THE INJECTOR SYSTEMS OF THE FAIR PROJECT

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Abstract

The present GSI accelerator chain will serve as an injector for FAIR (**F**acility for **A**ntiproton and **I**on **R**esearch). The linear accelerator UNILAC and the heavy ion synchrotron SIS18 should deliver up to $1 \cdot 10^{12}$ U^{28+}-particles/sec. In the past two years different hardware measures and a careful fine tuning of the UNILAC resulted in an 35% increase of the beam intensity to a new record of $1.25 \cdot 10^{11}$ U^{27+}-ions per 100 µs or 2.3 10^{10} U^{73+}-ions per 100 µs. The increased stripper gas density, the optimization of the Alvarez-matching, the use of various newly developed beam diagnostics devices, and a new charge state separator system in the foil stripper section comprised the successful development program. The contribution reports results of beam measurements during the high current operation with uranium beams (beam pulse power up to 0.65 MW). The UNILAC-upgrade for FAIR will be continued by assembling a new front-end for U^{4+}, stronger power supplies for the Alvarez quadrupoles, and versatile high current beam diagnostics devices. Additionally, the offered primary proton beam intensities will be increased by a new proton linac, which should be commissioned in 2013. We acknowledge the support of the European Community – Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395). Work supported by the European Community INTAS Project Ref. no. 06-1000012-8782.

INTRODUCTION

Meeting the FAIR science requirements higher intensities have to be achieved in the present GSI-accelerator complex, through faster cycling and, for heavy ions, lower charge state which enters quadratically into the space charge limit (SCL). The desired energy of up to 1.5 GeV/u for radioactive beam production is delivered by the synchrotron SIS 100, which also generates intense beams of energetic protons up to 30 GeV for pbar-production. Highly charged heavy ion beams with a maximum energy of 30 GeV/u have to be accelerated in the slower cycling synchrotron SIS 300. SIS 300 can also be used as a stretcher for radioactive beams, which can be injected, cooled, and stored in a system of rings with internal targets and in-ring experimentation.

Figure 1: The future accelerator facility FAIR at GSI in Darmstadt [1].

Table 1: FAIR-design Uranium Beam Parameters at UNILAC and SIS 18 Injection [2]

	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection	
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{28+}$	$^{238}U^{73+}$
El. Current [mA]	25	18	15	15.0	5.5
Part. per 100µs pulse	$3.9 \cdot 10^{12}$	$2.8 \cdot 10^{12}$	$3.3 \cdot 10^{11}$	$3.3 \cdot 10^{11}$	$5.0 \cdot 10^{10}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4	
$\Delta W/W$	-	$4 \cdot 10^{-3}$	$\pm 1 \cdot 10^{-2}$	$\pm 2 \cdot 10^{-3}$	
$\varepsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8	
$\varepsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5	

In the last years GSI put effort in increasing the uranium intensities delivered to the SIS 18. An advanced upgrade program for the UNILAC is still in progress to meet the FAIR requirements. For uranium (FAIR reference ion) the UNILAC has to deliver $3.3 \cdot 10^{11}$ U^{28+}-particles per 100 µs (see Table 1). Besides for a 15 emA $^{238}U^{4+}$ beam from the High Current Injector HSI [2] up to $5.5 \cdot 10^{10}$ U^{73+} particles should be delivered to the GSI heavy ion synchrotron SIS 18 (during 100 µs), while the SIS 18 SCL is reached by a 15 turn injection into the horizontal phase space.

In the 36 MHz-HSI [3] comprising ion sources of MEVVA-, MUCIS- or Penning-type, the IH-RFQ, a short 11 cell adapter RFQ (Super Lens), and two IH-tanks, the beam is accelerated up to 1.4 MeV/u. In the gas stripper section the charge state is increased and after charge separation the high intensity U^{28+}-beam is matched to the Alvarez DTL. After acceleration up to the final UNILAC-beam energy the transfer line (TK) to the synchrotron provides for a foil stripper and a new compact charge state separator system.

