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COHERENCE TIME CHARACTERIZATION FOR SELF-AMPLIFIED SPONTANEOUS EMISSION FREE-ELECTRON LASERS*

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Abstract

One of the key challenges in scientific researches based on free-electron lasers (FELs) is the characterization of the coherence time of the ultra-fast hard x-ray pulse, which fundamentally influences the interaction process between x-ray and materials. Conventional optical methods, based on autocorrelation, is very difficult to realize due to the lack of mirrors. Here, we experimentally demonstrate a conceptually new coherence time characterization method and a coherence time of 174.7 attoseonds has been measured for the 6.92 keV FEL pulses at Linac Coherent Light Source. In our experiment, a phase shifter is adopted to control the cross-correlation between x-ray and microbunched electrons. This approach provides critical temporal coherence diagnostics for x-ray FELs, and is decoupled from machine parameters, applicable for any photon energy, radiation brightness, repetition rate and FEL pulse duration, etc.

INTRODUCTION

Hard x-ray free-electron laser (FEL) [1–5] opens the door to a new era of x-ray experiments in various research fields, e.g., physics [6], chemistry [7], life [8] and material sciences [9]. Combined with ultra-short duration, refined resolution, high photon flux, hard x-ray FELs become powerful tools to capture simultaneous information on atomic structure and dynamics. At present, most of the hard x-ray FELs are operated in self-amplified spontaneous emission (SASE) scheme, in which spontaneous radiation from the electron beam is amplified along the magnetic field in undulators. Due to starting from electron shot noise, SASE FELs usually are generated with imperfect temporal coherence corresponding to temporal isolated spikes [10]. As one of the fundamental characteristics of the x-ray pulse, pre-known information about x-ray coherence time would potentially benefit experiments including but not limited to, ionization dynamics, spectro-holography [11], nonlinear mixing-wave experiment [12], etc. Hence, there is a growing demand for the community to develop a time-domain coherence time characterization method for the ultra-fast hard x-ray pulses.

For FEL coherence time characterization, the most straight forward way is to directly implement conventional optical method, autocorrelation. Autocorrelation is a widely used method for coherence time characterization for optical radiation pulses. However, the autocorrelation itself has a strong dependence on the mirrors to control optical delays, which, in turn, limits the photon energy range of its application. Although it has been proved that a combination of laser beam splitter and mirror based optical delay can be used to implement autocorrelation to characterize the FEL coherence time in the extreme ultraviolet and soft x-ray regime [13, 14], different from its implementation in these two scenarios, the autocorrelation is difficult to realize in hard x-ray regime due to the lack of mirrors. Meanwhile, x-ray pulse duration characterization method based on FEL dynamics has been well established recently [15, 16]. However, in this case, the coherence information is not included in the cross- correlation since the electrons are almost 'fresh'. Here, we further develop this idea to characterize the coherence time of hard x-ray FEL pulses by using the cross-correlation between the x-rays and microbunched electron beam.

In this work, we report the first direct measurement result of the coherence time of ultra-fast hard x-ray FEL pulses through a conceptually different approach. In this method, the temporal coherence characteristics of the x-ray pulses are mapped to the cross-correlation between the microbunched electron beam and the x-ray pulse and then the corresponding coherence time can be obtained by decoding the information from the measured cross-correlation.

METHOD

Figure 1 depicts how this coherence time characterization method works, where the whole undulator system is considered as two parts, the first part is used for SASE FEL generation and the second part works on converting the correlation to x-ray pulse energy. The phase shifter between these two parts is employed to manage the delay between the x-ray pulse and the microbunched electrons to control the correlation.

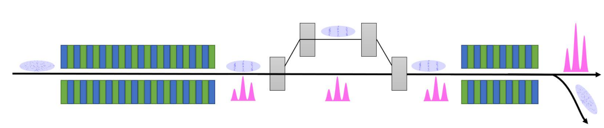

Figure 1: Schematic description of hard x-ray SASE FEL coherence time characterization based on cross-correlation between microbunched electrons and x-ray pulse.

