

DEVELOPMENT OF NEW HEAVY ION LINACS AT GSI

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Abstract

The heavy ion linac UNILAC at GSI will be upgraded in order to meet the beam requirements imposed by the upcoming FAIR facility. This upgrade includes several innovative techniques and applications. They comprise a new gaseous stripper with enhanced efficiency, full 4d transverse emittance measurements, a round-to-flat beam adaptor, asymmetric transverse focusing along the new Alvarez DTL, optimized shape of the drift tube surface w.r.t. shunt impedance per surface field, and a field stabilization and tuning scheme without post-couplers. Additionally, we report on the development of a super-conducting cw linac which will be dedicated to production of superheavy elements at energies close to the Coulomb barrier.

INTRODUCTION

GSI is currently constructing the Facility for Antiproton and Ion Research (FAIR) [1]. It aims at provision of 3×10^{11} /s uranium ions at 1.5 GeV/u. Due to its high rigidity uranium imposes the highest challenges to the accelerator chain w.r.t. fields and machine protection. The existing UNILAC will provide all primary ions but protons. In order to deal with the FAIR requirements in the upcoming decades, the UNILAC needs a considerable upgrade. While FAIR will be served by the upgraded UNILAC at low duty-cycles, the research program on superheavy elements (SHE) requires a linac providing energies at the Coulomb barrier with highest possible duty cycle. To this end a dedicated superconducting cw linac for heavy ions for SHE is under design as well. The following section will introduce the developments related to the upgrade of the UNILAC, while the third section is on the activities and achievements concerning the new cw linac.

DEVELOPMENTS FOR THE UPGRADE OF THE UNILAC

The existing UNILAC (Fig. 1) together with the subsequent synchrotron SIS18 serves as injector for FAIR. Three ion source terminals can be operated in pulse-to-pulse switching mode at 50 Hz. One terminal is equipped with an ECR source providing highly charged ions. Followed by an RFQ and an IH-cavity operated at 108 MHz it forms the High Charge Injector (HLI) providing beams at 1.4 MeV/u. Another terminal houses a Penning source (PIG) providing low intensity beams at intermediate charge states at 2.2 keV/u. The third terminal is dedicated to provision of intense beams of low-charged ions at 2.2 keV/u as well. Intense heavy ion beams are produced in a MEVVA or VARIS. Beams are bunched and pre-accelerated to 120 keV/u along a 9 m long RFQ operated at 36 MHz. Afterwards two IH-cavities pro-

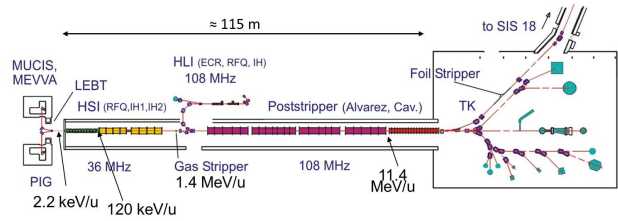


Figure 1: The UNILAC at GSI.

vide for acceleration to 1.4 MeV/u, being the exit energy of the High Current Injector (HSI). For uranium the highest particle numbers are obtained by using the charge state $^{238}\text{U}^{4+}$. After the IH-DTL the acceleration efficiency is increased by passing the beam through a gaseous stripper which delivers a mean charge state of $^{238}\text{U}^{28+}$ at its exit. This increase of charge state is at the expense of intrinsic particle loss. Prior to 2014 about 87% of the uranium ions were stripped to a charge state different from 28+. After dispersive selection of the desired charge state the beam is matched to the subsequent post-stripper Alvarez-type DTL. The latter is operated at 108 MHz and comprises five tanks. Its exit beam energy is 11.4 MeV/u being the injection energy for the synchrotron SIS18. The post-stripper DTL can be fed with beams from the HLI as well. The UNILAC design parameters are listed in Table 1.

