Special use of correctors for uncommon experiments: free electron orbital angular momentum and beyond

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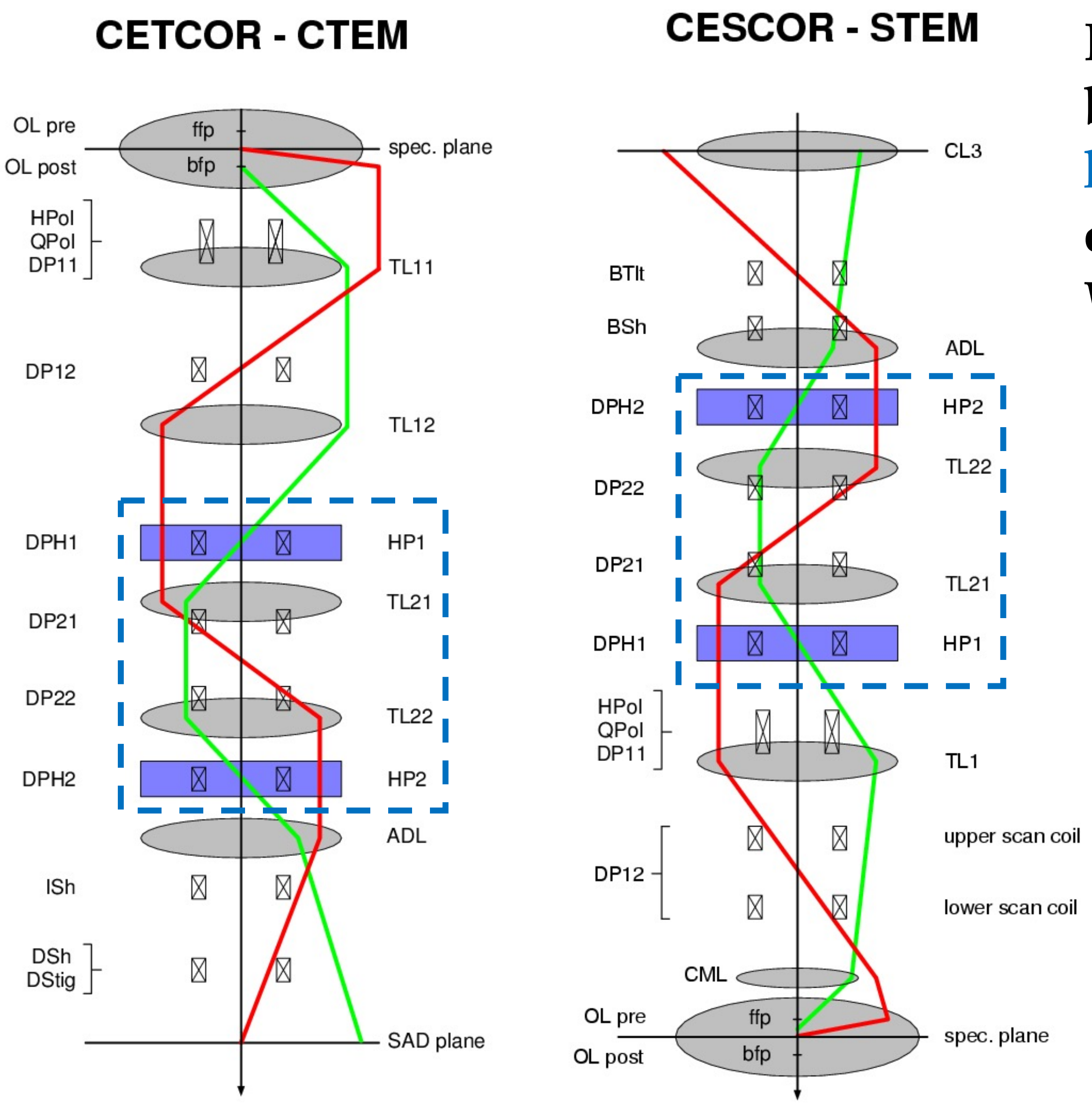
With contributions from
Vienna: Thomas Schachinger, Stefan Löffler, and Peter Schattschneider
Modena: Vincenzo Grillo and his co-workers
Heidelberg: Peter Hartel and Martin Linck
Berlin: Tolga Wagner
Juelich: Amir Tavabi and Rafal E. Dunin-Borkowski

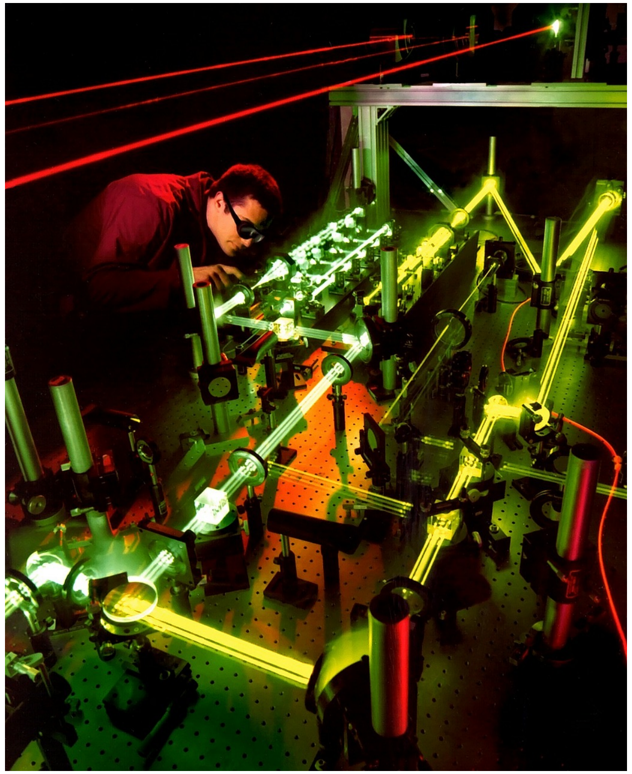
JÜLICH
Forschungszentrum

Cs corrector as an electron optical bench



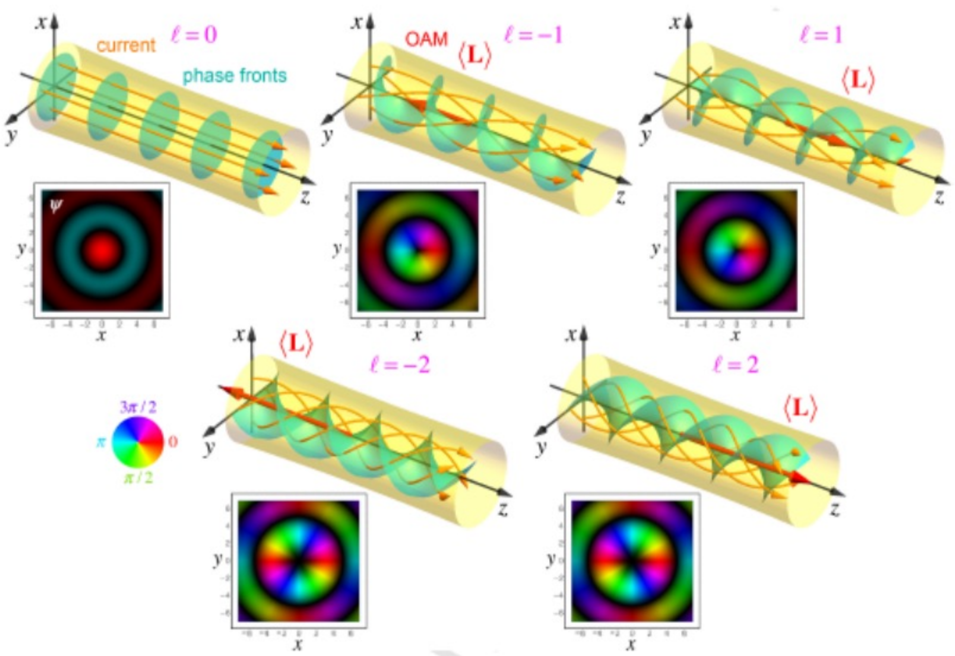
https://www.ceos-gmbh.de/en/produkte/residualsCEXCOR

Not only **double hexapole** for aberration correction, but also **additional deflectors, dipoles, quadrupoles, hexapoles and transfer lenses** for alignment and correcting parasitic aberrations.
We could also treat it as an electron optical bench!

