Generating Orbital Angular Momentum Beams in an FEL Oscillator

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Steve Benson (Jlab)

This work is part of PhD research of Peifan Liu

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TUNL

Outline

Duke UNIVERSITY

- Structured Light with Orbital Angular Momentum (OAM)
  - Basic Physics and its Applications
  - OAM Beam Generation

- Duke FEL Oscillator:

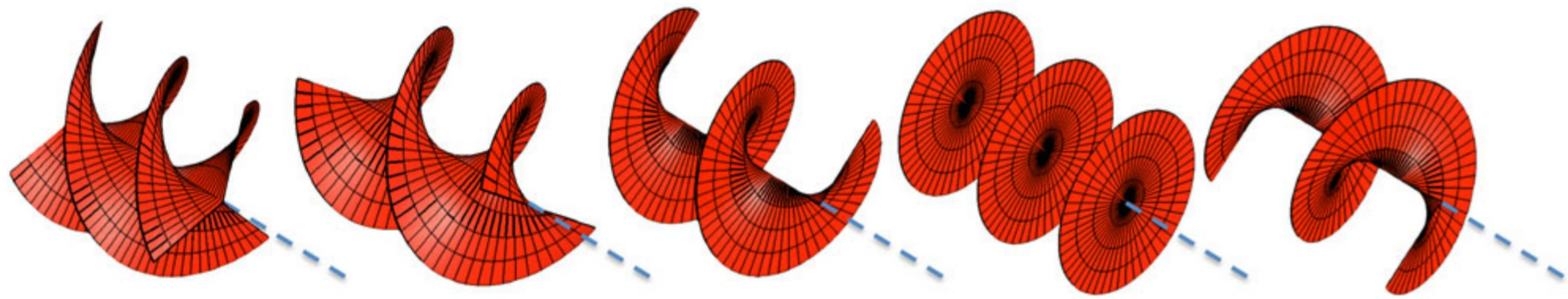
  OAM Beam Generation and Characterization

- Potential Research Applications

Structured Light

Light/photons

- Wave-particle duality
- "Photons" — Einstein's indivisible "light quanta," a "new" picture of light in 1905
- Energy: $E=h\upsilon$, momentum: $p=E/c$ (zero rest mass)
- Spin-1 boson, two eigenstates corresponding to spin angular momentum $\pm\hbar$ per photon
- Orbital angular momentum (OAM), $\pm l\hbar$ per photon, $|l\rangle \Leftrightarrow e^{il\theta}$



Structured light, twisted light, OAM beam, helical beam, vortex beam

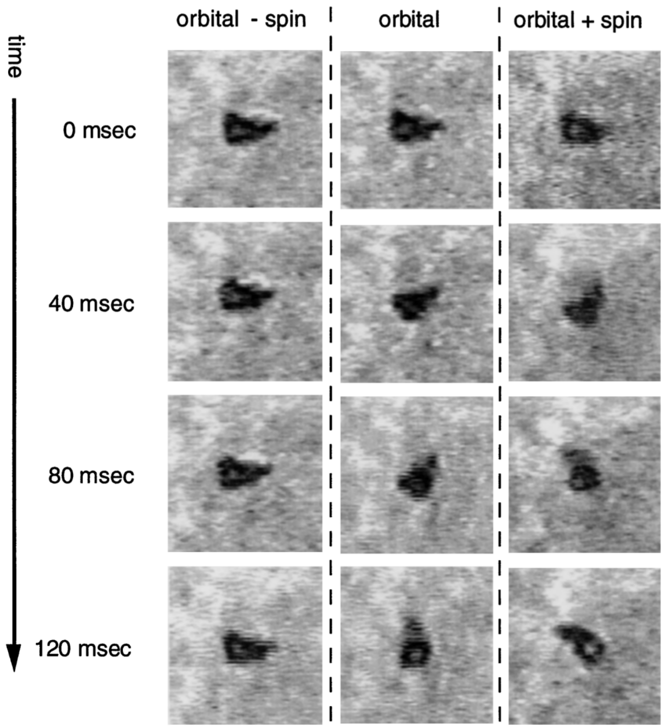
Applications:

- Optical tweezers — orientational manipulation of particles or particle aggregates
- Optical communications — high-bandwidth information encoding
- Quantum cryptography/computation — higher-dimensional quantum information encoding
- Sensitive optical detection
- Basic science research in atomic, nuclear, and particle physics (modified selection rules, dichroism)

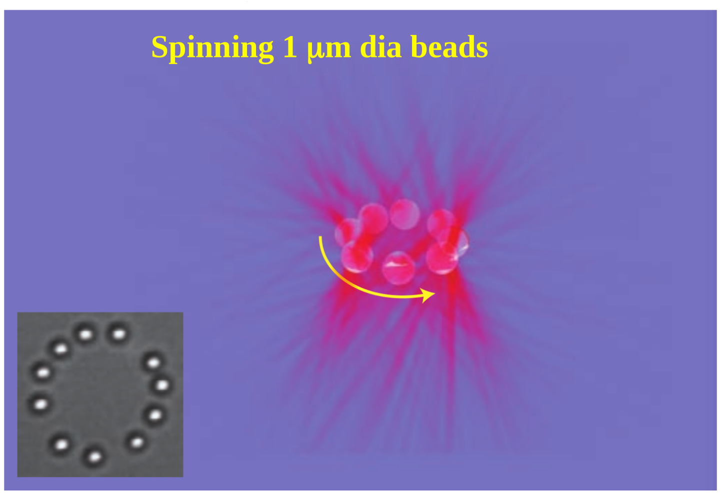
1. A. Einstein, Annalen der Physik, Vol.17, No.6, pp.132 – 148 (1905).
2. M. Padgett, "Light's twist." Proc. R. Soc. A. Vol. 470. No. 2172. The Royal Society, 2014. APA
3. http://www.popflock.com/learn?s=Angular_momentum_of_light

OAM Light Applications

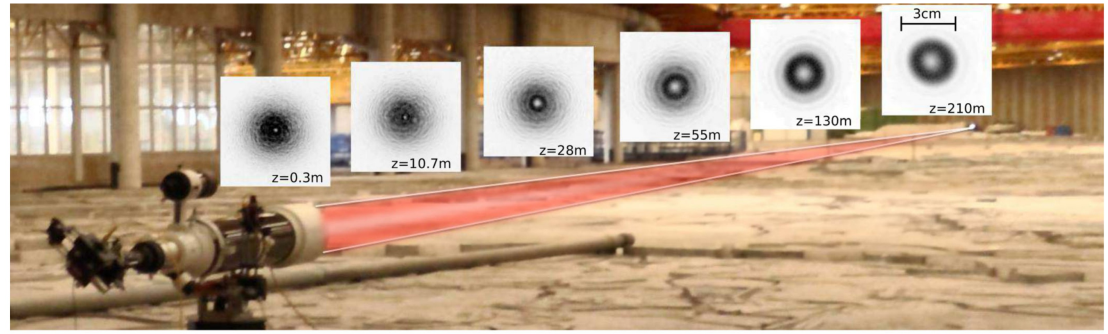
Optical tweezers using OAM beam



2 µm dia Teflon particles in fluid

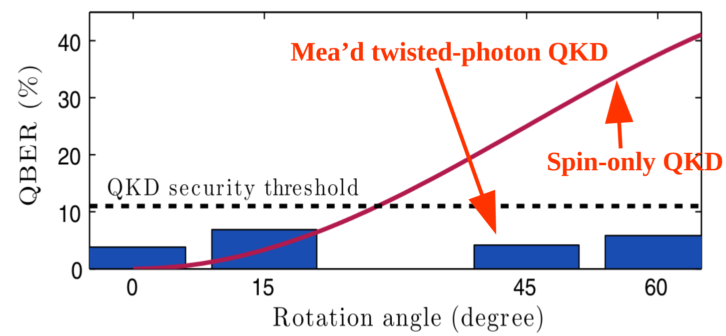


Quantum key distribution (QKD) in free-space



Basis set I: $\{|0\rangle = |L\rangle_{\text{spin}} \otimes |1\rangle_{\text{OAM}},\ |1\rangle = |R\rangle_{\text{spin}} \otimes |-1\rangle_{\text{OAM}}\}$

Basis set II: $\left\{\frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)\right\}$



- **Independent of local reference frame**
- **Reduced quantum bit error rate at large rotation angles**

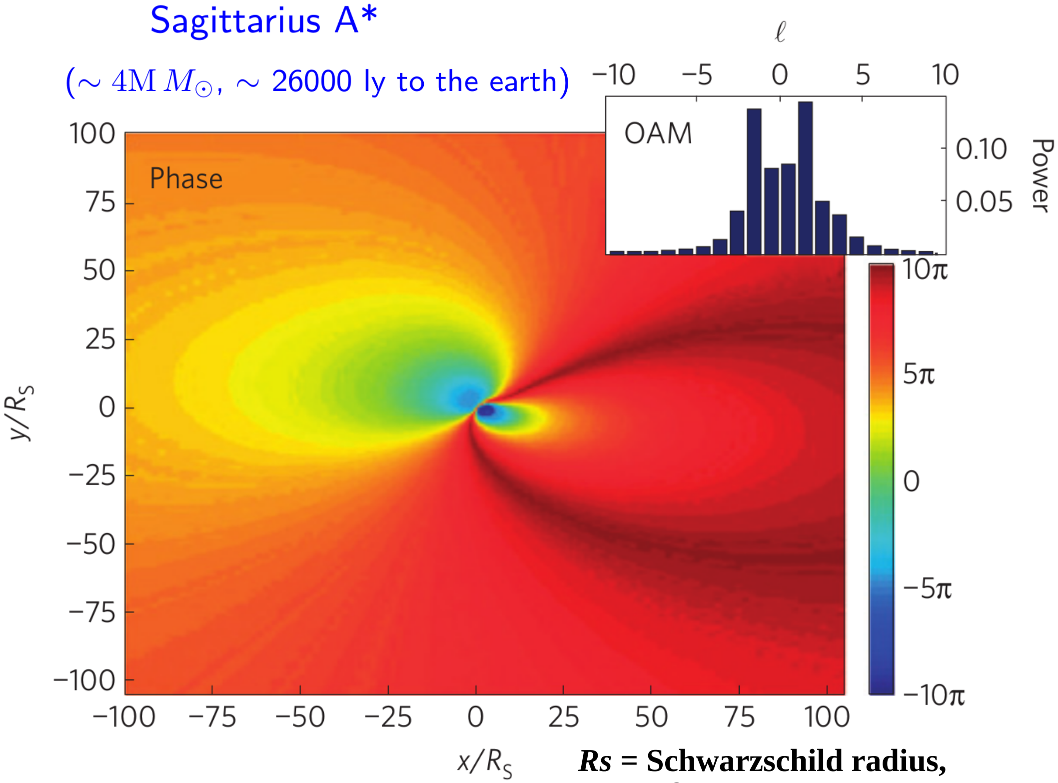
H. He *et al*. "Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity," PRL, 75, 826–829 (1995)
N.B. Simpson *et al*. "Mechanical equivalence of spin andorbital angular momentum of light: an optical spanner,"Opt. Lett. 22, 52–54 (1997)
M. Padgett *et al*. "Tweezers with a twist," Nat. Photon. 5, 343–348 (2011)
G. Vallone *et al*. "Free-space quantum key distribution by rotation-invariant twisted photons." PRL 113, 060503 (2014)

OAM Light Applications

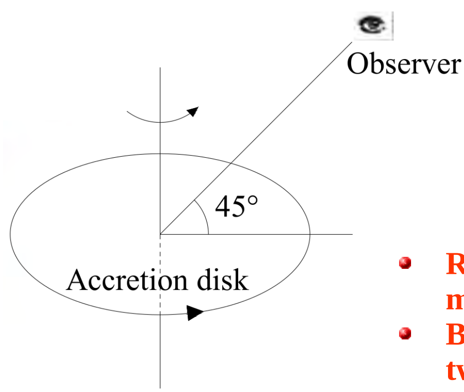
Twisting light around black holes

Sagittarius A*

($\sim 4\text{M}\,M_{\odot}$, $\sim$ 26000 ly to the earth)



