# DEVELOPMENT OF THE INTENSITY AND QUALITY OF THE HEAVY ION BEAMS AT GSI

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*Abstract*

For injection into the future FAIR SIS100 synchrotron the GSI linear accelerator UNILAC and synchrotron SIS18 have to provide $1.5{\cdot}10^{11}$ p/spill for the reference $U^{28+}$ beam. The MEVVA ion source extracts 37 emA of $U^{4+}$ beam. For improved transmission in the front end accelerator the RFQ vanes were revised and exchanged. A new ion source terminal with direct beam injection into the RFQ is calculated and partly realized for loss free beam transport to the RFQ. To improve the quality of the space charge dominated beam in the DFFD periodic focussing Alvarez section a transversal 4$^{th}$ order resonance was investigated by simulations and experimentally. The multi turn beam injection into the SIS18 requires emittances below $\beta\gamma\varepsilon x/\beta\gamma\varepsilon y = 0.8/2.5$ µm. This suggests introducing a new concept for emittance transfer by solenoidal stripping. A set-up for experimental proof of principle will be installed at the foil stripper. The SIS18 has been equipped with NEG-coated chambers for all magnets and the injection septum. Newly installed ion catchers improve especially the dynamic vacuum pressure. The effect on progress in beam quality development and intensity will be reported.

## INTRODUCTION

For the reference ion $U^{28+}$ the UNILAC has to inject $2{\cdot}10^{11}$ particles per 60 µs into the SIS18. This again injects four batches of $1.5{\cdot}10^{11}$ particles each into the future FAIR SIS100 synchrotron [1] with a repetition rate of 2.7 Hz to fill it finally with $6{\cdot}10^{11}$ particles for acceleration up to 2.7 GeV/u for radioactive beam production. Alternatively SIS100 accelerates intense proton beams up to 30 GeV for pbar-production.

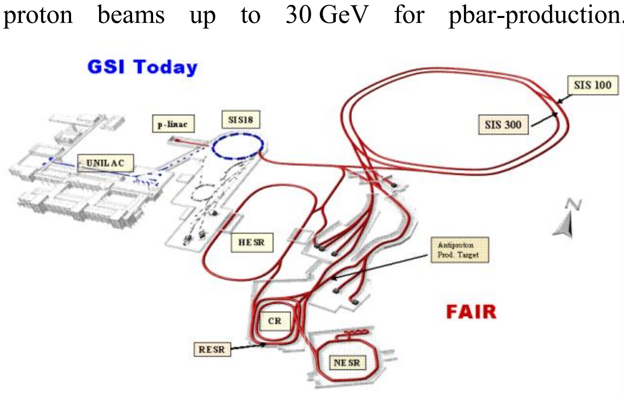


Fig. 1: The existing GSI accelerators UNILAC and SIS18 and the future accelerator facility FAIR.

This booster operation of the SIS18 [2] is the most challenging case concerning beam intensity, repetition rate, and dynamic vacuum challenges. 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 the production of 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.

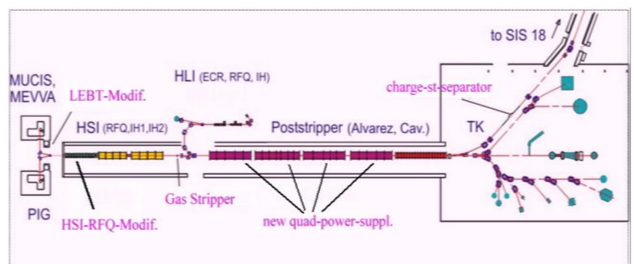


Fig. 2: Schematic overview of the UNILAC, experimental area, transfer channel to SIS, and locations of upgrades.

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 and is also suitable for 4 Hz pulse-to-pulse operation of beams from different ion species passing through different stripping foils.

The SIS18 rigidity is 18 Tm with warm magnets of 1.8 T maximum field strength. The present ramp power is limited to 4 T/s. This allows a repetition rate of ~ 1 Hz only. The ring includes 12 double dipole magnets with magnetic quadrupole triplet or doublet focussing in each of the 12 sections. Two rf-cavities with a frequency range of 800 kHz up to 5.6 MHz apply 32 kV acceleration voltage each. Depending on the mass to charge ratio the beam extraction energy is for example 220 MeV/u for $U^{28+}$, 1 GeV/u for $U^{73+}$, and up to 2 GeV/u for lighter heavy ions. A scheme of the SIS18 is given in Fig. 3.

