DESIGN STUDIES FOR A NEW HEAVY ION INJECTOR LINAC FOR FAIR

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Abstract

As the GSI UNILAC started operation in 1975, it will be more than 40 years old when the commissioning of the future Facility for Antiproton and Ion Research (FAIR) at GSI will start. To assure reliable operation for FAIR and to provide beams for a variety of experiments, three separate linacs were proposed and are under development: 1.) A dedicated 70 MeV proton linac will serve as injector for the FAIR pbar physics program. 2.) To deliver high-intensity heavy-ion beams for FAIR, the existing post-stripper linac at the UNILAC should be replaced by a new high energy heavy-ion linac with short beam pulses, low pulse repetition rate, and fixed end energy. 3.) A new superconducting cw heavy-ion linac behind the upgraded high charge state injector HLI shall provide ion beams with high duty cycle and adjustable energy in the MeV/u region for the super-heavy element program as well as for further UNILAC experiments. A conceptual design study for the second machine – a new heavy-ion linac injector for FAIR – using 108 MHz IH-type drift tube structures is presented, including a proposal to increase the ion charge states for synchrotron injection as well as a linac beam energy upgrade using 325 MHz CH structures.

INTRODUCTION

The Facility for Antiproton and Ion Research (FAIR) presently under development at GSI in Darmstadt (Fig. 1) will provide worldwide unique accelerator and experimental facilities allowing for a large variety of forefront research in physics and applied science. The FAIR accelerators will increase the intensity of primary proton and heavy ion beams available for experiments and for the production of secondary beams by up to two orders of magnitude with respect to the existing GSI facility [1]. Besides the realisation of the challenging FAIR SIS100 synchrotron, various upgrades of the UNILAC linear accelerator (Fig. 2) and of the SIS18 synchrotron play a key role to achieve the FAIR design intensities, since the existing GSI accelerators will serve as injection chain for FAIR [2–7]. As major design parameters, 15 emA U^{28+} beams at 11.4 MeV/u [2] and 70 mA proton beams at 70 MeV are required for SIS18 injection.

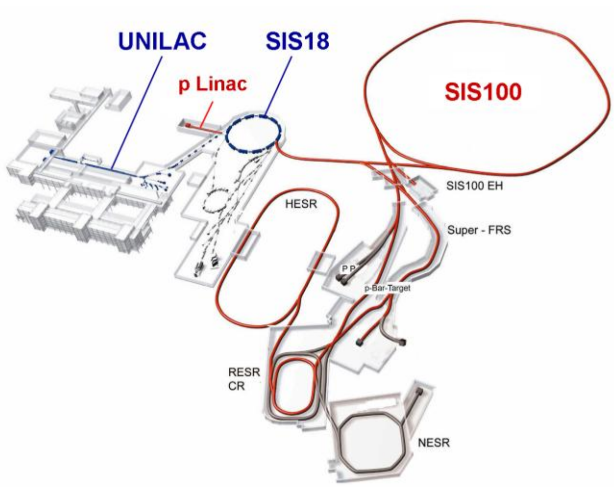

Figure 1: Sketch of the FAIR facility [1]. The existing GSI accelerators (indicated in blue) with the UNILAC heavy-ion linac and the SIS18 synchrotron will serve as injection chain for the new SIS100.

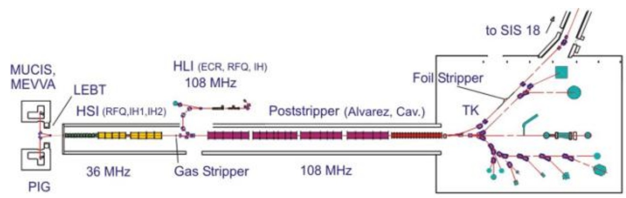

Figure 2: Layout of the present heavy-ion UNILAC accelerator at GSI and low-energy experimental area.

