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INTENSITY FLUCTUATIONS REDUCTION IN THE DOUBLE-BUNCH FEL AT LCLS*

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Abstract

In this paper we explore the possibility of reducing the intensity fluctuations of a hard X-ray double-bunch free-electron laser (DBFEL) by using an ultra-short, high peak current electron bunch to generate the seed signal, as studied recently for soft X-ray single bunch self-seeding. The ultra-short, nearly single-spike, SASE pulse is amplified to saturation, where a four-crystal monochromator selects a narrow bandwidth seed for the second bunch. Start-to-end simulation results for 7 keV photon energy are presented here for a DBFEL already studied for LCLS using the HXR undulator. We show that using this enhanced DBFEL (EDBFEL) system; the seed signal intensity fluctuations can be reduced from 85% to about 30%, and the second bunch intensity fluctuation at saturation to about 15%.

INTRODUCTION

The Free-electron laser (FEL) opens the door to a new frontier of high-intensity X-ray experiments in various research fields, e.g., physics, chemistry [1], life [2] and material sciences [3]. Combined with ultra-short duration, refined resolution, and high photon flux, hard X-ray FELs have become powerful tools to capture simultaneous information on atomic structure and dynamics, which have been exemplified by the successful operation of various X-ray FEL sources [4–7], as the Linac Coherent Light Source (LCLS). The process of X-ray generation in these machines is based on self-amplified spontaneous emission (SASE) [8], in which the electron beam spontaneous emission is amplified while the electron beam is traveling through an undulator magnet. The X-rays produced in the SASE process are transversely coherent. However, due to the stochastic nature of this process, the longitudinal coherence is limited, and the X-ray pulse is spiky [9–13].

One efficient way to improve the X-ray temporal properties is the self-seeding technique, demonstrated experimentally at LCLS [14]. With an inserted transmissive monochromator in the undulator system, the SASE FEL spectrum is filtered, and a narrow bandwidth wake seed is generated. The narrow bandwidth seed is amplified in the later undulator segments. In this way, the self-seeding scheme substantially improves the FEL spectral brightness.

A further improvement of the spectral brightness can be obtained with the DBFEL [15–18]. In this scheme, shown in Fig. 1, the first bunch generates a high power SASE X-ray pulse in the first undulator section and does not lase in the second undulator section. The second bunch does not lase in the first undulator section and is seeded at the entrance of the second tapered undulator section by the monochromatized high power SASE pulse generated by the first bunch. The frequency filtering occurs in a four crystals monochromator, also acting as a photon delay line. A fast transverse kicker is used to put the second bunch in oscillations around the undulator axis in the first section to suppress the lasing process, while the first bunch is on-axis. A magnetic chicane steers both electron bunches off the monochromator optics, and, at the same location, transverse orbit correctors are used to set the second bunch on-axis in the second undulator tapered section thus setting also the first bunch on an oscillating trajectory.

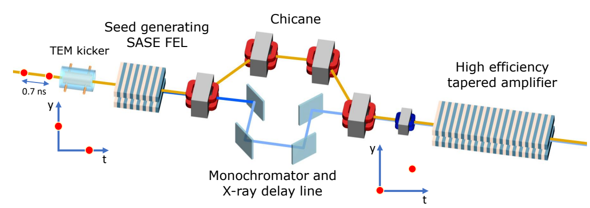

Figure 1: DBFEL schematics: Two bunches with 0.7 ns separation are produced in the injector, accelerated, and compressed in the copper Linac, propagating co-axially to the HXR undulator sections. At the TEM kicker location, the second bunch is kicked off-axis, while the first bunch propagates on-axis, generating a SASE X-ray pulse. The 4-bounce monochromator filters and delays the SASE X-ray pulse by 0.7 ns. The magnetic chicane steers the electrons off the monochromator optics creating a small delay of the electrons (some tens of fs). At the entrance to the second undulator section, the second bunch trajectory is steered back to propagate on-axis. This bunch is co-aligned and temporally overlapped with the filtered and delayed x-ray pulse that acts as a monochromatic seed, while the first bunch is kicked off-axis.

However, since self-seeding schemes, e.g., DBFEL, transmissive self-seeding [19], reflective self-seeding [20], fresh-slice self-seeding [21], use a SASE pulse generated in high gain regime and a monochromator to produce the seed, the seed power, due to the stochastic nature of SASE, has strong fluctuation . Hence, the output power amplified from the seed will inherit the strong fluctuation. To stabilize the output power of self-seeding, a novel scheme has been proposed to suppress the seed power fluctuation for soft X-rays [22], using an ultra-short seed signal with a nearly single SASE spike.

