ISBN: 978-3-95450-240-0 ISSN: 2673-5547 doi:10.18429/JACoW-HIAT2022-MO3I3

HEAVY ION STRIPPING

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

Abstract

Ion stripping is primarily an essential technique for heavy ion accelerators in order to reach higher beam energies within reasonable size and budget limits. Due to the stochastic nature of the stripping process, the resulting ion beam contains ions of different charge states. Therefore, high beam loss is typically associated, making the net stripping efficiency one of the decisive elements of the overall performance of an accelerator facility. Several technical implementations of strippers have been developed and are still being investigated in order to obtain optimal stripping for different ion beams by employing different kinds of stripping targets, namely gaseous, solid and more recently fluid materials. Strippers of the first two types are in operation at GSI. High beam intensities resulting in prohibitive energy deposition and target destruction are increasingly challenging. The foil stripper situated in the transfer line from the UNILAC to SIS18 employs a magnetic sweeper as a possible remedy. At the same time, it offers four stripping options to be used in parallel. Optimizing a stripper may potentially increase the overall performance by a large factor with less effort than other actions. This gave rise to the pulsed gas stripper project at the GSI UNILAC, which aims at the introduction of hydrogen as regular stripping target.

INTRODUCTION

The GSI accelerator facility consists of the UNIversal Linear ACcelerator UNILAC, the SchwerIonenSynchrotron (heavy ion synchrotron) SIS18, two storage rings (ESR and CRYRING@ESR) and the decelerator HITRAP. Several stripping devices are operated in the area of UNILAC and SIS18 in order to facilitate acceleration and deliver ions with the charge states required by the various experiments. Regarding the wide range of ion energies and beam intensities, different stripping technologies are applied. Figure 1 shows a schematic overview of the UNILAC and the locations of the stripping devices. Stripping at the lowest energy of 1.4 MeV/u between the high current injector and the Alvarez DTL is achieved by a gas stripper, while all subsequent strippers use foils or sheet metal. The SIS18 area and its strippers are not shown. UNILAC and SIS18 possess the unique feature to deliver individual beams made from up to three different ion species in a rapid time multiplex scheme. This has to be supported by the strippers as well.

UNILAC together with SIS18 will serve as the heavy ion injector chain for the Facility for Antiproton and Ion Research (FAIR) [1], currently under construction. The reference projectile for FAIR is the heavy ion ^{238}U. To meet the beam requirements for FAIR, upgrade programs for both accelerators have been and are being conducted to increase the delivered beam intensities especially for heavy ions. The task for the UNILAC 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 synchrotron. A major step in this pursuit will be the use of hydrogen in the gas stripper in addition to the traditional nitrogen operation. The hydrogen stripping target will improve the mean charge state of all stripped ions. For heavy ions, the width of the charge state distribution will be decreased, which results in an enhanced beam intensity of up to 60% [2]. This makes use of the electron capture suppression associated with low Z targets.

STRIPPING FUNDAMENTALS

A stripper consists of a gaseous or solid, infrequently liquid or plasma stripping target, which is placed in the beam line. While the ions cross it, they experience collisions with the target atoms. Many devices will therefore lead to stripping as a side effect. Stripping is the result of charge transfer processes caused by the collisions between the fast moving ions of the particle beam and the stationary target atoms.

