ECHO-SEEDING OPTIONS FOR LCLS-II*

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Abstract

The success of LCLS has opened up a new era of x-ray sciences. An upgrade to LCLS is currently being planned to enhance its capabilities. In this paper we study the feasibility of using the echo-enabled harmonic generation (EEHG) technique to generate narrow bandwidth soft x-ray radiation in the proposed LCLS-II soft x-ray beam line. We focus on the conceptual design, the technical implementation and the expected performances of the echo-seeding scheme. We will also show how the echo-seeding scheme allows one to generate two color x-ray pulses with the higher energy photons leading the lower energy ones as is favored in the x-ray pump-probe experiments.

INTRODUCTION

LCLS, the world's first hard x-ray FEL, has achieved saturation [1] and is now delivering unprecedented powerful x-rays that marks the beginning of a new era of x-ray sciences. An upgrade to LCLS (LCLS-II [2]) is currently being planned to enhance its capabilities and capacities. Specifically, the self-seeding and the echo-seeding techniques are considered to improve the temporal coherence of the x-rays. The self-seeding techniques for soft x-rays and hard x-rays for LCLS-II are discussed in [3, 4]. Here we focus on the implementation of the echo-enabled harmonic generation (EEHG) scheme [5, 6] to generate fully coherent soft x-rays for LCLS-II.

In the EEHG FEL, the beam is energy modulated in the first modulator and then sent through a dispersion section with strong dispersion after which 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 at higher harmonic then occurs as a recoherence effect.

Compared to the classic HGHG scheme [7] 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 has stimulated growing interest in using EEHG to achieve fully coherent radiation in the x-ray wavelength from UV seed lasers within a single stage [8–10]. While significantly relaxing the requirements on laser power and beam slice energy spread as compared to the HGHG scheme, EEHG requires more challenging control of the beam dynamics as the beam goes through the undulators and chicanes, because it involves a long-term memory of the beam phase space correlations. Recent proof-of-principle EEHG experiment at SLAC [11] with a relatively large emittance beam has demonstrated the basic physics behind this technique and indicates that we do can control the beam dynamics to preserve the correlations.

In this paper, we present detailed study for applying the EEHG technique to LCLS-II to generate narrow bandwidth soft x-ray radiation in the proposed soft x-ray beam line. We focus on the conceptual design, the technical implementation and the expected performances of the echo-seeding scheme. We will also show how the echo-seeding scheme allows one to generate two color x-ray pulses with the higher energy photons leading the lower energy ones, which is highly favorable for pump-probe applications.

DESIGN CONSIDERATIONS

Two new soft x-ray radiation beam lines (SXR1 and SXR2 with a chicane in between) are proposed for LCLS-II. The two new lines together with the chicane are able to provide the users with two-color x-rays with variable delay. The chicane also allows the so-called self-seeding technique to be implemented, in which the SASE FEL output in SXR1 is purified with a monochromator and is further amplified to saturation in SXR2 [3]. The EEHG is also considered for LCLS-II, because it provides a natural synchronization for the laser and x-rays. Various options for LCLS-II can be found in [2]. In this paper we limit ourselves in applying EEHG to SXR1 and SXR2 to enhance the LCLS-II capabilities in delivering narrow bandwidth and two-color x-rays.

The tentative baseline design for echo-seeding at LCLS-II is to generate fully coherent radiation at about 6 nm. We will show that the radiation wavelength can be easily varied from 3 nm to 6 nm, and extension to 1 nm is also feasible. While the electron beam energy for the soft x-ray beam line may be varied from 3.5 GeV to 7 GeV, we assume the beam energy is 4.3 GeV in our studies. The main parameters for the nominal 6 nm case are listed in Table. 1. The energy modulation amplitudes in the first (M1) and second modulator (M2) are both 1.4 MeV which is two times larger than beam slice energy spread. The modulators have a relatively long period length of 35 cm to reduce the undulator K value, thus allowing the mitigation of the quantum diffusion effects [12]. The modulator length is much shorter than the FEL gain length so the interaction between the electron beam and the radiation gen-

* Work supported by US DOE contracts DE-AC02-76SF00515.

