ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-THPF018

SIMULATION STUDIES OF PLASMA-BASED CHARGE STRIPPERS

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Abstract

Calculations on the charge state distributions in different charge stripping media are presented. The main focus of this work is the width and peak efficiency of the final charge state distribution. For equal number densities fully-stripped plasma stripping media achieve much higher charge states than gas stripping media of the same nuclear charge. This is due to the reduced electron capture rates of free target electrons compared to bound target electrons. Furthermore, targets with low nuclear charge like hydrogen achieve higher charge states than targets with high nuclear charge like nitrogen in the case of both a plasma and a gas target. Equal final mean charge states can thus be achieved with lower density for plasmas and targets with low nuclear charge. The widths of the charge state distributions are very similar, slightly smaller for plasmas due to the different scaling of the dielectronic recombination rate. In comparison with calculations and measurements published in literature this work underestimates the width of targets with higher nuclear charge like, e.g., nitrogen gas. This is mainly due to the omission of multiple loss processes in the presented calculations. In the future we intend to expand the methods and models used in this work to improve the agreement with different measurements on charge state distributions in plasmas and gases.

INTRODUCTION

Charge stripping of heavy ion beams at high intensities is a major challenge in current and future facilities with high intensity heavy ion beams. Conventional stripping techniques are often limited in their applicability, e.g. solid carbon foils suffer from short lifetimes at high intensities and common gas strippers usually achieve only low charge states. One possible alternative is the use of a plasma as a stripping medium. The presented work focuses on theoretical studies of the interaction of an heavy ion beam with a plasma and gases and accompanying effects in possible charge strippers. The main interest in the presented studies is the final charge state distribution of the ion beam, which determines the efficiency of the charge stripper as an accelerator component.

BASICS

The main focus of this work is on the charge state distribution or $F_q(t_{\mathrm{eq}})$, where the latter is the relative fraction of the beam in charge state q at time t. The beam loses or captures electrons in several different processes with rates

$$\alpha_{q(q\pm n)}(q) = v_{\mathrm{r}} n_{\mathrm{t}} \sigma_{q(q\pm n)}(q) \,, \qquad (1)$$

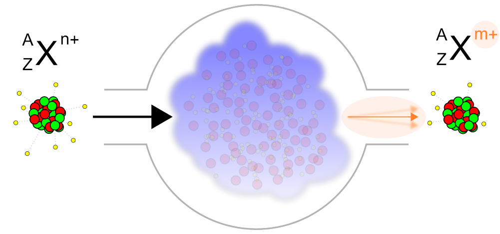

Figure 1: Sketch of a projectile getting stripped by a target.

where v_{r} is the relative velocity of projectile and target, n_{t} is the target density and $\sigma_{q(q\pm n)}(q)$ are the loss and capture cross sections. For every given beam energy the charge state distribution tends to an equilibrium. In the case of negligible multiple loss and capture rates the mean equilibrium charge q_{eq} is then given by

$$\alpha_{q(q+1)}(q_{\mathrm{eq}}) = \alpha_{q(q-1)}(q_{\mathrm{eq}}) \,. \qquad (2)$$

Furthermore the rates can be approximated as $\alpha_{q(q\pm1)} \propto \exp(b_i(q-q_{\mathrm{eq}}))$, leading to a Gaussian equilibrium charge state distribution with variance

$$\sigma^2_{q_{\mathrm{eq}}} = \left(\left| \frac{\alpha'_{q(q+1)}(q_{\mathrm{eq}})}{\alpha_{q(q+1)}(q_{\mathrm{eq}})} \right| + \left| \frac{\alpha'_{q(q-1)}(q_{\mathrm{eq}})}{\alpha_{q(q-1)}(q_{\mathrm{eq}})} \right| \right)^{-1} \,, \qquad (3)$$

where the prime denotes the derivative in respect to q. The peak efficiency is then given by $F_{q_{\mathrm{eq}}}(t_{\mathrm{eq}}) \approx 1/\left(\sigma_{q_{\mathrm{eq}}}\sqrt{2\pi}\right)$. It should be noted that Eq. (3) implies that the width of the equilibrium charge state distribution does not depend on the absolute value of the rate, but on the scaling with the projectile charge q.

While the approximations above are useful for the discussions in this work, actual results in the presented work are calculated by solving the rate equations for the charge state evolution

$$\frac{\mathrm{d}F_q(t)}{\mathrm{d}t} = \sum_{q'} F_{q'}(t)\alpha_{q'q} - F_q(t)\sum_{q'} \alpha_{qq'} \,. \qquad (4)$$

The system can be solved with a standard solver for differential equations, a Monte Carlo method or a matrix method (see Ref. [1]). The models used for the calculations of the rates are mostly summarized in Ref. [2] (which only includes single electron loss and capture) if not mentioned otherwise.

