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“Investing in Sustainable Development”

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

Ion acceleration with Gaussian and Vortex laser beam

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Laser-Plasma Accelerators Workshop 2025 (LPAW 2025, Ischia Island (Naples, Italy), 14 -18 April 2025

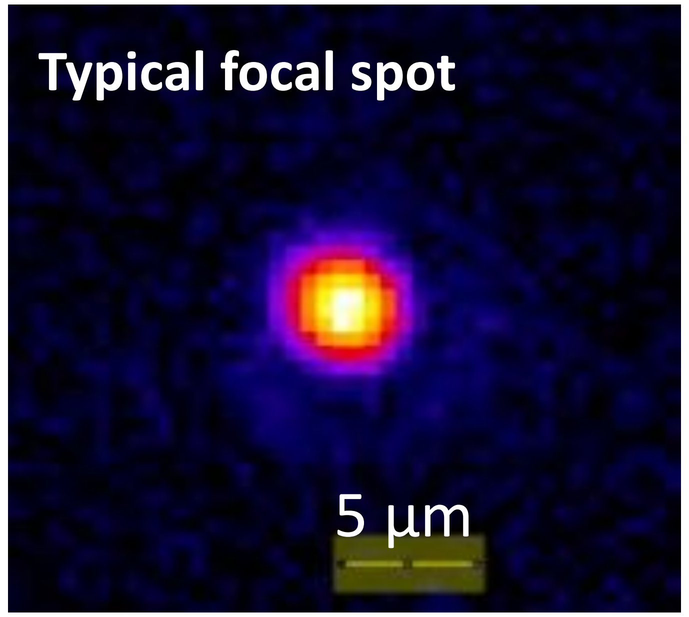
Outline

- **Introduction – typical results on ion acceleration with 1 PW Gaussian beam**
- Why using ultra-intense laser beams with Orbital Angular Momentum (OAM)?
- OAM laser pulses generation in the PW regime - how to diagnose and generate
- Ion acceleration with high-order OAM beams from a PW class laser

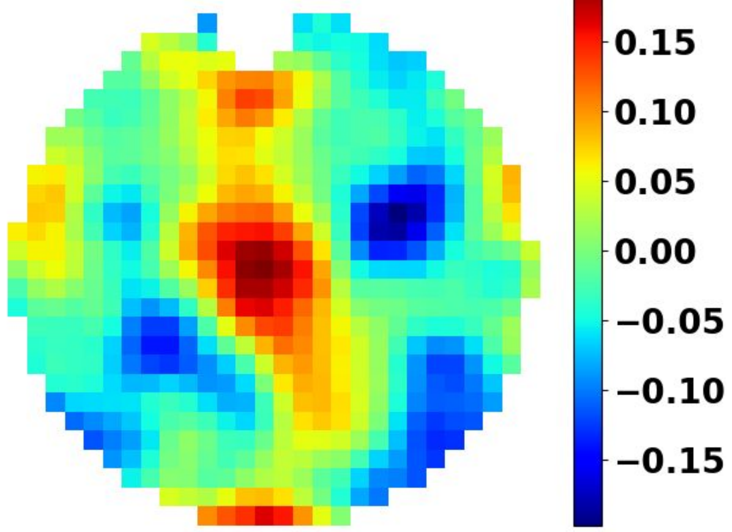
ELI-NP 1 PW short focal

Laser characteristics with the short focal mirror

Parabolic mirror: 707 mm focal length (F# ~3.7)
Spot size diameter: ~ 3.8 ± 0.2 µm at FWHM
Encircled energy: ~ 70% @ $1/e^2$ when represented over 12bit CCD dynamic range
~ 50% @ $1/e^2$ (ideal Gaussian beam is 86%) over ~ 4 orders
Laser energy stability at full power: ± 2%
Laser pointing stability on target: < 1 µrad

