APPROACHES TO HIGH INTENSITIES FOR FAIR (*)

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Abstract

An accelerator complex is planned to generate highest intensities of heavy ion and proton beams for the new Facility for Antiproton and Ion Research (FAIR) at GSI. The two new synchrotrons, SIS100 and SIS300 which generate the primary beams for the FAIR target stations, will be served by the existing GSI accelerators, UNILAC and SIS18. In order to reach the desired intensities close to 10^{12} uranium ions and 5 x 10^{13} protons per pulse, a substantial upgrade program of the existing facility is presently being conducted. The status and the technical subprojects of these upgrade programs and the concepts for approaching the FAIR intensity goals are described.

VARIS SOURCE FOR HIGH INTENSITY URANIUM BEAMS

MEVVA ion sources [1] are well suited to generate high current beams of metal ions. Especially for high density metallic ion beams, the MEVVA IV ion source has proven its capability at GSI over many years. However, until now it was not possible to reach the design current for uranium ions for injection into the UNILAC-RFQ. Therefore, based on a MEVVA ion source a new Vacuum **ARc Ion Source (VARIS)** has been developed and taken into operation successfully.



Figure 1: VARIS. 1: cathode flange with 17 single cathodes, 2: Uranium cathode, 3: anode, 4: 10 SmCo magnets in cusp field arrangement, 5: solenoid I, 6: solenoid II, 7: Plasma electrode, 8: screening electrode, 9: ground electrode, 10: high temperature insulators, 11: stainless steel grids

Figure 1 shows a cross sectional view of the ion source. The discharge arrangement has a tubular anode opposite to the cathode retainer carrying 17 cathodes. For charge state enhancement the anode material plays an important role as shown in [2]. With stainless steel a high arc voltage and thereby a high mean charge state could be achieved. The solenoids are responsible for a higher impedance of the arc discharge. The impedance of 0.044 Ω was increased by a factor of 1.7 for a flux density of 45 mT at an arc power of 21 kW. For extraction a multi aperture accel-decel system has been designed. It consists of 13 apertures each 3 mm in diameter made of molybdenum to ensure high gap field strength. Most important improvements compared to the MEVVA IV ion source are: higher beam current density, higher fraction of U⁴⁺-ions, better pulse to pulse stability, reduced power density and therefore higher efficiency and longer life time, reduced service time, faster start of operation after ion source replacement at the injector, better availability and better cost efficiency.

Ion Source Performance

Usually vacuum arc ion sources produce an ensemble of uranium ions with a mean charge state of q=3+. The fraction of U⁴⁺, required for injection into the UNILAC-RFQ, is typically about 30 %. To optimize the ion source for a high U⁴⁺-fraction, the influence of the plasma parameters and the geometry of the ion source on the mean charge state was investigated. It could be shown, that increasing the arc voltage and the power density at cathode and anode results in a higher mean charge state.



Figure 2: Ion fraction as a function of the flux density for 700 A arc current (solid line). Mean charge state as a function of the arc current for a flux density of 45 mT (dotted line).

Figure 2 shows the dependency of the charge distribution as a function of the flux density at an arc current of 700 A (solid line). We observed at maximum 67 % of U^{4+} at a flux density of around 40 mT of solenoid I. For the generation of U^{4+} -ions the arc voltage and therefore the electron energy distribution seem to be optimal at a flux density of 40 mT. However, the mean charge state increases continuously for increasing flux density as well as for increasing arc current in conjunction with the magnetic flux density (dotted line).

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Charge distribution	$U_{4+}^{3+} = 16\%, U_{4+}^{4+} = 67\%$
	$U^{5+} = 14\%, U^{6+} = 3\%$
Arc current /arc power	600-700 A / up to 30 kW
Pulse length / rep. rate	0.6 ms/1 Hz
Extraction system	13×3 mm, multi aperture
Emission current density	170 mA/cm^2
Full beam ion current	156 mA @ 35 kV
dc ion current	55 mA @ 131 kV
Analysed U ⁴⁺ current	25 mA
Noise full beam/analyzed	$<\pm 4\%$ / $\pm 5\%$
Pulse to pulse stability	Better than 80 %
Voltage break downs	2 per day
Cathode life time	12 hours @ 0.6 % dc
Life time	7 d for SIS inj. (0.2 ‰ dc)

