X-RAY SPECTRA AND PEAK POWER CONTROL WITH ISASE*

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Abstract

We report the first experiment demonstration of spectral bandwidth reduction in an improved Self-Amplified Spontaneous Emission (iSASE) X-ray Free-Electron Laser (FEL) obtained by introducing additional delays of the electron bunch with respect to the radiation field pulse.

Improved SASE (iSASE) Scheme

Hard X-ray Free-Electron Laser (FEL) facilities like LCLS [1] and SCALA [2] work in the Self-Amplified Spontaneous Emission (SASE) operation mode. It is well known that a SASE FEL has poor temporal coherence due to the random start-up of the FEL exponential growth process, therefore a spiky FEL profile both in the temporal and spectral domain [3]. A more careful and closer look at this poor temporal coherence reveals that the very reason which limits the temporal coherence is the very limited slippage between the photon and the electron. Recall that the electron is traveling almost at the speed of light: $v_l = \omega_r/(k_r + k_w)$, where $\omega_r = k_r c = 2\pi c/\lambda_r$ with c the speed of light in vacuum and λ_r the FEL wavelength; and $k_w = 2\pi/\lambda_w$ with λ_w the undulator period. During the exponential growth, the FEL group velocity is $v_g = \omega_r/(k_r + 2k_w/3)$ [4]. Hence around the saturation point, the FEL spike can only advance locally with a distance of $l_{slip} \sim 20\lambda_r L_G/(3\lambda_w)$ with respect to the local electrons which are coincident with it at the undulator entrance. Here, L_G is the FEL power gain length, and the FEL exponential growth saturates around $20L_G$. Indeed, the light within this slippage length l_{slip} has phase and amplitude correlation, and the well known coherence length is $l_{coh} = 2\pi l_{coop} = 2\pi L_G\lambda_r/\lambda_w \approx l_{slip}$. For LCLS with $\lambda_r = 1.5$ Å FEL normal operation, $L_G \sim 4.5$ m, and $\lambda_w = 3$ cm, the coherent length is only about $l_{coh} = 0.15$ μm, *i.e.*, about 0.5 fs. The electron bunch which drives the FEL is about 50 fs long FWHM, so there are about 100 spike, and each spike is coherent. If we can decrease the electron bunch duration to the one coherent spike duration, the single spike FEL radiation will automatically guarantee a good temporal coherence [5]. To improve the temporal coherence, the most popular approach is the external seeding. However, to reach hard x-ray, due to the fact that there is no hard x-ray Laser seed, one has to invoke various harmonic generation schemes [6, 7]. Yet, it is difficult to reach hard x-ray because of the coherence degradation during the harmonic generation process. One way to overcome this is to insert a monochromator in the SASE FEL undulator system to configure the so-called self-seeding scheme [8, 9]. In this approach, the first part of the undulator system works as a normal SASE FEL, which is purified after passing the monochromator. The purified seed then rejoins the electron bunch and is amplified to saturation in the second part of the undulator system. In those external seeding (including the harmonic generation) and self-seeding schemes, the longitudinal coherence is introduced externally, but not built up during the FEL process.

