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Initial Demonstration of Mercury Wavefront Correction System

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Subject: **Initial Demonstration of Mercury Wavefront Correction System**

I. **Introduction**

High average power operation of the Mercury Laser induces dynamic aberrations to the laser beam wavefront. Analysis of recent data indicates that up to 4 waves of low order aberration (mainly focus error or power, with spatial resolution < 0.5 cm^{-1}) could be expected at each pass. Because of the magnitude of the wavefront error, the logical position is to place a deformable mirror (DM) at the M11 position, where the DM will correct the beam between passes 1 & 2 and 3 & 4. Currently, there are only two established commercial vendors offering complete adaptive optic (AO) systems that can accommodate the Mercury beam size (45x75 mm) which are compatible with high damage threshold coatings. Xinetics (MA, USA) offers a complete AO system along with a Shack-Hartmann wavefront sensor. The Xinetics DM is based on lead magnesium niobate (PMN) technology. A number of US aerospace firms as well as NIF use Xinetics PMN technology for their DMs. Phasics (Paris, France) offers a complete AO solution with its proprietary SID-4, a four-way shearing interferometric wavefront sensor capable of high resolution (over 100 x 100 sampling points). The Phasics system includes a bimorph deformable mirror from Night-n-Opt (Moscow, Russia) that uses lead zirconate titanate (PZT) technology. Various high power laser laboratories around the world such as LULI (France), HELEN (UK), and GEKKO (Japan) are using the PZT-based bimorph DM in their system. While both DM technologies are equivalent and have been deployed in high-energy laser systems, the PZT based bimorph DM offers two distinct features that makes it more attractive for high average power laser systems. The bimorph DM uses two layers of PZT actuators with the outer layer acting as power correctors, capable of correcting up to 20 waves of power. The Xinetics DM offers a maximum stroke of 4 waves. In addition, Night-N-Opt has also designed a water-cooled DM with a silicon based substrate (as opposed to a glass substrate) specifically for high average power laser systems – an option that is currently not available for PMN based DMs.

A 100 mm diameter bimorph deformable mirror (DM) with 41 actuators (with a spacing of 10 mm) has been designed and procured for the Mercury Laser system (see Figure 1). The reflectivity of the coating witness sample was measured to be 99.98%. With a maximum incident energy of 35 J (after pass 3), this implies less than 100 mW of incident power will penetrate into the substrate. Due to the low average power, a water-cooled DM does not appear necessary for the 100-J Mercury Laser. Initial tests on the coating witness sample through SPICA technologies (NH, USA) with the NIF small optic protocol (NIF5008633, MEL01-013-OD) have shown no damage initiation up to 10 J/cm^2 (max. expected fluence is 1.5 J/cm^2) at 3.5 ns at 1064 nm. The SID-4 wavefront sensor is the first of the company's high-resolution series and uses the top of the line 12-bit CCD camera (1200 x 1200 resolution) to give a maximum of 300 x 300 sampling points. System integration is achieved using Labview for wavefront acquisition and DM control along with features such as Legendre decomposition, far field analysis, and alignment tools.

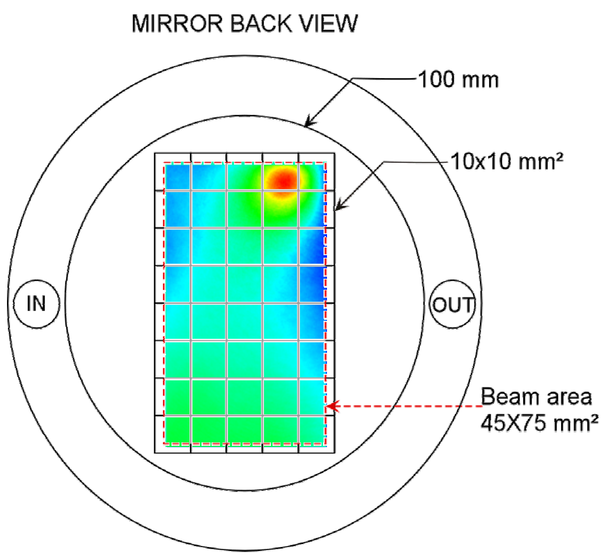


Figure 1: Mercury Laser's 100 mm diameter DM with 40+1 actuators arranged in 5x8 configuration. A typical influence function is overlay over the actuators.

