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SELF-SEEDING SCHEME FOR LCLS-II-HE*

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Abstract

Self-seeding is a reliable approach to generate fully coherent FEL pulses. Hard X-ray self-seeding can be realized by using a single crystal in Bragg transmission geometry. However, for a high repetition rate machine, the heat load on the crystal may become an issue. In this paper, we will study the facility performance of LCLS-II-HE by numerical simulations, and discuss the heat load and optimal undulator baseline configuration of LCLS-II-HE self-seeding scheme, and study the emittance tolerance of the LCLS-II-HE.

INTRODUCTION

The Linac Coherent Light Source (LCLS), the world's first hard X-ray Free Electron Laser(FEL), has been successfully operated both in Self-Amplified Spontaneous Emission (SASE) mode [1] and self-seeding mode [2]. The SASE FELs are characterized by fully transverse coherence, but only have limited temporal coherence because of starting from shot noise. Self-seeding scheme is proposed to reduce the bandwidth of SASE FELs [3]. In the soft X-ray regime, a grating monochromator is adopted [3]. In the hard X-ray regime, a single crystal monochromator is applied [4].

A self-seeding FEL can be simply divided into three parts. The first part is the SASE gain process, in which the electron beam goes through the first undulator part and generates the SASE. The second part is the monochromator and electron beam by-pass chicane. The SASE pulse from the first part goes through the monochromator and generates monochromatic seed, while the electron beam is sent through the by-pass chicane which can wash out the micro-bunching and adjust the delay between the monochromatic seed and electron beam. The third part is the FEL amplifier. The monochromatic seed is overlapped with the electron beam and is amplified in the second undulator part so that we can get a narrow-band output pulse.

However, the heat load on the crystal may lead us into trouble when the FEL is operated in a high repetition rate. Therefore, it is very important to figure out the damage mechanism. One is the non-thermal caused damage. For diamond crystal, the graphitization temperature is 1400 K, corresponding to an atomic dose of 0.213 eV/atom [5]. Another one is thermal caused damage. For this case, the instantaneous dose is lower than the graphitization threshold, but part of the pulse energy deposit in the crystal. The thermal damage may happen when the pulse repetition rate is lager than a certain value. In the experiments, a damage threshold of 8 kW/mm^2 is measured at 8 keV [6].

A successful single shot self-seeding design should include at least the following three rules whether it is one-stage, two-stage or multiple-stage configuration. Firstly, the location of the self-seeding station should be within the FEL exponential gain region, so that the electron beam qualities, such as the energy losses and energy spread, are small enough to allow for lasing in the output undulator. Secondly, the spontaneous dose and heat load should smaller than the damage threshold. Thirdly, the seed power after the monochromator should be enough to dominate over the shot noise so that we can get fully coherent output.

LCLS-II-HE is the LCLS-II High Energy upgrade project, in which the electron beam energy is increased from 4 GeV to 8 GeV and the photon energy is extended from 5 keV to 12.8 keV or more. The designed repetition rate is 1MHz. In our LCLS-II hard X-ray self-seeding (HXRSS) simulation work, we pointed out that the two-stage scheme has no advantage over the one-stage scheme [7]. In this paper, we will focus on the investigation of one-stage self-seeding schemes including the one-stage configuration optimization and emittance tolerance study.

NUMERICAL SIMULATION

Undulator Baseline

The current hard X-ray undulator baseline of LCLS-II has 34 slots to install 32 undulator cells and 2 self-seeding stations of which the locations are slot 8 and slot 16 shown in Fig. 1 corresponding to Line 1. For the one-stage self-seeding scheme, neither the slot 8 nor slot 16 is the optimal self-seeding station. According to the optimization, we suggest to move the second self-seeding station from slot 16 to slot 14 shown in Fig.1 corresponding to Line 2.

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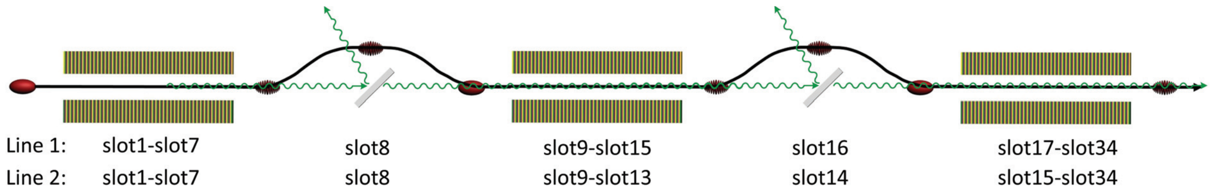

Figure 1: (Line 1) The current undulator baseline configuration of LCLS-II. The slot 8 and slot 16 are reserved for self-seeding station. (Line 2) The optimal one-stage undulator baseline. The self-seeding station is at slot 14.

