Optical properties of the output of a high-gain, self-amplified free-electron laser*

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Abstract: The temporal structure and phase evolutions of a high-gain, self-amplified free-electron laser are measured, including single-shot analysis and statistics over many shots. Excellent agreement with the theory of free-electron laser and photon statistics is found.

OCIS codes: (140.2600) Free electron lasers; (030.6600) Statistical optics; (140.7090) Ultrafast lasers

1. Introduction

A self-amplified spontaneous-emission (SASE) FEL starts from the shot noise in the electron bunch. Before saturation, the output field can be approximated as the superposition of the electromagnetic wave packets emitted from randomly distributed, individual electrons with a characteristic wave-packet width of s_t [1,2]. Hence the SASE FEL behavior can be very different from a conventional laser, and it is the purpose of this paper to characterize such behavior.

2. Experiment and results

The experiment was performed at the Low-Energy Undulator Test Line [3] at the Advanced Photon Source. The main parameters for the experiment can be found in [4,5]. The SASE FEL field was measured using a frequency-resolved optical gating (FROG) device in the second harmonic configuration. An example of the raw data, along with the retrieved field intensity and phase in the time and frequency domains, is given in Fig. 1. The field is composed of multiple intensity spikes, each representing a coherence mode, and can also be understood as the result of photo bunching.

Figures 2 (a) and (b) give the probability distribution of the normalized rms spike width $x=\Delta t/\langle\Delta t\rangle$ and the spike spacing $z=\Delta t/\langle\Delta t\rangle$, where $\langle\Delta t\rangle$ = 52 fs is the average value of Δt. The average of z is found at 3.25, in close agreement with the theoretical expectation for a totally chaotic optical field at 3.5.

Since an individual intensity spike corresponds to a coherent region, the phase within the spike is correlated. In contrast, due to the lack of communication, there can be a phase jump in the transition region between two spikes. This is quantified by measuring the time derivative of the phase of the slowly varying envelope at the intensity maxima (f'_+) and minima (f'_-), shown in Figs. 2 (c) and (d). Indeed the phase drift rate is small at the intensity maxima but may be much larger at the intensity minima.

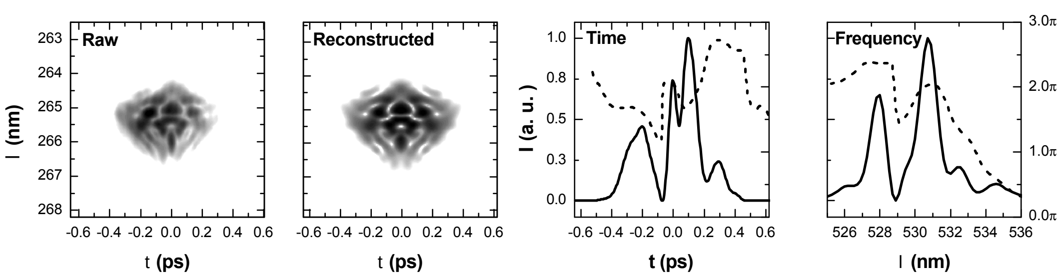

Fig. 1. A sample FROG trace with the reconstruction, and the retrieved fields in the time and frequency domains. Solid line: intensity; dashed line: phase.

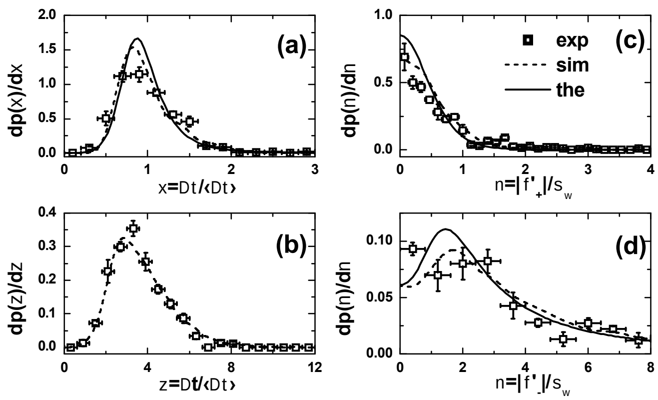

Fig. 2. Probability distribution of the normalized spike width (a) $x=\Delta t/\langle\Delta t\rangle$ and (b) the spike spacing $z=\Delta t/\langle\Delta t\rangle$; the normalized time derivative of the phase $|\phi'_{\pm}|/\sigma_{\omega}$ at intensity (c) maxima and (d) minima. Here σ_{ω} is the SASE bandwidth.

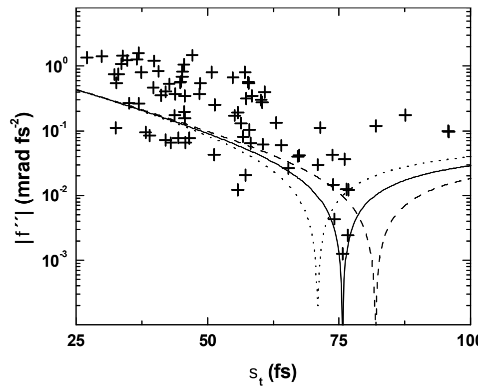

Fig. 3. Measured chirp $|\phi''|$ as a function of the spike width (pluses). The curves are fits using Eq. (1) with the effect in the collecting optics considered, where C = –24/m (dashed line), –28/m (solid line), and -33/m (dotted line).

In Fig. 2, we also show the result of a numerical simulation (dashed lines) performed using a simple model [5], as well as the result of an analytic calculation (solid line) using the method developed by Rice [6]. The agreement among the measurement, the simulation, and the analytical theory is excellent.

We also looked at the second-order phase of the FEL output. Theoretically, the chirp of each wave packet is,

$$\phi'' = \frac{1}{2\sigma_t^2\sqrt{3}} + 2C \cdot \qquad (1)$$

Here C is the energy chirp of the electron bunch normalized to the energy at time t_0. With a fixed C, the dependence on σ_t is obvious. This is illustrated in Fig. 3, which depicts the experimentally measured chirp $|\phi''|$ as a function of the spike width, which evidenced this dependency. Furthermore, a fit with Eq. (1) (plus the propagation effect in the collecting optics [4]) also reveals the dip in the distribution is caused by the cancellation between the two terms in Eq. (1) at C = -28/m (see curves in Fig. 3).

3. Conclusions

The data in Fig. 2 is a new class of experimental data on the temporal behavior of the chaotic optical field that underlies the SASE FEL output, differs from the traditional ensemble-averaged measurement in statistical optics. Figures 3 unambiguously reveals a positive intrinsic SASE and verifies that the electron beam energy chirp directly maps onto the FEL output. These measurements are important for the pulse manipulation for future X-ray FELs.

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