

SIMULATION OF GAS AND PLASMA CHARGE STRIPPERS*

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Abstract

Charge stripping of intense heavy ion beams is a major challenge in current and future linear heavy ion accelerators. Conventional stripping techniques are limited in their applicability, e.g. solid carbon foils suffer from short lifetimes at high intensities. One possible alternative is the use of a plasma as a stripping medium, which the presented work focuses on. The main goal of the studies is the prediction of the final charge state distribution of the ion beam. Rate equations were implemented numerically, taking into account different models for ionization, recombination and energy loss processes. First quantitative results are presented in form of an overview of the charge state distributions of different charge stripping media. For fixed projectile properties and target phase, it is observed that the mean charge state q_0 decreases for increasing nuclear charge Z_T of the target. Plasmas show significantly increased q_0 for the same Z_T . The width d of the charge state distributions is larger for higher Z_T . The latter is caused by multiple loss of the projectile and decreases the maximum stripping efficiency by typically less than a factor of 2.

INTRODUCTION

Future facilities like the FAIR project at GSI (see Ref. [1]) require viable methods for charge stripping of intense heavy ion beams at fairly low beam energies of 1 MeV/u to 10 MeV/u. Typically 80 – 90% of the beam can be lost in the charge stripping process due to a large fraction of the beam being in unwanted charge states, thus warranting a theoretical study of charge state distribution widths of different gases and plasmas.

PROBLEM FORMULATION

The analytical considerations in this section on the charge state distribution of the projectile is based on Ref. [2]. The evolution is given by the system of rate equations

$$\frac{dF_q(t)}{dt} = \sum_{q'} F_{q'}(t) \alpha_{q',q} - F_q(t) \sum_{q'} \alpha_{q,q'}, \quad (1)$$

where $F_q(t)$ are the relative fractions of the charge state q , and the $\alpha_{q,q';q',q}$ are the projectile charge changing rates. In most cases charge changing processes are fast and energy loss can be disregarded, then the charge state distribution approaches an equilibrium with mean charge q_0 . First we

assume only single electron loss and capture processes and an exponential dependence of the rates on the charge state

$$\alpha_{q,q+1} = A_{q,q+1} \exp(-b_{q,q+1}(q - q_0)) \quad (2)$$

$$\alpha_{q,q-1} = A_{q,q-1} \exp(b_{q,q-1}(q - q_0)), \quad (3)$$

where $b_{q,q+1}$, $b_{q,q-1}$, $A_{q,q+1}$ and $A_{q,q-1}$ are positive constants according to the respective charge changing process. The equilibrium charge state distribution is in this case Gaussian with the standard deviation

$$d_0 = \sqrt{\frac{1}{b_{q,q+1} + b_{q,q-1}}}. \quad (4)$$

Graphically in a semi-log plot of the rates the mean charge q_0 is given by the intersection point, and the width d_0 by the slopes. Numerically we solve the matrix of the rates $\alpha_{q,q'}$ with a singular value decomposition for the equilibrium charge states or integrate directly the rate equations with a high-order adaptive Runge-Kutta scheme for a time resolved evolution of the charge states.

As we will see later in the presented work at typical energies of 1 MeV/u to 10 MeV/u multiple loss cross sections can be almost as large as the single charge changing processes, but multiple electron capture is negligible. The multiple loss rates are approximately given by are roughly given by

$$\alpha_{q,q+n} \approx k_0^{n-1} \alpha_{q,q+1}, \quad (5)$$

where n is a positive integer representing the n -electron loss or capture process, and $0 < k_0 < 1$.

The standard distribution width of the charge state distribution including multiple loss rates is then given by

$$d = k d_0 \quad (6)$$

$$k \approx \left[\frac{\sum_{n=1}^{n=n_{\max}} n^2 k_0^{n-1}}{2 \sum_{n=1}^{n=n_{\max}} n k_0^{n-1}} + \frac{1}{2} \right]^{1/2}. \quad (7)$$

From this one can deduct that in case of large multiple loss rates the inclusion of high n is required to get an accurate value of d , e.g. if $k_0 = 0.7$ rates up to roughly $n_{\max} = 10$ should be included.

