National Institute of
Advanced Industrial Science
and Technology
AIST

Gamma-ray vortex beams carrying orbital angular momentum

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In this seminar...

I will talk about

so called
vortex beam,
orbital angular momentum beam,
twisted beam.

Does someone know that?

Outline

- Polairzation and wave fronts of light

- Optical vortex

  Electric field and Poynting vector

  Generation, Measurement, Application

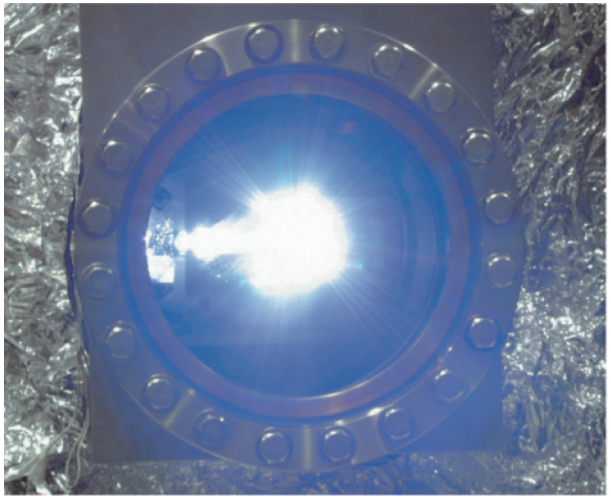
  Electron vortex, X-ray vortex

- Gamma-ray vortex

Light

Sun

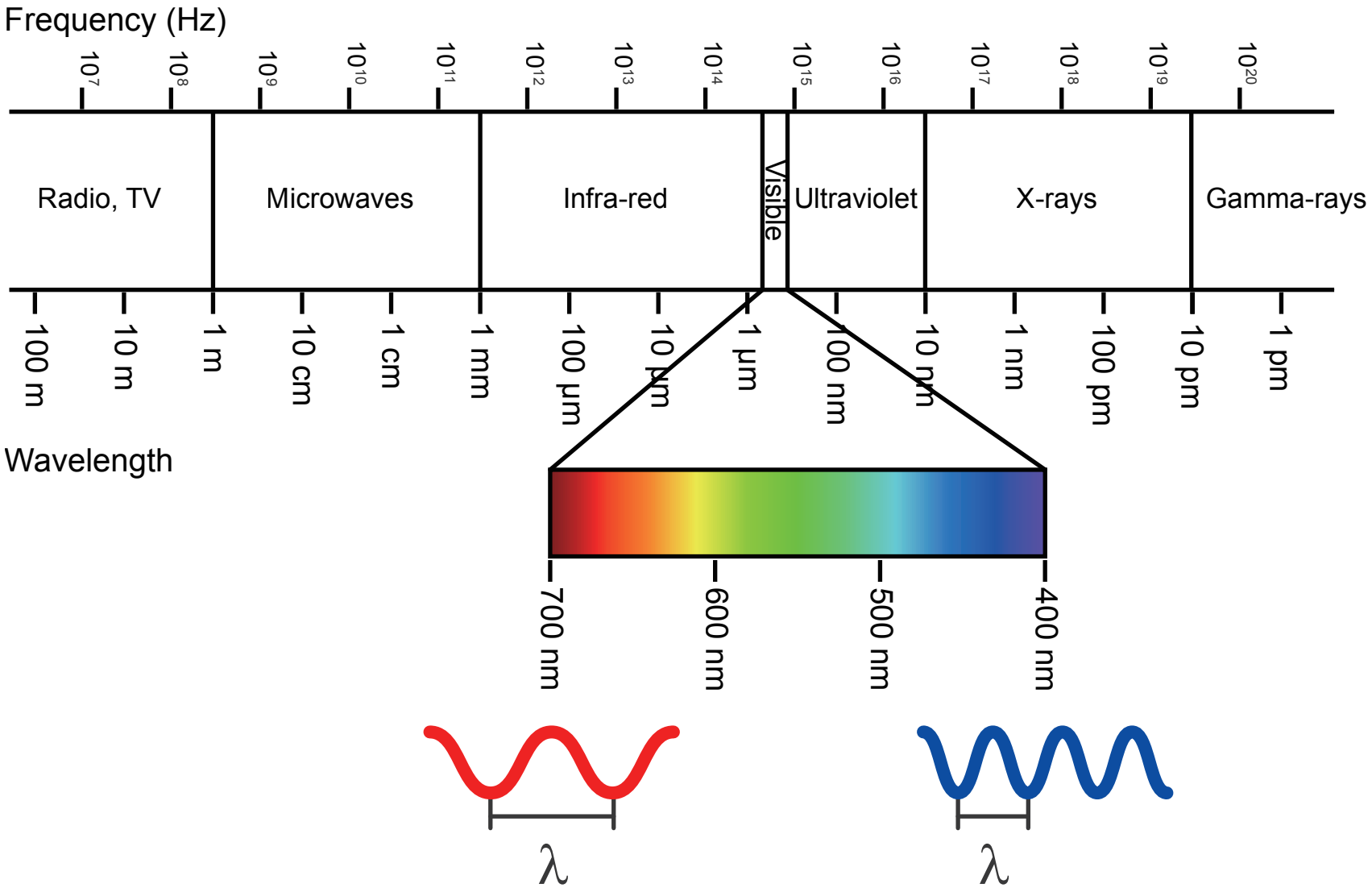
LED



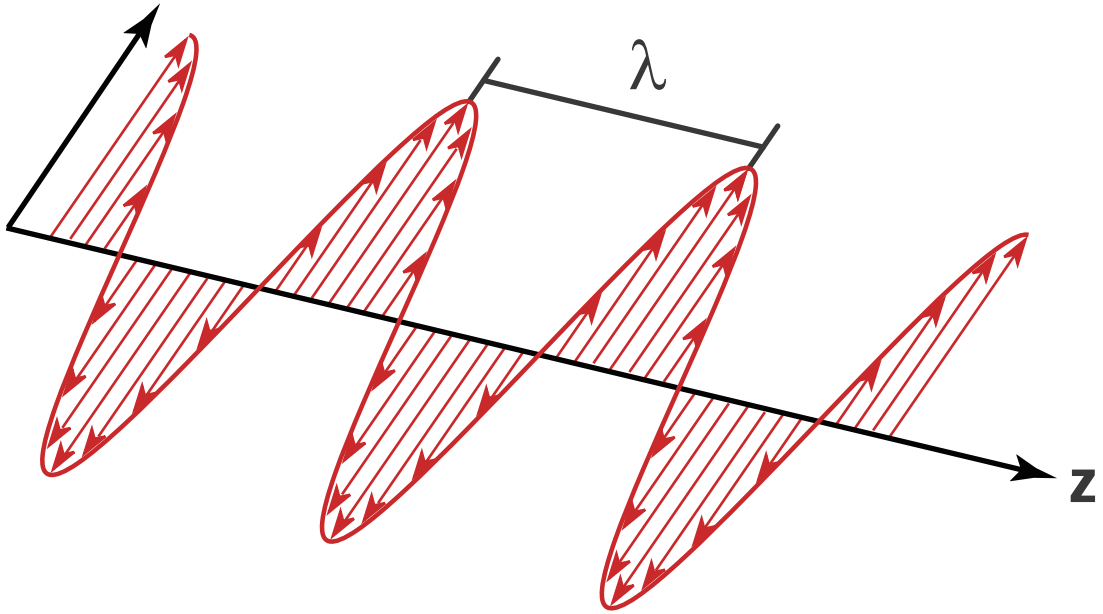
Synchrotron light

Wikipedia

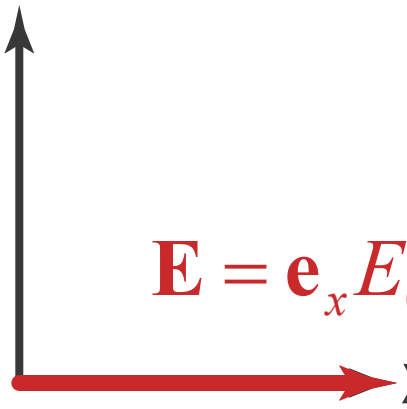
Electromagnetic wave spectrum



Linear polarization

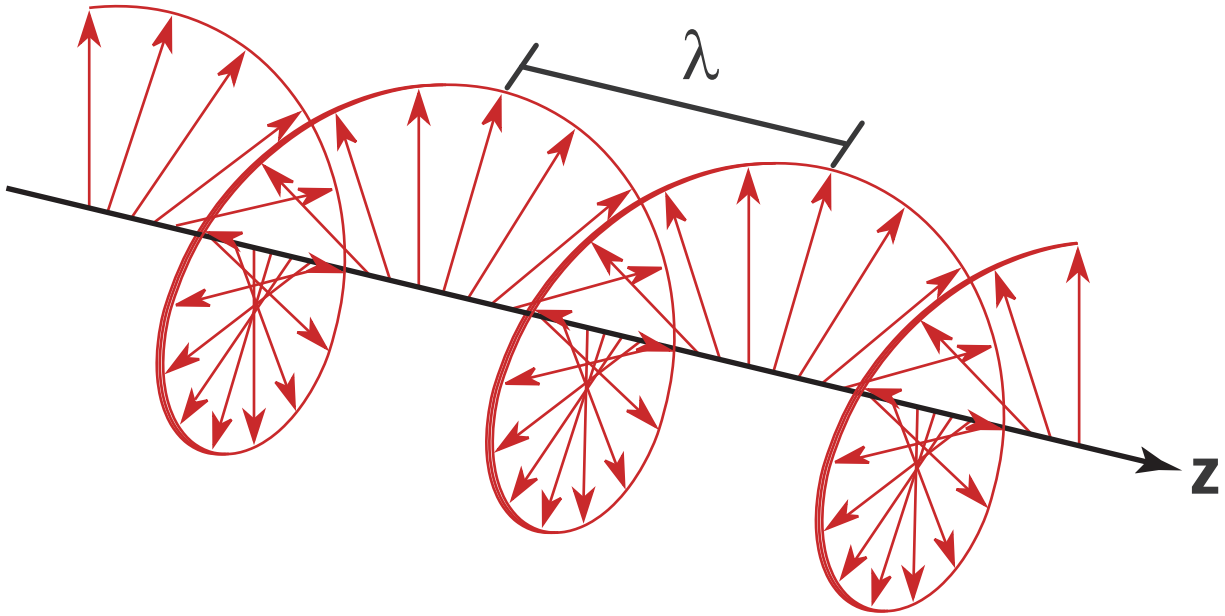


y Incoming electric field

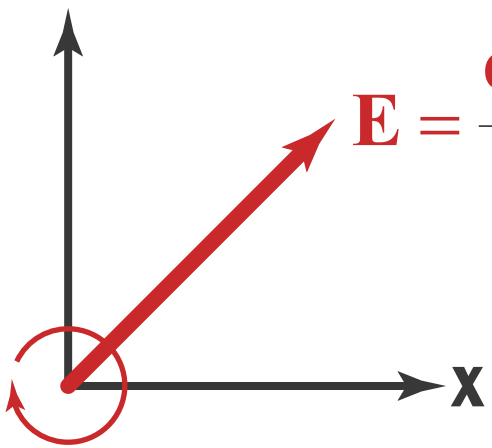


$$\mathbf{E} = \mathbf{e}_x E_0 \exp\left(ikz - i\omega t\right)$$

Circular polarization



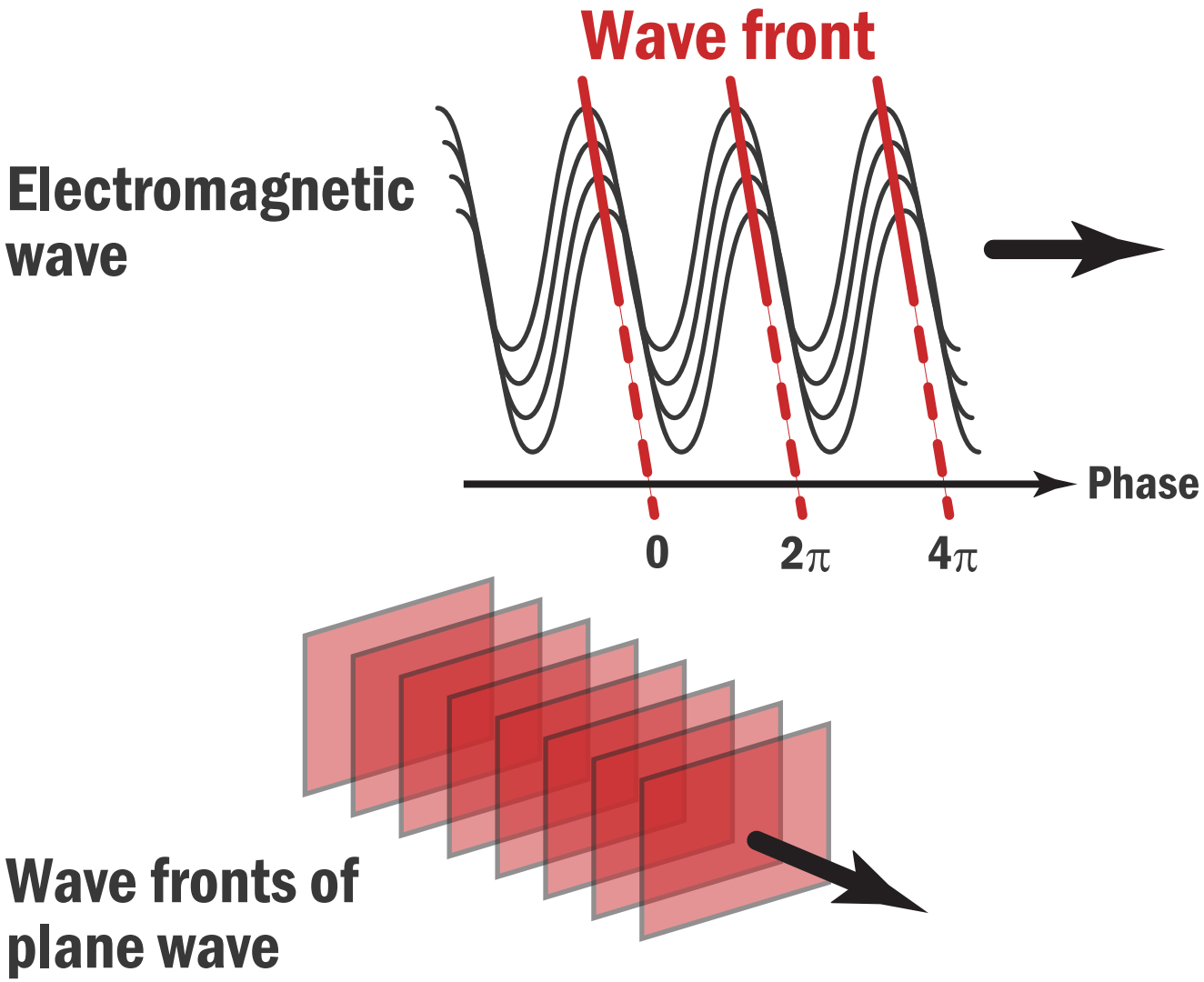
Incoming electric field



$$\mathbf{E} = \frac{\mathbf{e}_x + i\sigma\,\mathbf{e}_y}{\sqrt{2}} E_0 \exp\left(ikz - i\omega t\right)$$