II. **Offline Verification**

Individual component testing has been successfully carried out at each stage of the production process including coating witness sample testing at a NIF certified facility, wavefront sensor validation at Phasics, DM component tests at Night-N-Opt, and AO system integration tests at Phasics. Table 1 outlines a summary of some of the results.

Table I: Offline verification results.

Test	Test Facility	Specification	Test result
Maximum Stroke	Phasics	> 3 waves	> 6 waves
Mirror Flatness (focus corrected)	Night-N-Opt	< 1 waves	0.9 waves

Transmission	NIF	< 0.2 %	0.065 %
Damage Threshold	SPICA Technologies	3 J/cm² @ 3 ns	> 10 J/cm² @ 3.5 ns

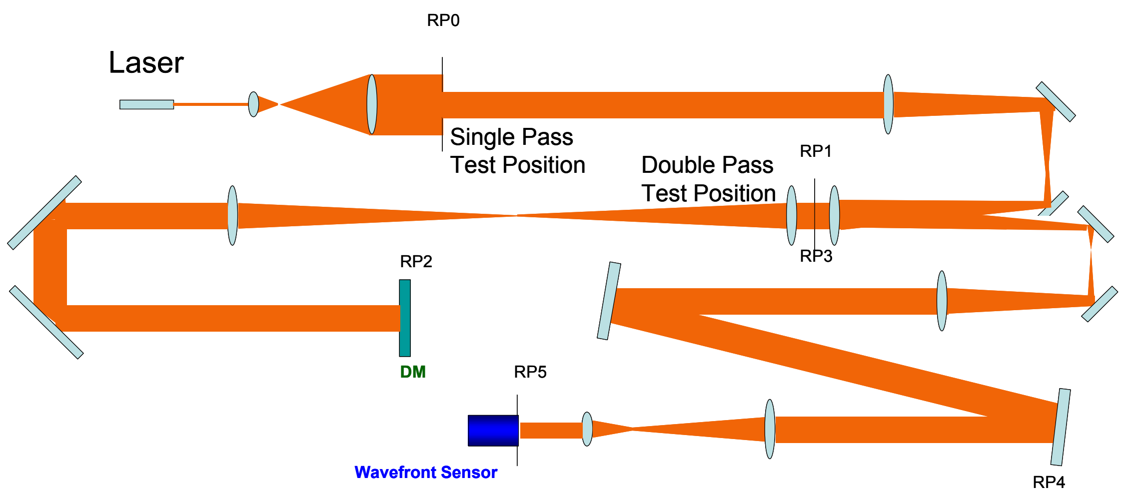
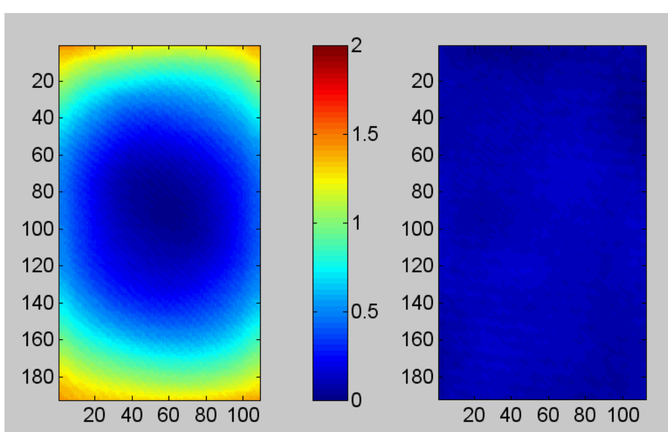


Figure 2: Mercury offline diagnostic beam layout.