The UNILAC brilliance for proton beams is at least two orders of magnitude below the FAIR-requirements. For the proposed time sharing scenario proton beam intensities of 35 mA and an energy of 70 MeV are required. Accordingly, a dedicated proton injector linac [4] being designed within FAIR will be operated independently from the existing UNILAC.

The UNILAC serving as a high duty factor heavy ion linac for physics experiments is in operation since more than 30 years. After completion of the FAIR complex in 2015 the running time for the accelerator facility will be 20 years at least, while the UNILAC will then be in operation for more than 60 years. Different proposals for a new advanced short pulse, heavy ion, high intensity, high energy linac, substituting the UNILAC as a synchrotron injector are still in discussion. This new "High Energy-UNILAC" will allow for complete multi-ion-operation, and should provide for reliable beam operation in the future.

The decelerator for HITRAP (Heavy Ion TRAP) is also a (linac-) project providing for ions of selected charge states up to U^{92+} at cryogenic temperatures. One of the HITRAP features will be the ability to decelerate heavy highly-charged ions from 4 MeV/u down to rest after ejection from the Experimental Storage Ring (ESR). After three years of operation at the ESR the HITRAP set-up will be an integral part of FAIR behind the NESR (New Experimental Storage Ring).

HSI FRONTEND-UPGRADE

Table 2: 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	

The bottleneck of the whole UNILAC is the front-end system of the High Current Injector. It is shown in an upgrade design study that the transverse RFQ-acceptance can be significantly increased while the emittance growth can be reduced. Both goals are achieved with only a moderate change of the RFQ electrode geometry; the intervane voltage rose from 125 kV to 155 kV [5], but keeping the design limit of the maximum field at the electrode surface. The changing resonant frequency can be compensated with a relatively small correction of the carrying rings. The beam parameters in the final focusing elements of the LEBT were optimized together with the improved design of the input radial matcher; the length of the gentle buncher section was considerably increased to provide slow and smooth bunching resulting in a reduced influence of space charge forces. The baseline design was optimized for an U^{4+} beam current of 20 emA and a total transverse emittance of 280 mm·mrad (unnorm.). These values were chosen on the base of the measurements in front of the RFQ (15 mA, 210 mm·mrad) assuming the same brilliance. The main parameters of the new design are summarized in Table 2. [6]

A comparison of the existing and the new RFQ is illustrated in Fig. 2. The beam current inside a given transverse emittance at the RFQ output is shown for both designs. Beam dynamics simulations were done for the same beam current (25 mA) and emittance (210 mm·mrad), but with different matching for each case. The new RFQ design provides for an increase of more than 40 % of the beam current compared to the old design. Higher beam emittance behind the new RFQ is formed by a few percent of the particles, while the core of the beam (20 mm·mrad) contains the required beam current. The HSI-RFQ upgrade will start in spring 2009.

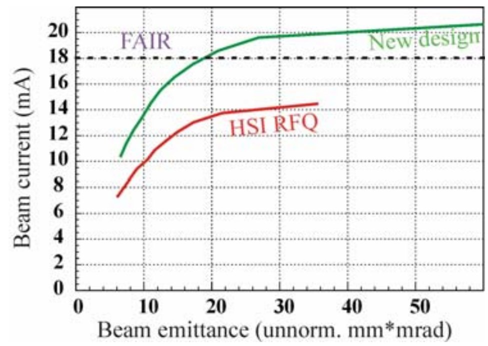

Figure 2: Beam current inside a given emittance at RFQ-output for the existing (red) and the new design (green).

