DEVELOPMENT OF PULSED GAS STRIPPERS FOR INTENSE BEAMS OF HEAVY AND INTERMEDIATE MASS IONS

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Abstract

The GSI UNILAC together with SIS18 will serve as a high current, heavy ion injector for the future FAIR. It has to deliver high beam brilliance at a low duty factor. A modified 1.4 MeV/u gas stripper setup has been developed, aiming at an increased yield into the particular desired charge state. The setup delivers short pulses of high gas density in synchronization with the beam pulse. This provides a higher gas density and at the same time reduces the gas load for the differential pumping system. Different gases as stripping targets were tested for optimum stripping results under operational conditions. Measurements with various isotopes and gas densities were conducted to investigate the stripping properties. High intensity beams of $^{238}U^{4+}$ were successfully stripped and separated using hydrogen as stripping gas. The stripping efficiency into the desired 28+ charge state was significantly increased by up to 60% while the beam quality remained suitable. The new stripper setup and major results achieved during the development are presented, including a comparison to the present gas stripper based on a N_2-gas jet.

During the last tests in 2016 problems with the fast valves arose while they were used at high back pressures for a longer duration for the first time. This triggered another revision of the setup and led to an exchange of the valves. In parallel, the installation of the required infrastructure for regular operation of the gas stripper using hydrogen was planned. These recent developments are reported in the last part.

INTRODUCTION

The UNIversal Linear ACcelerator (UNILAC) will serve as part of the heavy ion injector chain for the Facility for Antiproton and Ion Research (FAIR), currently under construction at GSI, Darmstadt, Germany. The reference projectile for FAIR is the heavy ion ^{238}U [1]. To meet the beam requirements for FAIR, an upgrade program of the UNILAC has been started to increase the delivered beam intensities especially for U. The task is to deliver $\approx 3 \cdot 10^{11}$ U^{28+} ions within 100 µs pulse length and adequate emittance at repetition rates of up to 2.7 Hz to the subsequent heavy ion synchrotron SIS18.

All ion beams for the UNILAC are delivered by three different ion sources in a time sharing mode. For the production of heavy ions like ^{238}U, a Vacuum ARc Ion Source [2] is used, which is one of the two sources located at the high current injector (HSI). The HSI comprises of a Radio Frequency Quadrupole (RFQ) structure and an Interdigital H-(IH-)structure Drift Tube Linac (DTL) [3]. After charge state and isotope separation in the LEBT ions with $A/q \leq 65$ are accelerated to 1.4 MeV/u by the HSI before they enter the gas stripper section (Fig. 1).

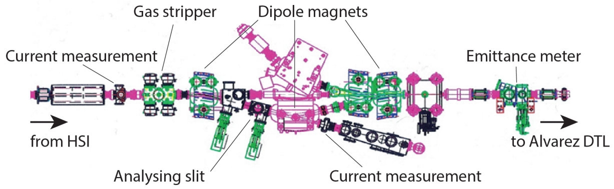

Figure 1: The UNILAC gas stripper section between the high current injector and the Alvarez DTL.

HEAVY ION STRIPPER

After the HSI, a gas stripper is used to increase the charge state of the ions. At this stage, the ions are stripped at an energy of 1.4 MeV/u, so far by a supersonic N_2-jet as a target, created by a Laval nozzle with a back pressure of up to 0.45 MPa [4]. In the gas stripper, the charge state of the ions is increased by charge changing processes occurring in the collisions between beam ions and neutral gas particles. After passing through the gas target, the ion beam is deflected by a fast switchable dipole magnet with a nominal deflection angle of 15°. Thereby the ions are separated according to their charge state, forming multiple beamlets. These are focused onto a charge analysing slit, which only ions having the desired charge state can pass. The remaining beam is then transported by two more fast switchable dipole magnets, matched and injected into the subsequent Alvarez DTL.

