NONLOCAL AND NONLINEAR SIMULATION OF HARMONIC UP CONVERSION IN TWO BEAM FREE ELECTRON LASER

B. Maraghechi [#] and M. H. Rouhani

Department of Physics, Amirkabir University of Technology, P. O. Box 15875-4413, Tehran, Iran

Abstract

A nonlocal and nonlinear simulation of harmonic up conversion in free electron laser amplifier operating simultaneously with two cold and relativistic electron beams of different energy is presented in the absence of slippage. By using slowly varying envelope approximation, the hyperbolic wave equations can be transformed into parabolic diffusion equations. By applying the source-dependent expansion to these 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 using 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. This set of equation describes self-consistently the longitudinal spatial dependence of radiation waists, curvatures and amplitudes together with the evaluation of the electron beam. The evolutions of the transverse modes, in this system, are investigated for fundamental and its harmonic up conversion.

INTRODUCTION

The main concern in free electron laser (FEL), nowadays, is the production of coherent high power short wavelength radiation because it has the potential to open new regimes in atomic and electronic processes. The main problem in this field is to find the processes or phenomena for seeding the FEL. In one method, the stochastic bunching in the electron beam, due to shot noise, was exploited [1]. Since the self amplified spontaneous emission (SASE) starts from electron beam shot noise, the output of the system typically has limited temporal coherence and relatively large shot-to-shot fluctuations in both the power and the spectrum even though it has transverse coherence [2].

For improving the longitudinal coherence, other methods were proposed such as injection of harmonics generated in gas [3], classical or non-classical high-gain harmonic generation [4, 5] and two-beam FEL for frequency up conversion [6]. In these methods, harmonic bunching play essential role. Radiation of the electron beam in the planar undulator contains rich harmonic spectrum. Higher harmonic radiation can significantly extend the operating band of the user facility.

In two-beam frequency up conversion method, which was proposed by McNeil et al., [6] two relativistic electron beams with different energies were used. The higher energy electron beam is chosen so that its fundamental resonance wavelength is a harmonic resonance wavelength of the lower energy beam. It should then be possible to seed the co-propagating electron beams with an externally injected seed radiation field at the fundamental of the lower energy electron beam. If such a seed field is significantly above the noise level then the lower energy electrons will begin to bunch at their fundamental resonance wavelength and retain the coherence properties of the seed. Such bunching at the fundamental also generates significant components of bunching at its harmonics which can also be expected to retain the coherence properties of the seed. This process should couple strongly with the co-propagating higher energy beam whose fundamental FEL interaction is at one of the lower energy beam's harmonics. This coupling between lower and higher energy FEL interactions may allow the transferral of the coherence properties of the longer wavelength seed field to the un-seeded shorter harmonic wavelength interaction.

Up to the authors knowledge, this phenomenon was not studied in three dimensions neither in the averaged form nor in the non averaged method. Therefore, three dimensional features such as diffraction, radiation guiding, and evolution of transverse modes were not considered in this system. The optical guiding of light in FEL is a well known phenomenon [7, 8] that results during amplification when the coherent interaction between the source electron beam and the electromagnetic field introduces an inward curvature in the phase front of the light, refracting it back toward the lasing core of the electron beam. During the gain process the electron beam can behave similar to a guiding structure that suppresses diffraction, reducing transverse power losses, and enhancing the electromagnetic field amplification. The evolution of transverse modes is important in planning for future user facilities that intend to employ radiation from this system [9]. Although the multiple electron beam FEL was studied in [10] in three dimensions but the harmonic up conversion was not considered. The main interest in the mentioned paper was reducing coherent synchrotron radiation in the bunch compressor by adding energy spread to the electron beam.

The purpose of the present study is to present a three-dimensional non-averaged simulation of two-beam FEL using source dependent expansion (SDE) [11]. The novel aspect of SDE method is that the characteristics of the modes are governed by the deriving current density. Therefore, instead of using the usual modal expansion

[#] behrouz@aut.ac.ir

consisting of vacuum Laguerre-Gaussian or Hermite-Gaussian functions [12], in SDE, the source function is incorporated self-consistently into the functional dependence of the radiation waist, the radiation wave front curvature, and the radiation amplitude.

