COHERENT SOFT X-RAY GENERATION IN THE WATER WINDOW WITH THE EEHG SCHEME*

D. Xiang† and G. Stupakov, SLAC, Menlo Park, CA 94025 USA

Abstract

Recently a scheme entitled echo-enabled harmonic generation (EEHG) was proposed for producing short wavelength FEL radiation that allows far higher harmonic numbers to be accessed as compared with the normal limit arising from incoherent energy spread. In this paper we study the feasibility of a single EEHG stage to generate coherent radiation in the "water window" (2- 4 nm wavelength) directly from a UV seed laser at 190-nm wavelength. We present time-dependent simulation results which demonstrate that the single-stage EEHG FEL can generate high power soft x-ray radiation in the water window with narrow bandwidth close to Fourier transform limit directly from a UV seed laser. The schemes to generate short x-ray pulse from femtosecond to attosecond using EEHG FEL are also discussed.

INTRODUCTION

A new method entitled echo-enabled harmonic generation (EEHG) was recently proposed for generation of high harmonics using the beam echo effect [1, 2]. In the EEHG FEL, the beam is energy modulated in the first modulator and then sent through a dispersion section with strong dispersion strength after which the modulation obtained in the first modulator is macroscopically smeared while simultaneously complicated fine structures (separated energy bands) are introduced into the phase space of the beam. A second laser is used to further modulate the beam energy in the second modulator. After passing through the second dispersion section, the separated energy bands will be converted to separated current bands and the echo signal then occurs as a recoherence effect caused by the mixing of the correlations between the modulation in the second modulator and the fine structures.

Compared to the classic HGHG scheme [3] where the bunching factor exponentially decays as the harmonic number increases, the EEHG scheme has a remarkable up-frequency conversion efficiency that the bunching factor for the nth harmonic scales as $n^{-1/3}$ which is a slow decaying function of the harmonic number. This unique feature allows one to generate in the beam a high-harmonic density modulation with a relatively small energy modulation. In addition, the EEHG scheme also offers a possibility to adjust the x-ray pulse duration by simply adjusting the overlapping region of the two lasers. It is more flexible in providing variable pulse length to meet the demand of various users, compared to the classic HGHG FEL where the output pulse duration is determined by that of the seed laser.

In this paper, we present detailed study for the EEHG FEL working at the 50th harmonic. Using the particle distribution obtained in a start-to-end simulation, we demonstrate that the single-stage EEHG FEL can generate high power soft x-ray radiation in the water window with narrow bandwidth close to the Fourier transform limit directly from a UV seed laser. In our study we used beam parameters based on the high repetition rate soft x-ray FEL under design in LBNL [4] which are summarized in Table 1.

Table 1: Main Beam Parameters

Electron beam energy	2.411 GeV
Peak current	1 kA
Normalized emittance	0.7 mm mrad
Slice energy spread	95 keV
Modulator period length	20 cm
Seed laser peak power	110 MW
Radiator period length	4 cm

CHOICE OF ENERGY MODULATION AMPLITUDES

Using Ming Xie's formulae [5], the power gain length for $\lambda_r = 3.8$ nm is calculated and shown in Fig. 1 for various slice energy spread at the entrance of the radiator.

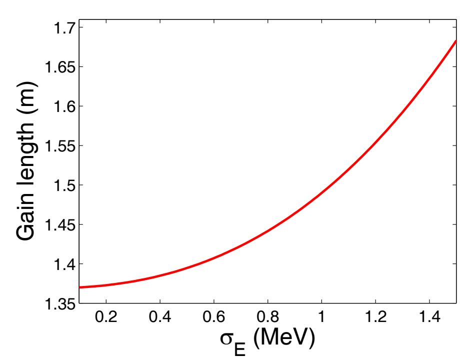

Figure 1: Gain length of the 3.8 nm radiation for various slice energy spread.

In order to limit the dispersion strength to a moderate value to mitigate the incoherent synchrotron radiation (ISR) effect [2] while not degrading the FEL performance, we choose $A_1 = \Delta E_1/\sigma_E = 3$, $A_2 = \Delta E_2/\sigma_E = 6$,

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† dxiang@slac.stanford.edu

where ΔE_1 and ΔE_2 are the energy modulation amplitudes in the first and the second modulator, and σ_E is the slice energy spread of the beam. A more thorough discussion of how to choose suitable energy modulation amplitudes is given in Ref. [6]. The corresponding dimensionless dispersion strengths that maximize the 50th harmonic of the 190 nm seed laser are $B_1 = 8.469$ and $B_2 = 0.180$.

