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# Three-Dimensional Simulation of Free Electron Laser with Prebunching and Efficiency Enhancement

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***Abstract*****—**Three-dimensional simulation of harmonic up generation in free electron laser amplifier operating simultaneously with a cold and relativistic electron beam is presented in steady-state regime where the slippage of the electromagnetic wave with respect to the electron beam is ignored. By using slowly varying envelope approximation and applying the source-dependent expansion to wave equations, electromagnetic fields are represented in terms of the Hermit Gaussian modes which are well suited for the planar wiggler configuration. The electron dynamics is described by the fully three-dimensional Lorentz force equation in presence of the realistic planar magnetostatic wiggler and electromagnetic fields. A set of coupled nonlinear first-order differential equations is derived and solved numerically. The fundamental and third harmonic radiation of the beam is considered. In addition to uniform beam, prebunched electron beam has also been studied. For this effect of sinusoidal distribution of entry times for the electron beam on the evolution of radiation is compared with uniform distribution. It is shown that prebunching reduces the saturation length substantially. For efficiency enhancement the wiggler is set to decrease linearly when the radiation of the third harmonic saturates. The optimum starting point of tapering and the slope of radiation in the amplitude of wiggler are found by successive run of the code.

***Keywords*****—**Free electron laser, Prebunching, Undulator, Wiggler.

## I. INTRODUCTION

THERE is considerable interest to produce coherent high power and short wavelength laser radiation. Prebunched beams are used in many coherent radiation sources. If the beam is bunched on scale lengths comparable to or shorter than the desired wavelength, then the resonant wavelength is excited without a drive signal and grows faster than exponential. A free-electron laser (FEL) with a prebunched beam combines the best characteristics of amplifiers and oscillators. In comparison with oscillators, no drive signal is needed and the wiggler is short. In comparison with amplifiers, no resonator is needed [1]. Simulation of enhanced bunching has been demonstrated using the MEDUSA simulation code [2]–[4] for optical klystrons [3] and high-gain harmonic generation [4]. In the latter case, modulation of the beam in one wiggler was enhanced in a magnetic chicane prior to injection into a second wiggler. We describe modifications to MEDUSA to simulate prebunching, and the application of the code to study requirements and limitations on the process. For simulation purposes, a prebunched beam model has been incorporated into the three dimensional, polychromatic FEL simulation code MEDUSA [2]. MEDUSA can model both planar and helical wiggler geometry and treats the electromagnetic field as a superposition of either Gauss–Hermite or Gauss–Laguerre modes. The field equations are integrated simultaneously with the three-dimensional Lorentz force equations for an ensemble of electrons. No wiggler-average orbit approximation is used [1].

The intrinsic efficiency of a FEL is low. For an undulator with fixed parameters, the FEL goes out of resonance and saturates; so the efficiency is limited to a few percent. However, the efficiency of FELs has been dramatically improved by using a tapered wiggler [6] – [7]. In the absence of tapering, the amplitude of the radiation oscillates beyond the saturation point of radiation. In one period, electrons give their energy to the radiation increasing the radiation amplitude. This reduces the energy of electrons. Therefore, these electrons lose their resonance with the electromagnetic radiation and go to the phase in which they gain energy from the radiation. Now the radiation amplitude decreases up to the point at which electrons gain enough energy to again become resonant with the radiation. From this point again the electrons give their energy to radiation. This cycle is repeated [5].

In the FEL, the radiation saturates in a relatively short distance, and so it has a low efficiency. In this paper, we use the concept of tapered wiggler field to increase the efficiency of the FEL. It is supposed that one cold and relativistic electron beam is injected into a wiggler which decreases linearly at the point where the FEL saturates.

It has been shown that by tapering the wiggler amplitude substantial increase in the power of the short wavelength third harmonic can be obtained.

The organization of the paper is as follows. The formulation of prebunching and efficiency enhancement are described in Sec. II, The simulation is preformed to study the effects of

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these phenomena in FEL in Sec. III. Sec IV is devoted to the summery.

## II. Basic Equations

Consider an electron beam copropagating in a simple FEL wiggler system of constant period $\lambda_w$ and a variable wiggler field $B_w(z)$. For unbunched electron beam the particles are uniformly distributed in phase for $0 \le \psi_0 \le 2\pi$ On the other hand, for the prebunched case, the beam is modeled by the distributions in initial phase,

$$\sigma(\psi_0) = \begin{cases} (4\pi / \psi_{\text{width}}) \sin^2(\pi\psi_0 / \psi_{\text{width}}) & 0 \le \psi_0 \le \psi_{\text{width}}, \\ 0 & \text{otherwise}, \end{cases}$$

Where $\psi_0 = -\omega_0 t$ denotes the initial ponderomotive phase, and $\psi_{width}$ describes the degree of prebunching in terms of the bunch width in initial phase. The prebunched beam model incorporated into MEDUSA assumes the above initial distribution in phase. It is important to note that prebunching can have a significant impact on FEL operation even if accomplished at subharmonics of the desired.

