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THREE DIMENSIONAL NON-LINEAR THEORY OF THE FREE ELECTRON LASER.(U)

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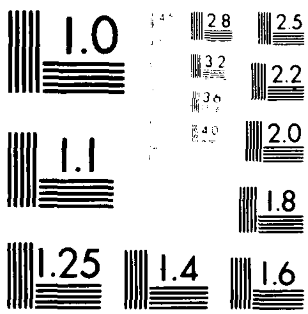

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This paper deals primarily with 3-D effects and efficiency enhancement methods in a steady state FEL amplifier configuration. We treat finite transverse dimension effects associated with i) the wiggler field, ii) electron beam and iii) radiation beam. Our formulation includes efficiency enhancement schemes such as spatially contouring the wiggler field as well as accelerating the electron beam. Finally, a 3-D example of a 10.6 μ FEL with enhanced efficiency is given.

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CONTENTS

THREE DIMENSIONAL NON-LINEAR THEORY OF THE FREE ELECTRON LASER

Numerous publications have treated the 1-D Free Electron Laser (FEL) mechanism.(1-10) As of the writing of this paper, 3-D effects in the FEL have received little attention.(11) It is the purpose of this paper to present a general non-linear 3-D formulation of the steady state FEL amplifier configuration including the various efficiency improvement schemes.

When a cold, axially propagating electron beam enters a physically real wiggler field, a shear in the axial electron velocity results.(12) The axial velocity shear across the electron beam is equivalent to a beam temperature, which if large would significantly reduce the fraction of electrons trapped in the ponderomotive buckets.

The radiation beam, which experiences both diffraction as well as refraction, can be represented as the superposition of the input field and excited field. In the absence of a detailed 3-D analysis, it could be argued that these two fields could destructively interfere on axis. This would result in a decrease in the depth of the ponderomotive potential buckets and could cause detrapping of the electrons. The results of our analysis, however, indicate that destructive interference does not take place. A number of efficiency enhancement schemes for the FEL have been identified.(7,9,10) These include: i) contouring, spatially, the amplitude and/or wavelength of the magnetic wiggler field, ii) accelerating the electron beam by applying an external D.C. accelerating electric field. Our formulation will include and show the equivalence of the above enhancement schemes.

A generalized pendulum like equation for the phase of the particles is obtained. The wiggler field has transverse spatial gradients as well as an amplitude and wavelength which are arbitrary functions of axial position. The infinitely long highly relativistic electron beam is assumed to

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be initially cold and tenuous enough so that space charge effects can be neglected. The inclusion of beam temperature and space charge are straightforward and have been included in 1-D formalisms.(7,9) The evolution of the radiation field governed by the particle dynamics is determined as a function of x,y,z. Then, simplifying assumptions are made which result in an analytic expression for the field on axis. Finally, the field off axis is numerically evaluated and applied to specific examples.

The generalized linearly polarized wiggler and radiation field are represented by the following vector potentials

$$\underset{\sim}{A}_w(y,z) = A_w(z)\ \cosh\ (k_w(z)y)\ \cos(\int_0^z k_w(z')dz')\hat{e}_x \tag{1a}$$

$$\underset{\sim}{A}_R(x,y,z,t) = A(x,y,z)\ \sin\ (\frac{\omega}{c}z - \omega t + \varphi\ (x,y,z))\hat{e}_x \tag{1b}$$

where $A_w(z)$ and $k_w(z) = 2\pi/\ell_w(z)$ are the slowly varying amplitude and wavenumber of the wiggler field, ℓ_w is the wiggler wavelength and A and φ are the slowly varying amplitude and phase of the total radiation field. We also include an external accelerating D.C. electric field $\underset{\sim}{E}_{ac}(z) = -\partial\phi_{ac}(z)/\partial z\ \hat{e}_z$. The equation (in Lagrangian independent variables) which describes the relative phase between the electrons and the ponderomotive wave can be shown to be governed by

