ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST012

HIGH CURRENT HEAVY ION BEAM INVESTIGATIONS AT GSI-UNILAC

H. Vormann[1], W. Barth[1, 2, 3], M. Miski-Oglu[1, 2], U. Scheeler[1], M. Vossberg[1], S. Yaramyshev[1],
Presenting Contributor M. Vossberg,
[1]GSI Helmholtzzentrum fuer Schwerionenforschung GmbH, Darmstadt, Germany
[2]HIM Helmholtz Institute Mainz, Mainz, Germany
[3]JGU Johannes-Gutenberg-University Mainz, Mainz, Germany

Abstract

The GSI Universal Linear Accelerator UNILAC and the synchrotron SIS18 will serve as injector for the upcoming FAIR-facility. The UNILAC-High Current Injector will be improved and modernized until FAIR is commissioned and the Alvarez post stripper accelerator is replaced.

The reference heavy ion f[1]or future FAIR-operation is uranium, with highest intensity requirements. To re-establish uranium beam operation and to improve high current beam operation, different subjects have been explored in dedicated machine investigation campaigns. After a beam line modification in 2017 the RFQ-performance had deteriorated significantly; new rods have been installed and the RF-working point has been redefined. Also the Superlens-performance had become unsatisfactory; improved with a modified RF-coupler. With a pulsed hydrogen gas stripper target the uranium beam stripping efficiency could be increased by 65%. Various work has already been carried out to establish this stripper device in routine operation. With medium heavy ion beams a very high beam brilliance at the end of transfer line to SIS18 was achieved.

Results of the measurement campaigns and the UNILAC upgrade activities will be presented.

INTRODUCTION

Before the year 2021, high current uranium beam machine experiments were conducted in October 2015 and July 2016 for the last time, only at the GSI-High Current Injector (HSI) and the gas stripper section. At this time only three of the five Alvarez DTL post stripper tanks were available, due to work on the post stripper RF-amplifier systems of the UNILAC (Fig.1). 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 [1-14].

During the long shutdown in the whole year 2017 there was no beam operation at all. After this shutdown, the beam times 2018 and 2019 had to be re-organised, as the HSI-RFQ performance had decreased strongly and required a time-consuming repair. In 2020 uranium beam operation was skipped due to the Corona crisis (Fig. 2).

The measurement campaigns in 2021 and 2022 have been conducted with high intensity heavy ion beams (uranium, bismuth, tantalum, xenon) and with medium and light ion beams (Argon, p+), to fully characterize the high intensity beam properties of the UNILAC.

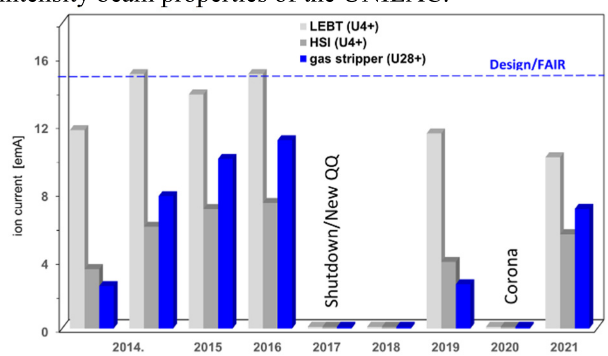

Figure 2: Uranium beam intensity at the UNILAC HSI [4].

HSI RFQ OPTIMISATION

The RF performance of the HSI-RFQ had decreased strongly after a beam line modification during the shutdown 2017, when the RFQ had been kept under atmosphere conditions for almost one year. During the re-commissioning campaign in 2018 only 70% of the nominal RF-voltage could be reached. Apparently the copper surface conditions were significantly degraded, due to many years of operation and additional humidity influence. Therefore new electrodes (rods) have been produced and installed (2018-2019). After successful recommissioning with light ions and also with U^{5+}, the working point of the HSI-RFQ has been re-defined: With a medium heavy ion beam (Ar^{2+} and Ar^{1+}), applying different RF-voltages for acceleration, the transmission through the HSI has been scanned in a wide range from voltages far below the working point to