To control the FEL spectrum during the FEL process, one will have to manipulate the cooperation length l_{coop}, the coherent length l_{coh}, or the slippage length l_{slip}. One approach is to follow those used in mode-locked broad bandwidth cavity lasers. A set of axial modes in the SASE FEL can be combined by applying a series of spatiotemporal shifts between the FEL pulse and the electron bunch. These shifts are achieved by repeatedly delaying the electron bunch using phase shifter (*e.g*, magnetic chicanes) between undulator modules [10, 11]. The phase shifter will provide additional "slippage", so that the FEL pulse can develop correlations with the electrons even more in front of it. This additional "slippage" occurring in the phase shifter between the undulator modules lengthens the spatiotemporal coupling range as compared to that of the simple SASE case, increasing both the cooperation and coherence lengths of the FEL process. Besides this geometric enhancement, the optical-klystron-type of gain enhancement also increases the cooperation length. Let us term the lengthened coherent length as $\hat{l}_{coh}$. For equal, periodic delays, the radiation spectrum develops discrete frequencies similar to the axial modes of a conventional laser. These modes are intrinsically coupled via their collective interaction within the electron bunch over regions of $\hat{l}_{coh}$ within which a series of regularly spaced radiation spikes of approximately equal width $\ll \hat{l}_{coh}$ may evolve. However, if $\hat{l}_{coh}$ is shorter than the electron bunch length, there are still more than one longitudinal mode. To do an even better job, one can introduce an interaction modulation at the mode frequency spacing $\Delta\omega_s$. Such periodic modulation can be a coherent modulation of the input electron bunch energy [11], or the density on the current profile [12]. A set of axial modes with mode space $\Delta\omega_s$ equal to the frequency of the introduced modulation will be phase locked. Each mode acquires sidebands that overlap neighboring modes.

After exploring the approaches above, we reemphasize here that in order to generate a narrow bandwidth FEL, one can introduce phase shifters (*e.g.*, magnetic chicane) in the breaks between undulator modules so that additional slip-

* Work supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract DE-AC02-76SF00515.

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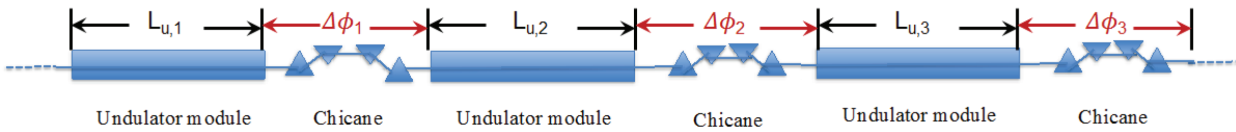

Figure 1: Illustration of implementing phase shifter (*e.g.*, a magnetic chicane) between undulator modules.

page is introduced between the FEL pulse and the electron bunch. Within this lengthened slippage distance, electric field phase and amplitude correlation within the FEL pulse is developed due to the gain mechanism. Hence, the coherence length is longer and the FEL pulse spectral bandwidth is narrower than that based on a conventional, simple SASE scheme. However, if the reason why the FEL pulse spectral bandwidth shrinks is due to the lengthened slippage distance, then it is not necessary that we need periodic and equal phase slippage in the phase shifters along the undulator modules, but rather perform a general phase slippage enhancement scheme as illustrated in Fig. 1. In such a scheme, the first undulator module with length $L_{u,1}$ is used to establish the FEL, therefore, $L_{u,1}$ should be a few power gain length long. Once the FEL signal is well established, the FEL and electron bunch traverse the first interruption, where the electron bunch will go through the phase shifter, (*e.g.*, a magnetic chicane in this example), so that the electron bunch acquires a phase delay of $\Delta\phi_1$ with respect to the FEL pulse which takes a straight path. The delayed electron bunch recombines with the FEL pulse in the second undulator module, where each coherent spike within the FEL pulse will interact with a new set of electrons; while the electrons which were interacting with a particular coherent spike within the FEL pulse will generate a new coherent spike within the FEL pulse. This is illustrated as the second row in Fig. 2, the new set of electrons and the new coherent spike within the FEL pulse are both shown in the box with dashed line boundary. In Fig. 2, the long green ellipse stands for the electron bunch, while the red pulse stands for a typical coherent spike within the FEL pulse. The new set of electrons and the new coherent spike together with the set of electrons and the coherent spike interacting in the previous undulator module ($L_{u,1}$) will go through the FEL interaction again in the second undulator module ($L_{u,2}$). The second undulator module ($L_{u,2}$) should be long enough for the signal to be well established through the FEL exponential growth, so that roughly speaking, the new coherent spike should have power similar to the coherent spike generated in the previous undulator module. The local FEL process with a lengthened FEL spike and a lengthened set of electrons is shown as the third row in Fig. 2. Notice that, the cooperation length in the second row is twice of that in the first row, while the coherent length in the third row is twice of that in the second row. Hence, the cooperation length or the coherent length is increasing geometrically with an ideal model. As shown in Fig. 1, this process will continue in the third undulator module ($L_{u,3}$) for the FEL signal to be well established

