Measurements of Beam Relaxation Length in an Electron Beam Plasma Experiment

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A double plasma device with multipole surface magnetic confinement is used to investigate the beam relaxation length of beam plasma interaction as a function of the beam plasma density ratio, $10^{-4} \leq n_b/n_0 \leq 2 \times 10^{-2}$, and beam energy $W_b \leq 200$ eV in an unmagnetized plasma, using argon and helium gases. The measured relaxation lengths show a transition from quasi-linear to nonlinear regime, as predicted by Galeev et al., 1977. There is evidence that for some range of the beam plasma parameters the threshold for modulational instability is reached. In that case it is possible to observe that the beam propagates relatively unperturbed for larger distances than the ones predicted by quasi-linear theory.

I. Introduction

An electron beam-plasma system constitutes one of the most interesting configuration to study plasma wave-particle interactions. The electron beam provides a free energy source for a rich variety of nonlinear processes. The interaction of an electron beam, with velocity v_b and density n_b, with a higher density ambient plasma, n_0, produces unstable electrostatic waves with frequency near the plasma frequency, ω_{pe}, and wave number given by $k_0 \approx \omega_{pe}/v_b$. For a cold beam, in the limit $n_b/n_0 << 1$, the instability is due to a feedback mechanism involving bunching of electrons leading to a growth in the space charge density (hydrodynamic regime). A thermal spread in the velocities of the beam particles (kinetic regime) tends to suppress the hydrodynamic instability. This has an important implication even when the velocity spread is initially small because the development of the instability itself causes the velocity spread to increase. The condition for neglecting the beam thermal spread (Δv) is $(n_b/n_0)^{1/3} \geq \Delta v/v_b$ [1, 2].

The collective relaxation of the electron beam depends on the resonant interaction between the beam and the wave that it has excited. For small wave amplitude, $W_0 << (k_0\lambda_D)^2$, λ_D is the Debye length, and warm beam case, quasi-linear theory predictes that the beam relaxation occurs through "plateau" formation by flattening the beam distribution function ($f_b(v)$) within a characteristic propagation distance, relaxation length (l), that depends on $(n_b/n_0)^{-1}$; $W_0 = E_0^2/(16\pi n_0 T_e)$ and $E_0^2/(16\pi)$ is the wave energy.

However, if the wave intensity is strong enough to reach the nonlinear threshold, $W_0 \simeq (k_0\lambda_D)^2$, the beam relaxation process is completely changed [3]. As a result, the electron beam can propagate through the plasma relatively unperturbed while retaining most of its energy. This effect has been observed in space and laboratory plasmas [4, 5, 6, 7], indicating that a nonlinear mechanism cuts off the plateau formation at an early stage of the beam relaxation process.

Twenty years ago, a detailed experimental test of quasi-linear theory was performed by Roberson and Gentle [8]. They measured the final state of the beam-plasma instability, and found good agreement with quasi-linear theory for the final spectrum and velocity distribution. However, they were unable to directly check for the presence of mode coupling. Whelan and Stenzel presented a series of papers treating a beam-

plasma system [9, 10, 11]. They clearly show mode coupling effects.

More recently, some experiments on weak warm beam instability have been done in a different way [12, 13]. They explore the fact that the essential physics of the interaction between a weak warm beam and the waves in a plasma is the same as that of the interaction between a weak warm beam and the waves on a slow wave structure. The results are in agreement with the assertion that quasi-linear theory is not complete since mode coupling effects are clearly observed and they are neglected in the quasi-linear approximation.

In this paper we present systematic measurements of beam relaxation length on a beam-plasma system in a wide range of n_b/n_0, for different beam energies, $W_b = (1/2)mv_b^2$, using Ar and He plasmas. As far as we know, although there is a lot of reported beam-plasma experiment results, nobody seems to have registered beam relaxation lengths as a function of n_b/n_0 in the three regimes predicted by Gallev et al. [3]. Our results show a transition from quasi-linear to non-linear regime, as predicted by them. We also find evidences that for some range of the beam plasma parameters the threshold for modulational instability is reached (a mode coupling effect).

This paper is organized as follows. In Sec. II, the experimental apparatus is described. The experimental results and discussion are given in Sec. III. Conclusions are summarized in Sec. IV.