In addition, complete system integration verification testing was first carried out on the Mercury offline diagnostic beam facility. The offline beam consists of a Spectra Physics CW 1047 nm laser that has been up collimated to the Mercury beam aperture (3 x 5 cm) along with multiple relay planes (RP) for various testing configurations (see Figure 2). The first test consists of having the DM correct to a perfectly flat wavefront at the output (RP5). The initial beam has a peak-to-valley (PV) of 1.5 waves and a root mean square (RMS) of 0.37 waves. The AO loop is closed and the corrected beam has a PV of 0.17 waves with a RMS of 0.026 waves (see Figure 3). The AO loop converged fairly quickly, at a moderate gain (feedback strength of the closed loop) setting, it only took 5 iterations to successfully close the loop. Figure 4 shows the PV and RMS of a larger beam (1.5x, 45 x 75 mm) as the loop is closed.



PV = 1.5, RMS = 0.37 PV = 0.17, RMS = 0.026

Figure 3: Initial wavefront (RMS = 0.37) and final wavefront (RMS = 0.026) after successful closed-loop.

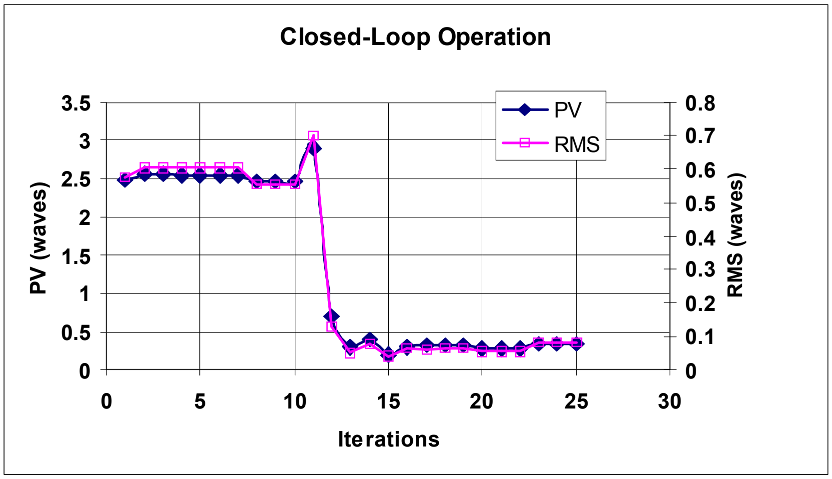
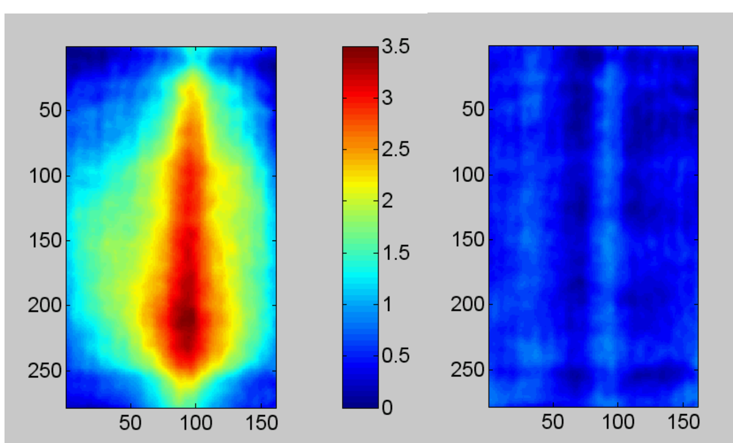


Figure 4: Closed loop operation of the DM system for a 45 x 75 mm beam, improving RMS from 0.6 waves to 0.04 waves.

