

DEVELOPMENT OF THE UNILAC TOWARDS A MEGAWATT BEAM INJECTOR

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Abstract

For the future Facility for Antiproton and Ion Research (FAIR) at Darmstadt the present GSI-accelerator complex, consisting of the linear accelerator UNILAC and the heavy ion synchrotron SIS 18, is foreseen to serve as U^{28+} -injector for up to 10^{12} particles/s. After a new High Current Injector (HSI) was installed, many different ion species were accelerated in the UNILAC for physics experiments. In 2001 a high energy physics experiment used up to $2 \cdot 10^9$ uranium ions per SIS18-spill (U^{73+}) while a MEVVA ion source was in routine operation for the first time. In the past two years, different hardware measures and careful fine tuning in all sections of the UNILAC resulted in an increase of the beam intensity to $9.5 \cdot 10^{10} U^{27+}$ -ions per $100 \mu s$ or $1.5 \cdot 10^{10} U^{73+}$ -ions per $100 \mu s$. The contribution reports results of beam measurements during the high current operation with uranium beams (pulse beam power up to 0.5 MW). One of the major tasks was to optimize the beam matching to the Alvarez-DTL. In addition further upgrades, including improved beam diagnostics, are described, which allow to fill the SIS 18 up to the space charge limit (SCL) of $2.7 \cdot 10^{11} U^{28+}$ -ions per cycle. We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395) and INTAS (project 03-54-3543).

INTRODUCTION

The conceptual design of the international Facility for Antiprotons and Ion Research (FAIR) at GSI in

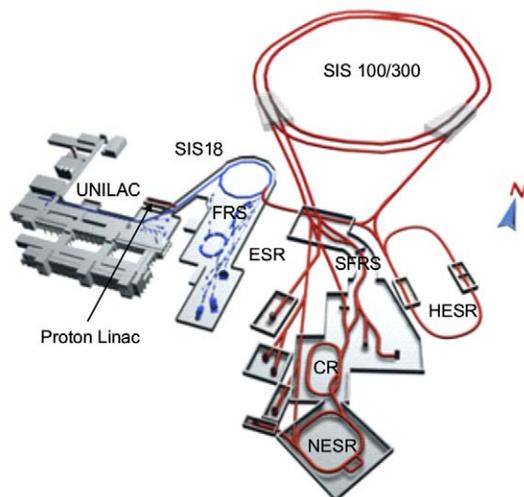


Figure 1: The proposed Accelerator facility FAIR at GSI in Darmstadt [1].

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Table 1: Design uranium beam parameters at UNILAC and SIS 18 injection [2]

	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection	Required for FAIR
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{73+}$	$^{238}U^{28+}$
El. Current [mA]	16.5	15	12.5	4.6	15.0
Part. per $100 \mu s$ pulse	$2.6 \cdot 10^{12}$	$2.3 \cdot 10^{12}$	$2.8 \cdot 10^{11}$	$4.2 \cdot 10^{10}$	$3.3 \cdot 10^{11}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4	11.4
$\Delta W/W$	-	$4 \cdot 10^{-3}$	$\pm 1 \cdot 10^{-2}$	$\pm 2 \cdot 10^{-3}$	$\pm 2 \cdot 10^{-3}$
$\epsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8	0.8
$\epsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5	2.5

Darmstadt (Fig. 1) has evolved from the science requirements: higher intensities will be achieved, compared to the present GSI accelerator facility, through faster cycling and, for heavy ions, lower charge state which enters quadratically into the 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. The energy of 30 GeV/u for heavy ions is generated by using higher charge states in combination with the slower cycling synchrotron SIS 300. The 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. The various rings may be shared for the use with different beams.

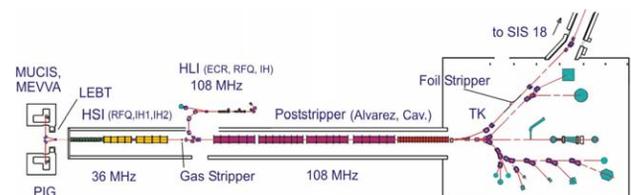


Figure 2: Schematic overview of the GSI UNILAC [3].

