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2-D NONLINEAR THEORY OF THE FREE ELECTRON LASER AMPLIFIER FOR A--ETC(U)
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This paper treats the growth of the radiation field in two-dimensions of a free electron laser on an electron beam with finite axial and transverse dimensions in the amplifying configuration. The general, self-consistent, nonlinear analysis includes various efficiency enhancement schemes, diffraction and refraction. In the axially symmetric, low gain, resonant macro particle limit, we obtain an analytical expression for the gain. An illustration at 10.6 μm is given.

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2-D Nonlinear Theory of the Free Electron Laser Amplifier for an Electron Beam with Finite Axial and Transverse Dimensions

Many current experiments of the free electron laser (FEL), ultilize electron beams from a millimeter to a few centimeters in pulse length. The short pulse length is typical of high energy accelerators such as RF Linacs and microtrons. The finite length effect of the electron beam on the radiation was found to be important in the Stanford oscillator experiment.(1) Currently, many experiments in the amplifying mode are being conducted with the short electron beam pulses. We have an analytical expression for the gain pulse of the radiation field, applicable to these experiments.

One-dimensional analysis of the radiation field for electron beams of finite length have been numerically simulated on computers.(2-4) The effect of the finite transverse dimensions was either not included, or incorporated through filling factors. On the other hand, previous three-dimensions self-consistent formulation(5) of the radiation field for a semi-infinitely long electron beam in the amplifying configuration has resulted in a number of interesting effects not obtainable by the 1-D formulation. Numerical effort to find the growth of the 3-D radiation field on the finite length electron beam began only recently.(6).

In this paper, we will present a fully 2-D, self-consistent, non-linear, analytical analysis of the FEL process in the amplifier mode of operation treating the finite length and transverse effects associated with both the electron beam and the radiation beam. Our formulism also includes various efficiency enhancement schemes: (i) contouring in the longitudinal direction the amplitude and/or the wavelength of the magnetic wiggler field, and (ii) applying an external

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D.C. electric field. Analytical results in the amplifying configuration are obtained in the low gain, trapped particle regime.

The schematic of the configuration is shown in Fig. 1. The generalized vector potentials of the right-handed, helical, static magnetic wiggler field and the electromagnetic radiation field are

$$\mathbf{A}_w(z) = A_w(z)\,[\cos(\int_0^z k_w(z')\,dz')\,\hat{e}_x + \sin(\int_0^z k_w(z')\,dz')\,\hat{e}_y] \tag{1}$$

$$\begin{aligned}\mathbf{A}_R(x, y, z, t) = A_R(x, y, z, t)\,[&\cos(\frac{\omega}{c}z - \omega t + \varphi(x, y, z, t))\,\hat{e}_x \\ &- \sin(\frac{\omega}{c}z - \omega t + \phi(x, y, z, t))\,\hat{e}_y]\end{aligned} \tag{2}$$

where A_w and k_w are all slowly varying amplitude and wave number of the wiggler field and A_R and φ are slowly varying amplitude and phase of the electromagnetic radiation field following the electron pulse. We also include an external DC electric field, $E_{\mathrm{DC}}(z) = -\partial\phi_{\mathrm{DC}}(z)/\partial z\;\hat{e}_z$ for the purpose of efficiency enhancement.

In this analysis we will not consider the gradient in the wiggler field. This is a good approximation if $k_w r_b << 1$, where r_b is the radius of the electron beam. If the FEL is operating in a trapped particle mode, we also require⁽⁵⁾ $r_b < (\gamma_{z0}\,k_w)^{-1}\,(8\sqrt{2}\,\gamma_{z0}/\beta_\perp)^{1/2}\,(A_R/A_w)^{1/4}$, where $\gamma_{z0} = (1 - v_{z0}^2/c^2)^{-1/2}$, $\beta_\perp = |e|\,A_w/(\gamma_0 m_0 c^2)$, $\gamma_0 = \gamma_{z0}\gamma_\perp$, $\gamma_\perp = (1 + |e|^2\,A_w^2(0)/(m_0^2\,c^4))^{1/2}$, and v_{z0} is the axial velocity at $z = 0$.

