High brilliance beam investigations at the universal linear accelerator

W. Barth,[1,2,3,*] U. Scheeler,[1] H. Vormann,[1] M. Miski-Oglu,[1,2] M. Vossberg,[1] and S. Yaramyshev[1]
[1]*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[2]*Helmholtz Institute Mainz, 55099 Mainz, Germany*
[3]*Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

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The more than 45-year-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 Facility for Antiproton and Ion Research (FAIR) synchrotron SIS100. UNILAC will serve together with the SIS18 as FAIR injector for short intense pulse operation; the newly developed heavy ion linac Helmholtz linear accelerator shall deliver cw beams, still required for the comprehensive research program at GSI. In the context of an advanced machine investigation program in combination with the ongoing UNILAC upgrade program, a dedicated beam investigation campaign has been carried out in order to characterize front-to-end high-current medium and heavy ion beam behavior at GSI-UNILAC. A very high beam brilliance at the end of transfer line from UNILAC to SIS18 was achieved recently for medium heavy ion beams 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 the novel technique of pulsed hydrogen gas stripping (at 1.4 MeV/u) will be presented as well.

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I. INTRODUCTION

High-current uranium beam machine experiments [1–6] at the GSI-high current injector (HSI) and the gas stripper section were conducted in October 2015 and July 2016 [7], while at this time, due to work on the rf-amplifier system of the universal linear accelerator (UNILAC) poststripper (Alvarez), only three of the five Alvarez tanks were available. The achievable high-current beam brilliance at injection into the heavy ion synchrotron SIS18 was estimated only by using front-to-end high-current measurements with a proton beam performed in 2014 [8].

The heavy ion linear accelerator UNILAC comprising HSI, high charge state injector (HLI), gas stripper section, poststripper (Alvarez-type) linac, and transfer line to the heavy ion synchrotron SIS18 is shown schematically in Fig. 1. In the HSI comprising two ion source terminals (PIG and VARIS), an Interdigital H-Mode-Radio Frequency Quadrupole, and an Interdigital H-Mode-Drift Tube Linear accelerator, the beam is accelerated up to 1.4 MeV/u. The gas stripper section provides for a higher charge state; during standard operation, a 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. The positions of the emittance meters (slit-grid devices) used for the measurements presented in this paper are also shown. 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.

For uranium measurements at UNILAC, a novel multihole extraction system for extracting a high brilliant ion beam from the VARIS ion source [9,10] was used. Moreover, the HSI RFQ has been operated 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 [11] has been further optimized in order to enable for increased target densities [12], as well as to determine the maximum achievable average charge state. It has been carried out that the average charge state can be increased by approximately three charge units (compared to the conventionally used nitrogen gas jet). The maximum beam brilliance in front of the Alvarez-DTL has been measured.

In routine operation, such peak values could be achieved only through a long-term and sustainable machine development program, which has been accomplished in the past two years. Uranium intensities available at UNILAC-HSI over the past seven years are summarized in Fig. 2.

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[*] Corresponding author.
w.barth@gsi.de