A phase plate with a representative phase distortion (~ 1.7 waves) is placed in the double pass test position (RP 1) to test the DM performance. This tests the ability of the DM to converge when the beam is twice reflected. Although the current Mercury amplifier slabs have been improved significantly such that it no longer uses bonded crystals, this test also helps to benchmark the performance of the DM on sharp features. As can be seen in Figure 5, the DM was able to operate closed-loop and significantly reduce the wavefront error by a factor of 5 on the RMS of the wavefront.



PV = 3.5, RMS = 0.75 PV = 0.9, RMS = 0.16

Figure 5: Wavefront of uncorrected beam double passing through phase plate with bond line before (left) and after correction (right) by the DM.

III. **Initial Online Demonstration**

Initial online demonstration on the Mercury Laser is intended to validate features and functions that are unique to the laser:

1. Pulse triggering using system provided trigger
2. Correction of system static wavefront
3. Correction of thermal wavefront
4. Correction of system wavefront after reflecting twice by the DM

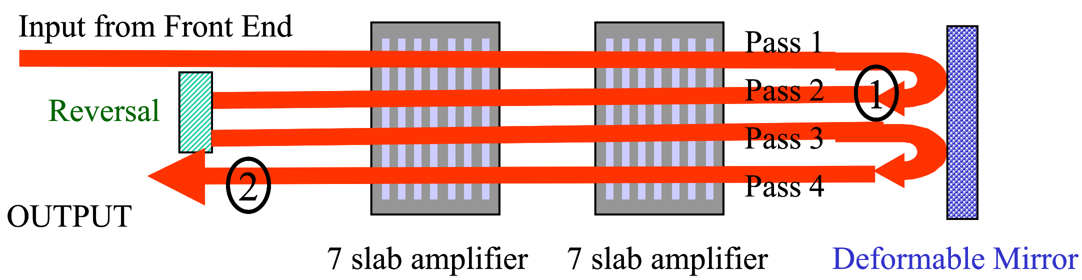
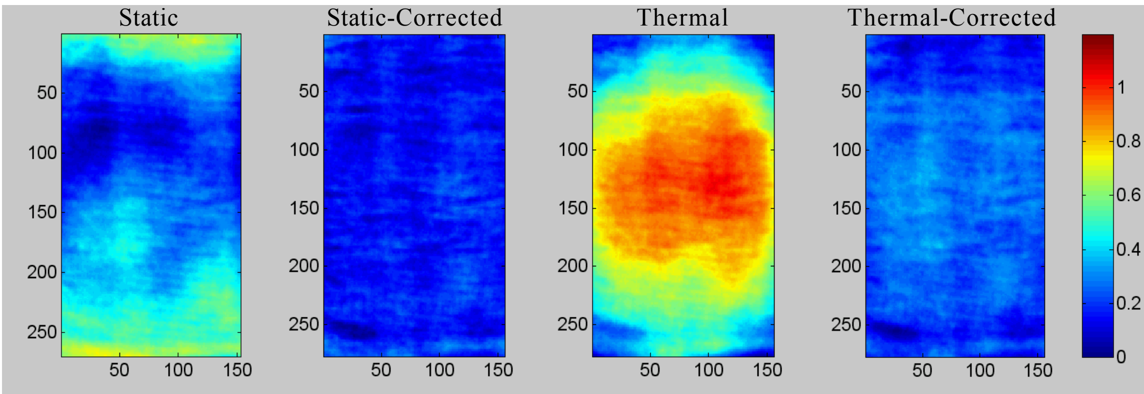


Figure 6: Mercury DM online experiment layout. The sensor is placed at position 1 for single pass DM correction and position 2 for four-pass DM correction. Beam is flipped horizontally after the reversal.

