Laser streaking of free-electron pulses at 25 keV

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Abstract: We demonstrate an optical-field-driven streak camera for temporal characterization of ultrashort free-electron pulses with sub-ångström de Broglie wavelength. This metrology reveals duration, chirp, and coherence of diffraction-capable electron pulses and potentially offers attosecond resolution.
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1. Introduction

Ultrafast electron microscopy and diffraction [1-2] can visualize atomic motion in space and time. However, the temporal resolution is limited to about 100 femtoseconds due to space charge broadening and electron dispersion. These problems can be overcome by combining single-electron pulses with a microwave cavity for temporal compression, offering the possibility to achieve a resolution in the few-femtosecond range or even below [3]. Eventually, this may allow visualizing primary reactions dynamics in condensed matter and, on the long run, the dynamics of atomic-scale electron densities [4].

However, approaching this new regime necessitates an electron pulse metrology with sufficient temporal resolution. Characterization by ponderomotive scattering [5] requires high-intensity laser pulses and the resolution is limited to about 100 fs. Here, we present an optical-field-driven streak camera for temporal characterization of diffraction-capable free-electron pulses [6]. Laser pulses with nJ energy provide a sufficient field strength and the temporal resolution is determined by the optical-field transients, i.e. in the sub-cycle regime.

2. Concept and experiment

Optical streaking is based on a rapid transition of the electrons into or out of a controlled optical field within a transition time below the duration of an optical cycle. This is the principle of the attosecond streak camera [7], where photoelectrons are released by attosecond extreme-ultraviolet pulses in the presence of an optical streaking field. The rapid transition – or "birth" – into the optical field imprints a momentum modulation onto the electrons, depending on the phase of the optical field.

We adapt this concept to 25-keV free-electron pulses by reflecting the streaking laser pulse off a 50-nm free-standing aluminum foil, creating a maximum longitudinal streaking field of about $1.8 \cdot 10^9$ V/m, while the electron pulses are partially transmitted (see Fig. 1). The optical field is shielded by the foil within a fraction of the wavelength, ensuring a sub-cycle transition of the electron pulse out of the field and therefore a momentum modulation. The noncollinear incidence angles of the two beams are chosen to match the sweeping velocity of the optical phase and electron pulse's group velocity along the foil's surface. A home-built time-of-flight spectrometer records the change of the electron's kinetic energy after the interaction as a function of the laser-electron delay time.

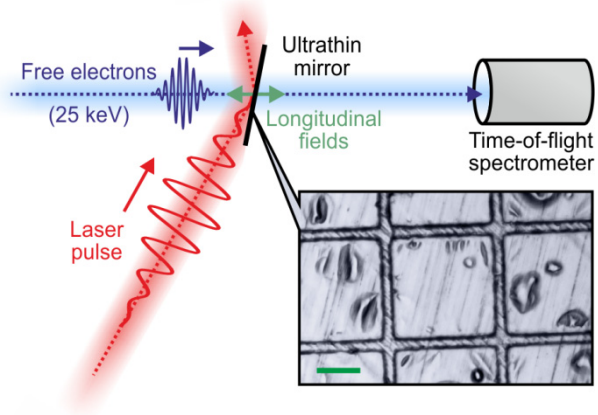

Fig. 1: Concept of the optical-field-driven streak camera for free-electron pulses at 25 keV. The inset shows the 50-nm thin aluminum foil (green scale bar denotes 100 µm).

3. Optical streaking results

In optical field streaking, the maximum energy gain (or loss) of the electrons is proportional to the peak field strength [7]. The 800-nm streaking laser pulses have a full-width-at-half-maximum (FWHM) duration of 50 fs (intensity envelope) and their carrier-envelope phase is not stabilized. Also, the electron pulses used here are much longer than an optical cycle. Therefore, a streaking spectrogram (energy spectrum as a function of delay time) yields a cycle-averaged cross-correlation between the electron pulse and the envelope of the laser field. The width of the cross-correlation at a particular energy gain is a convolution between the electron pulse duration and that portion of the field envelope that is sufficiently strong for inducing this energy gain. Thus, for higher energy gain values, the electron pulse is sampled with an effective probe of decreasing duration [6].

