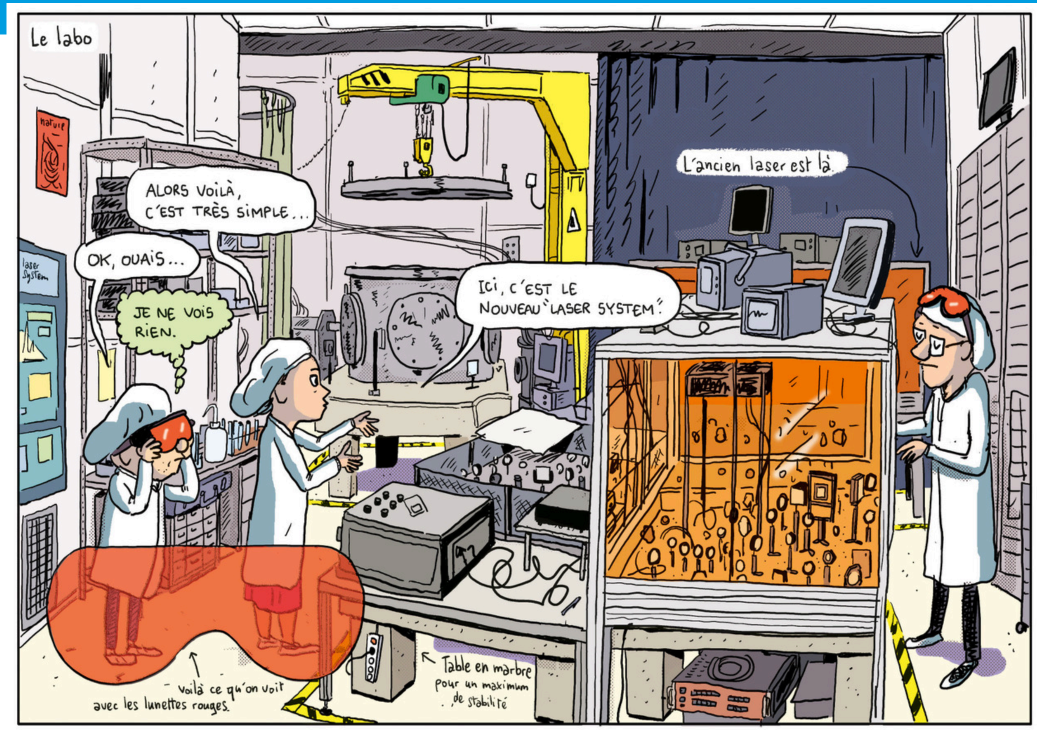
Laser manipulation



Twisted lasers can control the shape and topology of plasma waves

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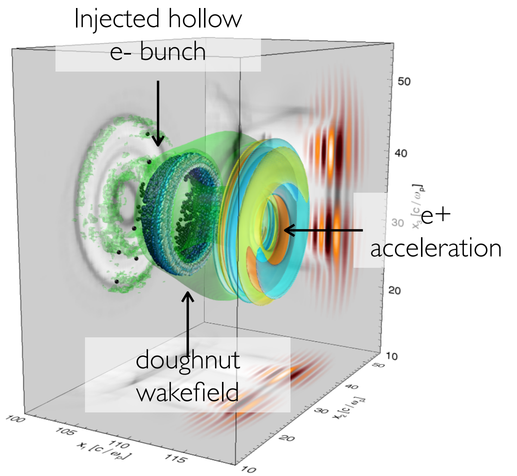
Positron acceleration*

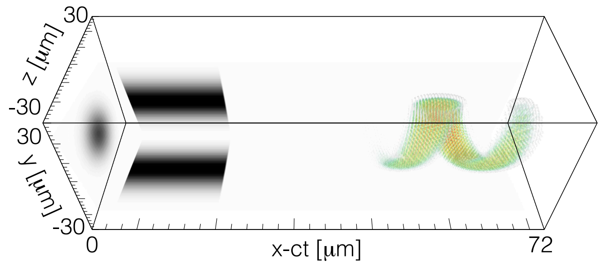


Doughnut wake
dense electron filament provides e+ focusing

Anular e-bunch
ion beam collimation**
driver for doughnut wakes***

*J. Vieira and J.T. Mendonça PRL **112**, 215001 (2014)
*J.T. Mendonça and J. Vieira PoP **21**, 033107 (2014)
G. Stancari et al. PRL PRL **107, 084802 (2011)
***N. Jain et al. PRL **115**, 195001 (2015)

Angular momentum control

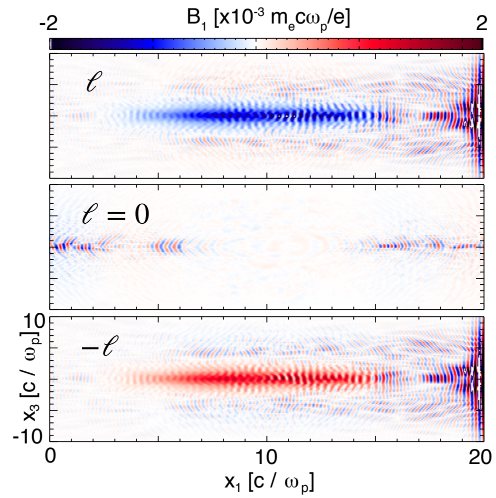


Light spring driver**
light with spiral intensity profile

Angular momentum transport*
twisted wakefield excitation
trapped electrons with angular momentum (quantised)

*J. Vieira et al PRL **121**, 054801 (2018)
M. Piccardo et al Nature Photonics **17, 822 (2024)
G. Pariente et al Optics Lett. **40, 2037-2040 (2015)

Magnetic field generation



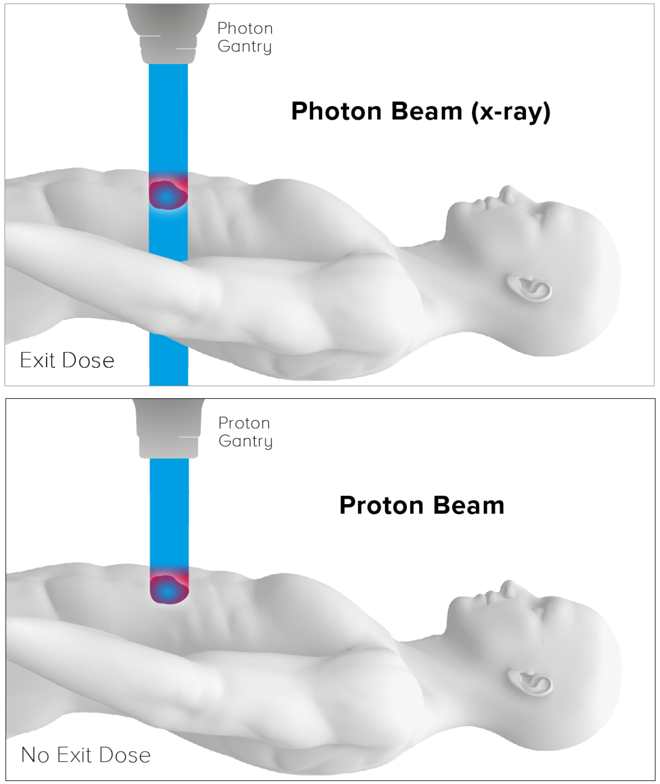
Intense (MG-class) axial magnetic fields

Y. Shi et al. PRL **121**, 145002 (2018)
A. Longman et al. PRR **3**, 043180 (2021)

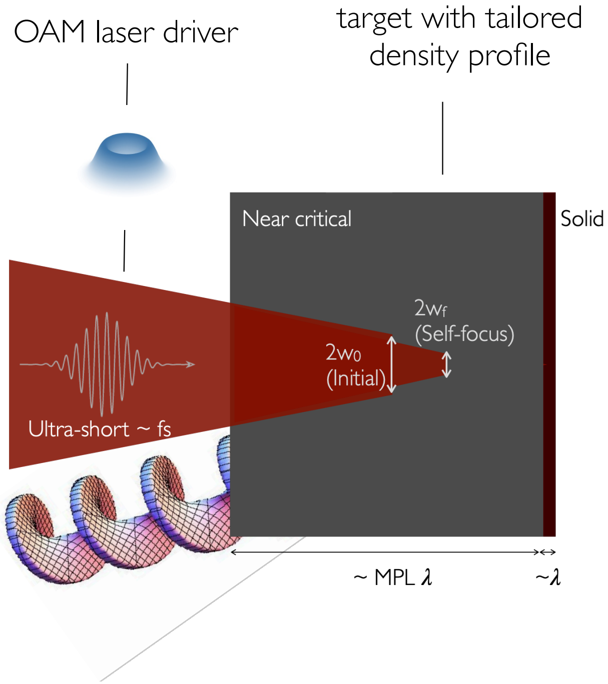
Collimated 40 MeV protons using a twisted laser driver

WEIZMANN INSTITUTE OF SCIENCE | TÉCNICO LISBOA

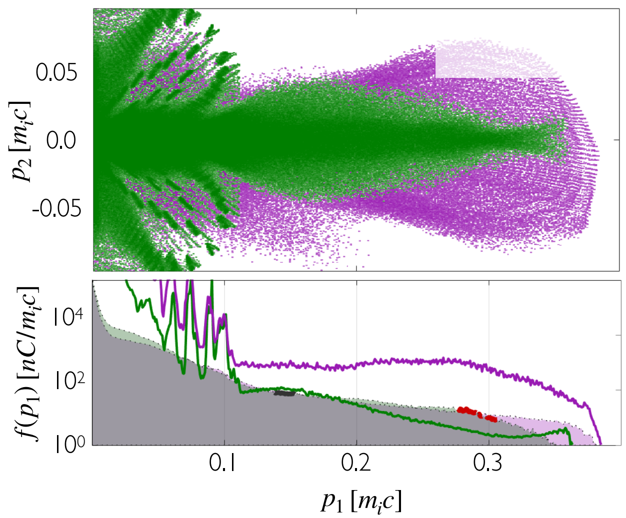
Proton therapy



Setup



$\lesssim 10\times$ divergence reduction



C.Willim et al., Phys. Rev. Research 5, 023083 (2023)

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Preserving focal spot quality

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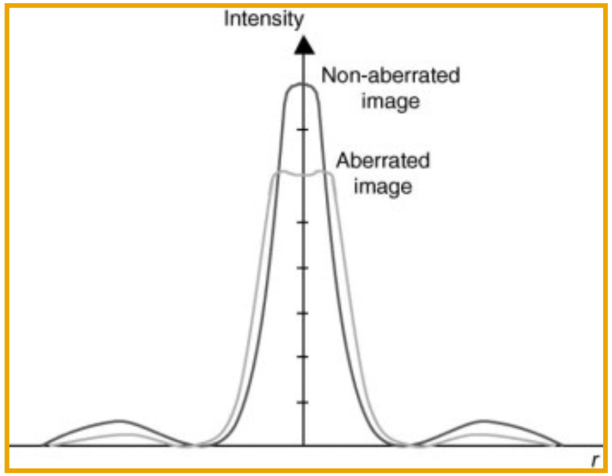
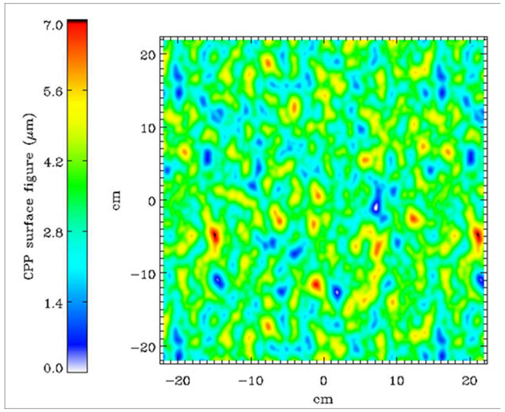
Preserving peak intensity

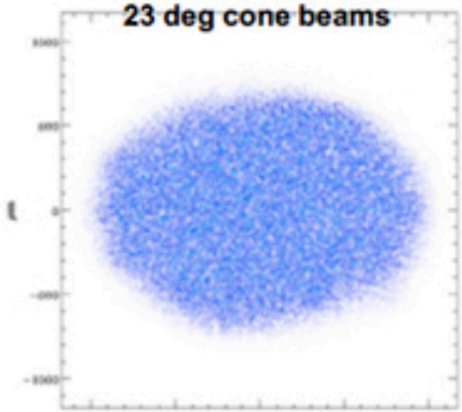


$$S = \frac{I_{\text{actual}}(0)}{I_{\text{ideal}}(0)}$$ Strehl Ratio

$$\sigma_\phi < \frac{\lambda}{14} \quad \Rightarrow \quad S > 0.8$$ Maréchal criterion

Getting the flattest possible profile

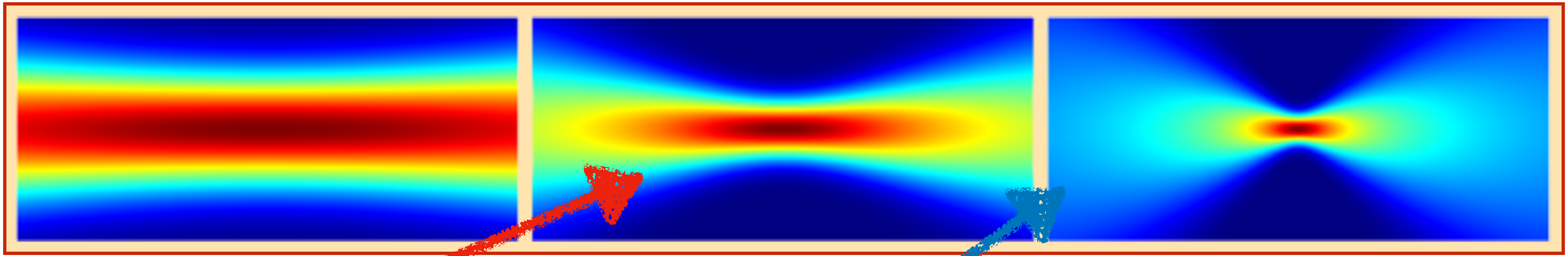




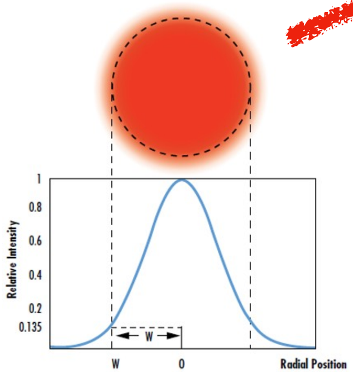
- Continuous phase plates,
- Smoothing by spectral dispersion,
- Polarization smoothing

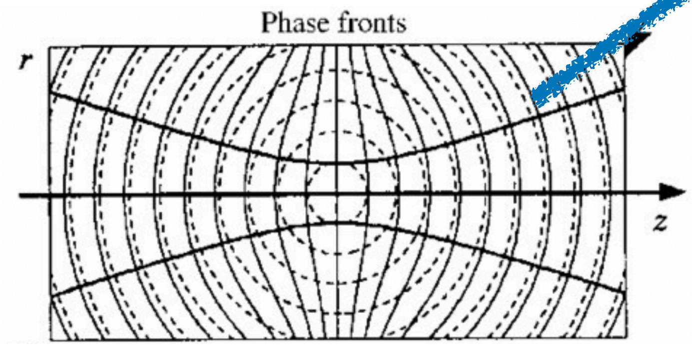
https://nifuserguide.llnl.gov/home/4-laser-system/46-focal-spot-conditioning

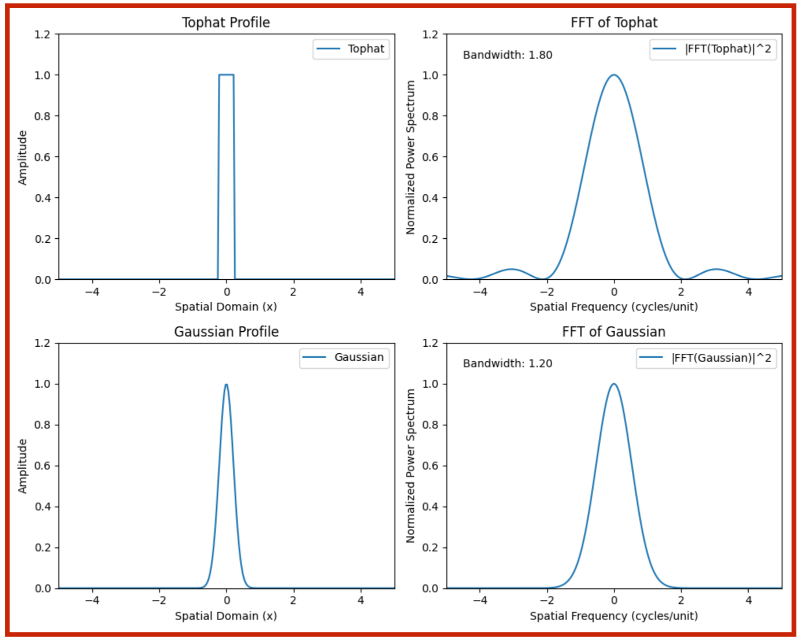
Idealised beams and aberration control: Gaussian beams



$w(z) = w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2}$:





