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UPGRADE OF THE UNILAC FOR FAIR

L. Groening, S. Mickat, R. Brodhage, A. Adonin, X. Du, R. Hollinger, O.K. Kester, A. Orzhekhovskaya, B. Schlitt, G. Schreiber, H. Vormann, C. Xiao, GSI, Darmstadt, Germany
H. Hähnel, U. Ratzinger, A. Seibel, R. Tiede, Goethe University of Frankfurt, Frankfurt, Germany

Abstract

The UNIversal Linear Accelerator (UNILAC) at GSI serves as injector for all ion species from protons to uranium since four decades. Its 108 MHz Alvarez type DTL providing acceleration from 1.4 MeV/u to 11.4 MeV/u has suffered from material fatigue. The DTL will be replaced by a completely new section with almost same design parameters, i.e. pulsed current of up to 15 mA of $^{238}U^{28+}$ at 11.4 MeV/u. A dedicated source terminal & LEBT for operation with $^{238}U^{4+}$ is currently constructed. The uranium source needs to be upgraded in order to provide increased beam brilliances and for operation at 2.7 Hz. In parallel a 70 MeV / 70 mA proton linac based on H-mode cavities is under design and construction.

THE FAIR PROJECT

GSI is currently constructing the Facility for Ion and Antiproton Research (FAIR) [1]. It aims at provision of 2×10^{11}/s uranium ions at 1.5 GeV/u. Due to its high rigidity uranium imposes the highest challenges to the accelerator chain wrt fields and machine protection. Additionally, a total of 2×10^{12}/s cooled anti-protons are to be delivered. The complete accelerator chain is depicted in Fig. 1 and its more detailed description as well as its current status of design and construction is given in [2]. These proceedings are on the injector linacs of the facility. The existing UNIversal Linear ACcelerator UNILAC will provide all primary ions but protons. A dedicated proton linac is currently under design and construction. In order to deal with the FAIR requirements in the upcoming decades the UNILAC needs a considerable upgrade. These upgrade activities are described in the next section. Afterwards the proton linac is presented together with its current status wrt design, construction, and commissioning of components.

UPGRADE OF THE UNIVERSAL LINEAR ACCELERATOR UNILAC

The existing UNILAC (Fig. 2) serves as injector for FAIR together with the subsequent synchrotron SIS18. The UNILAC has three ion source terminals that can be operated in pulse-to-pulse switching mode at 50 Hz. One terminal is equipped with an ECR source providing highly charged ions. Another terminal houses a Penning source providing low intensity beams at intermediate charge states. The third terminal is dedicated to provision of intense beams of low-charged ions. It can be equipped with various source types as MUCIS and CHORDIS for light to intermediate-mass ions for instance. Intense heavy ion beams are produced in a MEVVA or VARIS source at 2.2 keV/u. Beams are bunched

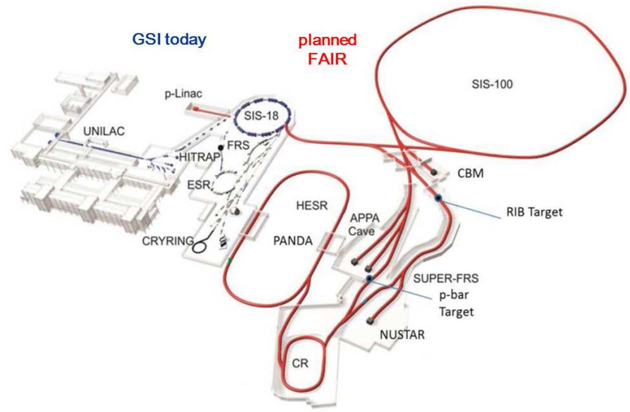

Figure 1: Facility for Anti proton and Ion Research (FAIR) to be built at GSI.

