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Electromagnetic emission due to nonlinear forces

K. K. Sarma* and S. N. Sarma
M. C. College, Barpeta 781 301, Assam, India

M. Nambu and T. Hada
College of General Education, Kyushu University, Ropponmatsu, Fukuoka 810, Japan
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A theory of emission of electromagnetic radiation in a plasma with Langmuir turbulence through the plasma-maser interaction owing to a dissipative nonlinear force is presented. The nonlinear force that arises as a result of the resonant interaction between electrons and modulated fields is shown to drive the instability. The growth rate of the electromagnetic emission is obtained, and the results are discussed.

I. INTRODUCTION

The plasma-maser effect, which is a recently discovered mode-coupling process in plasma turbulence, and is basically an energy up-conversion process,[1] has shown considerable potential as a radiation mechanism in several space and laboratory plasma radiation observations.[2–5] Simultaneously, it has also been subjected to careful scrutiny regarding its validity and probable limitations as an energy up-conversion process in plasma turbulence.[6–9] The energy down-conversion from a high-frequency resonant mode to a low-frequency nonresonant mode through the plasma-maser interaction has also been investigated.[10,11]

The plasma-maser effect coexists with the Landau or cyclotron damping and is effective without electron population inversion. As has been demonstrated,[1] the plasma-maser process can be best understood in terms of a high-frequency nonlinear force. This nonlinear force arises as a result of the resonant interaction between electrons and modulated fields caused by coupling between the turbulence fields and a test high-frequency field. This high-frequency nonlinear force accelerates or decelerates the electrons and the accelerated electrons can then emit electrostatic or electromagnetic radiation. It is well known that in the parametric interaction, a low-frequency nonlinear force (ponderomotive force) is produced by coupling between a high-frequency pump wave and a low-frequency wave to make the low-frequency wave unstable. However, in the plasma-maser interaction, a nonlinear high-frequency force is produced and it makes the high-frequency wave unstable. Further, the low-frequency turbulence wave acts as the pump wave in this mechanism.

In the present paper we study the emission of an electromagnetic wave caused by the nonlinear force discussed above in a plasma with Langmuir turbulence. The Langmuir turbulence is excited by a weak electron beam drifting through a background plasma of Maxwellian electrons and ions.[12] Further, the system is assumed open with particle source and sink. The plasma-maser effect is shown to be quite effective in an open system.[13] In Sec. II we calculate the nonlinear force arising from the resonant interaction between electron and modulated fields caused by coupling between Langmuir turbulence fields and a test electromagnetic-wave field. In Sec. III this nonlinear force is used in the high-frequency electron equation of motion to obtain a high-frequency electromagnetic instability. The growth rate of electromagnetic instability is obtained in Sec. IV. Finally, Sec. V contains the discussion and the conclusion.

II. CALCULATION OF THE NONLINEAR FORCE

We consider a homogeneous plasma in the presence of an enhanced Langmuir-wave stationary turbulence caused by an electron beam drifting through the plasma with a velocity v_0. The basic equations governing the interaction of Langmuir turbulence with a test electromagnetic wave are the Vlasov-Maxwell equations.

$$\left[\frac{\partial}{\partial t}+\mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}}-\frac{e}{m}\left[\mathbf{E}+\frac{\mathbf{v}\times\mathbf{B}}{C}\right]\cdot\frac{\partial}{\partial \mathbf{v}}\right]f_e(\mathbf{r},\mathbf{v},t)=0\ , \quad (1)$$

$$\nabla\times\mathbf{E}=-\frac{1}{C}\frac{\partial \mathbf{B}}{\partial t}\ , \quad (2)$$

$$\nabla\times\mathbf{B}=\frac{4\pi}{C}\mathbf{J}+\frac{1}{C}\frac{\partial \mathbf{E}}{\partial t}\ , \quad (3)$$

$$\mathbf{J}=-e\int \mathbf{v}f_e(\mathbf{r},\mathbf{v},t)d\mathbf{v}\ , \quad (4)$$

where $f_e(\mathbf{r},\mathbf{v},t)$ is the electron distribution function and the other notations are standard.