II. Experimental apparatus

Experiments were carried out in a double plasma device with multipole surface magnetic confinement. Fig. 1 shows a schematic diagram of the experimental apparatus. A discharge plasma is created by accelerating primary electrons produced by tungsten, oxyde coated, hot cathode filaments in argon or helium gases. The inner diameter (plasma diameter) of the device is 0.60 m and its total length is 1.20 m. The chamber is divided into a source ($l_s = 0.30$ m) and a target chamber ($l_t = 0.90$ m) by two grids. The first one is connected to the multipole magnetic structure inside the source chamber and the other is connected to the structure of the target chamber. The beam is generated biasing the source grid negatively with respect to the grounded target grid. This electron beam propagates into the target chamber and ionizes the gas, thus creating a plasma in that chamber.

Electron plasma density and temperature measurements were performed using cylindrical Langmuir probes, calibrated for the density measurements by detecting the cut-off frequency of a low amplitude electromagnetic wave (EMW), launched into the plasma. Plasma electric field oscillation measurements were performed with movable cylindrical probes at the floating potential connected to a spectrum analyzer or to an oscilloscope. We measure the position where the wave amplitude at ω_{pe} presents its maximum value, which in the quasi-linear regime coincides with the beam relaxation length ($\Delta v/v_b \simeq 1$) [11]. The beam electron energy distribution functions were investigated with an electrostatic multigrid energy analyzer using the method of retarding potential. The experimental devices and diagnostics have been described in details elsewhere [14].

Table 1 - Experimental parameters

Plasma density (m^{-3})	$n_0 \simeq 10^{14} - 10^{15}$
Plasma electron temperature	$T_e \simeq 2$ eV
Plasma density fluctuations	$(\delta n_0)/n_0 \leq 10^{-2}$
Beam energy	$W_b \leq 250$ eV
Beam plasma density ratio n_b/n_0	$10^{-4} - 2 \times 10^{-2}$
Electron-neutral collision rate	$\nu_{en} \simeq 5 \times 10^5$/ s
Electron ion temperature ratio	$T_e/T_i \simeq 10$
Beam thermal spread	$(\Delta v)/v_b \simeq 0.2$
Beam radius	$r_b \simeq 0.30$ m

Experiments were carried out in argon and helium gases at filling pressure range of $5\times10^{-5} < p < 5\times10^{-4}$ mbar. At this range of pressure the collisional damping rate due to electron-ion and electron-neutral collisions is smaller than the generation rate, the beam-plasma instability growth rate (γ_b). This leads to the conditions [15]

$$\pi\frac{n_b}{n_0}(\frac{v_b}{\Delta v})^2 > \frac{1}{n_0\lambda_D^3}$$

$$\pi\frac{n_b}{n_0}(\frac{v_b}{\Delta v})^2 > \frac{\nu_{en}}{\omega_{pe}} \quad (1)$$

where ν_{en} is the electron neutral collision rate. Once those conditions are satisfied, the excitation of Langmuir wave by the beam plasma instability is allowed. Using the typical beam plasma parameters obtained in our experiment, given in Table I, it is possible to verify that conditions given by Eq.1 are satisfied.

