Deutsches Elektronen-Synchrotron
A Research Centre of the Helmholtz Association

Study of a laser beam parameters with a Hartmann-Shack Wavefront Sensor

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Abstract

To measure events in femto- and picoseconds range FLASH users utilize pump-and-probe technique. Two pulses a required: pump pulse (from an optical laser) and probe pulse (from FEL)[1]. The optical laser is requested for many experiments. FS-FL group works on upgrading the parameter range and improving the quality of the output laser beam. The output beam has up to 20mJ pulse energy and 50fs pulse duration. When such a beam propagates through air or windows non-linear optical effects can occur. Even at lower pulse energy degradation of the beam profile already observed. My task was to study nature of this degradation using Hartmann-Shack wavefront sensor.

Hartmann-Shack Wavefront Sensor

Measuring principle.

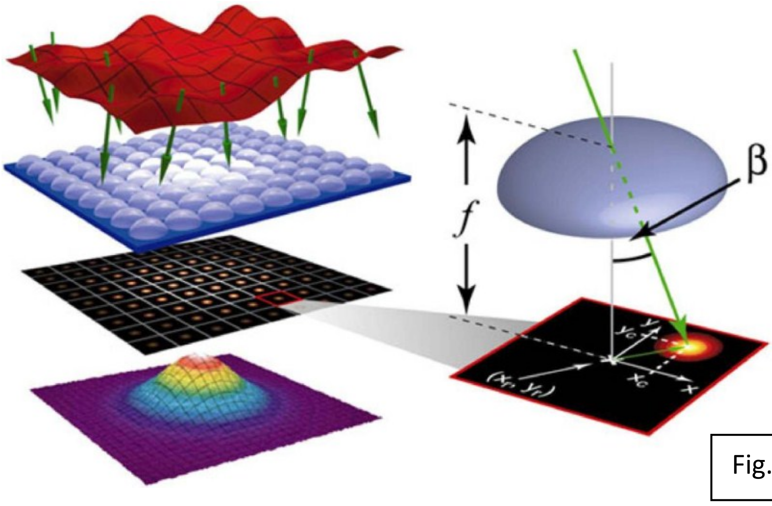


Fig.1

The wavefront $w(x,y;z_0)$ of a beam is defined as a surface perpendicular to its local direction of propagation; i.e., perpendicular to the Poynting vector **S** (x, y) at a position z_o on the optical axis. Hartmann-Shack wavefront measurements are based on the geometric-optical determination of the local radiation angles $(\beta_x, \beta_y)_{ij}$ by using a microlens array, which splits the incident wavefront into a variety of individual beams (see Fig. 1). A camera installed at a distance f behind the array allows

recording of the foci distribution, yielding the precise position of the partial beams by computing the respective centroids (1st moments). The deviation of these centroid positions $(x_c, y_c)_{ij}$ from given reference positions $(x_r,y_r)_{ij}$ (determined previously with a plane wavefront) describes the local radiation angle $(\beta_x, \beta_y)_{ij}$ and thus the wavefront gradient

$$\begin{pmatrix} \partial w/\partial x \\ \partial w/\partial y \end{pmatrix}_{ij} = \vec{\beta}_{ij} = 1/f \begin{pmatrix} x_c - x_r \\ y_c - y_r \end{pmatrix}_{ij}$$

Based on this information, the wavefront is reconstructed using mathematical algorithms. For spherical profiles a modal expansion in Zernike polynomials is most adequate, since the expansion coefficients correspond to the image aberrations in Seidel's aberration theory. Thus, by analogy to the quality assessment of optical components, the Hartmann-Shack sensor may also be utilized to measure aberrations of a laser beam.

In addition, the beam profile, i.e., the discrete power/energy density distribution, may be obtained from the acquired spot distribution by integrating the respective pixel counts (see also Fig. 1), with a lateral resolution given by the microlens pitch (typically about 150 um).[2]

Measuring of a CW-laser beam

In order to get acquaintance with principle of work of the wavefront sensor in the first place I've studied the quality of the beam of diode red (635nm) cw-laser. Initial beam profile shown on Fig.2.

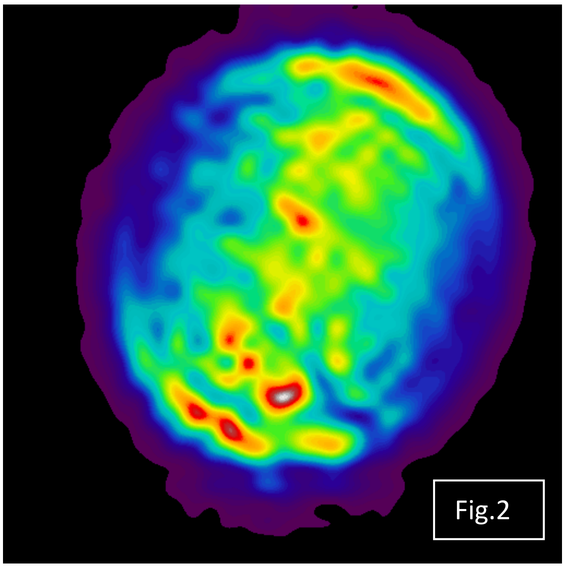


Fig.2

One of the easiest criteria one can check with a wavefront sensor is "defocus" parameter. For this purpose on the path of the laser beam was assembled a pinhole (a hole in aluminum foil was simply produced with a needle). As it's known in the waist of Gaussian beam we have a plane wavefront, so if at this point we put circle aperture with diameter less then waist of the beam we've got a spherical wavefront in the output beam. Thus now we can measure distance between pinhole and wavefront detector with a ruler and compare it with values obtained with sensor.