Table 1: Beam Design Parameters for the Upgraded UNILAC

Ion A/q	≤ 8.5	
Beam Current	1.76 A/q	mA
Input Beam Energy	1.4	MeV/u
Output Beam Energy	3.0 - 11.7	MeV/u
Emit. (norm., tot.) hor/ver	0.8/2.5	μm
Exit tot. Bunch Length	$\leq \pm 30$	deg
Beam Pulse Length	200	μs
Beam Repetition Rate	10	Hz
Rf Frequency	108.408	MHz

High Pressure H_2 -Stripper

So far, a continuous N_2 jet has been used as stripping medium. The achieved stripping efficiency from $^{238}\text{U}^{4+}$ to $^{238}\text{U}^{28+}$ was 13%. Since 2014 a pulsed gas stripper cell has been tested [2]. It injects short gas pulses, the length of which matches the beam pulse length into the stripping chamber, producing a high density target without overloading the differential pumping system toward adjacent accelerator systems. Using H_2 the efficiency of stripping into the most populated charge state has been increased from 14(1)% to 21(1)%. Figure 2 compares measured charge state spectra of

an uranium beam at 1.4 MeV/u applying a continuous N₂ jet with a spectrum resulting from a pulsed H₂ cell. The rms-width δq of the spectrum from the jet is about 3.6. The width from the cell is $\delta q \approx 2.3$, i.e. it is reduced by 36%. Another appealing feature of the pulsed stripper is its flexibility w.r.t. the applied back pressures of the single gas pulses as well as to the lengths of the individual pulses. Both can be changed in pulse-to-pulse switching mode of the UNILAC thus eliminating restrictions from the constant back pressure provided by the N₂ jet. Additionally, the set-up can be equipped with a second valve, thus allowing for pulse-to-pulse operation with a second stripper gas. Final optimization and imple-

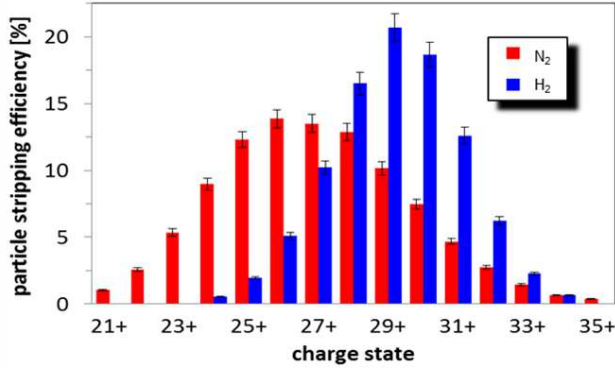


Figure 2: Comparison of measured uranium charge state spectra applying a continuous N₂ jet (red) with a spectrum resulting from a pulsed H₂ cell (blue).

mentation into routine operation of this new stripping set-up have started. A detailed description of the development and testing of the high pressure H₂ gas cell as well as the latest results obtained with the device are reported in [2, 3].

Complete Transverse 4D Beam Diagnostics

For any accelerator or transport lattice which does not include elements coupling the transverse planes, usual slit/grid emittance meters for one plane are sufficient to determine the corresponding beam envelopes and to perform optimizations. The horizontal beam properties can be determined without any knowledge of the vertical properties. This does not apply, if focusing elements are used that couple the transverse planes, as solenoids for instance (see next section). In this case complete 4d transverse beam diagnostics is required, i.e. the four 2nd order inter-plane correlations must be measured. To our knowledge such measurements never were conducted successfully before at ion energies beyond about 150 keV/u.

Applying a slit/grid emittance meter preceded by a skewed quadrupole triplet such measurements were done with an uranium beam at 11.4 MeV/u. Details on this method can be found in [4]. Additionally, the ROTating System for Emittance measurements (ROSE) was developed and commissioned [5, 6] with an ⁸³Kr¹³⁺ beam at 1.4 MeV/u and with an ²³⁸U²⁸⁺ beam at 5.9 MeV/u. It is a single-plane slit/grid emittance measurements device housed in a chamber which can be rotated around the beam axis (Fig. 3). For one transport setting (a) beam emittance measurements were performed

at rotation angles of 0°, 90°, and at an intermediate angle θ . One additional measurement at θ using a different setting (b) was done. The accuracy of the final result is sufficiently high to provide for a transport section, that can completely decouple the beam with skewed quadrupoles for instance [5].