It is assumed that the FEL has a constant wiggler field, $B_W$, up to the point $z_T$ at which FEL saturates, and after that the wiggler amplitude decreases by the slope m, i.e

$$a_w = \overline{a_w} f(\overline{z}) = \begin{cases} \overline{a_w} & , \quad \overline{z} < \overline{z_T} \\ \overline{a_w} - m(\overline{z} - \overline{z_T}) & , \quad \overline{z} \ge \overline{z_T} \end{cases}$$

where $\overline{a_w} = e\overline{B_W} / \sqrt{2} k_w mc^2$ is the wiggler parameter for the untapered wiggler and $\overline{z}$ is the scaled distance. The parameters m and $z_T$ are chosen so that the efficiency of the FEL is increased.

The nth harmonic wave number $\lambda_n = \lambda / n$ satisfies the resonance condition $\lambda_n = \lambda_w (1 + a_w^2) / 2\gamma_n^2$ so it can be easily shown that $\gamma_n = \sqrt{n}\gamma_1$. When the radiation of FEL at the harmonic wavelength begins to saturate, we decrease the wiggler amplitude linearly with an appropriate slope to retain the FEL at resonance. This will result in higher intensity x-ray radiation [5].

## III. Numerical Solution

The specific case under consideration is that of a 945MeV beam with a peak current of 300 A, a normalized emittance of 15 mm-mrad, and an energy spread of 0.25%. The wiggler has a 10.6 kG peak field on-axis with a period of 3.3 cm. These parameters result in peak gain for a uniform beam at wavelength of 1.06 mm. Nonlinear harmonic growth is also strong for prebunched beams. We plot the evolution of the third harmonic for a prebunched beam with $\psi_{width} = \pi$ in Fig.1. A comparison of the growth in power for a uniform beam and a prebunched beam with $\psi_{width} = \pi$ is shown in Fig. 1. The start power for the uniform beam is assumed to be 0.1W corresponding to the spontaneous noise power. This is in substantial agreement with the results of analytic theory in contrast; the power growth is much faster than exponential for the prebunched beam.

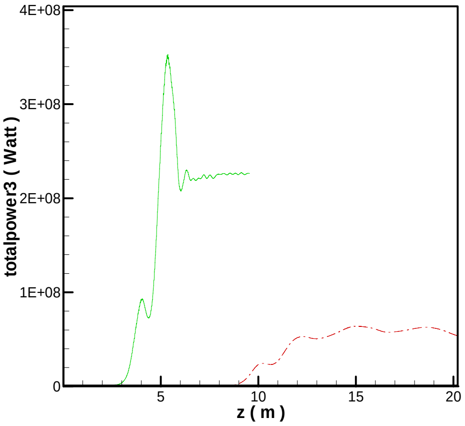

Fig. 1 Comparison of the growth in third harmonic power for a uniform (dashed line) and a prebunched beam

It is assumed that the wiggler is decreased at $z_T$=5.1 with the slope *m*=0.00037. The parameters m and $z_T$ are chosen so to obtain the maximum intensity of the third harmonic which is found by successive run of the code. Fig.2. shows the wiggler parameter profile, $a_w$, with $z_T$=5.1 and *m*=0.00037.This result is compared to that of an untapered wiggler (dashed lines) in Fig.3. We can see a significant increase in the third harmonic due to the tapering.

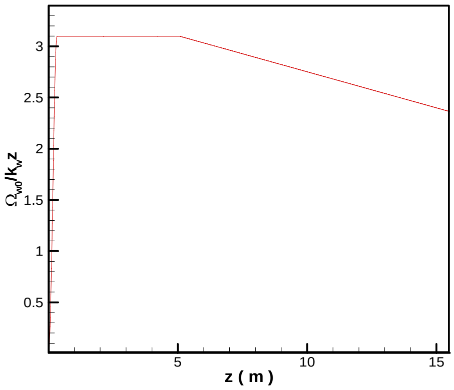

Fig. 3 the FEL has a constant wiggler field, up to the point $z_T$ =5.1 before FEL saturates, and after that the wiggler amplitude decreases by the slope 0.00037

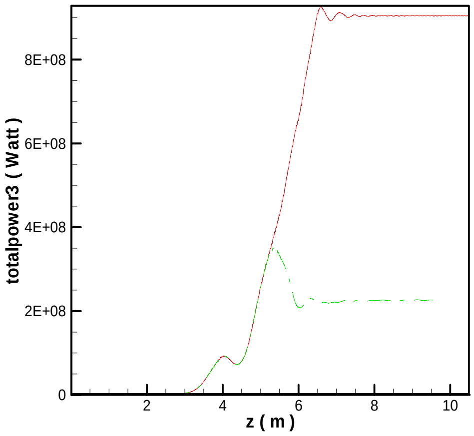

Fig. 3 Comparison of the growth in third harmonic power for a prebunched beam with tapered and untapered (dashed line) wiggler.

## IV. CONCLUSION

In summary, prebunched beams have substantial advantages for FEL operation and permit higher saturated powers (for density-modulated beams), shorter saturation lengths, and rapid startup from noise. It is found that by suitably tapering the amplitude of the wiggler field; saturation of the radiation for the shorter wavelength can be postponed leading to further amplification. Therefore, the efficiency will be enhanced dramatically by this technique.

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