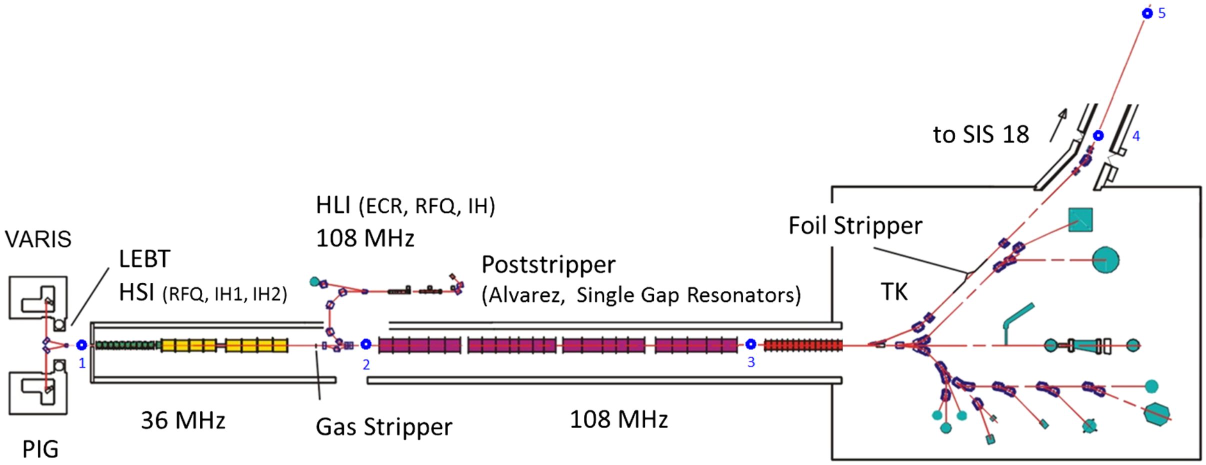

FIG. 1. GSI-UNILAC; the slit-grid-emittance measuring devices are shown in blue. 1, LEBT/UH1; 2, gas stripper section or US4; 3, poststripper or UA4; 4, transfer line or TK5; 5, transfer line or TK8.

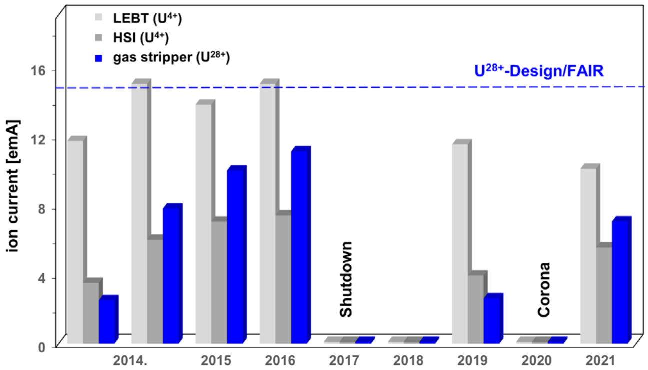

FIG. 2. Uranium beam intensities along the HSI from 2014 to 2021.

A charged particle beam in which the repulsive space charge forces are stronger than the outward force from thermal pressure is called space-charge dominated. In this regime, the Debye length is smaller than the beam size, and so particles interact mostly via the long-range collective potential, as in a non-neutral plasma [13]. Whereas many emerging accelerator applications require maintaining higher beam intensities, most beams are actually created in this intensity regime near their source, but also for heavy ion beam accelerators in the stripper section(s), in which there is a massive increase in the ionic charge and, thus, in the Coulomb interaction forces between the ions.

High-intensity heavy ion beams (uranium, bismuth, and xenon), as well as medium and light ion beams (argon and p^+), have been recently accelerated at GSI-UNILAC in order to fully characterize the high-intensity beam behavior in Facility for Antiproton and Ion Research (FAIR)-injector mode.

II. BEAM OPTIMIZATION AT HSI-RFQ

After a beam line modification during the shutdown in 2017, when the HSI RFQ has been kept under atmosphere conditions for almost one year, the resonator performance has deteriorated significantly. As a result of the recommissioning campaign in 2018, only up to 70% of the nominal rf voltage (155 kV for U^{4+} beam acceleration) at maximum forwarded rf power could be reached. The copper surface conditions were due to many years of operation and additional moisture ingress strongly degraded. New electrodes (rods) as a replica of the old have been produced (2018–2019) and installed. After successful recommissioning with light ion beam, efforts to restore the heavy ion beam operation (uranium, bismuth, lead, and gold) started with the acceleration of U^{5+}, which could be accelerated properly with high transmission.

In order to determine the working point of HSI-RFQ, first medium heavy ion beams (Ar^{2+} and Ar^{1+}) have been accelerated applying different rf voltages, in a range from voltages well below the working point to very high voltages well above. The result, as depicted in Fig. 3, has been verified with a U^{4+} beam, as this is the design ion for the

