# Sub-100-as soft x-ray pulses

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**Abstract:** We demonstrate the generation of powerful sub-100-as soft x-ray pulses by means of 1.5-cycle waveform-controlled laser fields. Our new tool opens the door for exploring electronic processes on a time scale approaching the atomic unit.

## Introduction

Attosecond pulses are emitted when energetic electron wave packets, created by the interaction of intense laser fields with atoms, recollide with the atomic core and radiate soft x-rays. Spectral filtering of radiation emerging from a single recollision event comprises the cornerstone of isolated attosecond pulse technology [1],[2]. Indeed, light wave packets emitted within the most intense half-cycle of a few-cycle laser pulse have allowed for generation of powerful attosecond pulses in the sub 200-as regime [3]. The duration of these pulses has been limited by the spectral width of the emitted soft x-ray continuum, which is inextricably related to the intensity contrast between adjacent half-cycles of the driving pulse. Combined with polarization gating, few-cycle, phase-controlled laser pulses have permitted the generation of even shorter bursts of radiation [4], though at the expense of the photon yield, which is highly crucial for a number of experiments.

Here, we demonstrate a new regime of attosecond pulse generation where waveform-controlled pulses, comprising merely 1.5 field oscillations [5], are employed to drive soft x-ray emission from atoms. Due to the high nonlinearity of the tunnelling process, the interaction is virtually restricted to within a single optical-cycle. This enables emission from only two electron trajectories, over a significant fraction (>50 %) of the emitted bandwidth. Adjusting the phase setting to enhance the contribution of a single, most-powerful electron trajectory, we generate a soft x-ray supercontinuum that extends over more than ~28 eV in FWHM. From the temporal characterization of the emitted soft x-rays, pulses were ascertained to have duration of 80±5 attoseconds.

## Experimental Methods

The soft x-rays are generated by gently focusing (f=600 mm) sub-4-fs laser pulses into a quasi-static gas cell filled with Neon at a pressure of ~ 350 mbar. The setup is discussed in detail in [2,3]. A quasi-monolithic double-mirror assembly, consisting of a Mo/Si multilayer mirror and an outer concentric perforated mirror is placed approximately 1.5 m downstream and is used to focus the soft x-rays and the laser beam into a second neon target. The multilayer mirror - consisting of a stack of four Mo/Si quarter wave layers - combined with Zr foils allows for a bandwidth greater than 30 eV. The delay between the laser and soft-x-ray pulses can be adjusted with nanometer precision. Electrons set free by the soft x-ray pulse, along the laser polarization, are collected by a time-of-flight (TOF) electron spectrometer. The resolution of the spectrometer is better than ~0.5 eV in the range 40-90 eV**.**

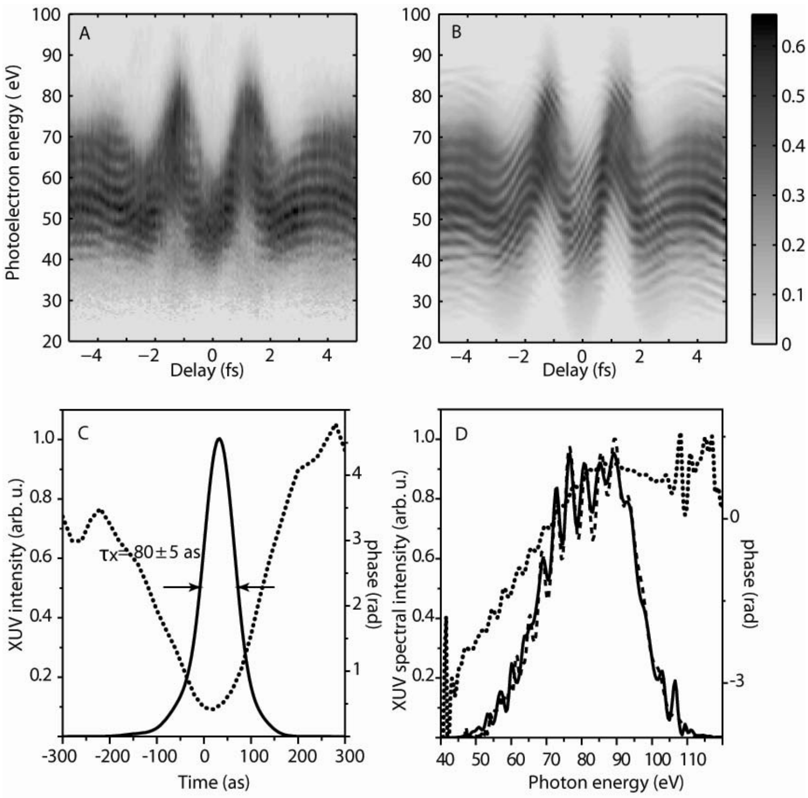


Fig.1. (a) Atomic-transient-recorder spectrogram of a sub-100-as soft x-ray pulse. (b) Reconstructed spectrogram after $10^3$ iterations of a FROG-based algorithm [9]. (c) Temporal intensity profile and phase of the pulse retrieved from the measured spectrogram depicted in (a). (d) Retrieved (solid line) and directly measured (dashed line) spectrum. The retrieved spectral phase is depicted as a thin dash.

## Results and Discussion

Figure 1.a shows a spectrogram recorded from our soft-x-ray attosecond pulse. The basic principles of the characterization technique have been put forward in [6] and realized for the first time in [1]. In order to guarantee a sufficient resolution, our streaking field is adjusted to produce spectral shifts comparable to the original bandwidth of the photoemission. We analyze our spectrogram utilizing an a version

of the FROG technique optimized for attosecond streaking [8,9]. The algorithm converges after ~ $10^3$ -$10^4$ iterations. The reconstructed spectrogram is depicted in Fig1.b, while the retrieved temporal intensity and phase of the 80 attosecond (in FWHM) soft x-ray pulse are depicted in figure 1.c. Figure 1.d shows the spectral phase as well as the retrieved spectrum. A soft x-ray spectrum measured directly is also shown for comparison.

The quasi monocycle nature of our driving pulses has played a key role in (i) enabling the generation of sub-100-as pulses and (ii) enhancing the photon yield by giving rise to favourable phase matching conditions in the generating medium. Indeed, utilizing our yield-calibrated soft x-ray camera, we can safely estimate an energy of ~0.5 nJ/pulse within the bandwidth of the attosecond pulse at the high harmonic source. This corresponds to generation efficiency on the order of $10^{-6}$.

## Conclusions

We have generated powerful sub-100-as pulses in the soft x-ray regime. These pulses, precisely synchronized to the generating laser field, will offer a dramatic improvement in temporally resolved experiments, and hold promise for the real time tracking of ultrafast dynamics on the time scale of electron correlation [10].


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