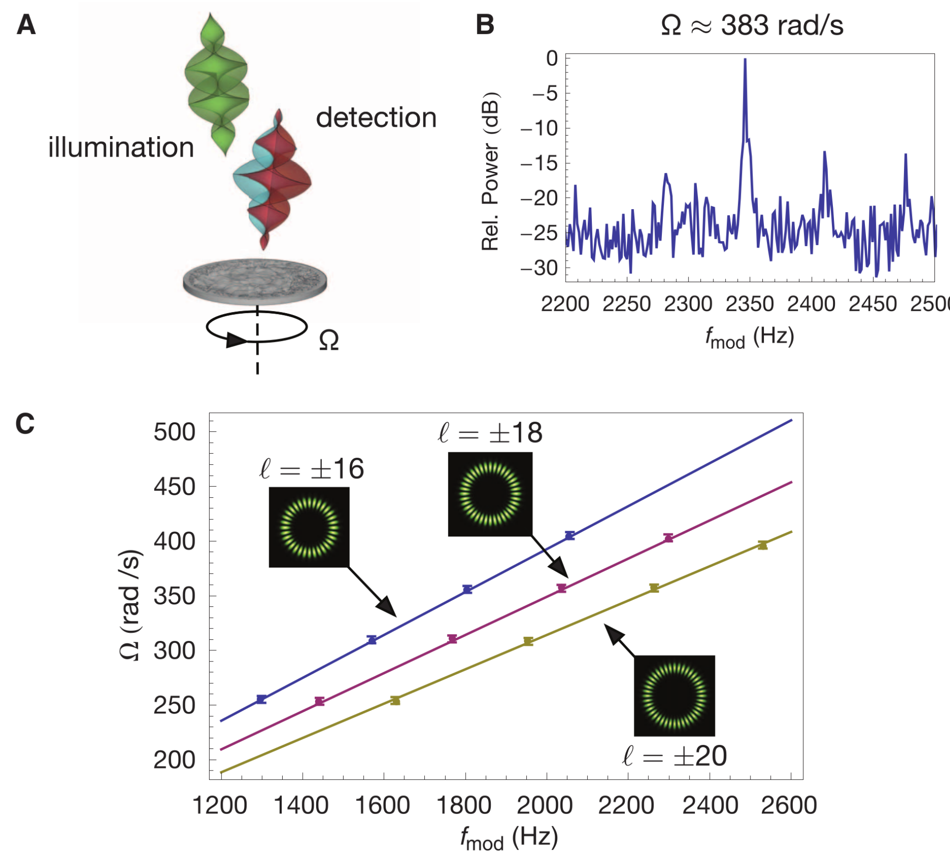
Rs **= Schwarzschild radius, $2GM/c^2$**

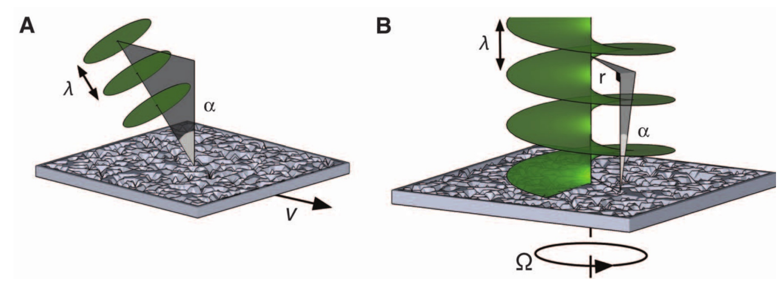


- **Rotating black hole deflects and phase-modifies light emitted near it**
- **Black hole detection via measurement of twisted light**

F. Tamburini, *et al*. "Twisting of light around rotating black holes." Nature Physics 7, pp. 195–197, (2011)

OAM to detect spinning object



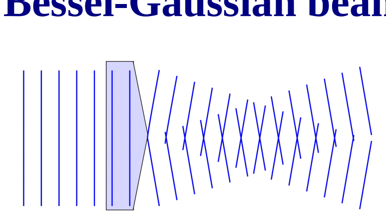


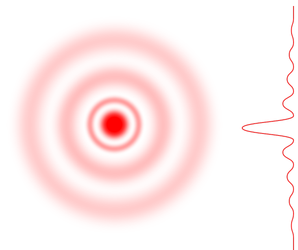
- **Rotational Doppler effect**
- **OAM based imaging and sensing of rotating bodies in astronomical setting**

M. Lavery *et al*. "Detection of a spinning object using lights orbital angular momentum." Science 341.6145, pp. 537–540 (2013)

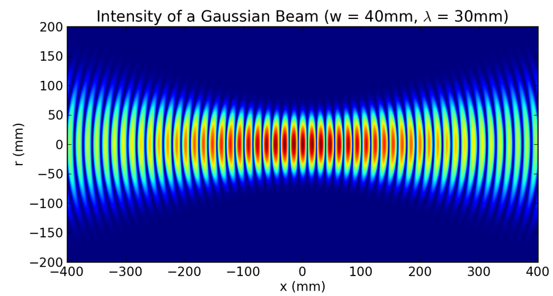
OAM Beams

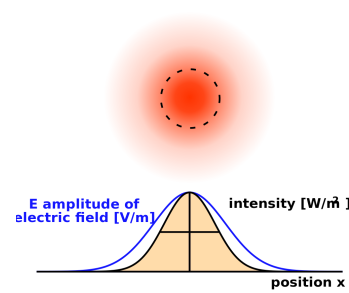
- Light beam with cylindrical coordinates
  - Hypergeometric-Gaussian modes (overcomplete, nonorthogonal)
  - Bessel beams
    - Diffraction-free, non-paraxial, infinity energy
    - Practical realization: Bessel-Gaussian beams





  - Gaussian beams
    - Diffracting, paraxial, finite energy
    - Cylindrical geometry: Laguerre-Gaussian modes (complete and orthogonal)
    - Rectangular geometry: Hermite-Gaussian modes (complete and orthogonal)



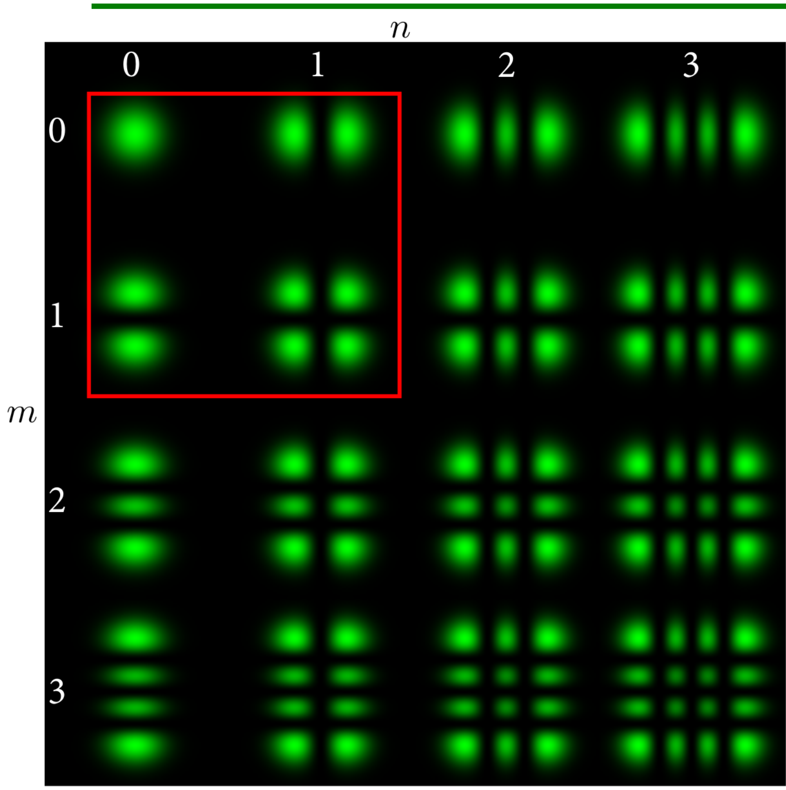


Hermite-Gaussian: $u_{m,n}(x,y,z)=\frac{C_{m,n}}{w(z)}H_m\left(\frac{\sqrt{2}x}{w(z)}\right)H_n\left(\frac{\sqrt{2}y}{w(z)}\right)\exp\left(-\frac{x^2+y^2}{w^2(z)}\right)\exp\left(-ik\frac{x^2+y^2}{2R(z)}\right)\ e^{i(m+n+1)\psi_0(z)}$

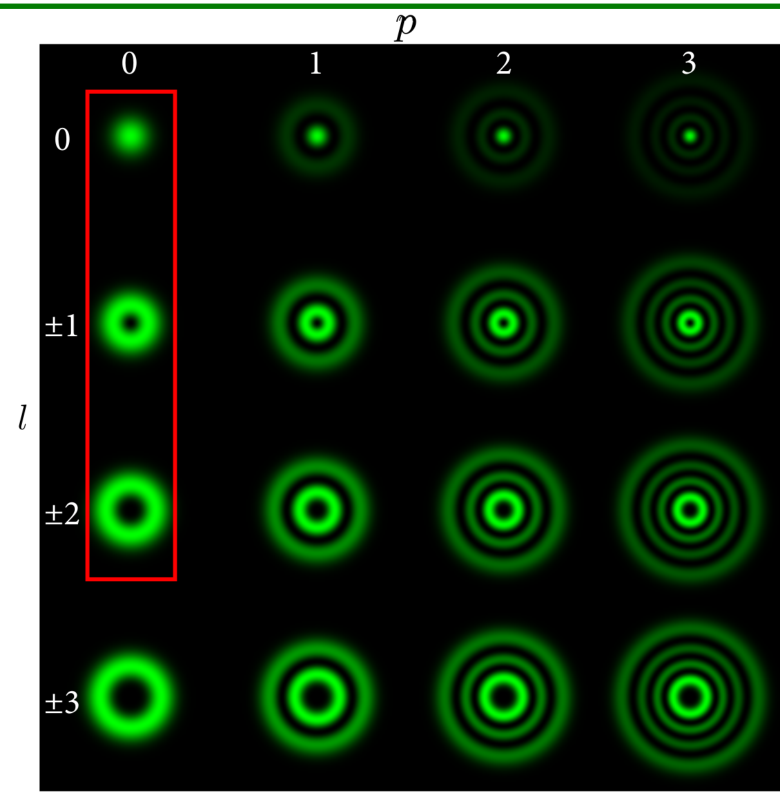
Laguerre Gaussian: $u_{l,p}(r,\phi,z)=\frac{C_{l,p}}{w(z)}\left(\frac{\sqrt{2}r}{w(z)}\right)^{|l|}L_p^{|l|}\left(\frac{2r^2}{w(z)^2}\right)\exp\left(\frac{-r^2}{w^2(z)}\right)\exp\left(-ik\frac{r^2}{2R(z)}\right)\ e^{-il\phi}e^{i(|l|+2p+1)\psi_0(z)}$

1. https://en.wikipedia.org/wiki/Bessel_beam; 2. https://en.wikipedia.org/wiki/Gaussian_beam