HSI END TO END SIMULATIONS

The beam dynamics for the HSI were simulated with different codes; the geometry of both RFQ designs were introduced in the DYNAMION-code. Alternatively PARMTEQ-M was used to cross check beam dynamics results; the simulation results of both codes showed high agreement. The DYNAMION macro particle distribution was directly matched to the intertank section comprising a magnetic quadrupole duplet and the super-lens, were the beam is matched to a 20 m IH-section simulated by LORASR. Fig. 3 shows a comparison of the beam performance at the IH-output for the existing and the new RFQ-design. A significant increase of beam brilliance for the total HSI-performance is visible if the new RFQ-design is considered. For a transverse emittance of 20 mm·mrad an U^{4+}-current of more than 18 emA is enclosed, meeting the FAIR-requirements. Further simulations will be performed to evaluate the overall improvement at the end of the whole UNILAC. The full FAIR-performance should be reached when the planned installation of ion source terminal and Compact LEBT [7] will be realized (2010-2011).

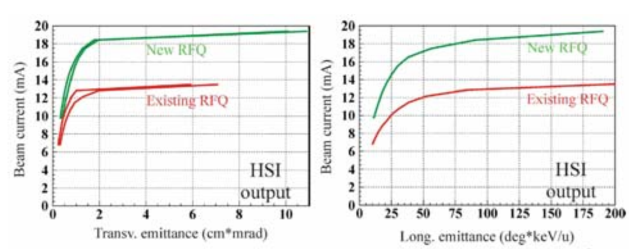

Figure 3: Beam current inside a given transverse (left) and longitudinal (right) emittance at HSI-output for the existing (red) and the new design (green). [6]

GASSTRIPPER PERFORMANCE

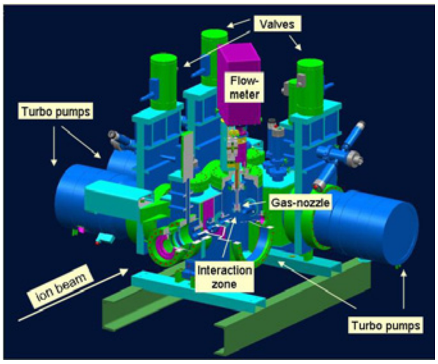

Figure 4: New gas stripper box.

With a reduction of the beam apertures in the old stripper box, it was possible to increase the stripper gas density by 50 %. For medium intense uranium beams this leads to the expected gain for the desired charge state 28+ (up to 12.8 % of the total particle number). The desired equilibrium charge state distribution was reached for a 70 % higher gas density. During long term operation the pumping speed of the old vacuum pumps was not sufficient to compensate this gas load. For high current operation, as required for FAIR, the defocusing effect of the space charge forces leads to particle loss in the transport section after the stripping area. In the new gas stripper box (as shown in Fig. 4) [8] the high stripper gas density for the necessarily enlarged apertures is provided by enhanced vacuum pumping speed.

BEAM MATCHING TO THE ALVAREZ

The improvement of beam quality at the end of the UNILAC Alvarez DTL section is a major concern with respect to the availability of the design beam parameters. The DTL comprises 177 accelerating gaps and 184 quadrupoles for periodic transverse beam focusing. The high currents arise non-linear space charge forces leading to emittance growth. This emittance growth depends on the beam envelope shape, which can be varied by the transverse phase advance σ. In case of low currents the zero current phase advance σ_o is calculated analytically considering the field strength of the quads.

The beam envelope also depends on the matching to the DTL injection. A beam is matched if its envelope inhabits the same periodicity as the focusing structure, mismatching is quantified by the mismatching factor M. In machine experiments the dependency of emittance growth on σ_o and M for the Alvarez DTL was investigated. The design beam for FAIR is 15 emA of $^{238}U^{28+}$ being space charge equivalent to 7.1 emA of $^{40}Ar^{10+}$. Since $^{40}Ar^{10+}$ is available with higher intensity and allows for a larger spectrum of focusing strengths, $^{40}Ar^{10+}$ was used. Phase space distributions were measured in front of the DTL. From the transverse measurements the rms-emittances were extracted. The DTL was set to different values of σ_o. From the measurement in front of the DTL M was calculated for