* p.gerhard@gsi.de

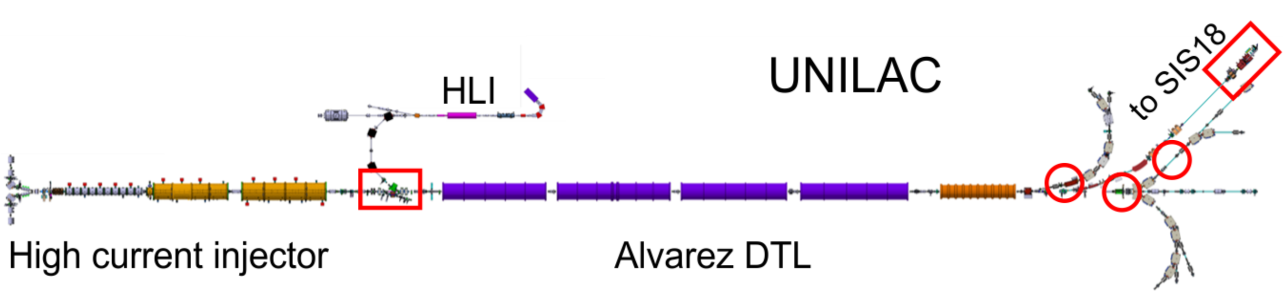

Figure 1: The UNILAC and its main constituents: The high current injector with two source terminals and an RFQ/IH-DT linac (left), the high charge state injector HLI (top centre), and the main Alvarez-DT linac (centre). To the right are several user branches and the transfer channel to the synchrotron. Stripper sections for general accelerator operation are framed with red boxes, strippers for special user requirements with red circles.

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Both electron loss and capture processes happen, increasing and reducing the ion's charge state respectively. Hence, stripping is a stochastic process. The corresponding cross sections σ_L and σ_C for electron loss and capture depend on several parameters: Ion charge state q, energy E and atomic number Z, target atomic number Z_T and density ρ, and the type of transfer process, i. e. single or multiple electron.

While the ions pass through the target, their charge state (and energy) changes, which means σ_L and σ_C change. Given a target of sufficient thickness $x = x_\infty$, i. e. the number of collisions high enough, the stripping approaches an equilibrium, where $\sigma_L = \sigma_C$[1]. Due to the statistical nature of the underlying electron loss and capture processes, the ions populate a charge state distribution. The correlation between the parameters above and the mean value $\bar{q}$ and width d of the distribution is generally described by semi-empirical relations, especially for low energy beams.

Due to the inherent collisions with the target, the beam will experience energy loss and emittance growth by straggling, both deteriorating the beam quality. The energy deposition leads to a degradation or even destruction of the stripping target, especially with solid targets. Special effort has to be made to keep this within reasonable limits. Recently, liquid targets have been developed [3] in order to circumvent this and still profit from the density effect. As mentioned above, stripping results in a charge state spectrum. Typically, a stripper is therefore followed by a charge state separator, which selects ions of one charge state and eliminates all others[2]. Thus, substantial loss of beam is always linked to stripping.

In most accelerator applications, one is interested in increasing the charge state in order to facilitate further acceleration of the ions. Figures of merit may be the resulting charge state and beam intensity. Optimizing the stripping may be achieved by choosing accessible target parameters accordingly. Changing the beam parameters would also do, but may rarely be possible or only at high cost. A more subtle optimization may make use of ion shell effects. The mean charge state can be increased by changes of the target density, especially for gaseous targets, or by using solid targets due to the density effect. If equilibrium is not yet reached, the target thickness may be increased, at the expense of more energy loss and emittance growth. Increasing the stripping efficiency is more challenging, because the width of the charge state distribution is generally not very sensitive to any of the parameters, including beam energy. Changing the target material can be an option: Especially low Z targets like hydrogen lead to the suppression of electron capture processes. This does not only increase the equilibrium mean charge state, but also leads to narrower distributions for heavy ions and hence to a higher fraction of ions with the charge state desired. For more basic information about stripping see for instance [4–7].

[1] Further collisions only lead to a slow change of the equilibrium due to the progressive energy loss.

[2] Applications using more then one charge state exist.

GAS STRIPPER

At low ion velocities, targets have to be thin but robust, since energy loss in the target is relatively high. This renders solid state targets inapplicable despite the desireable high charge states achievable. Gaseous targets are a suitable choice. The drawbacks are lower mean equilibrium charge states and the inevitable gas load in the accelerator vacuum system.

The first stripper along the UNILAC is applied to high current beams at an ion energy of 1.4 MeV/u. Figure 2 shows the corresponding stripper section schematically in its current form after the redesign, which was implemented together with the installation of the HSI in 1999 [8].

