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SLIPPAGE-ENHANCED SASE FEL*

Juhao Wu[1†], Kun Fang[1‡], Claudio Pellegrini[1§], Tor Raubenheimer[1], Guanqun Zhou[1¶], Axel Brachmann[1], Agostino Marinelli[1],Cheng-Ying Tsai[1], Chuan Yang[1‖], Moohyun Yoon[1**], Heung-Sik Kang[2††], Gyujin Kim[2], Inhyuk Nam[2], Andrew Chen[3], Claire Davidson-Rubin[4], Alexandra Li[5], Nancy Munoz[6], Bo Yang[7]

[1]SLAC, Stanford University, Stanford, CA, USA,
[2]PAL-XFEL, Pohang University of Science andTech., Pohang, Korea,
[3]Mission San Jose High School, Fremont, CA, USA,
[4]UC San Diego, La Jolla,CA, USA,
[5]Saratoga High School, Saratoga, CA, USA,
[6]Texas Tech University, Lubbock, TX, USA
[7]UT Arlington, Arlington, TX, USA

Abstract

High-brightness XFELs are in demand for many users, in particular for multiple types of imaging applications. Seeded FELs including self-seeding XFELs were successfully demonstrated. Alternative approaches by enhancing slippage between the x-ray pulse and the electron bunch were also demonstrated. This class of Slippage-enhanced SASE (SeSASE) schemes can be unique for FEL spectral range between 1.5 keV to 4 keV where neither grating-based soft x-ray self-seeding nor crystal-based hard x-ray self-seeding can easily access. SeSASE can provide high-brightness XFEL for high repetition rate machines not suffering from heat load on the crystal monochromator. We report start-to-end simulation results for LCLS-II project and preliminary experimental results for PAL-XFEL project.

SLIPPAGE-ENHANCED SASE (SESASE)

Free electron lasers (FEL) are perceived as the next-generation light source for many frontier scientific researches. Ultra-fast hard-X-ray FEL pulses, providing atomic and femtosecond spatial-temporal resolution, makes them a revolutionary tool attracting world-wide interest [1,2]. While an FEL provides high spatial coherence due to gain selection, *i.e.*, only the transverse mode which has the highest gain will dominate at the end of the undulator; the temporal coherence is rather poor. The temporal structure is spiky with coherent spikes with random relative phase among them [3]. In the high-gain region, the FEL group velocity is $v_g = \omega_0/(k_0 + 2k_u/3)$ and the electron longitudinal velocity is $v_l = \omega_0/(k_0 + k_u)$ where $\omega_0 = k_0 c = 2\pi c/\lambda_0$ with c speed of light in vacuum, λ_0 the FEL resonance wavelength; and $k_u = 2\pi/\lambda_u$ with λ_u the undulator period. So, the coherent spike duration, the cooperation duration, is only $\tau_s \approx N_u\lambda_0/(3c)$ where N_u is the total undulator period for the FEL to reach saturation. The so-called cooperation length is $\mathcal{Z}_c = \tau_s c$. For the LCLS 1.5-Å FEL, $N_u \approx 2000$ to reach saturation, so $\tau_s \approx 0.3$ fs, which is much shorter than the electron bunch duration on the order of 10 to 100 fs.

To improve the temporal coherence, seeding approaches: both external [4,5] and self-seeding [6,7] have been actively pursued. Another approach along this line is to try to increase the slippage between the electron bunch and the FEL pulse. Such Slippage-enhanced SASE (SeSASE) [8–11] can produce bandwidth much narrower than that of a conventional SASE. The first preliminary experimental results was reported in Ref. [10].

ONE-DIMENSIONAL THEORY

To understand the SeSASE mechanism, let us work with a 1-D theory here. Such analysis is very similar to those developed in Refs. [12–14].

