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OPERATION OF A PULSED GAS STRIPPER DURING REGULAR USER BEAM TIME AT GSI

P. Gerhard* and M. Maier
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

Abstract

The charge state spectrum of heavy ions like uranium stripped at 1.4 MeV/u using nitrogen as stripping target can be narrowed significantly by applying pulsed injection of hydrogen into a dedicated interaction chamber. Pulsing reduces the gas load of the pumping system to an acceptable amount. Such a setup is under construction at GSI. Time-resolved investigations of the build-up of the stripping target have been carried out. A prototype setup has been operated during six months of user beam time in 2024 and is currently again in operation for the user beam time 2025, mainly with nitrogen but also with hydrogen. A number of ion species has been stripped in the course of the beam times, and a considerable amount of data on stripping efficiencies have been measured using both gases. The contribution summarizes the challenges related to establishing such a setup, the results being obtained so far and lessons learned.

INTRODUCTION

The GSI accelerator facility, in particular the UNILAC (UNIversal Linear ACcelerator) and the heavy ion synchrotron SIS18, serve as injector for the upcoming Facility for Antiproton and Ion Research (FAIR), the commissioning of which will start in 2026. High intensity ion beams are provided by dedicated high current sources and pre-accelerated by the high current injector (HSI). The HSI is designed for handling ions with a mass-to-charge-ratio of up to $A/q = 65$, since the ions delivered by the high current sources have inherently low charge states [1]. A gas stripper is necessary to increase the charge state to enable efficient acceleration in the subsequent Alvarez drift tube linac. Stripping is applied at 1.4 MeV/u after acceleration in the HSI. Until recently, a continuous nitrogen gas jet was employed as stripping target [2]. Out of the charge state spectrum resulting from the stripping process, one charge state has to be separated for further acceleration. For heavy ions like uranium, this results in the loss of up to ≈87% of the beam.

In order to increase the yield into the desired charge state, introducing hydrogen and other gases as stripping targets was investigated [3]. With H_2, the width of the charge state distribution of heavy ions is significantly reduced and the stripping efficiency increased accordingly, e. g. by approximately 50% for $^{238}U^{28+}$. Additionally, an increase of the mean charge state can be achieved for all ions. The proof-of-principle was demonstrated successfully in 2016 [4–6].

The decision to introduce H_2 into regular operation induced several challenges. Since hydrogen is highly combustible, comprehensive safety measures have to be implemented. H_2 is also much more difficult to pump. It soon became clear that the gas load had to be reduced, which lead to the pulsed operation of the gas target. It exploits the low duty factor of the UNILAC by delivering only short pulses of high gas density synchronized with the beam pulse. This was realized via commercially available, fast injection valves. Together with the demand to have different gases (H_2 and N_2) and target densities available in parallel, the now pulsed gas stripper became a much more complex system than the jet stripper was. Therefore, a fully automated setup suitable for safe and regular operation has to be developed [7, 8].

In late 2023, it was decided to utilize the development setup for the user beam time 2024, putting the pulsed stripper into regular operation ahead of schedule. This was repeated for the beam time 2025. Several improvements were implemented to minimize the restrictions on operation given by the developmental status of the setup. The still incomplete implementation of the safety concept meant that only N_2 operation was possible for user operation.

DEVELOPMENT SETUP AND RECENT UPGRADES

A second generation stripper setup (Fig. 1) was designed after it was found during the proof-of-principle that the original valves would break down after only a few hours of operation [7]. It contains two fast injection valves of a new

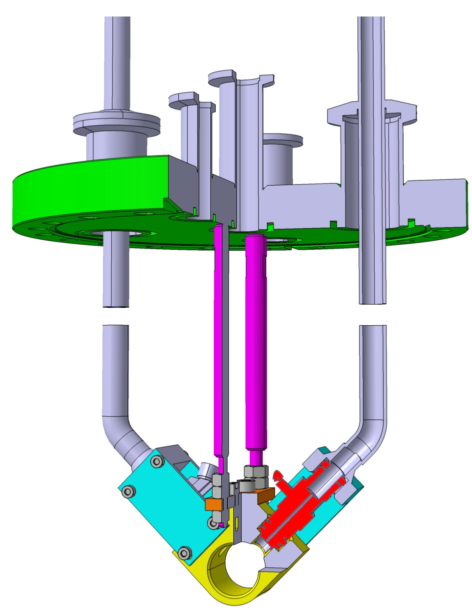

Figure 1: Sketch of the current pulsed stripper setup. The fast injection valve is indicated in red. More details in [7, 8].

