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# Spatiotemporal Control of Attosecond XUV Beams

C. Valentin<sup>1</sup>, J. Vabek<sup>1,2,3</sup>, K. Veyrinas<sup>1\*</sup>, S. Prawdziak<sup>1</sup>, D. Descamps<sup>1</sup>, C. Péjot<sup>1</sup>, F. Burgy<sup>1</sup>, E. Constant<sup>4</sup>, E. Mével<sup>1</sup>, and F. Catoire<sup>1</sup>

<sup>1</sup> Centre Lasers Intenses et Applications (CELIA), Université de Bordeaux-CNRS-CEA, 43 rue Pierre Noailles, 33405 F-33405 Talence, France

<sup>2</sup> ELI Beamlines, FZU, Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 188 21 Praha 8, Czech Republic

<sup>3</sup> Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering - Jugoslávských partyzánů 1580/3, 160 00 Praha 6, Czech Republic

<sup>4</sup> Institut Lumière Matière (ILM), Université de Lyon- CNRS, rue A. Byron, F-69622 Villeurbanne, France

Author e-mail address: constance.valentin@u-bordeaux.fr

**Abstract:** Spectral and spatial control of XUV beams is demonstrated combining divergence control at the generating plane with intermediate-field spatial filtering. This control is reproduced by simulations and shows a net improvement of attosecond beam homogeneity. © 2022 The Author(s)

## 1. Introduction

XUV beams produced by high-order Harmonic Generation (HHG) are commonly used as a table-top source of attosecond pulses, allowing high temporal resolution for ultrafast phenomena studies [1]. In order to perform XUV-pump-XUV-probe experiments with femtosecond and attosecond time resolution, the generation of intense XUV radiations becomes mandatory. Controlling the focusing properties of the XUV beam remains challenging as harmonic divergence depends on the harmonic order and the foci positions as well [2-5]. Recently, we have demonstrated the capability to control the XUV beam spatial properties [4,5]. Using an iris in the path of the XUV beam located in the intermediate field, we demonstrate that we can perform XUV spectral filtering with high contrast and selectivity [5]. We observe far field spatial filtering and show that this approach is a way to improve the spatiotemporal homogeneities of the XUV beam in far field.

## 2. Control of spatial properties of XUV beam

The experimental setup has been described in details in [4]. We used 9mJ of laser energy of the Terawatt Ti:sapphire laser system delivering 800-nm, 40-fs pulses at a 10-Hz repetition rate. Good infrared (IR) beam spatial quality is ensured by spatial filtering and wavefront correction by a deformable mirror (ISP System), coupled to a wavefront sensor (Imagine Optic). The beam is then focused by a 2-m focal length spherical mirror leading to an 85 $\mu$ m focused laser beam waist (estimated peak intensity of 4  $10^{14}$  Wcm<sup>-2</sup> at focus) in a gas jet of neon. The gas jet can be moved longitudinally over 15 cm around IR focus. The high-order harmonics are analyzed by a flat-field XUV spectrometer and the spatially resolved spectra are analyzed 2.9 m after the laser focus. A movable 140- $\mu$ m-diameter pinhole can be inserted 37 cm after the IR focal plane to characterize the intensity profile and wavefront of each harmonic using SWORD (Spectral Wavefront Optical Reconstruction by Diffraction) technique [6]. As pointed out in Veyrinas *et al.* [5], harmonic waist sizes and positions can be very different for different harmonic orders, depending on the gas jet positions. More precisely, we have determined that for a gas jet far before the IR focus ( $z_{\text{jet}} = -40$  mm), low harmonics are focused after the generating medium. The waists are then real and are positioned well after the IR focus, demonstrating convergent beams focused in a few micrometer size spots. On the contrary, XUV beams are divergent for  $z_{\text{jet}}$  near the IR focus and waists can be virtual. These measurements are in good qualitative agreement with the simulated results reported by Quintard *et al.* [4] where harmonic optics-free focusing was demonstrated.

