Full correction of a laser chain including final focusing optics

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Summary

The development in high-power and ultra-intense lasers aims at achieving the highest laser intensity on the target. To ensure highest intensity, one has to accurately control both spectral phase to get the shortest pulse and spatial phase to get the smallest focused spot. The spatial phase is controlled using adaptive optics systems with both a wavefront sensor to measure spatial phase and a deformable mirror to correct it. This adaptive optics system is commonly placed at the output of the laser chain (after a compressor) and it now becomes a standard feature on high-power laser chains. The usual strategy of adaptive optics correction is to separate a small fraction of the main beam and to measure its wavefront using a wavefront sensor. Software will then run a closed-loop correction by adjusting the shape of the deformable mirror with the information provided by the wavefront sensor in order to remove the wavefront aberration of the laser beam. However such strategy only ensures that the laser beam is free from aberrations at the location of the wavefront sensor. Aberrations induced by the optical elements located downstream of the wavefront sensor are not measured and therefore are not corrected by the adaptive optics loop. These aberrations contribute to final focal spot degradation. Importantly in order to get the highest intensity on the target, an aberration-free wavefront in the interaction chamber after the last focusing optics is required [1]. This is not the same as not having aberrations at the wavefront sensor location.

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Introduction

The usual closed-loop adaptive optics setup compensates the aberrations measured by the wavefront sensor. It does not correct the aberrations of the optics located downstream of the wavefront sensor, especially the ones introduced by the last focusing optics. There are a couple of methods listed below, which allow to correct aberrations after the wavefront sensor in high-power laser chains.

- Looking at the final focal spot with a camera, manual addition of low order deformations to the deformable mirror in order to improve the focal spot quality. This method was used the most but it requires time and it is not always reproducible. It highly depends on the operator's skills to recognize aberrations in the beam by looking at the focal spot image.
- Automated algorithms that automatically improve the focal spot quality by measuring some metric on the focused focal spot and adjusting deformation either deterministically or stochastically to improve this metric. Those algorithms usually take a lot of time to find the best solution and are only efficient with close-to-perfect focal spots.
- Placing the wavefront sensor after the focal spot and optimizing the shape of the deformable mirror with the laser set in low power mode so that the wavefront is perfect. Then putting back the wavefront sensor at its regular location and recording the current wavefront as the adaptive optics loop target. Then in high power, the aberrations of the beam are different but the adaptive optics loop is run so that it reproduces the wavefront that was perfect at focus, which gives a perfect focal spot in high power mode.

The latest development on this topic is the introduction of phase retrieval algorithms, which is proposed by Imagine Optic. These algorithms, by using a deformable mirror, wavefront sensor and focal spot camera, allow to measure aberrations from the optics located downstream of the wavefront sensor and to compensate these aberrations in a single step. These algorithms are typically monochromatic and are developed for sources with a rather narrow spectral range. The aim of this study is to evaluate the capability of phase diversity algorithms to converge with wider spectrum pulses (the typical badwidth of femtosecond laser: 750-850nm) [2].

Materials and Methods

Hardware items to build an adaptive optics loop with Phase Retrieval capability:

- **HASO Wavefront sensor :** HASO4 first, 32x40 microlens array, active area: 3.6x4.6 mm², Spectral bandwidth: 400-1100 nm, absolute measurement accuracy: λ/100 RMS and over 400 λ dynamic range (for details, see https://www.imagine-optic.com/product/haso4-first/).
- **ILAO Star deformable mirror**: 33 actuators, 40 mm useful diameter, optical quality: better than 10 nm RMS, no hysteresis, vacuum compatible (for details, see http://www.imagine-optic.com/product/ilao-star/).
- **Focal spot diagnostic camera**: 12 bits, GigaEthernet connection, 1628x1236 pixels, Pixel size: 4.4 µm.