The present GSI accelerator complex will serve as an injector for high intensity heavy ions to fill the SIS 100 to its space charge limit. In the last three years GSI put some effort in increasing the delivered uranium intensities to the SIS 18. An additional upgrade program for the UNILAC is foreseen to reach the required beam brilliance. For uranium (reference ion) the UNILAC has to deliver $3.3 \cdot 10^{11} U^{28+}$ -particles per $100 \mu s$ (see Table 1) to the present synchrotron SIS 18. Currently for a 15 eA $^{238}U^{4+}$ beam from the HSI [4] up to $4 \cdot 10^{10} U^{73+}$ particles should be delivered to the SIS 18 (during $100 \mu s$), while the SIS 18-SCL is reached by a 20 turn injection into the horizontal phase space. The HSI-front end consists of ion sources of MEVVA-, MUCIS- or Penning-type and a low

energy beam transport system (LEBT). The 36 MHz IH-RFQ accelerates the ion beam from 2.2 keV/u to 120 keV/u. In the following short 11 cell adapter RFQ (Super Lens) the beam is matched to the IH-DTL, consisting of two separate tanks accelerating the beam up to the final HSI-energy of 1.4 MeV/u. The HSI-beam is stripped and one charge state is selected (e.g. 28^+ for uranium beams). In the Alvarez DTL the high intensity HSI beam is accelerated without significant particle loss. The transfer line (TK) to the SIS 18 provides for a foil stripper and another charge state separator system.

The existing UNILAC had been designed for heavy ion operation. It could provide proton beams at 18 MeV with currents of max. 0.25 mA and an emittance of $1 \mu\text{m}$. However, the resulting brilliance is at least one order of magnitude below the FAIR-requirements. For the proposed time sharing scenario beam intensities of 70 mA and an energy of 70 MeV are required. Accordingly, a dedicated proton injector linac being designed within FAIR will be operated independently from the existing UNILAC [5].

Additionally, medium heavy ion beam with a high duty factor have to be developed to increase the target luminosity for the super heavy element production during the next five years. Plans are to investigate and to build a sc 28 GHz-ECR ion source [6], which should increase the primary beam intensities. The beam coming from the new ECR source will be delivered to the GSI-High Charge State Injector by a second LEBT-system. An upgrade program for the rf-amplifiers and the rf-structures is foreseen to increase the duty factor from 30 % to 50 % [7].

The decelerator for HITRAP (Heavy Ion TRAP) [8] is another (linac-) project described in a technical design report. The HITRAP-facility should provide for ions of selected charge states up to U^{92+} at cryogenic temperatures. It is intended to be ready for operation within 30 months after the start of the project. An IH-cavity and a 4-rod RFQ are the main decelerator structures. 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 successful operation at the ESR the HITRAP set-up will be an integral part of FAIR behind the NESR (New Experimental Storage Ring).

HSI-UPGRADE

Especially for the requested operation with intense uranium beams the performance of the UNILAC was significantly improved [9]: the MEVVA-ion source was renewed. The use of stabilized internal grids resulted in a long operation life (typically 7 days) and in high ion source beam availability. The pulse to pulse stability was enhanced. With the additional application of a strong pulsed magnetic field an U^{4+} fraction of up to 67 % was reached. Enhancements of the extraction system resulted in a higher extraction voltage and, accordingly, in a higher total current density. Due to the high rf surface field in the RFQ and in the Super Lens, rf-conditioning

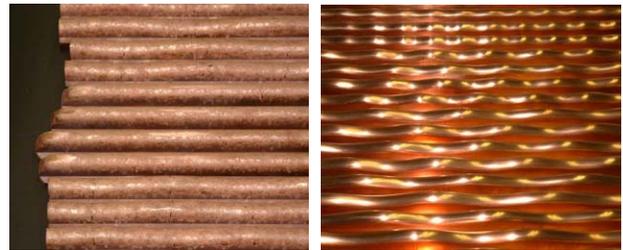


Figure 3: Upgrade of the HSI-RFQ; RFQ-electrodes after five years of operation (left), new electrodes before assembly (right).

has to be taken into account if low charged heavy ions must be accelerated in the HSI. Permanent rf-conditioning with a low duty factor (approx. 0.3 %) in a time sharing mode with the regular beam time allows for the required rf-amplitudes. In 2002 the Super Lens was completely dismantled. In an upgrade scheme the rf-performance was significantly improved: the maximum surface field strength was slightly decreased, the surface quality was improved and a new plunger design was applied [10].

