THE GSI UNILAC UPGRADE PROGRAM TO MEET FAIR REQUIREMENTS

L. Dahl, GSI Helmholtzcenter for Heavy Ion Research, Darmstadt, Germany

Abstract

The GSI linear accelerator UNILAC and the synchrotron SIS18 will feed the future accelerator facility FAIR (Facility for Antiproton and Ion Research) with heavy ion beams. Several hardware measures at the UNILAC are necessary to meet the FAIR requirement, implicating a beam intensity of $3.2{\cdot}10^{11}$ of U^{28+}-particles within an UNILAC macro pulse of 100 µs length and defined emittance space at SIS18 injection.

The stripper gas jet density was strongly increased to get the equilibrium charge state even for the heaviest ions. A procedure matching the 6-D-phase space for proper Alvarez DTL injection and increase of the transverse phase advance in the Alvarez accelerators reduces emittance growth. In front of SIS18 injection a new separator provides an immediate selection of the desired charge state after stripping and therefore reduces space charge induced emittance growth.

The front-end of the high current injector includes several bottle necks. A compact solenoid channel is planned providing straight line injection into the 4-rod-RFQ. The RFQ will be equipped with new designed electrodes for increased acceptance and reduced emittance growth.

The contribution gives an overview of end-to-end simulations, the different upgrade measures, the particular beam investigations, and the status of beam development satisfying FAIR requirements.

INTRODUCTION

For Uranium (reference ion) the UNILAC has to inject $3.2{\cdot}10^{11}$ U^{28+} particles per 100 µs ($4.8{\cdot}10^{10}$ U^{73+}) with a repetition rate of 4 Hz into the synchrotron SIS18.

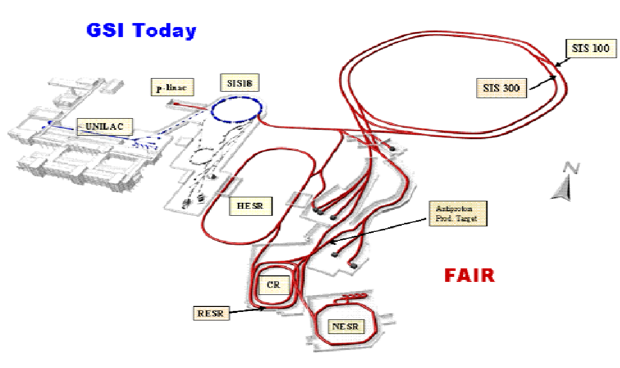

Figure 1: The existing GSI accelerators UNILAC and SIS18 and the future accelerator facility FAIR.

The low charge states for heavy ions (entering quadratic into the space charge limit SCL) enable intense beams. These are subsequently accelerated up to 1.5 GeV/u by the FAIR [1] synchrotron SIS100 for radioactive beam production. Alternatively SIS100 accelerates intense proton beams up to 30 GeV for pbar-production. Heavy ion beams of energies up to 30 GeV/u will be provided by the FAIR synchrotron SIS300, using higher charge states and a slower cycling rate. SIS300 can also serve as a stretcher for radioactive beams, which will be injected, cooled, and stored in a system of rings with internal targets and in-ring experiments (Fig. 1).

GSI uses heavy ion sources of e.g. MUCIS or Mevva type which generate for a whole string of low charged ions beams of sufficient intensity. As the UNILAC was originally not designed for space charge dominated beams different measures are necessary to reduce beam losses and improve beam quality.

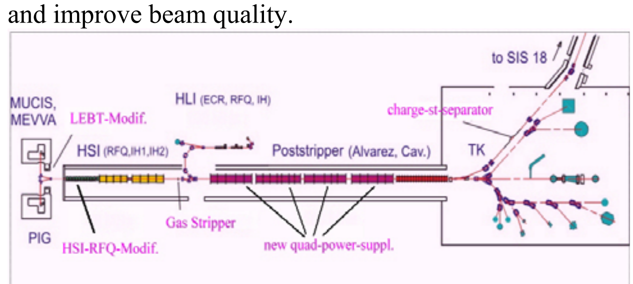

Figure 2: Schematic overview of the UNILAC, experimental area, transfer channel to SIS, and locations of upgrades.