The total fields and the electron distribution function can be written as

$$\mathbf{E}=\epsilon\mathbf{E}_l+\mu\delta\mathbf{E}_h+\mu\epsilon\delta\mathbf{E}_{lh}\ , \quad (5)$$

$$\mathbf{B}=\mu\delta\mathbf{B}_h+\mu\epsilon\delta\mathbf{B}_{lh}\ , \quad (6)$$

$$f_e=f_{0e}+\epsilon f_{1e}+\epsilon^2 f_{2e}+\mu\delta f_h+\mu\epsilon\delta f_{lh}+\mu\epsilon^2\Delta f\ . \quad (7)$$

In the above, f_{0e} is the space- and time-averaged part of the electron distribution function, and f_{1e} and f_{2e} are the fluctuating parts. ϵ is a small parameter representing the strength of the turbulence field $\mathbf{E}_l$. $\mu\delta\mathbf{E}_h$ and $\mu\delta\mathbf{B}_h$ are the electric and magnetic fields of the test high-frequency electromagnetic wave, and $\mu\delta f_h$ is the corresponding perturbed-electron distribution function. $\delta\mathbf{E}_{lh}$ and $\delta\mathbf{B}_{lh}$ are the modulation fields, and δf_{lh} and Δf are the corresponding perturbed-electron distribution functions. We assume that $\mu \ll \epsilon$.

To the order $\mu\epsilon^2$ we obtain from Eq. (1),

$$\left[\frac{\partial}{\partial t}+\mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}}\right]\Delta f=\left\langle\frac{e}{m}\mathbf{E}_l\cdot\frac{\partial}{\partial \mathbf{v}}f_{lh}\right\rangle+\left\langle\frac{e}{m}\left[\delta\mathbf{E}_{lh}+\frac{\mathbf{v}\times\delta\mathbf{B}_{lh}}{c}\right]\cdot\frac{\partial}{\partial \mathbf{v}}f_{1e}\right\rangle . \tag{8}$$

Writing the right-hand side of the above equation as F, we get

$$\left[\frac{\partial}{\partial t}+\mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}}\right]\Delta f=F , \tag{9}$$

which gives

$$\Delta f(\mathbf{K},\Omega)=\frac{F(\mathbf{K},\Omega)}{i(Kv_z-\Omega)} , \tag{10}$$

where $\mathbf{K}$ and Ω are the wave vector and the frequency, respectively, of the high-frequency electromagnetic perturbation with $\mathbf{K}=(0,0,K)$.

The nonlinear force can be defined as the rate of momentum change, and is given by

$$\frac{\partial}{\partial t}\int m\mathbf{v}\Delta f\, d\mathbf{v}=\frac{\partial}{\partial t}\int m\mathbf{v}\Delta f(\mathbf{K},\Omega)\exp[i(\mathbf{K}\cdot\mathbf{r}-\Omega t)]d\mathbf{v}$$
$$=\int\frac{m\Omega\mathbf{v}}{\Omega-Kv_z}F(\mathbf{K},\Omega)\exp[i(\mathbf{K}\cdot\mathbf{r}-\Omega t)]d\mathbf{v}. \tag{11}$$

In the above we have used Eq. (10) for $\Delta f(\mathbf{K},\Omega)$. The Fourier component of the dissipative high-frequency nonlinear force acting on unit volume of electrons is, therefore, given by

$$\mathbf{F}_{Nh}(\mathbf{K},\Omega)=\int\frac{mn_0\Omega}{\Omega-Kv_z}F(\mathbf{K},\Omega)\mathbf{v}\, d\mathbf{v} . \tag{12}$$

With $F=F(\mathbf{K},\Omega)\exp[i(\mathbf{K}\cdot\mathbf{r}-\Omega t)]$, we obtain the following substitution for $F(\mathbf{K},\Omega)$ in Eq. (12):

$$\mathbf{F}_{Nh}(\mathbf{K},\Omega)=en_0\sum_{\mathbf{k},\omega}\int\frac{\Omega}{\Omega-Kv_z}\left\langle\mathbf{E}_l(\mathbf{k},\omega)\cdot\frac{\partial}{\partial\mathbf{v}}\delta f_{lh}(\mathbf{K}-\mathbf{k},\Omega-\omega)+\left[\delta\mathbf{E}_{lh}(\mathbf{K}-\mathbf{k},\Omega-\omega)+\frac{1}{C}\mathbf{v}\times\delta\mathbf{B}_{lh}(\mathbf{K}-\mathbf{k},\Omega-\omega\right]\cdot\frac{\partial}{\partial\mathbf{v}}f_{1e}(\mathbf{k},\omega)\right\rangle\mathbf{v}\, d\mathbf{v} . \tag{13}$$

Here $\mathbf{k}$ and ω are the wave vector and the frequency of the Langmuir wave with $\mathbf{k}=(0,0,k)$.