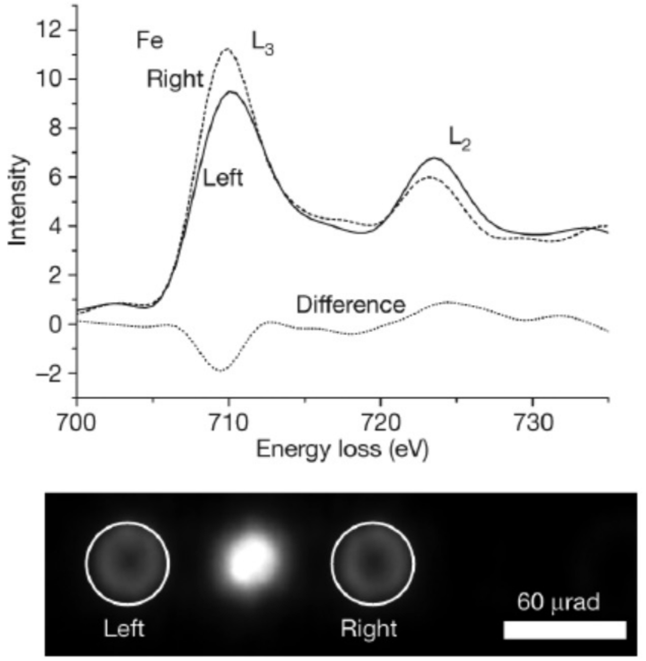


https://www.needpix.com/photo/47763/

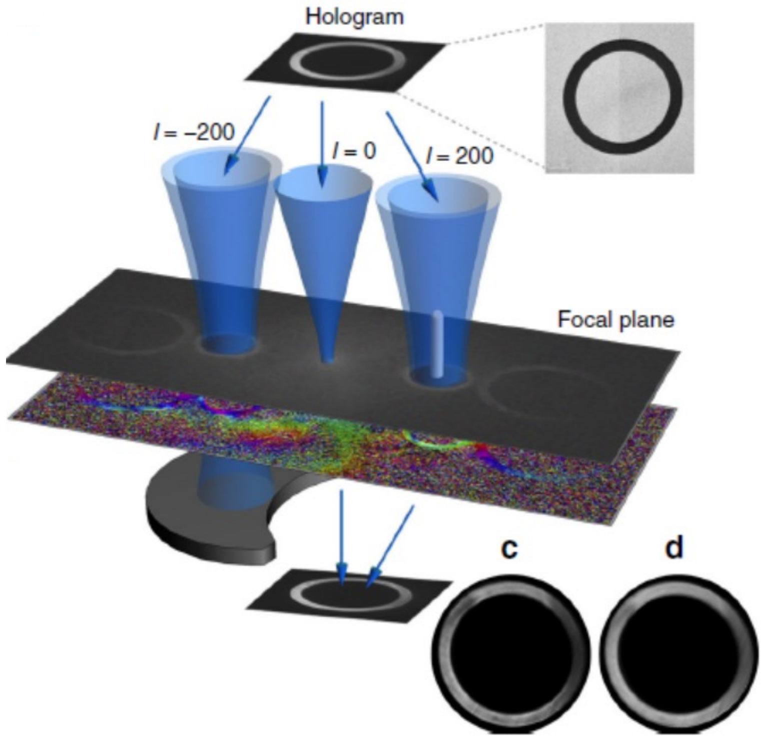
Orbital angular momentum of free electrons



K.Y. Bliokh *et al*. Physics Reports 690, 1 (2017)



J. Verbeeck *et al*. Nature 467, 301 (2010)



V. Grillo *et al*. Nat. Commun. 8, 689 (2017)
A. Edström *et al*. PRL 116, 127203 (2016)

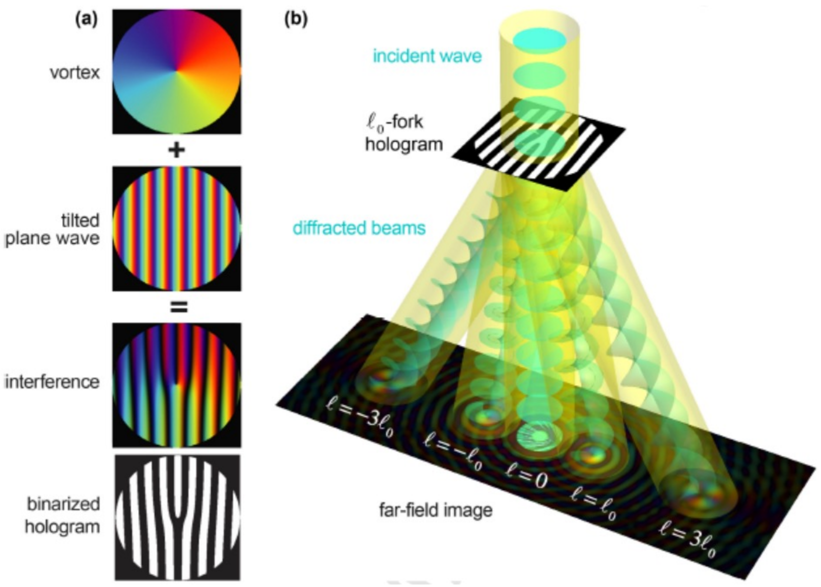
Helical phase front
Phase singularity on the axis
Orbital angular momentum
Magnetic moment

Inelastic scattering
Electron magnetic circular dichroism
break symmetry of the $p^{\pm}$ state excitation
$l = \pm 1$ (selection rule)

Elastic scattering
Zeeman energy shift
Intensity redistribution
larger OAM, better signal to noise ratio

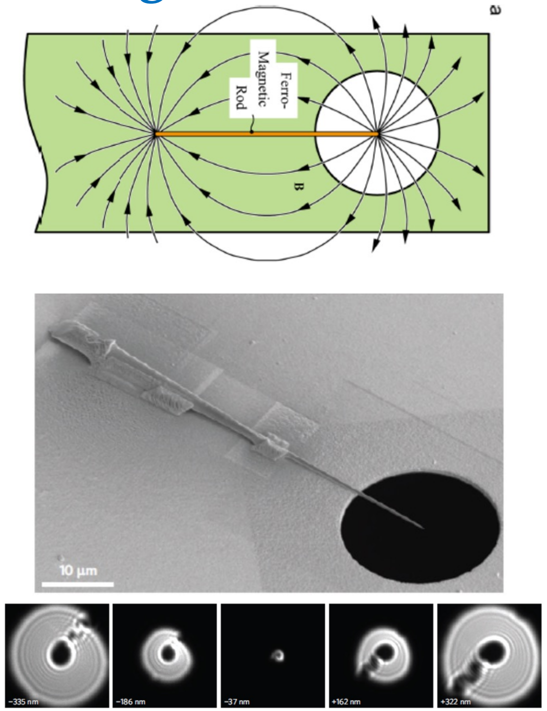
How to produce free electron OAM?