The coupled Maxwell-Vlasov equations for the FELs can be written as [14]:

$$\left(\frac{\partial}{\partial z} - 2ik_u\eta\nu\right) F(\nu,\eta,z) = \kappa_1 A(\nu;z)\frac{\partial}{\partial\eta}V(\eta), \qquad (1)$$

$$\left(\frac{\partial}{\partial z} - i\Delta\nu k_u\right) A(\nu;z) = \kappa_2 \int F(\nu,\eta;z)\,d\eta, \qquad (2)$$

where z is the coordinate along the undulator system; $\eta = (\gamma-\gamma_0)/\gamma_0$ the relative energy deviation with γ_0 the electron resonant energy; $\nu = \omega/\omega_0$ with ω the radiation frequency which is different from the FEL resonant frequency ω_0; $\Delta\nu = \nu - 1$ the detuning parameter; $F(\nu,\eta,z)$ is the electron bunch bunching factor; $A(\nu;z)$ is the slow varying envelop function of the FEL field, and $V(\eta)$ is the

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† jhwu@slac.stanford.edu
‡ Now at Wells Fargo & Co., San Francisco, CA, USA
§ Also as UCLA., Los Angeles, CA, USA
¶ Visiting Ph.D. student from Institute of High Energy Physics, and UCAS, Chinese Academy of Sciences, Beijing, China
‖ Visiting Ph.D. student from NSRL, University of Science and Technology of China, Hefei, Anhui, China
** On sabbatical leave from Department of Physics, Pohang University of Science and Technology, Pohang, Korea
†† hskang@postech.ac.kr

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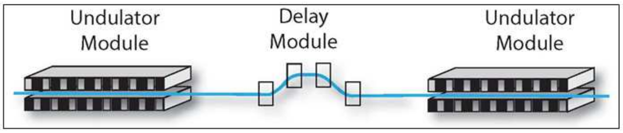

Figure 1: Schematics of an one-stage SeSASE FEL.

electron bunch initial energy spread distribution function. The coefficients κ_1 and κ_2 define the FEL parameter ρ [15]:

$$\kappa_1 \kappa_2 = k_u^2 \rho^3. \tag{3}$$

Passing through an undulator gap providing a distance of D, both the FEL field and the electron bunching factor acquire an additional phase:

$$A(\nu; z + D) = A(\nu; z) e^{i\Delta\nu k_u D}, \tag{4}$$

$$F(\nu, \eta; z + D) = F(\nu, \eta; z) e^{i\Delta\theta}. \tag{5}$$

One-stage SeSASE

Now let us discuss an undulator system with two undulator sections interrupted by a phase shifter in-between as shown in Fig. 1.

The analysis here is similar to Ref. [16]. The first stage is a SASE process with the initial conditions:

$$E_{1\nu}(0) = 0, \qquad \int F_{1\nu}(0) = \frac{1}{N_\lambda} \sum_{j=1}^{N_e} e^{i\nu\omega_{10} t_j(0)}, \tag{6}$$

where $\nu = \omega_1/\omega_{10}$ with $\omega_1 = k_1 c = 2\pi c/\lambda_1$ the radiation frequency and ω_{10} the resonant radiation frequency in the first undulator; N_λ is the number of electrons in one radiation wavelength; and $t_j(0)$ is the random arrival time of the j^{th} electron at the entrance of the first undulator. The first undulator will be operating in the exponential growth region, generating a SASE FEL with a bandwidth of

$$\mathcal{S}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_\nu} \exp\left[-\frac{(\nu - 1)^2}{2\sigma_\nu^2}\right], \tag{7}$$

where σ_ν is the rms bandwidth.

Now the electron bunch and the FEL field pass the phase shifter and restart the FEL amplification in the second undulator.

Short second undulator If the second undulator is short, then resulting FEL field is mostly from coherent emission after the transient startup, which can leads to interference. The field is:

$$E_{2\nu}(z) = E_{1\nu}(L_1)\left[e^{-i\psi}\left(1 - \mathcal{B}e^{i\Delta\theta}\right) + \mathcal{B}e^{i\Delta\theta}\right], \tag{8}$$

where z is now the distance starting from the entrance of the second undulator, L_1 is the first undulator length, and

$$\psi = \Delta\nu k_u z, \tag{9}$$

$$\mathcal{B} \equiv \frac{2\rho}{\Delta\nu \mu_g^2}\left(1 - \mu_g e^{i\alpha}\rho k_u z\right), \tag{10}$$

with the growth mode:

$$\mu_g = e^{i2\pi/3} + \frac{\Delta\nu}{6\rho} - e^{i\pi/3}\left(\frac{\Delta\nu}{6\rho}\right)^2. \tag{11}$$