The electron motion can be described in terms of their phase $\tilde{\psi}$ in the ponderomotive wave:

$$\begin{aligned}\frac{1}{c^2}\frac{d^2\tilde{\psi}}{dt^2} = \frac{1}{c^2}\frac{d^2\varphi(\tilde{z},t)}{dt^2} + \left.\frac{\partial k_w(\tilde{z})}{\partial\tilde{z}}\right|_{z=\tilde{z}} - \frac{1}{2}\frac{\omega}{c}\frac{1}{\tilde{\gamma}^2}\left(\frac{|e|}{m_0c^2}\right)^2\left.\frac{\partial A_w^2(\tilde{z})}{\partial\tilde{z}}\right|_{z=\tilde{z}} \\ + \frac{\omega}{c}\frac{1}{\tilde{\gamma}\tilde{\gamma}_z^2}\left(\frac{|e|}{m_0c^2}\right)\left.\frac{\partial\phi_{\mathrm{DC}}(\tilde{z})}{\partial\tilde{z}}\right|_{z=\tilde{z}} + \frac{2k_w(\tilde{z})}{\tilde{\gamma}^2}\frac{\omega}{c}\left(\frac{|e|}{m_0c^2}\right)^2 A_w(\tilde{z})\,A_R\sin\tilde{\psi}\end{aligned} \tag{3}$$

where $\tilde{\psi}(x_0, y_0, \xi_0, t) = \int_0^{\tilde{z}(x_0, y_0, \xi_0, t)} (k_w(z') + \omega/c)\,dz' + \omega t + \varphi(\tilde{x}, \tilde{y}, , \tilde{z}, t)$ is the phase for the electron, which was at (x_0, y_0, ξ_0) at $t = 0$, $\tilde{\gamma} = \tilde{\gamma}_z\tilde{\gamma}_\perp$, $\tilde{\gamma}_z = (1 - \tilde{v}_z^2/c^2)^{-1/2}$, $\tilde{\gamma}_\perp = (1 + |e|^2 A_w^2(\tilde{z})/(m_0^2c^4))^{1/2}$, $\tilde{v}_z = [d\tilde{\psi}/dt - d\varphi/dt + \omega]/[k_w(\tilde{z}) + \omega/c]$ is the axial velocity, $\tilde{z} =$

$\xi_0 + \int_0 \bar{v}_z\, (x_0, y_0, \xi_0, t')dt'$ is the axial position of the electron and ξ_0 is the axial position of the electron relative to the center of the electron beam at $t = 0$.

The wave equation for the radiation field is $(\nabla^2 - c^{-2}\partial^2/\partial t^2)\mathbf{A}_R = -4\pi c^{-1}\mathbf{J}$, where

$$\mathbf{J} = \frac{-|e|n_0}{m_0} \int_{-\infty}^{\infty} d\xi_0 \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 \theta(x_0, y_0) h(\xi_0)$$
$$\gamma^{-1}\mathbf{P}_\perp \delta(x - x_0)\delta(y - y_0)\delta(z - \bar{z}) \tag{4}$$

is the current, (x_0, y_0) are the particle's transverse positions at $t = 0$, $\theta(x_0, y_0)$ is the transverse current density profile, $h(\xi_0)$ is the macroscopic electron pulse shape, n_0 is the peak current density, and $\mathbf{P}_\perp \simeq \dfrac{|e|}{c}\, \mathbf{A}_w$ is the transverse momentum.

We can rewrite the radiation field as $\mathbf{A}_R = a_R(x, y, z, t) \exp[i(\omega z/c - \omega t)]\hat{e}_+ + c.c.$, where $a_r = A_R \exp(i\varphi)$ is the complex amplitude of the radiation field, and $\hat{e}_\pm = (\hat{e}_x \pm i\hat{e}_y)/2$ is a new coordinate system. The wave equation assumes the form

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + 2i\frac{\omega}{c}\left(\frac{\partial}{\partial z} + \frac{1}{c}\frac{\partial}{\partial t}\right)\right] a_R(x, y, z, t)$$
$$= \frac{\omega_b^2}{c^2} \int_{-\infty}^{\infty} d\xi_0 \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 \theta(x_0, y_0) h(\xi_0) \frac{A_w(z)}{\bar{\gamma}}$$
$$\exp\left[-i\left(\int_0^z (k_w(z') + \omega/c)dz' - \omega t\right)\right] \delta(x - x_0)\delta(y - y_0)\delta(z - \bar{z}). \tag{5}$$

In obtaining (5), we have used the fact that $|(\partial^2/\partial z^2 - c^{-2}\partial^2/\partial t^2)a_R| << 2\omega/c|(\partial/\partial z + c^{-1}\partial/\partial t)a_R|$.