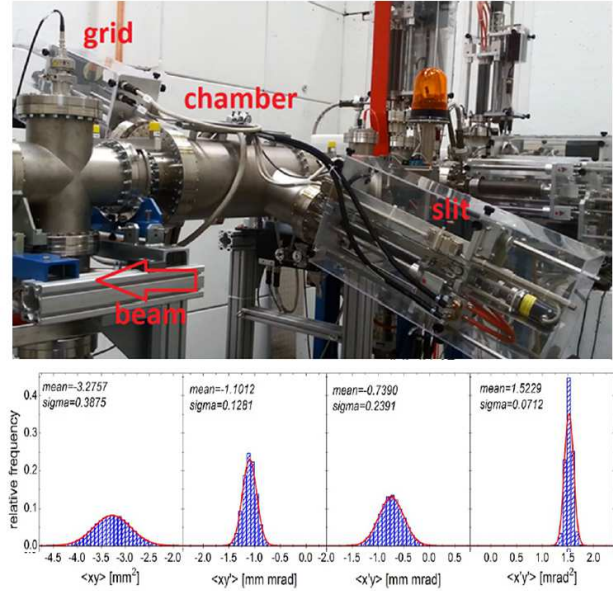


Figure 3: ROTating System for Emittance measurements ROSE (top). Measured 2nd order beam moments that quantify the amount of coupling between the horizontal and vertical plane (bottom).

Transverse Emittance Transfer without Beam Scraping

As seen from Table 1 the final transverse design emittances of the UNILAC differ by a factor of three. This requirement is imposed by the horizontal multi-turn injection (MTI) scheme to fill the synchrotron SIS18 [7]. Beams provided by linacs are generally round, i.e. the horizontal and the vertical emittance are equal. Thus a scheme for convenient emittance re-partitioning has been proposed and experimentally demonstrated at GSI. The EMittance Transfer EXperiment (EMTEX) beam line providing this round-to-flat adoption is depicted in Fig. 4 together with results from transverse emittance measurements at the exit of the beam line. A double-waisted beam is injected into a solenoid. In the centre of the solenoid the charge state of the beam is increased by a stripper. The combination of solenoid and charge state change forms a non-symplectic transformation that preserves the complete 4d transverse rms-emittance but that changes the two eigen-emittances [8] by transferring emittance from one to the other. Inter-plane correlations imposed by the solenoid are removed using a skewed triplet. By setting the solenoid field strength, the amount of transfer can be easily adjusted or even inverted under preservation of the Twiss parameters β and α in all planes (Fig. 4 (bottom)). Re-adoption of the skew triplet to the solenoid field strength is not required. Details on EMTEx are given in [9–11] and

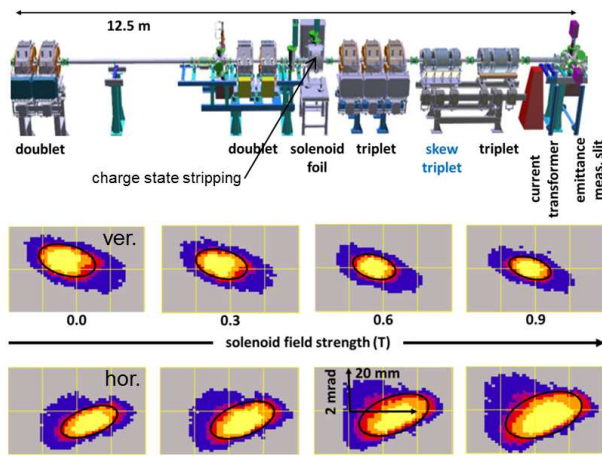


Figure 4: Beam line of the EMittance Transfer EXperiment (EMTEX) (top). Horizontal and vertical phase space distributions measured at the exit of EMTEX for different solenoid field strengths (bottom).

its successful application to increase the MTI efficiency is reported in [12].