Present Linac Constraints and Proposals

For high current operation of the UNILAC [2], the 36 MHz High Current Injector (HSI) [8] – comprising a 120 keV/u IH-RFQ and two IH-DTL tanks – accelerates ion beams up to U^{4+} ($A/q \leq 59.5$) to 1.4 MeV/u (pre-stripper linac). After the gas stripper and the charge separation section, further acceleration to 11.4 MeV/u for synchrotron injection is provided by the 108 MHz post-stripper linac ($A/q \leq 8.5$), consisting of five Alvarez DTL cavities and ten single gap resonators for fine tuning of the linac end energy.

High magnetic rigidity of the ion beams and high beam currents as needed for FAIR injection require very strong electric and magnetic fields for acceleration and focusing along the linac within short beam pulses and at low repetition rate and duty cycle.

On the other hand – contradictory to the requirements for the FAIR injector – experiments using low-energy beams in the MeV/u region behind the UNILAC, like the super-heavy element (SHE) program as well as material research, biophysics, and plasma physics experiments, are demanding ion beams with up to 100 % duty factor, resulting in very high average rf power requirements along the linac. These experiments are currently limited by the maximum duty cycle of the UNILAC of 25 % [9].

Moreover, the focusing magnets along the present post-stripper linac can be operated only in DC mode, which makes the machine inefficient in terms of short pulse operation and represents a major flexibility limitation since the focusing fields cannot be adapted to the varying needs when different ion beams have to be accelerated from pulse to pulse (diverse ion species, magnetic rigidities, and beam currents).

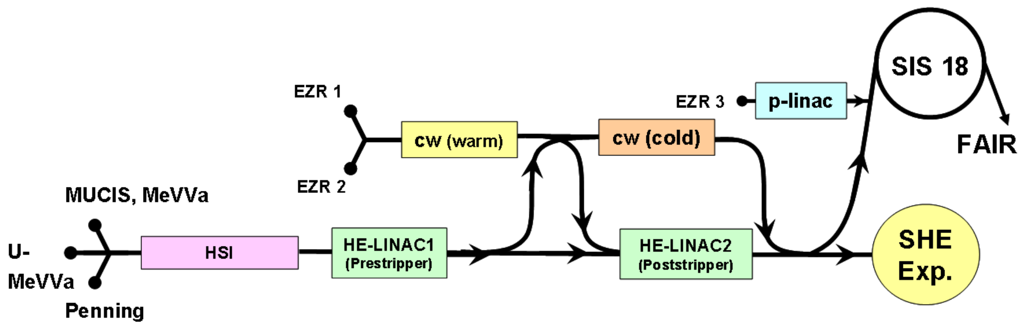

Figure 3: Proposed future GSI linac environment [4].

Finally, as the UNILAC started operation in 1975, most sections of the existing post-stripper linac will be more than 40 years old when the commissioning of FAIR will start. Due to an increased number of failures and problems at the Alvarez DTL, at the single-gap resonators, as well as at the corresponding rf systems during the last years, different proposals are under discussion to replace the post-stripper linac to allow for highly reliable operation of the future FAIR injector linac.

To fulfil the requirements of the various experiments at FAIR and behind the UNILAC, three separate linacs are proposed (Fig. 3) [4]:

1.) A dedicated 70 MeV, 70 mA, 325 MHz proton linac based on room temperature crossbar H-mode (CH) DTL cavities is under development and will serve as injector for the FAIR pbar physics program [10–11].

2.) To deliver high-intensity heavy-ion beams for FAIR, the existing post-stripper linac should be replaced by a new heavy ion high-energy (HE) linac with short beam pulses, low pulse repetition rate, and fixed linac end energy [12].

3.) A new superconducting cw heavy-ion linac [13–14] behind the upgraded high charge state injector HLI [9] should provide ion beams with high duty cycle and adjustable energy in the MeV/u region for the super-heavy element program as well as for further UNILAC experiments.

ACCELERATION OF INTERMEDIATE CHARGE STATES

No additional stripper is used behind the UNILAC in case of high current operation. For uranium beams, U^{28+} is selected behind the gas stripper for acceleration along the post-stripper linac and the synchrotron (FAIR reference ion). Due to the high cross sections for charge exchange processes at collisions with residual gas atoms for intermediate charge states at SIS18 energies [6], significant beam losses are generated in the synchrotron, resulting also in an increasing vacuum pressure caused by ion induced desorption during SIS operation (dynamic vacuum effects), generating over again rapidly rising beam losses. These effects caused severe intensity limitations in the SIS18. Due to a comprehensive upgrade program using dedicated low desorption charge scrapers and NEG coated vacuum chambers as well as further measures [5–7], the particle intensities extracted from SIS18 could be increased by almost two orders of magnitude during the last years.

