EUROPEAN UNION

Structural Instruments 2014-2020

Competitiveness Operational Programme (COP)

Extreme Light Infrastructure - Nuclear Physics (ELI-NP) – Phase II

Qualification and optimization of helical beam generation in PW-class laser systems

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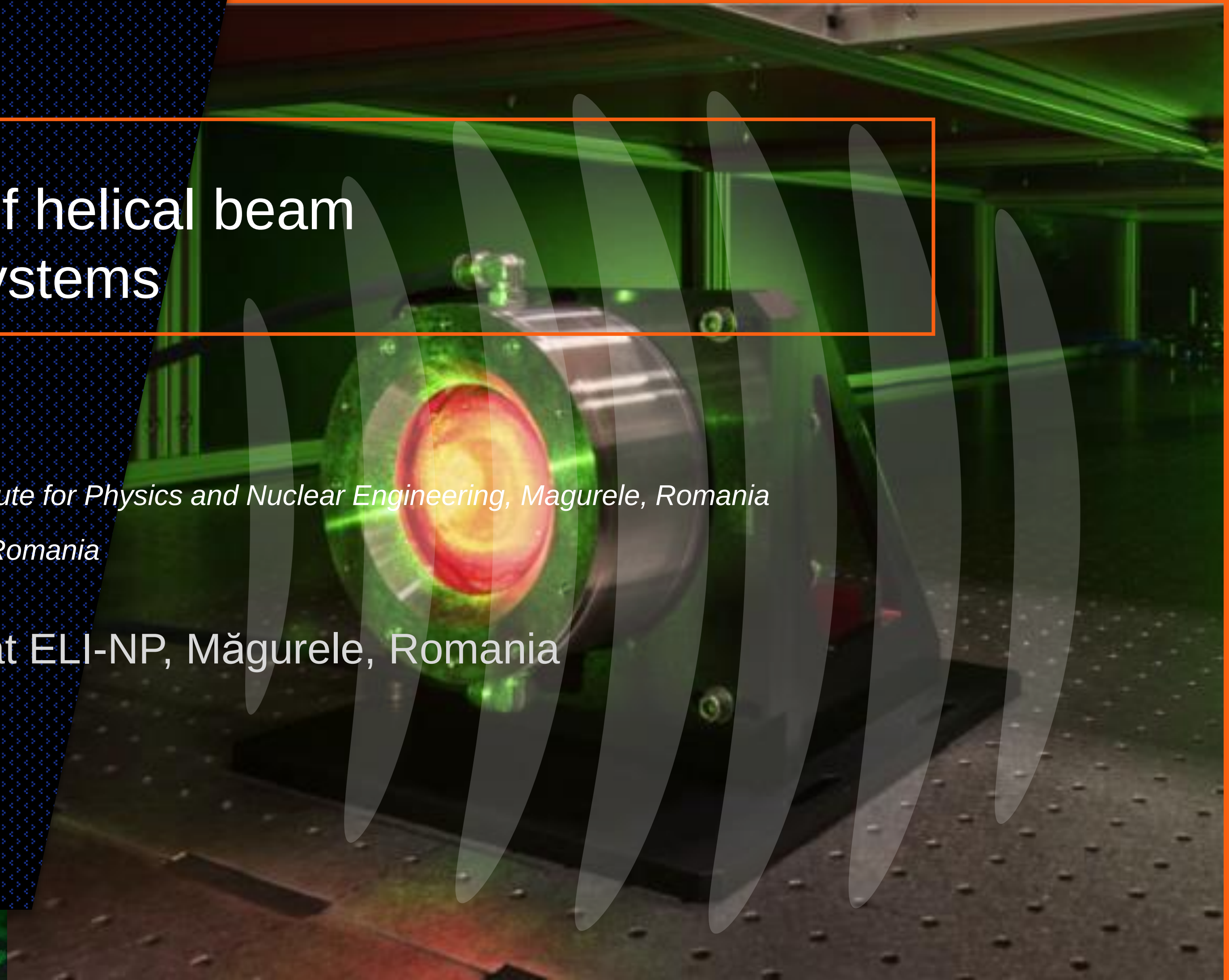
10.01.2022

Young Researchers and Engineers Day at ELI-NP, Măgurele, Romania



nuclear physics

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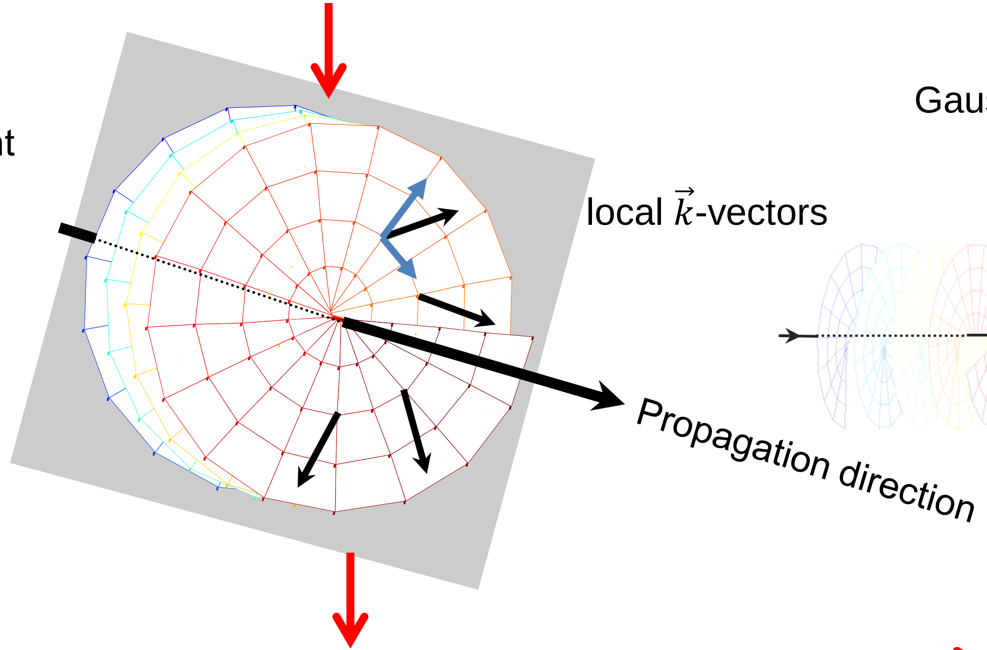
Contents

What is a helical wavefront?