Since the end of May 2004 a comparable upgrade measure for the RFQ has been in progress. In Fig. 3 (left) some of the dismantled RFQ-electrodes are shown. After five years of operation the electrode surface was damaged along the whole structure, requiring significantly higher input rf-power during operation at the design limit. The electrodes were reproduced; additional copper plating should lead to a reduction of "dark current" contributions during high power operation.

The RFQ input radial matcher (IRM) was redesigned to improve the matching to the RFQ with the DYNAMION-code. The new matching leads to a smaller beam diameter in the quadrupole channel, resulting in improved particle transmission. While the RFQ was de-installed for the proposed upgrade measures, the matching was investigated using beam transformers and emittance measurement devices before and after the quadrupole quartet in the LEBT-section. As predicted by simulations, based on high current uranium emittance measurements, the measured gain in particle number is close to 15 % (see Fig. 4). During recommissioning of the RFQ a high intensity Ar^{1+} beam was used. In Fig. 5 the measured beam transmission as a function of the rf-voltage is presented together with the data before the upgrade. At the working point the expected gain in RFQ-transmission is verified. The achieved maximum Ar-intensity (after RFQ) is 10.6 emA, being above the design limit (10 emA).

After a breakdown inside the IH1-structure of the HSI at the beginning of 2003 an inner triplet lens was substituted. The new advanced design provides for an improved electromagnetic performance and the outer walls of the big drift tube are now directly water-cooled. As shown in Fig. 6 the geometry of the subsequent small drift tube was slightly changed, leading to a different field distribution (E_z) and lower "dark current" contributions during operating at the highest rf-power level [11].

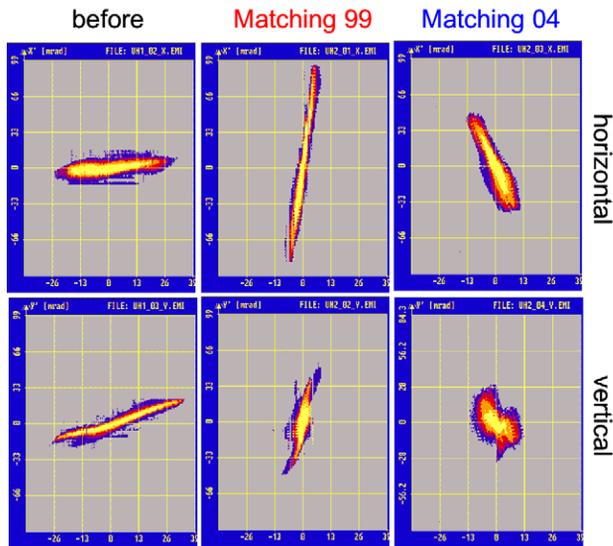


Figure 4: Measured U^{4+} emittance before and after the quadrupole quartet (left) for the two matching cases. The transmission for the new matching (2004) is 15 % higher.

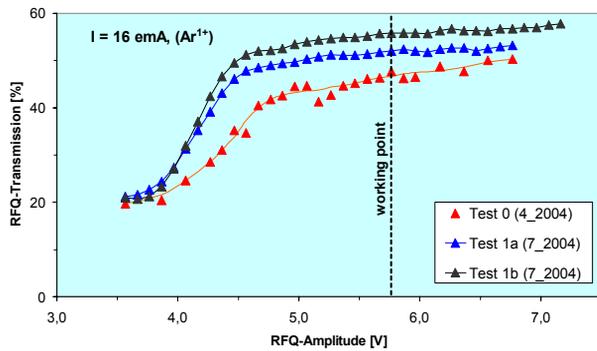


Figure 5: Measured transmission for a high current argon beam before and after the upgrade of the RFQ-electrodes.