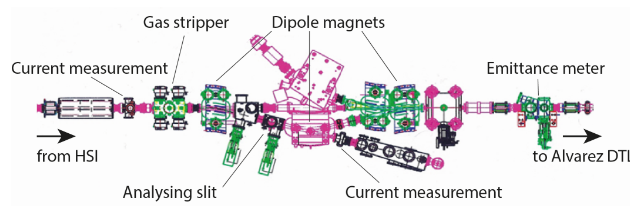

Figure 2: The UNILAC gas stripper section between the high current injector HSI and the Alvarez DTL. The central part consists of a 15°-30°-15° dogleg composed of three dipoles for charge state separation.

Heavy ions like $^{238}U^{4+}$ are provided at low charge states but with high intensity by two sources located at the high current injector (german "HochStromInjektor") HSI. This injector is designed to accelerate ions with a mass-to-charge ratio of $A/q \leq 65$ to 1.4 MeV/u. Since the following Alvarez DTL is limited to $A/q \leq 8.5$, a stripper is needed to increase A/q accordingly.

Historic Alternatives

In the early years of GSI both a foil and a gas stripper were operated between the then Wideröe type *prestripper* (today HSI) and the *poststripper* (Alvarez DTL). The foil stripper delivered higher charge states than the gas stripper (U^{41+} vs. U^{28+}) due to the density effect, which allowed for higher final energies. For particle currents above 1 µA the 40 µg/cm^2 target foils were destroyed in short time [9]. As beam intensities increased, foil operation was dropped. A comeback of foil stripping at this location was tried many years later and is described in a later section.

Current Jet Stripper

The stripping target is created by a supersonic N_2 jet generated by a Laval nozzle with a back pressure of up to 0.45 MPa, which crosses the beam line orthogonally. The main part of the gas load is pumped by a 10 000 m^3/h roots pump. Spreading of the gas along the beam line is reduced by the jet itself, which directs the gas into the pump, by two differential pumping sections next to the stripper and three aperture diaphragms reducing the conductance between them.

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H_2 Target Development

With the current N_2 jet stripper just about 12–15% of the incoming U^{4+} ions are stripped into the desired charge state 28+. In order to improve the stripping efficiency for heavy ions, the width d of the charge distribution has to be reduced. In principle changing the beam energy E and the target's x_∞, ρ, and Z_T are conceivable. Changing E is not really feasible and has no significant impact on the width, but on $\bar{q}$. Target thickness and density of the nitrogen jet essentially possess no potential for development, either. However, introducing a low Z gas as stripping target is known to have an effect on the width of the charge distribution for heavy ions. This is acceptable since for light ions the beam intensities achieved are already sufficient to fill the synchrotron up to the space charge limit. As a side effect, the mean equilibrium charge state for all ion species is also rising. A development was started accordingly, and about 10 years ago comparative tests using N_2, CH_4 and H_2 were carried out at the jet stripper [10]. The highest mean charge states achieved were 27+ for nitrogen and 25+ for methane, while for hydrogen no sufficient target thickness could be reached, the highest charge state observed being 21+. With methane at high pressures, the charge state separation deteriorated.

The tests revealed, that the stripper device had to be modified on order to reach sufficient target thickness for hydrogen. The pumping speed for light gases was identified as the main limiting factor. The basic idea to overcome this limitation is to exploit the low duty factor f of the ion beam. For synchrotron operation, which is the reference for FAIR, $f \ll 1\%$. The continuous operation of the jet is not required, and the gas load on the vacuum pumps can be reduced by about two orders of magnitude, if gas is injected only while a beam pulse passes the gas stripper. The pulsed gas injection was realized by applying a fast, electro-magnetically actuated gasoline valve normally used for direct fuel injection 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 target in the interaction zone, and closes immediately afterwards. A new setup was developed (Fig. 3), serving as a mount for the valve and replacing the Laval nozzle by a short tube enclosing the interaction zone of the stripper [11]. The gas is injected into this tube and is thereby confined, increasing the target density while at the same time reducing the gas load on the vacuum system.