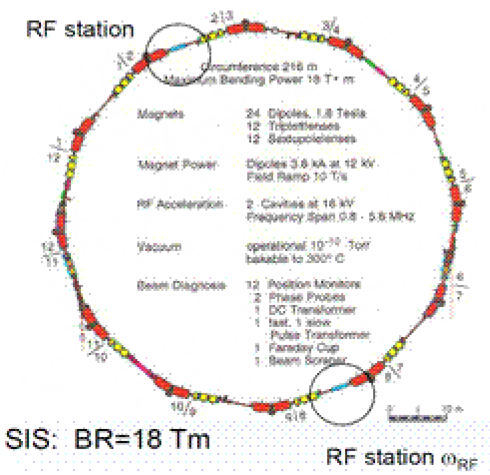


Fig. 3: The SIS18 synchrotron.

## BEAM DEVELOPMENT AT THE UNILAC

### *New Design for the RFQ Vanes*

In 2009 the 36 MHz RFQ accelerator was upgraded by exchange of the mini vanes [3]. The new vanes should provide for higher transverse acceptance and phase advance and finally improved beam transmission. This implies a new input radial matcher design and improved beam dynamics for gentle bunching to get rapid and uniform separatrix filling.

Table 1: Main RFQ parameters

| | New Design | Old Design (bef. Upgr. '09) |
|---|---|---|
| Inter vane voltage, kV ($U^{4+}$) | 155 | 125 |
| Average Aperture Radius, mm | 6.0 | 5.245 - 7.745 |
| Electrode Width, mm | 8.4 | 9.0 - 10.8 |
| Maximum field, kV/cm | 312.0 | 318.5 |
| Modulation | 1.012 - 1.93 | 1.012 - 2.09 |
| Synch. Phase, degree | -900 - -280 | -900 - -340 |
| Aperture, mm | 4.10 | 3.81 |
| Min. transverse phase advance, degree | 31.8 | 25.8 |
| Norm. transverse acceptance, mm mrad | 0.856 | 0.73 |
| Output energy, keV/u | 120 | 118.5 |
| Number of cells with modulation | 394 | 343 |
| Length of electrodes, mm | 9217.4 | 9217.4 |

Beam dynamics calculations were carried out with the codes DYNAMION and PARMTEQ-M and predicted 18 emA of $U^{4+}$ beam at the RFQ exit (see Table 1). This value meets the FAIR requirements.

Due to the enlarged normalized acceptance of 0.86 µm and the maximum rf voltage of 155 kV the $U^{4+}$ beam ou s
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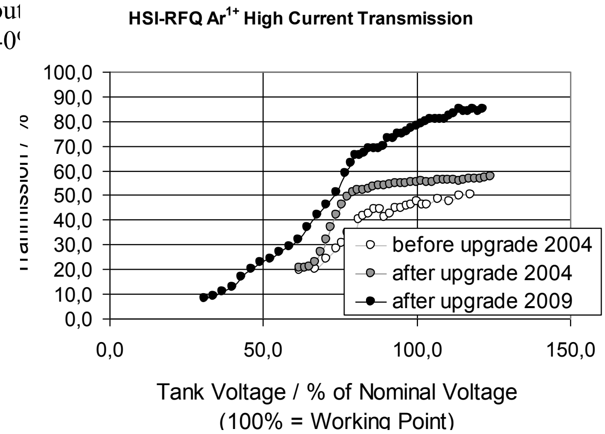


Fig. 4: Measured RFQ beam transmission of an $Ar^{+}$ beam of 10 emA intensity depending on rf voltage before and after exchange of the vanes.

Fig. 4 shows the increase of beam transmission up to 90%. Concerning space charge forces the 10 emA $Ar^{+}$ beam is equivalent to a 15 emA $U^{4+}$ beam.