Orbital angular momentum of a wave's phase dislocation: due to azimuthal component of local k-vectors

helical wavefront surface



local $\vec{k}$-vectors (normal to the wavefront surface) have azimuthal component. *Adapted from ref. [3]*

Fig. 1. Phase dislocated wavefront

$\vec{k}$-vector: momentum

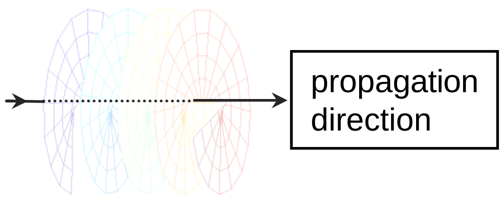
Orbital **A**ngular **M**omentum (**OAM**) in the wave

Eq. 1. Solutions of the paraxial wave equation in cylindrical coordinates. Amplitude that depends on three terms.

$$E(r) \propto r^{l} \exp\left(-\frac{r^2}{w^2}\right) L_p^l\left(\frac{2r^2}{w^2}\right)$$

Laguerre polynomial for coordinate *r*

Gaussian fall-off of amplitude



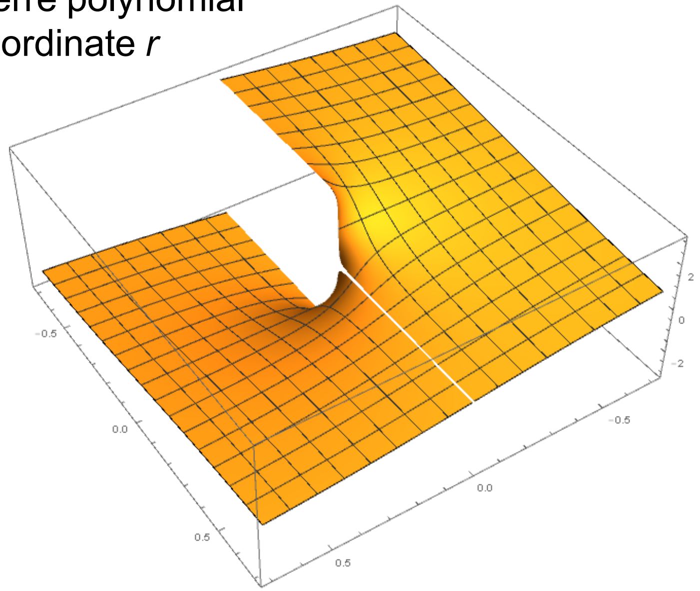


Fig. 2. Numerical simulation of an ideal helical wavefront structure (phase jump with continuous regular step along the radial direction).

[1] Physical Review E. 54, pp. R50-R53 (1996)
[2] Optics Letters Vol. 31 , No. 2 , pp. 181-183 (2006)
[3] Nature 464, 737–739 (2010)

Why optical vortices matter?

Motivation

- OAM coupling effects to laser produced plasma

Possible Applications

- Plasma generation by variable topological charge helical beams
  - Plasma dynamics and parametric instabilities modification
- Particle acceleration *via* variable topological charge laser beams

OAM leads to increased energy transfer from the laser to accelerated charged particles inside the plasma.

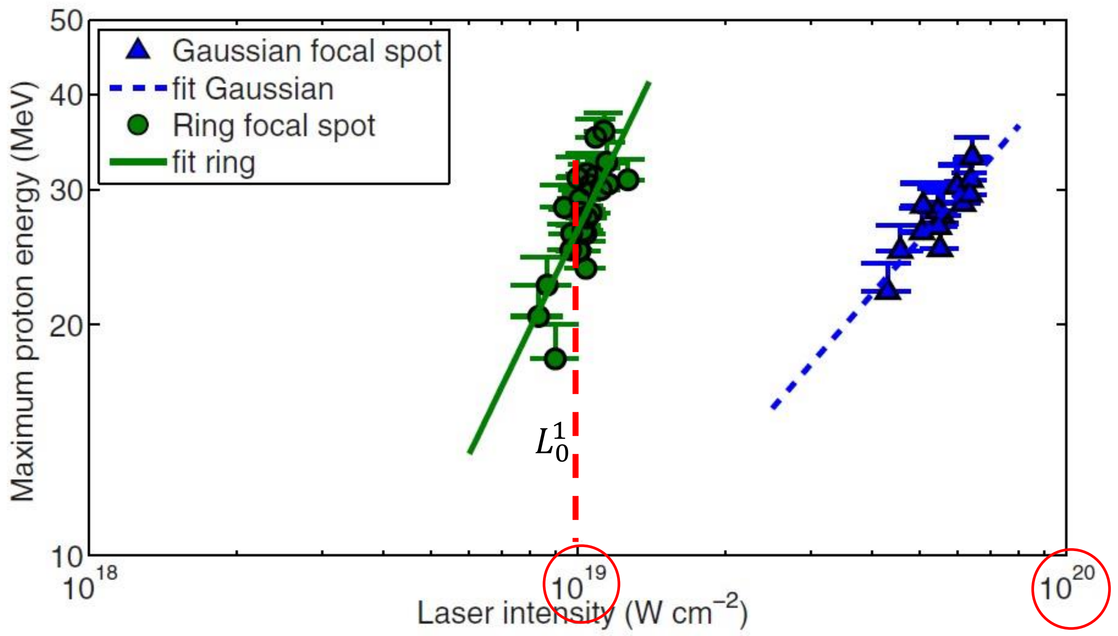
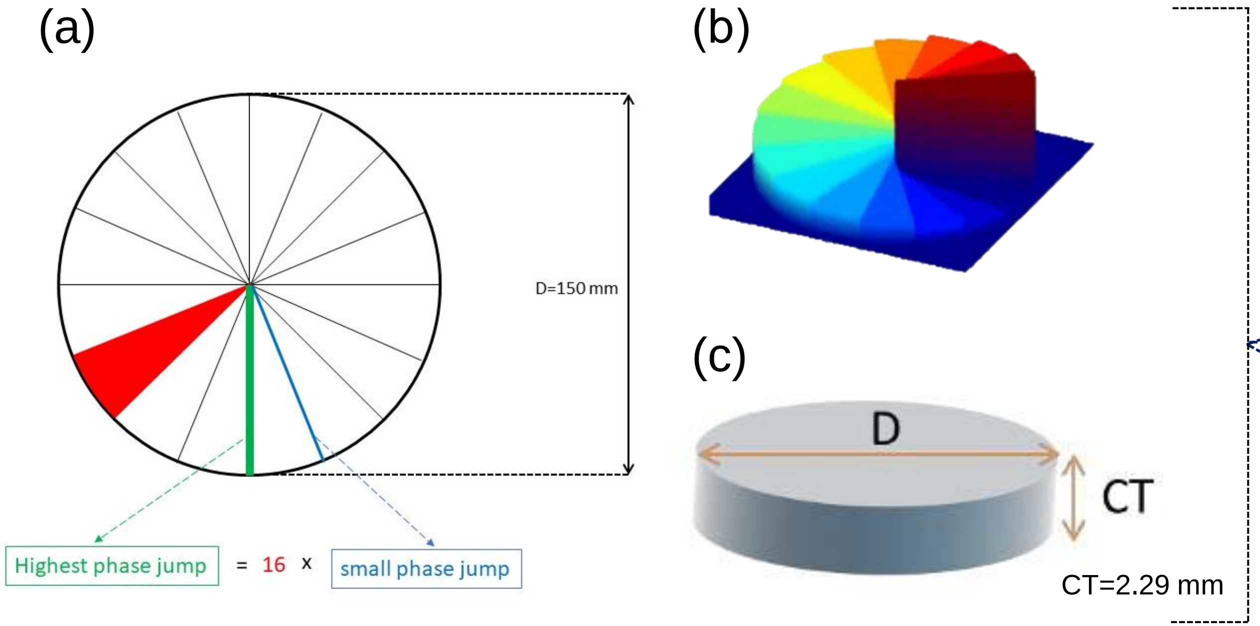


