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BROAD-BAND OPERATION IN A DIELECTRIC LOADED GYROTRON

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SUMMARY

The effect of bandwidth broadening with a dielectric load in a cylindrical gyrotron is investigated. The linear dispersion relation for the azimuthally symmetric, transverse electric (TE) modes reveals that the TE perturbations exhibit three unstable modes characterized by their wavelengths; one fast wave, the long wavelength mode (LWM) and two slow waves, the intermediate (IWM) and the short (SWM) wavelength modes. The wide band capability of each mode is examined in terms of the axial velocity spread of the beam electrons. It is shown that for a small spread the slow waves (SWM, IWM) are preferable for wide band applications, whereas the fast wave (LWM) is desirable for a large spread. By making use of the coexistence of the SWM with the IWM, even wider bandwidth of the mixed slow waves is discussed for a small spread. The enhanced bandwidth of the mixed mode is attributed to the increasing participation of the SWM with the reduction of the beam location. Moreover, the presence of the SWM reduces considerably the troublesome heat dissipation in the dielectric layer.

I. INTRODUCTION

The gyrotron[1] is a high power microwave device that makes use of the unstable coupling of the electron cyclotron wave with the waveguide mode. With a perfectly conducting waveguide, however, the bandwidth is usually very narrow. In this paper we will examine the gyrotron in a dielectric loaded waveguide for the wideband application.[2,3] The purpose of this work is to find optimal conditions on the broad range at physical parameters for wide band applications. In the process we will identify three unstable modes and examine their capabilities for broad bandwidth.

The dispersion relation for the azimuthally symmetric, transverse electric (TE) perturbations is obtained (Sec. II) within the framework of the linearized Maxwell-Vlasov system, including the influence of the axial velocity spread. By making use of the wave impedance matching,[3,4] it is possible to predict not only the instabilities from the usual beam-waveguide coupling [the long (LWM), and the intermediate (IWM) wavelength modes], but also the instability driven by the localized fields at the beam location [the short wavelength mode (SWM)]. The characteristics of the three unstable modes are discussed in Sec. II.

The optimum conditions on the physical parameters for wide band applications of each mode are obtained in terms of the axial velocity spread (Sec. III). It is found that the bandwidth and the choice of the operating mode for the wide band operations are primarily determined by the spread.

By making use of the coexistence of the SWM with the IWM, we investigate the mixed mode operation of two slow waves by reducing the beam location (Sec. IV). The resulting bandwidth of the mixed mode operation is broader than either of two individual modes for a small axial velocity spread. Moreover, the troublesome heat dissipation in the dielectric layer is considerably reduced for the mixed mode operation.

II. DISPERSION RELATION

The dielectric gyrotron consists of the conducting wall located at R_c, and the dielectric material (ε) filled from its inner radius R_w to R_c. The hollow electron beam under the influence of the strong axial magnetic field is confined inside, with its center at R_o. The cylindrical coordinate (r, θ, z) is employed.

Since the details of the procedures in obtaining the dispersion relation are given in Ref. 3, we give here only the outline. The dispersion relation is derived within the framework of the linearized Maxwell-Vlasov system for the electromagnetic fields and the beam distribution function. We limit our attention to the azimuthally symmetric, transverse electric (TE) perturbation with the frequency ω and the axial wavenumber k. It is assumed that the beam is tenuous and the beam thickness is small. The appropriate boundary conditions connect the perturbed field solutions for the beam-free regions. The contribution of the perturbed beam current, computed from the perturbed distribution function, is represented by a discontinuity in the perturbed field across the beam. To examine the effect of the axial velocity spread, the equilibrium distribution function is assumed to be Lorentzian[3] in the axial velocity with its average value given by $c\beta_z$ and the half-width spread by $c\beta_z\Delta$. Moreover, the beam is assumed to be monoenergetic with γmc^2, and the average transverse velocity is given by $c\beta_\perp$. Finally we obtain the dispersion relation for the azimuthally symmetric TE mode.[3]

$$B(\omega,k) = -\frac{\nu\beta_\perp^2}{2\gamma R_o^2\,[\omega-\omega_B+i\;k\;c\beta_z\gamma\Delta/\gamma_z^3]^2} \tag{1}$$

Here the Doppler-shifted beam mode ω_B is given by $\omega_B = kc\beta_z + \omega_c/\gamma$, and the wave admittance B is given in Ref. 3. In Eq. (1), the small quantity ν is the Budker parameter[3,4], ω_c is the non-relativistic electron cyclotron frequency under the strong applied axial magnetic field, and γ_z is the axial mass factor. We will limit our attention to the unstable modes only for the amplifier application.

