DEMONSTRATION OF FRESH SLICE SELF-SEEDING IN A HARD X-RAY FREE ELECTRON LASER*

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Abstract

We discuss the first demonstration of fresh slice self seeding, or Enhanced Self-Seeding (ESS) in a hard X-ray Free Electron Laser (XFEL). The ESS method utilizes a single electron beam to generate a strong seed pulse and amplify it with a small energy spread electron slice. This extends the capability of self seeded XFELs by producing short pulses, not limited by the duration set by the self-seeding monochromator system, with high peak intensity. The scheme relies on using a parallel plate dechirper to impart a spatial chirp on the beam, and appropriate orbit control to lase with different electron beam slices before and after the self-seeding monochromator. The performance of the ESS method is analyzed with start-to-end simulations for the Linac Coherent Light Source (LCLS). The simulations include the effect of the parallel plate dechirper and propagation of the radiation field through the monochromator. We also present results of the first successful demonstration of ESS at LCLS. The radiation properties of ESS X-ray pulses are compared with the Self-Amplified Spontaneous Emission (SASE) mode of FEL operation for the same electron beam parameters.

INTRODUCTION

X-ray Free Electron Lasers (XFELs) are tunable sources of coherent X-rays capable of generating high intensity pulses from nanometer down to sub-angstrom wavelengths [1]. The extraction efficiency and the bandwidth of typical Self Amplified Spontaneous Emission (SASE) [2] XFELs is characterized by the FEL parameter ρ, typically around 10^{-3}. The bandwidth can be narrowed, among other methods, via self-seeding [3], and the intensity can be increased via tapering of the undulator magnetic field [4] [5] [6] [7]. One major limitation of self-seeded tapered XFELs is the trade-off between seed power and energy spread at the start of the seeded undulator section. This trade-off limits the output power of tapered self-seeded systems. It has recently been shown that for high efficiency XFELs aiming to reach multi-TW peak powers, the output power can be greatly enhanced by generating a strong seed pulse and amplifying it with a small energy spread electron beam. This can be accomplished by using two different electron beam slices, one to generate the seed signal and the other to amplify it after the self-seeding monochromator in a tapered undulator. This method, termed fresh slice or Enhanced Self-Seeding (ESS), proposed in Ref. [5] has recently been experimentally demonstrated at the Linac Coherent Light Source (LCLS) [8]. Multi-color lasing using the fresh slice scheme has recently been reported in Ref. [9]. We present experimental results of ESS demonstration comparing the performance of the ESS scheme with SASE at the same photon energy. We also compare experimental ESS data with start-to-end simulations using the same LCLS machine parameters as the experimental demonstration.

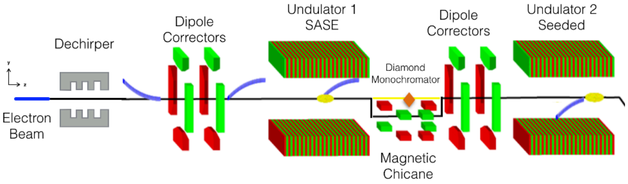

Figure 1: Schematic of the ESS experimental demonstration setup with the parallel plate dechirper installed at the LCLS. The beam travels off-axis through the vertical dechirper and acquires a quadratic spatial chirp. Dipole correctors are used to steer the tail on-axis in the SASE section and the core (head) on-axis in the seeded section. The X-ray seed pulse (yellow) is overlapped with the core (head) in the second section by adjusting the magnetic chicane delay.

ENHANCED SELF-SEEDING EXPERIMENTAL RESULTS

A schematic of the demonstration experiment for ESS at the LCLS is shown in Fig. 1. The electron beam parameters are 4kA current (core), 11.1 GeV energy, normalized transverse emittance 0.4 μm and 180 pC charge. The resonant photon energy is 5.5 keV. In our experiment the electron beam lases in the tail slices during the first SASE section and the seed pulse is amplified on the core slices in the seeded section after the monochromator. Selective lasing is achieved by imparting a spatial chirp on the electron beam and using appropriate orbit control to steer the tail and core slices on axis in the SASE and seeded section respectively. The spatial chirp is imparted on the electron beam in a passive manner by making use of the transverse wakefields of the parallel plate dechirper recently commissioned at LCLS [10] [11]. We adjust the dechirper jaw such that the beam travels off-axis near the vertical jaw and the dipole wake imparts a head-tail quadratic spatial chirp on the beam. We use vertical dipole correctors before the first undulator section to steer the tail on-axis and generate a saturated SASE pulse before the diamond monochromator. The photon beam travels through the diamond monochromator which transmits a wide bandwidth SASE pre-pulse and a long narrow bandwidth tail. The electron beam passes through the chicane around the diamond monochromator and dipole correctors are used to steer the core slices on axis in the undulator section downstream. The chicane delay is

