HIGH CURRENT U^{40+}-OPERATION IN THE GSI-UNILAC

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Abstract

A low current high duty factor U^{10+}-beam from a Penning Ion Source as well as a high current low duty factor U^{4+}-beam from a MeVVa ion source were used for machine investigations of the GSI-UNILAC and synchrotron (SIS18). Carbon stripper foils (20, 40 and 50 μg/cm^2) were used at 1.4 MeV/u to provide for highly charged uranium ions (40+) to be delivered to the SIS18 for beam life time measurements. High current tests were performed to check the durability of the carbon foils. No measurable variation of the stripped low and high current beam in the poststripper DTL could be detected during the life time of the foils. A U^{40+}-beam current of up to 10^{11} particles per 100 μs was obtained in the transfer line to the SIS18. This paper will report on the investigations of stripper foils with different thickness. Additionally, long time observation of all relevant beam parameters (transverse emittance, energy spread and energy loss, bunch shape and beam transmission up to the SIS-injection) are presented.

INTRODUCTION

Meeting the FAIR science requirements [1] higher beam intensities have to be achieved in the present GSI-accelerator complex, through faster cycling and, for heavy ions, lower charge state which enters quadratically into the space charge limit (SCL). The desired energy of up to 1.5 GeV/u for radioactive beam production will be delivered by the synchrotron SIS100. In the last years GSI put effort in increasing the uranium beam intensities delivered to the SIS18. An advanced upgrade program for the UNILAC aimed to meet the FAIR requirements. For uranium (FAIR reference ion) the UNILAC has to deliver $3.3 \cdot 10^{11}$ U^{28+}-particles per 100 μs (see Table 1). Besides for a 15 emA $^{238}U^{4+}$ beam from the High Current Injector HSI [2] up to $5.5 \cdot 10^{10}$ U^{73+} particles should be delivered to the SIS18 (during 100 μs), while the SCL is reached by a 15 turn injection into the horizontal phase space.

In the High Current Injector (HSI) comprising an IH-RFQ and an IH-DTL, the beam is accelerated up to 1.4 MeV/u. In the gas stripper section the charge state is increased; an U^{28+}-beam is matched to the Alvarez DTL. After acceleration up to the final UNILAC-beam energy of 11.4 MeV/u the transfer line (TK) to the SIS18 provides for foil stripping and a charge state separator.

Machine experiments with a foil (temporarily replacing the gas stripper) at 1.4 MeV/u were performed to investigate the capabilities accelerating highly charged high current uranium beams in the poststripper up to the final UNILAC-beam energy. The recently measured U^{39+}-beam current of 6 emA (see Table 1) at the end of the transfer line to the SIS18 offers additional opportunities to investigate space charge effects and to deliver high intensity beams at higher energies.

Table 1: FAIR-design Uranium Beam Parameters at the UNILAC; Measured U^{39+}-intensity (marked in red)

	HSI entrance	HSI exit	Alvarez entrance	SIS 18 injection		
Ion species	$^{238}U^{4+}$	$^{238}U^{4+}$	$^{238}U^{28+}$	$^{238}U^{28+}$	$^{238}U^{73+}$	$^{238}U^{39+}$
El. Current [mA]	25	18	15	15.0	5.5	6.0
Part./100μs pulse	$3.9 \cdot 10^{12}$	$2.8 \cdot 10^{12}$	$3.3 \cdot 10^{11}$	$3.3 \cdot 10^{11}$	$5.0 \cdot 10^{10}$	$1.0 \cdot 10^{11}$
Energy [MeV/u]	0.0022	1.4	1.4	11.4		11.4
ΔW/W	-	$4 \cdot 10^{-3}$	$\pm 1 \cdot 10^{-2}$	$\pm 2 \cdot 10^{-3}$		not meas.
$\varepsilon_{n,x}$ [mm mrad]	0.3	0.5	0.75	0.8		0.9
$\varepsilon_{n,y}$ [mm mrad]	0.3	0.5	0.75	2.5		0.7

HEAVY ION STRIPPER AT THE UNILAC

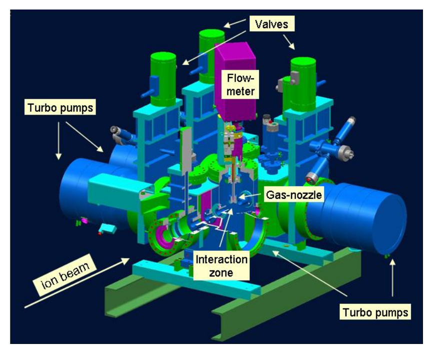

Figure 1: 1.4 MeV/u gas stripper of the GSI-UNILAC.