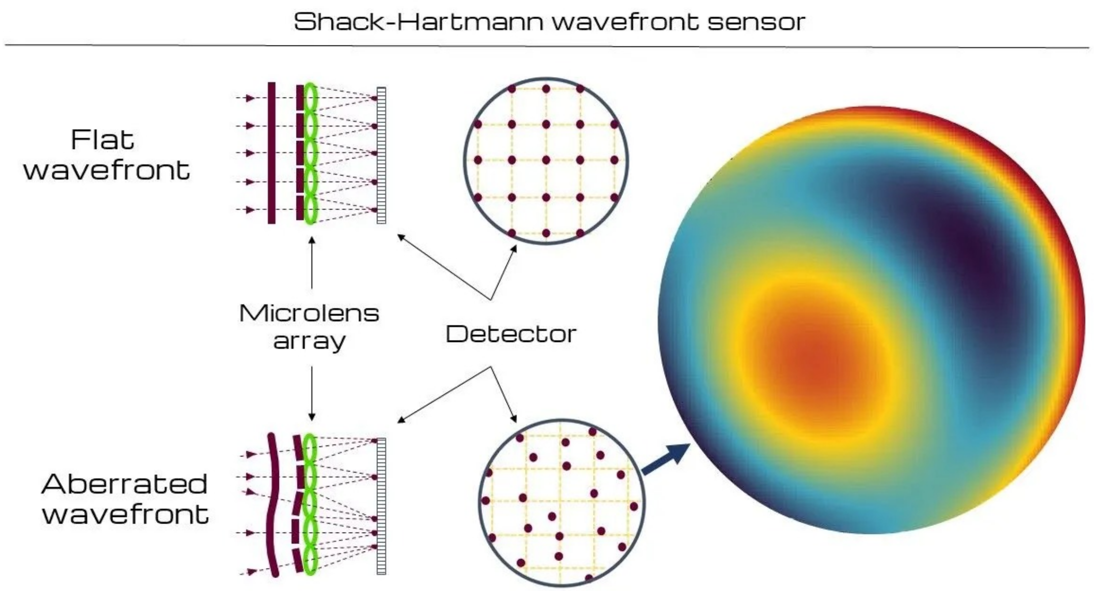


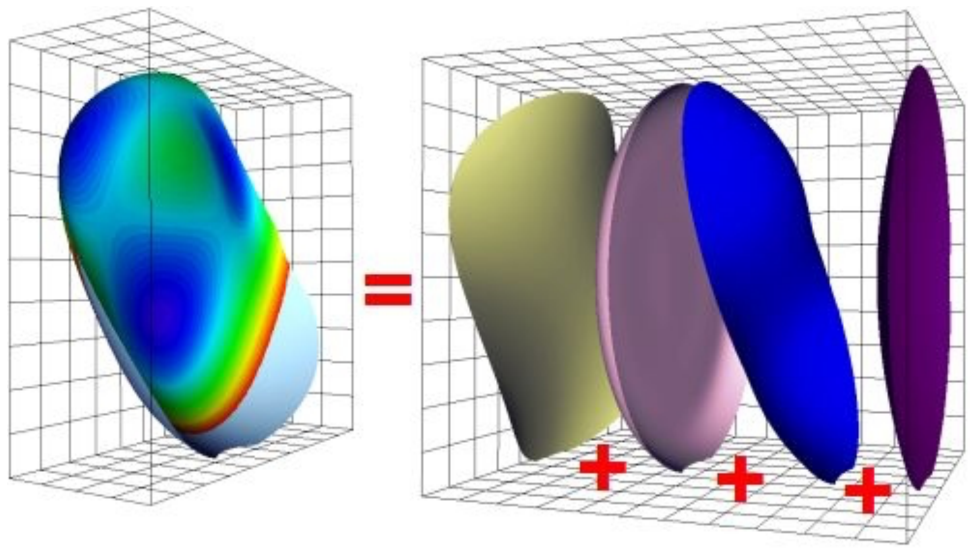
Minimizes beam waist for a given divergence (Fourier limit)

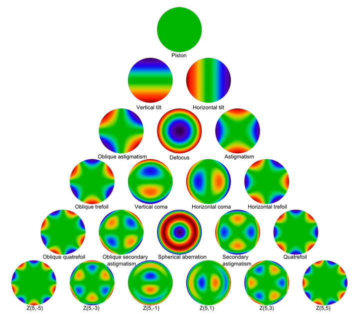
Provides tightest focal spot under scalar, paraxial optics

Used as the baseline for "diffraction-limited" focusing

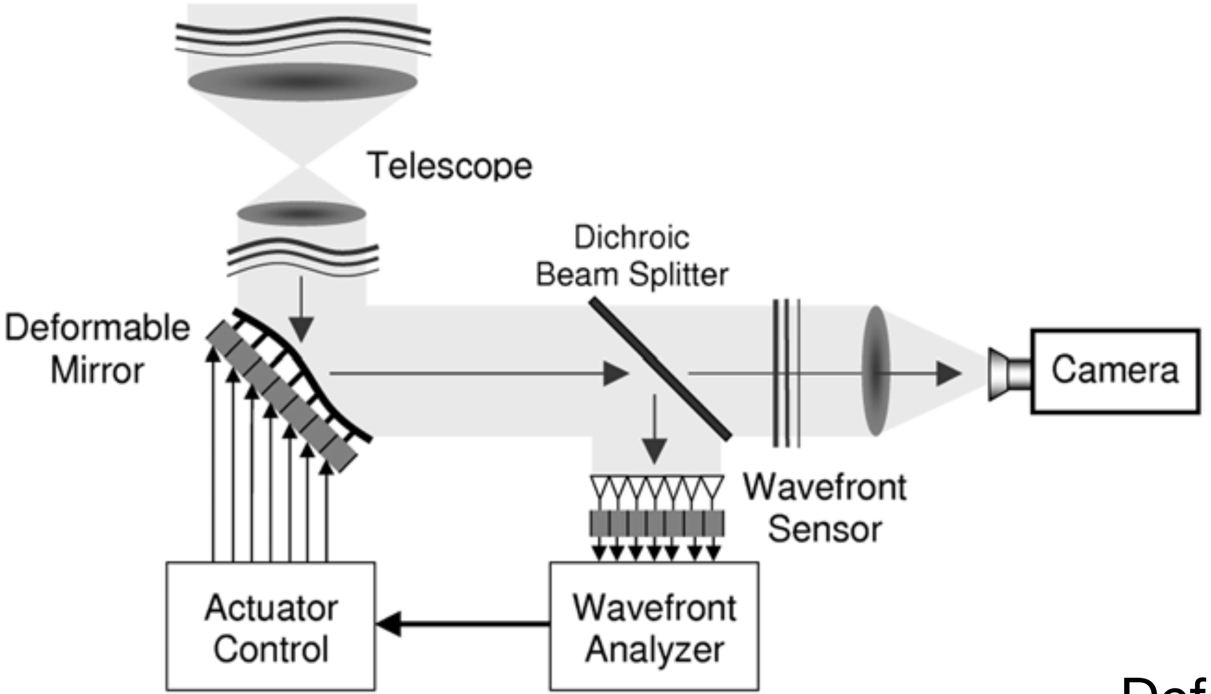
Diagnosing the spatial aberrations - Wavefront sensing

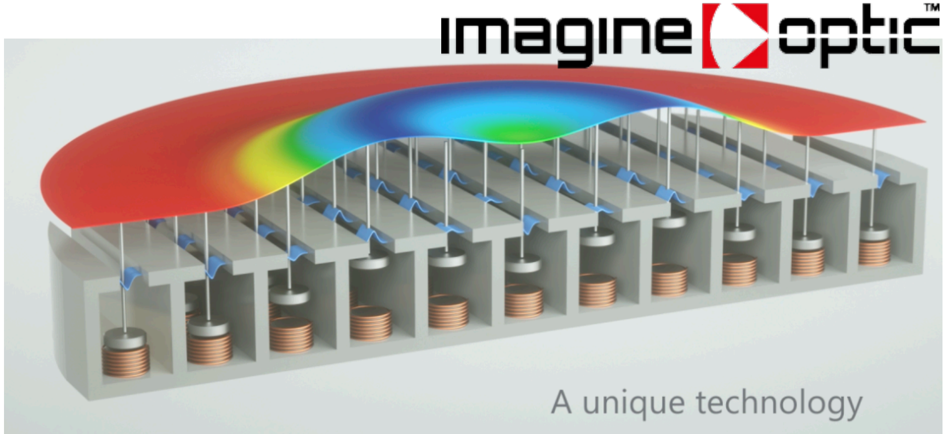


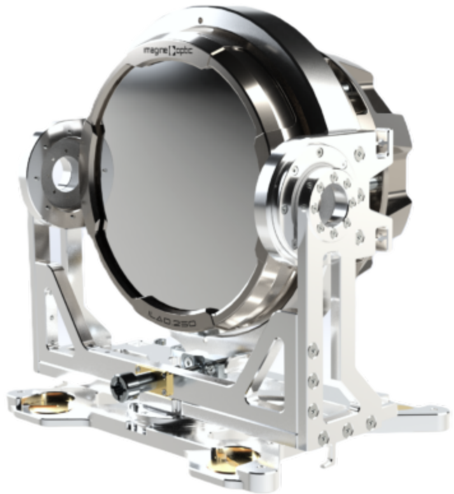




Spatial cleaning of the pulse





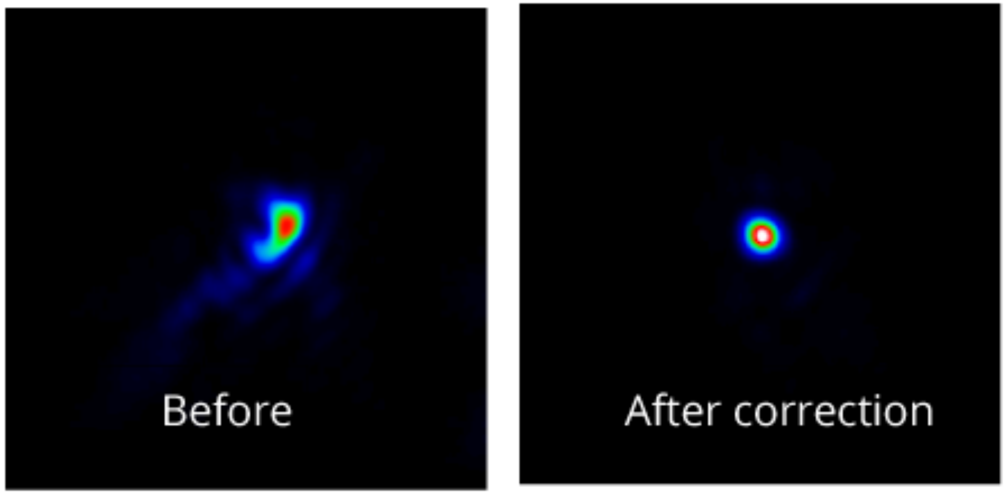


Deformable mirrors:

Piezo actuators, electromagnetic actuators

Corrected wavefronts for better energy deposition

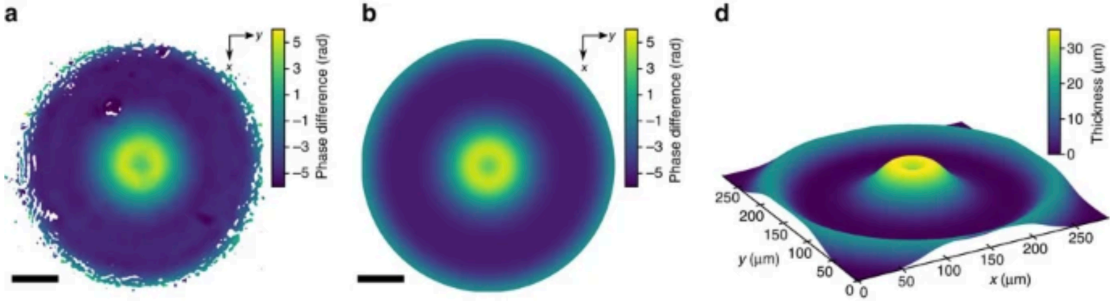
imagine optic

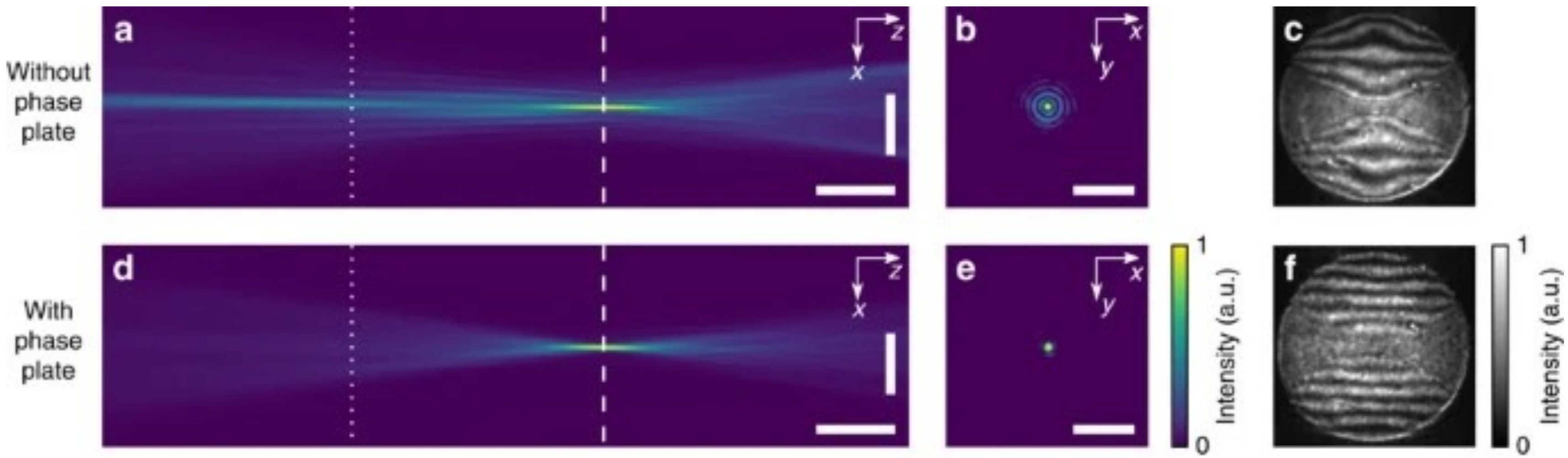


Corrected wavefronts for better energy deposition

Also at X-ray Free Electron Lasers…

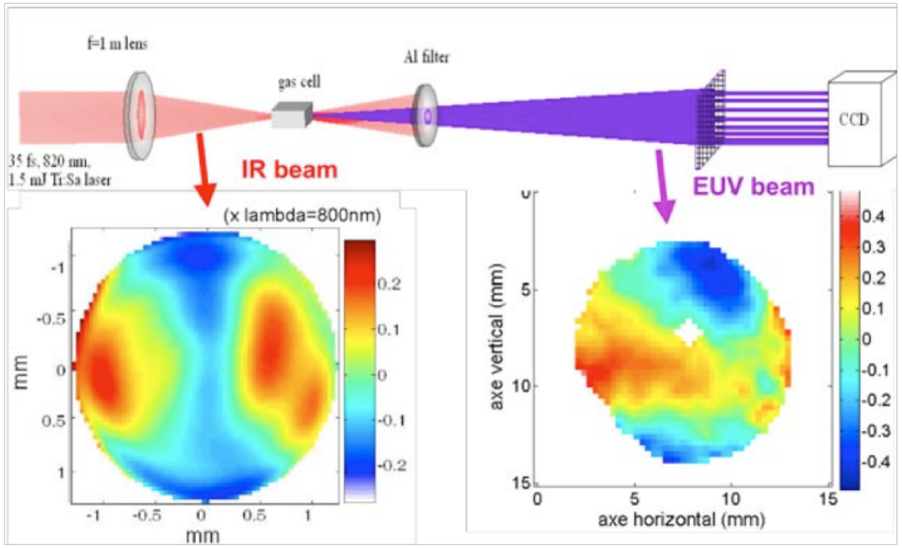
Seiboth, F., Schropp, A., Scholz, M. et al. Perfect X-ray focusing via fitting corrective glasses to aberrated optics. Nat Commun 8, 14623 (2017)





Controlling the aberrations of secondary sources

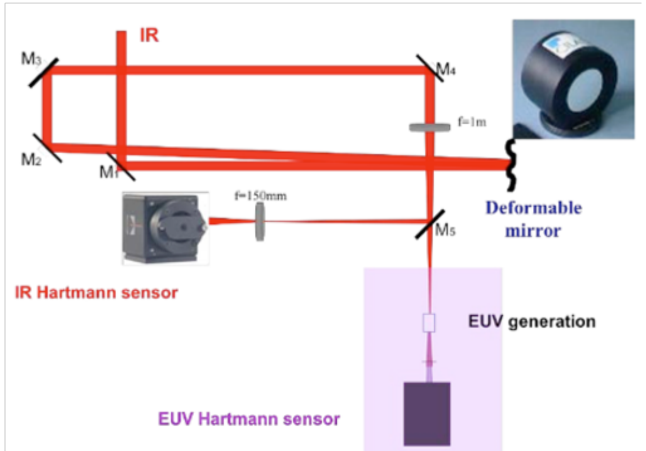
G. Lambert et al, Scientific Report, 5, 7786 (2015)
L. Lu et al, Opt. Lett. 38, 20, 4011 (2013)
G. Lambert et al, Euro. Phys. Lett. 89, 2, 24001 (2010)
G. Lambert et al, New J. of Phys, 11, 083033 (2009)
J. Gauthier et al, Euro. Phys. Jour. D, 48, 3, 459 (2008)
C. Valentin et al, J.O.S.A. B, 25, 7, B161 (2008)
P. Mercère et al, Opt. Lett., 28, 17, 1534 (2003)



VOXEL

S. Kunzel et al, JOSA B 2015

Using closed-loop correction, we achieved diffraction limited harmonics (<λ/14 rms)

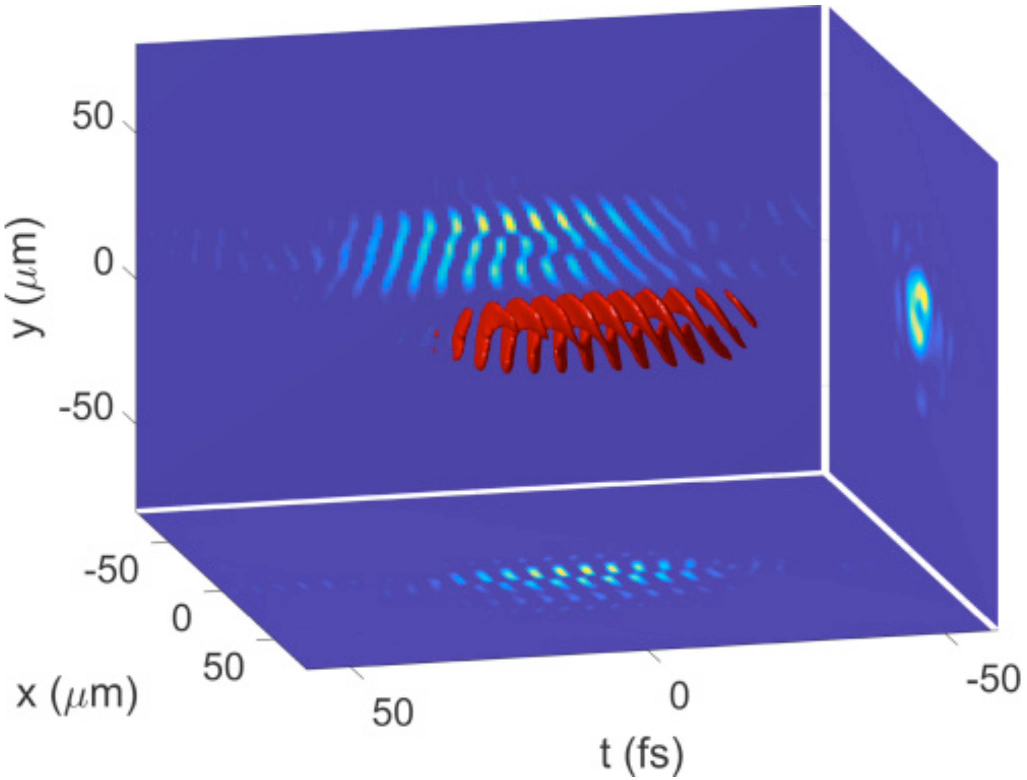


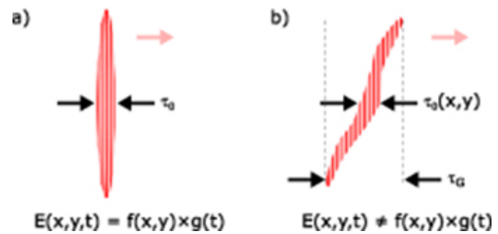
You can control what you can measure

Fabien Queré:

Spatio-temporal characterization of ultrashort laser beams: a tutorial

Spencer W Jolly et al 2020 J. Opt. 22 103501





2D-SPIDER,

SEA-SPIDER,

SRSI-ETE

SEA-TADPOLE,

STARFISH

TERMITES

Shackled-FROG

HAMSTER

CROAK

INSIGHT

STRIPED-FISH

…..