Numerical analysis of the azimuthally symmetric, TE perturbations shows that there exist three unstable modes; one fast wave, the long wavelength mode (LWM, $\omega>ck$) and two slow waves, the intermediate wavelength mode (IWM, $ck>\omega>ck\varepsilon^{-\frac{1}{2}}$) and the short wavelength mode (SWM), $\omega<ck$). The fast wave mode (LWM) is separated from the two slow waves (IWM, SWM) by a stable band near $\omega = ck$. Both the LWM and the IWM are originated from the coupling of the beam mode with the dielectric waveguide mode. On the other hand, the instability of the SWM is characterized by the highly localized fields near the beam location.[3] Therefore, while both the LWM and the IWM may disappear depending on the degree of synchronism between the beam-waveguide modes, the SWM is always present regardless of the dielectric parameters. The IWM mode is coexisting with the SWM mode, and the dominant mode is determined by the relevant physical parameters (see Sec. III, Table I).

Throughout the remainder of this paper, we assume the following beam parameters.

$$\beta_\perp = 0.4,\ \beta_z = 0.2,\ \nu = 0.002, \tag{2}$$

corresponding to 60.3 KV of the anode voltage and 6.8 Amp. of the total axial current. For future reference, we also define

$$R_o^o = 2.017\ c/\omega_c\ .\quad R_c^o = 4.197\ c/\omega_c \qquad (3)$$

It can be shown that R_o^o and R_c^o are the optimized beam center and the conducting wall locations, respectively, when the dielectric is abent.[3,4]

III. INDIVIDUAL MODE OPERATION

In a previous section we have found that the azimuthally symmetric, TE perturbations exhibit three unstable modes (LWM, IWM, and SWM). In this section we will examine the bandwidth and the growth rate of each mode in terms of the axial velocity spread. With the beam parameters given in Eq. (2), we perform extensive numerical investigations on the physical parameters to achieve the optimum bandwidth and growth rate.

The dispersion relation (1) reveals the dependence of the growth on the axial velocity spread. As the axial wavenumber k increases, the reduction in the growth rate due to the spread Δ becomes larger. Therefore, the vulnerability of the growth rate to the spread is the least for the LWM, moderate for the IWM, and the most for the SWM. The spread needed to absolutely stabilize the growth rate is >30%, ~10%, and ~2% for the LWM, IWM, and SWM, respectively. The potential for the wide bandwidth is, however, the highest for the SWM, intermediate for the IWM, and the lowest for the LWM when the spread is small. The bandwidth for the LWM, even without the spread, is intrinsically limited (<20%) due to its stabilization near $\omega = ck$. The different dependency on the spread for the modes drastically changes the picture as the spread increases.

The optimum dielectric constant ε for the wide bandwidth is found to be $\sim\frac{1}{2}(1/\beta_z + 1/\beta_z^2)$ for the IWM, and 1 for the SWM. However, it is a function of the spread for the LWM. When the spread is small (<5%), the optimum ε for the LWM is $\sim 1/\beta_z$ (designated as LWM$^{\varepsilon}$), but the simple waveguide ($\varepsilon = 1$, without dielectric) is preferable for the large spread (designated as LWM^1). The optimum values of the remaining parameters for the wide bandwidth are summarized in Table I.

Table I. Optimum parameters.

Mode	Δ	ε	R_c/R_c^o	R_w/R_c^o	R_o/R_o^o
LWM$^{\varepsilon}$	<5%	5.0	0.80	0.62	1.1
LWM^1	5~30%	1.0	1.0	---	1.0
LWM	<10%	15.2	0.63	0.53	0.9
SWM	<2%	1.0	1.0	---	0.5

Now we compare these modes in terms of the bandwidth and the maximum growth rate as the spread is varied. The bandwidth is defined by the full-width of the real frequency, at which the linear growth rate drops to $\exp(-\frac{1}{2})$ of its maximum value, normalized by the mean real frequency $\bar{\omega}$. The maximum growth rate is also normalized by $\bar{\omega}$. It is found that for a small spread ($\Delta \lesssim 1\%$) the bandwidth for the SWM (>60%) is the broadest, followed by the IWM (~45%), the dielectric LWM$^{\varepsilon}$ (~16%), and the simple LWM^1 (~12%). As the spread increases, the rate of the bandwidth reduction is the highest for the SWM, followed by the IWM, the LWM$^{\varepsilon}$ and the LWM^1, which stays almost unchanged. For a large spread ($\Delta \gtrsim 8\%$), the simple waveguide LWM^1 is wider in its bandwidth (~11%) than the dielectric LWM$^{\varepsilon}$ (~8%), even wider than the IWM (~9%). On the other hand the maximum growth rates for the slow waves (IWM, SWM) are considerably smaller than that for the fast waves (LWM^1, LWM$^{\varepsilon}$). Moreover, the growth rates for the IWM and SWM reduce very rapidly as the spread increases. On the other hand, the fast waves (LWM^1, LWM$^{\varepsilon}$) show insensitivity to the spread.

