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HIGH INTENSITY HEAVY ION BEAM OPTIMIZATION AT GSI UNILAC

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Abstract

In order to improve the UNILAC performance for the upcoming use as heavy ion injector for the FAIR accelerator chain, dedicated beam investigations have been carried out. In particular measurements with Bismuth and Uranium beam require the maximum accelerating voltage of rf cavities, power of rf transmitters and exciting current of magnet power converters. After four years without regular Uranium high current beam operation (2017-2020), recently the UNILAC has been operated again with full performance. Several upgrade measures will improve the UNILAC capability. In combination with the prototype pulsed hydrogen gas stripper, beam intensities close to the FAIR requirements are achievable.

INTRODUCTION

The UNILAC is designed as a universal linear accelerator for all ion types of different mass from protons to uranium. The UNILAC consists of different ion source terminals, the High Current Injector HSI with the adjacent stripping section, the poststripper, a chain of ten single gap resonators and the transfer channel to SIS18 (Fig. 1).

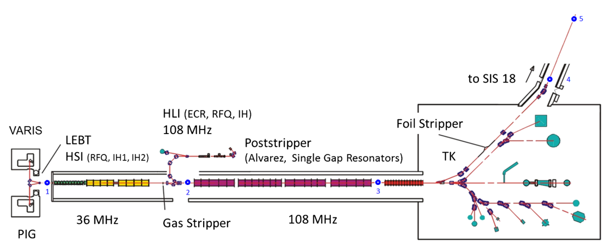

Figure 1: Overview of the GSI Universal Linear Accelerator (UNILAC) [1]; numbered blue dots mark positions of installed emittance measurement devices.

In the HSI ion beams are accelerated from 2.2 keV/u to 1.4 MeV/u with an RFQ and two IH-DTL-tanks. The poststripper contains five Alvarez tanks and ten single gap resonator cavities. Its nominal output beam energy is 11.4 MeV/u. Lower energy steps can be chosen by individually turning off Alvarez cavities, fine tuning is accomplished with the single gap resonator chain.

High current Uranium beam machine experiments were carried out in 2015 and 2016 for the last time before a four year break. At this time only three of the five Alvarez DTL post stripper tanks were available, due to upgrade and maintenance work at the RF-amplifier systems. For this the achievable high current beam brilliance at injection into the heavy ion synchrotron SIS18 could be estimated only on the base of front-to-end high-current measurements with proton beam performed in 2014 [1–14].

HEAVY ION BEAM INVESTIGATIONS

In 2021 and 2022 measurement campaigns have been conducted with high intensity heavy ion beams (Uranium, Bismuth, Tantalum, Xenon) and with medium and light ion beams (Argon, p^+). Bismuth and Uranium beams have been utilised for an advanced optimization campaign along entire UNILAC (described in this report), while an Argon beam has been used to test space charge dominated beam operation [15].

HSI-RFQ- and the superlens-operation (SL) were suffering from performance restrictions, nevertheless since heavy ion beam operation is again possible the U^{28+} beam performance at the end of the transfer channel could be significantly improved.

HSI RFQ and Superlens Optimization

After a beam line modification during shutdown 2017, the RF performance of the HSI-RFQ was strongly degradated (while RFQ kept under atmosphere conditions for almost one year). During recommissioning in 2018 only 70% of the nominal RF-voltage could be reached. As the the copper surfaces were degradated, new electrodes (rods) have been installed (2019). After recommissioning with light ions and U^{5+}, the working point of the HSI-RFQ has been redefined: With a medium heavy ion beam (Ar^{2+} and Ar^{1+}), the beam transmission through the HSI has been scanned in a wide range from voltages far below the working point to high voltages well above. The result was a surprisingly long plateau of almost full transmission and sufficient beam performance. The working point was sufficiently re-defined at an RF voltage closely above the kink point to the plateau. This was confirmed by measurements with Uranium (A/Z = 59.5), and also with ion beams of an even higher mass-over-charge ratio: $^{181}Ta^{3+}$ (A/Z = 60.3) and $^{124}Xe^{2+}$ (A/Z = 62) [16].

