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OVERTONE PRODUCTION OF SOFT X-RAYS WITH FREE-ELECTRON LASERS*

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ABSTRACT

Two one-dimensional free-electron laser codes have recently been written that include harmonic generation. A comparison of the results of these codes show that a self-consistent treatment of the harmonic interaction is not required in the presence of a strong fundamental field. Use of these codes to predict the effects of emittance on harmonic production have been conducted. The effects of wiggler-field amplitude fluctuations and odd-harmonic wiggler-field components on the harmonic-radiation production are also discussed.

INTRODUCTION

The harmonics generated in free-electron laser (FEL) oscillator experiments are produced primarily through coherent-spontaneous radiation of the fundamentally-bunched electron beam. This mechanism dominates over the much weaker harmonic linear-gain mechanism which cannot overcome cavity mirror losses. The amplitude of each harmonic is determined by its Fourier component of the transverse current, scaled by the harmonic coupling coefficient.

This paper explores the effects of emittance, wiggler-field amplitude fluctuations and odd-harmonic wiggler-field components on harmonic production. A comparison between the one-dimensional codes is discussed in Section I. In Section II the effects of emittance on the harmonic amplitudes are calculated assuming constant gain in the fundamental. Small amplitude fluctuations in the wiggler magnetic field are modeled in Section III. Modifications of the harmonic coupling coefficients resulting from a small third-harmonic wiggler-field component are given in Section IV along with their consequences on harmonic production.

I. HARMONIC FEL CODES

The equations describing the interaction of odd-harmonic frequencies with an electron beam in a FEL are well documented[1,2]. These equations have been incorporated into a one-dimensional (1D) code written by one of us (C. J. Elliott)

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to model both the radiation produced by the electron beam and the effect of the harmonic fields back on the electrons. This self-consistent code integrates the phase-averaged field equations given by

$$\frac{\partial \mathcal{E}_f}{\partial x} = -2\pi\rho K_f(\xi)\left\langle \frac{e^{-i(f\psi_j+\varphi_{0f})}}{\gamma_j} \right\rangle_{electrons} \tag{1}$$

and the energy equation for each electron that states

$$\frac{d\gamma_j}{dt} = \sum_{f=1}^{\infty} \frac{e\mathcal{E}_f}{2m_e c\gamma_j} K_f(\xi)\cos(f\psi_j + \varphi_{0f}) \tag{2}$$

where j denotes the jth electron and f is the harmonic number. This code has been compared to another code (HFELP) originally written by B. D. McVey and later modified by M. J. Schmitt to include the harmonic radiation produced by a fundamentally bunched electron beam. The effects of the harmonic radiation fields on the electrons are not included in HFELP so that the electrons are only affected by the fundamental electromagnetic field that is assumed to be much larger than the harmonic fields.

To analyze the coherent-spontaneous emission of a FEL operating at the fundamental we assume the oscillator to have reached saturation so that a large fundamental wave exists. A single-pass calculation is then performed assuming the saturated fundamental signal exists at the entrance to the wiggler. This calculation is valid assuming the mirror losses at the harmonics prevent the harmonic radiation from circulating in the cavity. Gain at the fundamental is adjusted through an effective fill factor to match that of the 3D calculation[3]. The results of both codes, for input parameters resembling those of the Los Alamos oscillator experiment[4], are shown in Figures 1a,b for the fifth harmonic.

