

# ILAO STAR

## Full correction of a laser chain including final focusing optics

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APPLICATION NOTE

### 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.

## 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 for 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).

## Materials and Methods

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

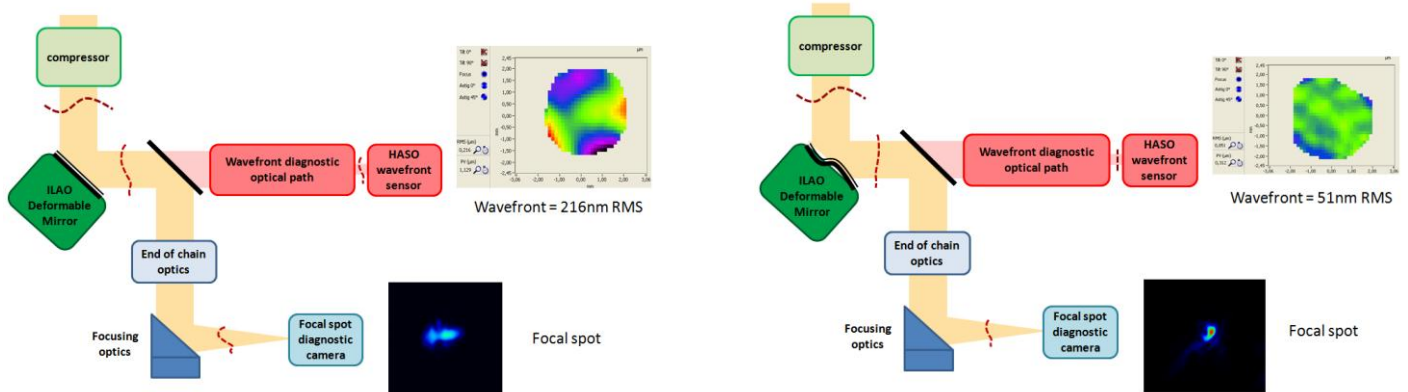
- **HASO Wavefront sensor** : HASO first, 32x40 microlens array, active area: 3.6x4.6mm<sup>2</sup>, Spectral bandwidth: 450-1100nm, absolute measurement accuracy:  $\lambda/100$  RMS (for details, see [http://www.imagine-optic.com/iop\\_products\\_wavefront-analysis\\_HASO-FIRST\\_shack-hartmann-wavefront-sensor\\_en.php](http://www.imagine-optic.com/iop_products_wavefront-analysis_HASO-FIRST_shack-hartmann-wavefront-sensor_en.php)).
- **ILAO Star deformable mirror**: 33 actuators, 40mm useful diameter, optical quality: better than 20nm RMS, linearity >95%, no hysteresis, vacuum compatible (for details, see <http://www.imagine-optic.com/en/product/ilao/0/0/>).
- **Focal spot diagnostic camera**: 12 bits, GigaEthernet connection, 1628x1236 pixels, Pixel size: 4.4 $\mu$ m.

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

- **Casao**: the standard closed-loop adaptive optics software for controlling HASO sensors and ILAO deformable mirrors.
- **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 phase retrieval calculation capability. It was initially proposed to deliver separate software to do phase retrieval calculation only and would communicate with Casao using network ports. However, the Wavetune software includes both the capability of Casao and Pharao in a single software, which is more 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.

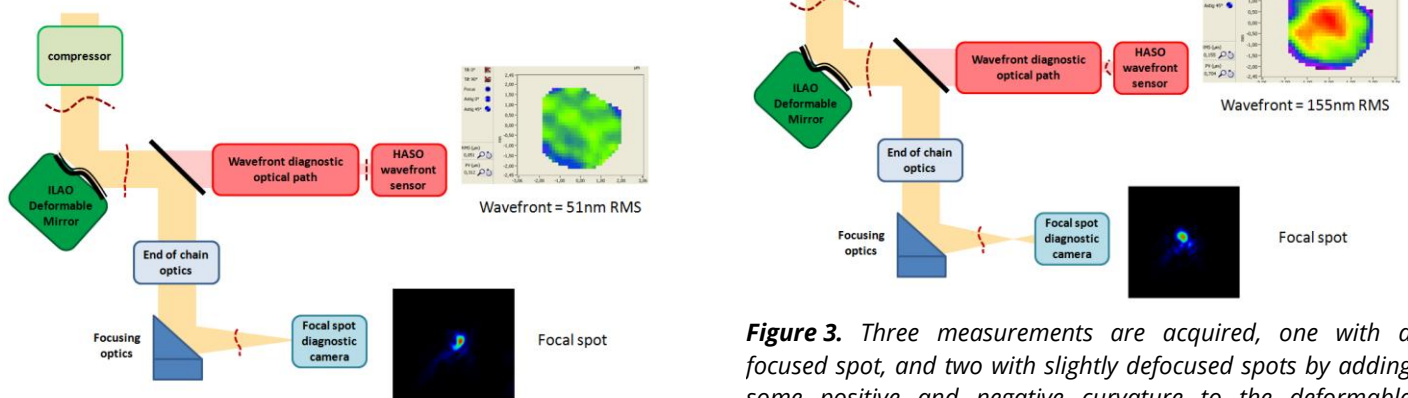
## Adaptive optics strategies for aberration correction of the full laser chain at high-power.