Substituting the values of $\delta f_{lh}(\mathbf{K}-\mathbf{k},\Omega-\omega)$, $\delta\mathbf{E}_{lh}(\mathbf{K}-\mathbf{k},\Omega-\omega)$, and $\delta\mathbf{B}_{lh}(\mathbf{K}-\mathbf{k},\Omega-\omega)$, and taking the average, we finally obtain the x component of the nonlinear dissipative force as

$$F_{Nhx}(\mathbf{K},\Omega)=F_{Nhx1}(\mathbf{K},\Omega)+F_{Nhx2}(\mathbf{K},\Omega) , \tag{14}$$

where

$$F_{Nhx1}(\mathbf{K},\Omega)=-en_0\Omega\left[\frac{e}{m}\right]^2\delta E_h(\mathbf{K},\Omega)\times\sum_{\mathbf{k},\omega}|E_l(\mathbf{k},\omega)|^2\int v_x\frac{1}{\Omega-Kv_z}\frac{\partial}{\partial v_z}\frac{1}{(\Omega-\omega)-(K-k)v_z}$$
$$\times\left\{\frac{\partial}{\partial v_z}\frac{1}{\Omega-Kv_z}\left[\left[1-\frac{Kv_z}{\Omega}\right]\frac{\partial}{\partial v_x}+\frac{Kv_x}{\Omega}\frac{\partial}{\partial v_z}\right]f_{0e}+\left[\left[1-\frac{Kv_z}{\Omega}\right]\frac{\partial}{\partial v_x}+\frac{Kv_x}{\Omega}\frac{\partial}{\partial v_z}\right]\frac{1}{-\omega+kv_z+i0}\frac{\partial}{\partial v_z}f_{0e}\right\}d\mathbf{v} , \tag{15}$$

$$F_{Nhx2}(\mathbf{K},\Omega)=en_0\Omega\left[\frac{e}{m}\right]^2\delta E_h(\mathbf{K},\Omega)$$

$$\times\sum_{\mathbf{k},\omega}|E_l(\mathbf{k},\omega)|^2$$

$$\times\int v_x\frac{1}{\Omega-Kv_z}\left\{\frac{\partial}{\partial v_z}\frac{1}{(\Omega-\omega)-(K-k)v_z}\left[\left[1-\frac{(K-k)v_z}{\Omega-\omega}\right]\frac{\partial}{\partial v_x}+\frac{(K-k)v_x}{\Omega-\omega}\frac{\partial}{\partial v_z}\right]f_{0e}\right.$$

$$\left.+\left[\left[1-\frac{(K-k)v_z}{\Omega-\omega}\right]\frac{\partial}{\partial v_x}+\frac{(K-k)v_x}{\Omega-\omega}\frac{\partial}{\partial v_z}\right]\frac{1}{\omega-kv_z+i0}\frac{\partial}{\partial v_z}f_{0e}\right\}d\mathbf{v}$$

$$\times\frac{\omega_{pe}^2(\Omega-\omega)}{R(\mathbf{K}-\mathbf{k},\Omega-\omega)[(\Omega-\omega)^2-C^2(K-k)^2]}$$

$$\times\int v_x\frac{1}{(\Omega-\omega)-(K-k)v_z}\left\{\frac{\partial}{\partial v_z}\frac{1}{\Omega-Kv_z}\left[\left[1-\frac{Kv_z}{\Omega}\right]\frac{\partial}{\partial v_x}+\frac{Kv_x}{\Omega}\frac{\partial}{\partial v_z}\right]f_{0e}\right.$$

$$\left.+\left[\left[1-\frac{Kv_z}{\Omega}\right]\frac{\partial}{\partial v_x}+\frac{Kv_x}{\Omega}\frac{\partial}{\partial v_z}\right]\frac{1}{-\omega+kv_z+i0}\frac{\partial}{\partial v_z}f_{0e}\right\}d\mathbf{v}\ . \quad (16)$$

