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Analytical Study of a Solid Beam Driven Plasma- Loaded Backward Wave Oscillator

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ANALYTICAL STUDY OF A SOLID BEAM DRIVEN PLASMA- LOADED BACKWARD WAVE OSCILLATOR

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Analytical Study of a Solid Beam Driven Plasma-Loaded Backward Wave Oscillator

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Abstract- In this paper, an analytical expression comprising linear instability phenomena leading to microwave generation in a solid beam driven plasma-loaded backward wave oscillator has been developed. This analytical treatment is a process of three-wave interaction and is based on the approximate linear theory of instability established for annular beam driven vacuum backward wave oscillator. The dispersion relation derived here is an approximate one and it can be successfully employed to study a backward wave oscillator system consisting of a sinusoidal corrugated structure having very smaller corrugation depth.

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I. Introduction

Backward wave oscillator (BWO) is a well-known device which transforms the kinetic energy of electron beam into microwave radiation [15]. In this device an electron beam is injected into a slow wave structure (SWS) with the guidance of a strong axial magnetic field. During the propagation of beam through the SWS it interacts with the normal electromagnetic modes of the structure. This leads to a transfer of electron kinetic energy to the radiation field. The BWO operates at the vicinity on the dispersion curve, where the group velocity of the structure wave is negative. This causes a propagation of the wave energy against the flow of beam electrons. That is why the device is so named. The phenomenon of interaction among the beam electrons and the normal modes of the BWO structure can be expressed by a linear dispersion relation.

This dispersion relation predicts the existence of an instability that leads to the generation of microwaves. It was found by some researchers that resonance enhancement of microwave radiation can be achieved when a BWO operates in presence of background gas and plasma [2,9]. With this achievement, it was also found theoretically as well as experimentally that plasma injection into the BWO structure enhances the power output, interaction efficiency and spatial growth rates much more than that of vacuum cases [1-8,11,16,17]. Effect of geometrical parameters of BWO structure on the dispersion characteristics and instability phenomena were presented by some researchers [12,14]. In some dissertation, the resonance interaction in the BWO with thin as well as thick annular electron beam has been studied [4, 10]. In this paper, plasma-loaded BWO structure having very smaller corrugation depth with solid electron beam is selected. Thus, it becomes possible to develop a simple analytical form of dispersion relation. To do this work, the cubic dispersion equation describing the frequency and wave number perturbations of the three-waves involved in the resonance interaction as developed earlier [13], is taken as the base. With the realization of the merits of plasma injection into the device, this theory for vacuum case with an annular electron beam is modified and extended for plasma-loaded BWO with a solid electron beam.

Section-2 of this paper contains model description, formulation and pre-requisite comparative studies about the accuracy and concreteness of the SWS model and necessary assumptions. In section-3, the derivation of the analytical dispersion relation has been presented. Section-4 presents discussions and conclusions.

II. Model Description and Formulation

In order to derive the analytical dispersion relation, a BWO system model as shown in Fig. 1 is considered. It consists of a sinusoidally corrugated wall structure, having very smaller corrugation depth, h (i.e., $h<<R_0$) according to the relation:

$$R(z)= R_0\ [1+a \cos(k_0 z)] \qquad (1)$$

where, R(z)=the inner surface radius of the structure; $a=h/R_0$; $k_0=2\pi/z_0$; z_0=period of corrugation. of the structure inner wall.

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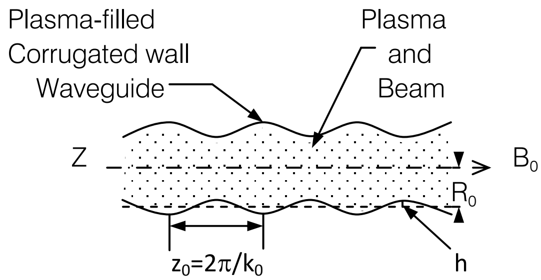

Figure 1. Plasma loaded sinusoidal corrugated slow wave structure and electron beam model.