**Step 1: Typical adaptive optics strategy.** Before adaptive optics correction, the wavefront sensor measures aberrations presented the laser chain and also



**Figure 1.** Before running adaptive optics loop, both focal spot and wavefront are aberrated.

in the wavefront diagnostic 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. 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



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

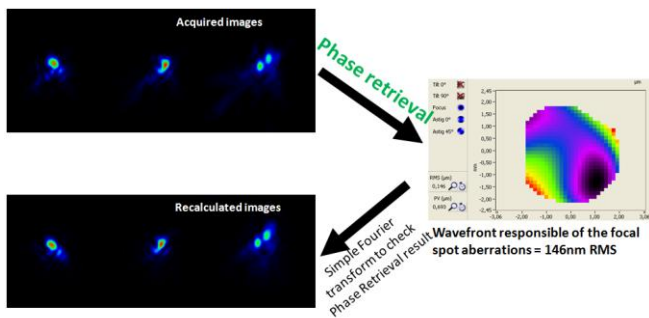
spot is not perfect.

**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. The amplitude of defocus is rather small, typically half a wavelength. Simultaneously with images of the focal spot, the wavefront measurements are also

**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.

acquired. This is done automatically by adjusting the deformable mirror shape and adding some very small positive and then negative curvature to the deformable mirror surface.

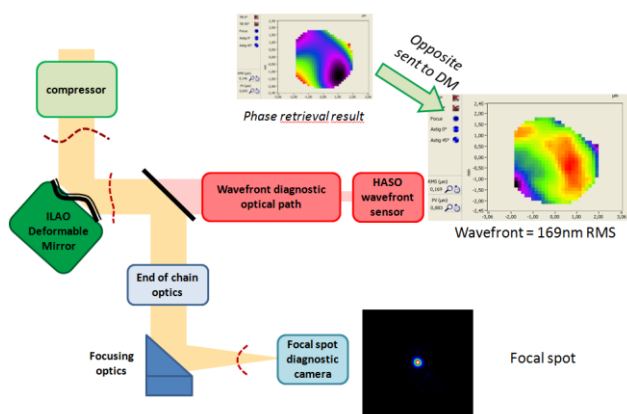
**Step 3: Phase Retrieval calculation.** The phase retrieval algorithm processes the acquired data and calculates the differential aberrations between the wavefront sensor and the focal spot camera. The result of these calculations



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

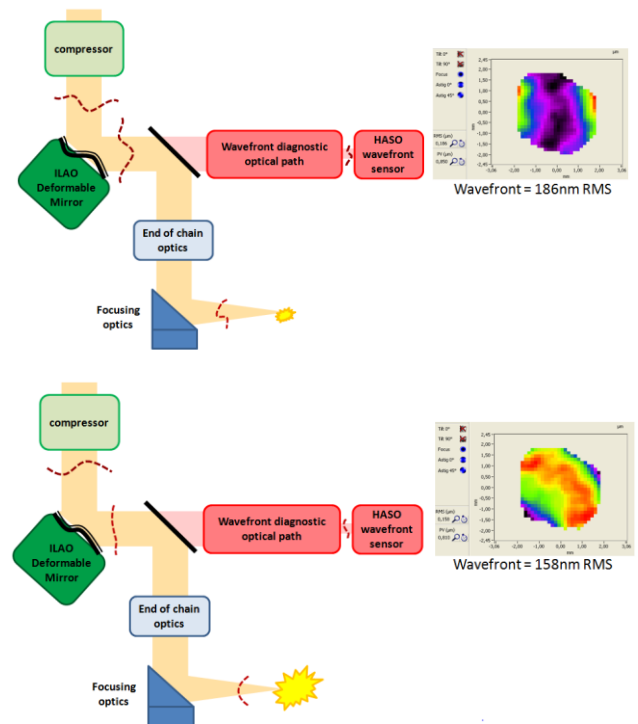
is the differential aberrations of the system, *i.e.* aberrations that are present either on the wavefront sensor path or on the main laser path up, but not on both path (as those were corrected in the first step). Results are crossed checked by doing recalculation of the focal spot of calculated differential aberrations and checking that they are indeed similar to the acquired images of the focal spot. 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 is necessary in order to get the full correction within a few minutes even if several iterations of steps 2, 3 and 4 are necessary to get the perfect focus beam.

**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.



**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.

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



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

### Reference

F. Canova, L. Canova, J. Chambaret, X. Levecq, E. Lavergne, G. Dovillaire, and T. Planchon, "Wavefront Correction and Aberrations Pre-Compensation in the Middle of Petawatt-Class CPA Laser Chains," in Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies, OSA Technical Digest Series (CD) (Optical Society of America, 2007), paper JThD125.