For heavy ion projectiles it is reasonable to take the limit $n_{\max} \rightarrow \infty$ for k , which enables us to derive a very simple expression

$$k \approx \left[\frac{1}{1 - k_0} \right]^{1/2}. \quad (8)$$

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As we will see for this work typically $0 < k_0 < 0.7$, which translates to roughly $1 < k < 2$. However, the charge state distribution width might be slightly further increased by secondary effects like energy loss and energy-loss straggling.

CALCULATION OF RATES

For the calculation of the rates we employ several methods. Most importantly for single and multiple electron loss we use the n -body classical trajectory Monte Carlo method (CTMC, see Refs. [3, 4]) with binding energies based on a screened hydrogenic ion model (see Ref. [5]) with Slater-type orbitals for the inactive electrons. In the case of a plasma the Debye screening of the target was included as well as an spherically symmetric approximated dynamical Debye screening for the projectile

$$\lambda_{D,dyn} = \lambda_D \sqrt{1 + \left(\frac{v_p}{v_{th}}\right)^2}, \quad (9)$$

where v_p is the projectile velocity and v_{th} the thermal velocity of the plasma. Other single charge changing rates were calculated according to numerous different models (see Ref. [6]), most notably charge exchange electron capture and dielectronic recombination as the dominating capture processes for atomic and fully ionized plasma targets, respectively. The same methods for the binding energy calculation as above were used. The so-called density effect – which mainly refers to the increased probability of the loss of electrons captured in highly excited states – was included according to Ref. [7].

The main example used in this work is an uranium projectile at 1.4 MeV/u in different stripping media due to its relevance for the FAIR project. As examples the calculated rates in atomic nitrogen and a fully ionized hydrogen plasma are given in Fig. 1 and Fig. 2, respectively.

Some general trends for the rates of different target materials can be observed in the presented work as well as in further studies not shown here: Electron loss rates depend mainly on the nuclear charge of the target and are similar for both plasmas and atomic targets. Plasmas show a highly increased mean charge due to much lower capture rates, as the dielectronic recombination with a free electron is much less likely than the charge exchange of outer shell electrons of an atomic target. Furthermore it should be noted that the charge exchange rate quickly dominates the capture processes if the ionization degree of the plasma decreases.

EQUAL TARGET DENSITY AND MEAN CHARGE

For a given number density of the charge stripping medium we calculate the charge distribution (see Fig. 3). The main observations are that targets with lower nuclear charge Z_T reach higher charge states, and in plasmas the charge stripping is significantly increased. This in principle explains the interest in the study of plasmas as charge

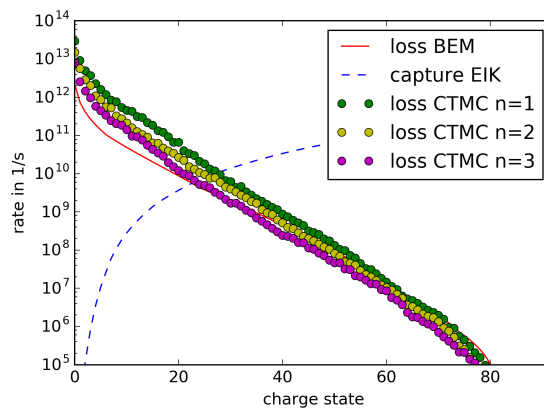


Figure 1: Rates of uranium projectile with 1.4 MeV/u in atomic nitrogen with atom number density $n_a = 10^{23} \text{m}^{-3}$. The rate calculation methods are given in Refs. [3, 4, 6]. With abbreviations CTMC: n -fold multiple loss, EIK: eikonal-corrected charge exchange and BEM: binary encounter model.