It is important to emphasize that, no average is performed over the Lorentz force equation therefore the Kroll-Morton-Rosenbluth (KMR) scheme is not used. In the KMR method [13-17], the electron trajectories are averaged over the wiggler period. Hence, only two equations are integrated per electrons, specifically, for the energy and ponderomotive phase. Advantages of the non-KMR approach are possibility to treat the injection of the beam into the wiggler, the ease of inclusion of external focusing or dispersive magnetic components in the beamline, and the facility for using an actual magnetic field in the numerical solution.

The code which is written for this purpose is named modified MEDUSA code. Because we did not have access to the original MEDUSA code [18], we first rewrote the code and then modified it to study the two-beam FEL.

NUMERICAL ANALYSIS

An electron beam with an energy of 219.5 MeV, a current of 150 A, and an initial radius of 0.02 cm is chosen as a low energy electron beam. An electron beam with an energy of 380.185 MeV, a current of 300 A, and an initial radius of 0.02 cm is exploited as a fast electron beam. The parabolically shaped pole faces and tapered planar wiggler magnetic field is used with $B_w = 10.06$ kG, $\lambda_w = 3.3$ cm, and an entry taper region $N_w = 10$ wiggler period in length. The initial condition on the radiation fields are chosen such that fundamental is seeded with 10W of optical power which is also assumed that totally in the lowest mode of fundamental. The harmonic is started at zero initial power. The initial radiation waists are 0.05 cm and the initial alpha parameters are chosen to be zero. For the chosen parameters of the electron beam and wiggler magnetic field the fundamental resonance takes place at 500.5 nm and third harmonic is at the 166.84 nm. The initial state of the electron beams are chosen to model the injection of a mono-energetic, uniform, axisymmetric electron beams with the flat-top density profiles, i.e., $\sigma_{\parallel} = \sigma_{\perp} = 1$. Therefore the prebunching case is not considered. The electron positions are chosen by means of the Gaussian quadrature algorithm within the ranges $-\pi \le \psi_0 \le \pi$, $0 \le \theta_0 \le 2\pi$, and $0 \le r \le R_b$. Where θ_0 is the polar coordinate. In the absence of energy spread, $p_{z0} = mc\left(\gamma_0^2 - 1\right)^{1/2}$, where γ_0 is the relativistic factor corresponding to the total beam energy. It is important to recognize, however, that the subsequent evolution of the beam is integrated self consistently, and the beam may bunch in axial phases as well as develop both energy and pitch angle spreads due to the nature of the interaction. The number of Gauss-Hermite modes necessary to describe the evolution of the electromagnetic field depends upon the detailed parameters of each particular example. Diffraction over the Rayleigh length is countered by optical guiding due to the beam, and detailed balance depends upon the Rayleigh length, the growth rate, and the evolution of the beam envelope in the wiggler. As a results, the specific number of modes used in each case is determined by an empirical procedure in which successive simulation runs are made with an increasing number of modes until convergence of the saturation power and saturation length are achieved. For each wavelength in the system thirty six modes are used with a total of 4096 particles for each electron beam therefore the total number of particles are 8192. The code is run on the AMD Phenom™ X3 Triple Core processor.

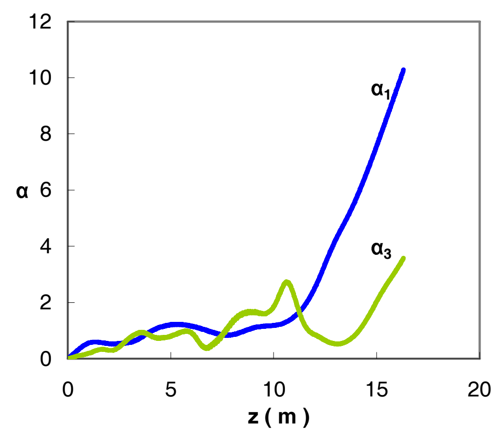

Figure 1: Variation of α with z.

In Fig. 1 the variation of α parameter is plotted versus longitudinal coordinate for fundamental and its harmonic up converted radiation at third harmonic.

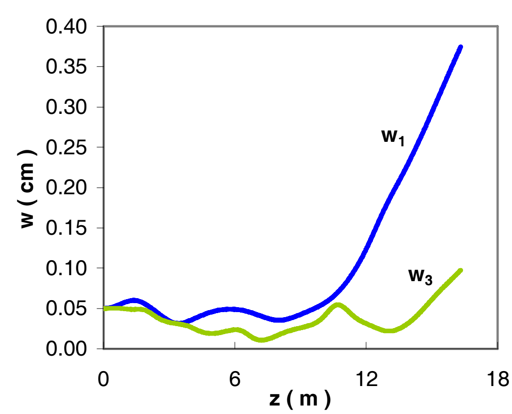

Figure 2: Evolution of radiation waist with z.