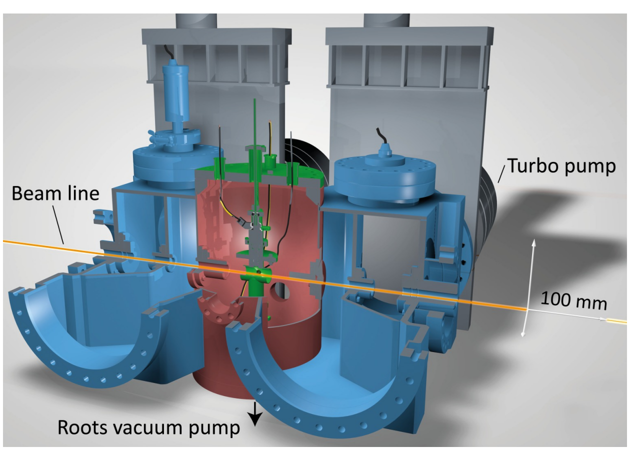

Figure 3: Schematic illustration of the pulsed gas stripper setup. The pulsed gas injection (green) is mounted on the top flange of the main chamber (red). Together with the adjacent sections (blue) this constitutes a four stage differential pumping system (from [11]).

Results for U ions stripped with several gases using this setup are shown in Fig. 4 [12]. For all gases except H_2, equilibrium distributions could be measured. In comparison to N_2, both He and H_2 lead to a reduced width and increased stripping efficiency of more than 20% for U^{28+}. Even though

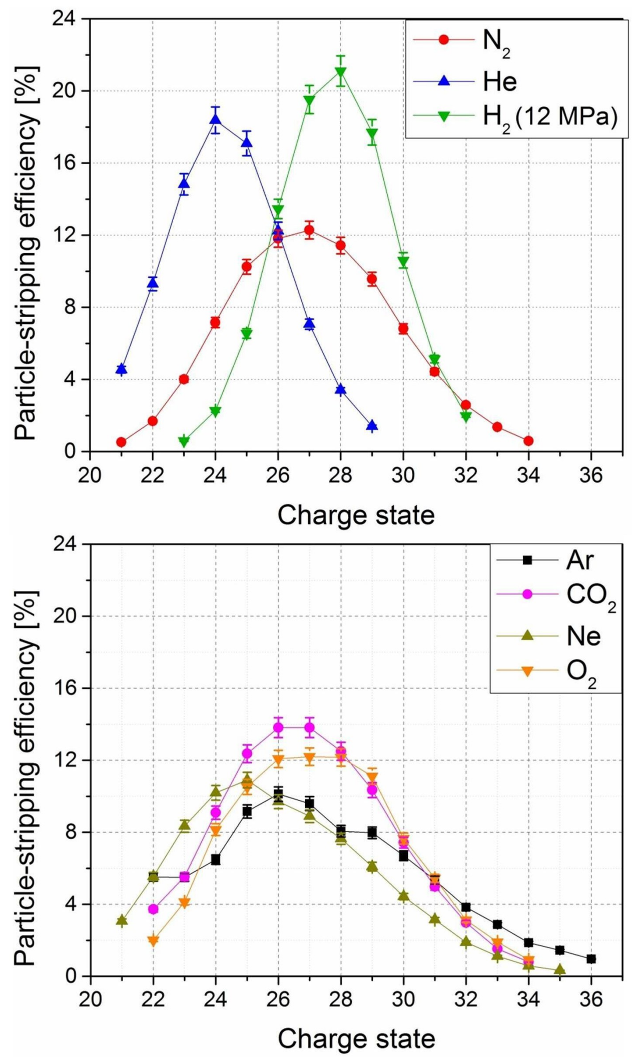

Figure 4: Charge state distributions for U stripped by N_2, He and H_2 (top), Ar, CO_2, Ne and O_2 (bottom), measured with the pulsed gas stripper at 1.4 MeV/u beam energy. The graphs show the equilibrium stripping efficiencies f_q as functions of the charge state q except for H_2, where the distribution was still not equilibrated at 12 MPa back pressure (from [12]).