* p.gerhard@gsi.de

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type designed for gas injection and was intended for further system development and experimental H_2 operation. The two valves allow for independent operation of two different stripping targets. Time-resolved measurements of the build-up and evolution of the gas target had been carried out with this setup using the ion beam to probe the target in order to qualify the new valve type [8].

The development gas control is shown in Fig. 2. Its main purpose is to control the gas pressure supplied to the injection valves and thereby the target density. It allows for providing H_2 and N_2 to two injection valves at the same time. To facilitate long-term operation during beam time, the gas control was connected to the central N_2 supply, while H_2 is supplied from gas cylinders. Each gas line is equipped with a pneumatically driven safety cut-off valve, which is controlled by a simple interlock system. In the event of a safety-relevant failure, the gas supply is cut-off quickly, providing enough safety for short-term experimental hydrogen operation and machine safety for long-term unattended operation with nitrogen during beam times. Both supply lines are equipped with a flow meter, which proved essential in the early detection of valve failures.

Stripping with N_2 requires gas pressures well below 1 bar(a), especially for light and intermediate ions. This was rarely done before and rather challenging with the cylinder pressure reducers used so far. To improve operation at low pressures, two dedicated, mechanical low-pressure regulators were added to the gas control setup before the beam time 2024. The operational flexibility was enhanced by adding a high-pressure bypass line and extending the corresponding purge lines.

A major step forward in terms of safety was achieved by the installation of a new, large, explosion safe roots pump station in 2023. Another upgrade of the vacuum system was the exchange of the four turbo-molecular pumps situated at the differential pumping sections of the gas stripper chamber [7]. The new pumps were selected to achieve maximum throughput for hydrogen at high vacuum pressures, allowing for higher gas loads.

MODUS OPERANDI

Since the current development stripper setup was never intended to be used for regular long-term operation, there was no automation or remote operation and monitoring foreseen. Partial remote control of the stripper was enabled by simply using remote access to a PC, which was used to control the setup locally. By this, the valve controller and later also the electronic pressure controller (see below) as well as monitoring of the gas flow was remotely accessible. Still, many settings and the daily inspections and manual logging have to be done locally. This is especially true for the gas handling, because all valves and pressure gauges are manually operated only, as were the two mechanical low-pressure regulators used during beam time 2024. The only valves automated are the two safety cut-off valves.

Despite the improvements done, the stripper remained being an expert system. Unlike the jet stripper, there was no control and, due also to technical limitations, no monitoring of the stripper available for the operators from the main control room. This was even more serious, because the pulsed stripper relies on the correct timing to trigger the valve opening and closing, which still needs to be adjusted manually by the stripper team on-site because the integration of the pulsed stripper into the accelerator control and timing system is still missing. An on-call service by the team was established to support the accelerator operating crews properly.

LESSONS LEARNED

During the first user beam time it quickly became evident that, due to the restrictions mentioned above, a simple operating scheme had to be devised in order to minimize the