The solution for a_R can be separated into the input radiation field a_{in}, and the excited radiation field, a_{ex}, such that $a_R = a_{in} + a_{ex}$. The excited radiation field can be shown to be

$$a_{ex} = \int_0^t dt' \int_{-\infty}^{\infty} d\xi_0 \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 f(x_0, y_0, \xi_0, x, y, z, t')\delta(z - c(t - t') - \bar{z}) \tag{6}$$

where

$$f = \frac{-1}{4\pi} \frac{\omega_b^2}{c^2} \theta(x_0, y_0) h(\xi_0) \frac{A_w(z - c(t - t'))}{(t - t')\bar{\gamma}}$$
$$\exp\left[i\left(\frac{(x - x_0)^2 + (y - y_0)^2}{2c(t - t')}\right)\frac{\omega}{c}\right] \exp\left[-i\left(\int_0^{z-c(t-t')} (k_w(z') + \omega/c)\, dz' - \omega t'\right)\right].$$

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The integral in time of Eq. (6) can be evaluated by changing the argument of the delta function.

$$
\begin{aligned}
a_{ex} &= \int_0^t dt' \int_{-\infty}^{\infty} d\xi_0 \int_{-\infty}^{\infty} dx_0 \int_{-\infty}^{\infty} dy_0 f(x_0, y_0, \xi_0, x, y, z, t') \frac{\delta(t'-\tau_0)}{c - \dfrac{\partial \bar{z}}{\partial t'}} \\
&= \int_{z-ct}^{z-\int_0^t \mathrm{v}_z(x_0, y_0, \xi_0, t')dt'} d\xi_0 \frac{f(x_0, y_0, \xi_0, x, y, z, \tau_0)}{c - \mathrm{v}_z(x_0, y_0, \xi_0, \tau_0)}
\end{aligned}
\tag{7}
$$

where $\tau_0(x_0, y_0, \xi_0, t)$ is the retarded time associated with the electron, which originated at (x_0, y_0, ξ_0) at $t = 0$. The retarded time satisfies the equation

$$
\xi_0 + z_c(\tau_0) + c(t - \tau_0) = \xi + z_c(t) \tag{8}
$$

where $z_c(t) = \int_0^t \mathrm{v}_{sc}(t')dt'$ is the macroscopic location of the center of the electron beam at time t, $\mathrm{v}_{sc}(t) = \omega/(k_w(z_c(t)) + \omega/c)$ is the macroscopic velocity of the electron pulse, ξ is the position of the electron relative to the center of the electron beam at time t.

The complex radiation amplitude in Eq. (8) can be evaluated if we make the following simplifying assumptions. For experimental parameters of interest, we can assume that the bunching mechanism does not alter the macroscopic electron pulse shape, hence, it travels undistorted through the interaction region. We will assume that the electron beam has an axially symmetric Gaussian profile in the transverse direction, i.e., $\theta(x_0, y_0) = \exp[-(x_0^2 + y_0^2)/r_0^2]$. Furthermore, we will assume that the waist of the input radiation field r_0 is much larger than the radius of the electron beam r_b, such that $\tilde{\psi}$ is approximately a function of ξ_0 and t only. The excited radiation field takes the form

$$
\begin{aligned}
a_{ex}(r, \xi, t) = &- \frac{r_b^2}{8\pi} \frac{\omega_b^2}{c^2} \int_{\xi + z_c(t) - ct}^{\xi} d\xi_0 h(\xi_0) \\
&\frac{A_w(\xi + z_c(t) - c(t - \tau_0))}{\bar{\gamma}} \frac{(1 + \bar{\mathrm{v}}_z/c)\bar{\gamma}_z^2}{c(t - \tau_0) - iz_b} \\
&\exp\left[i \left(\frac{r^2}{r_b^2} \frac{z_b}{c(t - \tau_0) - iz_b} \right) \right] \exp[-i(\tilde{\psi}(\xi_0, \tau_0) + \varphi(r, \xi, \tau_0))]
\end{aligned}
\tag{9}
$$

where $z_b = r_b^2\,\omega/2c$ is the Rayleigh length associated with the electron beam radius. Equations (3) and (9) describe self-consistently a general, nonlinear, 2-D, FEL amplifier with a macroscopic pulse shape $h(\xi_0)$.