The scheme of the UNILAC is presented in Fig. 2. The prestripper accelerator HSI (high current injector) comprises a 36 MHz RFQ and two IH-type drift tube DTLs for final energy of 1.4 MeV/u, suited for ions with mass to charge ratios up to 65. A gas stripper increases the charge states, e.g. U^{4+} delivered by the Mevva source is stripped to U^{28+}. Five 108 MHz Alvarez DTLs accelerate the ions up to 11.4 MeV/u. Finally a chain of ten single gap resonators allows exact adjusting of any energy between 3.6 and 12.4 MeV/u. A second injector HLI (high charge state injector) with an ECR source injects directly into the post stripper section. Finally, up to three different ion species can be accelerated interchangeably to different energies. Different experiments in any mixture on basis of a 50 Hz pulse-to-pulse switching mode can be accomplished. The transfer channel to SIS18 includes a foil stripper for another charge state increase.

BEAM DYNAMICS SIMULATIONS

Space Charge Parameter along the UNILAC

For the HSI commissioning end-to-end simulations for the entire UNILAC up to SIS18 injection were carried out with the multi particle codes PARMILA and PARMTRA. As result of these calculations the SCP (space charge parameter) along the UNILAC was extracted (Fig. 3). The SCP is very high in the gas stripper area, but it decreases rapidly with particle separation. Another significant peak at the entrance of the Alvarez DTL appears due to the small size of the beam in all three dimensions, as required for beam matching. A further space charge affected area is situated behind the foil stripper device in the transfer channel to SIS18.

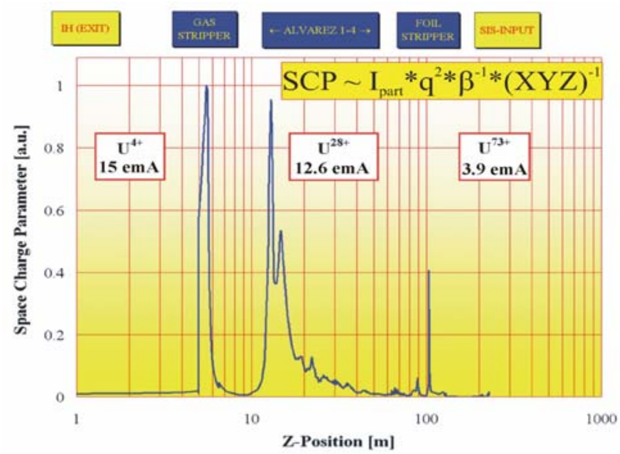

Figure 3: Space charge parameter along the UNILAC [2].

The separation of the required charge states behind both strippers and the beam matching to the DTL structure are taking place under extremely high space charge influence which are sources of emittance growth.

Matching Section for the Alvarez DTL

After the separation of the U^{28+} ions behind the gas stripper, the beam has to be matched to the periodic solution of the beta function of the first Alvarez DTL. The 6-D matching of the beam is carried out by a system comprising a 36 MHz rebuncher cavity, a quadrupole doublet and triplet, and a 108 MHz rebuncher cavity. In general the mismatched beam results in large beta function oscillations along the whole Alvarez DTL, which may cause emittance growth and beam losses (Fig. 4).

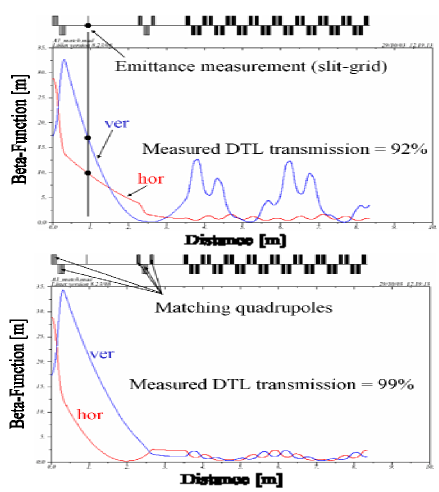

Figure 4: Horizontal and vertical beta-functions in the matching section and the first cells of the Alvarez DTL for mismatched (top) and matched (bottom) beam [2].