### *New Ion Source Terminal and Compact LEBT*

The existing LEBT includes a 77.5° mass spectrometer which causes filamentation of the transverse emittances and therefore an emittance growth of ~ 50%. For this reason a new ion source terminal with straight LEBT has been calculated and planned (see Fig.5) [4].

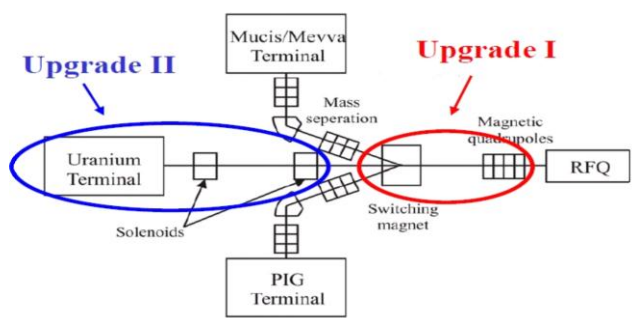


Fig. 5: New third ion source terminal and compact LEBT.

The red indicated area is already bought and partly installed. For the blue indicated area the first sc solenoid is in house and used for a high current ion source test bench. The aperture will be completely enlarged and all beam diagnostics are exchanged by aperture suited devices.

The ion sources deliver 37 emA of $U^{4+}$ beam and 18 emA of a $U^{3+}$. The compact LEBT transports the entire $U^{4+}$ fraction to the RFQ entrance. Calculations with the codes PARMILA-Transport and DYNAMION demonstrate that a part of the $U^{3+}$ fraction of the beam will be lost in front of the RFQ, another one in the RFQ tank. Finally only 1.6 emA reach the RFQ exit but 20.3 emA of $U^{4+}$ beam is accelerated in the RFQ (Table 2).

Table 2: $U^{4+}$ front end beam intensities for the existing and the future compact LEBT

| | MeVVa-ion source output | Entrance RFQ | Exit RFQ |
|---|---|---|---|
| Existing LEBT | 37 mA $U^{4+}$ analyzed | 16.0 mA | 14.0 mA |
| Compact LEBT | 37 mA $U^{4+}$ 18 mA $U^{3+}$ | 37 mA $U^{4+}$ 18 mA $U^{3+}$ | 20.3 mA $U^{4+}$ 1.6 mA $U^{3+}$ |

This injection scheme provides the necessary front end beam intensity to satisfy the requirements for FAIR.

### *4th Order Space Charge Driven Resonances*

Assumed is a periodically breathing beam envelope with phase advance $\sigma_{env}$ and envelope with radial symmetry. The single particles experience constant external focusing with $\sigma_o$ from magnets and electric field of breathing beam size. From this derives the resonance condition: $\sigma_{env} = 360° \rightarrow \sigma = 90°$. This means: 4th order space charge driven resonance occurs at $\sigma = 90°$, i.e. $\sigma_o \geq 90°$, envelope oscillates 4 times faster than single particle.

The UNILAC Alvarez DTL quadrupoles follow the DFFD periodic focusing. For this reason the Alvarez section including 180 quadrupoles is well suited for a 4<sup>th</sup> order resonance experiment [5, 6, 7].

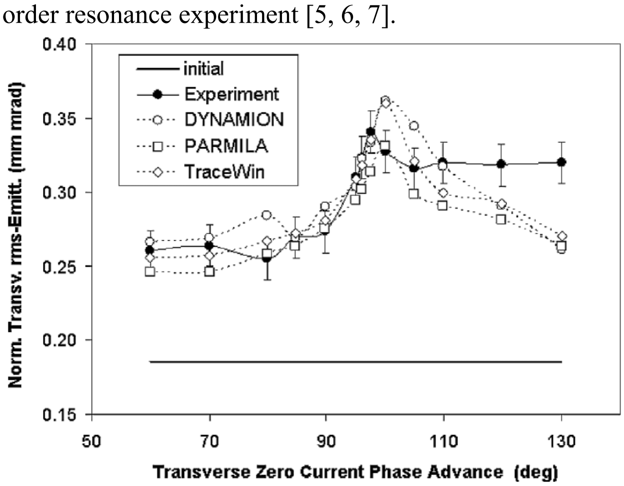


Fig. 6: A strong emittance growth in the Alvarez DTL calculated and measured.