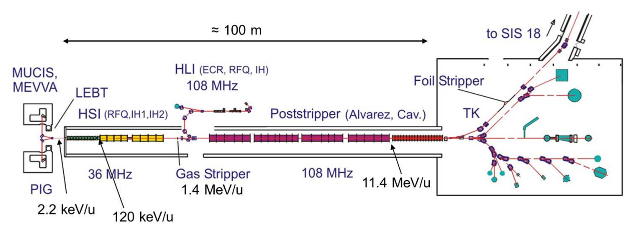

Figure 2: The UNIversal Linear ACcelerator (UNILAC) at GSI.

and pre-accelerated to 120 keV/u along a 9 m long RFQ operated at 36 MHz. Afterwards two IH-cavities provide for acceleration to 1.4 MeV/u. For uranium the highest particle numbers are obtained by using the charge state $^{238}U^{4+}$. After the IH-DTL the acceleration efficiency is increased by passing the beam through a gaseous stripper which delivers a mean charge state of $^{238}U^{28+}$ at its exit. This increase of charge state is at the expense of intrinsic particle loss as about 89% of the uranium ions are 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 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 UNILAC design parameters are listed in Table 1. The age of the UNILAC together with the requirement to provide reliable and intense beams for the upcoming FAIR era calls for a revision of the UNILAC. In the following the planned upgrade activities are illustrated.

Source, LEBT, MEBT, and RFQ

In order to provide the mean uranium intensity required for FAIR the source has to be operated with a repetition

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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
Beam Energy	11.4	MeV/u
Emit. (norm., tot.) hor/ver	0.8/2.5	µm
Beam Pulse Length	200	µs
Beam Repetition Rate	10	Hz
Rf Frequency	108.408	MHz

rate of 2.7 Hz. Although this target has been reached for ions of bismuth, gold, and tantalum, reliable operation with uranium is currently limited to about 1.5 Hz. Increase to 2.7 Hz is the goal for a dedicated development program of the next two years.

The existing LEBT includes two bends which impose dispersion and hexapolar fringe fields. Additionally, operation and handling of uranium comes along with restrictions from safety requirements. For these reasons a new and dedicated uranium branch is under design as shown in Fig. 3. It is a

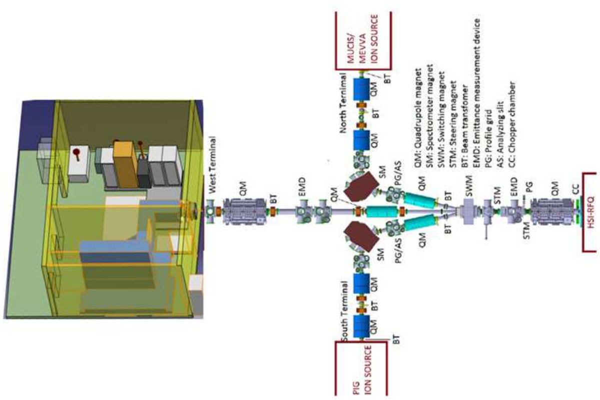

Figure 3: The existing north and south ion source terminals and LEBT branches together with the new uranium terminal (west).

straight LEBT comprising two quadruplets and one triplet. The source will deliver several charge states of uranium but only $^{238}U^{4+}$ is accepted by the RFQ. The fractions of other charge states (mainly 3+) are reduced by chromaticity together with an circular iris located at a beam waist of the charge state 4+. Reference [3] is on the detailed design of the new LEBT.

The RFQ suffered from sparking during operation with varying rf-duty cycles and rf-amplitudes. The attainable rf-voltages are about 10% below the required values for uranium. This leads to serious degradation of longitudinal beam quality from insufficient bunching. Additionally, the beam divergence at the RFQ exit is too large, triggering losses inside the subsequent super lens, which in consequence also has to be operated at lower voltages causing further degradation of beam quality. The design of the RFQ will be revised such that lower surface fields are applied at the expense of reduced acceptance.