Table 1: C	perating	data	of the	VARIS	ion	source
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Table 1 shows the operating data of the VARIS ion source. The acceptance of the ion source is dominated by the geometry of the multi aperture extraction system. It amounts to 200 mm mrad for an ion beam current of 156 mA with divergence angles of 20 mrad. Behind the dc post acceleration the emittance has increased by a factor of 1.75. The increase of the emittance is caused by a non homogeneous distribution in front and at the entrance of the acceleration gap where the space charge compensation is removed. Non homogeneous beam distributions tend to become homogeneous again to the disadvantage of an emittance increase. After the bending magnet the separated U⁴⁺ beam current for injection into the RFQ amounts to 25 mA.

The noise of the ion beam and the pulse to pulse stability has been optimized in a way that the ion source can be used in routine operation. 80 % of the pulse to pulse stability means that only 20 % of the ion beam pulses are below the threshold of 90 % current level. Given by the requirements from the synchrotron operation, the life time of the ion source reaches seven days.

At the required ion currents, the matching to the preacceleration gap and the optics in the gap are of high importance for the final emittance. Surveys on a combined system extraction and pre-acceleration lead to a new high voltage electrode design which reveals a brightness gain of approximately 1.5. A high current test injector HOSTI has been build to investigate the achieved improvements.

UNILAC - HIGH CURRENT HEAVY ION INJECTOR

In order to reach the desired heavy ion beam intensities for the final FAIR operation, UNILAC has to accelerate $3.3 \cdot 10^{11} \text{ U}^{28+}$ -particles in a macro pulse with a length of $100 \,\mu\text{s}$ (or $4 \cdot 10^{10} \text{ U}^{73+}$ in FAIR stage 1) [3, 4]. These pulses will be injected with a maximum repetition rate of 4 Hz at an energy of 11.4 MeV/u into the heavy ion synchrotron SIS18. The bottleneck for the planned high intensity operation is the low energy front end called High Current Injector (HSI). The High Current Injector [5] consists of a 36 MHz IH-RFQ accelerating ions from 2.2 keV/u to 120 keV/u and a short 11 cell adapter RFQ (Super Lens). The following IH-DTL, consists of two separate tanks and accelerates the beam up to the final HSI-energy of 1.4 MeV/u. Downstream the HSI, uranium beams with charge state q=4+ delivered from the source, are stripped in a supersonic gas jet and ions with charge state q=28+ are separated for injection into the following ALVAREZ section. The Alvarez DTL accelerates the beam to the SIS18 injection energy without significant particle loss. The transfer line (TK) between UNILAC and SIS 18 is equipped with a foil stripper and another charge state separator system. This system is required for the generation of highly charged ions for the operation (e.g. U^{73+}) in SIS18 and for FAIR stage 1.

UNILAC UPGRADE

High Current Injector HSI

For the requested operation with intense uranium beams, the performance of UNILAC has already been improved during the last years. The high Rf surface field in the RFQ and in the Super Lens, requires a careful Rfconditioning especially for low charge state heavy ion operation. Continuous Rf-conditioning with a low duty factor (of approx. 0.3 %) in a time sharing mode within the regular beam operation provides proper conditions for high Rf-amplitudes. In a revision were the Super Lens has been completely disassembled, the Rf-performance could be significantly improved: the required maximum surface field strength was slightly decreased, the surface quality was improved and a new plunger design was implemented [4]. A comparable maintenance has also been conducted for the HSI-RFQ; in Figure 3 (left) some of the dismantled RFO-electrodes are shown.



Figure 3: Revision of the HSI-RFQ; RFQ-electrodes after five years of operation (left), new electrodes before assembly (right).