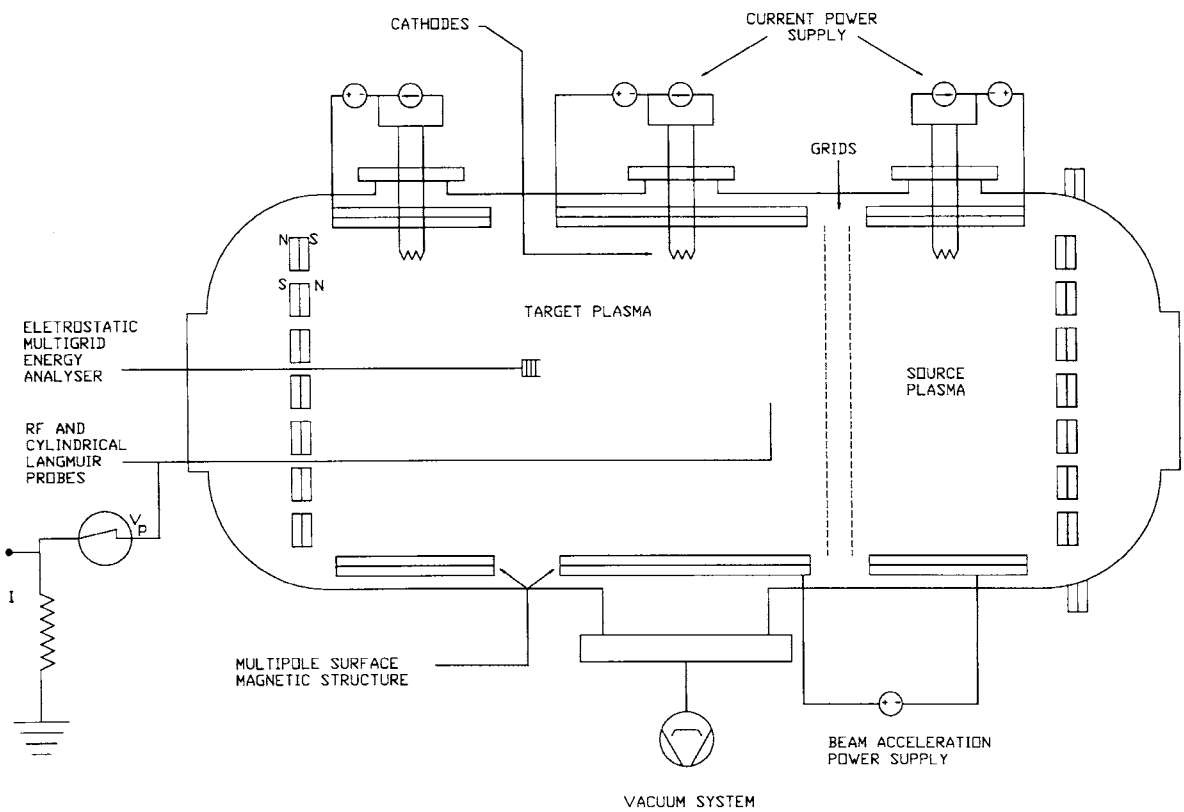

Figure 1. Schematic view of the PQUI device.

III. Experimental results and discussion

We systematically measure the relaxation length in a beam plasma system characterized by the parameters given in Table I. For those parameters the wave energy growth is governed by kinetic effects. We use Ar and He unmagnetized plasma. Differently from previous mentioned experiments, the beam and the plasma have the same radius.

The results of the beam relaxation length measurements for argon are shown in Fig. 2. One can see from this figure that the relaxation length dependence on the beam to plasma density ratio presents three regions, as predict by Galeev et al. [3].

The first region presents a dependence of the relaxation length, normalized to ω_{pe}/v_b, on $(n_b/n_0)^{-1}$. This dependence is predicted by quasi-linear theory where the unstable Langmuir waves are permitted to react back on the beam to a limited extent and remove its free energy. The beam generates waves whose phase velocities lie in the positive slope region of the distri-

bution function. The resonant interaction between the beam and the waves leads to velocity-space diffusion that removes or flattens the positive gradient in $f_b(v)$. This is called "plateau" formation and occurs at a characteristic distance:

$$l_{QL} \simeq 5\frac{v_b}{\omega_{pe}}\frac{T_e}{W_b}\frac{\Delta v}{v_b}(\frac{n_b}{n_0})^{-1} \quad (2)$$

The limit of applicability of the quasi-linear theory is given by:

$$\frac{n_b}{n_0} = \frac{10}{8}(\frac{T_e}{W_b})^3 \quad (3)$$

which gives, with $T_e = 2$ eV, $n_b/n_0 \leq 8.0 \times 10^{-5}$ for $W_b = 50$ eV, $n_b/n_0 \leq 10^{-5}$ for $W_b = 100$ eV, and $n_b/n_0 \leq 1.25 \times 10^{-6}$ for $W_b = 200$ eV. From the experimental results we have $n_b/n_0 \leq 2.0 \times 10^{-3}$ for $W_b = 50$ eV, $n_b/n_0 \leq 7.0 \times 10^{-4}$ for $W_b = 100$ eV. For $W_b = 200$ eV this limit is not observed due to operational conditions. These results are obtained by fitting the experimental points presented in Fig. 2 to a curve $\propto (n_b/n_0)^\beta$, which gives $\beta \simeq -0.78 \pm 0.31$ for $W_b = 50$ eV and $\beta \simeq -0.99 \pm 0.08$ for $W_b = 100$ eV. Observe that the value of β is close to -1 as in Eq. 2. In this region the time for the wave amplitude saturation is determined by the beam plasma instability growth rate (γ_b).