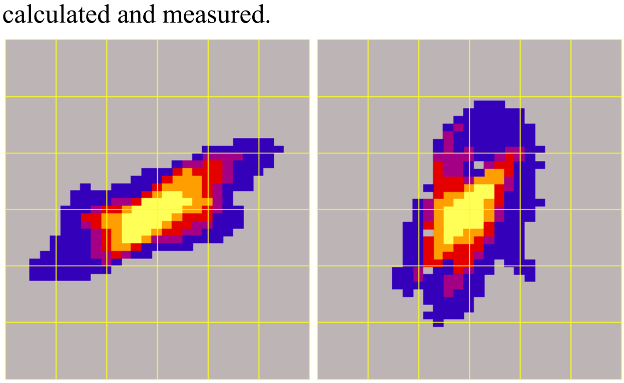

Fig. 7: Measured emittances behind the Alvarez DTL

An $Ar^{10+}$ beam of 7 emA was used to allow for high phase advance settings of the quadrupoles. This beam is equivalent to a 15 emA beam of $U^{28+}$, corresponding to the FAIR requirements. The results of different simulation codes and experimental data are shown in Fig. 6. A significant emittance growth occurs at $\sigma_o = 100°$. Considering tune depression $\sigma \approx 90° = 360° / 4$.

In the measurements four wings were observed in the transverse emittances at $\sigma_o = 100°$ in good agreement with three simulation codes (see Figure 7). For linacs so far resonances considered to be of no concern for operation. But there is evidence for enveloped matched operation of the UNILAC DTL.

### *Beam Quality Development*

Table 3 shows the requirements of beam intensity and quality for injection into SIS18 and the measured maximum intensity.

Table 3: $U^{28+}$ beam requirements on the UNILAC

| required ions/60µs | Transverse emittances [µm] | measured ions/60µs |
|---|---|---|
| $2.0 \cdot 10^{11}$ 15 emA | $\beta\gamma\varepsilon x = 0.8$ $\beta\gamma\varepsilon y = 2.5$ | $0.8 \cdot 10^{11}$ 5.7 emA |

With the $U^{28+}$ beam intensity the UNILAC currently reaches ~ 40% of the desired value. A big step towards 15 emA is expected with the operation of the new ion source terminal and compact LEBT. Particularly a progress in beam brilliance by optimizing the extraction and pre-acceleration cascade geometry is expected with the commissioning of this new accelerator part.

A further challenge is to adapt the horizontal and vertical emittances to the values derived from SIS18 multi turn injection scheme, see Table 3. Fig. 8 demonstrates the present discrepancies in terms of brilliances.

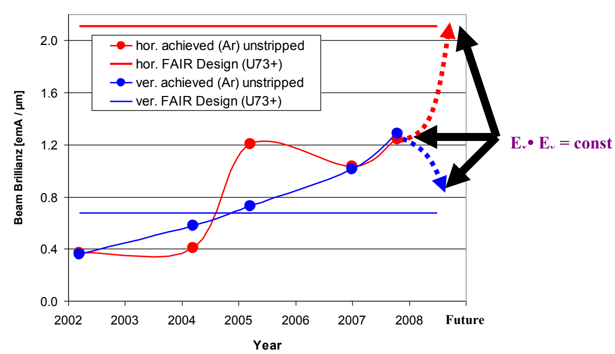


Fig. 8: Measured and required beam brilliances at Alvarez DTL exit.

To overcome this problem, an emittance transfer method was developed and an experimental proof of principal is foreseen [8]. This method requires a non-symplectic beam transformation creating x-y-coupling and skewed quadrupoles. The non-symplectic element will be given by a Helmholtz coil around the foil stripper chamber and a change of the magnetic rigidity by ionization in the midplane. The beam is correlated at the exit of the solenoid field. The skewed quadrupoles retract the correlation. A scheme of the experiment for proof of principle is given in Fig. 9. First experiments are foreseen to start in autumn 2013.