To reach the target beam parameters for FAIR injection, a development program for the gas stripper was conducted, aiming at increasing the stripping efficiency, e. g. into the 28+ charge state for uranium. Improving the performance of the gas stripper has proved difficult in the past especially for uranium operation. The main reason was the high gas load for the differential pumping system due to the continuous gas flow of the jet type stripper used [5]. With the existing N_2-jet stripper, the stripping efficiency into the U^{28+} charge state is about 12.7%, and the average charge state of the corresponding distribution is about 26.8 [6].

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In an attempt to use carbon foils instead of the N_2-jet, stripping efficiencies around 20% for U^{39+} and U^{40+} were achieved, depending on the foil thickness [7]. However, the lifetime of the foils was limited to a few hours due to thermal stress and irradiation effects. The use of stripper foils proved to be not feasible for uranium beam operation at FAIR intensity, pulse length and rate requirements. Another approach was taken to enhance the performance of the jet stripper by using gases other than nitrogen. Especially for hydrogen, applying sufficient gas densities in the interaction zone was hindered by the limitations of the pumping system. The equilibrium charge state distribution could not be reached using the continuous gas jet stripper [5].

PULSED GAS STRIPPER

The basic idea to overcome the limitation of the pumping speed is to exploit the low duty factor f of the ion beam. For synchrotron operation, which is the reference for FAIR, $f \ll 1\%$. Due to the low duty factor, most of the time there is no beam in the gas stripper, and the continuous operation of the jet is not required. If gas would only be injected while a beam pulse passes the gas stripper, the gas load on the vacuum pumps could be reduced by about two orders of magnitude. To accomplish this, a fast valve is needed. Additionally, higher gas densities for the stripping process could be attained by enabling a significantly increased back pressure on the gas inlet.

The pulsed gas injection was realized by implementing a fast gasoline valve normally used in automotive applications. Its operation is synchronized with the accelerator timing. Shortly (≈0.4 ms) before the beam pulse passes the gas stripper, the valve opens to build up the gas density in the interaction zone, and closes immediately afterwards. This was tested using a newly developed setup replacing the Laval nozzle. A schematic model of the main stripper setup is shown in Fig. 2. The flange on top of the main stripper chamber carries the actual stripper setup. It was exchanged with a newly developed flange incorporating the pulsed gas valve, as shown in the figure. The valve is placed directly above the beam line without a Laval nozzle, so no gas jet is formed. To prevent the gas from instantaneous exhaustion and to increase the gas density in the interaction zone, a T-fitting with 44 mm length in direction of the beam was added below the valve. This fitting matches the aperture of 22 mm of the beam line through the stripper. The surrounding setup was not changed, it uses the same pumping system as the gas jet stripper [8]. It consists of a roots vacuum pump (8000 m^3/h) directly below the main stripper chamber and four turbo pumps (1200 m^3/h each) in the four adjacent differential pumping sections. They are separated by diaphragms to minimize the molecular conductance between the sections.

A first setup of the pulsed gas injection was tested in 2014 [9]. The reduction of the gas load allowed increased densities even for gases like hydrogen as stripper targets, which are difficult to pump, in comparison to the N_2-jet. At the end of 2014, measurements were conducted using a wide range of different gases to test the stripping performance for uranium beams and to increase the stripping efficiency into U^{28+} [6, 8]. During this series, a limitation of the achievable average charge state was noticed, caused by the limited gas back pressure on the inlet. Therefore, the setup was modified to enable higher back pressures as well as shorter opening times [10–12].

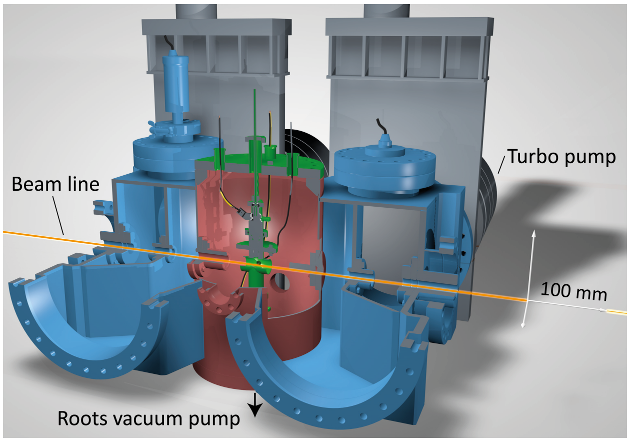

Figure 2: Main setup of the gas stripper (schematic). The pulsed gas injection is mounted on the top flange (green) of the main chamber (red). Together with the adjacent sections (blue) this constitutes a four stage differential pumping system [8].