Using the quadrupole settings in the first cells of the DTL the periodic solution for the first Alvarez tank is calculated. To match the periodic solution, a fitting routine involving the five quadrupoles and two bunchers is applied also considering space charge forces. The matched Twiss parameters decrease the measured losses along the Alvarez section from 8 % to less than 1 % [3].

Transverse Phase Advance in the Alvarez DTL

For U^{28+} beam the zero current transverse phase advance σ_0 in the Alvarez DTL is limited to 45° due to power supply currents. A $^{40}Ar^{10+}$ beam with less than half of the Uranium beam rigidity and the beam intensity of 7 emA is equivalent to the envisaged Uranium intensity. Therefore the influence of the phase advance on transverse emittance growth and transmission in the Alvarez DTL was investigated experimentally with a $^{40}Ar^{10+}$ beam up to σ_0-values of 90°. As shown in Fig. 5, a value of $\sigma_0 = 60°$ is required for an improved transverse brilliance for SIS18 injection. Transferred to Uranium, an increase of the maximum field gradients in the Alvarez DTL of 11% is necessary.

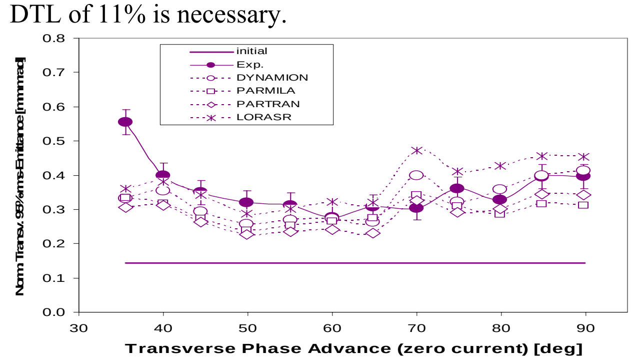

Figure 5: Transverse emittance at the exit of the Alvarez DTL calculated by different codes and measured as function of transv. phase advance. $\varepsilon_{norm} = (\varepsilon_x + \varepsilon_y) / 2$ [3].

Charge State Separation behind Foil Stripper

Formerly charge state separation was accomplished 25 m behind the foil stripper in the TK (transfer channel) to SIS18. For FAIR beam quality requirements it became necessary to increase the resolving power for space charge reasons. A new compact charge state separator with four vertical dipole magnets of 35° deflection angle each was designed. Fig. 6 shows the vertical fully separated beam envelopes for the Uranium charge states 72+, 73+, and 74+.

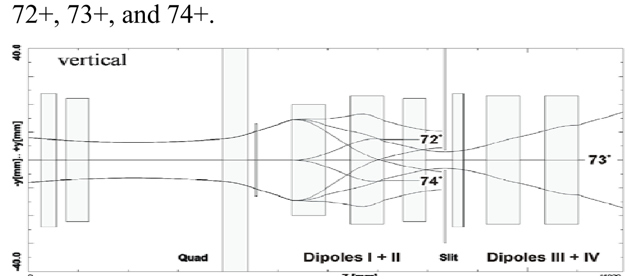

Figure 6: Beam dynamics layout of the charge state separator in the beam transfer line to SIS. Envelopes for Uranium charge states 72+, 73+, and 74+ [6].