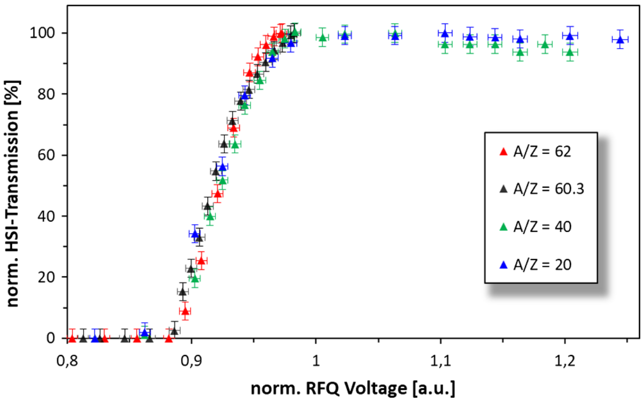

FIG. 3. Measured normalized beam transmission at HSI for Xe, Ta, and Ar beams as a function of norm. RFQ voltage, RFQ working point is set to norm. RFQ voltage = 1.

entire GSI facility. For better comparison, the rf voltage normalized to the mass to charge ratio was used. As known from simulations with the code DYNAMION [14], particles that are not or insufficiently accelerated also contribute to the RFQ particle transmission to a considerable extent. Since these particles are definitely lost in the subsequent IH drift tube accelerator, the full HSI-beam transmission—to which only particles accelerated to HSI final energy contribute—is displayed. Beam transmission has been normalized to the individual maximum as well, as transmission, in general, depends mainly also on the matching condition and the ion source performance, which is different for the ion species used. The measured transmission curves displayed a long plateau of almost maximum transmission. As a consequence, the working point of the RFQ has been set directly behind the kink point (norm RFQ voltage = 1; see Fig. 3), where the plateau with maximum beam transmission is safely reached. Further investigations with even heavier ions confirmed the newly defined working point: After a U^{4+} beam ($A/Z = 59.5$), $^{181}\mathrm{Ta}^{3+}$ ($A/Z = 60.3$) and $^{124}\mathrm{Xe}^{2+}$ beams ($A/Q = 62$) have been accelerated with maximum transmission at the same (normalized) rf voltage. Measurements for all ion beam rigidities showed that both the HSI design energy and transverse beam emittance remain unchanged.

III. HIGH-CURRENT URANIUM-BEAM STRIPPING AT A PULSED HYDROGEN-GAS CELL

After 5 years suspension, for the first time a U^{4+} beam current of 5.1 emA was available for heavy ion stripping at 1.4 MeV/u. After installation of the stripper gas cell [15], an optimal H_2 target thickness of up to 14 $\mu\mathrm{g/cm}^2$ (for stripping into charge state 28+) was again available. The charge separation procedure under high-current conditions was optimized, confirming an absolute stripping efficiency of 21% [12].

Characterizing the stripping performance, the particle-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. Applying a high-density H_2 target (instead of a N_2 target) [16], the yield is 65% higher, and the average of the charge distribution could be shifted by up to three charge units.

A pulse particle current of 0.250 mA was achieved at 1.4 MeV/u, 63% of the record intensity achieved almost 5 years ago. For the charge state 28+, the transversal beam emittance (Fig. 4) was measured at an electrical beam pulse intensity of 7.0 emA.

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 a uranium beam on a H_2 target (7.0 emA, U^{28+}) is significantly increased, while the horizontal emittance is decreased at higher beam current, confirming recent emittance measurements with a heavy ion beam ($^{209}\mathrm{Bi}^{26+}$) on a H_2 target. For the high-current heavy ion 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. Regarding high space charge power at higher ion beam current, the horizontal phase space distribution has to be reduced as well in order to provide for charge separation behind the stripper. Thus, horizontal beam brilliance (as shown in Fig. 4 for U^{28+}) at 1.4 MeV/u simply scales with the pulse current. As a result, the horizontal beam brilliance inside beam core is increased by a factor of 3 by applying a H_2-stripper target instead of the N_2 target, used in routine operation.