DTL Beam Dynamics

The existing post-stripper DTL suffered considerably from material fatigue during the last four decades and the amount of resources required for its maintenance increases continuously. Replacement by a completely new DTL is due. The beam parameters of the new post-stripper DTL are the same as for the existing one except for the beam duty cycle. It will be limited to beam pulse lengths of 200 μ s at a repetition rate of 10 Hz. The new UNILAC will serve as an injector for the FAIR facility. Additionally, it will serve nuclear physics experiments conducted close to the Coulomb barrier, i.e. it must deliver energies in the range from about 3.0 MeV/u up to 11.7 MeV/u. These non-FAIR scenarios require low beam currents but prolonged duty cycles.

In order to deal with the high intensity requirements imposed by FAIR on the one hand and by the low-intensity experiments at reduced energy on the other hand, the beam dynamics layout of the post-stripper is quite demanding. For high intensity operation, i.e. 35% of transverse phase advance depression, emittance growth from space charge must be minimized as much as possible. This is done by using a very regular periodic F-D-D-F focusing lattice along the single DTL cavities together with systematic matching to the lattice. Along the inter-tank section this periodicity is quasi-maintained by placing one quadrupole inside the half drift tubes of the cavities exits and entrances as well as one quadrupole in between. Additionally, one re-buncher is included in each inter-tank section to assure longitudinal periodicity and to preserve reasonable bunch length for low-energy operation of the DTL. Figure 5 (top) displays the transverse total beam envelopes along the DTL as obtained from simulations. The emittance growth rates are just about 5% in each plane. The DTL lattice must also preserve the beam flatness eventually imposed prior to the DTL. Flat

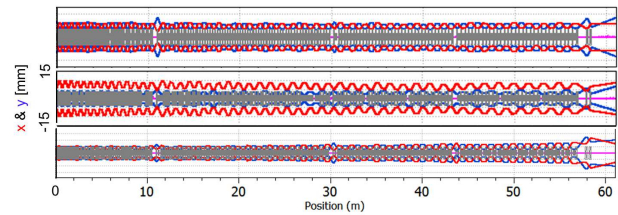


Figure 5: Beam envelopes along the new post-stripper DTL for an $^{238}\text{U}^{28+}$ beam for three different scenarios: acceleration to 11.4 MeV/u with beam current of 15 mA and initially equal horizontal and vertical normalized rms-emittances of 0.175 mm mrad (top); acceleration to 11.4 MeV/u with beam current 15 mA with an initially flat beam of horizontal rms-emittance of 0.0875 mm mrad and vertical rms-emittance of 0.35 mm mrad (middle); acceleration to 3.3 MeV/u with low beam current and initially equal horizontal and vertical normalized rms-emittances of 0.175 mm mrad (bottom).

beams are prone to re-partitioning from space charge, i.e. the two emittances tend to equalize if no proper measures are taken. Flatness is preserved by asymmetric transverse focusing instead [13]. Vertically focusing quadrupoles driven with some few percent of higher gradients w.r.t. the horizontally focusing ones such that the vertical phase advance exceeds the horizontal one. The middle part of Fig. 5 plots the corresponding envelopes for a beam with initial transverse emittance ratio of 4.0. The emittance growth rates are about 13/1/5% in the hor./ver./long. plane.

Finally, the DTL lattice must deal with partially accelerated (and bunched) beams for experiments requiring just few MeV/u. These energies are provided by powering just some DTL cavities with rf but leaving their quadrupoles turned on for transverse focusing. The inter-tank re-bunchers are used to assure short bunches at the DTL exit, such that the subsequent section of single-gap resonators serves for fine tuning of the energy. The bottom part of Fig. 5 shows transverse envelopes of a beam being just accelerated along the first DTL cavity. There is just a 2% growth of the longitudinal emittance.

Optimization of Cavity rf-Properties

The cavity design aims at optimization of the ratio of shunt-impedance to electric surface field [14]. The latter shall be limited to 1.0 Kilpatrick. For each tank a maximum rf-power of 1.35 MW including margins is available of which about 0.25 MW is beam load. New shapes of drift tubes plates have been found that do not include straight sections and are rather defined through about 200 fixed points each. This approach provides a smooth surface field distribution and mitigates sparking. It does not cause significant additional cost for production nor it imposes restrictions w.r.t. the achievable tolerances. Each drift tube along one tank will have the same end plate shape. The rf-frequency tuning of each cell is done through adoption of the drift tube length.