The structure filled completely and uniformly with cold, collisionless and neutralized plasma of density N_p and a monoenergatic relativistic electron beam of density N_b. The beam is moving along the waveguide axis with a velocity v_b relative to the background plasma with the guidance of a strong and infinite magnetic field B_0. The numerical dispersion relation of this system, $D(k, \omega) = 0$[14], where D is the value of the determinant of a square matrix with elements D_{mn} and k and ω are respectively the wave number and frequency.

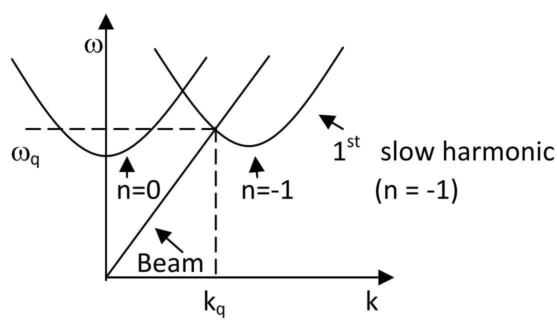

Figure 2: Resonance of the zeroth beam and electromagnetic first slow harmonic.

To derive the analytical expression for growth rates at the saddle point of this system, the resonance interaction of the zeroth beam harmonic with the electromagnetic first slow harmonic (n=-1) as shown in Fig.2 is considered. The approximate dispersion relation for this case is given below:

$$\begin{bmatrix} D_{-1-1} & D_{-10} \\ D_{0-1} & D_{00} \end{bmatrix} = 0 \qquad (2)$$

The matrix elements of the above relation are:

$$\left.\begin{aligned} D_{-1-1} &= J_0(X_{-1}) \\ D_{00} &= J_0(X_0) \\ D_{-10} &= \left(1 + \frac{k_0 k}{\frac{\omega^2}{c^2} - k^2}\right)\frac{a}{2} X_0 J_0'(X_0) \\ D_{0-1} &= \left(1 - \frac{k_0 k_{-1}}{\frac{\omega^2}{c^2} - k_{-1}^2}\right)\frac{a}{2} X_{-1} J_0'(X_{-1}) \end{aligned}\right\} \qquad (3)$$

Here,

$$\frac{X_n^2}{R_0^2} = \left(\frac{\omega^2}{c^2} - k_n^2\right)\left(1 - \frac{\omega_p^2}{\omega^2}\right) - \left[\left(\frac{\omega^2}{c^2} - k^2\right)\frac{\omega_b^2}{\gamma^3(\omega - k_n v_b)^2}\right]\delta_{n,0} \qquad (4)$$

where, c, ω_p, ω_b and v_b are light velocity, plasma frequency, beam frequency and light velocity respectively, and $\delta_{n,0} = 0$ unless $n = -1$; $k_n = (k + nk_0)$.

The oscillation frequency ω_q and hence the wave number k_q can be obtained by solving eq.(2) with $\omega_b = 0$. However, for the zeroth approximation of the corrugation depth, the approximate value of ω_q and k_q can be obtained by solving simultaneously the following two equations.

$$R_0^2\left(\frac{\omega_q^2}{c^2} - (k_q - k_0)^2\right)\left(1 - \frac{\omega_p^2}{\omega_q^2}\right) = (\mu_{0s})^2 \qquad (5)$$

$$\omega_q = k_q v_b \qquad (6)$$

Here $\mu_{0s} = 2.405$, is the first zero of $J_0(X_n)$ in absence of beam i.e., $X_b = 0$

Before approaching the derivation of the analytical dispersion equation, the following two comparative studies have been done, in order to verify it's degree of accuracy. For a full period of wave number of the corrugated structure, the dispersion characteristics of the corrugated as well as cylindrical waveguide have been drawn on the same graph in Fig.3, assuming the same average radius of the two structures. The dispersion curve of the corrugated structure is drawn with a corrugation period 0.02 cm, using the numerical dispersion relation $D(k, \omega) = 0$, and that of the cylindrical one is drawn using eq.(5) with $(k_q - k_0)$ replaced by k.

