# DEVELOPMENTS ON THE 1.4 MeV/u PULSED GAS STRIPPER CELL

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*Abstract*

The GSI UNILAC in combination with SIS18 will serve as a high-current, heavy-ion injector for the FAIR facility. It must meet high demands in terms of beam brilliance at a low duty factor. As part of an UNILAC upgrade program dedicated to FAIR, a pulsed gas stripper cell was developed, aiming for increased beam intensities inside the post-stripper.

The pulsed gas injection is synchronized with the beam pulse timing, enabling a highly-demanded increased gas density. First tests using uranium beams on a hydrogen target showed a 60 %-increase in the stripping efficiency into the desired 28+ charge state. In 2015, the setup was improved to achieve yet increased target thicknesses and enhanced flexibility of the gas injection.

Recently, the pulsed gas cell was used with various ion-beams, to test the capabilities for operation at the GSI UNILAC. The stripping of ions in different gases at different gas densities was successfully tested in mixed-beam operation. Charge fractions, beam emittance, and energy-loss were systematically measured using uranium, bismuth, titanium, and argon beams on hydrogen, helium, and nitrogen targets. Selected results are presented.

## INTRODUCTION

The GSI Universal Linear Accelerator (UNILAC) will serve as part of an injector system for the future Facility for Antiproton and Ion Research (FAIR), currently under construction at GSI in Darmstadt, Germany [1]. For operation at FAIR, the UNILAC has to deliver high-intensity $^{238}U^{28+}$-ion beams at a low duty cycle (approx. 100 $\mu$s beam pulse length, $\leq$ 2.7 Hz repetition rate) and an excellent beam brilliance.

In the course of an extensive upgrade program for the UNILAC [2], a new setup for the gas stripper at 1.4 MeV/u beam energy was developed to replace the previously existing $N_2$-jet gas stripper [3]. The aim was to increase the output beam brilliance for $^{238}U^{28+}$ ions. Pulsed gas valves, as originally designed for automotive aplications, were utilized to realize a pulsed gas injection, synchronized with the beam-pulse transit through the stripper. The pulsed gas injection enabled higher gas densities for the stripping process because the low repetition rates still result in a decreased effective gas load compared to the previously used continuous jet. This allowed for the practical use of lighter gases as stripper target, like $H_2$ and He, which require an increased mass flow into the stripper to achieve sufficient target thicknesses. This would overload the pumping system if applied continuously. By using $H_2$ as a stripper gas, the stripping efficiency for $^{238}U^{28+}$ ions could be significantly increased, still preserving a sufficient beam quality [4].

At the GSI UNILAC, various different ion beams, from protons up to uranium, are accelerated to be delivered to a wide range of experiments with varying requirements. In routine operation at the UNILAC, the gas stripper has to be used for all available projectile ions. Therefore, the pulsed gas stripper was tested with a selection of ion beams, including $^{238}$U, $^{209}$Bi, $^{50}$Ti, and $^{40}$Ar, using different gas targets, including $H_2$, He, and $N_2$.

