UPGRADE OF THE UNIVERSAL LINEAR ACCELERATOR UNILAC FOR FAIR

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Abstract

In order to meet the requirements on beam parameters for the upcoming FAIR facility at GSI, the injector linac UNILAC will be upgraded. The activities comprise development of the sources for stable provision of intense uranium beams at a repetition rate of 2.7 Hz, a revision of the beam dynamics layout of the 120 keV/u RFQ, the replacement of the matching section to the 1.4 MeV/u pre-stripper DTL, and enhancement of the gaseous stripping section efficiency. This section shall also include a round-to-flat emittance adaptor to prepare the beam for injection into the synchrotron SIS18 which has a flat transverse injection acceptance. Finally, the upgrade includes the complete replacement of the 40 year old 11.4 MeV/u Alvarez-type post-stripper DTL with a new DTL, preferably using Alvarez-type cavities with improved beam focusing features, as well as its rf-power sources.

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 UNIversal Linear ACcelerator 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.

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. 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. Intense heavy ion beams are produced in a MEVVA or VARIS source at 2.2 keV/u. Beams are bunched 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

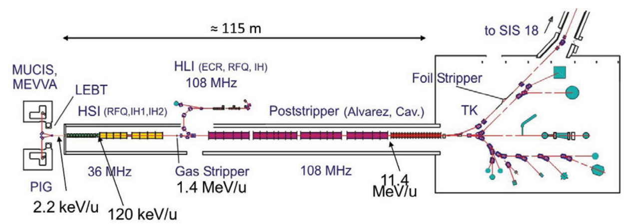

Figure 1: The UNIversal Linear ACcelerator (UNILAC) at GSI.

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	≤ ±30	deg
Beam Pulse Length	200	µs
Beam Repetition Rate	10	Hz
Rf Frequency	108.408	MHz

$^{238}U^{28+}$ 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 UNILAC design parameters are listed in Tab. 1.

ION SOURCE, LEBT, MEBT, AND RFQ

The ion source has to be operated with a repetition rate of 2.7 Hz. Although this target has been reached for some ions, reliable operation with uranium is currently limited to about 1.5 Hz. New uranium alloys are investigated as well as the reduction of the source beam pulse length in order to reduce the neutrals in the chamber. The existing LEBT includes two bends which impose dispersion and hexapolar fringe fields. Additionally, operation and handling of uranium

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comes along with restrictions from safety requirements. For these reasons a new and dedicated uranium branch has been designed. It has a straight LEBT comprising two quadruplets and one triplet. The ion 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+/5+) are reduced by chromaticity together with an circular iris located at a beam waist of the charge state 4+. Reference [2] is on the detailed design of the new LEBT.

The RFQ rods suffered from sparking during operation with varying rf-duty cycles and rf-amplitudes. Additionally, the beam divergence at the RFQ exit is too large. The design of the RFQ is revised [3] such that lower surface fields are applied at the expense of reduced acceptance together with an optimization of the beam envelope parameters at the RFQ exit.

The super lens is a non-accelerating RFQ, i.e. being 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 causes poor longitudinal matching to the subsequent IH-DTL. A new MEBT design foresees two symmetric triplets and one buncher, i.e. four additional tuning knobs [4].

HIGH PRESSURE H_2-STRIPPER

So far, a continuous N_2-jet has been used as stripping medium. The achieved stripping efficiency from $^{238}U^{4+}$ to $^{238}U^{28+}$ was 13%. Since 2014 a pulsed gas stripper cell has been tested [5]. 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. A relative increase of $^{238}U^{28+}$ intensity of 60% has been measured [6] using H_2. Final optimization and implementation into routine operation of this new stripping set-up have started. References [5–9] are on the successful campaign of increasing the stripping efficiency.

4D BEAM DYNAMICS OPTIMIZATION

As seen from Tab. 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 [10]. 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 with a nitrogen beam [11–13]. The corresponding increase in MTI efficiency was measured [14].

In this context complete 4d transverse beam diagnostics is required, i.e. the four 2nd order inter-plane correlations <xy>, <xy'>, <x'y>, and <x'y'> must be measurable. To our knowledge such measurements never were conducted successfully before at ion energies beyond about 150 keV/u. The ROtating System for Emittance measurements (ROSE) was successfully developed and commissioned at GSI [15, 16] with an ^{40}Ar beam at 1.4 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. 2). For different settings of a preceding skew quadrupole triplet 2nd beam moments have been measured and back-transformed to the entrance of the triplet. The observed agreement shown in Fig. 2 proofs the reliability of ROSE. A round-to-flat transformer will be installed along the gaseous stripper section if it is foreseeable that the other upgrade measures will not be sufficient to reach the UNILAC design beam parameters with uranium.