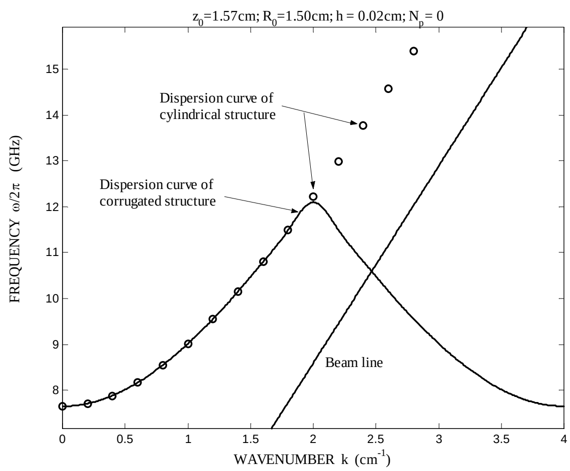

Figure3 : Dispersion characteristics of corrugated and cylindrical waveguides for TM_{01} mode.

The curves of solid line and open circles indicate the dispersion characteristics of corrugated and cylindrical waveguides respectively. Here, it has been carefully observed that, for very smaller corrugation depth, the dispersion curve of the corrugated structure within the range of wave number ($0 \le k \le k_0/2$), coincide completely with that of the cylindrical waveguide.

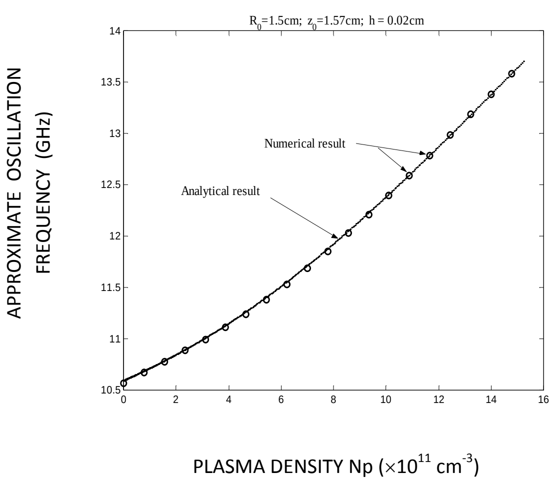

Figure4 : Approximate oscillation frequency versus plasma density characteristics.

This indicates the validity of the proposed analytical expression for resonance interaction as indicated in Fig.2. For the corrugated structure used in this paper having very smaller corrugation depth ($h = 0.02$cm), approximate oscillation frequency $\omega_q/2\pi$ versus plasma density N_p curves shown in Fig.4 have been drawn analytically as well as numerically in absence of electron beam. Here analytical curve is drawn using the equation that involves with the proposed expression and the numerical curve is obtained from the full dispersion relation [14].The curves of solid line and open circles indicate the analytical and numerical results respectively. In this observation, it is found that the analytical results are in excellent agreement with the numerical ones.

From the above two observations it is decided hopefully that, analytical dispersion expression of three-wave interaction (structure wave with n = 0, structure wave with n = -1 and the beam space charge wave) can be established successfully for the BWO structure used in this paper.

III. Derivation of the Dispersion Relation

At modest beam densities, $D_{mn}(\omega_q,k_q,X_b)$'s arround the root of $D_{mn}(\omega_q,k_q,X_b=0)$ is given by Tailor's series as,

$$D_{mn}(\omega_q,k_q,X_b) = D_{mn}(\omega_q,k_q,X_b=0) + \delta\omega \frac{\partial}{\partial\omega} D_{mn}(\omega_q,k_q,X_b=0) + \delta k \frac{\partial}{\partial k} D_{mn}(\omega_q,k_q,X_b=0) + X_b \frac{\partial}{\partial X_b} D_{mn}(\omega_q,k_q,X_b)\Big|_{\substack{\omega=\omega_q\\ k=k_q\\ X_b=0}} \qquad (7)$$

Here, $X_b = -\left(\frac{\gamma^{-3}\omega_b^2}{(\omega - k_n v_b)^2}\right)$ and $\delta\omega = \omega - \omega_q$, $\delta k = k - k_q$