MEASUREMENTS AND RESULTS

Target Investigations

To evaluate the quality as a stripper target, the stripping efficiency into each populated charge state and the beam quality, namely the energy loss and the horizontal and vertical beam emittance, were measured for various gases.

The stripping efficiency into a specific charge state i, $q_i = \frac{n_i}{n_{\text{total}}}$, is the ratio of the number of ions n_i going into this charge state and the total number of ions n_{total} in front of the stripper. To obtain n_i and n_{total}, the electrical beam current is measured and divided by the charge state of the ions. The energy loss due to the collisions between the beam ions and the stripper gas is determined by the difference of the beam energies behind the stripper with and without gas applied. The energy of the beam ions is measured by time-of-flight measurements using phase probes along the beam line. The beam emittance is measured using a slit grid measurement system behind the charge separation [13].

At a certain target thickness, the cross sections for the electron capture and electron loss processes reach an equilibrium. At this point, the charge state distribution does not change anymore with increasing target thickness.

The stripping properties of H_2, He, Ne, N_2, O_2, Ar, and CO_2 were investigated. Back pressures in the range of 2–12 MPa were applied for each type of gas. U^{4+} ions with a beam pulse length of 100 µs were used as stripping probes

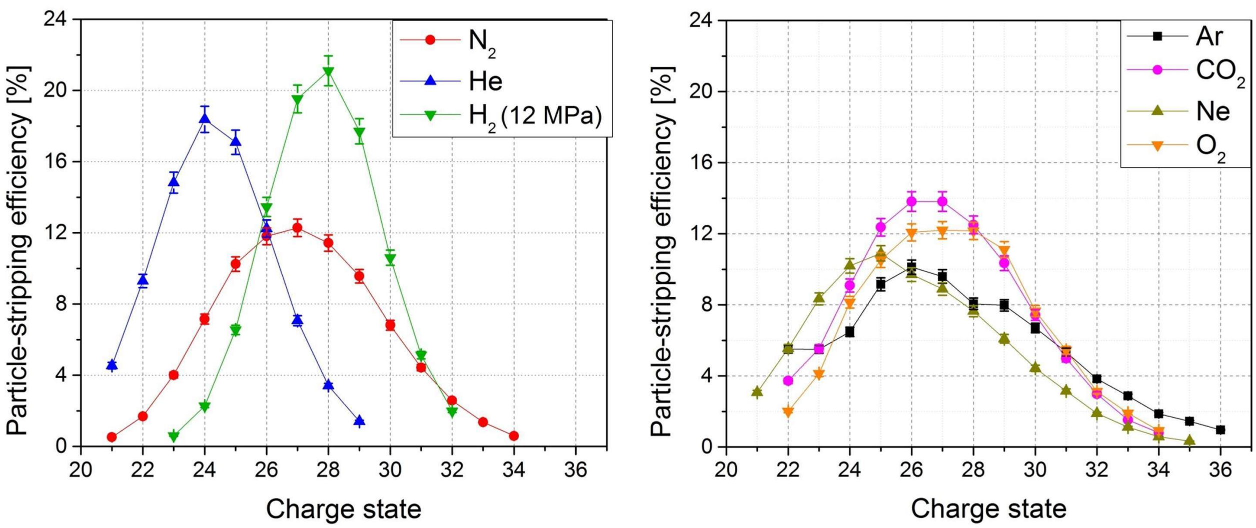

Figure 3: Charge state distributions for U stripped by N_2, He and H_2 (left), Ar, CO_2, Ne and O_2 (right), measured with the pulsed gas stripper at 1.4 MeV/u beam energy. The graphs show the equilibrated stripping efficiencies q_i as functions of the charge state i except for H_2, where the distribution was still not equilibrated at 12 MPa back pressure with the setup used [6].

at a repetition rate of 1 Hz. The opening time of the valve was set to 0.5 ms to achieve a maximum gas density during the beam transit.