Insofar as our pinhole was produced under the rustic conditions, size of aperture wasn't small enough. So we didn't get spherical wavefront after the pinhole only spatially filtered beam profile (Fig.3). But spatial filtering has improved quality of our beam. It can be easily seen on the picture and M^2 parameters became nicer $M_x^2 = 1.34, M_y^2 = 1.28$ instead of $M_x^2 = 1.61$, $M_y^2 = 3.10$.

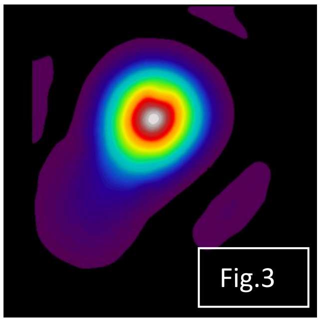
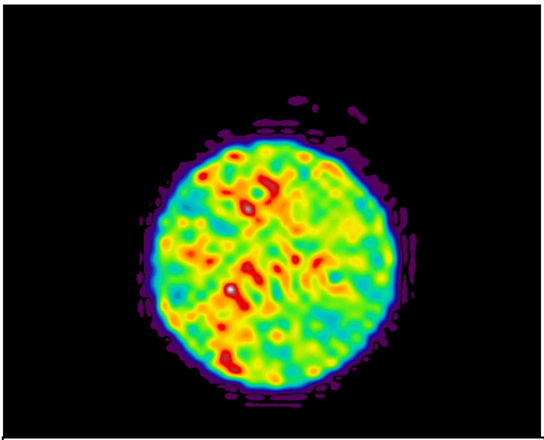


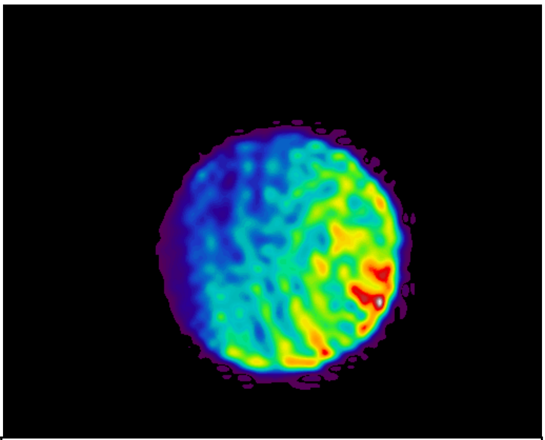
Fig.3

In order to test wavefront sensor before using it with pump-probe laser we decided to make a beam size of the cw-laser the same size as the beam of Hidra. For this purpose we build a telescope using 1 negative and 1 positive lenses and put a glass plate same size as a mirror utilizing in the laser hutch with Hidra. Results can be seen in the Fig.4.



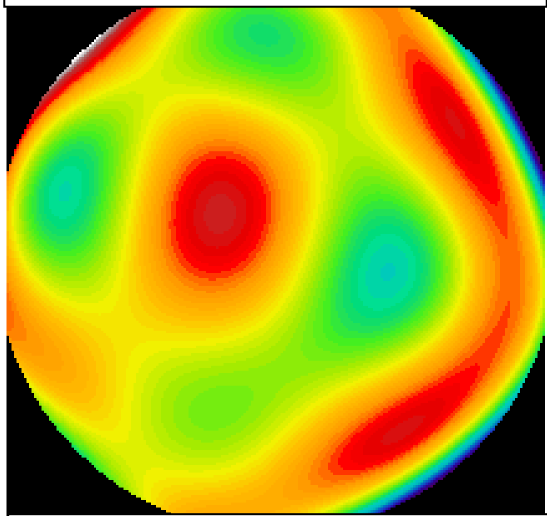
Beam profile of the cw-laser beam passing through telescope, aperture and glass plate 0^0.