STEADY-STATE SIMULATION

The simulation is performed with GENESIS 2.0 [7] and consisted of 3 separate runs: one run for the first modulator; another for the first dispersion section and the second modulator; and a third run for the frequency up-conversion and the radiator. During the simulation, the dispersion strength and power of the seed laser were finely tuned to maximize the bunching factor for the 50th harmonic at the entrance to the radiator. The longitudinal phase space at the entrance to the radiator obtained from GENESIS simulation is shown in Fig. 2.

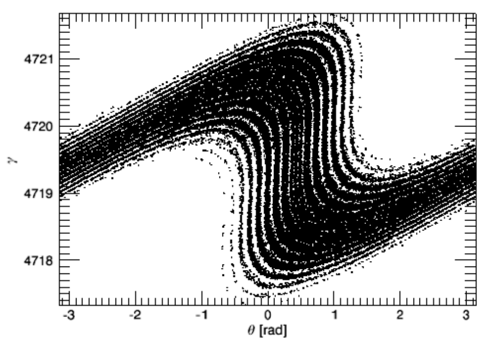

Figure 2: Longitudinal phase space at the entrance to the radiator. θ in x-axis scales with the seed laser wavelength.

The evolution of the bunching factor and radiation power in the radiator are shown in Fig. 3. The significant enhancement of the performance using the EEHG scheme is clearly seen in Fig. 3b where the peak power of the 50th harmonic radiation exceeds 4.4 GW and it saturates after 7 undulator sections with the length of each 2.4 m. The large bunching factor at the entrance to the radiator offered by the EEHG scheme is responsible for the initial steep quadratic growth of the power.

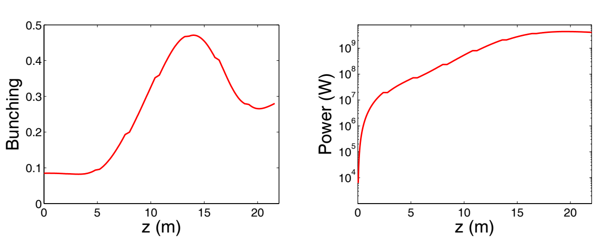

Figure 3: (a) Bunching factor vs radiator distance for the 3.8 nm radiation; (b) Power vs radiator distance for the 3.8 nm radiation.

TIME-DEPENDENT SIMULATION

Properties of the Electron Beam

The particle distribution used in GENESIS simulation was obtained from IMPACT-Z simulation [8] using 1 billion particles [9,10]. The current distribution and the slice energy spread of the beam are shown in Fig. 4a and Fig. 4b [10]. Due to the microbunching instability, there is a residual energy modulation with the modulation period 15 μm and the modulation amplitude of a few keV.

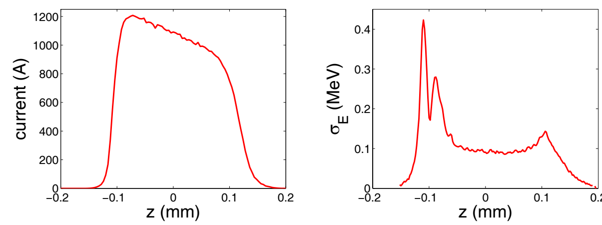

Figure 4: (a) Beam current distribution; (b) Slice energy spread. (bunch head at left)

Applicability of the Current FEL Code in Simulating EEHG FEL

The present FEL codes (e.g. GENESIS, GINGER [11], etc) all assume that the slices do not mix. This is well justified for the classic HGHG FEL where the dispersion strength of the chicane is small. But for the EEHG FEL, the slices within $(A_1 B_1/\pi)\lambda_l$ will mix after passing through the first dispersion section, where λ_l is the wavelength of the seed laser. For a steady-state simulation, the mixing does not affect the simulation results. However, for the time-dependent simulation, a dramatic variation of the beam properties within $(A_1 B_1/\pi)\lambda$ introduces a large error into simulations. In our simulation $(A_1 B_1/\pi)\lambda \approx 1.5$ μm, as one may see from above, the variation of beam properties within this scale is negligible. Progress has been made in GINGER which allows one to redivide the slices after passing through the first dispersion section [12]. Here we still use GENESIS to do the time-dependent simulations for the EEHG FEL.