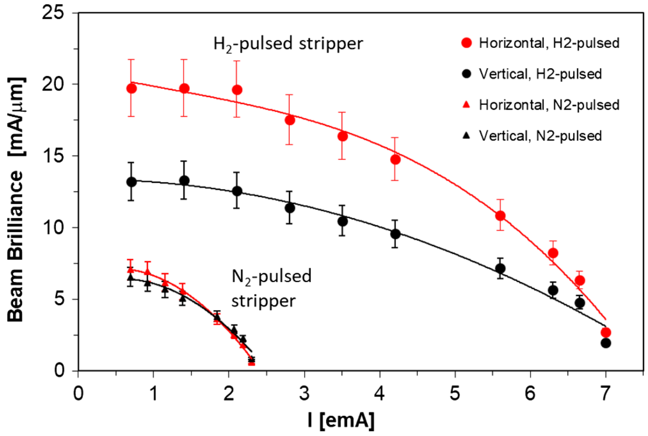

FIG. 4. Beam brilliance analysis for a $^{238}\mathrm{U}^{28+}$ beam on a N_2- or a H_2-stripper target.

IV. CARBON FOIL STRIPPING AT 11.4 MeV/u OF HIGH-CURRENT URANIUM BEAM

Foil stripping at the full UNILAC energy (11.4 MeV/u) is the favored option to gain for a beam energy of up to 1 GeV/u in the GSI-SIS18 for more moderate particle currents. Recently, the high-intensity uranium beam (5 emA, U^{28+}) accelerated at GSI poststripper to full UNILAC energy has been used to investigate beam emittance (Fig. 5 enlargement) due to stripping effects applying carbon foil targets. In order to increase the lifetime of the target by reducing the thermal load and to minimize beam spot enlargement due to straggling, the foil thickness was reduced from 600 to 400 μm for the first time. It was shown that this does not result in a lower stripping yield in the desired charge state (73+) but that the energy loss and, in particular, the transverse emittance growth, with about 30%, are significantly lower. A U^{73+}-beam intensity of up to 1.3×10^{10} particles per 100 μs was obtained in the transfer line to the SIS18.

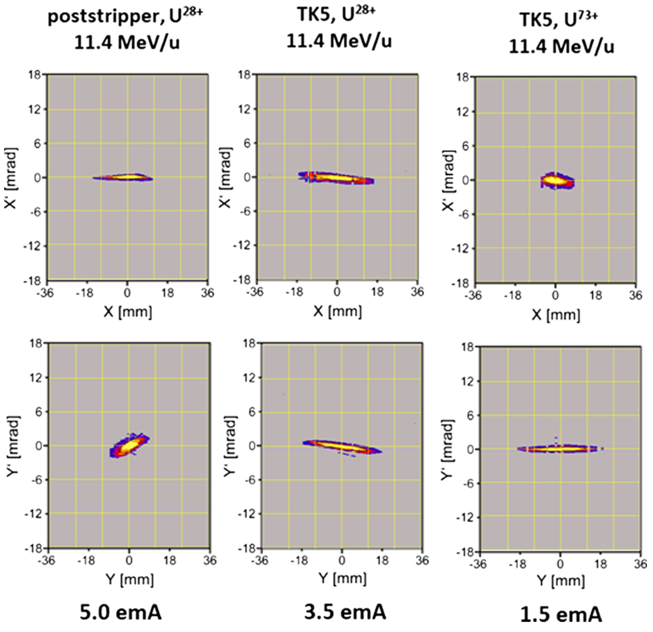

FIG. 5. Beam emittance measurements behind carbon foil stripping and charge separation of high-intensity U beam at 11.4 MeV/u in the transfer line to SIS18.

V. FRONT-TO-END HIGH-INTENSITY HEAVY ION BEAM MEASUREMNTS

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 the behavior of the UNILAC for heavy ion beams, in 2019–2021 high-intensity bismuth and uranium beams were used in several machine investigation runs for the first time to measure the transverse beam emittance at five selected measurement positions along the complete UNILAC.

The obtained angle vs position intensity distributions, as well as the integral beam intensities (measured with ac beam transformers), for bismuth are displayed in Fig. 6. The different measurement locations (see Fig. 1) are the LEBT (low energy beam transport) section (Bi^{4+}), in front of the HSI, behind the hydrogen-gas stripper and charge separation system at 1.4 MeV/u (Bi^{26+}), in front of the Alvarez section, and for the same charge state behind poststripper, in the middle of the 160-m-long transfer channel to the SIS18 (section TK5) and at its end (section TK8).