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equilibrium was not achieved, hydrogen also leads to a higher mean charge state of 28+, while helium shows a reduced $\bar{q}$ = 24 compared to 27+ achieved with nitrogen. Ne, O_2, Ar, and CO_2 generate relatively broad charge state distributions at average charge states between 25+ and 27+. They do not provide any advantage in relation to nitrogen. With an enhanced setup, equilibrium charge state distributions could later be measured for hydrogen, too [13]. For uranium, the most populated charge state 29+ reached a fraction of 21%. For medium heavy ions like Ti or Ar, there is no significant effect on the distribution width, but the mean charge state is raised by about 3. This may enable the use of shell effects for some ion species to increase the fraction stripped into a certain charge state.

To Regular Operation with H_2

After the proof of principle was achieved, the aim is to turn the test setup into a facility suitable for regular operation. At the end of a three week test run in 2016, the fast valves showed significant leakage problems. The reason lies in the valve seating, which relies on the damping by a liquid fuel when closing. The first step on the way therefore was to find and evaluate a suitable valve. A solution was found by employing intake-manifold fuel injection valves also originating from automotive applications, but designed for gaseous fuels. The main difference is that they are operated at much lower back pressures of up to 1.2 MPa, while the direct injection valves required up to 25 MPa. The characterisation of the electrical, temporal and gas dynamical properties was carried out on a newly established test bench. It revealed, that the new valves were much slower especially when closing. In the meantime, parameters for safe and efficient operation of the valves have been established and verified with beam, and a new stripper setup was designed to accomodate two of the new valves (Fig. 5) [14].

The introduction of pulsing implicates, that temporal aspects such as build up, depletion and stability of the target are now of importance. A measurement related to this is shown in Fig. 6, where a complete target cycle (build up, flattop and depletion) is probed by a 5 ms long Ar^{2+} beam pulse. The valve is opened by applying a voltage of 90 V (yellow curve) to the valve coil about 100 µs before the beam pulse starts (red curve). This induces a steep rise of the coil current (cyan curve) despite of the coil's inductance. After 180 µs, a current of 2 A is reached and the valve opens. The subsequent build up of the stripping target can be observed by the stripped Ar^{12+} beam current (green curve) rising. Then the valve is kept open by a lower current and voltage for the remaining pulse duration. After 4 ms, the voltage is reversed (steep drop in yellow curve) to purge the coil current and thereby close the valve quickly. As can be seen in the green curve, it takes about 600 µs for the valve to close and the target to diminish after the current purge was initiated. During the beam pulse, the stripping efficiency stays sufficiently constant. The voltage and current profiles can be controlled by a fast, dedicated magnetic valve controller and were optimised for minimal heat load on the coil. The