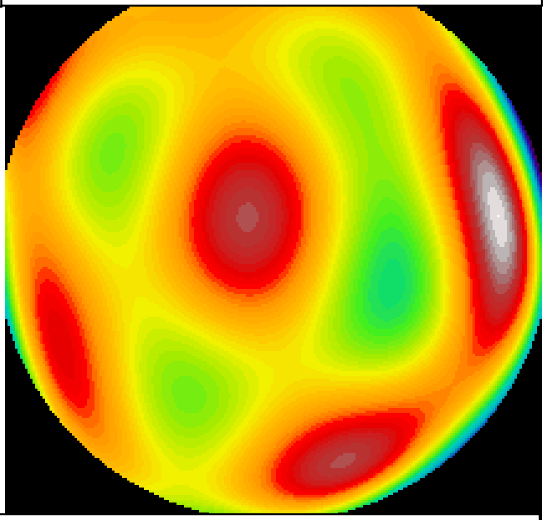
Corresponding wavefront (0.179[λ])



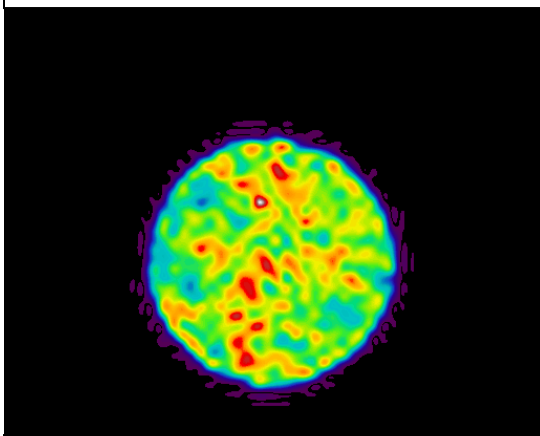
Beam profile of the cw-laser beam passing through telescope, aperture and glass plate 45^0.

Corresponding wavefront (0.212[λ])

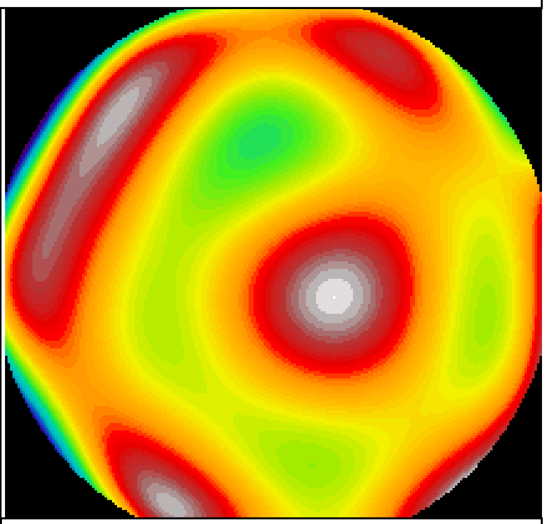




As soon as we put glass plate under 45^0 the beam was shifted that means one should align the camera according with shift resulted by glass plate.



Beam profile of the cw-laser beam passing through telescope, aperture and glass plate 45^0. Camera shifted.



Corresponding wavefront (0.125[λ])

Fig.4

We can easily see that glass plate does not influence on wavefront. So the distortion observed in Hidra pulses cannot be caused by first reflecting mirror assembled on the optical axis of pump-probe laser.

Measuring of Hidra laser beam

Since measurements had to be performed in a standard beam transport scheme, which utilizes to deliver short laser pulses for pump-probe experiments at the FLASH-Beamlines. The position of each element on the optical axis of pump-probe laser carefully thought out and we were not allowed to interfere which means there was not a lot of alternatives to assemble Wavefront sensor. But as pump-probe laser produces powerful short impulses (~3W) leakage from pellicle with high reflection coefficient (~99%) is already sufficient for measuring laser pulses. Another problem we struggled with is beam diameter (FWHM ~6mm) which does not fit active area of the wavefront sensor (8.8mm*6.6mm). One had to think about the way to decrease beam diameter. Two solutions we suggested (Fig.5): usage of a converging lens or usage of an iris in front of the camera. In the first case we have a deal with a beam profile with Gaussian-like intensity distribution, in the second case it is a beam profile with top-hat profile.