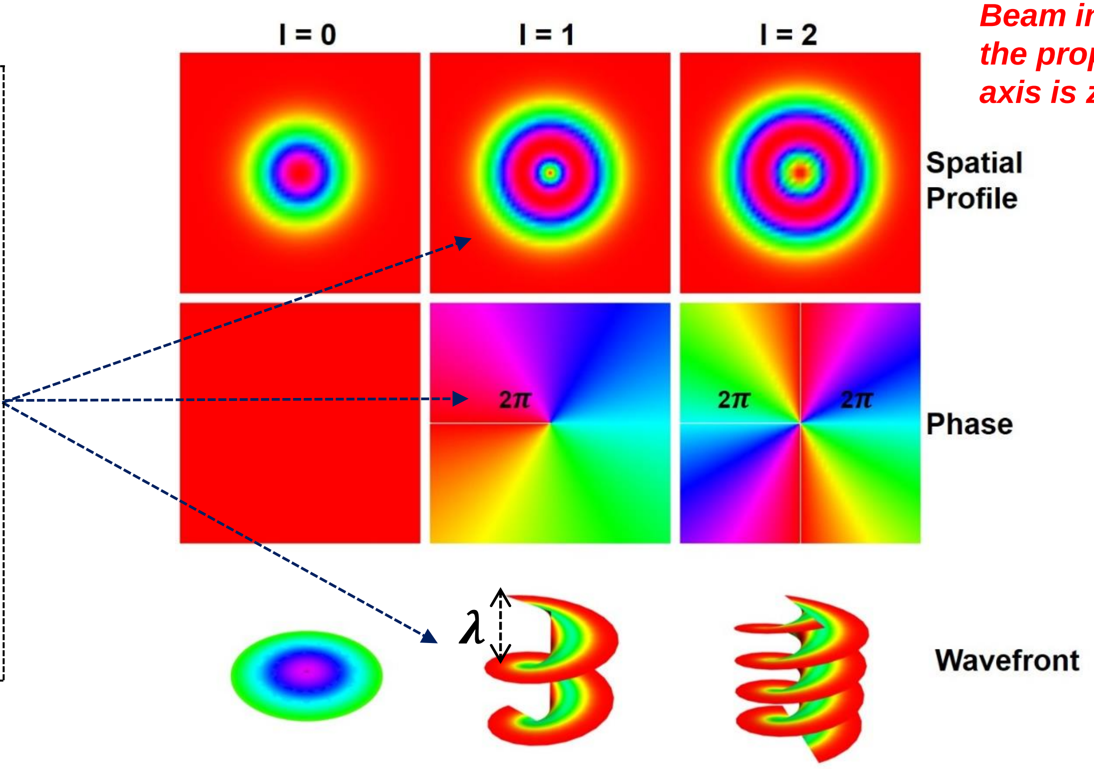
Fig. 3. Experiment with topological charge l = 1 and l =0 (Gaussian) laser beams in TNSA regime. *Reprinted with permission from ref. [8].*

Note: L_0^1 phase mask laser beams (green circles) and Gaussian focal spots (blue triangles)

[4] Phys. Rev. Lett. 112, 215001 (2014), DOI: 10.1103/PhysRevLett.112.215001
[5] Phys. Rev. A 45, 8185 (1992), DOI: 10.1103/PhysRevA.45.8185
[6] Phys. Rev. Lett. 105, 035001 (2010), DOI: 10.1103/PhysRevLett.105.035001
[7 Phys. Rev. Lett. 118, 094801 (2017), DOI: 10.1103/PhysRevLett.118.094801
[8] Phys. Plasmas 22, 013105 (2015), DOI: 10.1063/1.4905638

Helical Phase Plate Design





Beam intensity on the propagation axis is zero.

Fig. 4. Winding “Staircase” surface profile of diffractive vortex phase plate. **(a)** Geometric representation (2D) of the phase plate with topological charge *ℓ=1*. **(b)** Orientation varying from 0 to 2π induces a geometric phase from 0 to 4π along the azimuthal direction. *Reprinted from https://www.holor.co.il .* **(c)** Technical drawing of the phase plate element.

Fig. 5. A schematic representation of optical vortex beams. Numerical simulation of *ℓ=0, ℓ=1 and ℓ=2,* respectively, topological orders. **(a)** The spatial intensity distribution, **(b)** phase profile and **(c)** wavefront of a Gaussian beam (*ℓ=0*) and vortex laser beams.

Azimuthal phase dependence of $exp^{(i\emptyset)}$.

In case of l/= 0, optical vortex has phase singularity and helical equiphase surface.