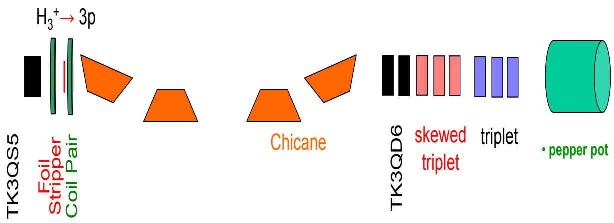


Fig. 9: Beam line configuration at the foil stripper section for an emittance transfer experiment.

Beam simulations with the PARMILA-Transport code were carried out with the result of complete beam transmission, a reduction of $\varepsilon_x$ of 41%, a growth of $\varepsilon_y$ of 142% and a growth of the $\varepsilon_{4d}$ of 42%. The emittance growth is due to foil scattering and unavoidable [9].

If these results will be confirmed by the beam experiments, the UNILAC beam quality would fit the SIS18 requests.

## BEAM DEVELOPMENT AT THE SIS18

### *Ionization Beam Loss and Dynamic Vacuum*

The most challenging task of the SIS18 synchrotron is the acceleration of ions with intermediate charge states in booster operation to fill the FAIR SIS100 with four batches of $1.5 \cdot 10^{11}$ $U^{28+}$ particles each.

Ionization beam loss with a desorption factor $\eta$ ~10,000 causes local pressure bumps and is by far the dominating loss process. It begins significantly earlier as space charge and current depending effects. This was observed from static residual gas pressure measurements and by means of current measurements on a charge catcher system one section downstream. Fig. 10 shows significant pressure bumps driven by the beam losses. Due to that, the main goal was the generation of the static vacuum pressure $p_0 < 5 \cdot 10^{-12}$ mbar by an average pumping speed increased by a factor of 100 and the stabilization of the dynamic pressure p (t) $< 1 \cdot 10^{9}$ [10].

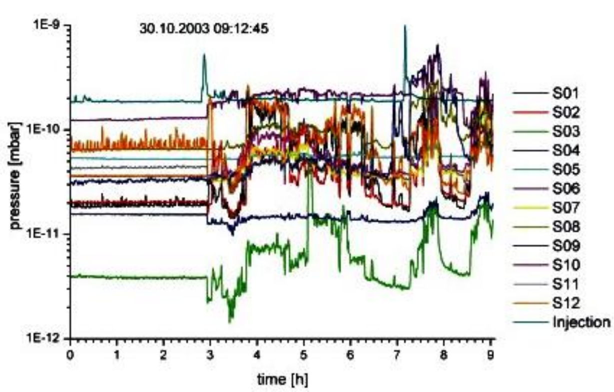


Fig. 10: Vacuum pressure in the 12 SIS18 sections during high current operation.

To improve the vacuum, GSI established a NEG (non evaporable getter) coating facility [11]. 24 dipole magnet chambers, 16 quadrupole chambers and 13 straight pipes were replaced between 2006 and 2009 by NEG coated chambers, which corresponds to 65% of the SIS18 circumference. Additionally, to overcome the dynamic vacuum instability 10 collimation systems equipped with thin film coated (see Fig. 11) absorbers were designed and commissioned. At the same time an upgrade of the bake-out system for a temperature of 300°C was completed.

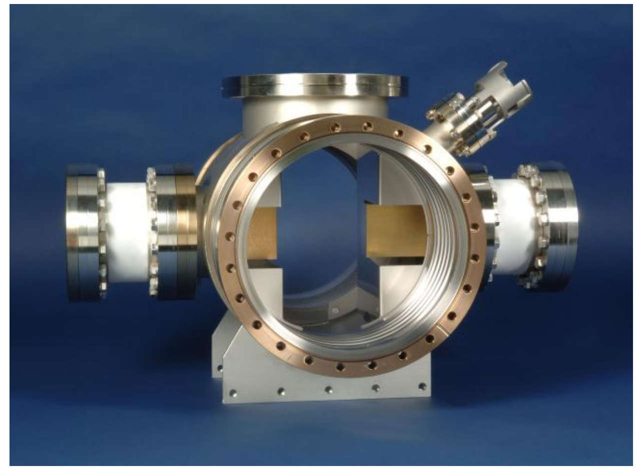

Fig. 11: NEG coated scraper chamber with Au coated Cu ion catcher blocks. Diagnostics: extractor ion gauge and current measurement of charge exchanged ions.