OAM Laser Modes



Hermite-Gaussian (HG) modes

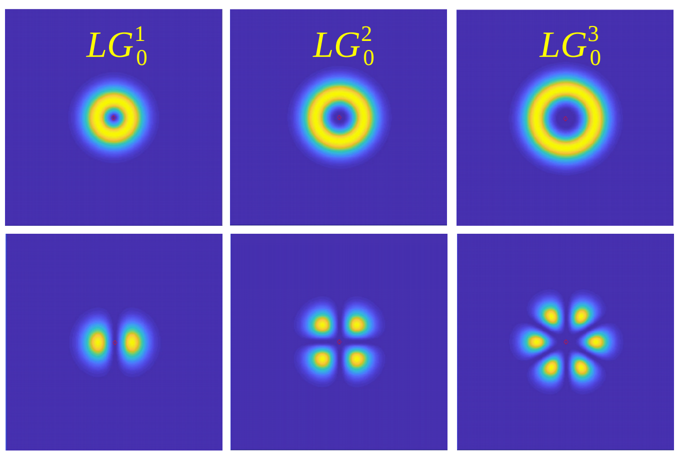


Laguerre-Gaussian (LG) modes

$HG_{0,0} = LG_0^0,\quad HG_{0,1} = \frac{i}{\sqrt{2}}(LG_0^1 - LG_0^{-1})\quad HG_{1,0} = \frac{1}{\sqrt{2}}(LG_0^1 + LG_0^{-1}),\quad HG_{1,1} = \frac{i}{\sqrt{2}}(LG_0^2 - LG_0^{-2})$

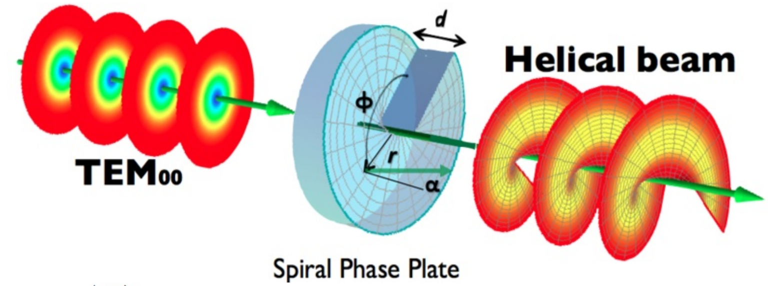
Pure LG modes

Coherently mixed modes
$LG_0^m \quad + \quad LG_0^{-m}$



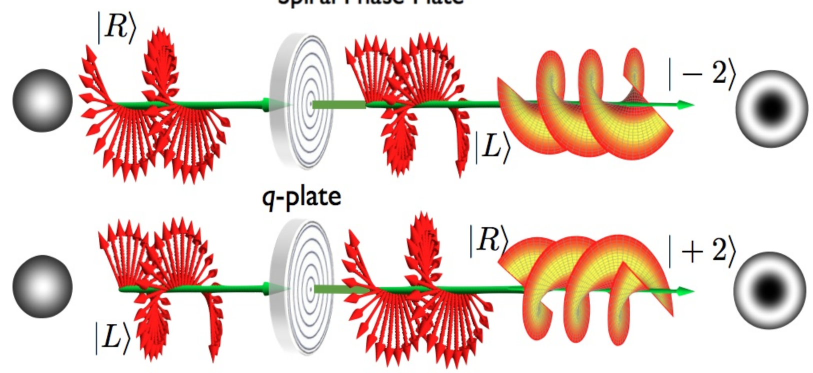
OAM Light Generation: Outside a Cavity

- Spiral Phase Plate

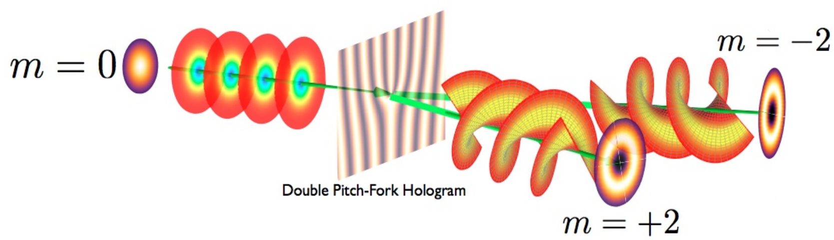


- Q-Plate

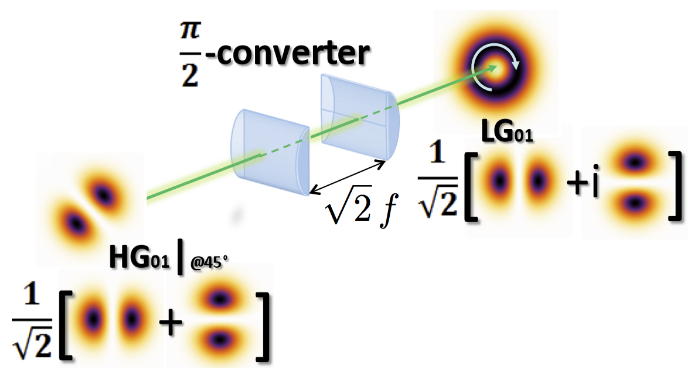
  (SAM-OAM coupling)



- Pitchfork-Hologram



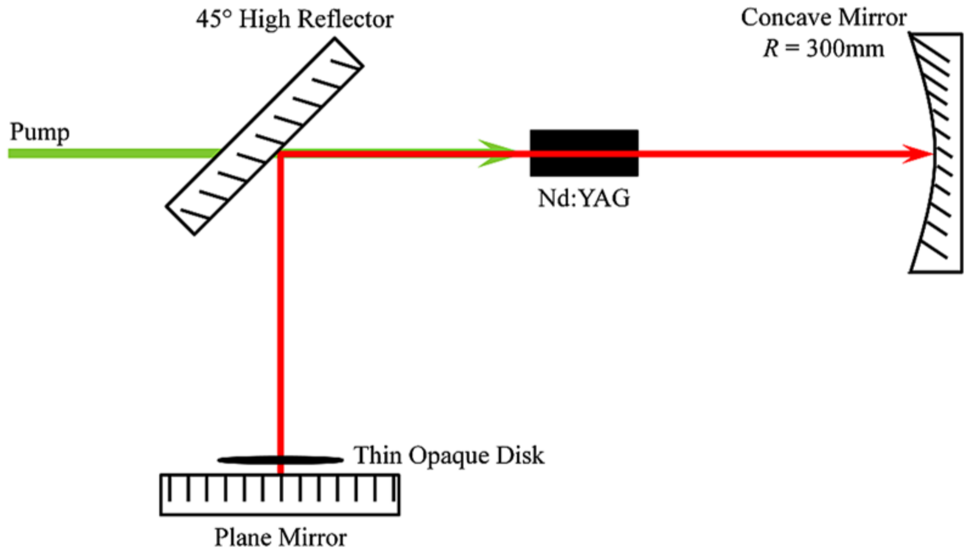
- Cylindrical Mode Converters

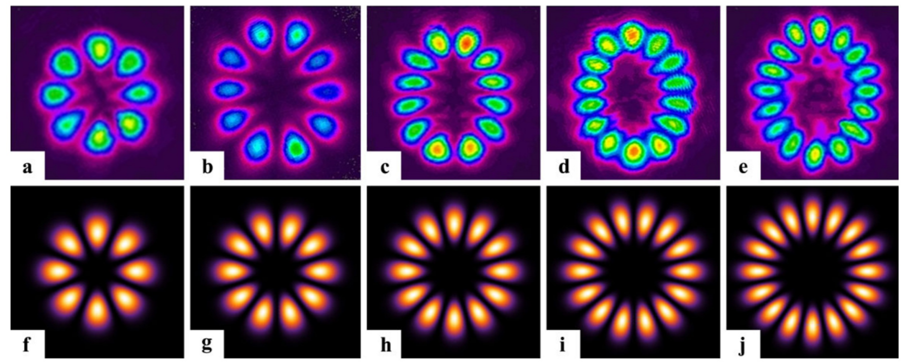


1. wikipeida.org;
2. http://www.popflock.com/learn?s=Angular_momentum_of_light

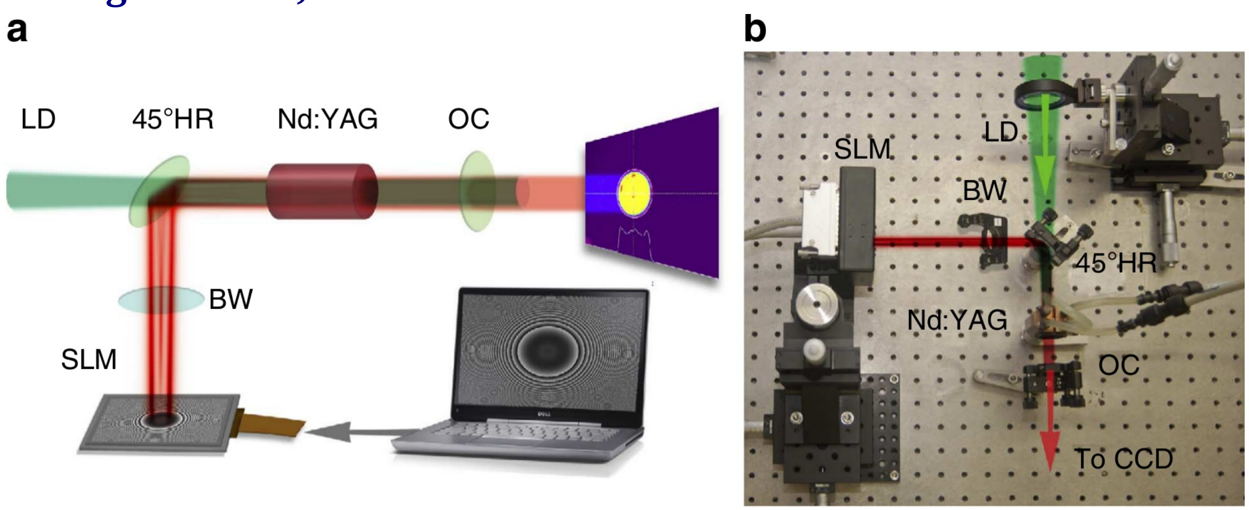
OAM Light Generation: Inside a Cavity

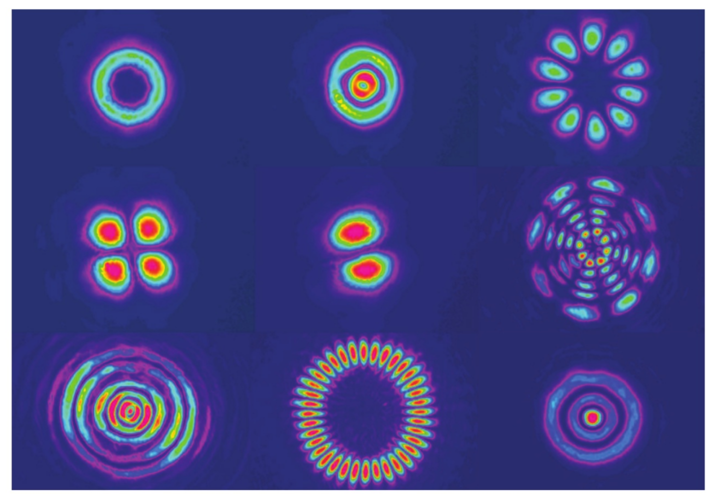
Intra-cavity mask: amplitude or phase mask





Digital Laser, with SLM





1. D. Naidoo *et al*. ”Intra-cavity generation of superpositions of LaguerreGaussian beams,” App. Phys. B, 106.3, pp. 683–690 (2012).
2. S. Ngcobo *et al*. ”A digital laser for on-demand laser modes,” Nat. Comm. 4:2289 (2013).