[9] J. Opt. Soc. A.;22:849–861) (2005)

Qualification Set-up – Adaptive Optics

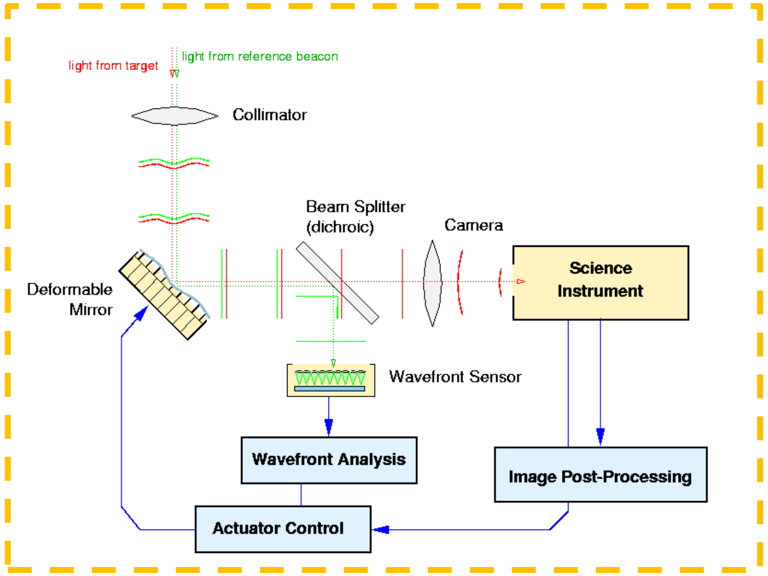


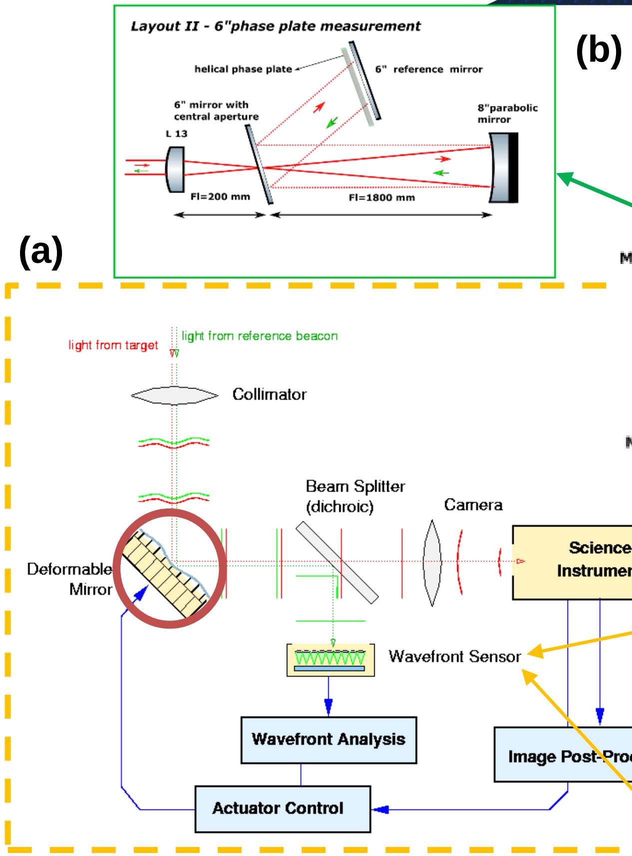
Fig. 7. Adaptive optics system working procedure. Step 1: acquisition (closed loop feedback);
Step 2: acquired images → phase retrieval → estimating spot aberrations as Zernike coefficients);
Step 3: correction by deformable mirror.
Reprinted from Center for Adaptive Optics; UCLA.

Why Adaptive Optics?

