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Abstract

We report numerical simulations (using the TDA code) and analytic verification of the generation of 64 Å high power soft X-rays from an exponential regime single pass seeded FEL. The seed is generated in the FEL using the High Gain Harmonic Generation (HGHG) technique combined with the 'Fresh bunch' technique. A seed pulse at 2944 Å is generated by conventional laser techniques. The seed pulse produces an intense energy modulation of the rear part of a 1 GeV, 1245 A electron beam in a 'modulator' wiggler. In the 'radiator' wiggler, (resonant to 64 Å), the energy modulation creates beam density modulation followed by radiation of the 46th harmonic of the seed. We use a magnetic delay to position the 64 Å radiation at the undisturbed front of the bunch to serve as a seed for a single pass, exponential growth FEL. After a 9 m long exponential section followed by a 7 m long tapered section the radiation power reaches 3.3 GW.

Introduction

In recent years there has been an enhanced interest in the generation of coherent, short pulse Free-Electron Laser (FEL) radiation [1,2,3]. Currently there are two possible paths to high-power, single-pass short-wavelength FELs: SASE and HGHG (High-Gain Harmonic-Generation,[4]). The HGHG technique seems to offer an order-of-magnitude better bandwidth, a signal free of noise, an improved wavelength stability and a shorter wiggler. In this paper we are extending the applicability of HGHG to a much shorter wavelength than has been previously discussed.

In HGHG, a seed laser is used to modulate the energy of an electron beam in a 'modulator' wiggler. The energy modulation is converted to spatial bunching in a dispersive section that follows the modulator. The bunched beam is introduced to a wiggler tuned to the desired harmonic of the seed. The radiation at the harmonic wavelength starts as a coherent spontaneous signal which quickly changes to exponential regime growth and, if the wiggler is long enough, tapering may follow.

To generate short wavelength we have to go to a high harmonic number. From a previous analysis [5], to have an efficient coherent harmonic generation, the ratio between the energy modulation by the seed and the energy spread of the electron beam needs to be comparable to the harmonic number. Therefore, for very high harmonics, the energy modulation becomes very large and this makes the exponential growth gain-length too large. More precisely, when the energy spread is larger than the Pierce parameter ρ, the growth rate is significantly reduced.

The solution to the modulation energy spread problem is to use the 'Fresh Bunch' technique [6]. In this technique we use a seed laser pulse that is shorter than half the electron beam bunch. The harmonic generation takes place at one part of the electron beam bunch, defined by the length of the seed laser pulse. Once the coherent harmonic generation process is over, the resulting radiation is shifted to the 'fresh' part of the electron bunch (the part that has not been modulated in energy by the seed laser). It is then a simple process of exponential amplification of a seeded radiation at the desired final wavelength.

The 'two wiggler' harmonic generation FEL was proposed by Boscolo and Stagno [7]. The theory was much improved by Schnitzer and Gover [8]. 1-D Numerical simulation of the coherent spontaneous harmonic radiation (with no gain) has been done for the 3rd harmonic [9] and the 50th harmonic [10]. The term 'High Gain Harmonic Generation (HGHG) [4] was coined to signify harmonic generation combined with high gain amplification.

In the following we will present the theory and simulations that we have done on the subject of high-power, high-harmonic generation.

The generation of high harmonics in HGHG

The layout for the HGHG FEL is shown schematically in Figure 1 as well as the relative position of the radiation and electrons before and after the Fresh Bunch shift.

A seed pulse, 100 fs long, with a peak power of 200 GW at 2944 Å is generated by conventional techniques from a titanium sapphire laser. The laser is focused with a Rayleigh range of 0.67 m and beam waist located at the center of the 0.51 m long 'Modulator' wiggler. The seed pulse produces an intense energy modulation with a maximum of $\Delta\gamma = 49$ of the electron beam in the Modulator wiggler. The modulator has a period of 7.5 cm, a magnetic field of 1.08 T and thus is resonant to 2944 Å. The electron bunch length is 300fs long and the seed laser modulates only the rear part of the electron bunch. In the 1.3 m long 'Radiator 1' wiggler, with the period of 2.73 cm and peak field of 0.497 T (resonant to 64 Å), the energy modulation creates beam density modulation followed by radiation of the 46th harmonic of the seed.