The wavefront sensor is first placed after pass 1 (through two amplifiers), just after the DM (indicated as position 1 on Figure 6); this allows testing of the DM performance without dealing with double reflection by the DM or beam flipping from the reverser. A Mercury Laser internal trigger is used to trigger the camera acquisition. Although the wavefront sensor has been able to run at a maximum repetition rate of 10 Hz in CW mode, the current software has limited its repetition rate to only 5 Hz in pulsed mode (Phasics is currently working on a software upgrade to fix this issue).

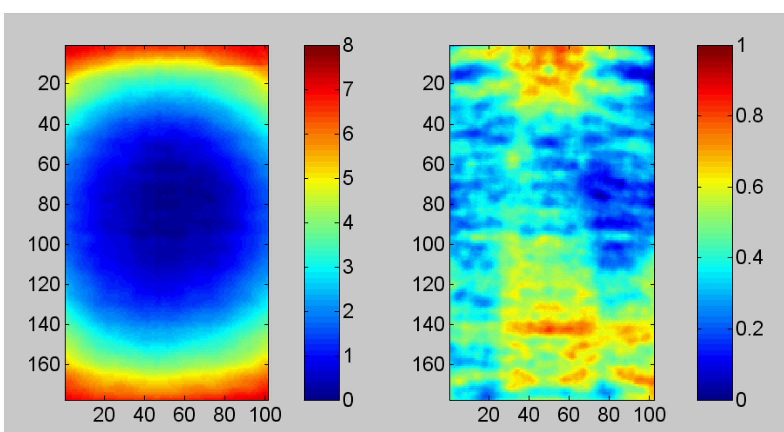
Initial single pass phase correction is done without turning on the system blowers or the pump diodes – this ensures that only static aberration corrections are evaluated. Static wavefront is taken before the DM replaces the mirror at the M11 location; it includes all wavefront distortion from lenses, mirrors, as well as crystals in the amplifier slab. Single-pass static wavefront (see Figure 7) through the system is surprisingly good with a PV of 0.95 waves considering the system consists of approximately 20 optics each having a $\lambda/10$ or better surface plus 14 S-FAP crystals each having $\lambda/5$ surface quality. The DM replaces the M11 mirror and the AO loop is closed so that the mirror corrects for all the static distortions (PV = 0.33, RMS = 0.04). Thermal wavefront distortion is deliberately added to the system by turning on the pump diode at full power (pulse width at 900 μs). The system is run for 15 minutes until steady state is reached, with PV of 1.07 and RMS of 0.22 waves (the thermal distortion is of opposite sign of the static distortion). Closed-loop corrected thermal wavefront shows a PV of 0.39 and RMS of 0.06, comparable to the corrected static wavefront. Design simulation with similar thermal phase data had showed a theoretical result of PV of 0.4 with RMS of 0.03 with the current 5 x 8 actuator configuration. Most of the residual wavefront can be attributed to the high order spatial frequency distortion of the S-FAP amplifier crystals.



PV = 0.95, RMS = 0.22 PV = 0.33, RMS = 0.04 PV = 1.07, RMS = 0.22 PV = 0.39, RMS = 0.06

Figure 7: Static wavefront without DM, closed-loop corrected static wavefront, 15 minutes thermal wavefront, and closed-loop corrected thermal wavefront after single pass through the amplifier system.

The wavefront sensor is then placed at the end of four passes at the output of the laser system (indicated as position (2) on Figure 6). This allows evaluation of the DM's ability to correct for a Mercury beam that has gone through all four passes as well as twice reflected by the DM with the beam flipped horizontally between the first and second reflection. With the DM in place but at rest, the wavefront after four passes has a PV of 7.2 waves with a RMS of 1.9 waves (see Figure 8). This static wavefront is due to the fact that the DM surface is not as flat as a conventional high quality static mirror. After the AO loop is closed, a PV of 0.8 with a RMS of 0.15 waves is obtained (see Figure 8), this is roughly twice that of a single-pass corrected wavefront (see Figure 7).



