Nuclear Instruments and Methods in Physics Research A 483 (2002) 101–106

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.com/locate/nima

The sensitivity of nonlinear harmonic generation to electron beam quality in free electron lasers ☆

Sandra G. Biedron[a,b,*], Zhirong Huang[a], Kwang-Je Kim[a], Stephen Milton[a], Giuseppe Dattoli[c], Pier Luigi Ottaviani[d], Alberto Renieri[c], William M. Fawley[e], Henry P. Freund[f], Heinz-Dieter Nuhn[g]

[a] *Advanced Photon Source, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA*
[b] *MAX-Laboratory, University of Lund, SE-221 00 Sweden*
[c] *ENEA, Divisione Fisica Applicata, Centro Ricerche Frascati, C.P. 65, 00044 Frascati, Rome, Italy*
[d] *ENEA, Divisione Fisica Applicata, Centro Ricerche E. Clementel, Via Don Fiammelli 2, Bologna, Italy*
[e] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[f] *Science Applications International Corporation, McLean, VA 22102, USA*
[g] *Stanford Linear Accelerator Center, Stanford University, Menlo Park, CA 94309-0210, USA*

Abstract

The generation of harmonics through a nonlinear mechanism driven by bunching at the fundamental has sparked interest as a path toward enhancing and extending the usefulness of an X-ray free-electron laser (FEL) facility. The sensitivity of the nonlinear harmonic generation to undulator imperfections, electron beam energy spread, peak current, and emittance is important in an evaluation of the process. Typically, linear instabilities in FELs are characterized by increased sensitivity to both electron beam and undulator quality with increasing harmonic number. However, since the nonlinear harmonic generation mechanism is driven by the growth of the fundamental, the sensitivity of the nonlinear harmonic mechanism is not expected to be significantly greater than that of the fundamental. In this paper, we study the effects of electron beam quality, more specifically, emittance, energy spread, and peak current, on the nonlinear harmonics in a 1.5-Å FEL, and show that the decline in the harmonic emission roughly follows that of the fundamental.
© 2002 Elsevier Science B.V. All rights reserved.

PACS: 41.60; 42.65.Ky; 52.59.−f

Keywords: Free-electron lasers; Harmonic generation; Frequency conversion; Intense particle beams and radiation sources

---

☆ The work of Biedron, Huang, Kim, and Milton is supported at Argonne National Laboratory by the US Department of Energy, Office of Basic Energy Sciences under Contract No. W-31-109-ENG-38. The activity and computational work for Freund is supported by Science Applications International Corporation's Advanced Technology Group under IR&D subproject 01-0060-73-0890-000. The activity of Fawley is supported at Lawrence Berkeley National Laboratory by the US Department of Energy under Contract No. DE-AC03-76SF00098. The work of Nuhn is supported by the US Department of Energy, Office of Basic Energy Sciences, Division of Material Sciences, under contract No. DE-AC03-76SF00515.

*Corresponding author. Advanced Photon Source, Argonne National Laboratory and MAX-Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA. Tel.: +1-630-252-1162; fax: +1-630-252-5703.
E-mail address: biedron@aps.anl.gov (S.G. Biedron).

PII: S0168-9002(02)00292-9

1. Introduction

There is an ongoing interest in the accelerator physics and synchrotron radiation user communities to develop 1.5-Å self-amplified spontaneous emission (SASE) [1,2] free-electron lasers (FELs) to serve as the next-generation synchrotron light sources [3–5]. The fundamental radiation wavelength is related to the electron beam energy and the strength of the undulator device. In addition to the fundamental, nonlinear harmonics also arise and experience gain similar to the fundamental and also achieve saturation, with their gain lengths scaling as the inverse of the harmonic number [6–9]. Two additional methods allow one to up-convert the fundamental radiation frequency via nonlinear harmonics. These alternative methods are the high-gain harmonic generation scheme [10–12] and the two-undulator harmonic generation scheme (TUHGS), also referred to as the "after-burner" method [13–15].