Stabilization of the accelerating field can be done through well-considered orientations of the stems that keep the drift

tubes [15]. As the drift tubes have to be provided with cooling water and electrical current for the quadrupoles, each tube is kept by two stems. It turned out that the orientation of the two stems plays a significant role in the suppression of parasitic rf-modes. In fact the field tilt sensitivity is reduced practically to zero by choosing a proper arrangement of stems as shown in Fig. 6. This concept of field stabi-

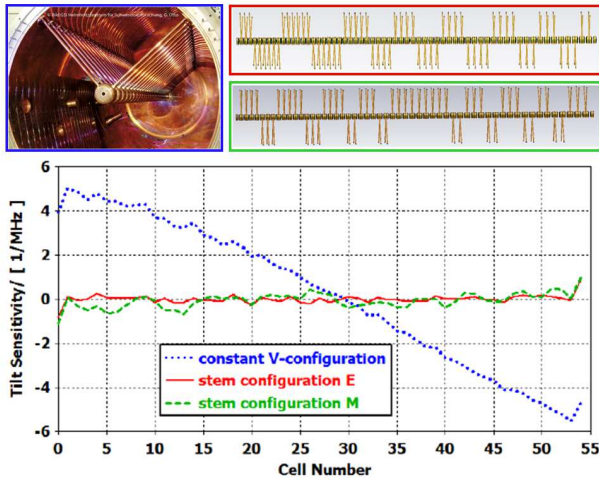


Figure 6: Field tilt sensitivity along the Alvarez-type cavity for three different stem configurations.

lization is under testing using a cold rf-model. Figure 7 illustrates how this model allows for variation of the stem orientation. Additionally, the end plates of each drift tube can be exchanged by simply unscrewing them from the main drift tube body.

In 2014 a substantial modernization of the rf-alimentation system for the post-stripper has been started [16]. A new 1.8 MW amplifier prototype for low-duty-cycle operation based on the TH558SC tetrode was built by THALES and recently delivered to GSI. Testing followed by routine operation is planned during the next beam time in 2018. Existing amplifiers are currently equipped with modern PLC systems for controls, new fast interlock and measurement units, and commercial grid power converters, which all of them are to be arranged in separate racks. The existing 1 MVA anode power supplies will be re-used and being equipped with PLC systems. Procurement of a 150 kW solid state amplifier prototype is under preparation. Development of a digital low-level rf-system based on MTCA.4 standard and commercial vector modulator and FPGA boards was started.

SUPERCONDUCTING CW LINAC FOR HEAVY IONS

The production and investigation of superheavy elements (SHE) is a major pillar of GSI's research program since many decades. The cross sections for the production of SHE are very small, i.e. significantly below 1 μb . For the time being the UNILAC has been used to provide the primary projectile beams of intermediate masses. For this

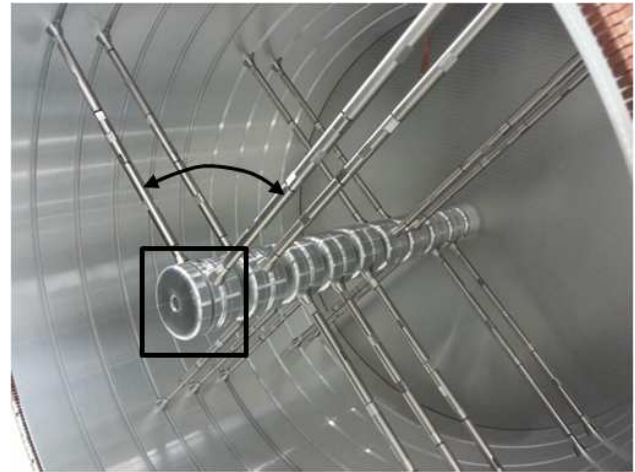


Figure 7: The 1:3 scaled cold model of the first new Alvarez cavity with a diameter of 67 cm.

the UNILAC was operated at its maximum duty cycle of 25%. For instance, the total beam time to be allocated for statistically undoubted production of the element $_{115}\text{ut}$ with 115 protons is about 3 weeks. This time can be shortened to approximately two days only, if a cw linac fed by a dedicated ECR source is available purely for SHE production.