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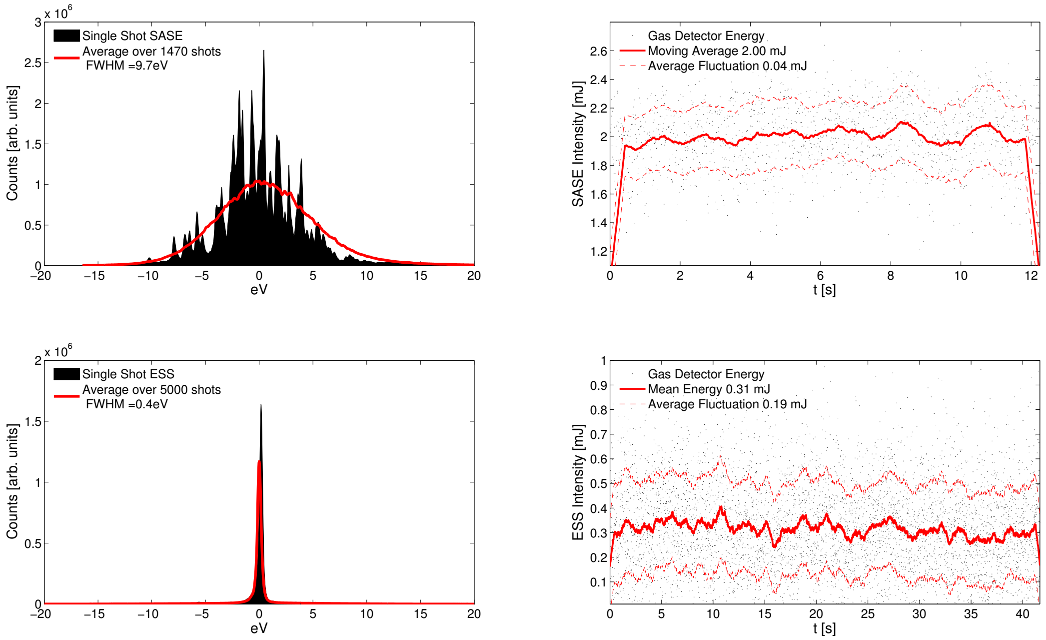

Figure 2: (left column) Measurement of the X-ray radiation spectrum for SASE (top) and ESS (bottom) at the LCLS with a photon energy of 5.5 keV. The ESS bandwidth is narrower by around a factor of 24. The pulse duration is typically 40 fs for SASE and 10 fs for ESS. (right column) X-ray intensity for the SASE (top) and ESS (bottom) in 1470 and 5000 consecutive shots respectively. The fluctuations in ESS intensity are due to electron bunch energy jitter and SASE intensity fluctuation at the monochromator.

also adjusted such that the core slices of the electron beam overlap with the narrow bandwidth seed pulse and amplify it downstream.

The bottom row of Fig. 2 shows the X-ray pulse intensity and spectrum for the ESS experiment measured on the gas detector and the hard X-ray bent crystal spectrometer [12]. The typical X-ray pulse duration measured on the X-band transverse deflecting cavity (not shown) is ~ 10 fs. The mean (± rms) intensity is energy is 310 ± 190 μ J with a mean spectral bandwidth of 0.4 eV. The peak X-ray intensity obtained with ESS is 1.04 mJ with a corresponding spectral bandwidth of 0.32 eV. The fluctuations in pulse intensity are due to electron beam energy jitter and the fluctuations of SASE intensity at the monochromator, and are similar in ESS and normal self-seeding [3] [8]. The top row of Fig. 2 shows the SASE spectrum and intensity for 1470 consecutive shots. The bandwidth of SASE is 9.7 eV, a factor 24 wider than ESS, and the pulse intensity (± rms) is 2 ± 0.04 mJ. The SASE pulse duration spans the entire electron bunch and is around 40 fs. We estimate the photon beam brightness is therefore around a factor of 12 larger for the ESS method compared to SASE.

