

# Aberration Compensation and Adaptive Optics in the PHELIX Laser

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## Introduction

The PHELIX (Petawatt High Energy Laser for Heavy Ion Research) laser project [1, 2] - currently under construction - is aiming at research using the combination of energetic heavy-ion pulses and high energy, ultra-high power laser pulses. The design goal requires ns-pulses to a level of 5 kJ and, alternatively, sub-ps-pulses reaching 1 Petawatt at energies of approx. 600 Joules using a CPA (chirped pulse amplification) scheme. Spatial phase aberrations occurring during beam transport and amplification process limit the

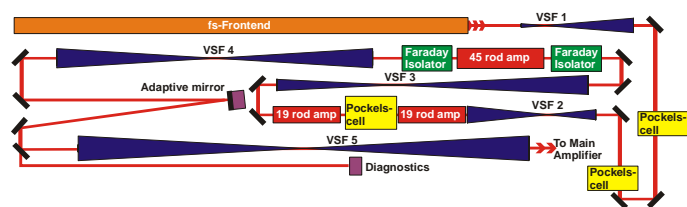


Fig. 1: Layout of the PHELIX-Preamplifier with Adaptive Mirror

focusability and hence the achievable irradiance on target dramatically. For generation of petawatt pulses with the CPA technology it is essential to have a plane wavefront on the compression gratings. Adaptive optics will be used for correction of residual aberrations accumulated in the preamplifier and precorrection of those generated in the main amplifier.

## Optimizing the laser design

Residual deviations from the perfect shape of optical surfaces and inhomogeneities in optical materials cause unavoidable distortions of the wavefront while the beam traverses the laser chain. Additional system design requirements such as deflection of ghost foci out of the beam path, spatial beam separation in the double-pass amplifier etc. make it necessary to tilt or deliberately misalign optical components. This adds to residual slight misalignments and collimation errors from stage to stage, resulting in both astigmatism and coma in the output beam wavefront. To minimize high-order aberrations, to decrease the flux on optics and control the intensity profile each amplification stage is separated by a magnifying telescope consisting of two lenses and a pinhole (vacuum spatial filter: "VSF"). In terms of back-reflected "Ghost Foci" the most critical point in the preamplifier (Fig.1) is the entrance lens of VSF4. A single reflection ghost of this lens would focus approx. 100 mJ very close to the polarizer of the preceding Faraday isolator. Tiltting the lens by 2° brings the focus out of the beam path.

Figure 2 shows different configurations (0°-2° with a step value of 1°). The introduced peak-to-valley wavefront distortion (mainly astigmatism and coma) is 0.03  $\lambda$  for no tilt, 0.11  $\lambda$  for 1° and 0.34  $\lambda$  for 2° tilt. To simplify telescope design we have chosen a fixed lens tilt of 2° for all input lenses in the preamplifier. The astigmatism of each input lens can be compensated by a tilt of the output lens, which is not the same angle due to different radii, and a 90° turn around the propagation axis of the next telescope. Therefore four telescopes are needed for a compensation of astigmatism. Thus a wavefront error of  $\sim 0.1 \lambda$  is achievable. A similar situation occurs within the two-pass main amplifier. On the return pass, a reflection from the second lens of the injection telescope (MSF A), creates a slightly divergent beam, which passes again through the amplifier chain, which has a gain of 100. In case of a damaged Antireflex (AR) coating, it would be amplified to a higher energy than the first laser pulse. To avoid this risk the lens needs to be tilted by more than 0.55°. Without compensation this would cause an aberration of around 3  $\lambda$ . Figure 3 shows the schematics of PHELIX and the calculated wavefront of the output (including only static aberrations).

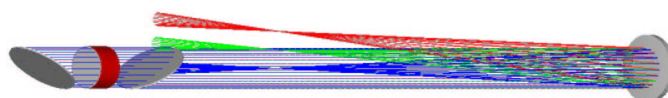


Fig. 2: Ghost reflection of VSF 4 input lens. The laser beam coming from the left is passing the Faraday isolator and reflected from the plane surface of the plano-convex

## Adaptive optics

The aim of adaptive optics is the active reduction of the residual static aberrations and also thermally caused wavefront distortions due to the heat disposal by pumping with flashlamps. Our calculations and the experiences of other high power laser facilities like the Central Laser Facility (CLF) or the Laboratoire pour l'Utilisation des Lasers Intenses (LULI) showed that this can dramatically improve the beam quality. At GSI we considered different types of adaptive systems and their position in our laser system. As a result, a dielectric-coated bimorph deformable mirror (DM) with 31 actuators and a diameter of 70 mm was chosen. This mirror is placed in the image plane of the laser rods after the preamplifier. The mirror can handle a flux up to 2 J/cm<sup>2</sup> and extensions of up to 6 waves. It will run closed loop with a Shack-Hartmann Sensor.

Within the European research network ADAPTOOL we were able to test our system in collaboration with CLF at the

VULCAN laser [3] and with LULI at the 100 TW laser facility. CLF developed a gold coated, 108 mm clear aperture bimorph mirror with 64 actuators [4] and an in-house fabricated Hartmann-sensor. The mirror in the LULI system is the same mirror as acquired by GSI, but is controlled with a Achromatic Three Wave Lateral Shearing Interferometer (ATWLSI) [5].

