SIMULATION OF THE FUNDAMENTAL AND NONLINEAR HARMONIC OUTPUT FROM AN FEL AMPLIFIER WITH A SOFT X-RAY SEED LASER*

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Abstract

A single-pass, high-gain free-electron laser (FEL) x-ray amplifier was simulated using the 3D, polychromatic simulation code MEDUSA. The seed for the system is a table-top, soft x-ray laser. The simulated fundamental and nonlinear harmonic x-ray output wavelengths are discussed.

1 INTRODUCTION

In a high-gain, single-pass free-electron laser (FEL) amplifier, the input seed laser determines the output wavelength. Nonlinear harmonic interactions in free-electron lasers have been previously discussed in the literature [1-4]. Previous amplifier systems have been limited in reaching soft x-ray wavelengths due to the available seed laser wavelengths. More recently, the advent of table-top, soft x-ray lasers [5] have opened the possibility of using this seed in a master oscillator power amplifier (MOPA) arrangement. Combined with the nonlinear harmonics, significantly shorter longitudinally coherent wavelengths can be achieved. In this paper, the 3D, polychromatic FEL simulation code MEDUSA [3,4] will be used to examine a soft x-ray, table-top laser as the seed in an amplifier FEL. In addition, the resulting nonlinear harmonic power in the system will be discussed.

2 REVIEW OF THEORY

2.1 High-Gain, Single-Pass Free-Electron Lasers

In a seeded high-gain, single-pass FEL, the seed laser is injected into an undulator in synchronization with a high-quality electron beam (low emittance and energy spread, high peak current, mostly uniform in the transverse and longitudinal planes). As the name suggests, the input seed laser is amplified by the coupling between the radiation and the transverse electron motion. The gain of the system depends upon the quality of the beams and undulator as well as the relative arrival time of the electron and laser beams. The 1D resonance condition for this FEL interaction is $\lambda_R = \lambda_U\left(1+K^2/2\right)/2\gamma^2$, where λ_R is the seed laser and output radiation wavelength, λ_U is the undulator period, γ is the relativistic factor for the electron beam, and K is the undulator parameter $K = 0.9377 B_U \lambda_U$ [T-cm], for the magnetic field B_U.

A seed laser is not necessary to create a high-gain, single-pass FEL, as the spontaneous radiation shot noise will also couple to the electron beam and begin microbunching. Saturation will be achieved if sufficient undulator periods are traversed. This phenomenon is known as self-amplified spontaneous emission (SASE). As SASE starts up from noise, the output is also noisy. In a MOPA arrangement, however, the output is more stable and can be fully longitudinally coherent.

2.2 Table-Top, Soft X-ray Lasers

Recently, the developments in table-top, soft x-ray lasers have proved a possible seed source for MOPA systems [5]. These table-top x-ray lasers use a variety of high temperature plasma media, with lasing wavelengths from 12 to 60 nm. One of the more versatile methods of generating such table-top x-ray lasers involves the combined use of a chirped pulse amplification (CPA) process [6] and the transient collisional excitation (TCE) scheme [7]. In TCE, a long, low-intensity laser pulse is used to generate a plasma on a target. Next, this plasma is heated briefly by an ultra-short, high-intensity laser pulse. Such heating causes a population inversion in neon- or nickel-like ions. Saturated laser output at a table-top scale from 33 nm down to 12 nm has been achieved with these systems [8,9].

2.3 Nonlinear Harmonic Generation

Harmonics of the fundamental are present in FELs. As saturation is approached, the bunching occurring at the fundamental due to the interaction of the radiation and electrons causes nonlinear growth of higher harmonics [1-4]. Due to the natural motion of the electron beam in a planar undulator system, however, odd harmonics are preferentially generated in the forward direction. The gain lengths of the harmonics vary in inverse proportion to the harmonic number. They also allow multiple-wavelength lasing in FEL systems employing planar undulator systems.

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A MOPA with a table-top, soft x-ray laser seed is useful because of its coherence properties, less noisy output (compared to a SASE design), and short wavelength. The nonlinear harmonic growth coupled with this type of amplifier would permit an even shorter wavelength source to be achieved with significant improvement in the coherence properties and reduced output noise as compared to a similar system (e-beam and undulators only) in a SASE mode of operation.

3 THE PROPOSED SYSTEM

The undulator in this system is identical to that of the undulators used in the Advanced Photon Source (APS) SASE FEL experiment at the Low-Energy Undulator Test Line (LEUTL) [10]. These undulator parameters are listed in Table 1.

Table 1: Undulator Parameters

Parameter	***Value***
On-axis undulator strength (kG)	10.6
Undulator period, λ_{UND} (cm)	3.3
K	3.1

The seed laser system to be employed in the simulation of this system is identical to the Ni-like Mo laser at 18.9 nm generated at Lawrence Livermore National Laboratory [8]. The 18.9-nm soft x-rays utilize a 1-cm-long target, and its maximum peak power is ~2.5 MW in 7 ps in the laser pulse over 1 mm^2 [8].

The electron beam energy is determined by the 1D resonance condition above for the given undulator and seed laser parameters. These parameters may be seen in Table 2.