For the purpose of illustrating the finite length pulse effects in an FEL amplifier operating in the low gain limit, i.e., $|a_{\text{in}}| >> |a_{\text{ex}}|$, we take the electron beam profile to be uniform, i.e., $h(\xi_0) = 1$ for $|\xi_0| \leqslant L_b/2$ and $h(\xi_0) = 0$ for $|\xi_0| > L_b/2$, where L_b is the length of the electron pulse. We also make the constant phase, resonant particle approximation. In this approximation all particles are assumed to have the same constant phase, $\tilde{\psi}_R$. The electron beam in this approximation consists of a pulse train of macro particles separated in distance by $2\pi v_{0z}/\omega$. Furthermore, we will limit ourselves at this point to a constant parameter wiggler and consider only an external DC electric potential. The amplitude and phase of the **total** field are

$$A_R(r, \xi, t) = A_{\text{in}} - \alpha_0^2 A_w [I_r \cos\tilde{\psi}_R + I_i \sin\tilde{\psi}_R] \tag{10a}$$

$$\varphi(r, \xi, t) = -\alpha_0^2 A_w [I_i \cos\tilde{\psi}_R - I_r \sin\tilde{\psi}_R] \tag{10b}$$

where $A_{\text{in}} = |a_{\text{in}}|$, $I_r = \text{Re}\,(I)$; $I_i = \text{Im}\,(I)$, $I = E_i\left(\frac{-r^2}{r_b^2} q_l\right) - E_i\left(\frac{-r^2}{r_b^2} q_u\right)$, E_i is the exponential integral function,

$$q_l = (-iz_b)(2\gamma_{zR}^2(\xi - \xi_{0,l}) - iz_b)^{-1},$$
$$q_u = (-iz_b)(2\gamma_{zR}^2(\xi - \xi_{0,u}) - iz_b)^{-1},$$

$\xi_{0,u} = \xi$ (for $\xi < L_b/2$) and $\xi = L_b/2$ (for $\xi \geqslant L_b/2$) is the upper limit of the integration, $\xi_{0,l} = \xi - (c - v_{sc})t$ (for $\xi - (c - v_{sc})t > -L_b/2$) and $\xi_{0,l} = -L_b/2$ (for $\xi - (c - v_{sc})t < -L_b/2$) is the lower limit of the integration, and γ_{zR} is the resonant gamma associated with the axial motion.

A more realistic electron beam profile $h(\xi_0) = 1 - (2\xi_0/L_b)^2$ (for $\xi_0 \leqslant L_b/2$) and $h(\xi_0) = 0$ (for $|\xi_0| \geqslant L_b/2$) can also be integrated. The result is not given here, because the more complicated expressions would obstruct the initial understanding of the physical process of the pulse propagation.

As an example of a 10.6 μm FEL utilizing a CO_2 laser as an input field, we choose an electron beam of energy 25 MeV ($\gamma_0 = 50$), current of $I = 5$ A and radius (Gaussian profile) of $r_b = 0.5$ mm and pulse length $L_b = 3$ mm. Such a beam has a peak density on axis of $n_0 = 1.3 \times 10^{11}$ cm^{-3} ($\omega_b = 2.0 \times 10^{10}$ sec^{-1}). The constant parameter wiggler has a magnitude of $B_w = 5.0$ kG and wavelength of $l_w = 2.8$ cm which gives $A_w = 2.2 \times 10^3$ statvolts. The wiggler velocity is $v_{0\perp} = 2.6 \times 10^{-2}$ c which gives $\gamma_\perp = 1.35$ and $\gamma_z = 37$. The input CO_2 power density is taken to the $P_{in} = 4 \times 10^8$ W/cm^2 which gives $A_{in} = 0.30$ statvolts. Our illustration assumes resonant macro particle approximation and an applied D.C. electric potential such that $\sin \tilde{\psi}_R = 0.6$.

