Effect of the azimuthal inhomogeneity of electron emission on gyrotron operation

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Gyrotrons are typically driven by electron beams produced by magnetron-type thermionic electron guns operating in the regime of temperature limited emission. Very often, the current density in such annular electron beams is azimuthally nonuniform. To describe the effect of this nonuniformity on gyrotron operation, the code MAGY [M. Botton *et al.*, IEEE Trans. Plasma Sci. **26**, 882 (1998)], which is widely used for modeling of slow and fast microwave sources, was properly modified. The results of numerical simulations demonstrate the effect of azimuthal inhomogeneity of the emission on the excitation of low- and high-frequency satellites of the operating mode and on the efficiency degradation. The calculations are done for parameters typical for megawatt-class, long-pulse, millimeter-wave gyrotrons, which are currently under development for electron cyclotron plasma heating and current drive experiments in controlled fusion reactors. [DOI: 10.1063/1.1379968]

I. INTRODUCTION

Gyrotron oscillators and amplifiers are usually driven by beams of gyrating electrons produced by magnetron-type injection guns (MIGs). Typically, these MIGs operate in the regime of temperature limited emission. Therefore, even a small azimuthal deviation of the emitter temperature results in an azimuthal inhomogeneity of the electron emission. Recent experimental studies[1–3] showed that sometimes this inhomogeneity can be very significant, which can lead to the degradation of the interaction efficiency.

So far, this issue has not been studied theoretically although the quasilinear theory of mode interaction in gyrotrons with azimuthally inhomogeneous electron emission has recently been developed.[4] In the present paper we study the effect of the azimuthal inhomogeneity of electron emission on gyrotron operation by more accurate means. For this purpose, we properly generalized the code MAGY[5] which has been successfully used for describing time-dependent, self-consistent, nonlinear processes in gyrotron oscillators[6] and amplifiers.[7] A new version of the code allowed us to study self-consistent, multifrequency processes in gyrodevices, in which the beam current is azimuthally inhomogeneous. It was taken into account that this inhomogeneity makes the velocity spread and the orbital-to-axial electron velocity ratio also azimuthally dependent.

Our paper is organized as follows. In Sec. II we discuss the effect of azimuthal nonuniformity of the emission on the mode interaction. In Sec. III we describe corresponding generalization of the source term in equations for wave excitation for the case of azimuthal inhomogeneity of the abovementioned electron beam parameters. In Sec. IV we present the results of multimode simulations for a 110 GHz gyrotron operating in the $TE_{22,6}$ mode. These simulations show the effect of the azimuthal inhomogeneity of the beam current on excitation of parasitic modes with different azimuthal indices, viz., $TE_{21,6}$ and $TE_{23,6}$ modes, which can accompany the operating $TE_{22,6}$ mode. In Sec. V we analyze the effect of beam azimuthal inhomogeneity on the gyrotron efficiency. Finally, in Sec. VI we discuss the results obtained and summarize our paper.

II. GENERAL REMARKS ON THE MODE INTERACTION IN GYROTRONS WITH AZIMUTHALLY UNIFORM AND NONUNIFORM EMISSION

Gyrotrons with cylindrical cavities and annular electron beams typically operate in one of the rotating transverse electric (TE) modes. In ideally symmetric devices, such orthogonal modes are uncoupled in the linear regime. This means that, if electrons excite several modes simultaneously, their amplitudes grow independently until nonlinear effects become important. At this nonlinear stage the mode interaction occurs.

The most common effect in the mode interaction is the mutual effect of mode intensities, which occurs even in the case of pairwise interaction.[8] For gyrotrons with cylindrical cavities operating in high-order azimuthally rotating modes

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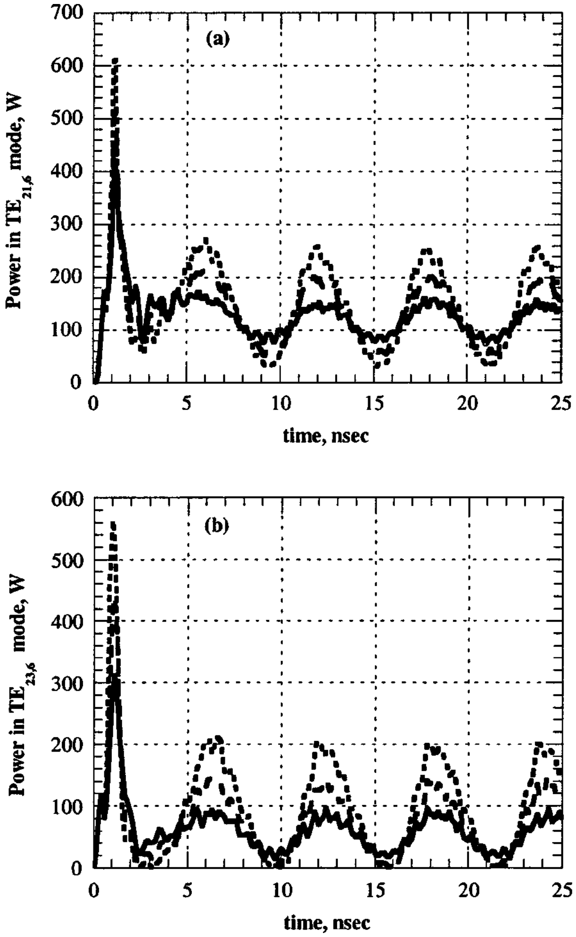