The superlense suffered from short breakdowns during beam operation at high RF voltages, probably when the SL electrodes were hit by the ion beam. In order to avoid further breakdowns, the beam was partly collimated in the LEBT right before RFQ-injection. Additionally an RF high power coupler with with an enlarged loop surface was mounted. However, this only slightly improved the HF peromace, so that the SL rods will be exchanged in the next shutdown.

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Stripper Development

The stripping efficiency for the desired U $^{28+}$-fraction is 65% higher, when a pulsed hydrogen gas target at 1.4 MeV/u is used, as confirmed in may diffent machine investigation campaigns (w.r.t. nitrogen gas target). Technical and safety issues do not yet allow a routine operation of the hydrogen gas target so far. Only short test periods of only three days have been performed applying the pulsed hydrogen gas stripping. After an upgrade of the stripper gas cell the optimal H_2 target thickness of up to 14 μg/cm^2 (for stripping to charge state 28+) was available from 2021 on, confirming an absolute stripping efficiency of 21%, while the efficiency for the standard N_2 gas stripping is only 12.5% (Fig. 2). Applying recent technical developments durability has been significantly improved (2022) [10].

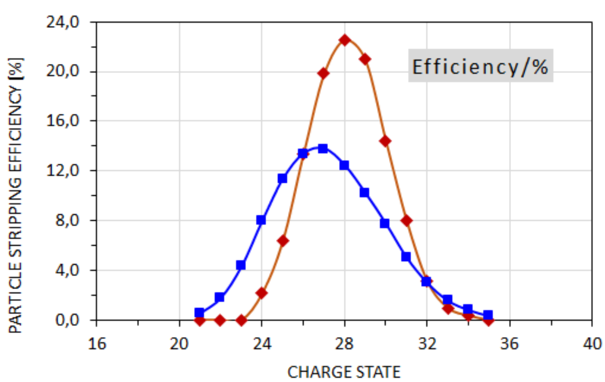

Figure 2: Uranium beam stripping efficiency for two different stripper targets (N_2(blue) and H_2(red)).

Injection into SIS18 requires a small horizontal beam emittance. For pulsed H_2-gas stripper operation, the vertical beam emittance for high intensity uranium beam (7.0 emA, U^{28+}) is increased, while the horizontal emittance is simultaneously decreased, confirming former emittance measurements with $^{209}Bi^{26+}$ at the H_2-target. The horizontal U^{28+} beam brilliance at 1.4 MeV/u scales inversely with the pulse current (Fig. 3). The horizontal beam brilliance inside the beam core is increased significantly by applying the H_2-stripper target instead of the N_2-target.

To achieve SIS18-heavy ion beam energies of up to 1 GeV/u, higher charge states of the ion beam are mandatory by foil stripping at full UNILAC beam-energy (11.4 MeV/u) in the transfer channel. The high intensity Uranium beam (5 emA U^{28+}) has been applied to investigate beam emittance blow up due to straggling effects at the carbon foil targets. In order to minimize beam spot enlargement, the foil thickness was reduced from 600 to 400 μg/cm^2 at a remaining stripping yield in the desired charge state (73+). However, the energy loss is thereby reduced, while in particular the horizontal emittance growth is significantly lowered by 30%.

Front-to-End Measurements

The horizontal beam emittance is the key beam parameter to estimate the high-current capability of a synchrotron injector. Emittance growth along UNILAC has been investigated in 2019, 2020 and 2022 with high intensity Bismuth and Uranium beams.

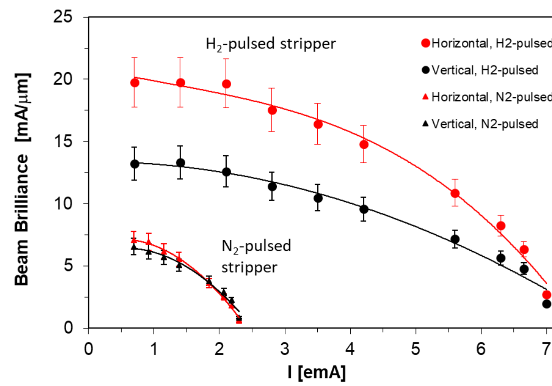

Figure 3: Transversal Uranium (U^{28+}) beam brilliance behind the gas stripper.