IMPALA

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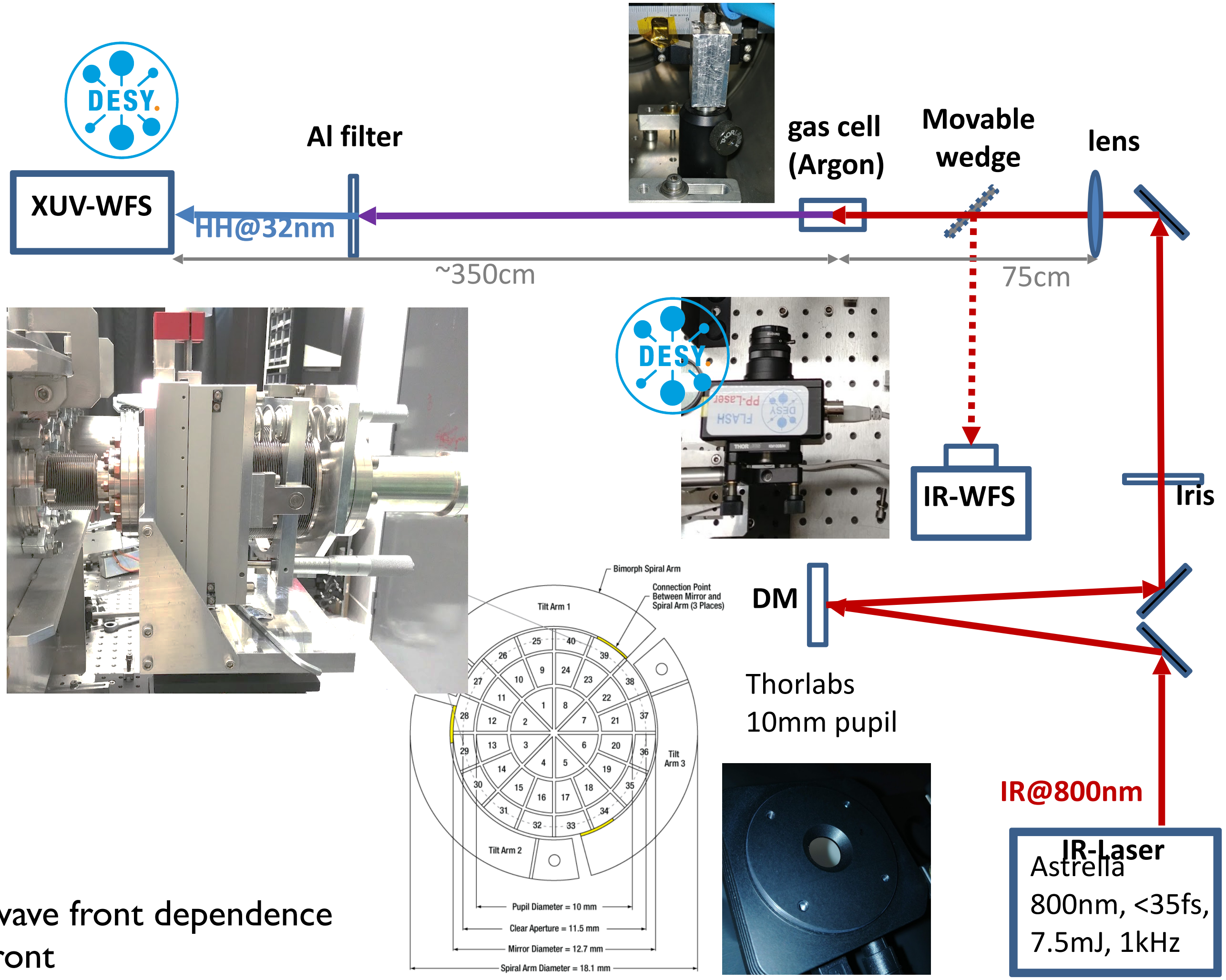
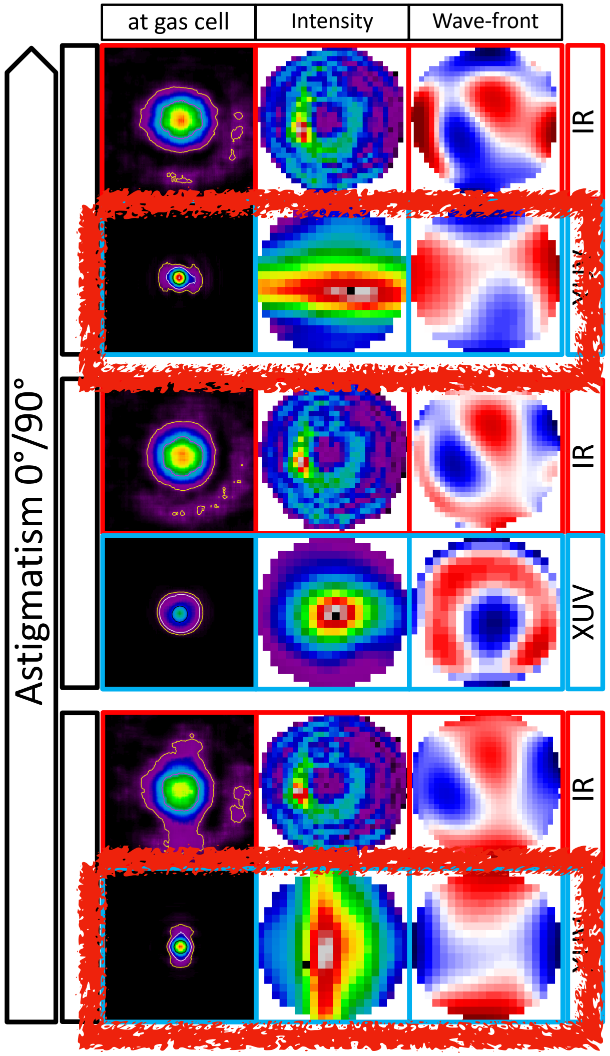
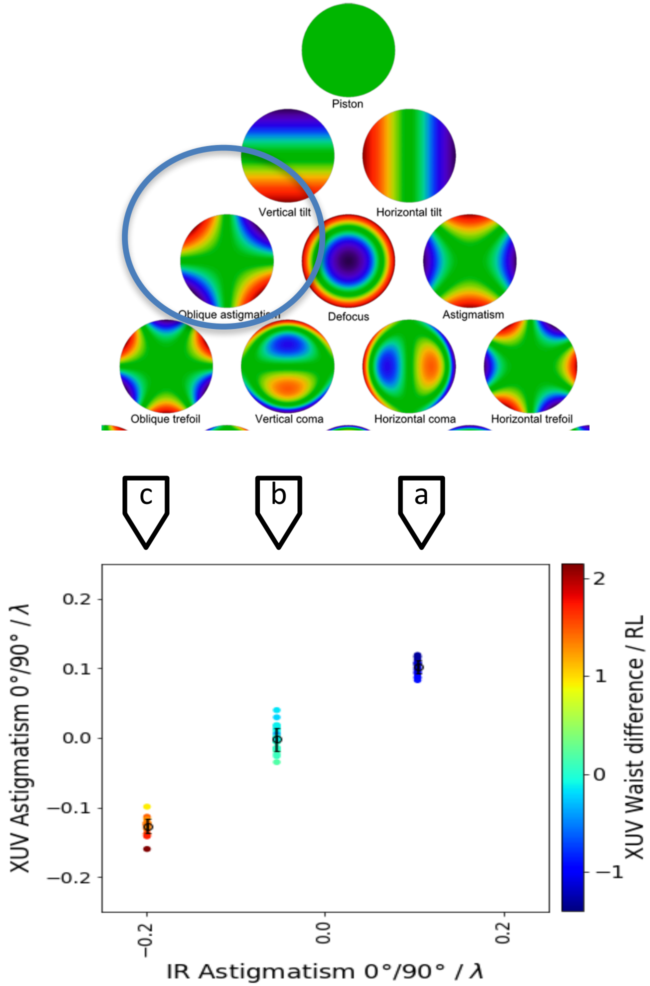
Early applications I: Controlling aberrations in secondary sources



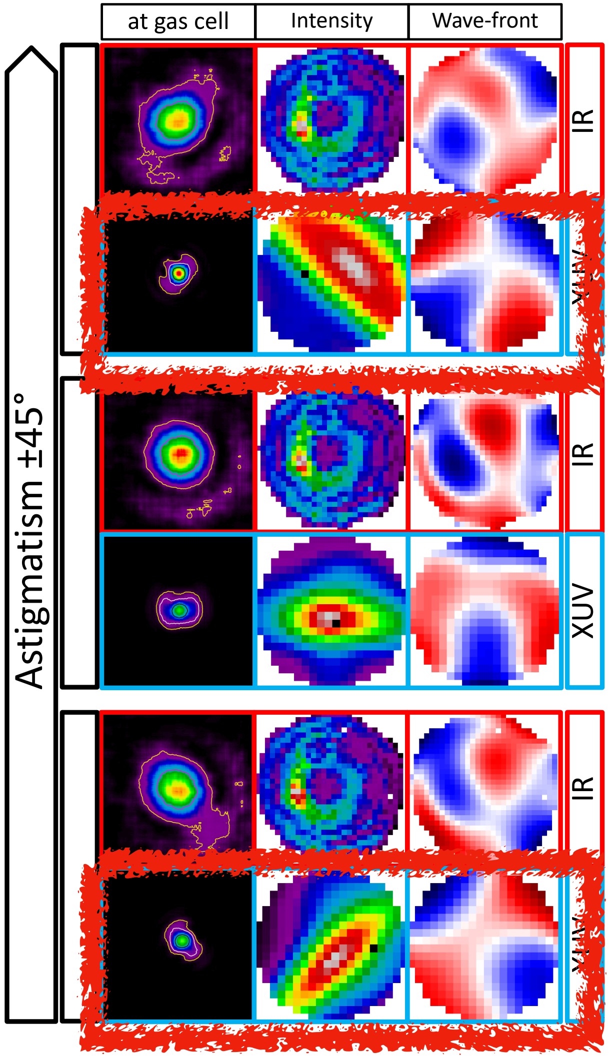
Th. Wodzinski et al,
High-harmonic generation wave front dependence on a driving infrared wave front
Applied Optics 2020

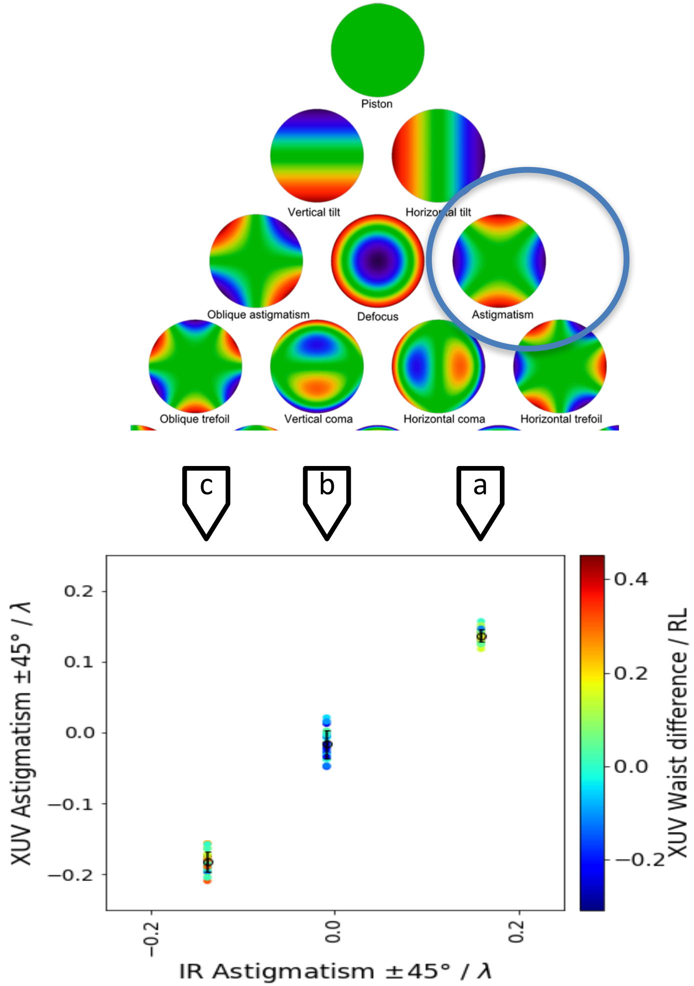
Early applications I: Controlling aberrations in secondary sources





Early applications I: Controlling aberrations in secondary sources





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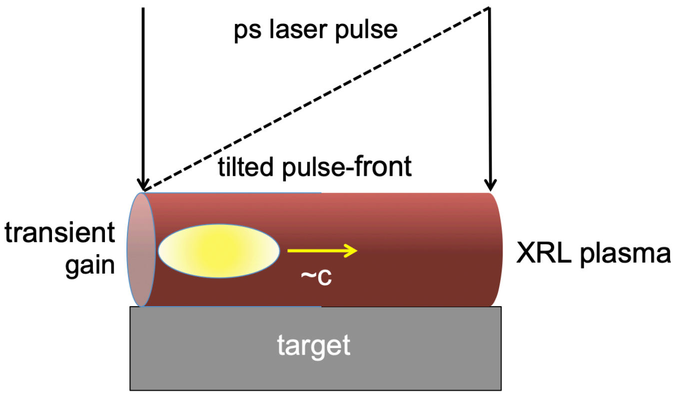
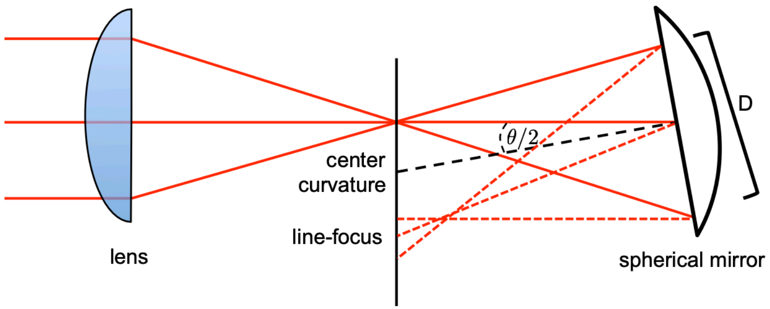
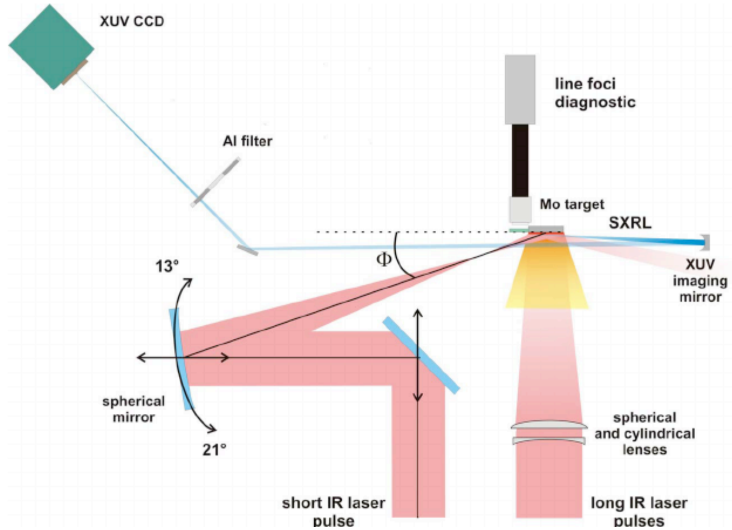
J. Rocca: transient traveling wave excitation using grazing incidence pumping (2000s)