The corresponding normalized emittance sizes are displayed in Fig. 7. The figure shows the effect of asymmetric emittance growth and reduction described above, which occurs at high intensities, especially when using the hydrogen stripper. This leads to an increase in vertical emittance, whereas the horizontal size remains. This effect occurs because emittance growth in the interaction zone of the stripper depends on the beam spot size. To ensure sufficient separation of the different charge states, the horizontal beam spot size must be minimized, especially when operating with heavy ions. For a given focusing strength of the quadrupole lenses, the vertical beam spot size depends on the defocusing effect generated by the high Coulomb forces in the stripper target. This results in an enlarged vertical beam spot (see Fig. 6) and, thus, the observed asymmetry in the two phase space planes. This effect can be detected behind the gas stripper along the

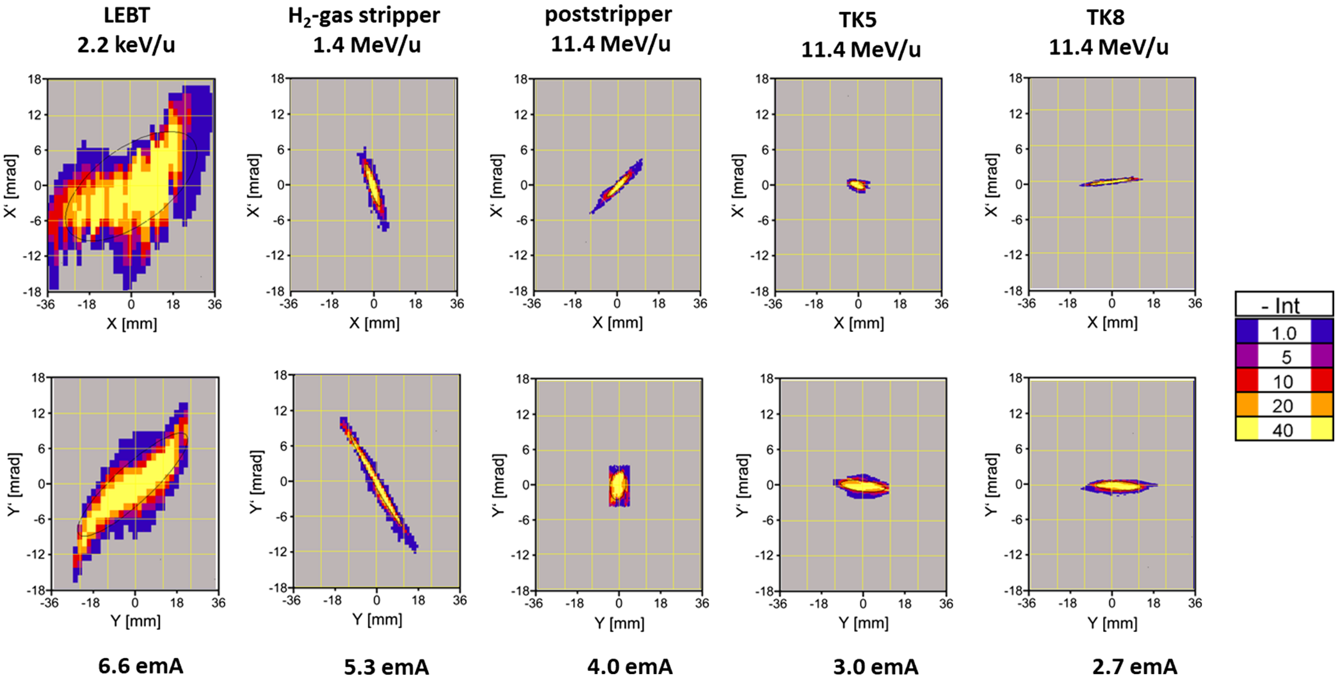

FIG. 6. High-intensity ^{209}Bi-beam emittance and current measurement along UNILAC and transfer line to SIS18.

