Adaptive optics and high power pulse lasers

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ABSTRACT

Some peculiarities of the use of adaptive optical elements and the whole system to correct for the aberrations of high power single pulse lasers are discussed in this paper. The examples of the use of adaptive system to correct for the aberrations of some lasers are presented. As a corrector we used bimorph multi electrode deformable mirror while as a sensor – Shack-Hartmann wavefront sensor.

Keywords: high power laser, active corrector, wavefront sensor, laser beam control.

1. INTRODUCTION

It is very well known that the wavefront of the radiation of most of high power lasers is highly aberrated. This does not allow to obtain a good focus and high concentration of the energy of laser beam. The reason for the wavefront distortions are first of all thermally induced aberrations in active elements and also some residual aberrations of various optical elements. In general the initial quality of each optical element is high enough (P-V about λ/10) but the whole optical setup consists of tens of such elements that altogether introduce sufficiently large aberration. One of the most modern ways to compensate for such aberrations is to use adaptive optics[1]. Originally, adaptive optical systems were invented to control for wavefront distortions in astronomy – the aberrations of the light from the stars that passed through atmospheric turbulence. Such systems had to compensate rapidly changing high order aberrations to improve the vision of the objects, in fact, not always the astronomical ones[2]. They were rather expensive (up to 2-3 million USD), large, and of course could not be used for commercial application in lasers and laser complexes. But the development of contemporary adaptive optics technique allowed nowadays to believe that such systems could be used in various apparatus, including lasers. In our Company together with Laboratory of Shatura branch of Moscow State Open University we managed to design commercially available adaptive optical system for laser beam control. Such system consists of wavefront corrector – in our case, bimorph deformable mirror, wavefront sensor – Shack-Hartmann type of sensor, control unit and software.

2. ADAPTIVE OPTICS FOR LASERS

The main tasks that could be resolved by methods and technique of adaptive optics are:

1. Stabilization and optimization of different laser radiation parameters.
2. Formation and maintenance of the given intensity distribution of laser beam on the given surface.

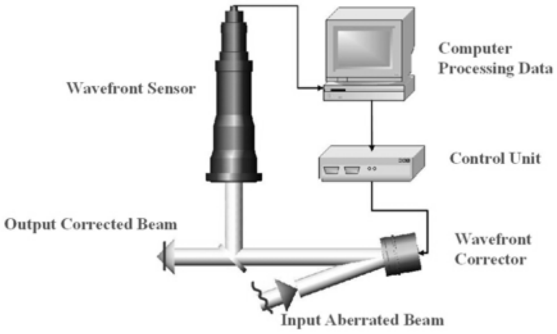


Fig. 1. Principle scheme of laser adaptive optical system.

Of course adaptive optical systems for lasers could be separated in two main groups – intracavity and extracavity ones. At the same time in high power lasers adaptive systems usually are installed either before or inside or after final amplifier. The general scheme of adaptive system for laser beam correction is given on fig. 1. Aberrated laser beam falls on wavefront corrector (bimorph deformable mirror in our case). Reflected radiation passes beamsplitter and goes to the target. Partly reflected radiation meets wavefront sensor (Shack-Hartmann sensor). Signals from PC proportional to the signals to be applied to deformable mirror are multiplied and directed by control unit to proper electrodes of deformable mirror. Deformable mirror in turn changes its surface in order to compensate for aberrations of the input laser beam.

To control for the wavefront the algorithm presented on fig. 2 was used.

