PFC/JA-90-44

LINEAR AND NONLINEAR THEORY OF CYCLOTRON AUTOSONANCE MASERS WITH MULTIPLE WAVEGUIDE MODES

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December, 1990

Submitted to Physics of Fluids B.

Research supported by the Department of Energy Office of Basic Energy Sciences and the High Energy Physics Division, the Office of Naval Resarch, and the Naval Research Laboratory Plasma Physics Division.
ABSTRACT

The interaction of multiple waveguide modes with a relativistic electron beam in an overmoded, single-frequency, cyclotron autoresonance maser amplifier is analyzed using a nonlinear self-consistent model and kinetic theory. It is shown analytically, and confirmed by simulation, that all of the coupled waveguide modes grow at the spatial growth rate of the dominant unstable mode, but suffer different launching losses which depend upon detuning. The phases of coupled modes are locked in the exponential gain regime, and remain approximately locked for some finite interaction length beyond saturation. The saturated power in each mode is found to be insensitive to the input modal rf power distribution, but sensitive to detuning. Simulations indicate that the saturated fractional rf power in a given mode reaches a maximum at its resonant magnetic field, and then decreases rapidly off resonance. Good agreement is found between the simulations and the kinetic theory in the linear regime.

PACS numbers: 42.52.+x, 52.35.Mw, 52.75.Ms
I. INTRODUCTION

The linear and nonlinear interaction of multiple electromagnetic eigenmodes with relativistic charged particle beams has been the subject of active research in the generation of coherent radiation using free electrons. Multimode phenomena occur in oscillator as well as in amplifier configurations. In oscillator systems, such as free electron laser (FEL) oscillators\(^1-^3\) and gyrotrons,\(^4\) mode competition determines the temporal behavior of the eigenmodes of the cavity and the radiation spectrum. In an overmoded, single-frequency amplifier, the temporal dependence of the eigenmodes is nearly sinusoidal, but the eigenmodes evolve spatially as the interaction length increases. A nonlinear, multimode theory is indispensable in order to predict the radiation power in each mode and the transverse field profile.

Multimode interactions have been investigated using linear theory\(^5\) and computer simulations\(^6\) for FEL amplifiers, but detailed comparison between theory and simulations are not (yet) available. Recently, Schill\(^7,^8\) and Seshadri\(^9\) have developed a linear kinetic theory of multimode cyclotron resonance masers. Also, competition among absolutely unstable modes has been investigated using simulation techniques.\(^9\) There have been few theoretical studies of the nonlinear interaction of multiple convective waveguide modes and the electron beam in overmoded cyclotron autoresonance maser (CARM) amplifiers. The goal of this paper is to develop a formalism which can treat the linear and nonlinear evolution of an overmoded, single-frequency CARM system with an arbitrary number of transverse-electric (TE) and transverse-magnetic (TM) waveguide modes coupling to the electron beam. The preliminary results of this paper have been reported earlier.\(^1^0\)

The CARM interaction\(^1^1,^1^2\) occurs when a relativistic electron beam undergoing cyclotron motion in a uniform magnetic field \(B_0 \hat{z}\) interacts with a co-propagating electromagnetic wave \((\omega, \bar{k})\). The cyclotron resonance condition is \(\omega = k_z v_x + \Omega_c / \gamma\). Here, \(v_x\) and \(\gamma\) are, respectively, the axial velocity and relativistic mass factor of the beam.
electrons; $l$ is the harmonic number; $\Omega_c = eB_0/m_0c$ is the nonrelativistic cyclotron frequency; $m_0$ and $-e$ are the electron mass and charge, respectively; and $c$ is the speed of light in vacuo.

The physics of CARMs\textsuperscript{13–15} has been studied theoretically and experimentally. Experimental results on CARM oscillators\textsuperscript{16,17} and amplifiers\textsuperscript{18,19} have been reported recently. Theoretical work has included one-dimensional linear and nonlinear theory,\textsuperscript{20,21} three-dimensional linear and nonlinear theory of the CARM interaction with a single TE or TM waveguide mode,\textsuperscript{12,22} the nonlinear efficiency studies,\textsuperscript{11} the investigation of efficiency enhancement by magnetic field tapering,\textsuperscript{21,23} the stability calculation of absolute instabilities,\textsuperscript{24} the stabilization of the CARM maser instability by an intense electron beam,\textsuperscript{25} and the studies of radiation guiding.\textsuperscript{26}

In this paper, we present a general treatment of multimode interactions in an overmoded single-frequency CARM amplifier. The present analysis consists of two approaches: linear kinetic theory and computer simulations based on a fully nonlinear, three-dimensional, self-consistent model. The Maxwell-Vlasov equations are linearized to derive amplitude equations for the coupled waveguide modes in the small-signal regime. The amplitude equations are solved with the Laplace transform techniques, resulting in a dispersion relation with cyclotron harmonics and an arbitrary number of TE and TM modes. The Laplace transform analysis allows for analytical calculation of launching losses and the three-dimensional field profile (amplitude and phase). A complete set of ordinary differential equations describing the nonlinear, self-consistent evolution of the waveguide modes and of the relativistic electron beam are derived, and integrated numerically for a wide range of system parameters. Detailed comparisons between theory and the simulations are made. The general features of the linear and nonlinear multimode interaction are illustrated.

It is shown analytically, and confirmed by simulation, that all of the coupled waveg-
uide modes grow with the dominant unstable mode at the same spatial growth rate, but suffer different launching losses which depend upon detuning characteristics. The phases of coupled modes are locked in the exponential gain regime, and remain approximately locked for some finite interaction length beyond saturation. The saturated rf power in each mode is found to be insensitive to input power distribution, but sensitive to detuning. Simulations indicate that the saturated fractional power for a given mode reaches a maximum at its resonant magnetic field, and then decreases rapidly off resonance. In the transition from one resonance to another, however, adjacent competing modes can have comparable rf power levels at saturation.

The organization of this paper is as follows. After formulating the problem in Sec. II, the Maxwell-Vlasov equations are used to derive the linearized amplitude equations and dispersion relation for the multimode CARM interaction in Sec. III. In Sec. IV, nonlinear CARM equations are derived from the standpoint of particle-wave interactions. In Sec. V, the single-mode CARM interaction is reviewed briefly in the linear and nonlinear regimes. In Sec. VI, the linear and nonlinear evolution of CARM amplifiers with two or more waveguide modes is analyzed, and the general features of multimode phenomena are illustrated.

II. GENERAL FORMULATION OF THE PROBLEM

We consider a relativistic electron beam undergoing cyclotron motion in an applied uniform magnetic field $B_0 \hat{e}_z$ and propagating axially through a cylindrical, perfectly conducting waveguide of radius $r_w$ (Fig. 1). The dynamics of each individual electron is described by the Lorentz force equation

$$\frac{d\vec{p}}{dt} = -e \left[ \vec{E} + \frac{\vec{v}}{c} \times (B_0 \hat{e}_z + \vec{B}) \right], \quad (1)$$
and the evolution of the electron beam is described by the Vlasov equation

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{x}} - e \left[ \vec{E} + \frac{\vec{v}}{c} \times (B_0 \vec{e}_z + \vec{B}) \right] \cdot \frac{\partial f}{\partial \vec{p}} = 0.$$  \hspace{1cm} (2)

Here, \( f(\vec{x}, \vec{p}, t) \) is the electron phase-space density function. In the present CARM amplifier theory, the temporal dependence of the electromagnetic perturbations \( \vec{E}(\vec{x}, t) \) and \( \vec{B}(\vec{x}, t) \) in Eqs. (1) and (2) are assumed to be sinusoidal and consist of TE and TM waveguide modes. It is readily shown from Maxwell’s equations that the axial field components of the TE and TM perturbations satisfy the wave equations

$$\left( \frac{d^2}{dz^2} + \nabla_t^2 + \frac{\omega^2}{c^2} \right) B_{z}^{TE}(r, \theta, z) \exp(-i\omega t) = -\frac{4\pi}{c} \vec{e}_{z} \cdot (\nabla \times \vec{J}),$$  \hspace{1cm} (3)

$$\left( \frac{d^2}{dz^2} + \nabla_t^2 + \frac{\omega^2}{c^2} \right) E_{z}^{TM}(r, \theta, z) \exp(-i\omega t) = 4\pi \frac{\partial J_{z}}{\partial z} + \frac{4\pi}{c^2} \frac{\partial J_{z}}{\partial t}. \hspace{1cm} (4)$$

In Eqs. (3) and (4), \( \nabla_t = \vec{e}_{x} \partial/\partial x + \vec{e}_{y} \partial/\partial y \), \( \omega = 2\pi f \) is the (angular) frequency of the perturbations, and the current and charge density perturbations are defined by

$$\vec{J}(\vec{x}, t) = -e \int \vec{v} f_1(\vec{x}, \vec{p}, t) d\vec{p},$$  \hspace{1cm} (5)

$$\rho(\vec{x}, t) = -e \int f_1(\vec{x}, \vec{p}, t) d\vec{p},$$  \hspace{1cm} (6)

where

$$f_1(\vec{x}, \vec{p}, t) = f(\vec{x}, \vec{p}, t) - f_0(r_p, \theta_p, p_\perp, p_z)$$  \hspace{1cm} (7)
is the distribution function perturbation, and $f_0(r_g, \theta_g, p_\perp, p_z)$ is the equilibrium distribution function. Note that the electron guiding-center radius and azimuthal angle, $r_g$ and $\theta_g$, and perpendicular and axial momentum components, $p_\perp = (p_x^2 + p_y^2)^{1/2}$ and $p_z$, are exact constants of motion for an individual electron in the applied magnetic field $B_0 \vec{e}_z$ (Fig. 2).

Expanding $B_{z,TE}(r, \theta, z)$ and $E_{z,TM}(r, \theta, z)$ in terms of the vacuum $\text{TE}_{mn}$ and $\text{TM}_{mn}$ eigenfunctions $\Psi_{mn}(r, \theta)$ and $\tilde{\Psi}_{mn}(r, \theta)$, respectively, the electromagnetic perturbations can be expressed in the general form

$$
\tilde{E}_t(\vec{x}, t) = \frac{1}{2} \sum_{mn} \left[ E_{mn}(z) \vec{e}_z \times \nabla_{\theta} \Psi_{mn}(r, \theta) + \frac{c}{\omega} \frac{dB_{mn}(z)}{dz} \nabla_t \tilde{\Psi}_{mn}(r, \theta) \right] \exp(-i\omega t) + c.c., \quad (8)
$$

$$
E_z(\vec{x}, t) = \frac{1}{2} \sum_{mn} \frac{c k_m^2}{\omega} B_{mn}(z) \tilde{\Psi}_{mn}(r, \theta) \exp(-i\omega t) + c.c., \quad (9)
$$

$$
\tilde{B}_t(\vec{x}, t) = \frac{1}{2} \sum_{mn} \left[ ic \frac{dE_{mn}(z)}{dz} \nabla_t \Psi_{mn}(r, \theta) + i B_{mn}(z) \vec{e}_z \times \nabla_t \tilde{\Psi}_{mn}(r, \theta) \right] \exp(-i\omega t) + c.c., \quad (10)
$$

$$
B_z(\vec{x}, t) = \frac{1}{2} \sum_{mn} \frac{i c k_m^2}{\omega} E_{mn}(z) \Psi_{mn}(r, \theta) + c.c. \quad (11)
$$

In Eqs. (8)-(11), $E_{mn}(z)$ and $B_{mn}(z)$ are the $z$-dependent amplitude of the $\text{TE}_{mn}$ and $\text{TE}_{mn}$ modes, which evolve due to the CARM interaction. The $\text{TE}_{mn}$ and $\text{TM}_{mn}$ eigenfunctions

$$
\Psi_{mn}(r, \theta) = C_{mn} J_m(k_{mn} r) \exp(i m \theta), \quad (12a)
$$

$$
\tilde{\Psi}_{mn}(r, \theta) = \tilde{C}_{mn} J_m(k_{mn} r) \exp(i m \theta) \quad (12b)
$$
satisfy the equations

\[(\nabla_t^2 + k_{mn}^2)\psi_{mn}(r, \theta) = 0\, ,\]  
\[(\nabla_t^2 + \tilde{k}_{mn}^2)\tilde{\psi}_{mn}(r, \theta) = 0\, ,\]  

and the boundary conditions

\[\frac{\partial\psi_{mn}(r = r_w, \theta)}{\partial r} = 0\, ,\]  
\[\tilde{\psi}_{mn}(r = r_w, \theta) = 0\, .\]