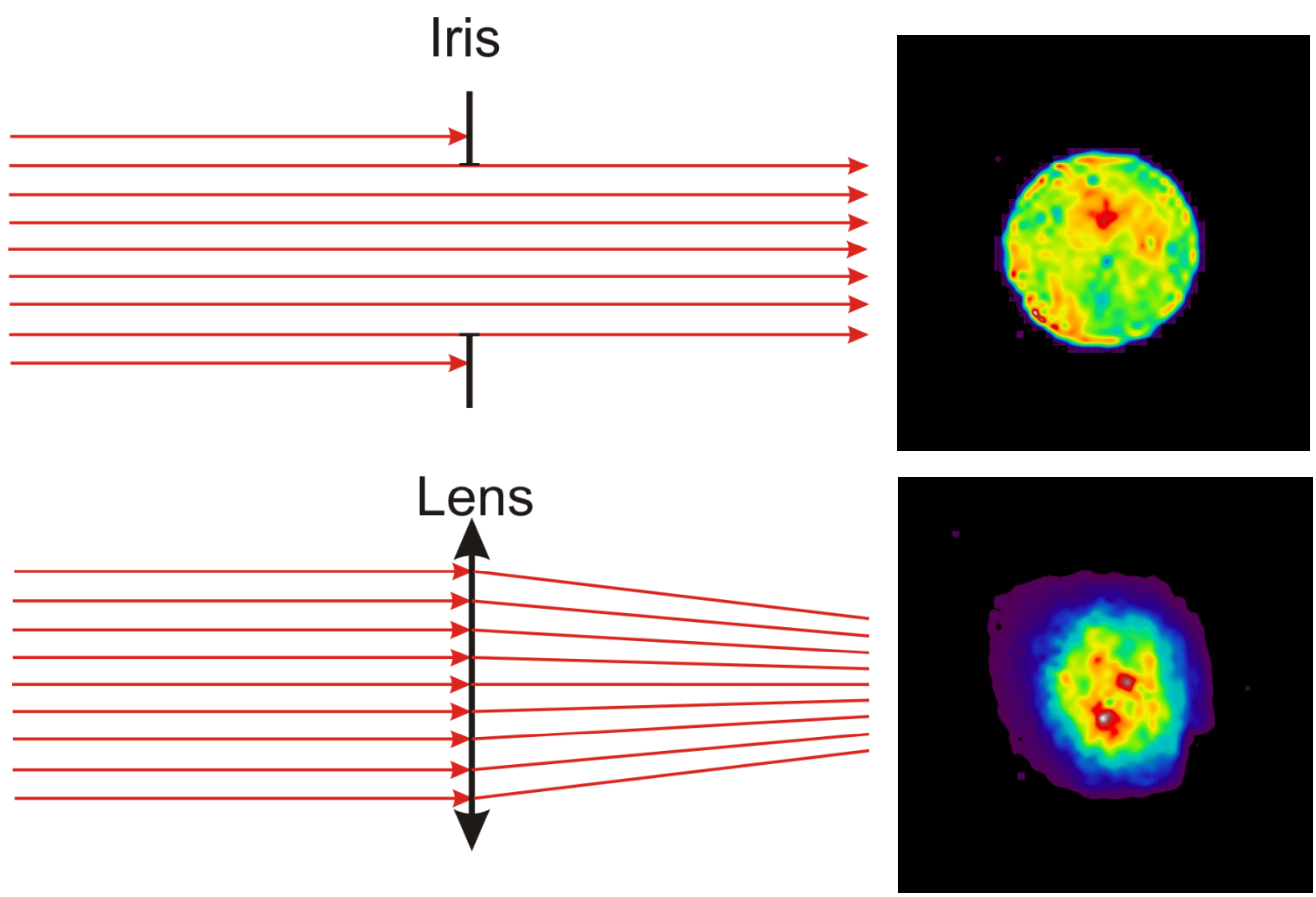
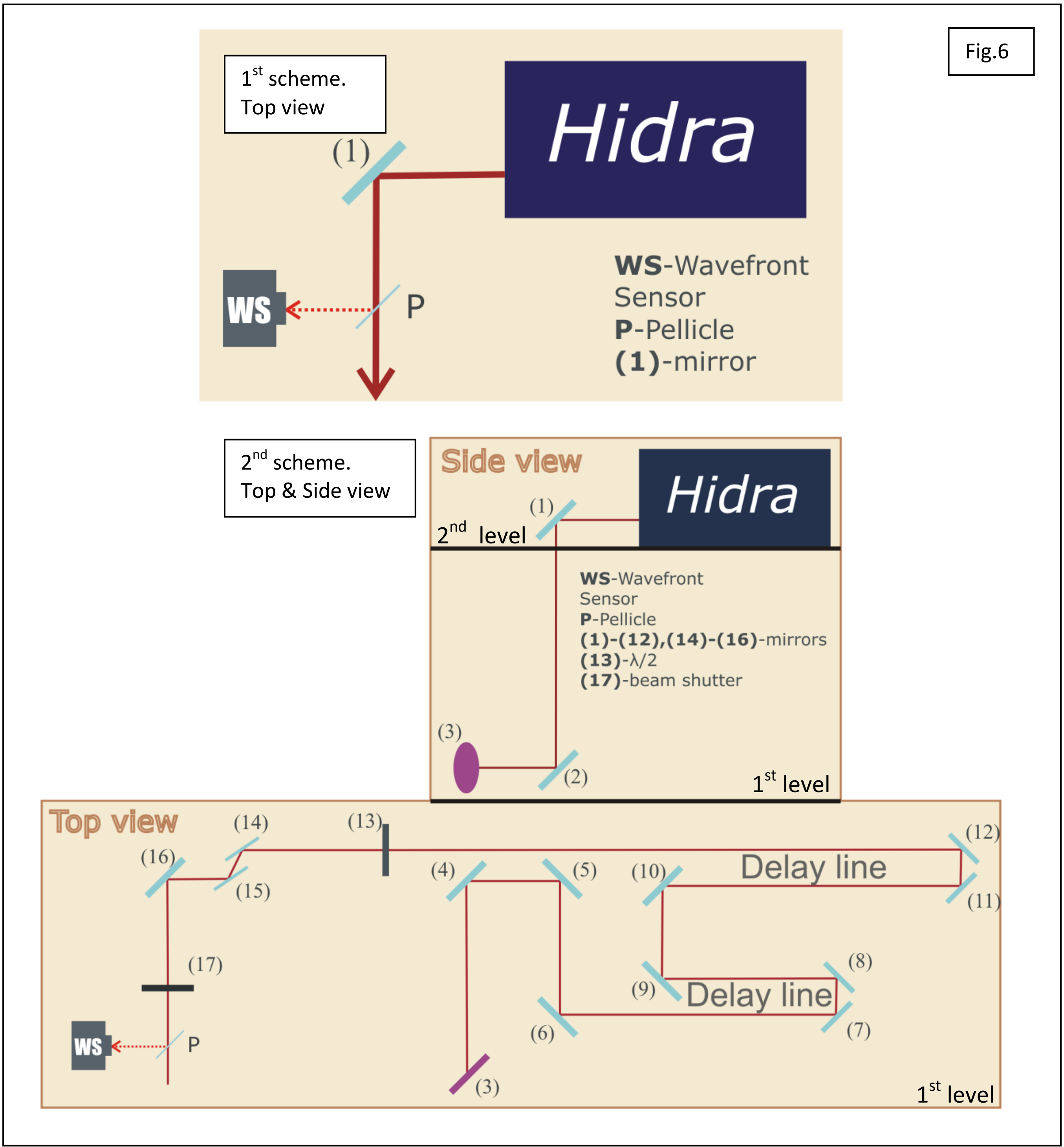