The super lens is an RFQ without acceleration, i.e. just used for focusing in all three planes. Accordingly, transverse and longitudinal focusing strengths are coupled. In total the present MEBT offers just four knobs to tune its matching performance to the IH-DTL: two quadrupole gradients, one rf-amplitude, and one rf-phase. This limitation together with too low rf-amplitudes (from sparking) causes poor longitudinal matching to the subsequent IH-DTL. A new MEBT design (Fig. 4) foresees two symmetric triplets and one buncher, i.e. four additional tuning knobs [4].

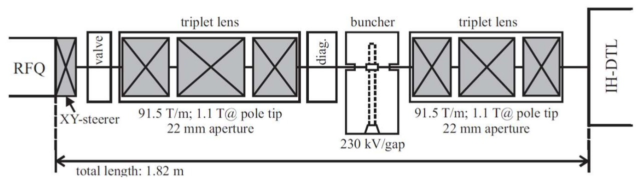

Figure 4: The new MEBT design.

High Pressure H_2-stripper

For time being as stripping medium a continuous jet of nitrogen has been used at a back pressure of 4 bar. The achieved stripping efficiency from $^{238}U^{4+}$ to $^{238}U^{28+}$ was 11%. Last year a pulsed valve has been tested that injects short pulses at up to 150 bar of few 100 µs in length of H_2 into the stripping chamber. The measured charge state spectra behind the stripper for the two set-ups are compared in Fig. 5. A relative increase of $^{238}U^{28+}$ intensity of 59% has been measured. Future tests aim at increase of the back pressure to about 200 bar and at routine operation of this new stripping set-up. Reference [5] is on the successful campaign of increasing the stripping efficiency.

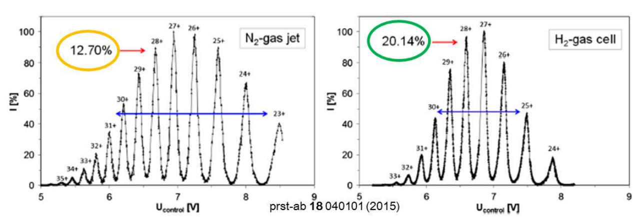

Figure 5: Measured increase of the stripping efficiency from $^{238}U^{4+}$ to $^{238}U^{28+}$.

Round to Flat Beam Transformation

As seen from Table 1 the final 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 [6]. Beams provided by linacs are generally around, i.e. the horizontal and the vertical emittances are equal. Although the product of the two linac emittances is smaller than the product of the two corresponding effective synchrotron acceptances, the horizontal linac emittance exceeds the effective horizontal acceptance. Thus

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a scheme for simple emittance re-partitioning has been proposed and experimentally demonstrated at GSI with a nitrogen beam [7]. The round-to-flat adopter is shown in Fig. 6 together with measured final phase space distributions at its exit. Charge state stripping inside a solenoid is required together with a skew triplet to arbitrarily partition the transverse emittances by varying the solenoid field strength only. A corresponding increase in MTI efficiency was measured as well [8]. GSI currently designs a set-up to flatten beams of uranium along the gaseous stripper section. This set-up will be installed if it is foreseeable that the other upgrade measures will definitely not be sufficient to reach the UNILAC design beam parameters with uranium.

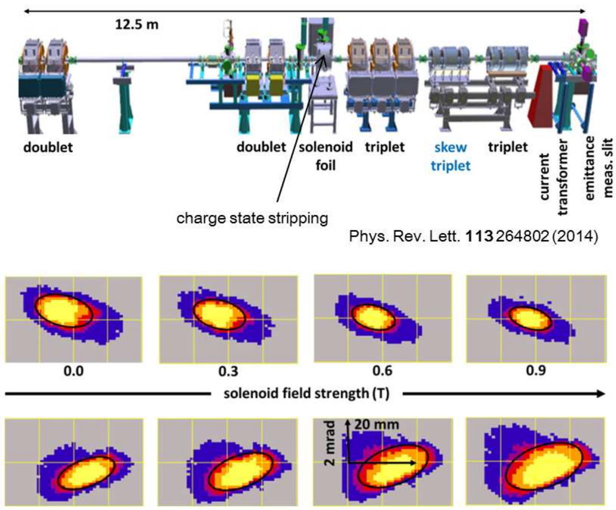

Figure 6: The EmTEx beam line providing round-to-flat transformation.