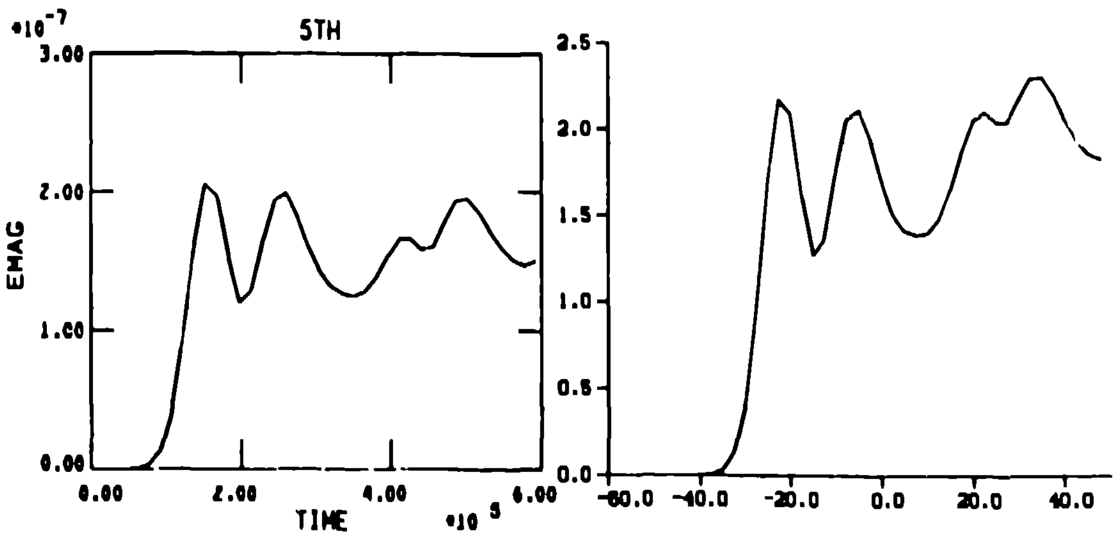

Fig. 1. Harmonic output from the self-consistent code (a) and from HFELP (b).

Results at the first few odd harmonics observed thus far all yield identical results. From this comparison it is seen that for small harmonic powers ($P_f/P_1 \ll 1$) a self-consistent analysis is not required to obtain the correct harmonic output levels. Thus, calculation of the harmonic radiation can be done economically.

II. EMITTANCE EFFECTS

The growth of electron beam emittance has deleterious effects on FEL gain and efficiency. To evaluate how emittance affects harmonic production, simulations were performed with the 1D code HFELP. Owing to the one-dimensional nature of the code, electron-beam emittance was modeled as an effective electron energy spread. The energy spread represents the effective axial energy of the electrons. A typical distribution for the electron beam used in the simulations for the proposed Los Alamos XUV FEL[5] is shown in Figure 2 for the case $\epsilon_n = 40\pi$mm·mrad.

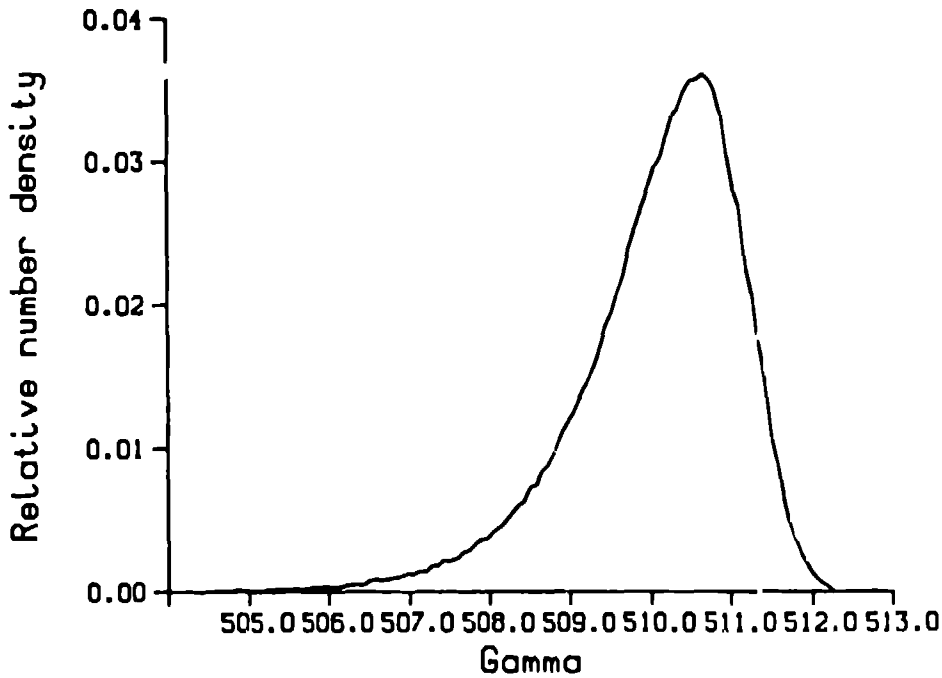

Fig. 2. Effective energy distribution for $\gamma = 511.5$, $\Delta\gamma/\gamma = .2\%$, $\epsilon_n = 40\pi$mm·mrad.

