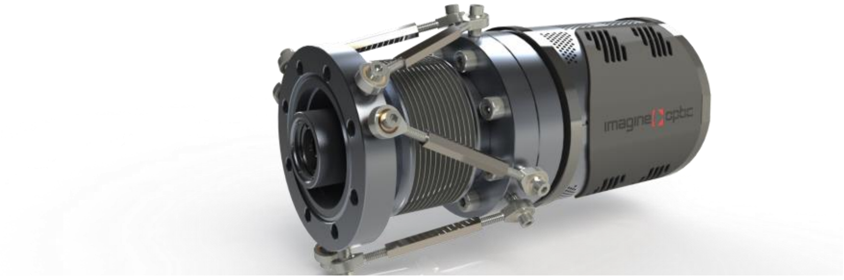
APPLICATION NOTE



Optimization of high harmonic beam line: from the source to the focal spot

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Summary

Today, high harmonics generated by the interaction of intense or ultra-intense lasers with gaseous or solid targets have reached extremely high level of robustness and performances. Thus there is a huge amount of new fully integrated experimental facilities emerging for applications such as in non-linear EUV optics and physics, material science, and biological imaging. These facilities are conceptually close to beamlines on free-electron lasers with the difference that the sources are the high harmonics. The transport of fully coherent, ultra-short pulses (high harmonic pulses reached 70 attoseconds) over meters needs to be controlled. A very accurate control and eventually correction of the beam wavefront all over the beamline aims achieving ultra-high intensities or to be used for coherent imaging.
Imagine Optic's wavefront sensors have demonstrated to be an excellent tool for optimizing the high harmonic's beam thus reaching $\lambda/20$ (at 30 nm) root-mean-square (rms) residual wavefront aberration while preserving a strong emission. Also Imagine Optic's wavefront sensors showed excellent performances in measuring the optical quality of mirrors used on high harmonic beamlines. A few examples are flat or curved optics being either static (polished shape) or dynamically curved (bender technology).
Imagine Optic's wavefront sensor or HASO EUV installed on high harmonic beamline is an indispensable tool for control and delivery day-to-day diffraction-limited beams to users.

Introduction

Nowadays high harmonics generated (HHG) from the interaction of intense, femtosecond laser with gas are becoming a common tool for applications from Biology, Chemistry, material Science, to atomic Physic. The high harmonics span from typically few tens of eV to few keV, for the most advanced. This spectral range is often called as "XUV" or "EUV" and "tender x-rays", for the highest energies. High harmonic exhibits two important characteristics: full spatial and high temporal coherences. The first characteristic has been widely used to downscale the coherent imaging experiments such as interferometry, diffraction and holography. They were commonly performed on large-scale facilities, namely synchrotrons and more recently free-electron lasers. The temporal coherence allows researchers to produce ultrashort bursts of EUV light, as short as 10's of attoseconds. It could be done by means of the phase locking between harmonics in case of a discrete harmonic's comb or all over the spectrum for continuous harmonics. The attosecond pulses are routinely used in atomic physic experiments to probe the ionization time or measure excited level lifetime. However, the combination of constantly increasing energy of the harmonic pulses with continuous reduction of pulse duration opens the path to exploring a very large variety of non-linear phenomena in the EUV range. Therefore, the intensity on target becomes a key parameter to optimize.

For decades, adaptive optics working in closed or opened-loop with a wavefront sensor has been successfully implemented on infrared and visible lasers. The objective was to concentrate the beam energy in the diffraction-limited focal spot. Dramatic increase of the IR/visible lasers intensities has been thus achieved.

EUV wavefront sensors are becoming essential tools for optimizing high harmonic beam with application on HHG physic or for their applications.

•Thanks to high sampling spatial rate, EUV Imagine Optic sensors or HASO EUV are able to catch the wavefront deformation at the same time as the intensity distribution of many beams. It is thus guiding the scientists or engineers to improving the beam quality by adjusting the condition of emission (gas pressure, length of interaction, IR focal spot properties, etc.).

In the race of achieving highest intensities, focusing optics becomes more and more complex with the ability of controlled surface deformation ("bender" mirrors, piezo or mechanical adaptive optics). Although the shapes of the first mirrors were often optimized by recording focal spots from the ablation of photoresists or metallic plates. That is why this technic cannot be sustainable since it is invasive and requires long data treatment. Moreover, it is a subject to errors coming from the complex interaction of intense XUV beam with matter. Imagine Optic's wavefront sensors demonstrated routinely minutes for optimization of complex mirrors (toroidal, off-axis parabola, or benders) with no perturbation to the beamlines for the benefit of users.

•Imagine Optic's EUV sensors have demonstrated the outstanding resolution of $\lambda/120$ rms with λ =13 nm ensuring the most stringent HHG beam or optics to be perfectly optimized. More compact Imagine Optic's EUV wavefront sensors operate at the reduced level of resolution of $\lambda/50$ rms with λ =30 nm. They are still warrantying diffraction-limited focal spot and very high Strehl ratio, only limited by the optic's polishing quality.

•Last and not least, Imagine Optic's EUV wavefront sensors are totally achromatic and demonstrated excellent and constant sensitivity over a very wide spectral range. This property is crucial for measuring and optimizing attosecond pulses that covers 10's to hundred eV. Incidentally, it has to be reminded that keeping a pulse duration at 30 as requires preserving the wavefront down to about 1 nm rms.