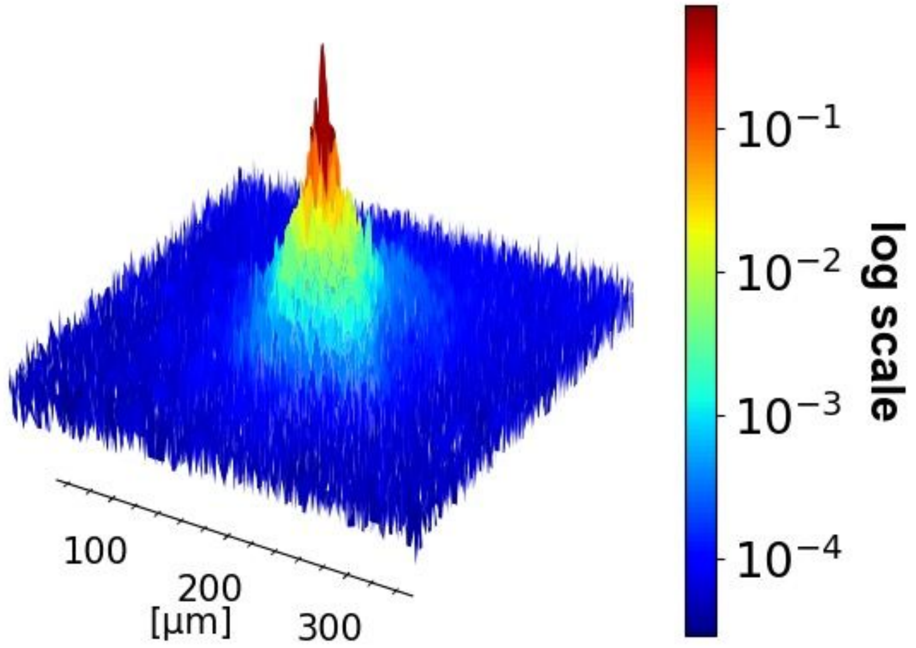


Beam wavefront sensor
HASO Imagine Optics

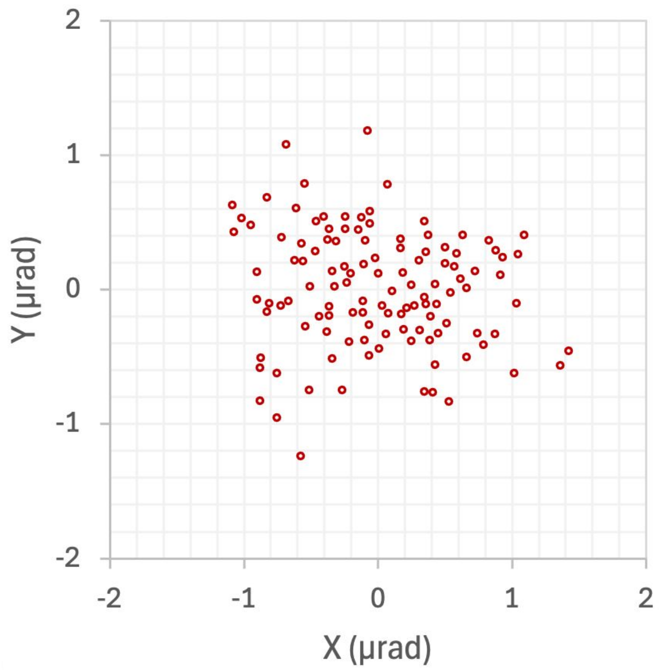


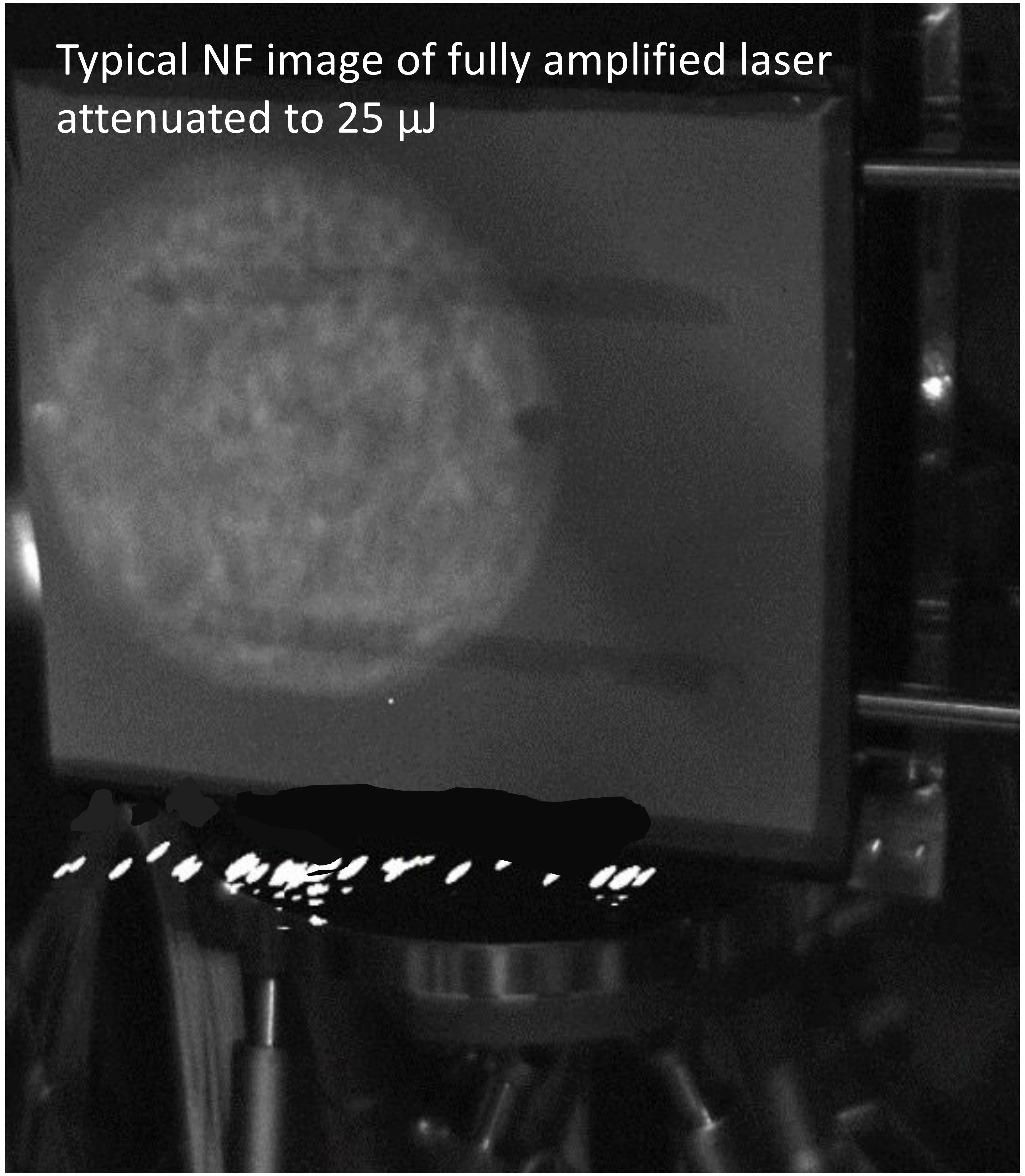
r.m.s. 60-70 nm

Focal spot measured over ~4 orders of magnitude



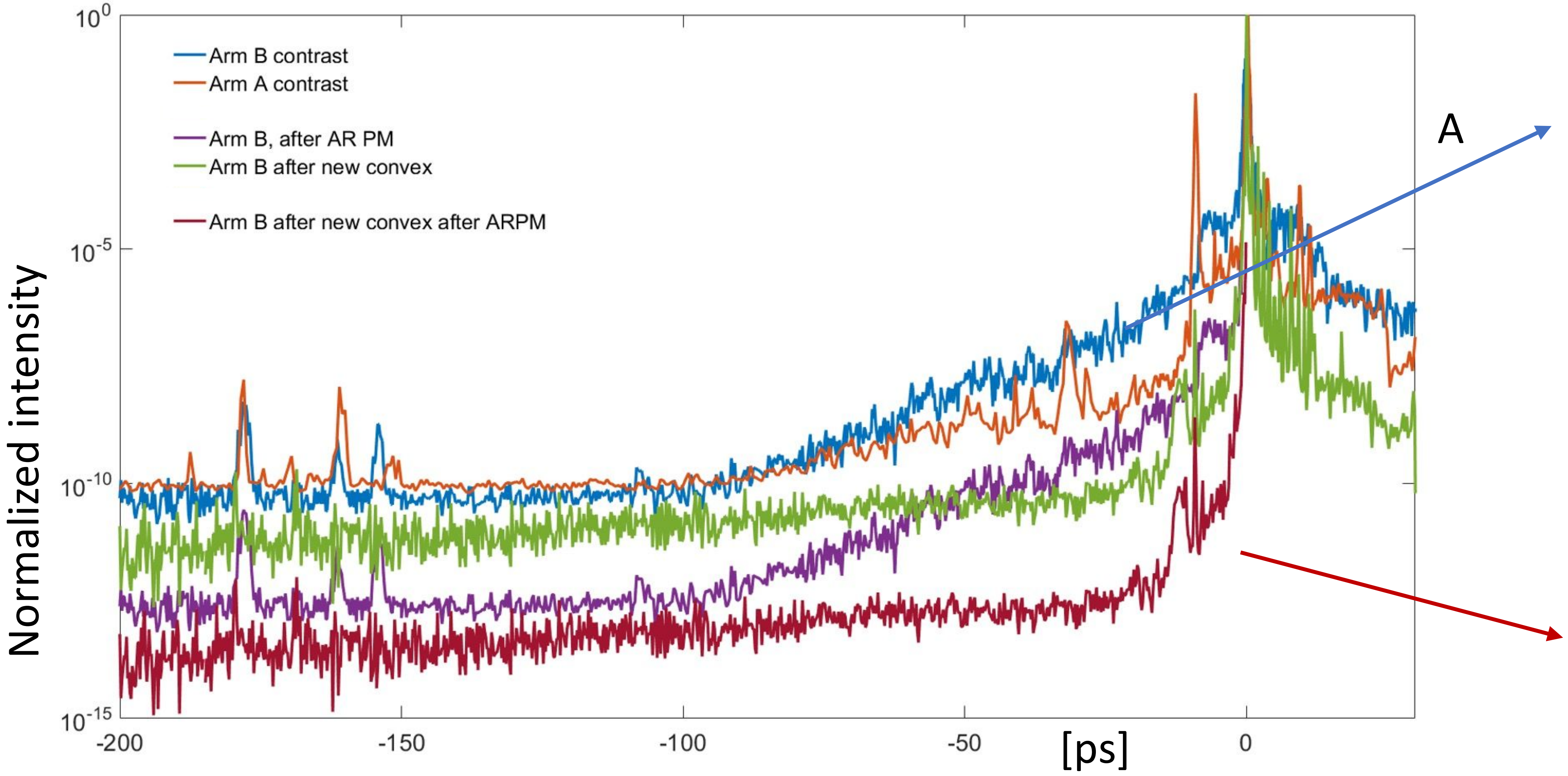
Pointing stability < 1 µm

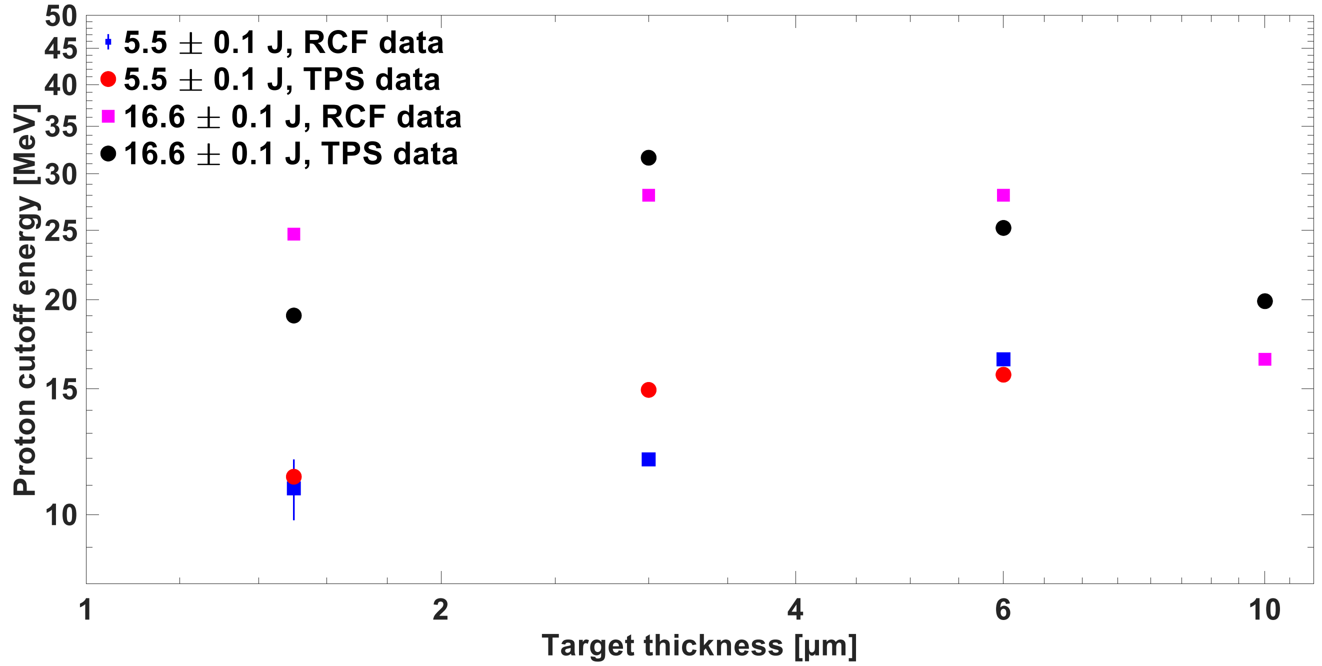


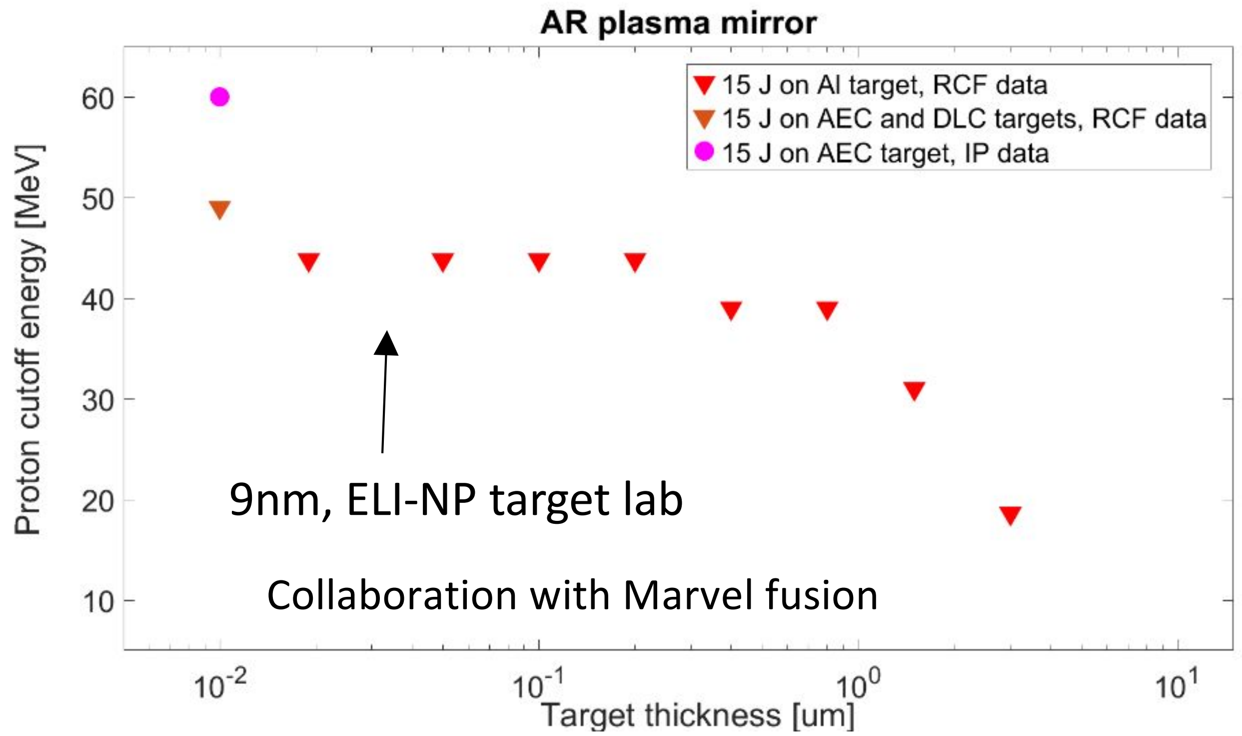


Effects of different laser temporal contrasts

Evolution of the 1 PW laser temporal contrast at ELI-NP





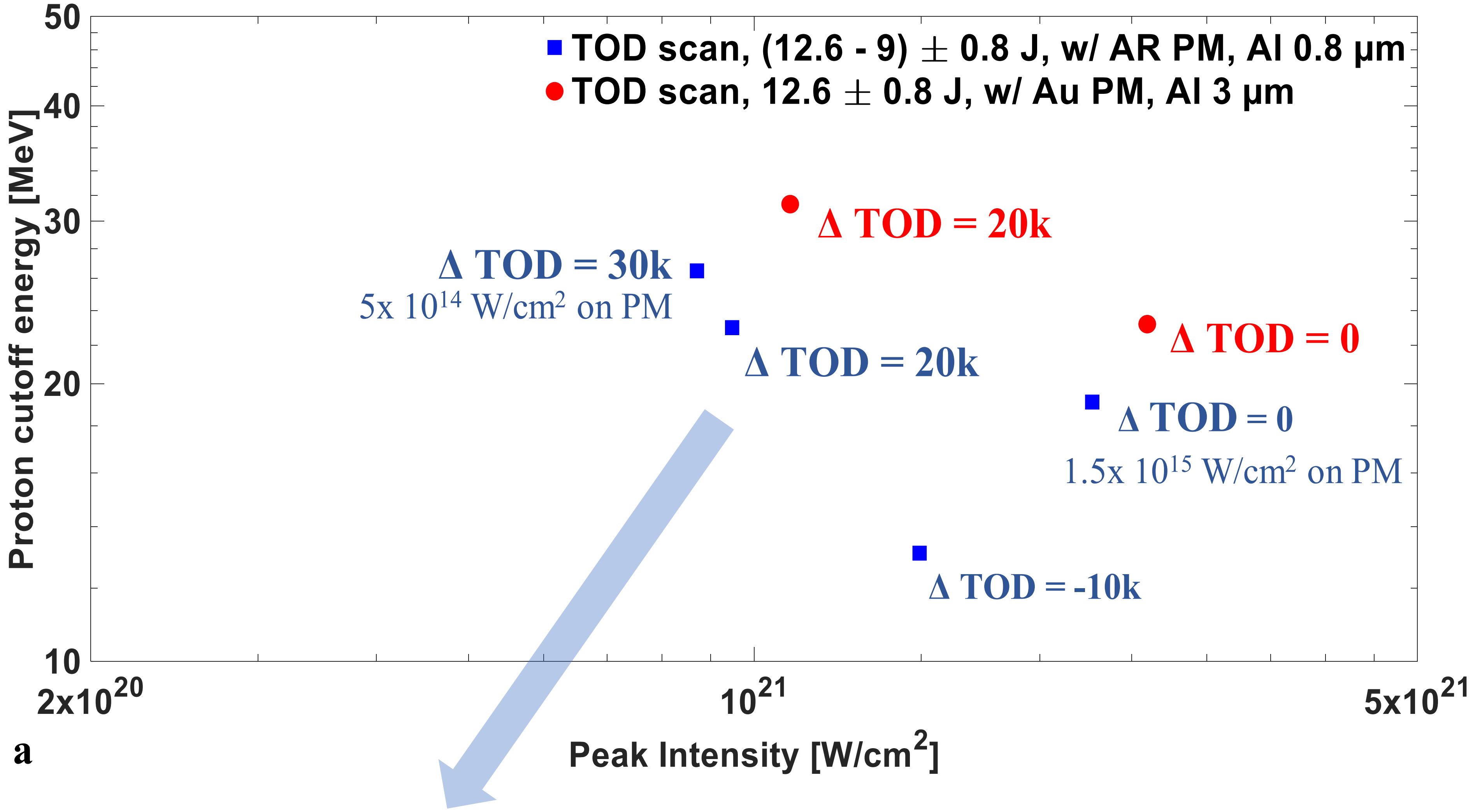


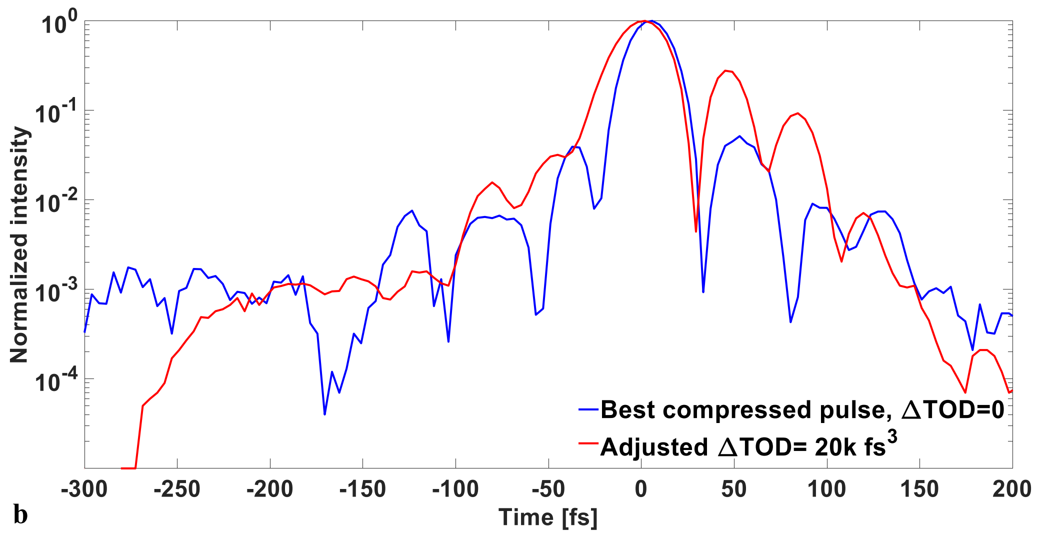
Improved temporal contrast allowed to accelerate protons up to more than ~45 MeV from ultra-thin films

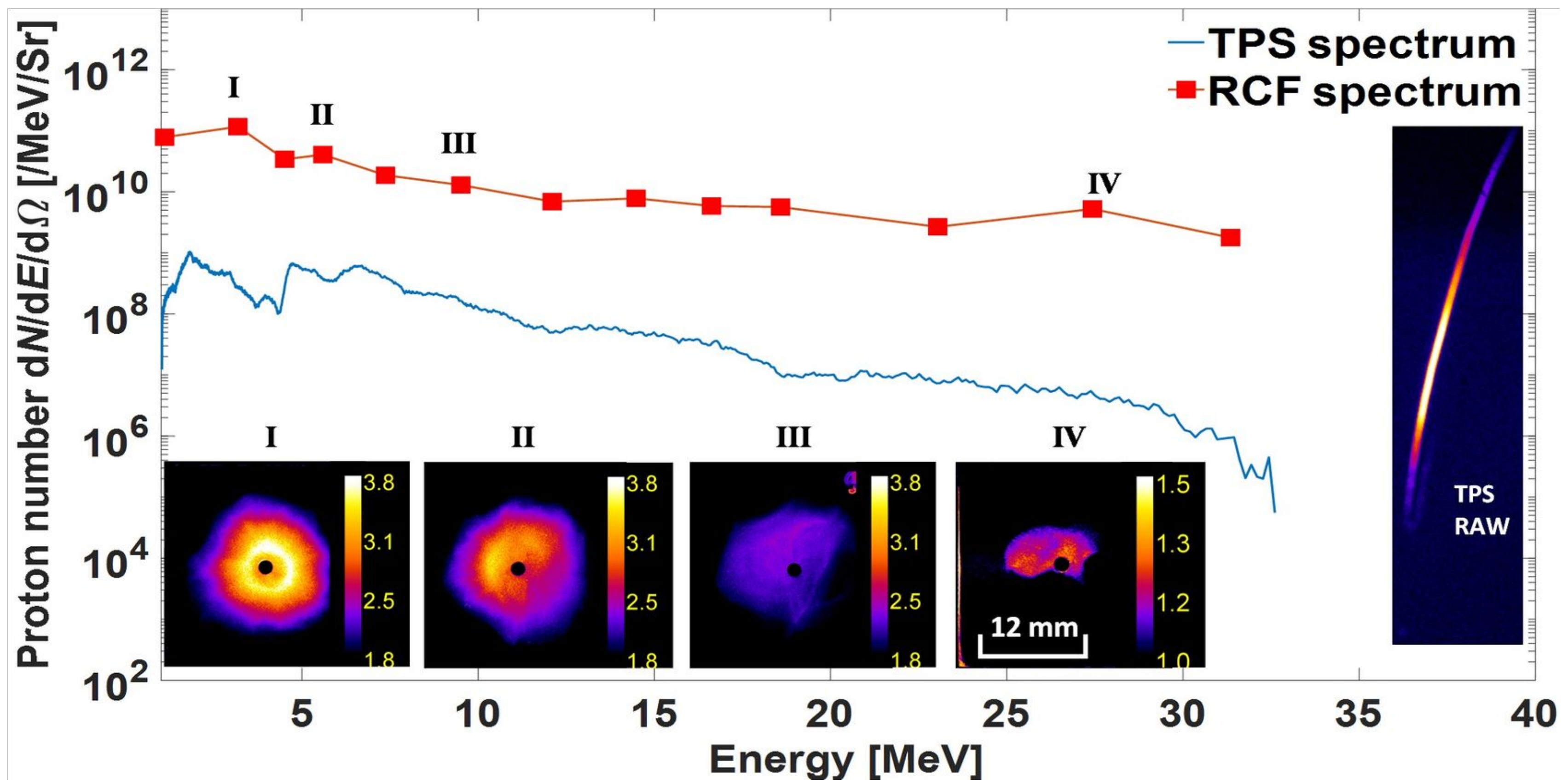
Other parameters to tune for efficient laser – plasma coupling

Further improvement through Third Order Dispersion optimization

TOD optimization yields a lower peak intensity on target and a gain for the proton cutoff energy





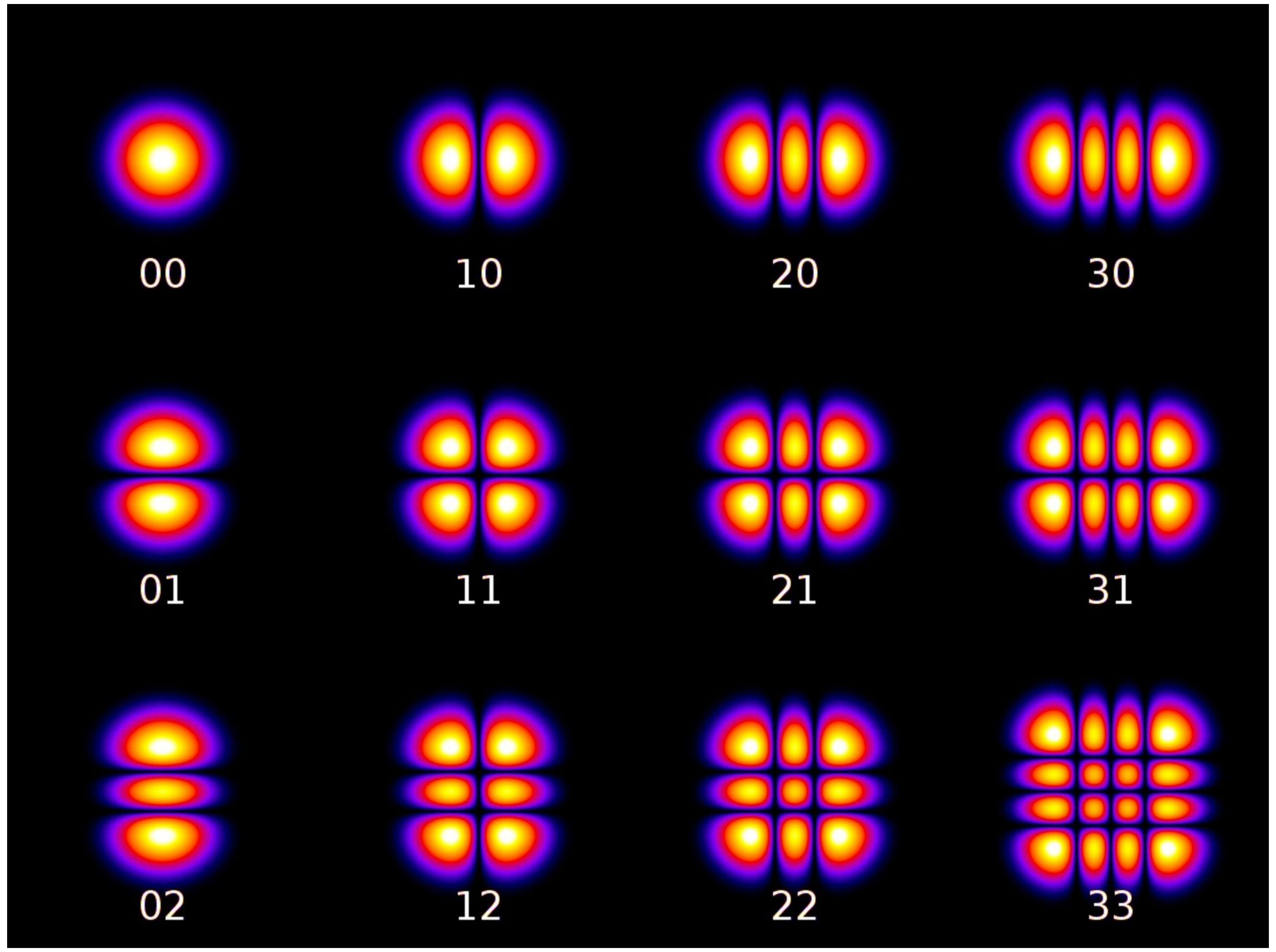


Large divergence of up to **0.3 Sr**

M.O. Cernaianu et. al, MRE 10, 027204 (2025)

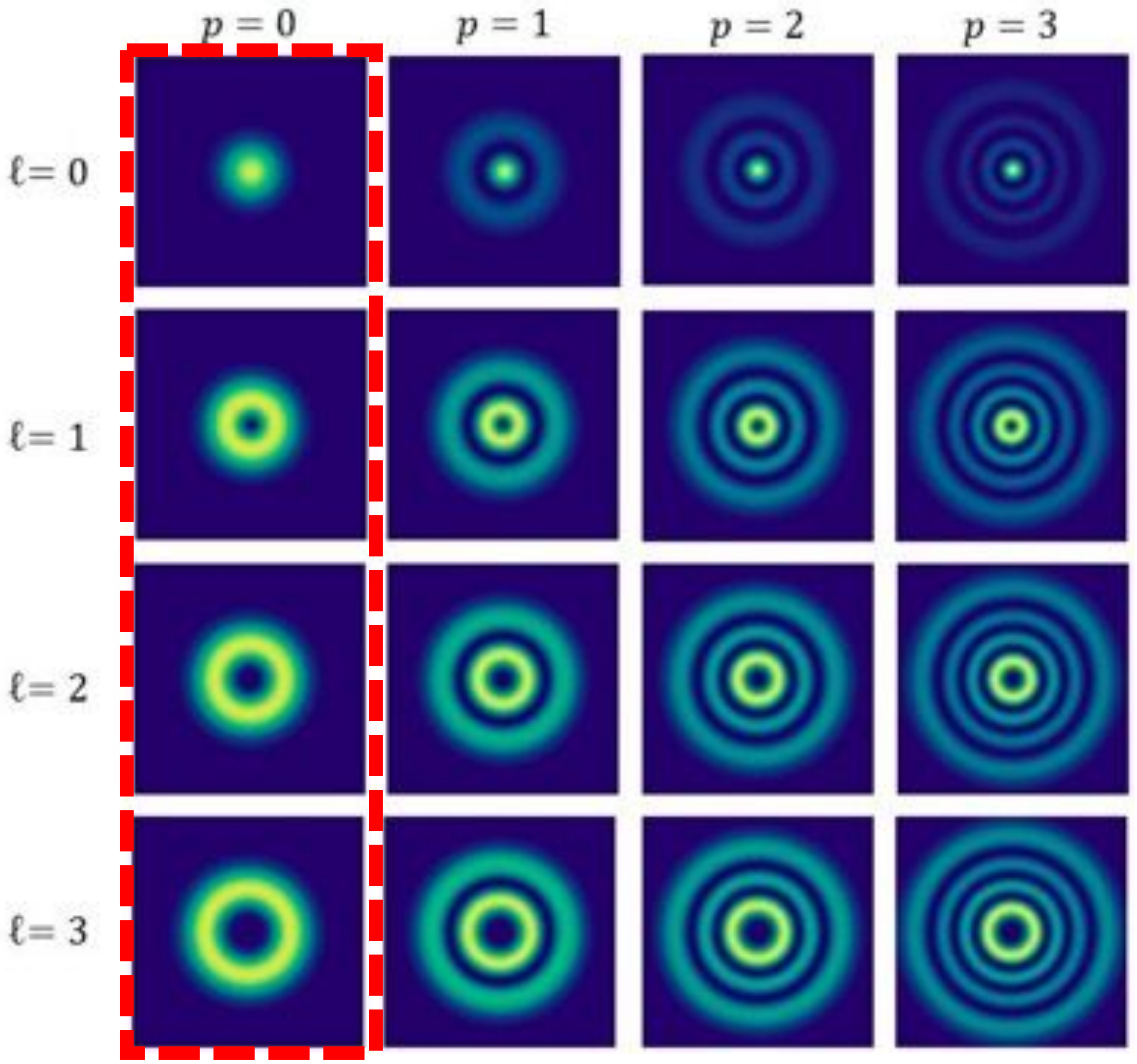
Gaussian and Vortex laser beam

The Hermite-Gaussian modes are the typical solutions of the paraxial beam approximation in the *x-y* coordinates, i.e. TEM_{lm} with *l,m* as orthogonal modes