Diffractive hologram



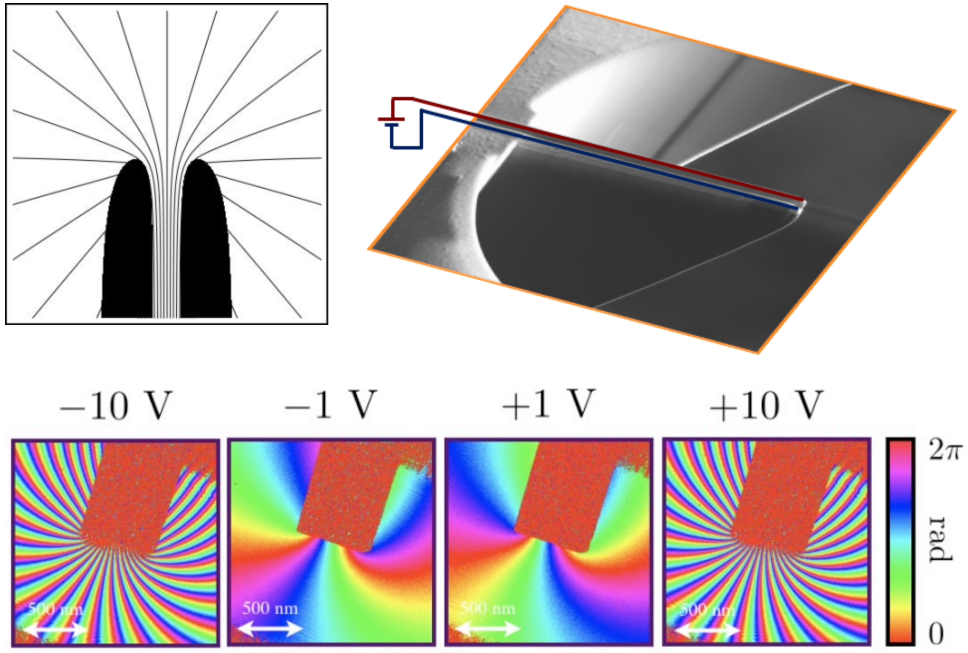
K.Y. Bliokh *et al*. Physics Reports 690, 1 (2017)

Magnetic needle



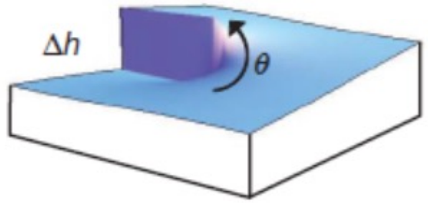
A. Béché *et al*. Nat. Phys. 10, 26 (2014)
A. M. Blackburn *et al*. Ultramic. 136, 127 (2014)

Electrostatic chopstick

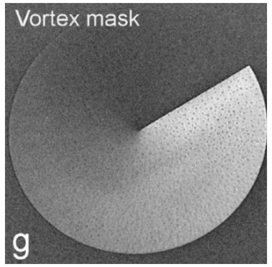


G. Pozzi *et al*. Ultramic. 181, 191 (2017)
A. Tavabi *et al*. Phys. Rev. Res. 2, 013185 (2020)

Refractive phase plate



M. Uchida & A. Tonomura, Nature 464, 737 (2010)

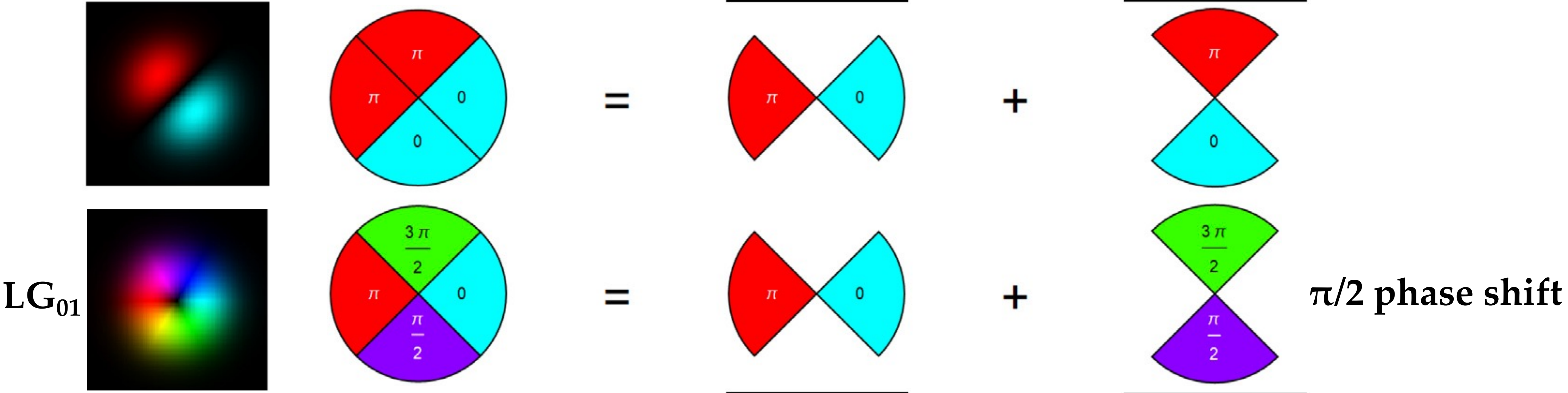


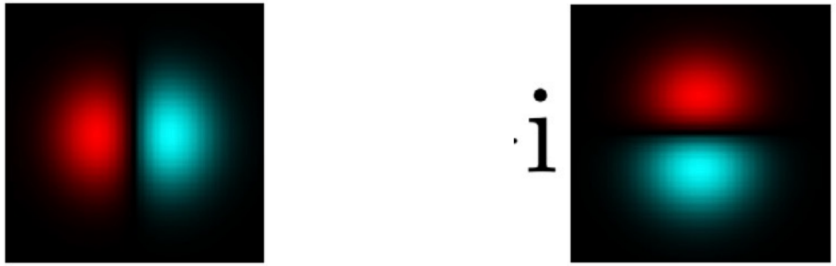
R. Shiloh *et al.* Ultramic. 144, 26 (2014)

- **Side lobes and transmission efficiency**
- **Device obstruction and possibly charging**
- **OAM mode purity**
- **Static or dynamic OAM modulation, etc.**

Alternative way: π/2 mode conversion

Collaboration:
TU Wien (Peter Schattschneider and his co-workers)
CEOS (Peter Hartel)
FZ Juelich (Penghan Lu and Rafal Dunin-Borkowski)
KIT (Dagmar Gerthen and her co-workers)

