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MEASUREMENT OF SHORT-WAVELENGTH HIGH-GAIN FEL TEMPORAL COHERENCE LENGTH BY A PHASE SHIFTER

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Abstract

Short-wavelength high-gain free-electron lasers (FELs) are now well established as ultra-fast, ultra-bright, longitudinally partial coherent sources. Since coherence is one of the fundamental properties of a light source, continuous efforts on high-gain free electron laser coherence measurements are made. In this work, we propose a possible approach, employing a phase shifter to induce electron beam delay to measure the temporal coherence length. Simple analysis, numerical simulation and preliminary experimental results are presented. This approach can be robust and independent of frequency.

INTRODUCTION

Free-electron lasers (FELs) greatly benefit fundamental research in physics, chemistry, materials science, biology, and medicine by producing intense tunable radiation ranging from the infrared to hard x-ray region [1]. Approaches like coherent x-ray diffraction imaging (CXDI), x-ray holography and nano-crystallography promise important new insights in biology, condensed matter physics and atomic physics [2]. Therefore, coherence property plays an important role in these experiments. Furthermore, [3-4] indicate that small deviations from perfect coherence can be considered in the CXDI method if the degree of coherence is known. Thus, a pre-knowledge of FEL coherence properties would help.

Young's experiment [5] is one of the most widely used methods for characterization of coherence, the transverse coherence properties could be measured with the interference pattern. Previous work regarding measurements of transverse coherence properties of FEL sources has been done earlier [6-8]. The other important statistical characteristic of the FEL radiation is its temporal coherence. Due to the FEL instabilities leading to partial coherence, the FEL pulses are not fully coherent in the time domain. In addition, the slippage effect in FEL results in the radiation pulse consisting of several spikes with a width of about the temporal coherence length. These longitudinal modes can be correlated and interfere with each other, which affects the temporal coherence length, which was recently observed experimentally [9]. Several optical methods are proposed to measure the FEL temporal coherence length. In the extreme ultraviolet regime, the feasibility of autocorrelation methods using laser beam splitter has been proved in [10]. Experimental measurement employing two-beam interference, analyzing the contrast of these interference fringes to get the temporal coherence length has been reported [11].

In this paper, we make use of high-gain FEL process to measure temporal coherence length. By introducing phase difference between the radiation field and the electron beam, the resultant radiation field can be represented by two waves with a constant phase difference, in which two-wave temporal interference should be expected [see Theory Section]. Based on this analysis, we propose a possible approach to measure the FEL temporal coherence length. In the theory part, we obtain solutions of high-gain FEL including phase shift in time domain. We further prove the feasibility of our approach with supports of numerical simulation. In the on-going experiment part, preliminary experimental results at Linac Coherent Light Source (LCLS) are presented and further experimental investigation is on our schedule.

THEORY

Following [12], we start from a one-dimension linear model described by:

$$\frac{\partial A(\bar{z},\bar{s})}{\partial \bar{z}}+\frac{\partial A(\bar{z},\bar{s})}{\partial \bar{s}}=B(\bar{z},\bar{s}), \tag{1}$$

$$\frac{\partial B(\bar{z},\bar{s})}{\partial \bar{z}}=P(\bar{z},\bar{s}), \tag{2}$$

$$\frac{\partial P(\bar{z},\bar{s})}{\partial \bar{z}}=iA(\bar{z},\bar{s}). \tag{3}$$

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In these equations, $\bar{z} = z/l_g$, $\bar{s} = -c(t-z/v_z)/l_c$, where z is the coordinate along the undulator axis, $\bar{s}$ is the scaled position along the bunch, v_z is the electron velocity in the z direction, and $l_g = \lambda_u/4\pi\rho$ and $l_c = \lambda_s/4\pi\rho$ are the gain length and the cooperation length, respectively. The other quantities are: λ_u, the wiggler period; λ_s, the radiation wavelength (satisfying the well-known resonance relation $\lambda_s = \lambda_u(1+a_u^2)/2\gamma^2$); A, the dimensionless field amplitude $E_0/(4\pi mc^2\gamma_0 n_e\rho)^{1/2}$ (which uses the average initial electron energy $mc^2\gamma_0$, beam density $n_e = I/ec\sigma$, and FEL parameter ρ [13]); B, the bunching parameter $\langle e^{-i\theta_j}\rangle$ (where the electron phase $\theta_j = (k_s + k_u)z - ck_st_j$); and P, the average momentum $\langle \eta_j e^{-i\theta_j}\rangle$ (where η_j is the normalized energy deviation $(\gamma_j-\gamma_0)/\rho\gamma_0$).