The reduction of the initial beam loss has an outstanding importance for the dynamic vacuum and FAIR booster operation. Initial beam loss originates initial pressure bumps, which dominate the dynamic vacuum situation and ionization beam loss in the machine cycle. Therefore, the reduction and control of the beam loss at multi turn injection was a major issue of the development program. Various experiments have been carried out to study the beam injection process. From these experiences a new injection system has been derived with the following characteristics:

- Increased acceptance
- Injection of $U^{28+}$ at 11.4 MeV/u
- Protection of septum electrodes
- (1.5 MW beam peak power)
- No HV break downs
- Reduced ionization beam loss
- Introduction of NEG panels
- Aim for reduced gas production.

Fig 12 demonstrates the implications of the vacuum improvement on the increase of life time for intermediate charged heavy ions of a factor of 10 with NEG coated vacuum chambers and even a factor of 40 considering the new injection chamber. Under these improved conditions a new intensity record was reached with only $3.0 \cdot 10^{10}$ $U^{27+}$ particles injected by the UNILAC due to device failures and $2.1 \cdot 10^{10}$ $U^{27+}$ particles extracted at the SIS18 (see Fig. 13) [12].

Another record of highest average intensity was reached in 2012. A Nitrogen beam with continually more than $10^{11}$ ions per cycle has been generated with an energy of 2 GeV/u. Due to fast ramping with 4 T/s and a short extraction time of 0.5 s, an average beam intensity of $3.0 \cdot 10^{10}$ ions/s has been extracted.

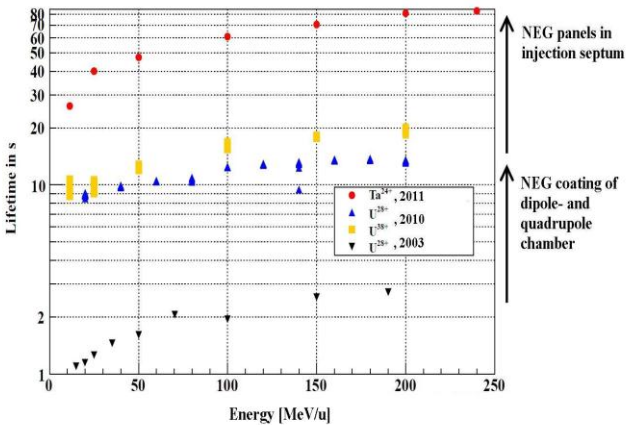


Fig. 12: Beam life time of intermediate charged heavy ion beams in the SIS18 for three developing stages.

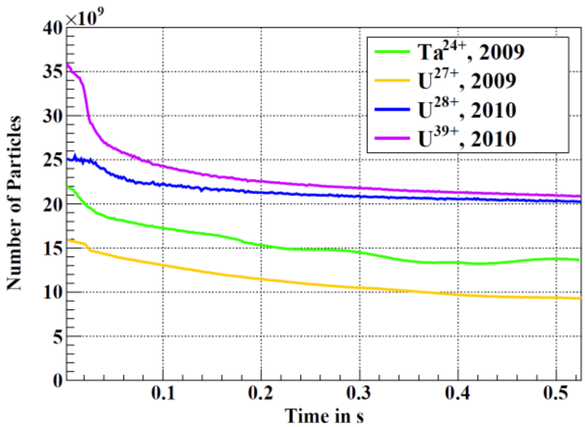


Fig. 13: Development of beam intensity at SIS18.

## SIS18 UPGRADES IN PROGRESS

### *Faster SIS18 Ramping Cycles*

Since 2011 GSI is connected with the 110 kV power grid. In 2013 high performance power supplies for all dipole and quadrupole magnets will be introduced. Thus, the ramping rates listed in Table 4 can be realized and a repetition rate of the SIS18 cycles $f_{rep}$ = 2.7 Hz eases additionally the booster operation by fast crossing of the still remaining rise of the dynamic vacuum by ionization effects.