By the time the beam is over-bunched in the radiator, the 64Å radiation power has reached 1.2 MW. The rear part of the bunch develops a large energy spread due to this process that prevents it from supporting an exponential growth FEL. Therefore we use a magnetic delay (shifter in Fig. 1) to position the 64 Å radiation at the undisturbed front of the bunch. This is the essence of the Fresh Bunch technique.

Now this 64 Å radiation serves as a seed for a single pass, exponential growth FEL. The electrons and the 64 Å radiation are introduced into the 'Radiator 2' wiggler. This wiggler has the same period and initial field strength as Radiator 1. After a 9m long exponential section followed by a 7 m long tapered section (2.1 % taper) the radiation power reaches 3.3 GW. The gain in power from 1 MW to 3.3 GW requires 8 gain lengths. With the 2 gain lengths for the lethargy, the wiggler length should be 10 gain lengths. The gain length is calculated to be 1.36 m using an analytical 3-D calculation [8]. Thus the expected wiggler length should be 14 m, but the power is nearing saturation an extra 2 m were required with the tapering.

The radiator wiggler parameters are the same as in the TTF-FEL proposal. The electron beam parameters, 1 GeV, 1245 A, normalized emittance of 2mm mrad and energy spread of $5x10^{-4}$ rms, are also those of the TTF-FEL except that we use less bunching of the beam, to get a bunch twice as long with half the peak current and half the energy spread. We obtain the same power and the same pulse energy as the TTF-FEL proposal but with a much shorter wiggler length. In addition, the bandwidth of our radiation is about an order of magnitude smaller and its central wavelength will have the stability of the seed laser rather than depend on the beam energy stability. The choice of the TTF FEL set of parameters was taken as a matter of convenience, to provide a comparison with a well-researched SASE FEL design. This is not necessarily the best set of parameters for our HGHG approach and it is possible that by optimization of the electron beam and wiggler parameters an even better result may be obtained.

At this point we must explain the non-trivial process of determining the various parameters used in the above proposed FEL. The first principle has to do with the selection of the seed laser power and the length of the modulator wiggler. As we have mentioned above, the energy modulation $\Delta\gamma$, introduced by the modulator, should be larger than the initial effective (including the finite emittance effect) energy spread σ_γ^{eff} of the beam by the harmonic number N, which is 46 in this case.

This requirement can be understood intuitively from longitudinal phase-space considerations. The bunching parameter in a 1-D approximation is given by:

$$\frac{1}{2}a_n(z) \equiv \left\langle e^{-i\psi_j} \right\rangle = e^{-\frac{1}{2}\left(\frac{\sigma_\gamma^{eff}}{\Delta\gamma}\right)^2(\psi+n\Theta)^2} J_n(\psi + n\Theta)$$

This notation is adopted for consistency with [5]. ψ is the ponderomotive phase, $\psi_j = (k_W + k_s)z - \omega_s t_j$ where the subscript j refers to the j[th] electron and the subscript s refers to the signal. $k_W = \frac{2\pi}{\lambda_W}$, λ_W is the radiator period and z is the longitudinal position in Radiator 1. The dispersion as a function of *z* is given by:

$$\frac{d\psi}{d\gamma} = 2k_W \frac{\Delta\gamma}{\gamma} z$$

Θ is the phase advance in the modulator. The behavior of a n^{th} order Bessel function is such that it is nearly zero until the argument is approximately n, then it reaches a maximum and starts oscillating. This region, about the first maximum, is to be used for the harmonic generation.