FIG. 1. Temporal dependence of the power of satellites [(a) $TE_{21,6}$ mode, (b) $TE_{23,6}$ mode] for different values of the parameter u describing azimuthal nonuniformity of the emission at the distance $L=8.5$ cm. Solid, dashed, and dotted lines correspond to $u=0.1$, 0.2, and 0.3, respectively.

($\sim\exp\{i(\omega_s t - m_s\psi)\}$, where ω_s and m_s are the mode frequency and azimuthal index, respectively) quite typical is the situation when three modes, which differ in azimuthal indices only, form a quasiequidistant spectrum. For such modes the conditions

$$|\omega_1+\omega_3-2\omega_2|\lesssim\frac{\omega}{Q}, \tag{1}$$

$$m_1+m_3=2m_2 \tag{2}$$

can be fulfilled, which makes the mode interaction dependent not only on mode intensities but also on certain phase relations.[8] [In Eqs. (1) and (2) the indices 2, 1, and 3 denote the operating mode and the low frequency and high frequency satellites, respectively.] These nonlinear processes may cause a self-modulation[9] or sideband[10] instability.

An azimuthal nonuniformity of the emission may cause the linear coupling between modes. This happens when the difference between azimuthal indices of two modes corresponds to the nonzero azimuthal harmonic in the Fourier transform of the function $u(\psi)=\Sigma_l u_l e^{il\psi}$, describing the azimuthal nonuniformity of the emission, i.e., $u_{m_2-m_1}\neq 0$. This linear coupling was taken into account in Ref. 4. In a certain sense, the result of the azimuthal nonuniformity of the emission is similar to the effect of displacement of an electron beam with respect to the resonator axis studied in Refs. 11 and 12. Certainly, this mode coupling due to the azimuthal nonuniformity can be important not only at the linear stage but also in nonlinear regimes, as will be shown in the following.

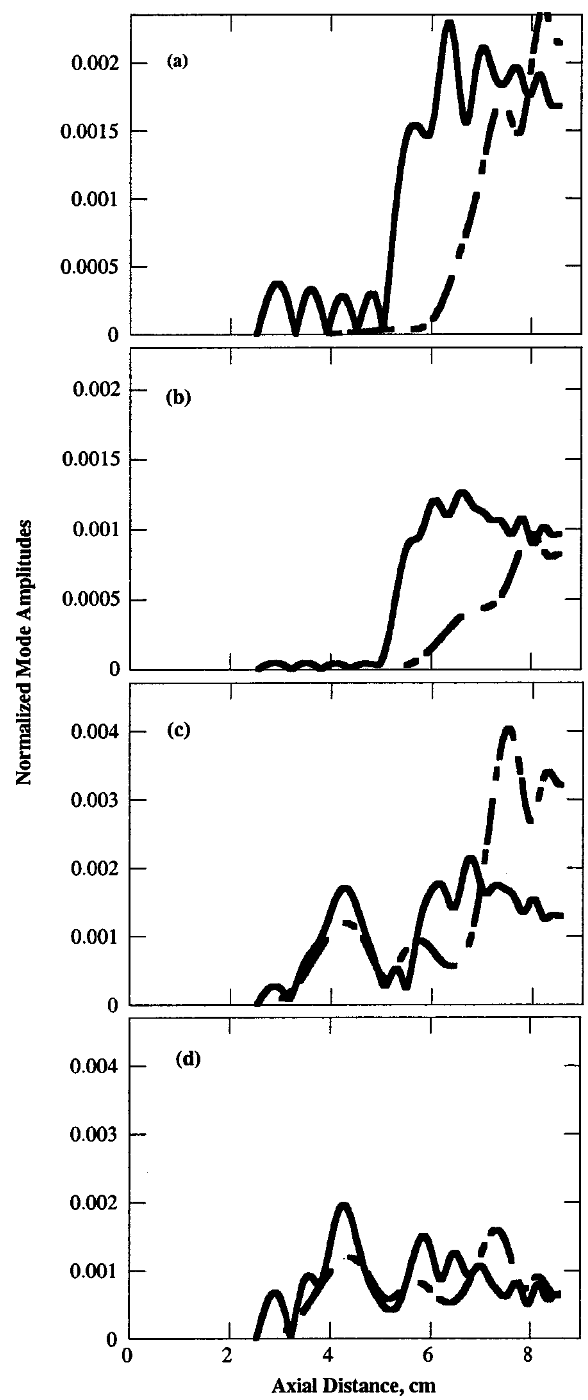

FIG. 2. Axial distribution of satellites at the given instant of time (25 ns) for four cases: (a) ideal beam, i.e., no velocity spread, uniform emission, (b) with velocity spread, uniform emission, (c) no velocity spread, nonuniform emission, $u=0.3$, (d) 5.5% orbital velocity spread, nonuniform emission, $u=0.3$. Solid and dash-dotted lines correspond to $TE_{21,6}$ and $TE_{23,6}$ modes, respectively.

