THE HITRAP-DECELERATOR FOR HEAVY HIGHLY-CHARGED IONS

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Abstract

The GSI accelerator facility provides highly-charged ions up to U^{92+} by stripping the ions at 400 MeV/u in the transfer line from the SIS18 (Heavy Ion Synchrotron) to the ESR (Experimental Storage Ring). The ESR provides high quality beams by means of stochastic cooling and electron cooling. Deceleration down to 4 MeV/u was already successfully demonstrated. After suitable rebunching, further deceleration down to 6 keV/u, necessary for the capture of the ions by a penning trap, is done by IH/RFQ-structures. All cavities are operated at 108 MHz. Recently the HITRAP-project (Heavy Ion Trap), described in a Technical Design Report, was approved. The layout of the decelerator and the beam dynamics in different sections are reported.

INTRODUCTION

Up to now, GSI is the world´s only facility (Fig. 1) which provides heavy highly-charged ions up to U^{92+} for atomic-physics experiments. The high energy, necessary for stripping the ions up to bare nuclei, is obtained by a first acceleration stage of Uranium to 11.4 MeV/u in the UNILAC. Through a transfer line the SIS18 is fed with single macro pulses of 100 µs length which are accelerated up to 400 MeV/u. After extraction and during the transfer to the ESR finally a foil stripper enables a high yield of U^{92+}-ions.

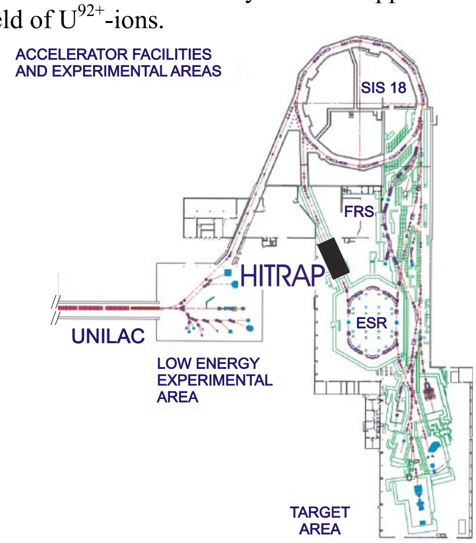

Figure 1: GSI accelerator facility and location of the HITRAP facility.

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In a multi-stage process the ESR decelerates the U^{92+}-beam down to 4 MeV/u and extracts it to the HITRAP-linear decelerator, described in a Technical Design Report [1]. This decelerator reduces the energy of the heavy highly-charged ions from 4 MeV/u down to 6 keV/u. After ejection from the ESR, the beam will be rebunched by a λ/4-resonator. In a subsequent step an IH-type structure will decelerate the beam from 4 MeV/u to 0.5 MeV/u. Another rebuncher tank of spiral-type will prepare the beam longitudinally for the second deceleration down to 6 keV/u by an RFQ-structure. With this energy the highly-charged ions can be captured in a cylindrical Penning trap and be cooled further by electron and resistive cooling to cryogenic temperatures. The cold ions can be extracted again and transported to the final experiments.

PRODUCTION OF BARE NUCLEI

To provide highly-charged ions up to U^{92+}, which is the design ion for the HITRAP facility, the beam has to pass through three stripping processes. After the U^{4+}-ions are generated either in a high current MEVVA ion source or in a PIG ion source they are accelerated to 1.4 MeV/u by the HSI (High Current Injector) [2] of the UNILAC. Subsequently, a nitrogen gas jet stripper increases the charge state from 4+ to 28+ as the equilibrium charge state, which is needed for acceleration in the Alvarez main accelerator. The fraction of U^{28+} particles amounts to 12 %.

At 11.4 MeV/u a foil stripper, located in the transfer beam line to the SIS18, increases the charge state to 73+ using carbon foils of 600 µg/cm². Again, by the loss of neighbouring charge states only 15 % of the uranium particles remain for injection of 100 µs macro beam pulses into the SIS18 for acceleration to 400 MeV/u. Finally, a copper sheet of 40 mg/cm², located in the beam transfer line between SIS18 extraction and ESR injection strips about 30 % of the uranium ions at the energy of 400 MeV/u to bare nuclei.

