Particle simulation of negative hydrogen ion transport

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In order to study the negative hydrogen ion (H^-) behavior in typical conditions for multicusp ion sources, with particular reference to laser photodetachment experiments results, a test particle Monte Carlo solution of the kinetic equation for H^- transport is used to analyze the ion energy distribution in H/H_2 mixtures. A non equilibrium ion energy distribution is obtained in agreement with the two temperature distribution deduced from the experimental data fit. A calculation of negative ion propagation, with velocity distribution obtained from the test particle simulation, allows to study the influence of the reduced electric field, the H atom concentration and temperature on the negative ion density recovery.

1. Introduction

The use of hydrogen plasmas as sources for the production of neutral beams to be used in nuclear fusion experiments is well stated [1, 2]. Diagnostic techniques for the analysis of negative ion kinetics and dynamics are thus very important.

One of the most used technique for the measurement of negative hydrogen ion density and thermal velocity [3, 4, 5] is based on laser induced photodetachment of the H^- ion into an atom and a free electron.

The theoretical explanation of the negative ion density recovery after laser photodetachment is not an easy task: the so called ballistic kinetic theory (BKT), which takes into account the field-free flux of the particles, is able to reproduce the trend of the experimental data only for the early stages of the H^- ion density recovery and for small laser beams diameters [3, 4]; for the other cases the effect of self-consistent electric field, following the first laser shot, and collisions have to be taken into account.

Much work has been done in the past and reported in numerous publications to study physical effects possibly affecting the shape of the negative ion density recovery following photodetachment.

As an example in ref. [6] an hybrid fluid-kinetic model, in which positive H^+ ions and electrons are treated following the fluid theory, explains the overshoot in time of the excess electron current after the photodetachment. However, H^- ions remain in the treatment of the BKT and the effect of the ambipolar electric field on the H^- ion motion is neglected.

In the recent work by Mizuno et al. [7], concerning a one dimensional analysis of the effect of the ambipolar potential by means of a particle in cell simulation, it is shown that the negative ion temperature can be influenced by the ambipolar potential especially for the cases in which the negative ion density is comparable with the positive ion one: nevertheless this effect does not reduce substantially the gap between theory and experiment.

In a paper by Ivanov [8] the existence of two negative ion groups with different temperatures in volume H^- sources is stated, starting from a bi-Maxwellian fit of photodetachment experimental data. The origin of these two populations is attributed to the existence of two H^- production regions with different plasma potentials.

In this work a test particle Monte Carlo simulation is performed in the frame of a uniform reduced electric field for the same H_2 pressure and dissociation degree of the experimental conditions in ref. [3]. A strong non equilibrium feature of the ion energy distribution function (iedf) is retrieved.

Moreover, an isotropic simulation of negative ion propagation, with velocity distribution obtained from the above test particle model, allows to study the influence of the reduced electric field, the H atom concentration and temperature on the negative ion density recovery after laser photodetachment.

2. Test particle Monte Carlo

A null collision test particle Monte Carlo method, that takes into account the thermal distribution of the target particles, has been used in order to calculate the H^- ion energy distribution function. In this model, two collision processes have been considered: the momentum transfer with the hydrogen molecule and the resonant charge exchange with the hydrogen atom. The cross sections used are the ones in ref. [9] and [10] respectively. The method of ref. [11] has been extended in order to calculate the collision frequency for a species colliding with two different neutral targets, in this case the H_2 and the H. The collision probabilities for the two processes, for a given H^- velocity, are :

$$p_{mt}(g_1) = \frac{\nu_{mt}(g_1)}{\nu_{max}} = \frac{n_{H_2}\sigma_{mt}(g_1)g_1}{\nu_{max}} \quad (1)$$

$$p_{ce}(g_2) = \frac{\nu_{ce}(g_2)}{\nu_{max}} = \frac{n_H\sigma_{ce}(g_2)g_2}{\nu_{max}} \quad (2)$$

$$\nu_{max} = \max_{g_1, g_2}(n_{H_2}\sigma_{mt}(g_1)g_1 + n_H\sigma_{ce}(g_2)g_2) \quad (3)$$

where n_{H_2} and n_H are, respectively, the H_2 and the H number densities, σ_{mt} and σ_{ce} are the momentum transfer and the resonant charge exchange cross sections, g_1 and g_2 are the relative speeds of the H^- with respect to the target H_2 and H and ν is the collision frequency. The velocity of the target particle is selected by means of the von Neumann rejection technique from a Maxwellian distribution with a temperature of 300K.