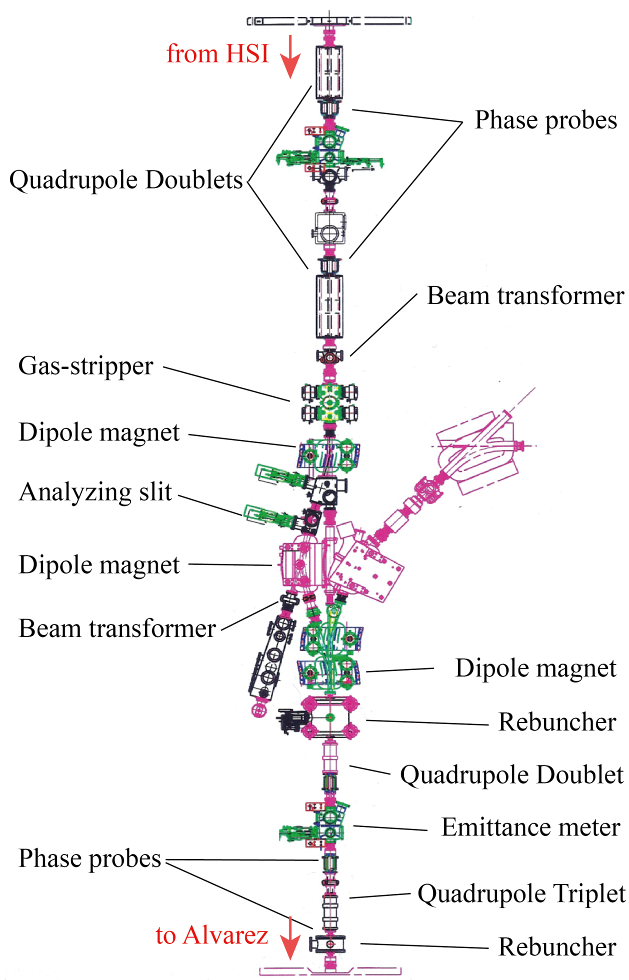


Figure 1: Stripper section of the GSI UNILAC

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## EXPERIMENTAL PROCEDURE

At the GSI UNILAC, ions are produced in one of three ion source terminals. The high-intensity ion beams are then accelerated to 1.4 MeV/u in the High Current Injector (HSI) [5], which is essentially composed of an RFQ and two IH-DTL accelerator structures. After the HSI, the ion beams enter the gas stripper section, shown in Fig. 1.

The ion beams are horizontally focused by two quadrupole doublets to enable charge separation at the analysing slits behind the stripper. By passing the gas target of the stripper, the charge state of the ions is changing due to charge changing processes in collisions with the gas particles. After passing the stripper, the charge state of the ions is distributed around an average charge state. The resulting charge state distribution depends on the ion energy, the ion and target type as well as the thickness and density of the gas target. With increasing thicknesses, the distribution eventually reaches a saturation and does not change anymore; this is the so-called charge state equilibrium [6].

The setup of the pulsed gas stripper is described in detail in [7]. To separate ions with a certain charge state, a system of three dipole magnets is used in combination with two analysing slits. The charge state distribution is measured behind the first dipole magnet, with the second dipole magnet turned off. For this, the stripping efficiency for every charge state is measured by gradually increasing the magnetic field of the dipole magnet.

The beam energy is measured via time-of-flight using signals from two phase probes behind the charge separation system. The beam energy measured with and without gas target allowed for quantifying the energy loss in the gas stripper. The beam emittance is measured using a slit-grid system [8].

## RESULTS

In Fig. 2, the saturated charge state distributions of $^{238}$U, $^{209}$Bi, $^{50}$Ti, and $^{40}$Ar ion beams (100 $\mu$s beam pulses, 1 Hz repetition rate) after passing the pulsed $H_2$-gas stripper are shown and compared to the distributions measured with the $N_2$-jet gas stripper. The sum of the stripping efficiencies of all populated charge states is the total transmission through the stripper, which is about 100 % within the error range, if optimal accelerator settings are provided. However, optimal accelerator settings could not be secured for all shown measurements. Therefore, the stripping efficiency is normalized to 1, showing the charge fractions of the ion beam behind the gas stripper.

For all measured ion beams, $H_2$ showed increased average charge states compared to all other applied gas targets (shown in [9] for $^{238}$U on various gases), including $N_2$, which is shown here. An increased average charge state of the charge state distribution enables a possible use of higher charge states without a loss of efficiency, allowing for a reduced power consumption of the adjacent accelerator structures. This comes at the expense of increased space charge forces, especially for high-intensity ion beams as being required by FAIR. The charge state distributions of the heavier ions, $^{238}$U and $^{209}$Bi, after passing the $H_2$ target are more narrow compared to the distributions with $N_2$. A more narrow charge state distribution results in increased stripping efficiencies for the remaining populated charge states. This allows for increased beam intensities for ions in the corresponding charge states. For $^{238}$U, the use of $H_2$ with the pulsed gas stripper resulted in a significant increase of beam intensity and the overall beam brilliance behind the gas stripper [10].

In Table 1, the estimated target thickness $X$, energy loss $dE$, average charge state of the saturated charge state distribution $q_{max}$, maximum measured stripping efficiency $\eta_{max}$, and horizontal and vertical beam emittance, $\epsilon_x$ and $\epsilon_y$, with the corresponding beam current are listed for the $N_2$-jet and pulsed $H_2$-gas stripper for $^{238}$U, $^{209}$Bi, $^{50}$Ti, and $^{40}$Ar ion beams, as shown in Fig. 2. The target thickness $X$ was estimated with energy loss measurements using the SRIM2013 computer code [11]. For the $N_2$-jet gas stripper, the differential pumping system reaches a limitation for the throughput. Because of the pulsed gas injection, the viable target thickness in the pulsed gas stripper is increased. Due to the overall higher applied target thickness, the energy loss is increased. The average charge state $q_{max}$ was obtained by using a Gaussian fit with a skewness correction on the charge state distributions. For U and Bi, the more narrow charge state distributions are accountable for the significantly increased $\eta_{max}$, as described above. In general, for a more dense gas target and the same initial beam width, the beam emittance is increased, which is also observed here.