In the present work, we investigate the effect of emittance, energy spread, and peak current on the nonlinear harmonic generation in a single-pass, high-gain, free-electron laser similar to the LCLS design parameters found in Ref. [2]. Recently, members of our group investigated the effect of wiggler errors on the fundamental and nonlinear harmonics for this same LCLS-like case and found the nonlinear harmonic output power followed that of the fundamental [16]. Also recently, our group studied the effect of the electron beam quality for the longer wavelength SASE case of the first phase of the Advanced Photon Source (APS) Low-Energy Undulator Test Line (LEUTL) SASE FEL operating at 517 nm [17,18]. For these longer wavelength case studies, we also found that the trend of the nonlinear harmonic bunching and output power clearly followed that of the fundamental.

The purpose of the described investigation is to assist in the prediction of any unforeseen problems regarding the usefulness of the nonlinear harmonic output in an LCLS-like system. Hopefully, this information will allow both users and source developers to plan, respectively, their experiments and machines with more knowledge.

2. Code descriptions

We first briefly describe the numerical simulation codes used in this study.

2.1. GINGER

GINGER is a multidimensional (3D macroparticle, 2D ($r-z$) radiation field), polychromatic FEL simulation code [19]. The equations of motion are averaged over an undulator period following the standard KMR [20] formulation while an eikonal approximation in time and space is used for field propagation. For polychromatic SASE simulations, GINGER can be initiated with either electron beam shot noise or, alternatively, photon noise. In monochromatic mode (which is true for nearly all the results presented here), the radiation is presumed to be at a single discrete wavelength. Macroparticle bunching in the longitudinal plane can be diagnosed through approximately the 9th harmonic (with the accuracy dependent upon macroparticle statistics); however, GINGER presently calculates and propagates radiation only within a narrow bandpass centered upon the fundamental wavelength. Thus, the effects of any emitted harmonic radiation upon the electron beam are ignored which, in general, is a good approximation up to saturation.

2.2. MEDUSA

MEDUSA is a 3D, multifrequency, macroparticle simulation code that represents the electromagnetic field as a superposition of Gauss–Hermite modes and uses a source-dependent expansion to determine the evolution of the optical mode radius [8,21–23]. The field equations are integrated simultaneously with the Lorentz force equations. MEDUSA differs from other nonlinear simulation codes in that no undulator-period averaging 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. MEDUSA is able to treat the fundamental and all harmonics simultaneously as well as treat sideband growth.

2.3. PROMETEO

PROMETEO is a 1D, multiparticle code [24] based on a modified version of the Prosnitz, Szoke, and Neil formulation of the FEL dynamical equations [25,26]. The original model has been generalized to include the effect of beam emittance and the undulator errors. The code is capable of accounting for the evolution of the fundamental harmonics and for the coherent generation of higher-order harmonics in SASE or oscillator FELs, including optical klystron and segmented undulators.

3. Case under study and results

For the LCLS-like case under investigation, the nominal design parameters are shown in Table 1. We simulate a single, long segment of undulator with curved pole-face focusing. For each of the three codes, we executed a number of runs to scan either the radiation wavelength (for MEDUSA and PROMETEO) or K (for GINGER) while holding all other parameters fixed to find the minimum exponential gain length. We ran our three codes in the amplifier case, each introducing an input seed power of 480 W to our three model systems, respectively. In addition, in each case, we simulated a Gaussian electron beam profile in the transverse phase space. The optimum fundamental gain length, wavelength, and undulator strength parameter K, are shown for each of our three codes in Table 2 while the saturation distance and power for the fundamental are given in Table 3.