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In this paper, we extend this approach to the hard X-ray DBFEL studied for LCLS to enhance its output power stability, using an ultra-short electron bunch to generate the seed. We call this approach enhanced DBFEL, EDBFEL. We present simulation results at 7 keV using the LCLS-II HXR undulator. The simulation results of DBFEL and EDBFEL show that the EDBFEL scheme can significantly suppress the intensity fluctuations of the seed signal power and the saturation power.

SIMULATIONS

DBFEL at 7 keV

For the simulations, we employ Genesis 1.3 - a 3D time-dependent FEL simulation code [23]. Seed characteristics after the monochromator, at 7 keV, for the DBFEL studied for LCLS are shown in Fig. 2 [17]. It is clear that if we look at the time or spectral domain, the seed power has a strong fluctuation. As summarized in Table 1, for the DBFEL we studied the seed fluctuation can be as high as 85%.

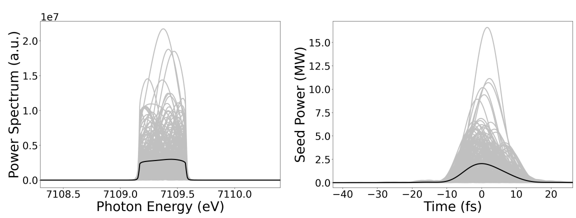

Figure 2: Seed pulse parameters at 7 keV after the four-bounce $C^*(111)$ monochromator: spectrum (left) and temporal profile (right). Gray lines represent shot-to-shot performance and the black curve is a multi-shot average.

Table 1: Electron Beam Properties Comparison Between DBFEL and EDBFEL

	DBFEL	EDBFEL	Units
1st bunch current	3.5	10	kA
1st bunch length	15	0.38	fs
2nd bunch current	3.5	3.5	kA
2nd bunch length	15	15	fs
1st stage length	28.6	53.1	m
Seed fluctuation	>85%	<30%	
Output FHWM	3.89×10^{-5}	4.09×10^{-5}	a.u.

EDBFEL at 7 keV

In this subsection, we describe the working principle of the EDBFEL scheme. As mentioned in the Introduction, the DBFEL employs two electron bunches with a separation of 0.7 ns. The first bunch is used to generate a high power seed. The second electron bunch is seeded and generates a high-power, narrow-bandwidth hard X-ray pulse. However, the SASE pulse generated by the first bunch in the high gain regime has a strong fluctuation due to the stochastic nature of SASE FEL. Hence, the seed generated by filtering the SASE pulse with a monochromator will inherit the fluctuations from SASE, and due to the narrow bandwidth of the frequency filter, the power fluctuation of the seed is even higher, close to 100%, as can be seen in Table 1.

However, using a single spike X-ray pulse amplified to saturation, the fluctuation can be significantly reduced. The effect of using a saturated seed pulse has been demonstrated in the soft X-ray self-seeding regime [22]. Here, we extend it to the DBFEL in the hard X-ray regime, also using a single spike seed signal generated by the first bunch. The detailed parameters list for the DBFEL already studied, and EDBFEL studied here is shown in Table 1. As we can see, the first bunch in EDBFEL has a much higher current to saturate earlier and a shorter bunch length to generate a single-spike pulse. The high current short bunch can be obtained by manipulating the first bunch with an external laser, and a compressor, as in an eSASE system [24]. To amplify the seed signal to saturation, the first stage of EDBFEL is longer than in the DBFEL case, as shown again in Table 1.

The current profile for the EDBFEL case is shown in Fig. 3. To understand the statistical performance of EDBFEL, 50 simulation runs with different initial shot noise have been done.

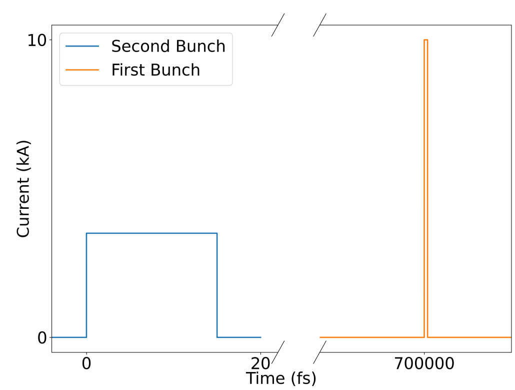

Figure 3: Current profile used in EDBFEL regime: a 10 kA, 0.38 fs electron bunch (orange line) as the first bunch, a 3.5 kA, 15 fs electron bunch as the second bunch (blue line), delayed 0.7 ns compared with the first bunch.