EQUAL DENSITY

As the basis of the theoretical discussion examples with parameters relevant for the GSI Unilac (see, e.g., Ref. [3]) are chosen. We assume an uranium projectile with energy $E = 1.4\,\mathrm{MeV/u}$ in a fully-stripped hydrogen plasma and hydrogen, helium and nitrogen gas. For now the calculations

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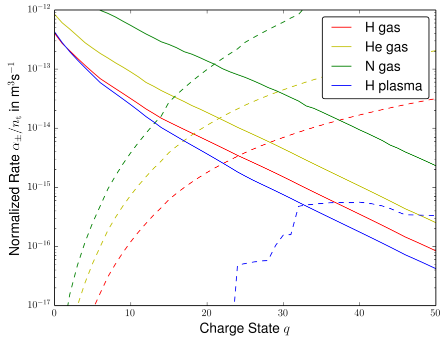

Figure 2: Rates of uranium projectile in different targets with equal number density. Solid and dashed lines are loss and capture rates, respectively.

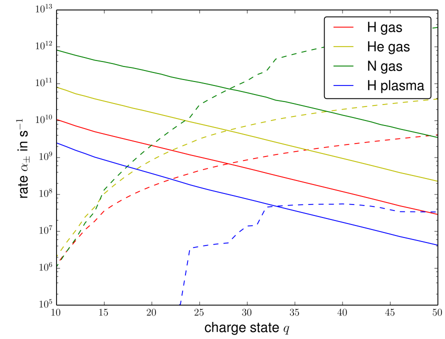

Figure 4: Rates of uranium projectile in different targets with equal final charge states. Solid and dashed lines are loss and capture rates, respectively.

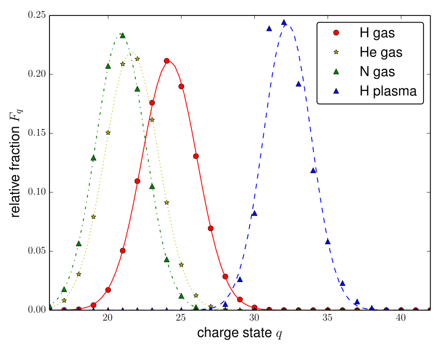

Figure 3: Equilibrium charge state distribution in different targets with equal density. Markers are values from solving the rate equations; lines are Gaussian approximations.

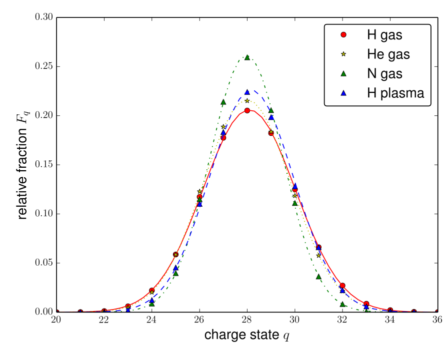

Figure 5: Charge state distribution in different targets with equal final charge states. Markers are values from solving the rate equations; lines are Gaussian approximations.

focus on the equilibrium charge state distribution for low densities (atomic/ionic number density $n_t < 10^{23}$ m^{-3}). In this region the equilibrium charge state distribution is independent of target density as both capture and loss rates scale linear with density.

The calculated rates are given in Fig. 2, the equilibrium charge state distribution is given in Fig. 3 and the corresponding values in Tab. 1.

	H plasma	H gas	He gas	N gas
q_{eq}	32.2	24.2	21.6	20.9
$\sigma_{q_{eq}}$	1.64	1.89	1.82	1.70
$F_{q_{eq}}(t_{eq})$	0.244	0.211	0.213	0.233

Table 1: Equilibrium charge state distribution values in different targets with equal number density.

It can be observed that the hydrogen plasma target achieves a much higher charge state than the three gas targets. The distribution widths however are quite similar, which can be explained by Eq. (3) and the similar shape of the rates in Fig. 2. All distributions are furthermore roughly Gaussian. The only exception in the case of the hydrogen plasma is due to the sharp edge in the the capture rate, which is caused by the contribution of dielectronic recombination exclusive to plasmas.

EQUAL CHARGE STATE

In this section the density is increased and the length of the target chosen such that the final charge state of the projectile for all targets each is $q_{eq} = 28$. The increased densities lead to an increased density effect.

The calculated rates are given in Fig. 4, the equilibrium charge state distribution is given in Fig. 5 and the corresponding values in Tab. 2.

	H plasma	H gas	He gas	N gas
n_t in 10^{23}m^{-3}	1.0	3.4	9.0	15.
$\sigma_{q_{eq}}$	1.77	1.94	1.84	1.52
$F_{q_{eq}}(t_{eq})$	0.224	0.205	0.215	0.259

Table 2: Charge state distribution values in different targets with equal final charge states.