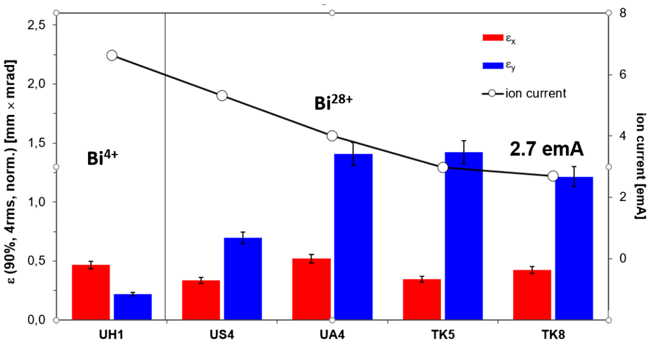

FIG. 7. Evaluation of high-intensity ^{209}Bi-beam emittance measurements corresponding to Fig. 6.

complete UNILAC; at the end of the transfer channel for the bismuth beam, an approximately 3 and a half times smaller horizontal emittance was measured compared to the vertical size. For injection into the SIS18, as desired, a very small horizontal emittance of 0.42 μm ($4 \times$ rms, 90%, normalized) is available. From the LEBT to TK9, no net emittance growth could be measured in the horizontal direction, whereas the vertical emittance increases by about a factor of 5. However, it must be considered that particle losses of more than 40% occurred along poststripper and TK, which may distort the emittance growth balance.

The complementary data for the uranium beam are summarized in Figs. 8 and 9. The effect of asymmetric emittance growth or reduction behavior has also been demonstrated for uranium beams. With a practically identical loss scenario in postripper and TK, but with slightly larger losses in the vertical plane, the effect is less pronounced. In summary, it can be stated that the horizontal emittance growth—approximately 35% smaller than in the vertical direction—is also lower for uranium beams when using the hydrogen stripper.

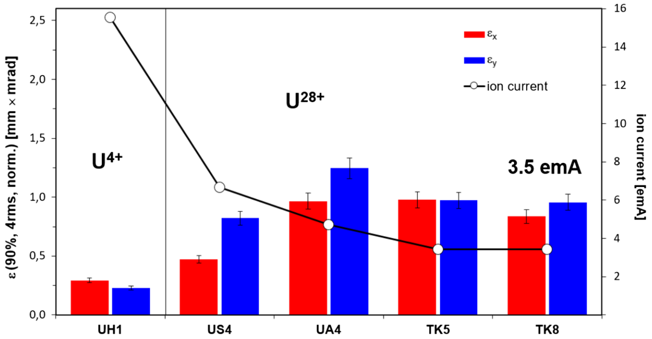

FIG. 9. Evaluation of measured high-intensity uranium-beam emittance corresponding to Fig. 8.

VI. SPACE-CHARGE-DOMINATED BEAM INVESTIGATIONS

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 us to investigate acceleration and transport for space-charge-dominated beams inside the entire UNILAC and transfer line to the SIS18. As depicted in Fig. 10, 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.