A detailed description of the complete experimental data set and a discussion of the relevant effects will be presented in [12].

## CONCLUSION

Measurements of saturated charge state distributions for $^{238}$U, $^{209}$Bi, $^{50}$Ti, and $^{40}$Ar ion beams are presented, using the pulsed gas stripper with $H_2$. These are compared to measurements using the previously existing $N_2$-jet gas stripper. By using the pulsed $H_2$ target, increased average charge states are achievable for all measured ion beams. For heavy ions, such as $^{238}$U and $^{209}$Bi, the use of the $H_2$ target causes a more narrow charge state distribution, which allows for significantly increased beam intensities behind the stripper. In general, the overall increased target thickness results in an increase of energy loss and beam emittance.

## ACKNOWLEDGEMENT

The authors are grateful for the support of the GSI ion-source and UNILAC staff.

## REFERENCES

[1] *FAIR Baseline Technical Report*, Vol. 2, GSI Darmstadt, Germany, 2006, p. 335.

[2] L. Groening *et al.*, "Development of New Heavy Ion Linacs at GSI", presented at LINAC'16, East Lansing, MI, USA, paper TH1A03, this conference.

[3] P. Scharrer *et al.*, *J. Radioanal. Nucl. Chem.* 305, 837-842, 2015.

[4] W. Barth *et al.*, *Phys. Rev. ST AB* 18, 040101, 2015.

