Recovery of a weakly magnetized negative-ion plasma after photodetachment

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The experimental investigation of the negative-ion recovery after photodetachment was effected using the two-laser-beam technique in the neighborhood of the extraction opening of a negative-ion source, a weakly magnetized plasma region limited by a positively biased plasma electrode. It was found that the application of a positive bias to the plasma electrode reduces the recovery time. This quicker recovery was attributed to the presence in the plasma of a directed negative-ion flow, crossing the laser channel, whose velocity increases as the positive bias of the plasma electrode is increased. The choice of a self-similar variable allows the negative-ion flow velocity to be determined from the shift of the experimental recovery curves, and the negative-ion temperature from the initial phase of the recovery. As expected, increasing the plasma electrode positive bias does not change the negative-ion temperature. [S1063-651X(97)06501-X]

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I. INTRODUCTION

The negative-ion current extracted from a plasma is, obviously, related to the negative-ion density in this plasma. Some authors assumed that the extracted negative-ion current is determined by the thermal flow of negative ions through the extraction opening [1,2], while others believed that the negative ions flow out of the plasma with the ion acoustic velocity. In relation to this problem, and also in order to evaluate the negative-ion beam emittance, a considerable effort has been dedicated to the measurement of the negative-ion temperature in the plasma of the negative-ion source using the two-laser-beam photodetachment technique [3,4]. The results were extremely encouraging, since it was shown that the negative-ion temperature is low, in the range 0.2–0.7 eV.

Recently we have applied the two-laser-beam photodetachment technique to the region next to the extraction opening. It was observed that the application of a positive bias to the plasma electrode considerably reduces the negative-ion recovery time after photodetachment. It is the purpose of this work to present these experiments and the theory, which is a new interpretation of the experimental results.

The observed accelerated recovery is attributed to the presence in the plasma of a negative-ion flow, directed toward the plasma electrode, perpendicular to the laser channel. Its velocity increases as positive bias of the plasma electrode is increased. The theoretical analysis and the choice of a self-similar variable allows the negative-ion flow velocity to be determined from the shift of the experimental recovery curves, corresponding to different values of the plasma electrode bias. The negative-ion temperature can be determined from the initial phase of the recovery. As expected, the increase of the plasma electrode positive bias does not change the negative-ion temperature.

These experiments and their theoretical interpretation indicate that the negative-ion extracted current is governed by the velocity of the directed negative-ion flow to the positively biased plasma electrode. In this experiment this velocity was determined to be $1.4C_s$ (C_s is the ion acoustic velocity) for a bias of the plasma electrode of 2 V. The directed negative-ion flow is the physical reason for the enhancement of the negative-ion fraction in the extracted beam when the plasma electrode is biased positive, observed by the experimentalists in this field [5].

The laser photodetachment diagnostic for measuring the density and temperature of negative ions, proposed and developed in Refs. [3,4,6,7], is of current interest, since it allows that the plasma may be investigated with little interference on the system as a whole.

This method implies measurements using a Langmuir probe of the plasma perturbation following the photodetachment of electrons from negative ions. The level of this perturbation is directly related to the negative-ion density in the system, and the recovery of the negative-ion density in the channel illuminated by the laser is related to its temperature. The present work is dedicated, in part, to the development of a theory that allows this relationship to be analyzed under the conditions relevant to the region near the extraction opening.

In the case of a small fraction of negative ions, one can consider that the plasma perturbation following photodetachment is small and the movement of the negative ions in the laser channel is a ballistic one. This allowed Stern *et al.* [3] to obtain an evaluation of the negative-ion temperature in the ballistic approximation. Further, Friedland *et al.* [9] used the method of Laplace-Fourier transforms, with the same assumption of small negative-ion fraction, to investigate the influence of electric fields on the dynamics of positive ions. They described in the first approximation the experimentally observed minimum in the electron density time evolution after photodetachment, designated as ''overshoot.''

Ivanov *et al.* [10] studied the dynamics of negative-ion plasma, when the movement of all plasma components occurred in a self-consistent electric field. In this work the assumption of small negative-ion fraction was not used. In the present work we apply the approach of Ref. [10] to the case where the negative ions have a directed velocity, and compare the time-dependent negative-ion distributions calculated

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with the model for various directed velocities to the time-dependent negative-ion distributions measured at different plasma electrode biases.