$$\frac{d^2\tilde{\Psi}}{dz^2} = \frac{d^2\varphi}{dz^2} + \frac{\partial k_w}{\partial z} + \frac{|e|\omega/c}{\tilde{\gamma}_z^2\tilde{\gamma} m_o c^2}\frac{\partial\phi_{ac}}{\partial z} - \frac{|e|^2\omega/c}{2\tilde{\gamma}^2 m_o^2 c^4}\left[\frac{\partial}{\partial z}(A_w\ \cosh\ (k_w\tilde{y})\cos\int_0^z k_w dz')^2 + 2k_w A_w\ \cosh\ (k_w\tilde{y})\ A(\tilde{x},\tilde{y},z)\ \cos\ \tilde{\Psi}\right] \tag{2}$$

where $\tilde{\Psi} = \tilde{\Psi}(z,t_o,x_o,y_o) = \int_0^z (\omega/c + k_w(z'))dz' - \omega\tilde{t} + \varphi(x,y,z)$ is the phase,

$\tilde{t} = t_o + \int_o^z dz'/\tilde{V}_z$, $\tilde{\gamma} = \tilde{\gamma}_z\gamma_{o\perp}$, $\tilde{\gamma}_z = (1 - \tilde{V}_z^2/c^2)^{-1/2}$, $\gamma_{o\perp} = (1 + (|e|\underset{\sim}{A}_w(z)/(m_o c^2))^2)^{1/2}$, $\tilde{V}_z = \omega/(\omega/c + k_w(z) - d\tilde{\Psi}/dz + d\phi/dz)$ is the electron axial velocity, $\tilde{x} \approx x_o + \beta_{o\perp}k_w^{-1}\sin\int_o^z k_w dz'$ and $\tilde{y} \approx y_o \cos K_o z$ are the zeroth order transverse electron coordinates, $\beta_{o\perp} = v_{o\perp}/c$, $v_{o\perp} = |e|A_w/(\gamma_o m_o c)$ is the wiggle velocity, $\gamma_o = (1 - v_o^2/c^2)^{-1/2}$, v_o is the magnitude of the total particle velocity and $K_o = \beta_{o\perp}k_w/\sqrt{2}$. The Lagrangian independent variables t_o, x_o, y_o are the time and transverse coordinates of a particle at the entrance to the interaction region, i.e. $z = 0$. In obtaining (2) we have used the fact that $\omega \approx \tilde{\gamma}_z^2(1 + \tilde{V}_z/c)\, ck_w$, the x component of electron momentum is $\approx (|e|/c)\ (\underset{\sim}{A}_w(\tilde{y},z) + \underset{\sim}{A}_R(\tilde{x},\tilde{y},z,\tilde{t}))\cdot\hat{e}_x$, $|\underset{\sim}{A}_w| \gg |\underset{\sim}{A}_R|$ and $V_z \approx v_o \approx c$. Equation (2) clearly shows the relationship between the various efficiency enhancement schemes. In the equation for the phase $\tilde{\Psi}$, contouring the wiggler wavelength or amplitude, i.e., $\partial k_w/\partial z$ or $\partial A_w^2/\partial z$ is equivalent to introducing an accelerating field, i.e. $\partial\phi_{ac}/\partial z$.

The axial velocity shear, due to the wiggler gradient is given by $\Delta V_{shear} = c(\beta_{o\perp}\ k_w y_o/2)^2$, while the energy shear is $\Delta\mathcal{E}_{shear} = \gamma_o^3(\Delta V_{shear}/c)m_o c^2$. The initial depth of the trapping potential is $|e|\phi_{trap} = 2\sqrt{2\gamma_o\gamma_{oz}\beta_{o\perp}}(A/A_w)^{1/2}m_o c^2$. In order to trap a substantial fraction of the electrons we require $\Delta\mathcal{E}_{shear} < |e|\phi_{trap}$, this places a limit on the electron beam radius given by

$$r_b < (\gamma_o k_w)^{-1} \left(\frac{8\sqrt{2}\,\gamma_{oz}}{\beta_{o\perp}}\right)^{1/2} \left(\frac{A}{A_w}\right)^{1/4}. \tag{3}$$