The fundamental Gaussian beam is the TEM_{00}

A beam with a circularly symmetric profile can be solved in cylindrical coordinates using the Laguerre-Gaussian modal decomposition. Each transverse mode can be described by two integers, the radial index $p \geq 0$ and the azimuthal index l as the Relative numbers $\mathbb{Z}$



Laguerre-Gaussian beam

$$E\,(r, z, \phi) = C^{LG}_{lp}\left(\frac{r\sqrt{2}}{w(z)}\right)^{|l|} L_p^{|l|}\left(\frac{2r^2}{w(z)^2}\right)\frac{w_0}{w(z)}\, e^{-\frac{r^2}{w(z)^2}}\, e^{-ik\frac{r^2}{2R(z)}}\, e^{-i\psi(z)}\, e^{-il\phi}$$

$L_p^{|l|}$ are the generalized Laguerre polynomials with azimuthal index l and radial index p

$$C^{LG}_{lp} = \sqrt{\frac{2p!}{\pi(p+|l|)!}} \Rightarrow \int_0^{2\pi} d\phi \int_0^{\infty} r dr |u(r,\phi,z)|^2 = 1$$

Definitions

$R(z) = z\left[1 + \left(\frac{z_R}{z}\right)^2\right]$

is the radius of curvature

z_R is the Rayleigh range

w_0 is the minimum waist

$\psi(z) = (N+1)\arctan\left(\frac{z}{z_R}\right)$

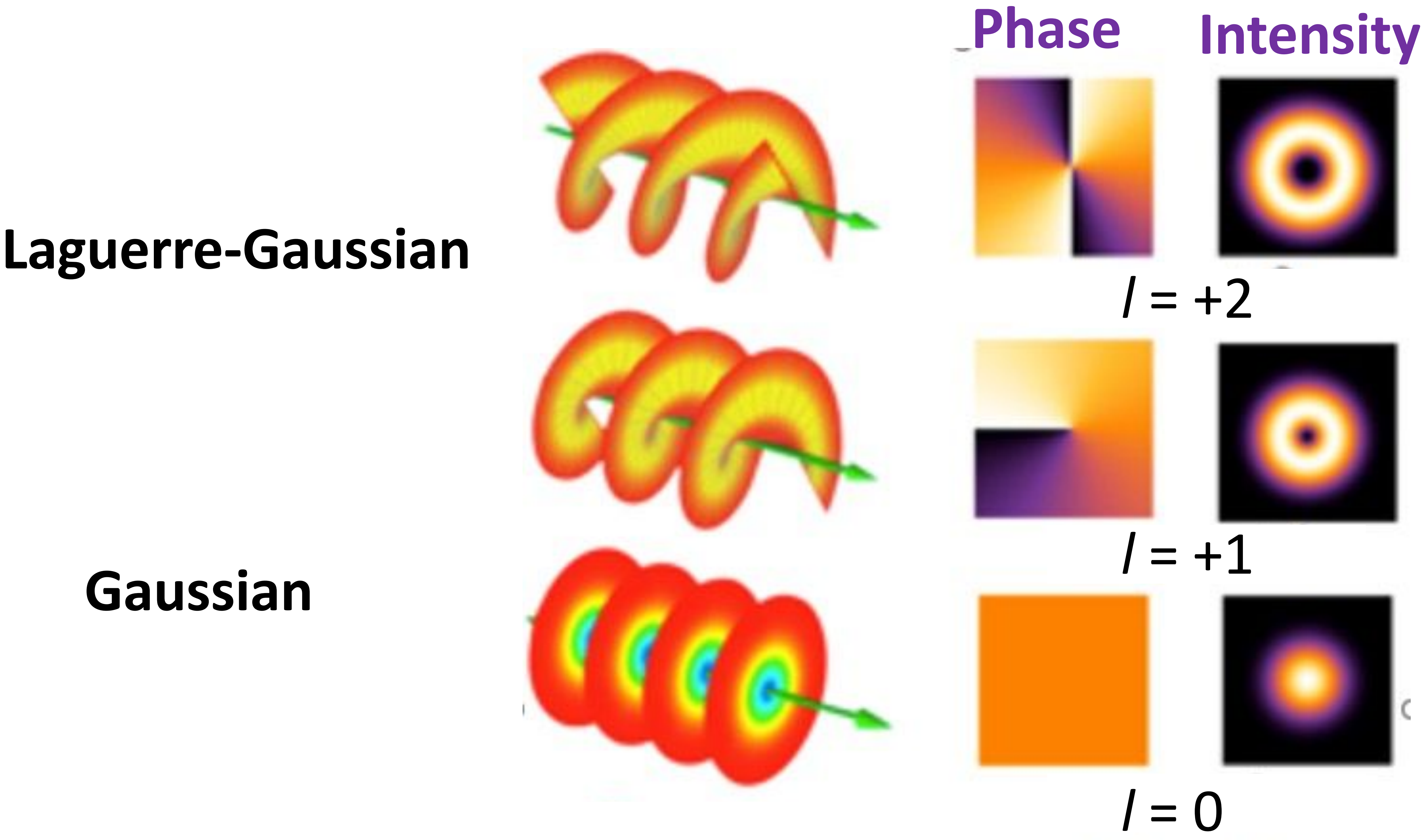
Is the Gouy phase with mode $N = |l| + 2p$

Gaussian beam

$$E\,(r, z) = \overset{\sqrt{\frac{2}{\pi}}}{C^{LG}_{00}}\ \overset{1\ =}{\cancel{\left(\frac{r\sqrt{2}}{w(z)}\right)^{|0|}}}\ \overset{1\ =}{\cancel{L_0^{|0|}\left(\frac{2r^2}{w(z)^2}\right)}}\ \frac{w_0}{w(z)}\, e^{-\frac{r^2}{w(z)^2}}\, e^{-ik\frac{r^2}{2R(z)}}\, e^{-i\psi(z)}\, e^{-i\cancel{l\phi}\,kz}$$

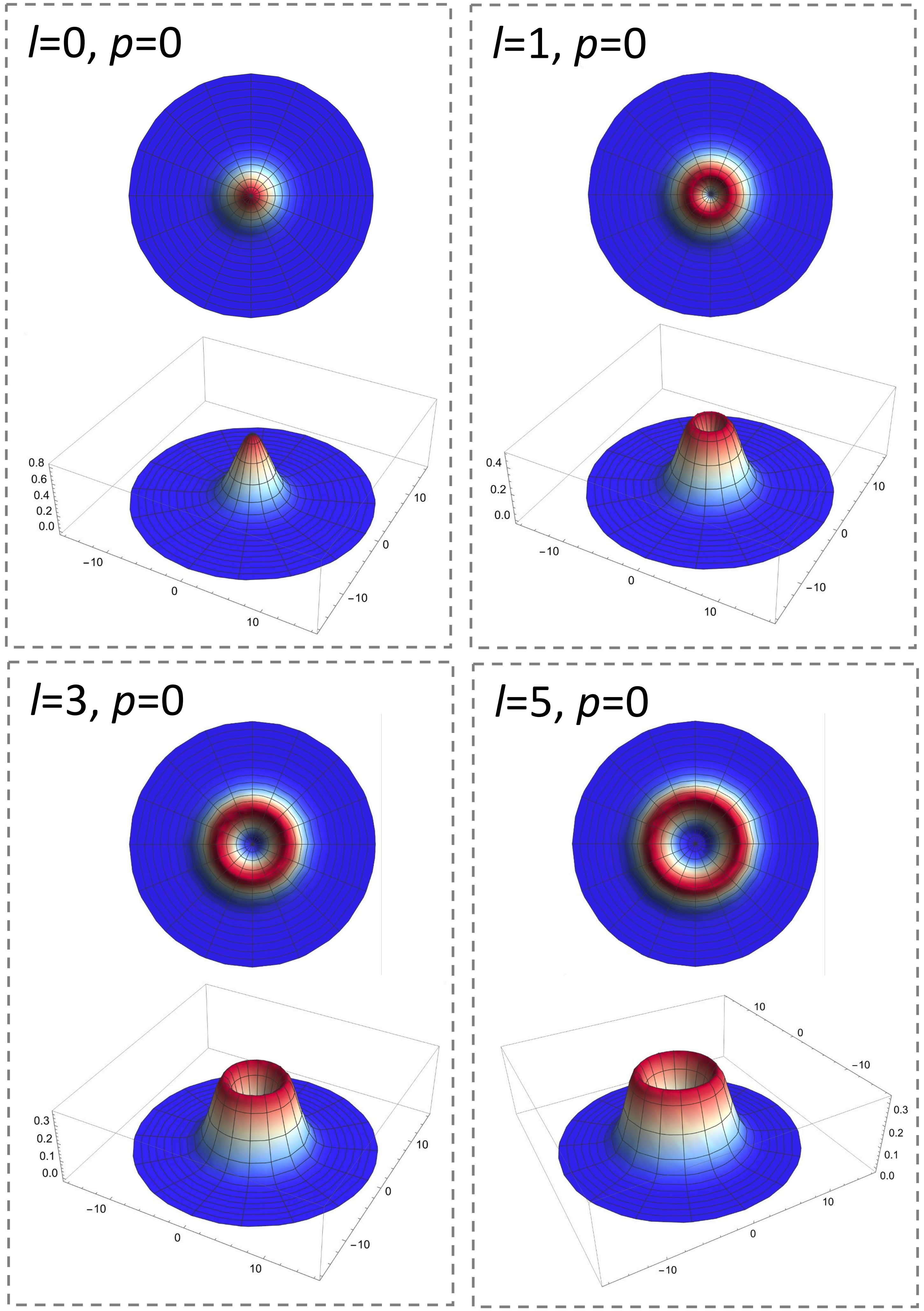
Gaussian and Vortex laser beam

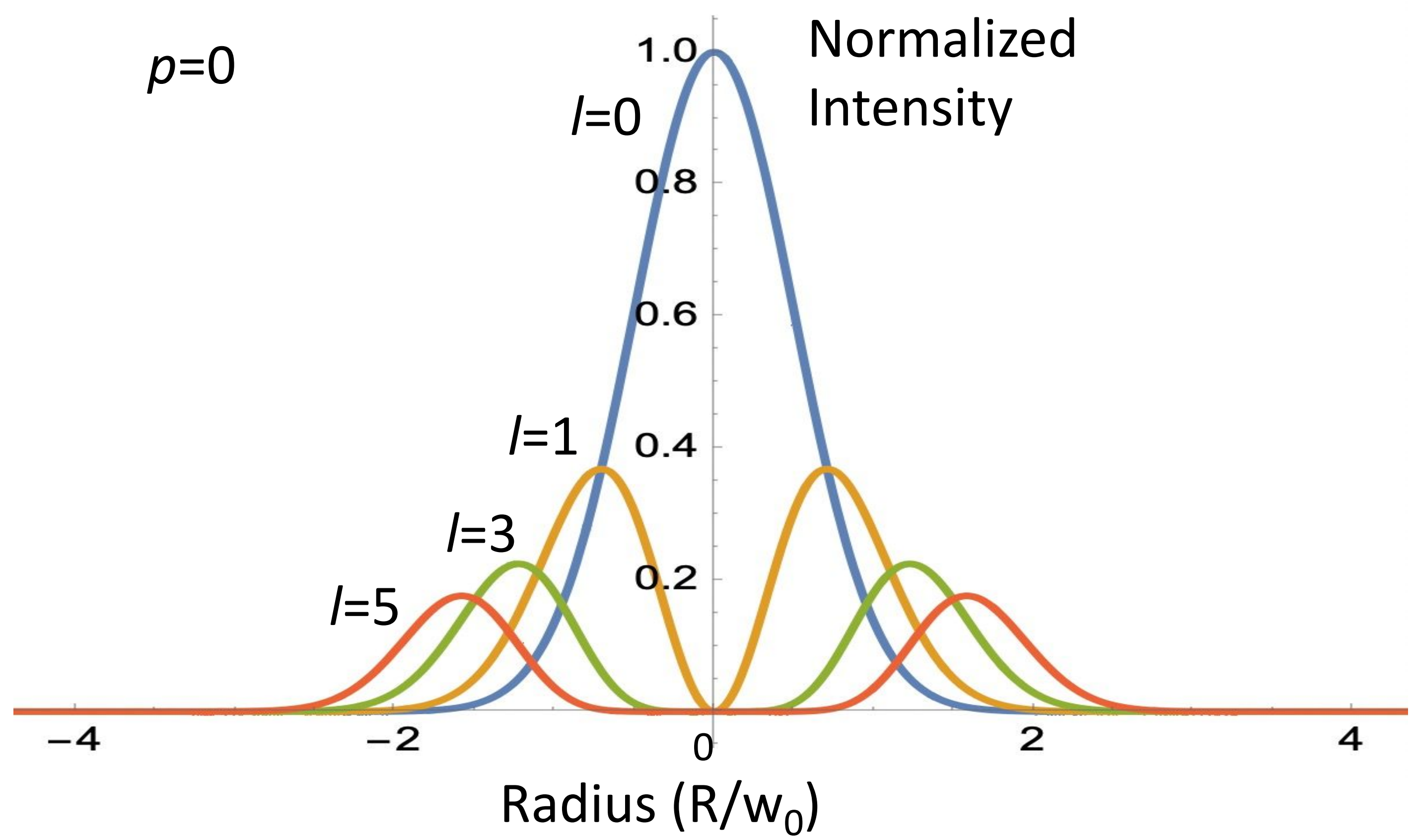
phase ~ exp(-**i**$l\phi$) l=1,2,…; ϕ azimuthal angle

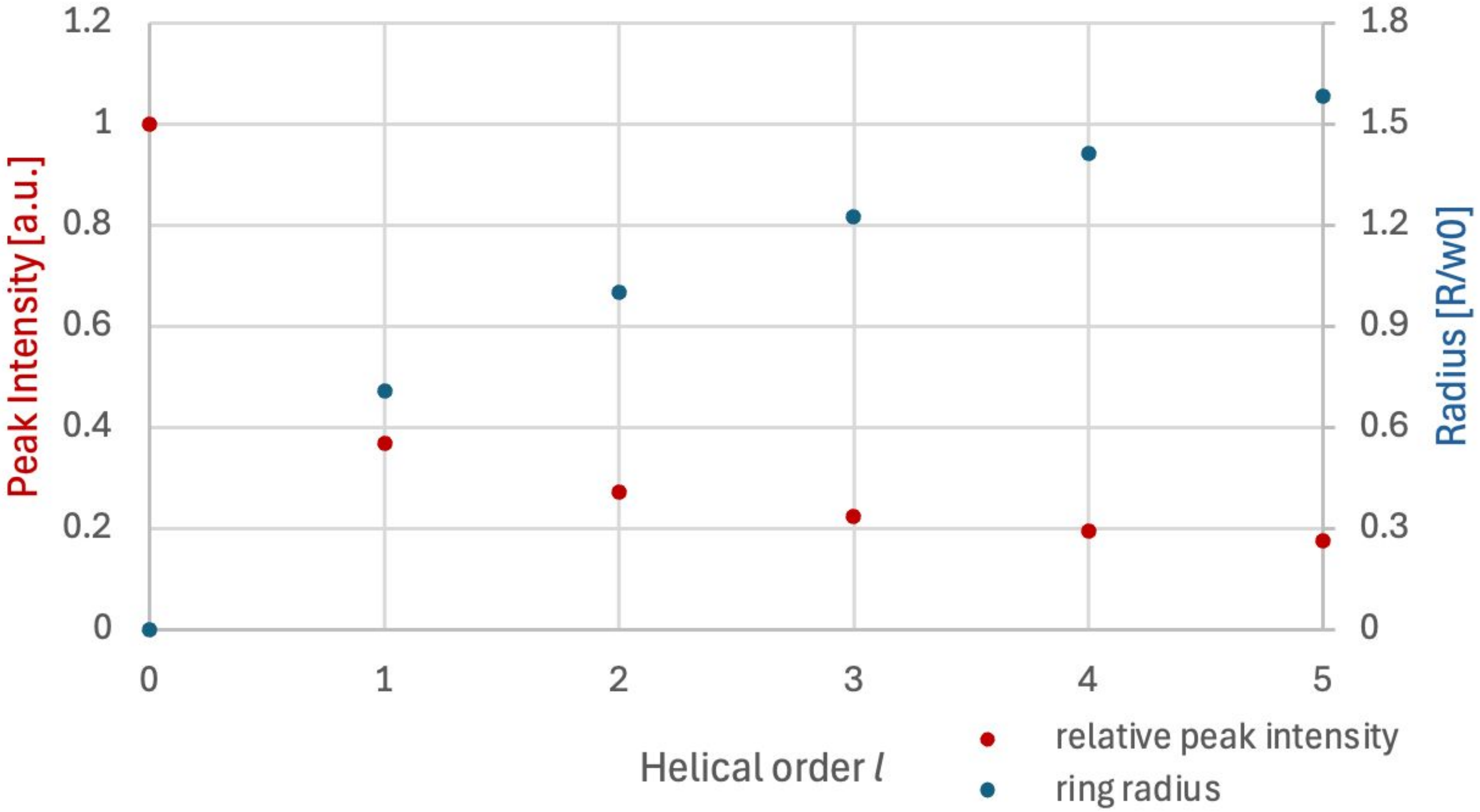


- Hollow intensity profile
- The Poynting vector (energy flux) has a spiral trajectory
- Orbital angular momentum (OAM) $l\hbar$ per photon (l can be >>1)
- “Helical” or “Vortex” photon = conical superposition of planar waves

Gaussian and Vortex laser beam







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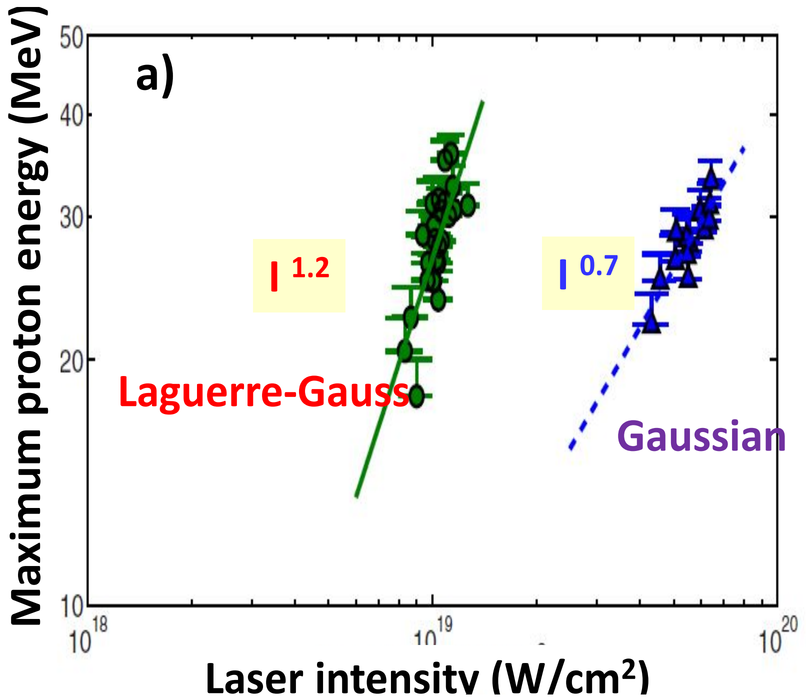
Why using Vortex beam