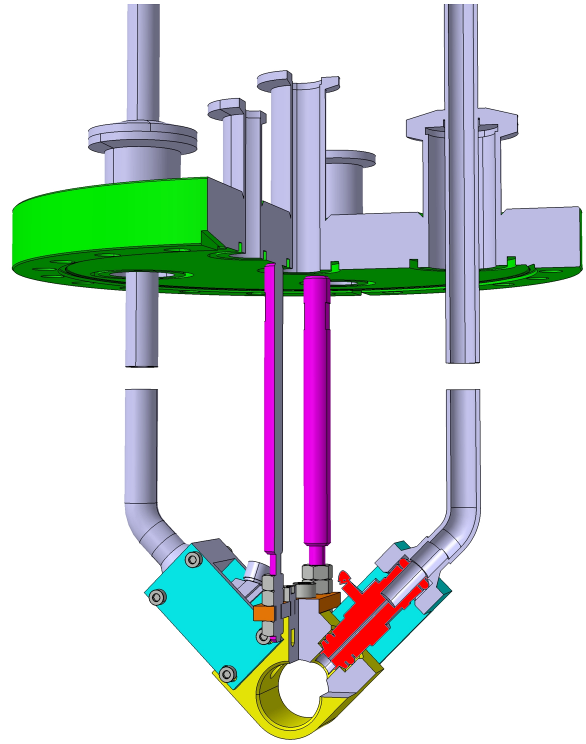

Figure 5: Sketch of the latest stripper setup accomodating two fast valves for gaseous media. One valve is indicated in red. Gas supply is from top via the tubes. The interaction zone is within the yellow tube at the bottom.

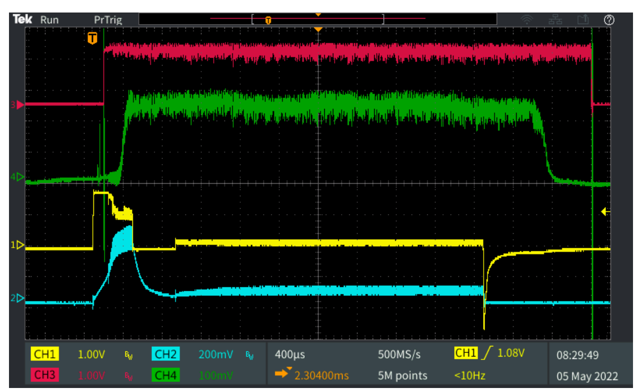

Figure 6: Stripping of Ar^{2+} ions with the pulsed gas stripper. Shown are the current of the incoming beam (red) and the stripped Ar^{12+} beam (green), voltage (yellow) and current (cyan) applied to the valve. Details see text.

timing for regular operation will be optimised for minimal gas load and stable target provisioning.

Several experimental beam times at the UNILAC have been succesfully conducted with the new setup. No valve failures occurred. A long-time test with hydrogen operation is still pending due to the lack of an adequate safety certificate. The main challenge remains in specifying and implementing a concept for fully automated, safe operation of the whole gas stripper facility, including the provision and disposal of the hydrogen.

15th Int. Conf. on Heavy Ion Acc. Technology HIAT2022, Darmstadt, Germany JACoW Publishing
ISBN: 978-3-95450-240-0 ISSN: 2673-5547 doi:10.18429/JACoW-HIAT2022-MO3I3

FOIL STRIPPER

The GSI facility was extended by the heavy ion synchrotron SIS18 and the experimental storage ring ESR at the end of the 1980s. Highly charged ions were to be provided for the synchrotron in order to reach highest beam energies for its users. Injection energy of the synchrotron was sufficiently high to allow for a foil stripper to be integrated into the beamline connecting the SIS18 to the UNILAC, the so-called transfer channel TK. For charge state separation, a dogleg inherent to the TK design consisting of two 11.25° dipoles was used. The drawback of this solution was the long distance of more than 20 m between the stripper and the charge state separation, resulting in prolonged degrading of the beam by strong space charge effects.

This foil stripper was upgraded in 1999 in the course of the HSI installation, when a fast sweeper magnet was added to distribute the energy loss over a larger foil area [15]. Another upgrade took place in 2008 with the installation of a dedicated charge state separation in the vertical plane directly behind the stripper [16]. The separator primarily consists of four 35° dipole magnets.

At the standard energy of 11.4 MeV/u, the mean charge state for uranium is 73+, exploiting the density effect of the solid target. Due to the varity of accelerated ions from Li to U and the substantial foil wear caused by the energy loss of up to 300 keV/u, the stripper is equipped with a foil carousel with 42 slots, each slot holding two foils in an aluminium frame (see Fig. 7).

Figure 7: Target frame of the transfer channel foil stripper with two foils mounted in a slot of the foil carousel. The large foil shows deformation caused by the energy deposition of the beam.