Software to run the hardware presented above, make adaptive optics loop correction, and perform phase retrieval calculations:

- **Wavetune:** an improved adaptive optics software that includes both standard closed-loop adaptive optics software for controlling HASO sensors and ILAO Star deformable mirrors as well as the PhaRAO phase retrieval calculation capability. It is a reliable adaptive optics solution for ultra-high intensity lasers. It offers advanced diagnostics and configurations of the interaction matrix, which is the major step in the process of getting the AO system to perform and to be secure as well as being user friendly.
- **Adaptive Optics SDK:** Software development kit (SDK) for adaptive optics allows the user to develop their own adaptive optics correction strategies and algorithms.

Adaptive optics strategies for aberration correction of the full laser chain at high-power.
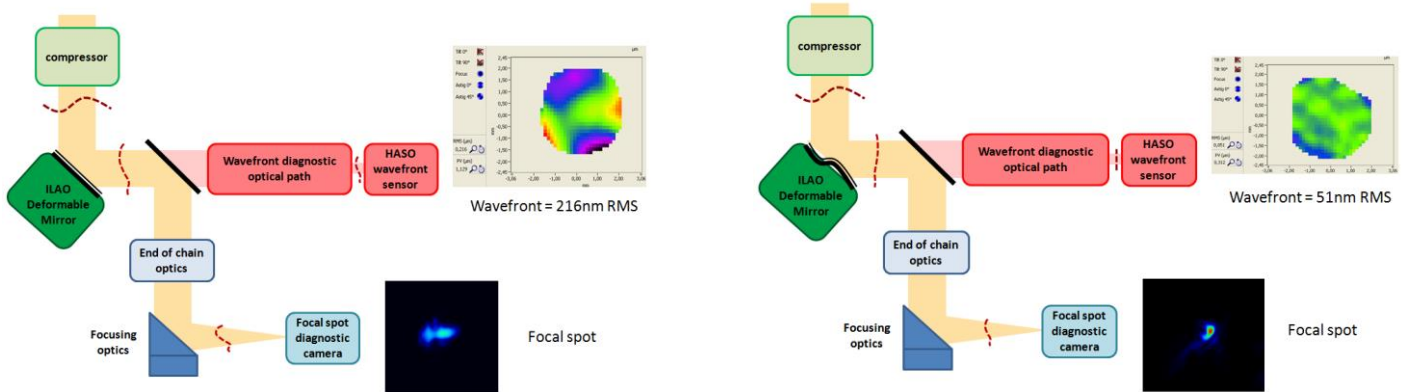
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Figure 1. Before running adaptive optics loop, both focal spot and wavefront are aberrated.

Step 1: Typical adaptive optics strategy. Before adaptive optics correction, the wavefront sensor measures aberrations presented the laser chain and also in the wavefront diagnostic's path. The typical adaptive optics closed-loop corrects the aberrations measured by the wavefront sensor. Up to this point in the laser chain the wavefront is perfect. In order to be able to make images of the focal spot without damaging the focal spot camera, the laser chain is operated in a low-power mode by switching off the last amplification stage.

Figure 2. After running the usual adaptive optics loop, the wavefront is very good, but the focal spot is not perfect yet.

But aberrations induced by the optical elements in the end of the chain and the focusing optics are not corrected and although the focal spot quality is improved, it is not perfect yet. The situation here is such that the wavefront sensor precisely measures the wavefront but the focal spot is not perfect (see Figure 2).
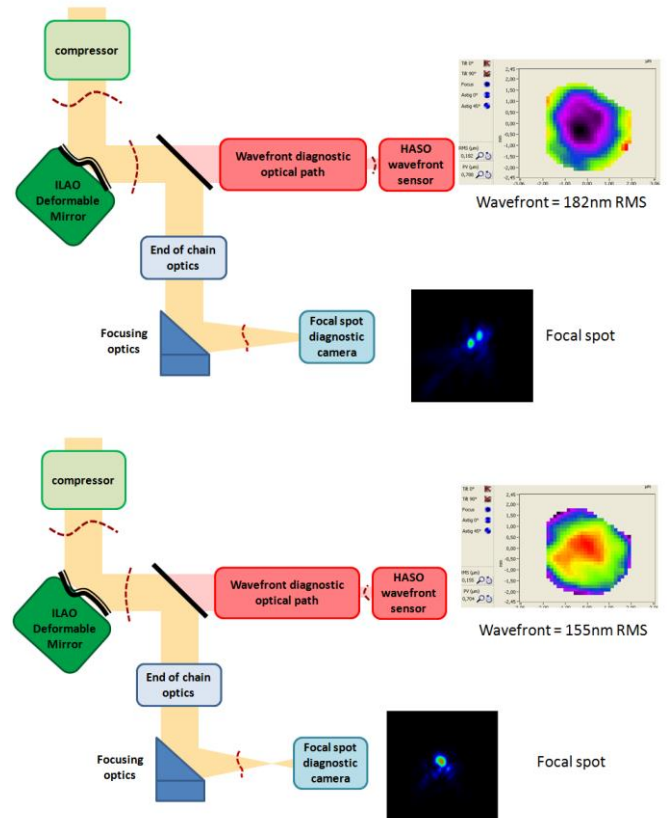