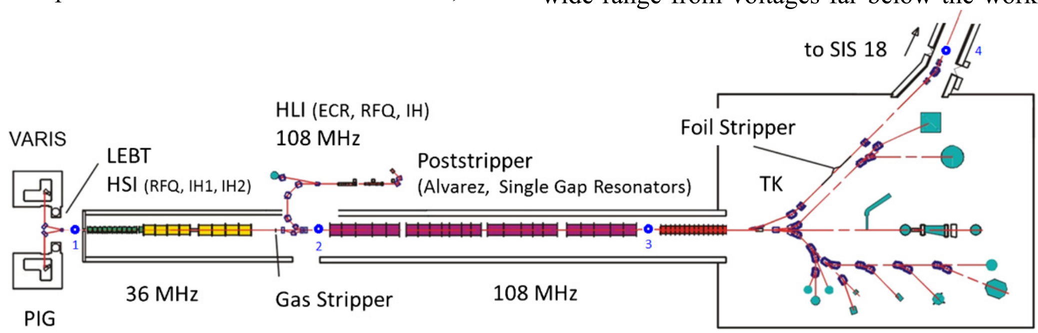

Figure 1: Overview of the GSI Universal Linear Accelerator UNILAC [4].

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST012

high voltages well above. The result was a surprisingly long plateau of almost full transmission and sufficient beam performance. The working point was defined at an RF voltage closely above the plateau beginning. This was confirmed by measurements with uranium, the FAIR design ion (A/Z = 59.5), and also with ions of even higher mass-over-charge ratio: $^{181}Ta^{3+}$ (A/Z = 60.3) and $^{124}Xe^{2+}$ (A/Z = 62). In Fig. 3 the RF voltage normalized to A/Z is displayed for the different cases.

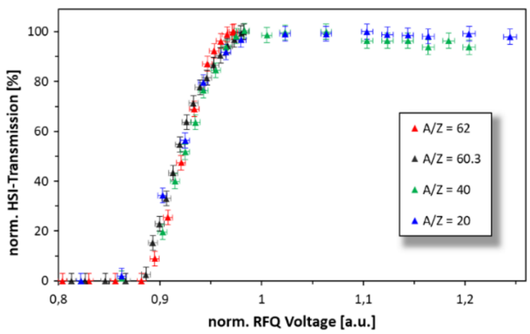

Figure 3: HSI-RFQ working point re-defined [4].

STRIPPER DEVELOPMENT

Investigations with a pulsed hydrogen gas target in the HSI gas stripper section (1.4 MeV/u) in 2015 and 2016 showed that the stripping efficiency for the desired U^{28+} fraction is by 65% higher than with the nitrogen gas target. Technical and safety issues do not yet allow a routine operation of a hydrogen gas target so far. Only short test periods (3 days each) have been performed with the pulsed hydrogen gas stripper since then. After an upgrade of the stripper gas cell the optimal H_2 target thickness of up to 14 mueg/cm^2 (for stripping to charge state 28+) was available in 2021, confirming an absolute stripping efficiency of 21%, while the efficiency for the standard N_2 gas stripping is only 13%. Technical developments have been pushed in parallel, using a dedicated test stand (vacuum operated, but without ion beam). While for the initial tests the used pulsed valves had been specified for gasoline fuels, the valves currently used are designed for gaseous media and let expect improved durability [10]. In order to provide safety and reliability GSI typical multi user operation of up to 15 different users, a dedicated on call service of the gas stripper experts is established. In the recent beam test campaign (2022) an advanced control rack was used, allowing reliable parallel operation of five virtual accelerators.