Fig.5

Two points on the optical axis have been chosen for studying evolution of the beam profile and wavefront of the beam as it propagates (Fig.6).

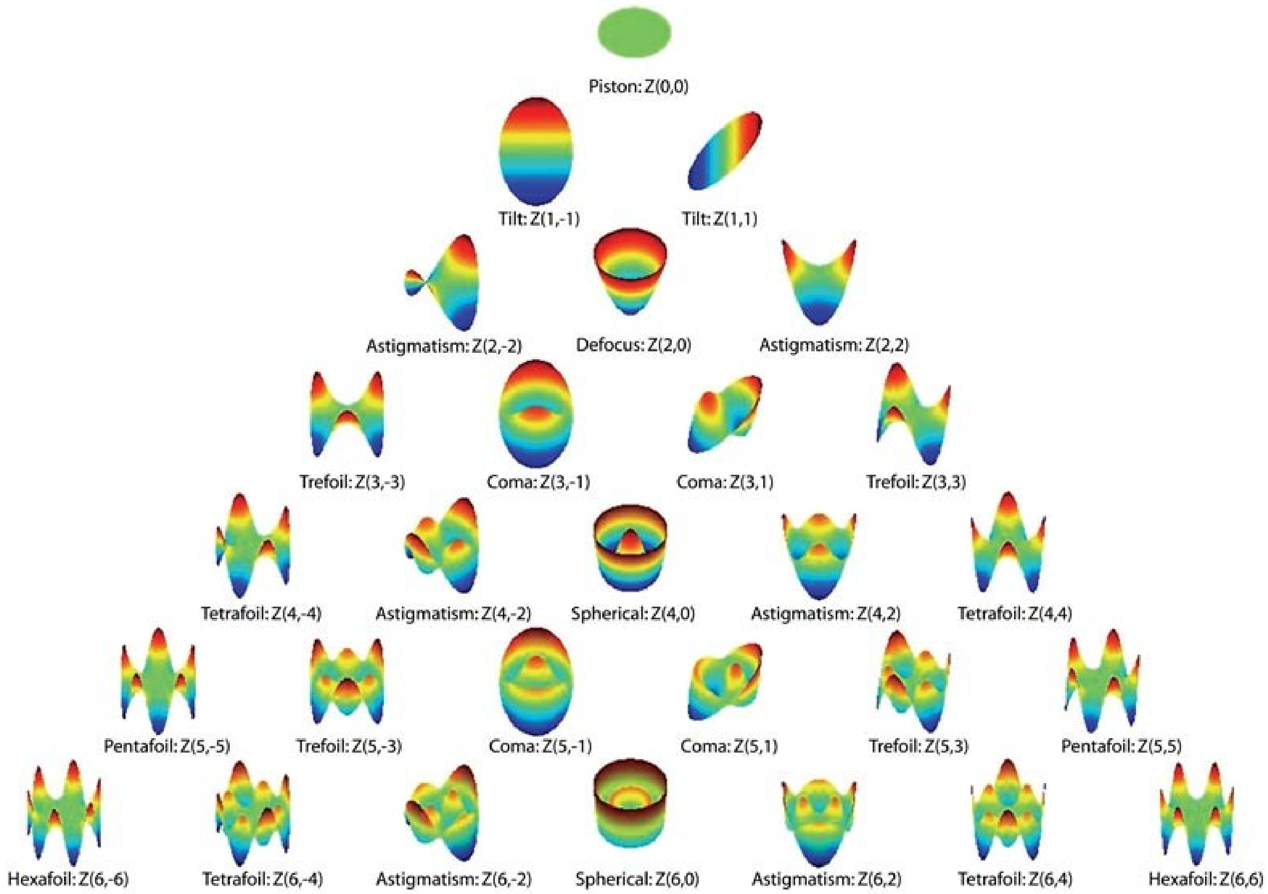


Data Analysis

Provided software "MrBeam" by Laser –Laboratorium Gottingen e.V. allows interpreting obtained results using Zernike polynomials and such parameters as beam width, divergences and M^2 values calculated from beam moments. Description of the software can be found in "MrBeam Hartmann-Shack Wavefront sensor – User Manual".