In the SASE FEL, a bunch of highly relativistic electrons are injected into a periodically varying magnetic field, known as undulator. While traveling through the undula-

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tor, the electrons are forced to wiggle transversely and emit spontaneous radiation. This process produces ultra-short bursts of x-rays at the wavelengths,$\lambda_r = \frac{\lambda_u}{2\gamma^2}(1 + a_u^2)$, where λ_u is the undulator period, γ is the electron beam Lorentz factor and a_u is the RMS undulator parameter.

Due to the on-axis speed difference between the electrons and x-rays, there is a natural slippage between the electrons and x-rays (slippage effect). While the electron beam traveling through the undulator, the slippage effect becomes stronger and stronger. This increasing slippage l_s between x-rays and electrons determines the cooperate-interaction range of them and drives coherence spike development. Hence, within cooperate-interaction range, the x-ray and electrons should have a strong correlation [17]. Since these coherence spikes are all evolved from shot noise, x-rays and electrons in different coherence spikes should not have clear correlation. Now, it is clear that the coherence time of the FEL pulse is determined by the length of the temporal coherence spike.

By employing a phase shifter to control the delay between the microbunched electrons and the x-rays, we can control the correlation between them. Then, additional undulators after the phase shifter, about one FEL gain length, can be used to convert the correlation to x-ray pulse energy, which can be measured by gas detector (shot to shot FEL pulse energy measurement element [18]). It can be expected that, the pulse energy should oscillate corresponding to the delay with an decaying oscillation amplitude. The pulse energy oscillation comes from the phase mismatch between the microbunched electrons and x-rays in the scale of x-ray wavelength, similar to two-wave interference. And the decaying amplitude comes from the shrinking correlation, in the scale of coherence time. According to this, we can infer that there is an oscillation amplitude diminishing point after which the amplitude is negligible. This feature of SASE FEL can be used to experimentally characterize the coherence time of hard x-ray pulses.

This process can be described with the well-known one-dimensional model analytically. Following the method in Ref. [19], universally scaled collective variables are induced to describe the FEL dynamics. The normalized radiation field is defined as $A = E/(4\pi mc^2\gamma\rho n_e)^{1/2}$ where E is the radiation field, m is the electron mass, c is the speed of light, n_e is the electron beam density and $\rho = (a_u\omega_p/4ck_u)^{2/3}/\gamma$ is the Pierce parameter, with $\omega_p = (4\pi e^2 n_e/m)^{1/2}$, the plasma frequency and $k_u = 2\pi/\lambda_u$, the undulator wave number. And the bunching factor can be defined as $B = \frac{1}{N_\lambda}\sum_{j=1}^{N_\lambda} e^{-i\theta_j}$, where $\theta_j = (k_u + k_r)z - ck_r t_j$ is the ponderomotive phase, k_r is the radiation wave number, z is the coordinate along the undulator axis, t_j is time and N_λ is the number of electrons within one radiation wavelength λ_r. Considering the part before the phase shifter, it is a typical high-gain SASE FEL process. Since we mainly care about the phase relationship between the radiation and microbunching in the time domain, the steady state model in the following is good enough to describe the FEL dynamics,

$$\begin{aligned}\frac{\partial A(\overline{z},t)}{\partial \overline{z}} &= B(\overline{z},t)\\ \frac{\partial^2 B(\overline{z},t)}{\partial \overline{z}^2} &= iA(\overline{z},t)\end{aligned} \tag{1}$$

where the normalized coordinate variables is introduced, $\overline{z} = z/l_g$, with $l_g = \lambda_u/4\pi\rho$, the gain length. Since the SASE FEL starts from shot noise, only the noisy bunching factor is considered as the initial condition, which means only $B(0,t) \neq 0$.