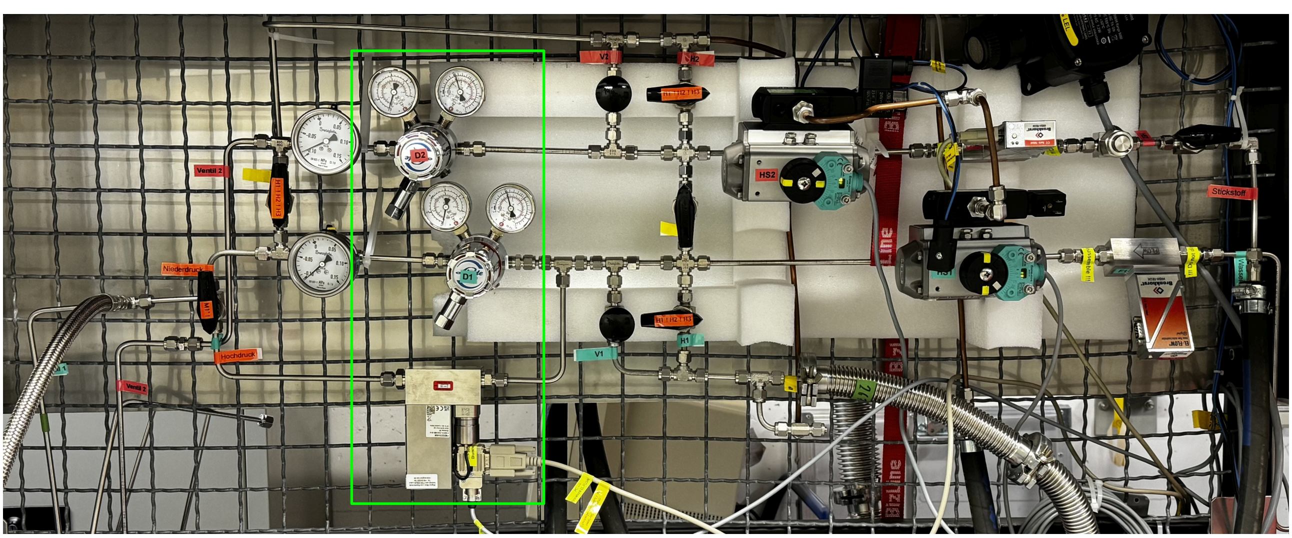

Figure 2: Foto of the gas control for the pulsed gas stripper. In the green frame are the two manual low-pressure regulators added early in 2024 (top and center) and the electronic pressure controller installed later (bottom).

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need for adaptations to the stripper settings and to allow the operators to keep track of it. Therefore, parallel operation with both injection valves at different pressures for different beams was rarely used. Most of the time, the stripper was set up to serve all beams with one valve set to one pressure and timing, reproducing the jet operation. The settings were usually only revised when a new ion species was accelerated. In 2025, two valve operation was tried again successfully thanks to the experience gained in the meantime, when the trade-off using only one pressure setting was not acceptable. This finally leads to the conclusion, that the pulsed stripper system is rightly intended to be fully automated and integrated into the accelerator control system.

In terms of stripping results, the pulsed stripper performed well, as was expected from the knowledge gained in previous machine beam times. No significant differences or drawbacks compared to the jet stripper were observed as long as the correct timing was applied.

The large variety of ion species operated gave a valuable overview of the pressure range needed, which was not known before. Especially the very low pressures needed for some ions turned out to be very demanding. In general, the mechanical pressure controllers added in preparation of the beam time proved to be essential, although achieving a desired low pressure setting precisely needed painstaking fine-tuning. They also turned out to be unstable under changing operating conditions, because of the lack of a strong, adjustable feedback. In the event, manual re-tuning was applied.

The main lesson learned was about the service life of the injection valves. Operation along the whole beam time offered the opportunity to collect long-term statistics, which would otherwise have been impossible. With the very short service life of the original valves in mind, a detailed book keeping of the operational parameters was established to be able to reconstruct the operational demands put on the individual valve in case it would fail. The results were alarming: two valves failed after ≈20% of their expected service life of $380 \cdot 10^6$ cycles as given by the manufacturer, a third valve showed irregularities after ≈14%. This corresponds to only a few weeks of high duty operation at cycle frequencies of 25–50 Hz. All valves that failed did so during or shortly after high duty operation by getting in open position. The cause for the failure and whether it is strictly linked to the high duty operation is unknown. None of the other valves that did not fail achieved anywhere near the number of cycles of the failed ones. This kind of failure was anticipated in the risk assessment as the worst case scenario for the hydrogen operation, because the maximum amount of H_2 would be released into the vacuum system, exposing the pumps and vacuum exhaust to the risk of overloading.

OPERATIONAL IMPROVEMENTS

In preparation for the beam time 2025, improvements based on the lessons learned were implemented. In addition to the mechanical pressure regulators, an electronic pressure controller was installed, offering several advantages:

- the connection to the local PC enabling remote setting and read out of the gas pressure;
- the integrated, configurable PID controller provided a precise feedback, mitigating the instability of the mechanical pressure regulators under changing operational conditions;
- any pressure within the range of the controller was easily achievable.