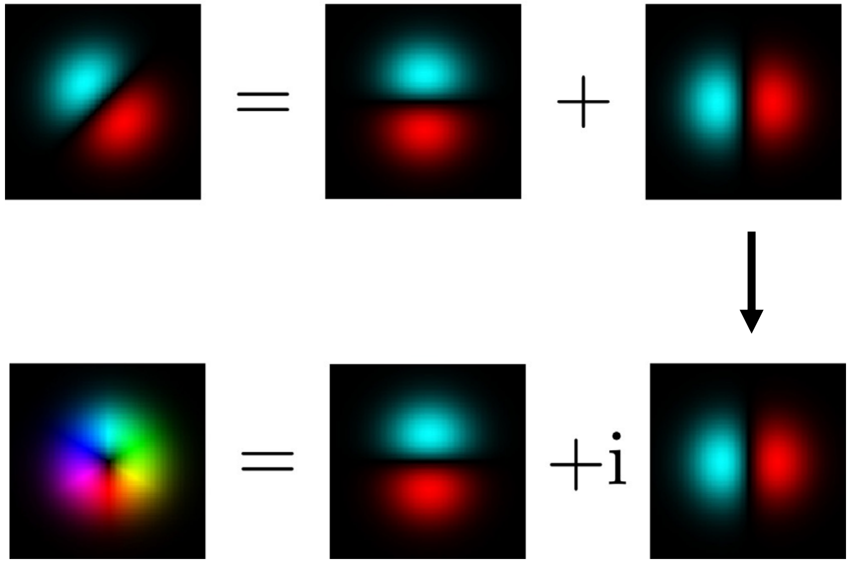




M. Beijersbergen *et al.* Opt. Commun. 96, 123 (1993)
C. Kramberger *et al.* Ultramic. 204, 27 (2019)
T. Schachinger *et al.* Ultramic. 229, 113340 (2021)

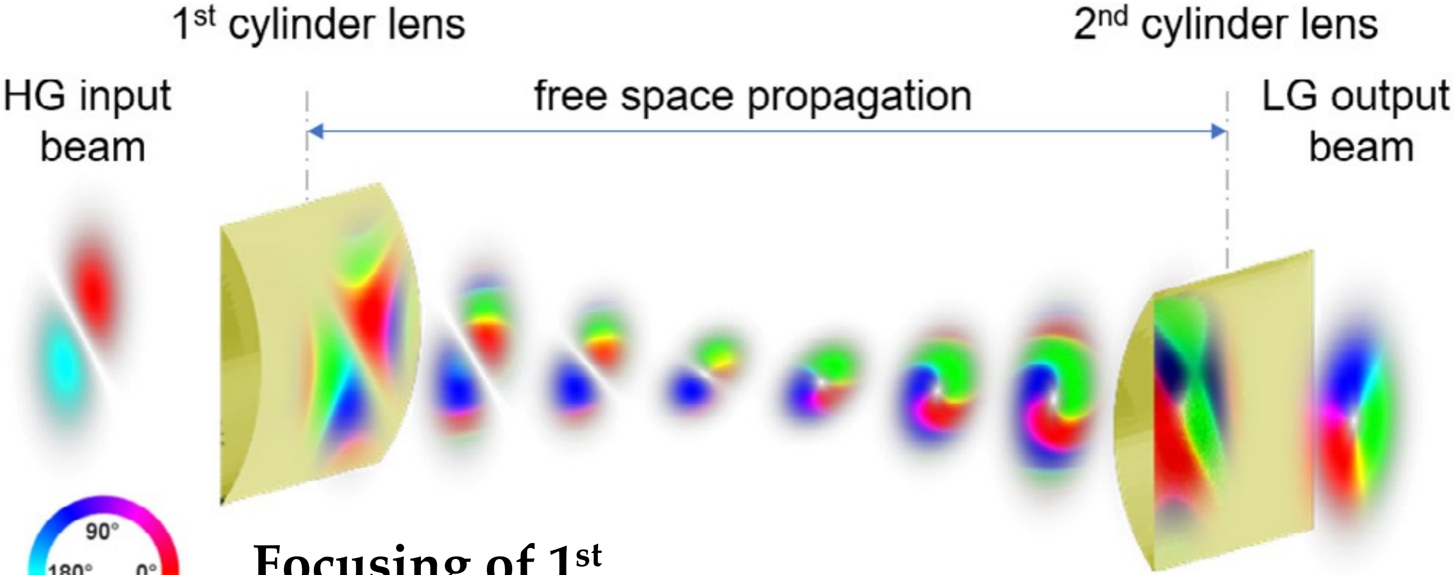
How to achieve π/2 mode conversion?

HG beam at an angle of 45º with respect to cylinder lens orientation: superposition of 2 orthogonal HG modes



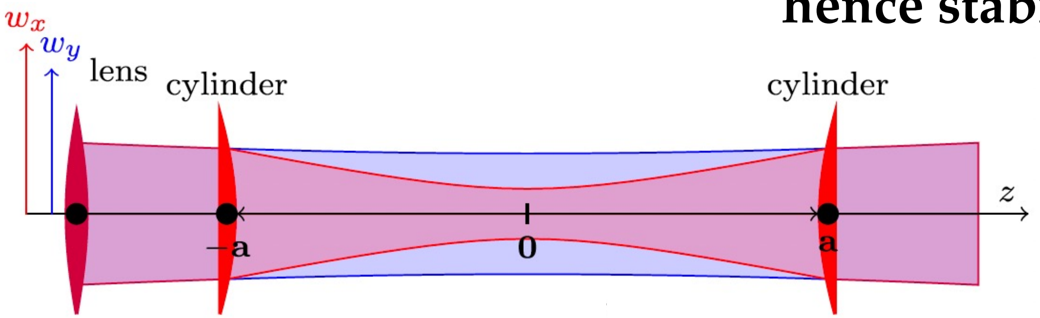
Focusing-induced Gouy phase retardation of π/2

C. Kramberger *et al.* Ultramic. 204, 27 (2019)
T. Schachinger *et al.* Ultramic. 229, 113340 (2021)



Focusing of 1st cylinder lens affects only one component of the incident beam

2nd cylinder lens is used to cancel the astigmatism introduced by the 1st one and hence stabilize the vortex state