The 1.4 MeV/u-stripper section is designed to match the beam apertures (∅ 22 mm) of the gas stripper box by two quadrupole doublets. The stripper device comprises the interaction zone (super-sonic N_2-jet) and three steps of differential pumping, upstream and downstream respectively [3]. Allowing for high current operation the free aperture was enlarged by a factor of six, ensuring a small beam size at the analyzing slit without any additional focusing. The charge separator comprises three bending magnets, operating in pulsed mode.

In the TK to the SIS18 the heavy ion beam is stripped to higher charge states in a carbon foil, if high final energies from the SIS18 are required. The TK is operated at 3 Hz pulse to pulse mode at maximum, with beams of different ion species and intensities, with or without stripping. A high current U^{28+}-beam of 15 emA (FAIR requirement) has a power of 1.5 MW (pulse length ≤ 300μs). After stripping, undesired charge states with 85 % of the beam power are separated and dumped in a charge separator system [4] comprising four vertical 1.6 T-dipole magnets providing high resolution and a field homogeneity ≥ 99.97 %. A huge stripper foil (width of 55 mm) is loaded with 3 % of the beam power. To avoid evaporation in a single beam pulse, the beam is rapidly swept over its width. To minimize emittance growth, a narrow, vertically elongated beam spot (4 mm · 20 mm) is prepared, and the distance to the separator is kept as short as possible.

1.4 MEV/U FOIL STRIPPING

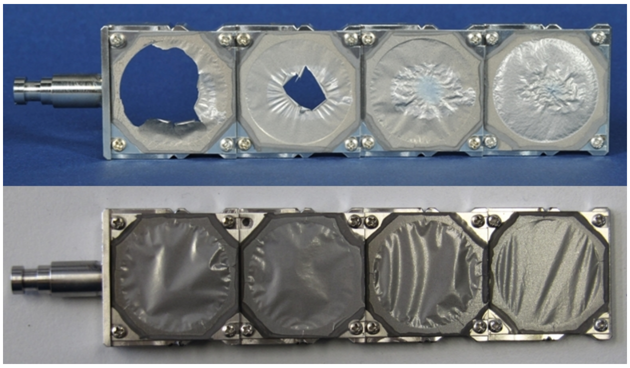

Figure 2: Foil stripper before (bottom) and after (top) high current operation. For the second foil (top, from the right) 11 kJ of beam energy were deposited without any observed influence on the beam parameters.

For a first test the UNILAC gas stripper had been replaced by a set of carbon foils (20, 40, 50 μg/cm^2). The foils (∅ 30 mm) were prepared and glued on a target holder in the GSI target laboratory (shown in Fig. 2). The tests have been carried out with high duty factor low current argon and uranium beams from a Penning ion source and with a high current uranium beam from a MEVVA ion source.

U^{40+}-HIGH CURRENT OPERATION

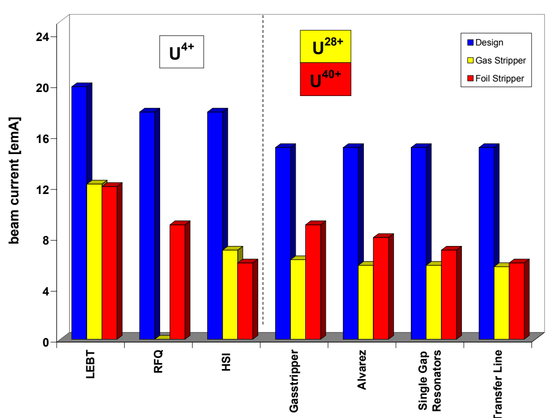

Figure 3: Comparison of the beam transmission for gas stripper and foil stripper operation.