↓

compensates for aberrations while the observations are in progress

Qualification Set-up – Full Aperture



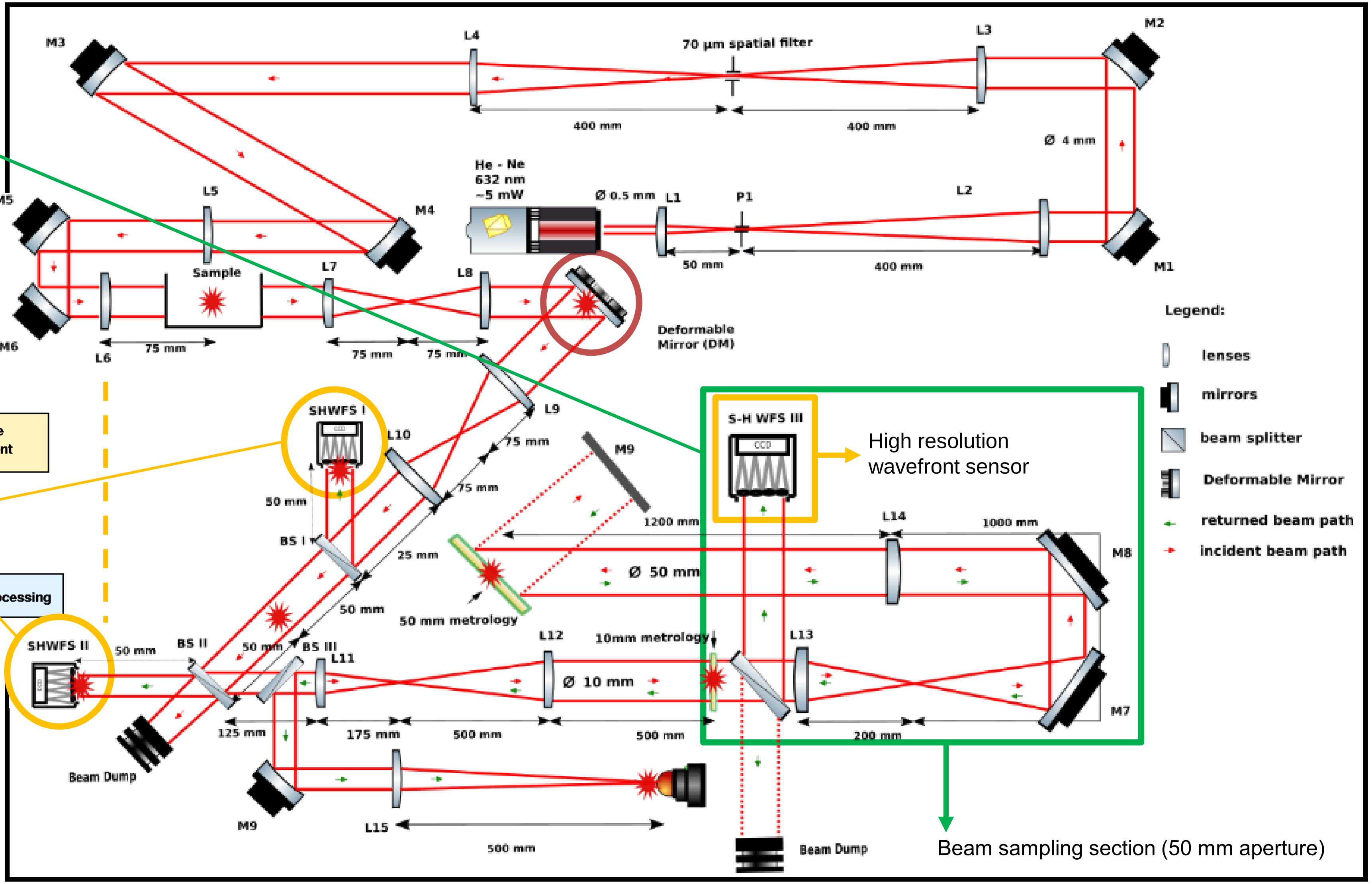


Fig. 7. **(a)** Adaptive optics system working procedure.
Step 1: acquisition (closed loop feedback);
Step 2: acquired images → phase retrieval → estimating spot aberrations as Zernike coefficients);
Step 3: correction by deformable mirror.
Reprinted from Center for Adaptive Optics; UCLA.
(b) High resolution wavefront qualification setup.

Preliminary Results – Reference Wavefront

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Sub-aperture reference wavefront aberrations

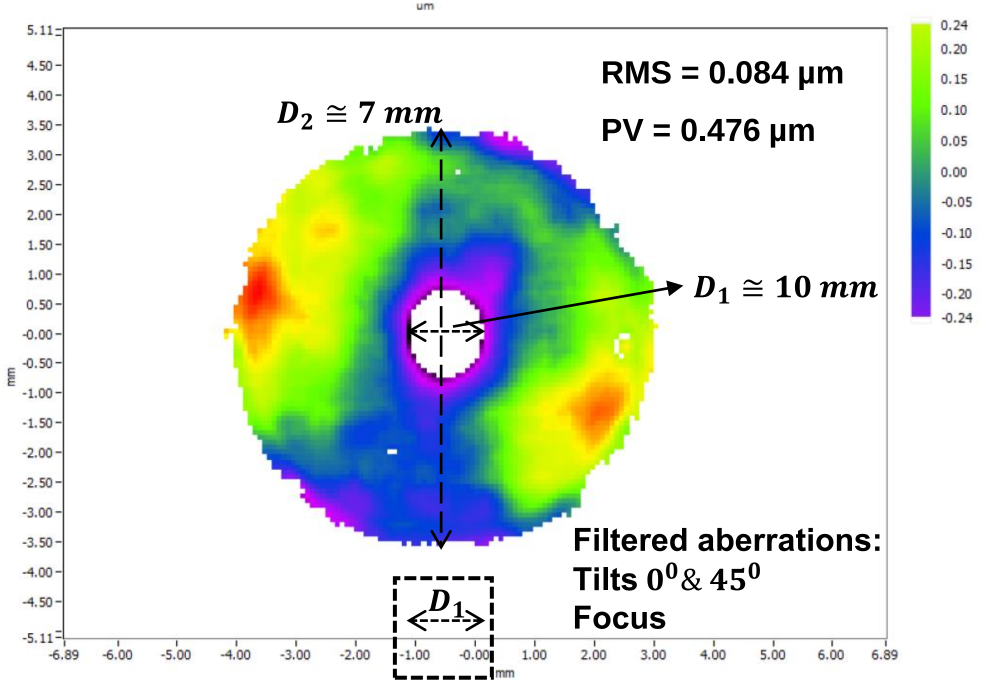
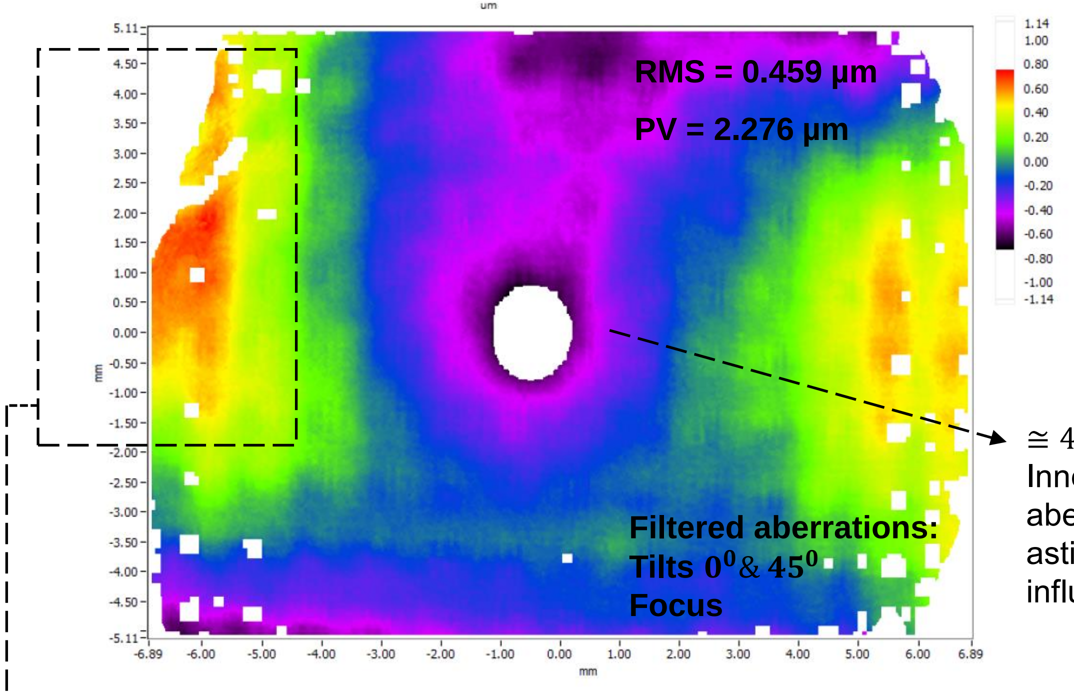


Fig. 8. Sub-aperture wavefront measurement.