The corresponding charge state distributions are shown in Fig. 3. For all gases except hydrogen equilibrium was reached within the measured back pressure range. The heavier gases generate relatively broad charge state distributions at average charge states between 25 and 27. For the light gases H_2 and He the charge state distributions are more narrow. This leads to increased stripping efficiencies for the populated charge states. For H_2 compared to He, the average charge state of the distribution is increased [14].

For different target thicknesses, the charge state distributions for U passing through H_2 are shown in Fig. 4. For increasing target thickness, the average charge state rises from about 23+ to 29+, while the width of the distributions as well as the maximum efficiency stays constant above ≈7 μg/cm^2 within the error range. These data were taken with the improved gas supply providing higher back pressures, therefore equilibrium could be achieved at ≈19 μm/cm^2.

By applying H_2 as a stripper gas at sufficient back pressure, the efficiency into U^{28+} could be increased from 13% for the N_2-jet stripper to 21% [6, 8, 10, 12]. Finally, hydrogen turned out to be the most preferable stripping target and was therefore chosen for further investigations.

Projectile Investigations

^{238}U is the reference ion for FAIR, nevertheless the UNILAC will also deliver other heavy ions in the future. To investigate the stripping properties of H_2 as target for different heavy ions, the equlibrated charge state distributions of ^{238}U, ^{209}Bi, ^{50}Ti, and ^{40}Ar after passing the pulsed gas stripper were measured under similar conditions [11]. In Fig. 5, the results are shown and compared to the distributions measured with the N_2-jet gas stripper[1].

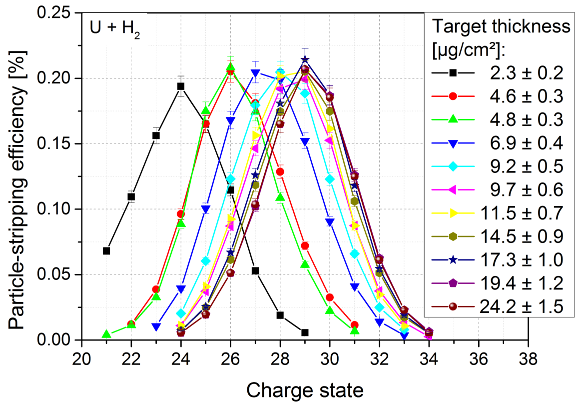

Figure 4: Charge state distributions for U on H_2 for different target thickness, measured at 1.4 MeV/u beam energy. The solid curves are fitted to the data using a gaussian fit with a skewness correction. Target thickness is estimated from energy loss measurements using SRIM2013 [10, 15].

For all measured isotopes, stripping with H_2 leads to an increase of the average charge state compared to N_2. Moreover, for the heavier ions, ^{238}U and ^{209}Bi, the distributions are more narrow for H_2 than for N_2, while there is no difference in the width for the lighter ions. This results in increased stripping efficiencies for the populated charge states for the heaviest isotopes. The Beam quality remains well acceptable, even though generally the transverse emittances

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[1] The sum $Q = \sum_i q_i = 1$ of the stripping efficiencies of all populated charge states is the total transmission through the stripper, which should be 100%. However, optimal accelerator settings could not be achieved for all shown measurements. Therefore, the total stripping efficiencies shown is normalized to 1, showing the charge fractions of the ion beam behind the gas stripper.