Table 2: Electron Beam Parameters

Parameter	***Value***
Electron beam energy (E_{EB})	1149.8 MeV
Normalized emittance (ε_n)	3 π mm-mrad
Peak current (I_{PK})	500 A
Energy spread ($\Delta\gamma/\gamma$)	0.0005

4 SIMULATIONS

The simulations were performed using the 3D polychromatic FEL code MEDUSA that is based on a Gauss-Hermite mode expansion [3,4]. Since the constant is the seed laser wavelength, scans in energy were first performed about the 1D resonance condition for the fundamental. These scans reveal the optimal, 3D FEL resonance condition. The energy was then set to 1151.5 MeV according to the maximum output power. These scans of output power at 18.9 nm are shown as a function of distance along the undulator line in Figure 1.

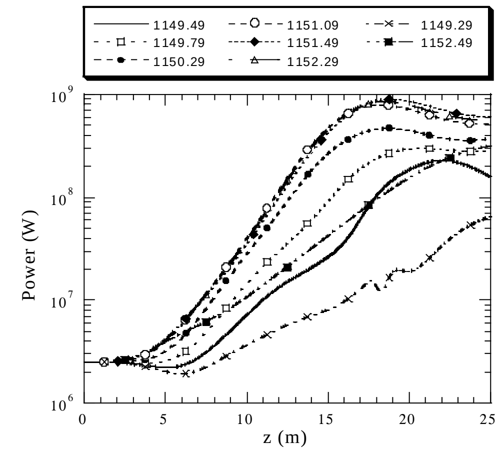

Figure 1: Power (W) versus distance, z (m), for the scans of the electron beam energy (MeV).

Next, eight higher harmonics were included in the simulations. In Figures 2 and 3 the output power is shown as a function of the distance of undulator traversed for the odd and even harmonics, respectively, both in comparison to the fundamental. In addition, Table 3 lists the power in each harmonic at its saturation point as well as the gain length. Figure 4 shows the inverse scaling characteristic of the nonlinear mechanism between harmonic number and gain length.

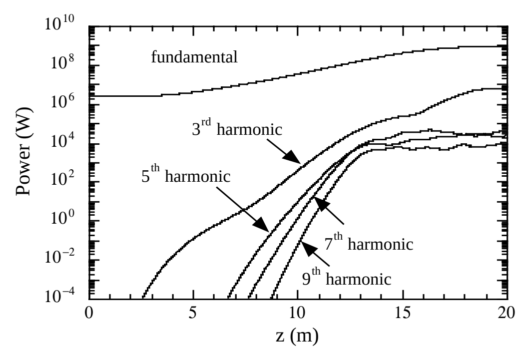

Figure 2: Output power (W) as a function of distance, z (m), along the undulator line for h = 1, 3, 5, 7, 9.

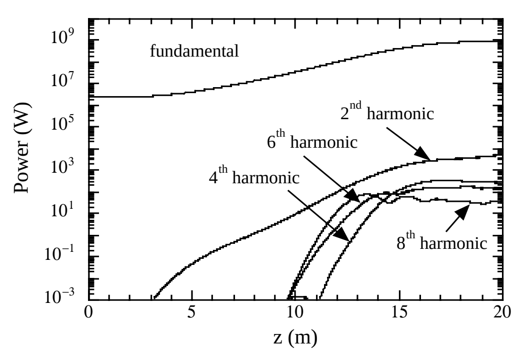

Figure 3: Output power (W) as a function of distance, z (m), along the undulator line for h = 1, 2, 4, 6, 8.

Table 3: Harmonic Output Powers

h	*λ (nm)*	*z (m)*	*Power*	L_G *(m)*
1	18.9	18.78	892 MW	2.15
2	9.45	18.62	3.82 kW	0.987
3	6.3	18.97	5.97 MW	0.649
4	4.725	18.63	292 W	0.464
5	3.78	15.07	0.120 MW	0.428
6	3.15	17.04	12.8 W	0.419
7	2.7	15.190	0.374 MW	0.312
8	2.3625	15.32	2.64W	0.302
9	2.1	16.21	6.18 kW	0.252

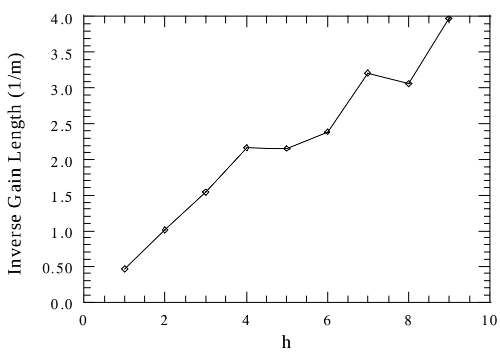

Figure 4: Inverse gain length versus harmonic number.

5 CONCLUSIONS

Using a 3D polychromatic FEL simulation code, a soft x-ray, high-gain, single-pass FEL amplifier was demonstrated with a 1151.5-MeV electron beam. In addition, the nonlinear harmonics were simulated to predict the amount of power expected in such a system in hopes of achieving a shorter wavelength, high-gain, single-pass FEL system that is less noisy and expresses the coherence of the seed laser in its output pulse. Currently, the repetition rate of such a table-top, soft x-ray laser is limited to once every four minutes. It is hoped that these systems will someday have higher repetition rates to accommodate those experimenters hoping for a higher average power. Finally, perhaps there will someday be a broader tunability of these system types.

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