START-TO-END SIMULATIONS WITH DIAMOND WAKE MONOCHROMATOR

We compare the performance of the ESS experimental demonstration with start-to-end simulations using the same electron beam parameters. The FEL simulation results performed using GENESIS [13] are shown in Fig. 3-4. We simulate the effect of the parallel plate dechirper by manually introducing a quadratic spatial chirp on the beam before the first undulator section, using the analytical formulas derived in Ref. [10]. The tail is placed on-axis in the first undulator section and the produces SASE radiation until the beam reaches the hard X-ray self-seeding chicane. The SASE power is around 12 GW in a short ~ 5 fs pulse on

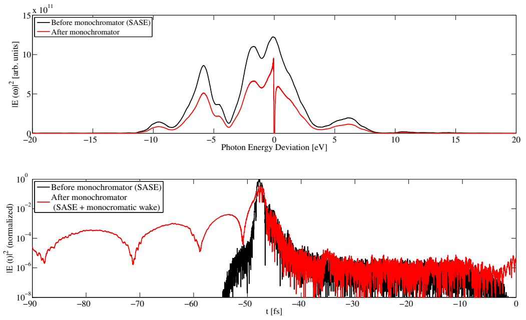

Figure 3: (top) SASE frequency filtering using the diamond forward Bragg diffraction monochromator and field obtained from GENESIS simulation. The notch filter removes the central photon energy of 5.5 keV from the SASE pre-pulse. (bottom) Time domain representation of the SASE field and the monochromatic wake pulses, the head of the beam is on the right.

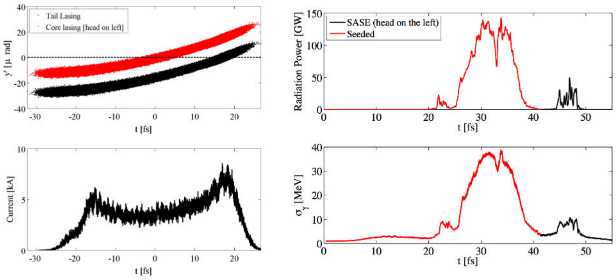

Figure 4: Start-to-end simulation results of the ESS demonstration experiment at the LCLS. (Top left) Electron beam angular kick given by the dechirper with the tail steered on axis in the first SASE section and the core on axis in the seeded section. (Bottom left) Electron beam current from start-to-end simulation. (Top right) Radiation power in the SASE and seeded undulator sections from the first and second undulator stage. The intensity matches the intensity measured in experiment on the best shots. (Bottom right) Electron slice energy spread at the exit of the second ESS undulator, the tail and the core have large energy spread signifying strong lasing.

the bunch tail. We then simulate the effect of the diamond monochromator by passing the radiation through a notch filter and applying a frequency notch filter using the formalism described in Ref. [14] [15]. The diamond monochromator amplitude and phase transmission function is calculated for the (-2 0 2) Bragg reflection used in the demonstration experiment. The first maximum of the monochromatic wake seed pulse is delayed by 11 fs with a peak intensity around 0.4 % of the SASE peak power and a full width duration of 8 fs (see Fig. 3). We overlap the seed pulse with the core of the electron bunch and manually steer the core on-axis in the first undulator section (see Fig. 4 top left). The core amplifies the seed radiation until the undulator exit and reaches an average power of 56 GW with a pulse intensity of 1.08 mJ, similar to the peak intensity recorded in experiment but 0.7 mJ larger than the mean intensity. The FWHM pulse duration is 8.6 fs, similar to what is measured in experiment. The source of the discrepancy between peak intensity in simulation and mean experimental intensity may be due to the effect of quadrupole wakes which cause the head-tail slices to be mismatched in the experiment and are not included in the simulation. Furthermore the dechirper causes some increase in the electron beam slice energy spread on the tail slices which has not yet been modeled numerically. Finally the electron beam energy jitter, largely responsible for the intensity fluctuations shown in Fig. 2, reduces the mean intensity compared to the intensity for on-energy shots. Experimental optimization of the ESS scheme as well as more detailed simulation studies are the subject of ongoing investigation.

CONCLUSION

We discuss results of the first demonstration of the ESS method in a hard X-ray FEL and compare ESS performance with SASE and start-to-end simulations at the same photon energy. Our results show that ESS is a promising method for generating short (~ 10 fs), high intensity (up to 1 mJ) narrow bandwidth (0.4 eV) X-ray pulses. We estimate the brightness of ESS is around a factor of 12 larger than SASE at this photon energy. Numerical simulations including the effect of the diamond wake monochromator are performed and the intensity as well as the FWHM spectral bandwidth agree with the measured values for the best shots. This successful demonstration opens the possibility of applying ESS to high efficiency XFELs to reach multi-TW peak powers with short pulses, an important characteristic for single particle imaging experiments.

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