

# CHARGE STRIPPING TESTS OF HIGH CURRENT URANIUM ION BEAMS WITH METHANE AND HYDROGEN GAS STRIPPERS AND CARBON FOILS AT THE GSI UNILAC

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## Abstract

A nitrogen gas stripper is routinely used for charge stripping of heavy ion beams at the GSI UNILAC at 1.4 MeV/u. Different approaches to optimize the stripping efficiency and to increase the ion charge states for delivery to the synchrotron SIS18 are under investigation. The existing gas stripper was operated with methane and hydrogen stripper gases to study the impact of low-Z gases on stripping of high current (4 emA)  $U^{4+}$  beams. The results and limitations of these tests are presented and are compared to standard nitrogen operation. In addition, newest results using differently prepared carbon stripping foils for the same ion beams are reported.

## INTRODUCTION

Suitable charge stripper technologies are crucial to meet the challenging demands of state-of-the-art heavy ion accelerator facilities like RIBF at RIKEN, FRIB at MSU, and FAIR at GSI [1–6]. At the future Facility for Antiproton and Ion Research (FAIR) presently under construction at GSI [1], the existing linear accelerator UNILAC and the synchrotron SIS18 will serve as injector chain for the FAIR SIS100 synchrotron. At the UNILAC (Fig. 1), the High Current Injector HSI (designed for  $U^{4+}$ ) accelerates heavy-ion beams up to 1.4 MeV/u. The ion charge state is increased in the subsequent gas stripper (in case of uranium beams to  $U^{28+}$ ) before acceleration in the post-stripper linac to 11.4 MeV/u. To provide highest primary beam intensities – for instance, for the production of rare isotope beams behind SIS100 – the  $U^{28+}$  beam will be used also for acceleration in SIS18 and SIS100. The existing foil stripper at 11.4 MeV/u [6] is used to produce higher charge states ( $U^{73+}$ ) just if higher synchrotron end energies are requested.

Within an advanced UNILAC upgrade program, aimed at meeting the FAIR demands, different approaches are investigated to increase the stripping efficiency at 1.4 MeV/u and to generate higher charge states [5–8]. This includes extensive studies with carbon foil strippers, the development of a plasma stripper setup at the Institute

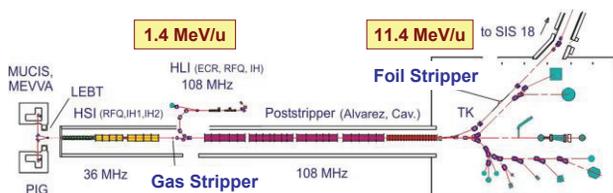


Figure 1: Layout of the GSI heavy-ion linear accelerator UNILAC. A gas stripper is installed behind the High Current Injector HSI at 1.4 MeV/u.

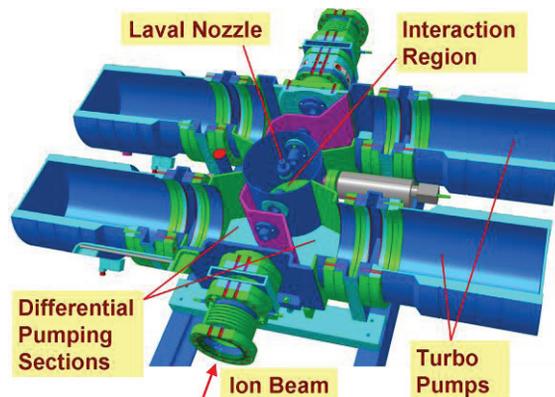


Figure 2: Sectional view of the UNILAC gas stripper box with differential pumping sections.

for Applied Physics (IAP) at Frankfurt University [9], and the application of alternative stripper gases.

For FAIR design beam currents, the stripper target at 1.4 MeV/u has to bear a very high ion beam power of up to 1.5 MW for 18 emA  $U^{4+}$  beams during short beam pulses ( $\leq 100 \mu s$ ) at low duty cycle (2.7 Hz rep. rate). Though for high beam powers gas or liquid strippers have clear advantages compared to foil strippers concerning durability and operational reliability, gas strippers lead to much lower equilibrium charge states due to the absence of the density effect [2, 3, 10]. Since electron capture cross sections are considerably suppressed for low-Z gases [10–11], in particular hydrogen promises higher equilibrium charge states as compared to nitrogen which is routinely used at the UNILAC gas stripper. Since hydrogen gas has a very low density, hydrocarbon gases provide for higher hydrogen concentrations and may be better suited for gas stripper applications. To study the impact of low-Z gases at 1.4 MeV/u, the existing UNILAC gas stripper was operated with methane and hydrogen for charge stripping of  $U^{4+}$  beams (4 emA, 100  $\mu s$ , 2 Hz beam pulses).

## GAS STRIPPER SETUP

A supersonic gas jet produced by a Laval nozzle crosses the ion beam in the central interaction region of the gas stripper box (Fig. 2). More than 99 % of the gas load is dumped by a large roots booster pumping station installed in the basement below the gas stripper for pumping of the central stripper box region. Two sections of differential pumping upstream and downstream of the central region are pumped by four powerful turbopumps (pumping speed 1200 l/s) to ensure a suitable vacuum in the adjacent beam lines.