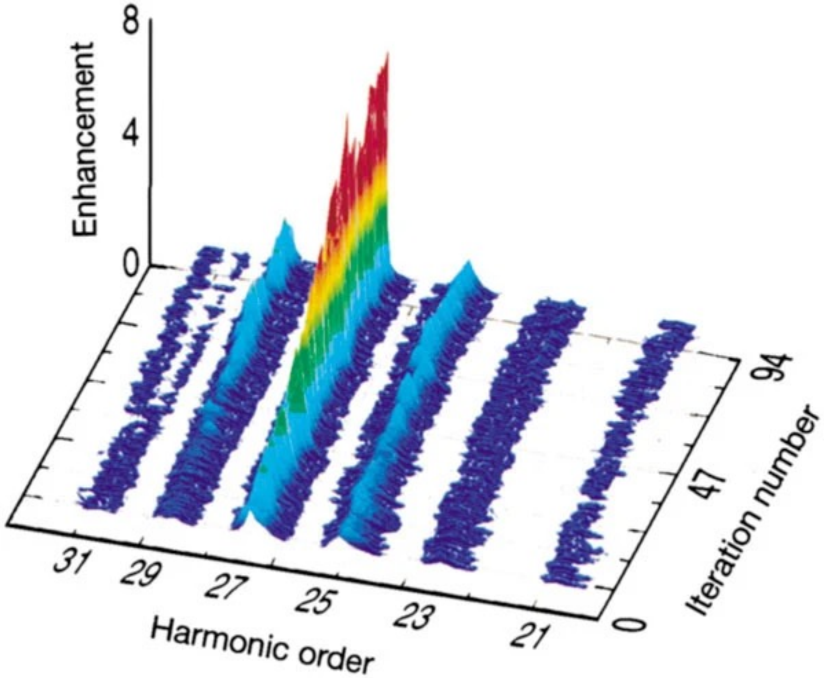
Characterization of a transient collisional Ni-like molybdenum soft-x-ray laser pumped in grazing incidence,

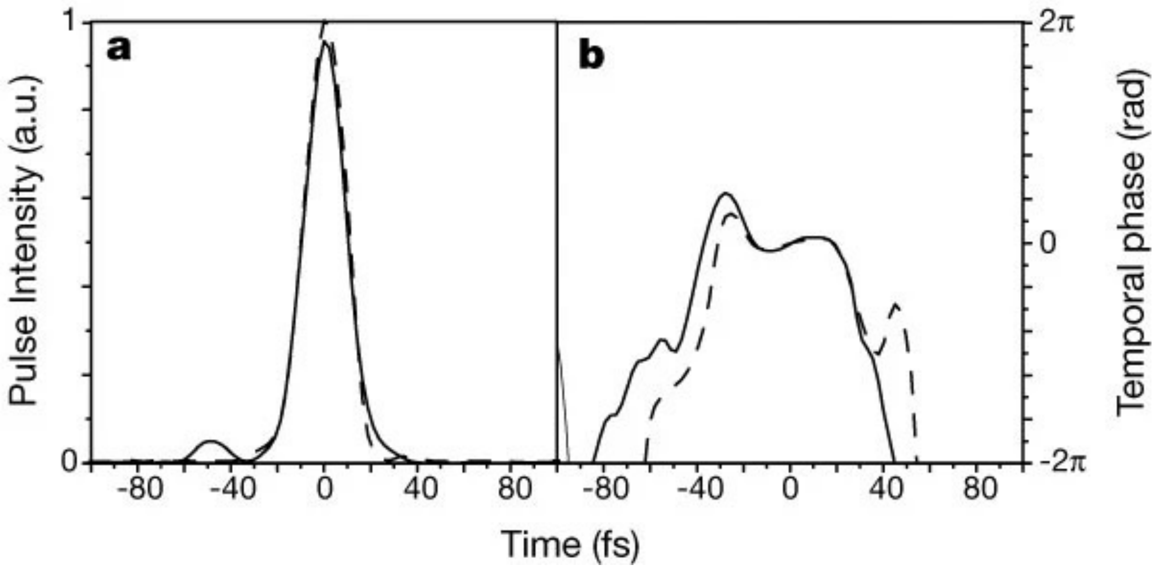
S. Kazamias et al Phys Rev A 2008

Early applications 3 - Spectral shaping

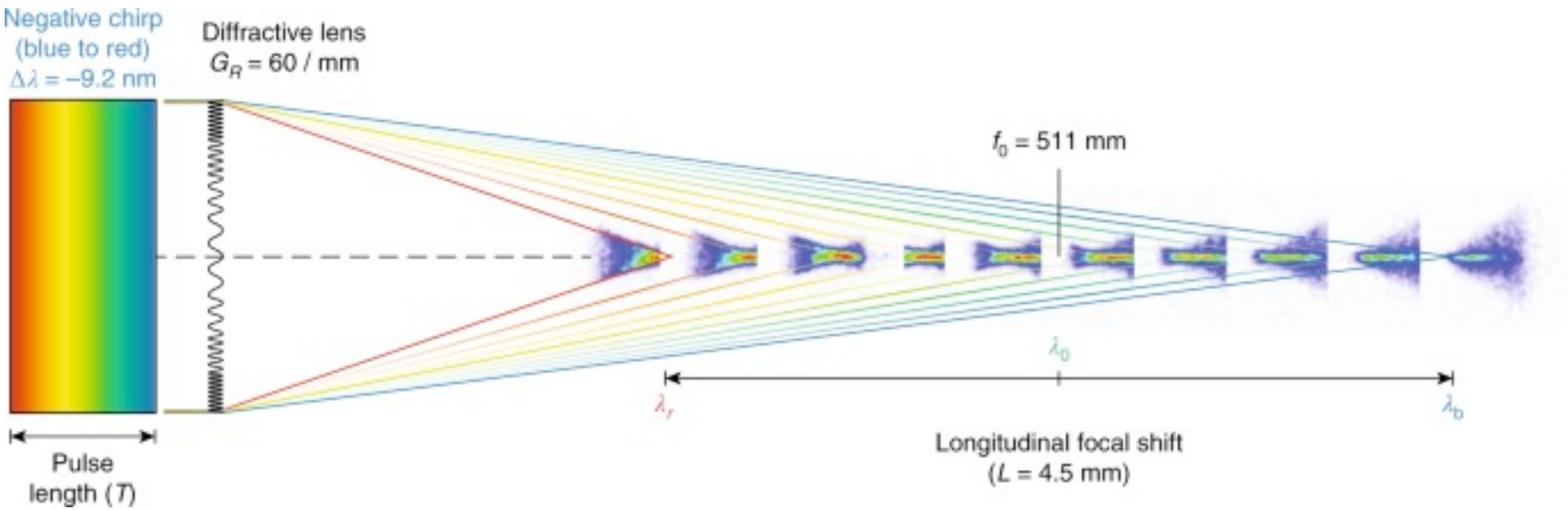
Bartels, R., Backus, S., Zeek, E. *et al.* Shaped-pulse optimization of coherent emission of high-harmonic soft X-rays.

Nature **406**, 164–166 (2000)



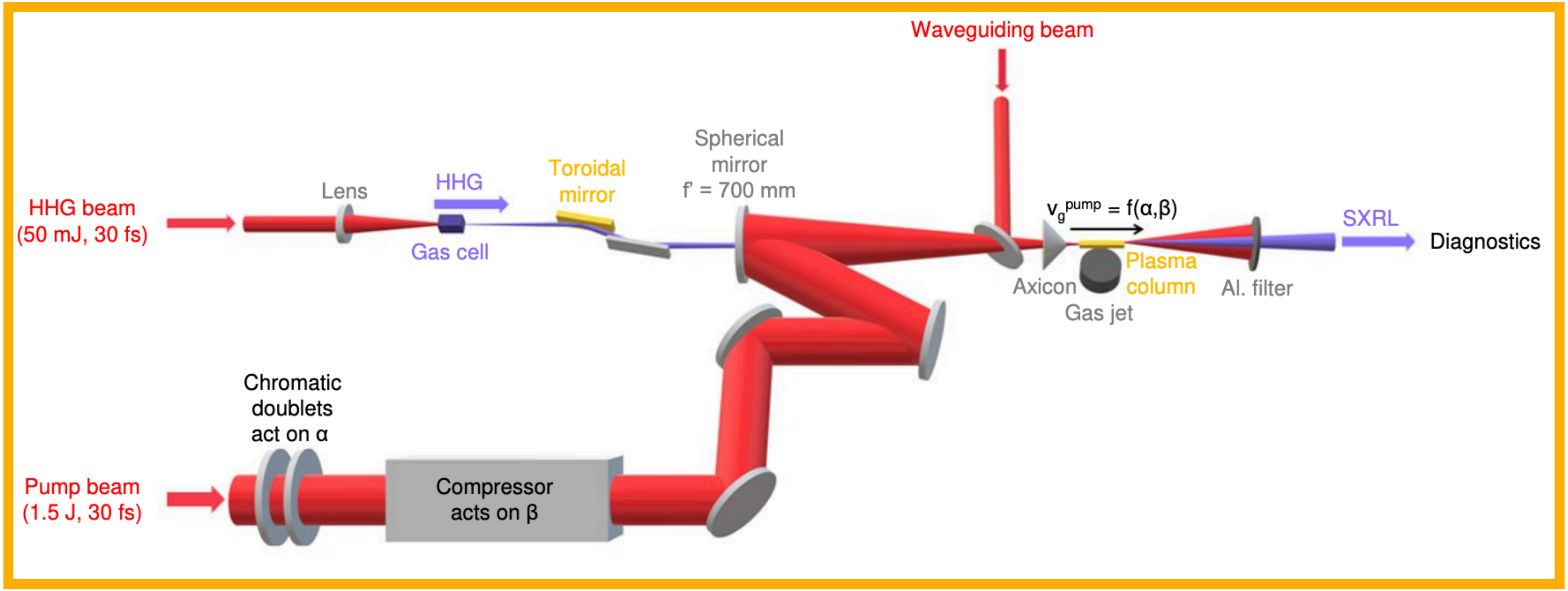


Modern examples: Flying focus



Dustin H. Froula, University of Rochester
Froula, D.H., Turnbull, D., Davies, A.S. *et al.* Spatiotemporal control of laser intensity. *Nature Photon* **12**, 262–265 (2018)

Modern examples: XRL OFI



Spatio-temporal couplings for controlling group velocity in longitudinally pumped seeded soft X-ray lasers,

A. Kabacinski, Nature Photonics, 2023

Flying focus to control group velocity of IR pump match seed,
3x energy extraction

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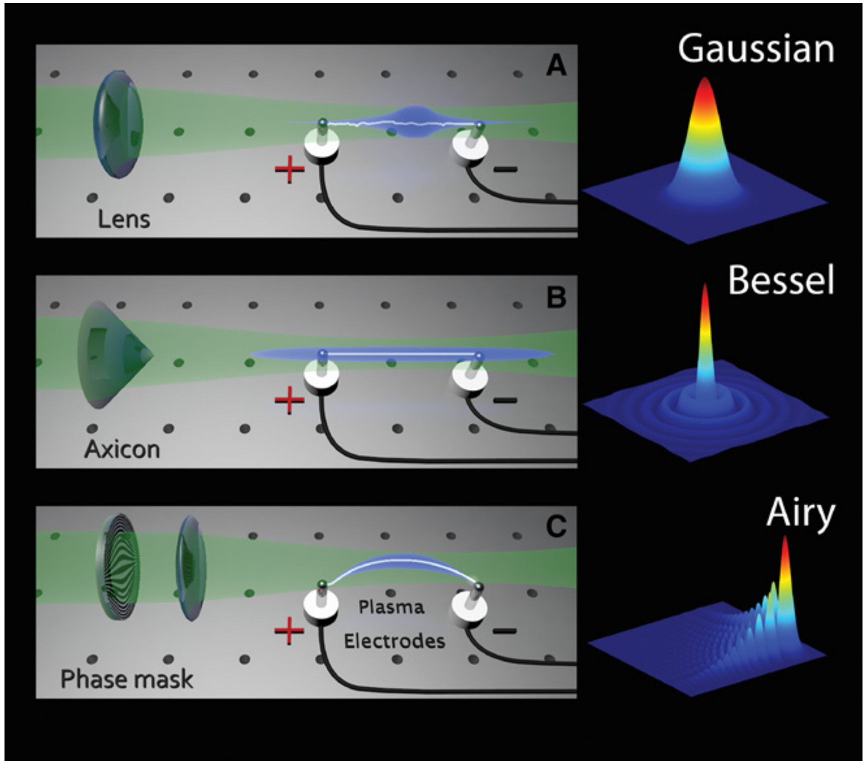
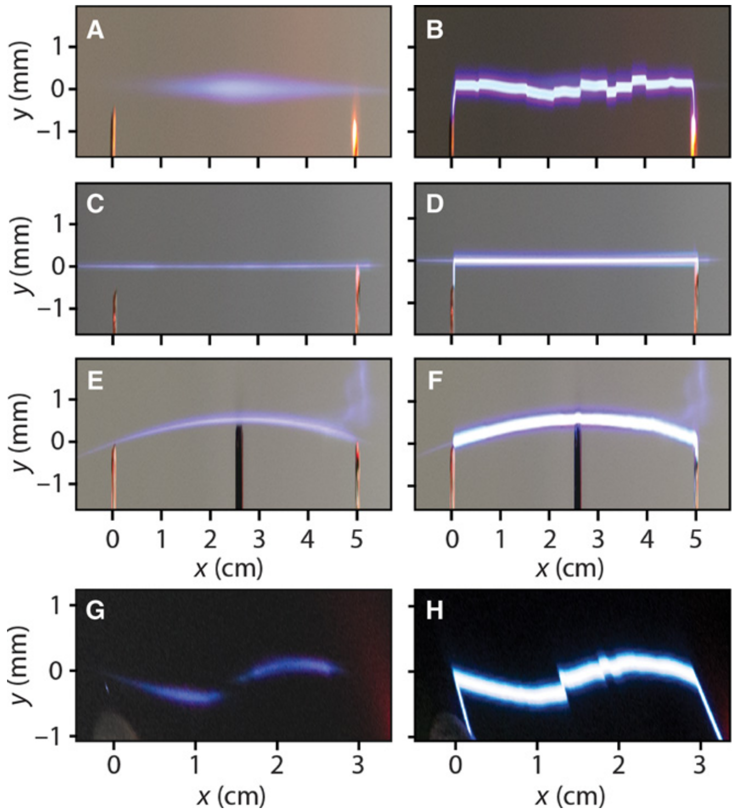
Structured light: low power experiments plasma effects



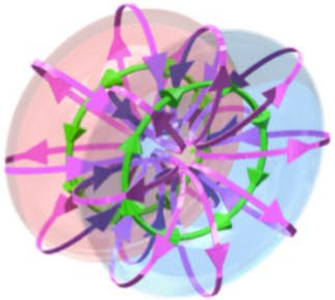


Laser-assisted guiding of electric discharges around objects
Clerici et al. Sci. Adv. 2015

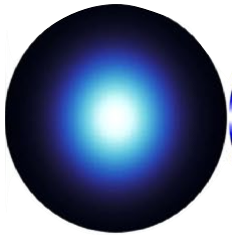
Zoo of structured light

How can we inject these complex electromagnetic wavepackets into PIC simulations to investigate the physics and predict experimental outcomes?

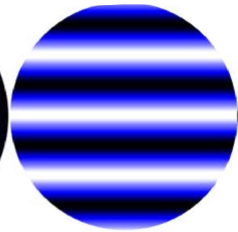
Flying doughnut (single cycle)



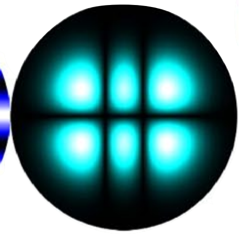
Gaussian



Propagation invariant

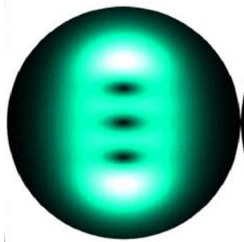


Hermite Gaussian

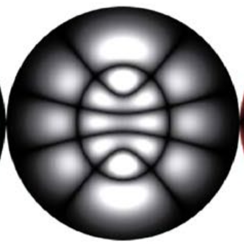


Laguerre Gaussian

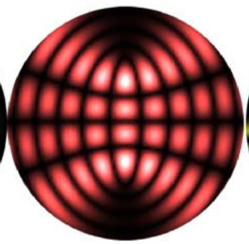
Hermite-Laguerre Gaussian beam



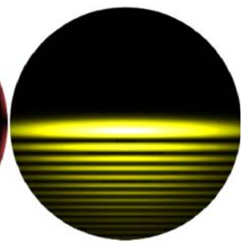
Ince Gaussian

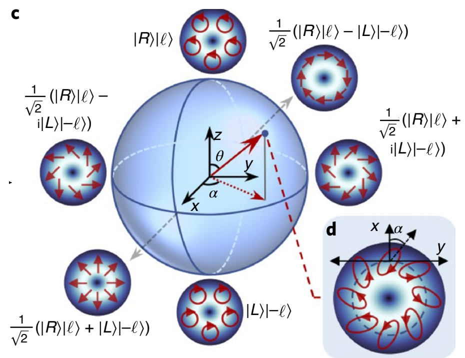


Mathieu beam



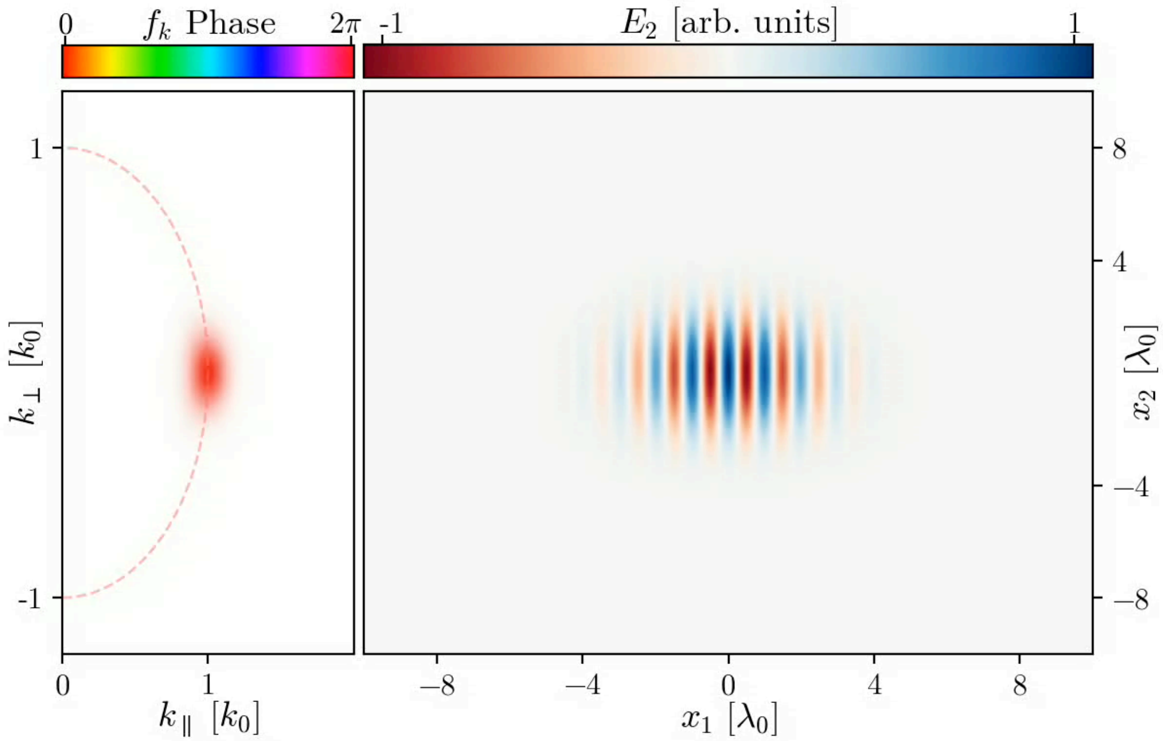
Airy beam





A. Forbes, et al. Nature Photonics, 15 253–262 (2021)

Controlling pulse properties with the f_k function



We can control:

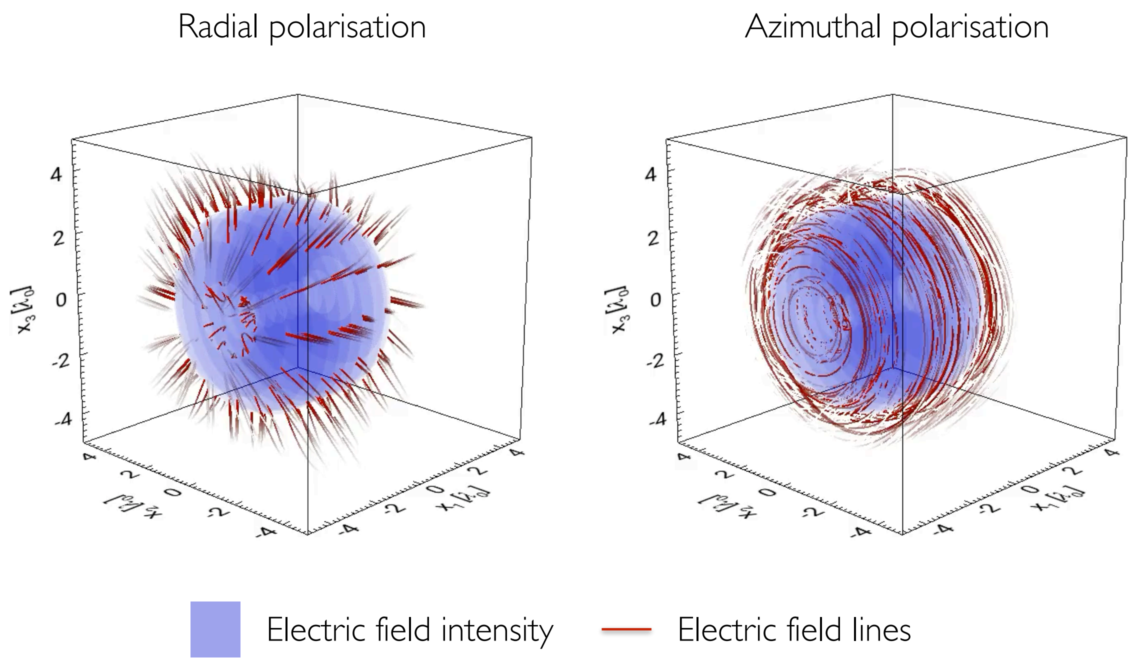
- Main Frequency
- Transverse Size
- Longitudinal Size
- Focus Position
- Relative Injection Position
- Transverse Profile

Basically Arbitrary Control over Pulse Shape

R. Almeida et al. in preparation (2025)

Arbitrary pulse initialisation in Osiris

✓ **Elliptical, radial and azimuthal polarisation built in**
Direct injection of new polarisation states

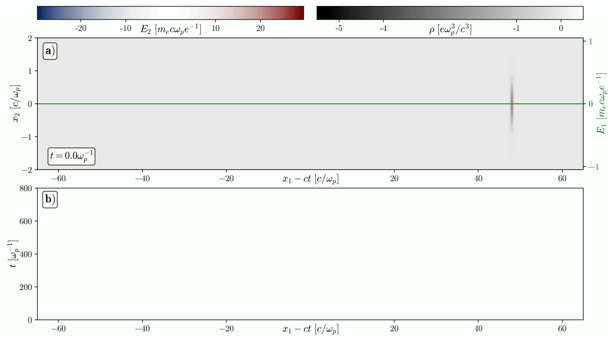


R.A. Almeida et al., in preparation (2025)

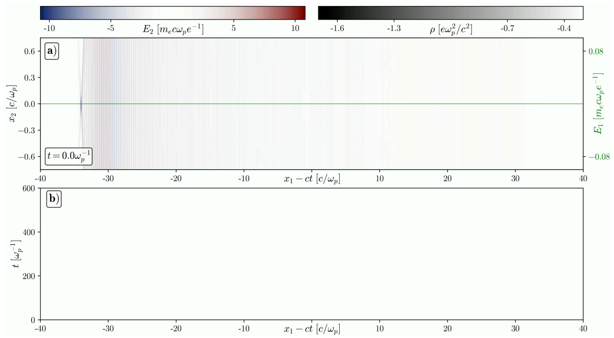
The laser focal plane speed controls the wake phase-velocity

Flying focus

Subluminal Focus Velocity - $v_f = 0.96c$



Superluminal Focus Velocity - $v_f = 1.1c$



D. Froula et al, Nature Photonics 12, 262–265 (2018); A. Sainte-Marie et al, Optica 4, 1298 (2017), R. A. Almeida et al. in preparation (2025)

Applications

Dephasingless plasma acceleration

J.P. Palastro et al PRL (2020)
C. Caizergues et al Nature Photonics (2020)

Non-relativistic particle acceleration

Z. Gong et al., PRL(2024)
C. Badiali et al, in preparation (2025)

Plasma waves phase velocity = Pulse's Focus Velocity

Accurate and arbitrary control of the phase velocity of plasma wakes
Tight focusing is key

Beam zoology

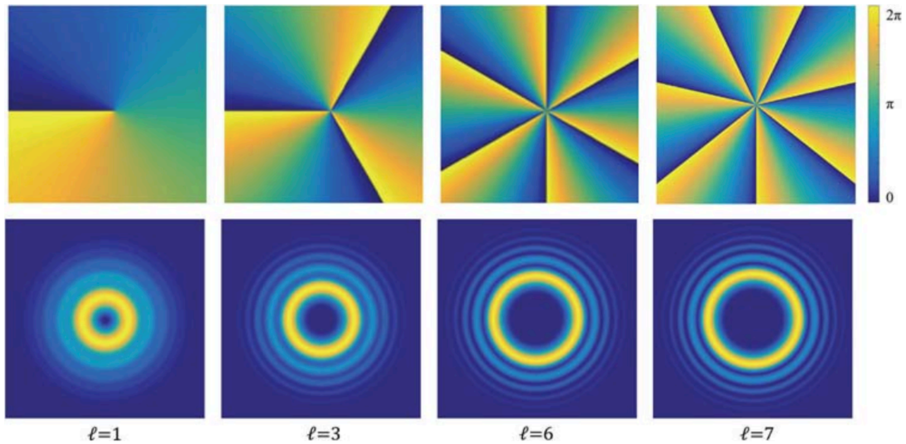


Figure 14 (top row) Phase and (bottom row) intensity profiles of a vortex beam.

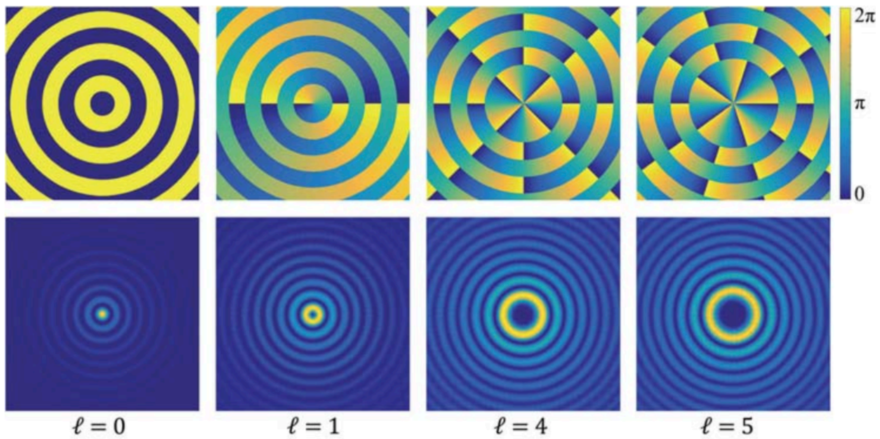


Figure 16 (top row) Phase and (bottom row) intensity profile of Bessel beams for different values of *l*.

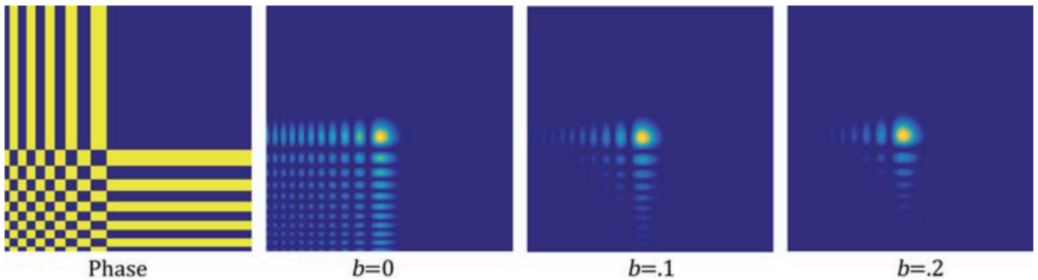


Figure 18 Phase (left) and intensity profiles (right) of finite-energy Airy beams.

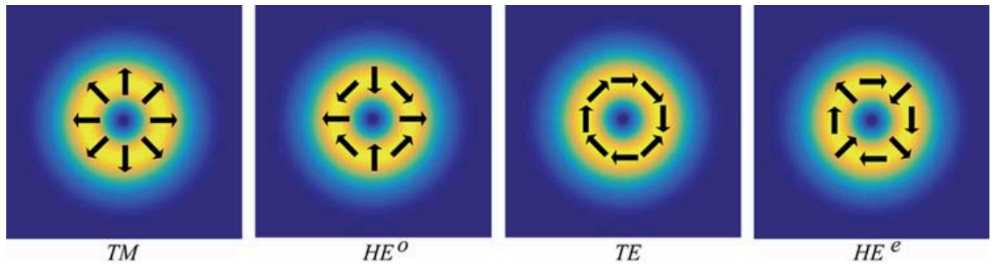
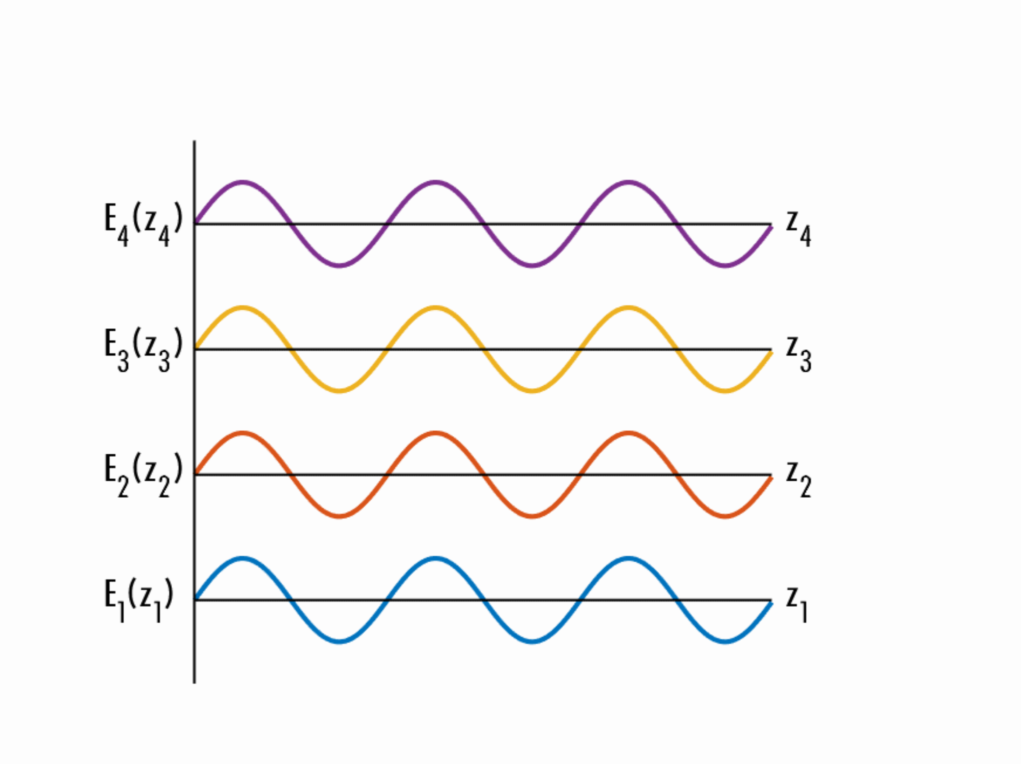


Figure 25 Cylindrical vector vortex modes, with the arrows depicting the local polarization angle.

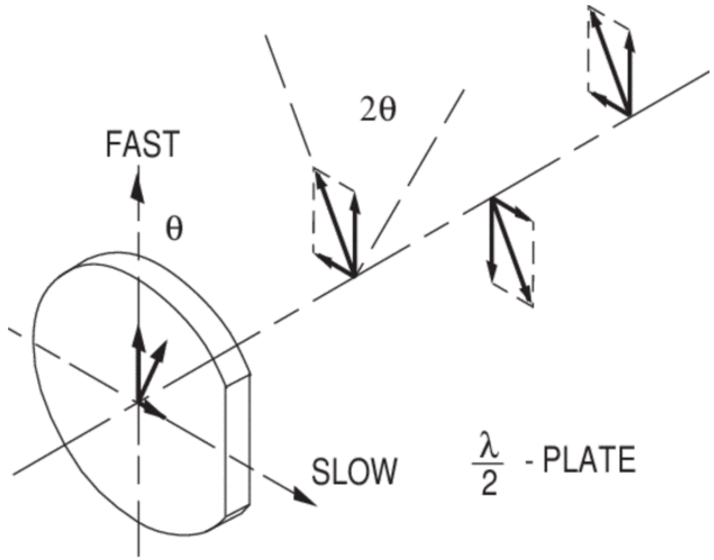
How to Shape Light with Spatial Light Modulators

Carmelo Rosales-Guzmán and Andrew Forbes
SPIE.spotlight

Experimental Tools for Spatiotemporal Control



https://www.edmundoptics.com/knowledge-center/application-notes/optics/understanding-waveplates/



https://www.newport.com/n/introduction-to-waveplates

Experimental Tools for Spatiotemporal Control

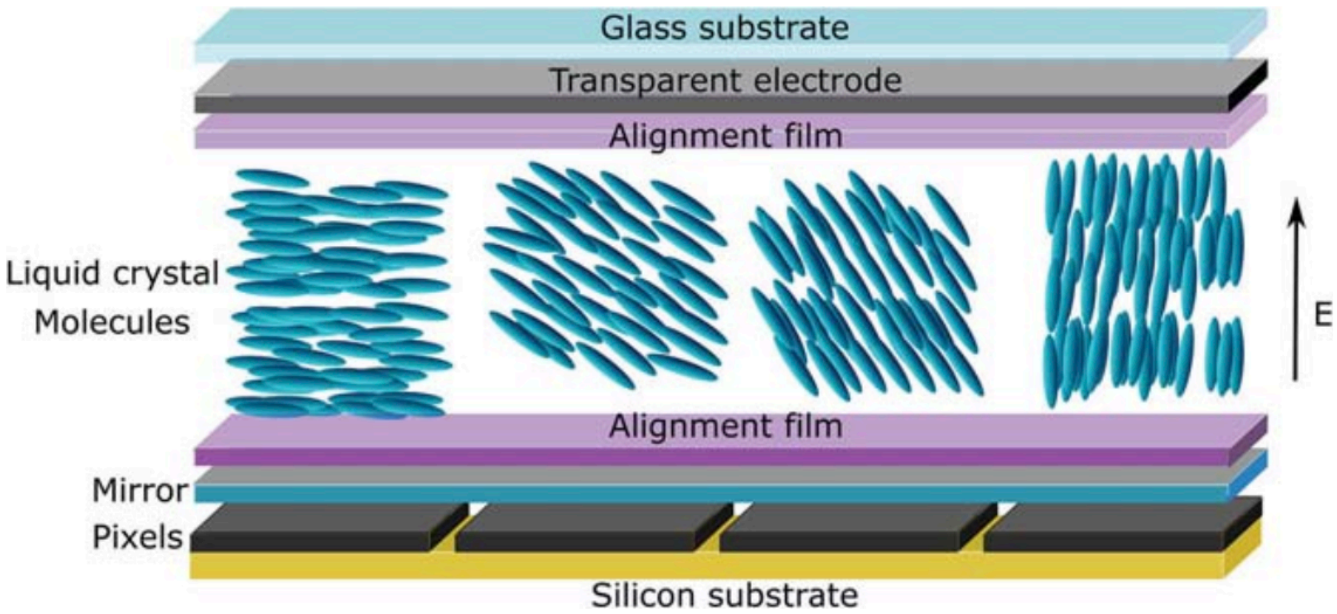
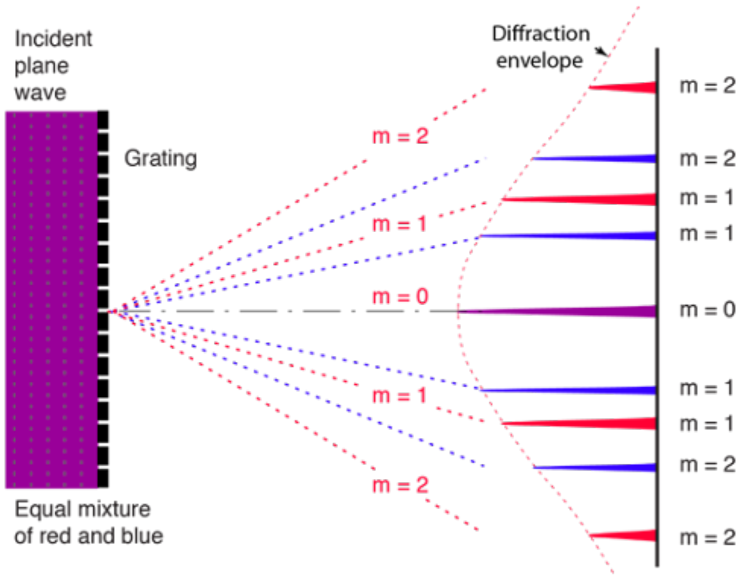


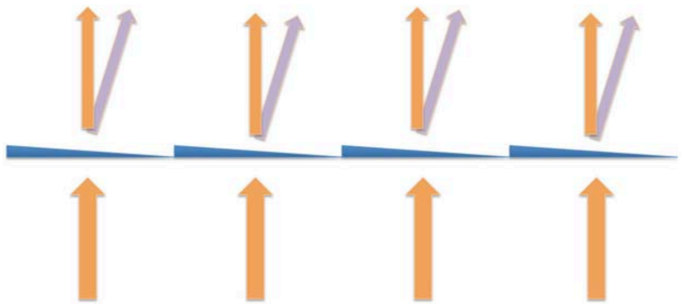
Figure 2 Schematic representation of a LCoS SLM.