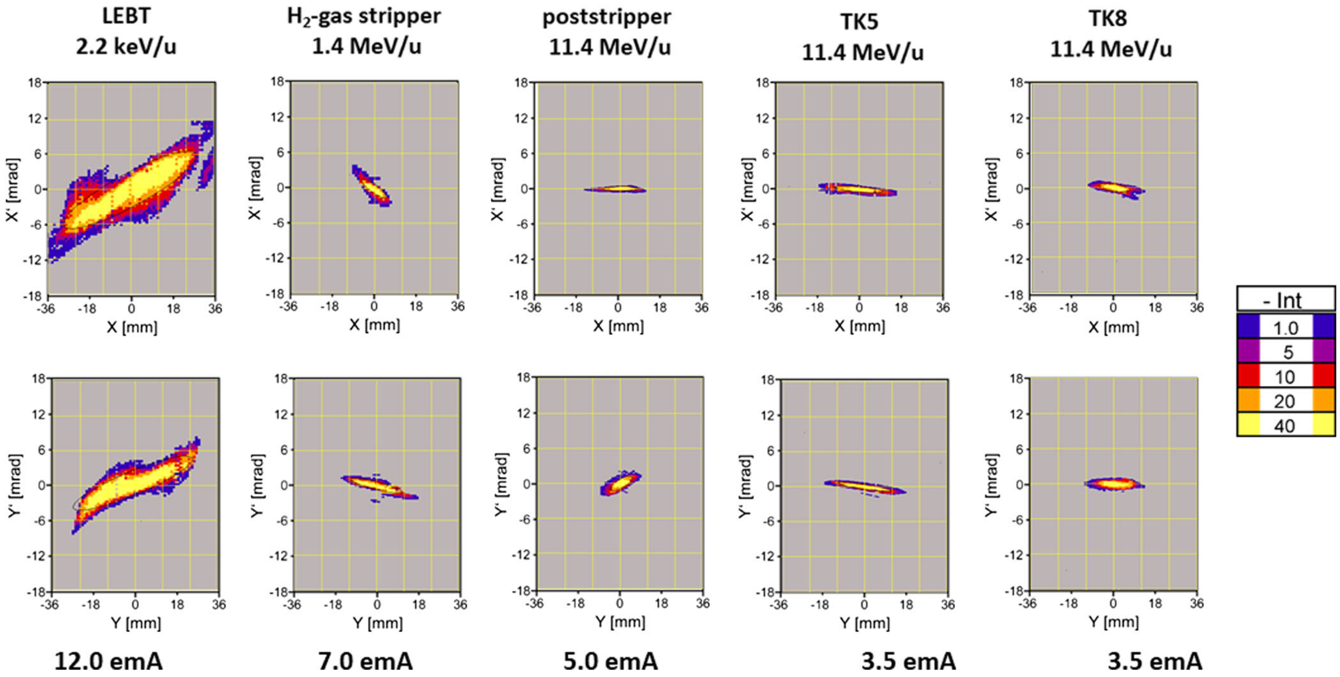

FIG. 8. High-intensity uranium-beam emittance and current measurement along UNILAC.

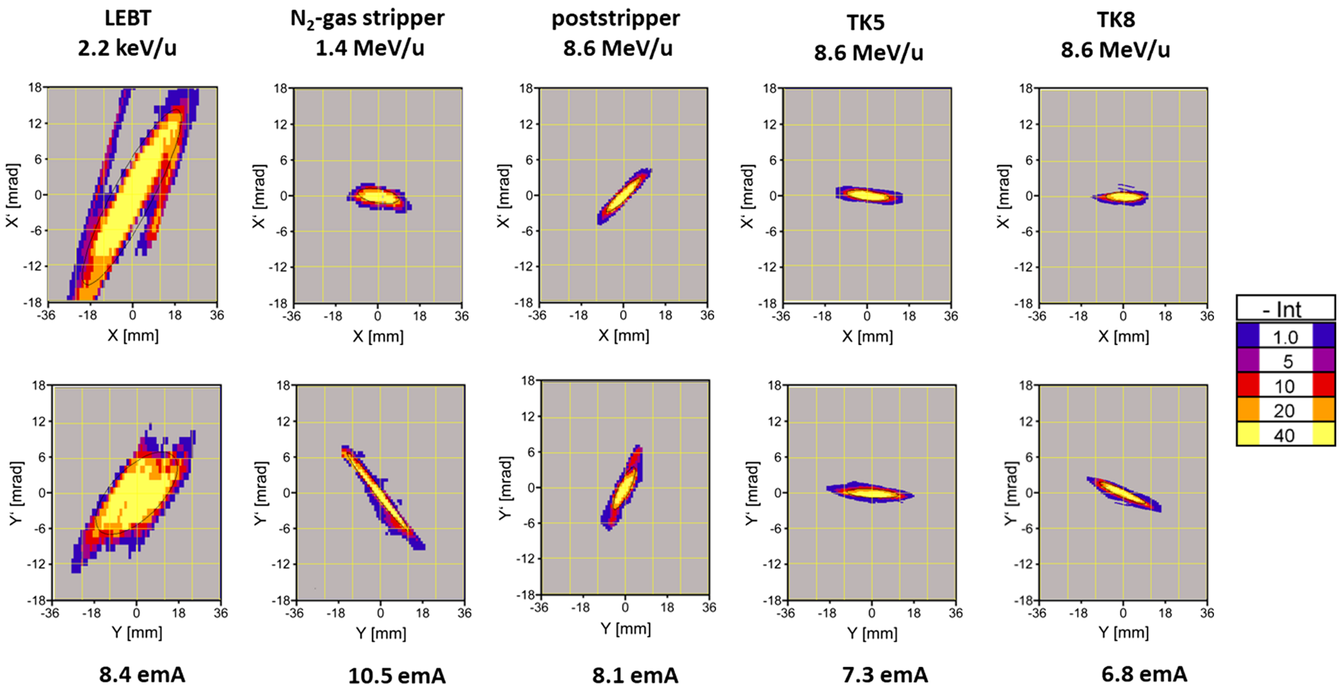

FIG. 10. High-intensity ^{40}Ar-beam emittance and current measurements along UNILAC and TK.