For the part of phase shifter, we only consider the delay effect rather than the phase space sketch induced by the R_{56} of the phase shifter, which is quite small compared with the radiation wavelength due to small electron beam modulation and R_{56}. If we note the radiation field and bunching factor at the end of the undulator, also the phase shifter entrance, as $A_s(\overline{z}_p,t)$ and $B_s(\overline{z}_p,t)$, where $\overline{z}_p$ is the position of phase shifter, the radiation field and bunching factor at the end of the phase shifter would be $A_s(\overline{z}_p,t)$ and $B_s(\overline{z}_p,t+\Delta t)$ respectively, where Δt is the delay induce by the phase shifter. Here, we suppose the phase shifter length is neglectable. For the after-delay part, we use a short radiator to convert the correlation between the microbunched electron beam and the x-ray to pulse energy. We can regard the process in the after-delay part as coherent emission, since the radiator length is not sufficient long for high-gain effects. During coherent emission, the electron beam bunching factor can be regarded as a constant and the radiation field keeps increasing. Namely, only the first equation in Eq. (1) is valid with the bunching term as a constant. In this way, we get the radiation field $A_c(\overline{z},t)$ at the end of the radiator as,

$$A_c(\overline{z},t) = A_s(\overline{z}_p,t) + B_s(\overline{z}_p,t+\Delta t)(\overline{z} - \overline{z}_p) \tag{2}$$

It is a good approximation that the SASE radiation field at the entrance of the phase shifter is a superposition of a bunch of Gaussian-envelop plane waves with different random relative phases, and intensity centers and similar variances which can be expressed as

$$A_s(\overline{z}_p,t) = \sum_{j=1}^{n} A_j e^{-\frac{(t-t_j)^2}{4\sigma_t^2}} e^{i(\omega t+\phi_j)} \tag{3}$$

Based on Eq. (3) and Eq. (2), the variance of the pulse energy can be obtained by,

$$\overline{(W-\overline{W})^2} = 4\pi\sigma_t^2\Big(\sum_{j=1}^{n} A_j^2\Big)^2 e^{-\frac{\Delta t^2}{4\sigma_t^2}} \tag{4}$$

where m is a small integer. Hence, by calculating the variance of the pulse energy in several wavelengths, we can obtain the value of σ_t by Gaussian fitting. According to the definition of coherence time by first-order time correlation function,

$$\begin{aligned}\tau_c &= \int_{-\infty}^{\infty} \Big|\frac{< A_c(t)A_c^*(t+\tau) >}{\sqrt{< |A_c(t)|^2 >< |A_c(t+\tau)|^2 >}}\Big|^2 d\tau\\ &= \sqrt{4\pi}\sigma_t\end{aligned} \tag{5}$$

the coherence time of the x-ray pulse can be resolved.

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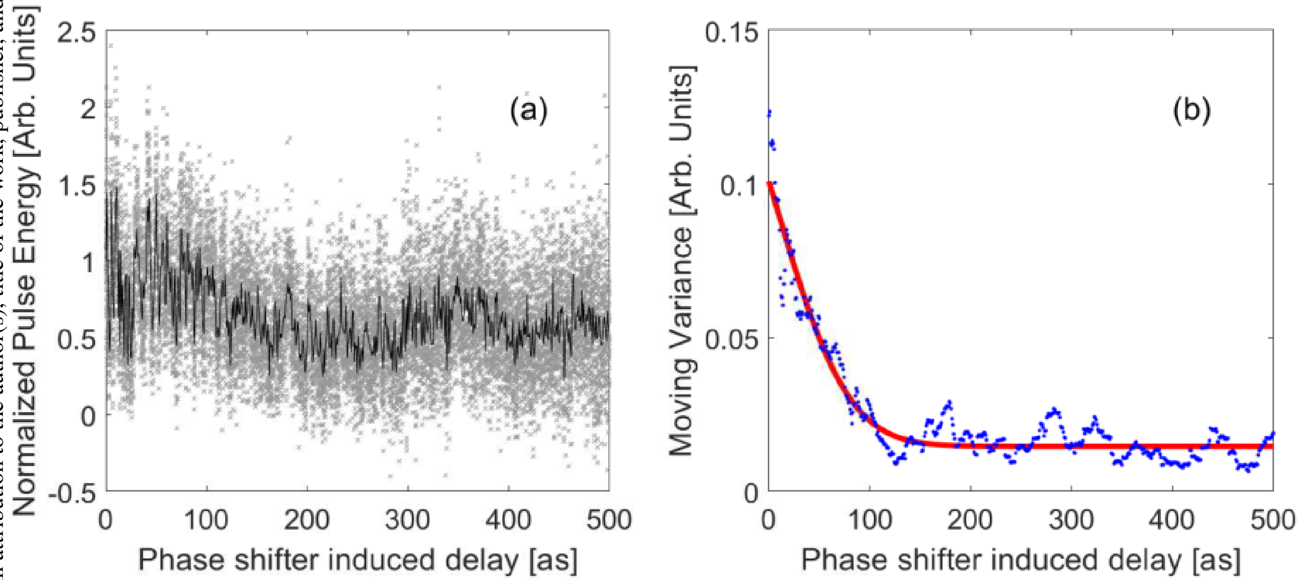

