

Plasma Perturbation Induced by Laser Photodetachment

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I. INTRODUCTION

Plasmas containing negative ions have been studied in the fields such as astrophysics, negative ion source development, and divertor plasma physics for nuclear fusion. Negative ion diagnostics in plasmas are required to optimize negative ion sources and to understand the production and destruction mechanisms of negative ions.

Laser photodetachment technique [1, 2] using a Langmuir probe is considered most useful as a diagnostic tool of negative ions in plasmas. In addition to negative ion densities, negative ion temperatures can be obtained by this technique with the theory deduced from the ballistic approximation [3]. However this technique has been applied to determine negative ion temperatures only when the Langmuir probe is placed at a laser axis.

Devynck et al.[4] and Nishiura et al.[5] have already studied the outward propagation of the perturbed potential excited by the photodetachment of hydrogen negative ions induced by a laser beam. They have confirmed that the peak of perturbed potential moves outward with the same velocity as the ion acoustic velocity. The peak value of the potential does not attenuate with $1/r$ dependence, where r is the distance between the laser axis and the probe. The perturbed potential profile seems to develop in both time and space and contain information on the negative ion density and other plasma parameters. Thus the solutions to the perturbed electron densities $dn_e(r, t)$ and the negative ion densities $dn_-(r, t)$ obtained from the hybrid fluid-kinetic model [6] are given in this paper, and are calculated numerically until the plasma recovers the original conditions in both inside and outside the laser beam. The results are compared with the typical experimental data in order to confirm the validity of the theoretical model.

II. EXPERIMENTAL CONFIGURATION

The schematic diagrams of experimental setup and measurement system are shown in

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Ref. [7]. The multicusp negative ion source is made of a stainless-steel vessel of 270 mm in length and 210 mm in diameter. Ten rows of ferrite magnets are attached on the cylindrical wall for the plasma confinement. Each end of the vessel has also four magnets. The vessel, which is an anode, is biased at ≈ 100 V with respect to the cathod. The hydrogen plasma is produced by electron emission from two tungsten filaments serving as the cathodes.

The L-shaped Langmuir probe is immersed into the plasma. The probe tip is made of a tungsten wire of 10 mm in length and 0.35 mm in diameter. The Nd-YAG laser is used for photodetachment. The laser beam diameter is limited to 4 mm using an aperture.

The produced dc plasma is uniform and unmagnetized in the central region of the vessel. Plasma parameters of $n_e = 10^{10} \sim 10^{11} \text{ cm}^{-3}$, $T_e = 0.5 \sim 3 \text{ eV}$, and $n_- / n_e \sim 0.05$ are obtained from the probe $I - V$ characteristics and photodetachment. When the photodetachment of all electrons from H^- ions is induced by enough laser power, the relation; $n_- / n_e = \delta I / I_{dc}$, is used for determining the n_- / n_e ratio, where δI and I_{dc} are the detached electron current and the electron saturation current, respectively.

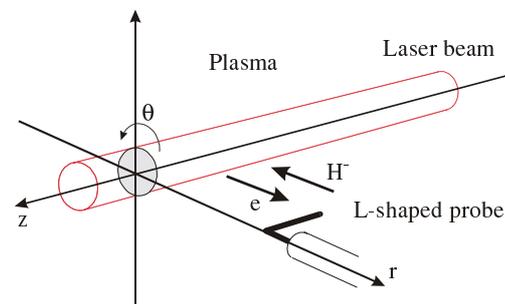


Figure 1. Configuration of the laser beam and the probe for experiments and model calculations.

III. BASIC EQUATION AND MODEL

For the purpose of the analysis of electron and negative ion motions in photodetachment reactions, the hybrid fluid kinetic model [6, 7] is applied to ion source plasmas. This model is appropriate for our experimental conditions. When v_{th}^- is the thermal velocity of negative ions, R the laser radius, and k the wave number, we introduce the following dimensionless quantities:

$$x = v / v_{th}^- ; \quad t = v_{th}^- t / R ; \quad a = \sqrt{g T_+ / T_e} ; \quad h = r / R ; \quad x = kR ,$$

As the following equations are given in Ref. [6] and [7], we omit the details. Final result of the density perturbation for electrons is given by:

$$\frac{dn_e(h, t)}{n_{-0}} = \frac{2}{\sqrt{p}} \int_0^{+\infty} \frac{\Psi(h, \sqrt{1+a^2} t) - (x^2 - a^2) \Psi(h, xt)}{1+a^2 - x^2} e^{-x^2} dx, \quad (1)$$

$$\text{where } \Psi(h, xt) = \int_0^{\infty} \cos(xt x) J_0(hx) J_1(x) dx ,$$

with J_0 and J_1 being the Bessel function of the first kind of the order 0 and the order 1.

For negative ions,

$$\frac{dn_-(h,t)}{n_{-0}} = \int_0^{+\infty} J_0(hx) J_1(x) e^{-(x/2)^2} dx . \quad (2)$$

It is clear that the recovery of the negative ion density depends on the thermal velocity of negative ions from Eq. (2), when the ballistic approximation is valid.