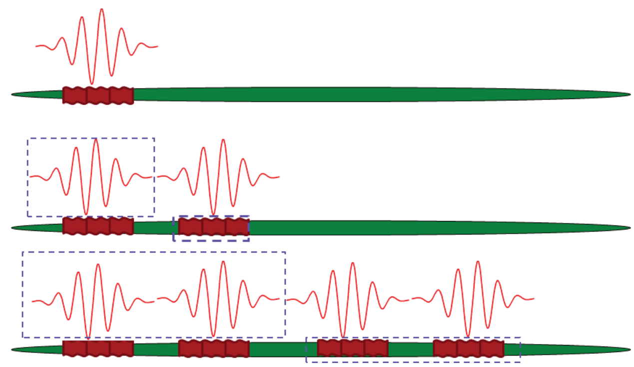

Figure 2: Schematic plot of a geometrically increasing cooperation length or coherence length.

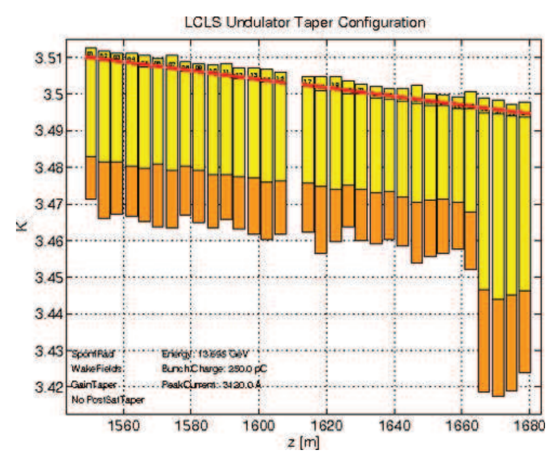

Figure 3: Undulator setup for SASE experiment at LCLS.

and for the electron bunch to acquire a phase delay of $\Delta\phi_3$. Such processes continue until the total slippage is comparable to the electron bunch duration. At such stage, a narrow bandwidth FEL pulse is generated. In general, we have to optimize the values of $L_{u,i}$ for $i = 1, \cdots, N_u$, and $\Delta\phi_i$ for $i = 1, \cdots, N_u - 1$ to generate a FEL pulse with a minimum bandwidth and a maximum power. The optimization is beyond the scope of this talk and will be reported elsewhere [13]. A particular scheme with an equal $L_{u,i}$ for $i = 2, \cdots, N_u$ and $\Delta\phi_{i+1} = 2\Delta\phi_i$ for $i = 1, \cdots, N_u - 2$ was reported in FEL'12 conference [14].

Experiment

At LCLS, there is no phase shifter between the undulator modules. To do a proof-of-principle experiment, we largely detune certain undulator segments, whose undula-

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ISBN 978-3-95450-122-9

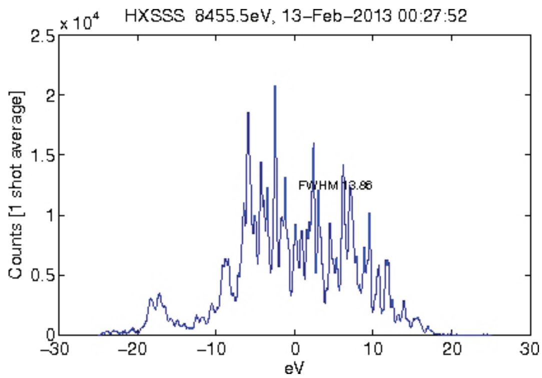

Figure 4: A SASE FEL spectrum with undulator in Fig. 3.