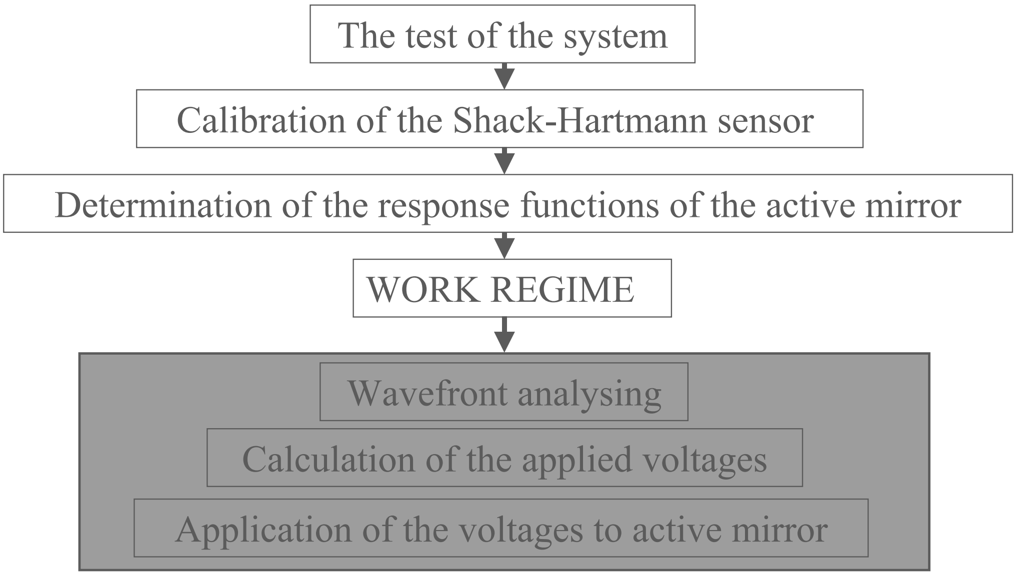


Fig. 2.

On the first stage the software is testing the existence of the elements of the whole adaptive system – framefrabber, control unit and the number of output channels.

On the second stage the calibration of the sensor is carried out – the reference picture is stored in computer memory and some preliminary calculations are made.

On the third stage system is determining the response functions of the electrodes of bimorph corrector applying 100 V consistently to all electrodes and grabbing the correspondent Shack-Hartmann pictures to computer memory.

After the preparation work was completed the WORK REGIME starts. Input wavefront is measured by Shack-Hartmann wavefront sensor. Then the voltages to be applied to all electrodes of the bimorph mirror are calculated. And these voltages multiplied by coefficient 0.9 are applied to electrodes of our corrector - second deformable mirror. In this case the wavefront is not absolutely compensated and the residual distortions are measured by sensor. Again voltages to be applied to corrector electrodes are calculated and applied with coefficient 0.9. And so on. The coefficient 0.9 a bit slows down the work of the whole system but improves the stability of the whole system.

Key elements of adaptive system (bimorph corrector and Shack-Hartmann wavefront sensor) would be described in the next sections.

3. WAVEFRONT CORRECTOR

The main element of any adaptive optical system, the element that determines the properties of the whole system is wavefront corrector. In our work we suggested to use the semipassive bimorph mirror to compensate for the aberrations of

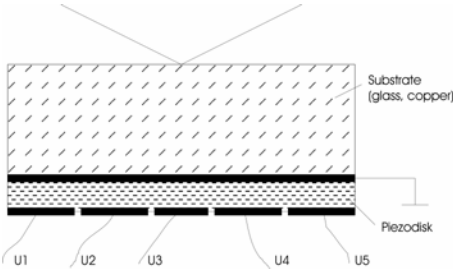


Fig. 3. Scheme of a semipassive bimorph corrector.

the laser beam[3]. The advantages of the use of such mirrors in adaptive system are: continues deformation for the mirror surface (no diffraction losses on the edges of controlled subapertures), large deformation of the surface (up to 30 microns), wide dynamic range (up to several kHz), ability to hold high radiation loading (up to 3 kW CW per cm^2) and one of the most important features – the possibility to correct for the low-order aberrations by minimal number of controlled elements (channels).

These properties of bimorph mirrors make nowadays them one of the most widely used correctors not only in laser beam control but also in astronomical and medical applications of adaptive optics.