An axially symmetric electron beam injected into the wiggler field in (1a) experiences a periodic focusing in the y-direction. The focusing wavelength along z is $2\pi K_o^{-1} \gg \ell_w$. A comment is in order concerning the neglect of space charge waves. It can be shown that the ponderomotive term in (2) (term proportional to $A_w A$) will dominate the space charge term if the beam density satisfies

$$n_o \ll (k_w^2 \gamma_{zo}^4 A_w A)(2\pi\gamma_o m_o c^2)^{-1} \tag{4}$$

The radiation field satisfies the wave equation $(\nabla^2 - c^{-2}\partial^2/\partial t^2)\underset{\sim}{A}_R = -4\pi c^{-1} J_x \hat{e}_x$ where the current density is given by

$$J_x(x,y,z,t) = -\frac{\omega_b^2}{4\pi c}\int_{-\infty}^{\infty} dt_o \int_{-\infty}^{\infty} dx_o \int_{-\infty}^{\infty} dy_o\, \theta(x_o,y_o)\delta(x-\tilde{x})\delta(y-\tilde{y})\delta(t-\tilde{t})\,\frac{A_w(\tilde{y},z)}{\tilde{\gamma}} \tag{5}$$

where $\omega_b = (4\pi |e|^2 n_o/m_o)^{1/2}$, n_o is the density on axis outside of the interaction region, and $\theta(x_o,y_o)$ is a function which describes the initial electron beam profile. The integrations in (5) are over all initial entrance times and transverse coordinates. The radiation field in (1b) can be represented in the form $\underset{\sim}{A}_R(x,y,z,t) = (2i)^{-1}a(x,y,z)\exp i\,(\omega z/c - \omega t)\hat{e}_x$ + c.c. where $a = A\exp(i\varphi)$ is the complex field amplitude which is a slowly varying function of z. Substituting (5) into the wave equation yields an equation for $a(x,y,z)$ which can readily be solved using Fourier transform techniques. We find that $a = a_1 + a_2$ where a_1 is the homogeneous solution (input field) given by $a_1(x,y,z) = \frac{1}{4\pi^2}\iint_{-\infty}^{\infty} \bar{a}(k_x,k_y,0)\exp\left(i(k_x x + k_y y - \frac{k^2 z}{2\omega/c})\right) dk_x dk_y$ where $k^2 = k_x^2 + k_y^2$ and $\bar{a}(k_x,k_y,0) = \iint_{-\infty}^{\infty} a(x,y,0)\exp(-i(k_x x + k_y y))\,dxdy$. At z = 0 the only field is the input signal. The expression for a_1 can be shown to give the well known Gaussian radiation beam modes. The particular solution (excited field) is

$$a_2(x,y,z) = -\frac{i}{4\pi}\frac{\omega_b^2}{c^2}\int_0^z dz' \int_0^{2\pi/\omega}\frac{dt_o}{2\pi/\omega}\int_{-\infty}^{\infty}dx_o\int_{-\infty}^{\infty}dy_o\,\theta(x_o,y_o)\,\frac{A_w'}{\tilde{\gamma}'}\cosh(k_w'\tilde{y}')$$

$$\frac{e^{i((x-\tilde{x}')^2 + (y-\tilde{y}')^2)\frac{\omega/c}{2(z-z')}}}{z-z'}\, e^{-i(\Psi' - \varphi')} \tag{6}$$

where primes on quantities denote that they are functions of z′. The expression for the excited field in (6) completes the formal part of our analysis. Equations (2) and (6) describe self-consistently the non-linear 3-D steady state FEL amplifier configuration.

Considering the case where $k_w y_o \ll 1$, $\tilde{x}$ and $\tilde{y}$ can be replaced by x_o and y_o in (6). Assuming a low gain situation, i.e. $|a_1| > |a_2|$, and a plane wave form for the input field, we can take the phase $\tilde{\Psi}(z,t_o,x_o,y_o)$ to be very nearly only a function of z and t_o. Choosing a Gaussian electron beam profile, i.e. $\theta(x_o,y_o) = \exp(-(x_o^2 + y_o^2)/r_b^2)$, (6) reduces to