For the injection into SIS18 the transversal beam emittance must be small, in particular the horizontal emittance. For pulsed gas H_2- stripper operation, the vertical beam emittance for high intensity uranium beam (7.0 emA, U^{28+}) is increased, while the horizontal emittance is decreased, confirming former emittance measurements with $^{209}Bi^{26+}$. at an H_2-target. The horizontal U^{28+} beam brilliance (Fig. 4) at 1.4 MeV/u scales inverse with the pulse current. It could be shown that the horizontal beam brilliance inside the beam core is increased by a factor of three by applying the H_2-stripper target instead of the N_2-target.

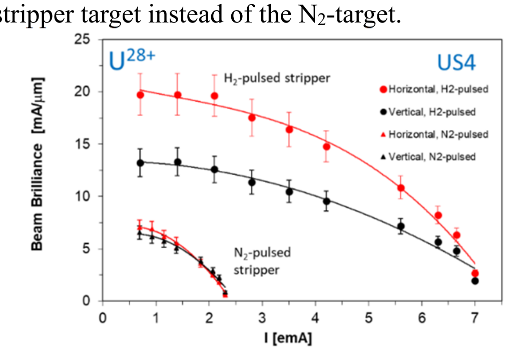

Figure 4: Transversal uranium (U^{28+}) beam brilliance behind the gas stripper.

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

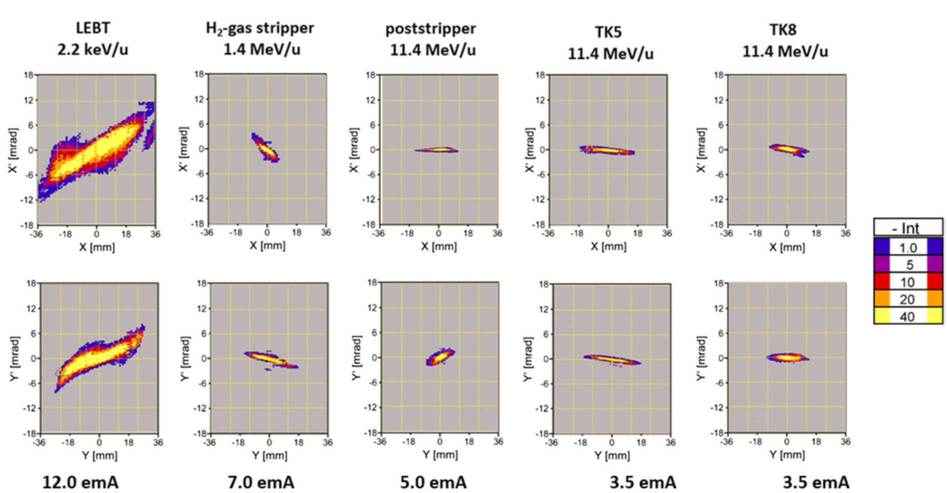

Figure 5: Transversal $U^{4+/28+}$ emittance shape along the UNILAC.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST012

FRONT-TO-END MEASUREMENTS

The horizontal beam emittance is a critical value to estimate the high-current capability of a synchrotron injector. The behaviour of the UNILAC was investigated in 2019, 2020 and 2022 with high intensity Bismuth and Uranium beams.

The measured transversal emittances and the beam pulse currents for uranium, shown in Fig. 5, 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 channel. For bismuth beam, an increase of the vertical emittance and a decrease of the horizontal emittance occurred behind gas stripper and stays different along the complete UNILAC. At the transfer channel end 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. (Note: Particle losses of > 40% occurred along post stripper and transfer channel, may distort the emittance growth balance.)

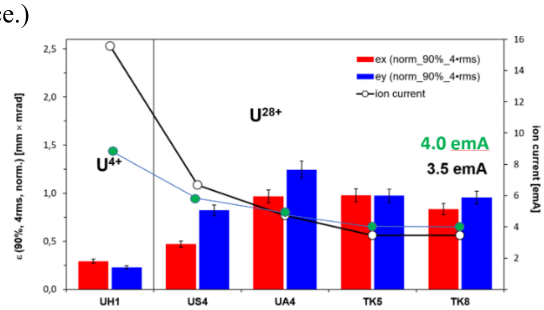

Figure 6: Transversal $U^{4+/28+}$emittance along UNILAC [15].