A bottleneck behind the Alvarez section was eliminated by the reduction of the number of the single gap resonators from 15 to 10 – allowing beam transport with smaller beta-function modulation and better transmission. Adjustments along all sections of the UNILAC were performed additionally with high accuracy.

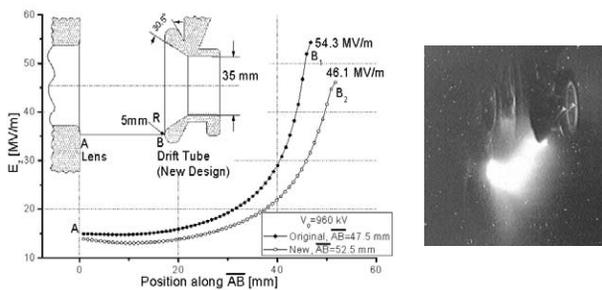


Figure 6: Maximum electric field between the first big drift tube (housing a triplet lens) and the subsequent small drift tube (left); before the improved drift tube geometry was applied (right).

GASSTRIPPER PERFORMANCE

With the reduction of the available apertures in the stripper box, it was possible to increase the stripper gas density by 50 %. For medium intense uranium beams ($6.5 \text{ emA, } U^{4+}$) this leads to the expected gain for the desired charge state $28+$ (up to 12.8 %). The desired equilibrium charge state distribution is reached for a 70 % higher gas density. Currently the power of the vacuum pumps is not sufficient to compensate this gas ballast. For a temporary 70%-increase of the gas density the measured total uranium current (all species) was increased to 41 emA. The defocusing effect of the space charge forces leads to particle loss in the transport section after the stripping area. This can be compensated by increasing the transverse beam spot in the space charge dominated beam transport. The high stripper gas density for the necessary enlarged apertures has to be provided by an enhanced vacuum pumping speed. For the proposed higher uranium intensities the present stripper section is not sufficient to meet the FAIR-requirements and has to be redesigned.

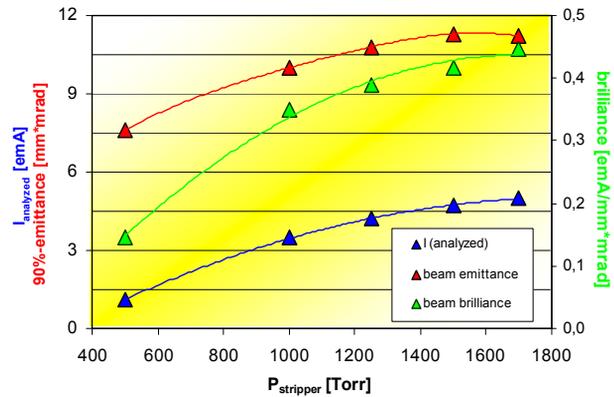


Figure 7: Measured U^{28+} -current, -emittance and -brilliance after charge state separation as a function of the stripper gas density; the input U^{28+} -current is 6 emA.

BEAM MATCHING TO THE ALVAREZ

Usually empirical matching can be done by variation of the quadrupole settings preceding the DTL until a sufficient transmission through the Alvarez section of more than 90% is achieved. In order to increase the transmission close to 100 %, a systematic matching procedure was proposed and realized during machine experiments. In general the beam is mismatched with an enlarged beta function oscillation along the Alvarez accelerator, which may cause transmission losses and emittance growth. Using the quadrupole settings in the first cells of the DTL the periodic solution for the Alvarez tank is calculated. To match the periodic DTL solution, a fitting routine involving the five matching quadrupoles is applied. For the highest available uranium intensity the losses along the Alvarez section are reduced from 8 % to less than 1 % [12].