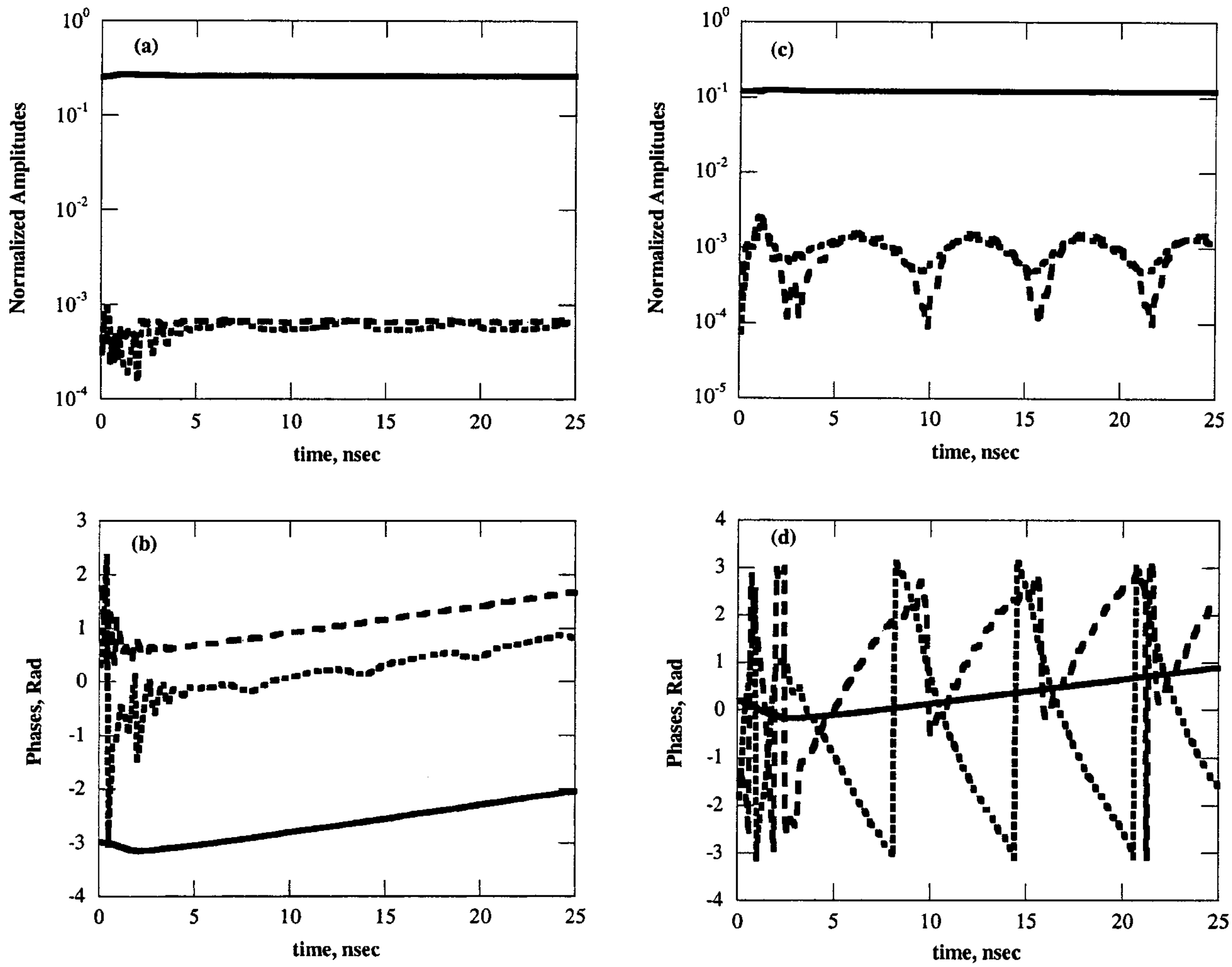

FIG. 3. Temporal dependencies of satellite amplitudes and phases in different cross sections: the amplitudes (a) and phases (b) at the end of the regular cavity ($L=5$ cm) and the amplitudes (c) and phases (d) at the end of the uptapered region ($L=8.5$ cm). All calculations are done for a 5.5% orbital velocity spread. Solid, dashed, and dotted lines correspond to $TE_{22,6}$, $TE_{23,6}$, and $TE_{21,6}$ modes, respectively.