PV = 7.2, RMS = 1.9 PV = 0.83, RMS = 0.15

Figure 8: Initial distorted wavefront with DM (left) and closed-loop corrected wavefront (right) after four passes through the system.

IV. **Discussion**

In evaluating the performance of the DM, it is important to limit the evaluation to the low spatial resolution wavefront errors that the DM is capable of correcting. The current DM has a 5 x 8 actuator configuration, this implies that it can correct for 2nd order and 4th order spatial aberrations, respectively. Legendre decomposition can be used to separate the spatial frequency content of the wavefront by decomposing the wavefront into Legendre polynomials (similar to Zernike polynomials for circular apertures) as follows

$$\Phi(x,y)=\sum_{m,n}^{m+n\leq L} a_{mn}L_{mn}(x,y), \qquad (1)$$

where Φ is the wavefront to be analyze, a_{mn} and L_{mn} are the projection coefficient and Legendre polynomial, of order m by n, respectively. Figure 9 shows the Mercury Laser corrected single-pass and four-pass wavefront after it has been separated into DM-correctable low spatial frequency wavefront (2 x 4 order, i.e. $\Phi_L(x,y)=\sum_m^2\sum_n^4 a_{mn}L_{mn}$) and the residual high spatial frequency wavefront ($\Phi_H = \Phi - \Phi_L$). It shows that for single pass, almost all of the uncorrected aberration is in the high order spatial frequency; the DM was able to correct within 0.1 waves PV and 0.02 waves RMS within the low spatial frequency domain. This is within the limits of DM performance (see Figure 3). For four passes, the DM is able to correct within 0.1 waves PV and 0.04 waves RMS within the low spatial frequency domain, the RMS is roughly double that of single pass and it is expected since the beam is reflected by the DM twice. In summary, the Mercury AO system is performing well with respect to the design specifications.

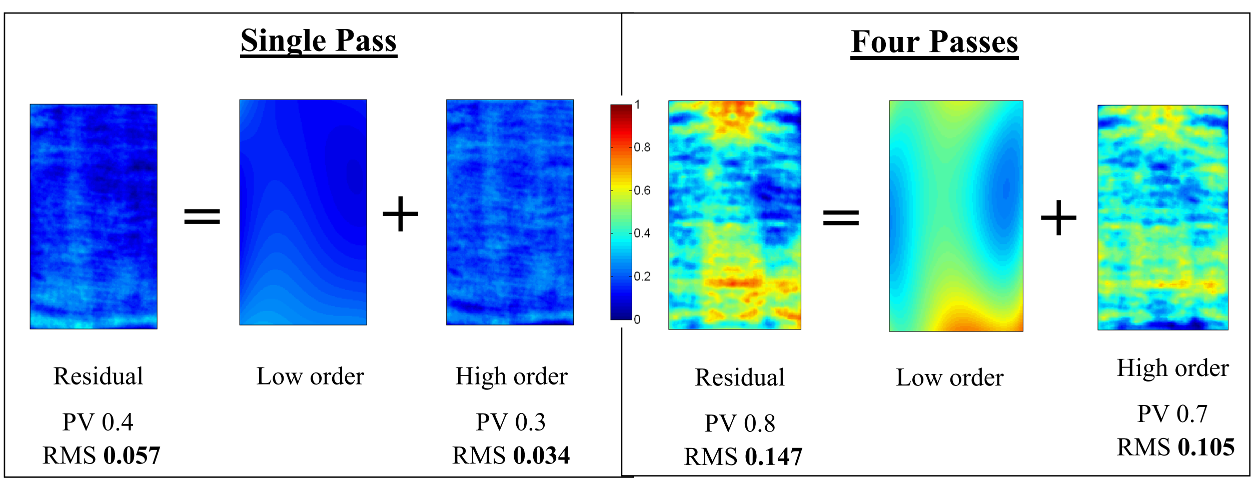


Figure 9: Legendre decomposition results for single pass (left) and four pass corrected wavefront.