In Sec. II we describe the volume negative-ion source in which the experiments have been performed, and the two-laser-beam photodetachment diagnostic technique, used for determining the negative-ion temperature. In Sec. III we present the experimental results on negative-ion recovery after photodetachment, obtained near the extraction opening. In Sec. IV we briefly describe the theoretical model, the self-similar method used for solving this problem, and the theoretical results on the relaxation of plasma with high negative-ion fraction in the laser illuminated channel. Here we discuss also the effect of the directed negative-ion movement due to the positive bias to the plasma electrode.

II. EXPERIMENTAL SETUP

A. The negative-ion source

The investigation has been performed in the hybrid multicusp plasma generator (Camembert III), which has been described in detail elsewhere [11]. For completeness, a brief description of the source will be given. The cylindrical stainless-steel chamber is 44.0 cm in diameter and 45.0 cm high. Its side wall has twelve openings for windows, probe holders, and a small turbo-molecular pump. Sixteen columns of samarium-cobalt magnets (with a surface magnetic field of 3500 G) are installed with the north and the south poles alternatively facing the plasma. These magnets are contained in water-cooled stainless-steel tubes (2.6 cm diam) welded to the internal surface of the source to allow steady-state high power discharge operation. The plasma diameter is therefore 38.8 cm.

The end plates are not magnetized. One end of the chamber is bounded, in part, by the stainless-steel plasma electrode of the extractor (10 cm in diameter), which contains an extraction hole of 0.8 cm in diameter, and in part by a water-cooled annular copper plate. This plate is connected to the plasma chamber side wall, which is grounded. The extractor has been described in detail elsewhere [12]. The neighboring plasma is magnetized, and due to this and to a small positive bias of the plasma electrode, large densities of volume-produced negative ions concentrate in this region [12,13].

The top of the source is bounded by a stainless-steel plate supporting the filaments. The centers of 16 hairpin-shaped filaments are arranged on a circle (33 cm in diameter); each filament is located in a radial plane, median between two neighboring magnet columns. The filaments are situated in the multicusp magnetic field. The electrons emitted by the hot tungsten filaments are accelerated to eV_d in the sheath surrounding the filaments (V_d is the discharge voltage applied between the filaments and the chamber wall). The primary electrons are thus confined in the multicusp magnetic field. This nonuniform magnetic field provides to the primary electrons a drift in a direction parallel to the magnets.

The hybrid source contains three distinct regions: (i) a driver region, located near the walls, containing the filaments; (ii) an extraction region, which extends over all the central, field-free region; (iii) a weakly magnetized region with high N_i^-/N_e, bounded by the plasma electrode, which contains the extraction opening (N_i^- and N_e are the negative

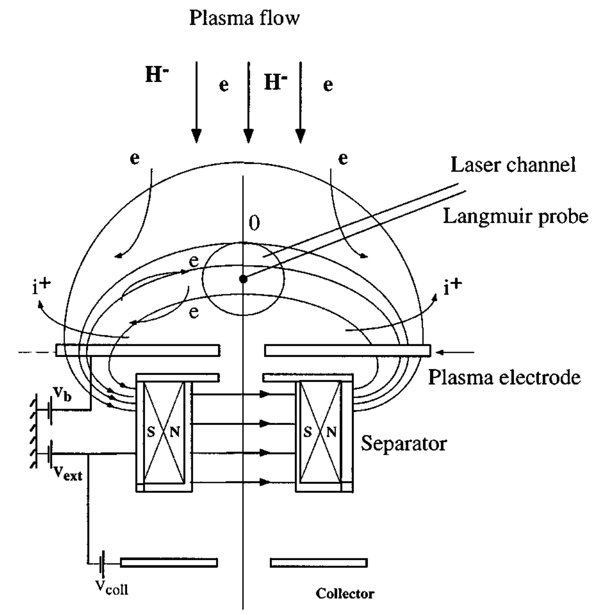

FIG. 1. Schematic presentation of the plasma region near the plasma electrode. The laser beam is also shown.

ion and electron densities, respectively). Figure 1 shows schematically the arrangement of this third region. Here the joint action of the positive bias on the plasma electrode and of the weak magnetic field (20 G at most) results in the redistribution of the plasma components [12,13]. The photodetachment measurements effected at a distance from the plasma electrode of up to 2 cm show a dramatic increase of the negative-ion to electron density ratio, N_i^-/N_e, from 0.5 to 10 (i.e., by a factor of 20) when the plasma electrode bias V_b is enhanced from 0 to 2.5 V. In this case, N_i^- increases approximately by a factor of 2, while N_e drops by a factor of 10 (see Figs. 8 and 9 in Ref. [13]). Note that the ratio N_i^-/N_e does not exceed 0.1 in the center of the extraction region [11].