$$a_2(r,z) = -\frac{i}{4}\frac{\omega_b^2/c^2}{\gamma_o} r_b^2 \int_0^{2\pi/\omega} \frac{dt_o}{2\pi/\omega}\int_0^z dz' \, A_w(z')\, e^{i\varphi(r,z')}\left(\frac{z-z'+iz_o}{(z-z')^2+z_o^2}\right)$$

$$\exp -i\left(\tilde{\Psi}(z',t_o) - z_o\left(\frac{z-z'+iz_o}{(z-z')^2+z_o^2}\right)\frac{r^2}{r_b^2}\right) \qquad (7)$$

where $z_o = r_b^2\,\omega/2c$ is the effective Rayleigh length associated with the excited radiation. The 1-D limit of (7) is obtained by letting z_o or r_b approach ∞. We will limit ourselves at this point to a constant parameter wiggler and consider only an external accelerating potential. Furthermore, we will make the constant phase resonant particle approximation. In this approximation all particles are assumed to have the same constant phase, $\tilde{\Psi}_R$. To obtain the total radiation field we first evaluate $a_2(r,z)$ under the assumption that $|\varphi| \ll 1$ (this will be shown to be valid). Taking a plane wave input field of amplitude A_{in}, the amplitude and phase of the <u>total</u> field, on axis, becomes

$$A(r=0,z) = A_{in} + \alpha_o^2 A_w\left[\tan^{-1}\left(\frac{z}{z_o}\right)\cos\tilde{\Psi}_R - \ln\left(\frac{z^2+z_o^2}{z_o^2}\right)^{1/2}\sin\tilde{\Psi}_R\right] \qquad (8a)$$

$$\varphi(r = 0, z) = -\alpha_o^2 (A_w/A) \left[\tan^{-1}\left(\frac{z}{z_o}\right) \sin \tilde{\Psi}_R + \ln \left(\frac{z^2 + z_o^2}{z_o^2}\right)^{1/2} \cos \tilde{\Psi}_R \right] \quad (8b)$$

where $\alpha_o = \omega_b r_b / 2c\, /\gamma_o$ and $\tilde{\Psi}_R$ is obtained from the stationary solution of (2).

As an example of a 10.6 μm FEL utilizing a high power CO_2 laser beam as an input field we choose an electron beam energy of 25 MeV ($\gamma_o = 50$), beam current of I = 5 A and beam radius (Gaussian profile) of $r_b = 0.5$ mm. Such a beam has a peak density on axis of $n_o = 1.3 \times 10^{11} cm^{-3}$ ($\omega_b = 2.0 \times 10^{10} sec^{-1}$). The constant parameter wiggler is taken to have a magnitude of $B_w = 5.0$ kG and wavelength of $\ell_w = 2.8$ cm which gives $A_w = 2.2 \times 10^3$ statvolt. The wiggle velocity is $v_{o\perp} = 2.6 \times 10^{-2} c$ and the input field power density is taken to be $P_{in} = 4 \times 10^6 W/cm^2$ which gives $A_{in} = 0.30$ statvolt. Note that the inequalities in (3) and (4) are well satisfied.

Our first numerical illustration is one in which the accelerating potential is zero, the stationary phase is, therefore, $\tilde{\Psi}_R = -\pi/2$. The particle energy remains constant and the total radiation amplitude and phase on axis is given by (8a, b). To obtain the radial dependence of the radiation amplitude and phase, (7) is solved numerically and the results are shown in Figs. (1) and (2).

The index of refraction, in this case, is greater than unity, $n = 1 + (c/\omega) \partial\varphi/\partial z > 1$. The input field, therefore, tends to focus along the axis and tends to defocus the electron beam. The net radiation energy flux along the z axis (integrated from r = 0 to r = ∞) is constant since for large r the radiation amplitude is less than the input field amplitude. The gain in the radiation amplitude at z = 4m is maximum on axis and is 0.17. The maximum value of φ is along the z axis and is approximately 0.067 rad which certainly satisfies our small phase approximation.

