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Report on the development of imaging techniques adapted to soft x-ray laser and HHG

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Deliverable Nature	
R = Report, P = Prototype, D = Demonstrator, O = Other	R
Dissemination Level	
PU = Public PP = Restricted to other programme participants (incl. the Commission Services) RE = Restricted to a group specified by the consortium (incl. the Commission Services) CO = Confidential, only for members of the consortium (incl. the Commission Services)	PU

A. Abstract / Executive Summary

New high resolution XUV imaging techniques have been developed to take advantage of the short light wavelength and the high XUV photon flux obtained with X-ray lasers or harmonic sources. The developments allowed to achieve polychromatic coherent diffraction imaging, 3 D imaging with multiple sources. They also allowed to observe the temporal evolution of the XUV sources via spectrally resolved single shot imaging of XUV beam or via ptychography of plasma. These observations were also supported by a large analysis effort and by the development of new codes that appeared to be crucial to confirm the validity of some imaging approaches.

B. Deliverable Report

1 Introduction

As a starting point, Laserlab partners decided to study and develop new imaging approaches where the short wavelength of the XUV sources, their coherence or even their extremely short duration could be used. Laserlab III was the ideal ground to perform these studies as it gathered expert in XUV source development and control and expert in imaging techniques.

2 Objectives

The main objective was to go above the current limits associated to the XUV imaging and to circumvent the difficulties associated to the diverse XUV sources that were being developed. For instance, coherent diffraction imaging required monochromatic sources while short pulses are by essence polychromatic and temporal resolution appeared non compatible with coherent diffraction imaging. One of our goals was to try to adapt monochromatic coherent diffraction imaging to polychromatic XUV sources such as harmonic generation. It was also envisioned that 3 D imaging would become possible but developing this technique also required lot of efforts. A final goal was to use directly the characteristics of the emitted XUV light to image the dynamical processes occurring during the ultrafast emission process itself.

3 Work performed / results / description

Lot of research has been devoted to **imaging the XUV sources** themselves even if their characteristics scales are at the femtosecond and micron level. Such scales are clearly accessible with the approaches that we developed.

CEA/SLIC developed a new technique for the spatial characterization on HHG sources [1,2], in amplitude and phase, and applied it to harmonics produced from plasma mirrors, both at relativistic and non-relativistic laser intensities ranging from 10^{16} W/cm^2 to a few 10^{19} W/cm^2, and for a broad range of harmonic orders. This technique, inspired from ptychography, consists in generating the harmonics from a medium with spatially-modulated properties (in the present case, an optically-controlled modulated plasma surface), and at the measuring the diffraction pattern induced on the harmonic beam, as a function of the relative position between this modulation and the driving laser focus. The obtained dataset can then be injected into a phase-retrieval algorithm to reconstruct both the harmonic source and the modulation of the generation medium. This versatile and powerful technique will be transposable to a wide variety of laser-driven short-wavelength sources, especially those relying on HHG.

CELIA used the coherence of the harmonic source in gases to image the femtosecond dynamics in intense field occurring directly during the generation process [3]. This was performed by developing an XUV spectrometer with high spatial resolution for moderate harmonic order. It is compatible with spatially and spectrally resolved single shot acquisition with an optimized XUV source based, at CELIA, on a high energy TW laser source. This allowed them to observe many fine structures in both the spectral and spatial domain in the far field. The analysis of these structures showed that they are due to an ultrafast evolution of the XUV emitters distribution that evolves rapidly combined with a rapid evolution of the central harmonic frequency that encoded time in the XUV wavelength. The observed structures provided a time resolved image of the generation process evolving on the few femtosecond time scale. CELIA also tested an achromatic imaging system based on the use of a single parabolic mirror with large magnification. This system was tested with a spatially filtered coherent IR beam and micrometric resolution has been achieved. The resolution could be improved by using XUV light with high flux sources but the many structures observed in the harmonics will have to be further studied to avoid limiting the achievable resolution.

LOA, IST and CEA-SPAM studied the stability of wavefront of high harmonic generate in Argon gas. Wave front is a key parameter for coherent diffraction imaging, as showed by CEA and LOA and more generally for any type of coherent imaging (interferometry, holography and diffraction). In our conditions, we measured a shot-to-shot wave front stability of λ /10 with an average value of λ/3 rms (λ =32 nm). This opens the way to correct the wave front either by using XUV adaptive optic or by modifying the IR driving laser.

XUV sources were also used to image many systems and the diversity of the approaches that have been developed is high.

CEA-SLIC has investigated nonlinear harmonic spectroscopy in small molecules (e.g., N2), where variations of the XUV spectral phase are accurately measured using optical “two-source” interferometry. Combination of optical (“two-source”) and quantum (RABBIT) interferometry has been worked out to provide extended mapping of the XUV spectral phase [4]. In collaboration with CELIA, CEA-SLIC has also demonstrated the efficiency of phase plates to produce two laser foci and use them for HHG to subsequently produce two mutually coherent XUV sources. This two-sources XUV interferometry scheme has been useful for several phase-resolved and time-resolved studies, with variable conditions of the system-field nonlinear interaction under study in the one source, and the other source as a reference [5].

A large collaboration led by Instituto Superior Tecnico and CEA and involving LOA (CNRS-LOA-IST-CEA-SLIC) has finalized a setup for achieving attosecond holography with the possibility to either keep the attosecond duration (polychromatic images are mixed together) or to use the hologram as a high spatial resolution spectrometer capable of 10’s nanometer resolution (in which case polychromatic images are separated in several monochromatic images of the same sample).