The measured transversal emittances and the beam pulse currents for Uranium, shown in Fig. 4, were measured at LEBT-section (U^{4+}), behind the H_2-gas stripper (U^{28+}), behind poststripper and in the middle (TK5) and at the end (TK8) of the transfer line to the SIS18.

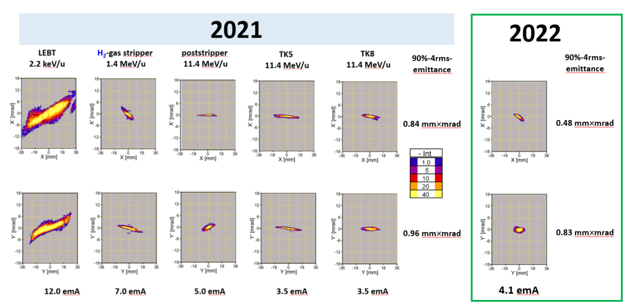

Figure 4: Transversal $U^{4+/28+}$ emittance measurements along UNILAC.

An increase of the vertical emittance and a significant decrease of the horizontal emittance appeared behind gas stripper, which remain constant along the complete UNILAC (Fig. 5). At the end of the transfer channel a three times smaller horizontal emittance was measured compared to the vertical plane. For injection into SIS18, a very small horizontal emittance of 0.42 mm mrad (4×rms, 90%, normalized) was measured. From the LEBT to the end of the transfer channel (TK8), no net emittance growth has been observed in the horizontal direction, whereas the vertical emittance increases by a factor of 5. (However, it has to be noted that particle losses of > 40% along post stripper and transfer channel must be taken into account.)

Comparable emittance measurements were performed with Uranium beam as shown in Fig. 6. The effect of asymmetric horizontal emittance growth and simultaneous vertical reduction was less pronounced compared to the Bismuth beam measurements.

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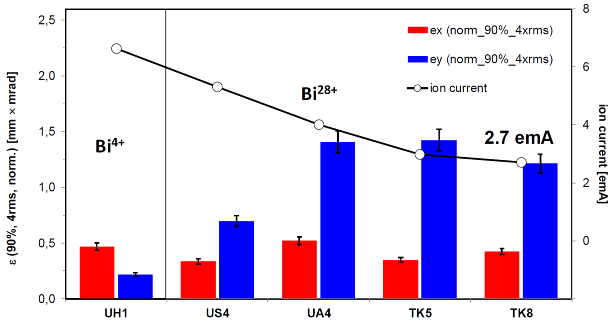

Figure 5: Transversal $Bi^{4+/28+}$ emittance along UNILAC [17].

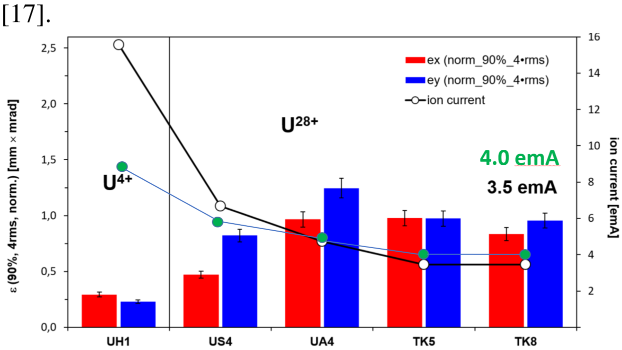

Figure 6: Measured transversal $U^{4+/28+}$ emittance along UNILAC for the 2022 and 2021 campaign.