Comparable emittance measurements were performed with uranium beam as shown in Fig. 6. The effect of asymmetric emittance growth and reduction behaviour was less pronounced compared to the bismuth beam emittance (4*rms, norm.). At least, also for uranium beams the horizontal emittance growth is lower when using the hydrogen stripper, appr. 35% compared to the vertical emittance.

The recent machine experiments (April 2022) confirmed the results from 2019 and 2020 applying hydrogen gas stripping. The high current emittances 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, fitting well into the acceptance of SIS18 of 0.75 mm mrad. The emittance blow up for the stripped U $^{73+}$ beam does not result in measurable larger emittance size.

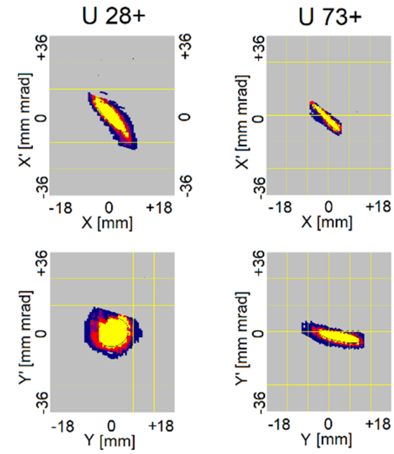

Figure 7: Transversal emittance at TK8, applying pulsed hydrogen gas stripper, 4.0 emA U^{28+}, 1.0 emA U^{73+}(2022).

Of significant relevance were the recent investigations of uranium beam matching from the UNILAC to the SIS18 injection. The fast current transformer analysis, displayed in Fig. 8, shows an RF capture efficiency inside SIS18 of more than 90% as a result of the optimization of the longitudinal beam shape applying the UNILAC rebuncher cavities behind the post stripper and in the transfer channel.

Figure 8: RF capture of the UNILAC beam in the SIS18.

SUMMARY

Among several GSI linac projects [16-23], one of the most important ones is an upgrade of UNILAC for FAIR. After an exchange of the HSI-RFQ rods and the re-definition of its working point, the full spectrum of ions can be accelerated again, after a five years interruption.

With the beam brilliance of the high current uranium beam is now sufficient to fill the SIS18 up to 30% of the space charge limit. This significant improvement in beam brilliance was achieved by using the pulsed hydrogen gas stripper. With heavy ion beams (Bi, U) very low horizontal emittances along the UNILAC up to the SIS injection have been achieved, as well as sufficient longitudinal matching to the SIS18 applying dedicated rebuncher settings.

ACKNOWLEDGEMENTS

The authors would like to thank all colleagues of the involved GSI departments for the support.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST012

REFERENCES

[1] W. Barth *et al.*, "High brilliance uranium beams for the GSI FAIR", *Phys. Rev. Accel. Beams,* vol. 20, p. 050101, May 2017. doi:10.1103/PhysRevAccelBeams.20.050101

[2] W. Barth *et al*., "Upgrade program of the high current heavy ion unilac as an injector for FAIR", *Nucl. Instrum. Methods Phys. Res*., *Sect. A*, vol. 577, pp. 211-214, July 2007.

[3] W. Barth *et al.*, "LINAC developments for heavy ion operation at GSI and FAIR", *Journal of Instrumentation*, vol. 15, number 12, p. T12012, 2020. doi:10.1088/1748-0221/15/12/t12012

[4] W. Barth *et al.*, "High Brilliance Beam Investigations at UNILAC", *Phys. Rev. Acc. Beams,* vol. 25, p. 040101, 2022.

[5] S. Yaramyshev *et al.*, "Development of the versatile multi-particle code DYNAMION", *Nucl. Instrum. Methods Phys. Res.*, *Sect. A*, vol. 558, pp. 90-94, March 2006.

[6] W. Barth *et al.*, "Heavy ion linac as a high current proton beam injector", *Phys. Rev. Accel. Beams,* vol. 18, p. 050102, 2015.