It is important to notice that beam plasma instability does not need to saturate by quasi-linear velocity-space "plateau" formation. Saturation of this instability can also occurs via non-linear effects such as wave-wave interactions (e.g. [2], [16]). When the energy of the waves in resonance with the beam, W_r, becomes greater than $(k_0\lambda_D)^2$, these waves become unstable to nonlinear instability. These instabilities act to transfer the field energy from wavelengths resonant with the beam to shorter wavelengths which are not resonants. When the energy transfer from W_r exceeds the rate at which field energy is generated by the beam, the beam instability will be stabilized.

The occurrence of a nonlinear process can be observed in the second region in Fig. 2. In this region it is assumed that modulational instability (MI) is the nonlinear effect to be considered. The development of the MI creates the mechanism for the dissipation of long wavelength Langmuir waves. The instability then "freezes" the energy of plasma oscillations at the threshold level and the relaxation length as a function of n_b/n_0 is given by

$$l_1^{NL} \simeq l_{QL} + \frac{2}{\pi}\frac{v_b}{\omega_{pe}}(\frac{W_b}{T_e})^2 \quad (4)$$

For our experimental conditions, the second term on the right hand side of Eq. 3 is two orders of magnitude larger than the first one and the relaxation length presents a very weak dependence on n_b/n_0. The upper limit for validity of Eq. 4 is determined by

$$\frac{n_b}{n_0} = \frac{M\alpha^4}{4m}(\frac{T_e}{W_b})^2 \quad (5)$$

which gives 3.6×10^{-1} for $W_b = 50$ eV, 9×10^{-2} for $W_b = 100$ eV and 2.3×10^{-2} for $W_b = 200$ eV, with $\alpha \simeq 1/3$, a numerical coefficient dependent on turbulence energy [17]. Experimental results give 7.0×10^{-3}, 3.5×10^{-3}, and 2.0×10^{-3} for $W_b = 50, 100$ and 200 eV, respectively. The best fit for the experimental points in the second region gives $\beta \simeq -0.28 \pm 0.03$ for $W_b = 50$ eV, $\beta \simeq -0.18\pm0.05$ for $W_b = 100$ eV and $\beta \simeq -0.20\pm0.03$ for $W_b = 200$ eV. In this region we can say that MI instability takes place when the growth rate of beam plasma instability is the same order or smaller than the MI growth rate ($\gamma_b \leq \gamma_{MI}$).

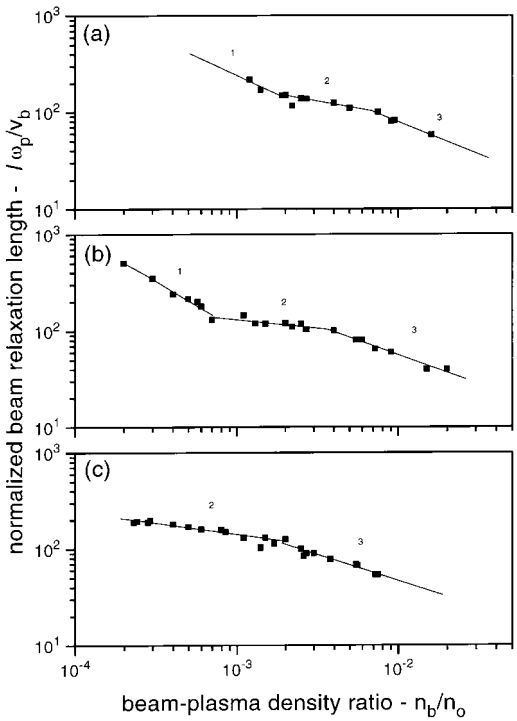

Figure 2. Normalized beam relaxation length as a function of beam to plasma density ratio for argon plasma with electron beam energy of (a) 50 eV, (b) 100 eV, and (c) 200 eV. Numbers 1,2 and 3 refer to first, second and third regions described in the text.