After five years of operation the electrode surfaces were damaged along the whole structure, leading to significantly higher Rf-power requirements. The damaged electrodes were replaced; and by additional copper plating, a reduction of the "dark current" contribution during high power operation could be reached. By means of the DYNAMION code, the RFQ input radial matcher (IRM) was re-designed to improve the matching to the RFQ. The new matching has lead to smaller beam diameters in the quadrupole channel, resulting in an improved particle transmission. The expected gain in RFQ-transmission could be verified during beam operation: the achieved intensity for intermediate heavy ions (e.g. Argon) is now above the design limit (10 emA). A new advanced design of the IH-inner triplet lens provides an improved electromagnetic performance. The outer walls of the big drift tube are now directly water-cooled. The geometry of the subsequent small drift tube was changed, leading to an optimized field distribution (E_z) and lower "dark current" contributions during operating at the highest Rf-power levels [7].

A bottleneck behind the Alvarez section was eliminated by removing a part of the single gap resonators (5 from 15) – allowing beam transport with smaller beta-function modulation and better transmission. Additional adjustments along all sections of the UNILAC were performed with high accuracy.

By reducing the apertures in the stripper box between the HSI and the ALVAREZ section, it was possible to increase the stripper gas density up to 50 %. Thereby, for medium intensity uranium beams, a gain in the desired charge state q=28+ could be reached (up to 12.8 %). The desired equilibrium charge state distribution is now reached at a 70 % higher gas density.

For further improvement, moderate modifications of the RFQ electrodes are considered. The length of the RFQ may be increased by 1 m, corresponding to the length of one tank section. The extension of the radial matcher decreases the effective emittance growth at the RFQ entrance to about 20 %. The dependence of modulation and synchronous phase along the RFQ was investigated to minimize the beam emittance growth in the gentle buncher and to increase the particle capture efficiency. These measures result in a total transmission of 38 %.



Fig. 4a: Emittance growth and transmission of the beam along the axis of the existing RFQ

Figure 4a shows the transverse emittance growth with respect to the initial values and the transmission of all particles along the axis of the existing RFQ. Figure 4b shows the results for an upgraded RFQ. Table 2 summarizes the performance of the present and the investigated new front end systems. An upgrade of the LEBT system improves the front end transmission only by 11 %. By an additional extension of the RFQ length and a modified rod design, a total transmission gain of



52 % compared to the existing accelerator front end may

Fig. 4b: Emittance growth and transmission of the beam along the axis of an upgraded RFQ

Table 2: Parameters of different LEBT and RFQ designs14.5 mA Ar¹⁺ correspond to 22 mA U⁴⁺ beam current

Ar ¹⁺	Existing LEBT and RFQ	New LEBT and RFQ	New LEBT and RFQ	
Source current	38 emA	38 emA	38 emA	
RFQ input current [emA]	21.7	35.7	35.7	
Emittance $\varepsilon_x/\varepsilon_{y,}$ (90%)[mm mrad]	316/190	345/473	345/473	
RFQ length	9 m	9 m	10 m	
RFQ radial matcher	4 cells	4 cells	11 cells	
RFQ transm.:				
accel. particles	44%	30%	41%	
(all particles)	(60%)	(38%)	(45%)	
RFQ output current [emA]	9.5	10.5	14.5	
Total transmission	25%	28%	38%	

ALVAREZ section

Usually empirical matching is done by variation of the quadrupole setting in front of the DTL until a sufficient transmission through the Alvarez section of more than 90 % is achieved. In order to increase the transmission up to 100 % a systematic matching procedure was proposed and realized during machine experiments. To match the periodic DTL structure, a fitting routine involving the five matching quadrupoles has been developed. For the highest available uranium intensity the losses along the Alvarez section are reduced from 8 % to less than 1 % [6]. The post-accelerator performance can also be improved by the optimization of the quadrupole settings in the Alvarez DTL, especially in the 1st Alvarez tank. Due to the high mass over charge ratio (m/ ζ) of $^{238}U^{28+}$ ions, the maximum zero current phase advance σ_0 in the Alvarez DTL is limited to 45° mainly due to limitations in the quadrupole power supplies. However, a phase

advance of $\sigma_0 > 50^\circ$ is required for an improved beam brilliance for injection into SIS18. An optimal matching of space charged dominated ion beams is essential for a loss free injection into SIS18. Especially at the planned low charge state operation, initial beam loss drives pressure bumps which may significantly reduce the beam life time. For the FAIR operation in stage 1 with highly charged ions, transverse beam emittance measurements at different positions along the TK were performed. In particular, different foil stripping modes were investigated. For the high current heavy ion beam operation e.g. a sweeping mode is routinely applied to minimize the thermal stress of the carbon stripper foil. A longitudinal emittance measurement set-up was commissioned at the entrance to the TK. It is used extensively to tune the rebuncher cavities in the UNILAC. In addition, a test bench is in use for measurements of longitudinal bunch profiles, which enables the investigation of the final debunching to SIS18.