Here, \(J_m(x)\) is the Bessel function of first kind of order \(m\), \(\nu_{mn} = k_{mn}r_w\) is the \(n\)th zero of \(J_m'(x) = dJ_m(x)/dx\), and \(\tilde{\nu}_{mn} = \tilde{k}_{mn}r_w\) is the \(n\)th zero of \(J_m(x)\). With the choice of the normalization factors

\[C_{mn}^2 = \frac{k_{mn}^2}{\pi(\nu_{mn}^2 - m^2)J_m^2(\nu_{mn})}\, ,\]  
\[\tilde{C}_{mn}^2 = \frac{\tilde{k}_{mn}^2}{\pi\nu_{mn}^2J_m^2(\nu_{mn})}\, ,\]

the orthogonality conditions can be expressed as

\[\int_{\pi r_e^2} \psi_{mn}^* \psi_{m'n'} d\sigma = \delta_{mm'}\delta_{nn'}\, ,\]  
\[\int_{\pi r_e^2} \tilde{\psi}_{mn}^* \tilde{\psi}_{m'n'} d\sigma = \delta_{mm'}\delta_{nn'}\, .\]

Substituting Eq. (11) into Eq. (3), multiplying the equation with \(\psi_{mn}^*\), and then integrating the equation over the cross section of the waveguide yields
\[
\left( \frac{d^2}{dz^2} - k_{mn}^2 + \frac{\omega^2}{c^2} \right) E_{mn}(z) = \frac{8\pi i e \exp(i\omega t)}{c^2 k_{mn}^2} \int (\vec{e}_z \times \nabla \tilde{\Psi}_m^* \cdot \vec{v}_f) d\vec{p} d\sigma
\] (17)

for the $TE_{mn}$ mode. Similarly, it is readily shown from Eqs. (4) and (9) that

\[
\left( \frac{d^2}{dz^2} - \tilde{k}_{mn}^2 + \frac{\omega^2}{c^2} \right) B_{mn}(z) = \frac{8\pi i e \omega^2 \exp(i\omega t)}{c^2 \tilde{k}_{mn}^2} \int \tilde{\Psi}_m^* \left( \frac{v_z}{c} + \frac{i c}{\omega} \frac{\partial}{\partial z} \right) f_1 d\vec{p} d\sigma
\] (18)

for the $TM_{mn}$ mode. The (average) rf power flow through the waveguide cross section as a function of interaction length, $z$, is given by

\[
P(z) = \frac{\alpha \omega}{8\pi^2} \int_0^{2\pi/\omega} dt \int (\vec{E} \times \vec{B}) \cdot d\vec{\sigma}.
\] (19)

Substituting Eqs. (8)-(11) into Eq. (19), we have

\[
P(z) = \sum_{mn} [P_{mn}(z) + \tilde{P}_{mn}(z)]
\] (20)

where

\[
P_{mn}(z) = \frac{i c^2 k_{mn}^2}{16\pi\omega} \left( E_{mn} \frac{dE_{mn}^*}{dz} - E_{mn}^* \frac{dE_{mn}}{dz} \right)
\] (21)

and

\[
\tilde{P}_{mn}(z) = \frac{i c^2 \tilde{k}_{mn}^2}{16\pi\omega} \left( B_{mn} \frac{dB_{mn}^*}{dz} - B_{mn}^* \frac{dB_{mn}}{dz} \right)
\] (22)

are the rf power in the $TE_{mn}$ and $TM_{mn}$ modes, respectively. In Secs. III and IV, use
is made of Eqs. (1), (2), (17) and (18) to establish a linear and nonlinear theory of the multimode CARM interaction.

III. LINEAR THEORY

In this section, the Maxwell-Vlasov equations are linearized to derive self-consistent amplitude equations [Eqs. (40) and (41)] in the small-signal regime. The amplitude equations are solved with the Laplace transform technique, resulting in a dispersion relation [Eqs. (44) and (45)] for the CARM instability which includes an arbitrary number of TE and TM waveguide modes. Our Laplace transform analysis allows for analytical calculation of launching losses and the three-dimensional radiation field profile.

A. The Linearized Vlasov Equation

For present purposes, we assume the electron beam to be cold and azimuthally symmetric with respect to the waveguide axis, and express the equilibrium distribution function as

$$f_0(r_\theta, p_\perp, p_z) = \frac{n_b}{2\pi p_{\perp 0}} \delta(p_\perp - p_{\perp 0}) \delta(p_z - p_{z 0}) G(r_\theta),$$  \hspace{1cm} (23)

where $n_b$ is the number of electrons per unit axial length, and

$$\int G(r_\theta) r_\theta dr_\theta d\theta_\theta = 1. \hspace{1cm} (24)$$

The electron phase-space density perturbation $f_1(\vec{z}, \vec{p}, t)$ evolves according to the linearized Vlasov equation

$$\nu_z \frac{df_1}{dz} = \frac{\partial f_1}{\partial t} + \vec{v} \cdot \frac{\partial f_1}{\partial \vec{x}} - \frac{e}{c} (\vec{v} \times \vec{B}_0) \cdot \frac{\partial f_1}{\partial \vec{p}} = e \left( \vec{E} + \frac{\vec{v}}{c} \times \vec{B} \right) \cdot \frac{\partial f_0}{\partial \vec{p}}. \hspace{1cm} (25)$$
Here, since the system is single frequency and the spatial evolution of the perturbations is of interest, the usual total time derivative is replaced by total derivative with respect to the axial distance \( z \). It is convenient to introduce guiding-center variables as illustrated in Fig. 2, where \( r_L = p_L/m_0 \Omega_c \) is the Larmor radius, \( p_x = p_\perp \cos \phi \), \( p_y = p_\perp \sin \phi \), \( \tilde{r}_\perp = \tilde{r}_r \cos(\phi - \theta) + \tilde{r}_\theta \sin(\phi - \theta) \), and \( \tilde{r}_\phi = -\tilde{r}_r \sin(\phi - \theta) + \tilde{r}_\theta \cos(\phi - \theta) \). Using

\[
\frac{\partial f_0}{\partial p} = \tilde{r}_\perp \left( \frac{\partial f_0}{\partial p_\perp} + \frac{\cos \phi_c \partial f_0}{m_0 \Omega_c \partial r_g} \right) - \tilde{r}_\phi \frac{\sin \phi_c \partial f_0}{m_0 \Omega_c \partial r_g} + \tilde{r}_z \frac{\partial f_0}{\partial p_z},
\]

Eq. (25) becomes

\[
v_x \frac{d}{dz} f_1(r, \theta, z, p_\perp, \phi, p_z, t) = e(E_\perp - \beta_z B_\phi) \frac{\partial f_0}{\partial p_\perp} + e(E_z + \beta_\perp B_\phi) \frac{\partial f_0}{\partial p_z} + \frac{e}{m_0 \Omega_c} \left[ (E_\perp \cos \phi_c - E_\phi \sin \phi_c) - \beta_z (B_\perp \sin \phi_c + B_\phi \cos \phi_c) + \beta_\perp B_z \sin \phi_c \right] \frac{\partial f_0}{\partial r_g},
\]

where \( \beta_\perp = v_\perp/c \) and \( \beta_z = v_z/c \). Substituting Eqs. (8)-(11) into Eq. (27) and making use of recurrence relations and Graf's theorem for Bessel functions,\(^{27}\) it can be shown (see Appendix A) that the linearized Vlasov equation can be expressed as

\[
\frac{df_1}{dz} = \frac{e}{2v_x} \sum_{mn} \sum_{q=-\infty}^{\infty} (k_{mn} C_{mn} O_{mnq} + \tilde{k}_{mn} \tilde{C}_{mn} \tilde{O}_{mnq}) f_0 \exp[i \Lambda_{mq}(\phi, \phi_c, t)] + \text{c.c.},
\]

where \( \Lambda_{mq}(\phi, \phi_c, t) = m\phi + q\phi_c - \omega t - m\pi/2 \), and the operators \( O_{mnq} \) and \( \tilde{O}_{mnq} \) are defined by

\[
O_{mnq}(z, r_g, r_L, \frac{\partial}{\partial r_g}, p_\perp, p_z, \frac{\partial}{\partial p_\perp}, \frac{\partial}{\partial p_z}, \frac{\partial}{\partial \phi_c}) = X_{mnq}(r_L, r_g) \left[ \left( \frac{E_{mn}}{\omega} \frac{dE_{mn}}{dz} \right) \frac{\partial}{\partial p_\perp} - \frac{iv_\perp dE_{mn}}{\omega} \frac{dz}{\partial p_z} \frac{\partial}{\partial p_z} \right]
\]
\[- \left[ \frac{Y_{mnq}(r_L, r_g)}{m_0 \Omega_c} \right] \left( E_{mn} + \frac{i v_z dE_{mn}}{\omega \ dz} \right) - \frac{Z_{mnq}(r_L, r_g)}{m_0 \Omega_c} \left( \frac{k_{mn} v_\perp}{2 \omega} \right) E_{mn} \right] \frac{\partial}{\partial r_g}, \quad (29)\]

\[\tilde{0}_{mnq}(z, r_g, r_L, \frac{\partial}{\partial r_g}, p_\perp, p_z, \frac{\partial}{\partial p_\perp}, \frac{\partial}{\partial p_z})\]

\[= \tilde{X}_{mnq}(r_L, r_g) \left\{ \left( \beta_z B_{mn} + \frac{ic dB_{mn}}{\omega \ dz} \right) \frac{\partial}{\partial p_\perp} - \left[ \beta_\perp - \frac{ck_{mn}^2 r_L}{(m + q) \omega} \right] B_{mn} \frac{\partial}{\partial p_z} \right\} \]

\[+ \tilde{Y}_{mnq}(r_L, r_g) \left( \beta_z B_{mn} + \frac{ic dB_{mn}}{\omega \ dz} \right) \frac{\partial}{\partial r_g}, \quad (30)\]

In Eqs. (29) and (30), the geometric factors \(X, Y, Z, \tilde{X}\) and \(\tilde{Y}\) are defined by

\[X_{mnq}(r_L, r_g) = J_{m+q}(k_{mn} r_L) J_q(k_{mn} r_g), \quad (31)\]

\[Y_{mnq}(r_L, r_g) = J_{m+q}(k_{mn} r_L) J_q'(k_{mn} r_g), \quad (32)\]

\[Z_{mnq}(r_L, r_g) = J_{m+q-1}(k_{mn} r_L) J_{q-1}(k_{mn} r_g) - J_{m+q+1}(k_{mn} r_L) J_{q+1}(k_{mn} r_g), \quad (33)\]

\[\tilde{X}_{mnq}(r_L, r_g) = (m + q) \frac{J_{m+q}(k_{mn} r_L)}{k_{mn} r_L} J_q(k_{mn} r_g), \quad (34)\]

\[\tilde{Y}_{mnq}(r_L, r_g) = q J_{m+q}(k_{mn} r_L) \frac{J_q(k_{mn} r_g)}{k_{mn} r_g}. \quad (35)\]

Integrating Eq. (28) along the line of characteristics defined by

\[\phi_e(z') = \phi_e + \frac{\Omega_e}{\gamma v_z} (z' - z), \quad (36a)\]

\[\phi(z') = \phi + \frac{\Omega_e}{\gamma v_z} (z' - z), \quad (36b)\]
\[
t(z') = t + \frac{1}{v_z} (z' - z) ,
\]

(36c)
yields

\[
f_1(r_g, \phi_c, z, p_{\perp}, \phi, p_z, t) = \frac{e}{2} \sum_{mq} \exp[i\Lambda_{mq}(\phi, \phi_c, t)] \\
\int_0^z \frac{dz'}{v_z} \exp\left\{ i \left[ (m + q) \frac{\Omega_c}{\gamma} - \omega \right] \frac{(z' - z)}{v_z} \right\} [k_{mn} C_{mn} O_{mq}(z') + \tilde{k}_{mn} \tilde{C}_{mn} \tilde{O}_{mq}(z')] f_0 + \text{c.c.}
\]

(37)

In deriving Eq. (37), we have assumed the initial condition \( f_1|_{z=0} = 0 \), corresponding to an initially unbunched electron beam. In Eq. (37), use has been made of the abbreviations \( O_{mq}(z') = O_{mq}(z', r_g, r_L, \partial/\partial r_g, p_{\perp}, p_z, \partial/\partial p_{\perp}, \partial/\partial p_z) \) and \( \tilde{O}_{mq}(z') = O_{mq}(z', r_g, r_L, \partial/\partial r_g, p_{\perp}, p_z, \partial/\partial p_{\perp}, \partial/\partial p_z) \), and the variables \((r, \theta, z)\) in \( f_1 \) have been replaced by the guiding-center variables \((r_g, \phi_c, z)\) via a scalar transformation.