If $\Delta\gamma < N\sigma_\gamma$, then there will be insufficient bunching due to the exponential factor in the bunching parameter. If $\Delta\gamma >> N\sigma_\gamma$, from the above expression for the bunching factor we know that the bunching will not increase beyond the first maximum of the Bessel function. The harmonic power P_n for a beam with a transverse parabolic beam profile in Radiator 1, is given in the 1-D approximation by:

$$P_n = \frac{1}{3} I_0^{\,2} Z_0 \frac{a_w^{\,2}[JJ]^2}{\gamma^2 A}\left(\frac{1}{2}\int_0^{z_1} a_n(z)dz\right)^2$$

where I_0 is the beam current, Z_0=377Ω, a_w is the rms wiggler parameter, *[JJ]* is the planar wiggler Bessel factor, and *A* is the area defined by the parabolic beam's edge. For $\Delta\gamma >> N\sigma_\gamma$, $a_n(z)$ will become oscillatory (due to the Bessel function) in a short distance, and the harmonic power will oscillate. Therefore we require $\Delta\gamma \sim N\sigma_\gamma$ and we set Z_1 to the first zero of the n[th] order Bessel function.

We have used a modified version of the code TDA [5]. A comparison of the bunching parameter from the simulation and the on-axis 1-D formula is shown in Figure 2 as a function of position *Z* in Radiator 1. The effective (including emittance effects) energy spread used in Figure 2 is $\sigma_\gamma^{\,eff} = 1.5$. Estimating the effective energy spread is not simple, since it is not constant across the radial cross-section of the beam. The betatron wavelength is much larger than the gain length, thus the electrons do not change appreciably their radial position in one gain length. The divergence spread vanishes for electrons at the peak of their betatron motion where $\sigma_\gamma^{eff} = \sigma_\gamma = 1.$, and is maximal at axis crossing, where $\sigma_\gamma^{eff} = 1.55$. On top of the angular spread we must consider detuning caused by the radial dependence of the wiggler field. If we estimate the effective energy spread across the whole transverse section, we get $\sigma_\gamma^{eff} = 1.7$. This is an overly pessimistic estimate because the bunching process is independent at different transverse positions. The bunching parameter from the analytical estimate is 20 % smaller than the simulation. This illustrates the approximate nature of the calculation.

Figure 3 shows the analytical calculation of the bunching integral $C_n \equiv \frac{1}{2}\int_0^{z_1} a_n(z)dz$ as a function of the modulation for $\sigma_\gamma^{eff} = 1.5$. The bunching integral peaks at a $\Delta\gamma \sim 65$. The seed laser power requirement is a steep function of the modulation. Therefore we choose a somewhat smaller modulation of $\Delta\gamma \sim 49$. The bunching coefficient C_n is 0.04 and this gives p_n=0.9 MW as compared with the simulation value of 1.2 MW.

Another important point is that we should produce a phase advance in the modulator Θ that is less than 1, since the Bessel function of the n^{th} order reaches its maximum at about n.

In the modulator, the phase advance Θ of the maximal modulation particle over a distance z_0 is given approximately by:

$\Theta = k_{W0} z_0 \frac{\Delta\gamma}{\gamma}$ where $k_{W0} = \frac{2\pi}{\lambda_{W0}}$. For a particular $\Delta\gamma$ and a given modulator length z_0 the laser intensity is determined by:

$$\Delta\gamma = \frac{1}{\gamma} k_{s0} a_{W0} [JJ] \bar{a}_{s0} z_0$$

where $k_{s0} = \frac{2\pi}{\lambda_{s0}}$, λ_{s0} is the seed laser wavelength, $\bar{a}_{s0}$ is the dimension-less vector potential of the input laser beam averaged over the wiggler length and a_{W0} is the rms wiggler parameter in the modulator. The most effective use of Radiator 1 requires $\Theta \sim 1$. This determines z_0 as well as the laser intensity.

The convergence of the simulation code for harmonic power was checked. As seen from Figure 4, it approaches the limit predicted by the above analytical estimates at about $5\text{x}10^5$ particles. These two tests, combined, give us confidence about the validity of the calculation.