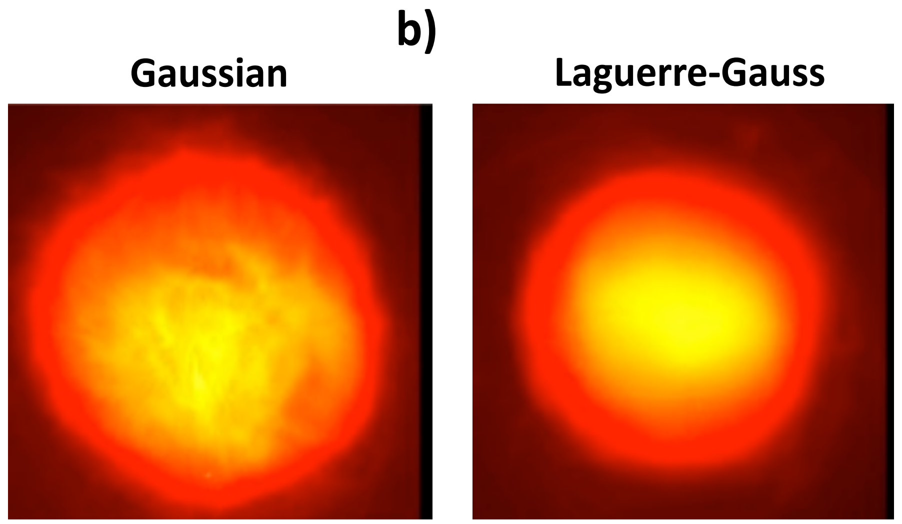
Helical beams can

1) Apply large torque to matter
2) Excite quantum transitions forbidden in the electric dipole approximation ($l \geq 2$)
3) Inwards ponderomotive force

Experimental results with Helical beams in literature

Example of Proton acceleration with Helical beams:

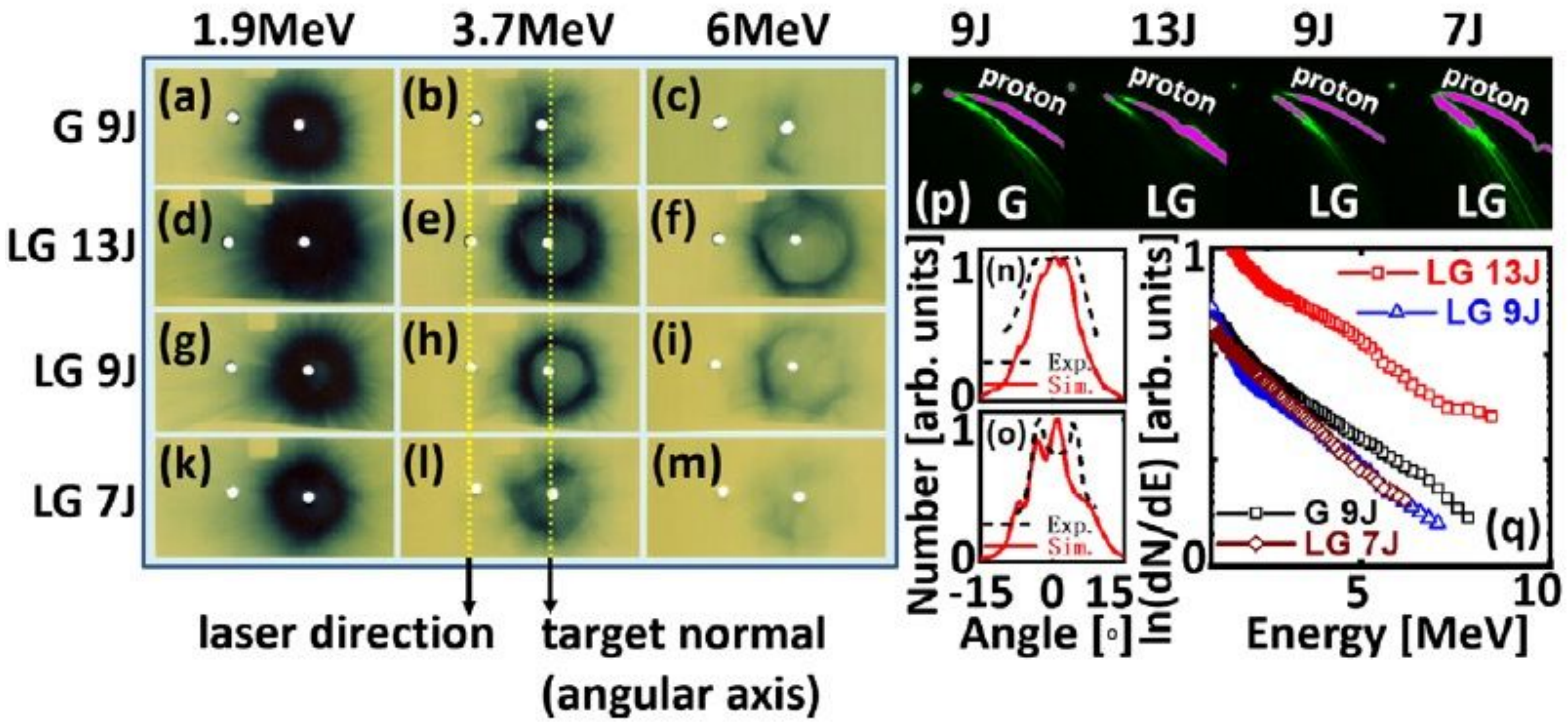




- The same proton energy is obtained with LG beam as with Gaussian beam, despite the lower intensity of the LG beam.
- The proton image with Gaussian beam has evident spatial non-uniformities, while the helical beam shows a more uniform proton beam, possibly indicating a more stable plasma and/or fast azimuthal rotation of the proton beam

C. Brabetz, *et al.,* Phys. Plasmas 22, 013105 (2015)

I =~6x10^{19} W/cm^2



- Hollow plasma profile

W. Wang, *et al.,* Phys. Rev. Lett. 125, 034801 (2020)

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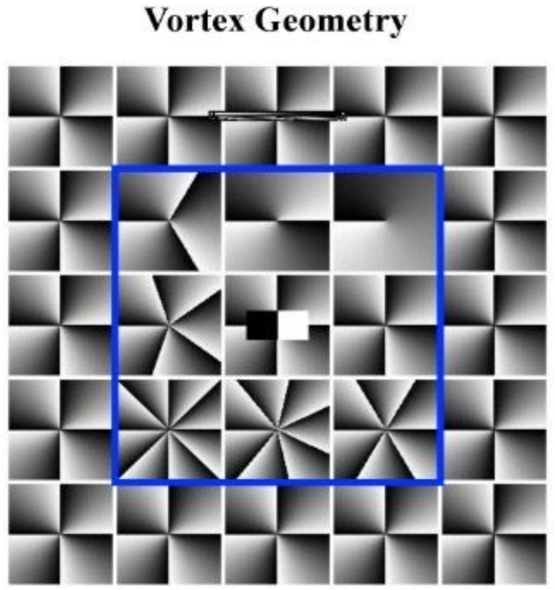
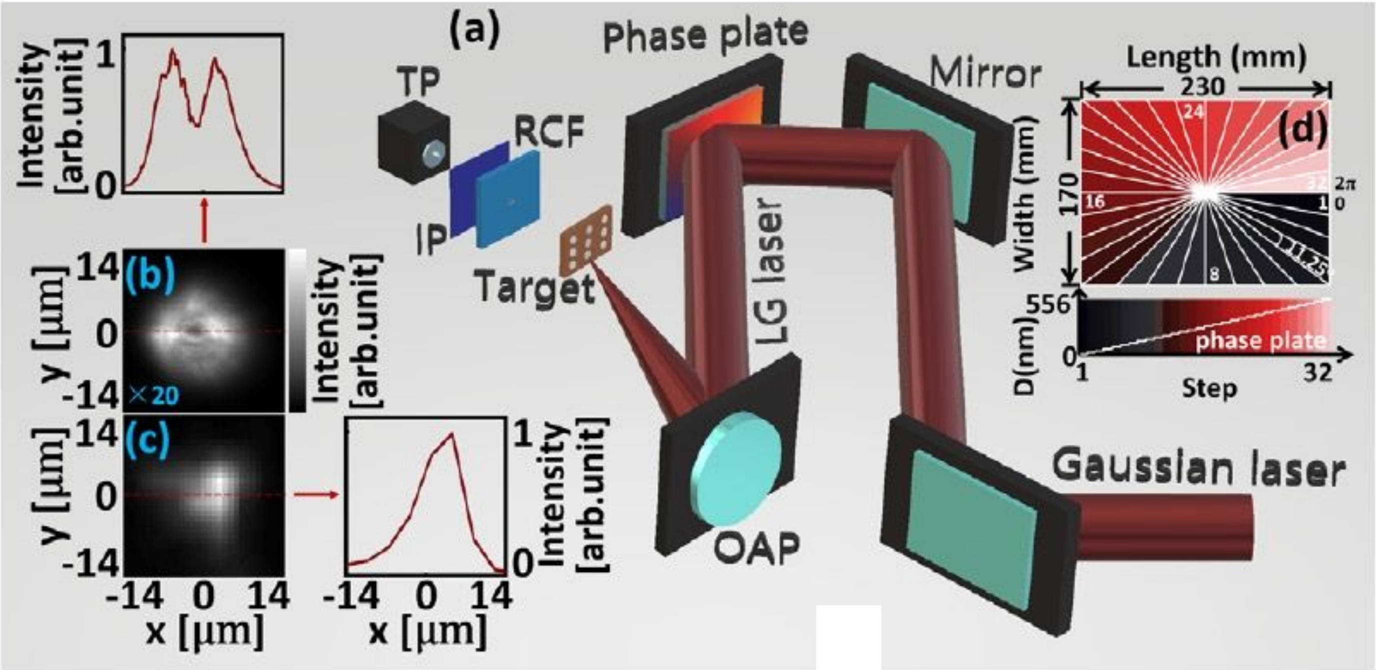
Typical ways of generating helical beams



HoloOr typical phase plate, typically suitable for CW beams

- Spiral phase plates - transmission

C. Brabetz, *et al.,* Phys. Plasmas 22, 013105 (2015)

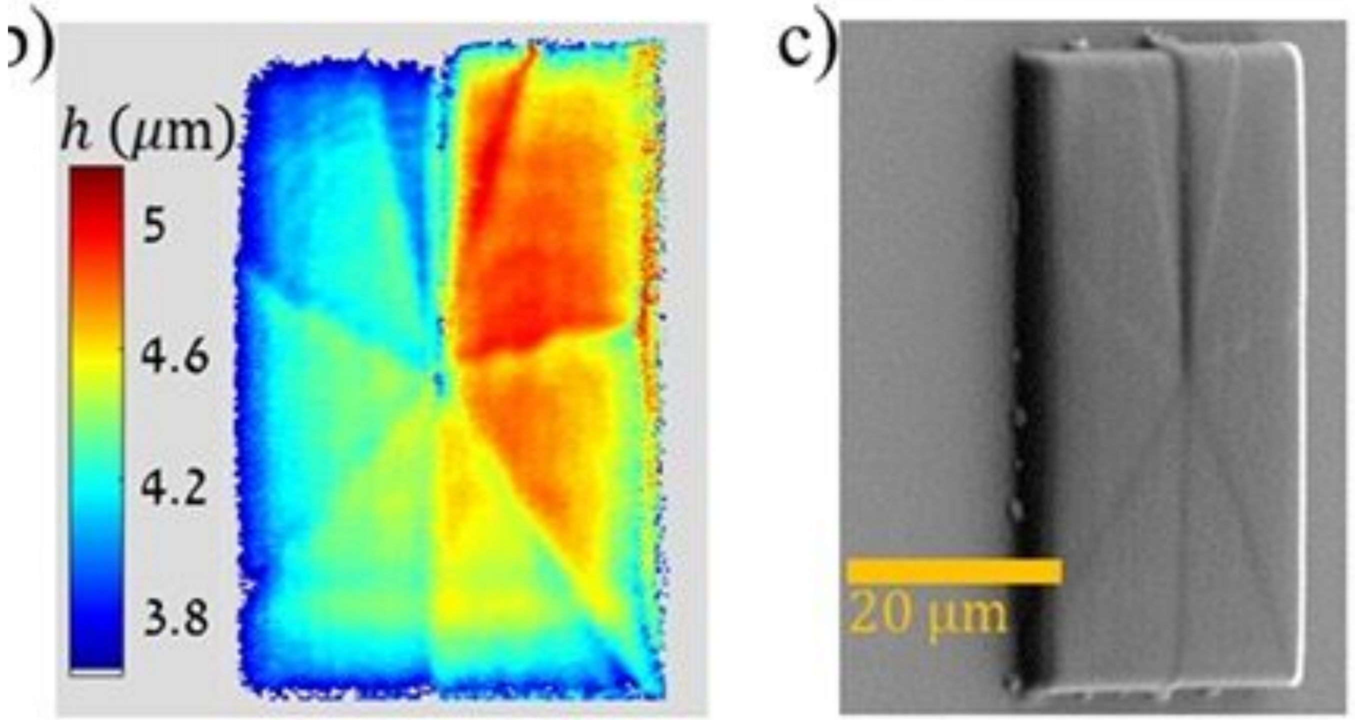


- Spiral mirrors - reflection

W. Wang, *et al.,* Phys. Rev. Lett. 125, 034801 (2020)

- Spiral phase plasma mirror – reflection plasma regime

E. Porat, *et al.,* J. Opt. 24, 085501 (2022)



Several challenges to overcome when using PW class lasers

- Transmission phase plates are typically inserted into the laser chain
  - Long propagation distances lead to high diffraction that can exceed the LIDT of the coatings (typically for fs pulses)

- Reflective mirrors may require very large dimensions:
  up to meter size for 10 PW, so technically challenging and expensive

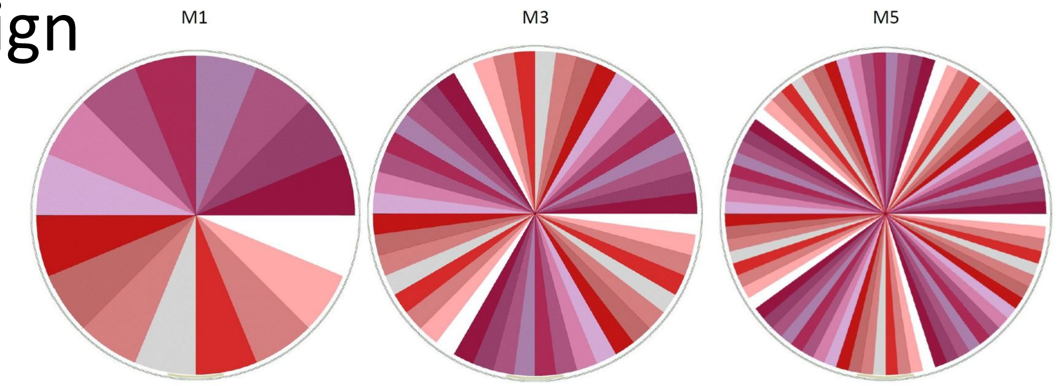
- Reflective plasma mirrors sensitive to laser temporal contrast and peak intensity:
  - Distorted spatial mode possible due to plasma evolution

- And how do we measure the helical laser pulse parameters?

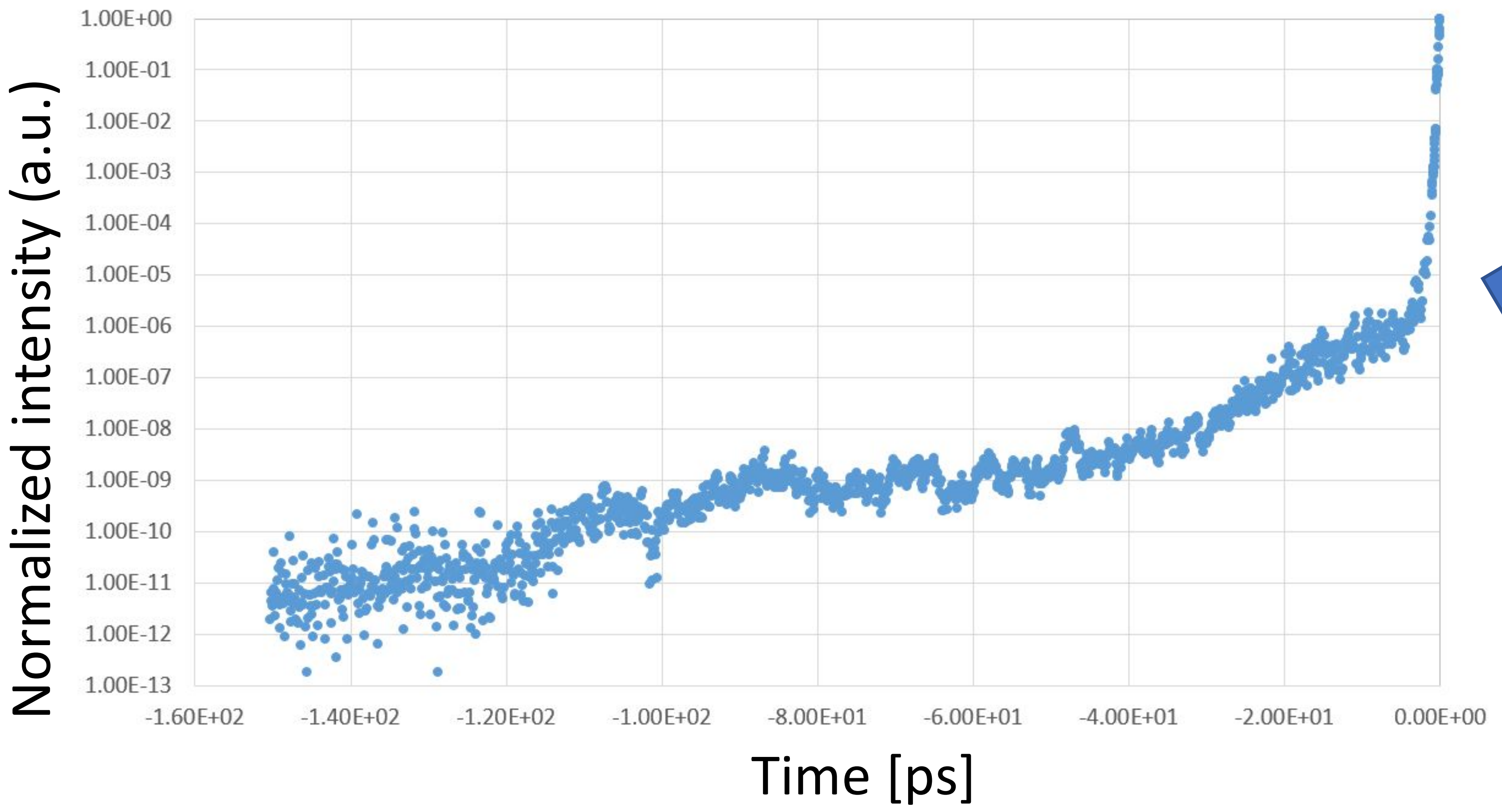
Our design is based on a single plasma mirror in between the focusing mirror and the target:

- Laser temporal contrast and peak fluence at the plasma mirror level to avoid WF distortions
    - Coating for laser energy/contrast tuning
    - Topological order
- Scalable to multi-PW regime

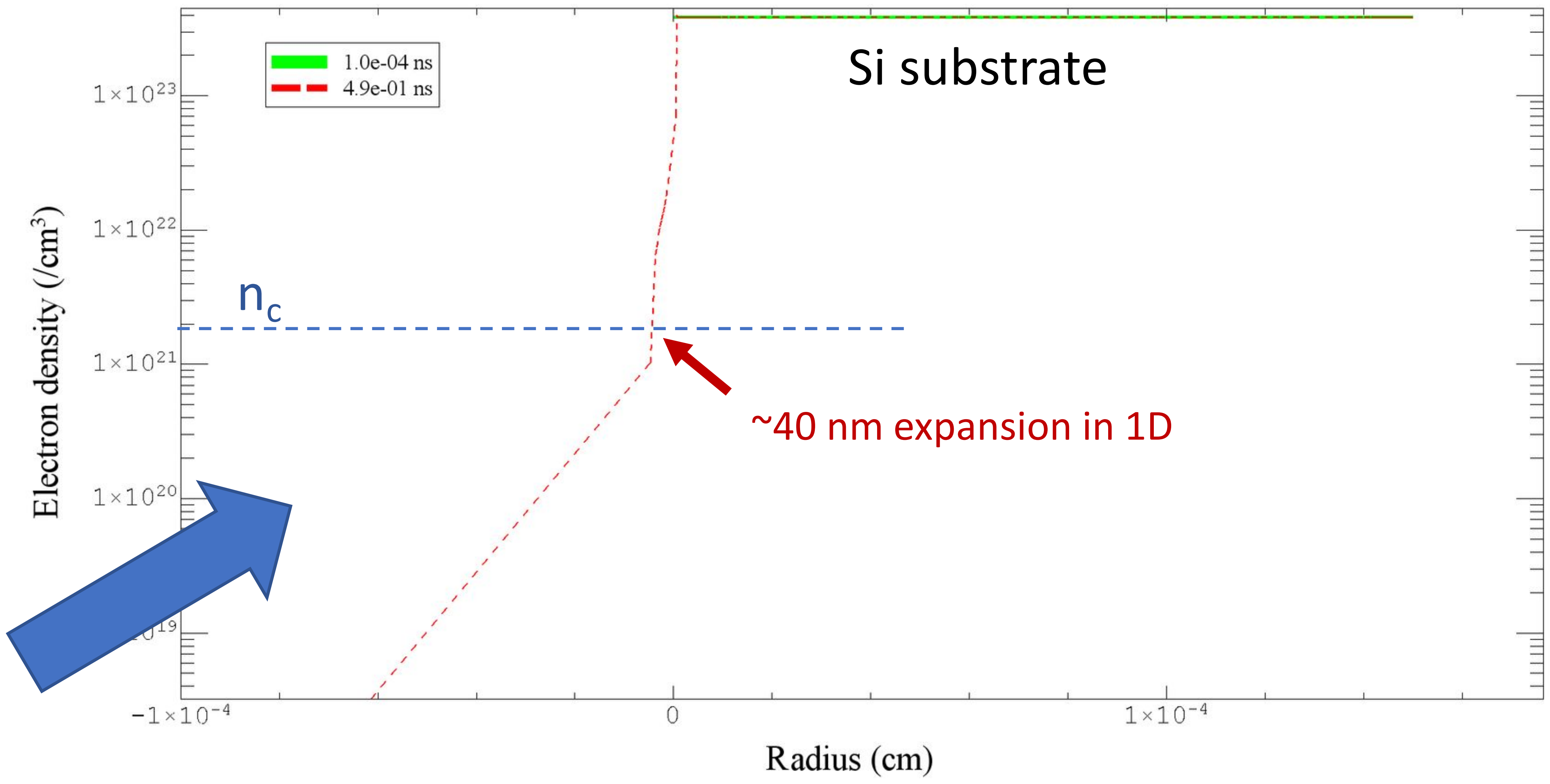
Step mirrors design



1 PW temporal contrast measurement



- Hydrodynamic simulations were done to optimize the optimum fluence w.r.t. measured laser temporal contrast

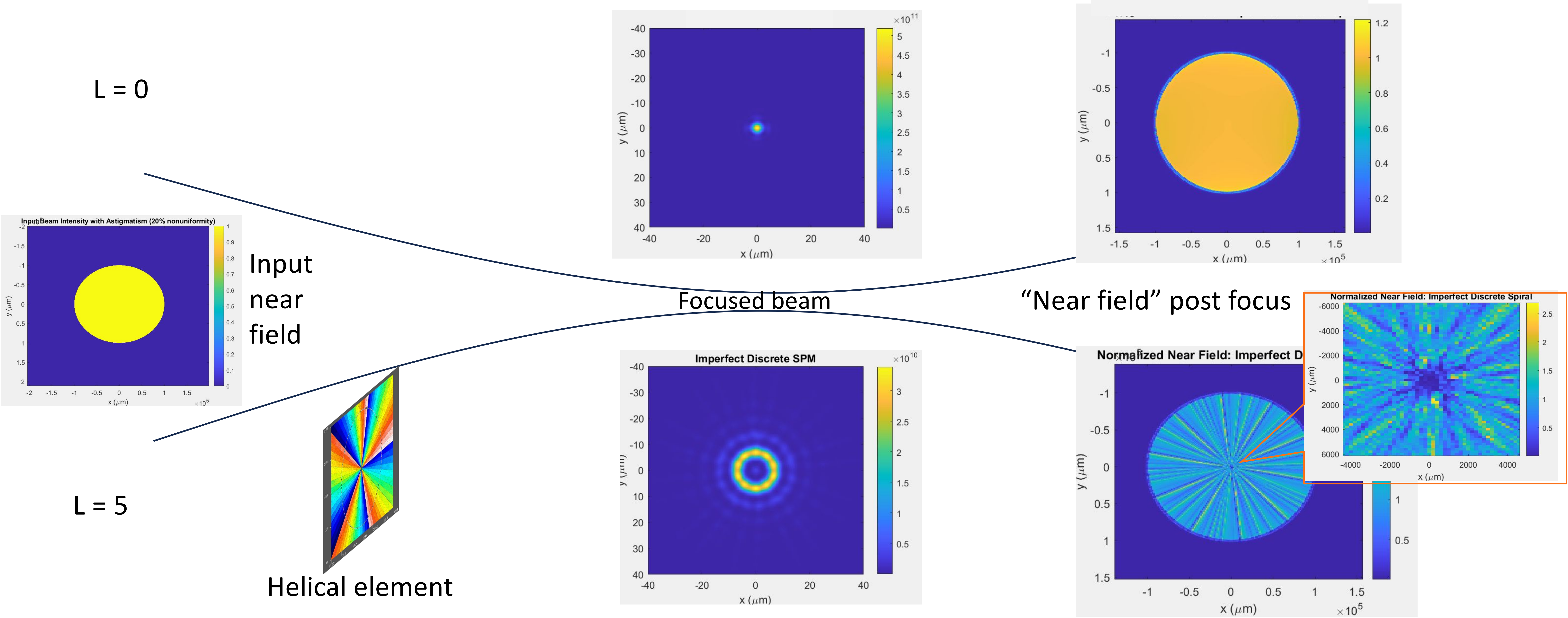


For a mirror with *l*=1, we have 16 steps, that is 25nm step height

Simulations demonstrate that optimizing the fluence is necessary to limit the plasma expansion and keeping it at the order of the step height

Propagation simulation of high order helical beams: How would it look in and after focus?

- Simulation code developed to investigate
  - Gaussian or helical beams generation and propagation in focus and after
  - Realistic spectrum, aberrations, manufacturing defects and diffraction patterns



Generation of helical beams and diagnosis with fs pulses

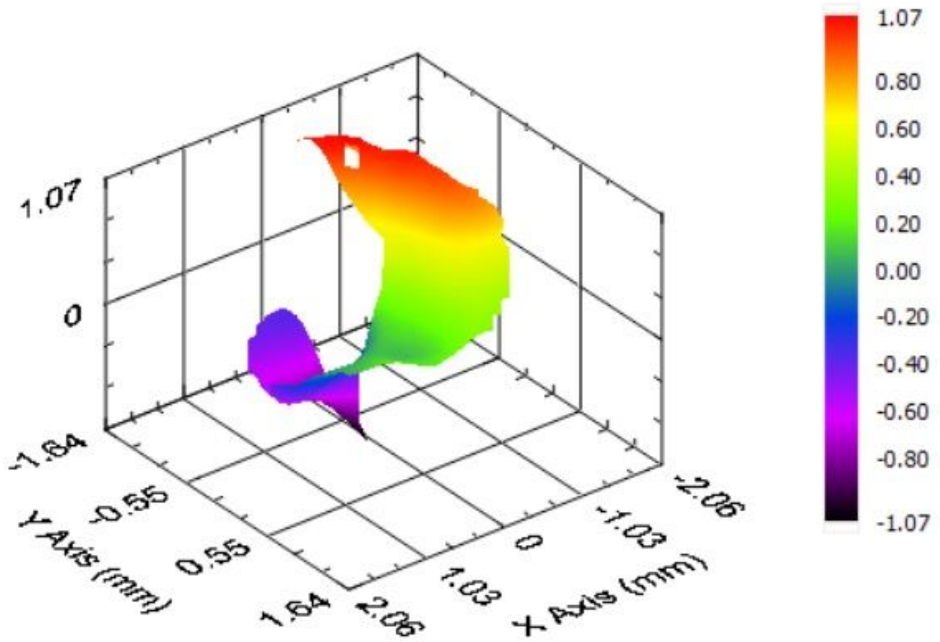
❑ Experimental setup and actual helical plasma mirrors implementation:

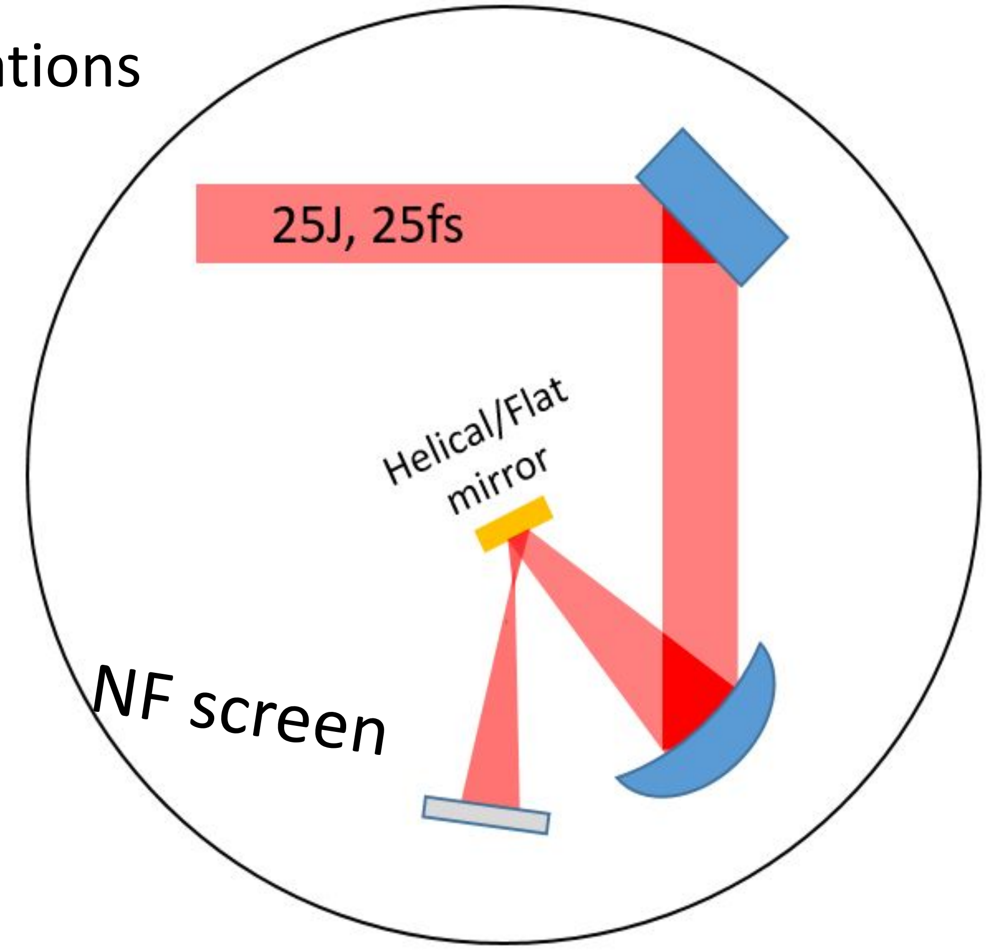
(M. Cernaianu et al., in preparation)

- Deformable mirror (DM) used to compensate aberrations
- WFS used to measure the wavefront