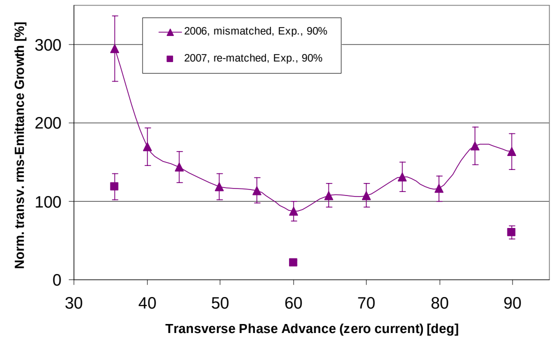

Figure 5: Measured transverse emittance growth as function of the phase advance [9]

each value of σ_o and corresponding Alvarez-emittances were measured. Emittance growth rates as function of σ_o are plotted in Fig. 5. The mismatch was large for low and for high phase advances. A minimum mismatch occurred at $\sigma_o \approx 55°$, resulting in a minimum emittance growth. Highest growth rates of 300 % were measured at $\sigma_o = 35°$. It decreases down to 100 % at about 60° and increases again to almost 200 % for highest σ_o. Compared to the 2006-campaign mismatch was reduced for all phase advances. The corresponding emittance growth rates are shown. It was demonstrated that by reducing M, emittance growth rates of just 20 % can be achieved. [9] A sufficient phase advance $\sigma_0 > 50°$ is also required for an improved high current beam brilliance for the SIS-injection of heavy ions. New stron-ger power supplies feeding the quads will be mounted in the winter shutdown 2008/2009 providing for the necessary quadrupole field strength for U^{28+}-operation.

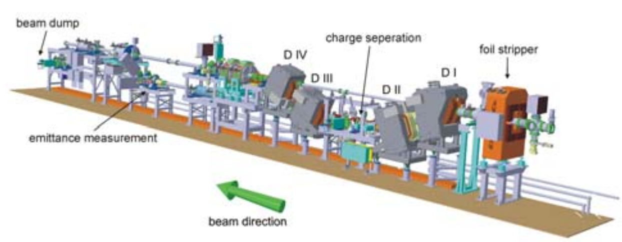

Figure 6: New Charge state separator system, integrated in the TK comprising the foil stripper, the four 35°-Dipole magnets (DI - DIV), and a beam diagnostics bench.

NEW CHARGE STATE SEPARATOR

A new charge state separator system was installed in the transfer line to the SIS 18 in December 2007. After commissioning of all components, in January 2008 beam commissioning was performed successfully with a medium intensity uranium beam and a high intensity argon beam; the measured beam transmission is close to 100 % for low and high current beams. The sweeper operation was tested with a high intensity argon beam as well as with an uranium beam. In general no emittance growth effects is driven by the sweeper operation. The stripping efficiency measured with the charge separator as a spectrometer is as expected. The improved charge separation capability was simulated with the PARMILA

Transport code and confirmed for heavy ion beams as well as for high current operation. Simulated and measured emittance growth effects for low current operation are caused by small angle straggling; additionally the vertical emittance inside the charge separator is increased by dispersion. Space charge forces act in the short drift length between stripper foil and charge separation in D I only – the space charge influenced emittance growth is 10 % (hor.) resp. 20 % (vert.). [10] The measured high current emittance potentially meets the FAIR requirement. With an advanced beam diagnostics bench behind dipole III high current beam measurements are accomplished to prepare for the injection into the SIS 18. Besides ion current the beam profile and position, the emittance, the beam energy, and the bunch structure can be measured.

^{238}U-BEAM INTENSITIES FOR THE SIS 18

In Fig. 7 the achieved uranium intensities in the UNILAC and TK are summarized (2001-2007), reached by ongoing upgrade measures and by an extended experimental program dedicated to improve the overall UNILAC performance for heavy ion high current operation. In June 2007 an U^{73+} intensity of 2.7 emA (37.1 pμA) was reached for the first time, which corresponds to $2.3 \cdot 10^{10}$ particles per 100 μs. Before foil stripping 5.7 emA (203 pμA) of U^{28+} beam intensity was achieved ($1.25 \cdot 10^{11}$ particles per 100 μs). The optimized total particle transmission through HSI, stripper section,