In the above equations,

$$R(\mathbf{K},\Omega)=1+\frac{4\pi e^2\Omega}{m(\Omega^2-C^2K^2)}\int v_x\frac{1}{\Omega-Kv_z}\left[\left[1-\frac{Kv_z}{\Omega}\right]\frac{\partial}{\partial v_x}+\frac{Kv_x}{\Omega}\frac{\partial}{\partial v_z}\right]f_{0e}d\mathbf{v}\ ,$$

and we have taken

$$f_{1e}(\mathbf{k},\omega)=\left[\frac{e}{m}E_l(\mathbf{k},\omega)\frac{\partial}{\partial v_z}f_{0e}\right]\Big/[-i(\omega-kv_z+i0)]\ .$$

Taking only the second term in the right-hand side of Eq. (15) as the first term does not contribute to the growth and/or damping of the electromagnetic wave through the plasma-maser interaction for which the condition is $\omega=kv_z$ [other resonance conditions, viz., $\Omega=Kv_z$ and $\Omega\pm\omega=(K\pm k)v_z$ are not satisfied], we get

$$F_{Nhx1}(\mathbf{K},\Omega)=-en_0\Omega\left[\frac{e}{m}\right]^2\delta E_h(\mathbf{K},\Omega)$$

$$\times\sum_{\mathbf{k},\omega}|E_l(\mathbf{k},\omega)|^2\int v_x\frac{1}{\Omega-Kv_z}\frac{\partial}{\partial v_z}\frac{1}{(\Omega-\omega)-(K-k)v_z}$$

$$\times\left[\left[1-\frac{Kv_z}{\Omega}\right]\frac{\partial}{\partial v_x}+\frac{Kv_x}{\Omega}\frac{\partial}{\partial v_z}\right]\frac{1}{-\omega+kv_z+i0}\frac{\partial}{\partial v_z}f_{0e}d\mathbf{v}\ . \quad (17)$$

We take the electron distribution function as

$$f_{0e}(\mathbf{v})=(1-\delta)\left[\frac{m}{2\pi T_b}\right]^{3/2}\exp(-mv^2/2T_b)+\delta\left[\frac{m}{2\pi T}\right]^{3/2}\exp[-m(v_x^2+v_y^2)/2T]\exp[-m(v_z-v_0)^2/2T]\ , \quad (18)$$

where T_b and T are the temperatures of the background and the beam plasma, respectively, and $\delta\ll 1$ is the ratio of the number densities of the beam and background plasma. We then obtain from Eq. (17)

$$F_{Nhx1}(\mathbf{K},\Omega)=if_{h1}\delta E_h(\mathbf{K},\Omega)\ , \quad (19)$$

where

$$f_{h1}=-\frac{en_0K}{\Omega^2}\left[\frac{e}{m}\right]^2\delta\sum_{\mathbf{k},\omega}|E_l(\mathbf{k},\omega)|^2\left[\frac{\pi m}{2T}\right]^{1/2}\frac{m(\omega/k-v_0)}{|k|T}\exp[-m(\omega/k-v_0)^2/2T]\ . \quad (20)$$

Similarly, we obtain from Eq. (16),[14]

$$F_{Nhx2}(\mathbf{K},\Omega)=if_{h2}\delta E_h(\mathbf{K},\Omega)\ , \quad (21)$$

where

$$f_{h2}=-en_0\left[\frac{e}{m}\right]^2\delta\sum_{\mathbf{k},\omega}|E_l(\mathbf{k},\omega)|^2\frac{\omega_{pe}^2}{(\Omega-\omega)^2KC^2}\left[\frac{\pi m}{2T}\right]^{1/2}\frac{m}{|k|T}(\omega/k-v_0)\exp[-m(\omega/k-v_0)^2/2T]\ . \tag{22}$$

Thus we can write

$$F_{Nhx}(\mathbf{K},\Omega)=i(f_{h1}+f_{h2})\delta E_h(\mathbf{K},\Omega)\ , \tag{23}$$

where f_{h1} and f_{h2} are given by Eqs. (20) and (22), respectively.