Therefore in presence of electron beam

$$D_{-1-1} = \left[J_0(X_{-1}) + J_0'(X_{-1})\left(\delta\omega\frac{\partial X_{-1}}{\partial\omega} + \delta k\frac{\partial X_{-1}}{\partial k}\right)\right]\Bigg|_{\substack{\omega=\omega_q\\ k=k_q}}$$

$$D_{00} = \left[J_0(X_0) + J_0'(X_0)\left(\delta\omega\frac{\partial X_0}{\partial\omega} + \delta k\frac{\partial X_0}{\partial k}\right)\right]\Bigg|_{\substack{\omega=\omega_q\\ k=k_q}}$$

$$D_{-10} = \left[1 + \frac{k_q k_0}{\frac{\omega_q^2}{c^2} - k_q^2}\right]\frac{a}{2}$$

$$\times\left\{\left[X_0 J_0'(X_0)\right]\Big|_{\substack{\omega=\omega_q\\ k=k_q}} + \left[X_b J_0'(X_0)\frac{\partial X_0}{\partial X_b} + X_b X_0 J_0''(X_0)\frac{\partial X_0}{\partial X_b}\right]\Bigg|_{\substack{\omega=\omega_q\\ k=k_q\\ X_b=0}}\right\}$$

$$D_{0-1} = \left(1 + \frac{k_0(k_q - k_0)}{\frac{\omega_q^2}{c^2} - (k_q - k_0)^2}\right)\frac{a}{2} X_{-1} J_0'(X_{-1})\Bigg|_{\substack{\omega=\omega_q\\ k=k_q}}$$

The terms $\delta\omega\frac{a}{2}$ and $\delta k\frac{a}{2}$ have been neglected.

Therefore, the solution of the determinant of eq.(2) is given by:

$$\left[J_0(\lambda_{-1}) + J_0'(\lambda_{-1})\left(\delta\omega\frac{\partial\lambda_{-1}}{\partial\omega} + \delta k\frac{\partial\lambda_{-1}}{\partial k}\right)\right]$$

$$\times\left[J_0(\lambda_0)+J_0'(\lambda_0)\left(\delta\omega\frac{\partial\lambda_0}{\partial\omega}+\delta k\frac{\partial\lambda_0}{\partial k}\right)\right]=\frac{a^2}{4}\lambda_{-1}J_0'(\lambda_{-1})$$

$$\times\left[1+\frac{k_0k_q}{\frac{\omega_q^2}{c^2}-k_q^2}\right]\left[1-\frac{k_0(k_q-k_0)}{\frac{\omega_q^2}{c^2}-(k_q-k_0)^2}\right]$$

$$\left[\lambda_0J_0'(\lambda_0)+\{J_0'(\lambda_0)+\lambda_0J_0''(\lambda_0)\}X_b\frac{\partial X_0}{\partial X_b}\right] \tag{8}$$

Here, $\lambda_n = X_n(\omega_q, k_q, X_b = 0)$

Defining $\left[1+\frac{k_0k_q}{\frac{\omega_q^2}{c^2}-k_q^2}\right]\left[1-\frac{k_0(k_q-k_0)}{\frac{\omega_q^2}{c^2}-(k_q-k_0)^2}\right]=\beta_1$,

Equation (8) becomes,

$$\left[J_0(\lambda_{-1})+J_0'(\lambda_{-1})\left(\delta\omega\frac{\partial\lambda_{-1}}{\partial\omega}+\delta k\frac{\partial\lambda_{-1}}{\partial k}\right)\right]$$

$$\times\left[J_0(\lambda_0)+J_0'(\lambda_0)\left(\delta\omega\frac{\partial\lambda_0}{\partial\omega}+\delta k\frac{\partial\lambda_0}{\partial k}\right)\right]$$

$$=\beta_1\frac{a^2}{4}\lambda_{-1}J_0'(\lambda_{-1})\left[\lambda_0J_0'(\lambda_0)+\{J_0'(\lambda_0)+\lambda_0J_0''(\lambda_0)\}X_b\frac{\partial X_0}{\partial X_b}\right] \tag{9}$$