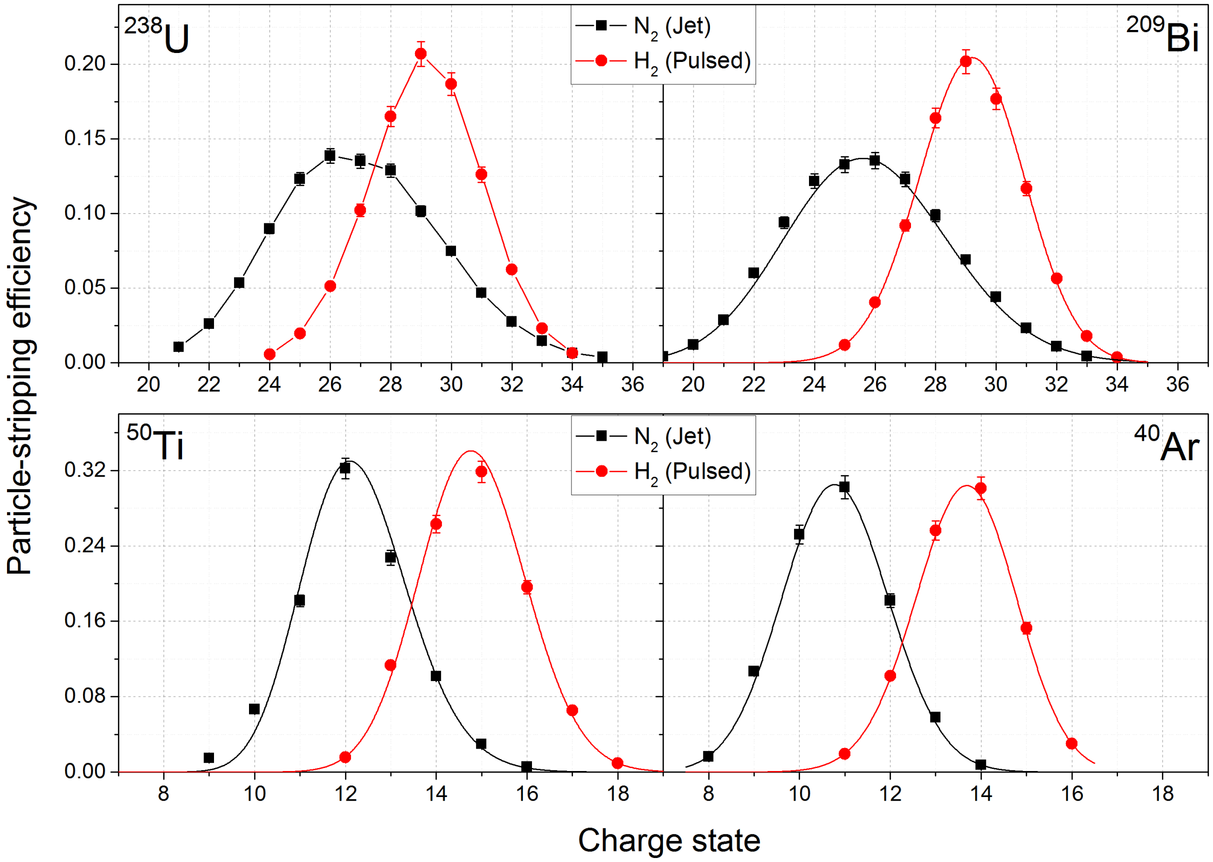

Figure 5: Equlibrated charge state distributions for ^{238}U, ^{209}Bi, ^{50}Ti, and ^{40}Ar ions after passing the N_2-jet gas stripper (black) and the pulsed gas stripper using H_2 as target (red) [11]. See text for details.

as well es the beam energy loss are higher with the pulsed gas stripper using hydrogen. This is due to the increased target thicknesses. More details can be found in [11]. A detailed description of the complete experimental data set and a discussion of the relevant effects can be found in [14].

LATEST REVISION

The measurements of the different stripping properties were complemented by a test run of three weeks with the pulsed gas stripper setup in 2016. During this period, a uranium beam stripped with H_2 was delivered to the SIS18 and different users. At the end of the test, the fast valves showed significant leakage problems. It turned out that this type of valves, which is originally designed for gasoline injection, can not be used with gaseous media for long term operation. The reason is the design of the valve seating, which relies on the damping by a liquid fuel when it is closing. Therefore another type of injection valves, which are also originally used for automotive applications, but designed for gaseous fuels, was chosen (Fig. 6). A new stripper setup was designed to accomodate two of the new, mechanically different valves (Fig. 7). These valves are slower compared to the gasoline valves, but still fast enough for the application in the UNILAC stripper, and they require a completely different, much lower range of back pressure. Therefore, the gas supply was modified to allow for proper gas supply to the valve at the much lower pressures. The properties regarding opening, closing and flow rates are also different. For evaluation of the new type of valves without beam, a test stand was built. A new valve controller was also commissioned.