Full aperture reference wavefront aberrations



$\cong 40\ nm$
Inner edge high aberration (focus & astigmatism) influence

Fig. 9. Full aperture reference wave form measurement in the full aperture work field.

high intensity modulation region

↓

major aberrations contributor

↓

require compensation/removal

Notes: (Fig. 8 and Fig. 9) Axes (xOy) stands for the field coordinates, in mm, and the axis (Oz/colormap) stands for the global RMS (Root Mean Square), in µm.

Preliminary Results – Full Aperture

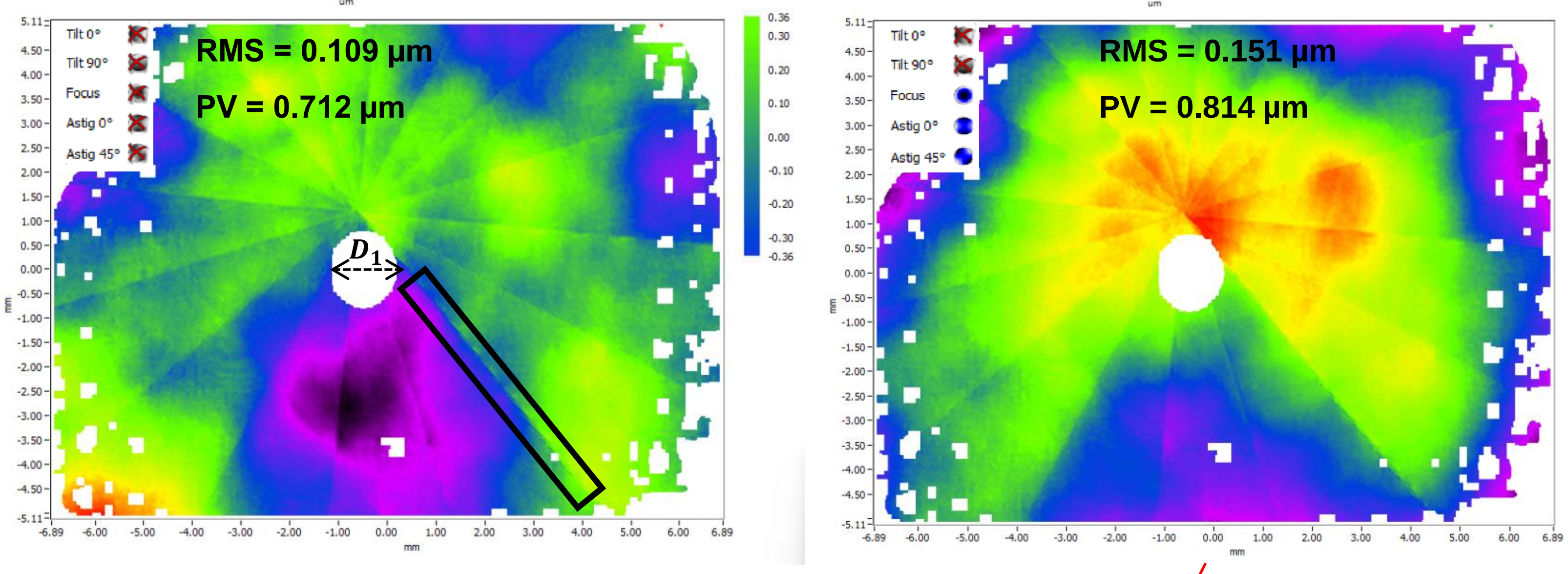
Wavefront aberrations of the phase plate with LIFT feature

(at the reference position)

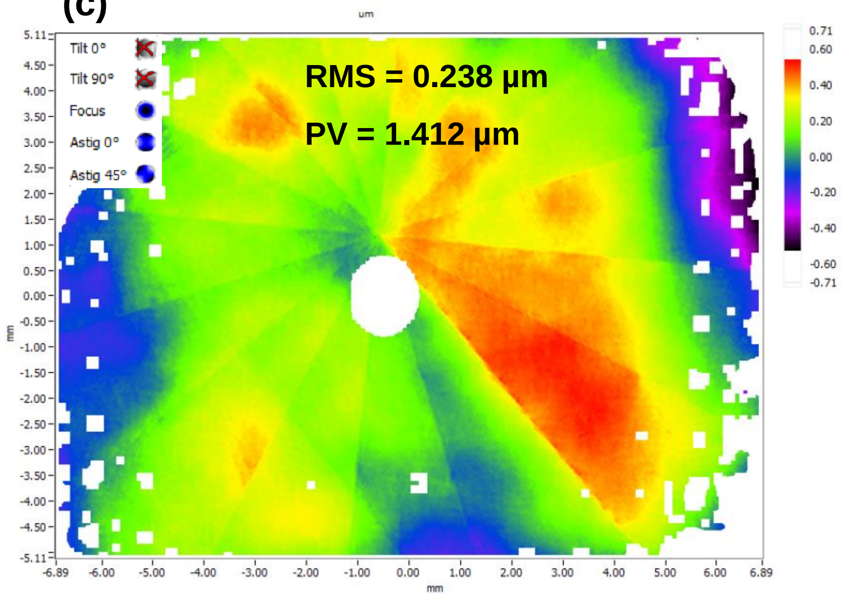
Wavefront distortions of the phase object

(at the reference position)

(a) (b)



(c)



Astigmatism appears with the field and prevails at the edge of the field

Fig. 10. Helical phase plate qualification in the full aperture work field with LIFT feature enabled (wavefront sensor), of **(a) – (b)** full low order aberration compensation and **(c)** of phase map with no distortions correction.

Fig. 11. Full aperture phase map retrieval with no compensation of low order aberration components.