After simplification, neglecting the terms containing $\delta^2\omega$, δ^2k, $\delta\omega\ \delta k$ and equating $J_0(\lambda_0)J_0(\lambda_{-1})-\beta_1\frac{a^2}{4}\lambda_0\lambda_{-1}J_0'(\lambda_0)J_0'(\lambda_{-1})$ to zero (as it is the original dispersion relation) yields,

$$J_0(\lambda_0)J_0'(\lambda_{-1})\left(\delta\omega\frac{\partial\lambda_{-1}}{\partial\omega}+\delta k\frac{\partial\lambda_{-1}}{\partial k}\right)=\beta_1\frac{a^2}{4}\lambda_{-1}J_0'(\lambda_{-1}) \tag{10}$$

$$\{J_0'(\lambda_0)+\lambda_0J_0''(\lambda_0)\}X_b\frac{\partial X_0}{\partial X_b}$$

Finally, the following form of analytical dispersion relation of a plasma loaded BWO is obtained:

$$(\delta\omega-v_b\delta k)^2(\delta\omega-v_g\delta k)=\Delta \tag{11}$$

Where, $\Delta=-\dfrac{\omega_b^2\gamma^{-3}\beta_1a^2\lambda_{-1}^2\left(\frac{\omega_q^2}{c^2}-k_q^2\right)}{8\lambda_0\left[\frac{\omega_q}{c^2}-\frac{\omega_p^2(k_q-k_0)^2}{\omega_q^3}\right]}\times\dfrac{J_0'(\lambda_{-1})}{J_0(\lambda_0)}\left[1+\lambda_0\dfrac{J_0''(\lambda_0)}{J_0'(\lambda_0)}\right];$

$$v_g=\frac{\partial\omega}{\partial k}\ \text{and}\ \frac{J_0'(\lambda_{-1})}{J_0(\lambda_0)}\left[1+\lambda_0\frac{J_0''(\lambda_0)}{J_0'(\lambda_0)}\right]=\begin{cases}1 \text{ for } \lambda_0 \text{ is imaginary}\\ -1 \text{ for } \lambda_0 \text{ is real}\end{cases}$$

Eq. (11) is a cubic equation describing the frequency and wave number perturbations of the three waves involved in the resonance interaction.

The properties of the dispersion relation can be conveniently investigated by converting eq.(11) into dimensionless form in the following way [13]:

$$\left\{|\alpha\Delta|^{\frac{1}{3}}\frac{\delta\omega}{|\alpha\Delta|^{\frac{1}{3}}}-|\alpha\Delta|^{\frac{1}{3}}\delta k\left|v_b^2v_g/\Delta\right|^{\frac{1}{3}}\right\}^2$$

$$\times\left\{|\alpha\Delta|^{\frac{1}{3}}\frac{\delta\omega}{|\alpha\Delta|^{\frac{1}{3}}}-|\alpha\Delta|^{\frac{1}{3}}v_g\delta k\left|\frac{v_g/v_b}{\Delta}\right|^{\frac{1}{3}}\right\}=\Delta$$

$$|\alpha\Delta|^{\frac{2}{3}}(x-y)^2\left(x-\frac{y}{\alpha}\right)|\alpha\Delta|^{\frac{1}{3}}=\Delta$$

$$(x-y)^2(y-\alpha x)=-\frac{\alpha\Delta}{|\alpha\Delta|}$$

$$(x-y)^2(y-\alpha x)=-u$$

Where, $\alpha=\frac{v_b}{v_g}$; $x=\frac{\delta\omega}{|\alpha\Delta|^{\frac{1}{3}}}$; $y=\delta k\left|\frac{v_b^2v_g}{\Delta}\right|^{\frac{1}{3}}$; $u=\frac{\alpha\Delta}{|\alpha\Delta|}=\pm1$

Thus, the dimensionless dispersion relation is obtained as,

$$D(x,y)=(y-x)^2(y-\alpha x)+u=0 \tag{12}$$

Equation (12) is quite simillar to that derived for vacum BWO driven by annular electron beam [13].