CNRS-LOA in collaboration with Mabel Ruiz-Lopez, Davide Bleiner from University of Bern, Switzerland, has progressed on the test of a XUV Schwarzschild microscope. They successfully measured the figure errors of a high-NA mirror at frequencies from cm-1 down to µm-1. This measurement had never been accomplished before. LOA and Bern university are preparing the measurement of the full Schwarzschild to publish all the results together.

CEA-SLIC developed a new XUV beam splitter, based on reflective wedge and focussing mirrors, for single shot 3D stereo imaging with nanometric spatial resolution.

In collaboration with IST (Lisbon) and LOA, CEA-SLIC has extended holographic imaging to very large spectral bandwidth ($\Delta\lambda/\lambda$) in the XUV range. This opens the way towards simultaneous coherent imaging at different wavelengths, as well as possible attosecond time-resolved imaging [6, 7].

In parallel, University of York and Universidad Politecnica de Madrid worked on the development of a new code describing the interaction of femtosecond X-ray source with matter. This appeared to be crucial for the development of 3D coherent imaging since the intensities used to perform such experiments are so high that the sample is generally turned into a plasma on a duration that might be shorter than the pulse duration. This may lead to an unknown and ultrafast modification of the index of refraction of the sample. Without good knowledge of the index of refraction, image reconstruction softwares might generate wrong images.

4 Conclusions

Lot of new developments and breakthrough have been achieved during the Laserlab III and collaborations have been either strengthened or created. These developments have opened new approaches that have been shared between partners and can now be used in the respective laboratories. A general trend in this work, is the transfer of techniques initially developed with X ray lasers toward high order harmonic sources. It led to approaches that can be used both with Xray laser or harmonic sources.These achievements open clearly new possibilities that were not accessible before the laserlab program. In return, they will widen the range of possibilities offered by the laserlab partners via access program and improve the access quality.

5 Persons involved

CNRS-LOA: H. Dacasa, L. Lu, B. Mahieu, P. Zeitoun;
CEA-SLIC: A. Camper, T. Ruchon, Rémy Cassin D. Gauthier, O. Gobert, P. Salières, B. Carré, T. Auguste. S. Monchocé, S. Kahaly, F. Réau, D. Garzella, P. D'Oliveira, Ph. Martin, F. Quéré. W. Boutu, A. Gonzales, H. Merdji;
CNRS-CELIA: L. Quintard, C. Ballage, A. Dubrouil, O. Hort, A. Férré, Y. Mairesse, F. Burgy, S. Petit, D. Descamps, E. Mével, E. Constant;
IST: M. Fajardo, S. Kunzel, G. Williams

6 Publications

Unless otherwise indicated, these publications are not on open access.

[1] Optically Controlled Solid-Density Transient Plasma Gratings
S. Monchocé, S. Kahaly, A. Leblanc, L. Videau, P. Combis, F. Réau, D. Garzella, P. D'Oliveira, Ph. Martin, and F. Quéré
Phys. Rev. Lett. **112**, 145008 DOI : http://dx.doi.org/10.1103/PhysRevLett.112.145008

[2] Ptychographic measurements of ultrahigh-intensity laser-plasma interactions
A. Leblanc, S. Monchocé, C. Bourassin-Bouché, S. Kahaly, F.Quéré
Nature Physics, accepted (2015)

[3] Spatio–spectral structures in high-order harmonic beams generated with Terawatt 10-fs pulses,
A. Dubrouil, O. Hort, F. Catoire, D. Descamps, S. Petit, E. Mével, V. Strelkov and E. Constant,
Nature Communication **5**:4637 (2014), http://dx.doi.org/10.1038/ncomms5637

[4] High-harmonic phase spectroscopy using a binary diffractive optical element,
A. Camper, T. Ruchon, D. Gauthier, O. Gobert, P. Salières, B. Carré, and T. Auguste,
Phys Rev A **89**, 043843 (2014), http://dx.doi.org/10.1103/PhysRevA.89.043843

[5] "Transverse Electromagnetic Mode Conversion for High-Harmonic Self-Probing Spectroscopy",
Camper A, Ferré A, Lin N, Skantzakis E, Staedter D, English E, Manschwetus B, Burgy F, Petit S, Descamps D, Auguste T, Gobert O, Carré B, Mairesse Y and Ruchon T,
Photonics. Vol. 2(1), pp. 184-199 - (2015), http://dx.doi.org/10.3390/photonics2010184

[6] "Fourier transform holography with high harmonic spectra for attosecond imaging applications",
Williams GO, Gonzalez AI, Künzel S, Li L, Lozano M, Oliva E, Iwan B, Daboussi S, Boutu W, Merdji H, Fajardo M, Zeitoun P.,
Optics Letters. Vol. 40(13), pp. 3205-3208. (2015), http://dx.doi.org/10.1364/OL.40.003205

[7] “Single shot studies of a Co/Pd thin film’s magnetic nanodomain structure using ultrafast xray scattering”,
M Ducousso, X Ge, W Boutu, D Gauthier, B Barbrel, F Wang, A Borta, A-I Gonzalez, M Billon, B Vodungbo, J Gautier, R Hawaldar, B Tudu, R Delaunay, M Tortarolo, P Zeitoun, J Lüning and H Merdji,
Laser Physics 24, 025301 (2014), http://dx.doi.org/10.1088/1054-660X/24/2/025301

[8] “Shot-to-shot intensity and wavefront stability of High-Harmonic Generation » S. Künzel, G. O. Williams, W. Boutu, E. Galtier, B. Barbrel, H. J. Lee, B. Nagler, U. Zastrau, G. Dovillaire, R. W. Lee, H. Merdji, Ph. Zeitoun, And M. Fajardo
Applied Optics **54**, 15, 4745-4749 (2015), http://dx.doi.org/10.1364/AO.54.004745