The magnetic field in the neighborhood of the plasma electrode is approximately parallel to this electrode; the electrons are magnetized on a distance of a few centimeters from it. A large fraction of the current into the extraction hole is transported by negative ions. The electrons, as lighter particles, flow to the periphery of the plasma electrode or to the periphery of the plasma chamber along the magnetic field lines.

B. Two laser beam photodetachment diagnostics

The H^- density N_i^- was measured by the photodetachment technique, described in detail in Refs. [6–8] and [13]. In this technique electrons are detached from the H^- ions by means of a pulsed laser beam and detected by the cylindrical tungsten probe placed along the axis of the laser beam. The probe is biased positively relative to the plasma and therefore attracts the detached electrons. This results in a probe current pulse whose height is proportional to the H^- density. The laser beam is provided by a Nd:YAG laser (photon energy 1.2 eV).

The H^- negative-ion thermal energy was measured using the two-laser-pulse photodetachment technique [3,4]. This nonresonant optical tagging technique combines two succes-

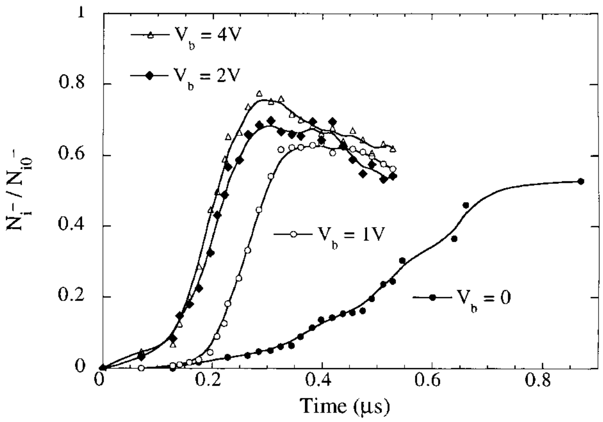

FIG. 2. Effect of plasma electrode bias on the negative-ion density recovery for V_b=0, 1, 2, and 4 V. 3 m Torr, 50 V, 30 A discharge, probe bias +50 V, R_L=0.4 cm.

sive laser pulses with simultaneous Langmuir probe measurements. The first laser pulse destroys all the negative ions in its path by photodetachment. A second laser pulse fired shortly after the first along the same path destroys the negative ions which have originated from outside the laser path. The time evolution of $N_i^-(t)$ is established by making repeated measurements while varying the time delay between the two laser shots. The negative-ion temperature T^- is determined from the negative-ion density recovery curve after the negative ions have been destroyed by photodetachment in a small cylindrical region.

The data obtained on the axis of the source at 15 cm of the plasma electrode, which corresponds to the center of the source extraction region, have been reported in Ref. [11]. It was shown there that the signal-to-noise ratio is approximately 40 at 2 m Torr and goes up when the pressure is enhanced.

III. NEGATIVE-ION DENSITY RECOVERY AFTER PHOTODETACHMENT IN THE REGION NEAR THE PLASMA ELECTRODE

Figure 2 presents a typical example of the negative-ion recovery observed using the two-laser beam technique. The measurements were effected on the axis of the source, in the neighborhood of the plasma electrode. The four curves shown in Fig. 2 correspond to four values of the plasma electrode bias, V_b (0, 1, 2, and 4 V) with respect to the grounded walls. A small change of V_b leads to a sharp increase of the slope on the time dependence of the negative-ion density. The average velocity can be calculated from the relation R_L/t_x, where R_L is the radius of the laser beam (0.4 cm in this case) and t_x is the time required for the increase of the normalized negative-ion density to a chosen value N_i^-/N_{i0}^- in the center of the laser channel. For example, for N_i^-/N_{i0}^-=0.5 the average velocity changes from $v \approx 5\times10^5$ cm/s at V_b=0 to $v \approx 1.33\times10^6$ cm/s at V_b=1 V, and up to $v \approx 2\times10^6$ cm/s at V_b=4 V. It is important to note that this velocity increases by approximately a factor of 4 for any N_i^-/N_{i0}^- from 0.1 to 0.5. If, as usual, this velocity is considered to be the thermal velocity of the negative ions, this would correspond to a nonrealistic increase of the temperature by a factor of 16. This leads us to assume that there is a flow of negative ions across the laser channel which dominates the negative-ion recovery. The velocity of this flow depends on V_b. This assumption will be verified in the course of this work.