Note that Eqs. (1-3) have been obtained from linearizing the Compton FEL equations [13], based on coasting beam approximation, and describe the exponential growth of the signal in the high-gain regime prior to saturation.

To solve Eqs. (1-3), we first Fourier transform $\bar{s}$ to Δ,

$$\frac{\partial a(\bar{z},\Delta)}{\partial \bar{z}} + i\Delta a(\bar{z},\Delta) = b(\bar{z},\Delta), \tag{4}$$

$$\frac{\partial b(\bar{z},\Delta)}{\partial \bar{z}} = p(\bar{z},\Delta), \tag{5}$$

$$\frac{\partial p(\bar{z},\Delta)}{\partial \bar{z}} = ia(\bar{z},\Delta), \tag{6}$$

where $a(\bar{z},\Delta)$, $b(\bar{z},\Delta)$ and $p(\bar{z},\Delta)$ are the Fourier transform of $A(\bar{z},\bar{s})$, $B(\bar{z},\bar{s})$ and $P(\bar{z},\bar{s})$ respectively. By assuming that $a(\bar{z},\Delta)$ is proportional to $e^{i\mu\bar{z}}$, we obtain the cubic equation,

$$\mu^3 - \Delta\mu^2 + 1 = 0. \tag{7}$$

Solving the eigenvalue in Eq. (7) to the first order of Δ and considering that the exponential gain will dominate the process, we obtain that $\mu = \frac{-\sqrt{3}}{2}i + \frac{1}{2} + \frac{\Delta}{3}$. After some proper approximation, the solution of these equations in frequency domain should be:

$$a(\bar{z},\bar{s}) = \frac{1}{3}[a(0,\Delta) + (-\frac{1}{2}\mathrm{i} + \frac{\sqrt{3}}{2})b(0,\Delta) + (\frac{1}{2} - \frac{\sqrt{3}}{2}i)p(0,\Delta)]e^{\frac{\sqrt{3}}{2}\bar{z} + (\frac{\Delta}{3}+\frac{1}{2})i\bar{z}}. \tag{8}$$

With inverse Fourier transform, we obtain the radiation field in time domain,

$$A(\bar{z},\bar{s}) = \frac{1}{3}[A(0,\bar{s}+\frac{\bar{z}}{3}) + (-\frac{1}{2}\mathrm{i} + \frac{\sqrt{3}}{2})B(0,\bar{s}+\frac{\bar{z}}{3}) + (\frac{1}{2} - \frac{\sqrt{3}}{2}i)P(0,\bar{s}+\frac{\bar{z}}{3})]e^{\frac{\sqrt{3}}{2}\bar{z} + \frac{i}{2}\bar{z}}. \tag{9}$$

The electric field at position $(\bar{z},\bar{s})$ is driven by the initial electric field A, bunching B, energy modulation P, at $\bar{s} + \bar{z}/3$ with exponential gain and $l_c = l_c\bar{z}/3 = N\lambda_s/3$ is the approximate temporal coherence length, where N is total number of undulator periods.

To add a phase shifter located at z_0, we assume that a sudden slippage is induced at z_0. Mathematically, this can be regarded as $B(\bar{z},\bar{s})$ and $P(\bar{z},\bar{s})$ in Eqs. (1-3) replaced by $B(\bar{z}, \bar{s}+\delta\bar{s})$ and $P(\bar{z}, \bar{s}+\delta\bar{s})$, so that we can get the equations to describe the FEL process including a phase shifter:

$$\frac{\partial A(\bar{z},\bar{s})}{\partial \bar{z}} + \frac{\partial A(\bar{z},\bar{s})}{\partial \bar{s}} = B(\bar{z},\bar{s}+\delta\bar{s}), \tag{10}$$

$$\frac{\partial B(\bar{z},\bar{s}+\delta\bar{s})}{\partial \bar{z}} = P(\bar{z},\bar{s}+\delta\bar{s}), \tag{11}$$

$$\frac{\partial P(\bar{z},\bar{s}+\delta\bar{s})}{\partial \bar{z}} = iA(\bar{z},\bar{s}+\delta\bar{s}). \tag{12}$$