Spin angular momentum (SAM)
= $\sigma\hbar$ (σ = ±1)

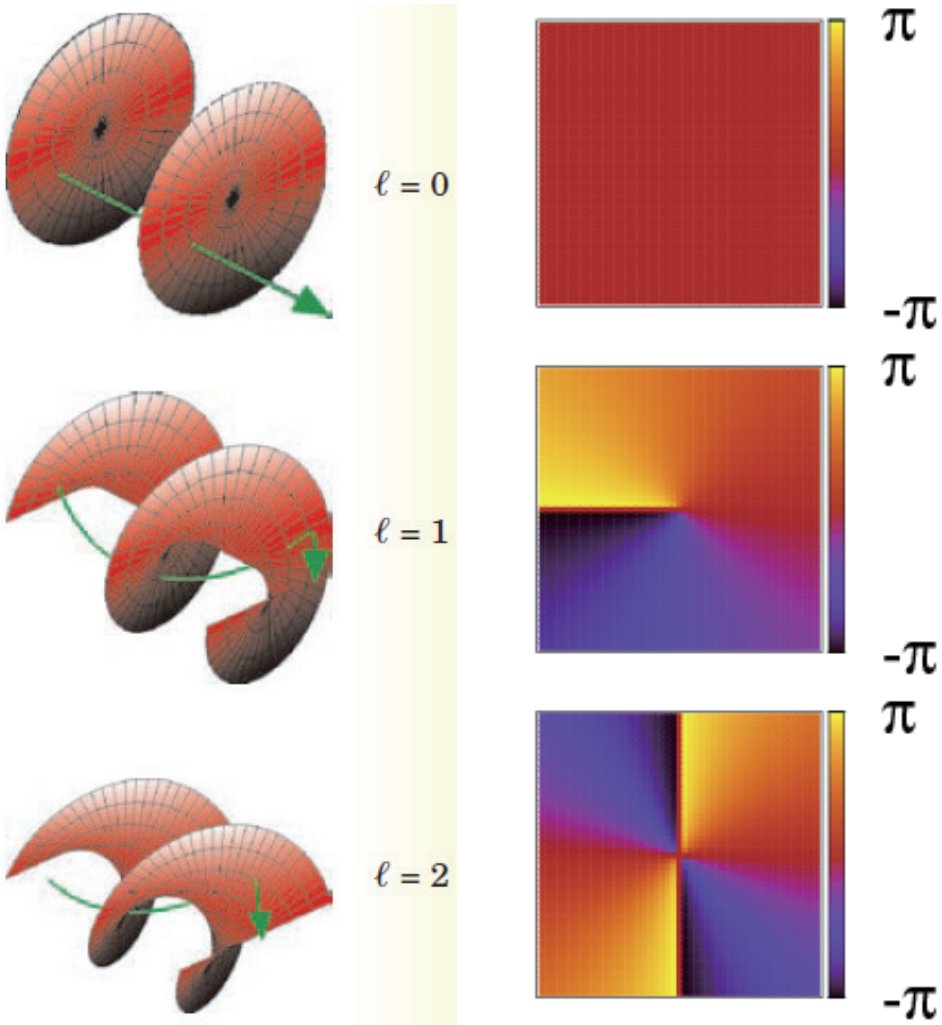
Wave front -position of the same phase-



Outline

- Polairzation and wave fronts of light
- Optical vortex
  - Electric field and Poynting vector
  - Generation, Measurement, Application
  - Electron vortex, X-ray vortex
- Gamma-ray vortex

Vortex beams -Helical wave front creation-



- Forming a helical wave front.

$$E \propto \exp\left(i\ell\phi\right)$$

- Carrying orbital angular momentum (OAM)

$$\ell\hbar$$

- Total AM
  = OAM + SAM
  = $\ell\hbar + \hbar$

M. Padgett et al., Phys. Today 57 (2004) 35.

Electric field and magnetic field

Electric field in the paraxial approximation

$$\mathbf{E} \propto \left(u\mathbf{e}_x + \frac{i}{k}\frac{\partial u}{\partial x}\mathbf{e}_z \right) \exp\left(ikz - i\omega t\right)$$

u: wave amplitude

Magnetic field

$$\mathbf{B} \propto \left(u\mathbf{e}_y + \frac{i}{k}\frac{\partial u}{\partial y}\mathbf{e}_z \right) \exp\left(ikz - i\omega t\right)$$

Electric and magnetic field is slightly inclined against the z-axis.