The postaccelerator performance can also be improved by the optimization of the quadrupole settings in the

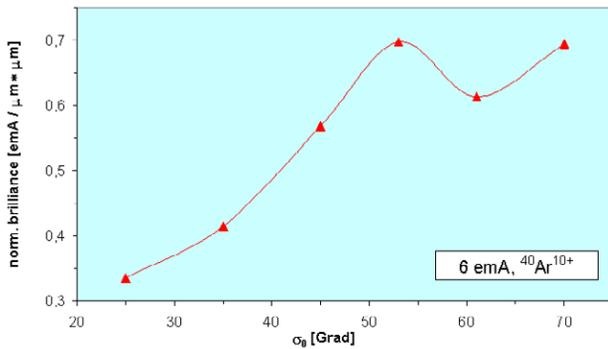


Figure 8: Normalized beam brilliance for a high current argon beam after the 4th Alvarez-tank as a function of σ_0 .

Alvarez DTL, being most important in the 1st Alvarez tank. Due to the high mass over charge ratio (m/ζ) of $^{238}\text{U}^{28+}$ ions, the maximum zero current phase advance σ_0 in the Alvarez DTL is limited to 45° mainly by limitations of the quadrupole power supplies. For a $^{40}\text{Ar}^{10+}$ beam the m/ζ is lower; so that the phase advance influence on the transmission in the Alvarez DTL can be investigated in the interesting range of σ_0 -values. As shown in Fig. 8, a phase advance $\sigma_0 > 50^\circ$ is required for an improved beam brilliance for the SIS-injection.

IMPROVED TRANSFER TO THE SIS 18

The optimized matching of space charged dominated ion beams is essential for a loss free injection into the SIS 18. Transverse beam emittance measurements at different positions along the TK were done. 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 SIS 18. Multi particle simulations by means of the PARMILA-code were performed allowing for a detailed analysis of experimental results for different ion currents [13].

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

Table 2: uranium beam intensities

	ζ	Dec 01	Dec-03
LEBT	4+	7,5	11,7
HSI	4+	3,75	6,4
gas stripper	4+	2,5	5,3
Alvarez	28+	1,8	4,8
Single Gap Resonators	28+	1,17	4,8
Foil Stripper	28+	0,94	4,5
SIS 18-Injection	73+	0,3	2,0

In Fig. 9 the achieved uranium intensities in the UNILAC and TK are summarized (2001-2003), reached by the measures mentioned above and by an extended

experimental program dedicated to improve the overall UNILAC performance for heavy ion high current operation. In December 2003 an U^{73+} intensity of 2.0 emA ($27.5 \mu\text{A}$) was reached for the first time at the injection to SIS 18, which corresponds to $1.7 \cdot 10^{10}$ particles per 100 μs . Before foil stripping 4.5 emA ($160 \mu\text{A}$) of U^{28+} beam intensity was achieved ($1.0 \cdot 10^{11}$ particles per 100 μs). The optimized total particle transmission through HSI, stripper section, Alvarez DTL, Single gap resonator chain, and TK is 50 %, if the particle losses during charge separation after the two strippers are taken into account. Compared to the design transmission (90 %) the lack is mainly caused by a bottle neck in the front end area of the HSI-linac.

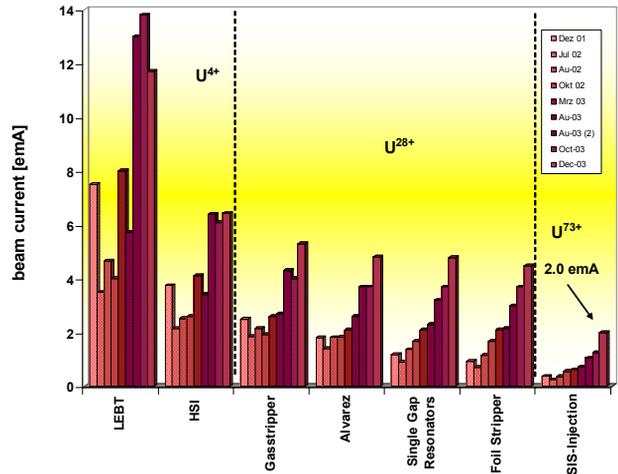
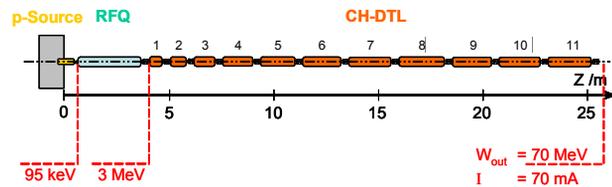


Figure 9: Improvement of the UNILAC-uranium beam intensities during the last three years.