The traditional semipassive bimorph mirror consists of a glass, copper or quartz substrate firmly glued to a plate actuator disk made from piezoelectric ceramic (lead zirconium titanate, PZT) (see fig. 3). Applying the electrical signal to the electrodes of the piezoceramic plate causes, for example, tension of the piezodisc. Glued substrate prevents this tension, and this result in the deformation of the reflective surface. To reproduce different types of aberrations with the help of such corrector the outer electrode is divided in several controlling electrodes, that have the shape of a part of a sector. The size as well as the number of such electrodes depends upon the number and the type of the aberrations to be corrected. In our work we usually used the geometry of the electrodes given on fig. 4. The behavior of the bimorph corrector (deformation of the surface when the voltage is applied to the particular electrode) is well described by the following equation[4]:

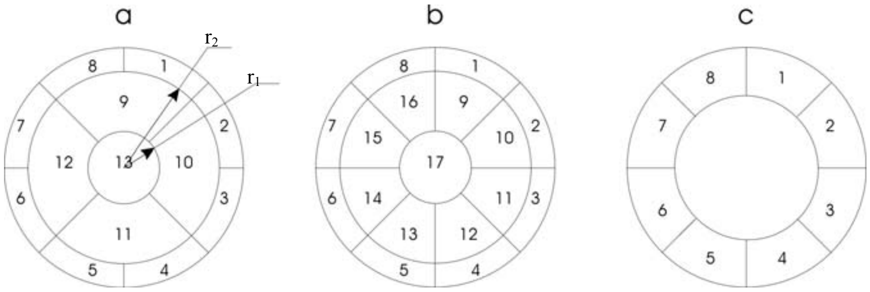


Fig. 4. Various schemes of the control electrodes on the surface of the piezodisk.

$$D'\nabla^2\nabla^2 W + (\rho_1 h_1 + \rho_2 h_2)\frac{d^2W}{dt^2} = \frac{d_{31}\nabla^2\widetilde{E}(x,y)E_1(2\Delta_1 h_1 - h_1^2)}{2(1-\nu)}$$

$$D' = \frac{E_2}{1-\nu^2}\left(\frac{\Delta_1^3}{3} + \frac{\Delta_2^3}{3} - \Delta_1^2 h_1 + \Delta_1 h_1^2 - \frac{h_1^3}{3}\right) + \frac{E_1}{1-\nu^2}\left(\Delta_1^2 h_1 - \Delta_1 h_1^2 + \frac{h_1^3}{3}\right)$$

$$\Delta_2 = \frac{E_2 h_2^2 + E_1(h^2 - h_1^2)}{2(E_2 h_2 + E_1 h_1)}; \quad \Delta_1 = h - \Delta_2$$

Here, h_1, h_2 – the thickness of a piezodisk, and substrate, E_1, E_2 – Young's modulus of a piezodisk and substrate, h – total thickness of the mirror, ν - the Poisson ratios, d_{31} – transverse piezo modulus, $\widetilde{E}(x,y)$ - the strength of the electric field applied uniformly to the given electrode. This equation was used to optimize radii r_1 and r_2 (fig. 4) for the best correction of the low order aberrations such as coma, astigmatism, spherical aberration.

Table 1.

Main features of a semipassive bimorph mirrors.
Substrate material – Glass, Si, PZT, Cu
PZT material – PKR-7M, Russia
Optical aperture –25 – 200 - …. Mm
Deformation Stroke – up to 40 m
Frequency range –up to 5 kHz
Number of electrodes –from 1 to 64 and more
Reflecting coatings - dielectric, metal-dielectric, protected metal (Cu, Al, Ag) with reflectivity up to 99.9%
Power holding – 2 kW/cm^2 for CW and 15 J /cm^2 for pulse radiation
Hysteresis – not more 15%

Several types of the bimorph correctors were produced in Adaptive Optics Group in Moscow State Open University together with Adopt Ltd.. The technology of fabrication of such a corrector was the following: semipassive bimorph plate was heated in a furnace for 4 - 5 h at 80^0 C until the glue had completely hardened. The plate was then cooled in a refrigerator to remove any residual thermal deformations before being reheated in the furnace. This procedure was repeated four or five times. The quartz substrate was then polished to obtain an optical-quality surface (the deviation from sphere should not be greater then 0.1 μ) before a high reflectivity dielectric of metal coating (up to 99.98%) was deposited on its surface.