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Table 1: Main Beam Parameters for the Nominal Echo-seeding at 6 nm

Beam energy	4.3 GeV
Peak current	800 A
Normalized slice emittance	0.6 mm mrad
Slice energy spread at linac exit	700 keV
$N_p \times \lambda_u$ for M1	8 ×35 cm
$N_p \times \lambda_u$ for M2	8 ×35 cm
Seed laser wavelength	202 nm
Seed laser peak power for M1 and M2	300 MW
Seed laser pulse length for M1 and M2	100 fs
Seed laser energy for M1 and M2	75 uJ
Energy modulation in M1 and M2	1.40 MeV
$R_{56}^{(1)}$	3.58 mm
$R_{56}^{(2)}$	109 μm
Slice energy spread at radiator entrance	1.6 MeV
Gain length for 6 nm radiation	1.6 m

erated from the modulated beam is negligible. The laser wavelength is assumed to be 202 nm which is quadrupled from a Ti:Sapphire laser to mitigate the strong absorption in crystals when laser wavelength is below 200 nm [13]. Assuming the laser rms duration is 100 fs, laser energy of about 75 uJ is needed in order to provide the required modulation amplitude. At such energy, the laser system may work reliably at 360 Hz, satisfying the user's requirements at the highest repetition rate. The final slice energy spread of the beam in the radiator is about 1.6 MeV to allow a relatively short gain length at short wavelength.

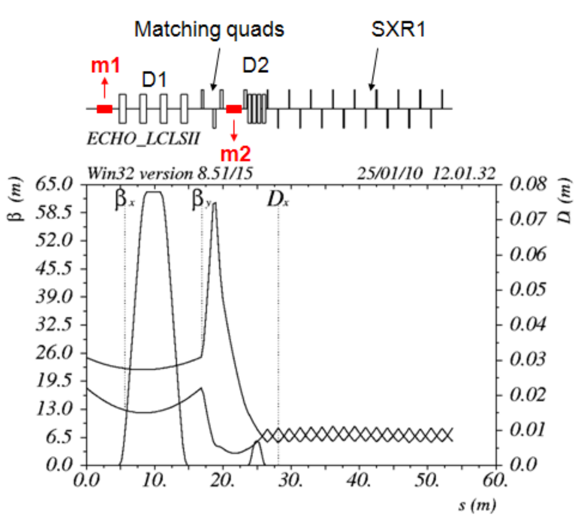

Figure 1: Lattice of the echo-seeding beam line

The lattice for the echo-seeding beam line is shown in Fig. 1. One of the concerns in designing the lattice is where to put the matching quadrupoles which are necessary to match the beam to the small beta function lattice in the radiator. Typically in the matching region, the beta function varies a lot and the path length difference from second order transport effects can result in considerable smearing to the fine structures. Considering the fact that the fine structures are on the order of laser wavelength before M2 and they become on the order of the harmonic radiation wavelength after it, the matching quadrupoles are put upstream of the second modulator M2. The average beta function in the modulators is about 15 m and that in the radiator SXR1 is 7 m. The laser sizes are 5 times larger than electron beam in the modulators to provide uniform modulation in the transverse direction. Weak dipoles with lengths of 1 m and the bending angles of 1.48 degrees are used in chicane D1 to mitigate the quantum diffusion from incoherent synchrotron radiation.

TIME-DEPENDENT SIMULATION

Full 3-D simulations are performed to confirm the excellent performances of the echo-seeding scheme for LCLS-II. The FEL simulation is performed with GENESIS code [14] which uses the particle files obtained in a start-to-end simulation using ELEGANT code [15]. The electron beam is optimized to have a flat-flat distribution (flat in both current and energy) in the central part by properly choosing the rf phases in the linac. The laser heater [16] is set to increase the slice energy spread of the beam to about 25 keV to suppress the microbunching instability. The peak current for the central part of the beam is about 800 A after the second bunch compressor and the corresponding slice energy spread is about 700 keV. The beam distributions are shown in Fig. 2.

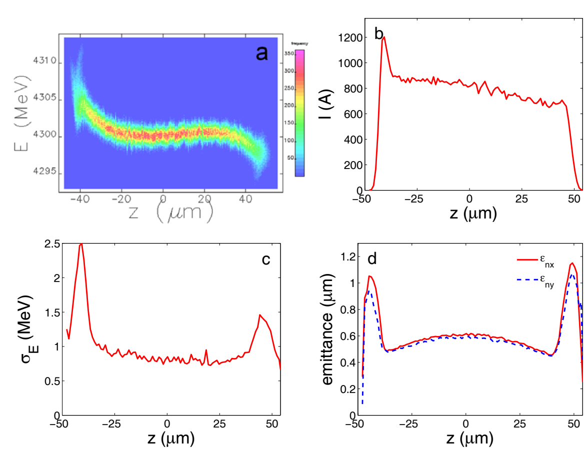

Figure 2: Beam distribution at the entrance to M1 (bunch head to the right). (a) Longitudinal phase space; (b) Beam current distribution; (c) Beam slice energy spread; (d) Normalized beam emittance

Seeding for 6 nm

Time-independent simulations are first performed to find the suitable settings for the laser power and chicane strength that yields high bunching factor at the exit of D2.