The recent machine investigation campaign (2022) confirmed the results from 2019 and 2020 applying hydrogen gas stripping. The high current emittances for low and high charge state measured at the end of the transfer channel (TK8) are displayed in Fig. 7. The measured horizontal emittance was sufficiently small; 0.46 mm mrad (4×rms, 90%, normalized) for the U^{28+} beam, and 0.42 mm mrad for the U^{73+} beam, matching the acceptance of SIS18 of 0.75 mm mrad. An additional emittance blow up for the U^{73+} beam does not result in measurable larger emittance size.

Despite superlens performance restrictions the recently measured U^{28+} beam performance at TK8 was significantly improved (compared to 2021). With an inverted polarity of the quadrupole quartet in front of the RFQ applying hydrogen gas stripping the horizontal emittance was considerably

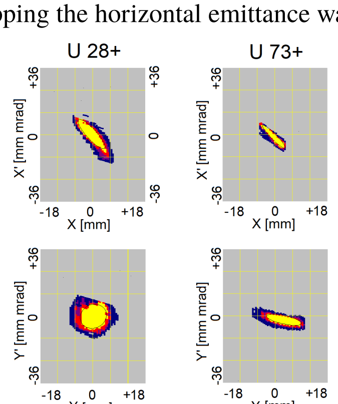

Figure 7: Transversal emittance at TK8, applying pulsed hydrogen gas stripping for 4.0 emA of U^{28+}, 1.0 emA of U^{73+} (2022).

smaller than in 2021, resulting in a brilliance increase of ≥150%, as shown in Fig. 8.

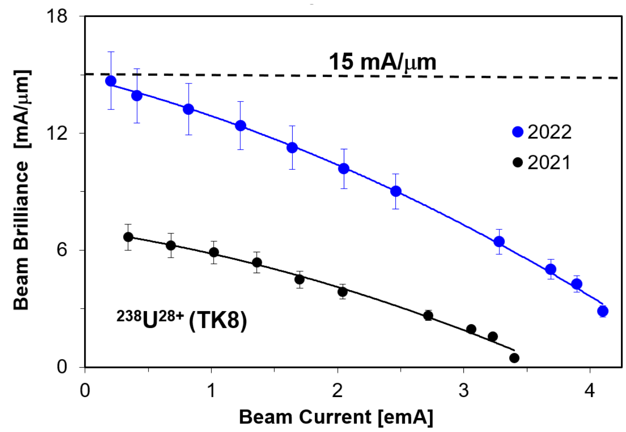

Figure 8: TK8 beam brilliance analysis.

Investigations of Uranium beam matching to the SIS18 were conducted in 2022. The fast current transformer analysis, displayed in Fig. 9, shows a SIS18-RF capture efficiency of more than 90% as a result of the longitudinal beam shape adaption applying UNILAC rebuncher cavities behind post stripper and in the transfer channel.

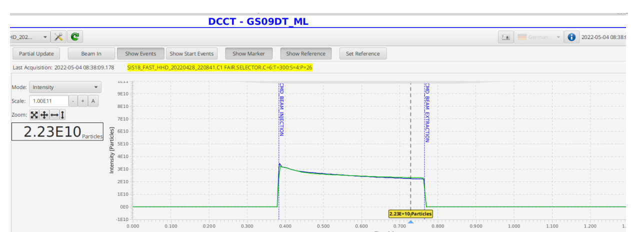

Figure 9: RF capture of the UNILAC beam in the SIS18.

SUMMARY

With heavy ion beams (Bi, U) sufficiently small horizontal beam emittances along the UNILAC up to the SIS injection have been achieved, as well as successful longitudinal matching to the SIS18 applying dedicated rebuncher settings. A significant improvement in beam brilliance (factor of ≥2.5) has been achieved by using the pulsed hydrogen gas stripper and through a reversion of the QQ polarity, allowing to fill the SIS18 up to 30% of its space charge limit.

Among several GSI linac projects [18–25], the upgrade of UNILAC in order to fulfill the FAIR requirements is already defined. Some upgrade measures have already been carried out; besides dedicated repair measures after damages (exchange of RFQ rods). Thus, the UNILAC operation is fully feasible again - furthermore, significant performance improvements on the way to a FAIR injector could be achieved in the last three years.

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