Self-seeding Schemes Discussion

In our 4 GeV electron beam operation mode of LCLS-II self-seeding, of which the photon energies cover from 3.25 keV to 4.25 keV, we demonstrated that two-stage scheme has no advantage over one-stage scheme [8]. Because the heat load on the crystal is smaller than the damage threshold, either one-stage or two-stage is okay. Furthermore, for the two-stage scheme, the seed power after the first crystal is too small to dominate the shot noise power, and the output pulse energy of two-stage scheme is smaller than that of one-stage scheme. That means we have no sufficient motivation to develop two-stage self-seeding scheme.

For LCLS-II-HE, the photon energy is higher than that of LCLS-II. We know that the FEL gain length and the transmission of high energy case are lager than the low photon energy case, so that the power density and the spontaneous dose on the crystal of LCLS-II-HE HXRSS are smaller than that of LCLS-II HXRSS. Therefore, we will focus on one-stage self-seeding scheme in the following discussion.

Electron Beam and Crystal Parameters

The 8 GeV electron beam is scaled from the 4 GeV start-to-end electron beam. The phase space and the emittance as a function of bunch length is shown in Fig. 2. The normalized emittance of the current electron beam at the core is about 0.35 μm *rad*, and the current around the core is about 800 A. The energy loss of electron beam caused by the wake field inside the undulators is also accounted shown in Fig. 2. For the emittance tolerance study, we increase the emittance to 120 percent of current electron beam. After the emittance scaling, the emittance at the core is about 0.42 μm *rad*. The overall electron beam parameters in our simulation are shown in Table 1.

Table 1: Relevant Simulation Parameters in This Paper

Parameters		**Units**
Beam energy	8.0	GeV
Energy spread	0.6	MeV
Peak current	800	A
Normalized emittance	0.35/0.42	μm *rad*
Undulator period	2.6	cm
Photon energy	10	keV
Charge	100	pC

For the diamond crystal, we choose symmetric diamond (004), and the thickness of the diamond is 110 μm. The transmissivity of the crystal is calculate with the help of Xop2.4 [9], and the phase of the transmissivity is retrieved by Kramers–Kronig relations.

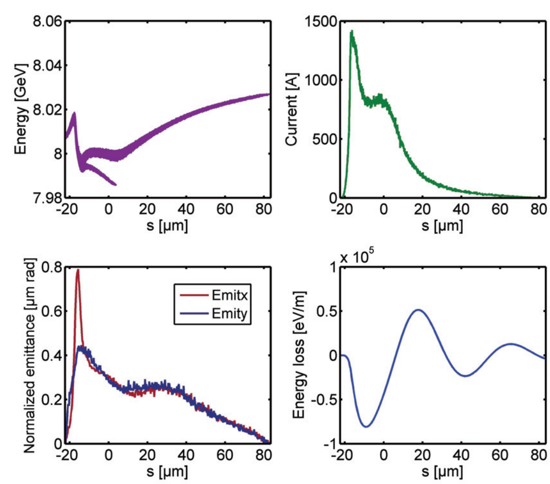

Figure 2: Start to end beam at the entrance of the undulator.(Top left) Electron beam phase space. (Top right) Current distribution. (Bottom left) Normalized emittance as a function of bunch length. (Bottom right) Electron energy loss caused by the undulators wakefields.

We present the self-seeing performance study with the help of FEL code GENESIS [10]. Firstly, we will focus on the operation of 10 keV which is the upper limit of LCLS-II-HE HXRSS. Secondly, we will investigate the optimal one-stage self-seeding configuration. Thirdly, we will present the emittance tolerance study. All the numerical analysis in this paper is based on 20 FEL runs.

In our simulations, the average beta-function is 20 m. The SASE gain curves of different emittance are shown in Fig. 3. We can find that both the slot 14 and slot 16 are within the exponential gain regime. Both the two different emittance cases can reach to saturation, but the saturation of 0.35 μm *rad* case is roughly 20 *m* earlier than that of 0.42 μm *rad* case (see Fig. 4).