New Post Stripper Alvarez DTL

The existing post stripper DTL suffered considerably from material fatigue during that last four decades thus the amount of resources required for its maintenance increases continuously. The section has to be replaced by a completely new DTL. The beam parameters of the new post stripper DTL are the same as for the existing one except the beam duty cycle. It will be limited to beam pulse lengths of 200 μs at a repetition rate of 10 Hz. The new UNILAC will serve just as an injector for the FAIR facility. Accordingly, the mixed operation between different rf-amplitudes and rf-pulse length, that caused damages at the cavity surface and limited the rf-amplitudes, will not be applied in the future.

As beam quality is of uttermost relevance for a low duty cycle injector. Alvarez DTLs proved to be reliable working horse accelerators. The related beam dynamics is fully understood even if considerable space charge is included. Periodic beam 3d-envelope solutions are properly defined as well as the procedure to match the incoming beam to that solution. For IH-DTLs for time being we did not find a procedure to assure matched beam transport and acceleration [9], that provides maximum mitigation of beam emittance growth from space charge. However, the issue is further studied at the University of Frankfurt. The results will enter into a proposal of an alternative post stripper design based on more rf-efficient IH-cavities that would allow even an augmentation of the final beam energy to ease in injection into the synchrotron.

Drift Tube Geometry The layout of the new cavities is at its beginning. It aims at optimization of the ratio of shunt-impedance to electric surface field [10]. The latter shall be limited to 1.0 Kilpatrick. Currently the beta-profiles for acceleration to 5.7 MeV/u are available. A new shape of drift tube plates (Fig. 7) has been found that allows saving 17% of rf-power with an increase of surface field strength by 8% wrt the existing design. The shape of the tube plate does

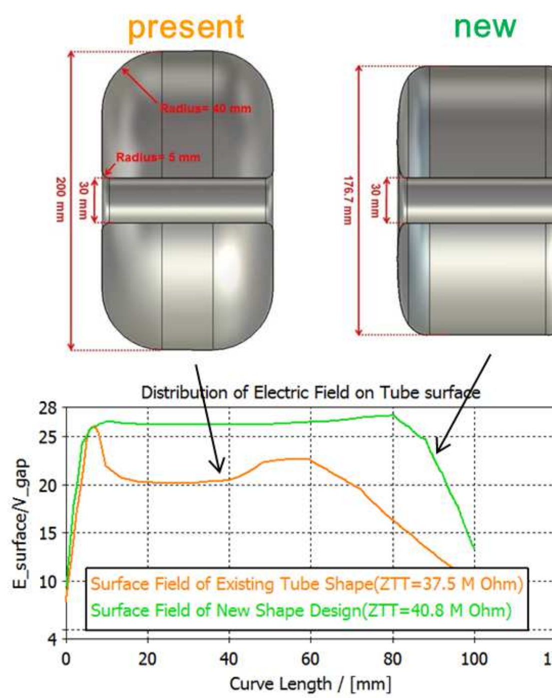

Figure 7: Comparison of the present and new drift tube design.

not include straight sections and is defined through about 200 fixed points. This approach provides a smooth surface field distribution and should lower the sparking rate. It does not cause significant additional cost for production nor it imposes restrictions wrt 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.

Stems Orientations Stability of the accelerating field is done through well-considered orientations of the stems that keep the drift tubes [10]. 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 modes as illustrated in Fig. 8. The new DTL will comprise five tanks. For each tank a maximum rf-power of 1.8 MW is available of which 0.3 MW is beam load.