B. Linearized Amplitude Equations for Coupled TE and TM Modes

To evaluate the overlap integrals in Eq. (17) and (18), we express \( \tilde{\beta} \cdot (\tilde{e}_z \times \nabla \Psi_{mn}^* \exp(i\omega t) \) and \( \tilde{\Psi}_{mn}^* \exp(i\omega t) \) in terms of guiding-center variables, i.e.,

\[
\tilde{\beta} \cdot (\tilde{e}_z \times \nabla \Psi_{mn}^*) \exp(i\omega t) = \beta_{\perp} k_{mn} C_{mn} \sum_q X_{mq}(r_L, r_g) \exp[-i\Lambda_{mq}(\phi, \phi_c, t)] ,
\]

(38)

\[
\tilde{\Psi}_{mn}^* \exp(i\omega t) = \tilde{C}_{mn} \sum_q \frac{\tilde{k}_{mn} r_L}{m + q} \tilde{X}_{mq}(r_L, r_g) \exp[-i\Lambda_{mq}(\phi, \phi_c, t)] .
\]

(39)

Substituting Eqs. (37)-(39) into Eqs. (17) and (18) and making use of the expressions \( d\sigma = rdrd\theta = r_g dr_g d\phi_c \) and \( d\tilde{p} = p_{\perp} dp_{\perp} dp_z d\phi \) result in the linearized amplitude equations

\[
\left( \frac{d^2}{dz^2} - k_{mn}^2 + \frac{\omega^2}{c^2} \right) E_{mn}(z)
\]

12
\[
\frac{16\pi^2 e^2}{c} \left( \frac{C_{mn}}{k_{mn}} \right) \sum_{n'} \sum_{l=-\infty}^{\infty} \int r_g d r_g X_{mn'l-m}(r_L, r_g) \int p_\perp dp_\perp dp_z \beta_{\perp} \\
\int_0^z \frac{dz'}{v_z} \exp \left[ i \left( \frac{\Omega_c}{\gamma} - \omega \right) \frac{(z' - z)}{v_z} \right] \left[ k_{mn'}C_{mn'}O_{mn'l-m}(z') + \tilde{k}_{mn'}\tilde{C}_{mn'}\tilde{O}_{mn'l-m}(z') \right] f_0 \quad (40)
\]

and

\[
\left( \frac{d^2}{dz^2} - \tilde{k}_{mn}^2 + \frac{\omega^2}{c^2} \right) B_{mn}(z) = i \frac{16\pi^2 e^2}{c^2 \tilde{k}_{mn}} \left( \frac{\tilde{C}_{mn}}{\tilde{k}_{mn}} \right) \sum_{n'} \sum_{l=-\infty}^{\infty} \int r_g d r_g \frac{\tilde{k}_{mn'} r_L}{l} \tilde{X}_{mnl-m}(r_L, r_g) \int p_\perp dp_\perp dp_z \left( \beta_z + \frac{ic \partial}{\omega \partial z} \right) \\
\int_0^z \frac{dz'}{v_z} \exp \left[ i \left( \frac{\Omega_c}{\gamma} - \omega \right) \frac{(z' - z)}{v_z} \right] \left[ k_{mn'}C_{mn'}O_{mn'l-m}(z') + \tilde{k}_{mn'}\tilde{C}_{mn'}\tilde{O}_{mn'l-m}(z') \right] f_0 . \quad (41)
\]

Equations (40) and (41) describe the linear evolution of coupled TE and TM waveguide modes in a CARM amplifier for an (arbitrary) azimuthally symmetric electron beam. Note in Eqs. (40) and (41) that TE and/or TM modes with different azimuthal numbers do not couple, which is a direct consequence of the assumption made of the azimuthal symmetry of the electron beam. (For an asymmetric electron beam, of course, the coupling of modes with different azimuthal numbers can not be excluded.)

C. Dispersion Relation and Launching Losses

To derive a dispersion relation for the CARM instability with TE and TM modes and to calculate launching losses, we solve Eqs. (40) and (41) with the Laplace transform defined by

\[
\tilde{E}_{mn}(s) = \int_0^\infty E_{mn}(z) \exp(-s z) dz , \quad (42)
\]

\[
\tilde{B}_{mn}(s) = \int_0^\infty B_{mn}(z) \exp(-s z) dz . \quad (43)
\]
A detailed derivation of the resulting dispersion relation is presented in Appendix B for the case of a thin \((k_{mn}r_g \ll 1\) and \(\tilde{k}_{mn}r_g \ll 1\) electron beam described by the equilibrium distribution function in Eq. (23). For the initial conditions

\[
E_{mn}\big|_{z=0} = E_{mn}(0), \quad B_{mn}\big|_{z=0} = B_{mn}(0), \quad \frac{dE_{mn}}{dz}\big|_{z=0} = \frac{dB_{mn}}{dz}\big|_{z=0} = 0,
\]

the dispersion relation can be expressed in the matrix form

\[
D_{mn}(s, \omega) \tilde{E}_{mn}(s) + \sum_{n'} \sum_{l=-\infty}^{\infty} \frac{k_{mn}^2(\omega^2 + c^2s^2)}{(\omega - l\Omega_c/\gamma + isv_z)^2} \tilde{E}_{mn'}(s) \\
+ \sum_{n'} \sum_{l=-\infty}^{\infty} \frac{EM_{mn'}}{\epsilon_{mn'l}} \frac{c^2k_{mn'}^2(\gamma/l\Omega_c)(\beta\omega + i cs)(\omega^2 + c^2s^2)}{(\omega - l\Omega_c/\gamma + isv_z)^2} \tilde{B}_{mn'}(s) \\
= sE_{mn}(0) + \sum_{n'} \sum_{l=-\infty}^{\infty} \left\{ \frac{TE_{mn'}}{\epsilon_{mn'l}} \frac{iv_s k_{mn'}^2(\gamma/l\Omega_c)(\beta\omega + i cs)}{(\omega - l\Omega_c/\gamma + isv_z)^2} E_{mn'}(0) \\
+ \frac{EM_{mn'}}{\epsilon_{mn'l}} \frac{ic k_{mn'}^2(\gamma/l\Omega_c)(\beta\omega + i cs)}{(\omega - l\Omega_c/\gamma + isv_z)^2} B_{mn'}(0) \right\}, \quad (44)
\]

\[
D_{mn}(s, \omega) \tilde{B}_{mn}(s) + \sum_{n'} \sum_{l=-\infty}^{\infty} \frac{ME_{mn'}}{\epsilon_{mn'l}} \frac{(k_{mn'}^2(\gamma/l\Omega_c)(\beta\omega + i cs)(\omega^2 + c^2s^2)}{(\omega - l\Omega_c/\gamma + isv_z)^2} \tilde{E}_{mn'}(s) \\
+ \sum_{n'} \sum_{l=-\infty}^{\infty} \frac{TM_{mn'}}{\epsilon_{mn'l}} \frac{l(c^2k_{mn'}^2(\gamma/l\Omega_c)(\beta\omega + i cs)^2}{(\omega - l\Omega_c/\gamma + isv_z)^2} \tilde{B}_{mn'}(s) \\
= sB_{mn}(0) + \sum_{n'} \sum_{l=-\infty}^{\infty} \left\{ \frac{ME_{mn'}}{\epsilon_{mn'l}} \frac{(c^2k_{mn'}^2(\gamma/l\Omega_c)(\beta\omega + i cs)}{(\omega - l\Omega_c/\gamma + isv_z)^2} E_{mn'}(0) \\
+ \frac{TM_{mn'}}{\epsilon_{mn'l}} \frac{ic k_{mn'}^3(\gamma/l\Omega_c)(\beta\omega + i cs)}{(\omega - l\Omega_c/\gamma + isv_z)^2} B_{mn'}(0) \right\}, \quad (45)
\]

where

\[
D_{mn}(s, \omega) = s^2 - k_{mn}^2 + \frac{\omega^2}{c^2} + \sum_{l=-\infty}^{\infty} \frac{k_{mn}^2(\omega^2 + c^2s^2)}{(\omega - l\Omega_c/\gamma + isv_z)^2} \quad (46)
\]
is the dielectric function for the (single) TE_{mn} mode, and

\[ D_{mn}^{TM}(s, \omega) = s^2 - \kappa_m^2 + \frac{\omega^2}{c^2} + \sum_{l=-\infty}^{\infty} \epsilon_{mn'l}^{TM} \frac{l(\kappa_m^2 \gamma/\Omega_c)^2(\beta_s \omega + is\gamma)^2}{(\omega - \Omega_c/\gamma + is\gamma)^2} \]  

(47)

for the (single) TM_{mn} mode. In Eqs. (44)-(47),

\[
\epsilon_{mn'l}^{TE} = \alpha \left( \frac{C_{mn}}{k_{mn}} \right) \left( \frac{C_{mn'}}{k_{mn'}} \right) X_{mn'l-m} (r_L, r_g) X_{mn'l-m} (r_L, r_g),
\]

(48)

\[
\epsilon_{mn'l}^{EM} = \alpha \left( \frac{C_{mn}}{k_{mn}} \right) \left( \frac{\tilde{C}_{mn'}}{k_{mn'}} \right) X_{mn'l-m} (r_L, r_g) \tilde{X}_{mn'l-m} (r_L, r_g),
\]

(49)

\[
\epsilon_{mn'l}^{TM} = \alpha \left( \frac{\tilde{C}_{mn}}{k_{mn}} \right) \left( \frac{\tilde{C}_{mn'}}{k_{mn'}} \right) \tilde{X}_{mn'l-m} (r_L, r_g) \tilde{X}_{mn'l-m} (r_L, r_g),
\]

(50)

\[
\epsilon_{mn'l}^{ME} = \alpha \left( \frac{\tilde{C}_{mn}}{k_{mn}} \right) \left( \frac{C_{mn'}}{k_{mn'}} \right) \tilde{X}_{mn'l-m} (r_L, r_g) X_{mn'l-m} (r_L, r_g)
\]

(51)

are dimensionless coupling constants. Here,

\[
\alpha = \frac{4\pi e^2 n_b \beta_s^2}{\gamma \mu_0 c^2} = \frac{4\pi \beta_s^2}{\gamma \beta_s} \left( \frac{I_b}{I_A} \right),
\]

(52)

\[ I_b = 2\pi e n_b c \int_0^\infty G(r_g) r_g dr_g \] is the beam current, \( r_m \) is the maximum guiding-center radius of the beam electrons, and \( I_A = \mu_0 c^3/e \approx 17 \text{ kA} \) is the Alfvén current. In Eqs. (44)-(47), we have kept only the terms of order \( c^2 k_m^2 / (\omega - \Omega_c/\gamma + is\gamma)^2 \), and neglected terms of order \( ck_m/ (\omega - \Omega_c/\gamma + is\gamma) \), etc. [More exact relations corresponding to Eqs. (44)-(47) which include the contributions of order \( ck_m/ (\omega - \Omega_c/\gamma + is\gamma) \) can be obtained from Eqs. (B5)-(B12) in Appendix B.]
The dispersion relation for the multimode CARM interaction is given by the zero
determinant of the coefficient matrix on the left-hand side of Eqs. (44) and (45). Moreover,
the amplitudes $\tilde{E}_{mn}(s)$ and $\tilde{B}_{mn}(s)$ are easily found by solving the linear algebraic
equations (44) and (45), and $E_{mn}(z)$ and $B_{mn}(z)$ can be obtained by performing the
inverse Laplace transform of $\tilde{E}_{mn}(s)$ and $\tilde{B}_{mn}(s)$,

$$E_{mn}(z) = \frac{1}{2\pi i} \int_{\sigma-i\infty}^{\sigma+i\infty} \tilde{E}_{mn}(s) \exp(sz) ds ,$$

$$B_{mn}(z) = \frac{1}{2\pi i} \int_{\sigma-i\infty}^{\sigma+i\infty} \tilde{B}_{mn}(s) \exp(sz) ds .$$

IV. NONLINEAR THEORY

We now present a fully nonlinear, three-dimensional, self-consistent theory of an
overmoded CARM amplifier for an (arbitrary) azimuthally symmetric electron beam.
The present nonlinear model is capable of dealing with a single TE or TM mode, multiple
TE and/or TM modes, cyclotron harmonics, magnetic field tapering, momentum and
energy spread, etc.