L. Allen et al., Prog. Opt. 39 (1999) 291.

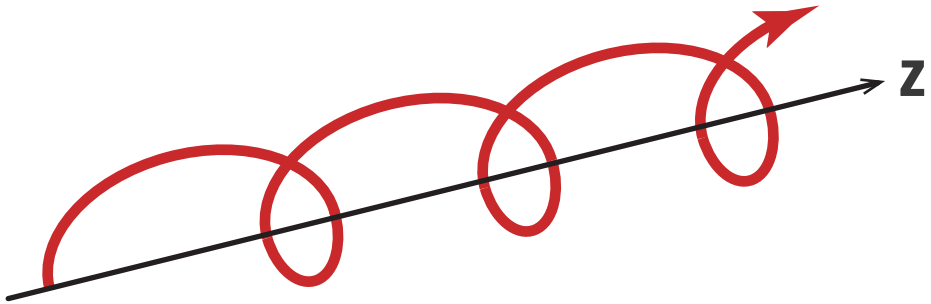
Poynting vector

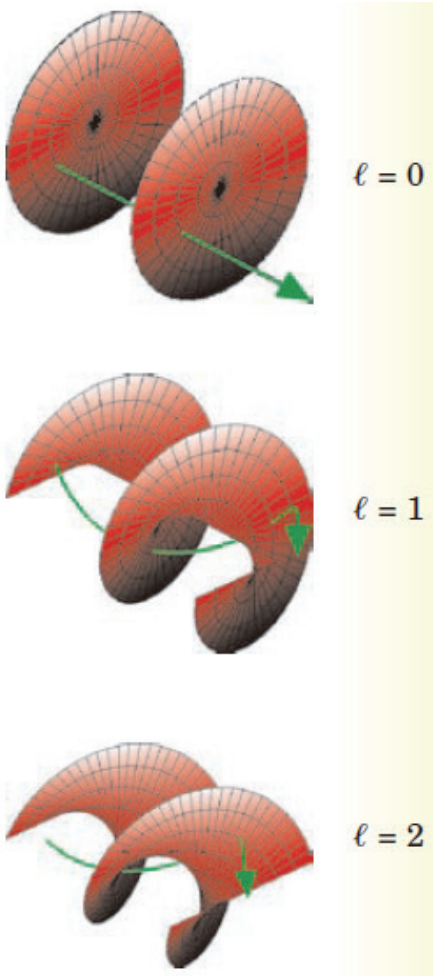
Poynting vector of Laguerre Guassian mode

$$\mathbf{S} = \mathbf{E} \times \mathbf{B} \propto \left(\frac{\rho z}{z^2 + z_R^2} \mathbf{e}_\rho + \frac{\ell}{k\rho} \mathbf{e}_\phi + \mathbf{e}_z \right)$$

spread of the beam

Spiral Poynting vector gives rise to OAM





Light carrying SAM and OAM

We can generate

Linerly polarized laser carrying OAM

SAM = 0, OAM = $\ell\hbar$,

Total AM = $\ell\hbar$

Circularly polarized laser carrying OAM

SAM = $\pm 1\hbar$, OAM = $\ell\hbar$,

Total AM = $\pm 1\hbar + \ell\hbar$

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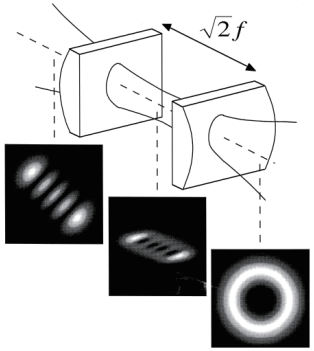
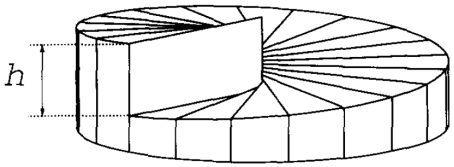
Generation of vortex beams