Similarly, we can solve Eqs. (10-12) to obtain the solution of radiation field in time domain:

$$A(\bar{z},\bar{s}) = \frac{1}{3}\{A(\bar{z}_0,\bar{s}+\frac{\bar{z}}{3}) + [(-\frac{1}{2}\mathrm{i} + \frac{\sqrt{3}}{2})B(\bar{z}_0,\bar{s}+\frac{\bar{z}}{3}) + (\frac{1}{2} - \frac{\sqrt{3}}{2}i)P(\bar{z}_0,\bar{s}+\frac{\bar{z}}{3})]e^{ik_s\delta\bar{s}}\}e^{\frac{\sqrt{3}}{2}\bar{z} + \frac{i}{2}\bar{z}}. \tag{13}$$

For Eq. (13), we can regard $A(\bar{z},\bar{s})$ as two waves with a constant phase difference $k_s\delta\bar{s}$. It is expected that there exists an interference phenomenon. If we change the phase difference within a small range, e.g. within 2π, we could find the radiation power oscillates with respect to the phase difference. However, if the phase difference is too large (greater than the temporal coherence length), the phase correlation between the two waves is destroyed. In this case, the two waves are no longer coherent. Therefore, by continuous scanning the phase difference and measuring the radiation power, we can obtain the FEL temporal coherence length. We could expect that the envelope of FEL power as a function of phase difference should gradually shrink.

NUMERICAL SIMULATION

In the previous section, we propose a possible approach to measure the temporal coherence length by tuning the phase shifter. To further investigate the feasibility, we have done some numerical simulations with GENESIS, a well-benchmarked, three dimensional, time-dependent FEL simulation code [14]. To more precisely simulate the FEL process with relatively large phase shift, we made some modifications on its source code. Because the large-scale GENESIS time-dependent simulations are computational intensive, we only sample five points (0, $\pi/2$, π, $3\pi/2$, 2π) within 2π (induced slippage is one wavelength) and then skip 32 wavelengths to sample another five points. In the simulation, we use LCLS parameters [15]

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listed in Table 1. Schematic LCLS undulator system is illustrated in Fig. 1 and hard x-ray self-seeding (HXRSS) chicane at Section 16 is employed as the phase shifter. The simulation results are shown in Fig. 2, in which the interference pattern can be clearly seen.

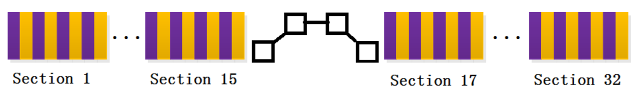

Figure 1: LCLS undulator system, the phase shifter is placed at Section 16.

Table 1: Main Parameters of LCLS for simulation

Parameter	Value
Radiation wavelength	0.2755 nm
Electron beam energy	10.1 GeV
RMS Undulator parameter	2.475
RMS Relative energy spread	1.29×10^{-4}
Normalized emittance	4×10^{-7} m
Undulator period	3 cm
Peak current	3.5kA

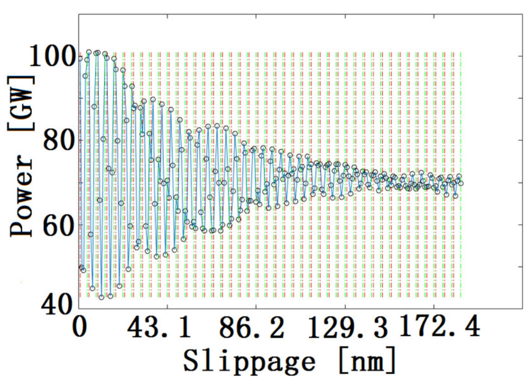

Figure 2: The radiation power as a function of slippage length. Every five points illustrate a wavelength, which is zoomed in. The wavelengths that we did not scan are zoomed out, shown as the space between the green line and red line.

In our case, the temporal coherence length is about $N\lambda_s/3$~151.53 nm, where N is total number of undulator periods. At the end of the 15th undulator, N is equal to 1650. From Fig. 2, we can find that the temporal coherence length is roughly about 150 nm.

ON-GOING EXPERIMENTAL EFFORTS

Since the analysis and simulation results are quite promising, we have done some preliminary experiments. Based on LCLS machine parameters shown in Table 1, we use HXRSS chicane as phase shifter and gas-detector to measure the FEL pulse energy. We change the magnetic field strength of the chicane to scan phase difference and measure multi-shot averaged FEL pulse energy. Figure 3 shows the experimental results.