As the beam to plasma density ratio becomes larger, third region, the beam relaxation length presents a dependence on $(n_b/n_0)^{-1/2}$. This behavior can be explained when it is assumed that the free development of MI is possible ($\gamma_b \ll \gamma_{MI}$)[3, 17]. The level of the noise in resonance with the beam which performs the role of a constantly acting long-wavelength pump can be found from the condition that the energy transfer to the resonance compensates the dissipation in that region as a result of the MI. This condition leads to a relaxation length of the beam appreciably larger than those of quasi-linear regime and is given by:

$$l_2^{NL} \simeq \frac{1}{\pi}\frac{v_b}{\omega_{pe}}\frac{W_b}{T_e}(\alpha^3\frac{M}{m})^{1/2}(\frac{n_b}{n_0})^{-1/2} \qquad (6)$$

The best fit for the experimental points presented in Fig. 2 in the third region gives $\beta \simeq -0.68 \pm 0.09$ for $W_b = 50$ eV, $\beta \simeq -0.60 \pm 0.05$ for $W_b = 100$ eV and $\beta \simeq -0.54 \pm 0.05$ for $W_b = 200$ eV, in agreement with Eq. 6.

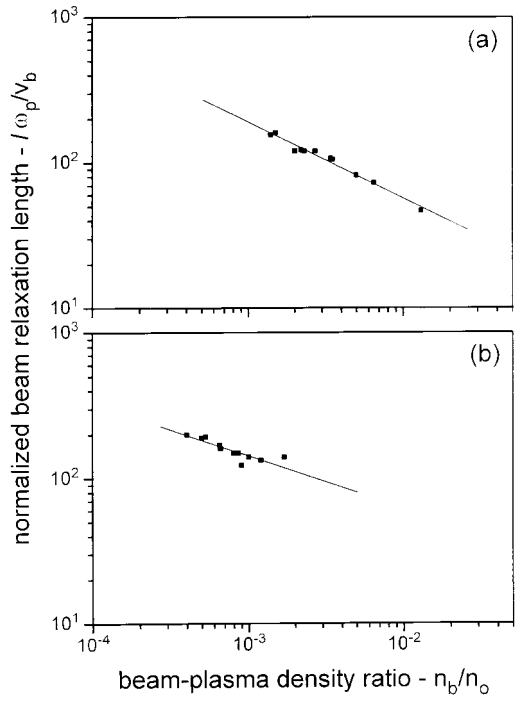

Figure 3. Normalized beam relaxation length as a function of beam plasma density ratio for helium plasma with electron beam energy of (a) 100 eV, and (b) 200 eV.

Fig. 3 shows the results obtained using helium gas. In this case, experimental limitations impedded us to cover the entire range of density ratio of the three regions. The best fit for the experimental points presented in Fig. 3 gives $\beta \simeq -0.52 \pm 0.03$ for $W_b = 100$ eV and $\beta \simeq -0.45 \pm 0.06$ for $W_b = 200$ eV. The range of experimental results exceeds the limit given by Eq. 5 which together with the values of β indicate that the relaxation length should be given by Eq. 6 (third region).

It is important to emphasize that Gallev et al. model is a phenomelogical approach to the problem, so we can not expect a very good quantitative agreement. In Fig. 4 we present the experimental and theoretical relaxation lengths for a beam with $W_b = 100$ eV in an argon plasma. To obtain the theoretical values we have used Eq. 2 for quasi-linear theory (ql), Eq. 4 for the first region of non-linear theory (nl1), and Eq. 6 for the second region of nonlinear theory (nl2). Observe that for $n_b/n_0 < 10^{-3}$, the experimental results (exp) agree very well with the ql ones. For $10^{-3} < n_b/n_0 < 3 \times 10^{-3}$, there is no variation of the relaxation length against n_b/n_0, in agreement with the first region of the non-linear theory (nl1), but quantitatively there is no agreement. One possible explanation for these results is that we are not really measuring the relaxation length once we enter to the non-linear regime. In fact, the total relaxation of the beam would occur out of the chamber. We will show examples of the evolution of the distribution function of the beam accross the system for two particular cases.