Summary: Intracvity OAM Light Generation

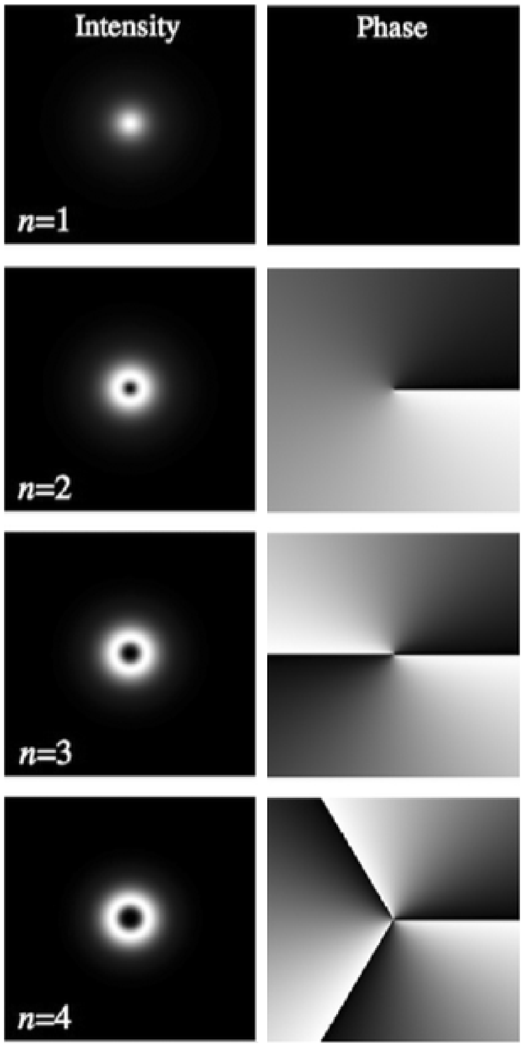
Author	Laser type	Wavelength	Roundtrip length	Output Power	Technique	Comment
A. Ito, 2010	Nd:YAG side pumped	1064 nm?	0.35–1.50 m	Not mentioned	Spot-defect mirror	Vector (scalar) polarization
D. Naidoo 2011	Microchip laser (Nd:YVO4) end pumped	1064 nm?	1 mm	~12 mW	Donut-shape pump	LG01, pi phase plate
M. P. Thirugnanasam bandam, 2011	Yb:YAG end pumped	1030 nm	0.8–2.4 m	Up to 60 mW	intra-cavity lens and birefringent uniaxial crystal	Radial, azimuthal polarization OAM
D.J. Kim 2013	Nd:YAG side pumped	1064 nm	Not mentioned	Average 25 mW (pulsed)	Q-switched, Donut-shape pump	Etalon for handness control
D. Lin 2014	Nd:YAG side pumped	1064 nm	0.44 m	~ 1 W	Donut-shape pump	Wires for handness control
D. J. Kim 2015	Nd:YVO4 end pumped	1064 nm	14 mm	100 mW	Donut-shape pump	Etalon for handness control
Y. Zhou 2016	All fiber laser	1547 nm	Fiber	Average 13 mW (pulsed)	Fiber Bragg grating	Mode locked, pulsed
D.J. Kim 2017	Nd:YAG side pumped	1064 nm?	Not mentioned	~ 500 mW	Dual cavity with two apetures	Etalon for handness control
S. Wang 2018	Yb:KYW,double end pumped	Not mentioned	~ 2.4 m	~ 220 mW	Cavity astigmatism	Double end pumped
D. Wei 2019	Nd:YVO4 side pupbed	1064 nm	0.5 –0.85 m	120 mW	Vortex wave plate	SAM-OAM conversion

All externally pumped

OAM Light Generation: Undulator Radiation

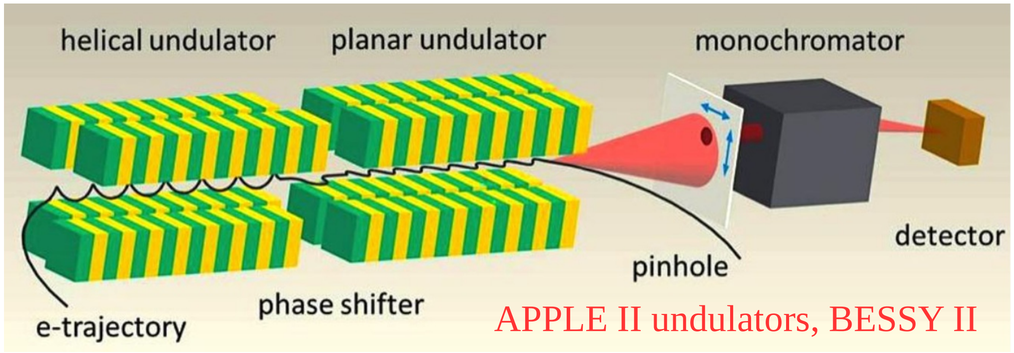
- **Helical undulator: Higher harmonic radiation**

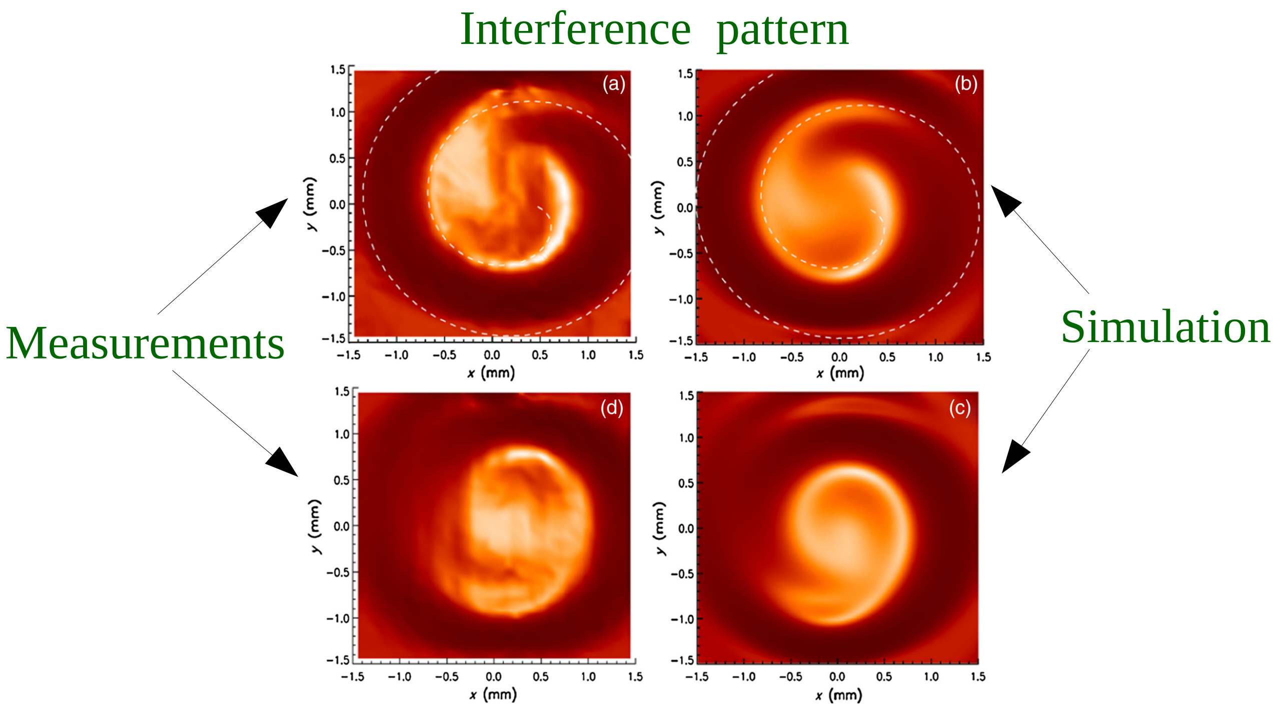
$$A = \sqrt{2}e^{i(n-1)\phi}\left\{\left(\gamma\theta - \frac{nK}{X}\right)J_n(X) - KJ_n{}'(X)\right\}$$



S. Sasaki and I. McNulty "Proposal for Generating Brilliant X-Ray Beams Carrying Orbital Angular Momentum" PRL 100, 124801 (2007)

- **First observation**

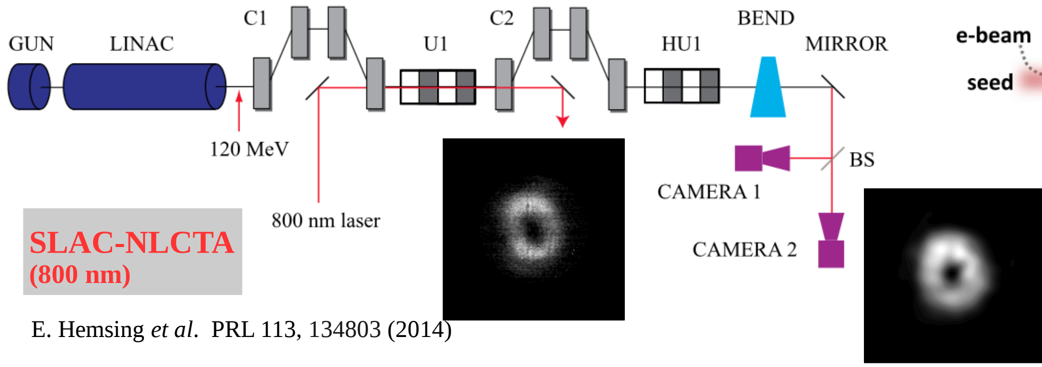




J. Bahrdt *et al.* "First Observation of Photons Carrying Orbital Angular Momentum in Undulator Radiation" PRL 111, 034801 (2013)

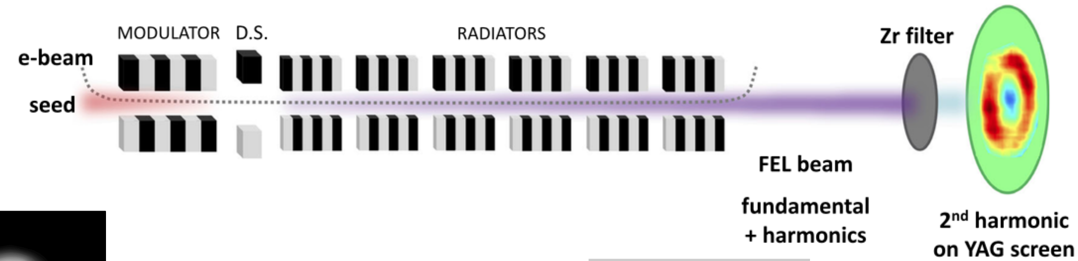
OAM Light Generation: FEL

Coherent undulator harmonic radiation



SLAC-NLCTA (800 nm)

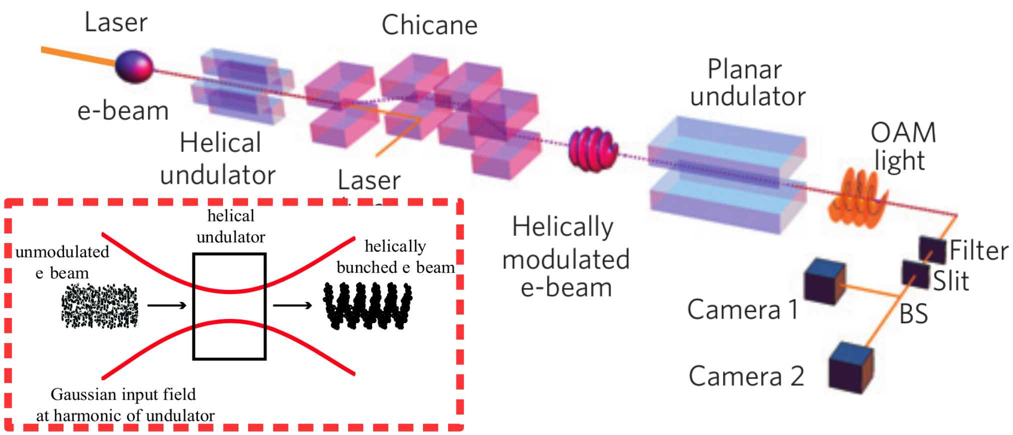
E. Hemsing *et al*. PRL 113, 134803 (2014)