In Fig. 2 the variation of spot size is plotted versus axial position for fundamental and its third harmonic up conversion. The variation in the spot size with axial position reflects the optical guiding of the wave. The spot size of the harmonic up conversion of fundamental is observed to expand during the initial stage of interaction as predicted by vacuum diffraction; however when the power becomes large, optical guiding becomes strong and focusing of this radiation is rapid. In this figure it is evident that the harmonic up conversion of fundamental is focused to a smaller spot size than the fundamental.

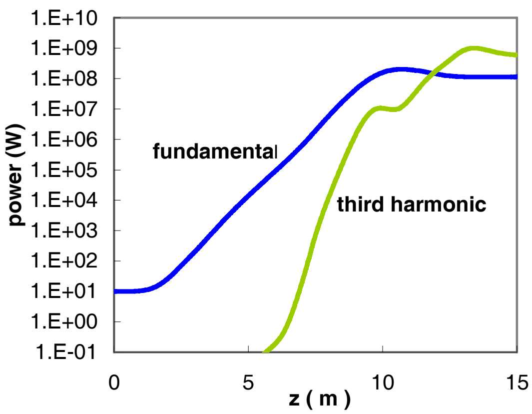

Figure 3: Variation of power with z.

The power of fundamental and harmonic up conversion at third harmonic are plotted in Fig. 3 as a function of distance through the system. In contrast to the nonlinear harmonic generation [18, 19], the intensity of the shorter wavelength is larger than the intensity of fundamental wavelength [6]. Note that the points of saturations vary for wavelength, as evidenced in Fig. 3.

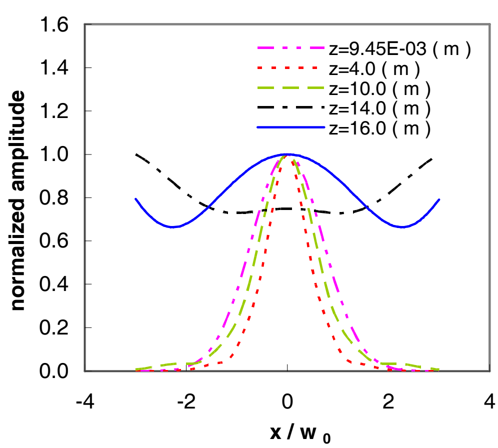

Figure 4: Normalized radiation amplitude cross-section for fundamental wavelength in the x-direction for y=0.

In Figs. 4 and 5 the horizontal (x-direction) radiation amplitude cross-section for y=0 are plotted as a function of distance for the fundamental and harmonic up conversion. All cross-sections are normalized to a peak intensity of 1. The fundamental saturation occurs at 10.70 m and its harmonic up conversion occurs at 13.40 m. To determine the exact positions of saturation for each wavelength, an extensive numerical undertaking is required with the code to write out many more modal maps in z. At the points of near saturation, the narrowing of modes is clear and the mode narrowing increases for harmonic up converted radiation. At saturation, the radiation waist begins to grow since the so called gain guiding is no longer effective. Also following saturation, additional modes tend to grow.

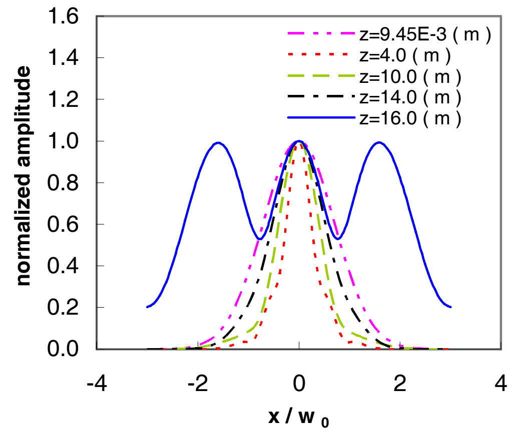

Figure 5: Normalized radiation amplitude cross-section for harmonic up converted at third harmonic in the x-direction for y=0.

The evolution of the cross-sectional distribution of the low energy electron beam is illustrated in Figs. 6-8.