The ESR [3] was designed for the deceleration of ions to a minimum energy of 3 MeV/u. Machine experiments have successfully demonstrated the feasibility of U^{92+}-beam deceleration. At 5 MeV/u a U^{92+}-beam intensity of $1 \cdot 10^6$ particles per cycle was achieved and $2 \cdot 10^5$ particles at 3 MeV/u. The corresponding momentum spread was $dp/p = 2.4 \cdot 10^{-4}$ and $dp/p = 1 \cdot 10^{-4}$, detected by Schottky diagnostics. Due to electron cooling the normalized transverse emittances were measured with

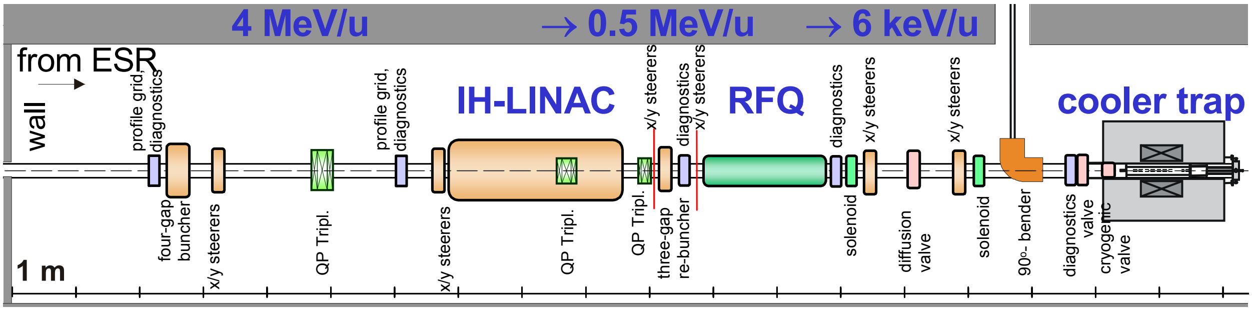

Figure 2: Outline of HITRAP in the re-injection channel between ESR and SIS18.

$\varepsilon_{x,y} = 0.093\ \pi$ mm mrad at 5 MeV/u only and $\varepsilon_{x,y} = 0.06\ \pi$ mm mrad at 3 MeV/u. The measured data are summarized in table 1.

For reliable operation of the ESR, the energy of 4 MeV/u was chosen as design input energy of the HITRAP-decelerator.

THE HITRAP LINEAR DECELERATOR

The experimentally defined beam parameters in the ESR extraction system are the basis for the HITRAP decelerator design. The task is the deceleration of the design ion U^{92+} down to 6 keV/u. Fig. 2 shows schematically the layout of the machine. It will be located in the re-injection channel from the ESR to the SIS18 (see Fig.1). The operating frequency for all structures is 108 MHz, except for the optionally foreseen second harmonic buncher. Table 1 gives an overview of the beam parameters along the HITRAP decelerator.

Table 1: Beam parameters along the HITRAP decelerator

HITRAP Section	Energy [MeV/u]	ΔT/T	$\varepsilon_{x,n}$ (= $\varepsilon_{y,n}$) [π·mm· mrad]	ε_x (=ε_y) [π·mm·mrad]	total Transmission	particles/ spill
ESR	5.0	$4.8\cdot10^{-4}$	0.093	0.9		$1\cdot10^6$ measured
	4.0		0.1	1.0	100%	$(6\cdot10^5)$ estimated
	3.0	$2\cdot10^{-4}$	0.06	0.7		$2\cdot10^5$ measured
Entrance Prebuncher	4.0	$4.8\cdot10^{-4}$	0.2	2.2	100 %	$6\cdot10^5$
Entrance IH	4.0	$\pm1.3\cdot10^{-2}$	0.2	2.2	28 %	$1.7\cdot10^5$
Exit IH / Entr. RFQ	0.5	$\pm2\cdot10^{-2}$	0.24	7.3	28 %	$1.7\cdot10^5$
Exit RFQ	0.006	$\pm7\cdot10^{-2}$	0.37	100	26 %	$1.5\cdot10^5$
LEBT, entrance of trap	0.006	$\pm7\cdot10^{-2}$	0.37	100	21 %	$1.2\cdot10^5$

First, a four-gap bunching cavity of quarter-wave coaxial line type with an applied effective voltage of 216 kV focuses the beam longitudinally into the IH-type decelerator in a distance of 4 m. This buncher type requests an RF power of only 2 kW. The transverse beam matching to the IH-structure is performed by magnetic quadrupoles.