The schematics of the gain

$$G(r, \xi, t) = (A_R(r, \xi, t) - A_{in})/A_{in}$$

are shown in Figs. 2 and 3. The slashed bars in the (z, t) plot of Fig. 2 denote the locations of the electron beams at $t_1 = 1$ m/c and $t = 2$ m/c, which c is the speed of light. The solid lines in the (z, t) plot are the light lines. The gain pulse on axis are plotted at times t_1 and t_2. We see that the excited radiation pulse grows and spreads beyond the electron beam pulse. The transverse variation of the gain at $\xi = 0$ for various times are plotted in Fig. 3. The decrease of radiation field far from the axis is due to refraction toward the center of the beam.

We have obtained a general expression for the growth of the 2-D, stimulated radiation pulse on an electron beam of finite axial and transverse dimensions in an FEL amplifier. We included diffraction as well as refraction. In the axially symmetric, low gain, resonant macro particle limit, we have an *analytical* expression for the radiation gain. The formalism presented here can be modified to study the radiation build up and "laser lethargy" in the FEL oscillator.

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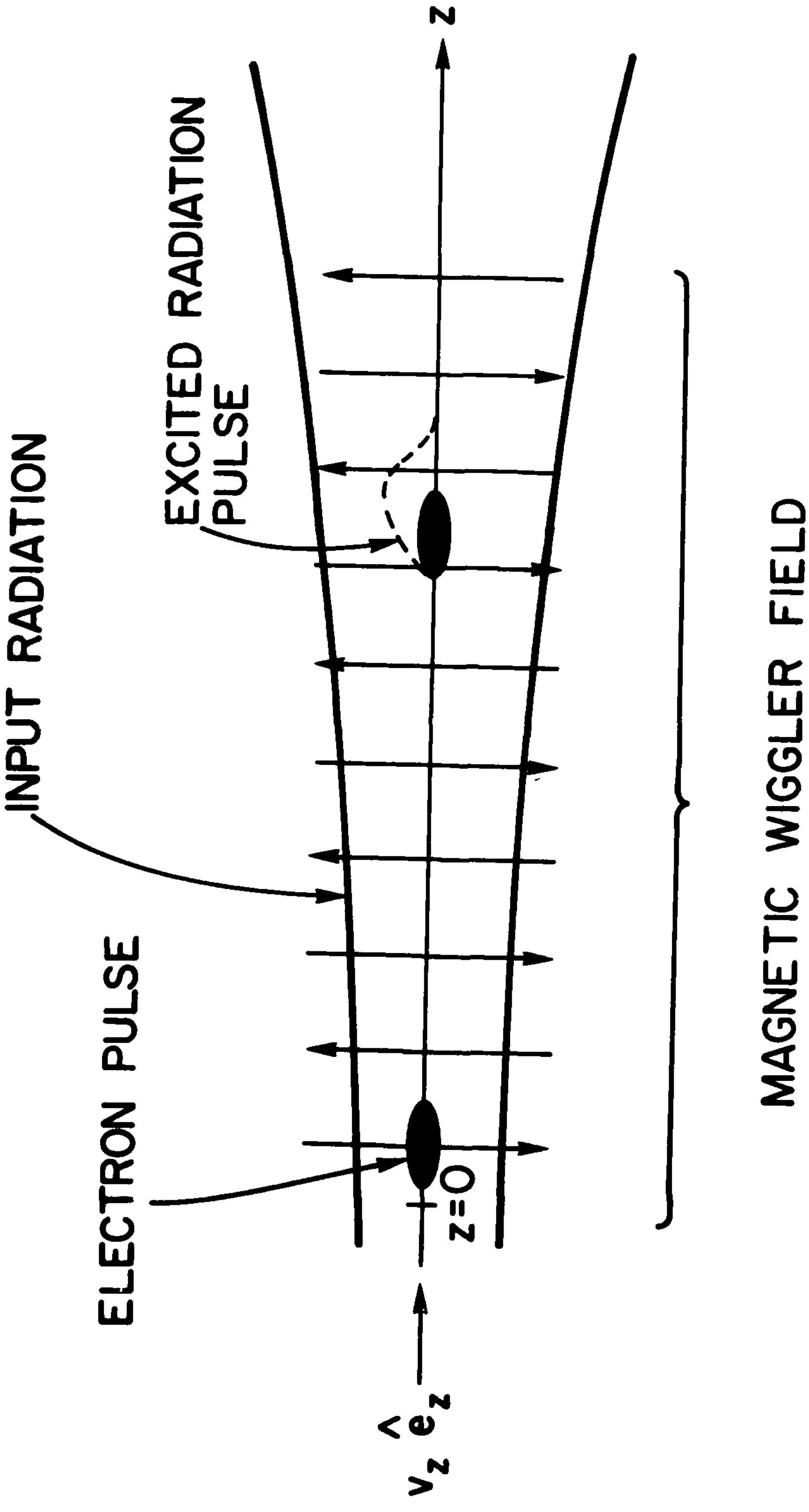