After careful optimization for maximum beam transmission with a low intensity beam from a PIG, a high current uranium beam from a MeVVa was in operation to accelerate a 0.5 MW-beam pulse (1 Hz, 100 μs) up to 1.4 MeV/u. A maximum beam intensity of 9 emA U^{39+} was achieved behind charge separation (Fig. 3,4). The poststripper transmission was optimized for 95%, while up to 6 emA could be delivered to the SIS18. The measured beam load for Alvarez tank no. 1 of 150 kW corresponds to the measured beam current (Fig. 4). In a high current beam test with a 20 μg/cm^2-foil no significant change of the beam emittance as well as the energy loss and the beam transmission could be observed during 6 hours of operation (Table 2).

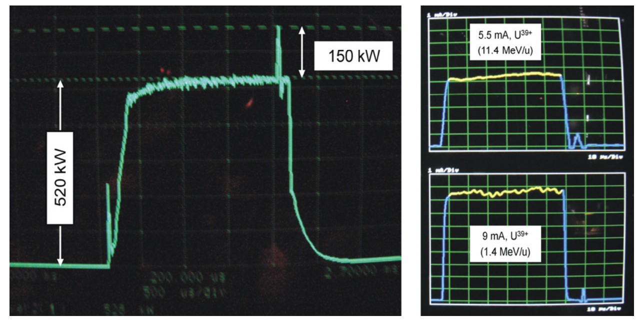

Figure 4: High power rf-pulse (520 kW + 150 kW beam load) feeding Alvarez tank 1 (left); beam transformator signal (right) of the high current U^{39+} beam behind foil stripper (bottom) and at the end of the transfer line (top).

Table 2: Beam Stability Tests (6 hours)

time [h]	trans. emittance (total) [μm]	beam current [emA]	brilliance [mA/μm]
0	18,4	5,9	0,32
2	18,7	5,4	0,29
4	18,8	6,5	0,35
6	19,6	6,6	0,34

As shown in Fig. 5 eleven carbon foils with different thicknesses were used during six days of operation. A maximum integral energy of 25 kJ was deposited by the heavy ion beam until the foil was destroyed. All foils were treated by a low intensity 10 Hz (4ms)-uranium beam from the Penning source – this irradiation prevents stripper foils from sudden rupture and may reduce a decrease of foil thickness by beam irradiation [5]. Nevertheless, in the target center the amorphous carbon was transformed to polycrystalline graphite at high temperature. Generally, the life time of the 20 μg/cm^2-foils is approx. three times higher compared to the thicker foils. An average operating time for the thin foils of 11±4 h was obtained for high current uranium beams injected into the synchrotron.

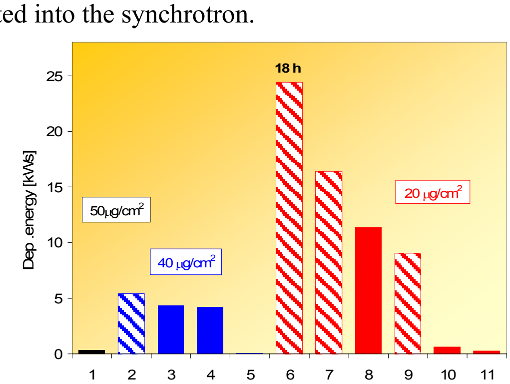

Figure 5: Deposited beam energy for the different stripper foils; streaky marked foils were destroyed.

BEAM MEASUREMENTS

Beam measurements applying foil stripping were carried out: As shown in Fig. 6 the high current beam profile in the charge separator and the low current longitudinal phase space distribution could be measured behind the stripper. Due to strong straggling effects the longitudinal emittance for thick foils is 35 % higher compared to gas stripper operation (Table 3).