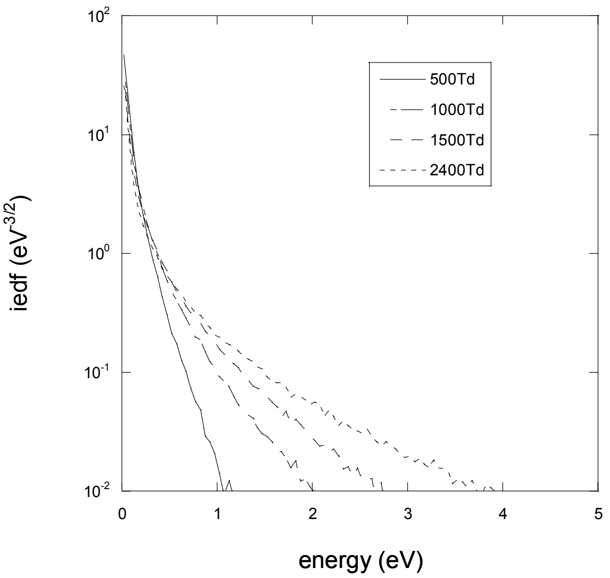

Fig. 1 H^- iedf calculated by means of the test particle Monte Carlo technique for different values of the reduced electric field, for a gas pressure of 3 mtorr and an H atom number density of $9\times10^{19}m^{-3}$.

The simulation has been performed for a gas pressure of 3mtorr, the density for the H atom is $9\times10^{19}m^{-3}$ (following the experimental conditions in ref. [3]). In fig.1 the H^- iedf for different values of the reduced electric field, calculated taking into account the density of both the H atom and the H_2 molecule, is shown. The non equilibrium features, mainly due to the charge exchange collisions, can be easily inferred, specially as regards the higher values of the reduced electric field. This implies that the BKT, that supposes an equilibrium energy distribution, should not correctly describe the negative ion density recovery after laser photodetachment. Our results are coherent with the two temperatures iedf hypothesis by Ivanov [8] obtained with a macroscopic approach. However they were obtained without any a priori assumption, and we have shown that the two temperature fit is in good agreement with the iedf obtained with the test particle in an uniform reduced electric field [12].

3. Negative ion density recovery

The results of the previous section suggest to study the negative ion density recovery after laser photodetachment using a generic iedf and not a two temperature distribution.

To this aim we used an isotropic propagation of the negative ions, starting from the non equilibrium ion energy distribution obtained by means of the test particle Monte Carlo model, under the hypothesis of laser beam dimensions much smaller than the negative ion mean free path.

The mathematical expression for the time dependence of the negative ion number density following laser photodetachment, in the laser spot center, is

$$n^-(t) = n_0^- \int d\mathrm{v} f(\mathrm{v}) k(\mathrm{v},\mathrm{t}) \quad (4)$$

where $n^-(t)$ is the value of the negative ion density at time t, n_0^- is the steady state negative ion number density, f(v) is the ion velocity distribution function and k(v,t) is an integral kernel given by

$$k(\mathrm{v},\mathrm{t}) = \begin{cases} \sqrt{1-\left(\frac{\mathrm{R}}{\mathrm{vt}}\right)^2} & \text{if } \mathrm{v} > \mathrm{R/t} \\ 0 & \text{if } \mathrm{v} \leq \mathrm{R/t} \end{cases} \quad (5)$$

In the expression above, R is the radius of the laser spot, supposed circular.

If f(v) is a Maxwellian distribution, the expression from BKT, that is

$$n^-(t) = n_0^- \exp\left(-R^2/(v_{th}t)^2\right) \quad (6)$$

is retrieved, where v_{th} is the ion thermal velocity.