Figure 2: Experimental results of hard x-ray SASE FEL coherence time measurement at LCLS: a) Pulse energy versus delay, in which the black line is the average pulse energy for each delay and the grey points represent for single-shot pulse energy. b) Moving variance with respect to delay, where blue points are obtained by Eq. (4) in Method and the red line is the fitting curve.

EXPERIMENT

We experimentally carry out the experiment to measure the coherence time of hard x-ray pulses at Linac Coherent Light Source with the method we propose above. The experimental setup is based on the normal LCLS SASE FEL configuration [20]. The hard x-ray self-seeding chicane is employed as the phase shifter. And the gas detector is used to record the x-ray pulse energy [18]. By distorting the electron beam orbit with quadroples, we can control the after-delay FEL interaction length to maximize the contrast of the pulse energy oscillation. Hysteresis-loop of magnets has also been carefully considered. Due to the accuracy of the driving current for the magnetic field of chicane, the step size of the delay scan is set to 0.875 attosecond and the total scan range is set to 520 attoseconds according to the coherence time estimation based on analytical works [21]. And to avoid the stochastic effects in the experiment as much as possible, we record 25 shots of FEL pulses for each delay and use the average value of effective shots to represent the pulse energy for corresponding delay. The photon energy is tuned to be 6.92 keV, the corresponding electron beam energy is 12.48 GeV and the current is around 3500 A.

The measured pulse energy versus delay is shown in Fig. 2(a), in which the black curve is the average pulse energy over effective shots and the grey points are the pulse energy for each shot. According to Eq. (4) in Method, we employ moving variance to extract the oscillation amplitude from the recorded pulse energy and use Gaussian-like function $(Aexp((t-t_0)^2/2\sigma^2)+C)$ to fit the data to obtain the value of σ_t, in which C is used to get rid of unexpected experimental noise. The blue line in Fig. 2(b) shows the decaying oscillation amplitude and the red line is the Gaussian-like fitting curve. According to the fitting results, the σ_t is 49.05 attoseconds and the corresponding coherence time is 174.7 attoseconds (see Method, Eq. (5)).

CONCLUSION

In conclusion, we first directly in time domain measure the coherence time of ultra-fast hard x-ray pulses with a conceptually new approach we proposed. The method itself fills the vacancy of coherence time characterization in time domain in the spectrum of hard x-ray for FELs. Looking forward, the pre-knowledge of coherence time of the x-ray pulse would potentially benefit experiments working on ultra-fast dynamics, structure imaging and spectrum phase reconstruction. It should be noted that the measured temporal coherence length is an average result of thousands of FEL shots. It shows the overall longitudinal property of radiation beam based on the current FEL setup rather than a single shot. The method itself making use of FEL physics, which means it be can be applied to any high-gain FEL regime, like high repetition facilities [22], ultra-fast FEL [23].

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