The only drawback observed so far were the comparatively coarse settings at very low pressures, while the stability and precision of the controller was flawless even at the very low settings, which are outside the recommended operating range. At the same time, this was used to test the electronic pressure controller extensively before its implementation in the fully automated gas control station.

The very short service life of the valves under high duty operation gave rise to additional modifications. With the cause of the failure still being unknown, it is obvious that the valves are operated at gas pressures far below their intended use. The gas also serves as a coolant. In order to bring the operating pressures into the recommended range, a valve was fitted with an orifice of 0.6 mm at the outlet, reducing the original opening by a factor of four (Fig. 3 right).

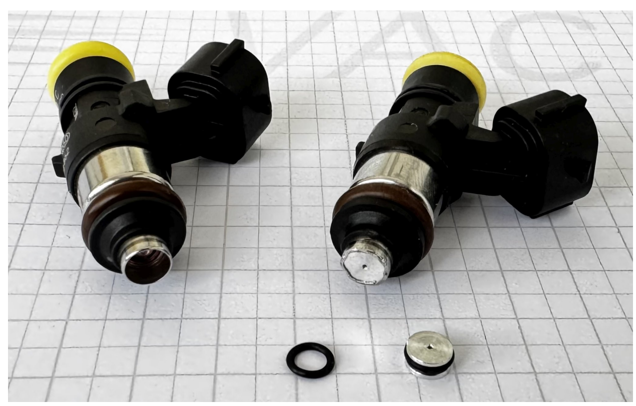

Figure 3: Injection valves used for the pulsed gas stripper. The valve on the right is modified by an orifice with a diameter of 0.6 mm placed in the outlet tube. On the left, an unmodified valve is shown for comparison. In front of the valves are an O-ring and another orifice with O-ring mounted.

With this modification, the same flow through the valve, which determines the target density, should be achieved at a pressure about four times higher than without the orifice. Comparison of stripping data acquired with and without orifice (see next section) showed that the increase in pressure was about a factor of 4.5. This should enhance the cooling and the damping of the impact of the valve tappet on the seat during the fast opening and closing. Further optimization could be achieved by slightly changing the diameter of the orifice. Additionally, the voltage and current profiles