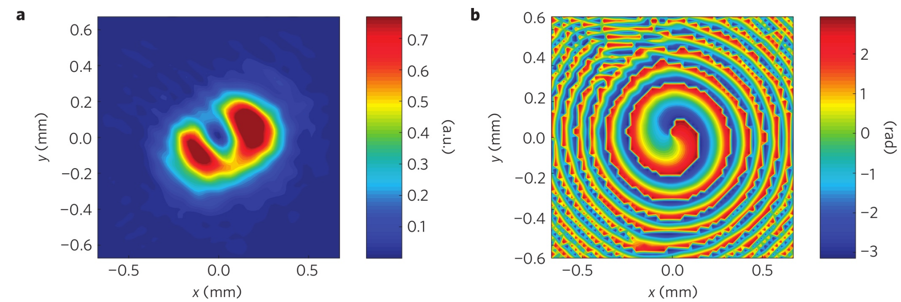


FERMI FEL
XUV (15.6 nm)

P.R. Ribič *et al*. PRX 7, 031036 (2017)

Fundamental radiation with helical bunching

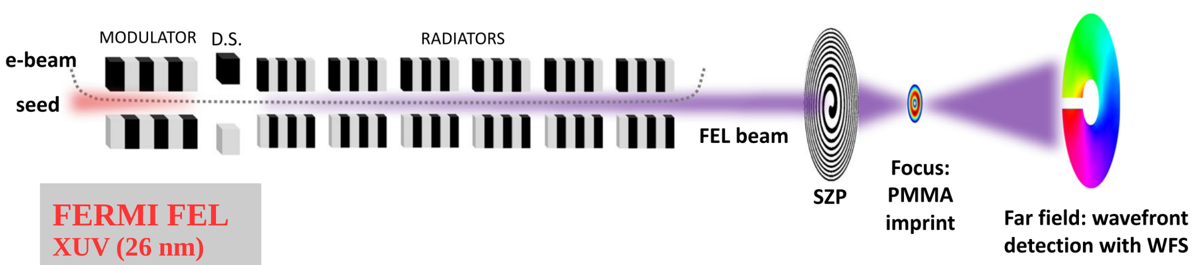




SLAC-NLCTA
(800 nm)

E. Hemsing *et al*. PRL 102, 174801 (2009)
E. Hemsing *et al*. Nat. Phys. 9, 549 (2013)

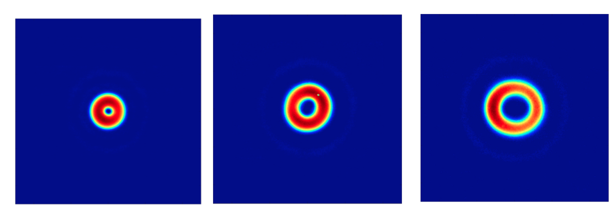
Fundamental lasing with spiral zone plate



FERMI FEL
XUV (26 nm)

P.R. Ribič *et al*. PRX 7, 031036 (2017)

l = 1 *l* = 2 *l* = 3



HIGS Facility

Facility/Project: HIGS

Institution: TUNL and Duke University

Country: US

Energy (MeV): 1 – 100

Accelerator: Storage Ring, 0.24 – 1.2 GeV

Laser: FEL, 1060 – 190 nm (1.17 – 6.53 eV)

Total flux: 10^{7} – $3x10^{10}$g/s (max ~10 MeV)

Spectral flux: 10^{3}g/s/eV (max ~10 MeV)

Status: User Program

Research: Nuclear physics, Astrophysics, National Security

Accelerator Facility

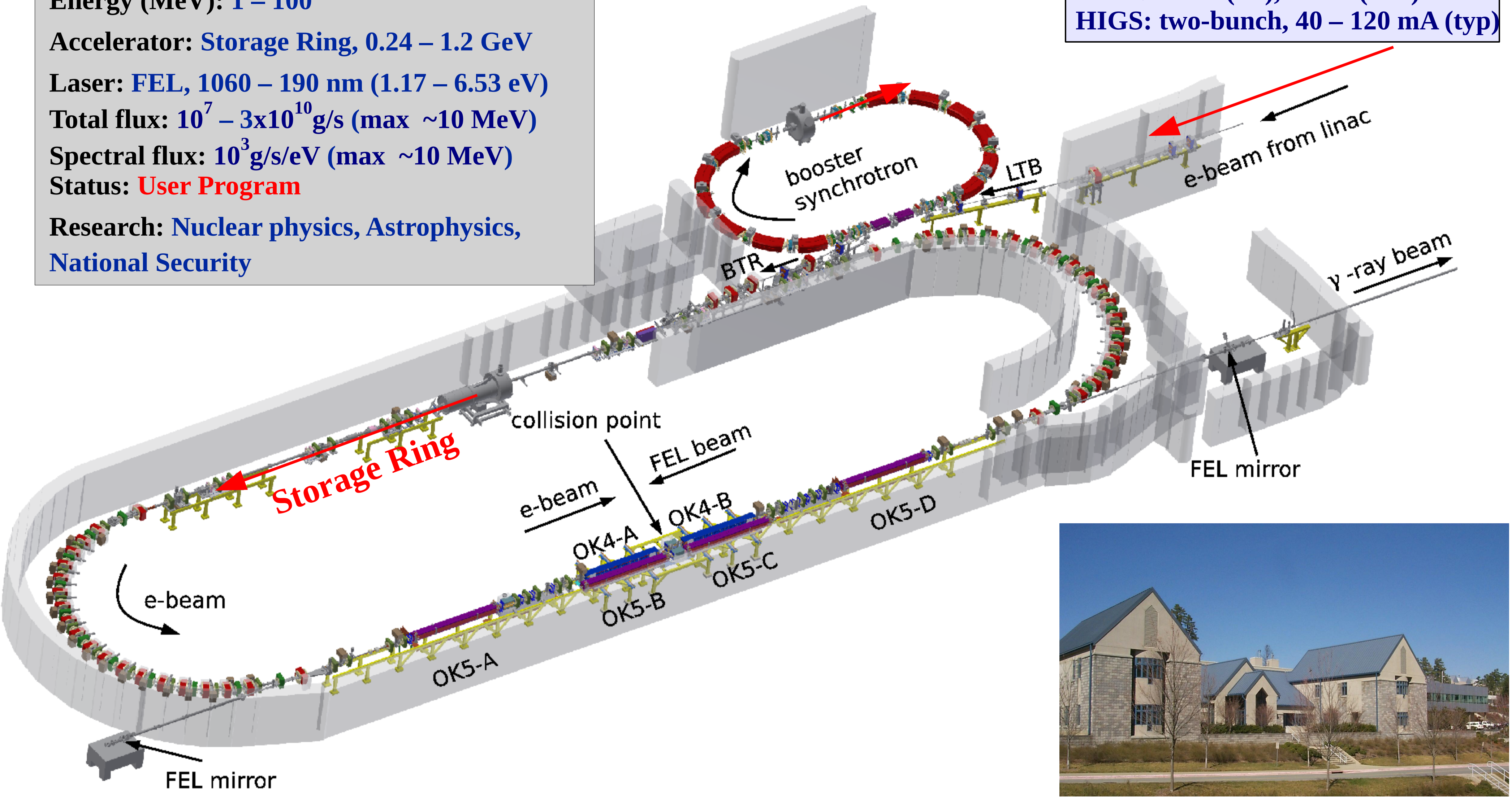
160 MeV Linac pre-injector

160 MeV – 1.2 GeV Booster injector

240 MeV – 1.2 GeV Storage ring

FELs: OK-4 (lin), OK-5 (circ)

HIGS: two-bunch, 40 – 120 mA (typ)

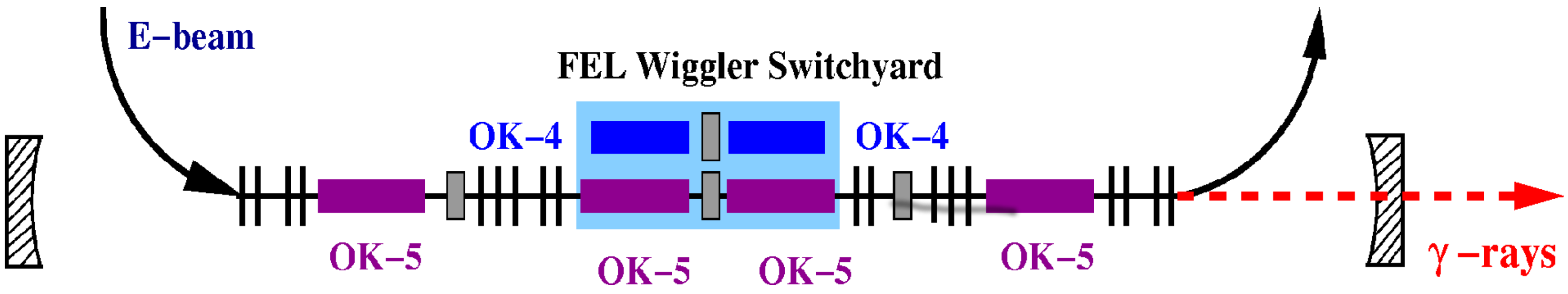


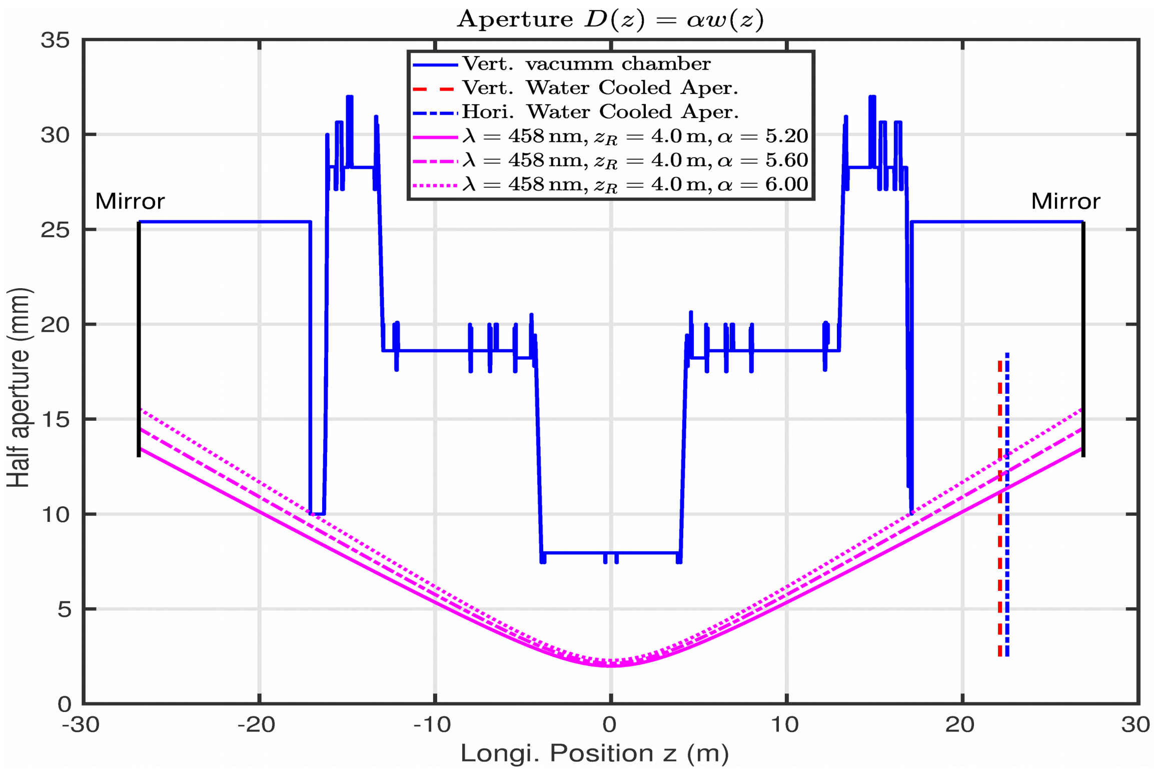
HIGS R&D Team (2004–2019): M. Busch, M. Emanian, J. Faircloth, B. Jia, H. Hao, S. Hartman, C. Howell, S. Huang, J. Li, S. Mikhailov, V. Popov, C. Sun, G. Swift, P. Wang, P. Wallace, W. Wu, Y.K. Wu, W. Xu. J. Yan