Table 1
LCLS-like case study parameters

Parameters	
γ	28085
Electron beam energy (GeV)	14.35
Normalized emittance (π mm-mrad)	1.5
Peak current (A)	3400
Undulator period (m)	0.03
Undulator strength (K)	3.7
Energy spread (%)	0.006
Fundamental wavelength (nm)	0.15

Table 2
Optimum fundamental gain length, wavelength, and undulator strength parameter, K, of each code

Code	Minimum L_{gain} (m)	Optimum λ (nm)	Optimum K
GINGER	5.85	0.150	3.71
MEDUSA	5.9	0.144	3.70
PROMETEO	5.7	0.150	3.70

Table 3
Fundamental saturated distance and power for each code

Code	z (m)	Power (GW)
GINGER	98	7.27
MEDUSA	116	8.74
PROMETEO	117	22

After performing these initial comparisons at the fundamental wavelength, the investigations of the variation of normalized emittance, energy spread, and peak current on the fundamental and nonlinear harmonics began. Recall that GINGER is able to provide the fundamental power and bunching as well as bunching of the nonlinear harmonics and MEDUSA and PROMETEO are able to simulate the fundamental and nonlinear harmonic powers and bunching. For comparison purposes, to lowest order, the power scales as the square of the bunching. The nonlinear harmonic bunching or power level for each parameter variation was recorded at the point in z of the fundamental saturation.

3.1. Emittance investigations

To examine harmonic output sensitivity to electron beam emittance, we varied the normalized emittance from 1.0 and 5.0 π mm-mrad. The fundamental and third nonlinear harmonic bunching fractions and the ratio of the third harmonic to fundamental (3:1) bunching ratio versus emittance for GINGER are shown in Fig. 1 and the fundamental and third nonlinear harmonic powers as well as the third harmonic to fundamental (3:1) power ratio versus emittance for the MEDUSA

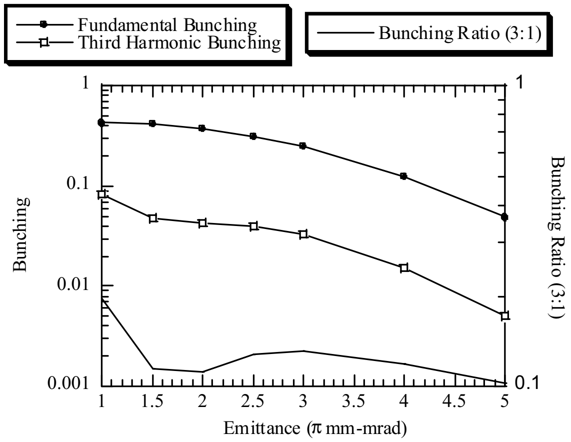

Fig. 1. Bunching of the fundamental and third nonlinear harmonic and bunching ratio versus electron beam emittance simulated by GINGER.

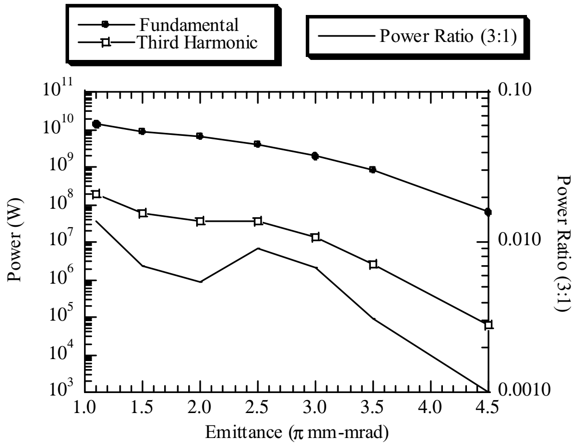

Fig. 2. Powers of the fundamental and third nonlinear harmonic versus electron beam emittance simulated by MEDUSA.

and PROMETEO runs are shown in Figs. 2 and 3, respectively.