Fig. 1 — Schematic of the free electron laser with short electron pulse in an amplifying configuration

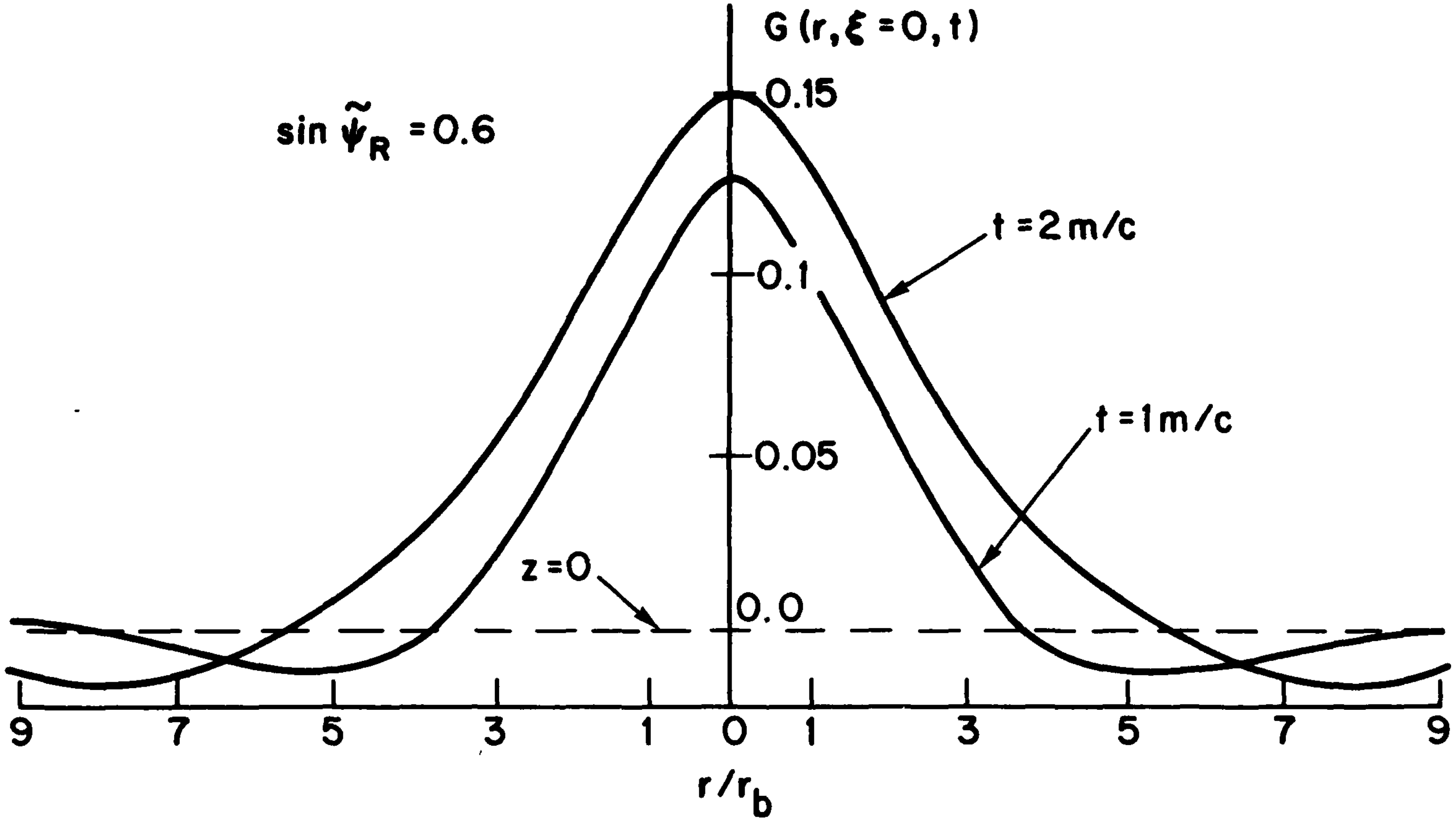

Fig. 2 — Plot of gain pulse on axis, $r = 0$, as a function of ξ at various times

