have been determined by using a measurement system [24] based on a slit and SEM-grid system for horizontal and vertical plane separately. For high resolution measurements three intermediate steps were chosen to improve momentum resolution for a sufficiently

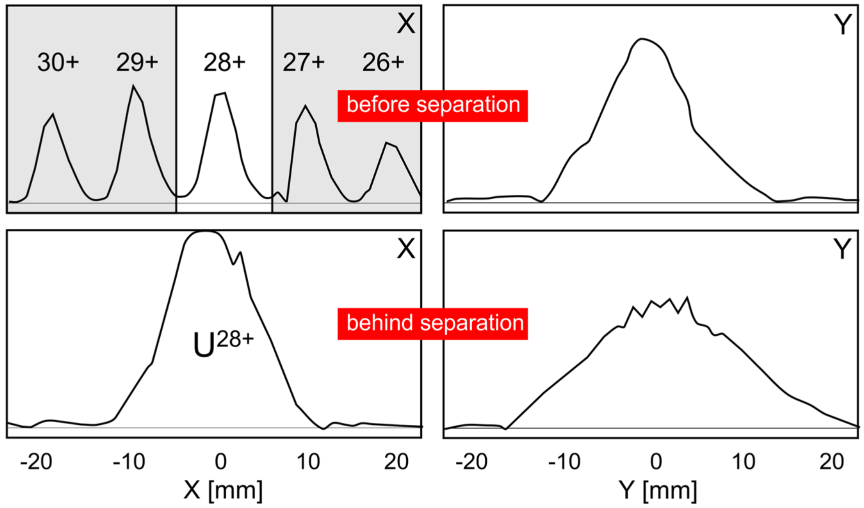

FIG. 7. High current uranium beam profile directly before and 150 cm behind separation slit applying H_2-gas cell; position of the charge separating slit is shown in grey. The desired charge state 28+ is purely separated from the neighboring charge states.

closed coverage of the relevant phase space area. Despite expected higher space charge driven emittance growth for the H_2-gas cell operation, for both targets the average transversal beam emittance remains the same inside a measurement error area of $\pm 2\%$, while the horizontal emittance for H-gas cell operation is 10% less. The shape (Twiss parameters) and position is not significantly affected by the use of different targets (shown in Fig. 8).