With the parameters shown in Table. 1, the bunching factor for the 34th harmonic of the seed laser ($\lambda = 5.94$ nm) is about 8% at the entrance to the SXR1. The large bunching factor allows the quick increase of the power of the coherent radiation to ~ 10 MW after one gain length and the radiation is further amplified to saturation after about 10 gain length. The radiation power and spectrum for the echo-seeded case with a 100 fs rms laser after 16 m in SXR1 are shown in Fig. 3. For convenience of comparison, the results of SASE radiation after 35 m in SXR1 is also shown in Fig. 3. Note SASE has a slow start-up, thus it needs about twice the undulator to reach saturation.

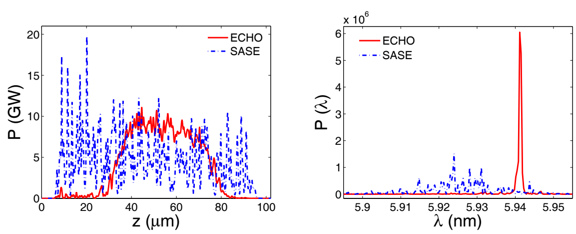

Figure 3: Performances of the echo-seeding scheme at 5.94 nm. (left) Radiation power profile; (right) Radiation spectrum.

The bandwidth of the radiation spectrum with echo-seeding scheme is $\Delta\lambda_{FWHM}/\lambda = 1.2 \times 10^{-4}$, which is about 40 times narrower than the SASE spectrum.

Statistic Performances at 6 nm

The initial seeds of the shot noise are varied in GENESIS simulation to reveal the statistic performances of echo-seeding scheme. The radiation power and spectrum for 3 different seeds are shown in Fig. 4. As compared to the SASE scheme where the radiation power and spectrum have large statistic fluctuation, the radiation power and spectrum from echo-seeding scheme are very stable. The stable operation of such an echo-seeded FEL is achieved because the large bunching factor yields sufficient coherent power to suppress the shot noise. Estimation shows that the coherent radiation power at 6 nm reaches about 10 MW after one gain length, which is much larger than the shot noise power (~ 400 W). Therefore, changing the initial seeds for the shot noise has little effect on the FEL performances.

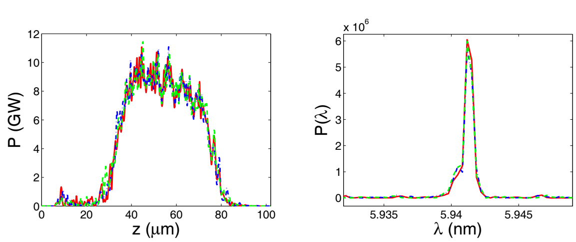

Figure 4: Performances of the echo-seeding scheme at 5.94 nm for various shot noise seeds in the simulation. (left) Radiation power; (right) Radiation spectrum.

Seeding for 3 nm

EEHG theory implies that when the chicanes are optimized to provide a large bunching factor for the nth harmonic, one also gets considerable bunching at the $2n$th and $3n$th harmonic. With the same set up for the chicanes, analysis shows that the bunching factor at the 68th harmonic of the seed laser can be as high as 3%, large enough to suppress the shot noise. Another simulation is performed in which the K value of the SXR1 undulator is changed to make it resonant at $\lambda = 2.97$ nm, and the results are shown in Fig. 5.

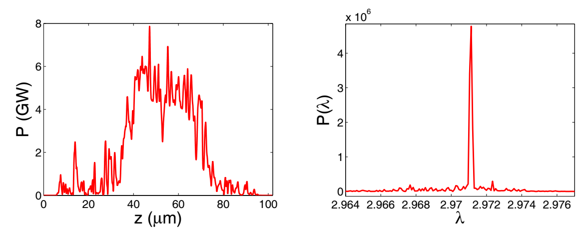

Figure 5: Performances of the echo-seeding scheme at 2.97 nm. (left) Radiation power profile; (right) Radiation spectrum.

In Fig. 5 the radiation power profile is taken at $z = 22$ m in SXR1 undulator. Since the gain length at shorter wavelength is longer, it takes more undulator sections to reach saturation. The peak power is about 6 GW and the bandwidth of the radiation spectrum is about $\Delta\lambda_{FWHM}/\lambda = 6 \times 10^{-5}$.