IV. MATHEMATICAL MODEL OF PLASMA DYNAMICS IN THE LASER CHANNEL AND THEORETICAL RESULTS

Since the voltage applied to electrodes placed at the plasma borders brings about the plasma flow existing in the field-free region (excluding the regions close to electrodes), we assume that the negative-ion distribution function before the laser pulse is a shifted Maxwellian, with unknown drift velocity and temperature.

The negative-ion flow crosses a channel of radius R_L containing negative-ion free plasma created for a short time by photodetachment. When the negative-ion flow velocity exceeds the negative-ion thermal velocity, the recovery of the channel plasma is due to the directed flow, rather than to the thermal velocity, so the problem under consideration can be treated in planar geometry and the one-dimensional approximation. The x axis should be directed along the direction of flow. To simplify we consider that the flow velocity is perpendicular to the laser channel. The point x=0 separates the laser channel from the unperturbed plasma. Thus the statement of the problem is similar to that of Ref. [10], except two points.

First, at the initial moment after the laser pulse the distribution function of the negative ions is supposed to be the well-known shifted Maxwellian distribution:

$$P_i^- = (N_{i0}^-/\pi^{1/2}V_i^-)\exp[-(V-V_0)/(V_i^-)^2] \tag{1}$$

outside the laser channel, at $x<0$, and $P_i^-=0$ inside the laser channel, at $x>0$. Here N_{i0}^- and V_i^- are the density and thermal velocity of the negative ions and V_0 is the velocity of the negative-ion flow in the unperturbed plasma near the laser channel. Note that the Maxwellian distribution is used as an example and does not decrease the generality of the solution. The influence of the second boundary, at $x=2R_L$, can be neglected because the flow velocity is large enough.

From the very beginning the negative-ion behavior is governed by the one-dimensional kinetic equation. When the laser radius is less than the ion gyroradius, i.e., for our case $B<250$ G, the ion movement inside the laser channel is not affected by the magnetic field.

Second, it is necessary to discuss the influence of the magnetic field on the validity of the Boltzmann equation. Since the Larmor radius of electrons is of the order of 0.1 cm, the electrons are magnetized in the vicinity of the plasma electrode. Thus the electrons can move freely along the magnetic lines and the Boltzmann distribution will be valid along these lines only:

$$N_e(\Phi) = N_0 \exp(e[\Phi(x,y) - \Psi(x)]/T_e), \tag{2}$$

where the x axis is directed across the magnetic field and the y axis is directed along the magnetic field. N_0 and Ψ are the electron density and the potential in the unperturbed plasma for $y\to\infty$, respectively.

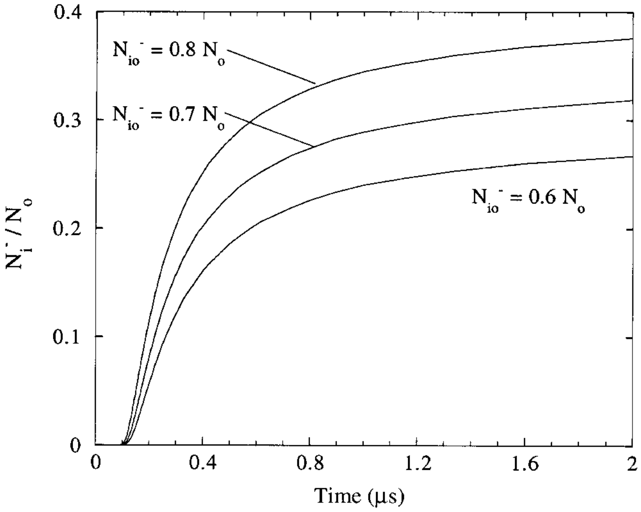

FIG. 3. Time dependence of the self-similar solution for N_i^-, without drift, with $x=R_L=2$ mm, $T_e=1$ eV, and $T_i^-/T_e=0.5$.