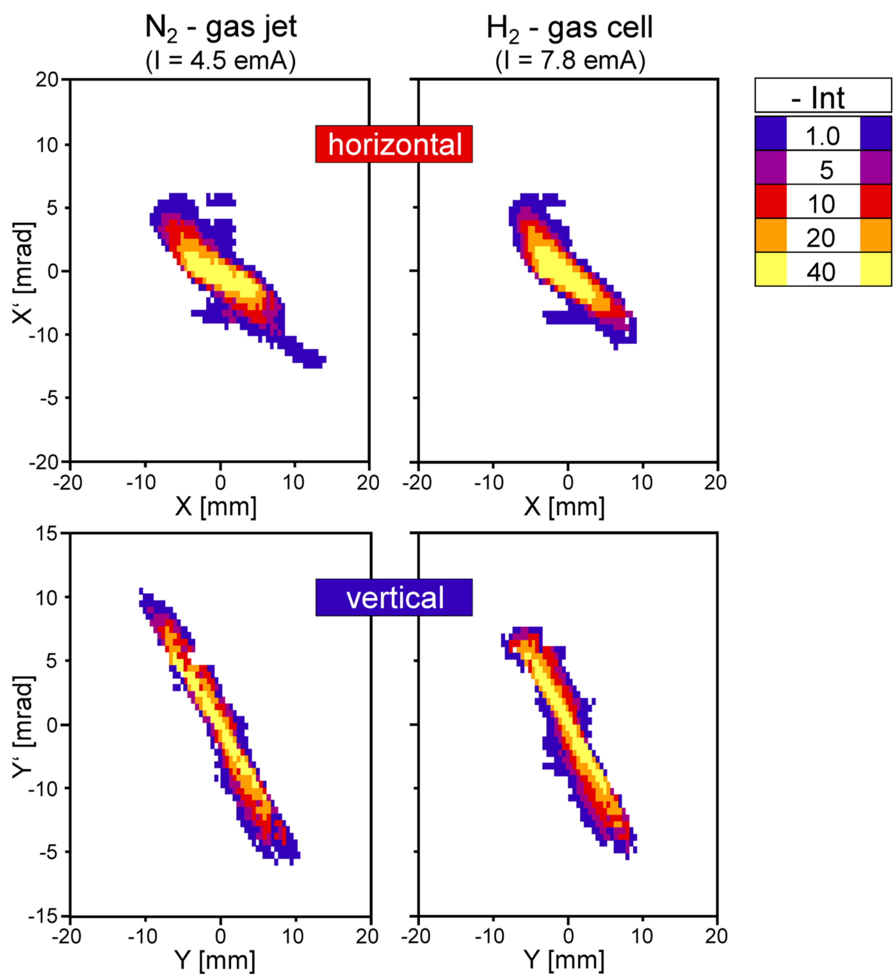

FIG. 8. Measured uranium beam emittance behind N_2-gas jet (left) and H_2-gas cell (right) for maximum available back pressure.

TABLE II. Summary of measured beam parameters.

	N_2-gas jet	H_2-pulsed gas cell
Stripper (pre)pressure	0.4 MPa	12.0 MPa (pulsed)
U^{4+} current (HSI)	≈6.0 emA	
Maximum U^{28+} current	4.5 emA	7.8 emA
Total current (stripped)	24 emA	34 emA
Stripping efficiency	12.70%	20.14%
Energy loss	30 keV/u	22 keV/u
ε_x (90%, total) norm.	0.76 μm	0.70 μm
ε_y (90%, total) norm.	0.84 μm	0.93 μm
Horizontal beam brilliance	5.32 mA/μm	10.03 mA/μm
FAIR requirement:		
ε_x (total) norm.	1 μm	
U^{28+} intensity	15 mA	
Horizontal beam brilliance	15 mA/μm	

FIG. 9. Beam transformer measurement after careful optimization of a VARIS-uranium beam in the HSI and new H_2-gas stripper cell.

The target driven losses of beam energy have been measured by the time of flight method using pickup probes in the matching section behind the gas stripper and separation system with high resolution (0.1%). The use of the N_2 target results in a beam energy loss of 20 keV/u, while for the operation with the thick H_2 target a loss of 12 keV/u was measured. Backward calculation of the target thickness resulted in 44.9 $\mu g/cm^2$ (LISE + + [25]) and 40.8 $\mu g/cm^2$ (SRIM [26]) for the N_2 target and 9.3 $\mu g/cm^2$ (LISE + +) and 6.3 $\mu g/cm^2$ (SRIM) for the H_2 target.

A detailed theoretical analysis has to be carried out. Nevertheless the beam energy loss in both cases is not a critical issue for further matching to fill the rf bucket of the poststripper DTL.

The high current uranium beam measurements (for both targets) of all relevant parameters are summarized in Table II. The FAIR requirements referring uranium beam intensity, emittance and beam brilliance are also included and are discussed in the next paragraph.

V. HIGH CURRENT URANIUM BEAM OPTIMIZATION

After successful commissioning of the new fast pulsed high density gas cell with a uranium beam from the GSI high current injector (HSI), the entire Injector system was optimized for high intensity operation. A newly developed multiaperture beam extraction system was installed. The VARIS ion source [27,28], the extraction system, the postacceleration gap, the low energy beam transport (LEBT) system and the matching line to the RFQ were optimized using a 25% higher U^{4+} beam current extracted from the ion source. As shown in Fig. 9 (bottom) a beam current of 15.3 emA was available for further acceleration in the HSI. In particular the most sensitive medium energy beam transport (MEBT) section was reoptimized for high current, high transmission beam transport applying a slightly different setup of rf parameters for the RFQ and superlens. As a result the HSI was enabled for stable and reliable high current uranium operation, necessary for advanced and careful matching of the high power (0.5 MW pulse power inside a pulse length of 100 μs) U^{4+} beam to the gas stripper cell. Finally a U^{28+} beam current of 7.8 emA (top of Fig. 9) was obtained at 1.4 MeV/u.