A. Particle Dynamics

Following Fliflet's treatment\textsuperscript{12} of the single-mode CARM interaction, we assume
that the electron guiding-center radius and angle are approximate constants of motion,
i.e.,

$$\frac{d_{r_g}}{dt} \approx 0 \quad \text{and} \quad \frac{d\theta_g}{dt} \approx 0 .$$

In addition, we approximate the Larmor radius (in the presence of rf field perturbations)
by the expression
where \( p_\perp = [(\gamma^2 - 1)\gamma^2c^2 - p_z^2]^{1/2} \). Under these assumptions, the motion of an electron can be described by three variables: the energy, \( \gamma m_0 c^2 \), the axial momentum, \( p_z \), and the azimuthal angle, \( \phi = \tan^{-1}(p_y/p_z) \). From the Lorentz force equation (1), the dynamics of each individual electron is then

\[
\frac{d\gamma}{dt} = -\frac{e}{\gamma m_0 c^2} (p_\perp E_\perp + p_z E_z),
\]

\[
\frac{dp_z}{dt} = -e \left( E_z + \frac{p_z B_\phi}{\gamma m_0 c} \right),
\]

\[
\frac{d\phi}{dt} = \Omega_c \frac{\gamma}{\gamma - p_\perp} \left( E_z + \frac{p_z B_\perp}{\gamma m_0 c} - \frac{p_\perp B_\phi}{\gamma m_0 c} \right).
\]

It is useful to introduce the dimensionless wave amplitudes, \( A_{mn}(z) \) and \( \tilde{A}_{mn}(z) \), and phase shifts, \( \delta_{mn}(z) \) and \( \tilde{\delta}_{mn}(z) \), for the TE\(_{mn}\) and TM\(_{mn}\) modes, so that

\[
E_{mn}(z) = \left( \frac{k_{mn}}{c_{mn}} \right) \left( \frac{\omega}{\omega_{mn}} \right)^2 \left( I_A \right) A_{mn}(z) \exp\{i[k_{mn}z + \delta_{mn}(z)]\},
\]

\[
B_{mn}(z) = \left( \frac{k_{mn}}{c_{mn}} \right) \left( \frac{\omega}{\omega_{mn}} \right)^2 \left( I_A \right) \tilde{A}_{mn}(z) \exp\{i[\tilde{k}_{mn}z + \tilde{\delta}_{mn}(z)]\}.
\]

The axial wavenumbers of the vacuum TE\(_{mn}\) and TM\(_{mn}\) waveguide modes, \( k_{mn} \) and \( \tilde{k}_{mn} \), are defined by

\[
\omega^2 = c^2(k_{mn}^2 + k_{mn}^2)
\]
\[ \omega^2 = c^2 (k_{zmn}^2 + \tilde{k}_{mn}^2) \, , \tag{62b} \]

respectively.

Substituting Eqs. (8)-(11) into Eqs. (57)-(59) and making use of Graf's theorem for Bessel functions (similar to Appendix A), it can be shown after some straightforward algebra that the normalized equations of motion for an electron are

\[
\frac{d\gamma}{d\tilde{z}} = -\frac{\hat{p}_\perp}{\hat{p}_z} \sum_{nml} X_{nml-m} (r_g, r_L) A_{mn} \cos \psi_{mn} \\
- \frac{\hat{p}_\perp}{\hat{p}_z} \sum_{nml} \tilde{X}_{nml-m} (r_g, r_L) \left\{ \left[ (\beta_{\phi mn}-\tilde{\beta}_{\phi mn}^{-1}) \gamma \right] \frac{\partial \tilde{A}_{mn}}{\partial \tilde{z}} \right\} \tilde{A}_{mn} \cos \tilde{\psi}_{mn} - d \tilde{A}_{mn} \frac{d\tilde{A}_{mn}}{d\tilde{z}} \sin \tilde{\psi}_{mn} \right\} \, , \tag{63} \]

\[
\frac{d\hat{p}_z}{d\tilde{z}} = -\frac{\hat{p}_\perp}{\hat{p}_z} \sum_{nml} X_{nml-m} \left[ (\beta_{\phi mn}^{-1} + \frac{d\delta_{mn}}{d\tilde{z}}) A_{mn} \cos \psi_{mn} + \frac{dA_{mn}}{d\tilde{z}} \sin \psi_{mn} \right] \\
- \frac{\hat{p}_\perp}{\hat{p}_z} \sum_{nml} \tilde{X}_{nml-m} \left( \frac{\gamma \tilde{\omega}_{\phi mn}^2}{l\tilde{\Omega}_c} - 1 \right) \tilde{A}_{mn} \cos \tilde{\psi}_{mn} - \left( \frac{\hat{p}_\perp^2}{2\hat{p}_z \tilde{\Omega}_c} \right) \frac{d\tilde{\Omega}_c}{d\tilde{z}} \, , \tag{64} \]

\[
\frac{d\phi}{d\tilde{z}} = \frac{\tilde{\Omega}_c}{\hat{p}_z} + \frac{1}{\hat{p}_z \hat{p}_\perp} \sum_{nml} W_{mn} \left\{ \left[ \gamma - \hat{p}_z \left( \beta_{\phi mn}^{-1} + \frac{d\delta_{mn}}{d\tilde{z}} \right) \right] A_{mn} \sin \psi_{mn} + \hat{p}_z \frac{dA_{mn}}{d\tilde{z}} \cos \psi_{mn} \right\} \\
+ \frac{1}{\hat{p}_z \hat{p}_\perp} \sum_{nml} \tilde{W}_{mn} \left\{ \left[ \hat{p}_z - \gamma \left( \beta_{\phi mn}^{-1} + \frac{d\delta_{mn}}{d\tilde{z}} \right) \right] \tilde{A}_{mn} \sin \tilde{\psi}_{mn} + \gamma \frac{d\tilde{A}_{mn}}{d\tilde{z}} \cos \tilde{\psi}_{mn} \right\} \, . \tag{65} \]

In Eqs. (63)-(65), the phase variables, \( \psi_{mn} \) and \( \tilde{\psi}_{mn} \), are related to the phase \( \phi \) by the expressions

\[
\psi_{mn} = k_{zmn} z + \delta_{mn}(z) + l\phi - \omega t - (l - m)\theta_\phi + (l - 2m)\pi/2 \, , \tag{66} \]
\[ \ddot{\psi}_{mnl} = \dot{k}_{zm} z + \ddot{\delta}_{mn}(z) + i\phi - \omega t - (1 - m)\theta_g + (1 - 2m)\pi/2 ; \]  

(67)

The normalized variables and parameters are defined by

\[ \dot{p}_z = p_z/\gamma m_0 c, \quad \dot{p}_\perp = p_\perp/\gamma m_0 c, \quad \dot{z} = \omega z/c ; \]

\[ \dot{\omega}_{cmn}/\omega = c k_{mn}/w, \quad \dot{\omega}_{cmn}/\omega = c k_{mn}/w ; \]  

(68)

\[ \beta_{\phi m} = \omega/c k_{zm}, \quad \dot{\beta}_{\phi m} = \omega/c k_{zm}, \quad \hat{\Omega}_c = \Omega_c/\omega ; \]

The geometric factors \( X_{mnl-m} \) and \( \hat{X}_{mnl-m} \) are defined in Eqs. (31) and (34), and

\[ W_{mnl-m}(r_L, r_g) = J_l(k_{mn} r_L)/k_{mn} r_L J_{l-m}(k_{mn} r_g) , \]  

(69)

\[ \hat{W}_{mnl-m}(r_L, r_g) = J'_l(k_{mn} r_L) J_{l-m}(\hat{k}_{mn} r_g) . \]  

(70)

Moreover, the term \( (\dot{p}_\perp^2/2\dot{p}_z \hat{\Omega}_c)d\hat{\Omega}_c/d\dot{z} \) has been added to the right-hand side of Eq. (64) to allow for modeling magnetic field tapering and efficiency enhancement.\(^{21,23}\)

**B. Wave Equations**

For an azimuthally symmetric electron beam, the nonlinear charge and current density perturbations can be expressed as\(^{28}\)

\[ \rho(\vec{z}, t) = -en_b G(r) v_{*0} \int_{-\infty}^{\infty} \frac{m_0 \gamma(t_0, t)}{p_z(t_0, t)} \delta[t - \tau(t_0, z)] dt_0 , \]

(71)

\[ \vec{J}(\vec{z}, t) = -en_b G(r) v_{*0} \int_{-\infty}^{\infty} \frac{\vec{p}(t_0, t)}{p_z(t_0, t)} \delta[t - \tau(t_0, z)] dt_0 , \]

(72)
where \( \bar{p}(t_0, t) \) and \( \gamma(t_0, t)m_0c^2 \) are the instantaneous momentum and energy of an electron (at time \( t \)) which crossed the plane \( z = 0 \) at time \( t_0 \), and \( \tau(t_0, z) \) is time when this electron reaches the axial distance \( z \). Substituting Eqs. (71) and (72) into Eqs. (17) and (18) and averaging over one period \( 2\pi/\omega \), the wave equations for the TE and TM modes can be expressed in the normalized form

\[
\left( \frac{d^2}{d\hat{z}^2} + \beta_{\phi mn}^{-2} \right) A_{mn}(\hat{z}) \exp\{i[\hat{z} / \beta_{\phi mn} + \delta_{mn}(\hat{z})]\} = \frac{2i g_{mn}}{\beta_{\phi mn}} \left( X_{mn0} - m(r_g, r_L) \frac{\hat{b}_z}{\hat{b}_x} \exp(i\psi_{mn}) \right) \exp\{i[\hat{z} / \beta_{\phi mn} + \delta_{mn}(\hat{z})]\},
\]

(73)

\[
\left( \frac{d^2}{d\hat{z}^2} + \beta_{\phi mn}^{-2} \right) \tilde{A}_{mn}(\hat{z}) \exp\{i[\hat{z} / \beta_{\phi mn} + \tilde{\delta}_{mn}(\hat{z})]\} = \frac{2ig_{mn}}{\beta_{\phi mn}} \left( \tilde{X}_{mn0} - m(r_g, r_L) \frac{\hat{b}_z}{\hat{b}_x} \exp(i\tilde{\psi}_{mn}) \right) \exp\{i[\hat{z} / \beta_{\phi mn} + \tilde{\delta}_{mn}(\hat{z})]\},
\]

(74)

where \( \langle F \rangle = N^{-1} \sum_{i=1}^{N} F_i \) denotes the ensemble average over the particle distribution, \( N \) is the number of particles used in the simulations, and

\[
g_{mn} = 4\pi \beta_{\phi mn} \left( \frac{c k_{mn}}{\omega} \right)^2 \left( \frac{C_{mn}}{k_{mn}} \right)^2 \left( \frac{I_b}{I_A} \right)^2,
\]

(75a)

\[
\tilde{g}_{mn} = 4\pi \beta_{\phi mn} \left( \frac{c k_{mn}}{\omega} \right)^2 \left( \frac{\tilde{C}_{mn}}{k_{mn}} \right)^2 \left( \frac{\gamma_0}{l\Omega_c} \right) \left( \beta_{z0} - \frac{1}{\beta_{\phi mn}} \right) \left( \frac{I_b}{I_A} \right)^2,
\]

(75b)

are the normalized coupling constants for the TE\( mn \) and TM\( mn \) modes, respectively.

Substituting Eq. (60) into Eq. (21), and Eq. (61) into Eq. (22) yields the rf power associated with TE\( mn \) and TM\( mn \) modes,

\[
P_{mn}(\hat{z}) = \frac{1}{8\pi} \left( \frac{m_0^2 c^5}{\varepsilon^2} \right) \left( \beta_{\phi mn}^{-1} + \frac{d\delta_{mn}}{d\hat{z}} \right) \left( \frac{\omega}{c k_{mn}} \right)^2 \left( \frac{k_{mn}}{C_{mn}} \right)^2 A_{mn}^2,
\]

(76)
\[ \tilde{P}_{mn}(\tilde{z}) = \frac{1}{8\pi} \left( \frac{m_0^2 c^5}{e^2} \right) \left( \tilde{\beta}_{mn}^{-1} + \frac{d\delta_{mn}}{d\tilde{z}} \right) \left( \frac{\omega}{c \tilde{k}_{mn}} \right)^2 \left( \frac{\tilde{k}_{mn}}{C_{mn}} \right)^2 \tilde{A}_{mn}^2, \]  

where \( m_0^2 c^5 / e^2 \approx 8.7 \text{ GW} \).