Materials and Methods

Available wavefront sensors are as follows.

1) Standard Imagine Optic's Wavefront sensor

HASO EUV, 72x72 hole array, active area: 13x13 mm², spectral bandwidth: 30-300 eV, absolute measurement accuracy: $\lambda/75$ RMS with λ =30 nm. Sensors are delivered with CF flange and manual hexapod for alignment (for details, see the following website.

http://www.imagine-optic.com/en/product/haso-euv/0/0/

2) High Numerical Aperture Wavefront sensor

The standard EUV sensor has a numerical aperture limited to about 0.02. We have developed a new HASO EUV with numerical aperture as high as 0.15.

3) On-demand HASO Wavefront sensor

Some applications need a customized wavefront sensors such as pushing the energy range to near 1 keV or implementing more pupils (100x100). Several options have been successfully tested on our standard HASO EUV in order to better answer user needs.

Direct optimization of high harmonic beams

HASO wavefront sensor may be used to directly optimize harmonic's emission by modifying the parameters of the interaction between the driving laser and the gas (or solid target) (see Figure 1).

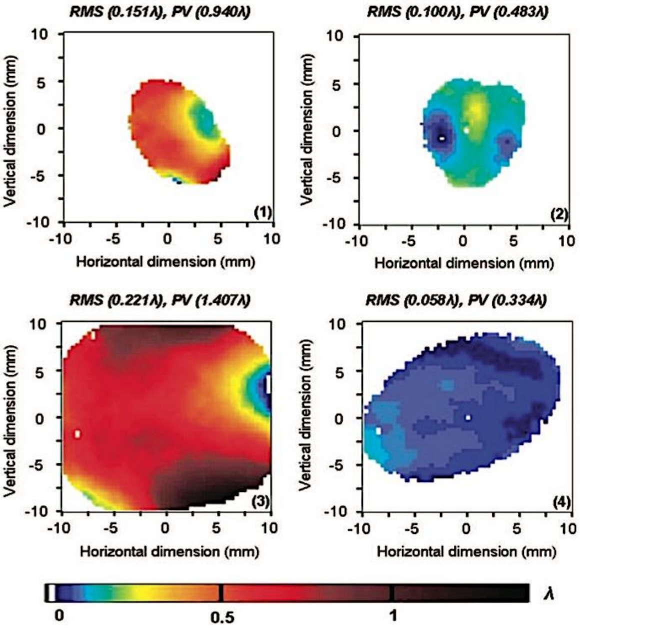

***Figure 1** Maps of harmonics wavefronts acquired under different conditions. (1) λ=800 nm laser field* (20 mm aperture), (2) *λ=800 nm laser field with wavefront correction by Imagine Optic's Mirao adaptive optics* (15 mm aperture), (3) *λ=800nm+ 400 nm mixed fields (60mm* full aperture), (4) *λ=800nm+ 400nm mixed fields* (20 mm aperture).

EUV HASO has the possibility to be operated at 1 Hz thus opening the way to on-line optimization. Also, it demonstrates its usefulness for following the evolution of harmonic's wavefronts over long periods (see Figure 2).

Placing the EUV HASO directly on the beam path will give full-spectrum measurements. Moreover, it is also possible to use a multilayer mirror to redirect the beam to the EUV HASO for selecting a single or a group of harmonics.

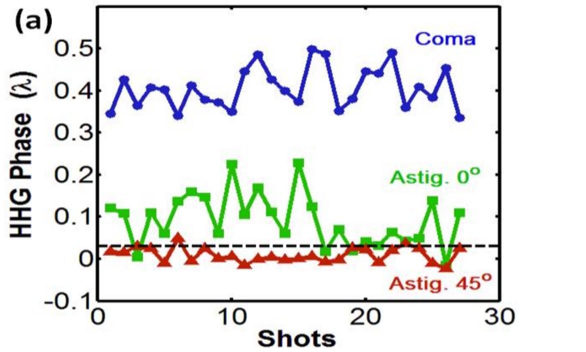

***Figure 2** High Harmonic's wavefront recorded over 30 consecutive shots, with independent display of the first most important aberrations (astigmatism at 0° and 45° and coma). The tilt and curvature have been removed.*

Thanks to the ability of recording simultaneously the amplitude and the phase of the full incoming beam, the full electric field is recordable. By retropropagation algorythm, WaveView™ software generates the intensity and wavefront map at any distance from the sensor and in particular at and around the focal plane, as shown in Figure 3.

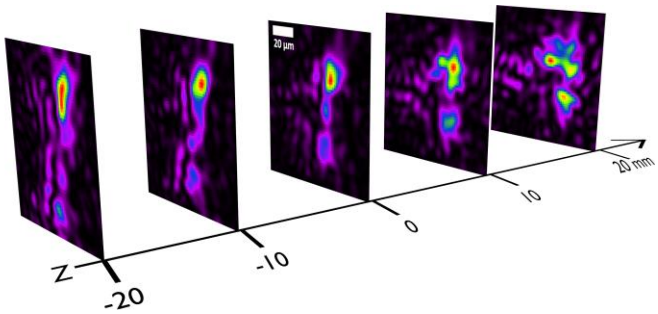

***Figure 3** Intensity maps around the source exit (z=0 mm) as calculated by retro-propagating the full high harmonic's field.*

References

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