Figure 10 shows the FAIR-uranium beam intensity requirements (blue) along UNILAC and transfer line to the SIS18. The latest peak record had been achieved in 2007 (green); with 30% of the FAIR-U^{28+} beam current accomplished at the end of the transfer line. More recently

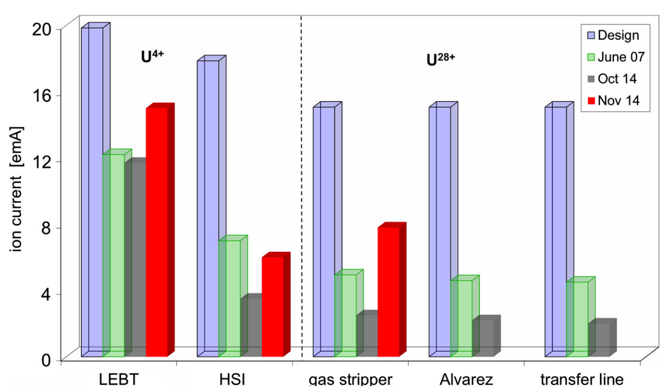

FIG. 10. Achievement of a new uranium beam (28+) intensity record at GSI-HSI and gas stripper section. A newly developed extraction system was in use as well as the fast pulsed H_2-gas stripper cell. The former U^{28+}-peak value (2007) was exceeded by 56%.

(black), the available beam current at this position was 13% of the design value only, caused by strong HSI-performance degradation. After reoptimization of the complete front-end system (ion source, LEBT, RFQ and MEBT), the HSI is again able to deliver a high uranium beam current. In the short run with the new fast pulsed high density H_2-gas cell, in combination with the high intensity beam from the HSI more than a factor of 3 higher U^{28+} beam current is now available at 1.4 MeV/u. A new U^{28+} intensity record (7.8 emA) was accomplished exceeding the latest peak record by 56% (red).

VI. OUTLOOK

After three days of beam time the world intensity record for U^{28+} pulse operation could be reached, including 15 hour beam time spent for H_2-gas cell-stripper operation. More than 50% of U^{28+}-FAIR intensity requirements and 65% of U^{28+}-FAIR beam brilliance was accomplished recently. The stripper performance could be optimized applying significantly higher target densities. Higher primary beam intensity was available after installation of a new extraction system.

Increased beam currents for all heavy ions are expected and are required to be tested; stripper tests have to be initiated using Pb-, Au-, Ta-, Xe-, Kr-, p-beams. An upgrade of the HSI [29–31] is potentially sufficient to meet the FAIR performance at the GSI-UNILAC. Generally multibeam operation with the pulsed stripper varying target thickness and/or target material from pulse to pulse is an attractive option for the future and could influence the overall machine performance and availability.

Further optimization of stripper performance should be started inside an advanced machine experiment program. Beam acceleration up to 11.4 MeV/u and transport to SIS18 is the next step to confirm high intensity operation in the SIS18.

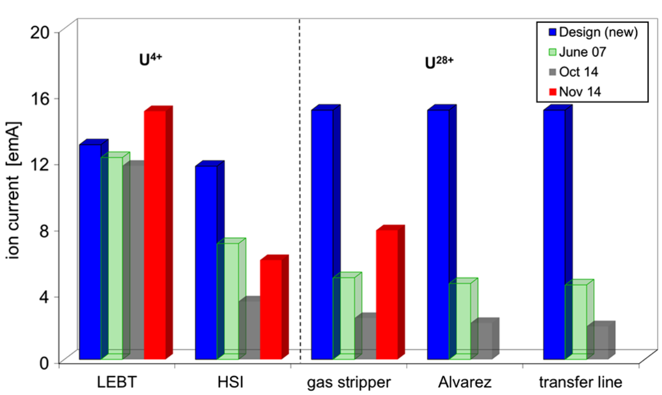

FIG. 11. Due to the availability of the new gas cell stripper FAIR-HSI requirements could be reduced accordingly; an upgrade of the HSI-front-end is obviously necessary to provide for the required U^{4+} current at 1.4 MeV/u.

Applying high density fast pulsed H_2-gas cell operation about 60% higher stripping efficiency reduces the requirements for HSI performance accordingly. As shown in Fig. 11, the HSI has to deliver 12 emA (instead of 18 emA applying N_2-gas jet stripping), if the new hydrogen stripping device is established.

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