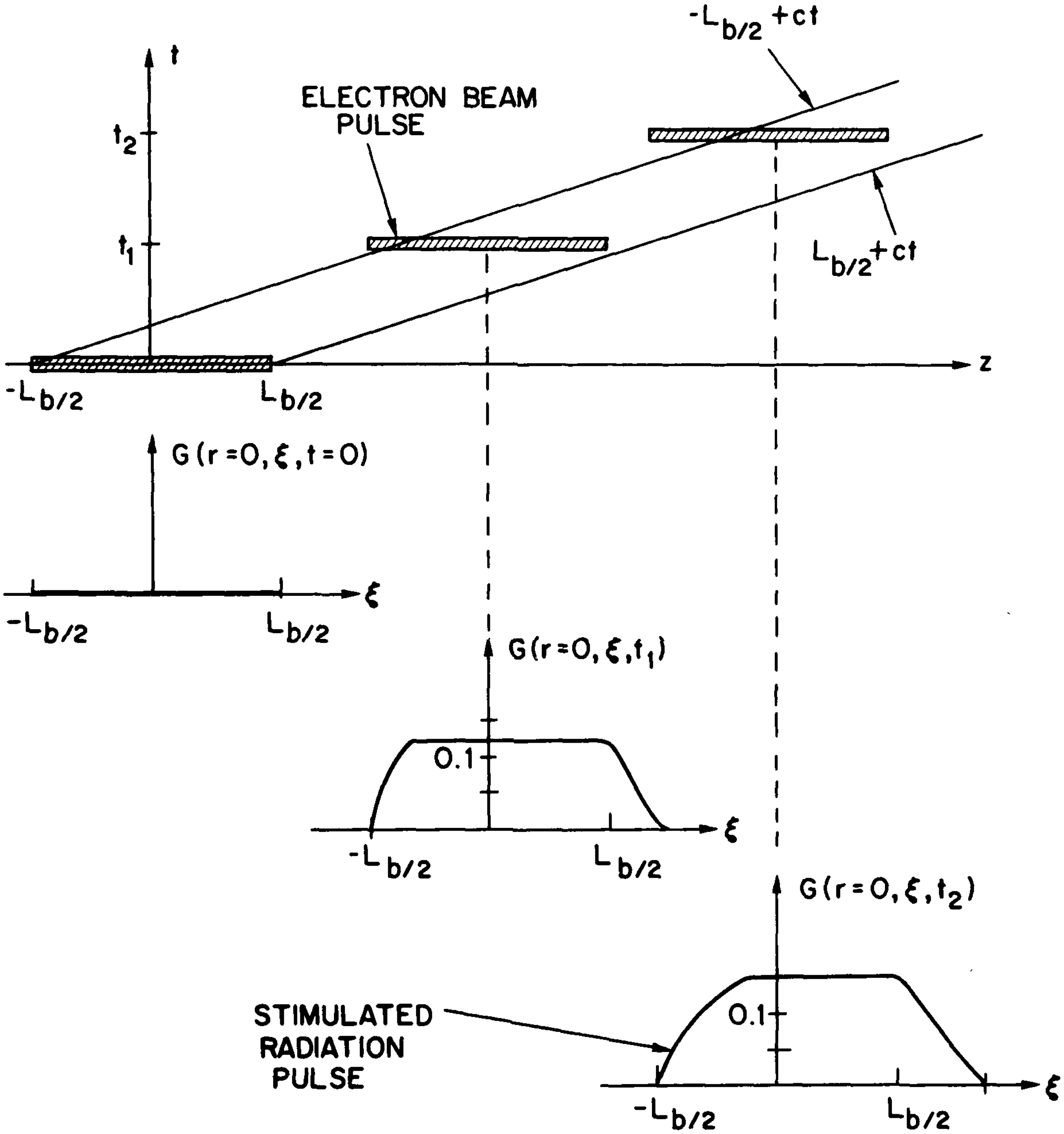

Fig. 3 — The transverse variation of the gain at $\xi = 0$ for various times

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