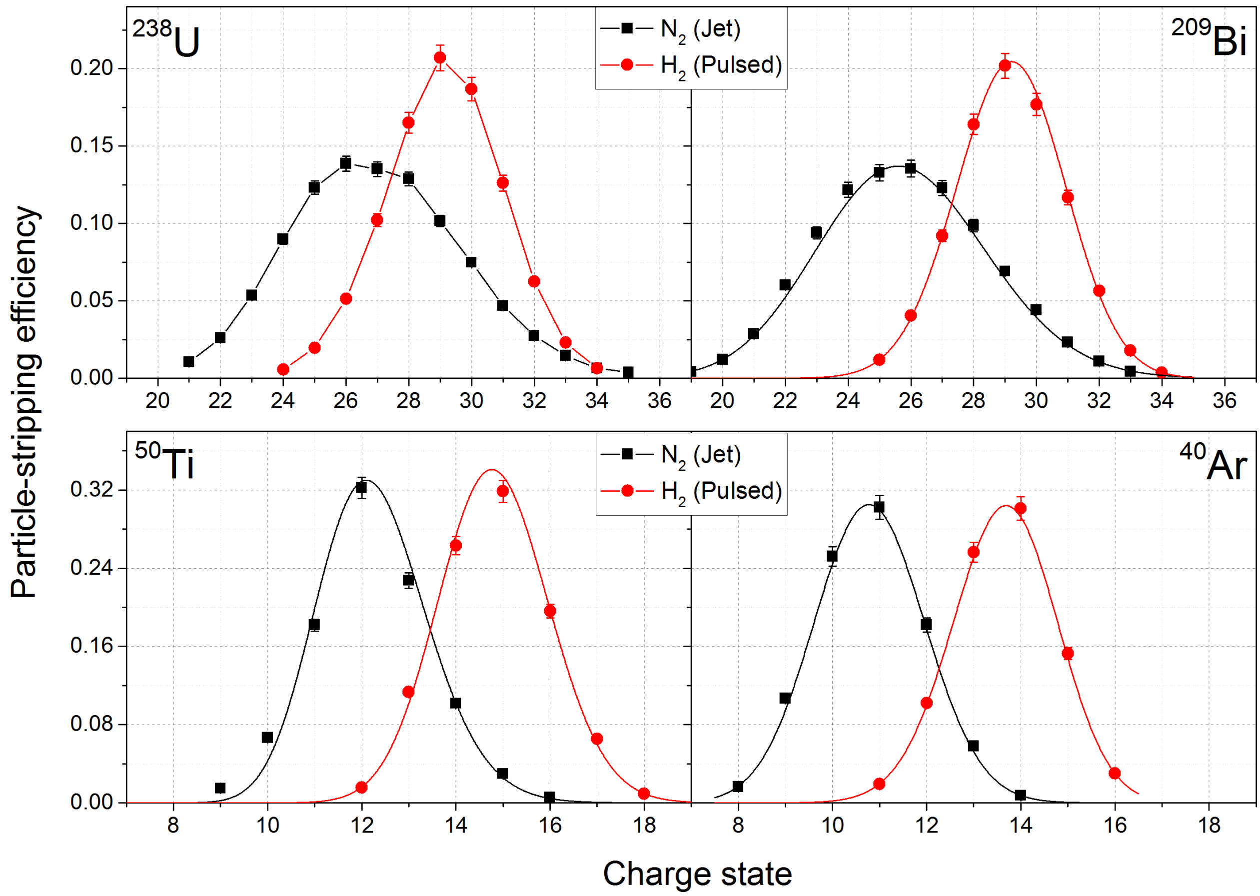


Figure 2: Saturated charge state distributions for $^{238}U$, $^{209}Bi$, $^{50}Ti$, and $^{40}Ar$ ion beams after passing the $N_2$-jet gas stripper (black) and the pulsed $H_2$-gas stripper (red).

Table 1: Comparison of the performance of the $N_2$-jet gas stripper and the pulsed $H_2$-gas stripper for $^{238}U$, $^{209}Bi$, $^{50}Ti$, and $^{40}Ar$ ion beams. For the beam emittances, the charge state and corresponding, measured beam current is listed in brackets.

| Ion | Stripper | $X$ [$\mu$m/cm$^2$] | $dE$ [keV/u (%)] | $q_{max}$ | $\eta_{max}$ [%] | $\epsilon_x$ (tot., norm., 90 %) [mm·mrad] | $\epsilon_y$ (tot., norm., 90 %) [mm·mrad] |
|---|---|---|---|---|---|---|---|
| $^{238}U$ | $N_2$ (Jet) | 8 | $14 \pm 5$ (1) | 26.6 | $13.9 \pm 0.5$ | 0.76 (at 3.7 mA, 28+) | 0.84 |
| | $H_2$ (Pulsed) | 21 | $40 \pm 5$ (2.9) | 29.2 | $21.0 \pm 0.8$ | 0.56 (at 6.1 mA, 29+) | 1.07 |
| $^{209}Bi$ | $N_2$ (Jet) | 8 | - | 25.5 | $13.9 \pm 0.6$ | 0.61 (at 1.8 mA, 26+) | 0.72 |
| | $H_2$ (Pulsed) | 37 | $80 \pm 5$ (6.4) | 29.1 | $20.2 \pm 0.8$ | 0.82 (at 2.8 mA, 29+) | 0.82 |
| $^{50}Ti$ | $N_2$ (Jet) | 7 | - | 12.1 | $32.2 \pm 1.3$ | - | - |
| | $H_2$ (Pulsed) | 32 | $76 \pm 5$ (5.4) | 14.8 | $31.9 \pm 1.3$ | - | - |
| $^{40}Ar$ | $N_2$ (Jet) | 6 | - | 10.8 | $29.6 \pm 1.2$ | 0.39 (at 102 $\mu$A, 11+) | 0.42 |
| | $H_2$ (Pulsed) | 37 | $100 \pm 5$ (7.1) | 13.7 | $30.1 \pm 1.2$ | 0.83 (at 126 $\mu$A, 14+) | 0.72 |


[5] W. Barth *et al.*, "Commissioning of the 1.4 MeV/u High Current Heavy Ion Linac at GSI" in *Proc. LINAC'00*, paper FR201.

[6] H.D. Betz, 1972, *Rev. Mod. Phys.* 44, 3, 465-539.

[7] P. Scharrer *et al.*, "An Upgrade for the 1.4 MeV/u Gas Stripper at the GSI UNILAC", in *Proc. IPAC'16*, 8-13 May 2016, Busan, Korea, paper TUPMR058.

[8] G. Riehl *et al.*, "A Multifunctional Profile and Emittance Measurement System", in *Proc. EPAC'90*, 12-16 June 1990, Nice, France, p. 756-758.

[9] P. Scharrer *et al.*, "A Pulsed Gas Stripper for Stripping of High-Intensity, Heavy-Ion Beams at 1.4 MeV/u at the GSI UNILAC", in *Proc. HIAT'15*, 7-11 September 2015, Yokohama, Japan, paper TUA1C01.

[10] W. Barth *et al.*, "High Current Uranium Beam Measurements at GSI-UNILAC for FAIR", in *Proc. HB'16*, 3-8 July 2016, Malmö, Sweden, paper TUAM7Y11.

[11] J.F. Ziegler *et al.*, "The Stopping and Range of Ions in Solids", Vol. 1, Pergamon Press, New York, 1985.

[12] P. Scharrer *et al.*, to be published.





ISBN 978-3-95450-169-4