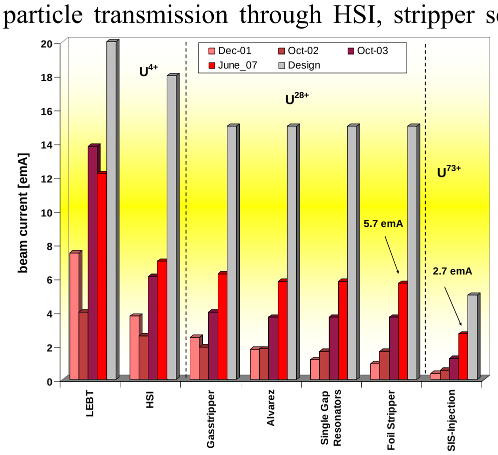

Figure 7: Improvement of the UNILAC-uranium beam intensities during the last three years.

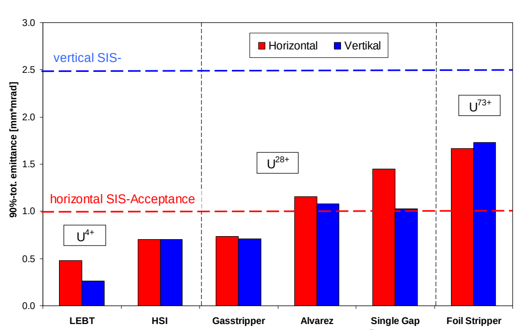

Figure 8: High current beam emittance measured during the measurement campaign in June 2008.

Alvarez DTL, Single gap resonator chain, and TK is larger than 50 % if the particle losses during charge state separation behind the two strippers are taken into account. The measured transverse beam emittance (see Fig. 8) exceeds the acceptance of the synchrotron. The planned front end upgrade and the resulting improvement of the beam brilliance will serve to overcome these bottlenecks.

LAYOUT OF THE FAIR-PROTON LINAC

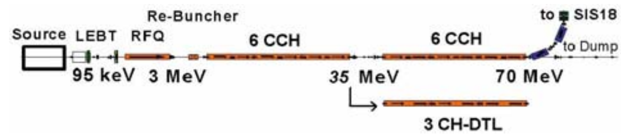

Figure 9: Two proposed schemes for the FAIR p-linac. [11]

To provide the primary proton intensities a dedicated proton linac is planned comprising a proton source, an RFQ, and a DTL, both with an operation frequency of 325 MHz allowing for acceleration up to 70 MeV. For the first time normal conducting Crossed-bar H-cavities (CH) are used. The beam pulses with a length of 36 μs, a current of 35 mA, and total transverse emittances of 7 μm will allow filling the existing synchrotron SIS 18 within a multi-turn-injection up to its SCL of $7 \cdot 10^{12}$ protons. The GSI Proton injector will be the fist machine based on CH-DTL cavities applying a KONUS beam dynamics scheme. The beam dynamics layout has been designed assuming an input current up to 70 mA, twice the value required during operation. Two different layouts are still under investigation, the first design appropriates coupled cavities only and the second makes use of a standard cavity in the high energy section. Beam dynamics investigations including loss studies show that both designs can fulfil the FAIR requirements, and they are robust enough against inevitable errors. At present time technical drawings of the second resonator of the proton injector are in preparation; after validating the coupling scheme with the construction of a scaled model. The construction of the FAIR Proton injector should start in 2010, while the commissioning phase should be finished in 2013. [11]