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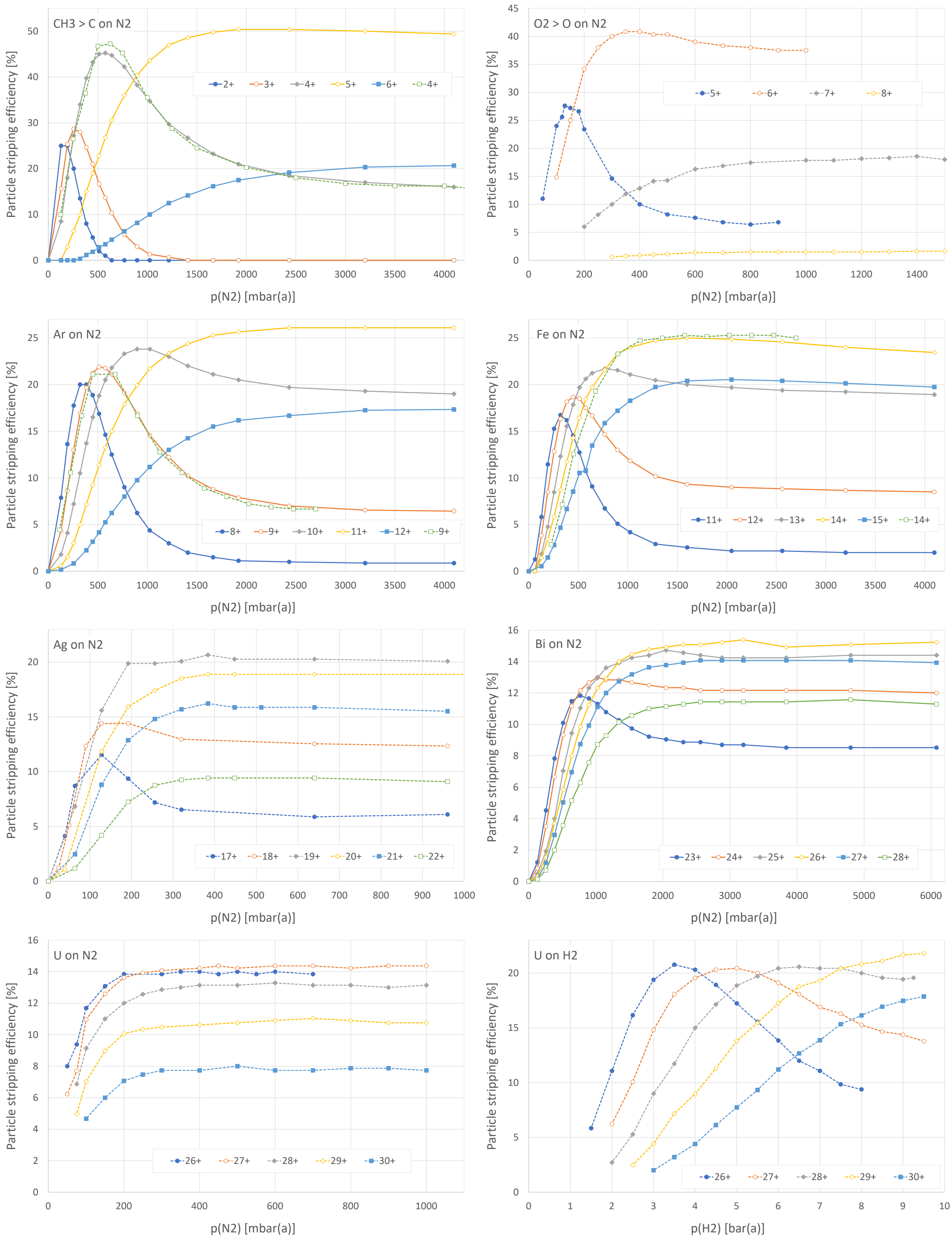

Figure 4: Particle stripping efficiencies measured for different ions and molecules, charge states and stripping gases. Dashed and solid lines indicate data taken with a standard or modified injection valve respectively, refer to the text for details.

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for driving the valves were adapted in order to reduce the mechanical stress on the valves.

STRIPPING DATA

The beam time operation permitted the acquisition of stripping data for a large number of ion species. This is difficult to achieve during dedicated machine development beam times, because every change of the ion species requires an exchange of the ion source and a complete setup of the beam up to the gas stripper, which takes up a lot of time. With a new ion species set up during user beam time routinely every few weeks, this now comes for free. The drawback is, that the time for data taking is extremely limited because it requires exclusive operation of the accelerator while the users are already waiting for the beam. To support this, during beam time 2025 the data taking was approved as an official accompanying machine experiment, allowing for ≈ 1 h of beam time per ion species.

The graphs in Fig. 4 show exemplary stripping data for light, intermediate and heavy ions and the molecule CH_3 stripped by H_2 or N_2 as indicated in the upper left corner of each graph. The plotted data are particle stripping efficiencies as a function of the applied system pressure for several charge states per ion species. They were taken using valves without and with the added orifice, indicated by dashed and solid lines respectively. For CH_3, Ar and Fe, a single curve measured without orifice is plotted together with several curves measured with orifice in the same graph for comparison, with the single curve's pressure being scaled by a factor of 5 for CH_3 and 4.5 for Ar and Fe, respectively. It has to be mentioned, that all data were taken manually during the user beam time. Due to various reasons, significant systematic and random errors should be considered, as is obvious for some data points.

During both beam times, similar data were also taken for O_2, Ar, Ti, Cr, Fe, Ni, Kr, Mo, Ag, Er, Au, Pb, Bi, and U. All species were exclusively stripped by N_2 except uranium, which was also stripped by H_2.

CONCLUSIONS AND OUTLOOK

The opportunity to extensively test the pulsed gas stripper before the system is completed and ready for regular operation was unexpected and on short notice. Nevertheless, after a short preparation period, about one year of successful operation during two user beam times was achieved and yielded results, which could not have been gained otherwise. Several issues have been identified or confirmed, some of them being anticipated. Some improvements have already been implemented and tested, others are planned to be realized soon. The latest status report of the pulsed hydrogen gas stripper project with more details is available in [9]. Valuable experiences and a significant amount of stripping data was acquired for a broad range of ion species, demonstrating that the performance of the pulsed gas stripper covers all operational expectations.