Conductors were then glued to the common and controlled electrodes. The corrector was inserted in a mounting at the back of which there was a connection to the control voltages. The main features of a semipassive bimorph corrector are shown in Table 1.

Table 2.
RMS errors of several aberrations approximation by 17-electrode bimorph corrector.

Type of aberration	RMS error
Defocus	0.1 %
Astigmatism	0.2 %
Coma	3.0 %
Spherical aberration	5.3 %

The static and dynamic characteristics of the mirrors were studied by an interference method. We used Zygo Mark-3 phase-shifting interferometer. The sensitivity of correctors was estimated from the displacement of the interference fringes at the center of the pattern when the voltage of 100 V was applied to all electrodes. The frequency of the first resonance of our correctors was in the range of 3 - 5 kHz. Table 2 presents the measured RMS errors of approximation of some low-order aberrations by 17-electrode bimorph corrector.

Unique feature of any kind of optics for high power lasers is that they should not change their parameters under high optical load. It means that the coating of the surface must be a very high quality. Moreover the size of the optics usually is very large – about 100 mm in diameter or even more. For high average power lasers there is the problem of constructing controllable cooled mirrors, production of which is rather complicated.

In our Laboratory we had developed large aperture bimorph mirrors. The main problem in manufacturing large aperture bimorph mirrors is the absence of large-aperture piezo disks. For example in Russia the largest piezo disk that could be manufactured is limited by size 110x110 mm. Matroc Morgan Ltd. from UK can bake piezo ceramics with the size of 200x200 mm, but with thickness at least about 1 mm. One of the ways to overcome this problem is to use not one, but several pieces of piezoceramics glued on one substrate. Fig. 5 shows the example of 220x220 mm bimorph corrector with 4 square piezo ceramics combined on the substrate.

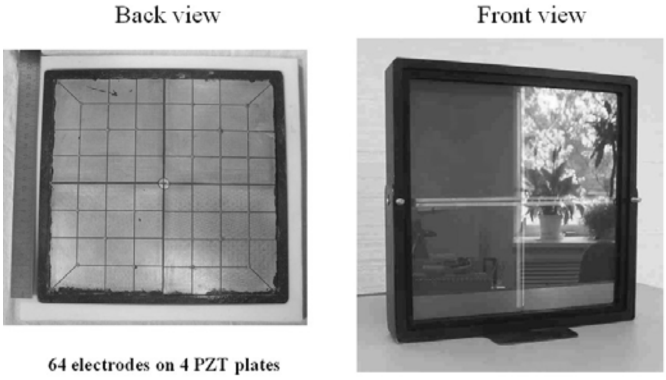


Fig. 5. Photo of a 220x220 mm bimorph mirror.

4. LOW-COST SHACK-HARTMANN WAVEFRONT SENSOR.

One of the demands of any optical system – is its reliability and ability to work not only in laboratory, but also in the real conditions, so that every student could use it and not break it. From this point of view Shack-Hartmann wavefront sensor is the most suitable one to be included in AO system. These kinds of sensors are widely used by astronomers or in medical research but in fact never were applied to control for laser beam. One of the shortcoming of existing wavefront sensors – is their relatively high price, that varies from 25,000$ to 60,000$ or even to 200,000$ (it depends on the tasks and parameters of the system). In Russia we do not have any commercially available Shack-Hartmann wavefront sensor, though the attempts to fabricate it were made by different institutes and research groups. That is why we concentrated our efforts on making our own low-cost version of the sensor.

The wavefront measurements by Shack-Hartmann wavefront sensor (SHS) are based on the measurements of a local slopes of a distorted wave front $\partial\varphi/\partial n$. So, the whole wavefront is divided in several subapertures by some phase plate or lenslet array and the deviation of the focal spot from some reference position in each subaperture is measured. Fig. 6 provides some idea about the work of the SHS. For the measurements a standard CCD camera is used.