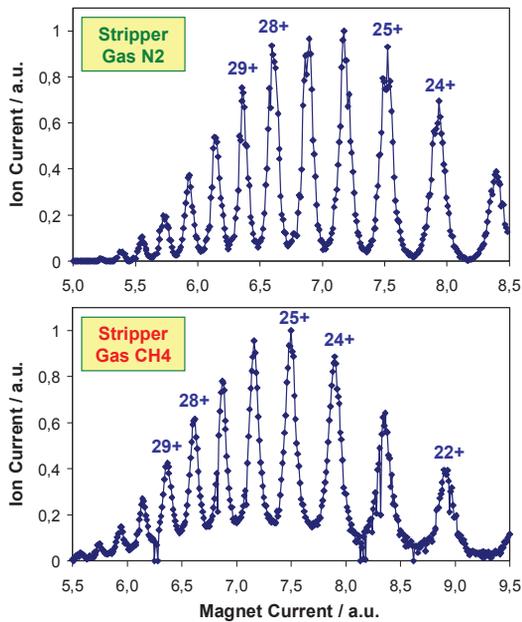


Figure 3: Uranium ion beam spectra measured behind the gas stripper at routine nitrogen operation (upper plot) and at the highest attainable methane flow rate (lower plot). Some uranium charge states are indicated.

To allow for operation with high-current ion beams, the total length of the stripper and of the subsequent charge separator was minimized and the free apertures of the beam tubes separating the differential pumping sections in the stripper box are sufficiently large ( $\varnothing 20 - 22$  mm). The length of the stripper box comprising the central interaction region and the differential pumping sections is 580 mm. The charge separator comprises three bending magnets ( $15^\circ$ ,  $-30^\circ$ , and  $15^\circ$ ) with an analyzing slit downstream of the first magnet. Transverse ion beam matching is provided by two magnetic quadrupole doublets upstream of the stripper without any additional quadrupole focusing along the charge separator.

### Operation with Explosive Gases

To avoid explosive gas mixtures, nitrogen was injected as inert gas into the vacuum exhaust pipe of the stripper and of the neighbouring vacuum sections to provide for a methane (hydrogen) concentration in the exhaust air below 2.2 % (2.0 %), a factor of two below the lower explosion limits. After injection of the inert gas, the exhaust air was extracted by a blower and was discharged to atmosphere.

The stripper gas flow rate and thus the resulting gas pressure at the gas inlet upstream of the Laval nozzle is controlled by a calibrated mass flow controller. The

Table 1: Maximum Gas Stripper Operation Parameters

Stripper gas	Max. flow rate		Max. pressure at gas inlet (mbar)
	(l/min)	(g/min)	
N <sub>2</sub>	21	26	4000
CH <sub>4</sub>	32	23	4500
H <sub>2</sub>	16	1.4	830

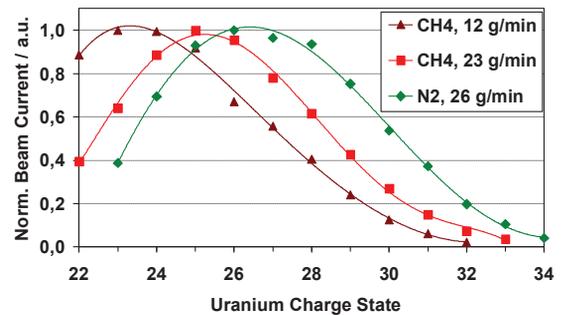


Figure 4: Measured uranium charge state distributions after stripping at different gases and gas flow rates.

maximum operation parameters achieved for routine nitrogen operation as well as for methane and hydrogen are listed in Table 1. For methane, the highest attainable flow rate was limited by the maximum pumping speed of the turbopumps at the stripper box. A mass flow rate of about 88 % compared to nitrogen could be achieved. For hydrogen, merely a maximum mass flow rate of about 1.4 g/min could be reached due to the low mass density of hydrogen gas and because of steeply rising vacuum pressures in the stripper box and in the neighbouring vacuum sections, since hydrogen is only very poorly pumped by the vacuum pumps.

## BEAM MEASUREMENTS

### Methane Gas Stripper

For increasing methane mass flow rates between 12 g/min and 23 g/min, corresponding to methane gas pressures between 2.4 bar and 4.5 bar at the gas inlet, the mean uranium charge states measured behind the stripper increased from about 23+ to 25+ (Figs. 3, 4). For standard nitrogen operation of the stripper, a higher mean charge state around 27+ is achieved. Whereas individual charge states were completely separated for nitrogen operation and for methane at lower flow rates, separation became worse for increasing methane pressure (Fig. 3).