Long second undulator If on the other hand, the second undulator is long and supports high-gain exponential growth, which will also lead to interference. The FEL field reads:

$$E_{2\nu}(z) \approx \frac{e^{-i2\rho\mu_g k_u z} E_{1\nu}(L_1)}{(\mu_g - \mu_o)(\mu_g - \mu_d)}\left(\mu_g^2 - \frac{2e^{i\Delta\theta}}{\mu_g}\right), \tag{12}$$

where, besides the exponential growth mode defined in Eq. (11), we also have the oscillating mode:

$$\mu_o = 1 + \frac{\Delta\nu}{6\rho} + \left(\frac{\Delta\nu}{6\rho}\right)^2, \tag{13}$$

and the decay mode:

$$\mu_d = -e^{i\pi/3} + \frac{\Delta\nu}{6\rho} + e^{i2\pi/3}\left(\frac{\Delta\nu}{6\rho}\right)^2. \tag{14}$$

Spectrum narrowing Neglecting the optical-klystron type power enhancement, we find that at the exit of the second undulator, the temporal field is:

$$E_2(t) = \int \frac{\omega_1 d\nu}{\sqrt{2\pi}} E_{2\nu}(L_2) e^{i\Delta\nu[(k_1 + k_u)L_2 - \omega_1 t]}, \tag{15}$$

where L_2 is the second undulator length.

We can now computing the SeSASE bandwidth:

$$|R(\nu)|^2 \mathcal{S}(\nu), \tag{16}$$

where $\mathcal{S}(\nu)$ is the SASE spectrum in Eq. (7). The frequency filter function is:

$$R(\nu) = \frac{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu - \xi)^2} e^{-i\rho k_1 \nu R_{56} \xi} e^{ik_1 \nu R_{56}/2}}{1 - \int d\xi \frac{dV(\xi)/d\xi}{(\mu - \xi)^2}}, \tag{17}$$

where R_{56} is the transport matrix element, μ is the mode defined in Eq. (11), Eq. (13), and Eq. (14).

For a cold electron bunch, the frequency filter function is simplified as:

$$|R(\nu)|^2 = \frac{5 + 4\cos(k_1 R_{56}\nu/2)}{9}. \tag{18}$$

Now, with this frequency filter function, for multi-stage SeSASE, we can step-by-step multiple the $|R(\nu)|^2$. Shown in Fig. 2, the red curve is for the baseline SASE. The blue is for the case of 5 phase shifters, each provides 2 cooperation length slippage: $2\mathcal{Z}_c$. The green is to add 5 phase shifters each providing 4 cooperation length. The yellow is for a geometrically increasing configuration, the 5 phase shifters provide 1, 2, 4, 8, and 16 cooperation length slippage.

As this point, we want to comment that, the above analysis is very crude; however, it illustrates the bandwidth narrowing effect with slippage-enhanced scheme.

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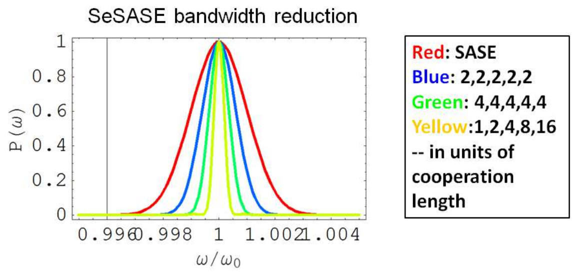

Figure 2: FEL bandwidth reduction with different slippage configuration.

SeSASE FOR FEL PROJECTS

As mentioned above, self-seeding is a demonstrated approach to generate coherent seed to improve the FEL temporal coherence. For soft X-ray it is normally grating-based. For such monochromators, it is very difficult to reach FEL energy higher than 1.5 keV. While for hard X-ray, normally, we can adopt thin crystal monochromator, like diamond. However, due to the strong absorption, it is very difficult to produce coherent seed below 4 keV. So, in short, self-seeding is difficult to access the FEL energy range of 1.5 keV to 4 keV. Besides, for the high repetition rate FELs, like the LCLS-II, or the Euro-XFEL, the thermal load, the vibration effect, the stress and strain effects on the thin crystal monochromator where the FEL pulses impinge on can cause large detrimental effects on the coherent seed generation. Therefore, SeSASE scheme can be an alternative.