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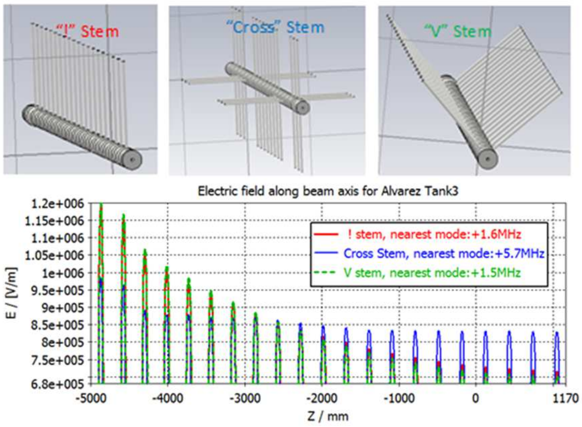

Figure 8: Several schemes of orientations of the DTL stems and their effect on the field stabilization.

Transverse Focusing The transverse phase advance (zero current) has to be increased from 53° to 67° in order to avoid emittance growth from space charge driven resonances. Additionally, the emittance partition of the flattened beams shall be preserved along the DTL by asymmetric focusing, i.e. the vertically focusing quadrupoles will be driven with stronger gradients wrt horizontally focusing quadrupoles [11]. Special care will be taken for proper beam envelope matching along inter-tank sections. These sections impose interruptions of the periodicity of the DTL lattice. If not being well-designed they will trigger emittance growth from mismatch in all three planes.

Estimated Performance after Upgrade

Table 2 summarizes the presented upgrade activities together with the corresponding estimated gains in beam current and emittance. The estimate is conservative. Recent modifications of the source extraction system may indicate that currents in excess of 20 mA can be extracted under preservation of the emittances. But further investigations are required prior to commit to this value.

PROTON LINAC

The UNILAC can provide protons with currents of at least 1.5 mA at an energy of 16 MeV [12]. It was designed as a linac for heavy ion beams thus its beta profile limits the maximum current and energy being achievable with light ions. The performance with protons is not sufficient to deliver the required amount of primary protons for FAIR's anti proton program. The limitation is given by the space charge limit of the synchrotron SIS18 that scales with the energy as $\beta^2\gamma^3$ together with the repetition rate of the accelerator chain. Accordingly, a dedicated proton injector is currently constructed. The layout of the proton linac [13] is sketched in Fig. 9 and its main parameters are listed in Table 3. By choosing the design energy of 70 MeV and a repetition rate of 4 Hz the mean intensity limitation for anti protons is shifted from the synchrotron SIS18 towards the anti proton cooling chain.

Table 2: Estimate of Expected $^{238}U^{28+}$ Performance after the Upgrade

section	I [mA]	ϵ [µm]	activity
	18.0	0.55	source development
LEBT + RFQ			new LEBT, RFQ upgrade
	16.2	0.63	
MEBT + IH-DTL			new MEBT
	14.6	1.1	
stripper			high press. H_2- jet
	18.4	1.2	
round-to-flat			installation
	16.5	0.49	
Alv. DTL			new DTL
	14.1	**0.73**	
target	*15.0*	*0.80*	

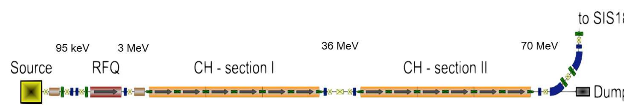

Figure 9: The future proton linac at FAIR.

This new linac comprises an ECR-type proton source without hexapolar magnets. It can provide up to 100 mA of protons at 95 keV of energy. The subsequent LEBT is made from two solenoids with integrated steering magnets. In between the solenoids a diagnostic box houses a movable Faraday cup, transverse profile grids, a Wien filter to separate the H-, H_2^+- and H_3^+-fractions from the beam, and an iris. The latter serves for controlled beam intensity reduction. The proton source and the LEBT as well as the subsequent chopper are currently assembled at CEA/Saclay (Fig. 10). Installation of an FAIR-type local control system at the CEA site is ongoing. Beam commissioning at Saclay will start at the beginning of 2016. The source and LEBT will be shipped to GSI after civil construction at GSI is ready.