Special filters

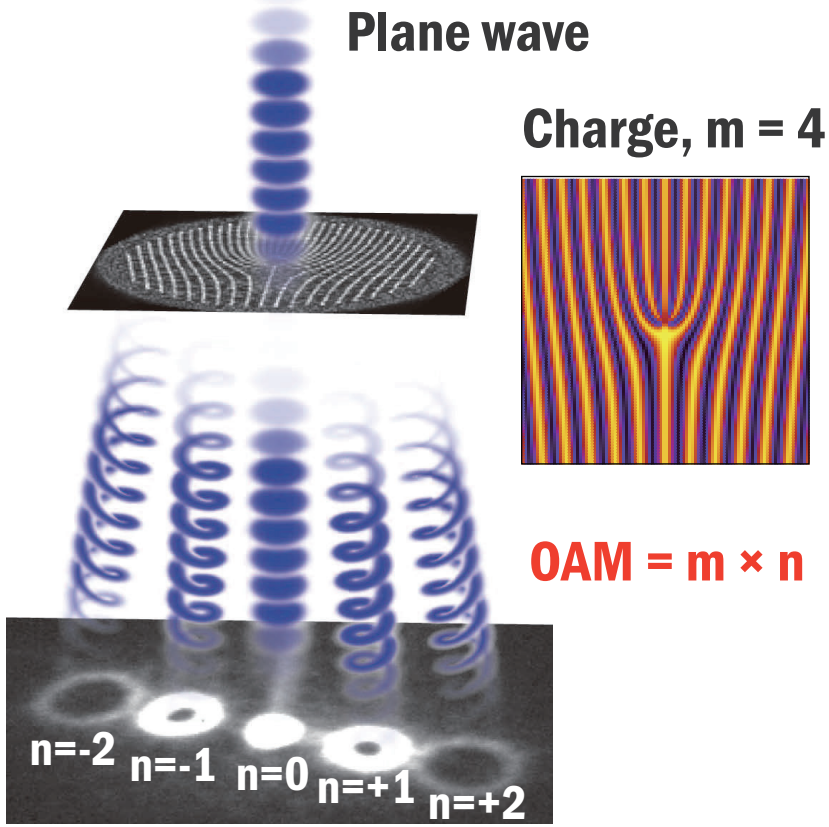
Cylindrical lens



Spiral phase plate



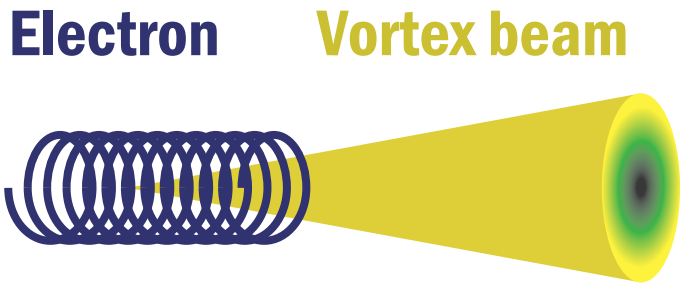
Holographic fork grating



J. Courtial et al., Opt. Comm. 159 (1999) 13.
M. W. Beijersbergen et al., Opt. Comm. 112 (1994) 321.

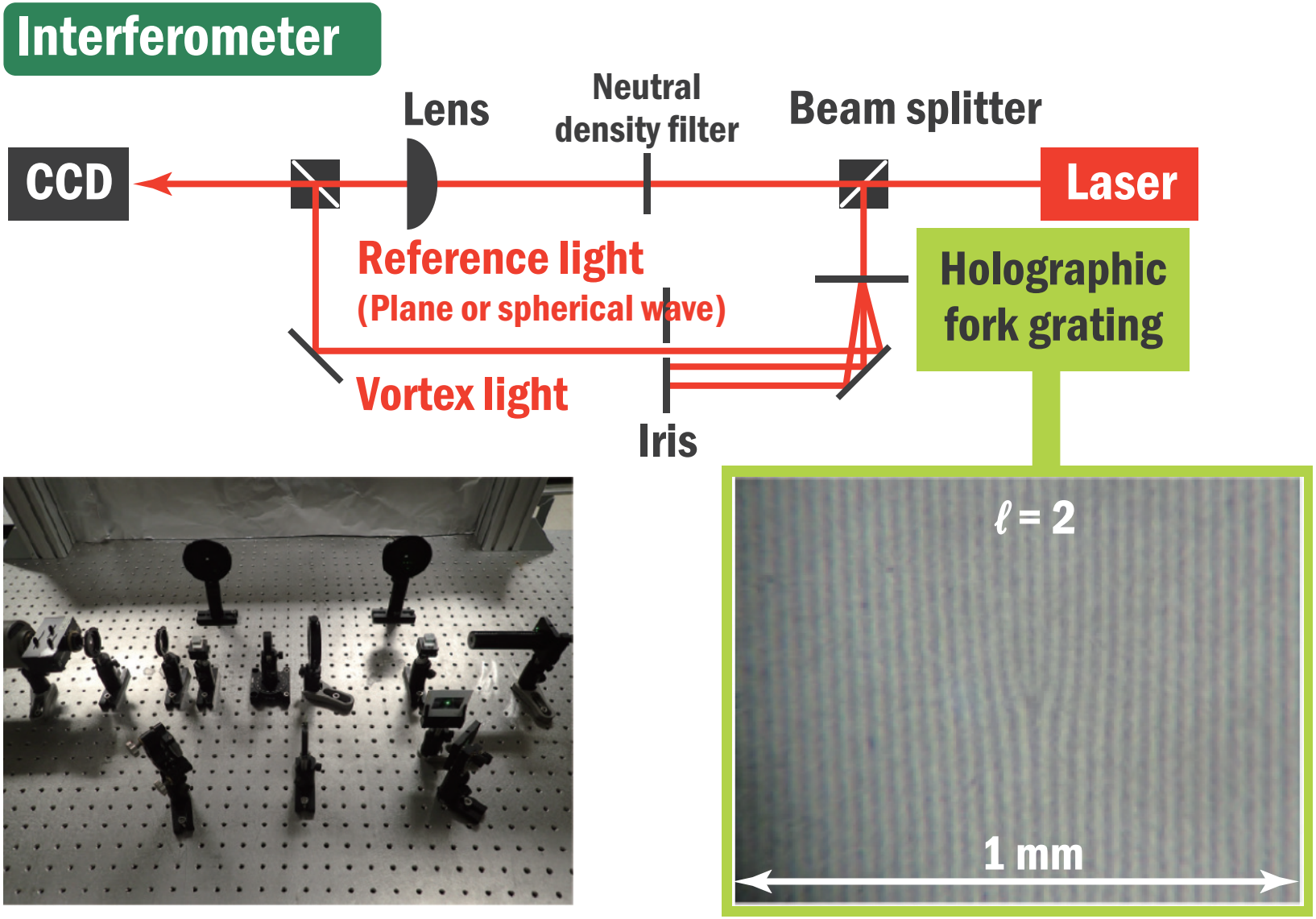
Generation of vortex beams

Without filters

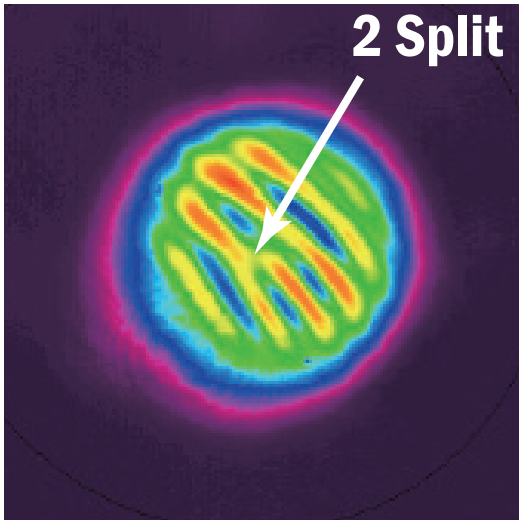
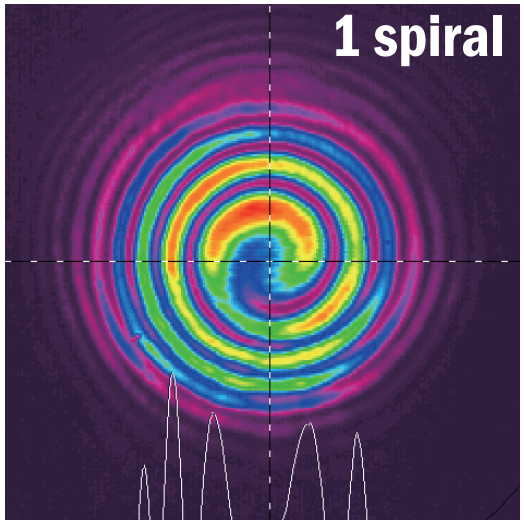
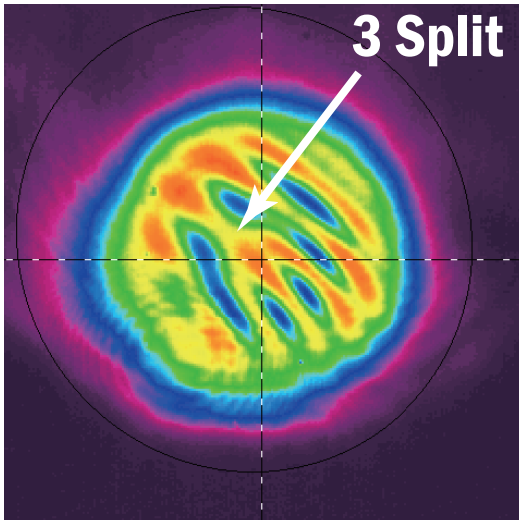
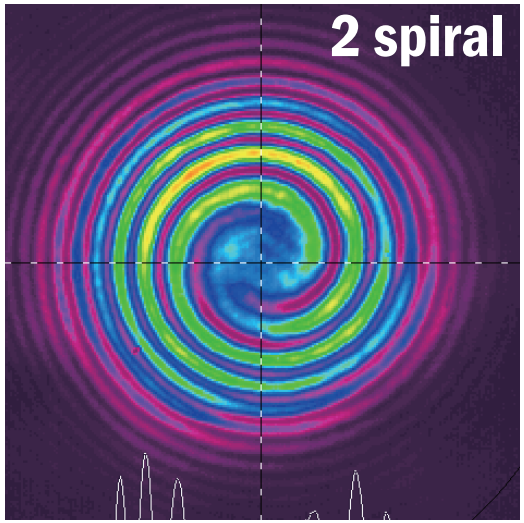


Electromagnetic radiation from an electron

Measurement of vortex beams

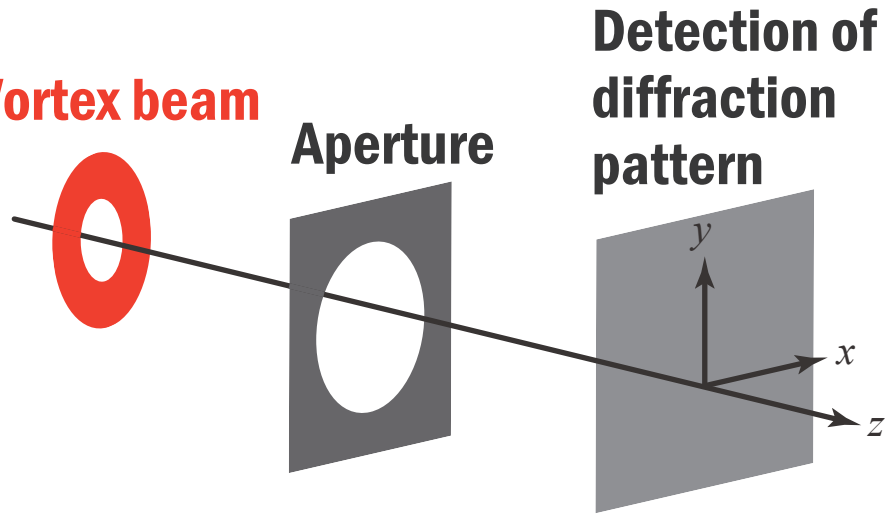


Interference fringe pattern

OAM value ℓ	Plane wave + vortex	Spherical wave + vortex
1		
2		

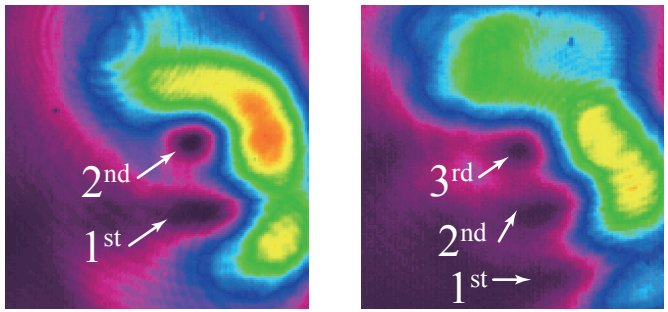
Measurement of vortex beams

Diffraction methods



Circle

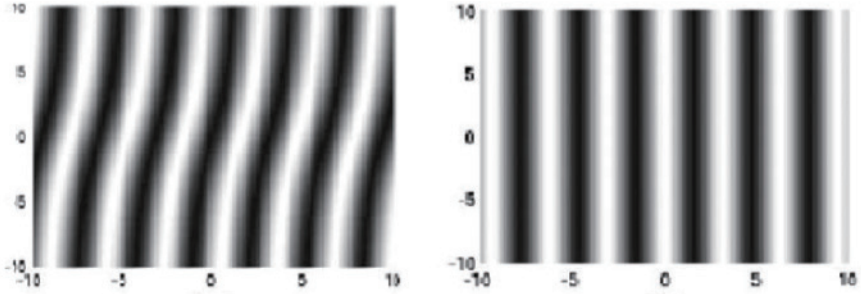
$\ell = 2$ $\ell = 3$



Y. Taira et al., Opt. Lett. (2017).

Double slit

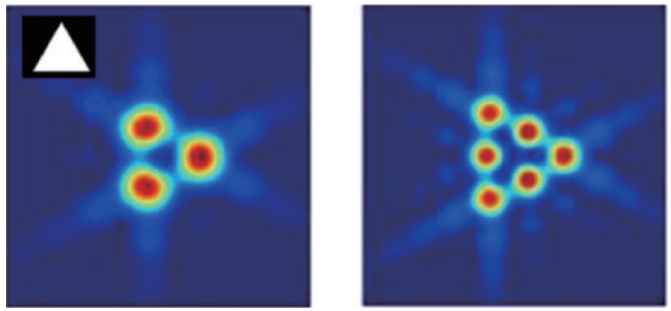
$\ell = 1$ $\ell = 0$



H. I. Sztul et al., Opt. Lett. 31 (2006) 999.

Triangle

$\ell = 1$ $\ell = 2$

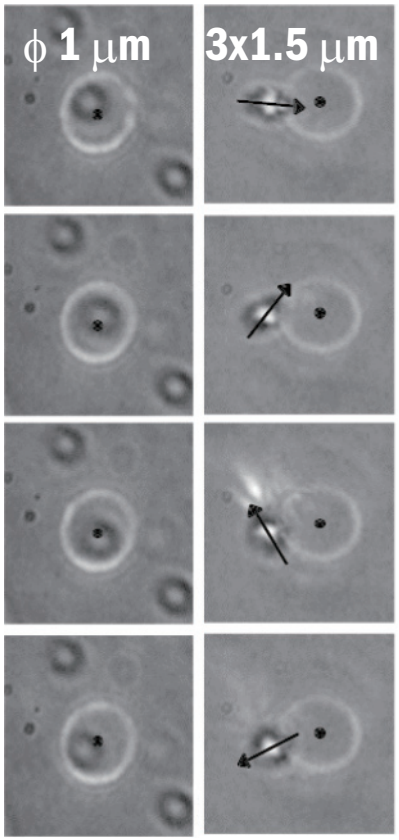


J. M. Hickmann et al., PRL 105 (2010) 053904.

Application of vortex beams

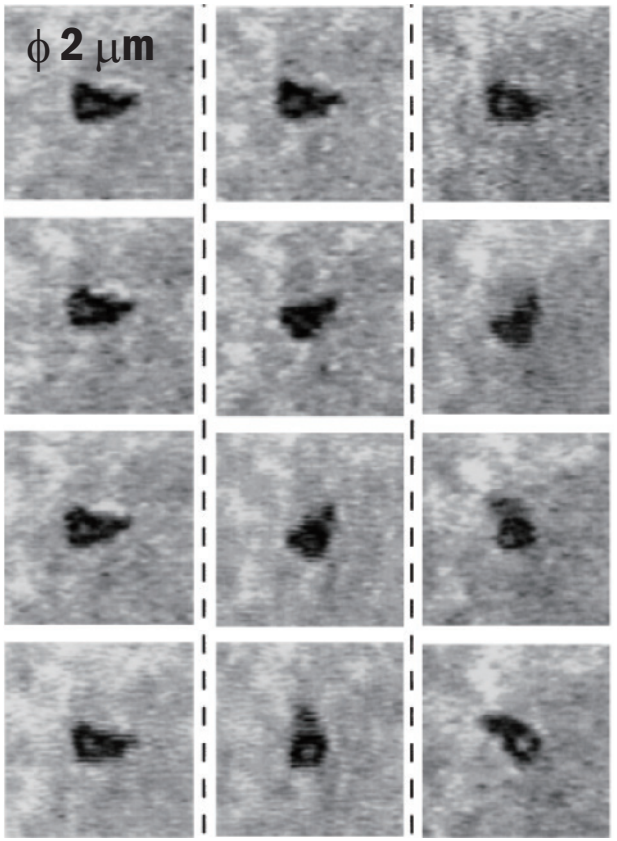
Tweezer (OAM transfer to micro particle)