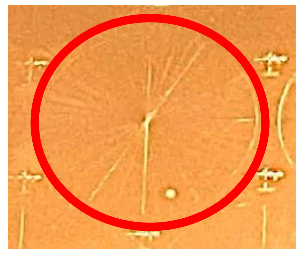
l=3 helical WF

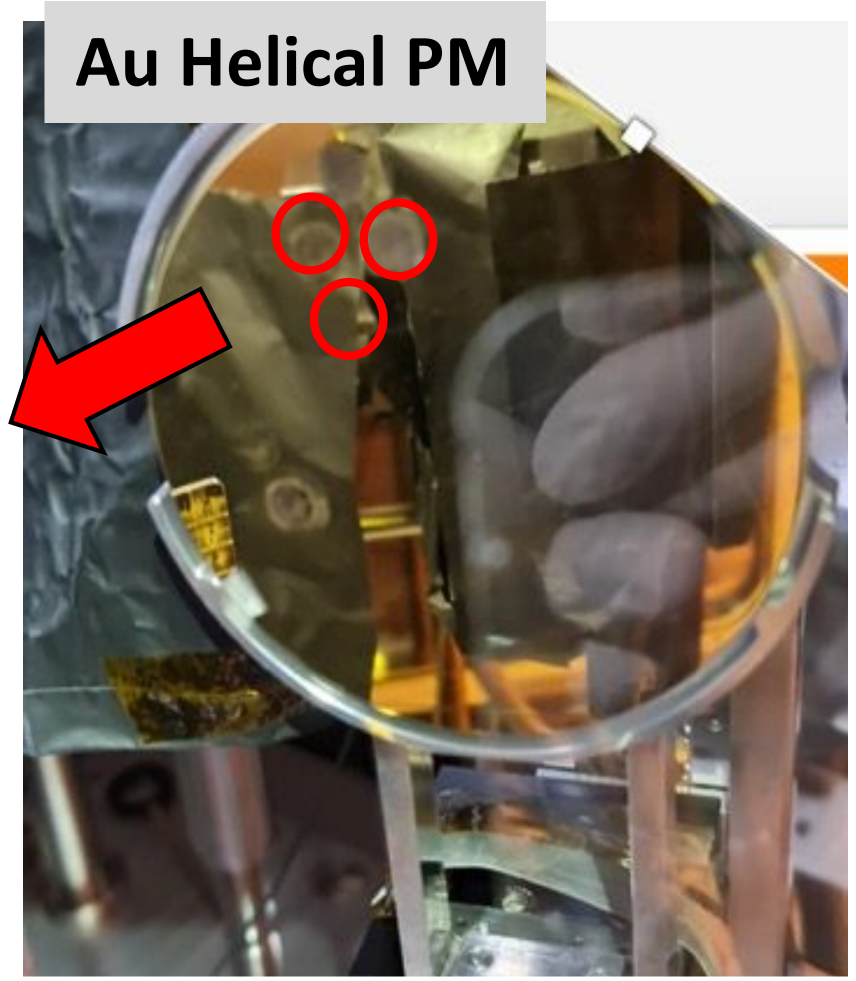
PV (µm):
~2.1 µm



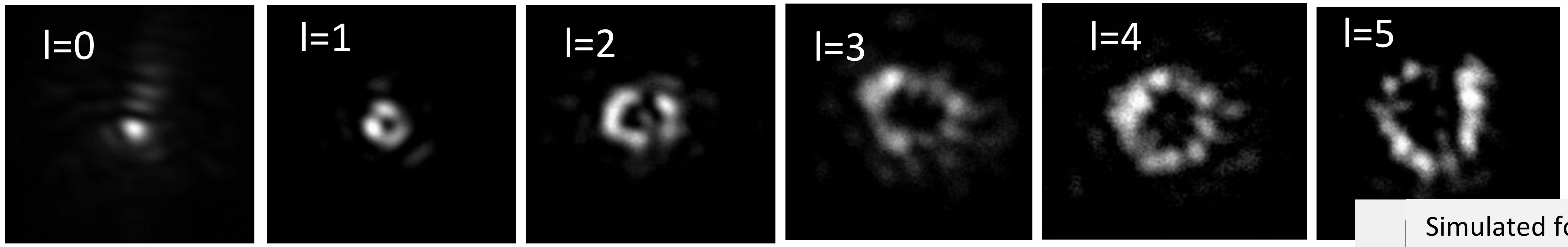


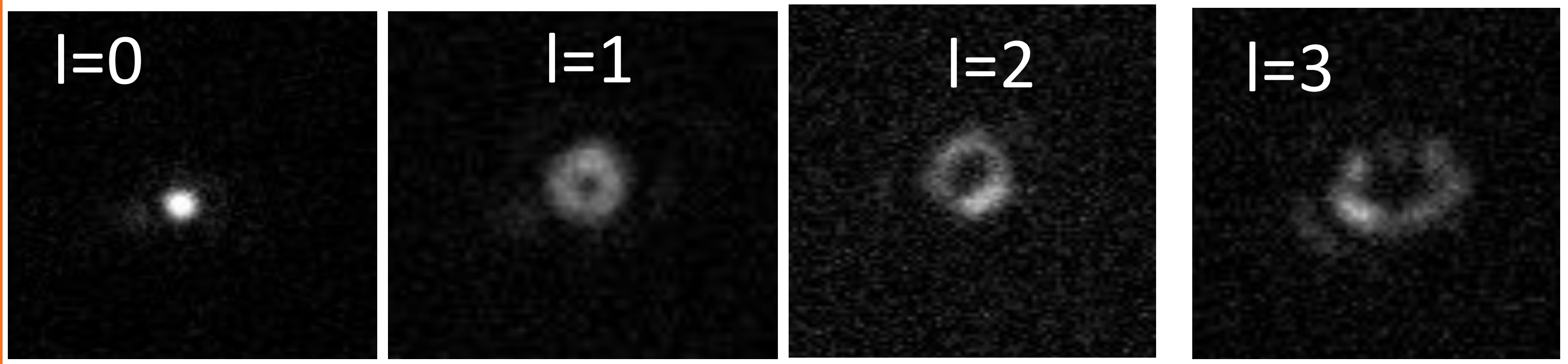
Helical mirror element



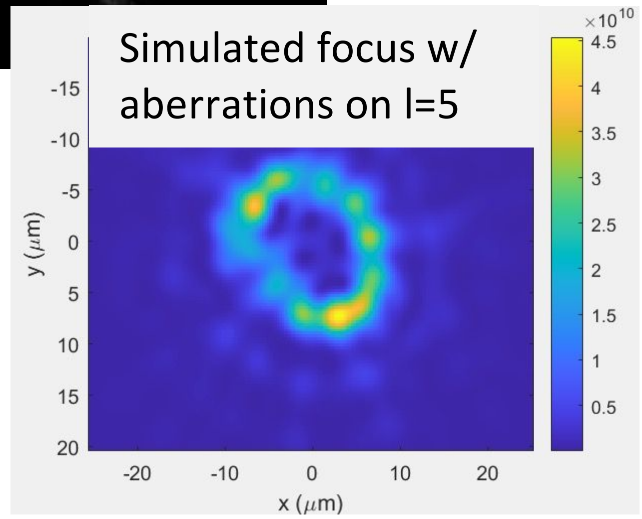


- Far-field (focus): 25 µJ, 25 fs

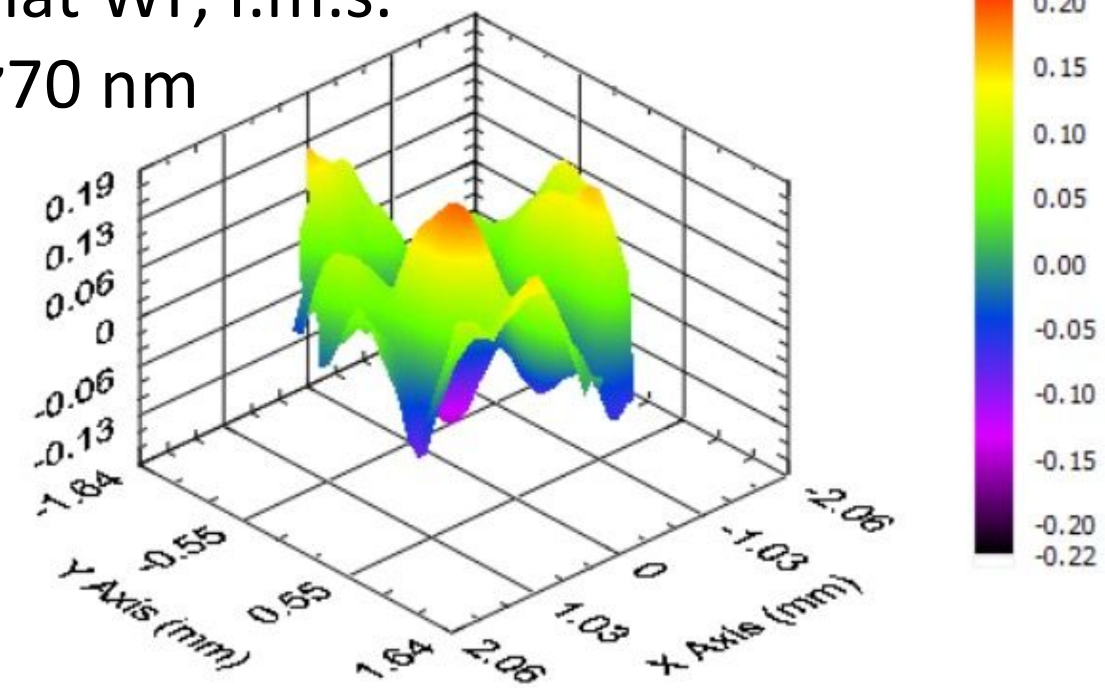




Optimized with DM



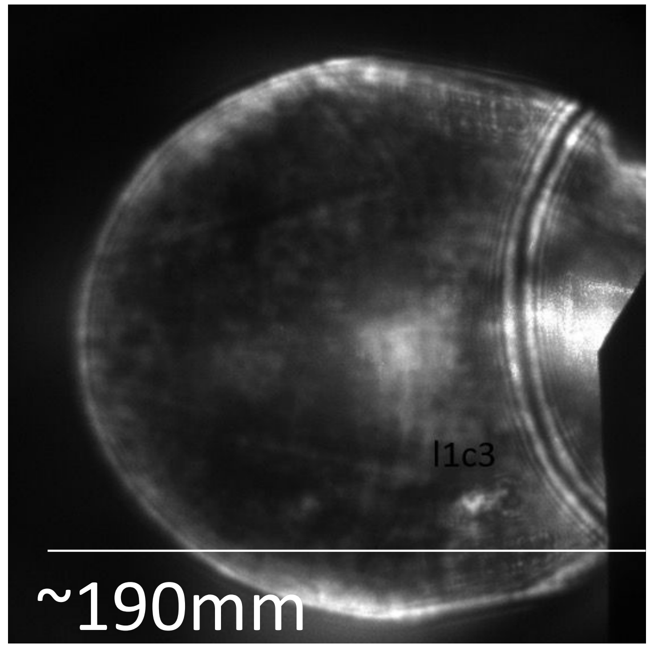
Flat WF, r.m.s. ~70 nm

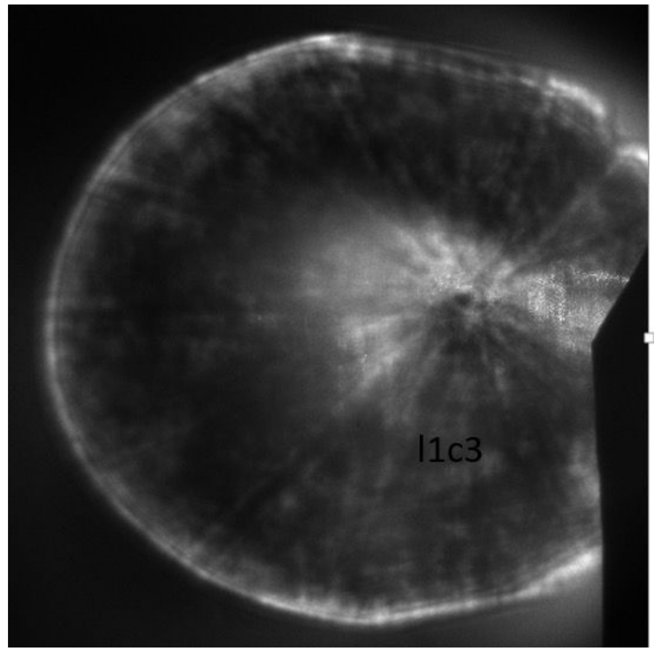


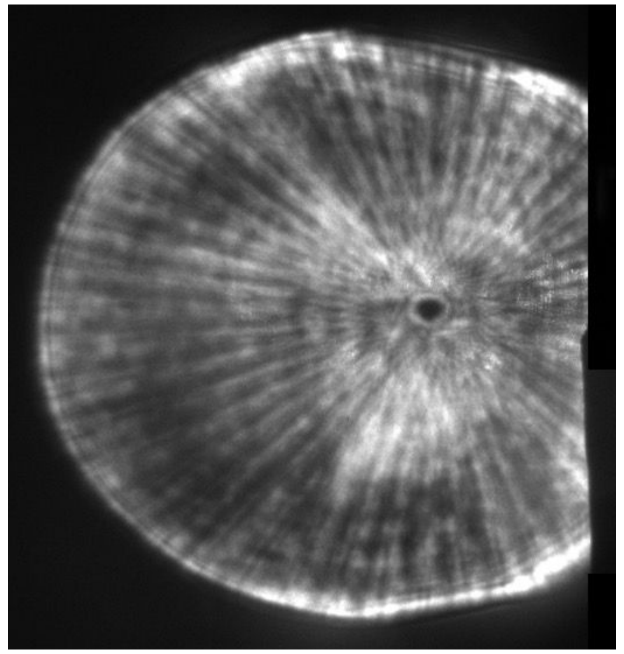
Successful generation and demonstration of the vortex beams with high orders in low-field

Generation of PW class helical beams, currently up to *l*=5

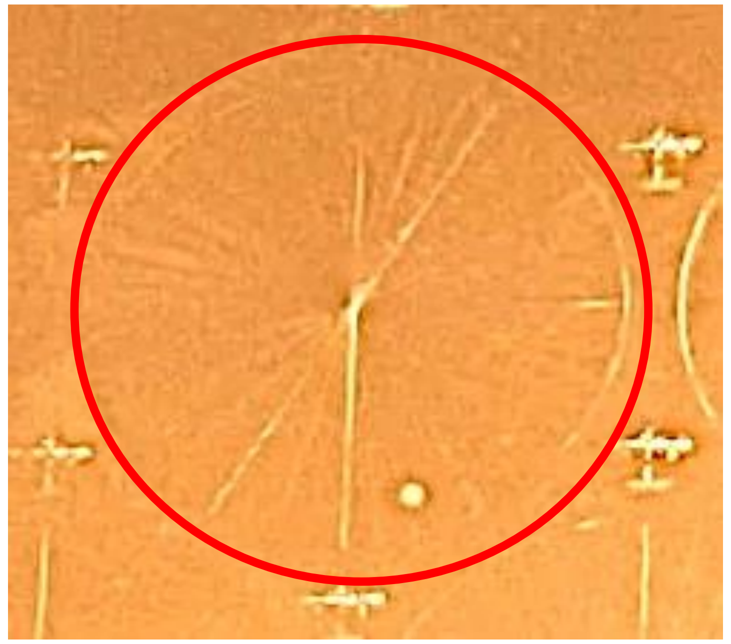
- ❑ Near field measurements in the low field: 25 uJ, 25 fs



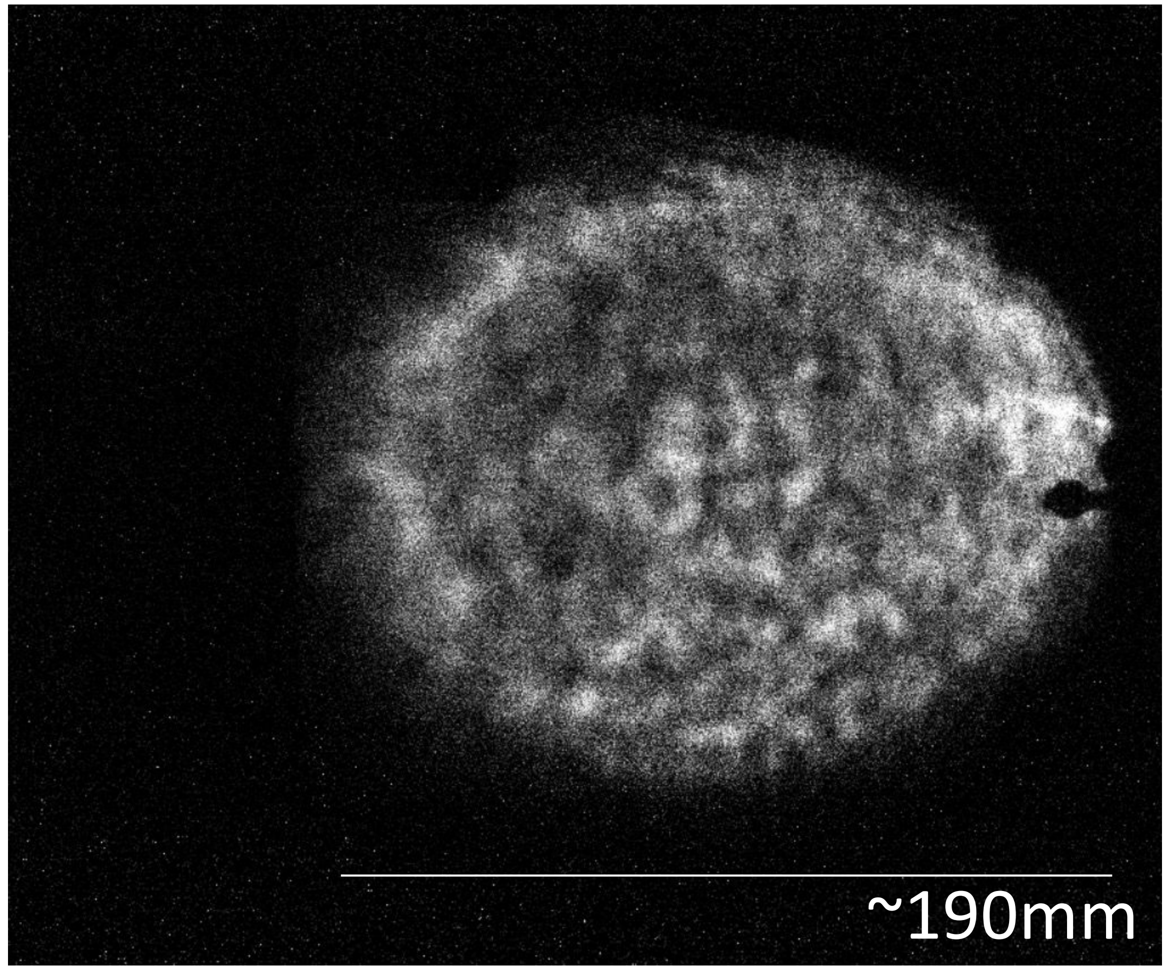


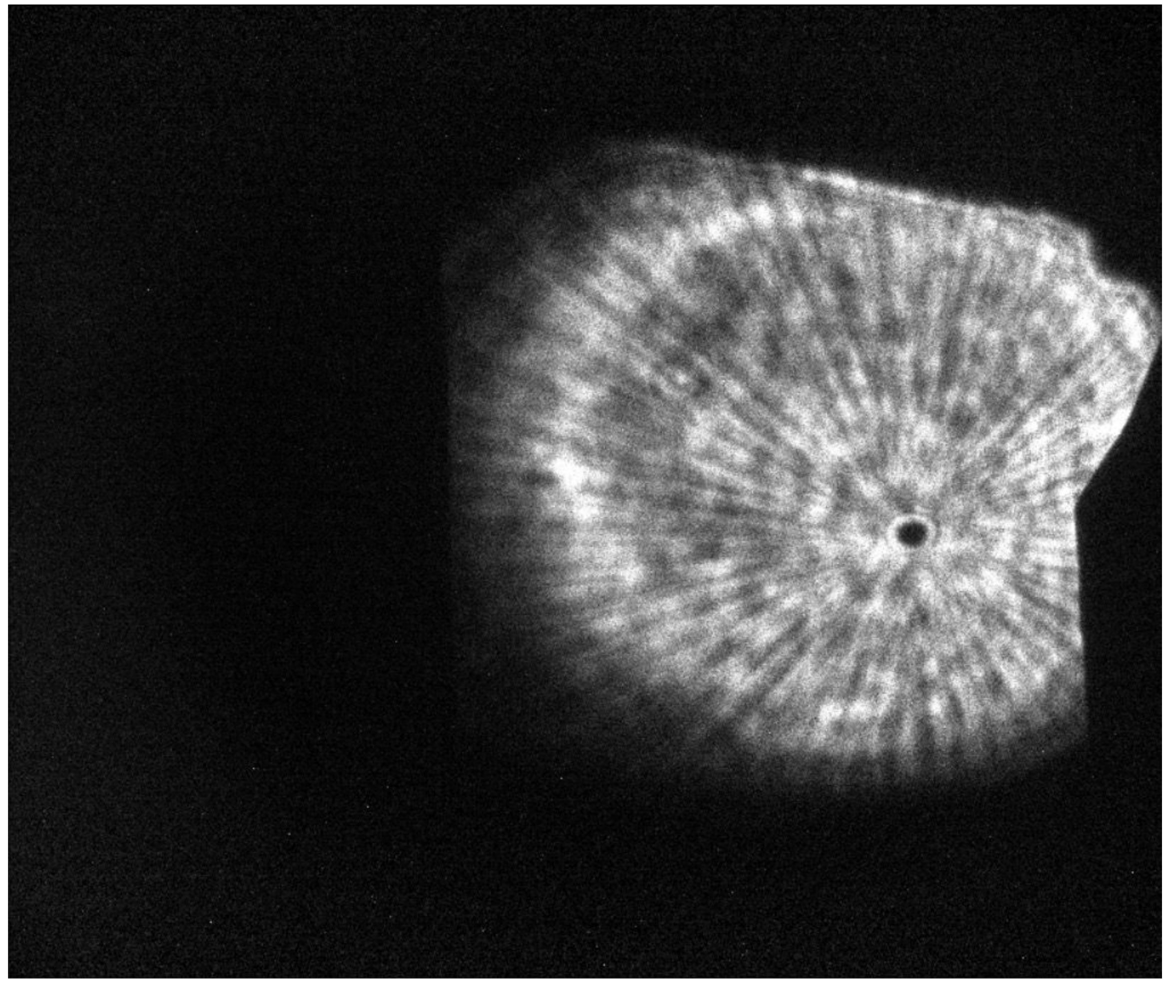


- ❑ Generation and measurements in the high energy regime: 22 J 25 fs



Near-field high power shot ~22 J, 25 fs ,~900 TW





Successful generation and demonstration of the OAM beams with high orders in the PW regime at ELI-NP