The IH-structure [4] is designed with only one inner magnetic triplet. The power consumption is below 200 kW, determined by the available RF-amplifiers. For the deceleration of bare Uranium ions from 4 MeV/u down to 0.5 MeV/u a total effective RF voltage of 11.35 MV is applied over 25 gaps in a tank of the length of 2.7 m. Pointing instability of the beam extracted from the ESR has already been investigated. A beam displacement at the entrance of the IH-structure of up to ±1.5 mm does not cause particle losses in the structure. A safety margin of a factor of 2 is considered in the emittance value of 0.2 π mm mrad. Fig. 3 shows the transverse beam envelope from the ESR extraction to the RFQ entrance.

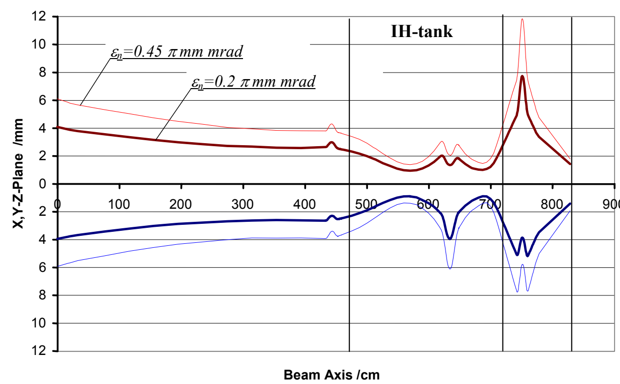

Figure 3: Transverse 98%-beam envelopes for two different emittances. The emittance of 0.45 π mm mrad refers to the acceptance of the IH-structure.

The rebuncher between the IH-structure and the RFQ has to provide a longitudinal focus at the RFQ entrance at 0.5 MeV/u. An existing spiral loaded cavity, equipped with a three-gap electrode structure with a total length of 5•βλ/2, consumes a power below 2 kW.

Finally, a 4-rod RFQ decelerates the beam down to 6 keV/u. The low mass to charge ratio of $m/q \leq 3$ prevents any RF power problem and allows for a compact tank of 1.9 m length. The maximum electrode voltage is 70 kV, the power consumption amounts to 80 kW, fitting to an available RF-amplifier.

The low energy beam transport system (LEBT) (Fig. 4) matches the transverse beam parameters at the RFQ exit onto the required focus at the ion trap entrance. The normalized emittance of $\varepsilon_{x,y} = 0.55\ \pi$ mm mrad includes a safety margin of 50 %. Horizontal and vertical emittances have the same orientations. This permits the use of solenoid magnets. The expected beam energy spread of ΔT/T = ±7 % causes a beam halo. Further optimization studies may reduce the energy spread at the exit of the RFQ.

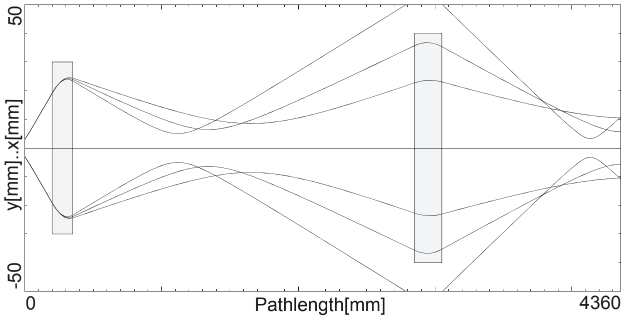

Figure 4: Beam envelopes of the LEBT section for a normalized emittance of $\varepsilon_{x,y,n} = 0.55\,\pi$ mm mrad and energy deviations of ±7 %.