The reasonable agreement between the 1-D theory and the simulation is due to two factors. The very short wavelength of the harmonic radiation results a long Rayleigh range and the long betatron wavelength results a negligible transverse motion in Radiator 1.

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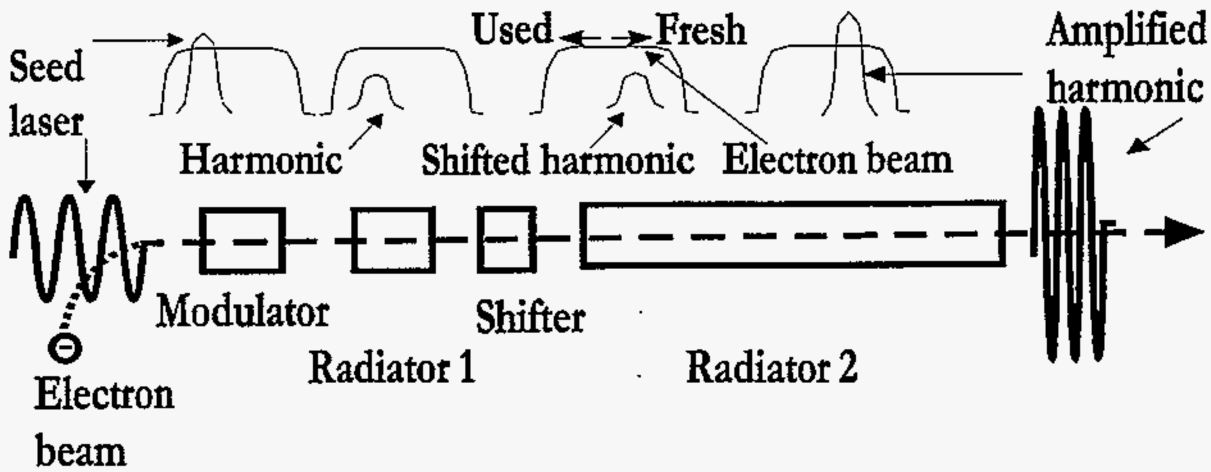
Figure captions

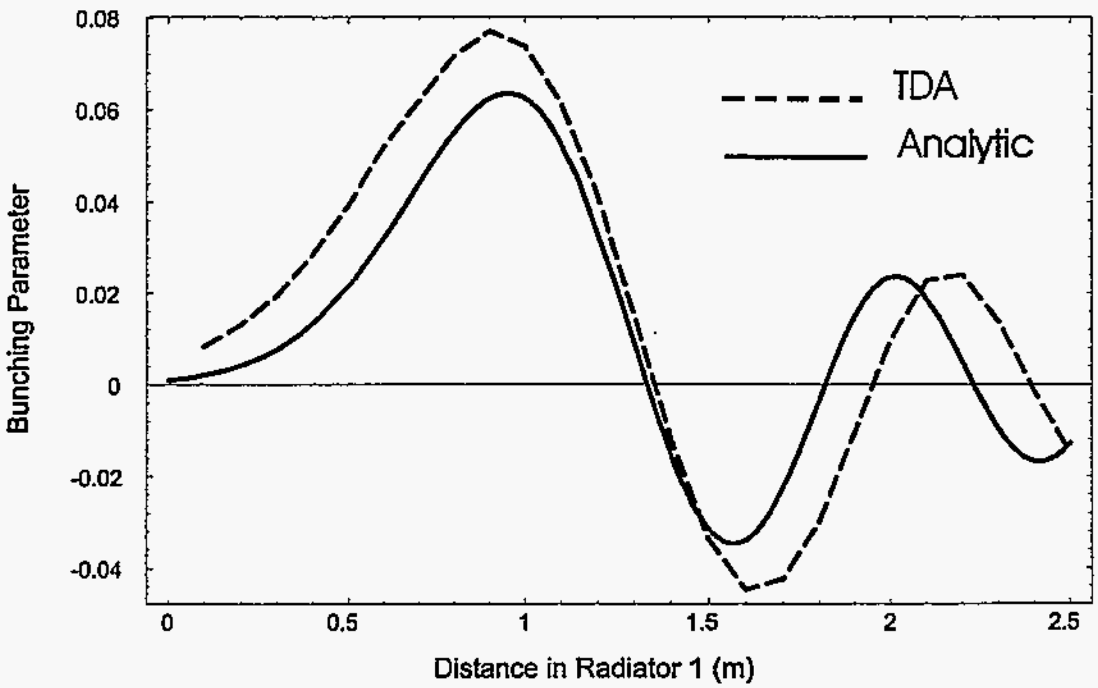
1. Schematic diagram of a High-Gain Harmonic-Generation with a Fresh-Bunch shifter for the generation of soft X-rays. The position of the seed and harmonic relative to the electron bunch are shown above the relevant wiggler sections.