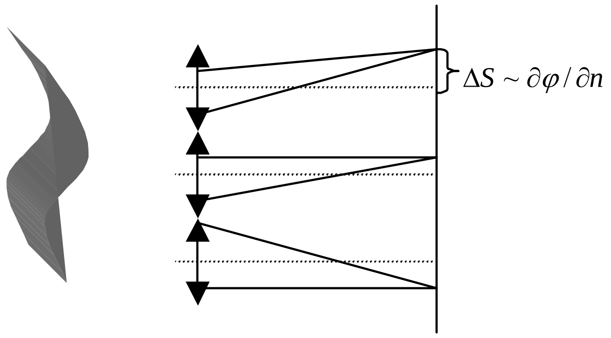
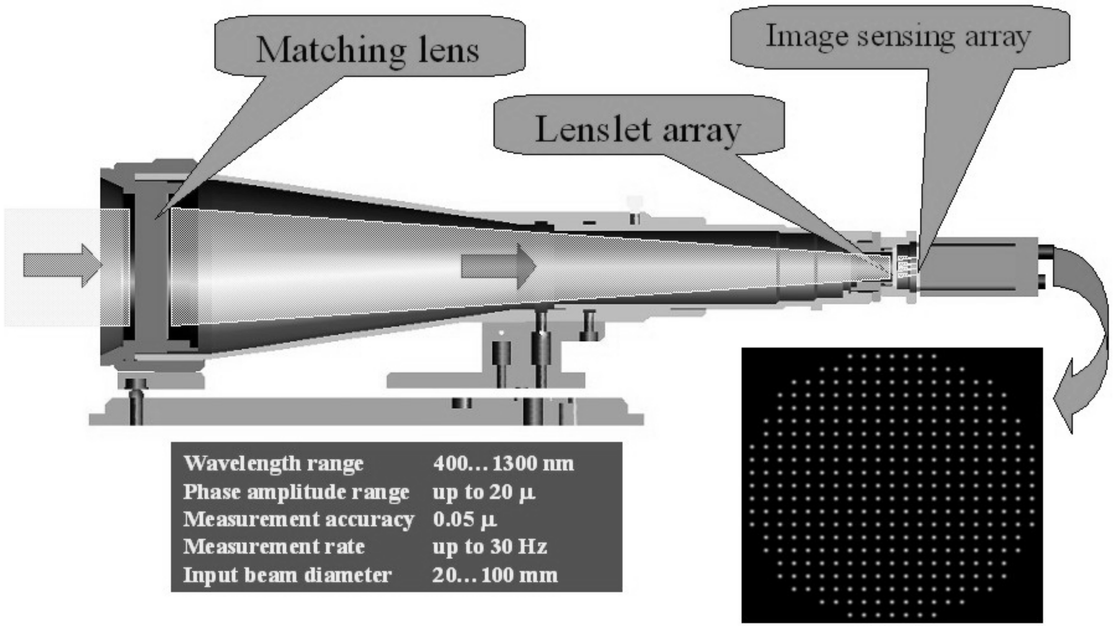


Fig. 6. Idea of SHW

The experimental setup of SHS for laser beam diagnostics is shown on Figure 7. To synchronise the beam size of the incoming beam with the size of the CCD (1/2”) we suggest to use a simple lens. Of course in this case we would be able to determine the phase front up to defocus but this does not harm the correct measurements of the rest aberrations of the beam.

In our work we used CCD camera Pulnex-6M CN with frimegrabber Matrox Meteor II or firewire camera Basler 301A, The experimental sample of the SHS was able to analyse wavefront aberrations with the frequency of 25 Hz.



Wavelength range	**400…1300 nm**
Phase amplitude range	**up to 20 µ**
Measurement accuracy	**0.05 µ**
Measurement rate	**up to 30 Hz**
Input beam diameter	**20…100 mm**

Fig. 7. Design of the wavefront sensor.