The present stripper section in the transfer channel to SIS18 is not sufficient to meet the FAIR-requirements and has to be re-designed. Therefore, a new dedicated stripper with vertical separation and strongly increased resolving power is under development.

²³⁸U-BEAM INTENSITY STATUS

Figure 5 summarizes the achieved uranium intensities in UNILAC and TK.



Figure 5: Improvement of the UNILAC uranium beam current during the last three years.

In December 2003, for the first time a U^{73+} intensity of 2 emA (27.5 pµA) could be generated for injection into SIS18, which corresponds to $1.7 \cdot 10^{10}$ particles per 100 µs. In front of the TK foil stripper, 4.5 emA (160 pµA) of U^{28+} beam intensity was measured ($1 \cdot 10^{11}$ particles per 100 µs). The total particle transmission through HSI, stripper section, Alvarez DTL, Single gap resonator chain, and TK reached is 50 %. The major losses are caused by the front end section of the HSI-linac. The

upgrade already started will be continued with the investigation of

- a new front end for U⁴⁺ [9],
- stronger power supplies for higher field gradients of the Alvarez quadrupoles,
- a charge state separator system [10] in the foil stripper section and
- versatile (partly non-destructive) beam diagnostics devices [11], sufficient for the operation with megawatt heavy ion beams.

SIS18 UPGRADE

The existing heavy ion synchrotron SIS18 will be used in two different operation modes within the FAIR project. In FAIR stage 1, SIS18 will serve as high energy accelerator, providing e.g. U^{73+} -ions at energies up to 1 GeV/u for the radioactive beam program involving the Super-FRS and the connected storage rings CR and NESR. In FAIR stage 2 and 3, SIS18 will be used in a fast repetition mode as booster for SIS100.



Figure 6: Present status of maximum number of particles of ions with different atomic numbers and low charge states accelerated in SIS18.

a) SIS18 operation in phase 1 as driver for the radioactive beam program requires:

- Operation with one cycle per second (1 Hz) and
- High intensity operation with highly charged heavy ion beams, especially acceleration of 2.10¹⁰ U⁷³⁺ ions per machine cycle,

b) SIS18 operation in phase 2 and 3 as booster synchrotron for SIS100 requires:

- Operation with 4 Hz for protons or 2.7 Hz for heavy ions and
- High intensity operation with intermediate charge state heavy ion beams, especially acceleration of
 - $2 \cdot 10^{11} \text{ U}^{28+}$ -ions per machine cycle or
 - \circ 5.10¹² protons per machine cycle
- Pulse-to-pulse switching between different ion species.

As described, in the FAIR stages 2 and 3, low charged ion beams shall be injected directly from the UNILAC into the booster synchrotron SIS18 without additional stripping in the transfer channel. Such an operation mode is well suited to provide high intensity heavy ion beams for two reasons: (a) the UNILAC beam current (in terms of number of particles) for injection of U^{28+} -ions into SIS18 is higher by a factor of 6 compared to the current of U^{73+} -ion beams, which is usually injected using the transfer channel stripper and (b) the incoherent space charge limit scales with A/q^2 such that the desired high beam intensities may be reached in both synchrotrons SIS18 and SIS100.

During the last three years GSI could increase the Uranium intensities for injection into SIS18 significantly. The described upgrade projects for the UNILAC will further raise the U^{28+} beam current from the present 2.5 emA to the required 15 emA. With this intensity, 2.7·10¹¹ U^{28+} -particles will be injected within 82 µs into SIS18.