In the actual situation the magnetic lines cross the plasma electrode, which is an equipotential surface for the electrons. Its potential can be set equal to zero. Therefore we can use the Boltzmann relation across the magnetic field.

When these conditions are satisfied, the problem will have the self-similar solution so one could make use of dimensionless variables $\xi'=\xi-(V_0/C_s)$ $v'=(V-V_0)/C_s$, where $\xi=x/tC_s$ is the self-similar variable. As a result we have to solve the kinetic equation in the form of a nonlinear integro-differential equation [10]:

$$(v'-\xi')\,\frac{\partial f_i^-}{\partial \xi'}+\frac{\partial \varphi}{\partial \xi'}\,\ln\left(1-\int_{-\infty}^{\infty} f_i^-\,dv\right)\frac{\partial f_i^-}{\partial v'}=0. \quad (3)$$

This equation was solved in Ref. [10] and we will use the solution found there, taking into account the change in argument. We remind the reader that the typical shape of the resulting negative-ion distribution function, which was shown in Fig. 3 of Ref. [10], demonstrates that during the recovery process both acceleration and anisotropic cooling of negative ions occurs.

We will now discuss the self-similar solution of the problem at sufficiently high negative-ion fraction in the system. At $\xi\to-\infty$, i.e., far away from the laser channel region $x\to-\infty$, one can consider the plasma as unperturbed, and the distribution function of the negative ions is described by Eq. (1). The initial value of ξ was $\xi_{\min}=-3$. It can be shown that a lower value does not change the results.

Let us consider first the recovery process without drift ($V_0=0$). Figure 3 presents the results of a typical calculation, for $V_0=0$, of the self-similar widening of the border between two plasma regions for $T_i^-=0.5T_e$ and for several values of the density N_{i0}^{-1} as function of time $t=R_L/(\xi C_s-V_0)$. Figure 3 shows the time dependences of N_i^-/N_0 for which the following initial conditions have been chosen: $R_L=2$ mm, $T_e=1$ eV. Note a steeper increase of the ratio N_i^-/N_0 for higher N_{i0}^-, in agreement with the experimental data (Fig. 2). We also note in Fig. 3 that the characteristic appearance time of the negative ions in the probe collection region for a laser channel radius $R_L=2$ mm is practically invariant. However, one can note from the experimental curves (see Fig. 2) that the negative ions appear earlier as the plasma electrode bias V_b is increased.

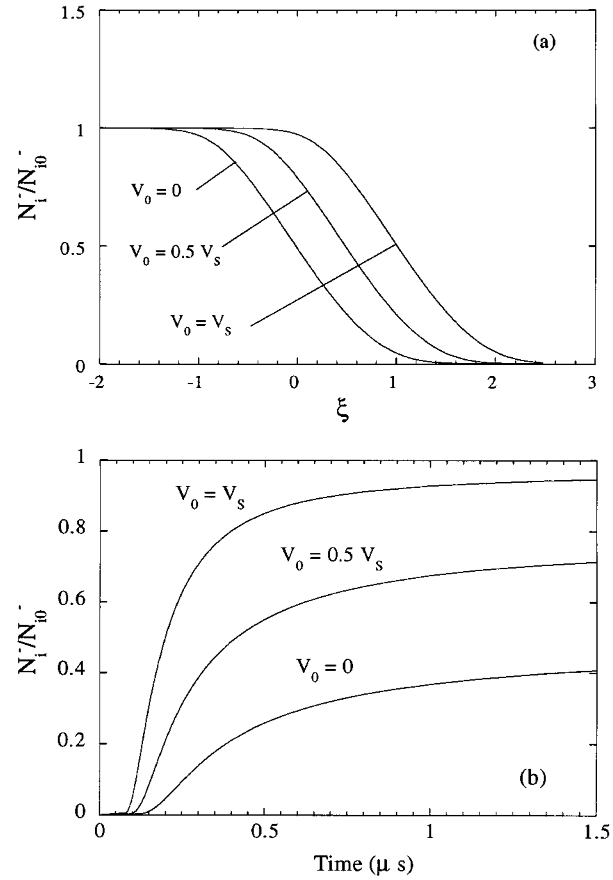

FIG. 4. Dependence of the negative-ion density on (a) the self-similar variable $\xi=R_L/(tC_s)$ and (b) on time, at $T_i^-/T_e=0.5$ and $N_{i0}^-/N_0=0.275$. In (b) the following parameters were chosen: $T_e=1$ eV, $x=R_L=2$ mm.