[7] A. Adonin and R. Hollinger, "Beam brilliance investigation of high current ion beams at GSI heavy ion accelerator facility", *Rev. Sci. Instrum*. vol. 85, p. 02A727, 2014. doi:10.1063/1.4833931

[8] S. Yaramyshev *et al.*, "Virtual charge state separator as an advanced tool coupling measurements and simulations", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 050103, May 2015. doi:10.1103/PhysRevSTAB.18.050103

[9] W. Barth *et al.*, "U28+-intensity record applying a H2-gas-stripper cell", *Phys. Rev. Accel. Beams*, vol. 18, p. 040101, 2015.

[10] P. Gerhard *et al.*, "Development of Pulsed Gas Strippers for Intense Beams of Heavy and Intermediate Mass Ions", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 982-987. doi:10.18429/JACoW-LINAC2018-FR1A05

[11] P. Scharrer *et al.*, "Electron stripping of Bi ions using a modified 1.4 MeV/u gas stripper with pulsed gas injection", *J. Radioanal. Nucl. Chem.,* vol. 305, pp. 837-842, Mar. 2015.

[12] P. Scharrer *et al.*, "Applications of the pulsed gas stripper technique at the GSI UNILAC", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 863, pp. 20-25, 2017.

[13] A. Adonin *et al.*, "Production of high current proton beams using complex H-rich molecules at GSI", *Rev. Sci. Instrum*., vol. 87, no. 2, 2016. doi:10.1063/1.4934620

[14] S. Appel *et al.*, "Injection optimization in a heavy-ion synchrotron using genetic algorithms", *Nucl. Instrum. Methods Phys. Res*., *Sect. A*, vol. 852, p. 73, 2017. doi:10.1016/j.nima.2016.11.069

[15] W. Barth, "Summary of the UNILAC machine experiments in April and May 2022", presentation in the GSI Machine meeting, May 2022.

[16] W. Barth *et al.*, "First heavy ion beam tests with a superconducting multigap CH cavity", *Phys. Rev. Accel. Beams*, vol. 21, p. 020102, Feb. 2018. doi:10.1103/PhysRevAccelBeams.21.020102

[17] S. Lauber *et al.*, "Longitudinal phase space reconstruction for a heavy ion accelerator", *Phys. Rev. Accel. Beams*, vol. 23, p. 114201, 2020. doi:10.1103/PhysRevAccelBeams.23.114201

[18] F. Herfurth *et al.*, "The HITRAP facility for slow highly charged ions", *Physica Scripta,* vol. 2015, no. T166, p. 014065, Nov. 2015. doi:10.1088/0031-8949/2015/T166/014065

[19] M. Schwarz, S. Yaramyshev, K. Aulenbacher, W. Barth, M. Basten, *et al.*, "Reference beam dynamics layout for the SC CW heavy ion HELIAC at GSI", *Nucl. Instrum. Meth. Phys. Res. Sect. A,* p. 163044, 2019. doi:10.1016/j.nima.2019.163044

[20] S. Busold *et al.*, "Shaping laser accelerated ions for future applications – the LIGHT collaboration", *Nucl. Instrum. Meth. Phys. Res. Sect. A*, vol. 740, pp. 94–98, 2014. doi:10.1016/j.nima.2013.10.025

[21] S. Lauber *et al.*, "A dynamic collimation and alignment system for the Helmholtz linear accelerator", *Review of Scientific Instruments*, vol. 92, no. 11, p. 113306, 2021. doi.org/10.1063/5.0069824

[22] W. Barth *et al.*, "A superconducting CW-linac for heavy ion acceleration at GSIX", *EPJ Web Conf.* 138, p. 01026, 2017. doi:10.1051/epjconf/201713801026

[23] U. Ratzinger *et al.*, "The 70 MeV p-injector design for FAIR", in*: AIP Conf. Proc.*, vol. 773, pp. 249–253, 2005. doi:10.1063/1.1949539