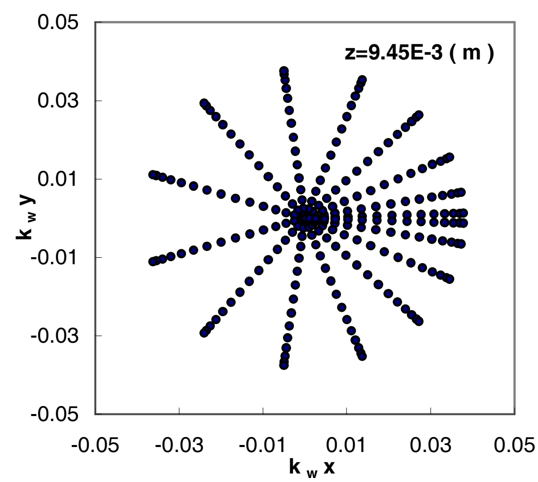

Figure 6: Cross-section of the low energy electron beam.

The cross-sectional distribution at the start of the wiggler region is shown in Fig. 6. The bulk motion exhibits essential features.

The first is the primary wiggler induced oscillation which is aligned along the x axis. The second feature is that the transverse wiggler gradient has a focusing effect on the beam which results in a reduction in the maximum beam radius relative to the initial value which is seen in Fig. 7. The third feature is that the transverse wiggler gradient introduces a betatron oscillation which causes a macroscopic scalloping of the beam envelope. In addition, on the microscopic level, the individual electrons come into a focus and out again on the opposite side of the beam which is seen in Fig. 8.

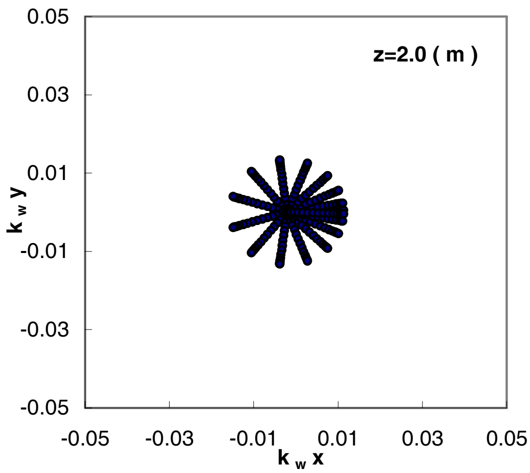

Figure 7: Cross-section of low energy electron beam.

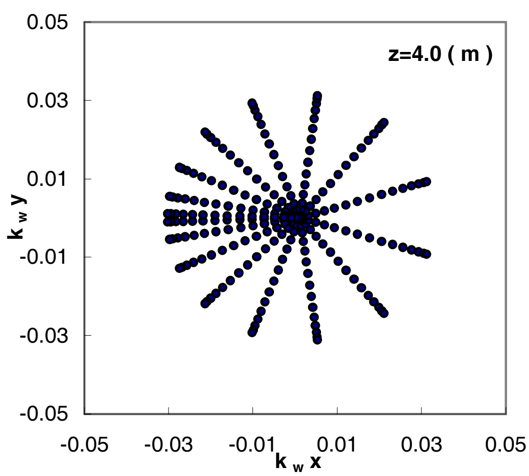

Figure 8: Cross-section of low energy electron beam.

CONCLUSION

A non averaged and 3D simulation of harmonic up conversion in a FEL amplifier operating simultaneously with two cold and relativistic electron beams with different energy is presented in the absence of slippage. The variation of radiation waists, curvatures, and amplitudes for fundamental and its harmonic up conversion are studied. Transverse mode evolution of fundamental and harmonic up conversion at third harmonic are investigated in more details. The radiation power of harmonic up conversion is larger than the radiation power at fundamental. This is in contrast to the nonlinear harmonic generation. It is also in contrast to the radiation up conversion method in which the wiggler is filled by plasma [20]. The waist of harmonic up converted radiation is focused to the smaller spot size than the fundamental. This phenomenon is similar to the nonlinear harmonic generation. Extension of this work for studying the optical properties of harmonic up converted radiation by using the M^2 parameter [21] for the two-beam FEL is in progress. The effect of wiggler contouring for increasing efficiency enhancement and adding the effect of shot noise on the start up of harmonic up converted radiation will be studied in the future.

ACKNOWLEDGEMENT

B. M. would like to thank the Center of Excellence in Computational Aerospace Engineering for financial support.

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