Table 4: SIS18/100/300 field ramping rates

| | Pulse Power | Field Rate |
|---|---|---|
| SIS18 (now) | + 5 MW | 1.3 T/s |
| SIS18 (2013) | + 42 MW | 10 T/s |
| SIS100 | ± 26 MW | 4 T/s |
| SIS300 | ± 23 MW | 1 T/s |

### *New h=2 Acceleration Cavity*

A new h=2 accelerator cavity [13, 14, 15] is under construction as complementary cavity to the both existing cavities for h=4 operation. These provide 32 kV acceleration voltage and a frequency range of 800 kHz to 5.6 MHz. The new cavity will provide 50 kV by three modules each driven with two tetrode tubes of 300 kW anode dissipation power working in push-pull-operation able to operate independently from each other. According to h=2 operation the frequency range is 400 kHz to 2.7 MHz. Since the cavities are filled with lossy MA-ring-cores, which are iron based Finemet FT3M ring cores from Hitachi, the cavities show a broadband behaviour and thus no cavity tuning during the acceleration ramp will be necessary. Due to limited installation space in the SIS18 ring, the cavities are based on nano-crystalline novel magnetic alloy materials (MA-materials). The Q-value is 0.5. A comparable ferrite driven system would have a length of 7 m. The overall consumption is 1.6 MW. The cavity is cooled by oil, suppressing parasitic modes and avoiding corrosion. A parameter overview is given in table 5.

Table 5: Broadband cavity with power unit

| | |
|---|---|
| Duty cycle | 100% |
| Frequency range with the hardest requirements | 0,429 MHz - 1,6 MHz (full range 0,4 - 2,7 MHz) |
| Overall voltage | 16.7 kV |
| Number of gaps | 2 |
| Number of ring cores per unit | 16 |
| Shunt impedance Rp per half gap (one stack of 4 ring cores) at 429 kHz | 440 Ω |
| Parallel inductance Lp per half gap at 429 kHz | 308 μH |
| Parallel capacitance Cp per half gap | 50 pF |
| RF dissipation power per unit | 80 kW |
| RF dissipation power per ring core | 5 kW |

The advantages of the h=2 cavities are the following:

- Sufficient rf voltage for fast ramping with low charge state heavy ions:
  $U^{73+}$ acceleration with 4 T/s ($2 \cdot 10^{10}$ ions)
  $U^{28+}$ acceleration with 10 T/s ($2 \cdot 10^{11}$ ions)
- Bucket area for loss free acceleration and 30% safety
- Flat bunch profile for lower inc. tune shift
- Two harmonic acceleration:
  h=4 (existing cavity) and h=2 (new cavity)
- Compatible with SIS100 RF-cycle
- 50 kV – high power requirements – additional space provided in tunnel.

Commissioning of the first module is planned for 2013.

## CONCLUSION AND OUTLOOK

With the sequence of upgrade measures at the UNILAC a maximum beam intensity of ~ 40% of the desired values was reached already in 2007. Unfortunately this intensity was not reproducible afterwards due to successive different hardware failures. Particularly the Alvarez DTL, which is in operation since 40 years, had different prolonged break downs. Therefore the SIS18 performance could not be proofed with the maximum beam intensity of the UNILAC afterwards. This means, the intensity records of the UNILAC and SIS18 do not correspond to each other and the SIS18 output intensity is to be seen under these temporary restrictions. Scaling linearly the SIS18 record with the best reached UNILAC intensity of $8.0 \cdot 10^{10}$ $U^{28+}$ particles/60 µs, the SIS18 output intensity would be $5.6 \cdot 10^{10}$ particles. Consequently both machines perform presently about 40% of the FAIR requirements.

Presently the UNILAC as well as the SIS18 have reached full performance. In July and September 2013 machine experiments are planned to confirm or even to overshoot the intensity records in combined operation.

The missing intensity factor for FAIR of roughly 2.5 can be gained by the planned straight LEBT and new ion source terminal. The SIS18 performance will be increased by the introduction of the powerful h=2 cavities and the 2.7 Hz cycle frequency. These residual measures are realizable easily before FAIR commissioning will start.

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