Bunching and acceleration to 3 MeV is along an RFQ operated at 325.224 MHz which is of about 3.2 m in length. The favoured option of cavity type is a 4-vane type to be built in collaboration with INFN/Legnaro. Nevertheless, at the University of Frankfurt two alternative designs, i.e. a 4-rod cavity and a 4-ladder cavity, are under investigation. Delivery of the RFQ is currently expected in 2018.

Acceleration to the final energy of 70 MeV is along two DTL sections based on crossed-bar H-cavities (CH). The first section uses three rf-coupled CH-cavities separated by quadrupole triplets. They inhabit an inner triplet lens which additionally rf-couples the CH sections in front of and behind this lens. Reference [14] summarizes the development of the CH-cavities. A prototype cavity (Fig. 11) was successfully built at the University of Frankfurt and later successfully copper plated at GSI. Recently, low level-rf measurements

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Table 3: Beam Design Parameters of the FAIR Proton Linac

Beam Current	70	mA
Beam Energy	70	MeV
Output Emit. (norm., tot.)	4.2	mm mrad
Beam Pulse Length	36	µs
Beam Repetition Rate	4	Hz
Rf Frequency	325.224	MHz
Total Length	43	m

Figure 10: Proton source assembled at CEA/Saclay.

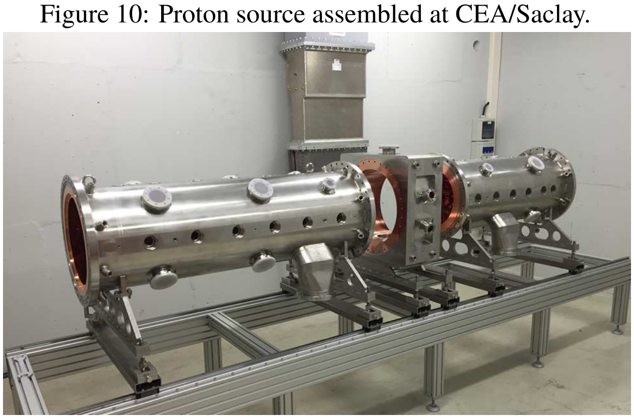

Figure 11: Prototype of coupled crossed-bar H-cavity.

with the plated cavity have been started and they show good agreement with the rf-properties expected from simulations. The first DTL section provides acceleration to 36 MeV. Afterwards the amount of transverse focusing per length can be reduced. Accordingly, the second DTL section is made from three CH-cavities without inner triplet lenses. Triplets are installed just between two adjacent cavities. The two DTL sections are separated by an extended beam instrumentation section that allows for measuring beam current, profiles, and emittances. Optionally, it may be equipped with an additional re-buncher.

The total of seven accelerating cavities will be powered each by one klystron which in turn is fed by one modulator each. A first of series klystron is on site. It is currently fed by a modulator leased from CERN. Both have been put into operation successfully on GSI site recently and 2.5 MW of rf-power have been reached [15]. By end of the year the rf-power chain and the prototype cavity should be ready for first high power testing of an rf-coupled CH-cavity.

The types of beam diagnostic devices, their locations along the linac, and their specifications are defined and are described in [16]. The most challenging devices are combinations of beam position monitors and phase probes. Each of these devices comprises four knobs which are to be installed close to triplet lenses between two CH-cavities, see Fig. 12. Special care has to be taken in order to shield the probes from primary rf leaking from the cavities towards the probes.

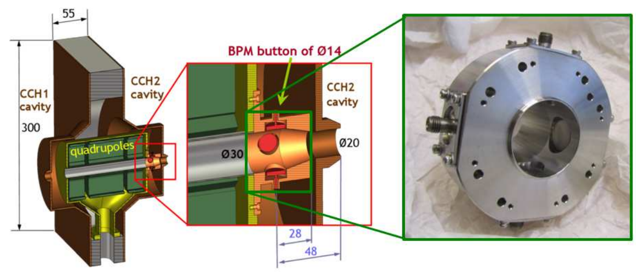

Figure 12: Combination of BPM and phase probe installed close to a triplet.

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