The preferable mode for a wideband operation in terms of the axial velocity spread (Δ) is summarized in Table II. The modes with asterisk (*) are desired when the high gain is also needed.

Table II. Preferable mode

Δ	Use	Bandwidth
< 1%	SWM	> 60%
	IWM (*)	> 40%
1 ~ 7%	IWM	40 - 25%
	LWM$^{\varepsilon}$(*)	16 - 10%
> 7%	LWM^1	~ 10%

IV. MIXED MODE OPERATION

In the previous section we have found that at small axial velocity spread (e.g., Δ=1%), either of two slow wave modes (IWM or SWM) has a wide band capability. However, this individual mode operation has intrinsic difficulties. The IWM requires the beam center location (R_o) to be close to the dielectric inner wall (R_w), since the perturbed fields tend to concentrate in the dielectric layer. This concentration of the field energy in the layer and the closeness of the beam to the inner wall location pose serious difficulties in the experimental setup through the intense heat dissipation. On the other hand, in the SWM utilization, it is extremely difficult to excite the wave initially, since the optimized SWM requires no dielectric layer and the natural propagation of the slow wave is impossible. However, each mode operation has a remedy for the difficulties of the other mode when two modes exist in mixture. The SWM, which tends to localize the fields at the beam location, not only reduces the field energy in the dielectric layer, but also requires the beam location to be away from the inner wall. On the other hand the IWM, which needs high ε dielectric layer, makes it possible to propagate wide range of the slow waves, thereby providing the necessary initial wave for the SWM operation. Thus the mixed mode gyrotron eliminates difficulties encountered from the individual mode operations. Moreover, the bandwidth of the mixed mode operation is greatly enhanced. Evidently the relevant parameter for the mixed mode is the beam location (R_o).

Now we examine the normalized bandwidth and maximum growth rate in terms of R_o. The other parameters are those given for the IWM (Table I) except R_o, with the beam parameters in Eq. (2). The axial velocity spread is assumed to be 1%. The bandwidth increases from 46% for the pure IWM (R_o/R_o^o=0.9) to 90% bandwidth for the mixed mode (R_o/R_o^o = 0.5). Out of 90% bandwidth for the mixed mode, 78% is from the SWM. On the other hand, the normalized maximum growth rate decreases from 0.77% for the pure IWM to 0.36% for the mixed mode. As R_o decreases, the contribution of the SWM increases, thereby accounting for the wider bandwidth and the lower growth rate.

Although our model does not include the dielectric loss mechanism, we can relatively examine the heat dissipation in the dielectric layer by comparing the energy contained in the layer when the beam location is reduced from R_o/R_o^o=0.9 (pure IWM) to =0.5 (mixed mode). The ratio of the bandwidth-integrated field energy in the dielectric layer (W_D) to that in the total cross section (W_T) is examined with the variation of the beam location R_o. The intensity of the input wave is assumed to be the same over the whole region of the bandwidth. The ratio W_D/W_T is reduced from 83% for the pure IWM to 24% for the mixed mode. Therefore, for example, if the dielectric layer withstands 50 KW of the wave power for the pure IWM operation, it can withstand 175 KW (3.5 times) of the power for the mixed mode. The reduction of W_D/W_T with decreasing R_o is attributed to the increasing participation of the SWM.

V. CONCLUSION

We have examined the linear dispersion relation for the azimuthally symmetric, TE perturbation in a dielectric loaded gyrotron. It is found that there exist three unstable modes characterized by their wave lengths: the long (LWM), the intermediate (IWM) and the short (SWM) wavelength modes. Both the LWM and the IWM arise from the beam-waveguide mode coupling, whereas the SWM is driven by the localized fields or the beam location.

The optimum conditions for the wide operation are obtained for individual mode operation (Table I). The bandwidth in excess of 40% is possible for the slow waves (SWM, IWM) at a small axial velocity spread, and it decreases rapidly as the spread increases. On the other hand the LWM yields approximately 10% of the bandwidth insensitive to the spread. It is also shown that as the spread increases, the preferable choice of the mode changes from the SWM, to the IWM, and to the LWM (Table II).

By reducing the beam location, the usual IWM is integrated with the SWM, and the resulting bandwidth for the mixed mode is broader than that for either of the two individual modes. It is found that up to 90% of the bandwidth is attainable at the small spread ($\lesssim$ 1%) with substantial contribution of the SWM. Moreover, the presence of the SWM reduces considerably the troublesome heat dissipation in the dielectric layer. Therefore the mixed mode operation can withstand up to 3.5 times of the power compared to that for the usual IWM operation.

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