In order to explain this effect, let us examine the role of the directed negative-ion velocity in the process of recovery. Let us assume a negative-ion flow across the laser channel with $V_0\neq0$.

Figure 4(a) shows the negative-ion densities obtained for various values of the flow velocity. This result becomes clearer when we return in Fig. 4(b) to the time dependence for several typical values of the electron temperature T_e and for several ion flow velocities. The faster return of the negative ions to the probe and the steeper increase of N_i^- in time can be noted in Fig. 4(b). Note that in Fig. 4(b), N_i^- does not tend asymptotically at large t to the initial negative-ion density N_{i0}^-. This is related with the use of the planar geometry, when at the initial moment the negative ions fill the half-space $x<0$. However, the initial stage of the plasma recovery in the laser channel does not depend on the geometry of the problem, and consequently we can apply the proposed model at this stage.

V. DETERMINATION OF THE NEGATIVE-ION TEMPERATURE AND FLOW VELOCITY

It can be noted that the obtained solutions depend on three parameters N_{i0}^-/N_0, V_0/C_s, and T_i^-/T_e. The first parameter

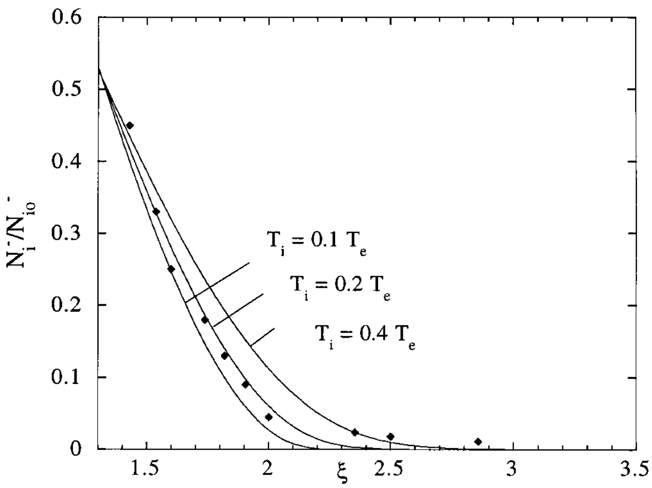

FIG. 5. Theoretical dependence of the negative-ion density on the self-similar variable ξ for $T_i^-/T_e=0.1$, 0.2, and 0.4. The experimental points are for 50 V, 30 A, 3 m Torr discharge with $V_b=1$ V. $R_L=0.4$ cm.

is determined by laser photodetachment rather precisely [13]. The two other parameters can be found from measurements of the negative-ion density recovery at different V_b values.

We noticed the increase of the negative-ion flow velocity when discussing the data shown in Fig. 2 (Sec. III). This velocity can be determined more precisely by using the self-similar variable $\xi=R_L/(tC_s)$. Note that from the symmetry of the one-dimensional problem N_i^-/N_{i0}^- is equal to 0.5 at the point $\xi=0$ without flow for any density and temperature. In the case when the flow is present, this point moves exactly with the flow velocity V_0. Actually the negative ions can reach the probe, placed in the center of the laser channel, from all directions and we should have used the cylindrical geometry. However, in the case when the flow velocity exceeds the thermal velocity, the growth of the negative-ion current to the probe is determined mainly by the ions arriving from the flow direction. Therefore we can use our planar model when $V_0>V_i^-$. This is usually the case. In the example shown in Fig. 2 this velocity is 1.33×10^6 cm/s for $V_b=1$ V, while V_i^- is usually lower than this value [4]. It was shown in Sec. IV that the presence of the flow velocity results only in the parallel translation along the axis ξ.