Our next illustration is one involving efficiency enhancement. An accelerating potential $\phi_{ac}(z)$ is chosen such that $\cos\tilde{\Psi}_R = 0.3$. The gain in radiation amplitude on axis at $z = 4m$ is 0.185, see Fig. 1. Since the energy gained in propagating the electron beam through the potential ϕ_{ac} is converted into radiation, the efficiency can be defined as

$$\eta = |e| \, (\phi_{ac}(z) - \phi_{ac}(0))/\gamma_o m_o c^2 = -\left(\frac{|e|}{m_o c^2}\right)^2 \frac{\omega/c}{2\gamma_o^2} \int_o^z A_w A(r = 0,z') \cos\tilde{\Psi}_R \, dz'.$$

The efficiency at the end of $z = 4m$ is $\sim 3.6\%$. Figure (2) shows the phase φ as a function of z. Notice that the index of refraction $n = 1 + (c/\omega)\partial\varphi/\partial z$ for large z is less than unity on axis (defocusing of radiation) and becomes greater than unity for large r (focusing of radiation). Equations (8a,b) are in excellent agreement with the above numerical illustrations for $r = 0$.

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12. The velocity shear can in principle be reduced if the electron beam distribution is injected into the wiggler with an appropriate initial velocity shear.

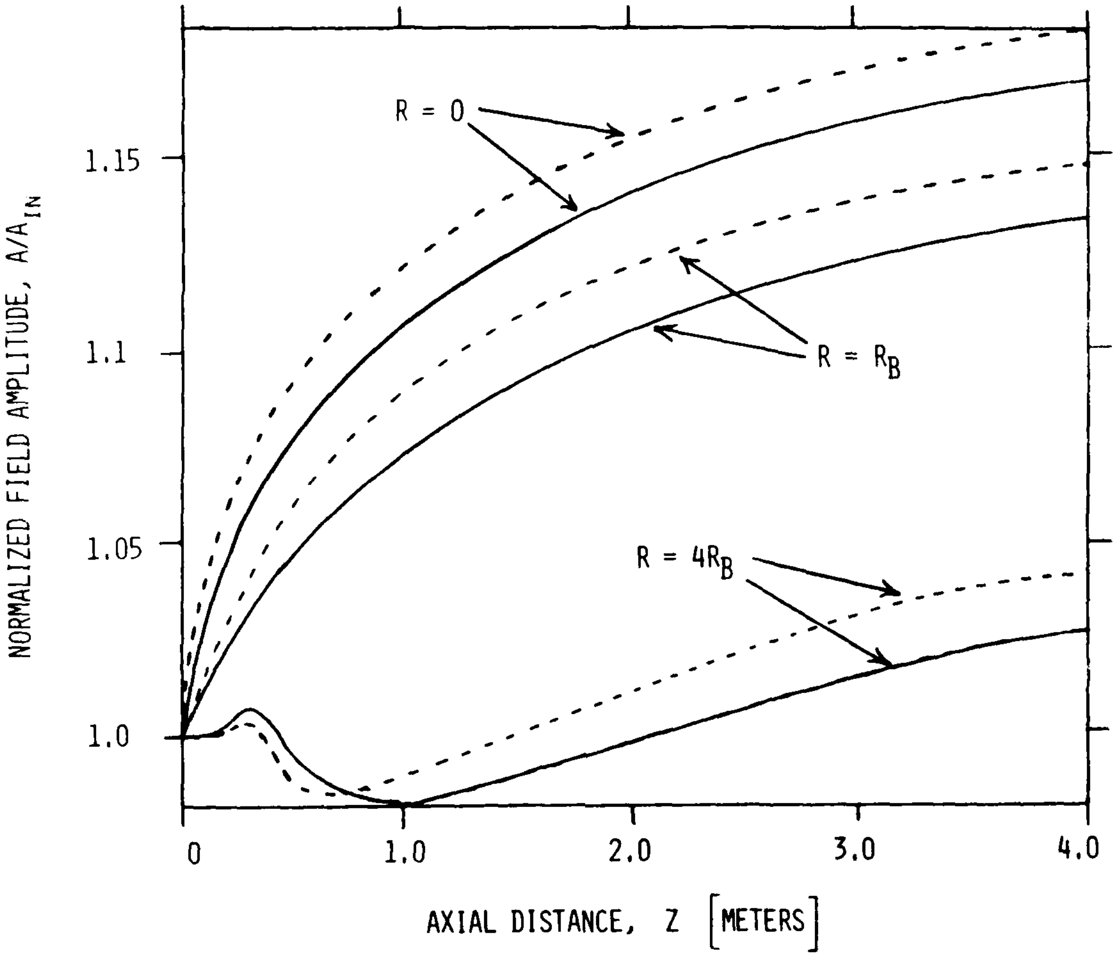

Fig. 1 — Normalized radiation amplitude, A/A_{in}, as a function of z at various radial positions (solid curves for $\tilde{\Psi}_R = -\pi/2$ and dashed curves for $\tilde{\Psi}_R = -1.27$).