Independent OAM and SAM



A. T. ONeil et al., PRL 88 (2002) 053601.

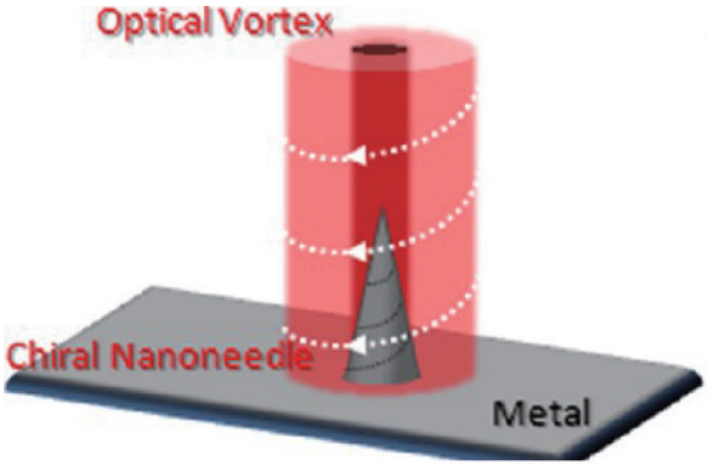
Combination of OAM and SAM

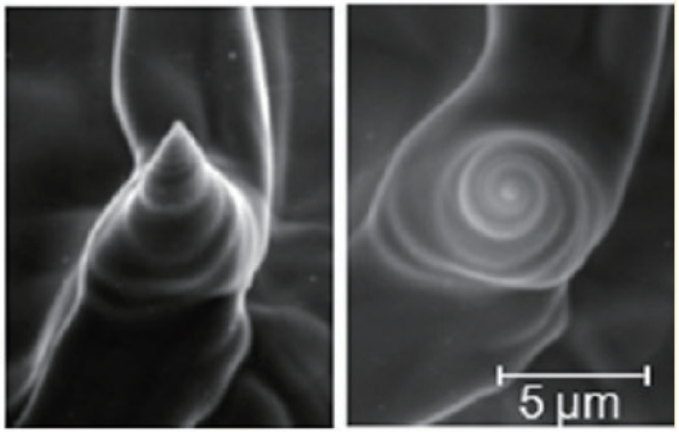


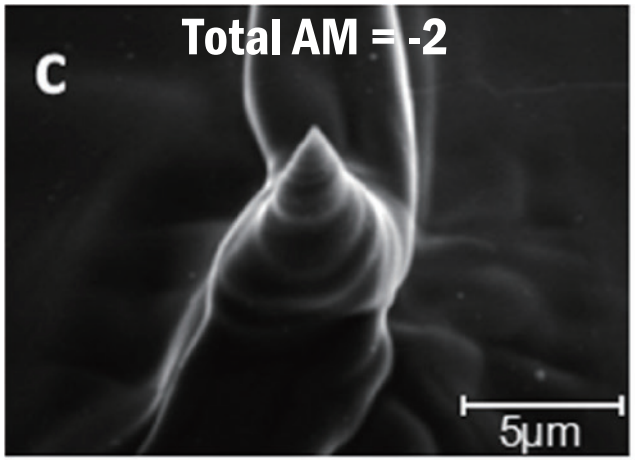
N. B. Simpson et al., Opt. Lett. 22 (1997) 52.

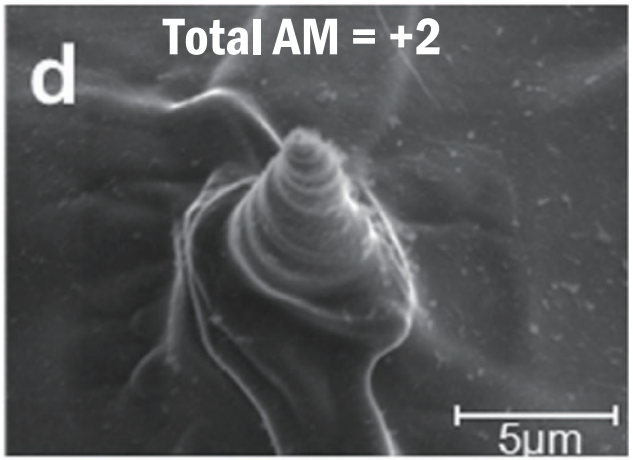
Application of vortex beams

Creation of metal nano needle (tantalum target)







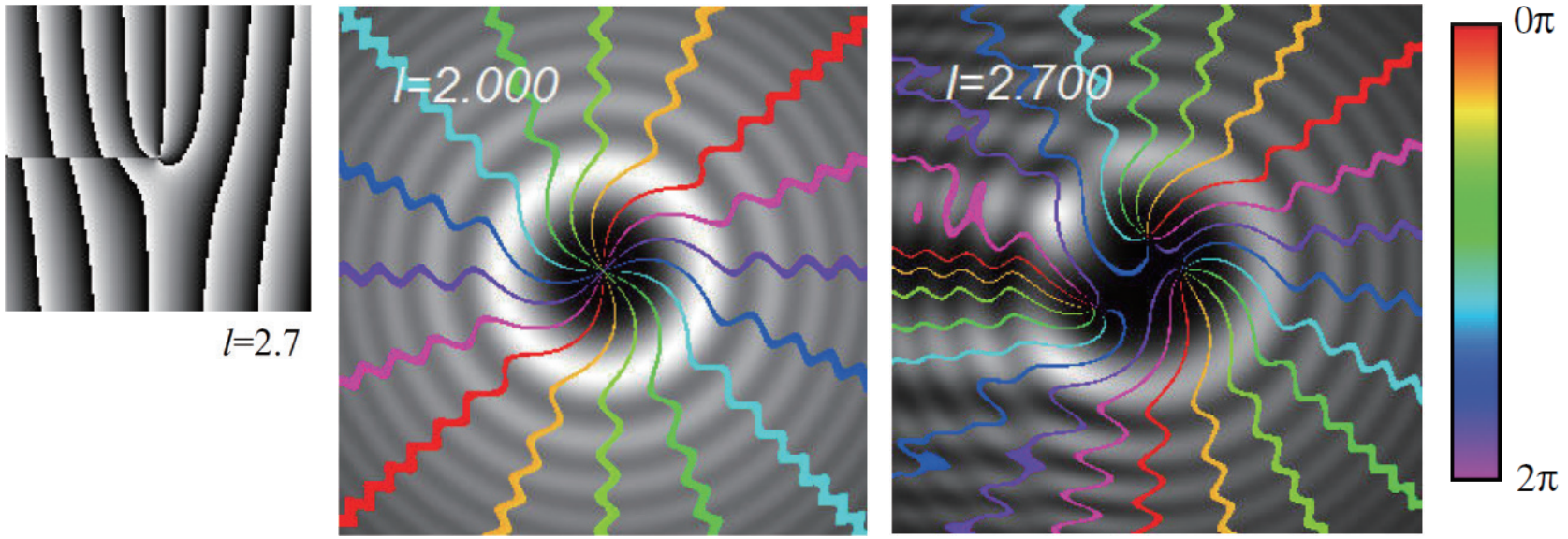


K. Toyoda et al., Nano Lett. 12 (2012) 3645.

Application of vortex beam

Non-integer OAM

Fork grating | **Intensity distribution** | **Phase**



J. Leach et al., New J. Phys. 6 (2004) 71.

Other applications of optical vortex

- Quantum entanglement
- Terabit data transmission
- Direct observation of rotating black hole
- Excitation of atom

Outline

- Polairzation and wave fronts of light
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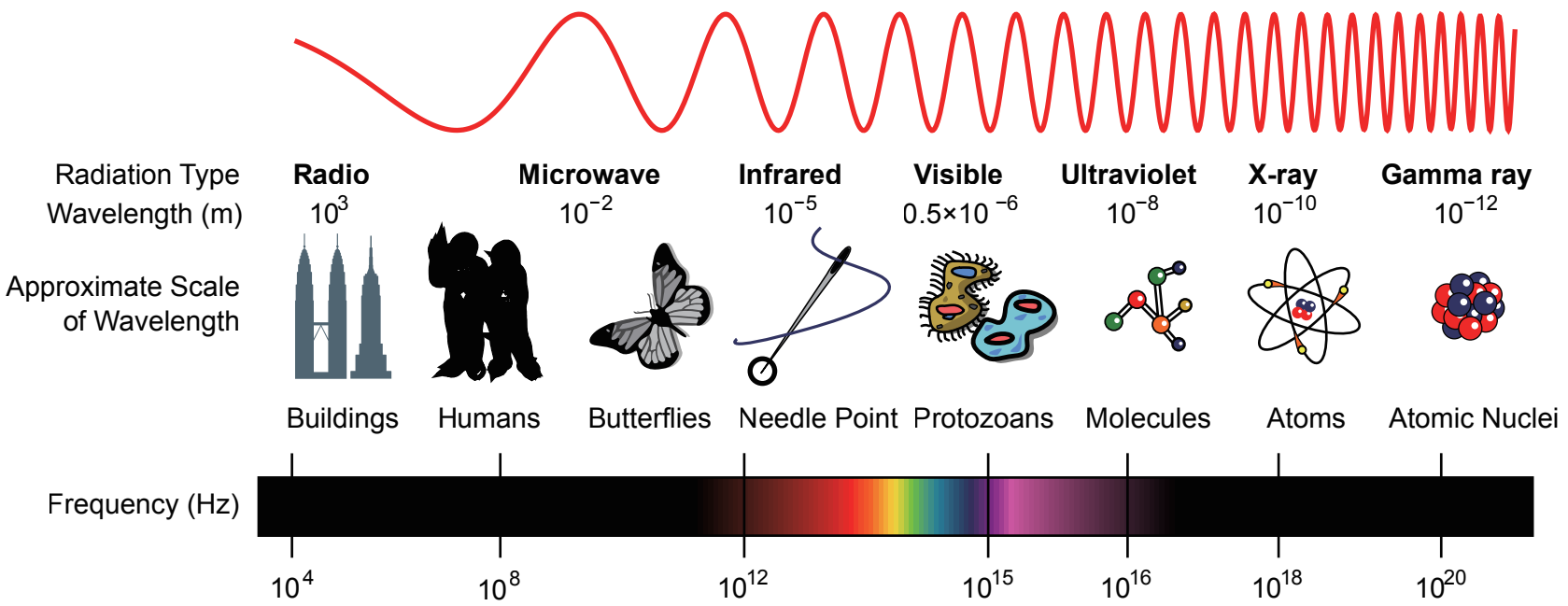
  Electron vortex, X-ray vortex
- Gamma-ray vortex