Beam currents measured behind the analyzing slit for individual uranium charge states increased continuously with stripper gas pressure (Fig. 5). Some convergence against upper beam current values is visible at the highest gas pressures, especially, in case of the nitrogen stripper and for U<sup>28+</sup> produced with methane stripper gas. Most probably, in particular for CH<sub>4</sub>, maximum beam currents and equilibrium charge state distributions were not yet reached completely. Finally, at most a moderate gain of the U<sup>28+</sup> current may be expected for further increasing N<sub>2</sub> pressure and possibly none in case of CH<sub>4</sub>. The maximum U<sup>28+</sup> current reached for N<sub>2</sub> was about 3.6 mA (stripping efficiency  $\approx 12\%$ ), 70 % higher than measured for CH<sub>4</sub> (2.1 mA, stripping efficiency roughly 7 %).

Beam energy loss of 13 keV/u was measured for U<sup>28+</sup> within the range of the methane flow rates given above, compared to 15 keV/u in case of nitrogen. Measured U<sup>28+</sup> beam emittances increased slightly for increasing methane flow rates and were comparable to the values measured for nitrogen.

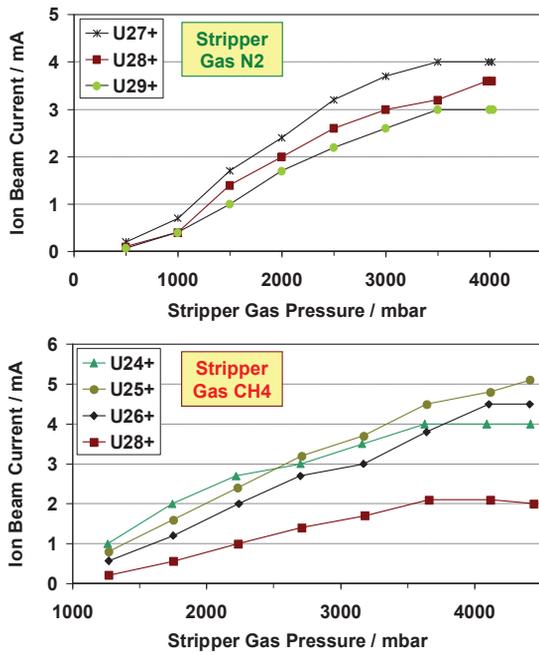


Figure 5: Measured ion beam currents vs. stripper gas pressure for selected uranium charge states for nitrogen (upper plot) and methane (lower plot) stripper gases.

### Hydrogen Gas Stripper

Due to the low mass density of the hydrogen gas jet, the highest charge state which could be measured was about  $U^{21+}$  (Fig. 6). The maximum of the charge state spectrum could not be measured due to the limited field strength of the bending magnet. Analyzed beam currents for  $U^{20+}$  and  $U^{21+}$  were steeply rising with increasing gas pressure. Thus, the obtained hydrogen target thickness was far too low to reach an equilibrium charge state distribution and to allow for final conclusions.

### FOIL STRIPPER TESTS

Various investigations using carbon stripping foils (20 to 30  $\mu\text{g}/\text{cm}^2$ , fixed and rotating targets) were performed at the UNILAC with different heavy ion beams since 2010 [5–7]. A mean charge state around  $U^{39+}$  is achieved at 1.4 MeV/u. Different behaviour during beam irradiation was observed for different foil types (different

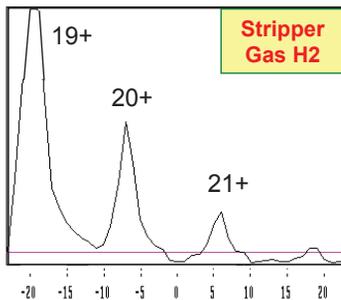


Figure 6: Measured uranium ion beam profiles behind the bending magnet (at maximum excitation current) with opened analyzing slits at the highest attainable hydrogen stripper gas flow rate of 1.4 g/min.

production methods and suppliers). Some foils broke down within a few minutes of irradiation with 5 emA  $U^{4+}$  beams at 1.4 MeV/u (100  $\mu\text{s}$ , 2 Hz) [7]. Amorphous carbon foils produced at the GSI target laboratory could be used up to several hours. Nevertheless, most of the foils were damaged after irradiation. Off-line analysis of the irradiated foils performed by the GSI material physics department indicated graphitization of the amorphous carbon foils after a certain fluence, while thermal stresses and shock waves during pulsed beam operation combined with sublimation at high temperature and low pressure seem to be the dominating processes for foil damaging [12]. Thermal simulations of the foil heating indicate that foil temperatures around 2000 K are reached for presently achieved beam currents, increasing to over 3000 K for FAIR design values [13].

### CONCLUSIONS

Currently, neither methane nor hydrogen are promising alternatives to nitrogen for the existing UNILAC gas stripper, since, so far, the highest uranium charge states and  $U^{28+}$  beam currents were achieved using nitrogen. To investigate higher pressures for methane and hydrogen gas strippers, substantial technical modifications of the stripper setup would be necessary (in particular for  $H_2$ ). Alternatively, a gas cell may be more beneficial instead of a supersonic gas jet. A carbon foil stripper seems not to be a reliable option at 1.4 MeV/u for the future FAIR injector linac, in particular, at FAIR design beam intensities.

### ACKNOWLEDGMENTS

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