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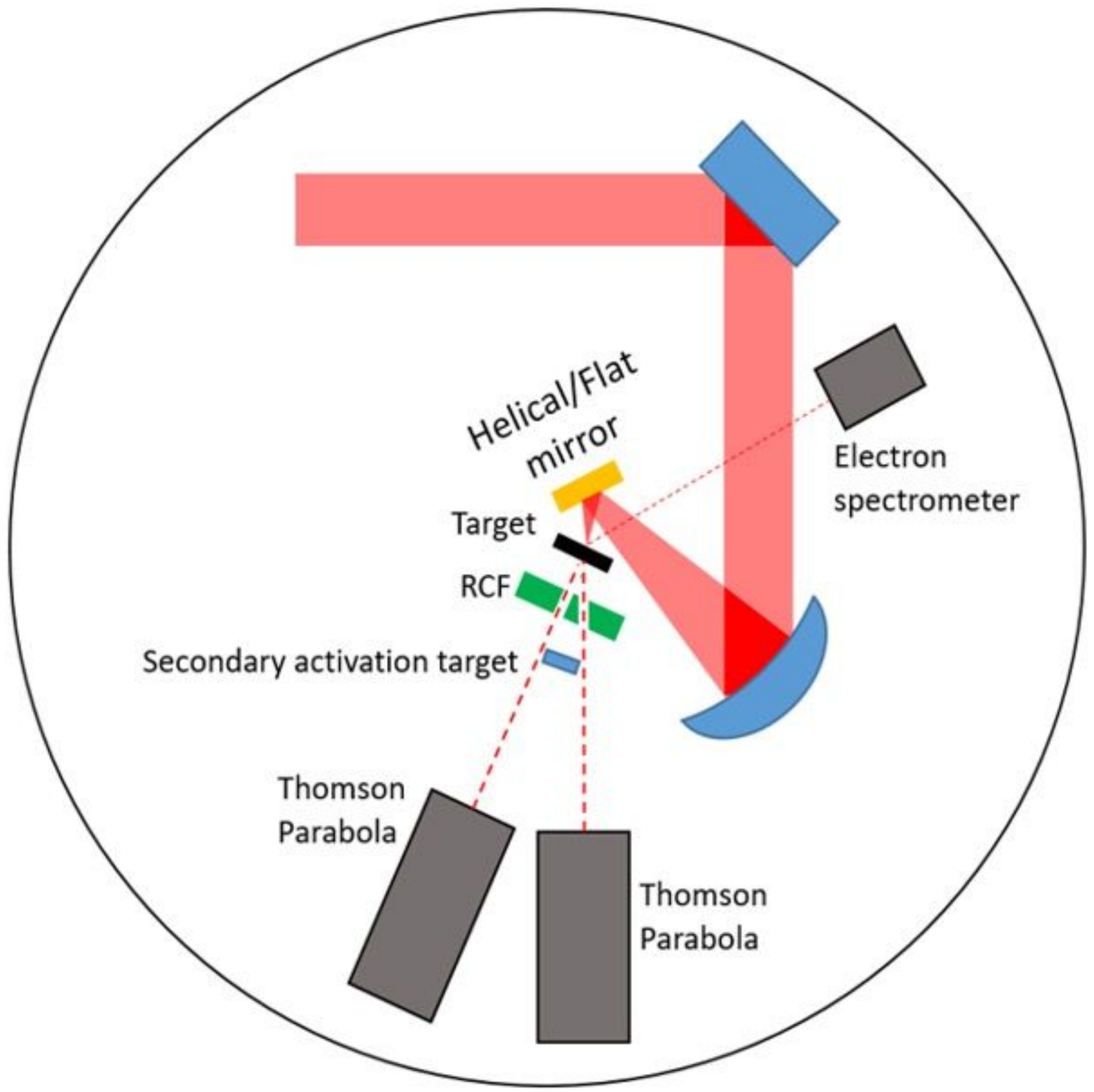
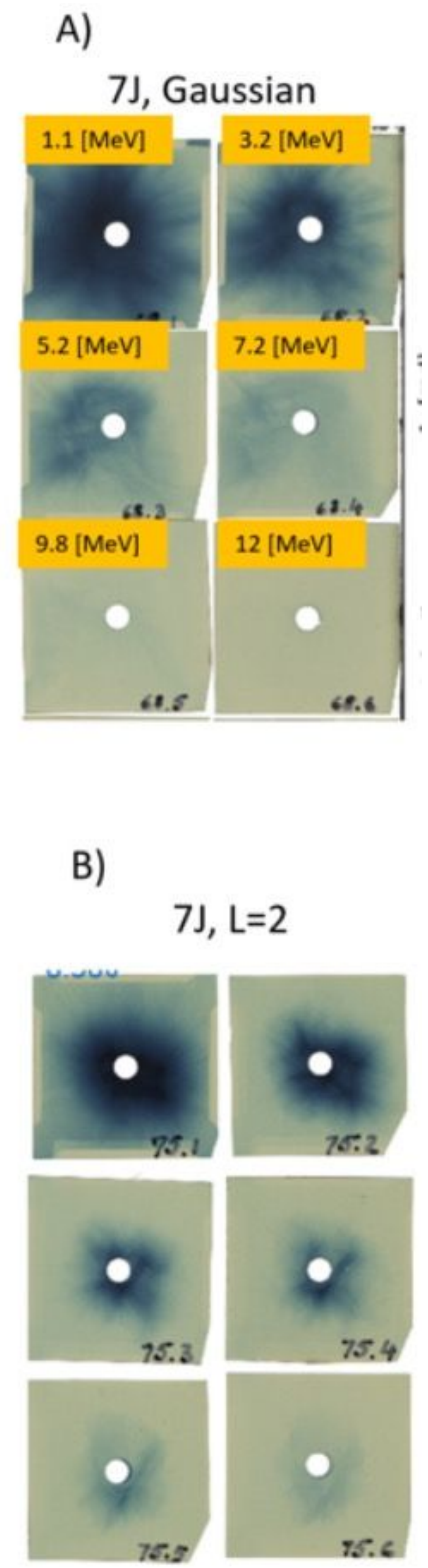
PW class high order helical laser beam interaction with solid targets

Acceleration of protons with PW class helical beams and thick targets

- 3 um Al targets, Au coated helical PM, intensity contrast ~1e-7 at -25 ps
- Diagnostics based on RCF stacks and ion spectrometers
- 3D PIC simulations performed with realistic laser and plasma parameters





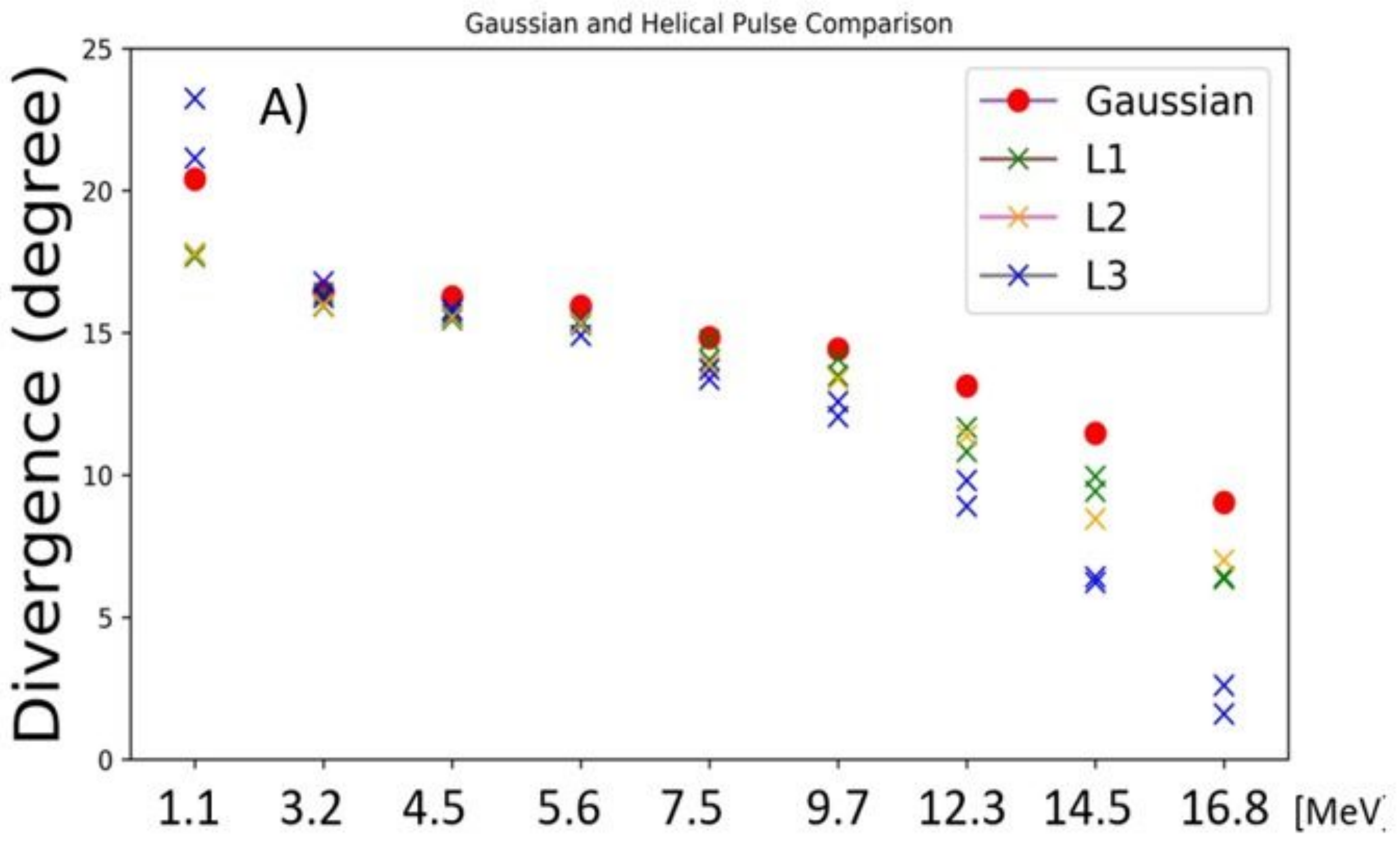
Reduction in divergence for the helical mode as well as a dose redistribution in the central part of the beam observed in the RCF data.

PW high order helical laser beam interaction with solid targets

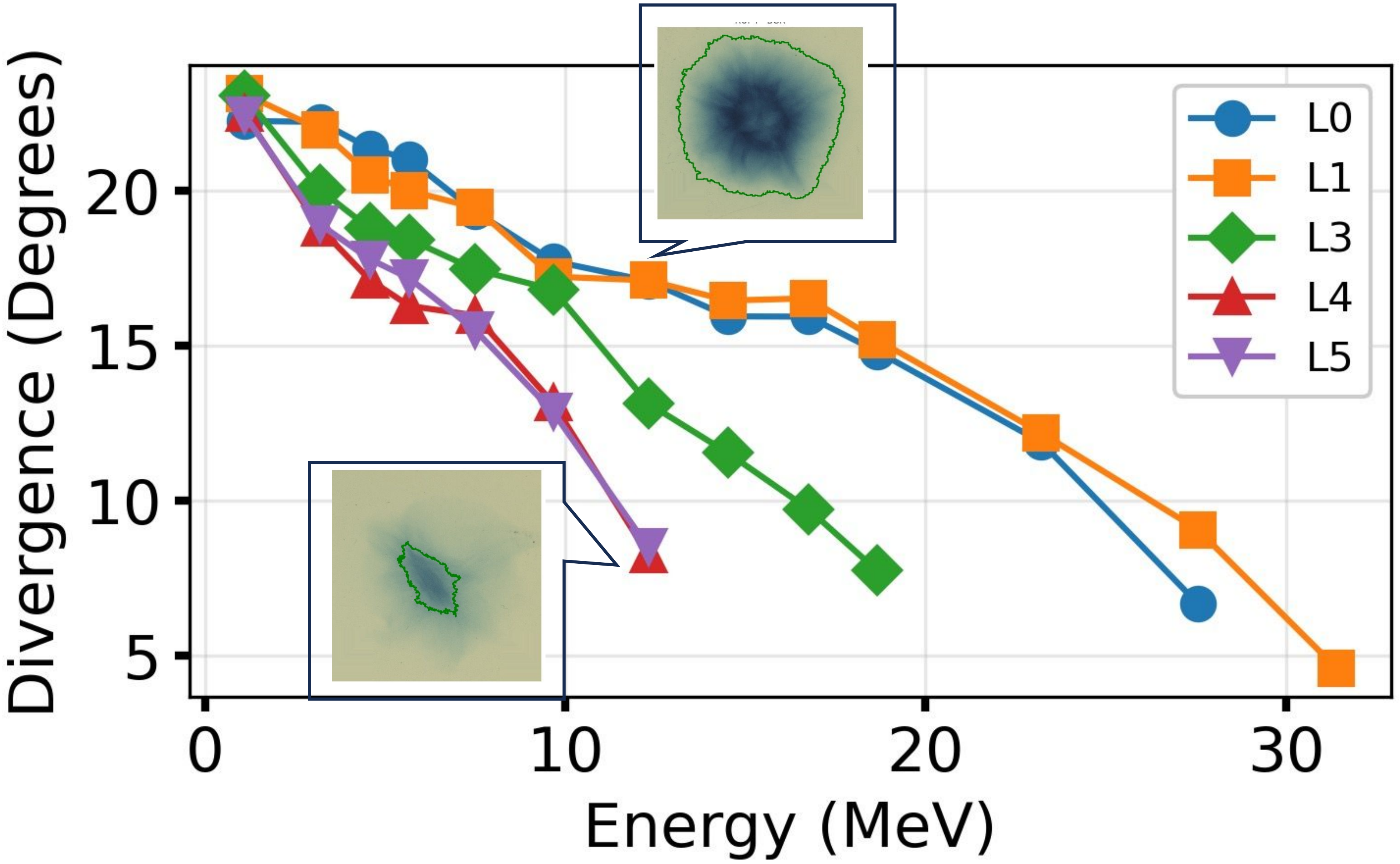
Proton acceleration experiments done with target thicknesses from µm to nm, different temporal contrasts:

- Improved contrast by developing AR helical PM, ~10^{-10} @-25ps and down to 10^{-11} @-25ps
- 10 nm- 400nm Al and Au targets
- Similar diagnostics

10^{21} W/cm^2, 200 nm Au, experiment ELI-NP



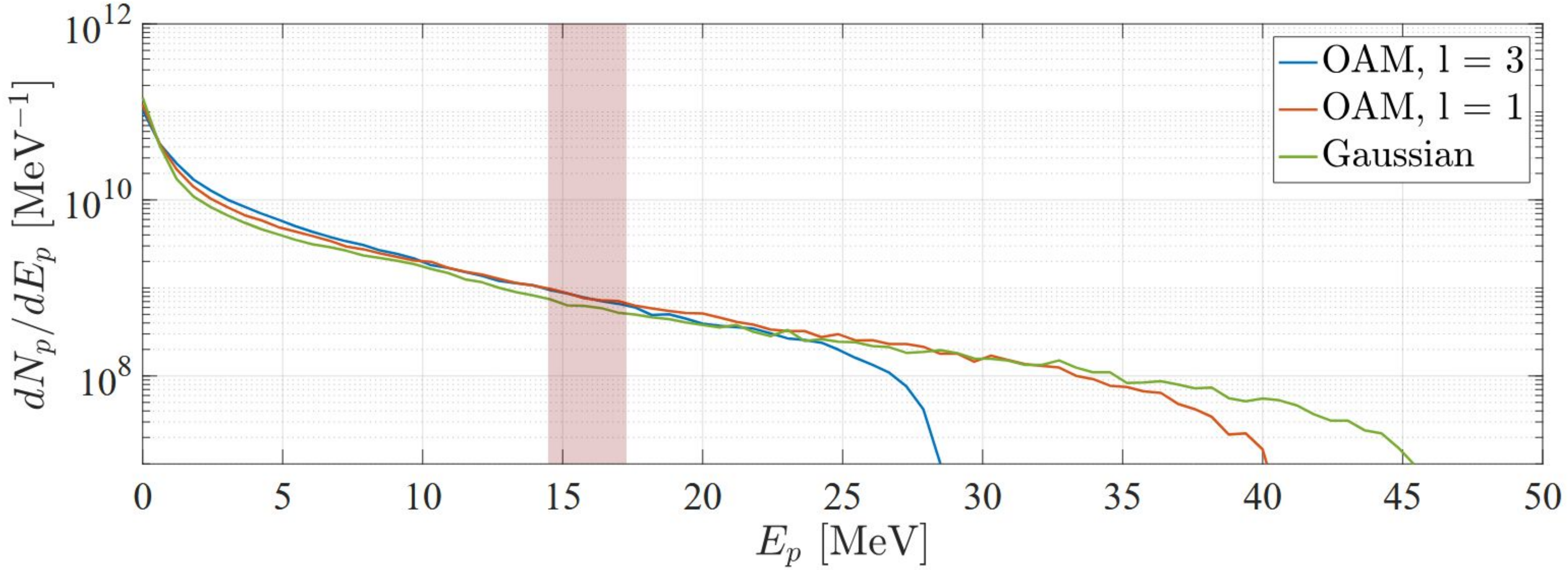
10^{20}-10^{21} W/cm^2, 100 nm Al, best contrast ELI-NP

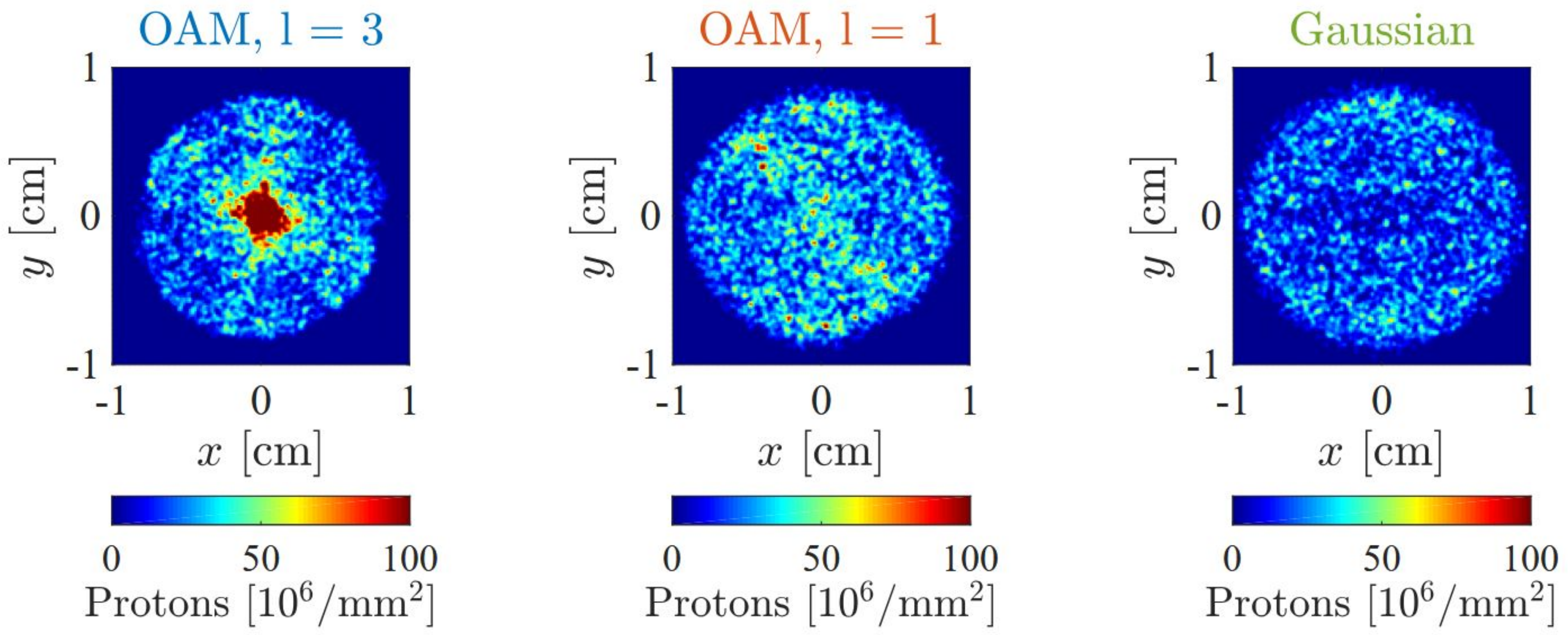


Lower divergence H+ beam with increased helical order, different power scaling law than for typical Gaussian beams -> of interest for applications