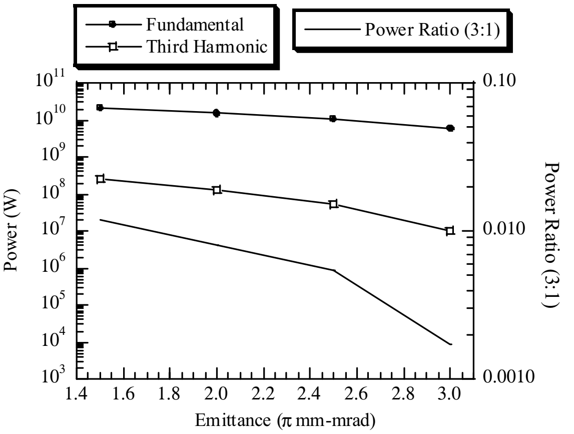

Fig. 3. Powers of the fundamental and third nonlinear harmonic versus electron beam emittance simulated by PROMETEO.

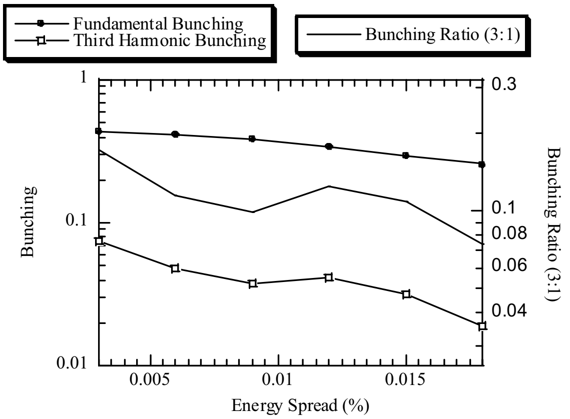

Fig. 4. Bunching of the fundamental and third nonlinear harmonic and bunching ratio versus electron beam energy spread simulated by GINGER.

3.2. Energy spread investigations

For energy spread sensitivity studies, we varied σ_γ from 0.00% to 0.025%. The fundamental and third nonlinear harmonic bunching fractions and the ratio of the third harmonic to fundamental (3:1) bunching ratio versus energy spread for GINGER are shown in Fig. 4, and the fundamental and third nonlinear harmonic powers as well as the third harmonic to fundamental (3:1) power ratio versus σ_γ for the MEDUSA and PROMETEO runs are shown in Figs. 5 and 6, respectively. Note PROMETEO seems to predict a smoother behavior of the third harmonic versus the energy spread than GINGER and MEDUSA. Although the reason for the difference is not yet clear, we do not believe this is due to the 1D nature of PROMETEO.

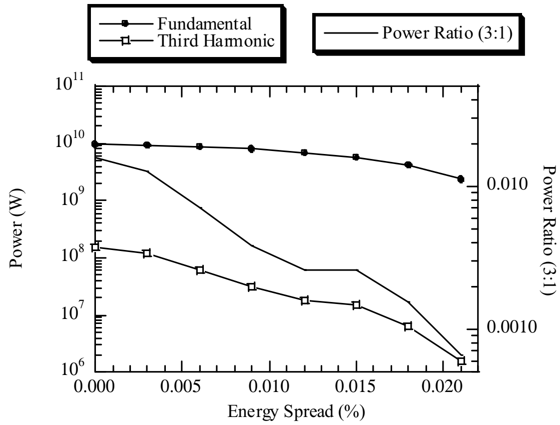

Fig. 5. Powers of the fundamental and third nonlinear harmonic versus electron beam energy spread simulated by MEDUSA.

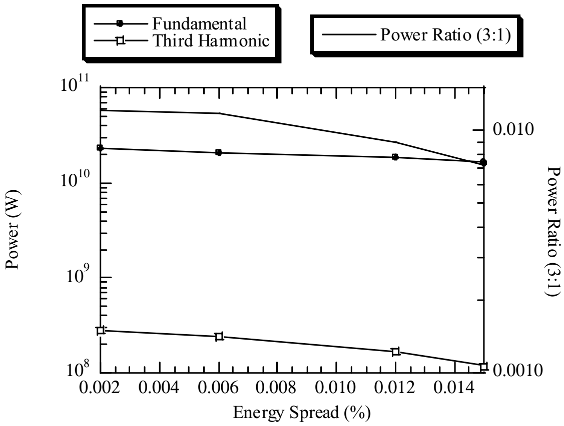

Fig. 6. Powers of the fundamental and third nonlinear harmonic versus electron beam energy spread simulated by PROMETEO.