It should be noted that in the case of the hydrogen plasma the length of the target had to be shorter than required to achieve the equilibrium charge state distribution. This explains the rather Gaussian shape of the charge state distribu-

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tion in the case of a hydrogen plasma – the sharp edge caused by the dielectronic capture rate is not reached. However, the general trend holds that in direct comparison of hydrogen gas and plasma the plasma has slightly thinner distribution and thus a higher peak efficiency. Furthermore, low-Z gases require a much lower density than high-Z targets.

DISCUSSION

We will focus first on the calculations done in this work for the gas targets to evaluate the presented results. In Ref. [3, 4] calculations and measurements have been carried out which show that the calculation of charge state distributions for low-Z gas targets with the methods used in our work agrees very well with experimental results (accuracy better than 10%). However, higher-Z gas targets like nitrogen show a much broader distribution in experiments. There are several effects which increase the width of the charge state distribution, but are too small to explain the discrepancy between the references mentioned above and the calculated results here. Namely these effects are energy loss (including straggling effects), energy spread of the beam, longitudinal inhomogeneities of the target, and target ionization by the beam. Transversal inhomogeneities of the target could cause a significantly broadened distribution, but it is unlikely that density distributions significantly change for different gas targets in the same setup in, e.g., Ref. [3].

For high-Z gases the multiple loss rates can be of the same order of magnitude as the single loss rates, while multiple capture rates are still negligible (see Ref. [5]). We assume multiple loss rates to scale for the given beam and nitrogen target parameters given in the previous section as

$$\alpha_{q(q+n)}(q) \approx (0.6)^n \alpha_{q(q+1)}(q) \,, \qquad (5)$$

which is used only as a rough estimate here to gauge the importance of multiple loss processes in this case. More accurate calculations and measurements of multiple loss done for slightly different parameters can be found in Ref. [5]. Again we adjust the density of the target such that we achieve an equilibrium charge state $q_{\mathrm{eq}} = 28$ as in the previous section to produce the results in Fig. 6. It can be seen that the width of the charge state distribution is significantly increased by the multiple loss process by roughly 60%. Furthermore the multiple loss processes lead to an asymmetric shape of the charge state distribution, which can be observed in experiments as well (see Ref. [3]). As of now we can not provide more detailed calculations for high-Z targets.

As given in Ref. [5] the multiple electron loss and capture rates in the case of low-Z targets like hydrogen (plasma and gas) are negligible. Thus the overall results presented for low-Z targets remain valid.

CONCLUSION & OUTLOOK

The widths of the charge state distribution only agree with results published in several references for low-Z targets. The

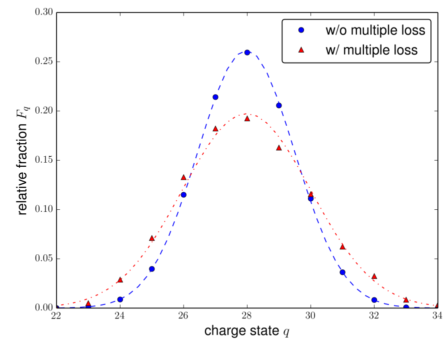

Figure 6: Charge state distribution in nitrogen with and without multiple electron loss. Markers are values from solving the rate equations; lines are Gaussian approximations.

difference in the width for higher-Z targets is most likely caused by multiple loss processes for which a very rough estimate was given.

Accordingly to this, the main goal of future work is to expand the calculation to better models including multiple loss and in general more accurate electron loss and capture rates (see, e.g., Ref. [5, 6]). As detailed density profile measurements are usually not done in charge stripping measurements, we intend to study the target properties in simulations of the gas and plasma dynamics in setups like in Ref. [3, 4, 7]. Especially in the case of a plasma target the dynamic and inhomogeneities might significantly affect the charge state distribution and further effects – like strong magnetic fields in the plasma – might affect the beam dynamics of the projectile beam.

As soon as more detailed models are established we intend to do a thorough comparison with experimental result published or results of setups soon to have further publications by our colleagues (e.g. Ref [3, 4, 7]).

REFERENCES

[1] O. Osmani, *Irradiation effects of swift heavy ions in matter*, Universität Duisburg-Essen (2011).

[2] T. Peter et al., Phys. Rev. A 43, 2015 (1991).

[3] W. Barth et al., Phys. Rev. ST Accel. Beams 18, 040101 (2015).

[4] H. Kuboki et al., Phys. Rev. ST Accel Beams 17, 123501 (2014).

[5] R.E. Olson et al., J. Phys. B: At., Mol. Opt. Phys. 37, 22, 4539 (2004).

[6] V. Shevelko et al., *Atomic Processes in Basic and Applied Physics*, Springer Series on Atomic, Optical, and Plasma Physics, Springer (2012).

[7] G. Loisch et al., IEEE Trans. Plasma Sci. 42, 1163 (2014).