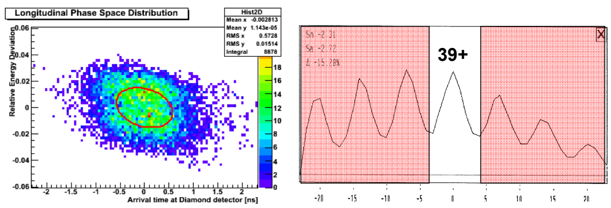

Figure 6: Long. emittance [7] of an uranium beam behind 40 μg/cm^2 stripper foil and charge separator (left); high current beam profile with opened analyzing slits (right).

The energy loss also depends on the thickness of the target; for the favorable 20 μg/cm^2-foil a decrease by 1.2±0.3% is acceptable for further acceleration and transport in the poststripper section. During high current operation no significant change of the beam loss could be observed.

Table 3: Measured Long. Emittance, Bunch Length and Energy Loss for Different Target Densities

ion species	Foil thickness [μg/cm^2]	bunch length [ns]	long. emittance [keV ns]	energy loss [%]
U^{40+}	50	0.57	11.65	2.5
U^{40+}	40	0.57	11.82	1.9±0.2
U^{39+}	20	not meas.	not meas.	1.2±0.3
U^{27+}	≈1	0.61	8.81	0.2

The charge state distribution for the different foils are shown in Fig. 7. Applying the 20 μg/cm^2-target 20% of the main charge state 39+ could be analyzed, while for thicker foils the distribution is shifted to 40+.

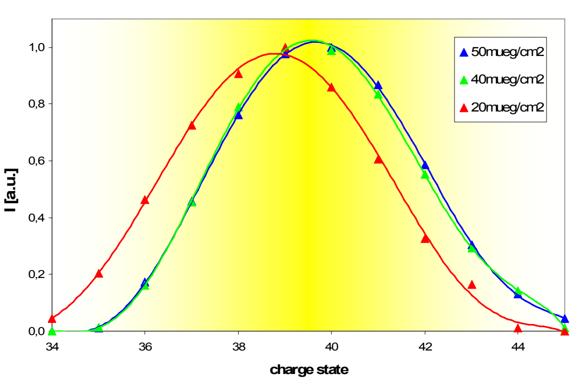

Figure 7: Charge distribution for different foil thicknesses; 20% of the uranium ions are stripped to charge state 39+.

Finally emittance measurements of high current beams for different stripping scenarios are compared (Fig. 8): For the 1.4 MeV/u-foil stripper approach the emittance in the poststripper section is 50% higher than for uranium beams passing a gas stripper. Due to significant beam loss the U^{39+}-beam emittance matches the SIS-acceptance. Applying foil stripping at 11.4 MeV/u the beam emittance for U^{73+} exceeds significantly the emittance for U^{39+}.

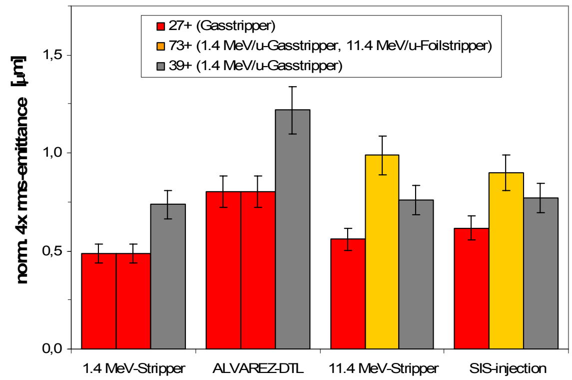

Figure 8: Measured emittance for different stripper scenarios.

SUMMARRY

The maximum uranium particle current could be achieved for U^{27+}-operation obtained from a gas stripper. Foil stripping at the full UNILAC-energy is the favored option to gain for beam energy of up to 1 GeV/u in the SIS18 for more moderate particle currents. A 1.4 MeV/u foil stripping approach is investigated. A foil life time of more than 8 h were obtained during high current operation, while the basic beam parameters did not change. The measured beam quality was favorable. For this reason high current U^{39+} operation is a notable option for short and long term [5]. Additionally, the high current U^{39+} beam offers the opportunity to investigate FAIR relevant space charge effects for heavy ion beams in the GSI-accelerator complex.

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