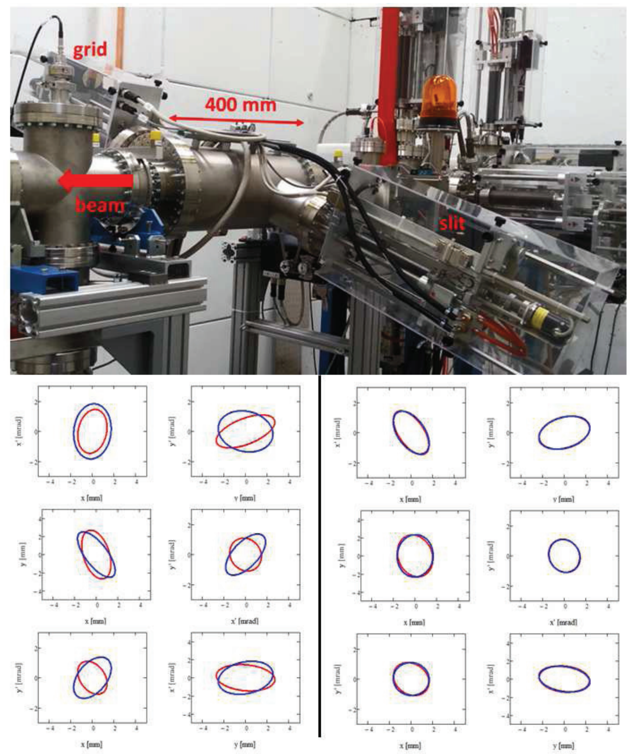

Figure 2: ROtating System for Emittance measurements ROSE (upper). Measured rms-ellipses of the transverse projections as measured at ROSE behind the triplet (lower left) and from back-transformation to the entrance of the skew triplet (lower right). Measurements were done for two different skew triplet settings.

NEW POST-STRIPPER ALVAREZ DTL

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 μs 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

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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 high duty cycles.

As beam quality is of utmost relevance for the low duty cycle FAIR injector, GSI aims at an Alvarez-type DTL. These DTLs proved to be reliable work horse accelerators. The related beam dynamics is fully understood even if considerable space charge is included. Periodic 3d envelope solutions are properly defined. Procedures to match the incoming beam to these solutions are established even for acceleration of flat beams [17]. The new DTL will comprise five tanks. Figure 3 shows beam envelopes and rms-emittances along the new DTL for an $^{238}U^{4+}$ beam of 15 mA accelerated to 11.4 MeV/u. The envelopes are very periodic and the inter-tank matching works fine. As a result the rms-emittance growth is less than 4% in transverse and about 1% in longitudinal direction. In case an experiment requires an energy

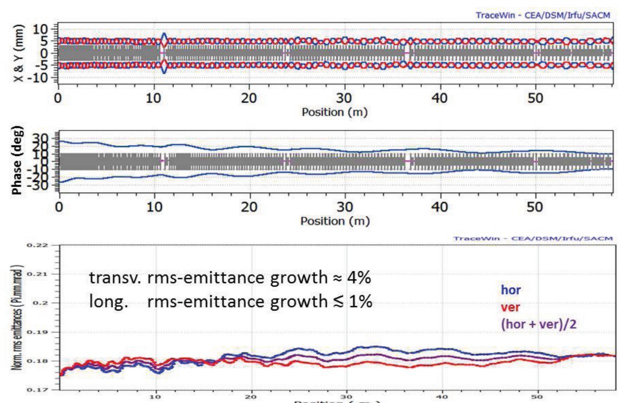

Figure 3: Simulated transverse (upper) and longitudinal (middle) rms-envelopes and transverse rms-emittances (lower) along the beam line of the new post-stripper Alvarez-type DTL for provision of 15 mA of $^{238}U^{28+}$ at 11.4 MeV/u.

of 3.0 MeV/u for instance, the rf-power of the last four tanks is switched off and the inter-tank bunchers are used to maintain a reasonable bunch length up to the DTL exit. This scenario is illustrated in Fig. 4. Low energy / low current beams are delivered to the exit of the DTL without emittance growth and preserving short bunch length. The DTL is followed by a single-gap resonators section (Fig. 1) that will do the deceleration from 3.3 MeV/u to 3.0 MeV/u for instance. Reference [18] reports on the rf-design of the cavities including innovative shapes of the drift tube surfaces as well as on a new rf-tuning scheme based on alternating stem configurations.

ALTERNATIVE DTL DESIGN BASED ON IH-CAVITIES

Compared to Alvarez cavities H-mode resonators feature much higher shunt impedances. Additionally, they require much less transverse focusing quadrupoles. They have the potential to impose an alternative to Alvarez-type DTLs at reduced cost and even allow for an eventual future energy

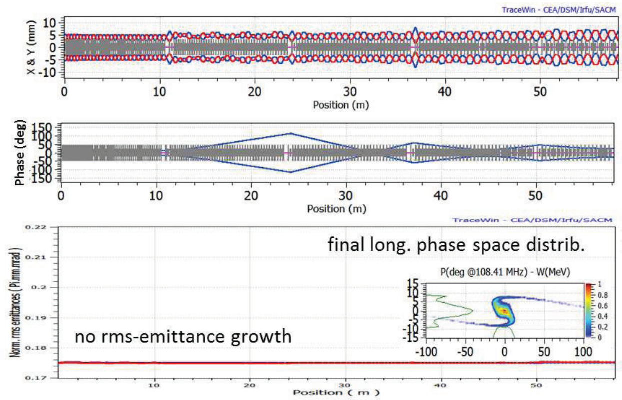

Figure 4: Simulated transverse (upper) and longitudinal (middle) rms-envelopes and transverse rms-emittances (lower) along the beam line of the new post-stripper Alvarez-type DTL for provision of $^{238}U^{28+}$ at 3.3 MeV/u at low current.

upgrade to about 50 MeV/u using the existing linac tunnel. A post-stripper linac design based on IH-cavities has been developed at the Goethe University of Frankfurt. The rms-emittance growth simulated with the LORASR code is less than 30%. However, this code tends to overestimate the growth [19]. The total DTL length is about 25 m and further information about this design can be found in [20].

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