Since the reaction cross sections for charge exchange processes are decreasing significantly for highly charged ions, the use of higher uranium charge states for injection and acceleration in the SIS18 was investigated experimentally [6, 15] and by simulations [16]. Higher uranium charge states were produced at the UNILAC by using a foil stripper set-up at 1.4 MeV/u instead of the gas stripper [15]. Highest extracted particle intensities were achieved behind the SIS18 for U^{39+} beams [6]. In recent experiments, single particle lifetimes of almost 80 s have been measured in the SIS18 at injection energy for U^{38+}, more than two times higher as measured for U^{28+} in the same experiment (≈ 35 s) [16]. For higher beam energies during SIS18 acceleration up to the SIS100 injection energy of 200 MeV/u, the lifetime enhancement for the higher charge states is even larger. These results represent a significant improvement as compared to earlier measurements of about 11 s for U^{28+} in 2010 and 3 s in earlier years [1]. In spite of that, the use of U^{38+} may be advantageous because of even higher lifetimes.

On the other hand, since the space charge tune shift in the synchrotron

$$\Delta Q_y^{sc} \propto -N \frac{q^2}{A} \frac{1}{\beta^2 \gamma^3}$$

is increasing rapidly for higher charge states q, the injection of intense U^{38+} beams into the SIS18 at the

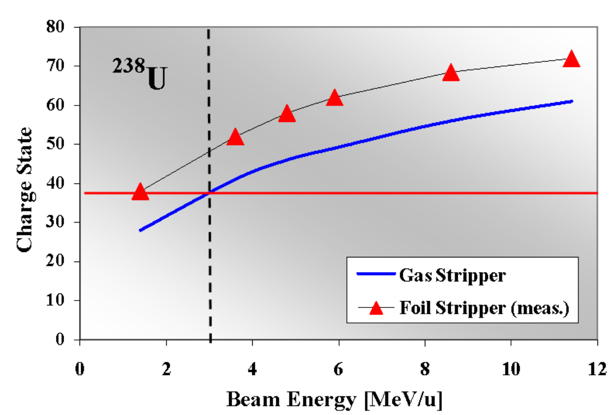

Figure 4: Main uranium charge state after stripping at different stripper materials as function of beam energy.

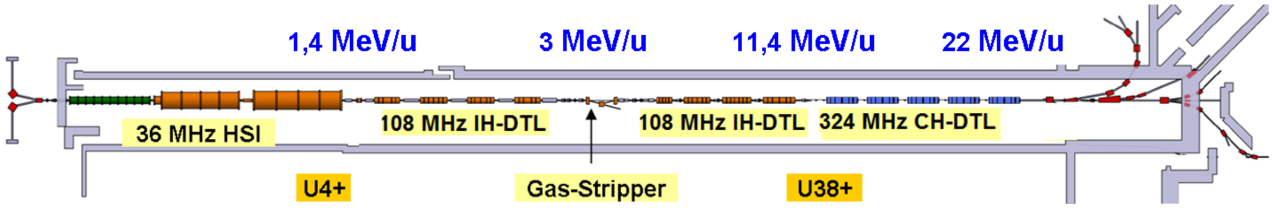

Figure 5: The investigated high-energy (HE) linac concept.

present injection energy of 11.4 MeV/u would cause a significant increase of space charge problems. Hence, the injection energy for U^{38+} beams has to be increased to about 22 MeV/u for compensation.

To verify these considerations, beam loss simulations were performed using the STRAHLSIM Code [17–18]. Preliminary results confirmed a distinct reduction of beam losses during SIS18 booster operation using U^{40+} injected into SIS18 at 23 MeV/u as compared to U^{28+} injected at 11.4 MeV/u [16]. Good agreement between simulations and measurements was achieved for U^{28+}, whereas verifications are needed for U^{38+} operation.