The parameters used in the XUV simulations were; $\gamma = 511.5$, $\Delta\gamma/\gamma = .2\%$, $\lambda_s = 500$Å, $I = 150$Amps, $B_w = .75$T, $L_w = 800$cm, $\lambda_w = 1.6$cm and the emittance was varied from 20π to 40π. The harmonic electric-field amplitudes at the end of the wiggler for these conditions are plotted in Figure 3 for the first three odd-harmonics. All harmonics show a significant reduction in field amplitude. The third-harmonic amplitude shows the greatest effect with a reduction of ten in field or two orders-of-magnitude in power. These results clearly show that

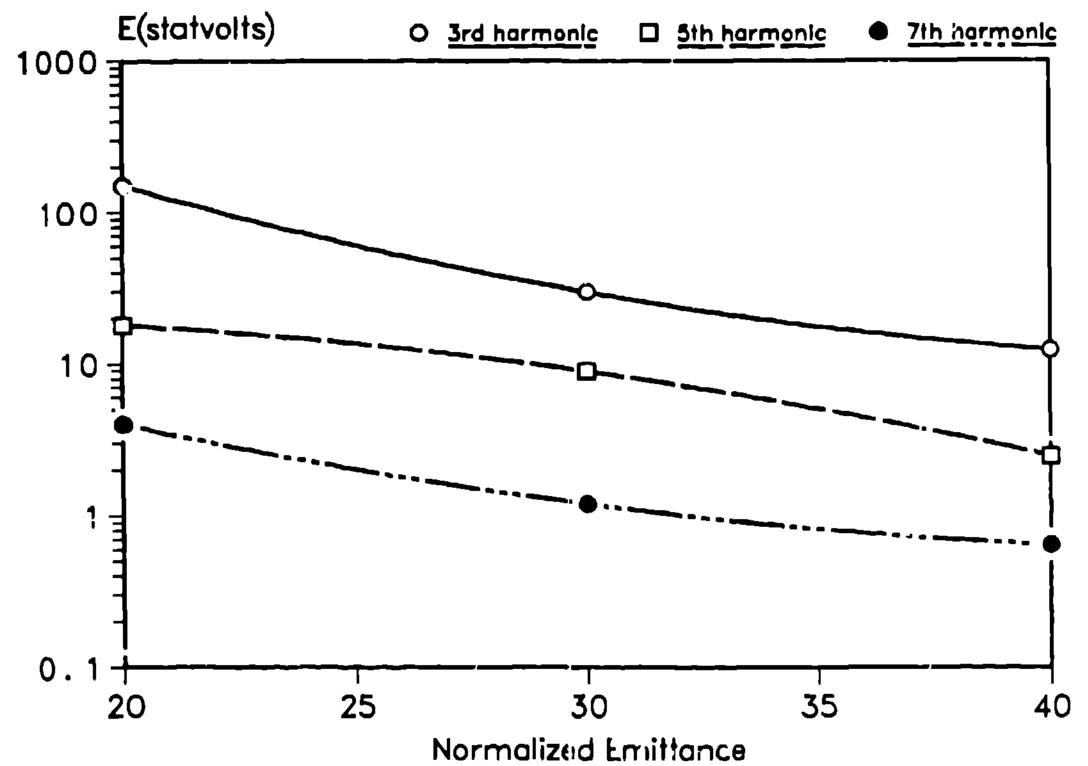

Fig. 3. Harmonic electric-field amplitudes as a function of normalized emittance (30–30πmm-mrad) for the proposed Los Alamos XUV FEL.

the minimization of emittance is critical for maximization of harmonic output.

III. WIGGLER FIELD ERRORS

The magnetic field that results after the construction of a wiggler magnet is not a pure sinusoid. Differences in the magnetization of each magnet and machining tolerances guarantee that the resultant field will have variations in both amplitude and wavelength. In this section we consider the effects of magnetic amplitude fluctuations on harmonic production. Although we are not treating magnetic wavenumber fluctuations directly, their treatment can be handled using this same formalism. Since this is a 1D treatment it is tacitly assumed that any random walk of the electron beam is compensated at the appropriate intervals to keep the electron and optical beams concentric.

To model the variation of the amplitude of the wiggler field in the phase-averaged equations one can calculate an effective variation in the electron phase ψ due to the change in the magnetic-field amplitude. The electron phase in the wiggler and optical fields is given by

$$\psi = (k_w + k_s)z - \omega t \tag{3}$$

where z is determined by the average electron velocity in the axial direction.