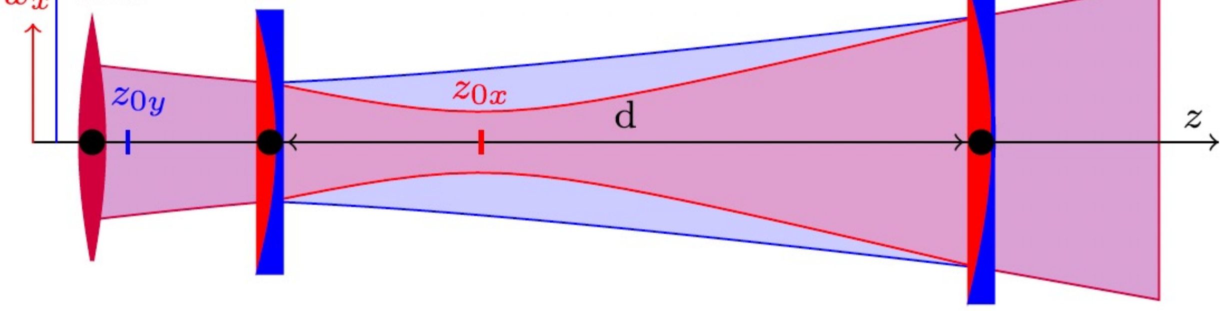


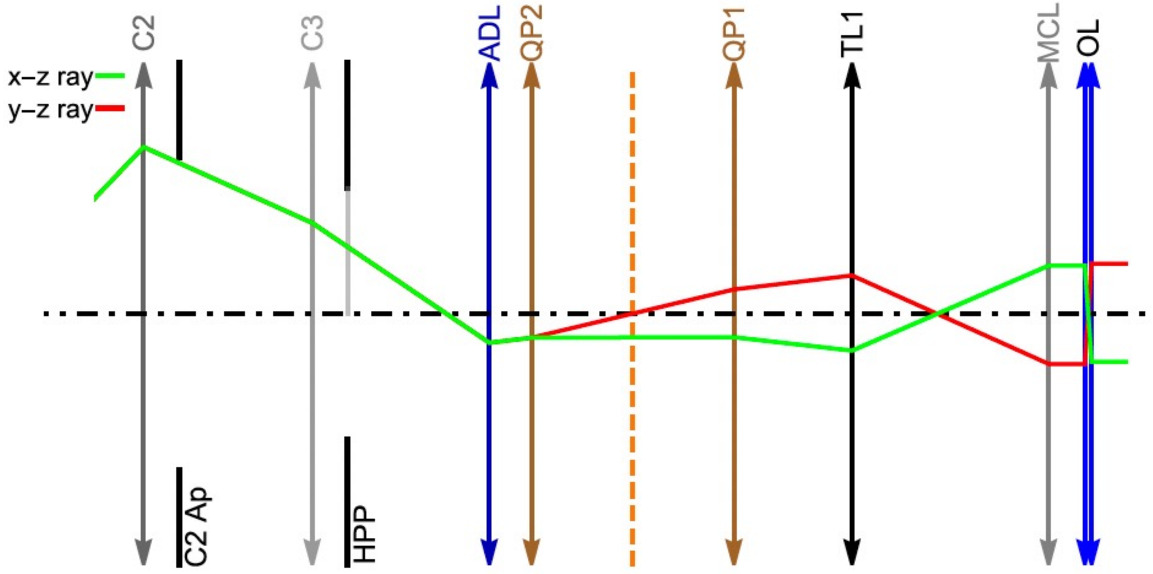
But we don't have cylinder lens in the TEM…

Asymmetric mode conversion

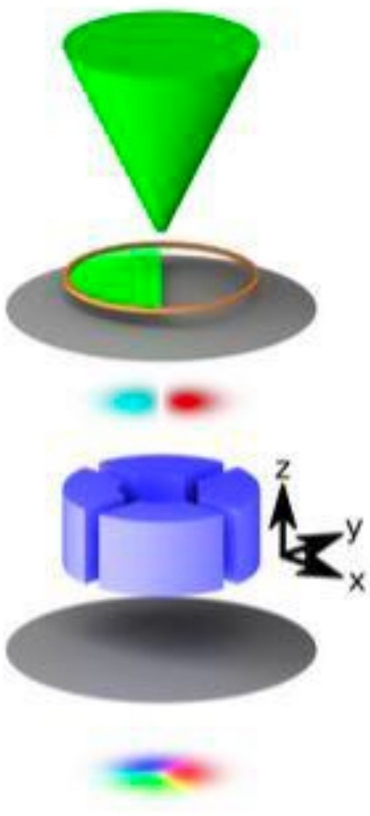
$$w_i = \sqrt{\frac{2f_i}{k}},$$

$$f_i \cdot f_o = 2 \cdot d^2,$$





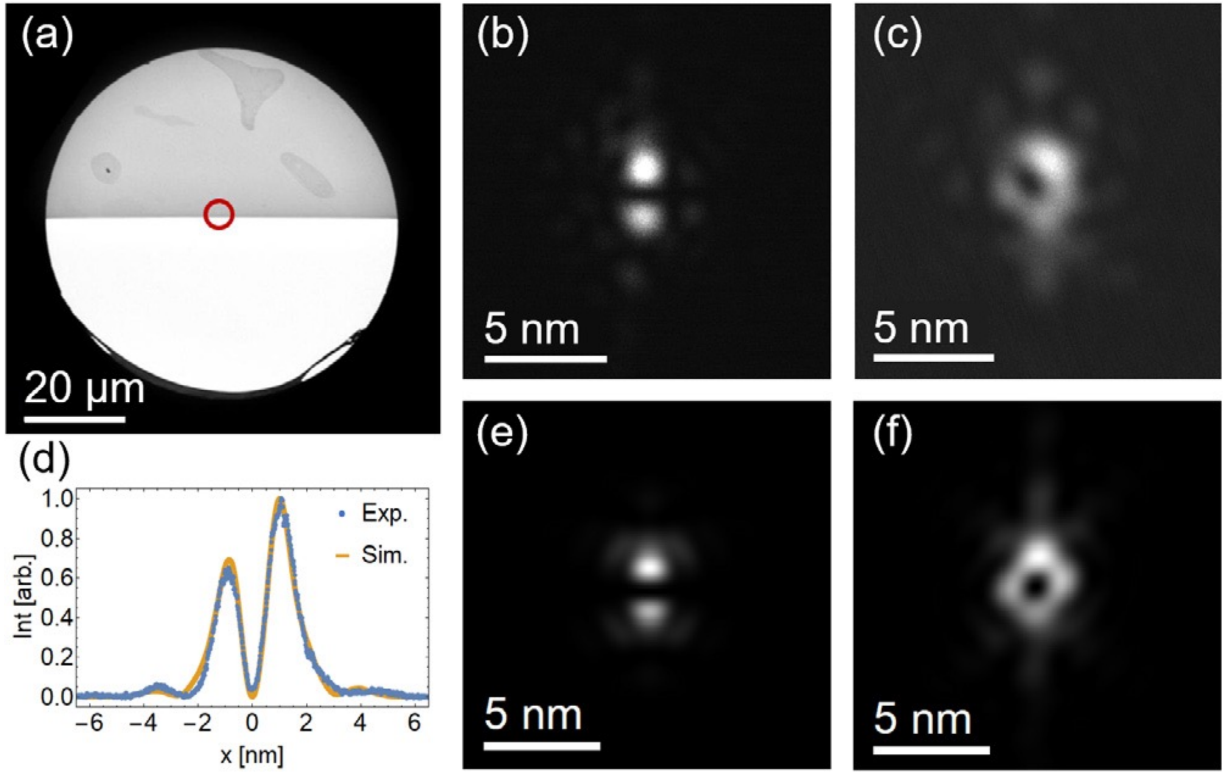
Instead we used 2 quadrupoles in the CEOS DCOR probe corrector on Juelich Titan PICO microscope