CONCEPTUAL HE LINAC STUDY

Because of the increasing lifetimes for higher charge states, a linac concept using U^{38+} for synchrotron injection was investigated. Since the gas-stripper provides for a highly reliable operation, it would be preferred for future FAIR operation instead of the foil stripper used for the recent experiments. Hence, the gas stripper must be shifted to higher beam energies to achieve higher charge states with sufficient intensities (Fig. 4).

Finally, a stepwise realisation of a new heavy ion high-energy linac was proposed (Fig. 5, Table 1):

1.) Complete replacement of the existing post-stripper linac: An extension of the present high current injector HSI by four new 108 MHz IH-DTL cavities leads to a pre-stripper end energy of 3 MeV/u and to an uranium charge state around 38+ behind the gas stripper (Fig. 4). The existing gas-stripper and charge separation section could be used again at the new stripper energy but must be dismounted and must be reassembled at the new location. Further acceleration after stripping will be performed by another four 108 MHz post-stripper IH tanks up to beam energies of 11.4 MeV/u.

2.) In a second stage, a 325 MHz linac using crossbar H-mode (CH) drift-tube structures will boost the linac end energy up to 22 MeV/u within the existing UNILAC tunnel.

Table 1: Main design parameters of the investigated high-energy linac concept (for ^{238}U)

HE Linac	**Stage 1**		**St. 2**	
Operation freq.	108.4		325.2	MHz
Linac length	53		29	m
	pre-	**post-** **stripper**		
Design charge state	4+	38+	38+	
Beam energy, in	1.4	3.0	11.4	MeV/u
Beam energy, out	3.0	11.4	22	MeV/u
Magn. rigidity, out	14.8	3.1	4.25	Tm
Max. mass / charge	59.5	6.26	6.26	
Design ion current	20	24	24	mA
Tot. accel. voltage	95	53	67	MV
No. of rf cavities (Bu = buncher)	1 Bu 4 IH	1 Bu 4 IH	1 Bu 6 CH	
No. of high-power rf amplifiers	5	5	6+1	

Beam Dynamics

The beam dynamics of the entire HE linac is based on the KONUS concept [19], with an external magnetic quadrupole triplet lens behind each cavity. No magnets will be installed inside the cavities – both for the 108 MHz as well as for the 325 MHz sections. Particle tracking simulations were performed for the full 108 MHz linac using the LORASR code [20], starting at the HSI exit with a 20 mA U^{4+} beam [12]. The input particle distributions for the HE linac (Fig. 6) were derived from the design output particle distribution of the HSI [8]. Immediately behind the 36 MHz HSI structures a

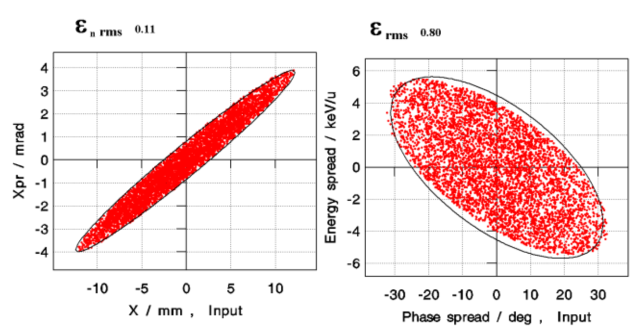

Figure 6: U^{4+} input particle distribution used for simulations of the new 108 MHz pre-stripper section starting at the HSI exit at 1.4 MeV/u.

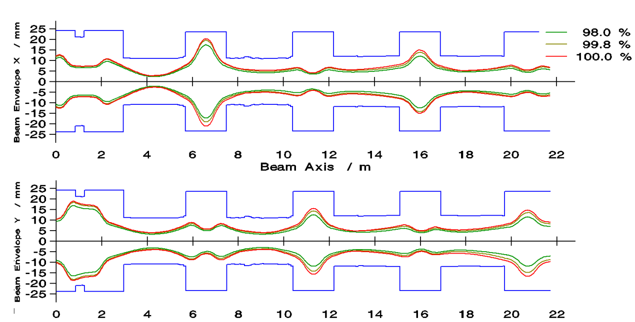

Figure 7: Transverse beam envelopes in the horizontal (top) and in the vertical plane (bottom) along the new 108 MHz pre-stripper section starting at the HSI exit.