The calculation of the integral in (4) at any time t consists in a statistical sampling of the velocity distribution.

The test particle simulation was performed using different values for the reduced electric field, dissociation degree and H atom temperature.

As an example, in fig.2, the ratio $n^{-}(t)/n_0^{-}$ is shown for the same conditions of fig.1, but with a reduced electric field of 270Td, a dissociation degree of 0.1 and varying the H atom temperature. In the same figure, experimental results for a laser beam radius of 4mm [3] together with the BKT fit proposed in the same reference are shown. It can be noted a better agreement for the results with a suitable temperature for H atoms. A further improvement could be reached by relaxing the hypothesis of a single temperature distribution for H atoms, that, as shown in ref. [13] are not in equilibrium with the gas and have a hot component.

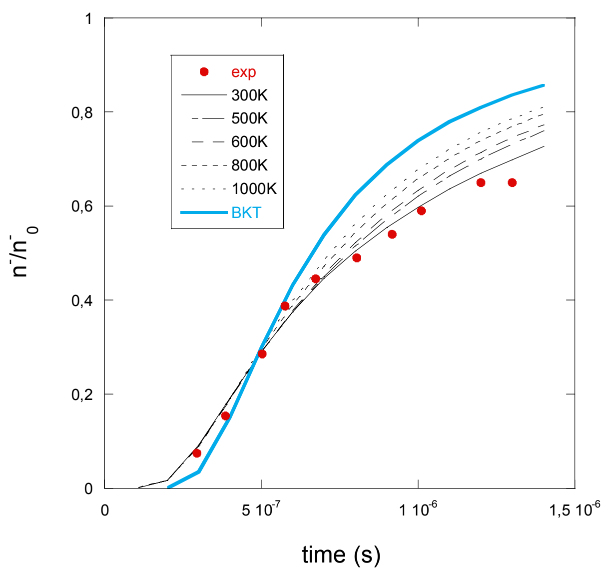

Fig. 2 Negative ion density recovery after laser photodetachment in the center of the laser spot calculated for different H atom temperatures and a reduced electric field of 270Td. Also shown are the experimental results and their fit from BKT reported in ref.[3].

The effect of the variation of the reduced electric field can be evaluated by examining fig. 3, in which the model is applied to ion energy distributions obtained with a dissociation degree of 0.1 and an H atom temperature of 1000K. The laser beam radius is 2mm in this test case. Also reported are the experimental results and their BKT fit as reported in ref. [3]. Though in this case the agreement with the BKT fit is fairly good, a further improvement can be obtained, especially at early times.

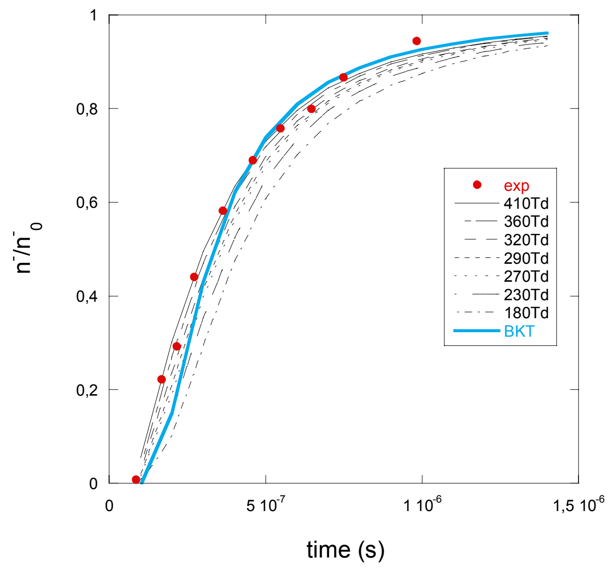

Fig. 3 Negative ion density recovery after laser photodetachment in the center of the laser spot calculated for different reduced electric fields and an atom temperature of 1000K. Also shown are the experimental results and their fit from BKT reported in ref.[3].

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