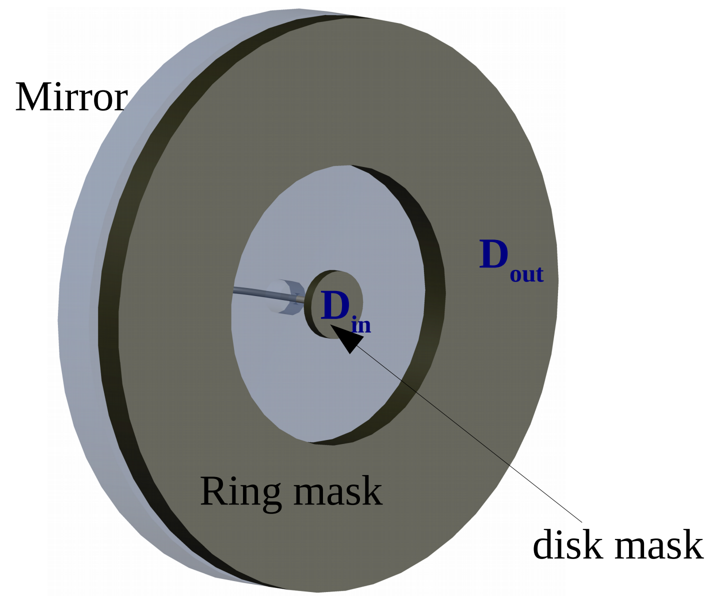
Duke FEL with OK-5 and OK-4 Wigglers

Wiggler Configurations with the Switchyard

1. Two OK-4 and Two OK-5 wigglers
2. Four OK-5 wigglers

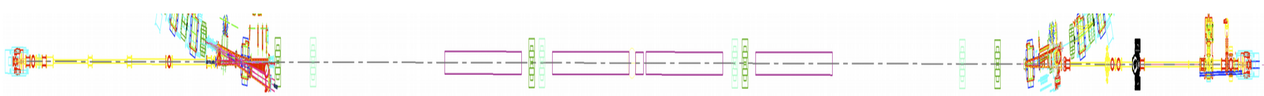




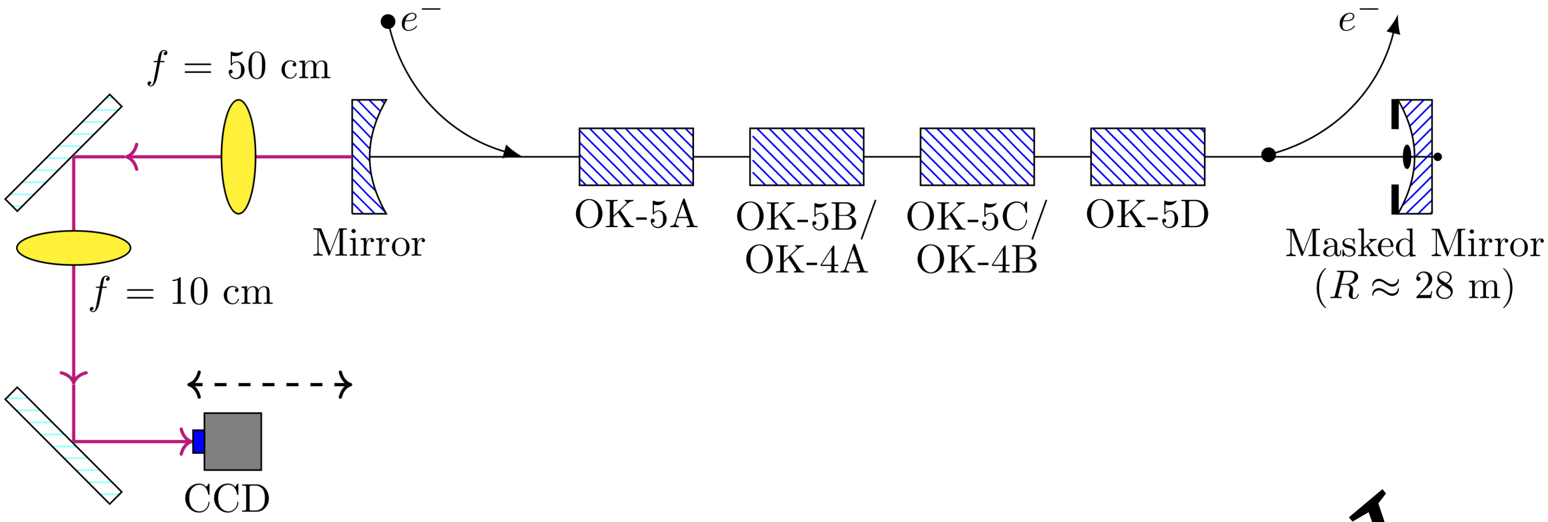


D_{out} = 26 mm

D_{in} = 2.0, 3.7, 4.2 mm

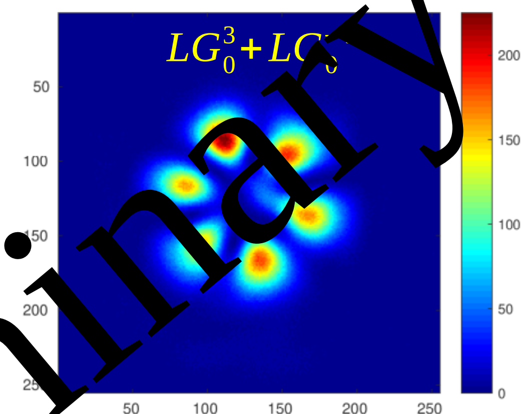


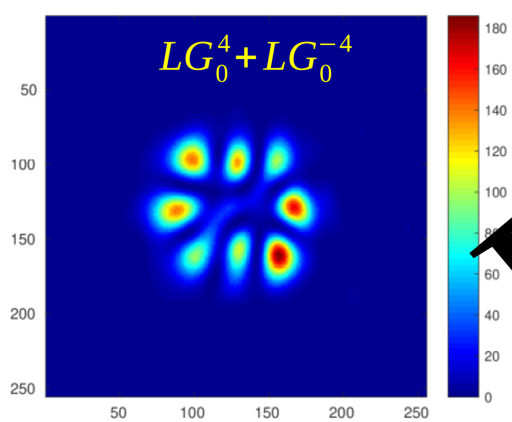
Oscillator FEL with OAM Beams

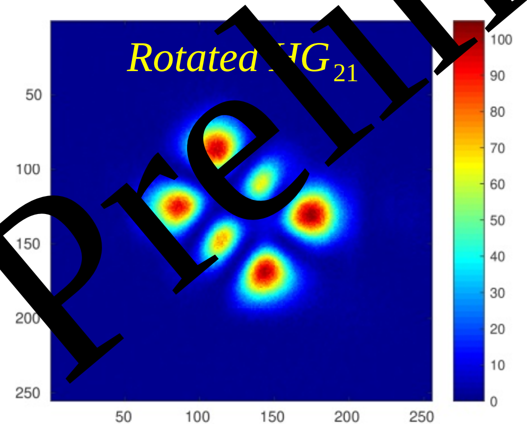


$LG_0^1 + LG_0^{-1}$

$LG_0^2 + LG_0^{-2}$







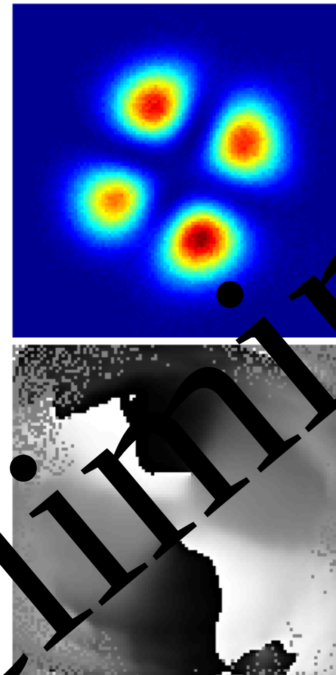
Outer ring diameter: 26 mm
Inner disk diameters: 2, 3.7, 4.2 mm