3D PIC simulations in very good agreement with the experiment

Target: 1.5 um Al
Laser energy: 21J
Pulse duration: 25fs
Focal spot: 4 um FWHM
Linear Polarization
Exp. AoI: 26 deg
Sim. AoI: 0 deg
Laser contrast: w/o PM





Collaboration with
C. Willim, J. Vieira (IST)

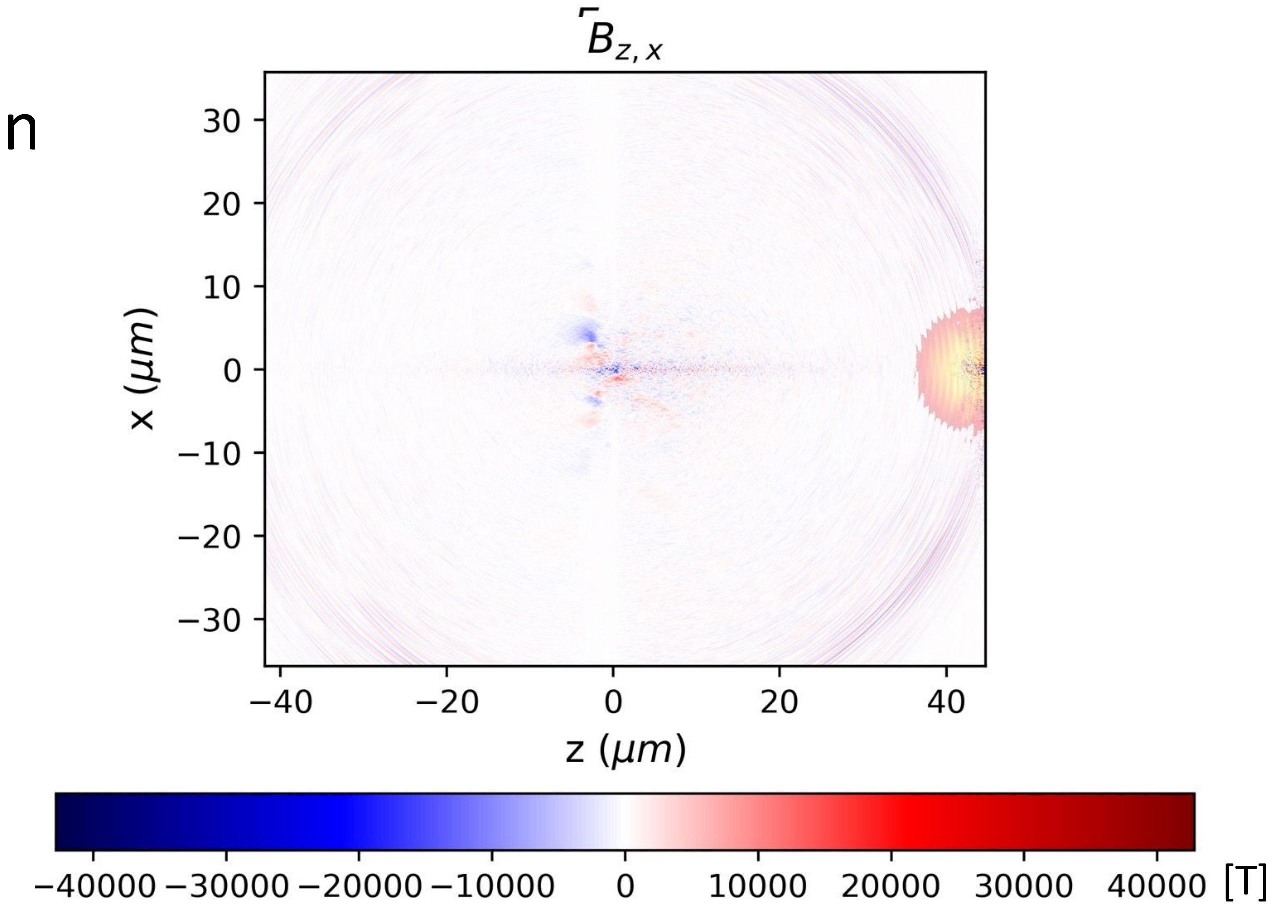
Similarly, lower divergence H+ beam with increased helical order
Hydrodynamic simulation of the preplasma is crucial

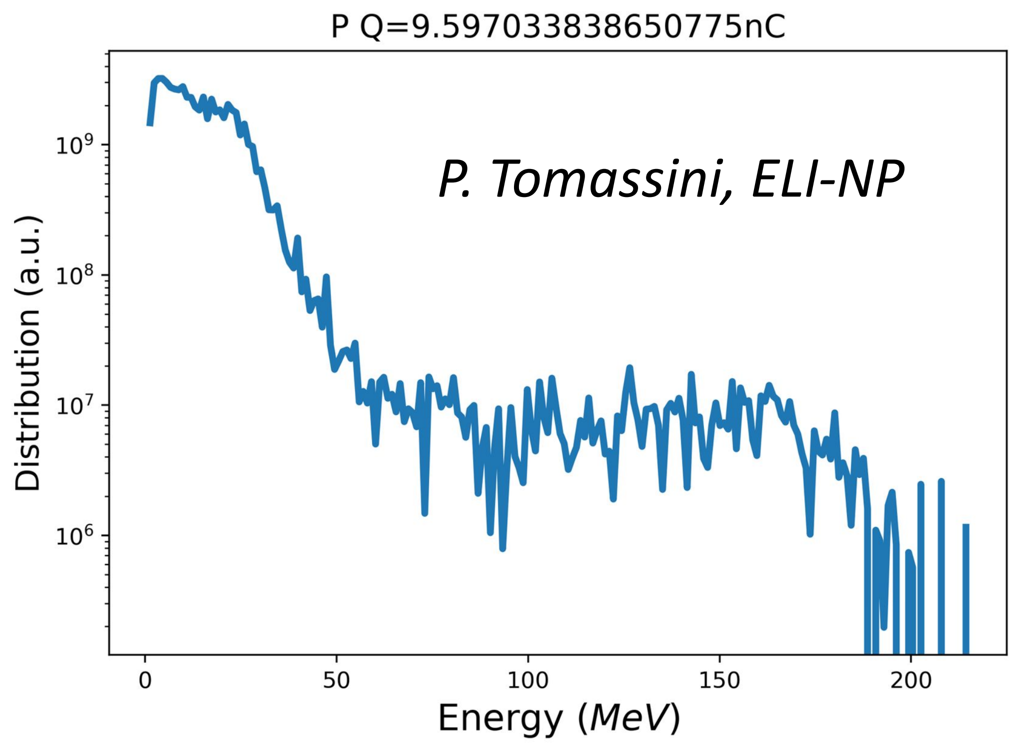
PIC simulations with thin targets @ multi PW - similar dependency

Simulations with 5 PW on 200nm target to study the scaling of the processes at 10 PW

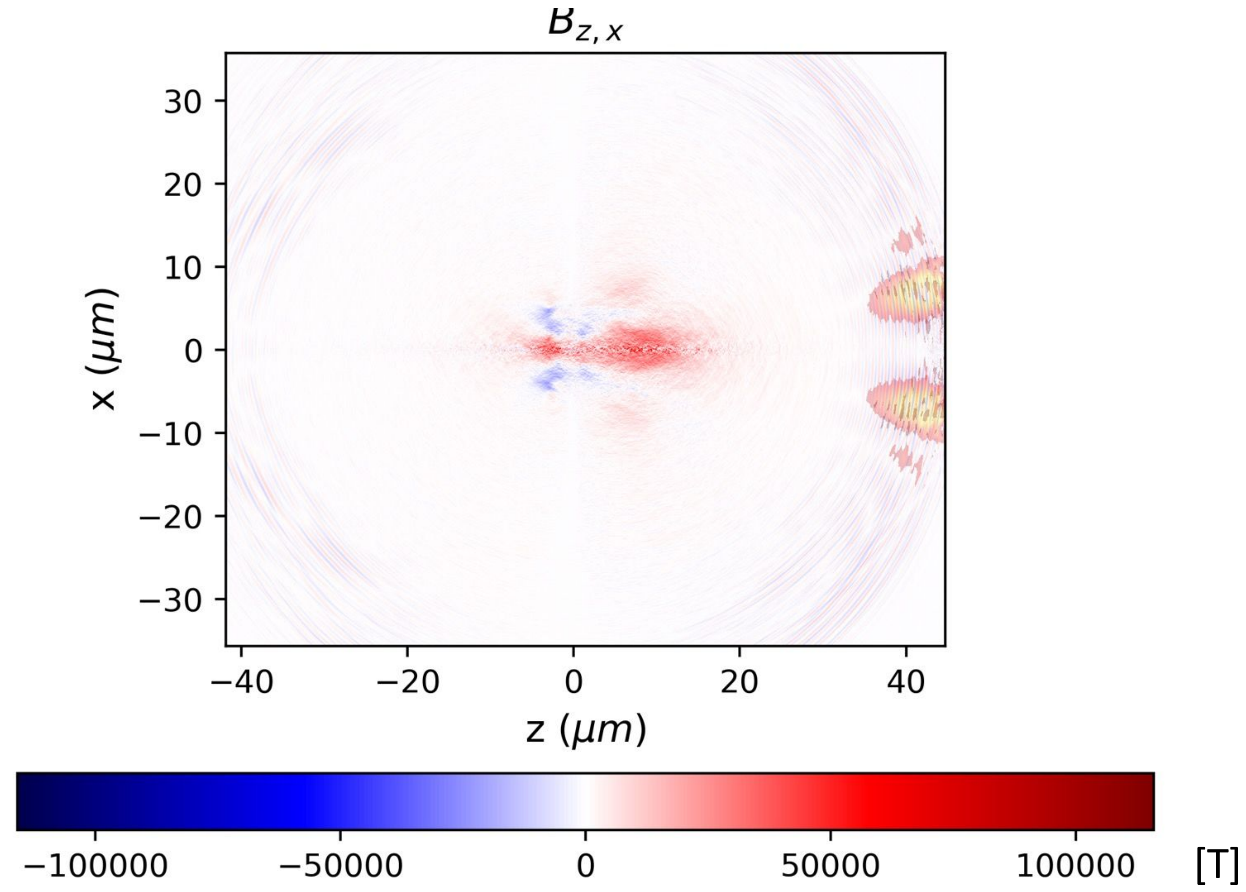
(M. Cernaianu et al., in preparation)

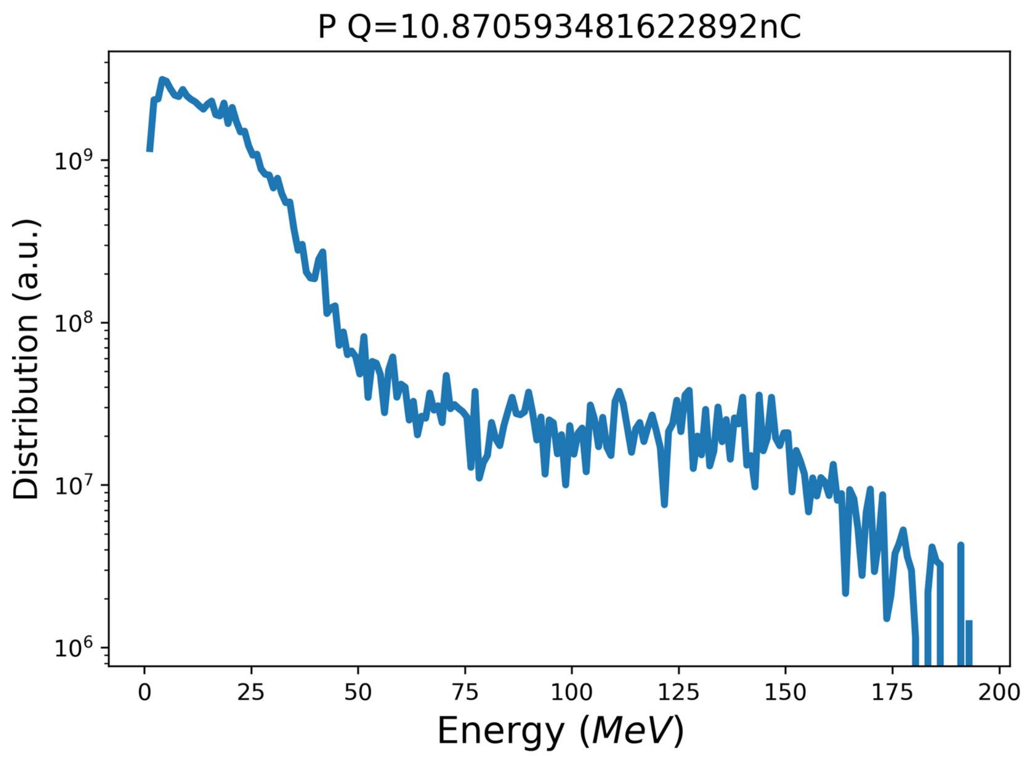
Gaussian



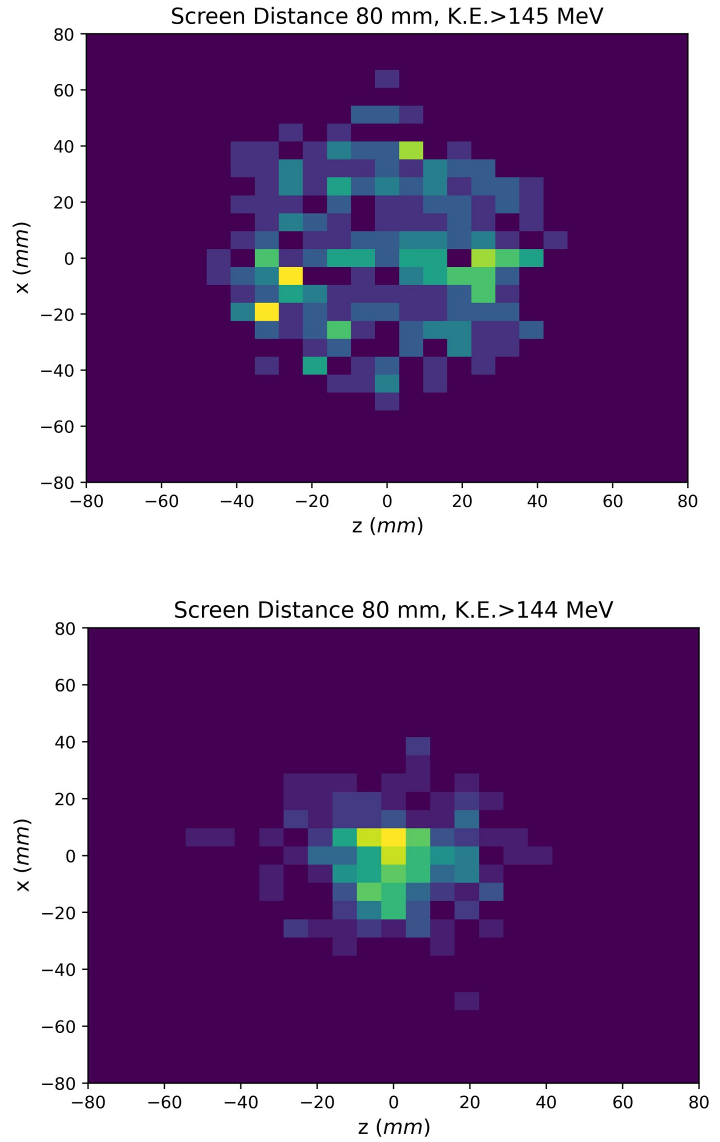


Helical
l=3

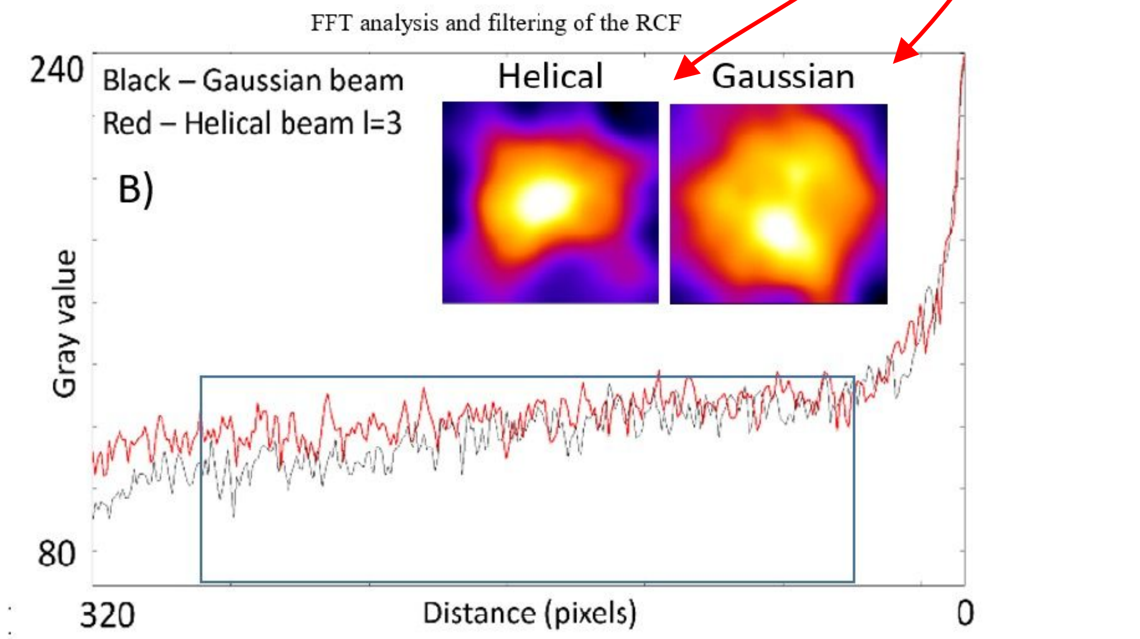




Proton beam spatial distribution, **simulation**



Proton beam spatial distribution, **experiment at 1PW**



A complex fields structure is developing during interaction, currently under study

Conclusions

- Solution for generating helical beams strongly depends on laser parameters
- Using our novel technique we can successfully generate, diagnose and use PW class fs helical beams of high topological order
- Higher orders possible, suitable to multi-PW experiments
- Accelerated ion beams show different spatial dose distribution and divergence and a complex field structure under study

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Thank you!

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