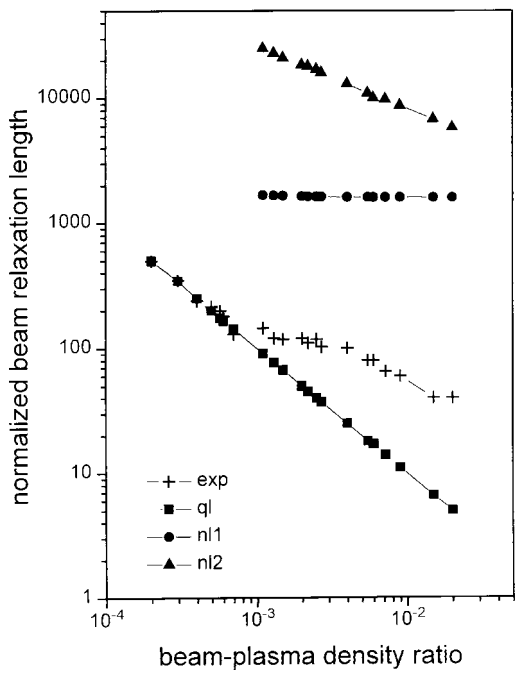

Figure 4. Comparison between experimental and theoretical relaxation lengths for a beam with $W_b = 100$ eV in an argon plasma.

At quasi-linear theory the energy transferred to the plasma waves by the beam during the relaxation process is given by the expression:

$$W_s = \frac{1}{15}\frac{n_b}{n_0}(\frac{v_b}{v_{te}})^4 \qquad (7)$$

where W_s is the saturation energy of the wave normalized to $n_0 T_e$ and v_{te} is the electron thermal velocity [18]. The threshold value of modulational instability is $W_0 \geq (k_0\lambda_D)^2$. We can say that when the MI growth rate, $\gamma_{MI} = \omega_{pe}((m_e W_0)/m_i)^{1/2}$, is larger then the growth rate of beam plasma instability, $\gamma_b = \omega_{pe}(n_b/n_0)(v_b/\Delta v)^2$, and $W_0 \geq (k_0\lambda_D)^2$, the modulational instability takes place. Assuming $W_0 = W_s$, $\gamma_{MI} > \gamma_b$ gives $\Delta v/v_b \geq 0.6$ for argon and $\Delta v/v_b \geq 0.3$ for helium.

Let us consider a particular case for argon plasma, with $n_b/n_0 \simeq 10^{-3}, n_0 = 2 \times 10^{14}$ m^{-3} and $W_b = 100$ eV (region2, $\gamma_{MI} \simeq \gamma_b$, Fig. 2 (b)). Using these experimental values with $\Delta v/v_b \simeq 0.6$ in Eq. 2 we obtain $l_{QL} = 0.4$ m. Fig. 5 (a) shows the measured space profile for the plasma wave amplitude. Observe that the maximum occurs at $x = 0.4$ m, as predicted. At the same position, there is the appearence of the radiation at second harmonic. Fig. 5 (b) presents the electron beam energy distribution function at different positions across the system, showing that the beam is almost "relaxed", $\Delta v/v_b \simeq 0.7$, at $x = 0.6$ m.

For helium plasma, with the same values of $n_b/n_0, n_0$, and W_b given above, we are in region 3 ($\gamma_{MI} \geq \gamma_b$, Fig. 3 (a)). Fig. 6 (a) shows the measured space profile for the plasma wave amplitude. Notice that the maximum occurs at $x \simeq 0.2$ m. At the same position we also observe the appearence of the radiation at second harmonic. Using the experimental values with $\Delta v/v_b \simeq 0.3$ in Eq. 2 we obtain $l_{QL} = 0.2$ m, in good agreement with the experimental result. Fig. 6 (b) presents the evolution of the electron beam energy distribution function across the system, showing that in this regime the beam propagates through the plasma relatively unperturbed, $\Delta v/v_b \simeq 0.2$, for $x \geq 0.2$ m.