Vortex beams



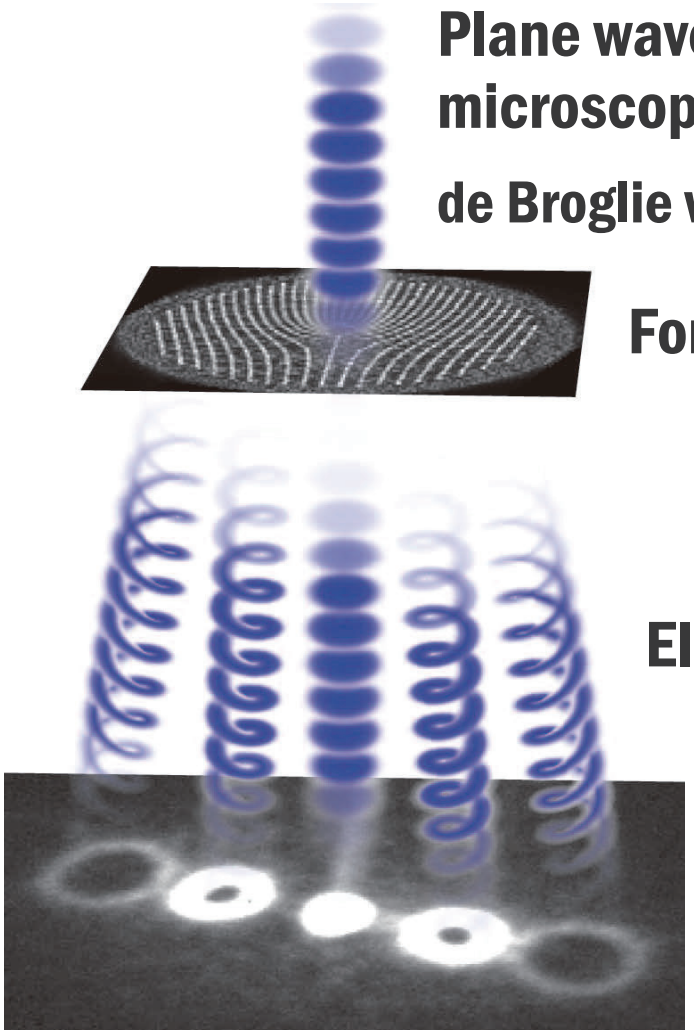
Micro/THz wave **Laser** **10 keV X-ray**

Except for the electromagnetic wave

300 kV electron **Cold neutron**

Wikipedia.

Generation of electron vortex



Plane wave electron from electron microscope (E < 300 keV)

de Broglie wavelength = 2 pm

Fork grating (pitch = 50 nm)

Electron vortices

Application of electron vortices

Magnetic mapping with atomic resolution

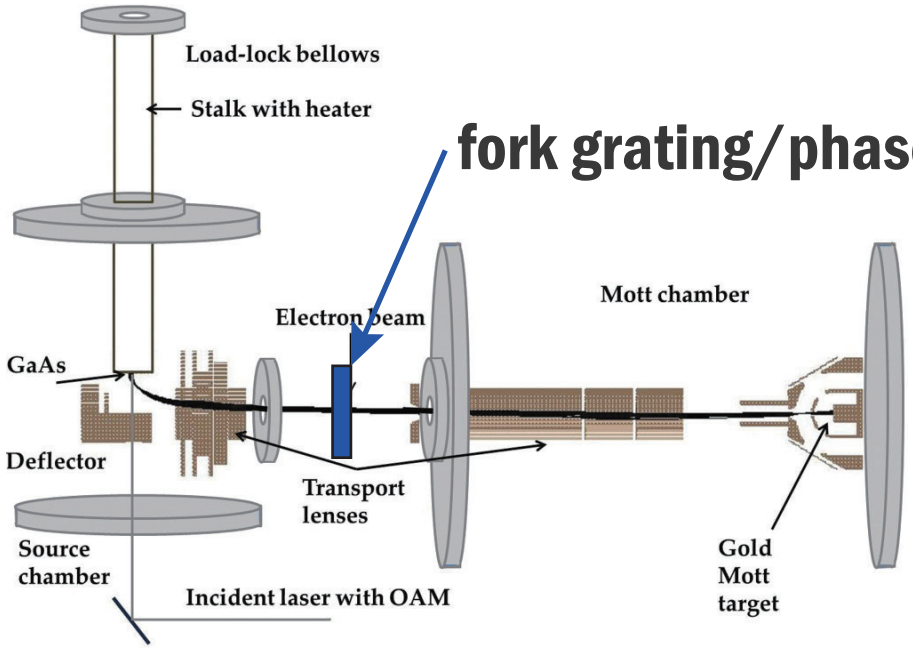
B. J. McMorran et al., Science 331 (2011) 192.

High energy electron vortex development

at JLab

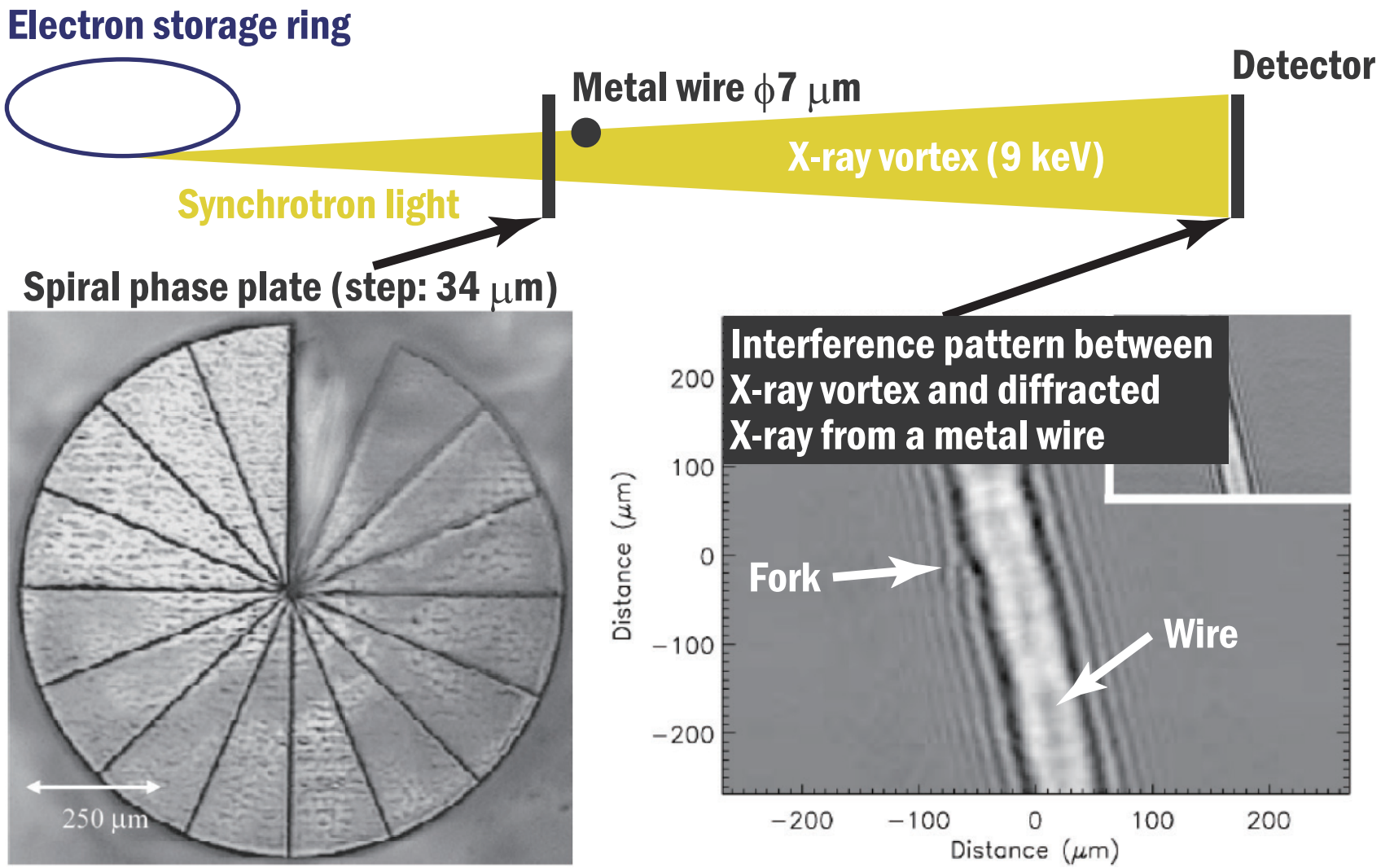
R&D of twisted electron acceleration at CEBAF injector

Final goal: srudy of the proton structure (e.g. quark OAM)