III. FORMALISM DESCRIBING THE EFFECT OF AZIMUTHAL INHOMOGENEITY

As is known, the amplitude of any mode excited in a cavity by an electron beam at the frequency ω is proportional to the source term

$$S=\left\langle \int_V \mathbf{j}_\omega \mathbf{E}_s^* \, dv \right\rangle. \tag{3}$$

Here V is the resonator volume, the beam current density is represented as $\mathbf{j}=\mathrm{Re}\{\mathbf{j}_\omega e^{i\omega t}\}$, and the electric field of the mode is represented as $\mathbf{E}=\mathrm{Re}\{A_s\mathbf{E}_s(\mathbf{r})e^{i\omega t}\}$, where A_s is the mode amplitude and the function $\mathbf{E}_s(\mathbf{r})$ describes the spatial structure of the sth mode. Angular brackets in (3) designate the averaging over all stationary distributions of electrons, viz., initial distributions in electron coordinates and velocities. These distributions will be described in the following by the function $W(\mathbf{R}_{\perp 0},\boldsymbol{\beta}_0)$, where $\mathbf{R}_{\perp 0}=(R_0,\psi)$ determines transverse coordinates of electron guiding centers and $\boldsymbol{\beta}_0=\mathbf{v}_0/c$ is the initial electron velocity $\mathbf{v}_0$ normalized to the speed of light c.

The simplest model of an electron beam is a thin annular electron beam in which the current density is azimuthally homogeneous and the electron spread in velocities and guiding center radii is negligibly small. In such a case $W(\mathbf{R}_{\perp 0},\boldsymbol{\beta}_0)=(1/2\pi R_0)\delta(r-R_0)\delta(\beta_\perp-\beta_{\perp 0})\delta(\beta_z-\beta_{z0})$, so the averaging over distributions in electron velocities and beam cross section in Eq. (3) is reduced to the averaging over ψ, which in the case of a single-mode operation can be eliminated[13,14] (see also Ref. 5). In the case of a multimode large-signal operation, this averaging, however, cannot be eliminated because electrons undergo the effect of the azimuthally dependent, multimode field $\mathbf{E}_\Sigma=\Sigma_s A_s\mathbf{E}_s(r)e^{i(\omega_s t-m_s\psi)}$. Consideration of the simplest cubic nonlinearity, which corresponds to the account in the current density $\mathbf{j}_\omega$ in Eq. (3) of the terms proportional to $\mathbf{E}_\Sigma|\mathbf{E}_\Sigma|^2 e^{-i\omega t}$, shows that in this case there are some azimuthally dependent terms, which give zero contribution after averaging over ψ. There are also some terms obeying conditions given by Eqs. (1) and (2). These terms do not depend on ψ and they are responsible for nonlinear phase-correlated processes discussed previously. When one cannot neglect the velocity spread, while the beam current density is still azimuthally homogeneous, the function $W(\mathbf{R}_{\perp 0},\boldsymbol{\beta}_0)$ for a thin annular electron beam can be written as $(1/2\pi R_0)\delta(r-R_0)f(\beta_{\perp 0},\beta_{z0})$. Typically, in gyrotron electron beams the electrons acquire a certain spread in pitch ratios α

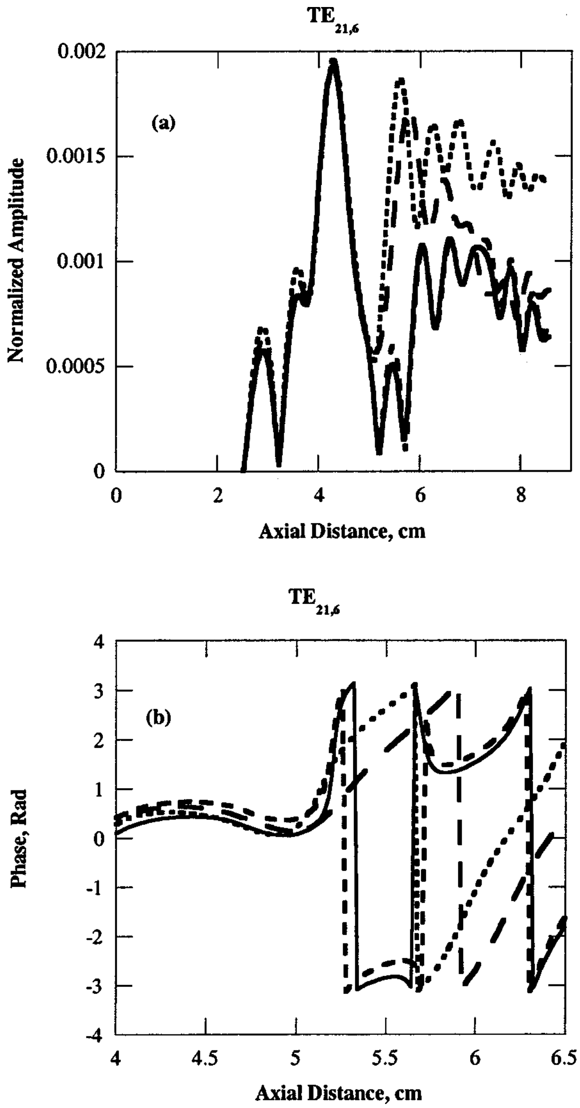

FIG. 4. Variations in the axial profile of the amplitude (a) and phase (b) of the $TE_{21,6}$ mode within one beating period. Solid, dotted, long dash, and short dash lines correspond to $t=10$, 12, 14, and 16 ns, respectively.