We have developed a three-dimensional simulation code, CSPOT, which solves the complete CARM amplifier equations (63), (64), (65), (73) and (74). For simulation with \( N \) particles and \( M \) modes, the code integrates numerically a total of \( 3N + 2M \) first-order ordinary differential equations (typically, \( N \geq 1024 \)). This code has been benchmarked against the linear theory presented in Sec. III, and can model a single TE or TM mode, multiple TE and/or TM modes, cyclotron harmonics, magnetic field tapering, momentum and energy spread, waveguide losses, and various beam loading options. After reviewing the single-mode CARM interaction (Sec. V), we use our linear and nonlinear theory to analyze CARM amplifiers with two or more waveguide modes, and illustrate the general features of multimode phenomena (Sec. VI).

V. NUMERICAL ANALYSIS FOR A SINGLE MODE

In this section, we review the stability properties of single-mode CARM interaction. Here, emphasis is placed on the analytical calculation of launching losses using the Laplace transform formalism, and on detailed comparisons between linear theory and results from computer simulations.

A. Single TE Mode

As stated in Sec. I, the CARM interaction occurs when the cyclotron resonance condition

\[ \omega - \Omega_c/\gamma - k_z v_z = 0 \]  

(78)
is approximately satisfied (Fig. 3). Here, \( k_z = -i \lambda \), \( \lambda \) is the harmonic number. To leading order in \( c^2 k_{mn}^2/(\omega - i\Omega_c/\gamma - k_z v_z)^2 \), it follows from Eqs. (44) and (46) that the dispersion relation with the single \( \text{TE}_{mn} \) mode can be expressed as

\[
D^{\text{TE}}(ik_z, \omega) = \frac{\omega^2}{c^2} - k_z^2 - k_{mn}^2 + \varepsilon_{mn}^{\text{TE}} \frac{k_{mn}^2(\omega^2 - c^2 k_z^2)}{(\omega - i\Omega_c/\gamma - k_z v_z)^2} = 0 ,
\]  

(79)

which is in agreement with earlier results.\textsuperscript{12,22,29} The maximum spatial growth rate for the single \( \text{TE}_{mn} \) mode occurs when \( \omega^2 - c^2(k_{mn}^2 + k_z^2) \approx 0 \) and \( \omega - i\Omega_c/\gamma - k_z v_z \approx 0 \), corresponding to the intersection of the uncoupled \( \text{TE}_{mn} \) and beam cyclotron modes. Therefore, expanding \( k_z = k_{zm} + \delta k_z \) with \( k_{zm} = (\omega^2/c^2 - k_{mn}^2)^{1/2} \approx (\omega - i\Omega_c/\gamma)/v_z \), and using Eq. (79), the maximum growth rate for the \( \text{TE}_{mn} \) mode is shown to be approximately

\[
\Gamma_{mn} = \frac{3^{1/2}}{2^{4/3}} \left( \frac{\varepsilon_{mn}^{\text{TE}} k_{mn}^4}{k_{zm}^2} \right)^{1/3} .
\]  

(80)

Furthermore, from Eq. (44), the amplitude \( \tilde{E}_{mn}(ik_z) \) for the single \( \text{TE}_{mn} \) mode can be expressed as

\[
\tilde{E}_{mn}(i k_z) \frac{i}{i E_{mn}(0)} = \frac{k_z(\omega - i\Omega_c/\gamma - k_z v_z)^2 + \varepsilon_{mn}^{\text{TE}} v_z k_{mn}^2 \omega}{(\omega^2/c^2 - k_{mn}^2 - k_z^2)(\omega - i\Omega_c/\gamma - k_z v_z)^2 + \varepsilon_{mn}^{\text{TE}} k_{mn}^2(\omega^2 - c^2 k_z^2)} .
\]  

(81)

Therefore, the three-dimensional radiation field profile (amplitude and phase) for each individual \( \text{TE} \) mode can be calculated analytically by the inverse Laplace transform of Eq. (81) with \( s = i k_z \). In particular, the rf power in the \( \text{TE}_{mn} \) mode is given by

\[
\frac{P_{mn}(z)}{P_{mn}(0)} = \left| \frac{1}{2 \pi i} \int_{-\infty}^{\infty} \frac{\tilde{E}_{mn}(s)}{E_{mn}(0)} \exp(sz)ds \right|^2 .
\]  

(82)
Typical gain bandwidth and dependence of rf power on the interaction length \( z \) are plotted, respectively, in Figs. 4 and 5.

Figure 4 shows the gain bandwidth for the TE_{11} mode at the fundamental cyclotron frequency \( (l = 1) \). Here, the solid curve is obtained from Eq. (79). The dots are from the computer simulations using CSPOT. The choice of system parameters corresponds to beam current \( I_b = 500 \) A, initial pitch angle \( \theta_{p0} = p_{10}/p_{s0} = 0.5 \), beam energy \( E_b = 1.0 \) MeV \( (\gamma \approx 2.96) \), normalized axial momentum spread \( \delta_{px} = \langle (\hat{p}_x - \bar{p}_x)^2 \rangle^{1/2} = 0 \), maximum guiding-center radius \( r_m = 0 \), waveguide radius \( r_w = 1.4 \) cm, and axial magnetic field \( B_0 = 4.01 \) kG. Good agreement is found between linear theory and results from the simulations, except for some discrepancies near the cut-off frequency. Note in Fig. 4 that the spatial growth rate vanishes at \( \omega/\omega_{c11} = \omega/c k_{11} \approx 3.8 \) due to the cancelation of force bunching and inertial bunching. Indeed, the effective bunching parameter (or effective detuning parameter)\(^{23}\)

\[
D_{11}^{eff} = 1 - \beta_{\phi 11}^2 + \left[ \left( \frac{\beta_{\phi 11}}{\beta_{s0}} - 1 \right) + \frac{1}{\theta_{p0}^2} \left( \frac{\beta_{\phi 11}}{\beta_{s0}} - 1 \right)^2 \right] \left[ 1 - \frac{\Omega_c}{\gamma \omega (1 - \beta_{s0}/\beta_{\phi 11})} \right] \tag{83}
\]

vanishes at \( \omega/\omega_{c11} \approx 3.8 \). \( D_{11}^{eff} \) is positive (negative) when \( \omega/\omega_{c11} > 3.8 \) (\( \omega/\omega_{c11} < 3.8 \)).

Figure 5 shows the rf power in the TE_{11} mode as a function of the interaction length \( z \), for the same parameters used in Fig. 4, except that \( \omega/\omega_{c11} = 2.87 \) \( (f = 18 \) GHz) is chosen so that the TE_{11} mode is in resonance with the electron beam. In Fig. 5, the solid curve is obtained from the computer simulations, and the dashed curve is calculated analytically from Eqs. (81) and (82). Again, there is good agreement between the linear theory and results from the simulations, even in the launching loss region \( (z < 20 \) cm).

We have used our nonlinear, single-mode CARM theory to interpret the recent experimental results from a 35 GHz CARM amplifier.\(^{18,19}\) In the experiments, a rf power of 12 MW, with an overall gain of 30 dB, has been measured, using a 128 A, 1.5 MeV
relativistic electron beam. This amplifier operates in the TE\textsubscript{11} mode in a cylindrical waveguide. Figure 6 shows the comparison of the measured and computed rf power as a function of interaction length. The system parameters used in the simulation (and in the experiment) correspond to beam energy $E_b = 1.5$ MeV ($\gamma = 3.96$), beam current $I_b = 128$ A, parallel energy spread $\Delta \gamma_{\parallel}/\gamma_{\parallel} = 0.044$ [$\gamma_{\parallel} = (1 - \beta_z^2)^{-1/2}$], average guiding-center radius $\langle r_s \rangle = 0.15$ cm, initial pitch angle $\theta_{p0} = p_{\perp0}/p_{z0} = 0.27$, axial magnetic field $B_z = 5.4$ kG, waveguide radius $r_w = 0.793$ cm, and an input power of 17 kW.

In Fig. 6, the solid curve is from the CSPOT code, while the dotted curve is from the experiment. Good quantitative agreement is found between the theory and the results from the experiment.

**B. Single TM Mode**

Similar analyses can be carried out for a single TM mode. To leading order in $c^2 \frac{\tilde{k}_m^2}{(\omega - l\Omega_c/\gamma - k_z v_z)^2}$, it follows from Eqs. (45) and (47) that the dispersion relation for the single TM\textsubscript{mn} mode is

$$D_{mn}^TM(ik_z, \omega) = \frac{\omega^2}{c^2} - k_z^2 - \tilde{k}_m^2 + \frac{\epsilon_{mn}^TM l(c\tilde{k}_m^2 \gamma/\Omega_c)^2(\beta_z \omega - ck_z)^2}{(\omega - l\Omega_c/\gamma - k_z v_z)^2} = 0 ,$$  

(84)

which is in agreement with earlier results.\textsuperscript{12} The maximum growth rate for the TM\textsubscript{mn} occurs when $\omega^2 - c^2(\tilde{k}_m^2 + k_z^2) \equiv 0$ and $\omega - l\Omega_c/\gamma - k_z v_z \equiv 0$, and it is given by

$$\tilde{\Gamma}_{mnl} = \frac{3^{1/2}}{24^{1/3}}(\epsilon_{mn}^TM \tilde{k}_m^2 \tilde{k}_z^2)^{1/3}(\frac{c\tilde{k}_m^2 \gamma}{\Omega_c})^{2/3}(1 - \frac{1}{\beta_z \beta_{\phi mn}})^{2/3}.$$  

(85)

Note in Eq. (85) that $\tilde{\Gamma}_{mnl}$ vanishes when $\beta_z \beta_{\phi mn} = 1$, as pointed out by several authors.\textsuperscript{12,30,31} From Eq. (45), the amplitude $\tilde{B}_{mn}(ik_z)$ for the TM\textsubscript{mn} mode can be expressed as
\[
\frac{\tilde{B}_{mn}(ik_z)}{iB_{mn}(0)} = \frac{k_z(\omega - l\Omega_c/\gamma - k_zv_z)^2 + \epsilon_{txt}^2(\tilde{k}_{mn}^2\gamma\omega/l\Omega_c)(\beta_z\omega - ck_z)}{(\omega^2/c^2 - \tilde{k}_{mn}^2 - k_z^2)(\omega - l\Omega_c/\gamma - k_zv_z)^2 + \epsilon_{txt}^2 l(\tilde{k}_{mn}^2\gamma/l\Omega_c)(\beta_z\omega - ck_z)^2}.
\]

which can be used to calculate the radiation field profile and power. Typical gain bandwidth and dependence of rf power on the interaction length \( z \) are plotted, respectively, in Figs. 7 and 8.

Figure 7 shows the gain bandwidth for the TM\(_{11} \) mode at the fundamental cyclotron frequency \( (l = 1) \) with system parameters: \( I_b = 500 \text{ A}, \theta_p = 0.6, \gamma = 2.96, \delta_p = 0, \)
\( r_m = 0, r_w = 1.4 \text{ cm}, \) and \( B_0 = 8.45 \text{ kG}. \) Here, the solid curve is obtained from Eq. (84), and the dotted curve is from the computer simulations. Note in Fig. 7 that the gain bandwidth consists of two frequency domains separated by the condition \( \beta_{s_0}\beta_{\phi_{11}} = 1 \) at \( \omega/\tilde{\omega}_{c11} = \omega/c\tilde{k}_{11} \cong 1.7. \) Figure 8 depicts the rf power in the TM\(_{11} \) as a function of \( z \), for the same parameters used in Fig. 7, except that \( \omega/\tilde{\omega}_{c11} = 1.38 \) (\( f = 18 \text{ GHz} \)) is chosen so that the TM\(_{11} \) mode is in resonance with the electron beam. In Fig. 8, the solid curve is obtained from the computer simulations, and the dashed curve is from Eq. (86).