In the booster mode, SIS18 will be operated with a dipole ramp rate of 10 T/s up to a maximum dipole field of 1.8 T, which corresponds to a maximum magnetic rigidity of 18 Tm. This operation mode requires a replacement of the main dipole power converters. Starting from July 2006, GSI is being connected via an individual 110 kV power line to a main transformer station nearby. This new power grid connection has been build in order to avoid local undesired disturbance of the power grid stability and thereby overcome the present power limits for SIS18 operation. An extended upgrade program has been launched to achieve the described operation parameters. Nearly all main technical subsystems are involved. The most important upgrade tasks and the scheduled year of installation (in brackets) are:

- Task 1: RF System New h=2 acceleration cavity and bunch compression system for FAIR stage 0, 1 (2009 and 2006/2007)
- Task 2: UHV System New, NEG coated dipoleand quadrupole chambers (2008/2009)
- Task 3: Insertions Set-up of a "desorption" scraper system (2008/2009)
- Task 4: Injection/extraction systems New injection septum, HV power supply and large acceptance extraction channel (2006)
- Task 5: Beam diagnostics system Fast residual gas profile monitor and high current transformer (2007)
- Task 6: Injector Set-up of a new transfer channel charge separator (2007)

The world wide unique synchrotron operation with low charge state heavy ions is one of the most crucial issues of the FAIR project. In order to be able to make predictions on the effectiveness of the proposed UHV system upgrade, a new simulation code (STRAHLSIM) has been developed. The results show, the UHV system upgrade alone does not lead to the desired stable conditions. The operation at a stable dynamic pressure of about $4 \cdot 10^{-10}$ mbar for injection and acceleration of $2.7 \cdot 10^{11}$ U²⁸⁺-ions does moreover require an R&D phase for the development and testing of a new dedicated scraper system [12], including R&D in the field of gas desorption physics. However, it is expected that even after the full UHV upgrade has been realized, a significant amount of ionization beam loss must be accepted (see Figure 7).



Figure 7: Expected U^{28+} -beam intensity evolution in SIS18 during a 4 Hz booster sequence, calculated with StrahlSim. It was assumed that only 8 % of the gases desorbed inside the "desorption" scrapers are able to interact with the revolving beam.

REFERENCES

- [1] The Physics and Technology of ion sources, Edited by I. G. Brown
- [2] M. Galonska et. al., Vacuum arc ion sources: Charge state enhancement and arc voltage, emerging applications of vacuum-arc-produced plasma ion and electron beams, Editors: E. Oks and I. Brown, 2002
- [3] W. Barth, Development of the UNILAC towards a Megawatt Beam Injector, LINAC2004, Lübeck, Germany
- [4] W. Barth, Commissioning of the 1.4 MeV/u High Current Heavy Ion Linac at GSI, LINAC2000, Monterey, U.S.A., p. 1033 (2000)
- [5] U. Ratzinger, The New GSI Pre-stripper Linac for High Current Heavy Ion Beams, LINAC96, Geneva, Switzerland, p. 288 (1996)
- [6] W. Barth, Experience during Operation with High Current U⁴⁺ Beams in the new HSI, LINAC2002, Gyeongju, Korea, p. 347 (2002)
- [7] W. Barth, et. al., GSI-an. rep. p. 207 (2003)
- [8] S. Yaramishev, et. al., Investigation of the Beam Matching to the GSI-Alvarez DTL under Space Charge Conditions, Proceedings LINAC2004
- [9] L. Dahl, et. al., Transport and Injection of heavy ion Beams with High Brilliance for the GSI-HSI, LINAC2002, Gyeongju, Korea, p. 350 (2002)
- [10] J. Glatz. B. Langenbeck, The High Current Charge Stripper, Charge Separator, and their Magnets for the Beam Transfer line to the Heavy Ion Synchrotron SIS, Conf. on Magnet Technology, IEEE Transactions on Magnetics (2000)
- [11] W. Barth, et. al, Application of Beam Diagnostics for Intense Heavy Ion Beams at the GSI UNILAC, DIPAC 2003, Mainz, Germany, p. 161 (2003)
- [12] P. Spiller, GSI internal note, GSI-SIS18-02-02, 2002
- [13] Fair Baseline Technical Report (FBTR), GSI (2006)