$=\beta_\perp/\beta_z$, while the spread in energies is negligibly small. Then, just one function [typically $f(\beta_{\perp 0})$] is enough to describe the electron velocity distribution, since, after specifying $\beta_{\perp 0}$, one can find the corresponding value of β_{z0} from $\beta_{z0}^2=1-\gamma_0^{-2}-\beta_{\perp 0}^2$, i.e., $f(\beta_{\perp 0},\beta_{z0})=f(\beta_{\perp 0})\,\delta(\beta_{z0}-\sqrt{1-\gamma_0^{-2}-\beta_{\perp 0}^2})$. Here γ_0 is the initial energy of electrons normalized to the rest energy.

When the beam current is azimuthally inhomogeneous, the distribution function, at the first step, can be written as $W=(1/2\pi R_0)\,\delta(r-R_0)u(\psi)f(\beta_{\perp 0})$, where the function $u(\psi)$ introduced previously describes the azimuthal inhomogeneity. (The normalization condition for this function is $\int_0^{2\pi}u\,d\psi=2\pi$.) As discussed previously, the presence of nonzero terms $u_{l\neq 0}$ in the Fourier transform of the function $u(\psi)=\Sigma_l u_l e^{il\psi}$ may cause additional coupling between modes. This follows from the fact that earlier-mentioned terms, which give zero contribution after averaging over ψ in the case of the uniform emission, can give nonzero contribution in the case of nonuniform beams.

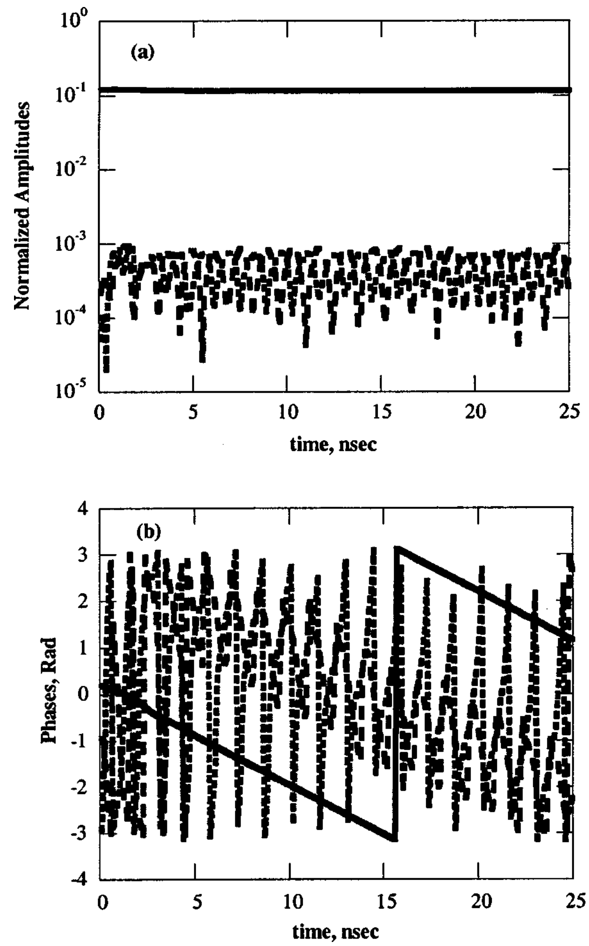

FIG. 5. Modes' amplitudes (a) and phases (b) at higher magnetic field: $B_0=44.518$ kG, $\alpha=1.435$, 5.5% orbital velocity spread, $u=0.3$. Solid, dotted, and dashed lines correspond to $TE_{22,6}$, $TE_{21,6}$, and $TE_{23,6}$ modes, respectively.

In real devices the situation is, however, more complicated because typically the electron velocity spread and the pitch-ratio α depend on the beam current. Therefore, even ignoring the "cross-talks" between beamlets via the space charge fields, we should take into account the fact that the

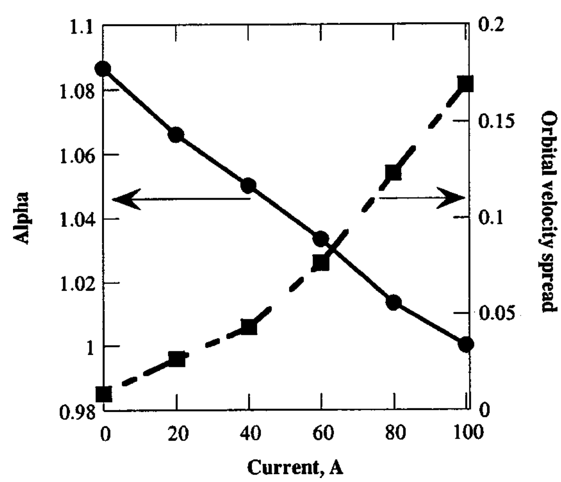

FIG. 6. Orbital-to-axial velocity ratio (α) and orbital velocity spread as the function of beam current.