Now the thermal energy of the negative ions can be found by comparing the experimental curves with the theoretical ones using the method illustrated in Fig. 5. The experimental data are those plotted in Fig. 2 for $V_b=1$ V. The theoretical curves are calculated for various T_i^- and with $V_0=1.33C_s$. Using the method of least squares we found the negative-ion temperature $T_i^-=0.2T_e$. A close value for the ratio T_i^-/T_e was reported in Ref. [11] for the central region of the source Camembert III under similar discharge conditions. The variation of the plasma electrode positive bias does not change the negative-ion temperature.

Note that apparently the increase of T_i^- or of V_0 gives a similar result: the acceleration of the negative-ion recovery. However, one can see that the increase of V_0 results in a parallel shift of the density recovery curves [Fig. 4(a)], while the increase of T_i^- results in the change in slope of the

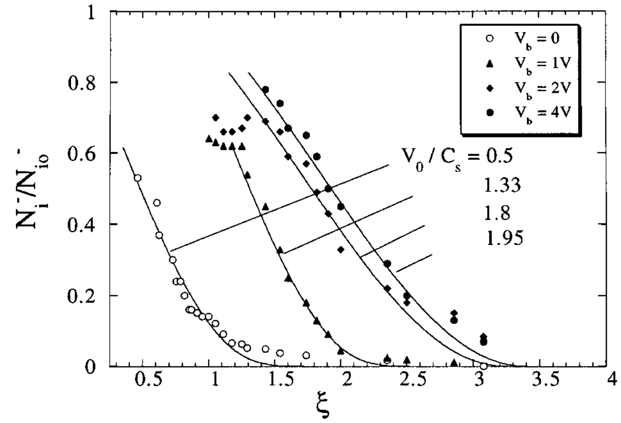

FIG. 6. Same as Fig. 2, with the variable $\xi=R_L/(tC_s)$. All theoretical curves found by the least-square approximation have $T_i^-/T_e\sim0.2$.

density curves (Fig. 5). Thus one can distinguish these parameters in the fit.

Finally we plotted all the data of Fig. 2 in Fig. 6, where N_i^-/N_{i0}^- is represented as a function of the self-similar variable ξ. Note that the curves are similar, i.e., can be superposed by a translation along the axis ξ. The flow velocity V_0 and the thermal velocity V_i^- were found for the theoretical curves by the method of least squares. Thus we determine the flow velocity V_0 corresponding to each case, as indicated in Fig. 6. V_0 varies from $0.5C_s$ at $V_b=0$ to $1.95C_s$ for $V_b=4$ V. There is good agreement for $\xi\approx V_0/C_s$.

Note that the small discrepancy of the experimental data and the theoretical curves occurs for large values of $\xi\gg V_0/C_s$, i.e., for very short time $t=R_L/\xi C_s\ll R_L/V_0$. This discrepancy is related to the low negative-ion density in the laser channel immediately after the laser pulse and is not understood yet.

VI. CONCLUSION

The experimental investigation of the negative-ion recovery after photodetachment was effected using the two-laser beam technique in the neighborhood of the extraction opening of a negative-ion source, a region weakly magnetized and limited by a positively biased plasma electrode. It was found that the application of a positive bias to the plasma electrode reduces the recovery time. This accelerated recovery was attributed to the presence in the plasma of a directed negative-ion flow, crossing the laser channel, the velocity of which is going up when the positive bias of the plasma electrode is increased. The choice of a self-similar variable allows us to determine the negative-ion flow velocity from the shift of the experimental recovery curves, and to determine the negative-ion temperature from the initial phase of the recovery. As expected, the increase of the plasma electrode positive bias does not change the negative-ion temperature.

These experiments and their theoretical interpretation indicate that the negative-ion extracted current is governed by the velocity of the directed negative-ion flow to the positively biased plasma electrode. In this experiment we found a value as high as $1.95C_s$ for a bias of the plasma electrode of 4 V. This explains the physical reason for enhancing the negative-ion fraction in the extracted beam when the plasma electrode is biased positive, which was observed by the experimentalists in this field.

Note that the negative-ion dynamics is governed by the one-dimensional collisionless Vlasov equation. Thus the initial distribution function chosen in the form of a shifted Maxwellian can change during the recovery process and one can see both the acceleration and the anisotropic cooling of the negative ions in the self-consistent electrical field as a function of the initial parameters (initial negative-ion drift velocity and temperature) which can be determined by fitting.

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