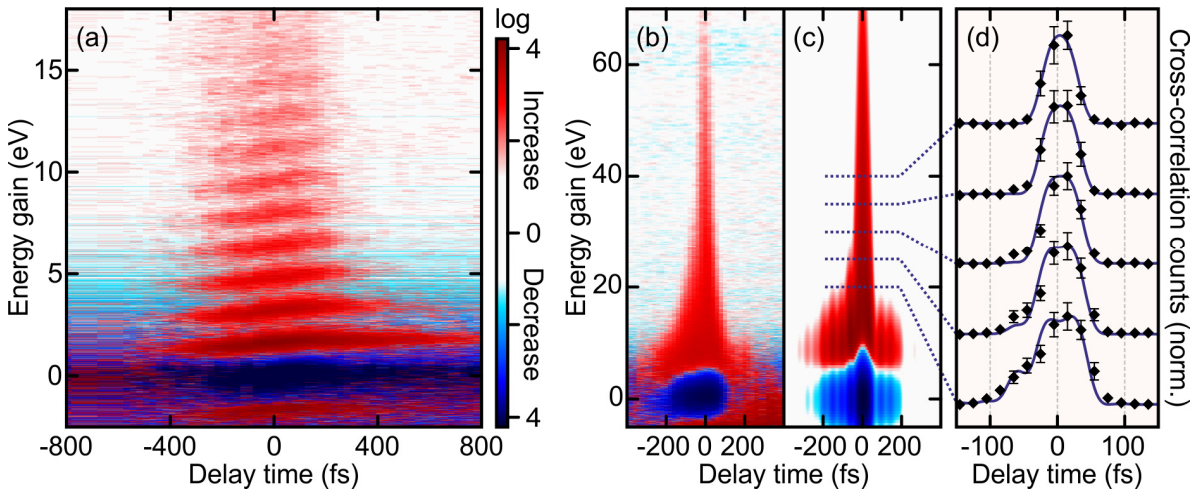

Fig. 2: Laser streaking results, yielding cross-correlations between laser and electron pulses. The unstreaked electron spectrum is subtracted from the spectrograms in order to enhance changes. Negative delay times denote an earlier arrival of the electron pulse at the streaking foil. (a) Dispersed electron pulse without compression. The duration is (360±20) fs FWHM and a linear chirp is evident. (b) Electron pulse after microwave compression. The dispersion is compensated, revealing a duration of (28±5) fs FWHM. (c) Result of semi-classical simulations fitted for electron pulse duration. (d) A series of lineouts at distinct energy gain values shows the good agreement between measurement (diamonds) and simulation (blue lines).

Figure 2a shows a streaking spectrogram of dispersed uncompressed electron pulses with about three electrons per pulse. A spectral interference with a period of about 1.6 eV, corresponding to the photon energy, is visible. This is a consequence of the electron's longitudinal coherence extending over more than one optical cycle, causing different parts of the electron's wave function leaving the field coherently in subsequent optical cycles. The measured maximum energy gain is about 65 eV, in agreement with calculations based on the peak streaking field [6]. The width of the cross-correlation converges to (360±20) fs FWHM at above ~10 eV of energy gain. This denotes the electron pulse duration. The tilt of the interference features indicates a linear chirp of ~0.9 ps/eV.

Figure 2b shows the results for single-electron pulses after microwave compression. The lack of interference features is due to a compressed and therefore reduced longitudinal coherence. Also, no tilt (i.e. chirp) is visible in the loss feature at zero energy gain, denoting a well-compensated dispersion. The electron pulses are shorter than the field envelope of the 50-fs streaking pulse and deconvolution hence requires a numerical approach. A semi-classical simulation [6], fitted for the electron pulse duration and the laser pulse's third-order dispersion, agrees well with the measurement (see Fig. 2c and the lineouts in Fig. 2d) and indicates an electron pulse's duration of (28±5) fs FWHM.

4. Simulated performance for attosecond electron pulses

Extension of this metrology technique to few-femtosecond or attosecond free-electron pulses is straightforward if applying few-cycle laser pulses with stabilized carrier-envelope phase. The simulations [6] reveal a transition between the coherent interference regime (Fig. 2a) and field-resolved sampling (see Fig. 3), similar to extreme-ultraviolet attosecond streaking.

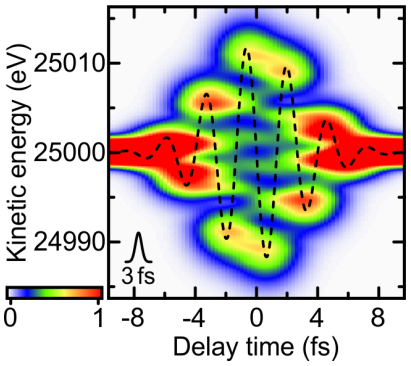

Fig. 3: Semi-classical simulation of free-electron streaking showing sampling of a 5-fs laser field (dashed) with stabilized carrier-envelope phase by a 3-fs free-electron pulse.

5. Conclusion

The here reported optical-field-driven streak camera constitutes a powerful tool for electron pulse metrology in the time and energy domain. Pulse durations in the ten-femtosecond range have successfully been characterized and sub-femtosecond resolution is in reach. This now provides the crucial metrology for advancing the temporal resolution of electron diffraction into novel resolution regimes.

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