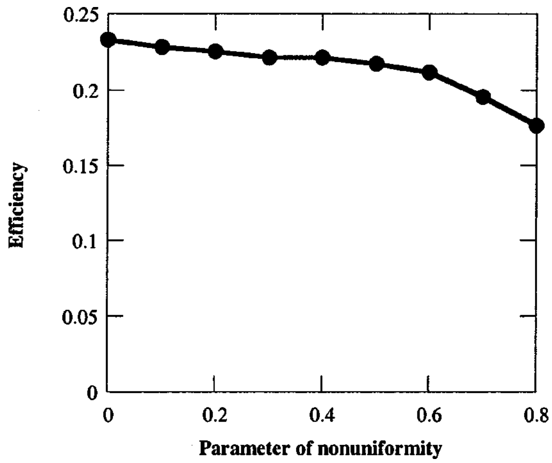

FIG. 7. Efficiency as the function of emission inhomogeneity.

pitch ratio α and the velocity spread $\Delta\beta_{\perp 0}/\overline{\beta_{\perp 0}}$ become azimuthally dependent. (Here $\overline{\beta_{\perp 0}}$ is the mean value of $\beta_{\perp 0}$.) A simple way to treat this problem can be based on the information about the azimuthal dependence of the current density (similar to that measured in Refs. 1–3) and the dependence of α and velocity spread on the beam current, which can be obtained from e-gun[15] simulations. Then, we can assume that in each beamlet with the azimuthal coordinate ψ the pitch ratio α and velocity spread correspond to the beam current $I_b(\psi)$, which is the real beam current multiplied by $u(\psi)$. This means that now $W=(1/2\pi R_0)\delta(r-R_0)u(\psi)f(\beta_{\perp 0},\psi)$, i.e., we should, first, prescribe specific α and spread to each beamlet and then average in Eq. (3) over all beamlets in order to correctly calculate the source term.

In Sec. IV we will use a simplified approach, in which the azimuthal dependence of α and spread is neglected, for studying the effect of azimuthal inhomogeneity on excitation of parasitic modes. Then, in Sec. V we will do a more careful analysis of the effect of beam inhomogeneity on gyrotron efficiency. In this study the azimuthal dependence of α and velocity spread will be taken into account.

IV. EXCITATION OF SATELLITES

In the following we present the results of simulations done for a 110 GHz gyrotron operating in the $TE_{22,6}$ mode. The parameters chosen in our simulations were close to the parameters of a 110 GHz gyrotron developed at CPI.[16] More exactly, we used a new set of beam parameters which would enable operation at power levels up to 1.5 MW, namely: a 96 kV, 40 A electron beam with an orbital-to-axial velocity ratio of 1.435 and 5.5% rms spread in orbital velocities. Simultaneously with excitation of the operating $TE_{22,6}$ mode we considered the excitation of satellite $TE_{21,6}$ and $TE_{23,6}$ modes. At the fixed value of the external magnetic field, $B_0=44.318$ kG, which provides a 1.5 MW power level of the operating mode, the power of satellites was calculated for different values of the degree of azimuthal inhomogeneity u: the function $u(\psi)$ introduced previously was represented as $1+u\sin\psi$.

The temporal dependence of the power of these two modes for different u's is shown in Fig. 1 where Figs. 1(a) and 1(b) correspond to $TE_{21,6}$ and $TE_{23,6}$ modes, respectively. It was found that, even in the case of uniform emission ($u=0$), the satellites are present due to the above-discussed parametric processes, which can be associated with the self-modulation or sideband instability of the operating mode. As the emission inhomogeneity increases, the beating effects in the satellites' behavior increase as well. At the same time, the average value of the satellite power remains at the level from 100 to 200 W. Note that in the absence of electron velocity spread the power of satellites is several times higher.

This is illustrated by Fig. 2, which shows the axial distribution of satellites at $t=25$ ns for four cases: (a) no velocity spread and azimuthally uniform emission, (b) with velocity spread, the current is still uniform, (c) no velocity spread, the emission is inhomogeneous, (d) there are both velocity spread and azimuthal nonuniformity of the emission. The quasiregular section of the cavity is located between 2.5 and 5.2 cm. The two first cases [(a) and (b)] indicate that in the case of azimuthally uniform emission the high-frequency $TE_{23,6}$ mode is excited in the output uptaper when the amplitude of the low-frequency $TE_{21,6}$ mode is large enough. (Note that the amplitude of the operating $TE_{22,6}$ mode is larger than the satellite amplitudes shown in Fig. 2 by more than two orders of magnitude.) It was also found that the power level of satellites is quite sensitive to the shape of uptaper; in smooth uptapers it is much lower. The velocity spread reduces the satellite amplitudes by a factor of 2 [cf., Figs. 2(a) and 2(b)].