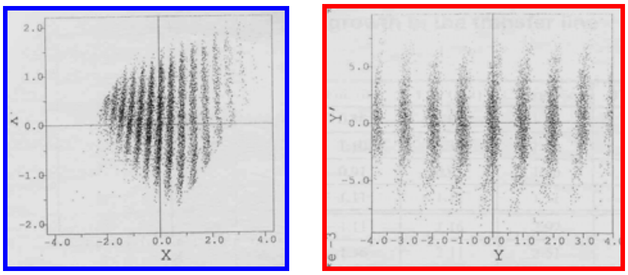

Figure 7: Multi particle calculations for high Uranium charge states in the dispersion plane for the old (left) and the new transfer channel charge state separator (right) [6].

The enormous progress of improved and direct charge state separation with evident impact on space charge forces reduction is pictured in Fig. 7. Measurements are reported below.

REALIZED UPGRADE MEASURES

Increase of Gas Stripper Pressure

To get charge state equilibrium and maximum exploitation of U^{28+} ions the nitrogen gas jet pressure was increased from 2,900 mbar to 4,500 mbar measured in front of the nozzle. The gas density is estimated as 1 µg/cm^2. Besides the huge roots pump four 1,000 l/s turbo pumps were installed. The new stripper chamber with enlarged beam apertures is shown in Fig. 8. The measurements illustrated in Fig. 9 show the exploitation of different Uranium charge states depending on the gas pressure. Fig. 10 shows uranium charge state spectrum recorded behind the 15° analyzing and selecting magnet, proving the envisaged equilibrium.

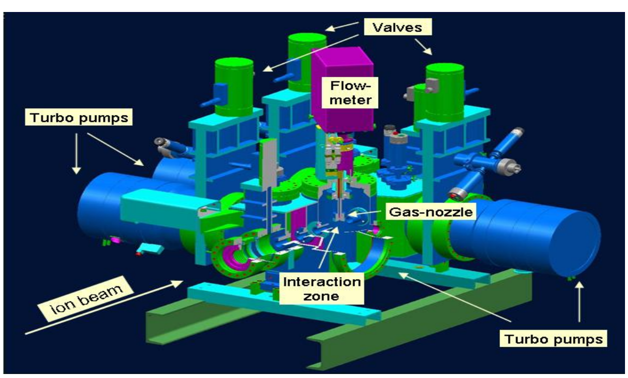

Figure 8: Improved nitrogen gas stripper chamber [4].

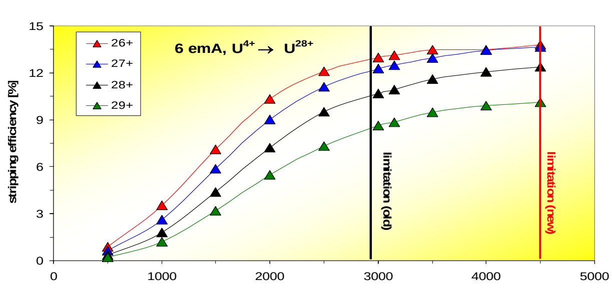

Figure 9: Yield of uranium charge states depending on nitrogen gas pressure [6].

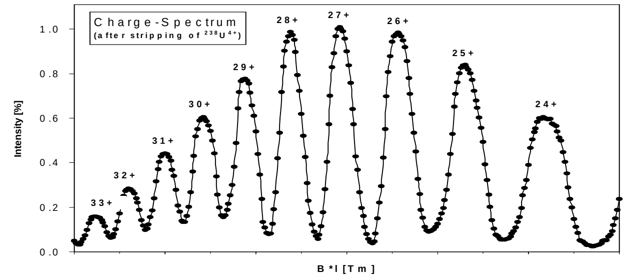

Figure 10: Uranium charge states after stripping [6].

Alvarez DTL Beam Brilliance Increase

As learned from the above described simulations, a sophisticated 6-D beam matching to the Alvarez DTL and an increased transverse phase advance of $\sigma_0 = 60°$ promises a significant gain in beam brilliance.