COMMISSIONING OF THE HITRAP DECELERATOR

Accelerated and highly stripped heavy ions from the GSI accelerator complex are stored, decelerated down to 4 MeV/u, and finally cooled in the ESR. After beam extraction the ions have to be further decelerated down to 6 keV/u. An IH drift tube cavity and a 4-rod RFQ, both operating at 108 MHz, decelerate the beam down to the final beam energy in two steps. Longitudinal matching to the IH structure is applied by a double-drift-buncher combination comprising a 108 MHz λ/4-resonator and a 2nd harmonic cavity. A third rebuncher of spiral type is located between IH and RFQ. Finally, a low power spiral type debuncher inside the RFQ tank provides for the reduced beam pulse spread sufficient for beam capture in the super conducting penning trap. Within three commissioning periods the technical and physical functionality of the HITRAP-decelerator was proofed (see Fig. 10). No major problems occurred. Additional magnetic steering devices turned out to be necessary for proper beam transport tuning, the setting values were slightly modified by experience, and the working points of the rf-structures were fixed. For improved beam energy analysis a bending magnet and an additional scintillation screen will be installed temporarily behind the IH tank. The RFQ high power conditioning already began. The tank will be finally installed in autumn 2008. HITRAP commissioning will be finished until mid of 2009. [12]

LONGTERM PERSPECTIVES

After recommissioning of the UNILAC with the highest heavy ion beam intensities, the replacement of the existing Alvarez-DTL is proposed, leading to a sustain operation for the next decades. Additionally a dedicated new cw-Linac could deliver high duty factor beams for the SHIP experiment with energies up to 7.5 MeV/u. A first conceptual layout is shown in Fig. 11. Behind the HSI a new 4 MV/m 108 MHz IH-LINAC (50 m total length) provides a high intensity 5 MeV/u U^{4+}-beam. The existing gas stripper section is reused to perform a beam intensity of 24 emA in charge state 42+. The present LINAC-tunnel may house a high efficient 325 MHz-CH-LINAC (35 m), able to boost the beam energy up to 30 MeV/u. In the transfer line to the SIS 18 the foil stripper and the new compact charge state separator will be able to provide for charge state 82+. If the gas stripper will be replaced by a solid state stripper a beam energy of 42 MeV/u (charge state 63+) will be realized. A further upgrade option may provide a second 100 m-CH-LINAC (325 MHz) to enhance the beam energy to up to 100 MeV/u (U^{41+})/150 MeV/u (U^{63+}), sufficient to feed the FAIR 100 Tm synchrotron directly. [13]

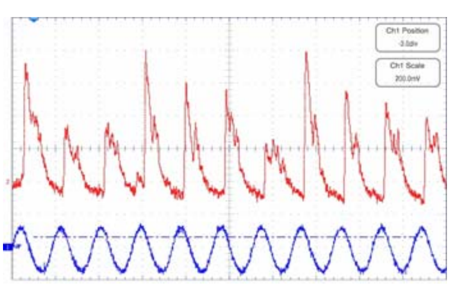

Figure 10: Bunch measurement of a 4 MeV/u $^{20}Ne^{10+}$- beam with the diamond detector (top) and 108 MHz reference signal (bottom) [12]

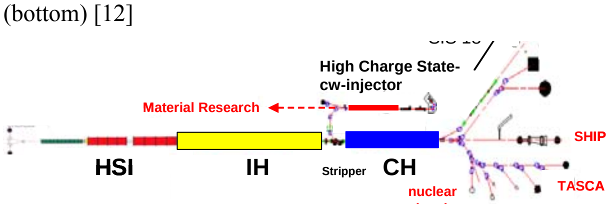

Figure 11: Conceptual layout of a multipurpose high intensity heavy ion linac at GSI [13]

OUTLOOK

- The UNILAC-upgrade program for FAIR will be finished until 2011; the required U^{28+}-beam intensity of 15 emA (for SIS 18 injection) should be available especially after the complete front end upgrade.
- The replacement of the Alvarez-DTL by a new 5 MeV/u, high Bρ IH-DTL and an advanced 30 MeV/u high energy linac is advised to provide a robust and safe operation for the next decades.
- An additional linac-upgrade option sufficient to boost the beam energy up to 150 MeV/u will help to reach the desired heavy ion intensities in the SIS 100.
- An enhanced primary beam intensity at the target is required for different experimental programs with heavy ion beams up to an energy of 7.5 MeV/u. It is recommended to build a cw-heavy heavy ion-LINAC.
- A design study of a multipurpose high intensity heavy ion injector considering all future requirements will be prepared.

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