Note: reference wavefront subtracted and double pass configuration

HPLS Technical Schematics

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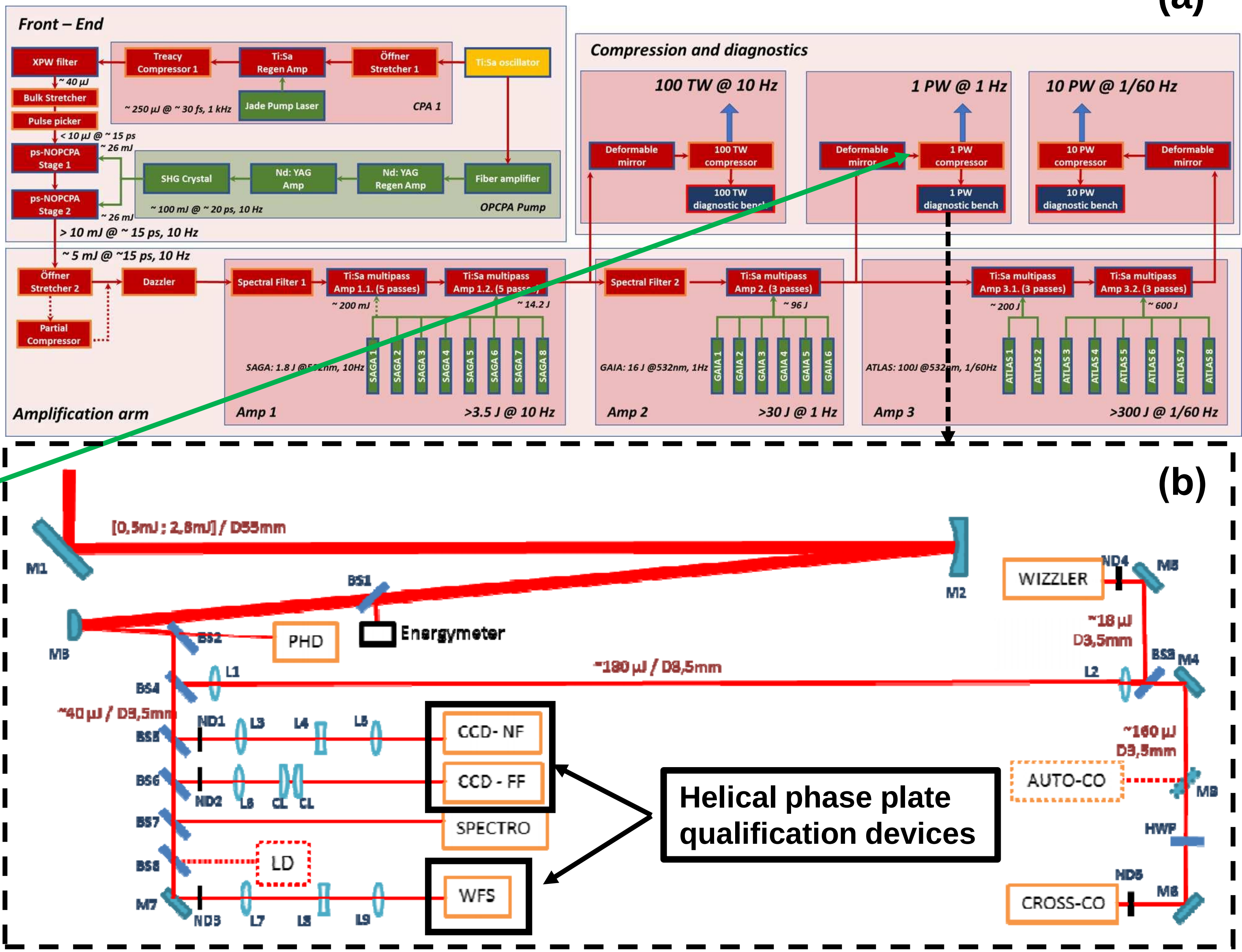
Fig. 12. (a) High Power Laser System (HPLS) technical layout. (b) Schematic representation of the 1 PW line, arm B, diagnostics bench.

Reprinted, with permission, from ref.

(a)



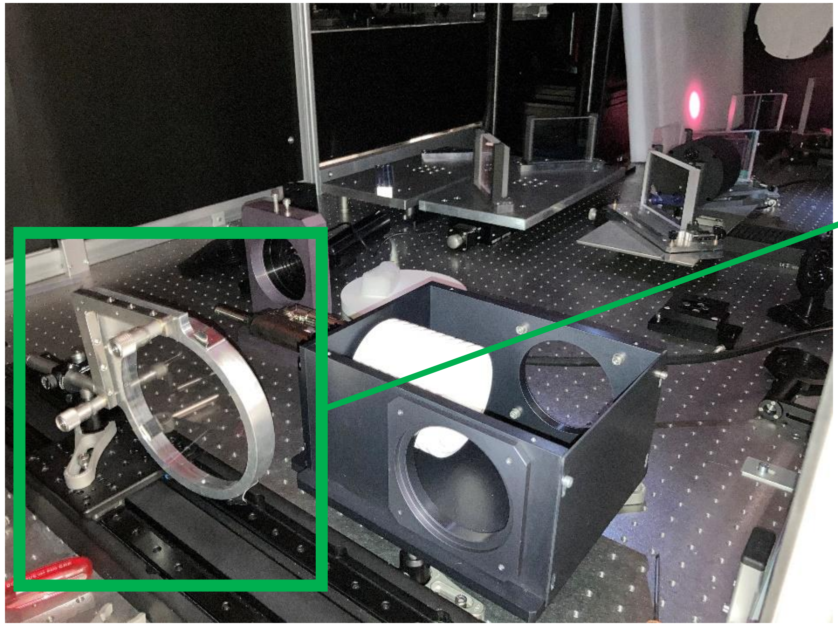


Fig. 13. Schematic representation of the helical phase plate implemented within the 1 PW line of arm B, placed after the AMP 2 output.