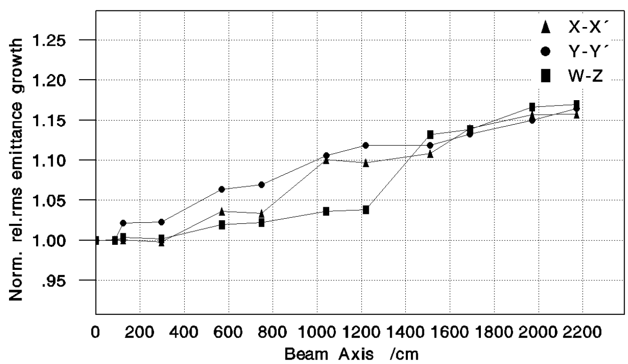

Figure 8: Relative rms emittance growth from HSI exit down to the stripper position for a 20 mA U^{4+} beam.

powerful six gaps 108 MHz buncher will compensate the phase jump and will match the beams longitudinally for the acceleration along the 108 MHz IH linac. Transverse beam envelopes presented in Fig. 7 show that the particle dynamics and the design apertures are robust against beam losses. The relative rms emittance growth along the ~22 m long new pre-stripper section is limited to around 16 % in each phase plane as shown in Fig. 8.

Post-stripper Linac

Beam dynamics simulations of the new post-stripper linac included investigations of the beam energy best suited for the transition to 325 MHz CH-DTL cavities. Since the ion beams are arranged in a 36 MHz bunch structure generated by the high current injector HSI, only every ninth bucket of the 325 MHz structures can be used for ion acceleration. Hence, very high space charge forces occur due to the large bunch currents corresponding to equivalent macro-pulse currents of >200 emA for a real averaged macro-pulse current of 24 emA. Therefore, 108 MHz IH cavities are used in the investigated design up to the present UNILAC end energy.

CAVITY DESIGN

The HE linac study is entirely based on H-mode cavities representing the state of the art for ion acceleration in terms of rf efficiency in the low to medium β range (up to $\beta \approx 0.2$). The very high shunt

Table 2: Main parameters of the 108 MHz IH-DTL cavities of the investigated HE linac concept (for ^{238}U)

Cavity	ΔW (MeV/u)	Eff. Voltage (MV)	Length (m)
Pre-Stripper (U4+)			
IH3	0.400	25.0	≈ 2.9
IH4	0.450	26.7	≈ 3.1
IH5	0.416	26.8	≈ 3.1
IH6	0.396	23.9	≈ 3.0
Post-Stripper (U38+)			
IH7	1.800	11.5	≈ 1.8
IH8	2.370	15.9	≈ 3.0
IH9	2.200	15.3	≈ 3.3
IH10	2.200	15.0	≈ 3.7

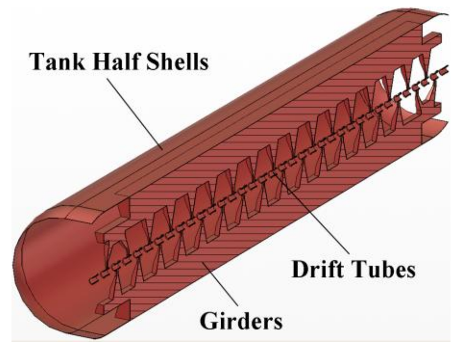

Figure 9: Simulation model of the first 108 MHz IH cavity of the presented HE linac study.

impedances of that kind of cavities allow to cover this energy range within a shorter length when compared to any other solution based on Alvarez DTL [21]. Since no quadrupole magnets need to be installed inside the drift tubes due to the KONUS beam dynamics, the rf power demands will be much lower. At the same time, highest acceleration fields and highest effective voltage gain can be achieved.