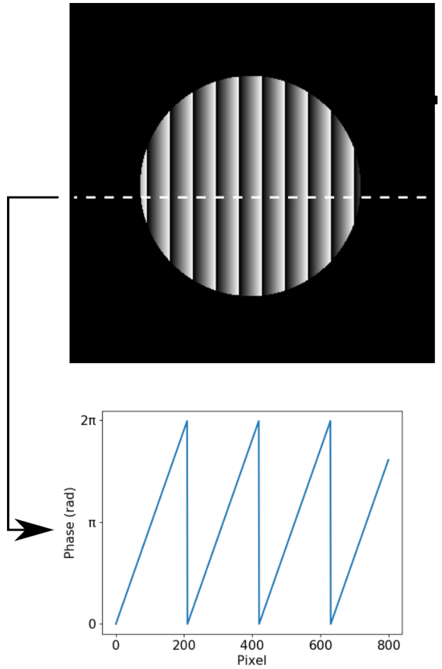
Experimental Tools for Spatiotemporal Control

Spatial Light Modulators (SLMs) — dynamic, programmable

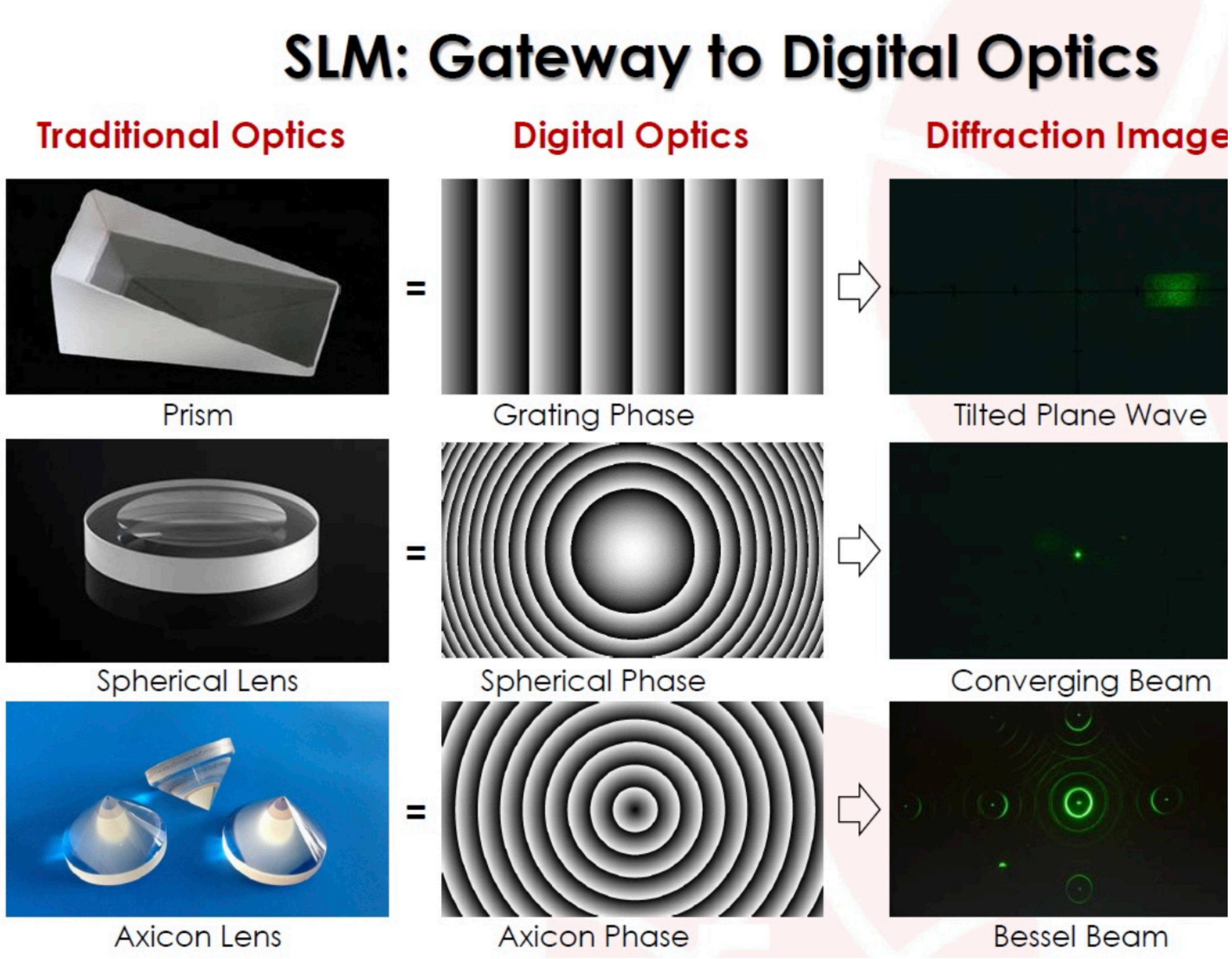
Blazed grating - maximum efficiency in 1st order





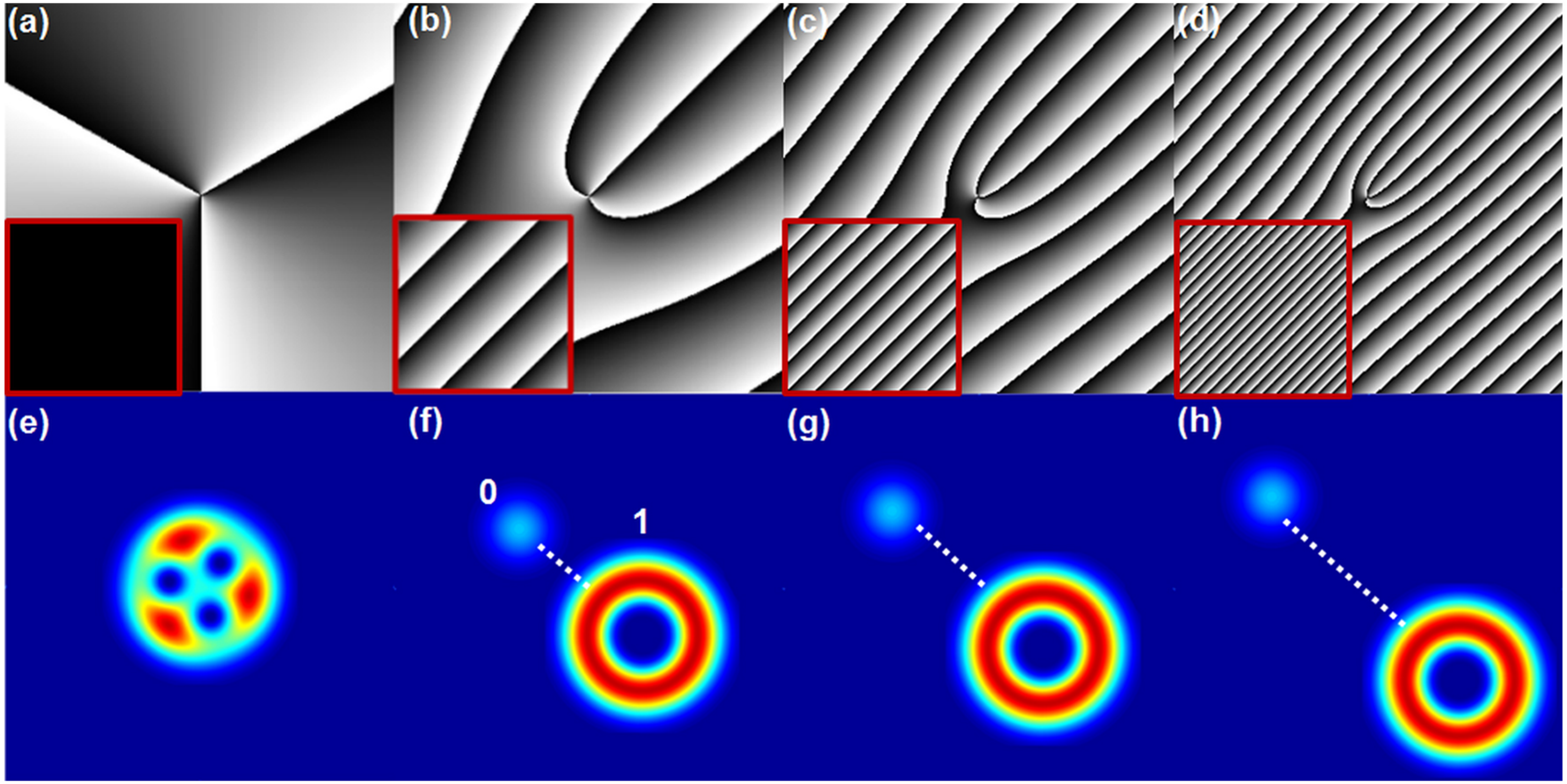


Experimental Tools for Spatiotemporal Control



https://cightech.com/

Experimental Tools for Spatiotemporal Control

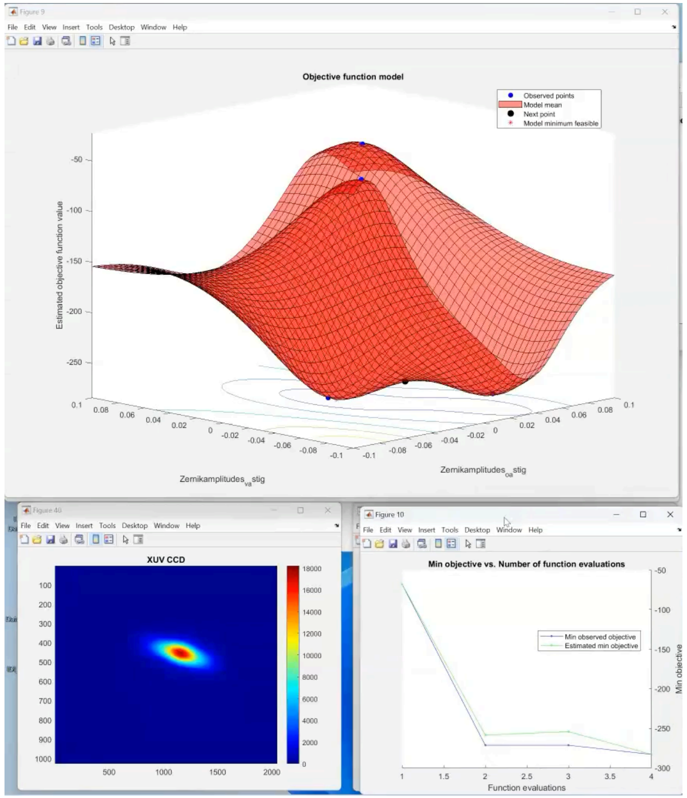


How to Shape Light with Spatial Light Modulators, https://doi.org/10.1117/3.2281295.ch1