Dipangkar Dutta,
twisted meeting, 1/26/2015

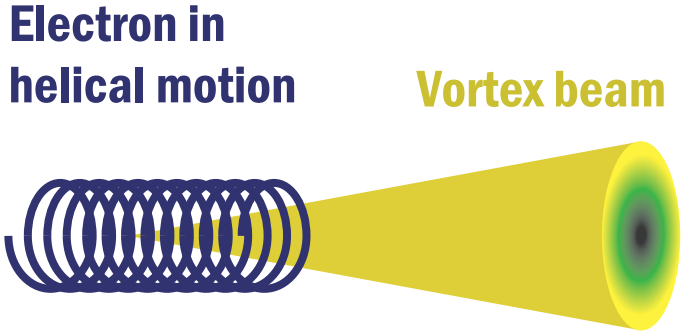
Generation of X-ray vortex (9 keV)



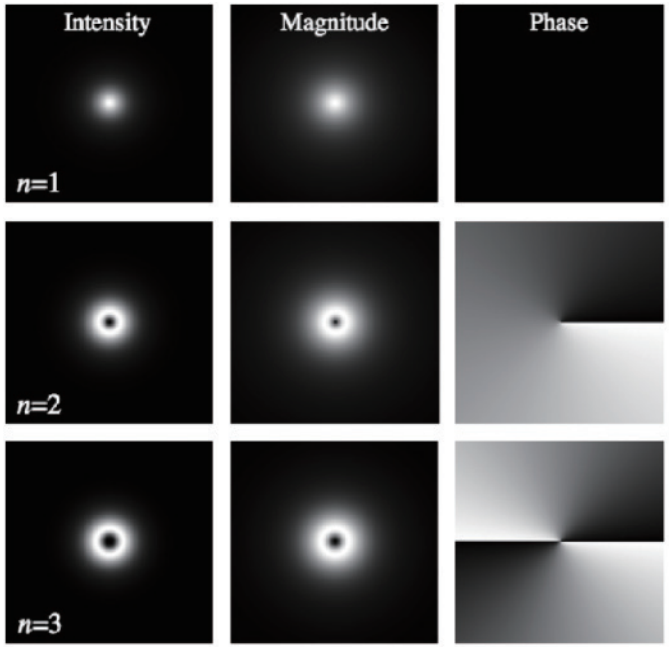
A. G. Peele et al., Opt. Lett. 27 (2002) 1752.

X-ray vortex beams from electrons

X-ray vortex generation using helical undulator was proposed in 2008.



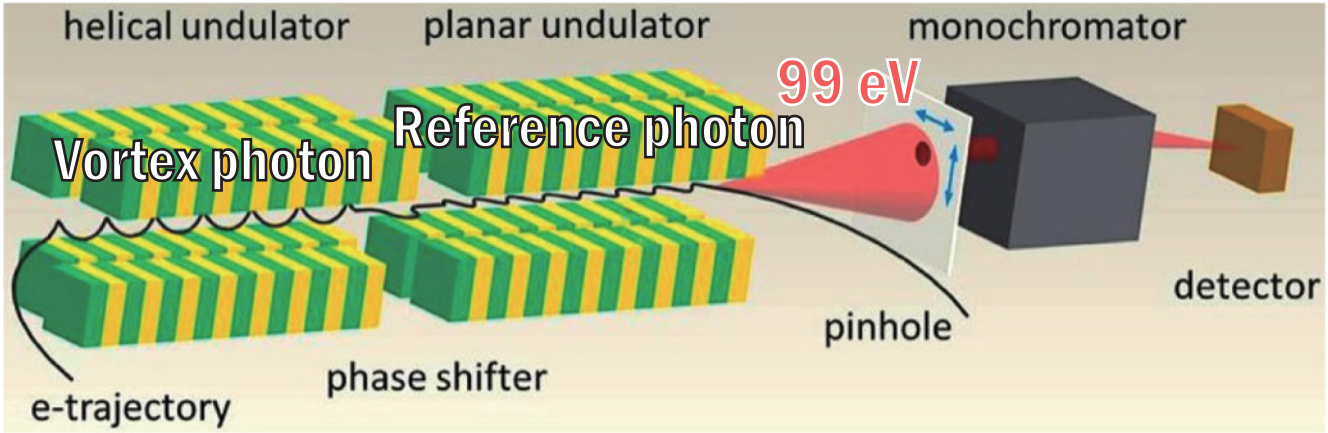
Transverse motion produces higher harmonics.



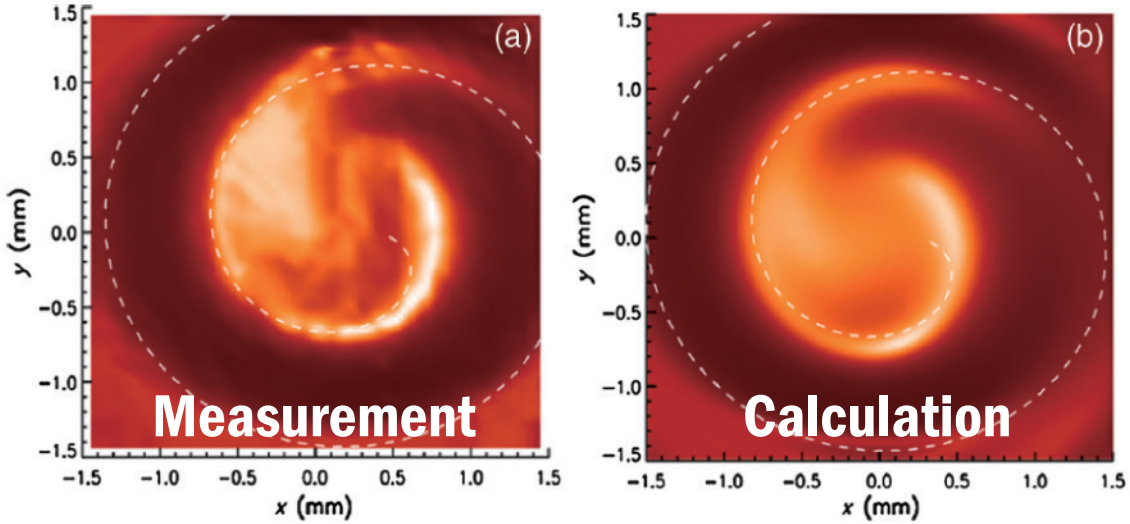
Higher harmonics carry OAM of (n-1)ħ .

S. Sasaki et al., PRL. 100 124801 (2008).

Soft X-ray (99 eV) generation



Interference pattern between vortex photon and spherical reference photon



J. Bahrdt et al., PRL 111 (2013) 034801.

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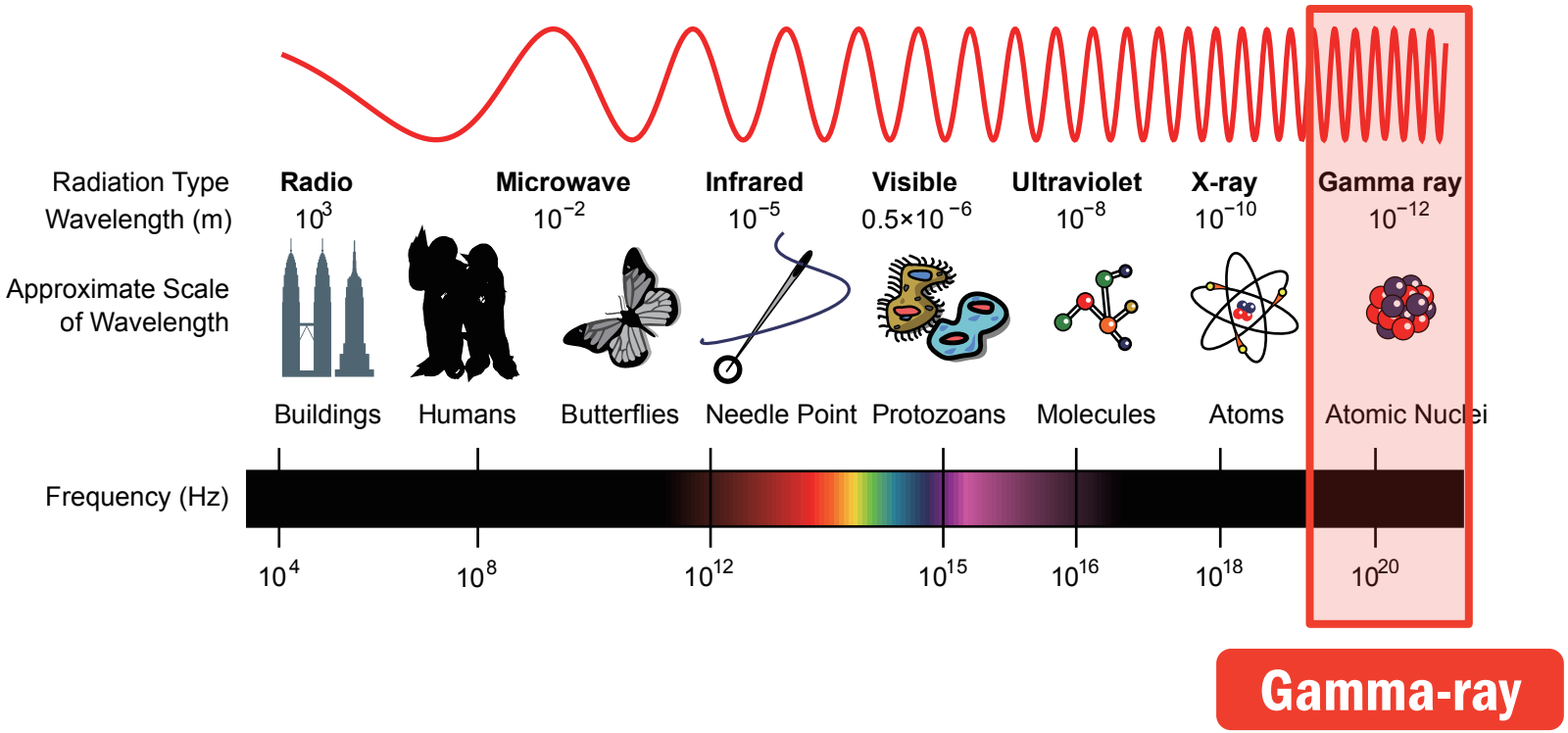
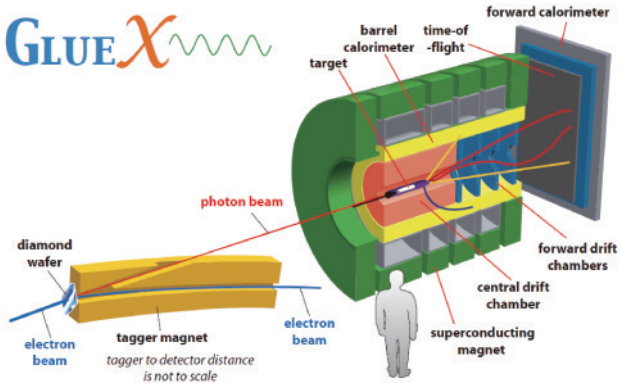
My interest -Gamma-ray vortex generation-

Generation of gamma ray vortex (> MeV) and development its application.