Preliminary Results – 1 PW diagnostics bench

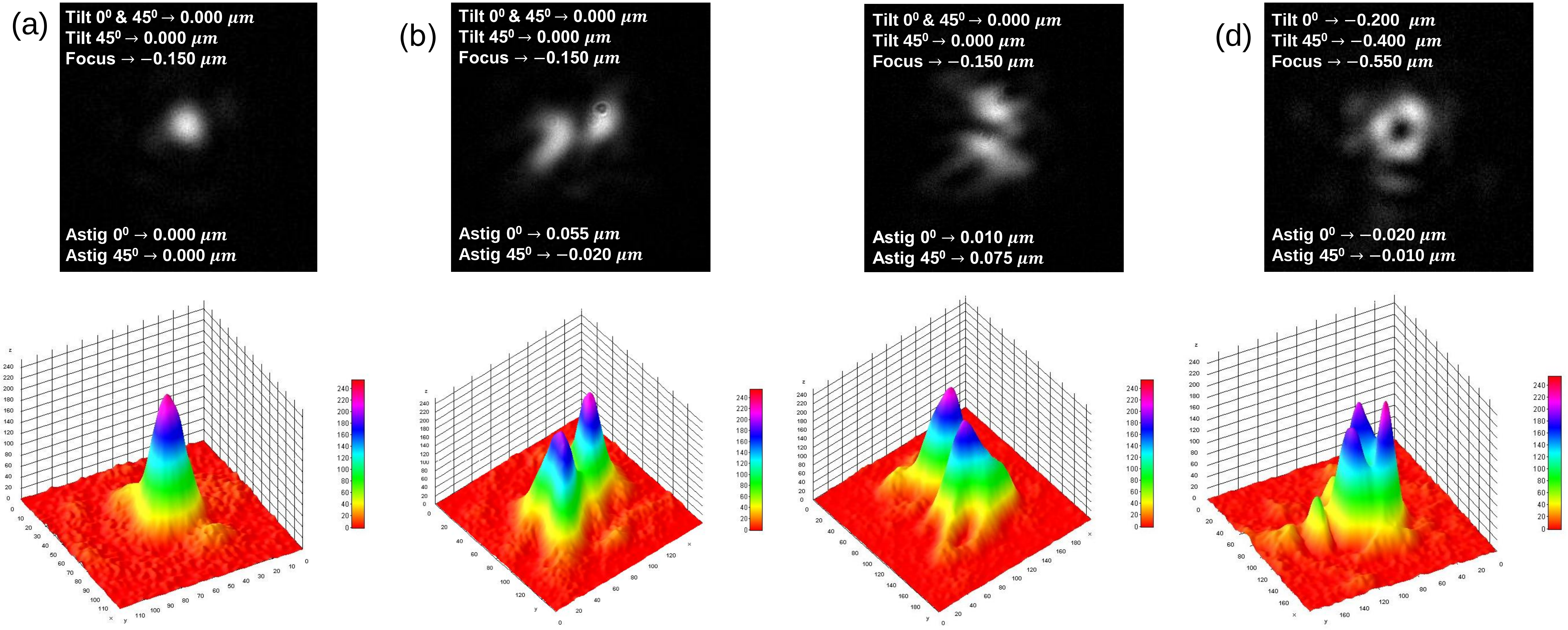


Fig. 14. Far field intensity distribution (2D → top and 3D → bottom) of a collimated **(a)** 1 PW Gaussian beam (waist w_0) normally incident onto the ℓ=1 topological charge phase plate (radius R) located in the focal plane of the incident beam, **(b) – (c)** optical vortex with various low order induced aberrations and **(d)** a doughnut (helical) shape like structure.

[10] ***Appl. Phys. B*** **125, 202 (2019)**

[11] Optics Letters Vol. 45, No. 8, 2187-2190 (2020)

Preliminary Results – E5

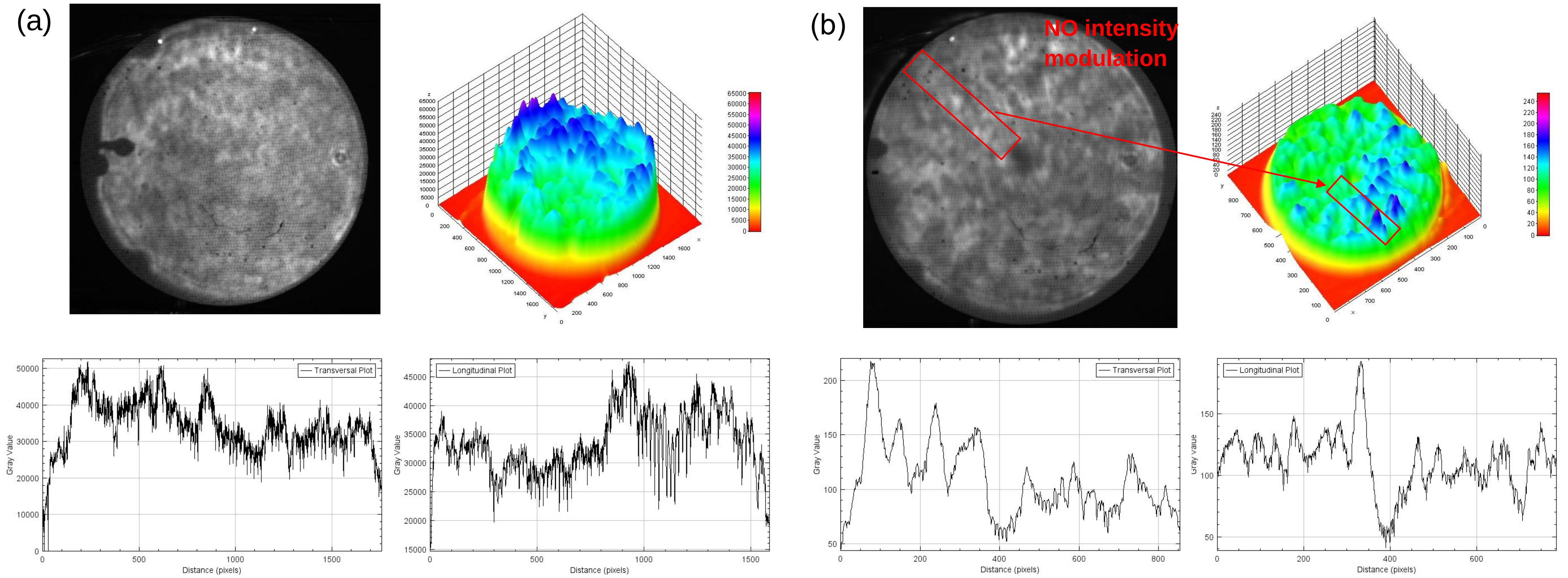


Fig. 15. Intensity distribution representation, (2D (left) and 3D (right) – of 1 PW Gaussian beam propagated within the experimental area E5 - of **(a)** the near field reference and **(b)** helical phase plate.

Conclusion and Outlook

CONCLUSION

- Generate *ℓ=1* Laguerre–Gaussian-like laser beam and applied selection of common low-order wavefront aberrations optimization
- Experimentally demonstrated that donut-like shape laser field structure is extremely sensitive to off-axis wavefront deformations
- Modulation intensity effects (*local hot-spots*) upon propagation in E5 **not observed**
- Promising preliminary results of helical beam generation for driving experiments with high-intensity lasers
- OAM beams can be used for detection & correction systems in laser facilities

OUTLOOK

- Adaptive Optics (AO) optimization of far field intensity distribution in experimental chambers
- Low energy TNSA campaign

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“Investments for Your Future!”

Thank you for your attention