Such a cw linac is currently under design by a collaboration of the Helmholtz-Institute Mainz, the University of Frankfurt [17, 18], and GSI. Its basic layout is depicted in Fig. 8 and its design beam parameters are listed in Table 2. Currently it is foreseen to use the UNILAC's HLI as an in-

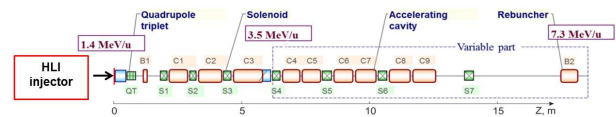


Figure 8: Layout of the superconducting cw linac for heavy ions.

jector to the cw linac. Acceleration from 1.4 MeV/u to the final energy is done along nine crossed-bar H-mode (CH) cavities. The gradients are about 5 MV/m. The cavities feature a constant velocity profile each, applying the EQUUS scheme for the longitudinal dynamics [19]. Injection to each cavity is at positive rf-phase w.r.t. the crest and with energy excess. Transverse focusing is provided by superconducting solenoids as they provide focusing in both transverse planes simultaneously, i.e. they require less space than quadrupole doublets. This is at the expense of the limitation of the attainable mass-to-charge ratio of the ions to about 6.0. At energies below 3.5 MeV/u each cavity is preceded by one solenoid. Relaxed focusing requirements beyond that energy allow for two cavities per solenoid.

The cw linac will be built from several cryo-modules, each of them housing several solenoids and cavities. This implies the challenge to keep the solenoid fringe field off from the cavity. Additionally, the alignment of the elements must be monitored and preserved during the cooling down. In order to address these and other issues the cw-linac project

Table 2: Beam Design Parameters for the Superconducting cw Linac for Heavy Ions

Ion A/q	≤ 6.0	
Beam Current	≤ 1.0	mA
Input Beam Energy	1.4	MeV/u
Output Beam Energy	3.5 – 7.3	MeV/u
Rf Frequency	216.816	MHz

is staged into three steps: a cw-demonstrator comprising one cryostat, an advanced demonstrator built from four cryostats, and the complete cw-linac.

W-demonstrator

The cw-demonstrator has been installed at GSI and partially tested with beam. Its single cryostat currently houses two solenoids. The cryostat was successfully cooled down to 4 K and both solenoids were ramped up to their nominal field strength of 9.3 T. A beam of $^{40}\text{Ca}^{10+}$ was transported through the solenoids with 100% of transmission. The delivery of the CH-cavity (Fig. 9) is expected for October of this year. The high power rf-coupler has been built and in-



Figure 9: Superconducting crossed-bar H-mode (CH) cavity.

tegrated into the cavity. During tests the cavity reached its nominal gradient of 5 MV/m with the specified Q_0 value of $5 \cdot 10^9$. The construction of a clean room (class ISO 2) on GSI site has been finished recently. An re-buncher operated at 108.408 MHz to be installed at the entrance to the cw-linac beam line is available. Testing of the complete cryostat including the CH-cavity, that shall provide acceleration to 1.88 MeV/u, is scheduled for May of 2017. During 2017 and 2018 the cw-demonstrator will be enhanced by two more cavities mounted inside an additional cryostat thus providing beams at 2.4 MeV/u.

Advanced cw-demonstrator

In parallel to the construction and testing of the cw-demonstrator, the so-called advanced demonstrator is un-

der design. It will comprise four cryostats and it is shown in Fig. 10. Seven CH-cavities and five solenoids will provide 3.6 MeV/u in 2020. This advanced demonstrator may already serve physics experiments in routine operation.

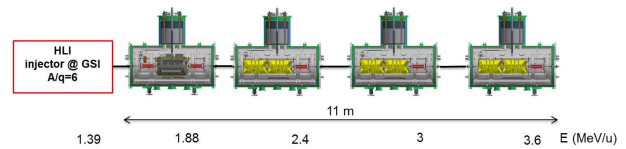


Figure 10: Sketch of the advanced cw linac demonstrator.

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