Zernike polynomials

In mathematics, the Zernike polynomials are a sequence of polynomials that are orthogonal on the unit disk. Named after Frits Zernike, they play an important role in beam optics.



[4]

There are even and odd Zernike polynomials. The even ones are defined as

$$Z_n^m(\rho,\varphi) = R_n^m(\rho)\cos(\mathrm{m}\varphi)$$

and the odd ones as

$$Z_n^{-m}(\rho,\varphi) = R_n^m(\rho)\sin(\mathrm{m}\varphi)$$

where m and n are nonnegative integers with n≥m, φ is the azimuthal angle, and ρ is the radial distance $0 \leq \rho \leq 1$. The radial polynomials R_n^m are defined as

$$R_n^m(\rho) = \sum_{k=0}^{(n-m/2)} \frac{(-1)^k (n-k)!}{k!\left(\frac{n+m}{2}-k\right)\left(\frac{n-m}{2}-k\right)!}\rho^{n-2k}$$

for n − m even, and are identically 0 for n − m odd.[3]

Wavefront analysis using *MrBeam*

If one has a deal with non-Gaussian beams, then it is important to set up Beamtype parameters on "Options" tab carefully. Parameters of this tab (Beamtype, Set Grid, Select Sub-Aperture) have a significant influence on Zernike polynomials calculations. Two screenshots are given to compare the difference between the results obtained with automatically or manually set parameters (Fig.3).