## 3. Spectral filtering and control of attosecond pulse structure

We demonstrate a direct application of the XUV beam properties control by performing XUV spectral filtering without using any XUV optics. Spectral filtering is shown by comparing the spatially-resolved HHG spectrum obtained with the pinhole centered on the pathway of the harmonic beam and the spectrum obtained without the pinhole. The pinhole is specifically located in the intermediate field, that is far from the IR focus but possibly near the XUV foci. The transmittance (T) is then defined as the ratio of the HHG spectra obtained after integrating over the spatial coordinate with and without pinhole. Measured transmittance (Fig.1a) for three gas jet positions show clearly filter characteristics such as tunability and high contrast: high pass (in blue), low pass (in black) and broadband (in red) filters have been obtained. We simulated the observed effect to observe the temporal impact of this filtering. The spatial distribution of the XUV beam in far field is expressed by a Fraunhofer integral where the

source term, located in a single plane, is obtained by solving the Time-Dependent Schrödinger Equation (TDSE [7]). From this model, we determine the size of each harmonic beam on the pinhole and calculate its transmittance (Fig.1b). These simulated curves are in good agreement with experimental results and confirm that short pass, long pass or bandpass filters can be obtained. Moreover, this filtering is followed by high IR beam rejection (transmission < 0.1%) which can prevent using metallic filters which reduce drastically harmonic signals.

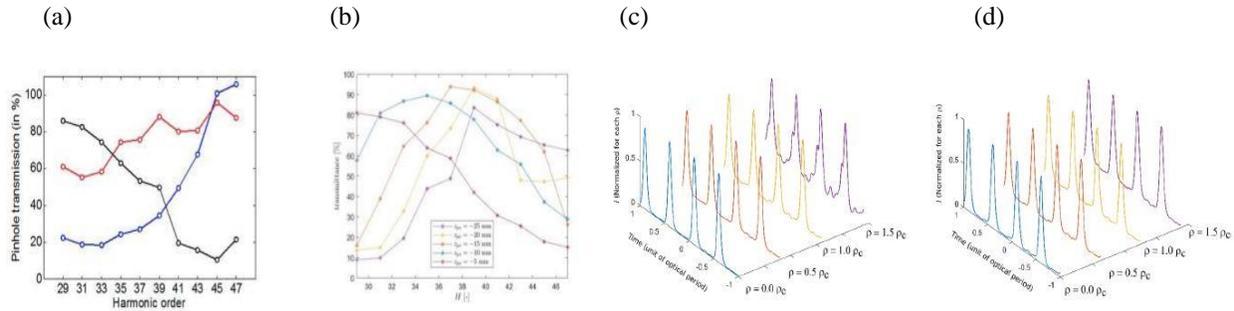


Fig. 1. (a) Transmittance measured for all harmonics from H29 to H47 for  $z_{jet} = -58$  mm (blue),  $-36$  mm (red) and  $-20$  mm (black). (b) Simulated transmittance versus harmonic order for five gas jet positions. Temporal structures are depicted in (c) for free propagation and (d) with filtering. We define  $\rho_c$  as the radius that contains 50 % of the XUV beam power.

We have simulated spatially resolved spectra, and temporal structure of attosecond pulse trains after propagation without and with filtering for  $z_{jet} = -15$  mm. Simulations show that the temporal profile changes significantly with the radius without spatial filtering and the attosecond pulse shows strong structures for half of the XUV beam energy (Fig. 1c). After intermediate field filtering, the XUV beam is radially more regular and we observe that the temporal structure does not evolve significantly with the radius  $\rho$  after propagation (Fig. 1d).

#### 4. Conclusion

We have experimentally demonstrated control of spatial properties of XUV harmonic beams and observed that optics-free focusing of high-order harmonics can be combined with intermediate field spatial filtering. We have demonstrated experimentally and theoretically adjustable XUV spectral filtering with high contrast without resorting any XUV optics. We have developed a model that shows that spatiotemporal structure homogeneity strongly benefits from the filtering, leading to better control of the spatiotemporal structure of attosecond pulses and a significantly improved homogeneity of the attosecond beams.

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\*present address: Amplitude Lasers, 2 rue du Bois Chaland, 91090 Lisses, France.