The maximal P-V aberrations determinations are in the range of +/- 8 μ. Sensitivity of the proposed SHS depends on the number of lenses on the aperture of the CCD window and for lenslet array 25x19 is about λ/5 - λ/10.

5. APPLICATION OF ADAPTIVE OPTICS FOR SINGLE PULSE LASERS.

From the point of view of application of adaptive optics all single pulse lasers could be divided in two groups – lasers with identical phase aberrations in each pulse and lasers with “unpredictable” phase aberrations in the pulse. Depending on the type of laser different algorithms could be suggested to improve beam quality.

The first example of laser to be corrected belongs to the first group – **LULI, Ecole Politechnique, Paleseau, France**.

5.1. Adaptive Optics for LULI (Ecole Politechnique, Paleseau, France)

The LULI 6x100 J laser is an in-line rod-amplifiers laser chain. A Nd:YLF oscillator delivers at a wavelength of λ=1053 nm a train of temporally Gaussian pulses of 600 ps full width at half maximum (FWHM) duration[4]. One of these pulses, selected by a Pockels cell, is amplified to about 50 J and split into 6 arms. Each beam is finally amplified to a maximum of 100 J with a beam diameter of 85 mm. The amplifier material is phosphate glass doped with Neodymium. The laser beams propagate over 30 m from the laser room to the experimental hall. Wavefront correction is applied to one beam, the interaction beam. It is focused on the plasma by a f_1=500 mm doublet. To monitor the far-field pattern of the interaction beam, we collect the transmitted beam after the focal point through a ×9 telescope (two doublets: f_2=250 mm and f_3=2200 mm) associated with a x4 microscope objective. The images are recorded using a 12-bit CCD camera. Figure 8 presents the experimental setup for close loop laser beam control. As a deformable mirror we used a 100 mm bimorph

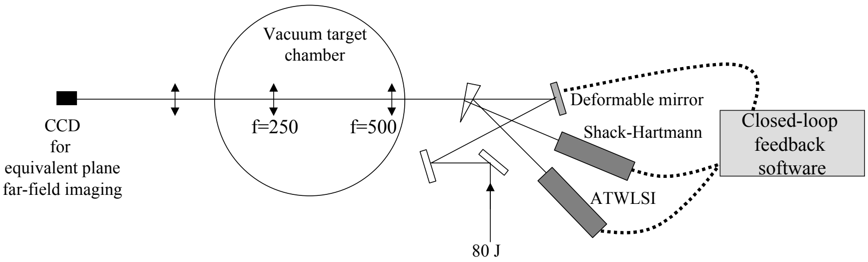


Fig. 8. Set-up of the wavefront correction.

