A PULSED GAS STRIPPER FOR STRIPPING OF HIGH-INTENSITY, HEAVY-ION BEAMS AT 1.4 MeV/u AT THE GSI UNILAC

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Abstract

The GSI UNILAC in combination with SIS18 will serve as a high-current, heavy-ion injector for the future FAIR. It has to meet high demands in terms of beam brilliance at a low duty factor (100 µs beam pulse length, 2.7 Hz repetition rate). An advanced 1.4 MeV/u gas stripper setup has been developed, aiming at an enhanced yield into the required charge states. The setup delivers short, high-density gas pulses in synchronization with the beam pulse. This provides an increased gas density at a reduced gas load for the differential pumping system. In recent measurements, high-intensity, heavy-ion beams of U^{4+} were successfully stripped and separated for the desired charge state. The modified stripper setup, as well as major results, are presented, including a comparison to the present gas stripper based on a N_2 gas-jet. The stripping efficiency into the desired 28^+ charge state was significantly increased by up to 60 % using a hydrogen stripper target while the beam quality remained similar.

INTRODUCTION

The UNIversal Linear ACcelerator (UNILAC) will serve as part of an injector system for the Facility for Antiproton and Ion Research (FAIR), currently under construction at GSI in Darmstadt, Germany. A key projectile for FAIR is the heavy ion ^{238}U [1]. To meet the beam requirements for FAIR, an upgrade program of the UNILAC has started to increase the delivered uranium beam intensities. The aim is to deliver short-pulsed, high-current, high-intensity U^{28+} beams with a repetition rate of 2.7 Hz to the subsequent SIS18 accelerator.

In the UNILAC, a gas stripper is used to increase the charge state of the beam ions at an energy of 1.4 MeV/u. Currently, the gas stripper operates with a super-sonic N_2-jet as a target, created by a laval nozzle with a back-pressure of up to 0.45 MPa [2]. To be able to deliver the desired beam parameters for FAIR-injection, an upgrade program of the gas stripper is ongoing, aiming at increasing the stripping efficiency into the U^{28+} charge state. Improving the performance of the gas stripper for uranium operation has proved difficult in the past, predominantly because of the high gas load for the differential pumping system using the continuous gas-jet [3].

A new approach was tested by applying a pulsed gas injection to the existing stripper setup, using a newly developed setup replacing the laval nozzle. The aim is to temporally increase the gas density in the interaction zone of the gas stripper just when a beam pulse is passing. The reduction of the gas load allows increased gas densities, which enables the practical use of other promising gases as stripper targets by providing the conditions to reach equilibrated charge-state distributions.

In first measurements in February 2014, the functionality of the pulsed gas cell was tested. At the end of 2014, another measurement series was 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+}.

HEAVY-ION STRIPPER OPERATION

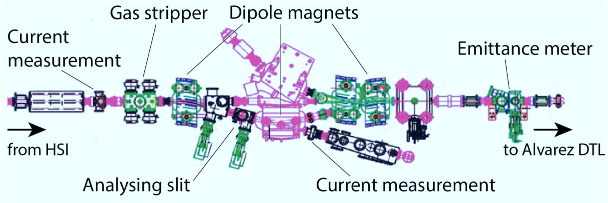

Figure 1: Layout of the UNILAC gas stripper section between the HSI and the Alvarez DTL.

In the UNILAC, the ion beams are delivered by three different ion sources in a time sharing mode. For the production of heavy ions like ^{238}U, a new Vacuum ARc Ion Source [4] is used. The prepared ion beams are delivered to the High Current Injector (HSI) [5]. The HSI comprises of a combination of a Radio Frequency Quadrupole structure (RFQ) and an interdigital H-structure drift tube linac (DTL), and accelerates the ion beams up to 1.4 MeV/u. Behind the HSI, the ion beams are focused onto a charge-analysing slit behind the gas stripper by two quadrupole doublets. The UNILAC stripper section is shown in Fig. 1. In the gas stripper, the charge state of the beam ions is increased by charge-changing processes occurring in the collisions between beam ions and neutral gas particles. Behind the stripper, the beam ions are separated by their charge state using a system of three dipole magnets. To select a charge state for further acceleration, an analysing slit is used behind the first dipole magnet at a deflection angle of 15°.

With the existing N_2-jet stripper, the stripping efficiency into the U^{28+} charge state at maximum back-pressure of

0.45 MPa is about 12.7 %. The average charge state of the corresponding charge-state distribution is about 26.8.

In the course of the ongoing upgrade program, several measurements were conducted with the aim to increasing the uranium stripping performance. In an attempt to use carbon foils instead of the N_2-jet, average charge states up to +39 were achieved at stripping efficiencies of about 20 % [6]. However, the lifetime of the foils was strongly limited to a few hours due to thermal and irradiation stress effects. At increased beam currents at FAIR, the use of stripper foils is not feasible for uranium beam operation and would set a limitation for the repetition rate. The practical use of other promising gas targets, like hydrogen, at sufficient densities was hindered by the limitation of the pumping system due to an increased gas load, using the continuous gas-jet stripper [3].