III. DISPERSION RELATION OF THE ELECTROMAGNETIC WAVE

Maxwell equations governing the high-frequency electromagnetic perturbations can be written as

$$\nabla\times\delta\mathbf{E}_h=-\frac{1}{C}\frac{\partial}{\partial t}\delta\mathbf{B}_h\ , \tag{24}$$

$$\nabla\times\delta\mathbf{B}_h=\frac{4\pi}{C}\mathbf{J}_h+\frac{1}{C}\frac{\partial}{\partial t}\delta\mathbf{E}_h\ . \tag{25}$$

From these equations we then obtain

$$(\Omega^2-C^2K^2)\delta\mathbf{E}_h(\mathbf{K},\Omega)=-4\pi i\Omega\mathbf{J}_h(\mathbf{K},\Omega)\ . \tag{26}$$

The linearized high-frequency electron equation of motion can be written, with the nonlinear high-frequency force term as

$$mn_0\frac{\partial\mathbf{v}_h}{\partial t}=-en_0\delta\mathbf{E}_h+\mathbf{F}_{Nh}\ . \tag{27}$$

By Fourier analyzing, we get

$$-i\Omega mn_0\mathbf{v}_h=-en_0\delta\mathbf{E}_h(\mathbf{K},\Omega)+if_h\delta\mathbf{E}_h(\mathbf{K},\Omega)\ ,$$

where we have replaced $\mathbf{F}_{Nh}(\mathbf{K},\Omega)$ by $if_h\delta\mathbf{E}_h(\mathbf{K},\Omega)$. Then we get

$$\mathbf{v}_h=\frac{i}{mn_0\Omega}(if_h-en_0)\delta\mathbf{E}_h(\mathbf{K},\Omega)\ . \tag{28}$$

Taking $\mathbf{J}_h(\mathbf{K},\Omega)=-en_0\mathbf{v}_h$ and substituting $\mathbf{v}_h$ from Eq. (28), we obtain from (26)

$$\Omega^2-C^2K^2-\omega_{pe}^2=-\frac{4\pi ie}{m}f_h\ . \tag{29}$$

This is the dispersion relation of the electromagnetic wave with the nonlinear force term represented by the right-hand side of the equation.

IV. GROWTH RATE OF THE ELECTROMAGNETIC INSTABILITY

To obtain the growth rate of the electromagnetic instability, we now put $\Omega=\Omega+i\gamma$, where Ω and γ are, respectively, the real frequency and the growth rae of the electromagnetic wave. Then Eq. (29) gives

$$\Omega=(\omega_{pe}^2+C^2K^2)^{1/2}\ , \tag{30}$$

$$\gamma=-\frac{2\pi ef_h}{m\Omega}\ . \tag{31}$$

Equation (31) very clearly shows that the nonlinear growth and/or damping of the test electromagnetic wave solely arises from the high-frequency nonlinear force term.

We have already taken

$$\mathbf{F}_{Nh}(\mathbf{K},\Omega)=if_h\delta\mathbf{E}_h(\mathbf{K},\Omega)\ .$$

We therefore get

$$F_{Nhx}(\mathbf{K},\Omega)=if_h\delta E_h(\mathbf{K},\Omega)\ .$$

This gives

$$f_h=f_{h1}+f_{h2}\ . \tag{32}$$

Substituting the values of f_{h1} and f_{h2}, we finally obtain the growth rate of the electromagnetic wave as

$$\gamma=\frac{\Omega\pi^{1/2}\delta}{2}\left[\frac{\omega_{pe}}{\Omega}\right]^4\sum_{\mathbf{k},\omega}\left[\frac{K}{|k|}+\frac{\omega_{pe}^2}{K|k|C^2}\right]\times\frac{|E_l(\mathbf{k},\omega)|^2}{4\pi n_0T}\left[\frac{\omega-kv_0}{kv_e}\right]\times\exp[-m(\omega/k-v_0)^2/2T]\ . \tag{33}$$

where v_e is the electron thermal velocity.

V. DISCUSSION AND CONCLUSION

Equation (33) gives the growth rate of the electromagnetic wave in the presence of a stationary Langmuir turbulence through the plasma-maser interaction. The expression for the growth rate contains two parts: the first part corresponds to the direct coupling contribution and the second part corresponds to polarization contribution as shown in detail in Ref. 14. Further, the results we obtain from the nonlinear force consideration agree fully with those obtained from the standard formulation (Ref. 14).

Equation (33) shows that the growth of the electromagnetic wave occurs in a plasma with stationary Langmuir turbulence for the condition $\Omega/K<0$ under the condition of Langmuir wave growth, viz., $\omega/k<v_0$. This means that a test electromagnetic wave with $\Omega/K<0$ experiences growth, while with $\Omega/K>0$, it experiences damping in the presence of stationary Langmuir turbulence.