IV. RESULTS AND DISCUSSION

Two-dimensional view of perturbed density

Figure 2 shows comparisons between the perturbed electron densities calculated using Eq. (1) and those measured from $t = 0$ to 3.0. The negative ion vacant region inside the laser channel is filled with the negative ions gradually from the boundary of the laser beam path. Although the laser radius is limited to $h = 0.8$ ($r = 2$ mm), the gradient of the actual electron density starts at $h = 0.7$ and decreases exponentially to about 2.0, as shown at $t = 0$. This would be due to the spatial resolution of the Langmuir probe. Until $t = 0.6$, the perturbed density at $h < 1$ shows a contraction of electron rich region of the initial density, while the perturbation beyond $h > 1$ is pushed outward. The propagation of perturbed density causes two-step-shape density profile with the two boundaries moving symmetrically inward and outward across the $h = 1$ boundary. When $t = 1.1$, the overshoot emerges at $h = 0$. The discrepancy between calculations and measurements is small and would be partly due to calculation error of numerical integration. The height of the outward propagating wave depends on the plasma parameters of every particle.

From the comparison between experiments and calculations, it is found that the hybrid fluid-kinetic model represents the plasma responses induced by laser photodetachment well. The physical picture of plasma responses in photodetachment becomes clear. From the measurements not only inside, but also outside the laser channel, negative ion densities are determined.

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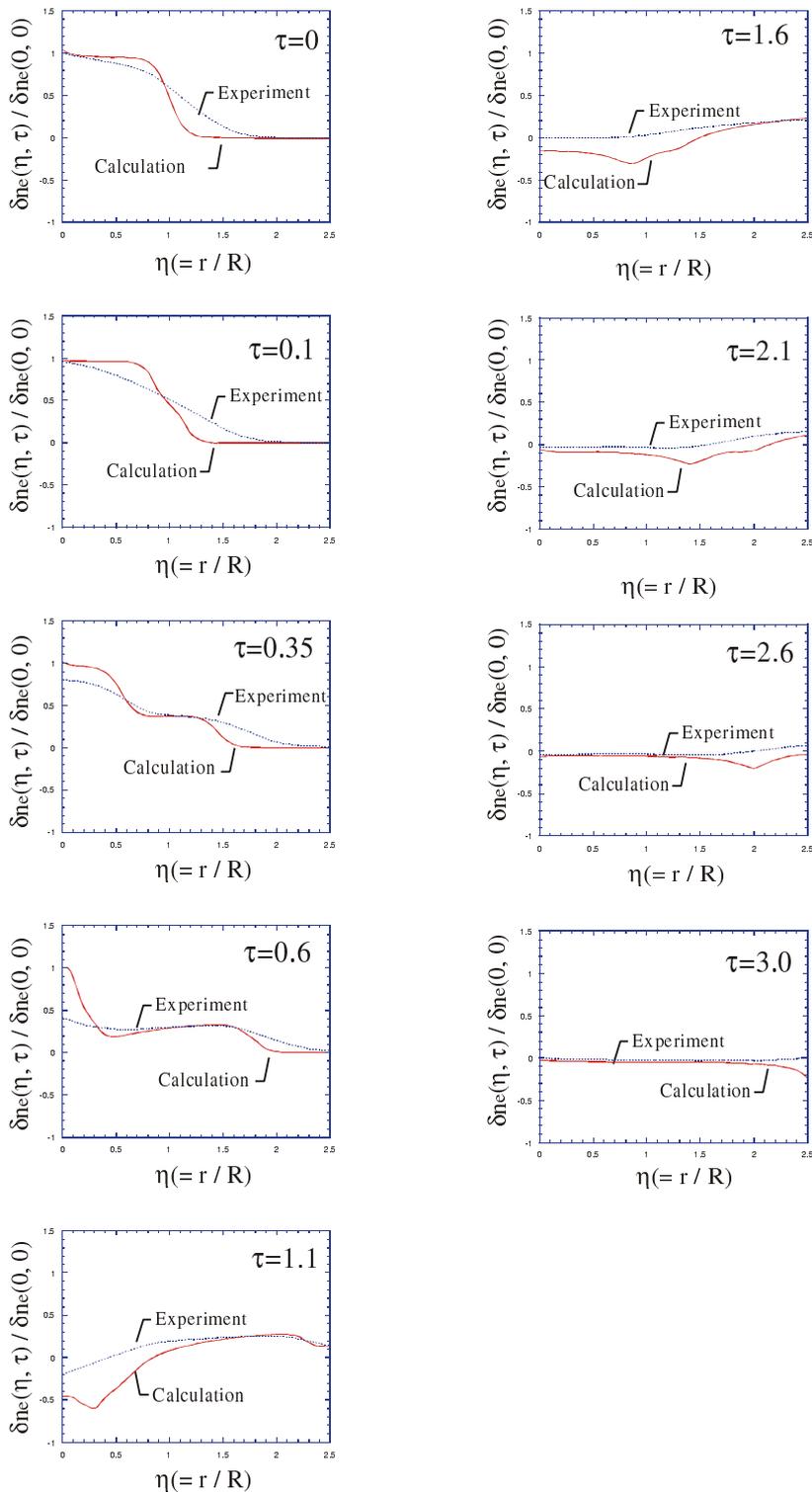


Figure 2. Comparison of spatiotemporal transition changes of perturbed electron densities between the observed data and the calculations at $t = 0, 0.1, \dots, 3.0$ under the conditions that $a = 0.59$ and $R = 2.5$ mm. Experimental data for electrons are obtained under the condition where $n_i/n_e = 0.01$, $n_e = 7 \cdot 10^{10} \text{ cm}^{-3}$, and $T_e = 0.86 \text{ eV}$ in a hydrogen plasma. The perturbed electron density moves from left to right. The speed of the wave is nearly equal to the ion acoustic speed.