2. The on-axis bunching-parameter as a function of position in Radiator 1. The effective energy spread, σ_γ^{eff} is taken as 1.5, the dashed curve is for the TDA numerical simulation and the continuos curve represents the analytic approximation.

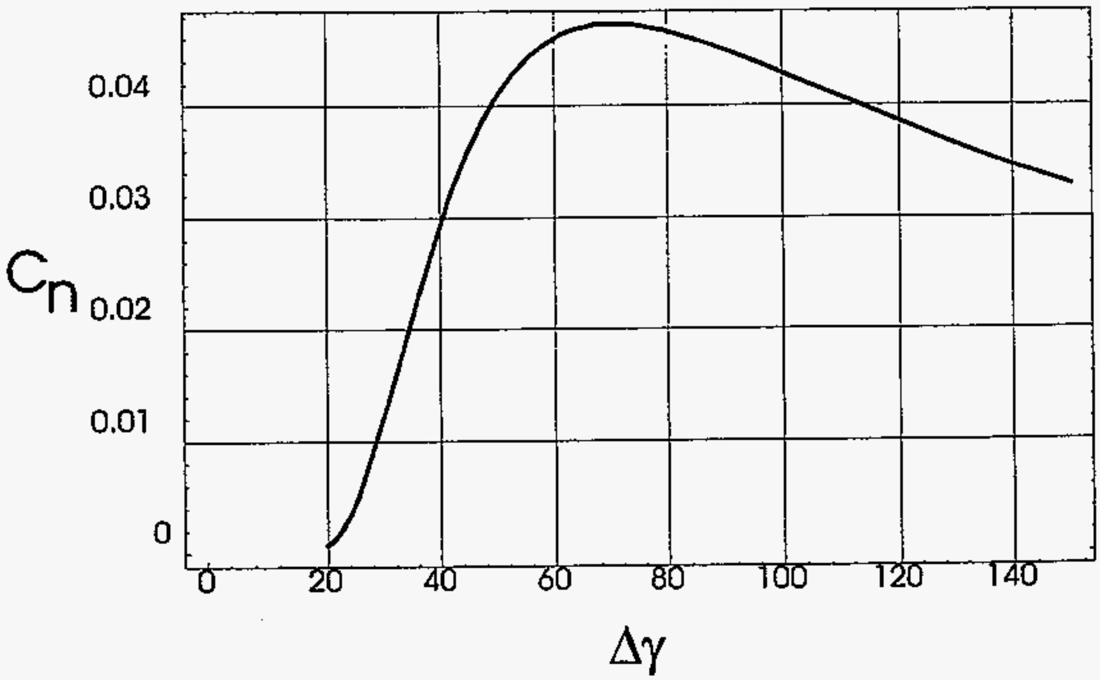
3. The coherent harmonic integral C_n as a function of the modulation $\Delta\gamma$.

