THE USE OF HARMONICS TO ACHIEVE COHERENT SHORT WAVELENGTHS*

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Abstract

Harmonics of the fundamental radiation are generated through both linear and nonlinear interactions during the self-amplified spontaneous emission (SASE) process. Ultimately the nonlinear harmonics dominate over those generated through the linear process. It has been shown that at saturation, power levels in the first few nonlinear harmonics can reach significant, useful values [1,2]. The nonlinear harmonics are driven by the fundamental radiation producing microbunching with strong harmonic content. As such, these harmonics are dominated by the fundamental interaction; therefore, beam requirements to achieve these wavelengths are relaxed and are predominately driven by the needs of the fundamental. Here we explore the use of these harmonics in achieving coherent short wavelengths and discuss the beam requirements and output power levels as compared to presently proposed next-generation light source experiments such as the Linac Coherent Light Source (LCLS) [3].

1 INTRODUCTION

Nonlinear harmonic generation occurs in free-electron lasers (FELs) [1,2,4,5]. In a planar undulator configuration, the odd harmonics are favored as the coupling to power predominantly occurs at the micro-bunching that mimics the sinusoidal-like electron motion in the undulator. The growth of these harmonics is quite rapid as saturation is approached, and the powers in the first few odd harmonics are substantial. Since it is the fundamental microbunching that drives the FEL process, one might then imagine a system operating with the fundamental at a longer wavelength and simply relying upon the nonlinear harmonic generation to drive the experiments. This would greatly reduce the electron-beam energy and quality required to drive such a nonlinear-harmonic-based, single-pass, high-gain FEL.

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2 CASE STUDY

Currently, there are several proposals for projects that address achieving coherent short wavelengths (a few Ångstroms) utilizing a single-pass, high-gain FEL: the LCLS at SLAC [3], the TESLA Project at DESY [6], and the SCSS at SPring-8 [7]. These projects require a substantial electron beam energy and rather small emittance to achieve FEL saturation using the self-amplified spontaneous emission (SASE) process [8]. Here, we have chosen to examine the LCLS project parameters proper, where the fundamental output wavelength is 1.5 Å (Case 1) and then examine a similar system that reduces the electron beam energy such that the third nonlinear harmonic is at 1.5 Å (Case 2). Notice that the emittance has also been allowed to increase in the related case. The parameters for the LCLS proper case and related, harmonic-based case are shown in Table 1.

Table 1: LCLS and Related Cases

Parameter	Case 1	Case 2
γ	28085	16171
Electron beam energy (GeV)	14.35	8.26
Normalized emittance (π mm-mrad)	1.5	3
Peak current (A)	3400	3400
Undulator period (cm)	3.0	3.0
Undulator strength (K)	3.7	3.7
Energy* spread (%)	0.02	0.02
Fundamental wavelength (Å)	1.5	4.5
1.5 Å achieved at	Funda-mental	Third harmonic

*Note, the MEDUSA simulations employ energy spreads of 0.006% and 0.02%, for Cases 1 and 2, respectively.

3 METHODS OF EXAMINATION

These cases were examined both by a simulation code and a numerical analysis of the three-dimensional

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nonlinear harmonic theory. The fundamental and third-harmonic output powers of these two methods have been previously compared for a longer wavelength case [2]. Here, a brief description of each method is presented.

3.1 MEDUSA

MEDUSA is a 3D, multifrequency, macroparticle simulation code where the electromagnetic field is represented as a superposition of Gauss-Hermite modes and where a source-dependent expansion is used to determine the evolution of the optical mode radius [9,10]. The field equations are integrated simultaneously with the 3D Lorentz force equations. As such, MEDUSA differs from other nonlinear simulation codes in that no undulator-period average is imposed on the electron dynamics. It is capable of treating quadrupole and corrector fields, magnet errors, and multiple segment undulators of various quantities and types. Finally, it is able to predict the powers of the fundamental and all harmonics [11].