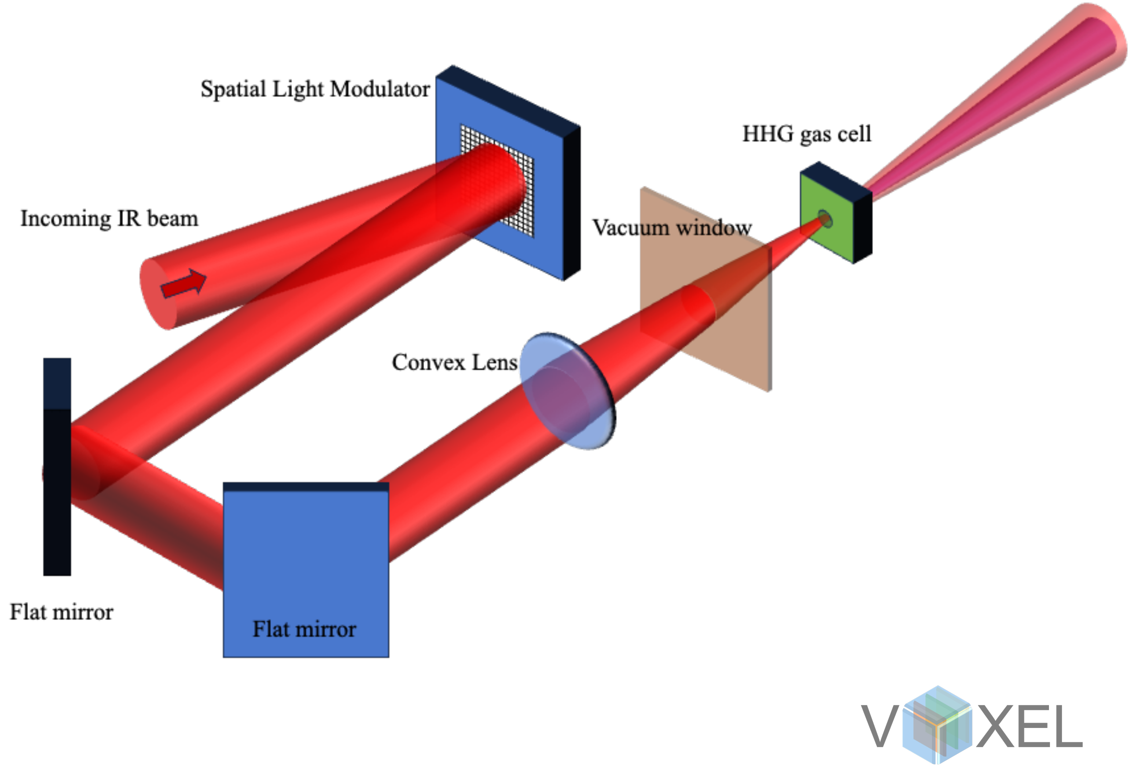
Optimising HHG with SLM at IST

Real time bayesian optimisation

Optimising IR vertical and oblique astigmatisms for maximum HHG yield



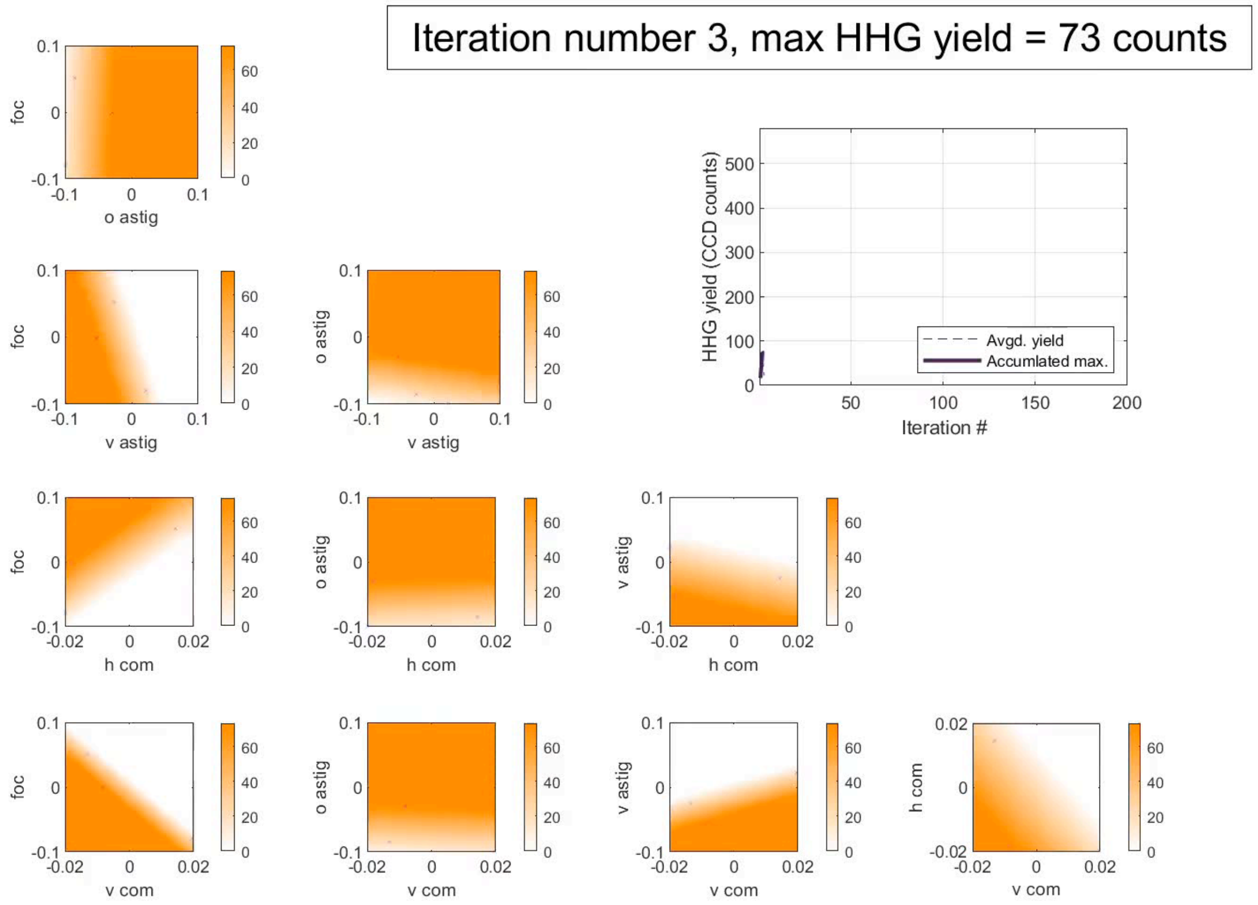
Experimental set-up



Optimisation video

TÉCNICO LISBOA

Bayesian exploration of parameter space - Zernika coefficients

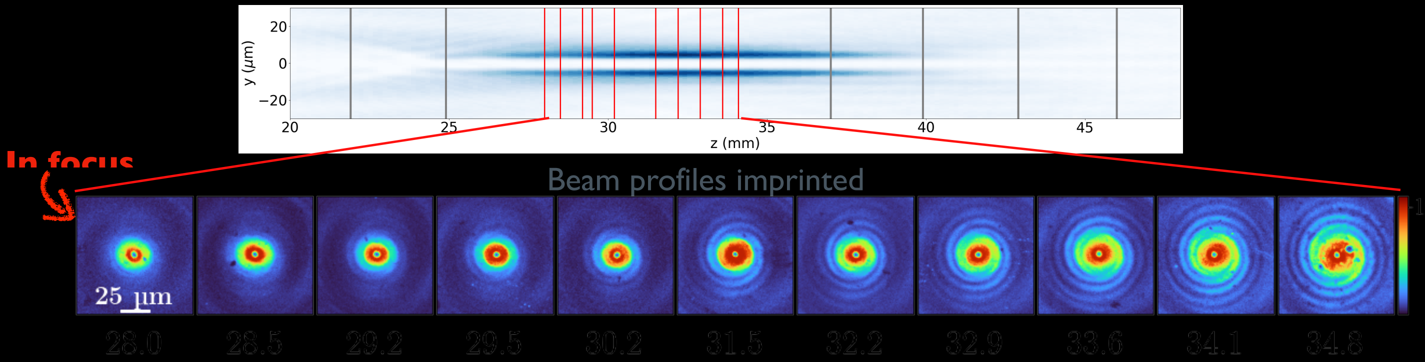


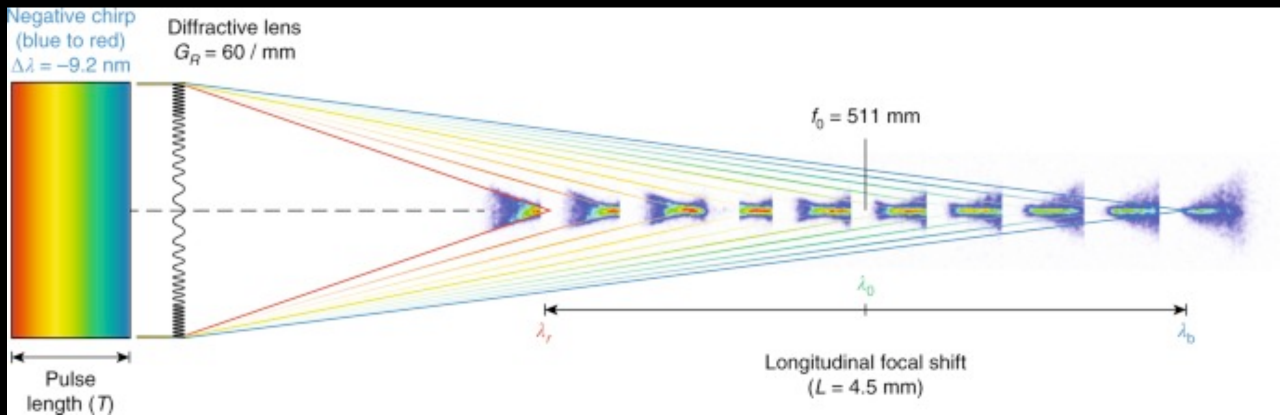
5D bayesian optimisation of HHG yield:

- Defocus
- Vertical astigmatism
- Oblique astigmatism
- Vertical coma
- Horizontal coma

Compared to astigmatism-only optimisation, factor of 2 improvement in HHG average yield

Spatio-temporal pulse shaping





Dustin H. Froula, University of Rochester
Froula, D.H., Turnbull, D., Davies, A.S. *et al.* Spatiotemporal control of laser intensity. *Nature Photon* **12**, 262–265 (2018)

Contents

Peak brightness control
Clean beam era

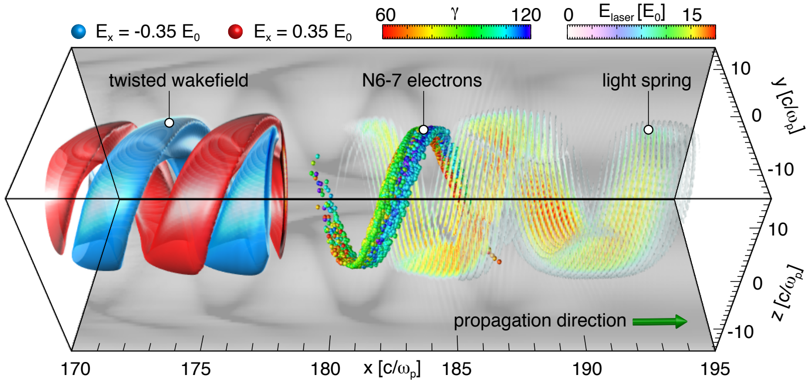
Breaking free from the Gaussian pulse
When Aberration Becomes Design

Other types of structured pulses
From Gaussian to Airy, Vortex, and Vector Beams

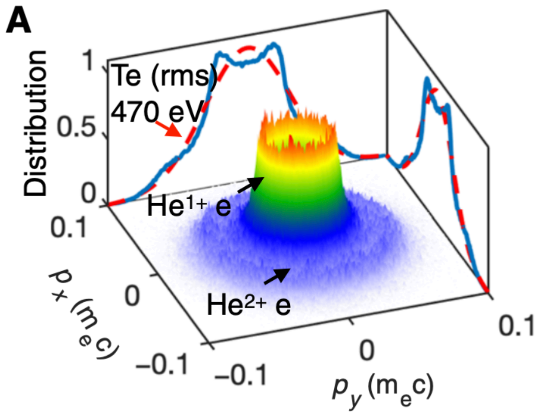
Recent results and high power manipulation
Toward High-Energy and High-Average Power Applications

Structured light for novel laser-plasma interaction conditions

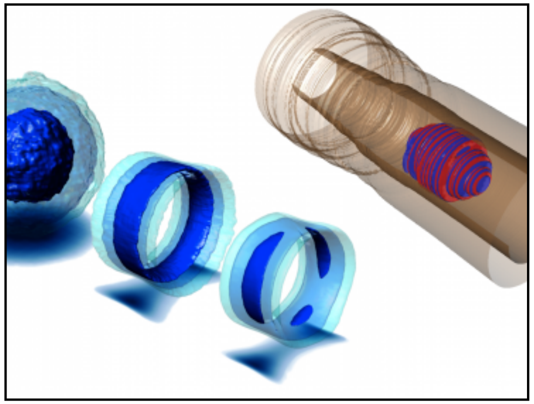
J.Vieira et al PRL **121**, 054801 (2018)



Light spring drives twisted wakefield excitation
trapped electrons with angular momentum



Ultrafast optical field–ionized gases - A laboratory platform for studying kinetic plasma instabilities
Chaojie Zhang et al, Science Advances 2019



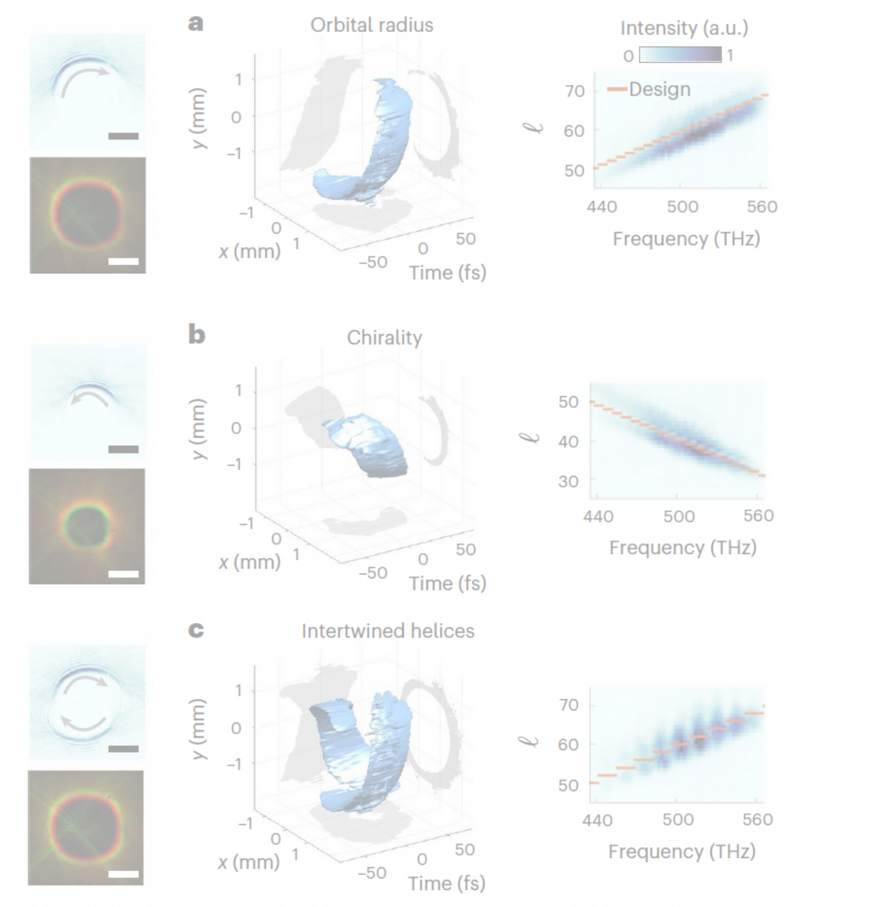
T. Silva et al, Phys Rev E 2021, Weibel instability beyond bi-Maxwellian anisotropy

J.P. Bilbao et al, Phys Plasmas 2024

shape of the anisotropic velocity distribution function, non maxwellian, dictating the dynamics of self-generated magnetic fields

Light Springs

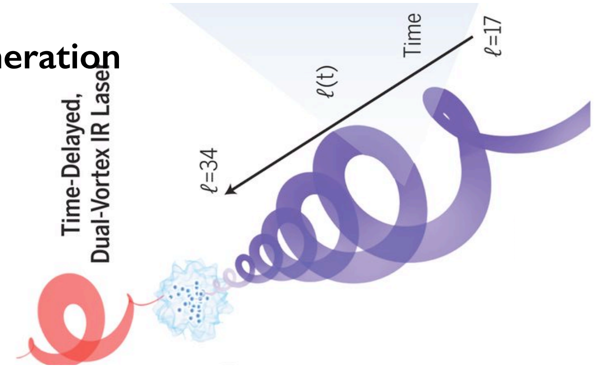
Topological charge - wavelength correlation



Piccardo, M., et al. Nat. Photon. 17, 822–828 (2023)

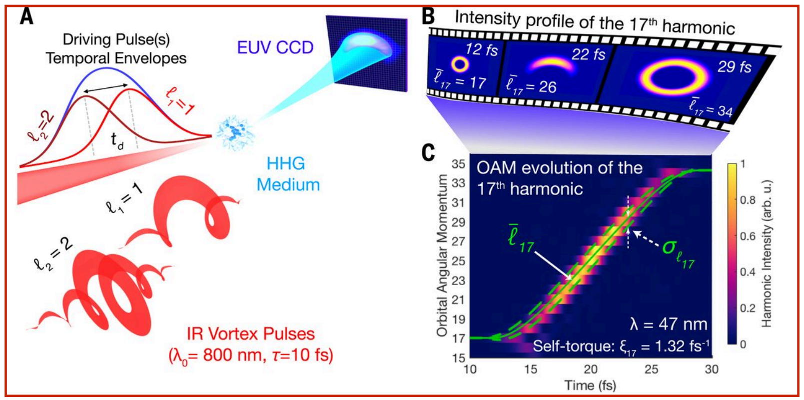
At high power laser facilities

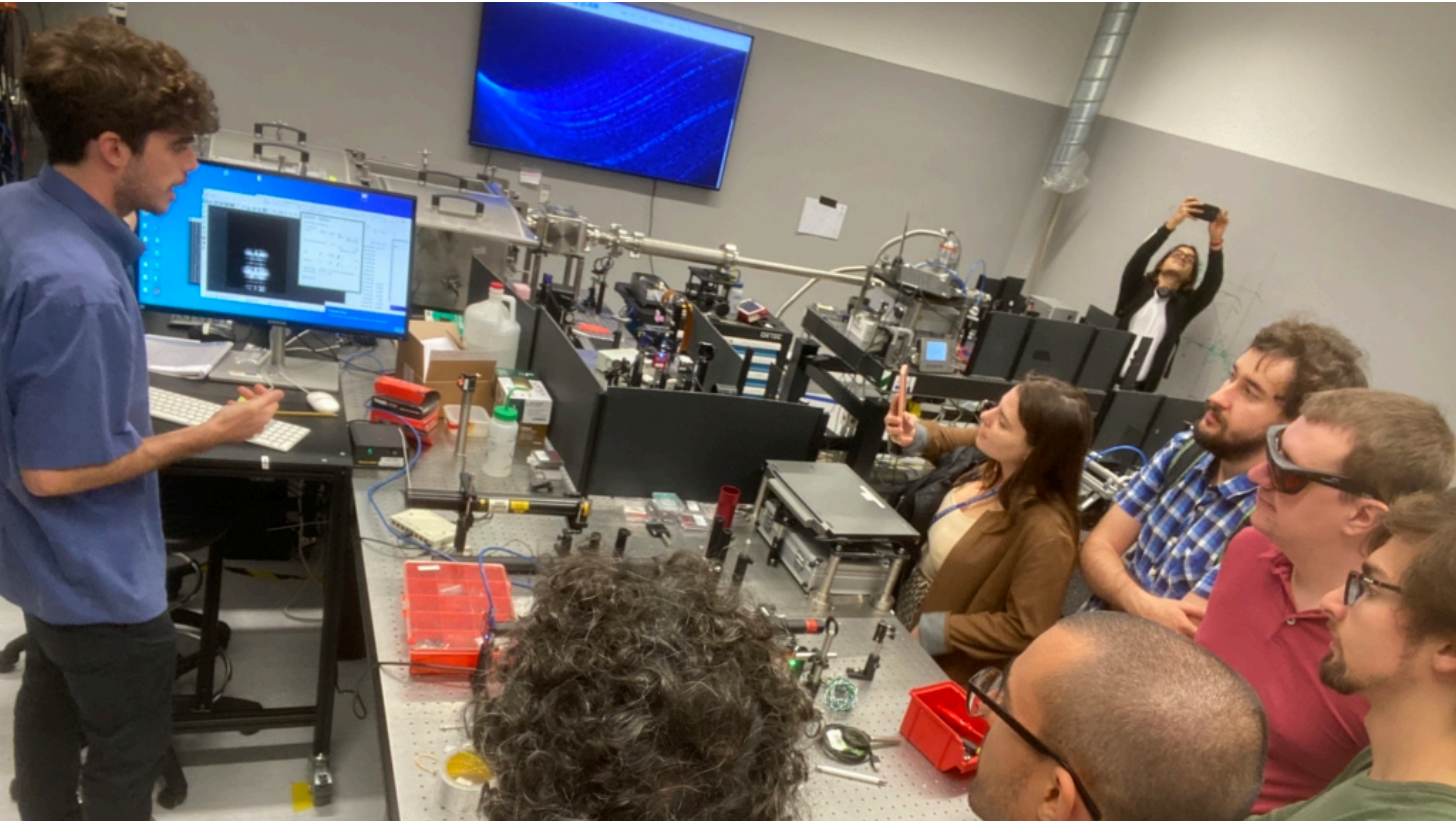
- **High Harmonic Generation**



Laura Rego *et al*. *Science* (2019).