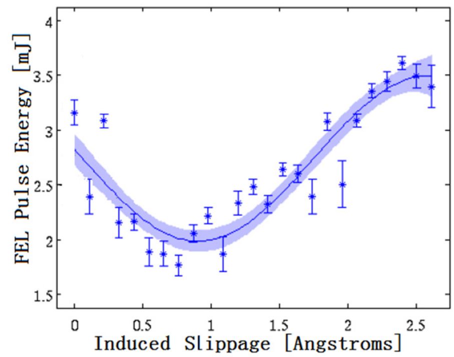

Figure 3: The FEL pulse energy as a function of slippage length.

At this point in time, we have scanned the phase difference within 2π. The experimental results agree with our analysis and simulation well. It is worth to point out that this approach is frequency-independent.

SUMMARY AND OUTLOOK

In this paper, we have presented a simple analysis of FEL including a phase shifter in time domain. We find that when phase difference is quite small, FEL power oscillates with respect to the electron beam delay. However, when the phase difference is greater than the temporal coherence length, the radiation would not change much. Based on the analysis, we propose an approach to measure the FEL temporal coherence length by scanning the electron beam delay. Numerical simulation and preliminary experiments at LCLS show that this approach can be potentially developed to measure the FEL temporal coherence length. Effects of the momentum compact factor R_{56} on temporal coherence will be presented in further studies and the experiments using this approach to measure the FEL temporal coherence length at LCLS is on our schedule. Also, this study will help us understand the performance of slippage enhanced SASE.

REFERENCES

[1] E. Hemsing, G. Stupakov, D. Xiang, and A. Zholents, *Rev. Mod. Phys.*, vol. 86, p. 897, 2014.

[2] A. Singer *et al.*, "Spatial and temporal coherence properties of single free-electron laser pulses," *Opt. Express*, vol. 20, p. 17480-17495, 2012.

[3] L.W. Whitehead *et al.*, “Diffractive imaging using partially coherent X-rays”, *Phys. Rev. Lett.*, vol. 103, p. 243902, 2009.

[4] B. Abbey *et al.*, “Lensless imaging using broadband x-ray sources”, *Nat. Photon*, vol. 5, p. 420-424, 2011.

[5] J. W. Goodman, *Statistical Optics*, New York, NY, USA: Wiley, 1985.

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[6] A. Singer *et al.*, “Transverse-coherence properties of the free-electron-laser FLASH at DESY”, *Phys. Rev. Lett.*, vol. 101, p. 254801, 2008.

[7] I. A. Vartanyants, A. P. Mancuso, A. Singer, O. M. Yefanov, and J. Gulden, “Coherence measurements and coherent diffractive imaging at FLASH”, *J. Phys. B: At., Mol. Opt. Phys.*, vol. 43, p. 194016, 2010.

[8] S. Roling *et al.*, “Temporal and spatial coherence properties of free-electron-laser pulses in the extreme ultraviolet regime”, *Phys. Rev. ST Accel. Beams*, vol. 14, p. 050703, 2011.

[9] W. F. Schlotter *et al.*, “Longitudinal coherence measurements of an extreme-ultraviolet free-electron laser”, *Opt. Lett.*, vol. 35, p. 372- 374, 2010.

[10] S. Roling *et al.*, "Temporal and spatial coherence properties of free-electron-laser pulses in the extreme ultraviolet regime", *Phys. Rev. ST Accel. Beams* 14, 080701, 2011.

[11] I. A. Vartanyants, “Coherence properties of individual femtosecond pulses of an X-ray free-electron laser”, *Phys. Rev. Lett.*, vol. 107, p. 144801, 2011.

[12] R. Bonifacio, L. De Salvo, P. Pierini, N. Piovella, and C. Pellegrini, “Spectrum, temporal structure, and fluctuations in a high-gain free-electron laser starting from noise”, *Phys. Rev. Lett.*, vol. 73, p. 70, 1994.

[13] R. Bonifacio, C. Pellegrini, and L. Narducci, *Opt. Commun.*, vol. 50, p. 313, 1984.

[14] S. Reiche, *Nucl. Instrum. Methods Phys. Res.*, Sect. A, vol. 429, p. 243, 1999.

[15] J. Arthur *et al.*, “Linac Coherent Light Source (LCLS) Conceptual Design Report”, SLAC, USA, SLAC–R–593, UC-414, April 2002.