

KINETIC DYNAMICS OF INITIAL ION PLASMA PERTURBATION

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Hydrogen negative ion sources are an important component of neutral beam injectors. The latter are used for heating plasma in tokamak and for diagnostics of thermonuclear plasmas. In order to improve the characteristics of H⁻ ion sources it is necessary to know the parameters of all particle species and, in particular, to be able to distinguish negative ions from electrons, as they have identical charges. In view of measuring the density and temperature of negative ions in hydrogen plasma, the laser photodetachment technique was developed at Ecole Polytechnique [1,2]. In a limited plasma region all the negative ions are destroyed by the laser beam. Using a Langmuir probe, the change of the electron current to this probe and the relaxation time of perturbation to the initial steady state are measured. Thus, analyzing the perturbation in the easily measurable electron plasma component, it is possible to measure both the density and the temperature of negative ions. This research is also important from the point of view of the multicomponent plasma theory.

Let us consider the problem of determining the negative ion temperature in more detail. The laser photodetachment associated with the Langmuir probe allows to find the characteristic relaxation time of the plasma produced in the laser channel by a short laser pulse and to estimate the negative ion temperature. The rough estimate of the characteristic negative ion speed v_- , given by the ratio of the laser radius, R_L , to the characteristic relaxation time, can give a considerable error. Since the laser channel has a cylindrical shape, it is possible to correct this estimate, taking into account the channel geometry and assuming the ballistic movement of the negative ions [2] :

$$N_i \sim n_0 \cdot \text{Exp}(- (R_L / v_- \cdot t)^2), \quad (1)$$

where n_0 is the negative ion density before the laser pulse and N_i is the negative ion density at the time t after photodetachment. The comparison of the theoretical curves (see Fig. 1) and the experimental curves for the negative ion density [2] leads to the evaluation of the negative ion temperature. Note that the relaxation process described by Eq. (1) has the self-similar features. This model was improved, using instead of R_L the difference between the channel radius and the effective probe radius. However, this method does not take into account the self-consistent electric field.

The ballistic movement of charged particles in plasmas occurs rather seldom and it is necessary to use mathematical models, taking into account the self-consistent electric field. A plasma with the density $n_p \sim 10^{10} \text{ cm}^{-3}$ and both the temperature $T_e \sim 1 \text{ eV}$ has the Debye length $\sim 0.1 \text{ mm}$. The electric field plays an appreciable role for the channel with the radius

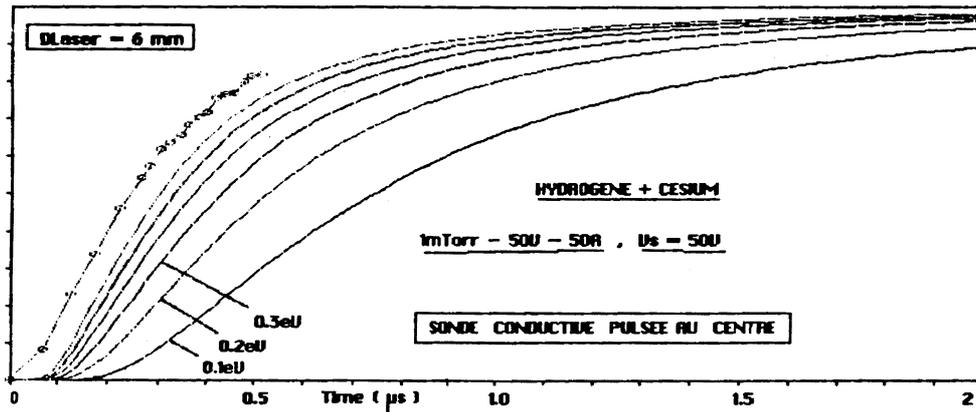


Fig. 1. Normalized H^- density versus time delay after laser photodetachment, at the center of the source extraction region. Laser diameter 6 mm. 50 V, 50 A, 1 mTorr discharge in hydrogen with cesium seeding.

3-8mm. In [3] we took into account the self-consistent electric field and showed that the error in the estimate of the negative ion temperature, T_i , from Eq. 1 can be large when the ratio of negative ion to positive ion densities is higher than 0.1. This can be important in the case of cesium seeded plasma [4] where the negative ion density is enhanced.

The self-consistent self-similar model [3] of the one-dimensional non-linear kinetic equation for negative ions in a quasineutral plasma gives their temperature with sufficient accuracy. In this case, the basic role in the recovery is played by the electric field created by electrons escaping from the channel. The self-consistent field can accelerate the negative ions to the center of the channel and to the ion-sound speed. This acceleration can be observed comparing the experimental curves and the theoretical curves from the ballistic model, shown in Fig. 1.

The use of the photodetachment method in the extraction region, where a weak transverse magnetic field, ($B \sim 40G$), is present, shows a substantial growth of the negative ion density [5]. Therefore it is not surprising that the ions arrive to the probe much faster than in the experiments effected in the center of the source because the self-consistent electric field is stronger in the extraction region. However, the reasons for such a negative ion density growth are not clear yet. Haas and Holmes [5] came to the paradoxical conclusion that the negative ion density increase (by a factor of three) occurs directly in the extractor on a short distance, due to the dissociative attachment of electrons to hydrogen molecules. This paradox is easily resolved, if one assumes that the magnetic field in the extractor region creates a negative ion flow within the extractor as into a funnel.