Due to the low duty cycle, room-temperature structures are planned for the new linac. Each of the eight 108 MHz IH cavities will have a length between ~3 to ~3.6 meters (Table 2). Preliminary Microwave Studio simulations indicate that the total rf power – including beam loading – will be less than 1.3 MW for each cavity. For example, Figure 9 shows a simulation model of the first IH cavity. Estimated shunt impedances of the pre-stripper structures are compared to different multi-gap structures in Fig. 10, indicating a rf power loss reduction of more than a factor of five as compared to conventional structures. For the second stage of the HE linac, 325 MHz CH-DTL structures will be used, taking significant advantage from the R&D work performed for the FAIR proton linac [11].

RF CONCEPTS

To achieve a sufficient reliability of the existing 108 MHz rf amplifiers from the Alvarez DTL for the

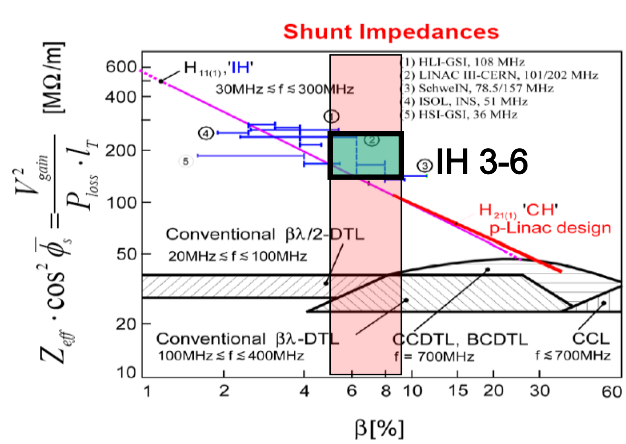

Figure 10: Estimated effective shunt impedances of the new 108 MHz pre-stripper IH cavities as compared to conventional structures and further H-mode cavities.

coming decades, an extensive, very costly, and manpower intensive overhauling would be necessary, including the replacement of many components. Hence, a complete substitution by new 108 MHz, 1.8 MW amplifiers for low duty cycle operation with short pulse length was proposed. A design study for a high-power cavity amplifier has been started recently at THALES based on the TH 558SC tetrode. 120 kW solid state amplifiers are being considered for the drivers and new digital low-level rf systems are planned.

For stage 2 of the presented HE linac study and for possible future linac energy upgrades, respectively, 325 MHz klystron amplifiers similar to those presently under development for the FAIR proton linac are proposed. Since the existing UNILAC rf gallery would be needed completely for the new 108 MHz systems, an extension of the existing building would be necessary for the 325 MHz klystron gallery.

OUTLOOK

The HE linac concept reported here was proposed to the GSI supervisory board, but no final decision was taken. As an alternative solution, a 108 MHz IH-DTL linac for U^{28+} as direct replacement of the existing UNILAC post-stripper section is being investigated – but in contrary to the existing machine only for short pulses, low duty cycle, and fixed linac end energy. Ion charge states and beam energy at SIS18 injection would not be increased. On the other hand, the U^{28+} machine would save significant costs and efforts as compared to the U^{38+} linac concept. Only about five new IH tanks and five new rf amplifiers would be required, the gas-stripper section need not to be moved to a new position, and no extension of the rf gallery would be necessary.

Design and construction of prototype cavities for a 108 MHz IH structure and for a 325 MHz CH structure for future energy upgrades are planned. An extension of the new high-energy linac up to 100 – 150 MeV/u for direct beam injection into SIS100 maybe subject to future studies as long-term option.

Future activities will also focus on the development of alternative stripper techniques to achieve higher charge states at the present stripper position. Further experiments with foil strippers are ongoing. Beam tests of a plasma stripper set-up developed at the Institute for Applied Physics (IAP) at the Goethe-University in Frankfurt [22] are planned. This would still allow for acceleration of higher charge states for synchrotron injection even with a new post-stripper linac designed for U^{28+}.

The commissioning start of the FAIR accelerators is planned for 2017 using ion beams delivered by the existing UNILAC. Beam commissioning of the FAIR proton linac is scheduled for 2019. Afterwards, the replacement of the post-stripper section of the UNILAC is planned, while beams for FAIR operation will be provided by the proton linac and possibly by the sc cw heavy-ion linac. First ion beams from a new high energy heavy-ion linac for FAIR are expected for 2022.