3.2 Numerical Analysis of Analytical Theory

A 3-D theory of harmonic generation has been developed [2], using the coupled Maxwell-Klimontovich equations, that includes electron energy spread and emittance, the radiation diffraction, and optical guiding. In general, each harmonic field is a sum of a linear amplification term and a term driven by nonlinear harmonic interactions. After a certain stage of exponential growth, the dominant nonlinear term is determined by interactions of the lower nonlinear harmonics and the fundamental radiation. As a result, the gain length, transverse profile, and temporal structure of the first few harmonics are eventually governed by those of the fundamental. For example, driven by the third power of the radiation field in the fundamental, the third nonlinear harmonic grows three times faster, has an equally coherent transverse mode (with a smaller spot size), and has a more spiky temporal structure than the fundamental of SASE FELs. For the LCLS design study case (0.02% energy spread), the evolution of the third-harmonic power is given by [2] as

$$\frac{P_3}{\rho P_{beam}} = 0.11\left(\frac{P_1}{\rho P_{beam}}\right)^3 .$$

Taking $P_1 = P_{sat}/2$ or roughly 4 GW just before the saturation point, one can estimate the third-harmonic (0.5 Å) power to be 15 MW, about 0.4% of the fundamental power level. Note that ρ, the dimensionless FEL scaling parameter [12], is, for this case, roughly 4.5×10^{-4}.

In the second case (0.02% energy spread), everything is the same except one should replace 0.11 with 0.17 in the equation above. In Case 2, we therefore expect 40 MW in the third harmonic (1.5 Å) and ρ is now equal to 5.3×10^{-4} [2]. The analytical theory does not calculate the fifth nonlinear harmonic.

4 RESULTS

4.1 Case 1

The results of the simulated Case 1 can be viewed in Figure 1, in which the peak power (W) at the fundamental (1.5 Å), third (0.5 Å), and fifth (0.3 Å) nonlinear harmonics are shown as functions of distance for the MEDUSA simulations. The simulated and analytical results of Case 1 are shown in Table 2.

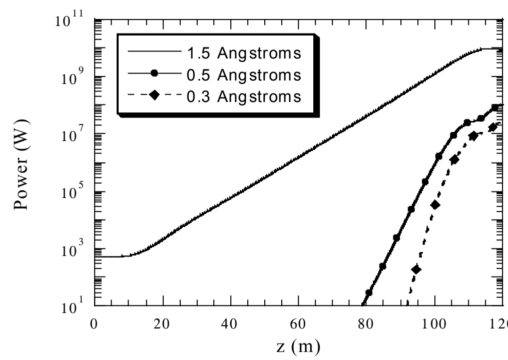

Figure 1: Case 1 – MEDUSA, power (W) versus z (m).

Table 2: Results of Case 1

Parameter	MEDUSA	Analytical Theory
Fundamental wavelength (Å)	1.5	
Electron beam energy (GeV)	14.35	
Normalized emittance (π mm-mrad)	1.5	
Peak current (A)	3400	
Energy spread (%)	0.006	0.02
Fundamental (1.5 Å) saturated power (GW)	9.1	8
Fundamental saturation length (m)	116	100
Third harmonic (0.5 Å) power (MW)	34	15
Fifth harmonic (0.3 Å) power (MW)	10.2	-na-
Peak brightness at 1.5 Å	-na-	12×10^{32}

4.2 Case 2

The results of the simulated Case 2 can be viewed in Figure 2, in which the peak power (W) at the fundamental (4.5 Å), third (1.5 Å), and fifth (0.5 Å) nonlinear harmonics are shown as functions of distance for the MEDUSA simulations. The simulated and analytical results of Case 2 are shown in Table 3.

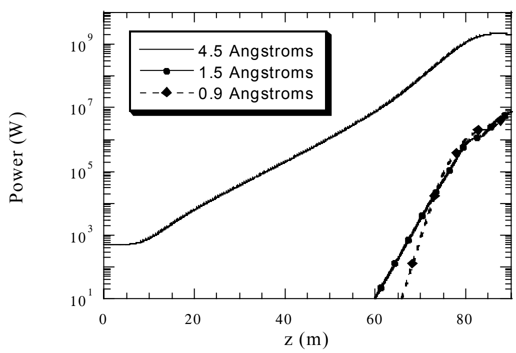

Figure 2: Case 2 – MEDUSA, power (W) versus z (m).