PULSED GAS CELL

To be able to increase the gas density, the continuous gas-jet is replaced with a pulsed gas injection. The short beam pulse width at a relatively low duty cycle is exploited to lower the total gas load for the pumping system, by only applying gas when a beam pulse passes the gas stripper. Due to this decrease of the gas-load, the back-pressure on the gas inlet can be increased significantly, enabling higher gas densities during the stripping process.

The short pulsed gas injection is realized by a pulsed gas valve, normally used in automotive applications. The valve is synchronized with a timing signal from the accelerator main control unit. When a beam pulse passes the gas stripper, the valve opens to increase the gas density during the stripping process and closes immediately afterwards.

The flange on top of the main stripper chamber was exchanged with a newly-developed flange featuring the pulsed gas valve. The pulsed gas valve is placed directly above the beam line in a specially designed build-up. To prevent the gas from instantaneous exhaustion, a T-fitting (44 mm length in beam direction) was added below the injection point matching the apperture of the beam line in the stripper (22 mm). The stripper-setup uses the same pumping system as the gas-jet stripper (see [7]). It consists of a roots vacuum pump (pumping performance: 8000 m^3/h) directly below the main stripper chamber and four turbo pumps (pumping performance: 1200 m^3/h each) in the adjacent differential pumping sections. Several additional vacuum pumps are installed along the adjacent beam line.

A first setup of the pulsed gas cell was tested in the beginning 2014 [8]. It was since adjusted to enable higher back-pressures as well as shorter opening times. This modified setup is described in [7, 9].

MEASUREMENTS AND RESULTS

During the second measurement series in November 2014, various different gases were applied covering a wide range for the back-pressure on the valve (2–12 MPa). The stripper gases H_2, He, Ne, N_2, O_2, Ar, and CO_2 were used. An U^{4+} beam with a beam pulse length of 0.1 ms at a repetition rate of 1 Hz was used as a reference beam for FAIR-injection. The opening time of the valve was set to 0.5 ms to achieve a maximum gas density during beam pulse transit for the applied back-pressure range.

To evaluate the quality as a stripper gas, 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. The stripping efficiency into a specific charge state, q_i, is the ratio of the number of ions going into this charge state and the total number of ions in the incident charge state (+4 for uranium beam operation) in front of the stripper. To obtain the number of ions, the beam current is measured using beam transformers (see current measurements in Fig. 1) and then divided by the charge state of the ions. The energy of the beam ions is measured in time-of-flight measurements using phase probes along the beam line. To determine the energy-loss due to the collisions inside the stripper gas, the beam energy with and without applied gas is measured behind the stripper and subtracted from each other. The beam emittance was measured using a slit-grid measurement system behind the charge separation (see Fig. 1) [10]. 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. For all gases, except hydrogen, this equilibrium was reached within the measured pressure range of 2-12 MPa and the corresponding charge-state distributions are shown in Fig. 2. The charge-state distributions of uranium after passing different gas-targets is shown, plotting the stripping efficiency against the populated charge states. The heavier gases measured show broad charge-state distributions at average charge states between 25 and 27. For the light gases, H_2 and He, the charge-state distribution is more narrow, resulting in increased stripping efficiencies for the populated charge states. For H_2 compared to He, the average charge state of the distribution is increased. For H_2, the shown distribution was measured at 12 MPa. The charge-state distributions for uranium after passing through H_2 for an increasing target thickness are shown in Fig. 3. The target thickness is estimated from energy-loss measurements using SRIM2013 [11]. The solid lines are curves fitted to the data using a gaussian fit with a skewness correction. For increasing target thickness, the average charge state rises from about +23 to +28. The width of the distribution, as well as the maximum charge fraction, does not change within the error range for increasing target thickness.

By applying H_2 as a stripper gas, the stripping efficiency into U^{28+} could be increased from 12.7 % for the N_2-jet stripper to 20.4 %. Together with an optimization of the prestripper UNILAC for high-current uranium beam transport, an U^{28+}-intensity record was achieved behind the charge separation, using the new pulsed gas cell. An U^{28+}-beam current of 7.8 mA was measured behind the charge separation. The beam emittance as well as the energy-loss show a beam quality similar to the N_2-jet stripper. This achieve-