Introduces a new property of light beams with time-varying OAM along the light pulse: **the self-torque of light**

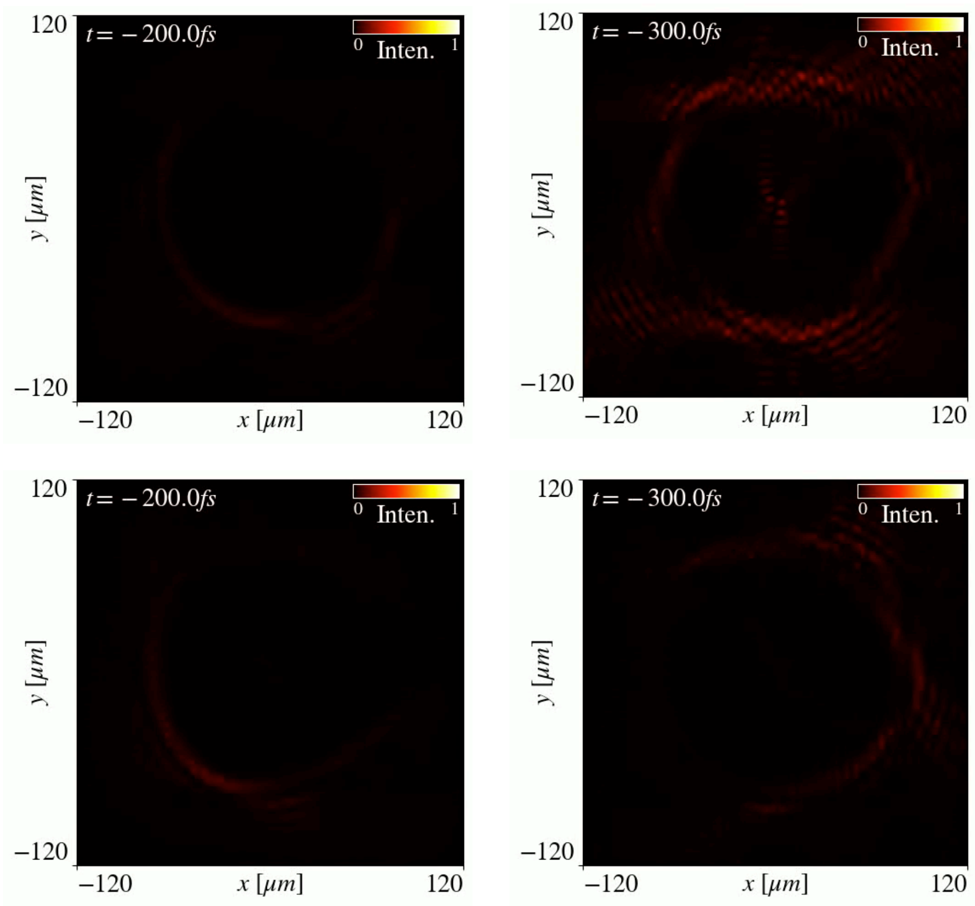




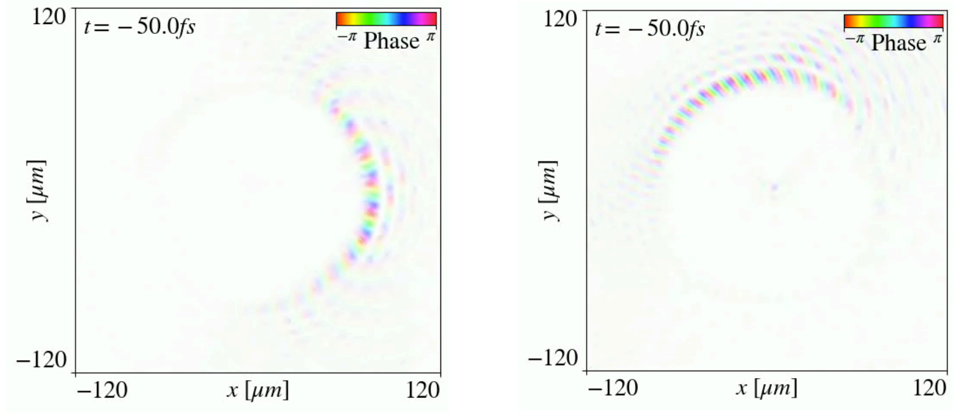
OAH results

Data Analysis and plots by R. Almeida

LightSprings movies



Orbital Group Velocity



[1] Joaquim Vaz Pereira, PIC1 Report (Supervision: Marco Piccardo)

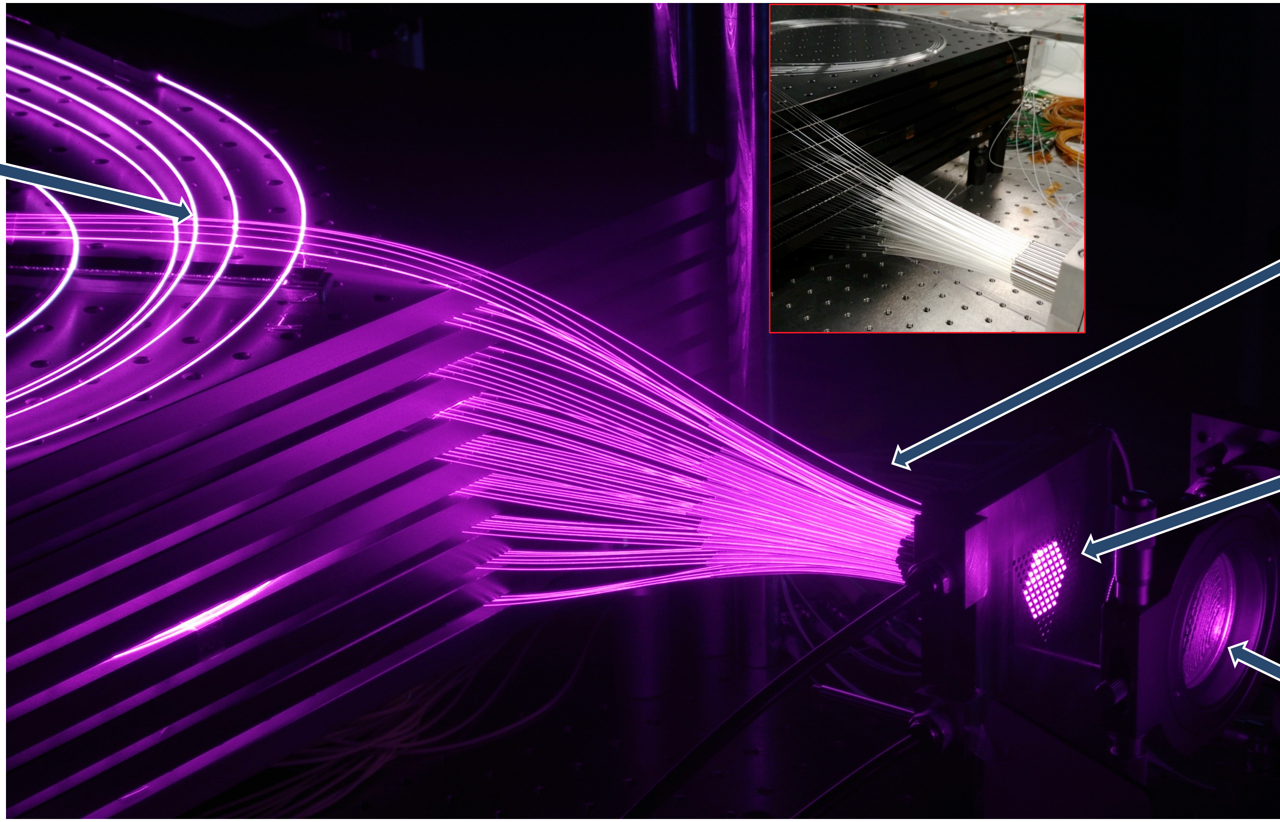
Expanding the power of shaped pulses

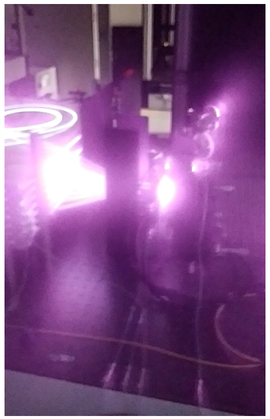
TÉCNICO LISBOA

NanoXCAN

XCAN Experimental setup

NKT 40/200
Yb doped
fiber amplifier





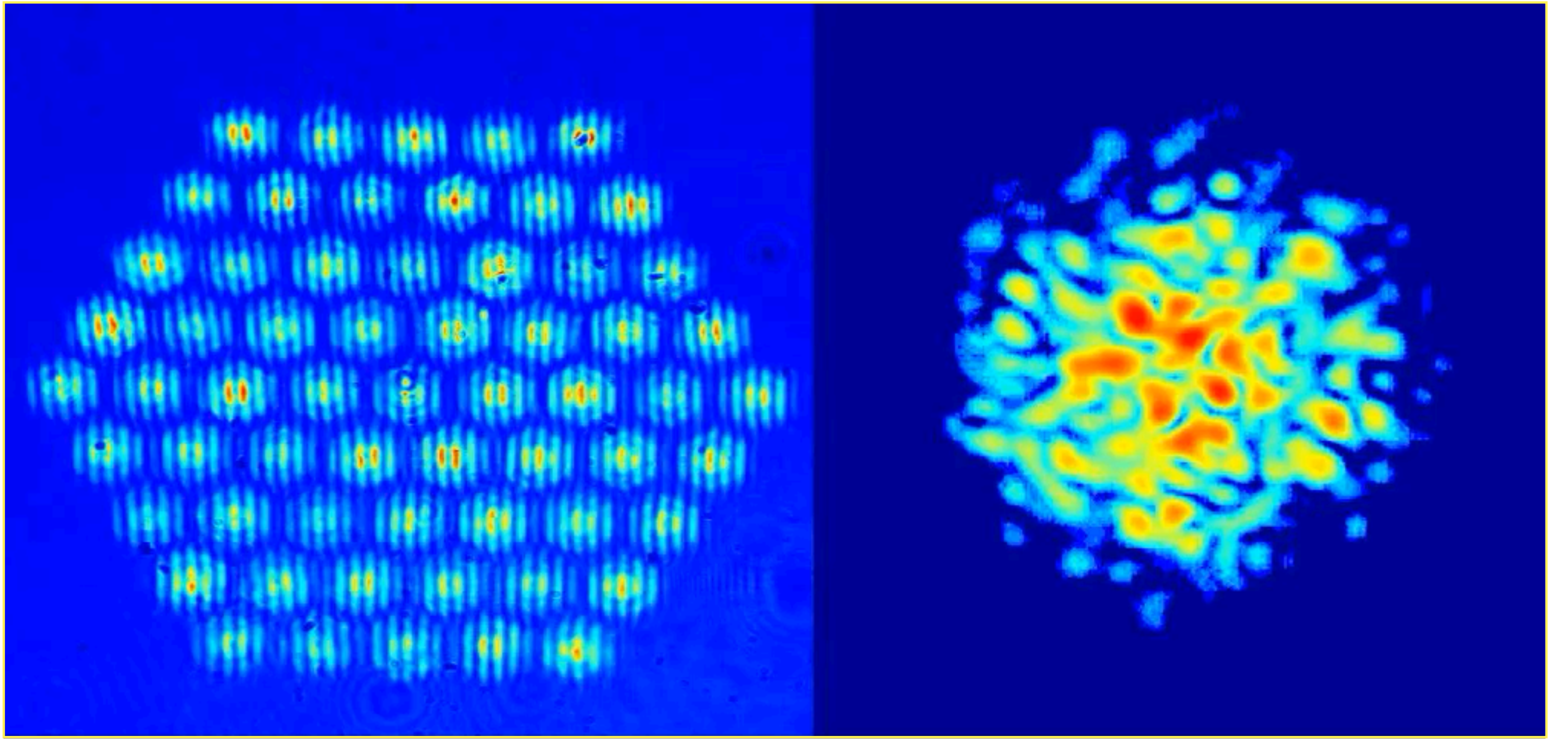
61 channels
bundle

Laser head

Microlenses
array

JEAN-CHRISTOPHE CHANTELOUP

Full 61 channels phasing sequence



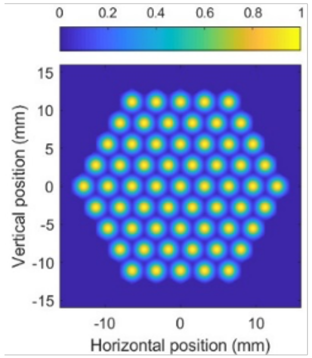
Digital pulse shaping

High average power, high peak power

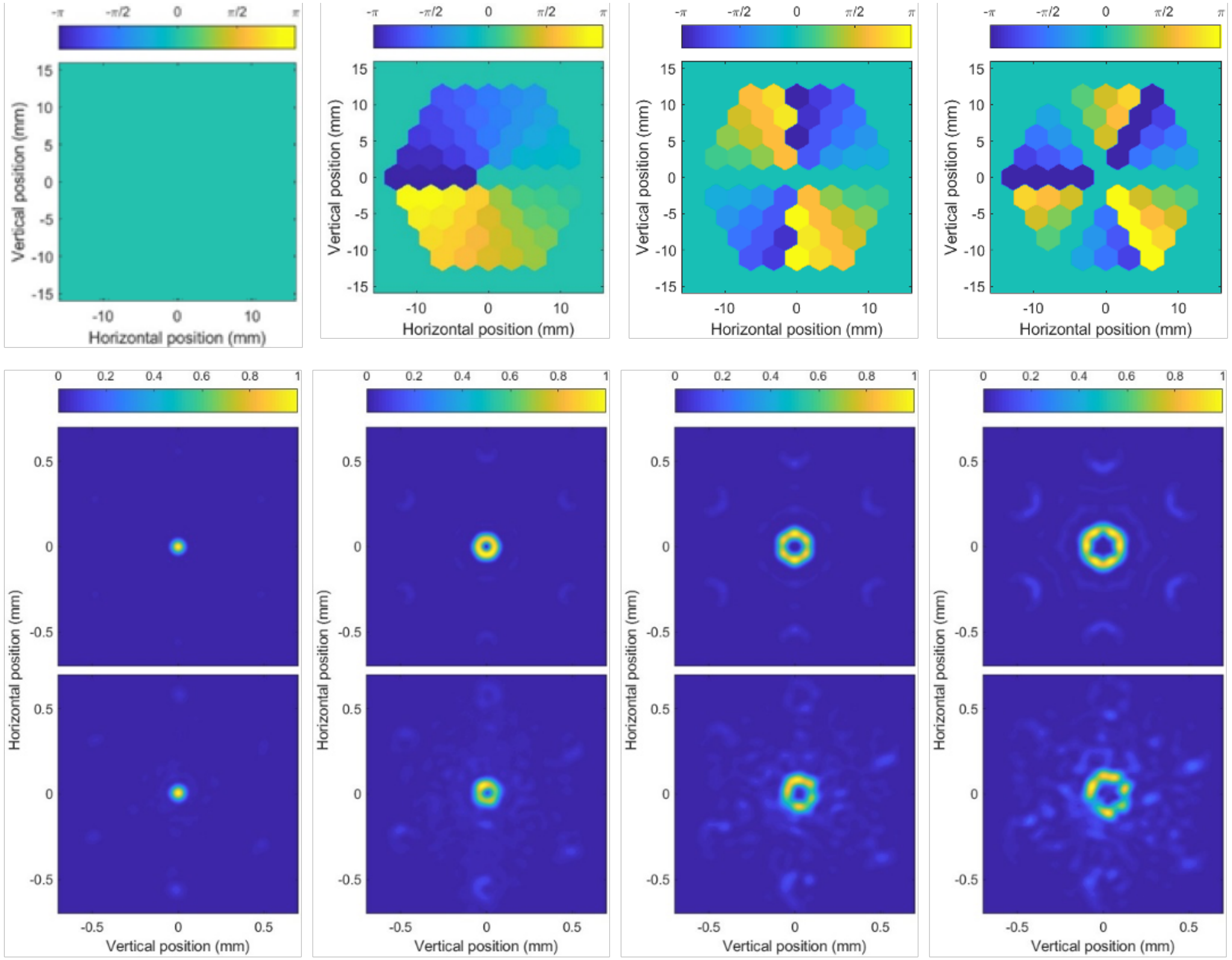
NanoXCAN

TÉCNICO LISBOA

ARCoptix Switzerland



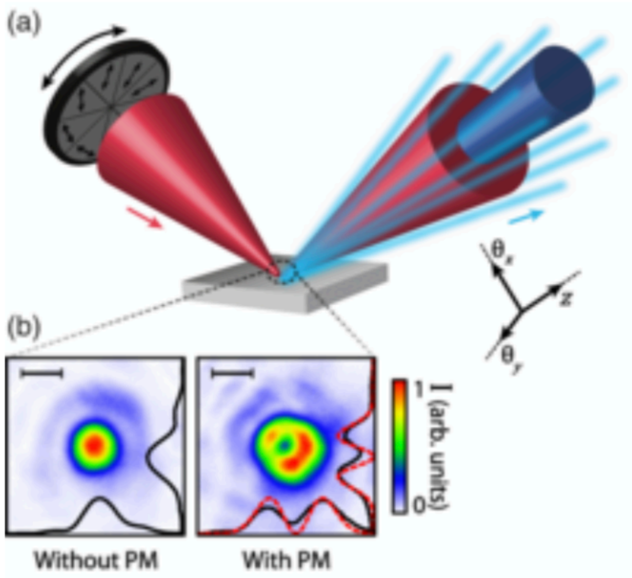
61 control pixels



C. Lechevalier, C. -A. Ranély-Vergé-Dépré, I. Fsaifes, R. Becheker, G. Boer and J. -C. Chanteloup, "Controlled Generation of Orbital Angular Momentum Beams With Coherent Beam Combining Digital Laser and Liquid-Crystal q-Plate," *IEEE Photonics Journal*, vol. 16, no. 4, pp. 1-5, Aug. 2024,

We are just getting started

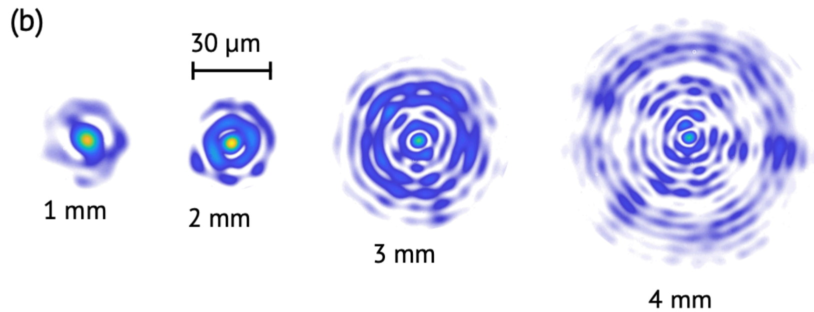
J. Faure & R. Lopez-Martens, LOA



Interaction of Ultraintense Radially-Polarized Laser Pulses with Plasma Mirrors

N. Zaim et al, Phys. Rev. X 10 (2020)

V. Malka, Weizmann Institute of Science



First Direct Observation of a Wakefield Generated with Structured Light
Aaron Liberman, Arxiv 2025