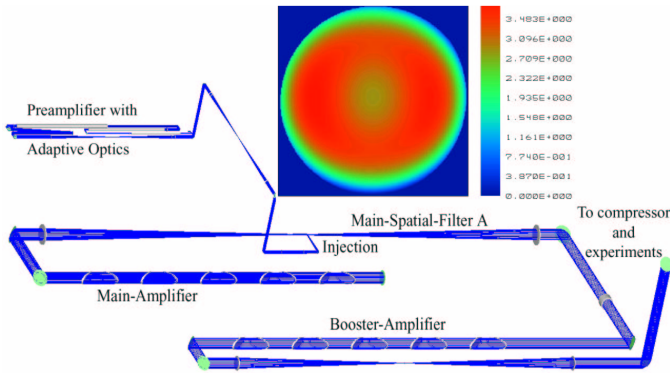


Fig. 3: Schematics of PHELIX and calculated OPD-map (optical path difference) of the output wavefront.

At Vulcan we compared the performance of the Hartmann- (HS) to the SHS in a closed loop adaptive system. The DM was placed as a retro reflector in the first double-pass disk amplifier. The laser propagates about 35 m through another disk amplifier, a telescope and the 208 mm power amplifier. The sensors were installed at the output of the laser chain. The number of sub-apertures is approx. equal for both sensors. The difference between the HS and the SHS is mainly the beam size where the sensing occurs. The HS, operating at full beam diameter (208 mm), is easy and inexpensive to make. The SHS needs a down collimating telescope because its micro-lenslet array is only the size of a CCD chip. For the comparison only the sensors were interchanged, by bringing the output image of the sensors to identical size, and using the same AO-software of CLF. The comparison showed very clearly that the adaptive mirror in closed loop was running much more stable with the SHS. It

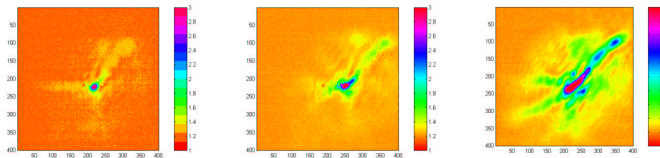


Fig. 4: Spot degrading at the LULI 100TW chain for a sequence of 30 J shots every 20 minutes due to heat accumulation in the laser amplifiers. The pictures show the 1<sup>st</sup>, 3<sup>rd</sup> and 5<sup>th</sup> shot (intensities in log-scale!).

showed superior resistance against various kinds of noise in the system such as vibrations of optical components, air flow, and intensity fluctuations. The adaptive mirror performed very well with the SHS and was able to correct the beam to the reference. The reason for this difference is that both sensors are sensitive to the gradient of the wavefront. This gradient is increased by the square of the demagnification of the down collimating optics. This leads to enlarged spot displacements and therefore a higher signal-to-noise ratio in the SHS system.

At LULI the performance of the dielectric mirror for correction was tested in a sequence of full power shots before [6] and after compressing [7] the pulse from the CPA. The mirror is the same as the GSI mirror but has a slightly bigger clear aperture. To avoid putting the DM in the vacuum between the compressor and the final focusing optics it was installed as the 0° retro mirror in the last double passed disk amplifier (similar to the VULCAN setup). The wavefronts were measured with ATWLSIs at two different locations: at the image plane of the mirror after the laser chain and at the image plane of a plane in the compressor. We used both in closed loop with the DM. This allowed us to compare their potential to improve the focal spot quality in the target chamber. After compression the beam was focused and the focal spot imaged onto a 16 bit CCD camera.

The focal spot was recorded for a sequence of 30 J shots every 20 minutes with and without correction by the DM. In the case of the uncorrected shots the increasing degradation of the spot and the loss of intensity due to heat accumulation in the disk amplifier is evident (Fig.4). In the second case we

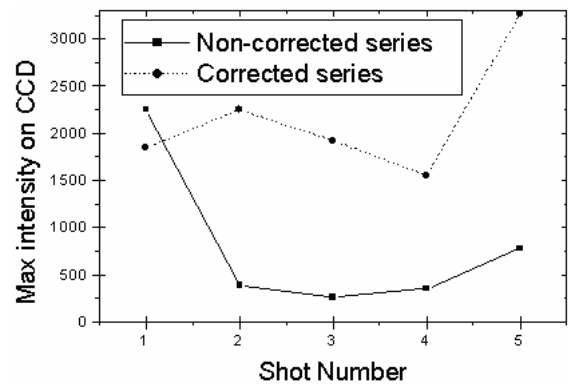


Fig. 5: Evolution of maximum intensity on the CCD recording the focal spot pattern vs. shot number.

converged to a nearly flat phase just before the shot and froze the shape of the mirror during the shot itself. This resulted in a reproducible, nearly diffraction limited focal spot for any shot in the sequence, and in average an increase of a factor of 4 in the peak intensity (Fig. 5).

The experiments in this successful collaborations showed impressively the potential of adaptive optics (AO) in high power lasers and give a promising outlook to its performance in the PHELIX laser. This work was sponsored partly by the European Commission through the ADAPTOOL network, and by the BMBF.

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