In the first stage of EDBFEL, the high current first bunch will lase, and, due to the short bunch length and high current, will saturate quickly (about 50 m) and generate a single-spike pulse. The gain curve and spectrum of the first bunch at the end of the first stage are shown in Fig. 4. As we can see in Fig. 4, due to the saturation effects, at the end of the first stage, the pulse energy fluctuation is much smaller than it is in the high gain regime, and as a result of that, the spectrum fluctuation is pretty small as well.

After the monochromator, we obtain a low fluctuation, narrow bandwidth, high-power seed signal, as shown in Fig. 5, where we see that the seed power fluctuation is quite small, it has been reduced down to 30%, as given in Table 1.

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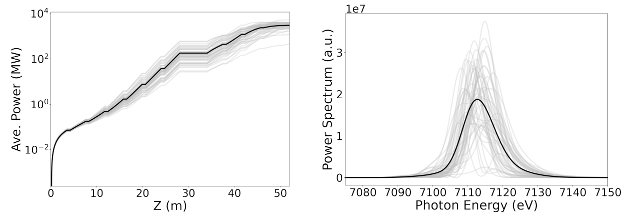

Figure 4: First bunch performance: gain curve (left), spectrum at the end of first stage (right).Gray lines represent shot-to-shot performance and the black curve is a multi-shot average.

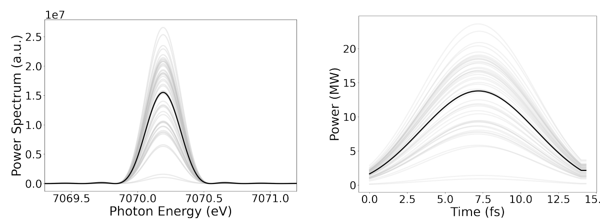

Figure 5: Seed performance: frequency domain (left), time domain (right). Gray lines represent shot-to-shot performance and the black curve is a multi-shot average.

Note that, the length of the seed pulse in the time domain plot has been increased to about 15 fs, corresponding to the monochromator bandwidth. Hence, even if the duration of the pulse impinging on the monochromator is short, the duration of the seed signal after the monochromator to seed the second bunch is much longer. We have chosen the length of the second bunch to match the seed signal length.

The seeded second bunch generates an X-ray pulse that is amplified to saturation in the second part of the undulator, following the monochromator. Thanks to the low power fluctuation of the seed, the saturation power fluctuation of the second bunch is reduced to 15%, as shown in Table 1. The time domain profile of the saturated pulses and the corresponding frequency domain power spectra are shown in Fig. 6. Among the 50 shots simulated, with different initial noise, there are only two cases with very low power respect to the average. The saturation bandwidth is 4.09×10^{-5}.

SUMMARY

In this paper, we have demonstrated that the EDBFEL system can significantly suppress power fluctuations for 7 keV photons while providing a narrow bandwidth and good longitudinal coherence. The simulation results show that the seed power fluctuation can be suppressed down to 30%, and the saturation power fluctuation can be reduced to 15%. Compared with the original DBFEL scheme, with seed power fluctuation as high as 85%, EDBFEL provides a much more stable narrow bandwidth signal providing more capabilities for scientific experiments. It is worth mentioning that

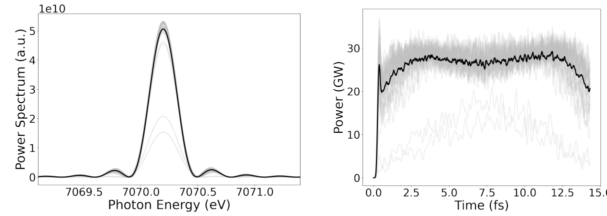

Figure 6: Second bunch performance at saturation: frequency domain (left), time domain (right). Gray lines represent shot-to-shot performance and the black curve is a multi-shot average.

the seeding efficiency can be further improved by crystal tuning [25] and that the FEL performance may be further improved with taper optimization [26, 27].

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