VI. NUMERICAL ANALYSIS FOR MULTIPLE MODES

In this section, we use linear and nonlinear theory in Secs. III and IV to analyze the multimode CARM interaction with two or more waveguide modes, and illustrate the general features of multimode phenomena in an overmoded CARM amplifier. We show analytically that all of the coupled waveguide modes grow with the dominant unstable mode at the same growth rate, and that the phases of coupled modes are locked in the exponential gain regime, and remain approximately locked for some finite interaction length beyond saturation. The simulations indicate that the saturated power in each mode is insensitive to input rf power distribution among the coupled modes, but it is
sensitive to detuning.

A. Two-Mode Coupling

We first examine the CARM interaction with the TE\textsubscript{mn} and TE\textsubscript{m'n'} waveguide modes coupling to a cold, thin ($k_{mn}r_g \ll 1$ and $k_{m'n'}r_g \ll 1$), azimuthally symmetric electron beam at a given harmonic cyclotron frequency $l\Omega_c/\gamma$. In this case, the general matrix equation in Eqs. (44) and (45) reduces to a 2 $\times$ 2 matrix equation of the form

$$M \begin{pmatrix} \bar{E}_{mn}(s) \\ \bar{E}_{m'n'}(s) \end{pmatrix} = S \begin{pmatrix} E_{mn}(0) \\ E_{m'n'}(0) \end{pmatrix},$$

(87)

where the 2 $\times$ 2 matrices $M$ and $S$ are defined by

$$M = \begin{pmatrix} \epsilon_{TEmn,nn,l}k_{mn}^2(\omega^2 + c^2s^2)\Delta^{-2} & \epsilon_{TEmn,mn',l}k_{mn}^2(\omega^2 + c^2s^2)\Delta^{-2} \\ \epsilon_{TEmn',mn',l}k_{mn}^2(\omega^2 + c^2s^2)\Delta^{-2} & \epsilon_{TEmn,mn,n',l}k_{mn}^2(\omega^2 + c^2s^2)\Delta^{-2} \end{pmatrix},$$

(88)

$$S = \begin{pmatrix} s + i\epsilon_{TEmn,nn,l}v_zk_{mn}^2\Delta^{-2} & i\epsilon_{TEmn,mn',l}v_zk_{mn}^2\Delta^{-2} \\ i\epsilon_{TEmn',mn',l}v_zk_{mn}^2\Delta^{-2} & s + i\epsilon_{TEmn,mn,n',l}v_zk_{mn}^2\Delta^{-2} \end{pmatrix},$$

(89)

and $\Delta = \Delta(s, \omega) = \omega - l\Omega_c/\gamma + isv_z$. Here, $D_{mn}^{TE}(s, \omega)$ is defined in Eq. (46), and $\epsilon_{TEmn,l}$ in Eq. (48). Solving Eq. (87) for $\bar{E}_{mn}(s)$ and $\bar{E}_{m'n'}(s)$ yields

$$\begin{pmatrix} \bar{E}_{mn}(s) \\ \bar{E}_{m'n'}(s) \end{pmatrix} = M^{-1}S \begin{pmatrix} E_{mn}(0) \\ E_{m'n'}(0) \end{pmatrix},$$

(90)

where

$$M^{-1} = \frac{1}{\det M} \begin{pmatrix} m_{22} & -m_{12} \\ -m_{21} & m_{11} \end{pmatrix}$$

(91)

is the inverse of $M$, and $m_{ij}$ are the elements of $M$. Therefore, the three-dimensional radiation field profile and power is readily calculated by the inverse Laplace transform of
\( \tilde{E}_{mn}(s) \) in Eq. (90). Note that the singularities in the integrand of the inverse Laplace transform of \( \tilde{E}_{mn}(s) \) are determined from the dispersion relation

\[
det M = 0 \tag{92}
\]

for the coupled TE\(_{mn}\) and TE\(_{mn'}\) modes. Making use of the relation \( \epsilon_{mn'l}^T \epsilon_{mn'n'l}^T = \epsilon_{mn'l}^T \epsilon_{mn'n'l}^T \), and substituting \( s = ik_z \), the coupled-mode dispersion relation in Eq. (92) can be expressed as

\[
\left( k_z^2 + k_{mn}^2 - \frac{\omega^2}{c^2} \right) \left( k_z^2 + k_{mn'}^2 - \frac{\omega^2}{c^2} \right) \left( \omega - \frac{\Omega_c}{\gamma} - k_z v_s \right)^2
= \left[ \epsilon_{mn'l}^T k_{mn}^2 \left( k_z^2 + k_{mn}^2 - \frac{\omega^2}{c^2} \right) + \epsilon_{mn'n'l}^T k_{mn'}^2 \left( k_z^2 + k_{mn'}^2 - \frac{\omega^2}{c^2} \right) \right] \left( \omega^2 - c^2 k_z^2 \right), \tag{93}
\]

which is a sixth-order polynomial of \( k_z \) with real coefficients and therefore has six roots. When the two waveguide modes are well separated, and

\[
\epsilon_{mn'l}^T k_{mn}^2 \left( k_z^2 + k_{mn}^2 - \frac{\omega^2}{c^2} \right) \gg \epsilon_{mn'n'l}^T k_{mn'}^2 \left( k_z^2 + k_{mn'}^2 - \frac{\omega^2}{c^2} \right), \tag{94}
\]

which corresponds to the beam cyclotron mode, \( \omega = k_z v_s + \Omega_c / \gamma \), being in resonance with the TE\(_{mn}\) waveguide mode, \( \omega = c(k_z^2 + k_{mn}^2)^{1/2} \), Eq. (93) becomes the usual single-mode dispersion relation, Eq. (79).

Typical results from the computer simulations and (linear) kinetic theory are summarized in Figs. (9)-(12). Figure 9 shows the dependence of rf power, in the TE\(_{11}\) and TE\(_{12}\) modes, on the interaction length \( z \), for (a) single-mode CARM interactions and (b) the CARM interaction with the two modes coupling to the beam. The system parameters in Fig. 9 are: frequency \( f = 18 \) GHz, beam current \( I_b = 500 \) A, beam energy \( E_b = 1.0 \) MeV \( (\gamma = 2.96) \), initial pitch angle \( \theta_{p0} = \beta_{10}/\beta_{40} = 0.6 \), normalized axial momentum
spread $\delta_{ps} = 0$, maximum guiding-center radius $r_m = 0$, waveguide radius $r_w = 2.7$ cm, and axial magnetic field $B_0 = 3.92$ kG, corresponding to the TE$_{11}$ mode in resonance, and the TE$_{12}$ mode off resonance, with the electron beam at the fundamental cyclotron frequency ($l = 1$).

In Fig. 9, the solid curves are the results obtained from the computer simulations using CSPOT with 1024 particles. The dashed curves in Fig. 9(a) are obtained analytically from the single-mode linear theory [Eq. (81)], while the dashed curves in Fig. 9(b) are from the multimode linear theory [Eq. (90)]. The inclusion of the coupling of the TE$_{11}$ and TE$_{12}$ modes results in the instability of the TE$_{12}$ mode, as seen in Fig. 9(b), while the single-mode theory would predict stability for the TE$_{12}$ mode, as seen in Fig. 9(a). In fact, in Fig. 9(b), the TE$_{12}$ mode grows parasitically with the dominant unstable TE$_{11}$ mode, and the two coupled modes have the same spatial growth rate, $-\text{Im} \Delta k_z > 0$, corresponding to the most unstable solution of the coupled-mode dispersion relation in Eq. (93). Because the TE$_{11}$ mode is in resonance with the electron beam and the TE$_{12}$ mode is detuned from resonance, the TE$_{12}$ mode suffers greater launching losses than the TE$_{11}$ mode. Excellent agreement is found between the simulation and linear theory in the linear regime. In particular, numerous amplitude oscillations of the TE$_{12}$ mode are well described by our linear theory throughout the launching loss region, from $z = 0$ to $z \cong 100$ cm, as is evident in Fig. 9(b).

The evolution of relative rf phase, $\Delta \Phi(z) = \Phi_{12} - \Phi_{11} = (k_{z12} - k_{z11})z + \delta_{12}(z) - \delta_{11}(z)$, is plotted as a function of $z$ in Fig. 10, for the simulations used in Fig. 9. In Fig. 10, the dashed curve, designated by label (a), is obtained by subtracting the rf phases which result from the single-mode simulations of the TE$_{11}$ mode and of the TE$_{12}$ mode used in Fig. 9(a); The solid curve, designated by label (b), is calculated by subtracting the rf phases in the multimode simulation of Fig. 9(b). As a result of the mode coupling, the relative rf phase $\Delta \Phi(z)$, as shown in Fig. 10(b), is approximately constant (with
variation less than $0.2\pi$) in the exponential gain regime from $z \approx 100$ cm to $z \approx 175$ cm, which is usually referred to as phase locking. The phenomenon of phase locking of transverse modes in the exponential gain regime is predicted by linear theory, because the multimode dispersion relation in Eq. (93) yields a unique $k_z$, with a negative imaginary part, which determines the growth rate and phase shifts for the coupled modes. What is more remarkable is that phase locking (with phase variation less than $0.6\pi$) persists even in the nonlinear region, (at least for some finite interaction length beyond saturation), as seen in Fig. 10(b).

Figures 9(b) and 10(b) reveal two general features of the multimode CARM interaction: (1) all of the coupled waveguide modes have the same small-signal growth rate, but they suffer different launching losses, which depend strongly upon the detuning; (2) the phases of coupled modes are locked in the exponential gain regime, and remain approximately locked for some interaction length beyond saturation.

Another interesting feature of the multimode CARM interaction is that the saturated rf power of each mode is insensitive to input rf power distribution among the coupled modes at $z = 0$. Figure 11 shows the results of simulations for the coupled TE$_{11}$ and TE$_{12}$ modes with two different distributions of input rf power. In Fig. 11, the two solid curves depict the linear and nonlinear evolution of the rf power in the TE$_{12}$ mode that was generated by the simulations with input power distributions: (a) $P_0$(TE$_{11}$) = $P_0$(TE$_{12}$) = 100 W, and (b) $P_0$(TE$_{11}$) = 100 W and $P_0$(TE$_{12}$) = 1 W; the two dashed curves are the corresponding analytical results from Eq. (90). Here, only the TE$_{12}$ mode is plotted, because the TE$_{11}$ mode remains virtually unchanged for the two distributions.

The gain bandwidth and efficiency are plotted in Fig. 12, for the coupled TE$_{11}$ and TE$_{12}$ modes, with the same system parameters used in Figs. 9(b) and 10(b), except that $\omega$ varies from $3\omega_{11}$ to $9\omega_{c11}$. Here, the efficiency is defined by $\eta = (\gamma_0 - \langle\gamma\rangle)/(\gamma_0 - 1)$. In Fig. 12(a), the solid curve shows the growth rate from the simulations; the dashed curve
is the corresponding analytical result predicted from Eq. (93). Quantitative agreement is
found for $\omega/\omega_{e11} > 5.5$, while only qualitative agreement can be found for $\omega/\omega_{e11} < 5.5$.
As is the case of the single-mode CARM interaction discussed in Sec. V.A, the gain
bandwidth for the two coupled modes consists of two frequency domains. Although
the growth rates in both domains are comparable, as seen in Fig. 12(a), it is shown in
Fig. 12(b) that efficiency reaches a sharp maximum of approximately 26% at $\omega/\omega_{e11} \approx 5.8$
($f \approx 18.5$ GHz), corresponding to the $\text{TE}_{11}$ mode being nearly in resonance with the
electron beam. Note in Fig. 12(b) that there is a small peak at $\omega/\omega_{e11} \approx 6.0$ in the high
frequency domain, which is also true in the corresponding single-mode CARM interaction.

Another example is shown in Figs. 13 and 14, where we plot the dependence of rf
power and relative rf phase on the interaction length $z$ for a CARM with the $\text{TE}_{11}$ and
$\text{TM}_{11}$ modes. In Figs. 13 and 14, the system parameters are $f = 18$ GHz, $I_b = 500$
A, $\gamma = 2.96$, $\beta_{p0} = \beta_{0}/\beta_{e0} = 0.6$, $\dot{\sigma}_{pz} = 0$, $r_m = 0$, $r_w = 1.7$ cm, and $B_0 = 4.84$
kG, corresponding to the $\text{TE}_{11}$ mode in resonance, and the $\text{TM}_{11}$ mode off resonance,
with the electron beam at the fundamental cyclotron frequency. The general features of
the coupling of the $\text{TE}_{11}$ and $\text{TE}_{12}$ modes [Figs. 9(b) and 10(b)] hold true also for the
coupling of the $\text{TE}_{11}$ and $\text{TM}_{11}$ modes, as shown in Figs. 13 and 14.