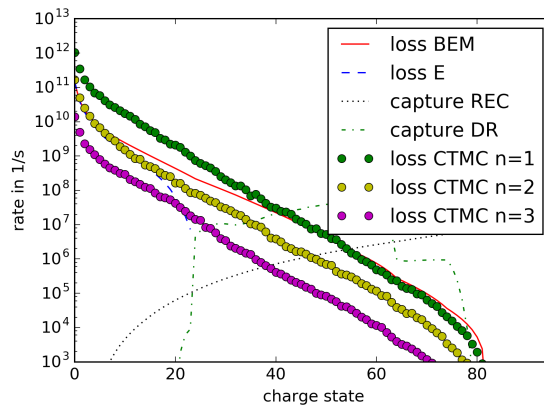


Figure 2: Rates of uranium projectile with 1.4 MeV/u in a fully ionized hydrogen plasma with ion and electron number density $n_{i,e} = 10^{23} \text{m}^{-3}$. With abbreviations E: electron loss by electron impact, DR: dielectronic recombination and REC: radiative electron capture. The remaining rate calculation methods as in Fig. 1.

stripping media. The widths are smaller for smaller Z_T and slightly smaller in case of fully ionized plasmas. Furthermore the slightly different shape of the charge state distribution in the case of a hydrogen plasma can be explained by the different shape of the dielectronic recombination rate as seen in Fig. 1.

EQUAL MEAN CHARGE AND CHARGE DISTRIBUTION WIDTH

To get more comparable peak efficiencies for different charge stripping media the simulation parameters were adjusted such that the final charge state of the projectile uranium is $q_0 = 28$. For that the densities of the atomic materi-

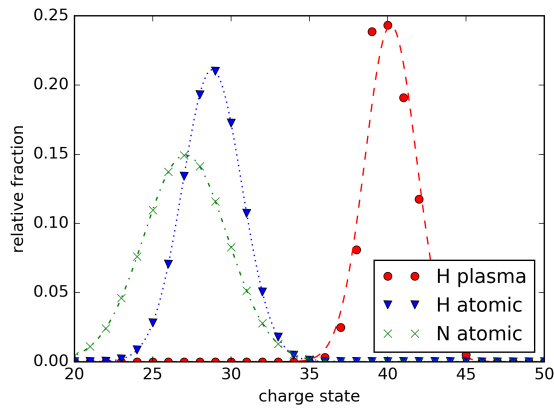


Figure 3: Charge state distribution of uranium projectile with 1.4 MeV/u in different materials with number density $n_{a,i,e} = 10^{23} \text{ m}^{-3}$.

als was increased until the density effect reduces the capture rates such that this is achieved. In the case of the plasmas the length of the plasma had to be adjusted, such that charge state equilibrium is not achieved. Note that this slightly increases the widths d for plasmas with small nuclear charge as the non-equilibrium width are larger than the equilibrium ones (see Fig. 4). Similar to the previous section it can be seen

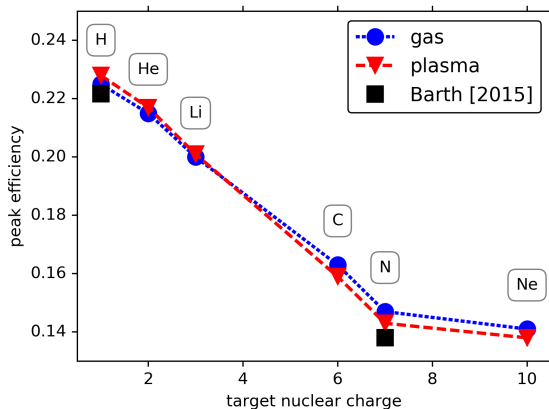


Figure 4: Peak efficiencies of uranium projectile with 1.4 MeV/u in different stripping media. The measured peak efficiency depicted from Ref. [8] has been normalized to account for beam loss in the experiment.

that the width d of the charge state distributions is larger for higher Z_T . We note that the widths of the distribution are all within the expected range from previous discussion.

CONCLUSION

In the present work the use of a plasma as a stripping medium is discussed with the main focus on the final charge state distribution width and peak efficiency. Although fully ionized plasmas show significantly increased q_0 for the same Z_T , the peak efficiency is similar as for atomic target. In that regard, unless very high final charge states are required, plasmas have no significant advantage over atomic targets. For fixed projectile properties and target phase, it is observed that the mean charge state q_0 decreases for increasing nuclear charge Z_T of the target. The width d of the charge state distributions is larger for higher Z_T . The latter is caused by multiple loss of the projectile and decreases the maximum stripping efficiency by typically less than a factor of 2. More practical consideration of course should address the difficulty of producing a highly ionized plasma with large nuclear charge. The production of a fully ionized hydrogen plasma is the most likely the only feasible alternative in a laboratory environment.

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