Assuming a perturbation in the wiggler field amplitude given by ΔB_w, a resultant perturbation in the axial position will result that will in turn produce a variation in the electron phase given by

$$\Delta\psi = (k_w + k_s)\Delta\bar{z} \tag{4}$$

and upon substitution for the appropriate value of $\Delta\bar{z}$ gives

$$\Delta\psi_j = -\frac{\pi}{2}\frac{(1 + k_s/k_w)}{\gamma_j^2} a_w \Delta a_w \tag{5}$$

where a_w is the dimensionless magnetic vector potential defined

$$a_w = \frac{eB_w}{m_e c^2 k_w} \quad . \tag{6}$$

Implementation of Eq(5) in the 1D code HFELP was conducted by calculating the phase error correction for each electron caused by small magnetic-field amplitude fluctuation at each wiggler half-period section. This correction was then added to the electron's phase after it had traverse each wiggler half-period. The errors were assumed to have a gaussian distribution with the $1/e^2$ point defined as an input variable. Simulations were performed for the parameters given in Section II for the proposed Los Alamos XUV FEL assuming a 1% error in the magnetic field amplitude and an emittance of 20π. The results showed a 10 to 20% decrease in the electric field amplitude of the first few odd-harmonics concurrent with a 7% drop in the fundamental electric-field amplitude.

Errors in wavenumber can likewise be treated by calculating an effective phase change $\Delta\psi_\lambda = \Delta k_w z$ and incorporating it into each electron's phase after every wiggler wavelength. A simple calculation shows that for the above parameters a 1% wiggler magnetic-field amplitude fluctuation is equivalent to a .75% fluctuation in the wiggler wavelength. Thus, wiggler amplitude and wavenumber errors should be kept below 1% for harmonic amplitudes to remain uneffected.

IV. HARMONIC WIGGLER FIELD COMPONENTS

To increase the strength of the FEL interaction, experimenters strive to achieve normalized magnetic vector potentials of order unity or greater. The construction of such wigglers results in highly peaked magnetic field intensities near the pole faces significantly deviating from the analytically assumed sinusoid. A Fourier decomposition of these fields yield third-harmonic field components approaching 20% or more that of the fundamental[6]. The effects of these harmonic wiggler fields *cannot* be included by linear superposition. We have calculated how these components change the coupling coefficients for the odd-harmonic radiation and examine below how a small third-harmonic wiggler field modifies the fundamental and third-harmonic radiation.

To include the effect of a third-harmonic wiggler field we first define the transverse velocity produced by a sum of harmonic wiggler fields as

$$\beta_\perp^2 = \left(\frac{eA_w}{m_e c^2 \gamma}\right)^2 = \frac{e^2}{m_e^2 c^4 \gamma^2} \left\{ \sum_{m=1}^{\infty} A_{wm} \cos(mk_0 z) \right\}^2 \tag{7}$$

which can be used to derive a new resonance condition in the high-γ limit given by

$$k_0 = \frac{k_s}{2\gamma_0^2} \left\{ 1 + \sum_{m=1}^{\infty} \frac{a_{wm}^2}{2} \right\} \tag{8}$$

These equations can then be used to derive new coupling coefficients for use in Eqs(1),(2). Assuming only a third-harmonic wiggler field with $a_{w3}/a_{w1} \ll 1$, the new coupling terms for the fundamental and third-harmonic are

$$\begin{aligned} K_1(\xi) = {} & J_0\left(\xi_1 \frac{a_{w3}}{a_{w1}}\right) J_0(\xi_3) \\ & \cdot \left[a_{w1} \{ J_0(\alpha_1) - J_1(\alpha_1) \} + a_{w3} \{ J_1(\alpha_1) + J_2(\alpha_1) \} \right] \end{aligned} \tag{9}$$

and

$$\begin{aligned} K_3(\xi) = {} & J_0\left(3\xi_1 \frac{a_{w3}}{a_{w1}}\right) J_0(3\xi_3) \\ & \cdot \left[a_{w1} \{ J_2(\alpha_3) - J_1(\alpha_3) \} + a_{w3} \{ J_0(\alpha_3) - J_3(\alpha_3) \} \right] \end{aligned} \tag{10}$$

where

$$\alpha_n = n\xi_1 \left(1 + 2\frac{a_{w3}}{a_{w1}}\right) \tag{11}$$

and

$$\xi_m = \frac{a_{wm}^2}{4m} \left(1 + \sum_{n=1,3} \frac{a_{wn}^2}{2}\right)^{-1} . \tag{12}$$

A comparisen of these new coefficients (assuming a 10% third-harmonic contribution) with the old[1] coefficients for parameters consistent with those of the Los Alamos oscillator experiment show that while the fundamental term is unaffected, the third-harmonic term has changed by 33%. Note that we have assumed the magnitude of a_{w3} opposite that of a_{w1} such that the resultant magnetic field is more peaked than a sinusoid. For this configuration the third-harmonic power is enhanced by 75%. This example dramatically shows how the harmonics can be affected by harmonic wiggler components. A more thorough analysis of this effect is presented elsewhere[7].

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