B. Many-Mode Coupling

The multimode CARM interaction with more than two waveguide modes can be
analyzed with the same method as two-mode coupling. Here, we only present the detuning
characteristics of a CARM amplifier with four coupled $\text{TE}_{1n}$ modes ($n = 1, 2, 3, 4$).
Figure 15 depicts the dependence of the (fractional) saturated $\text{TE}_{1n}$ power on the axial
magnetic field $B_0$, as obtained from the simulation with an input power of 100 W per
mode. By increasing the axial magnetic field $B_0$ in Fig. 15, the beam mode is successively
tuned through the resonances with the $\text{TE}_{11}$, $\text{TE}_{12}$, $\text{TE}_{13}$, and $\text{TE}_{14}$ modes at $B_0 = 3.74$,
4.29, 5.33, and 6.98 kG, respectively. The fractional rf power for a given mode at sat-
uration reaches a maximum at its resonant magnetic field, and then decreases rapidly off resonance. In the transition from one resonance to another, however, two adjacent competing modes can have comparable rf power levels at saturation.

Figure 16 shows the dependence of the $\text{TE}_{1n}$ rf power on the interaction length, for the choice of system parameters used in Fig. 16. Here, the value of magnetic field $B_0 = 5.33 \text{ kG}$ corresponds to the $\text{TE}_{13}$ mode in resonance with the electron beam. Again, the growth rates are the same for all of the coupled modes, as in the two-mode coupling as seen in Figs. 9(b) and 13.

VII. CONCLUSIONS

In conclusion, we have presented a general treatment of multiple waveguide mode interactions in an overmoded cyclotron autoresonance maser amplifier using kinetic theory and a fully nonlinear, there-dimensional, self-consistent model. Good agreement has been found between the simulations and linear theory in the linear regime. The general features of multimode phenomena have been illustrated in the linear and nonlinear regimes.

It was shown analytically, and confirmed in the simulations, that all of the coupled waveguide modes grow with the dominant unstable mode at the same spatial growth rate, but they suffer different launching losses which depend upon detuning characteristics. The phases of coupled modes are locked in the exponential gain regime, and remain approximately locked for some finite interaction length beyond saturation.

The saturated rf power in each mode was found to be insensitive to input rf power distribution among the coupled modes, but it is sensitive to detuning. Simulations indicated that the fractional rf power for a given mode at saturation reaches a maximum at its resonant magnetic field, then decreases rapidly off resonance.

As a general conclusion, based on the results of this paper, an accurate calculation
of the growth rate, saturation levels, and radiation field profile in overmoded CARM amplifiers requires the use of a multimode theory in the linear and nonlinear regimes. We believe that the present analysis can be generalized to treat multimode phenomena in a large class of free electron devices including free electron lasers, gyrotron traveling-wave tubes, and Cerenkov masers. It can be easily extended to include non-axisymmetric beams and, with more effect, used to study high-gain overmoded oscillators.

ACKNOWLEDGMENTS

The authors wish to thank Bruce Danly and Henry Freund for helpful discussions. The development of the CSPOT code was based on its single-mode version written originally by Bruce G. Danly, Kenneth D. Pendergast, T.M. Tran, and Jessie Dotson. This work was supported by the Department of Energy, Office of Basic Energy Sciences, the Department of Energy, High Energy Physics Division, the Office of Naval Research, and the Naval Research Laboratory Plasma Physics Division.
APPENDIX A: MODE DECOMPOSITION FOR
THE LINEARIZED VLASOV EQUATION

To derive Eq. (28) from Eq. (27), we follow Refs. 12 and 22 and make use of
recurrence relations and Graf’s theorem for Bessel functions\(^{27}\) to express the radiation
field components in Eq. (27). It is straightforward to show from Eq. (8)-(11) that

\[ E_\perp = E_r \cos(\phi - \theta) + E_\theta \sin(\phi - \theta) \]

\[ = \sum_{mnq} \exp[i\Lambda_m(q, \phi_c, t)] \left[ k_{mn}C_{mn}X_{mnq}E_{mn}(z) + \dot{k}_{mn}C_{mn}X_{mnq} \left( \frac{ic}{\omega} \right) \frac{dB_{mn}(z)}{dz} \right], \quad (A1) \]

\[ E_\perp \cos \phi_c - E_\phi \sin \phi_c = E_r \cos(\phi - \theta - \phi_c) + E_\theta \sin(\phi - \theta - \phi_c) \]

\[ = \sum_{mnq} \exp[i\Lambda_m(q, \phi_c, t)] \left[ -k_{mn}C_{mn}Y_{mnq}E_{mn}(z) + \dot{k}_{mn}C_{mn}Y_{mnq} \left( \frac{ic}{\omega} \right) \frac{dB_{mn}(z)}{dz} \right], \quad (A2) \]

\[ E_z = \sum_{mnq} \exp[i\Lambda_m(q, \phi_c, t)] \dot{k}_{mn}C_{mn}X_{mnq} \left( \frac{c^2}{m + q} \right) B_{mn}(z), \quad (A3) \]

\[ B_\phi = -B_r \sin(\phi - \theta) + B_\theta \cos(\phi - \theta) \]

\[ = \sum_{mnq} \exp[i\Lambda_m(\phi, \phi_c, t)] \left[ -k_{mn}C_{mn}X_{mnq} \left( \frac{ic}{\omega} \right) \frac{dE_{mn}(z)}{dz} - \dot{k}_{mn}C_{mn}X_{mnq}B_{mn}(z) \right], \quad (A4) \]

\[ B_\perp \sin \phi_c + B_\phi \cos \phi_c = -B_r \sin(\phi - \theta - \phi_c) + B_\theta \cos(\phi - \theta - \phi_c) \]

\[ = \sum_{mnq} \exp[i\Lambda_m(q, \phi_c, t)] \left[ k_{mn}C_{mn}Y_{mnq} \left( \frac{ic}{\omega} \right) \frac{dE_{mn}(z)}{dz} - \dot{k}_{mn}C_{mn}Y_{mnq}B_{mn}(z) \right], \quad (A5) \]

\[ B_z \sin \phi_c = \sum_{mnq} \exp[i\Lambda_m(q, \phi_c, t)] k_{mn}C_{mn}Z_{mnq} \left( \frac{ck_{mn}}{2\omega} \right) E_{mn}(z), \quad (A6) \]

where \( \Lambda_{mn}(\phi, \phi_c, t) = m\phi + q\phi_c - \omega t - m\pi/2 \), and the geometric factors \( X, Y, Z, \dot{X} \) and \( \dot{Y} \)
are defined in Eqs. (31)-(35). Substituting Eqs. (A1)-(A6) into Eq. (27) and performing
some algebra then yields Eq. (28).
APPENDIX B: DERIVATION OF LINEARIZED AMPLITUDE EQUATIONS

The linearized amplitude equations (44) and (45) can be derived as follows. Multiplying Eqs. (40) and (41) with \( \exp(-sz) \) and integrating over \( z \), respectively, some straightforward algebra then yields

\[
D_{mn}^{TE}(s, \omega) \hat{E}_{mn}(s) = \sum_{n'(n' \neq n)} \sum_{l=-\infty}^{\infty} \left[ \chi_{mn'l}^{TE} \hat{E}_{mn'}(s) + \chi_{mn'l}^{EM} \hat{B}_{mn'}(s) \right] \\
= sE_{mn}(0) + \sum_{n'} \sum_{l=-\infty}^{\infty} \left[ \mu_{mn'l}^{TE} E_{mn'}(0) + \mu_{mn'l}^{EM} B_{mn'}(0) \right] \tag{B1}
\]

\[
D_{mn}^{TM}(s, \omega) \hat{B}_{mn}(s) = \sum_{n'(n' \neq n)} \sum_{l=-\infty}^{\infty} \left[ \chi_{mn'l}^{ME} \hat{E}_{mn'}(s) + \chi_{mn'l}^{TM} \hat{B}_{mn'}(s) \right] \\
= sB_{mn}(0) + \sum_{n'} \sum_{l=-\infty}^{\infty} \left[ \mu_{mn'l}^{ME} E_{mn'}(0) + \mu_{mn'l}^{TM} B_{mn'}(0) \right] \tag{B2}
\]

In Eqs. (B1) and (B2),

\[
D_{mn}^{TE}(s, \omega) = s^2 - k_{mn}^2 + \frac{\omega^2}{c^2} - \sum_{l=-\infty}^{\infty} \chi_{mn'l}(s, \omega) \tag{B3}
\]

and

\[
D_{mn}^{TM}(s, \omega) = s^2 - k_{mn}^2 + \frac{\omega^2}{c^2} - \sum_{l=-\infty}^{\infty} \chi_{mn'l}(s, \omega) \tag{B4}
\]

are the \( TE_{mn} \) and \( TM_{mn} \) dielectric functions, respectively; the susceptibility functions are defined by

\[
\chi_{mn'l}^{TE}(s, \omega) = -\frac{16\pi^3 e^2 \omega k_{mn'}^2}{c} \left( \frac{C_{mn}}{k_{mn}} \right) \left( \frac{C_{mn'}}{k_{mn'}} \right)
\]
\[
\int r_g dr_g X_{mn'l-m} \int p_{\perp} dp_{\perp} dp_z \frac{\beta_{\perp}}{\omega - i\Omega_c / \gamma + isv_z} \left\{ X_{mn'l-m} \left[ \left( 1 + \frac{isv_z}{\omega} \right) \frac{\partial f_0}{\partial p_{\perp}} - \frac{isv_z}{\omega} \frac{\partial f_0}{\partial p_z} \right] - \left[ \frac{Y_{mn'l-m}}{m_0 \Omega_c} \left( 1 + \frac{isv_z}{\omega} \right) - \frac{Z_{mn'l-m}}{m_0 \Omega_c} \left( \frac{k_{mn'l} v_{\perp}}{2 \omega} \right) \right] \frac{\partial f_0}{\partial r_g} \right\},
\]

(B5)

\[
\chi_{mn'l}(s, \omega) = - \frac{16\pi^2 e^2 \omega k_{mn'l}^2}{c} \left( \frac{C_{mn}}{k_{mn}} \right) \left( \frac{\hat{C}_{mn'}}{\hat{k}_{mn'}} \right)
\]

\[
\int r_g dr_g X_{mn'l-m} \int p_{\perp} dp_{\perp} dp_z \frac{\beta_{\perp}}{\omega - i\Omega_c / \gamma + isv_z} \left\{ X_{mn'l-m} \left[ \left( 1 + \frac{isv_z}{\omega} \right) \frac{\partial f_0}{\partial p_{\perp}} - \frac{isv_z}{\omega} \frac{\partial f_0}{\partial p_z} \right] - \left[ \frac{Y_{mn'l-m}}{m_0 \Omega_c} \left( 1 + \frac{isv_z}{\omega} \right) - \frac{Z_{mn'l-m}}{m_0 \Omega_c} \left( \frac{k_{mn'l} v_{\perp}}{2 \omega} \right) \right] \frac{\partial f_0}{\partial r_g} \right\},
\]

(B6)

\[
\chi_{mn'l}(s, \omega) = - \frac{16\pi^2 e^2 \omega^2 \hat{k}_{mn'l}^2}{c^2} \left( \frac{\hat{C}_{mn}}{\hat{k}_{mn}} \right) \left( \frac{\hat{C}_{mn'}}{\hat{k}_{mn'}} \right)
\]

\[
\int r_g dr_g \frac{\hat{k}_{mn'l} r_L}{l} X_{mn'l-m} \int p_{\perp} dp_{\perp} dp_z \frac{\beta_{\perp}}{\omega - i\Omega_c / \gamma + isv_z} \left\{ X_{mn'l-m} \left[ \left( 1 + \frac{isv_z}{\omega} \right) \frac{\partial f_0}{\partial p_{\perp}} - \frac{isv_z}{\omega} \frac{\partial f_0}{\partial p_z} \right] - \left[ \frac{Y_{mn'l-m}}{m_0 \Omega_c} \left( 1 + \frac{isv_z}{\omega} \right) - \frac{Z_{mn'l-m}}{m_0 \Omega_c} \left( \frac{k_{mn'l} v_{\perp}}{2 \omega} \right) \right] \frac{\partial f_0}{\partial r_g} \right\},
\]

(B7)