As shown in Table 1, the overall transmission amounts to only 21 % of the particles extracted from the ESR. A gain of factor of two can be achieved by an optional additional second harmonic buncher installed between the first rebuncher and the IH-cavity.

As the ESR ultra-high vacuum system as well as the ion trap runs at a base pressure in the low 10^{-9} Pa region, differential pumping sections have to be integrated into the beam transport line in front of the decelerator and in front of the ion trap. The vacuum of the decelerator itself is planned to be in the low 10^{-5} Pa region.

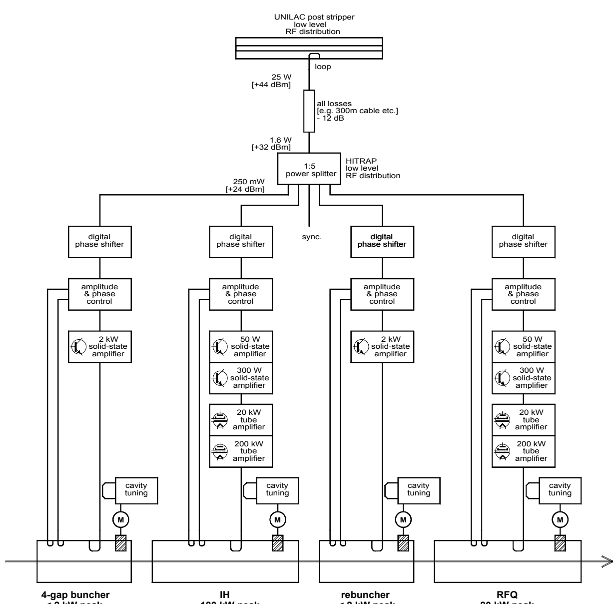

Figure 5: HITRAP RF-system with cavity tuning

Plans are to use two available 30-year-old 200 kW tube amplifiers for the RF-supply. To match the present state of the art they have been upgraded by programmable controls and new amplitude and phase controls. One available power supply can serve for both amplifier chains. To feed the two bunchers, two 2 kW solid-state amplifiers have to be purchased.

The total costs for the HITRAP-facility willl amount to a sum of 4.69 M€. Table 2 summarizes the costs for each component. Due to available equipment the actual costs are only 2.86 M€.

Table 2: Total costs of the HITRAP facility

Investment, equipment, construction (cf. chapter/section)	**Costs[k€]**	**Savings[k€]**
IH structure and bunchers	486	Rebuncher
RFQ cavity	197	
RF supplies	405	1,655
Cooler trap, including 90° bender and valves	306	
Magnets and steerers	80	75
Power supplies for magnets and steerers	319	98
Beam diagnostics	185	
Controls	111	
Vacuum	479	
Civil engineering	103	
Media supply	108	
Safety	81	
Total sum:	**2,860**	**1,828**

OUTLOOK

The HITRAP-project has already been approved but not yet funded. The facility is envisaged to be ready for operation within 30 months after the start of the project in January 2005. Elaborative work was invested in a technical design report taking into consideration all physical, technical, financial, and manpower aspects. In particular, possibilities to save money by the use of existing equipment were taken into account, covering 40 % of the total costs. The two main decelerator structures, the IH-cavity and a 4-rod RFQ, as well as the rebuncher cavities are beeing designed by the Institute of Applied Physics of the University of Frankfurt.

The new HITRAP facility will be the first ever set-up to abundantly provide ions of selected charge states up to U^{92+} at cryogenic temperatures in the laboratory frame, thus allowing to investigate them in a trap or for low energy collision experiments with surfaces or other atoms, ions, and molecules. Experiments of this kind have been impossible up to now.

After successful operation at the ESR and the final shut-down of this storage ring, the HITRAP set-up will be an integral part of the GSI future facility FAIR [5] at a new location behind the NESR (New Experimental Storage Ring). The major areas of investigations with HITRAP will be extended to antiprotons.

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