In the BWO, the instability is absolute and this occurs when the two roots of y in eq.(12) merge with one another for some value of x with positive imaginary part. This value of x can be found from the simultaneous solutions to eq. (12) and eq. (13).

$$\frac{\partial D}{\partial y}=(y-x)[3y-(1+2\alpha)x]=0 \tag{13}$$

The values of x at which the roots of y of the dispersion relation merge are:

$$\left.\begin{aligned}x_b&=\left[\frac{3}{2^{\frac{2}{3}}(\alpha-1)}\right](-u)^{\frac{1}{3}}\\&=\frac{3}{2^{\frac{2}{3}}(\alpha-1)}\left[\exp\left(\frac{i\pi}{3}\right),\ -1,\ \exp\left(\frac{i5\pi}{3}\right)\right],\ u=1\\&=\frac{3}{2^{\frac{2}{3}}(\alpha-1)}\left[1,\ \exp\left(\frac{i2\pi}{3}\right),\ \exp\left(\frac{i4\pi}{3}\right)\right],\ u=-1\end{aligned}\right\} \tag{14}$$

And the three roots of y are:

$$\left.\begin{aligned} y_1 &= s_1 + s_2 + \frac{x}{3}(2+\alpha), \\ y_2 &= \exp\left(\frac{i2\pi}{3}\right)s_1 + \exp\left(\frac{i4\pi}{3}\right)s_2 + \frac{x}{3}(2+\alpha), \\ y_3 &= \exp\left(\frac{i4\pi}{3}\right)s_1 + \exp\left(\frac{i2\pi}{3}\right)s_2 + \frac{x}{3}(2+\alpha) \end{aligned}\right\} \quad (15)$$

Then the equation (12) can be rearranged as,

$$y^3 - x_{bo}(2+\alpha)y^2 + x_{bo}^2(1+2\alpha)y - \alpha x_{bo}^3 + u = 0 \quad (16)$$

where, x_{bo} is the x_b in eq.(14) lying in the upper half plane.

Using the values of x_{bo} and y_1 (which merges with y_2 or y_3) the values of $\delta\omega$ and δk and thus the values of complex angular frequency ω_s and complex wavenumber k_s at the saddle point can be obtained as:

$$\delta\omega = x_{bo}|\alpha\Delta|^{\frac{1}{3}}; \quad \delta k = \frac{y_1}{\left|\frac{v_b^2 v_g}{\Delta}\right|^{\frac{1}{3}}}; \quad \omega_s = \omega_q + \delta\omega$$

and $k_s = k_q + \delta k$

The expression of group velocity, v_g is:

$$v_g = -\frac{\partial\omega}{\partial k} = \frac{\left[\left(1-\frac{\omega_p^2}{\omega_q^2}\right)(k_q - k_0)\right]}{\left[\frac{\omega_q}{c^2} - \frac{\omega_p^2}{\omega_q^3}(k_q - k_0)^2\right]} \quad (17)$$

One can also express the arbitrary signal strength as,

$$f \propto e^{-j\left(j\omega_i \frac{L}{v_g} - jk_i L\right)} \quad (18)$$

where, L is the distance traversed by the wave in time $t = L/v_g$, and is equal to the axial length of the structure and, ω_i and k_i are the imaginary part of angular frequency and wave number respectively.

IV. Conclusion

This paper contains a derivation of an analytical dispersion relation leading to microwave generation in a plasma-loaded BWO. The analytical equation obtained here, is limited in validity to the SWSs having very smaller corrugation depth in comparison to the structure average radius (i.e., $h << R_0$). This dispersion relation is an approximate one and is applicable only in the vicinity of the three-wave resonance point on the dispersion curves. The resulting approximate dispersion relation is cubic in both ω and k, which verifies the three-wave nature of the interaction process involving two normal modes of the SWS (which near resonance are merged into a complex conjugate pair of solutions to the dispersion relation) and a beam space charge wave. From this cubic dispersion relation, temporal as well as spatial growth rates of a solid beam driven plasma-loaded backward wave oscillator can be computed and analyzed with the variation of structure parameters and plasma density.

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