When the emission is nonuniform, the $TE_{23,6}$ mode is excited directly inside the cavity, as shown in Figs. 2(c) and 2(d). This clearly indicates the enhancement of the mode coupling due to the emission nonuniformity. In the case of the beam without velocity spread, the emission nonuniformity can significantly enhance the intensity of satellites, as follows from comparison of Fig. 2(a) with Fig. 2(c). However, the presence of velocity spread greatly mitigates the effect of emission nonuniformity, as follows from comparison of Fig. 2(c) with Fig. 2(d).

There is also another, even more interesting effect, which is a different temporal dependence of amplitudes and phases of satellites in different cross sections. This effect is illustrated by Fig. 3, where in Figs. 3(a) and 3(b) the amplitudes and phases, respectively, are shown at the distance $L=5$ cm while Figs. 3(c) and 3(d) show, respectively, the amplitudes and phases at the distance $L=8.5$ cm. (Results shown in Fig. 3 correspond to 5.5% orbital velocity spread.) As follows from comparison of two pairs of these figures, at the end of a regular cavity ($L=5$ cm) the satellites are phase locked and they oscillate at the frequency of the operating mode. However, at the output of the uptapered region ($L=8.5$ cm) the satellites oscillate at their own frequencies, which are different from the operating mode frequency and these modes exhibit pulsations, also shown in Fig. 1 for the cases of nonzero u's.

These results clearly indicate the importance of interaction processes in the gyrotron uptapers. (Recently, the importance of this effect for operation of gyroamplifiers was discussed in Ref. 17.) To better illustrate this conclusion, in Fig. 4 the axial dependencies of the amplitude [Fig. 4(a)] and phase [Fig. 4(b)] of the low-frequency satellite, $TE_{21,6}$ mode are shown for several instances of time within one beating period. [As is seen in Figs. 3(a) and 3(b), the beating period is about 6 ns.] Results presented in Fig. 4(a) show that the amplitude of this satellite inside the cavity remains practically constant but it oscillates in the uptaper. Results shown in Fig. 4(b) demonstrate that the most important changes in the phase occur just in the region where the regular part of the cavity is connected to the uptaper, just in this small region of cavity opening (between 5 and 5.5 cm) temporal changes in the phase are the most significant. At larger distance this mode operates further from cutoff and, therefore, its phase changes in a more regular manner.

Since the gyrotron operation strongly depends on the external magnetic field B_0, even relatively small changes in B_0 may cause significant changes in the beating period. An example is shown in Fig. 5(a) for the magnetic field which is 200 G higher than in the previous case. As follows from comparison of Fig. 5(a) with Figs. 3(c) and 3(d) this small increase in B_0 does not cause any serious changes in the amplitude of the operating mode. At the same time it causes a small decrease in the amplitudes of parasites and drastically shortens the beating period of these satellites: from 6 ns to about 1.5 ns. As the temporal dependencies of phases indicate, there are significant changes in the frequency pulling of all three modes.

These results show that the azimuthal inhomogeneity of electron emission transforms constant amplitude satellites into the spikes whose peak amplitudes can be several times larger than in the azimuthally homogeneous case. They also show the importance of processes in the uptapered region for satellite excitation.

V. EFFICIENCY DEGRADATION

As we discussed in Sec. II, the azimuthal nonuniformity of the electron emission should affect the interaction efficiency, because it affects the electron velocity spread and the pitch ratio α. This statement is illustrated by Fig. 6, in which the results of e-gun simulations for a 1 MW, 110 GHz gyrotron are shown as the dependencies of the pitch ratio α and transverse velocity spread on the beam current. As we discussed previously, when the azimuthal dependence of the beam current is given by $I_b = I_{b0} u(\psi)$ (here I_{b0} is the mean value of the current), the pitch ratio and the velocity spread for each beamlet should be taken correspondingly to a given $I_b(\psi)$. So, the dependencies shown in Fig. 6, in combination with the azimuthal dependence of the beam current given by $u(\psi)$, allow one to analyze the effect of the azimuthal nonuniformity of the emission on the gyrotron efficiency.

For the case when the nonuniformity can be approximated by $u(\psi) = 1 + u \sin\psi$, the dependence of the efficiency on the nonuniformity parameter u is shown in Fig. 7. The calculations were done for a 1 MW, 110 GHz tube operating at the beam voltage 80 kV, the beam current 40 A and the pitch ratio $\alpha = 1.066$. The external magnetic field of a superconducting solenoid in the interaction region is equal to 44.318 kG. The results shown in Fig. 7 indicate that the efficiency degradation becomes significant when the nonuniformity parameter u is larger than 0.5.

In order to describe this effect more accurately, we replaced our approximation of the nonuniformity given by $u(\psi) = 1 + u \sin\psi$ by the real dependence $u(\psi)$ which was experimentally measured for the same tube, for which the predicted pitch ratio and velocity spread were shown in Fig. 6. These measurements were compiled by Bishofberger.[18] The simulations predict an efficiency of 21.4% when this measured nonuniformity is taken into account; while in the same gyrotron with the uniform emission, the efficiency for $u = 0$ is 23.3% (Fig. 7). This difference indicates the relative change in efficiency by more than 8%. For gyrotrons with optimal parameters, which in the case of ideally uniform emission yield efficiency of about 35%, this corresponds to degradation from 35% to nearly 32%.