C. Kramberger *et al.* Ultramic. 204, 27 (2019)
T. Schachinger *et al.* Ultramic. 229, 113340 (2021)

Experimental demonstration

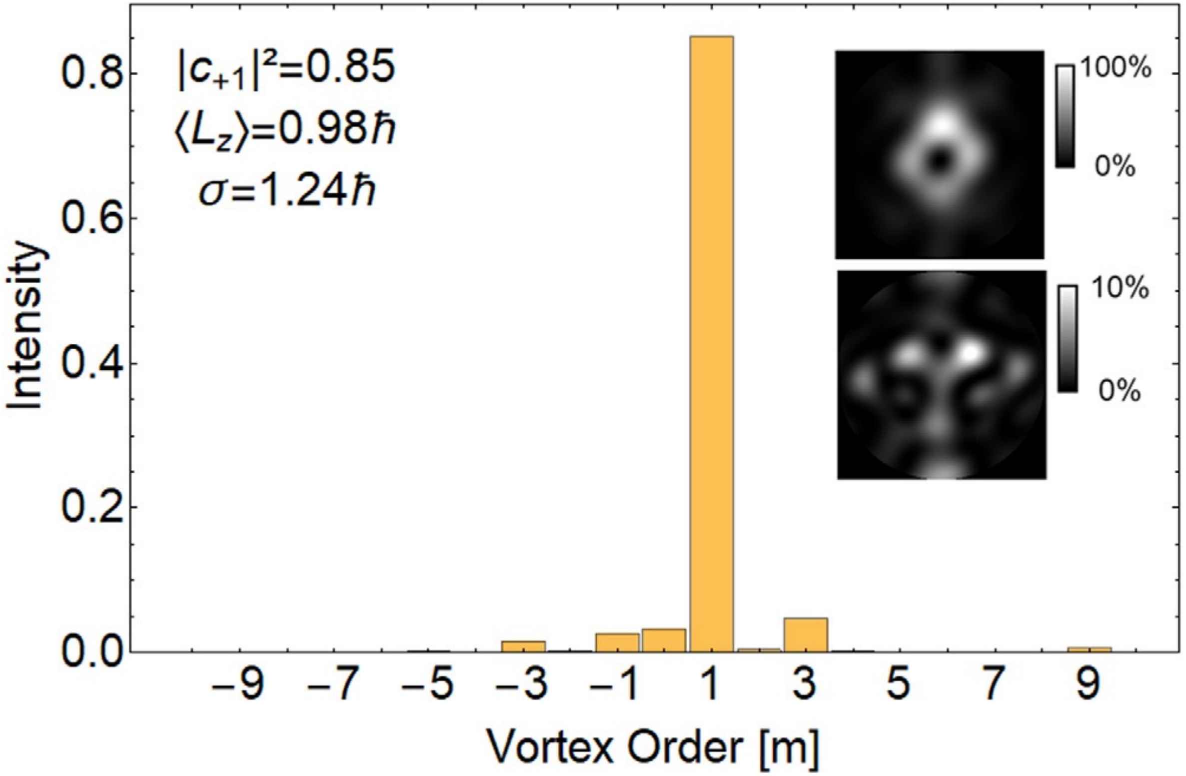
Experimental



Simulation

T. Schachinger *et al.* Ultramic. 229, 113340 (2021)

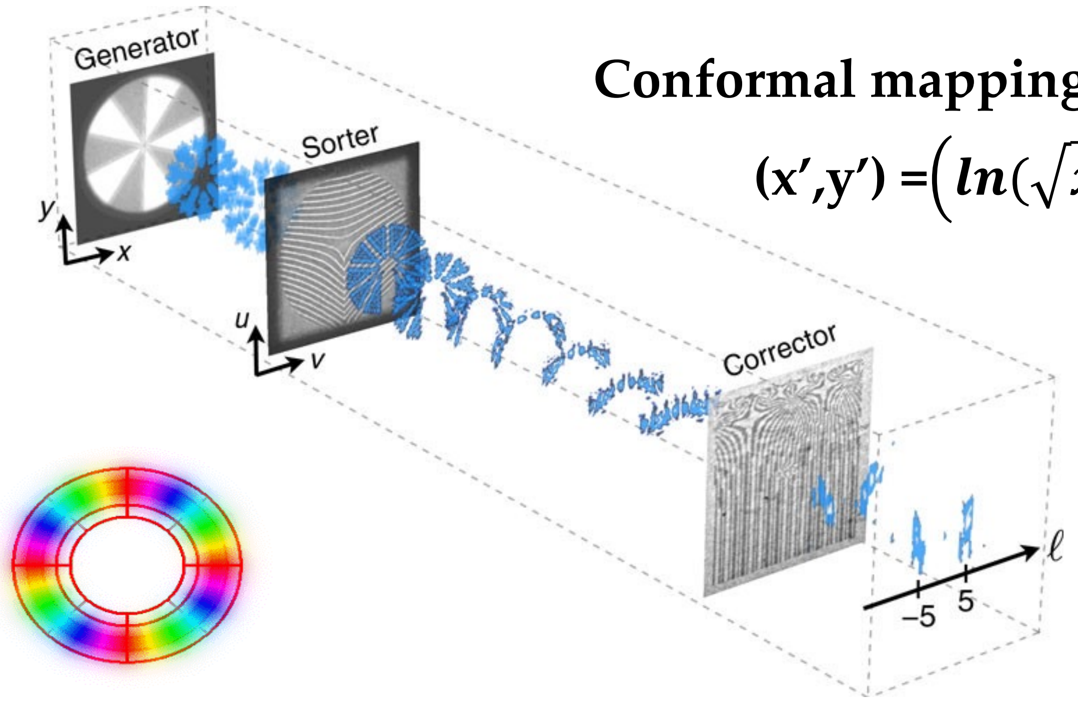
OAM spectrum decomposition by comparing with image simulation



Can we measure free electron OAM modes directly as a spectrum like e.g. EELS?

OAM sorter

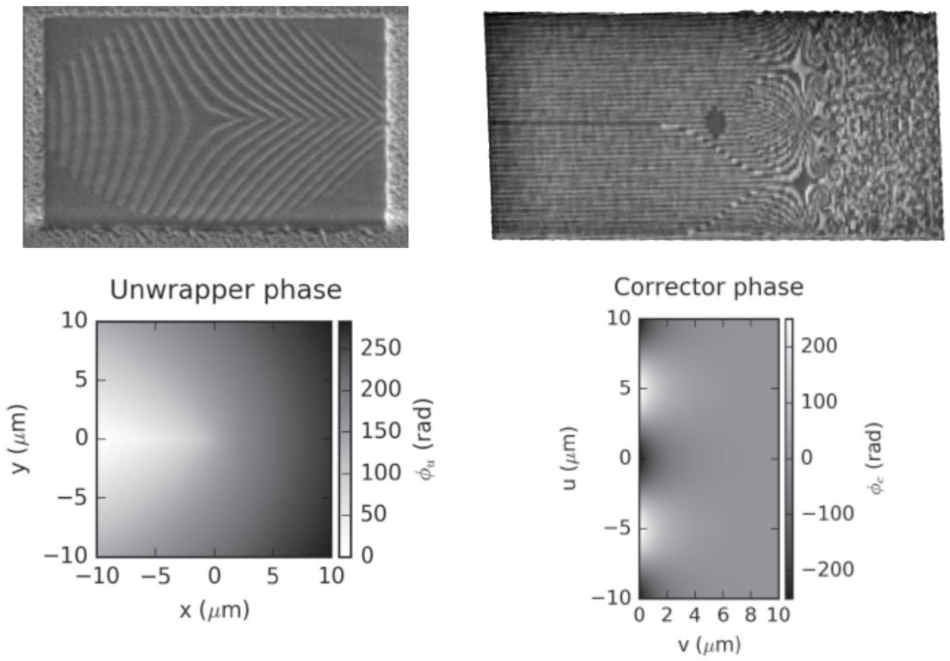
Collaboration:
CNR (Vincenzo Grillo and his co-workers)
FZ Juelich (Amir Tavabi and others)
TFS (Peter Tiemeijer)