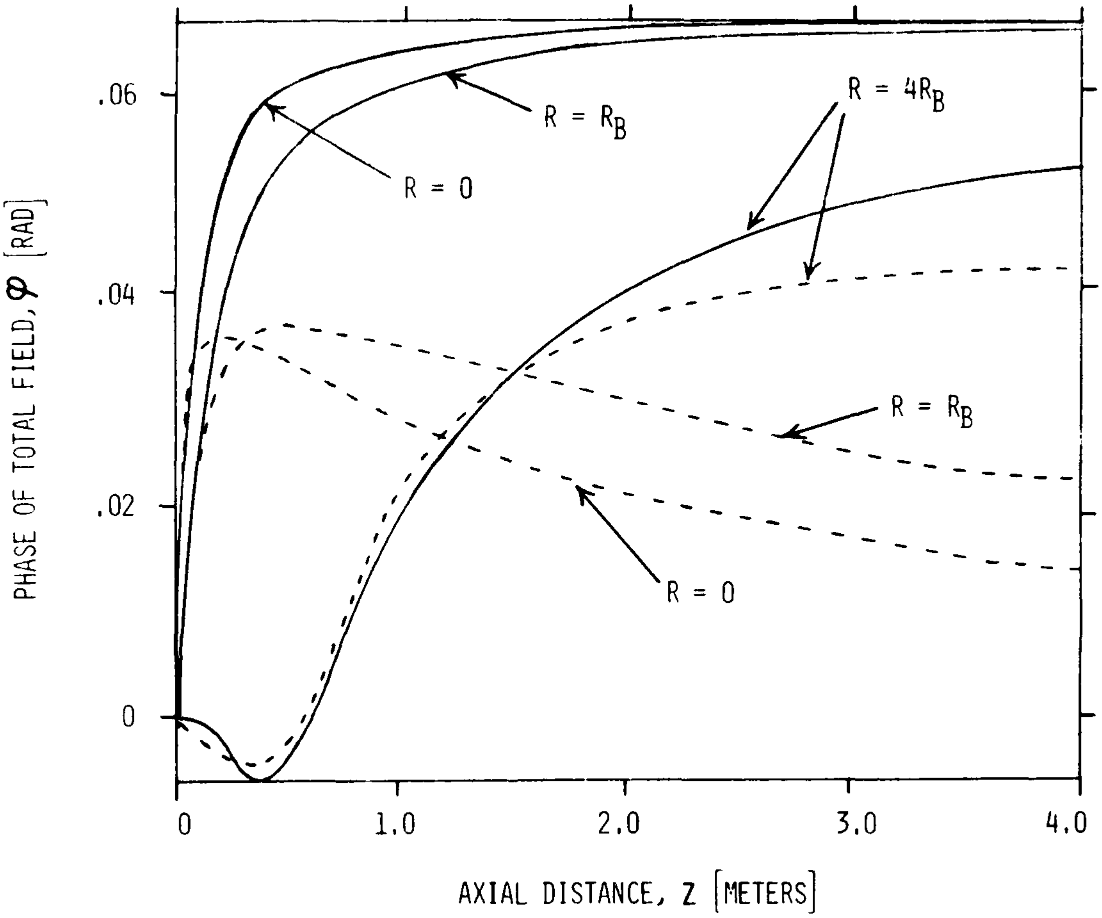

Fig. 2 — Radiation phase, φ, as a function of z at various radial positions (solid curves for $\tilde{\Psi}_R = -\pi/2$ and dashed curves for $\tilde{\Psi}_R = -1.27$).

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