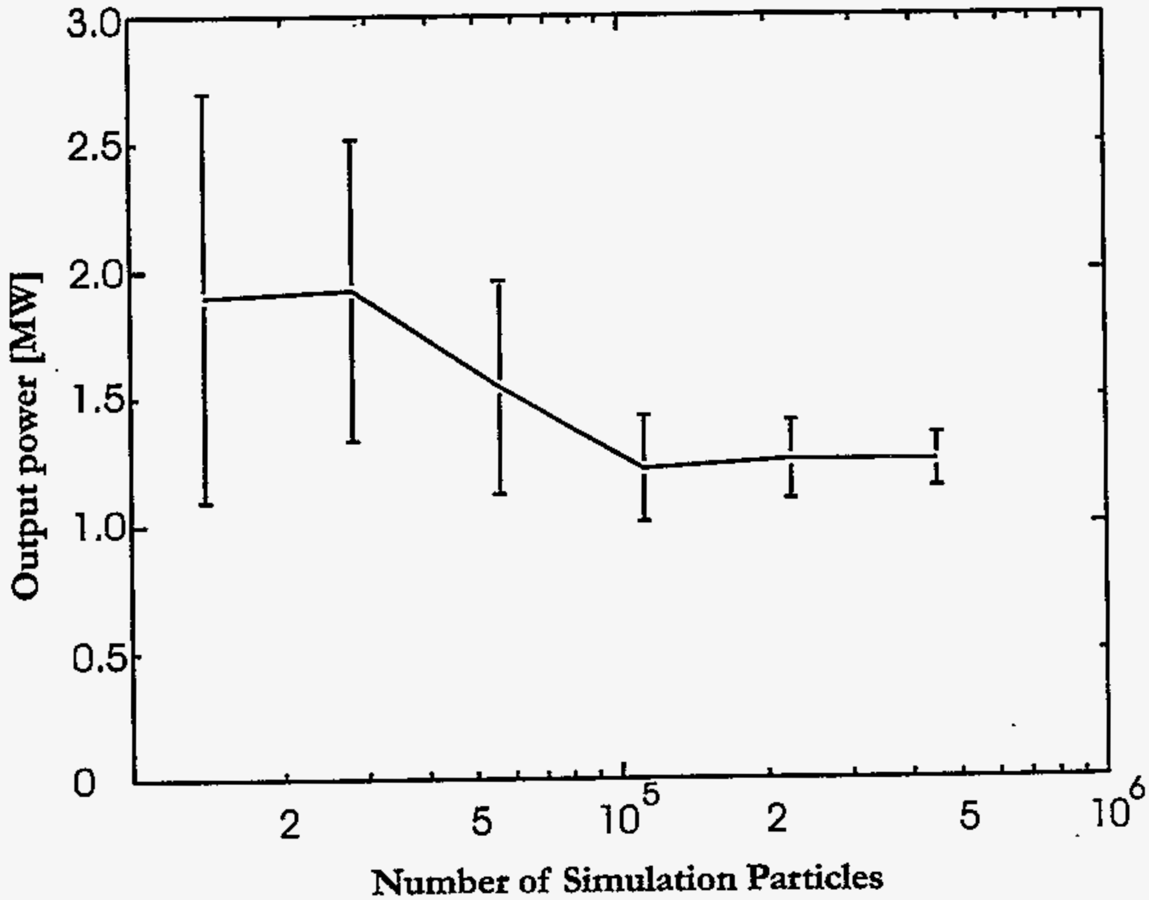
4. Convergence test: The output power as a function of the number of simulation particles in the numerical code TDA.


Seed
laser
Used
Fresh
Amplified
harmonic
Harmonic
Shifted harmonic
Electron beam
Modulator
Shifter
Radiator 1
Radiator 2
Electron
beam



0.08
0.06
0.04
0.02
0
-0.02
-0.04
Bunching Parameter
TDA
Analytic
0
0.5
1
1.5
2
2.5
Distance in Radiator 1 (m)


0.04
0.03
C_n
0.02
0.01
0
0
20
40
60
80
100
120
140
$\Delta\gamma$



3.0
2.5
2.0
1.5
1.0
0.5
0
Output power [MW]
2
5
10^5
2
5
10^6
Number of Simulation Particles