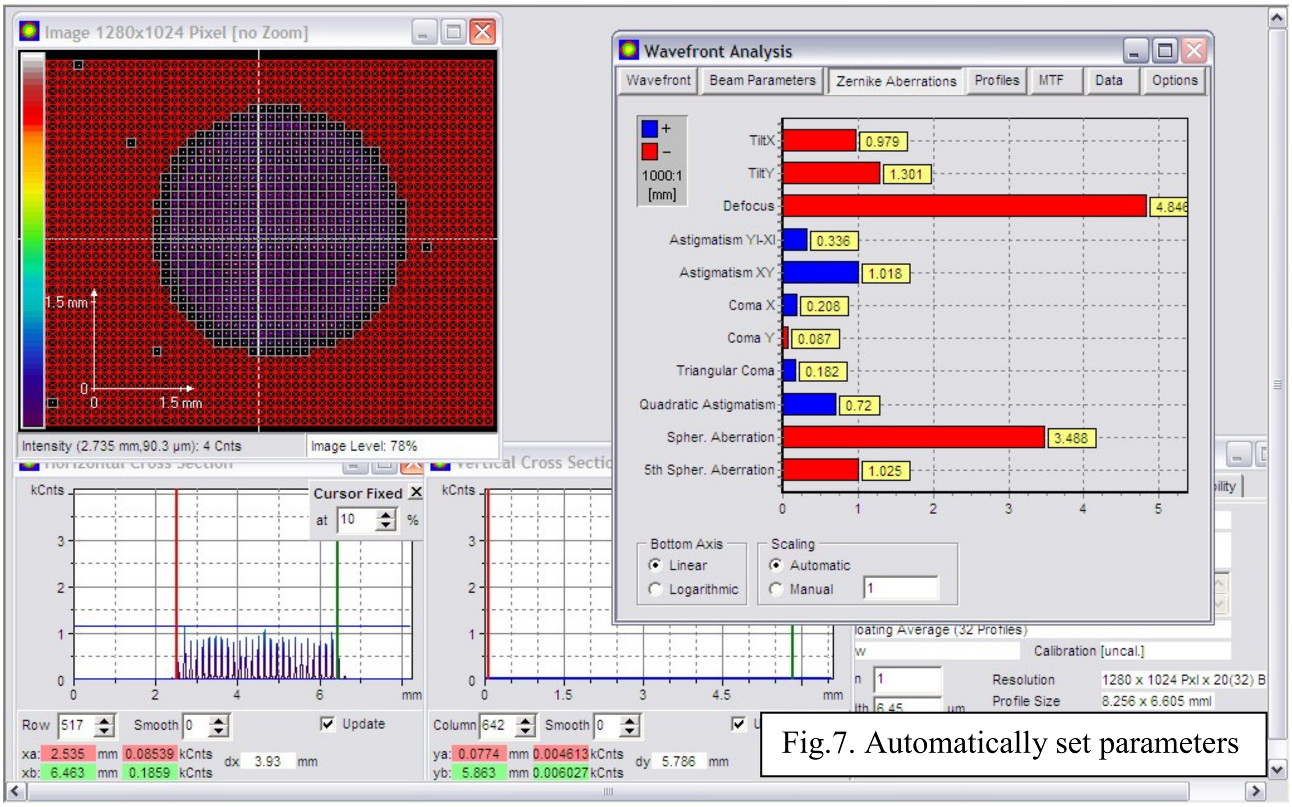


Fig.7. Automatically set parameters

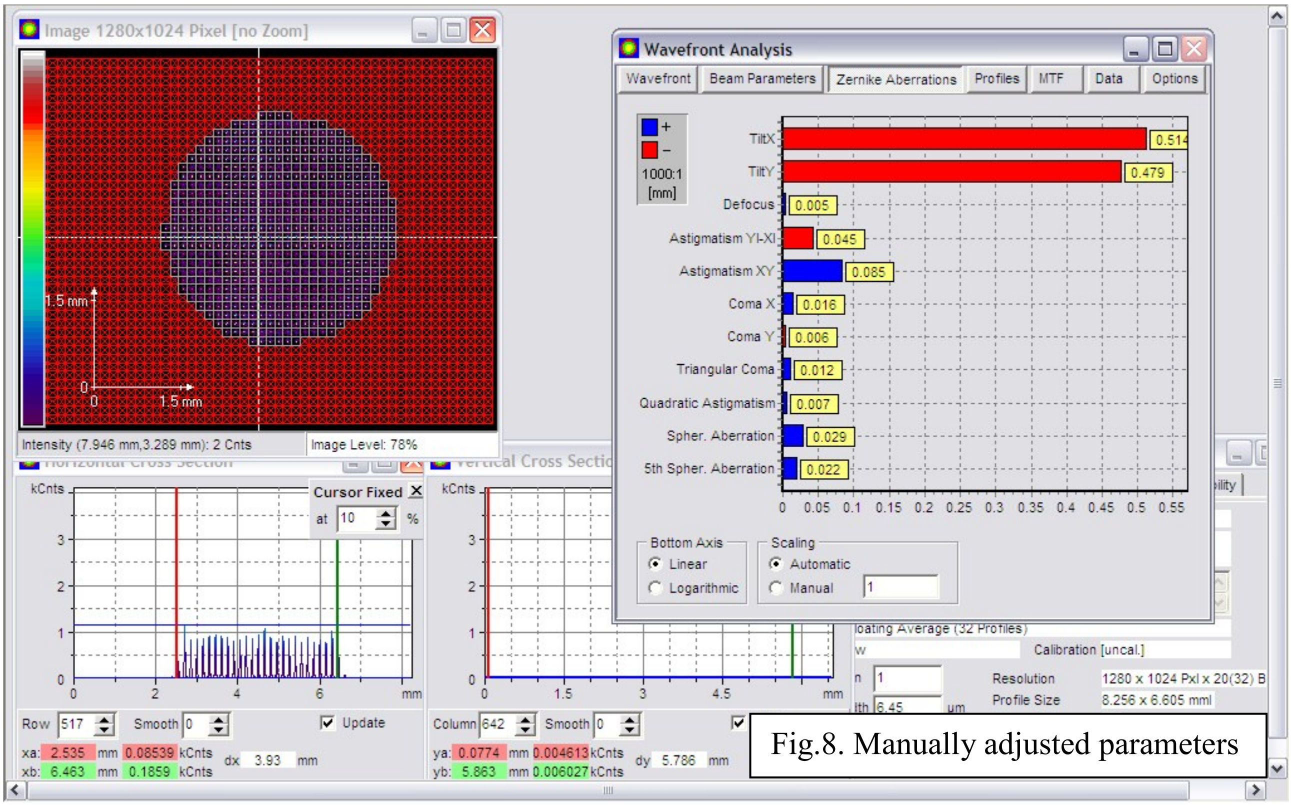


Fig.8. Manually adjusted parameters

ZEMAX simulations

Zemax is a widely-used optical design program sold by Zemax Development Corporation of Bellevue, Washington (formerly Focus Software). It is used for the design and analysis of optical systems. Zemax can perform standard sequential ray tracing through optical elements, non-sequential ray tracing for analysis of stray light, and physical optics beam propagation [5].

In our case we used “Optics beam propagation” feature of Zemax to simulate the propagation of pump-probe laser’s beam. Input files have been taken from *MrBeam* which allows exporting data to Zemax. The idea was to propagate our beam through the ideal system and had a look on the wavefront of the beam whether it has some distortion after propagation or not, if not that means that distortion of the beam’s wavefront observed at the end of the transport scheme in the laser hutch caused by optics utilizing in the transport scheme. Unfortunately we’ve discovered that there is no possibility to use obtained files to simulate propagation of the beam in the way we needed. The reason is that we didn’t take in account that Zemax will propagate the beam including information about elements we used to decrease the beam diameter. As a result we’ve got patterns with some diffraction if we propagate input files for some distance even without any obstacles (Fig.9) and changes of the beam diameter if we use image acquired after lens (Fig.10). Also it is important to have a zero-intensity area on the edges in the input file because otherwise we’ve got some diffraction from the image boarders.