The four operating modes are illustrated in Fig. 8. Both foils can be used with low current beams in two static modes without engaging the fast sweeper. This is accomplished by deflecting the beam onto the required foil by a kicker magnet. The large foil may additionally be used in the sweeping mode for high current beams. In this mode, the beam spot is swept over the large foil within a minimal beam pulse length of 120 µs, starting at maximum deflection and ending on the regular beam axis. This is accomplished by sweeper magnets, which are precharged to maximum deflection before the beam pulse starts, and then discharged linearly within

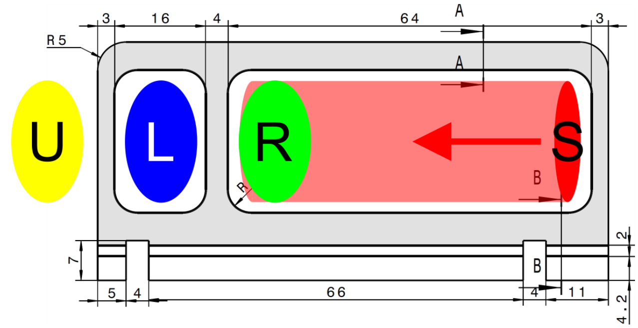

Figure 8: Illustration of the four operating modes of the transfer channel foil stripper. Coloured ellipses indicate the beam spot positions wrt the foil frame (grey) for the different operating modes. Blue spot (L) and Green spot (R): Static stripping via the left, small foil and the right, large foil, respectively. Yellow spot, U: Unstripped mode. Red spot, S: Sweeper mode, the beam spot position at the start of the beam pulse is indicated, while the light red area depicts the foil painting.

the beam pulse length. Pulses shorter than 120 µs are only painted over a part of the foil due to the limited discharge speed. The static mode can also be used to deflect the beam out of the frame and circumvent the stripper. This enables the delivery of the same ion in a high and low charge state simultaneously and represents the fourth, unstripped mode of operation.

Both modes use different beam dynamics. For the static mode, the beam spot on the foil is maximised in order to spread the energy loss over the foil. In the sweeper mode, the beam is focused in the horizontal plane, which is used for sweeping and also for filling the phase space of the synchrotron during injection. Thereby, the emittance growth in that plane is minimised, which matches the reduced acceptance of the synchrotron in that plane. In the vertical plane, the beam spot is matched to the foil size again to spread the heat.

For regular operation, carbon foils made by the GSI target laboratory with thicknesses of approximately 200, 400 and 600 µg/cm^2 are used. For special purposes, foils between 50 and 1000 µg/cm^2 have been applied. Each slot is equipped with foils of different thicknesses and all combinations of the standard types are loaded into the carousel. This enables the optimal stripping of different light and heavy ions at the same time in terms of energy loss, foil degradation, emittance growth and charge state. The number of slots usually holds enough spare foil combinations to last for a whole beam time.

Other Foil Strippers At GSI

In the experimental hall of the UNILAC, three more foil strippers are operated for the low energy beam branches. According to the needs of the different users, each of these strippers contains a simple target ladder mounted on a linear drive actuated either by a stepper motor or pneumatically, depending on the number of target positions. The ladders

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are equipped with carbon foils with thicknesses typically in the range of 50–150 µg/cm². A similar ladder is shown in Fig. 9.

High Energy Stripper Another stripper is located in the High Energy Beam Line HEBT following the SIS18. It offers nine target positions arranged in a 3-by-3 matrix, containing thin sheet metal targets made from copper, tantalum, and beryllium as well as carbon targets. Corresponding to the much higher energies of the ions accelerated in the synchrotron, target thicknesses range from 5 to 100 mg/cm². The mean charge state for uranium at 300 MeV/u stripped through a 40 mg/cm² Cu target equals 91+, i. e. hydrogen like uranium. Fully stripped heavy ions can be produced with high efficiencies given high enough ion velocity, as the mean equilibrium charge state can be pushed above the atomic number, eliminating the width of the charge distribution. Another consequence of the high ion velocities is the negligible energy deposition, which means that the targets show no deterioration. This stripper can therefore be operated for long times with high intensity beams without the need for a target service.