One-stage Self-seeding Performance Study

In this part, we will present the self-seeding configuration and the emittance tolerance discussion. For one-stage self-

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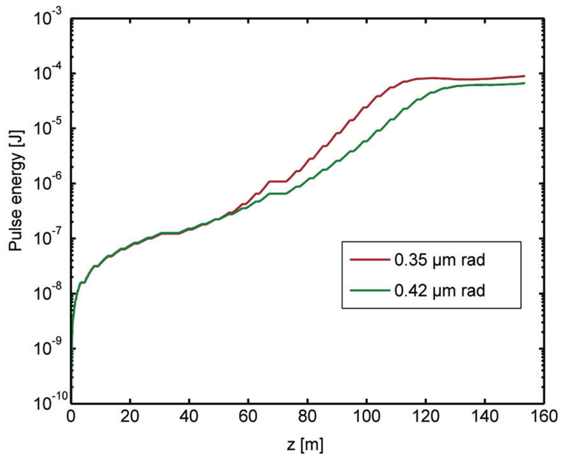

Figure 3: The 10 keV SASE gain curves of LCLS-II-HE based on the configuration Line 1.

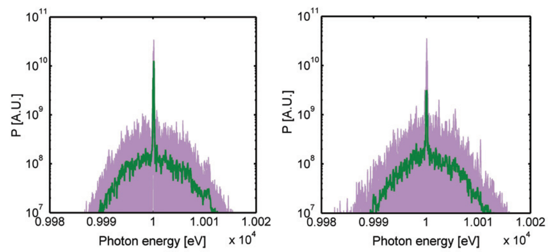

Figure 4: (Left) The saturation spectrum of 0.35 μm *rad* emittance based on configuration Line 2. (Right) The saturation spectrum of 0.42 μm *rad* emittance based on configuration Line 2. The green curve refers to the average. The purple curves refer to single shot.

seeding scheme, the slot8 acts as a drift. The self-seeding station of the first configuration is at slot 14 and that of another configuration is at slot 16. The simulation results are summarized in Table 2.

Table 2: 10 keV simulation results.P_s is the average seed power. P_d is the power density on the crystal. $M1$, $M2$ are the diamond monochromators. E_p is the output pulse energy. std is the standard deviation. Sat.: Saturation. $L1$, $L2$: Line1, Line2

Parameters	**0.35 μm** *rad*	**0.42 μm** *rad*	**Units**
P_s after slot14	56	30	kW
P_s after slot16	145	100	kW
Sat. SNR ($L1$)	120	35	-
Sat. SNR ($L2$)	100	20	-
E_p ($L1$)	57.63	35.84	μJ
E_p ($L2$)	71.67	49.41	μJ

The simulation results indicate that the output pulse energy of configuration Line 2 is larger than that of configuration Line 1. For the 0.35 μm *rad* emittance case, the signal noise ratio (SNR) at saturation of configuration Line 1 and Line 2 are 120 and 100 respectively. For the 0.42 μm *rad* emittance case, the SNR at saturation of configuration Line 1 and Line 2 are 35 and 20 respectively.

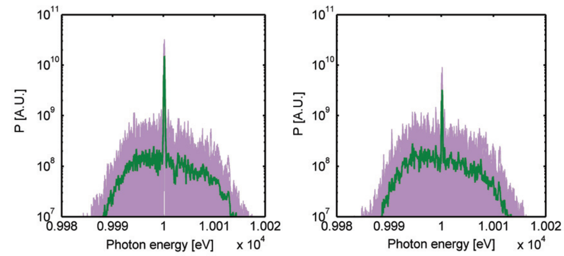

Figure 5: (Left) The saturation spectrum of 0.35 μm *rad* emittance based on configuration Line 1. (Right) The saturation spectrum of 0.42 μm *rad* emittance based on configuration Line 1. The green curve refers to the average. The purple curves refer to single shot.

SUMMARY

The LCLS-II-HE FEL will provide fully transverse coherent beams but the temporal coherence is limited. The self-seeding scheme can improve the longitudinal coherence and increase the brightness. We discussed the self-seeding schemes of LCLS-II-HE and suggested an one-stage self-seeding configuration. Furthermore, we studied the facility performance with the help of numerical simulation and discussed the optimal one-stage self-seeding configuration and investigated the emittance tolerance of the machine. The results of our analysis indicated the optimal one-stage self-seeding station is at slot 14 and the upper limit of the emittance should be smaller than 120 percent of current due of the emittance.

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