3.3. *Beam current investigations*

Our last sensitivity study involved beam current. Here, we varied I_b from 3000 to 4000 A. The fundamental and third nonlinear harmonic bunching fractions and the ratio of the third harmonic to fundamental (3:1) bunching ratio versus peak current for GINGER are shown in Fig. 7, and the fundamental and third nonlinear harmonic powers as well as the third harmonic to fundamental (3:1) power ratio versus peak current for MEDUSA are shown in Fig. 8.

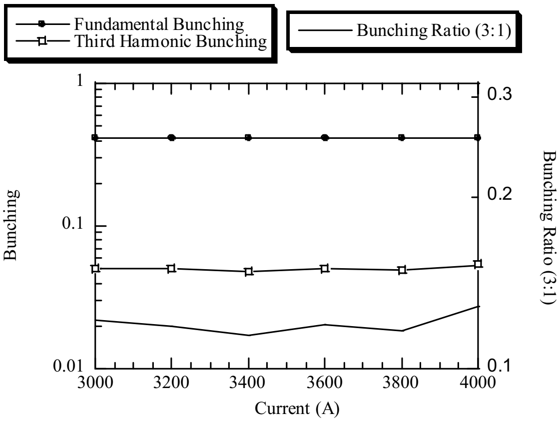

Fig. 7. Bunching of the fundamental and third nonlinear harmonic and bunching ratio versus electron beam peak current simulated by GINGER.

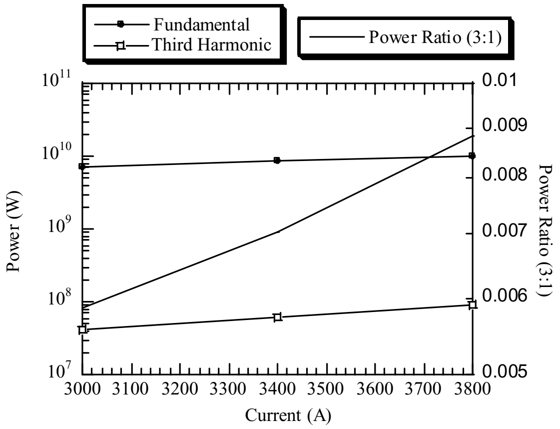

Fig. 8. Powers of the fundamental and third nonlinear harmonic and power ratio versus electron beam peak current simulated by MEDUSA.

4. Conclusions

In this paper, we have examined the sensitivity of nonlinear harmonic bunching and radiation output power to variations in electron beam transverse emittance, instantaneous energy spread, and peak current centered around the standard parameters believed appropriate to the LCLS X-ray FEL. Our results suggest that the third harmonic bunching and power are not significantly more sensitive (in a power-law sense) to beam quality than the equivalent quantities at the fundamental wavelength, at least until the degradation begins to severely affect the latter. Specifically, even when the energy spread or emittance is doubled relative to the standard case value, the ratios of harmonic to fundamental bunching and radiation power decrease by less than a factor of 2 and 4, respectively. These new results are similar to those found by us at much longer wavelengths (e.g., the visible) for the LEUTL project for which diffraction effects are far more pronounced [17,18]. They are also similar to our previous examination of the sensitivity of nonlinear harmonic emission to undulator errors [16]. Consequently, we have confidence that potential users of both future short wavelength FELs (e.g., LCLS) and existing longer wavelength FELs (e.g., LEUTL, TTF) operating in the high gain regime can within reason safely proceed with plans to use the nonlinear harmonic emission as a radiation source even if the actual (i.e., experimental) electron beam quality turns out to be somewhat poorer than hoped for in design proposals.

References

[1] A.M. Kondratenko, E.L. Saldin, Sov. Phys. Dokl. 24 (12) (1979) 986.