A NEW GSI-PROTON LINAC

The antiproton physics program of FAIR is based on a rate of $7 \cdot 10^{10}$ cooled antiprotons per hour. To provide the primary proton intensities a proton linac is planned. The



Source	H^+ , ECR, 95 keV, 110 mA
LEBT	2-solenoid focusing 95 keV, 100 mA, $0.3 \mu\text{m}^*$
RFQ (4-rod or 4-windows)	3 MeV, 90 mA, $0.4 \mu\text{m}^*$ *(norm.,rms)
DTL - Section	352.21 MHz, rt, rel. momentum spread 11 CH-structures rf pulse length 70 MeV, 70 mA, $2.8 \mu\text{m}^{**}$ beam pulse length $\pm 5 \cdot 10^{-4}$ 250 μs max. repetition rate 100 μs 5 Hz **(norm., tot)

Figure 10: The proposed high current proton linac for the injection into the SIS 18 [5].

proposed linac (see Fig. 10) comprises a proton source, an RFQ, and a DTL, both with an operation frequency of 352 MHz allowing for acceleration up to 70 MeV. For the first time normal conducting Crossed-bar H-cavities (CH) [14] promising high shunt impedances in the required energy range are used. The beam pulses with a length of 25 μ s, a current of 70 mA, and total transverse emittances of 7 μ m will allow filling the existing synchrotron SIS 18 within a multi-turn-injection up to its SCL of $7 \cdot 10^{12}$ protons. The maximum SIS 18 ramping rate limits the applied proton linac repetition rate to 4 Hz.

A DECELERATOR FOR HIGHLY CHARGED HEAVY IONS FROM THE ESR

The GSI accelerator facility delivers highly-charged ions up to U^{92+} by stripping the ions at 400 MeV/u in the transfer line from the SIS 18 to the ESR. The ESR itself provides high quality beams by means of stochastic@electron cooling. Deceleration down to 4 MeV/u has already been successfully demonstrated. After suitable rebunching, further deceleration down to 6 keV/u is done by a combination of an IH-DTL and an RFQ-structure. All cavities are operated at 108 MHz. Recently the HITRAP-project was described in a Technical Design Report. The layout of the decelerator is shown in Fig. 11.

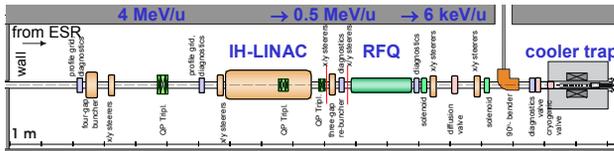


Figure 11: Outline of HITRAP in the re-injection channel between ESR and SIS 18 [8].

CONCLUSION AND OUTLOOK

An extended upgrade program in the UNILAC and TK in combination with machine investigations resulted in a seven times higher uranium beam intensity offered for the injection into the synchrotron SIS 18. Mainly the improved ion source performance, an upgrade of the HSI-structures, the increased stripper gas density, the optimization of the Alvarez-matching, the reduction in the Single Gap Resonator section, the applied sweeper mode for foil stripper operation, and the use of various newly developed beam diagnostics devices were responsible for the successful development program. The UNILAC-upgrade already started will be continued with the investigation of a new front end for U^{4+} [15], stronger power supplies for the Alvarez quadrupoles, a charge state separator system [16] in the foil stripper section and versatile (partly non-destructive) beam diagnostics devices [17], sufficient for the operation with megawatt heavy ion beams. Additionally, the offered primary proton beam intensities will be increased by a new ambitious proton linac, which should be commissioned in 2007. The decelerator for the HITRAP is another GSI-

linac project, ready for operation in 2008. Last but not least, the advanced experimental program for the production of super heavy elements requires efforts to improve the average target luminosity for medium heavy ions in the MeV/u-range – for this a five year linac development program is proposed.

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