Helical undulator (3): OK5A, B, C
Ebeam: 518 MeV
FEL: ~460 nm

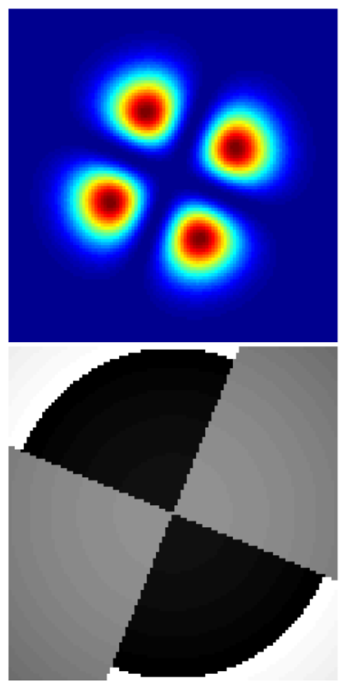
Oscillator FEL with OAM Beams

$LG_0^2 + LG_0^{-2}$

Measured
Intensity &
Reconstructed
Phase

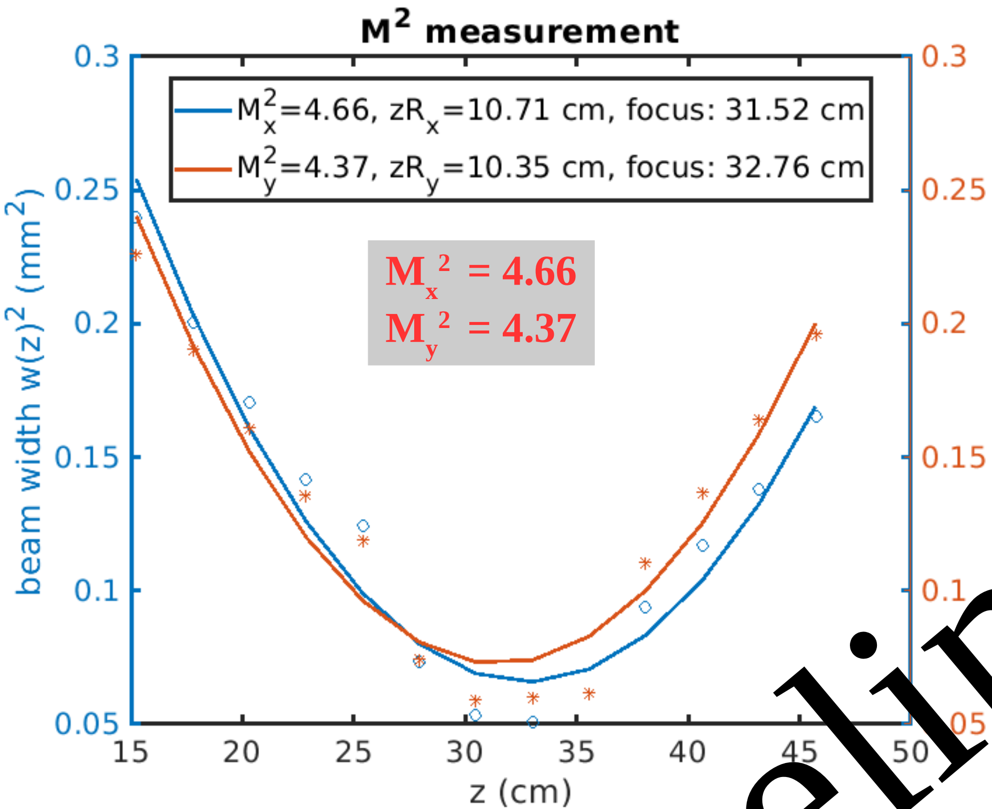


Calculated
Intensity &
Phase

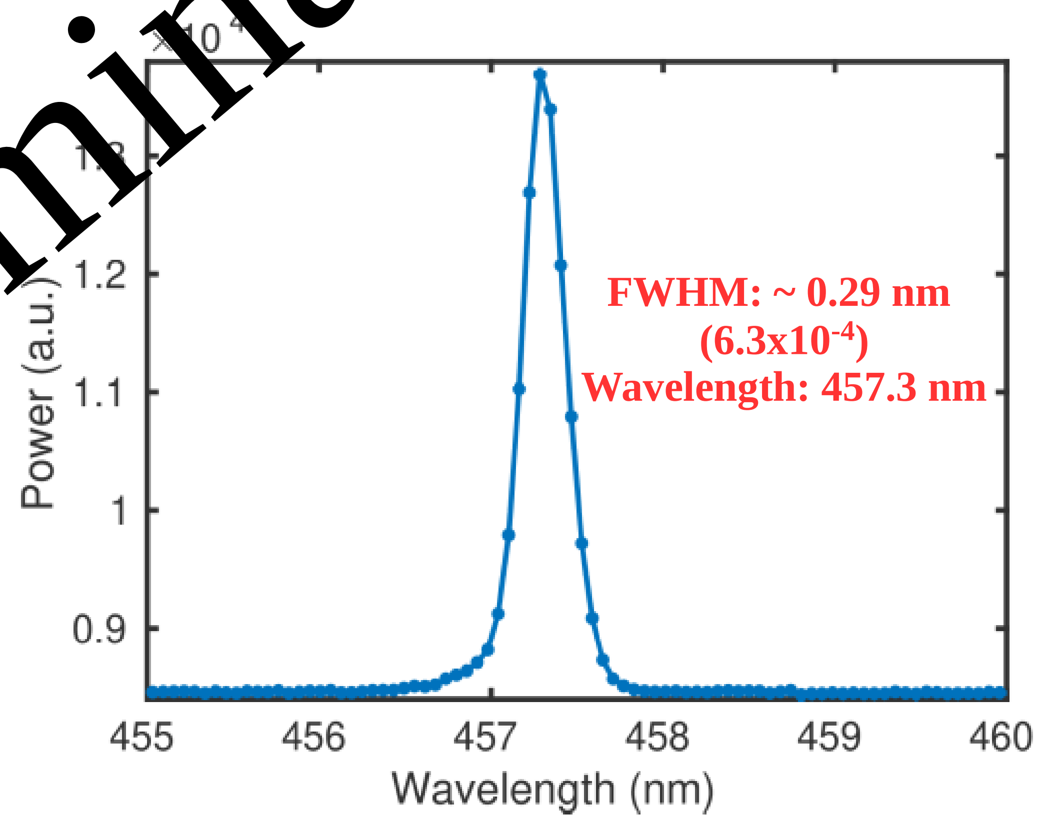


Oscillator FEL with OAM Beams

Coherently mixed LG02 beam: M² and Spectrum measurements

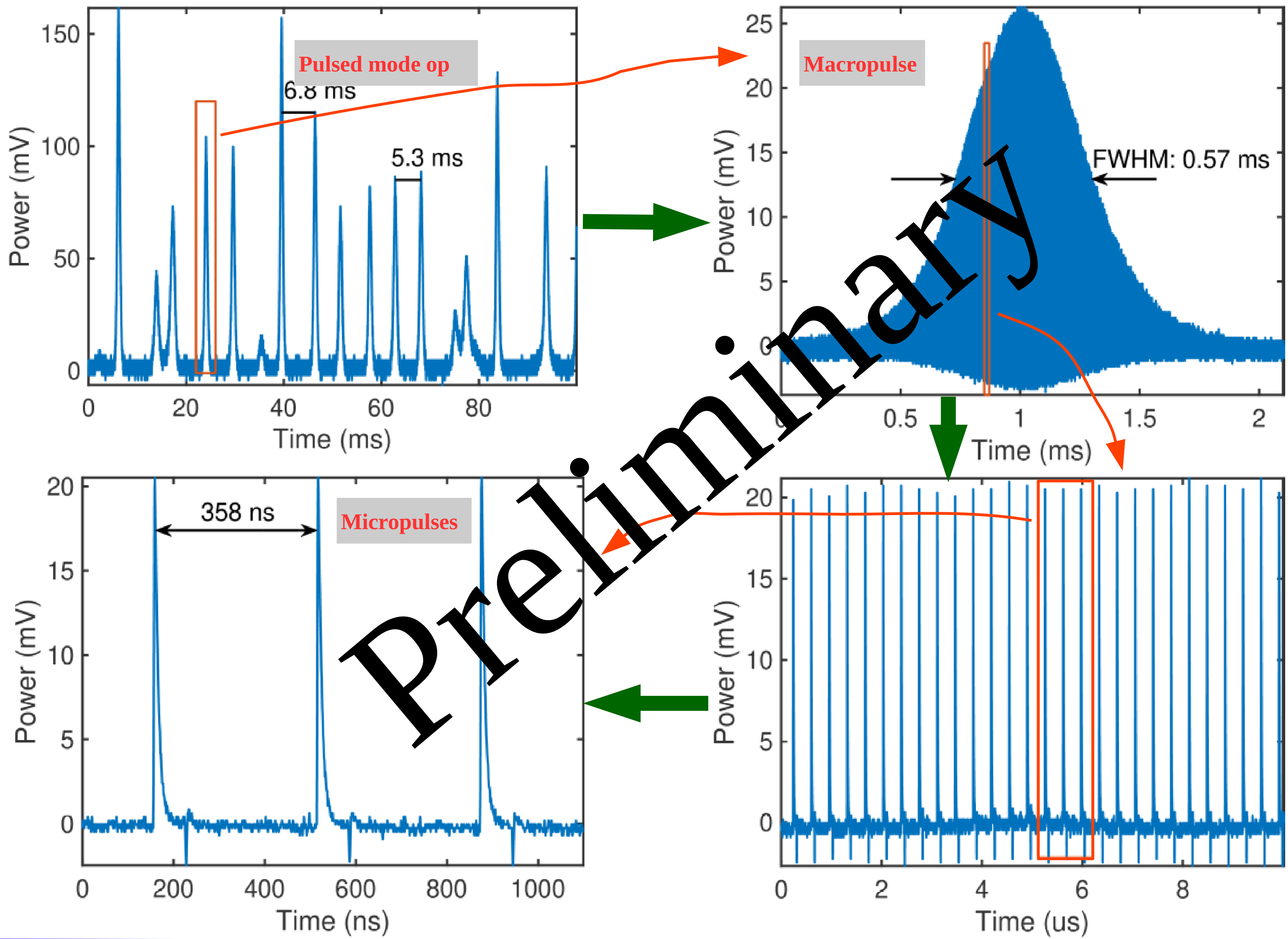


Theoretical: $M_x^2 = 3, \; M_y^2 = 3$



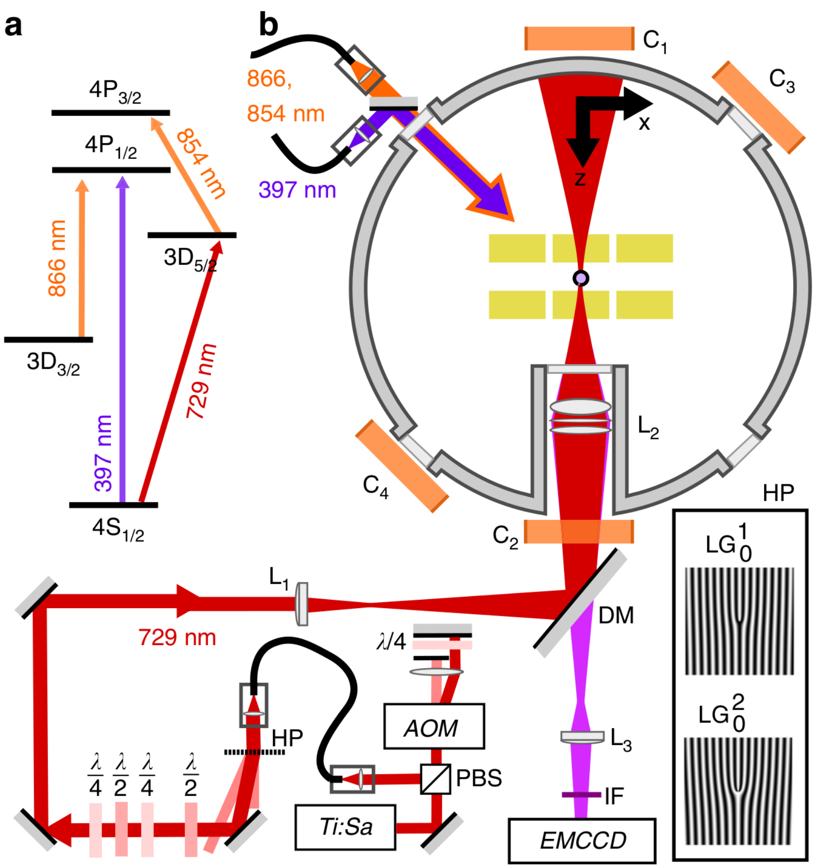
Oscillator FEL with OAM Beams

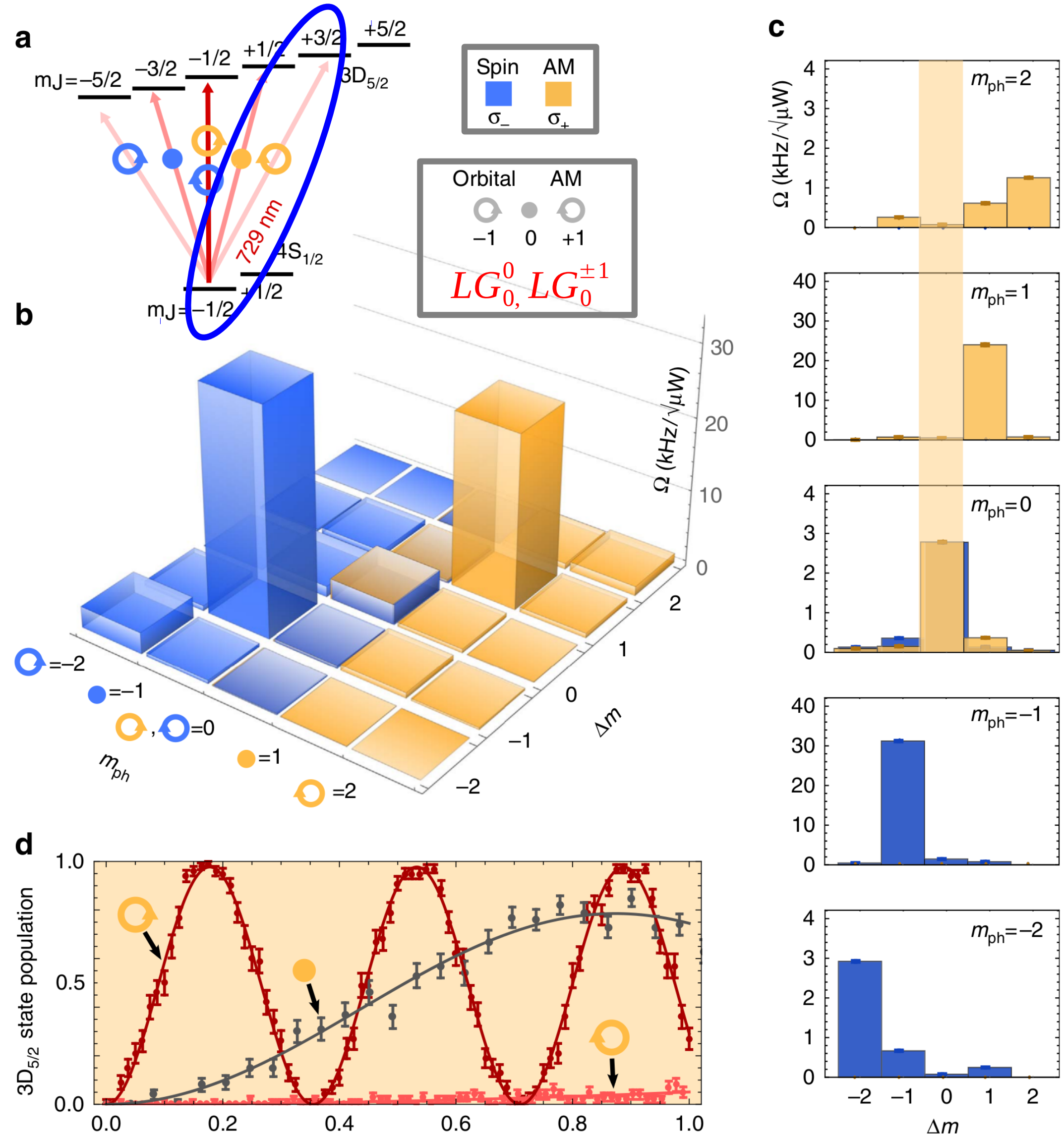
Coherently mixed LG02: Temporal structure