REFERENCES

[1] O. Boine-Frankenheim, The FAIR accelerators: highlights and challenges, in: Proc. IPAC2010, Kyoto, Japan, p. 2430.

[2] W. Barth, The injector systems for the FAIR project, in: Proc. LINAC08, Victoria, Canada, 2008. p. 31.

[3] H. Vormann et al., Advanced UNILAC upgrade for FAIR, in: Proc. LINAC2010, Tsukuba, Japan, 2010, p. 142.

[4] W. Barth et al., Future heavy ion linacs at GSI, in: Proc. IPAC2011, San Sebastian, Spain, p. 2550.

[5] L. Dahl et al., Development of the intensity and quality of the heavy ion beams at GSI, these proceedings.

[6] P. Spiller, L. Bozyk, and P. Puppel, SIS18-intensity record with intermediate charge state heavy ions, in: Proc. IPAC2011, San Sebastian, Spain, p. 2484.

[7] P. Spiller et al., High intensity intermediate charge state heavy ions in synchrotrons, in: Proc. IPAC2012, New Orleans, USA, THPPP001.

[8] U. Ratzinger, The new GSI pre-stripper linac for high current heavy ion beams, in: Proc. LINAC96, Geneva, Switzerland, 1996, p. 288.

[9] L. Dahl et al., UNILAC upgrades for Coulomb barrier energy experiments, Proc. LINAC2010, Tsukuba, Japan, 2010, p. 148.

[10] G. Clemente, et al., The FAIR proton linac: The first linac based on a room temperature CH-DTL, in: Proc. ICFA ABDW HB2010, Morschach, Switzerland, 2010, p. 115.

[11] G. Clemente, U. Ratzinger, H. Podlech, L. Groening, R. Brodhage, and W. Barth, Development of room temperature crossbar-H-mode cavities for proton and ion acceleration in the low to medium beta range, Phys. Rev. ST Accel. Beams **14**, 110101 (2011).

[12] G. Clemente, W. Barth, and B. Schlitt, Conceptual study of a new high energy linac at GSI, in: Proc. IPAC2011, San Sebastian, Spain, p. 2553.

[13] S. Minaev, U. Ratzinger, H. Podlech, M. Busch, and W. Barth, Superconducting, energy variable heavy ion linac with constant β, multicell cavities of CH-type, Phys. Rev. ST Accel. Beams **12**, 120101 (2009).

[14] S. Mickat et al., The sc cw linac demonstrator – 1st test of a sc CH-cavity with heavy ions, these proceedings.

[15] W. Barth et al., High current U40+ operation in the GSI-UNILAC, in: Proc. LINAC2010, Tsukuba, Japan, p. 154.

[16] L. Bozyk, P. Puppel, and P. Spiller, internal communication.

[17] P. Puppel, P. Spiller, L. Bozyk, and U. Ratzinger, StrahlSim, a computer code for the simulation of charge exchange beam losses and dynamic vacuum in heavy ion synchrotrons, in: Proc. IPAC2010, Kyoto, Japan, p. 594.

[18] P. Puppel, P. Spiller, and U. Ratzinger, Simulation of the long term beam intensity performance of the NEG-coated SIS18, in: Proc. ICFA ABDW HB2010, Morschach, Switzerland, 2010, p. 91.

[19] R. Tiede, U. Ratzinger, H. Podlech, C. Zhang, and G. Clemente, KONUS beam dynamics designs using H-mode cavities, in: Proc. Hadron Beams 2008, Nashville, USA, 2008, p. 223.

[20] R. Tiede, G. Clemente, H. Podlech, U. Ratzinger, A. Sauer, and S. Minaev, LORASR code development, in: Proc. EPAC2006, Edinburgh, Scotland, 2006, p. 2194.

[21] U. Ratzinger and R. Tiede, Status of the HIIF RF linac study based on H-mode cavities, Nucl. Instr. and Meth. in Phys. Res., Sect. A **415**, 229 (1998).

[22] C. Teske, Y. Liu, S. Blaes, and J. Jacoby, Physics of Plasmas **19**, 033505 (2012).