In the argon high-current operation, the effect of emittance asymmetry described above 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 (Bi and U). For the argon high-current experiments, 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 65% for poststripper and transfer line could be achieved for this high intensity.

Bearing in mind the very high ion current in this UNILAC section, 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. 11. High-current front-to-end simulations at GSI-UNILAC were published in Ref. [17]. 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%.

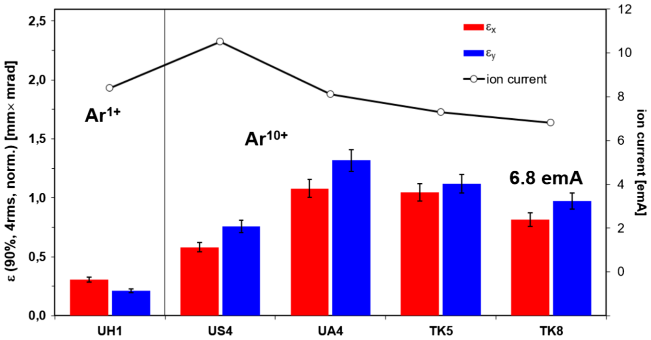

FIG. 11. Evaluation of high-intensity ^{40}Ar-beam emittance measurements corresponding to Fig. 10.

VII. 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 postanalysis so that 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. Figure 12 shows the fractional high-current (fractional) brilliance as a function of the

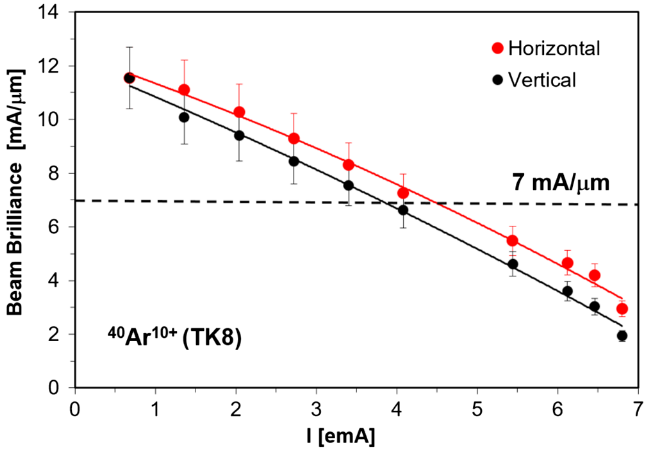

FIG. 12. Ar^{10+}- (fractional) beam brilliance analysis based on beam emittance and corresponding beam intensity measurements at the end of the transfer line (TK8) to the SIS18; FAIR requirement ($A/Z = 4$; $I = 7$ emA, horizontal emittance $=$ 1 mm × mrad).

associated measured beam current. Also plotted is the horizontal brilliance of the injected UNILAC beam required to reach the SIS 18 space charge limit by multiturn 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 4 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.

VIII. SUMMARY AND OUTLOOK

In preparation for successful high-current operation with medium and heavy ions, HSI-RFQ electrodes were exchanged, enabling the full spectrum of ions at high intensity for the first time in five 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 [18,19]. The conducted high-current argon beam measurements throughout the UNILAC post-stripper and TK show a transversal emittance growth of only 35% for the design current of 7 emA ($^{40}\mathrm{Ar}^{10+}$) 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. A significant improvement in beam brilliance was achieved by using the pulsed hydrogen stripper. When using heavy projectile beams (Bi and U), it could be shown that extremely low horizontal emittances, i.e., very high brilliances, are achieved along the complete UNILAC up to the SIS injection. Further improvements in brilliance can be expected from the planned upgrade measures, in particular, on the high-current injector linac.

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