Conformal mapping: Log-polar transformation

$$(x',y') = \left(ln\left(\sqrt{x^2 + y^2}\right), \mathrm{atan}(y/x) \right)$$

Thin film-based holographic masks

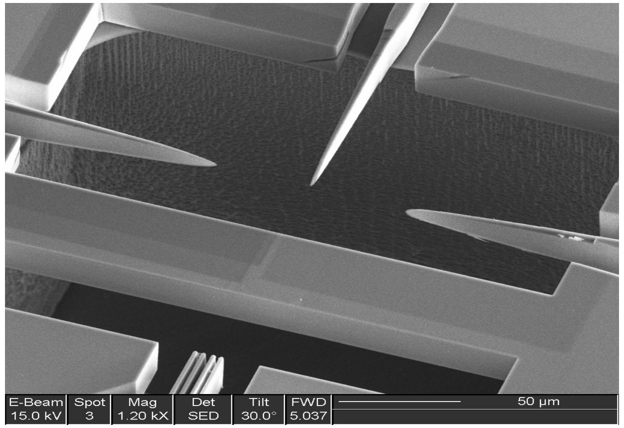


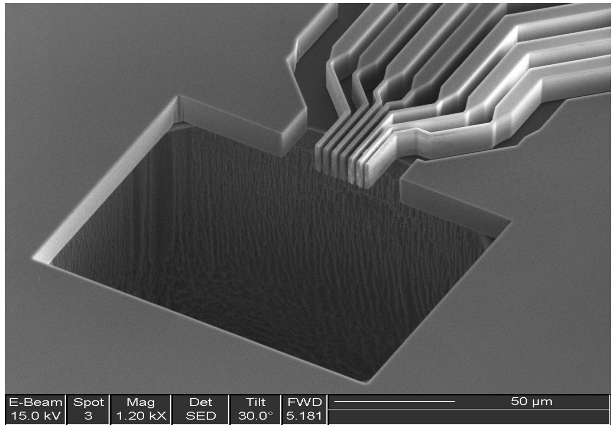
The transformation of coordinates (in geometric optics approximation) transforms a vortex into a plane wave that can be analysed by a diffraction lens

G.C.G. Berkhout *et al.* Phys. Rev. Lett. 105, 153601 (2010)
V. Grillo *et al.* Nature Commun. 8, 15536 (2017)