VI. SUMMARY

The operation of gyrotrons with azimuthally inhomogeneous electron current has been studied. To do this, the code MAGY was properly modified. It was shown that the azimuthal inhomogeneity may cause the appearance of pulsating satellites in the vicinity of a high-order operating mode. It was found that interaction in the output uptaper region can be important for satellite excitation: In some cases the satellites excited inside the cavity at the frequency of the operating mode oscillate at different frequencies at the output. It was also shown that, in the case of typical nonuniformity of the emission and typical dependence of the velocity spread on the beam current, the efficiency can be by 2%–3% lower than in gyrotrons with ideally uniform emission.

Note that in this paper we ignored the influence of the ''cross-talk'' between beamlets with different current density on the properties of the beamlets. However, the difference between the self-fields of these beamlets may cause the appearance of an azimuthal component in the electric self-fields of the beam. In combination with the axial external magnetic field this will cause a radial drift of electrons. Needless to say, this drift can be especially important for mirroring particles trapped either in the region between the cavity entrance and the electron gun or between the cavity exit and the depressed collector.[19]

ACKNOWLEDGMENTS

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[1] R. Advani, M. Pedrozzi, K. E. Kreischer, and R. Temkin, *23rd International Conference on Infrared and Millimeter Waves, University of Essex, UK, 7–11 September 1998, Conference Digest*, edited by T. J. Parker and S. R. P. Smith (Hops Reprographics, Colchester, UK, 1998), p. 173.

[2] R. Advani, S. Korbly, K. Kreischer, M. Shapiro, and R. Temkin, *24th International Conference on Infrared and Millimeter Waves, Monterey,*

CA, 6–10 September 1999, Conference Digest, edited by L. A. Lombardo (University of California, Davis, 1999), paper W-A3.
[3] M. Yu. Glyavin, A. L. Goldenberg, A. N. Kuftin, V. K. Lygin, A. S. Postnikova, and V. E. Zapevalov, IEEE Trans. Plasma Sci. **27**, 474 (1999).
[4] G. S. Nusinovich and M. Botton, Phys. Plasmas **8**, 1029 (2001).
[5] M. Botton, T. M. Antonsen, Jr., B. Levush, K. T. Nguyen, and A. N. Vlasov, IEEE Trans. Plasma Sci. **26**, 882 (1998).
[6] W. C. Guss, M. A. Basten, K. E. Kreischer, R. J. Temkin, T. M. Antonsen, Jr., S. Y. Cai, G. Saraph, and B. Levush, IEEE Trans. Plasma Sci. **22**, 871 (1994).
[7] J. P. Calame, M. Garven, J. J. Choi, K. Nguyen, F. Wood, M. Blank, B. G. Danly, and B. Levush, Phys. Plasmas **6**, 285 (1999).
[8] G. S. Nusinovich, IEEE Trans. Plasma Sci. **27**, 313 (1999).
[9] G. S. Nusinovich and V. E. Zapevalov, Radiotekh. Elektron. (Moscow) **30**, 563 (1985).
[10] B. Levush and T. M. Antonsen, Jr., IEEE Trans. Plasma Sci. **18**, 260 (1990).
[11] O. Dumbrajs and S. Liu, IEEE Trans. Plasma Sci. **20**, 126 (1992).
[12] G. S. Nusinovich, O. Dumbrajs, and B. Levush, Phys. Plasmas **2**, 4621 (1995).
[13] A. V. Gaponov, M. I. Petelin, and V. K. Yulpatov, Radiophys. Quantum Electron. **10**, 794 (1967).
[14] M. A. Moiseev and G. S. Nusinovich, Radiophys. Quantum Electron. **17**, 1305 (1974).
[15] W. B. Herrmannsfeldt, SLAC Report No. 226, Stanford, CA, November 1979; also Nucl. Instrum. Methods Phys. Res. **187**, 245 (1981).
[16] K. Felch, M. Blank, P. Borchard, T. S. Chu, J. Feinstein, H. R. Jory, J. A. Lorbeck, C. M. Loring, Y. M. Mizuhara, J. M. Neilson, R. Schumacher, and R. J. Temkin, IEEE Trans. Plasma Sci. **24**, 558 (1996).
[17] K. Nguyen, J. Calame, B. Levush, B. Danly, and M. Garven, APS-DPP Meeting, Quebec City, Quebec, Canada, 23–27 October 2000; Bull. Am. Phys. Soc. **45**, 294 (2000), paper UI3 2.
[18] K. A. Bishofberger, B. Sci. thesis, MIT, June 1996.
[19] C. B. Liu and T. M. Antonsen, Jr., IEEE Trans. Plasma Sci. **26**, 825 (1998).