Extension to 1 nm and Below

To generate radiation at 1 nm or below using a UV seed laser in a single stage with EEHG technique may be technically challenging. Alternatively, one may use some simple configurations to extend the wavelength to 1 nm. Specifically, the so-called frequency doubler&tripler [17] scheme may be used together with the echo-seeding technique to extend the radiation wavelength to 1 nm and below. For instance, one can first pre-bunch the beam at 3 nm with the EEHG technique and send the beam to SXR1. One then extracts out the beam at some position well before the FEL reaches saturation where the beam gets effective energy modulation comparable to the slice energy spread from the coherent radiation generated in SXR1. A small chicane can then be used to convert the energy modulation into density modulation and one gets considerable bunching at the 2nd and 3rd harmonic of the coherent radiation. The undulators downstream can be tuned to the harmonic frequency to amplify the radiation further to saturation.

Noise Amplification in Seeding

It is well known that the shot noise is amplified in the process of HGHG seeding [18]. A 1D theory of the noise amplification in EEHG seeding is recently developed in

Ref. [19]. Our preliminary estimates of the noise amplification for the LCLS-II EEHG shows that the noise remains tolerable. We plan further studies of the noise amplification in the future.

GENERATION OF TWO COLOR X-RAYS

The proposed two soft x-ray radiation beam lines, SXR1 and SXR2, together with a chicane in between in LCLS-II allows the generation of two-color x-rays with variable delay. In the simplest case the beam is first used to generate FEL radiation at a wavelength λ_1 in SXR1, and after the time delay in the chicane, the beam will go through SXR2 to generate FEL radiation at a wavelength λ_2. The radiation with the wavelength λ_1 is ahead of that with wavelength λ_2 in time by about $R_{56}/2c$, where R_{56} is the momentum compaction of the chicane and c is the speed of light. It should be pointed out that after the FEL interaction in SXR1 the beam energy spread is significantly increased. The spoiled beam is difficult to drive a FEL at shorter wavelength to saturation in SXR2, but may be good for a longer wavelength radiation. Therefore, typically we have $\lambda_1 < \lambda_2$, which means the higher energy photons are leading the lower energy ones. However, for X-ray pump X-ray probe experiments, more favorable case is the other way around.

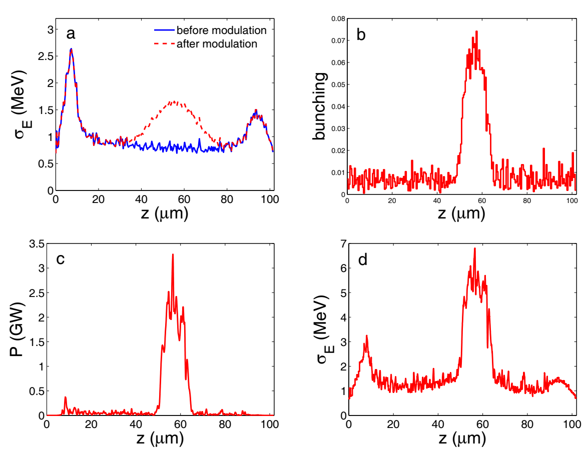

Figure 6: Beam distribution with a short-pulse seed laser. (a) Energy spread before and after modulation; (b) Bunching factor at 6 nm; (c) Radiation power at 12 m in SXR1; (d) Energy spread at 12 m in SXR1

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Here we show that the echo-seeding technique offers a simple solution to achieve this. The trick here is to use a short pulse laser to seed the FEL. Figure 6a shows the beam energy spread before and after the interaction with a short-pulse laser where one can see only part of the beam is modulated by the lasers. Accordingly, after passing through D2, only part of the bunch that gets sufficient modulation is effectively pre-bunched, as can be seen in Fig. 6b. Pre-bunching the beam speeds up the lasing process, so that after about 12 m in SXR1, GW radiation is generated from the pre-bunched beam while other part of the beam is still in the early stage of the exponential growth regime where the beam is almost 'unspoiled'. Terminating the FEL interaction here and further sending the beam through SXR2 will allow the generation of shorter wavelength radiation from the 'unspoiled' beam. This scheme allows the generation of two-color x-rays with the lower energy photons leading the higher energy ones.

ACKNOWLEDGEMENTS

We thank Y. Ding for providing the particle file used in our simulations, and Y. Ding, P. Emma, Z. Huang, W. White, and J. Wu for helpful discussions.

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