LCLS-II

Here, we show some preliminary results for LCLS-II project. As we mentioned about, we are interested in the FEL energy range between 1.5 keV to 4 keV. Figure 3 presents the results of the 3.25 keV FEL (or FEL wavelength λ_1 = 3.15 Å). We develop two-options for LCLS-II using new hardware (Stanford Linear Collider Damp Ring-based chicane) and no new hardware (detuned undulator only).

Case A In this option, we will introduce new hardware. We will introduce 4-dipole chicanes in three undulator slots: the 5^{th}, the 8^{th}, and the 16^{th}. According to the LCLS-II baseline design, the 16^{th} has been planned for 1-stage hard X-ray self-seeding and the 8^{th} has been reserved for 2-stage hard X-ray self-seeding.

Case B In this option, we will not introduce new hardware, but use detuned undulator in the 5^{th} and the 8^{th} slot. So there is only a chicane in the 16^{th} undulator slot, which will be there anyway for the hard X-ray self-seeding.

Preliminary results indicate that with Case B, the SeSASE bandwidth can be 4 to 5 times narrower than that of the baseline SASE FEL. With additional two new chicanes in the 5^{th} and the 8^{th} undulator slot, *i.e.*, Case A, there is another factor of 3 to 4 reduction in the bandwidth. A single-shot spectrum is shown in Fig. 3 just to illustrate the bandwidth narrowing.

PAL-XFEL

We conducted SeSASE experimental study on the Soft X-Ray undulator line in PAL-XFEL. There are 7 undulators total. There is a phase shifter in each undulator interruption, *i.e.*, there are total of 6 phase shifters. Each phase shifter can provide a maximum of $50\lambda_1$ slippage. In the experiment, we turn the 6 phase shifters all to the maximum strength to produce a total of $300\lambda_1$ slippage. With this enhanced slippage, the SeSASE FEL bandwidth is about 3 times nar-

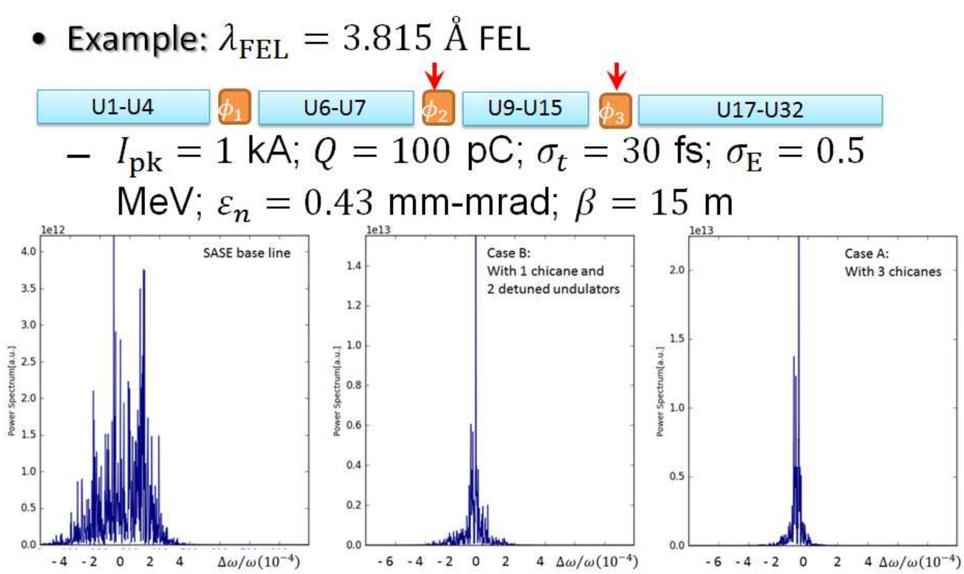

Figure 3: SeSASE FEL study for LCLS-II.

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rower than the SASE baseline bandwidth. The details of the experimental results are still being analyzed and will be reported in the near future.

CONCLUSION

To improve the SASE FEL temporal coherence, one can introduce phase shifters in-between the undulator section to increase the slippage between the FEL pulse and the electron bunch. We call these schemes as SeSASE. We developed a simple 1-D theory for the SeSASE FEL operation mode. We conducted *Genesis* [17] simulations for LCLS-II project and show that a factor of 20 reduction in bandwidth is possible with three-chicane configuration. We also conducted experimental work in PAL-XFEL. With very limited 300 wavelength total slippage, the SeSASE bandwidth is 3 times narrower than the SASE baseline bandwidth.

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