Figure 3. Three measurements are acquired, one with a focused spot, and two with slightly defocused spots by adding some positive and negative curvature to the deformable mirror.
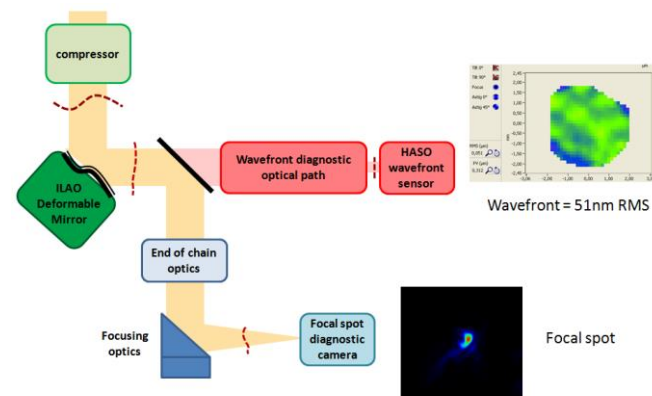
Step 2: Data acquisition for phase retrieval. To make the focal spot even better we use the phase retrieval algorithm. This algorithm is using three images of laser spot, one at the focus and two defocused ones on each side (see Figure 3). The amplitude of defocus is rather small, typically half of a wavelength. Simultaneously with images of the focal spot, the wavefront measurements are also acquired. This is done automatically by adjusting the deformable mirror shape and adding some very small

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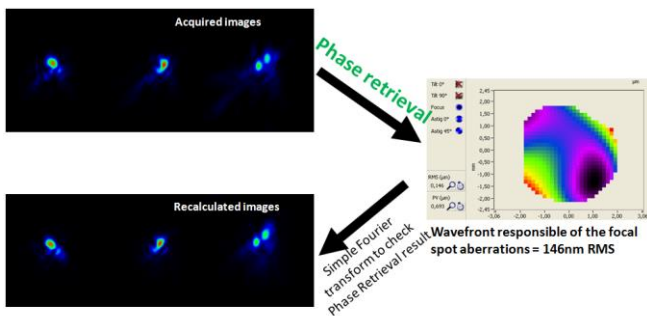positive and then negative curvature to the deformable mirror surface.

Figure 4. *Results of the phase retrieval algorithm.*

Step 3: Phase Retrieval calculation. The phase retrieval algorithm processes the acquired data and calculates the differential aberrations between the wavefront sensor and the focal spot camera. The result of these calculations is the differential aberrations of the system, *i.e.* aberrations that are present either on the wavefront sensor path or on the main laser path up, but not on both path (as those were corrected in the first step). Results are crossed checked by doing recalculation of the focal spot of calculated differential aberrations and checking that they are indeed similar to the acquired images of the focal spot (see Figure 4). The phase retrieval algorithm has been optimized in terms of calculation speed. It can take several minutes for the usual algorithm to calculate a single wavelength. The optimized algorithm now takes only a few seconds. This increase of speed was necessary

because if the measurement on the attosecond laser driver shows that the wavelength dependence prevents for using regular algorithm, it will be necessary to account for the broad spectrum inside the algorithm and therefore to use several wavelength. An algorithm taking few minutes per wavelength would end up in a calculation time over one hour for a polychromatic spectrum, which would interfer with a convenient use. With the calculation time reduced to a few seconds, the calculation of a polychromatic spectrum can be done within a few minutes.