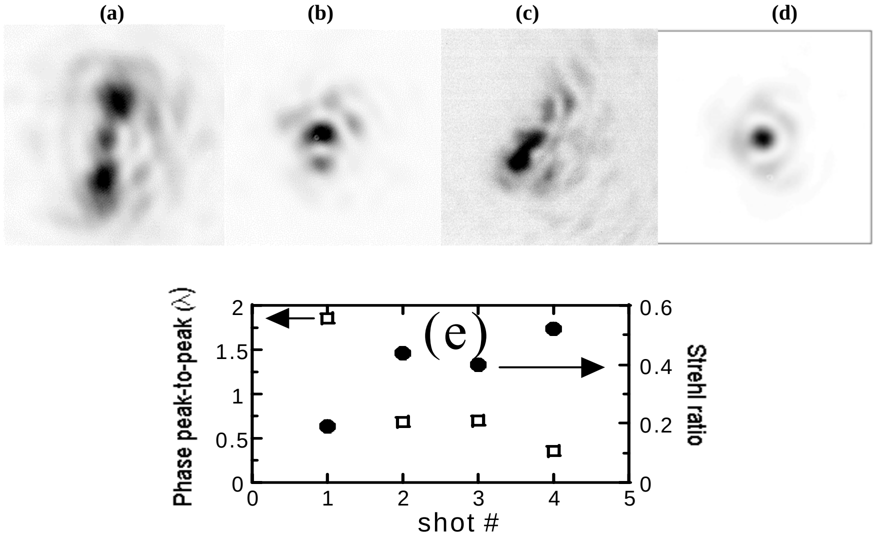


Fig. 9. (a-d) far-field patterns of high-energy shots (50 J) during a converging sequence. (e) corresponding evolution of the amplitude of the maximum wavefront phase distortion (boxes, left scale) and of the Strehl ratio (filled circles, right scale).

corrector with 31 electrodes placed in 3 rings. To measure the wavefront two types of sensors were applied – SHS and an achromatic three-wave lateral shearing interferometer (ATWLSI). The correction procedure included the measurement of phase of the first pulse, then introduce phase distortions by means of deformable mirror to compensate for these distortions. After this, to measure again aberrations of the second phase, correct for residual aberrations and so on until we get the "ideal" wavefront. This procedure is very similar to correction of the CW laser. Simple it takes longer time. And it is possible only in case if the phase front in every pulse is the same. The results of the laser beam correction of described laser are given on Figure 9. The loop converges in less than four iterations, as shown in Figure 9, where we display the wavefront phase and focal spot evolution along the convergence (starting from a mirror at rest) and we plot the evolution of the associated Strehl ratio and of the wavefront average P-V. Since the phase distortions of the laser chain are stable as long as it is fired at its nominal rate, the performances of the correction can be maintained for hours, once the convergence is achieved, by keeping the voltages that drive the deformable mirror fixed.

5.2. Adaptive Optics for HELEN Laser (AWE, UK).

HELEN laser is a flash-lamp pumped 4-path amplifier Nd doped glass laser[5]. The main parameters of HELEN laser are – pulse duration – 100 ps, output energy – up to 1 kJ, repetition rate of shots – 1 shot per 3 – 4 hours. Our deformable mirror was installed before the final amplifiers to avoid extremely high radiation load on the surface of bimorph mirror. While wavefront sensor was placed right before the interaction chamber. The deformable mirror was introducing the aberrations to be "corrected" by aberrated optical elements – so, right before the chamber, wavefront should be close to the flat one. One unique feature of such laser was that from the point of view of aberrations all output pulses are different one from another. In this case three ways of correction of the aberrations of laser pulses could be suggested:

1. correct for the aberrations measured during the previous pulse before the next pulse and put a set of voltage to DM to eliminate them – like we did it in LULI. Unfortunately this way will never bring the desired result as there is no correlation between pulses.
2. measure the residual aberrations before the pulse (***Res1***) and correct them before the pulse. In this case we do not take into account the aberrations that appear during the pulse itself. We only compensate static aberrations of the optical elements of the whole laser. This is the possible way to improve the beam quality.aberrations of the pulse includes both some static residual aberrations before the shot (***Res1***) and the aberrations introduced during the pulse itself (***Pul1***). So, we suggest to measure pure aberrations introduced during the **first** pulse (***Pul1***), then measure aberrations right before the second pulse (residual static aberrations – ***Res2***). Add these aberrations and by means of adaptive system compensate for these aberrations right before the **second** pulse. Make a shot and see the result.

Fig. 10 presents the results of the correction of aberrations of the pulses corrected according case number 2.