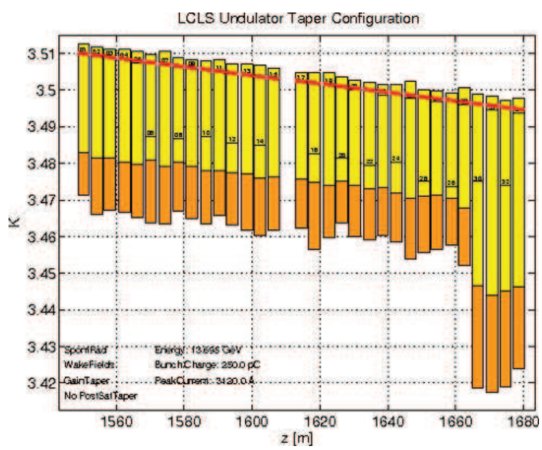

Figure 5: Undulator setup for iSASE experiment at LCLS.

tor strength K is very different from that determined by the resonant condition, so that it is out of the FEL amplification bandwidth. Therefore, rather than amplifying the FEL signal, such largely detuned undulator segments provide phase delay to the electrons with respect to the FEL pulse. During the experiment, we first setup undulator system for a regular SASE FEL as in Fig. 3. Each vertical bar stands for a undulator segment with the yellow region for magnetic field well calibrated and the orange region

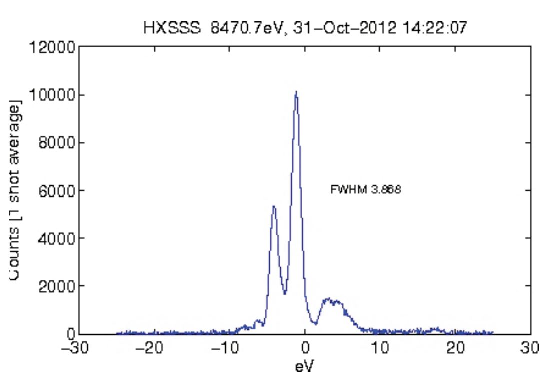

Figure 6: An iSASE FEL spectrum with undulator in Fig. 5.

less calibrated. The 16^{th} undulator segment was removed for the self-seeding experiment; hence, the location for the 16^{th} bar is empty. The red straight line stands for the undulator K desired value for each undulator segment. The black short segment line almost onto the red line is the real time value of the undulator K setting for that particular segment. The slope of the red line indicating a decreasing K value to maintain the resonant condition, since the electron bunch is losing energy due to the spontaneous undulator emission, the undulator wakefield effect, and of course the FEL process. The experiment was conducted for electron bunch having charge of 150 pC, and compressed to about 3 kA peak current. Given the undulator setup as in Fig. 3, a typical single shot SASE FEL spectrum with FWHM bandwidth of about 14 keV is shown in Fig. 4. Now, we keep the first 5 undulator segments to establish the FEL signal. From the 6^{th} undulator segment on, the even number undulator segments are largely detuned as the black short line segment on each vertical bar. The relative separation $\Delta K/K \sim 0.5\%$, hence $\Delta\lambda/\lambda \sim 1\%$ is much larger than the FEL parameter ρ. Therefore, these even number undulator segments won't be able to amplify the signal established in the first 5 undulator segments. Instead, these undulator segments are providing additional phase shifter, therefore lengthening the cooperation length. This undulator configuration then sets up an iSASE FEL. A typical iSASE FEL spectrum with FWHM bandwidth of about 4 keV is shown in Fig. 6. By comparing the iSASE spectrum in Fig. 6 to the SASE spectrum in Fig. 4, one can find that a factor of 3.5 decrement in the FEL spectral bandwidth is realized with this poor man's set up for an iSASE FEL. We are grateful to T.O. Raubenheimer and G.V. Stupakov for suggesting the use of detuned LCLS undulator modules as delay elements, to Z. Huang, A.W. Chao, S. Reiche, Y. Cai, and J. Welch for many useful discussions and comments.

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