Acceleration of the bulk electrons, which can be observed in Figs. 4 (b) and 5 (b), together with the appearence of second harmonic are evidences that the nonlinear regime is driven by modulational instability [19].

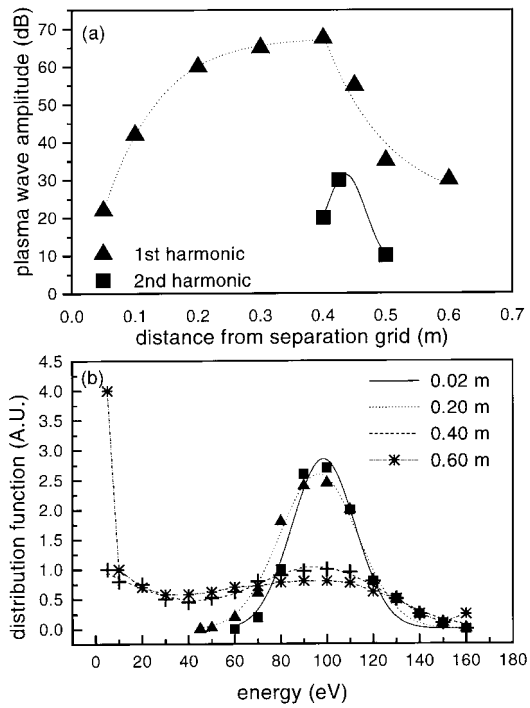

Figure 5. (a) Space evolution of wave amplitude at ω_{pe} and at $2\omega_{pe}$ observed in the experiment for argon. (b) Electron beam energy distribution function for argon plasma at different distances from the separation grid: 0.02, 0.2, 0.4 and 0.6 m, as indicated by legends.

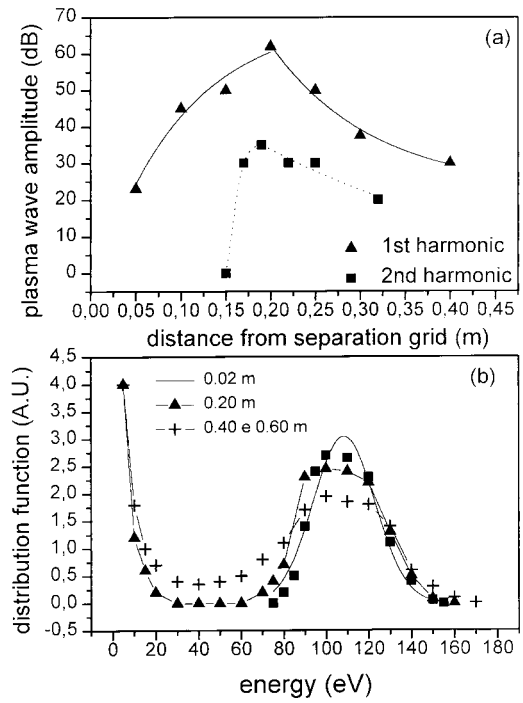

Figure 6. (a) Space evolution of wave amplitude at ω_{pe} and at $2\omega_{pe}$ observed in the experiment for helium. (b) Electron beam energy distribution function for helium plasma at different distances from the separation grid: 0.02, 0.2, 0.4 and 0.6 m, as indicated by legends.

IV. Conclusions

We have presented systematic measurements of the relaxation length of the beam versus beam to plasma density ratio in a double plasma machine. The measured relaxation length dependence on the beam to plasma density ratio presents three different regions as predicted by Galeev and coworkers [3]. The good agreement between theory and experimental results leads to the conclusion that for the argon case, the beam relaxes quasi-linearly by velocity diffusion; nonlinear processes take place at distances larger than 0.4 m, when the beam is practically already relaxed (Fig. 5 (b)). On the other hand, for helium case, nonlinear processes take place at early positions, $x \geq 0.2$ m, (Fig. 5 (b)) and the beam can pass through the plasma without significative changes on energy distribution. MI growth rate has an inverse ion mass dependence, which explains the nonlinear processes at earlier positions for helium case. The appearance of second harmonic radiation and the acceleration of the plasma electrons also indicates that the nonlinear regime is driven by modulational instability.

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