Figure 6: Fast valve for gasoline operation (left) and for gaseous media (right).

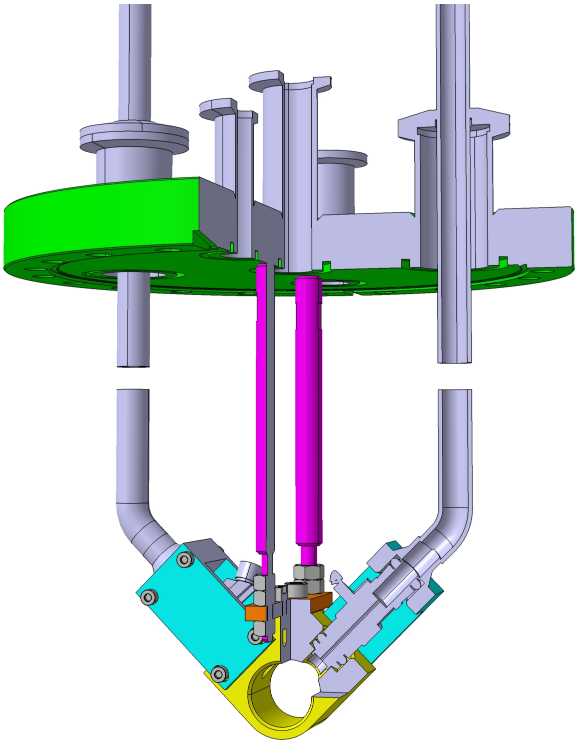

Figure 7: Latest stripper setup accomodating two fast valves for gaseous media.

All tests were successfully accomplished beginning of 2018. The setup with the new valves is now being prepared for evaluation with beam.

CONCLUSION AND OUTLOOK

The original continuous flow jet gas stripper was replaced by a pulsed gas stripper. This reduced the average gas load on the pumping system, which limits the effective performance of the stripper. Various gases were tested regarding their performance as stripping targets. H_2 could be applied as stripping target at increased target thickness, enabled by the pulsed valves and an improved gas supply. Equilibrium charge state distributions could be achieved and the distributions are more narrow with H_2 compared to N_2, resulting in an overall increase of the particle stripping efficiency of about 60% for ^{238}U.

H_2 turned out to be the most preferable stripper gas. Further investigations with different ions stripped by H_2 were conducted. For all ions, a higher average charge state was found. Only for heavy ions the width of the distribution is reduced, leading to an increase in stripping efficiency. This results in higher beam intensities for the heavy ions, which is important for the future operation of the UNILAC and FAIR. Due to the increased target thickness, the energy loss and the beam emittance is generally increased, which affects the beam quality and the matching to the subsequent Alvarez DTL.

A first long term test showed that the fast valves used so far are not suitable for operation with gases. Different valves, designed for gaseous fuels, are adopted and enable higher gas flow at reduced back pressures due to an enlarged orifice. Evaluation at a test stand was successful, measurements with beam for the newly revised setup are anticipated for end of 2018.

The planning of the infrastructure necessary for regular operation of the gas stripper with hydrogen is in progress. This includes

- a gas supply station capable of continuous operation at a maximum flow rate of 200 l/min H_2,
- an explosion protected and radiation safe exhaust gas system able to dispose of the same amount of H_2 from the vacuum pumps exhaust safely to the outside,
- a comprehensive explosion protection upgrade for the vacuum system in the gas stripper area, and
- incorporation of the pulsing functionality of the new gas stripper into the accelerator control system.

Realization is planned for 2019, first regular operation of the pulsed stripper for 2020.

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