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 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 (≤100 μs) 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 μs, 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 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.
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 (Ø 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°, −30°, and 15°) 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 at gas inlet pressures 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 at 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.

**Table 1: Maximum Gas Stripper Operation Parameters**

<table>
<thead>
<tr>
<th>Stripper gas</th>
<th>Max. flow rate (l/min)</th>
<th>Max. pressure at gas inlet (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>21</td>
<td>4000</td>
</tr>
<tr>
<td>CH₄</td>
<td>32</td>
<td>4500</td>
</tr>
<tr>
<td>H₂</td>
<td>16</td>
<td>830</td>
</tr>
</tbody>
</table>

**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.

**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 U²₈⁺ produced with methane stripper gas. Most probably, in particular for CH₄, maximum beam currents and equilibrium charge state distributions were not yet reached completely. Finally, at most a moderate gain of the U²₈⁺ current may be expected for further increasing N₂ pressure and possibly none in case of CH₄. The maximum U²₈⁺ current reached for N₂ was about 3.6 mA (stripping efficiency ≈ 12 %), 70 % higher than measured for CH₄ (2.1 mA, stripping efficiency roughly 7 %).

Beam energy loss of 13 keV/u was measured for U²₈⁺ within the range of the methane flow rates given above, compared to 15 keV/u in case of nitrogen. Measured U²₈⁺ beam emittances increased slightly for increasing methane flow rates and were comparable to the values measured for nitrogen.
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.

**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 H₂). 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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**REFERENCES**

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