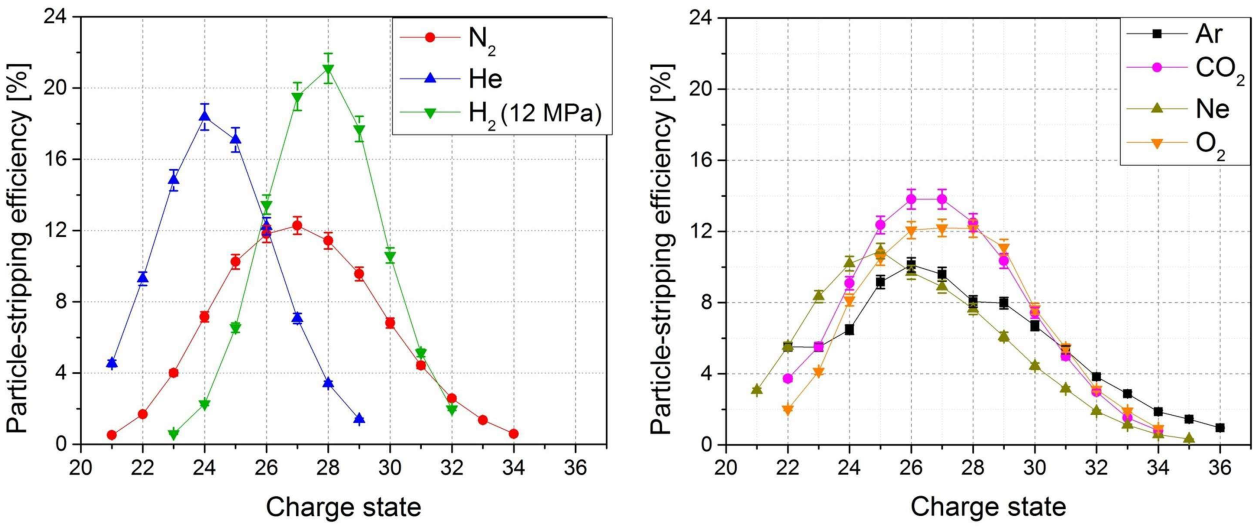

Figure 2: Equilibrated charge-state distributions showing the stripping efficiencies for U on He, Ne, N_2, O_2, Ar, and CO_2, measured with the pulsed gas cell at 1.4 MeV/u beam energy. For H_2, the shown charge-state distribution is still not equilibrated and obtained at 12 MPa.

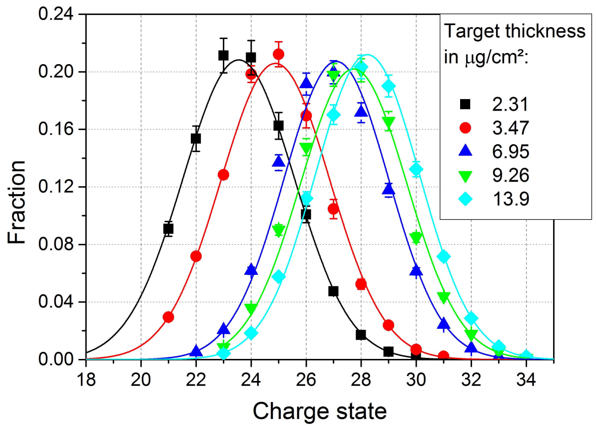

Figure 3: Charge-state distributions for U on H_2 at increasing target thickness, measured at 1.4 MeV/u beam energy. The solid curves are fitted to the data using a gaussian fit with a skewness correction.

ment is described in [9]. The beam quality, i.e. the measured beam emittance and energy-loss, compared to the preceding N_2-jet stripper is shown in Table 1.

Table 1: Comparison of U^{28+} Stripping Performance

Value	**N_2-jet**	**pulsed H_2**
Max. U^{28+} current	4.5 mA	7.8 mA
Stripping efficiency (U^{28+})	12.7 %	20.4 %
ϵ_x (90 %, total, norm.)	0.76 µm	0.7 µm
ϵ_y (90 %, total, norm.)	0.84 µm	0.93 µm
Energy-loss	20 keV/u	12 keV/u

CONCLUSION AND OUTLOOK

The modified setup of the pulsed gas cell was tested with an uranium beam applying various gases. The light gases hydrogen and helium show more narrow charge-state distributions then the heavier gases, resulting in increased stripping efficiencies into the populated charge states. Measurements with hydrogen at maximum back-pressure (12 MPa) show increased stripping efficiencies into the desired U^{28+}-charge state. This improvement resulted in higher beam currents behind the stripper, enabling a new U^{28+}-intensity record at the GSI UNILAC. However, an equilibrated charge-state distribution for uranium on hydrogen could not be observed in the applied back-pressure range.

To be able to measure equilibrated charge-state distributions using hydrogen, a new setup for the pulsed gas cell is currently being developed, featuring advanced pulsed gas valves. The new generation of valves enables increased back-pressures as well as an increased gas flow due to an enlarged opening. In addition to this, two valves are used to be able to increase the gas density inside the interaction zone even more. A new control unit for the valves enables a reduction of the opening time due to faster opening of the valve. In the course of a measurement series with this enhanced setup in July 2015, back-pressures up to 25 MPa were used at a reduced opening time of 0.4 ms. Increased gas densities for the stripping process are expected. With the new enhanced setup, additional measurements with uranium beams are envisaged.

ACKNOWLEDGEMENT

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