Low Energy Foil Stripping In 2010 an attempt was made again to use carbon foils instead of the gaseous N_2 target at the location of the gas stripper. Stripping efficiencies around 20% for U^{39+} and U^{40+} were achieved, depending on the foil thickness of 20–50 µg/cm² [17]. However, the lifetime of the foils was generally limited to a few hours due to thermal stress and irradiation effects. Some foils survived only a few beam pulses. Figure 9 shows one of the foil target holders used during these tests before and after the foils were irradiated with a high current beam. Considerable effort was put into investigations on the strongly differing lifetimes of individual foils, and to develop a procedure how to enhance the durability. The initiative was not successful, and foil stripping was not adopted for regular operation at this location.

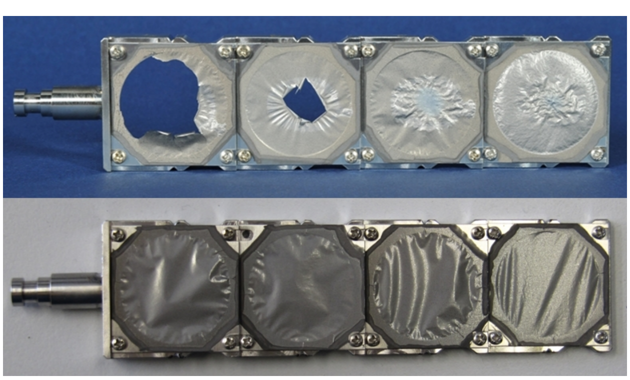

Figure 9: Foil ladders used during the 2010 low energy foil stripper tests. The same foil stripper before (bottom) and after (top) high current operation. 11 kJ were deposited in the third foil from left without any observed influence on the beam parameters [17].

LIQUID STRIPPER

Over the past years, a stripper based on a liquid lithium target has been developed and recently commissioned at FRIB [3, 18] for high current, medium energy heavy ion beams. This approach tries to combine the advantages of a quickly renewing target like a gas stripper with the beneficial stripping properties of a solid state stripper. The obvious challenge is handling of the liquid and therefore hot and highly reactive lithium. Special development and effort also had to be put into generating a sufficiently large, thin and homogeneous target without any backing in the interaction zone.

PLASMA STRIPPER

End of the 1980s, an experiment about energy loss of heavy ions in a plasma target was conducted by Hoffmann *et al.* at the location of the UNILAC gas stripper [19]. While the main topic was energy loss, this work also deals with the stripping of heavy ions in a plasma target. The results show that at 1.4 MeV/u, far higher charge states can be achieved by stripping in a hydrogen plasma in comparison to a conventional cold gas target. The drawback, of course, is the increased energy loss.

CONCLUSION

The operation of the GSI heavy ion accelerator facility would not be feasible without the repeated application of stripping devices along the beam line in order to increase the charge state. The physics of stripping requires different technological solutions and links significant beam loss inseparably to it. At low energies, target destruction by high current beams make gaseous targets the best choice, limiting the charge states reachable. Improvements can be achieved by introducing low Z targets. This is pursued at GSI by replacing the standard nitrogen with hydrogen. The main goal is to increase the stripping efficiency for heavy ions. A corresponding development is in progress, but safety requirements are especially challenging in the environment of a nearly 50 year old accelerator facility. Commissioning of the regular hydrogen stripping is anticipated for 2025. At medium energies, foil stripping can already be applied operationally, permitting access to higher charge states by the density effect. Additional effort is necessary to spread the energy loss over extended foil areas. At GSI, this is achieved by a magnetic sweeper. Stripping at high energies after the synchrotron is more relaxed since it involves no energy deposition in the target. The targets need to be thicker and are mechanically more robust.

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