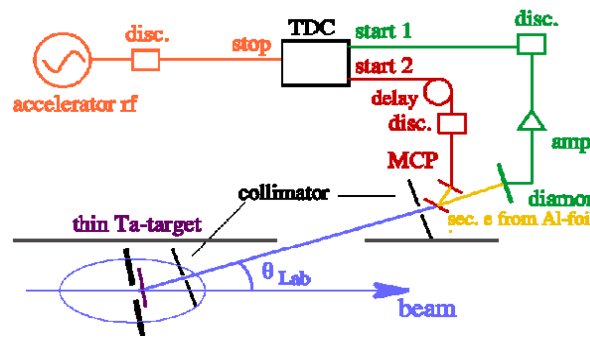

Figure 11: Scheme of the longitudinal bunch structure measurement device in front of the Alvarez DTL [5].

Additional to a slit-grid transverse emittance meter a TOF measurement of secondary electrons with Multi Channel Plate and a diamond detector (Fig. 11) was developed and installed in the matching section for the Alvarez DTL. On basis of MAD8-code the six measured phase space parameters are fitted to the Alvarez periodic FDDF focussing channel considering space charge power. The Alvarez magnetic quadrupole cooling allowed increasing the currents up to 20 %. Therefore new power converters were ordered and partly already installed.

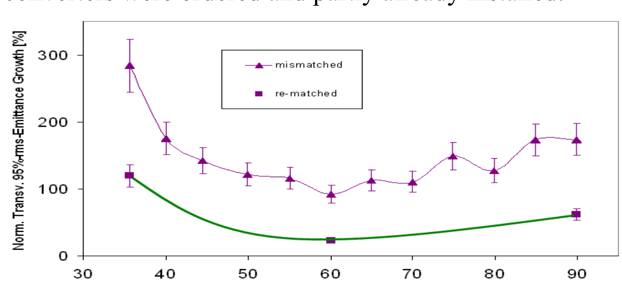

Figure 12: Measured emittance growth in the Alvarez DTL for mismatched and matched beam for different σ_0 [3].

After applying the procedure for matched beam injection and transverse phase advance of $\sigma_0 = 60°$ for the Alvarez DTL a reduction of the transverse emittance growth from 100 % to 20 % was measured (Fig. 12) [3].

New Charge State Separator

In the transfer line to SIS18 the beam is stripped to higher charge states by a carbon foil, if high final energies from SIS18 are required. The TK is operated at 4 Hz pulse-to-pulse mode, with beams of different ion species and intensities, with or without stripping. An U^{28+}-beam of 15 emA has a power of 1.5 MW (100 µs pulse length). After stripping, undesired charge states with 85 % of the beam power must be separated and dumped.

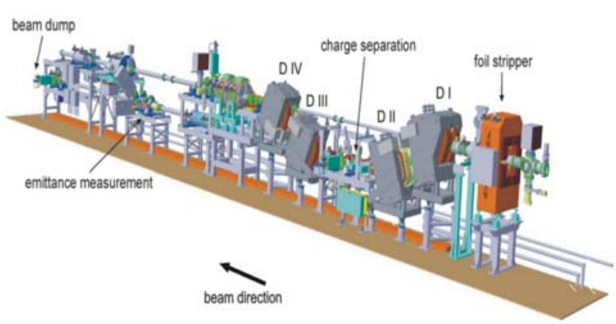

Figure 13: Charge state separator behind the foil stripper [6].

A stripper foil is loaded with 3 % of the beam power. To avoid evaporation in a single beam pulse, the beam is swept within 100 µs over its width of 55 mm. Emittance growth in the TK is caused by small angle scattering in the stripper foil and by space charge forces. To minimize emittance growth, a beam of spotsize 4 mm · 20 mm is prepared, and the distance to the separator is kept as short as possible. Focused beams pass the stripper by use of a kicker or sweeper magnet horizontally off-axis and are bend back by a quadrupole magnet into the horizontally 90 mm wide gaps of the first two dipoles of the analyzing system. A second kicker or sweeper magnet realigns the beams on axis. Vertically the charge states are separated by the first dipole magnet. Pole face rotation angle of -20° focuses the beam into the analyzing slit. The charge resolution q/Δq is about 100. The slot width is 10 mm; the dispersion is 7.5 mm/%. The complete system (Fig. 13) is designed achromatically [6].