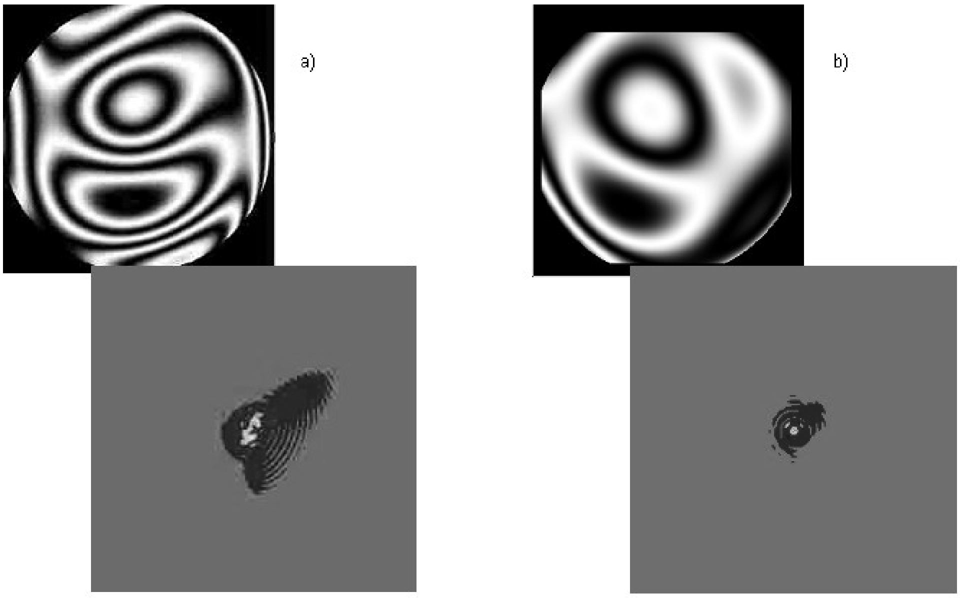


Fig. 10. Aberrations and far field intensity distribution of the first pulse a) and second pulse b) (corrected). Correction was done following case 2.

Here it is clearly seen that the phase front of the pulse was improved and the far field intensity distribution is closer to diffraction limited, but still is far from it. The result was rather predictable because here we did not compensate for the aberrations of the pulse itself.

We also made the correction of the pulses following method number 3. Unfortunately this case did not provide any positive result. Fig. 11 clearly demonstrates this result.

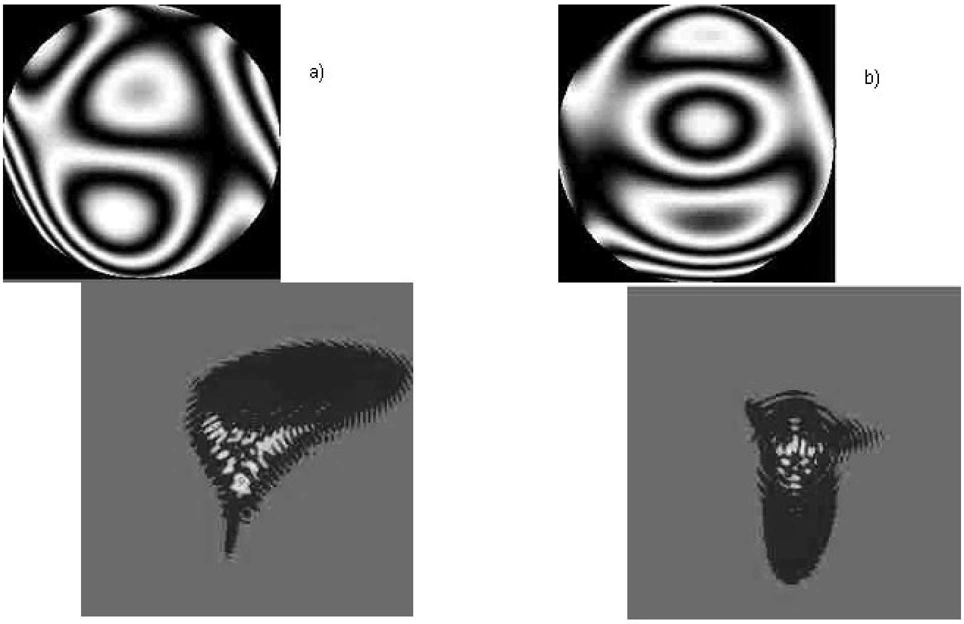


Fig. 11. Aberrations and far field intensity distribution of the first pulse a) and second pulse b) ("corrected"). Correction was done following case 3.

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