The essential feature of this nonlinear force formulation is that the high-frequency nonlinear force is explicitly calculated and is shown to be responsible for driving the high-frequency instability. Also, the physical picture of the plasma-maser interaction becomes more apparent with the nonlinear force consideration.

In the earlier works on the plasma-maser effect through the high-frequency nonlinear force (Ref. 1 and subsequent works), the definition of the nonlinear force was not complete. A factor was missing in its expression. In our present work, we have removed this anomaly and the nonlinear force has been calculated correctly to show finally that this method gives identical results with those obtained from the standard formulation (Ref. 1).

The plasma-maser effect is a recently discovered elementary process in plasma turbulence. This manuscript clarifies the physical mechanism of the plasma maser based on nonlinear force. The plasma-maser effect is one of the three mode-mode coupling processes in plasmas, viz., the three-wave interaction, the nonlinear Landau interaction, and the plasma-maser interaction. These belong to the lowest-order mode-coupling process and potentially give the same order of magnitude contribution for the growth rate. However, unfortunately, most of the previous authors consider the plasma-maser interaction between resonant ion-sound and nonresonant Langmuir waves. They consider the growth rate of the Langmuir wave through the resonant interaction between electrons and ion-sound waves. Unfortunately, the resonant interaction between electrons and ion-sound waves is very weak because $\omega/k \ll v_e$. Here ω, k, and v_e are frequency, the wave number of ion-sound waves, and electron thermal velocity. Thus, the growth rate of the Langmuir wave is small.

On the other hand, we consider the plasma-maser interaction between the resonant Langmuir wave and the nonresonant electromagnetic mode. Because the resonant interaction between the electrons and the Langmuir wave is very strong, the growth rate of the electromagnetic mode is large as is shown in Eq. (33). Now, we compare the growth rate [Eq. (33)] with the other two processes. According to the parameters estimated in Ref. 14, we take $\omega/k=10v_e$, $v_0=11v_e$, and $k=|K|=1/10k_e$. Then, the growth of the electromagnetic mode occurs for $\Omega/K<0$. Equation (33) reduces to

$$\gamma/\Omega \simeq A+B \ , \tag{34}$$

with

$$A=\delta|E_l|^2/4\pi n_0 T \ , \tag{35}$$

$$B=\delta|E_l|^2/4\pi n_0 T(k_e^2/K|k|)(v_e/C)^2 \ . \tag{36}$$

On the other hand, according to Eq. (4.79) in Ref. 12, the growth rate due to the resonant three-wave interaction is

$$\gamma/\Omega \simeq |E_l|^2 4\pi n_0 T(v_e/C)^2 \ , \tag{37}$$

and the growth rate from the nonlinear scattering is given by Eq. (4.81),

$$\gamma/\Omega \simeq |E_l|^2/4\pi n_0 T(k/k_e)^3 \ . \tag{38}$$

It is clear that the growth rate of the electromagnetic mode through the polarization term [Eq. (36)] is dominant over the three-wave contribution [Eq. (37)] if beam density $\delta > K|k|/k_e^2=10^{-2}$. Furthermore, the plasma-maser contribution due to the direct coupling term [Eq. (35)] is larger than that of the nonlinear scattering [Eq. (38)] if $\delta>(k/k_e)^3=10^{-3}$. Accordingly, we can conclude that the plasma-maser interaction between the resonant Langmuir wave and the nonresonant electromagnetic mode considered here is by no means negligibly small in a real beam-plasma system.

This paper is a straightforward perturbation calculation of the nonlinear emission of electromagnetic waves from a plasma with Langmuir turbulence driven by a weak beam. Accordingly, the Langmuir turbulence energy density as a fraction of the thermal plasma energy must satisfy

$$|E_l(\mathbf{k},\omega)|^2/4\pi n_0 T < \Delta k^2 \lambda_D^2 \ .$$

Here Δk and λ_D are the width of the spectrum and the Debye length, respectively. Finally, we comment on the difference between the plasma-maser effect and the resonance broadening due to stochastic forces acting on the linear trajectory of the resonant electrons.[15] Based on a diagrammatic approach, it is shown that the plasma maser and resonance broadening correspond to the vertex correction and the propagator correction, respectively.[16]

*Permanent address: Birjhora Mahavidyalaya, Bongaigaon 783 380, Assam, India.

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