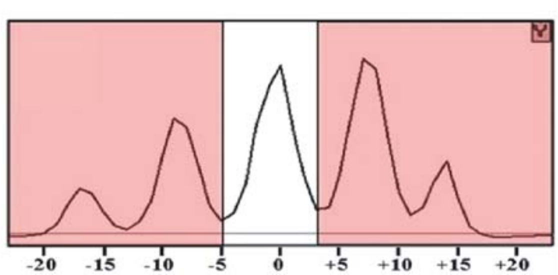

Figure 14: Measured uranium charge states 71 – 75+ [6].

The stripper foil device keeps ready 40 frames, each equipped with a small foil for kicker magnet operation and a large foil for sweeper or kicker magnet operation. The foil thicknesses are 200, 400, and 600 µg/cm^2. E.g., 400 µg/cm^2 provides equilibrium charge state distribution for an Ar beam. The 600 µg/cm^2 foil serves for stripping of heavy ions, e.g. the U^{73+} yield reaches 15 % (Fig. 14).

Space charge forces act in the short region between stripper foil and charge separation only. The space charge influenced emittance growth is 10 % (hor.) and 20 % (vert.). The measured high current emittance potentially meets the requirement defined by the FAIR project.

ACHIEVED URANIUM INTENSITY

The revision of space charge dominated sections of the UNILAC implicated both an increase of beam intensity towards the goal of 15 emA of the design U^{28+} beam and 5 emA of the foil stripped U^{73+} beam, and significantly higher beam brilliance. As represented in Fig. 15 the measured normalized vertical emittance area is below the required limit for SIS injection of $\varepsilon_{y,norm}$ = 2.5 µm whereas the horizontal emittance still exceeds the SIS18 limitation of $\varepsilon_{x,norm}$ = 1.0 µm up to 60 % in terms of the total emittance area. As shown in Fig. 16 the absolute uranium beam intensities developed with the upgrade measures and sophisticated machine tuning towards 5.7 emA for U^{28+} beam and 2.7 emA for U^{73+} beam.

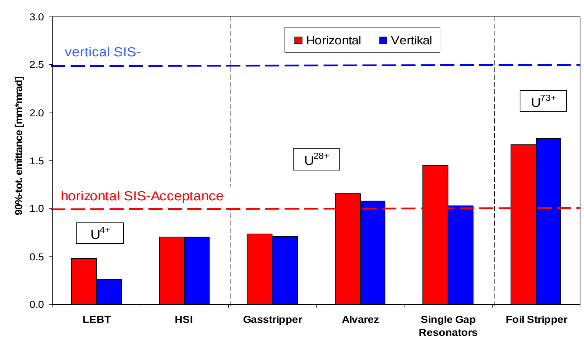

Figure 15: Normalized high current beam emittance measurements in June 2008 and SIS requirements [4].

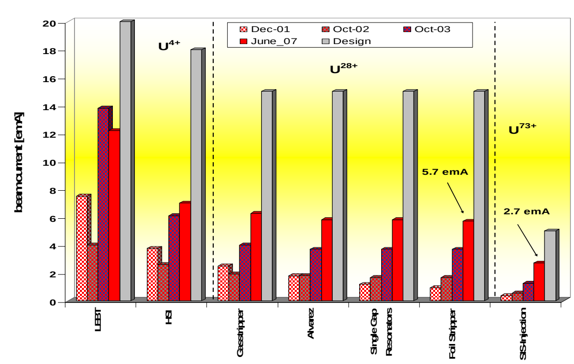

Figure 16: Improvement of the uranium beam intensities during the last years along the UNILAC [7].

ACTUAL UPGRADES

The Mevva ion source generates 37 emA of U^{4+} beam theoretically sufficient to meet the FAIR requirements. Nevertheless only 12 emA are calculated at the output of the HSI. There are two bottle necks in the front-end system: the LEBT and the 36 MHz RFQ. Currently the RFQ is reengineered.