[2] S.V. Milton, et al. (originally published in Science Express as 10.1126/science.1059955 on May 17, 2001) Science 292 (2001) 2037–2041.

[3] Linac Coherent Light Source Design Study Report, SLAC-R-521, Rev. 1998 UC-414.

[4] LCLS: The First Experiments, SLAC Report for the US Department of Energy, BESAC Committee (Basic Energy and Sciences Committee), 10–11 October 2000, Washington, DC, September 2000.

[5] TESLA: The superconducting electron–positron linear collider with an integrated X-ray laser laboratory, Technical Design Report, TESLA Report 2001-23, 2001.

[6] R. Bonifacio, et al., Nucl. Instr. and Meth. A 293 (1990) 627.

[7] G. Dattoli, P.L. Ottaviani, J. Appl. Phys. 86 (1991) 5331.

[8] H.P. Freund, S.G. Biedron, S.V. Milton, IEEE J. Quantum Electron. 36 (2000) 275.

[9] Z. Huang, K.-J. Kim, Phys. Rev. E 62 (2000) 7295.

[10] L.-H. Yu, Phys. Rev. A 44 (1991) 5178.

[11] I. Ben-Zvi, et al., Nucl. Instr. and Meth. A 318 (1992) 208.

[12] L.-H. Yu, et al., Science 289 (2000) 1932.

[13] R. Bonifacio, et al., Nucl. Instr. and Meth. A 296 (1990) 787.

[14] F. Ciocci, et al., IEEE J. Quantum Electron. 31 (1995) 1242.

[15] W.M. Fawley et al., Proceedings of the IEEE 1995 Particle Accelerator Conference, 1996, p. 219.

[16] H.P. Freund, S.G. Biedron, S.V. Milton, H.-D. Nuhn, IEEE J. Quantum Electron. 37 (2001) 790.

[17] S.G. Biedron, G. Dattoli, H.P. Freund, Z. Huang, S.V. Milton, H.-D. Nuhn, P.L. Ottaviani, A. Renieri, in: M. Cornacchia, C. Pellegrini, S. Chattopadhyay, I. Lindau (Eds.), High-gain free-electron lasers and harmonic generation, physics of, and science with, the X-ray free-electron laser, 19th Advanced ICFA Beam Dynamics Workshop, August 2001, 0-7354-0022-9, CP 581, p. 203.

[18] 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, A. Renieri, Impact of electron beam quality on nonlinear harmonic generation in high-gain free-electron lasers, Proceedings of the 21st ICFA Beam Dynamics Workshop on LASER-BEAM INTERACTIONS, Stony Brook, USA, June 11–15, 2001; Phys. Rev. (Special Topics, Accelerators and Beams, special conference edition), submitted for publication.

[19] W.M. Fawley, An informal manual for GINGER and its post-processor XPLOTGIN, LBID-2141, CBP Technical Note-104, UC-414, 1995.

[20] N.M. Kroll, P.L. Morton, M.R. Rosenbluth, IEEE J. Quant. Electron. QE-17 (1981) 1436.

[21] H.P. Freund, T.M. Antonsen Jr., Principles of Free-electron Lasers, 2nd Edition, Chapman & Hall, London, 1986.

[22] H.P. Freund, Phys. Rev. E 52 (1995) 5401.

[23] S.G. Biedron, H.P. Freund, S.V. Milton, Development of a 3D FEL code for the simulation of a high-gain harmonic generation experiment, in: Harold E. Bennett, David. H. Dowell (Eds.), Free Electron Laser Challenges II, Proceedings of the SPIE, Vol. 3614, 1999, p. 96.

[24] G. Dattoli, M. Galli, P.L. Ottaviani, 1-dimensional simulation of FEL including high gain regime saturation, Prebunching, and Harmonic Generation, ENEA Internal Report RT/INN/93/09, 1993.

[25] D. Prosnitz, A. Szoke, V.K. Neil, Phys. Rev. A 24 (1981) 1436.

[26] T. Scharlemann, J. Appl. Phys. 58 (1985) 2154.