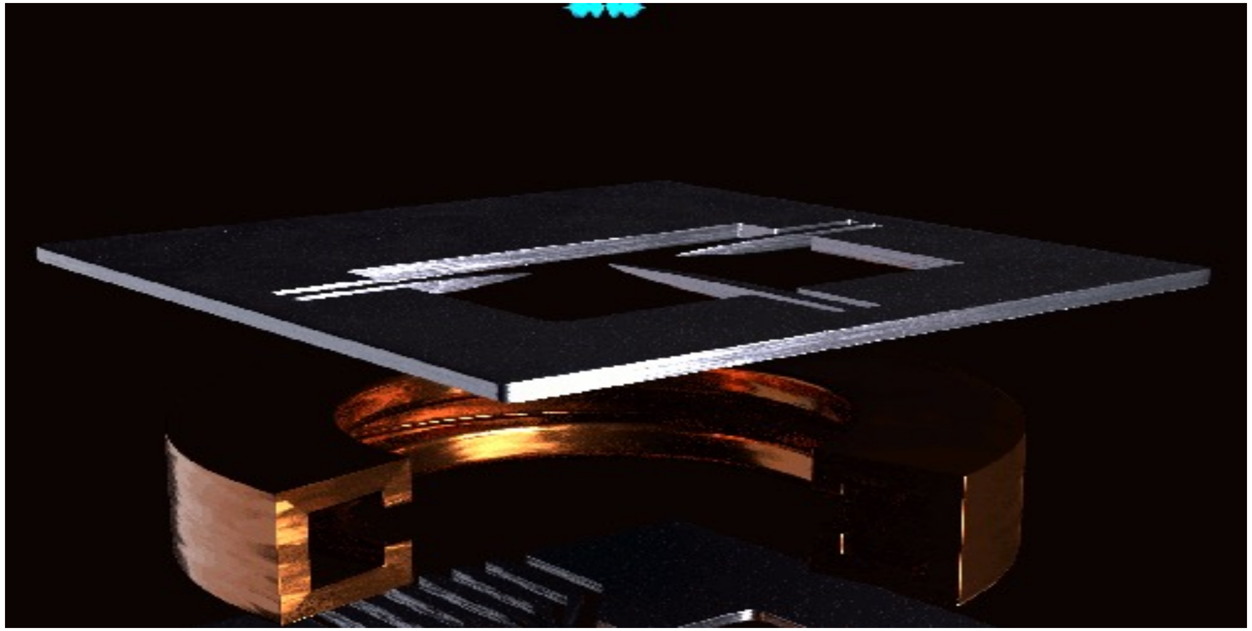
Electrostatic OAM sorter

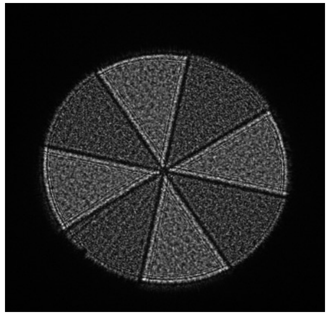
Sorter-1 - OBJ aperture



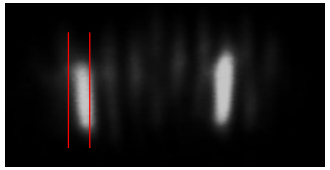


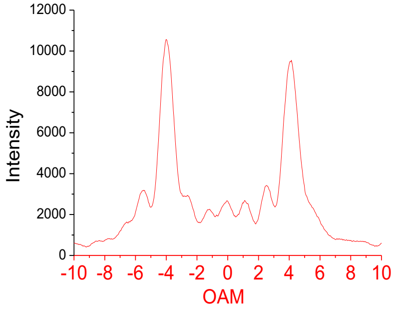
Sorter-2 - SAD aperture





$\Delta L = 1.1\,\hbar$

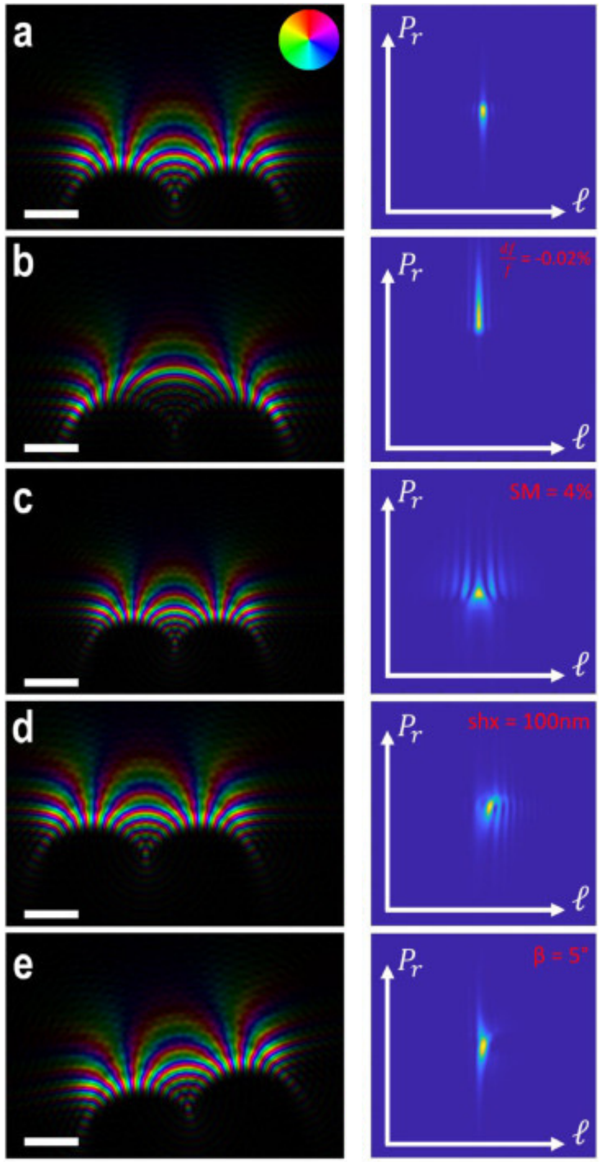




A. Tavabi *et al.* Phys. Rev. Lett 126, 094802 (2021)

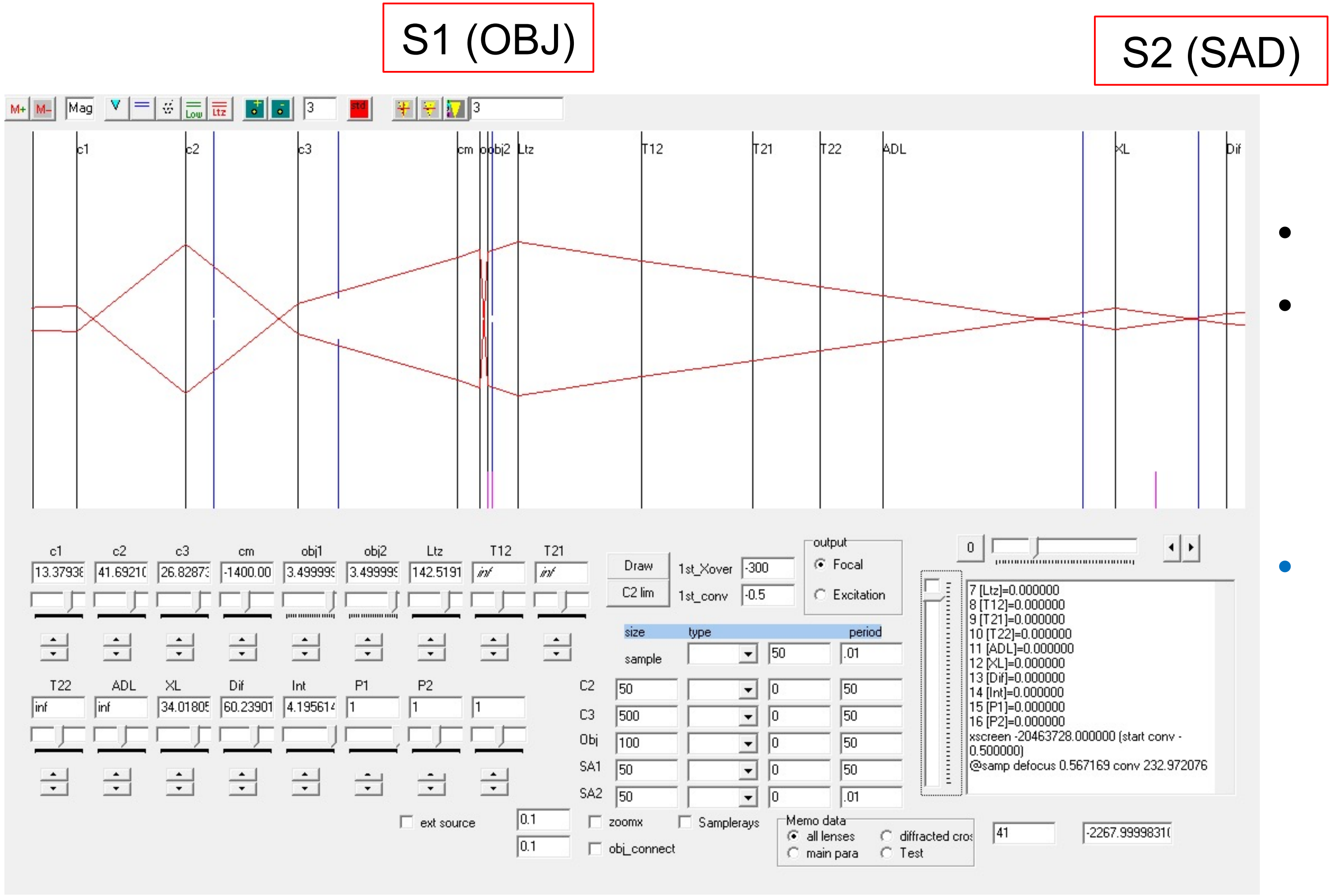
Align sorter devices

Match between S1 (OBJ) and S2 (SAD) – image corrector and XL lenses



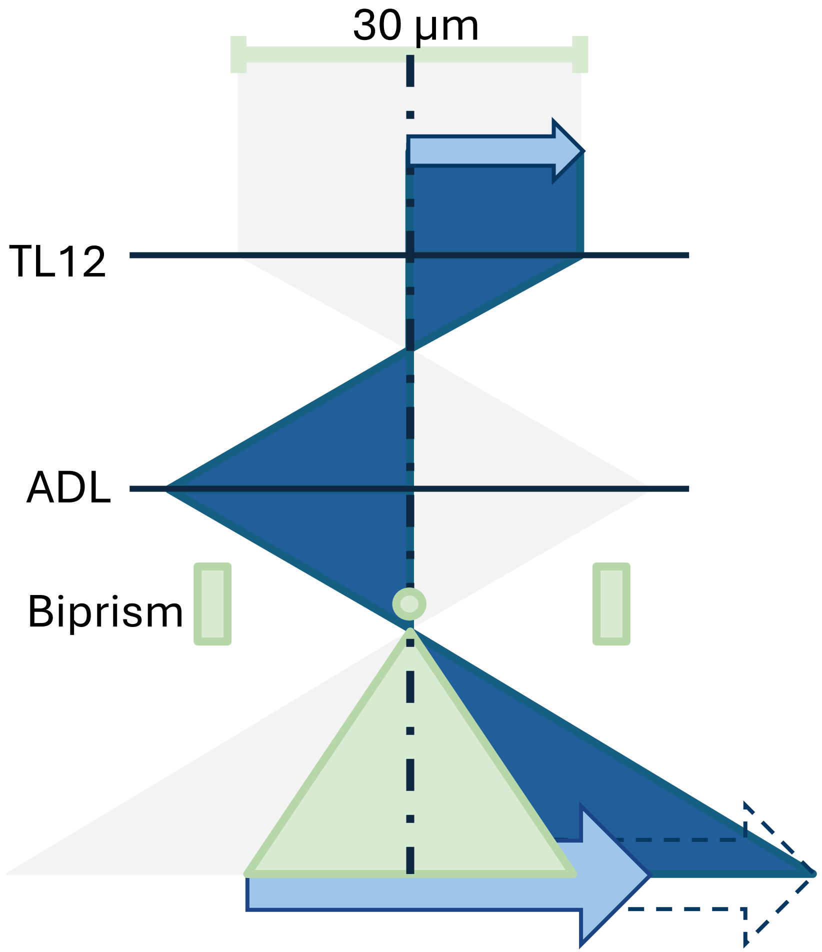
Ideal	
Out of focus	Image corrector + XL lens combination to change focus
Size mismatch	Image corrector + XL lens combination to change size
Lateral shift	Deflectors
Rotation	Image corrector + XL lens combination to change rotation

Magnifying S1 image to S2



- **Nanofabrication limit to make S2 small**
- **Tuning the electrostatic field of S1 can help but a large excitation is undesirable because of parasitic large aberration**
- **Image corrector off (except TL11 and sometimes ADL) and excitation of XL produces an effective long camera length of f =1.4 m**

Similar tweaking corrector lens for large FoV holography



Credit: Tolga Wagner (HU Berlin) and Martin Linck (CEOS)

The large field of view holography was achieved by tuning final transfer lenses (TL12, ADL) of image corrector as a demagnifying objective and placing the crossover closer to the biprism plane, thus allowing a wide width of the interference pattern at medium interference fringe spacings.

Alternative setup (developed by myself)
in OL-off LM mode reaching (10-40 µm)^2 interference FoV.
As an example, a 22µm*22µm FoV holography reconstructed phase image from a phase plate device.