The main parts remaining for the completion of the pulsed stripper are the automated gas control station and the integration into the accelerator control system, a dilution device for the safe disposal of the hydrogen, a fully-fledged interlock system and the production version of the stripper setup. The call for tenders for the gas control station was recently published, installation and commissioning are planned for 2026. The dilution device is currently in development, simulations for a proof-of-concept are in progress. The design of the interlock system is in an early planning stage, while the design of the production stripper is in a final stage (Fig. 5). It will contain four valves, two for each gas type with one for operation at high and low pressure each.

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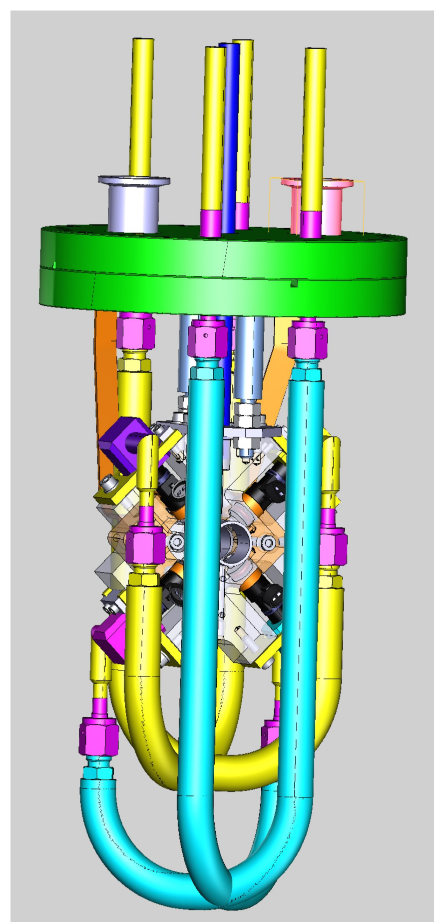

Figure 5: Sketch showing the current design status of the production stripper, containing four injection valves in an X-configuration.

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REFERENCES

[1] U. Ratzinger, "The New GSI Prestripper Linac for High Current Heavy Ion Beams", in *Proc. LINAC'96*, Geneva, Switzerland, Aug. 1996, paper TU202, pp. 288–292.

[2] W. Barth and P. Forck, "The New Gas Stripper and Charge State Separator of the GSI High Current Injector", in *Proc. LINAC'00*, Monterey, CA, USA, Aug. 2000, paper MOD13, pp. 235–237.

[3] B. Schlitt *et al.*, "Charge Stripping Tests of High Current Uranium Ion Beams with Methane and Hydrogen Gas Strippers and Carbon Foils at the GSI UNILAC", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper THPWO010, pp. 3779–3781.

[4] P. Scharrer *et al.*, "Stripping of High Intensity Heavy-Ion Beams in a Pulsed Gas Stripper Device at 1.4 MeV/u", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 3773–3775. doi:10.18429/JACoW-IPAC2015-THPF035

[5] 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*, Yokohama, Japan, Sep. 2015, paper TUA1C01, pp. 144–147.

[6] P. Scharrer *et al.*, "Developments on the 1.4 MeV/u Pulsed Gas Stripper Cell", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, pp. 387–389. doi:10.18429/JACoW-LINAC2016-TUOP03

[7] P. Gerhard *et al.*, "Development of Pulsed Gas Strippers for Intense Beams of Heavy and Intermediate Mass Ions", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp. 982–987. doi:10.18429/JACoW-LINAC2018-FR1A05

[8] P. Gerhard and M. T. Maier, "On the UNILAC Pulsed Gas Stripper at GSI", in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 258–261. doi:10.18429/JACoW-LINAC2022-MOPORI13

[9] M. Maier, P. Gerhard, and L. Groening, "Status of the pulsed hydrogen gas stripper project at GSI", presented at the IPAC'25, Taipei, Taiwan, Jun. 2025, paper TUPB034, unpublished.