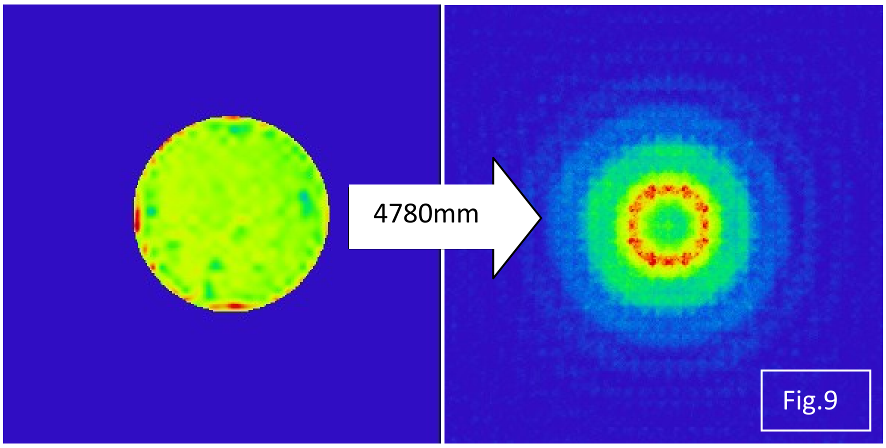


Fig.9

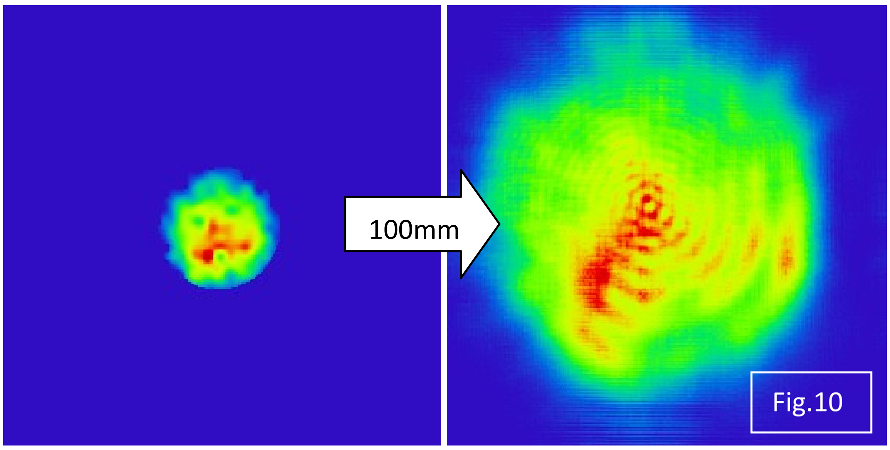


Fig.10

Some suggestions to solve the problem

We assume that one possible way to solve the problem is to use such a scheme where distortion of the wavefront obtained after passing Convergent lens compensates by Divergent lens (Fig.11). Lenses according to this scheme must be assembled on one stage with fixed distance between lenses.

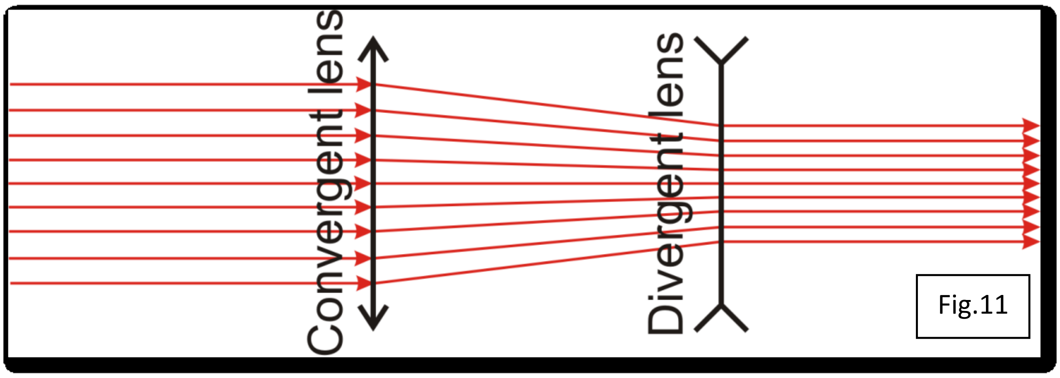


Fig.11

Another way to get reliable information about wavefront and beam parameters working with a beam with a large diameter is to use camera with larger active area (costs extra money, probably cannot be utilized with small beams).

Acknowledgments

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References

[1] FLASH. The Free-Electron Laser in Hamburg. Brochure. 2007

[2] *"MrBeam",* Hartmann-Shack Wavefront Sensor, User's Manual, Vers. 3.5, Laser-Laboratorium Göttingen e.V.

[3] http://en.wikipedia.org/wiki/Zernike_polynomials

[4] http://cms.revoptom.com/osc/105418/figure1-large.jpg

[5] http://en.wikipedia.org/wiki/Zemax