Step 4: Low power full correction. From this calculation, the opposite of the differential aberrations is sent to the deformable mirror and the focal spot is corrected in a single iteration (see Figure 5).

Step 5: High power full correction. When switching back to the high-power mode, the focal spot camera has to be removed, and usually, some thermal effects change the wavefront of the laser.
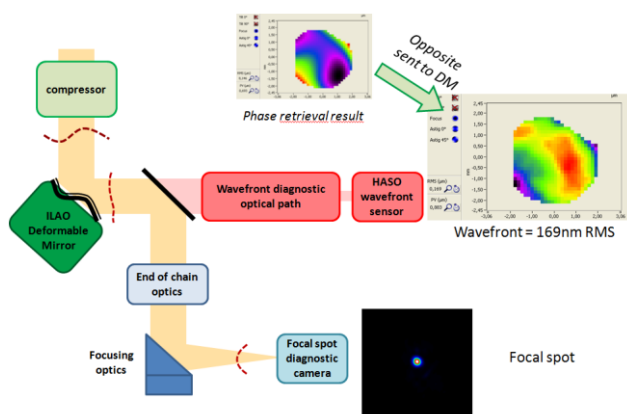

Figure 6. The optical scheme and measured wavefront in low-power and high-power modes.

So the high-power focal spot becomes again distorted. At this point, adaptive optics loop is run so that the deformable mirror reproduces the previous wavefront

Figure 5. *After adding the opposite of the phase retrieval result to the deformable mirror, wavefront error is 169nm RMS but focal spot is perfect. This is the exact symmetrical situation as the usual adaptive optics where the wavefront is perfect but the focal spot is not.*
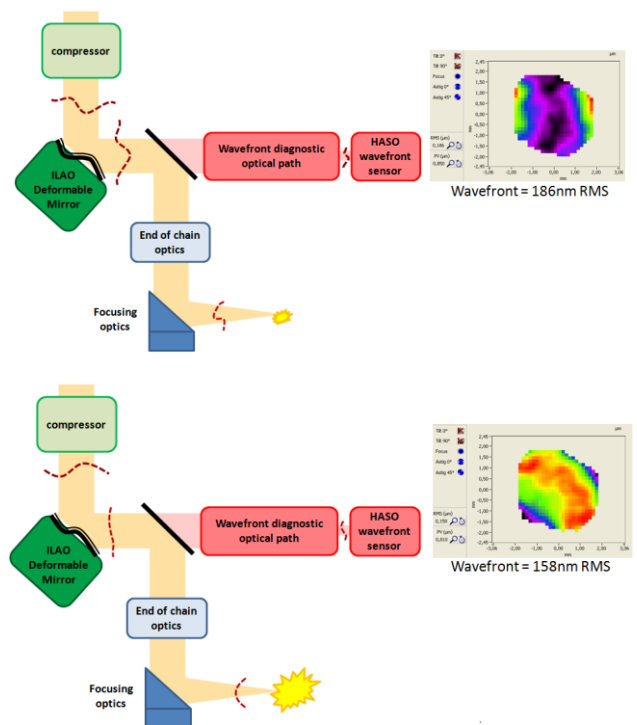
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that was giving a perfect focal spot (same wavefront as in step 4). Since differential aberrations are not power dependent, the focal spot is indeed perfect in high-power mode.

For more information, please visit
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References

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2) N. Varkentina, G. Dovillaire, J. Legrand, G. Beaugrand, I. Stefanon, P. Treimany, X. Levecq, "New adaptive optics control strategy for petawatt-class laser chains", Quantum Electronics 47 (8) 711 – 717 (2017).

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