Table 3: Results of Case 2

Parameter	MEDUSA	Analytical Theory
Fundamental wavelength (Å)	4.5	
Electron beam energy (GeV)	8	
Normalized emittance (π mm-mrad)	3	
Peak current (A)	3400	
Energy Spread (%)	0.02	
Fundamental (4.5 Å) saturated Power (GW)	2.1	6.5
Fundamental saturation Length (m)	84	80
Third harmonic (1.5 Å) power (MW)	5.4	40
Fifth harmonic (0.5 Å) power (MW)	0.7	-na-
Peak brightness at 1.5 Å	-na-	2×10^{30}

5 SUMMARY

MEDUSA and the analytical theory display the usefulness of the nonlinear harmonics in the short wavelength regime. Although there is a power reduction in the nonlinear harmonic output powers in such next-generation sources, these harmonic powers will be useful in that the electron beam energy and beam qualities may be relaxed while still achieving the shortest wavelengths. This was demonstrated by reducing the electron beam energy in Case 2 to place the resultant third harmonic wavelength at 1.5 Å, the fundamental of Case 1, while also incurring a reduction in the electron beam quality in both emittance and energy spread.

In general, we expect on the order of one percent of the power in the third harmonic relative to the fundamental power and at least ten percent of the power in the fifth harmonic relative to the third harmonic. These are quite significant, especially when the power in the fundamental is expected to exceed GW levels [3].

Although not included in this paper, further analyses of the sensitivities of systems based on nonlinear harmonic generation have been examined [13,14,15]. In these analyses, it has been shown that the nonlinear harmonics are not affected more substantially than the fundamental by undulator errors and/or electron beam quality degradation.

6 REFERENCES

[1] H.P. Freund, S.G. Biedron, and S.V. Milton, *IEEE J. Quant. Electron.* **36**, 275-281 (2000) and references therein.
[2] Z. Huang and K.J. Kim, *Phys. Rev.* **62E**, 7295-7308 (2000) and references therein.
[3] LCLS Design Study Report, SLAC-R-521, Rev. Dec. 1998.
[4] R. Bonifacio et al., Nucl. Instr. Meth. **A293**, p. 627 (1990).
[5] G. Dattoli and P.L. Ottaviani, J. Appl. Phys. **86**, p. 5331 (1999).
[6] The TESLA Technical Design Report, DESY 2001-011, March 2001.
[7] T. Shintake, private communication.
[8] A.M. Kondratenko and E.L. Saldin, Sov. Phys. Dokl. **24 (12)**, p. 986 (1979).
[9] H.P. Freund and T.M. Antonsen, Jr., Principles of Free-electron Lasers (Chapman & Hall, London, 1986), 2nd edition.
[10] H.P. Freund, Phys. Rev. E, **52**, 5401 (1995).
[11] S.G. Biedron, H.P. Freund, and S.V. Milton, *in Free Electron Laser Challenges II*, Harold E. Bennett, David H. Dowell, Editors, Proceedings of SPIE, Vol. 3614, 96-108 (1999).
[12] R. Bonifacio, C. Pellegrini and L.M. Narducci, Opt. Comm. **50**, 373 (1984).
[13] S.G. Biedron G. Dattoli, H.P. Freund, Z. Huang, S.V. Milton, H.-D. Nuhn, P.L. Ottaviani, and A. Renieri, Proceedings of the Physics of and Science with the X-Ray Free-electron Laser, American Insititute of Physics, in press, to be published 2001.
[14] S.G. Biedron G. Dattoli, W.M. Fawley, H.P. Freund, Z. Huang, K.-J. Kim, S.V. Milton, H.-D. Nuhn, P.L. Ottaviani, and A. Renieri, ICFA Workshop on Laser-Beam Interactions, Stony Brook, New York, 11-17 June 2001, submitted to Physical Review Special Topics, Accelerators and Beams.
[15] H.P. Freund, S.G. Biedron, S.V. Milton, and H.D. Nuhn, *IEEE J. Quant. Electron.* **37**, 290-793 (2001).