CHARACTERIZATION OF PARTIALLY COHERENT ULTRASHORT FEL PULSES

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Abstract

The lack of longitudinal coherence, that is shot-to-shot fluctuations, of Free-Electron Lasers (FEL) has prevented so far their full amplitude and phase temporal characterization. To sort out this issue, we propose a solution inspired from attosecond metrology, where XUV pulse measurement techniques already exist, and from coherent diffraction imaging, where numerical solutions have been developed for processing partially coherent diffraction patterns. The experimental protocole implies the measurement of photoelectron spectra obtained through XUV-laser photoionisation. The spectra are then processed with an algorithm in order to retrieve the partially coherent FEL pulse. When applied to SASE FELs, the technique gives access to the full statistics of the emitted pulses. With seeded-FELs, the pulse shape becomes stable from shot-to-shot, but an XUV-laser time jitter remains. In that case, the technique enables the joint measurement of the FEL pulse shape (in amplitude and phase) and of the laser/FEL jitter envelope.

ADAPTING FROG TO FREE-ELECTRON LASERS

Temporal metrology is a major need for emerging ultrashort Extreme Ultraviolet and X-ray (XUV) sources, such as attosecond (1 as = 10^{-18} s) sources based on high-harmonic generation [1, 2] or free electron lasers (FEL) [3, 4]. In attosecond metrology, the most mature technique for temporal characterization is known as the FROG-CRAB technique (*Frequency-Resolved Optical Gating for Complete Reconstruction of Attosecond Bursts*) [5], adapted from the FROG technique used in conventional near-visible ultrafast laser metrology [6]. By sending the XUV pulse through a gas jet in the presence of a laser field, two-color XUV+IR photoionisation is induced. Measuring the spectrum of the produced photoelectrons while varying the IR/XUV delay gives a two dimensional trace called a spectrogram. Such a spectrogram can then be processed with a phase-retrieval algorithm in order to obtain the temporal profile of the XUV pulse.

Ideally, one would like to transpose directly the FROG-CRAB technique to FELs. However, for FELs relying on Self-Amplified Spontaneous Emission (SASE), the XUV pulse changes on a shot-to-shot basis. With seeded FELs, the pulse shape becomes stable from shot to shot, but the synchronization of FEL pulses with an external laser source remains challenging, so that in practice an optical/XUV jitter of a few tens of femtoseconds is often present. For these reasons, FELs have remained incompatible with FROG-CRAB measurements so far. The problem can be understood by considering the XUV pulse as partially coherent, and by seeing the shot-to-shot fluctuations as the source of decoherence in the experiment. As modern ultrafast metrology relies on the hypothesis that the pulse to measure is fully coherent, it fails in the presence of partial coherence.

FEL PULSE MEASUREMENT IN THE PRESENCE OF PARTIAL COHERENCE

To overcome this problem, we propose a solution based on the recent advances in the domain of coherent diffraction imaging (CDI). This microscopy technique consists in reconstructing an object by processing numerically the diffraction patterns that it produces in the far field. The key is to illuminate the object with a fully coherent light beam, and the imaging quality is rapidly degraded as the degree of coherence decreases. However, strong efforts have been made to enable sample reconstructions even with a partially coherent beam [7, 8], simply by adapting the numerical processing used for the inversion of the diffraction patterns.

By adapting algorithms used in CDI, we have developed a numerical treatment for FROG spectrograms that enables the reconstruction of ultrashort pulses even in the presence of partial coherence [9]. In the case of SASE FELs, the statistics of SASE waveforms (temporal intensity and phase) accumulated during the measurement is recovered. Moreover in the case of seeded FELs, this statistics takes a very specific form, since the waveform is constant from shot to shot up to a random arrival time. It is then possible to recover both the XUV pulse shape and the form of the optical/XUV jitter envelope.

CONCLUSION

This work will also benefit to other domains where the FROG technique is used. In attosecond metrology, it will become possible to determine up to which extent the coherence of an optical wave packet, that is the XUV light pulse, is transferred to the electron wave packet during photoionisation [10]. But FROG is mainly used for the metrology of near visible pulses. One can for example expect applications for the coherent control in molecules [11]. This will also enable one to probe the coherence of complex nonlinear processes, such as the generation of supercontinuum pulses from photonics crystal fibers [12].

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