Actually, in the extraction region electrons are magnetized and move to the positively-charged plasma electrode along the magnetic lines. The extraction region is depleted in electrons. An electric field is formed and accelerates negative ions, for which the magnetic field is rather weak, to the extractor. In the meantime, the magnetic field has no essential influence on the probe measurement. In [7] we have described the geometry of extraction region and the dynamics of particles there. Probe measurements at various plasma

electrode bias allows to find both the directed velocity and the thermal velocity of negative ions with this bias (Fig. 2). Thus, the measurement of the negative ion temperature becomes possible when the suitable instrumentation, including the computer code, and its calibration, are available.

On the other hand, the laser photodetachment technique can be used for the experimental verification of the collisionless theory of Landau damping. On the basis of a kinetic plasma response theory let us consider the initial perturbation of a negative-ion plasma by laser photodetachment. Let us use a kinetic equation linearization method for positive ions and electrons and apply the Fourier method and the Laplace transformation. Omitting the complex calculations from [8], we shall present, for example, the electron density along the system axis :

$$\frac{n_e(t)}{n_{e0}} = \frac{e}{T_e} \varphi(t) = \frac{4n_0^-}{\sqrt{\pi} v_- n_{e0}} \int_{-\infty}^{\infty} e^{-v^2/v_-^2} \sum_{n=0}^{\infty} F_n(v) dv, \quad (2)$$

where

$$F_0(v) = \text{Re} \left[\frac{\pi \Delta(vt)}{g(v/v_+)} - \frac{i}{g(v/v_+)} \ln \left| \frac{d-vt}{d+vt} \right| \right] \quad (3)$$

$$F_n(v) = \frac{1}{\frac{\partial g}{\partial u} \Big|_{u'_n} (u'_n + v)} \left(\text{arctg} \frac{d+u'_n t}{-u'_n t} + \text{arctg} \frac{d-u'_n t}{-u'_n t} \right) +$$

$$\frac{1}{\frac{\partial g}{\partial u} \Big|_{u'_n} (u'_n - v)} \left(\text{arctg} \frac{d+u'_n t}{-u'_n t} + \text{arctg} \frac{d-u'_n t}{-u'_n t} \right) +$$

$$\frac{i}{2 \frac{\partial g}{\partial u} \Big|_{u'_n} (u'_n + v)} \ln \left(\frac{(u_{ni} t)^2 + (d - u_{nr} t)^2}{(u_{ni} t)^2 + (d + u_{nr} t)^2} \right) +$$

$$\frac{i}{2 \frac{\partial g}{\partial u} \Big|_{u'_n} (u'_n - v)} \ln \left(\frac{(u_{ni} t)^2 + (d + u_{nr} t)^2}{(u_{ni} t)^2 + (d - u_{nr} t)^2} \right)$$

d is the diameter of the canal, $u_n = u_{nr} + i u_{ni}$ are the complex roots of the linear plasma dispersion equation, $g(u) = 0$ [8]

$$g\left(\frac{\omega}{|k|v_T^+}\right) = \frac{1}{k^2 d_e^2} + \frac{1}{k^2 d_i^2} \left(1 + i\sqrt{\pi} \frac{\omega}{|k|v_T^+} W\left(\frac{\omega}{|k|v_T^+}\right) \right), \quad (4)$$

$$\Delta(x) = \begin{cases} 1, & |x| < d \\ 0, & |x| > d \end{cases}$$

The solution of Eq. 2 shows that the problem for cold positive ions ($T_+ \ll T_e$) is reduced to the hydrodynamic model. The phenomenon of the electron density reduction below its initial level (overshoot) has been considered in [9]. It is necessary to use the kinetic theory of plasma

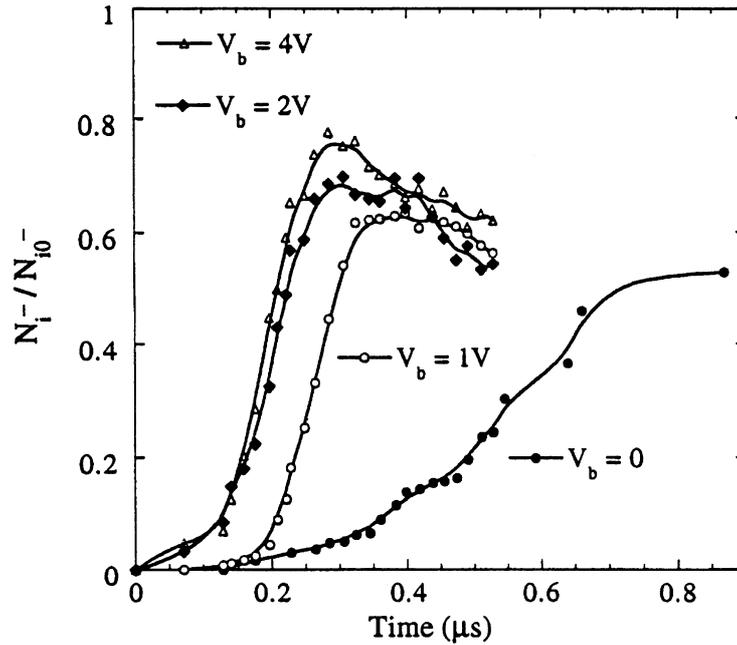


Fig. 2. Normalized H density vs. time delay near the plasma electrode for different values of its bias, in pure hydrogen.

for higher temperatures of ions ($T_+ \sim T_e$). It is shown that the disappearance of the overshoot is related with the collisionless Landau damping. The last conclusion allows, in particular, to carry out qualitative and quantitative comparisons of the theory under consideration with the results of the probe measurements. This allows to estimate the relationship between the positive and negative ion temperature in the negative ion sources.

Acknowledgement

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