RFQ Redesign

The ten HSI-RFQ modules are currently equipped with new electrodes comprising a new designed input radial matcher and a smooth gentle buncher (Table 1). Important is the enlarged normalized acceptance of 0.86 µm. The maximum RF voltage grew from 125 to 155 kV. The U^{4+} beam output current and therefore the beam brilliance increases 40 % within an emittance of 20 µm (Fig. 17) [8]. After RF conditioning and beam commissioning the upgraded RFQ will go into routine operation in August 2009.

Table 1: Main RFQ Parameters

	New Design	Existing Design
Voltage, kV	155.0	125.0
Average radius, cm	0.6	0.52-0.77
Electrode width, cm	0.84	0.9-1.08
Maximum field, kV/cm	312.0	318.5
Modulation	1.012-1.93	1.012-2.09
Synch. Phase, degree	-90 to -28	-90 to -34
Aperture, cm	0.41	0.38
Min. transverse phase advance, rad	0.56	0.45
Norm. transverse acceptance, cm mrad	0.086	0.73
Output energy, MeV/u	0.120	
Electrode length, mm	9208.4	

Compact LEBT

Beam simulations on the existing LEBT demonstrate emittance filamentation and growth arising in the analyzing magnet, mismatch to the RFQ, and resulting significant beam loss in the front-end. In an upgrade I (see Fig. 18) foreseen in 2010, switching and quadrupole magnets will be substituted by magnets with enlarged apertures for proper beam matching to the increased RFQ acceptance. But this improves only partly the LEBT.

Simulation studies on alternative LEBT [9] show that a new straight line system based on sc solenoids (upgrade II in Fig. 18) provides the most efficient beam transport of the radial symmetric beam to the RFQ. The ions with wrong rigidity will be mainly lost in the LEBT. This system will be primarily used for mono isotopes and enriched heavy ion source material as it contains no charge analyzing section.

Together with the ongoing RFQ upgrade the compact LEBT enables an HSI output current of 20 emA U^{4+} beam meeting the FAIR requirement (see Fig. 16).

CONCLUSION AND OUTLOOK

The described sequence of upgrade measures of the UNILAC mainly applied to strong space charge influenced sections will fulfil the beam quality and quantity requirements at SIS injection. Nevertheless, it is

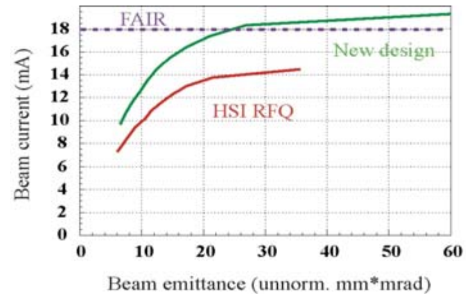

Figure 17: Simulation data of the modified HSI-RFQ (red: existing status, green: new design) [8].

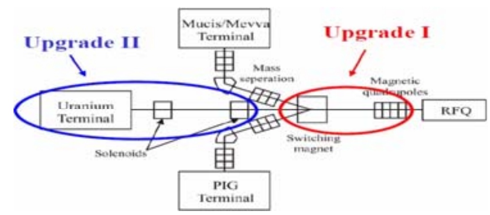

Figure 18: Modifications of the HSI LEBT system [9].

a challenge for the UNILAC to satisfy in multi ion pulse-to-pulse operation the requirements of the high duty factor (5 ms and 50 Hz) experiment program below 7.5 MeV/u and simultaneously the 4 Hz demand of high intensity 11.4 MeV/u beams in 100 µs pulses for FAIR. Both injectors, HSI and HLI, are modernized so far. But all beams are passing the 60 m long Alvarez DTL in operation since 1974 and fed by RF amplifiers with pulse power up to 1.6 MW. Long term plans are developed to separate these functions by a dedicated short 7.5 MeV/u sc linac and a substitution of the Alvarez DTL by IH and CH structures providing the beams for FAIR [7].

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