Moreover, the \( \mu \)'s are defined by

\[
\mu_{mn'l}(s, \omega) = \frac{16\pi^2 e^2 \omega^2 k_{mn'l}^2}{c^2} \left( \frac{C_{mn}}{k_{mn}} \right) \left( \frac{C_{mn'}}{k_{mn'}} \right)
\]

\[
\int r_g dr_g X_{mn'l-m} \int p_{\perp} dp_{\perp} dp_z \frac{\beta_{\perp}}{\omega - i\Omega_c / \gamma + isv_z} \left\{ X_{mn'l-m} \left[ \left( 1 + \frac{isv_z}{\omega} \right) \frac{\partial f_0}{\partial p_{\perp}} - \frac{isv_z}{\omega} \frac{\partial f_0}{\partial p_z} \right] - \left[ \frac{Y_{mn'l-m}}{m_0 \Omega_c} \left( 1 + \frac{isv_z}{\omega} \right) - \frac{Z_{mn'l-m}}{m_0 \Omega_c} \left( \frac{k_{mn'l} v_{\perp}}{2 \omega} \right) \right] \frac{\partial f_0}{\partial r_g} \right\},
\]

(B8)
\[ \mu_{mn'1}^{EM}(s, \omega) = i16\pi^2 e^2 k_{mn'}^2 \left( \frac{C_{mn}}{k_{mn}} \right) \left( \frac{\dot{C}_{mn'}}{k_{mn'}} \right) \]

\[ \int r_g dr_g X_{mnl-m} \int p_{\perp} dp_{\perp} dp_z \frac{\beta_{\perp}}{\omega - \Omega_c/\gamma + isv_z} \left( \dot{X}_{mn'1-m} \frac{\partial f_0}{\partial p_{\perp}} + \frac{\dot{Y}_{mn'1-m}}{m_0 \Omega_c} \frac{\partial f_0}{\partial r_g} \right), \quad (B10) \]

\[ \mu_{mn'1}^{TM}(s, \omega) = i16\pi^2 e^2 k_{mn'}^2 \left( \frac{\omega}{c k_{mn}} \right) \left( \frac{\dot{C}_{mn}}{k_{mn}} \right) \left( \frac{\dot{C}_{mn'}}{k_{mn'}} \right) \]

\[ \int r_g dr_g \frac{k_{mnL}}{l} \dot{X}_{mnl-m} \int p_{\perp} dp_{\perp} dp_z \frac{(\beta_{\perp} + i cs/\omega)}{\omega - \Omega_c/\gamma + isv_z} \left\{ \dot{X}_{mn'1-m} \frac{\partial f_0}{\partial p_{\perp}} + \frac{\dot{Y}_{mn'1-m}}{m_0 \Omega_c} \frac{\partial f_0}{\partial r_g} \right\}, \quad (B11) \]

\[ \mu_{mn'1}^{MB}(s, \omega) = i16\pi^2 e^2 k_{mn'}^2 \left( \frac{\omega}{c k_{mn}} \right) \left( \frac{\dot{C}_{mn}}{k_{mn}} \right) \left( \frac{C_{mn'}}{k_{mn'}} \right) \]

\[ \int r_g dr_g \frac{k_{mnL}}{l} \dot{X}_{mnl-m} \int p_{\perp} dp_{\perp} dp_z \frac{(\beta_{\perp} + i cs/\omega)}{\omega - \Omega_c/\gamma + isv_z} \left[ X_{mn'1-m} \left( \beta_{\perp} \frac{\partial f_0}{\partial p_{\perp}} - \frac{\partial f_0}{\partial p_z} \right) - \beta_{\perp} \frac{\partial f_0}{\partial r_g} \right], \quad (B12) \]

By performing the integrals in Eqs. (B5)-(B12) for the distribution function defined in Eq. (23), the linearized amplitude equations correct to leading order in \( c^2 k_{mn}^2 / (\omega - \Omega_c/\gamma - k_z v_z)^2 \) can be expressed by Eqs. (44) and (45).
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FIGURE CAPTIONS

Fig. 1 Schematic of a CARM system in the interaction region.

Fig. 2 Guiding-center coordinate system.

Fig. 3 Schematic of the uncoupled waveguide dispersion relation and the beam cyclotron mode. The CARM interaction occurs near the upshifted intersection of the waveguide and beam modes.

Fig. 4 Gain bandwidth for the $TE_{11}$ mode at the fundamental cyclotron frequency ($l = 1$). Here, the solid curve is obtained from Eq. (79), while the dots are from the simulations using CSPOT. Note that the growth rate vanishes at $\omega/\omega_{c11} \approx 3.8$, where the force bunching cancels the inertial bunching, i.e., $D_{11}^{eff} = 0$ [Eq. (83)].

Fig. 5 The $TE_{11}$ rf power is plotted as a function of the interaction length $z$. Here, the system parameters are the same as in Fig. 4, but with $\omega/c k_{11} = 2.87$ ($f = 18$ GHz). The solid curve is from the simulations, while the dashed curve is from Eqs. (81) and (82).

Fig. 6 Comparison of the measured and computed rf power as a function of interaction length for a 35 GHz CARM amplifier experiment operating in the $TE_{11}$.

Fig. 7 Gain bandwidth for the $TM_{11}$ mode at the fundamental cyclotron frequency ($l = 1$). The solid curve is obtained from Eq. (84), while the dotted curve is from the simulations. Note that the gain bandwidth consists of two frequency domains separated when the condition $\beta_{20}\beta_{\phi11} = 1$ is satisfied at $\omega/\omega_{c11} \approx 1.7$.

Fig. 8 The $TM_{11}$ rf power is plotted as a function of the interaction length $z$. The system parameters are the same as in Fig. 7 with $\omega/c k_{11} = 1.38$ ($f = 18$ GHz). The solid curve is from the simulations, while the dashed curve is from Eq. (86).
Fig. 9  The rf power in the TE$_{11}$ and TE$_{12}$ is plotted as a function of interaction length for (a) single-mode CARM interactions and (b) the CARM interaction with the two waveguide modes coupling to the electron beam. Note that in Fig. 8(b) the TE$_{12}$ mode grows parasitically with the dominant unstable TE$_{11}$ mode at the same growth rate due to mode coupling, despite the differences in launching losses.

Fig. 10  The relative rf phase $\Delta \Phi = (k_{z12} - k_{z11})z + \delta_{12}(z) - \delta_{11}(z)$ is plotted as a function of the interaction length $z$. Here, the two curves, (a) and (b), correspond to the single-mode simulations in Fig. 9(a), and to the multimode simulation in Fig. 9(b), respectively.

Fig. 11  The TE$_{12}$ rf power is plotted as a function of the interaction length $z$ for a CARM with the TE$_{11}$ and TE$_{12}$ modes. The two solid curves depict the linear and nonlinear evolution of rf power in the TE$_{12}$ mode obtained from the simulations with two input rf power distributions: (a) $P_0(\text{TE}_{11}) = P_0(\text{TE}_{12}) = 100$ W, and (b) $P_0(\text{TE}_{11}) = 100$ W and $P_0(\text{TE}_{12}) = 1$ W, while the dashed curves are the corresponding analytical results from Eq. (90).

Fig. 12  (a) Gain bandwidth for the CARM interaction with the TE$_{11}$ and TE$_{12}$ modes coupling to the electron beam for the same system parameters used in Figs. 9(b) and 10(b), except that $\omega$ varies from $3\omega_{c11}$ to $9\omega_{c11}$. Here, the solid curve is obtained from Eq. (84), while the dots are results from the simulations. (b) The saturated efficiency is plotted as a function of frequency for the same system, as obtained from the simulations.

Fig. 13  The rf power is plotted as a function of the interaction length $z$ for a CARM with the TE$_{11}$ and TM$_{11}$ modes. Here, the choice of system parameters corresponds to the TE$_{11}$ mode in resonance, and the TM$_{11}$
mode off resonance, with the electron beam. The solid curve is obtained from
the simulation, while the dashed curve is from the multimode linear theory.

Fig. 14 The relative rf phase \( \Delta \Phi = (k_{z11} - k_{z11})z + \delta_{11}(z) - \delta_{11}(z) \) is plotted as a
function of the interaction length \( z \), as obtained from the simulation for
the system used in Fig. 13.

Fig. 15 The fractional rf power at saturation in four coupled TE_{1n} modes is plotted
as a function of the axial magnetic field \( B_0 \). Here, the values of the resonant
magnetic field for the TE_{11}, TE_{12}, TE_{13}, and TE_{14} modes correspond to
\( B_0 = 3.74, 4.29, 5.33, \) and \( 6.98 \) kG, respectively.

Fig. 16 The rf power in four coupled TE_{1n} modes is plotted as a function of the
interaction length \( z \), as obtained from the simulation for the system used
in Fig. 15. Here, the value of the magnetic field \( B_0 = 5.33 \) kG corresponds
to the TE_{13} mode in resonance with the electron beam.
Fig. 1
Fig. 2
\[ \omega = (c^2 k_z^2 + \omega_c^2)^{1/2} \]

\[ \omega = k_z v_z + \frac{\Omega_c}{\gamma} \]

Fig. 3
\[
\frac{-c \text{Im} \Delta k_z}{\omega_{ci}}\]

Fig. 4

- \( \gamma = 2.96 \)
- \( I_b = 500 \text{A} \)
- \( \theta_{po} = 0.5 \)
- \( B_o = 4.0 \text{kG} \)
- \( r_w = 1.4 \text{cm} \)
\( \text{TE}_{11} \text{ MODE} \)

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**Simulation vs Linear Theory**

- \( f = 18 \text{GHz} \)
- \( B_0 = 4.01 \text{ kG} \)
- \( \gamma = 2.96 \)
- \( \theta_{po} = 0.5 \)
- \( I_b = 500 \text{A} \)
- \( r_w = 1.4 \text{cm} \)

**Fig. 5**
Fig. 6
Fig. 7

TM$_{II}$ MODE

\[ \gamma = 2.96, \theta_{po} = 0.6 \]
\[ I_b = 500A, B_0 = 8.45kG \]
\[ r_w = 1.4cm \]
Fig. 8

- **TM_{11} MODE**
- **RF POWER (W)**
- **Z (cm)**

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**SIMULATION**

- \( f = 18 \text{GHz} \)
- \( \gamma = 2.96 \)
- \( I_b = 500 \text{A} \)
- \( r_w = 1.4 \text{cm} \)

**LINEAR THEORY**

- \( B_0 = 8.45 \text{kG} \)
- \( \theta_{po} = 0.6 \)
Fig. 9

(a) Simulation vs. Linear Theory

(b) Simulation vs. Linear Theory

Parameters:
- $f = 18 \text{GHz}$
- $B_0 = 3.92 \text{kG}$
- $\gamma = 2.96$
- $\theta_{po} = 0.6$
- $I_b = 500 \text{A}$
- $r_w = 2.7 \text{cm}$
Fig. 10
Fig. 11

- Simulation
- Linear Theory

- TE_{12}  
- f = 18 GHz  
- r_w = 2.7 cm  
- B_0 = 3.92 kG  
- \gamma = 2.96  
- \theta_p = 0.6  
- I_b = 500 A
(b) \[ \gamma = 2.96 \]
\[ I_b = 500A \]
\[ \theta_{po} = 0.6 \]
\[ B_0 = 3.92 \text{ kG} \]
\[ r_w = 2.7 \text{ cm} \]
Fig. 13

Simulated and linear theory results for the RF power as a function of position (Z) for the modes $\text{TE}_{II}$ and $\text{TM}_{II}$. The parameters used in the simulation are:

- Frequency ($f$): 18 GHz
- Magnetic field ($B_0$): 4.84 kG
- Current density ($\gamma$): 2.96
- Plasma density ($\theta_{po}$): 0.6
- Current ($I_b$): 500 A
- Wall radius ($r_w$): 1.27 cm
Fig. 14

$\Delta \phi / \pi$

$Z$ (cm)

$TE_{11} - TM_{11}$

- $f = 18$ GHz
- $B_0 = 4.84$ kG
- $\gamma = 2.96$
- $\theta_{po} = 0.6$
- $I_b = 500$A
- $r_w = 1.27$ cm
Fig. 15

Fractional RF Power vs. $B_0$ (kG)

- $TE_{11}$
- $TE_{12}$
- $TE_{13}$
- $TE_{14}$

$f = 18 \text{GHz}$
$r_w = 5 \text{ cm}$
$\gamma = 2.96$
$I_b = 500 \text{A}$
$\theta_{po} = 0.6$
Fig. 16