Transfer of photon OAM to valence electron of a trapped ion $^{40}Ca^{+}$

$$Quadrupole\ transition\ ,729\ nm:\ \ 4\,^2S_{1/2} \rightarrow 3\,^2D_{5/2}$$



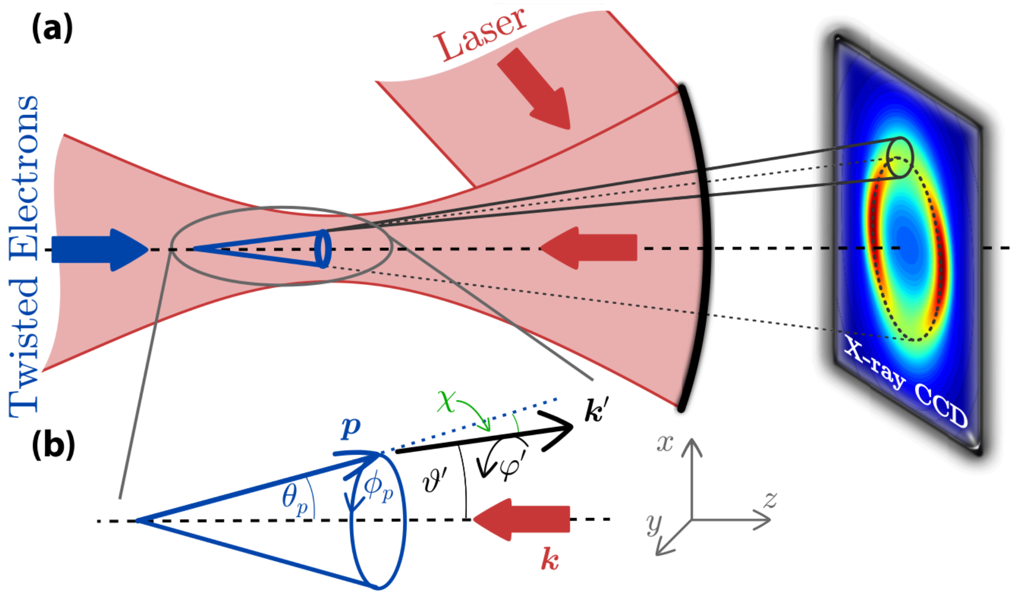


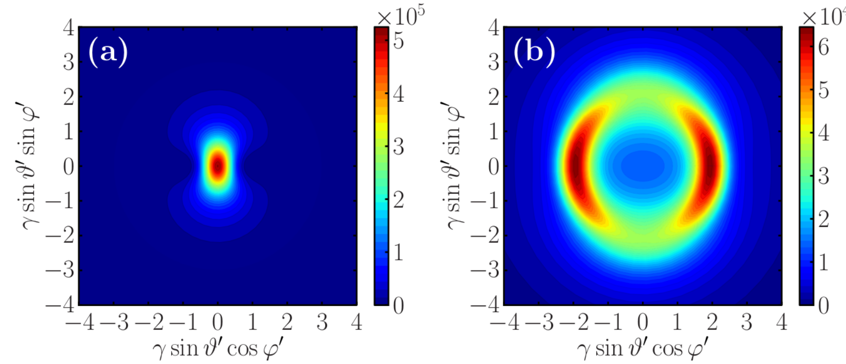
Modified selection rules:
An atom can absorb two quanta of angular momentum from a single photon

C.T. Schmiegelow *et al.* "Transfer of optical orbital angular momentum to a bound electron," Nat. Comm. 7:12998 (2016).

Compton Scattering: Twist X-ray, Gamma-ray Photons

Twist laser beam + relativistic electrons





Twisted x-ray and gamma-ray beams generated by Compton scattering

New c rules, strong dichroism, etc.

- **X-ray spectroscopy in orbital physics and magnetism**
- **Nuclear spectroscopy**
- **Nuclear resonance fluorescence**
- **Nuclear photoionization**
- **Probe for hadron structurec**

Question remain:

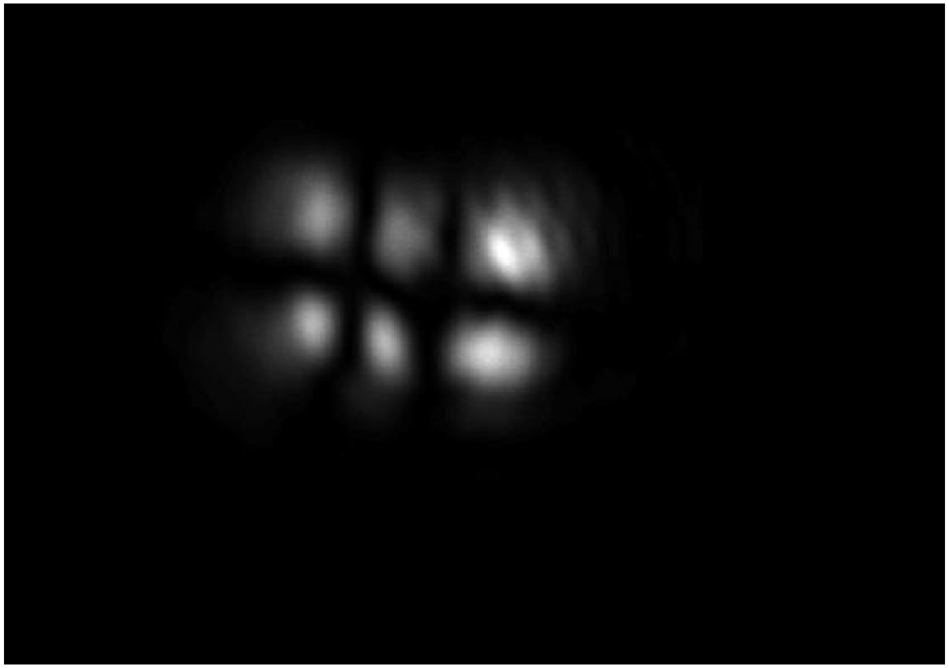
- **Can Compton scattering produce twisted x-ray and gamma-ray efficiently?**
- **What can be done to improve the production rate of these high energy OAM photons?**

D. Seipt *et al*. "Structured x-ray beams from twisted electrons by inverse Compton scattering of laser light," PRA 90, 012118 (2014).

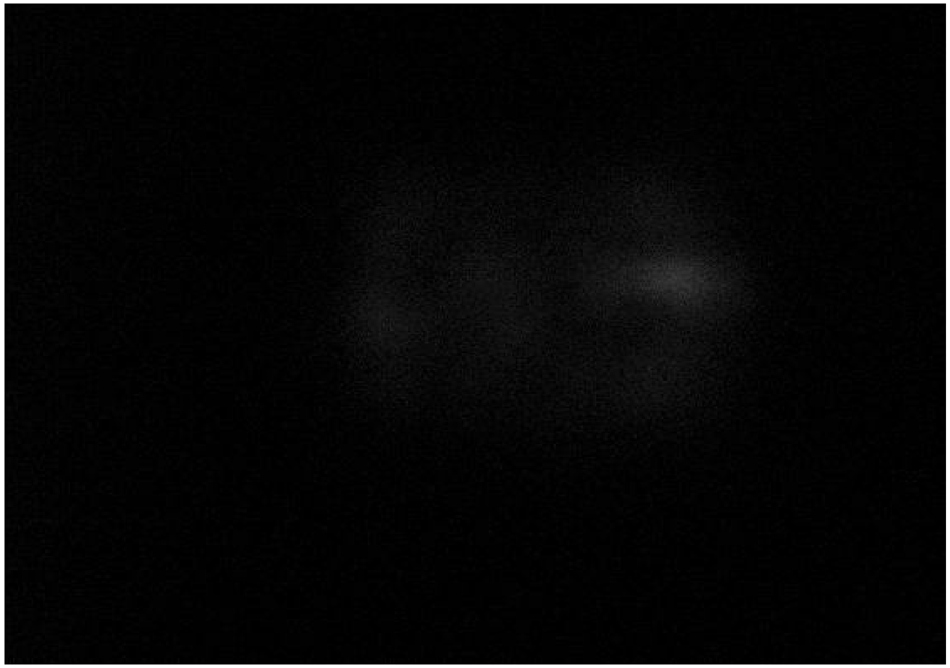
TUNL

Duke UNIVERSITY

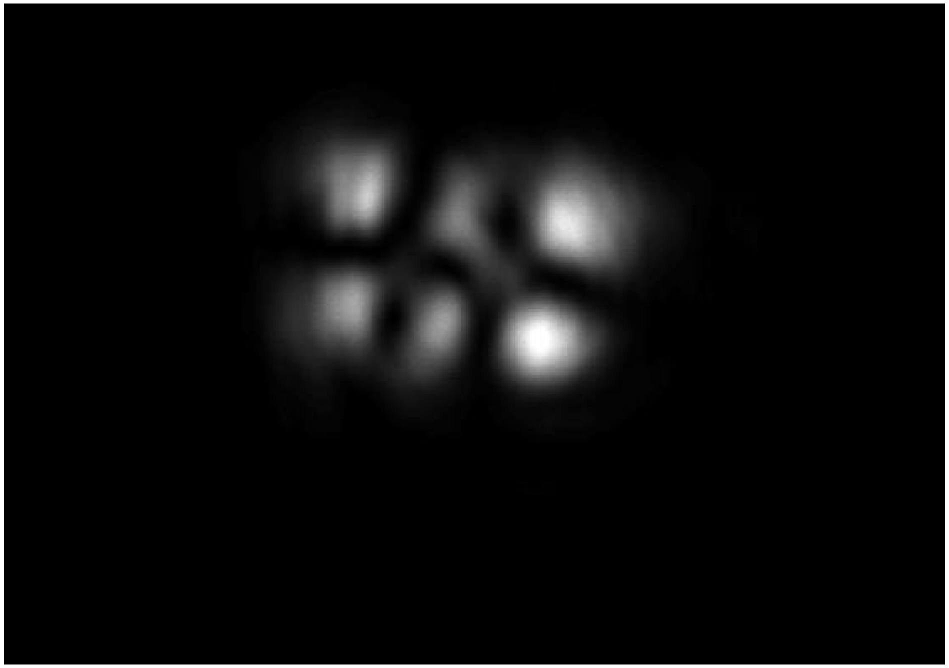
Tuning optical axis: horizontal position



Tuning optical axis: **horizontal angle**



Tuning optical axis: vertical position



Tuning optical axis: vertical angle