Simulation Results

In order to provide sufficient overlap between the seed laser and the electron beam, the duration of the flat part of the electron beam should be longer than the full length of the seed laser plus at least 2 times the rms timing jitter. As can be seen in Fig. 4a, the beam has a flat part of about 400 fs. Assuming the rms timing jitter to be ~100 fs, we used a Gaussian laser with 30 fs (rms) duration and a peak power of about 100 MW. In the simulation we simulated 7700 slices with a separation of 7.6 nm. Each slice contains 104448 macro-particles and it takes about 8 days to finish one simulation in a PC. The output power profiles and spectrums corresponding to 3 different seed positions along the bunch obtained through time-dependent simulation using GENESIS code are shown in Fig. 5. The output pulse length is about 12 fs (rms) and the relative spectral bandwidth is 2.7×10^{-4}, about 1.3 times larger than the Fourier transform limit. The spectrum broadening is probably caused by the fluctuations of the current and the residual energy modulation of the beam.

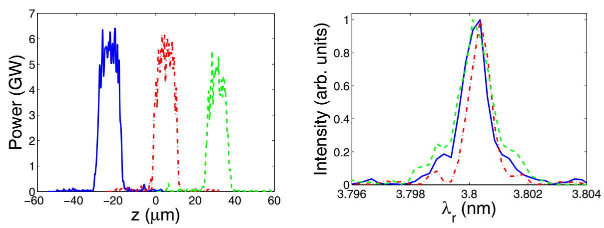

Figure 5: (a) Power profiles corresponding to different seed positions along the bunch; (b) Corresponding spectrum profiles.

A remarkable progress is being made lately to achieve a jitter of about 10 fs with the superconducting linac [13]. For this case we may use a Gaussian laser with 80 fs duration as the seed laser. The power profile of the output pulse is shown in Fig. 6a and the corresponding spectrum is shown in Fig. 6b. The rms pulse length is about 30 fs and the relative bandwidth is about 9.5×10^{-5}, very close to the Fourier transform limit.

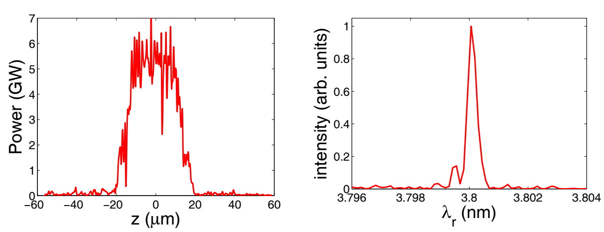

Figure 6: (a) Power profile for a long seed laser; (b) Corresponding spectrum profile.

GENERATION OF FEMTOSECOND TO ATTOSECOND PULSES

To generate a sub-10 fs pulse, the laser may need to be shaped into a flat-top distribution. The duration of the output pulse can be varied by simply adjusting the overlapping region of the two lasers, as illustrated in Fig. 7. Mixing of slices after the first dispersion section limits the shortest pulse length to about $(A_1B_1/\pi)\lambda_l$, which is about 5 fs in our example.

To generate attosecond x-ray pulse, one may use a few-cycle intense laser to interact with the beam and select a short slice to lase. As shown in [14], when combining the EEHG with the bunch compression, with the assistance of

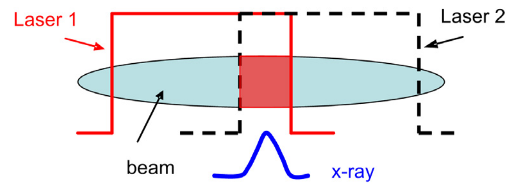

Figure 7: Scheme to provide variable pulse length by adjusting the overlapping region of the two lasers.

a few-cycle intense laser, one can generate a 20 as x-ray pulse at 1 nm directly from a 200 nm UV seed laser.

CONCLUSIONS

We have studied the feasibility of a single EEHG stage to generate coherent radiation in the "water window" directly from a UV seed laser at 190-nm wavelength. Our time-dependent simulation results implies that the single-stage EEHG FEL is able to generate high power soft x-ray radiation with narrow bandwidth close to Fourier transform limit directly from a UV seed laser.

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