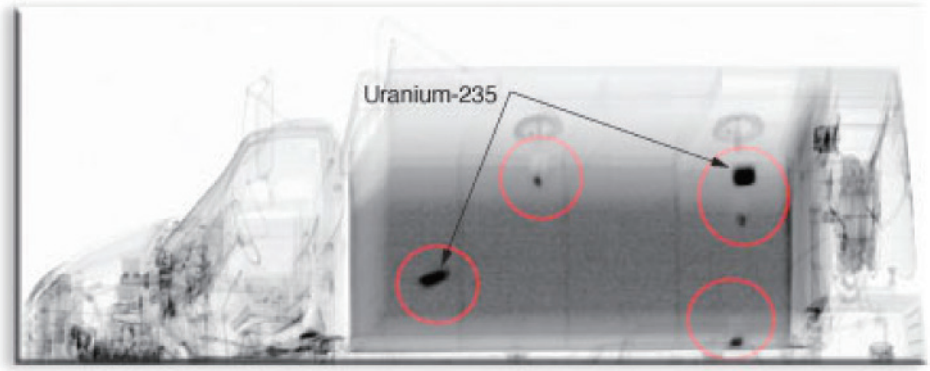
Applications of gamma-rays

Nuclear physics



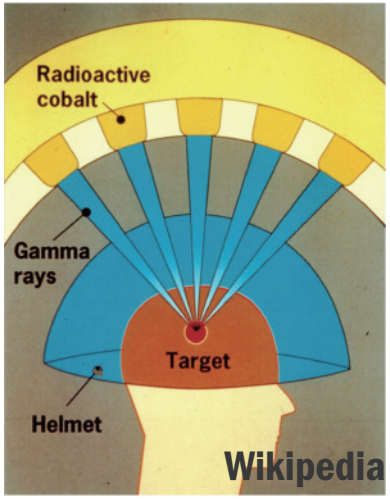
arXiv 1210 4508 (2012).

Homeland security



https://str.llnl.gov/AprMay11/barty.html

Cancer therapy



Positron production for a linear collider

Non-destructive inspection

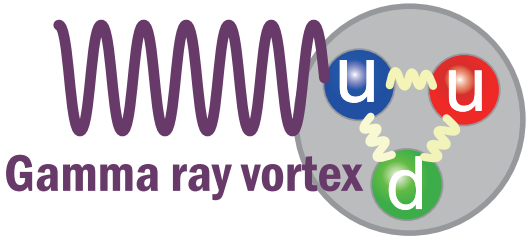
Astrophysics (gamma-ray burst)

Solid state physics (magnetic Compton scattering)

Possible applications of gamma-ray vortex

Insight into the proton structure

I. P. Ivanov, Phys. Rev. D 83 (2011) 093001.



If the OAM of gamma ray is transferred to the quark/gluon, it becomes novel probe of the proton spin.

Nuclear physics

Y. Taira et al., arXiv 1608 (2016) 04894.

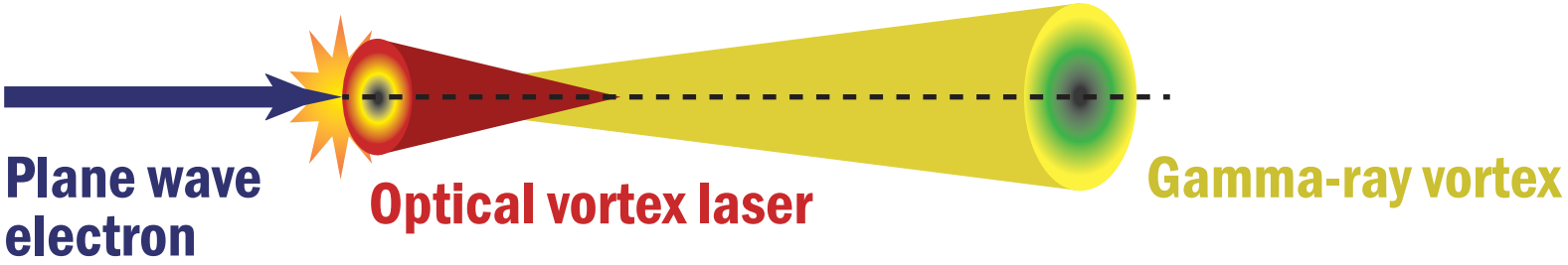
Excited states can be populated by high order transition.
Photon-induced reaction cross section will be changed.

Generation of positron vortex via pair production

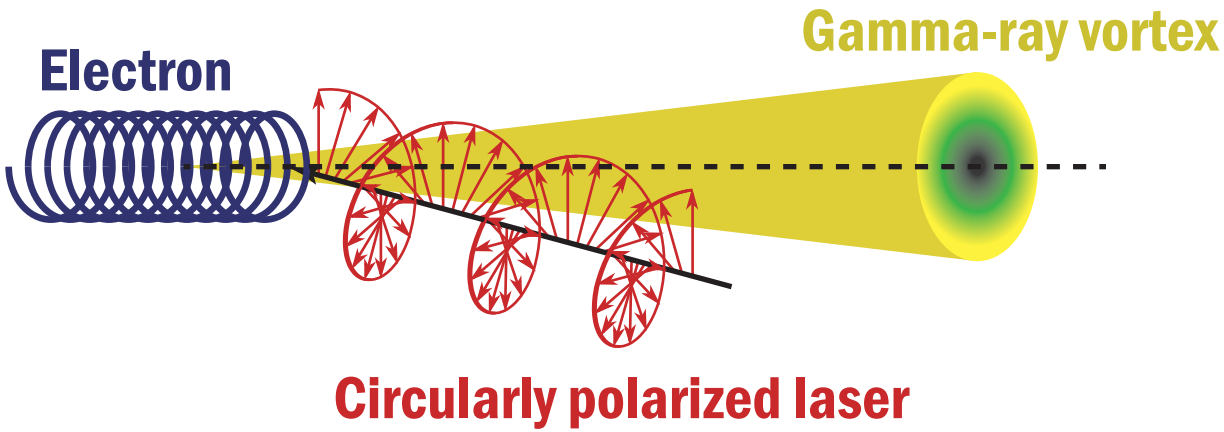
As a new particle source for high energy physics.

How to generate gamma-ray vortices?

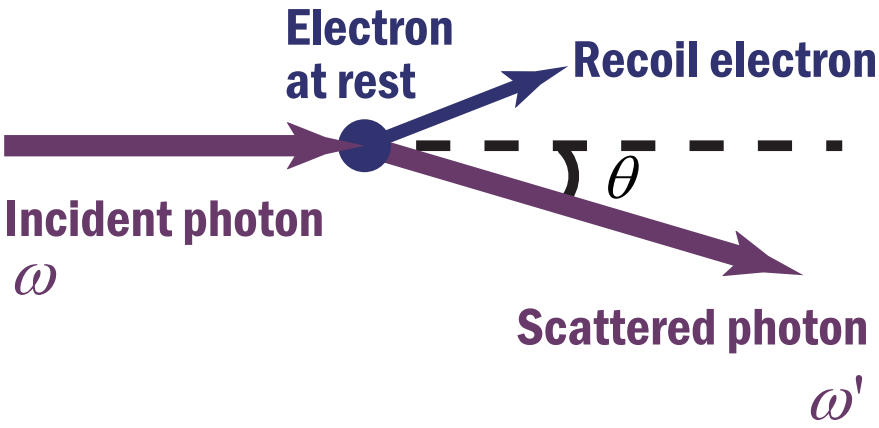
1. Inverse Compton scattering (ICS) of an optical vortex laser by a relativistic electron



2. Nonlinear ICS of intense circularly polarized laser (not vortex laser)



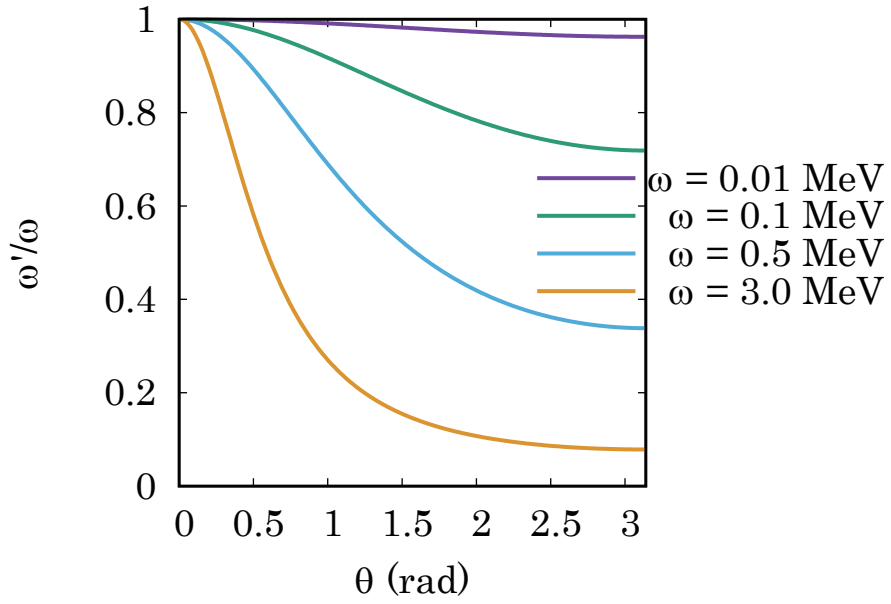
Compton scattering



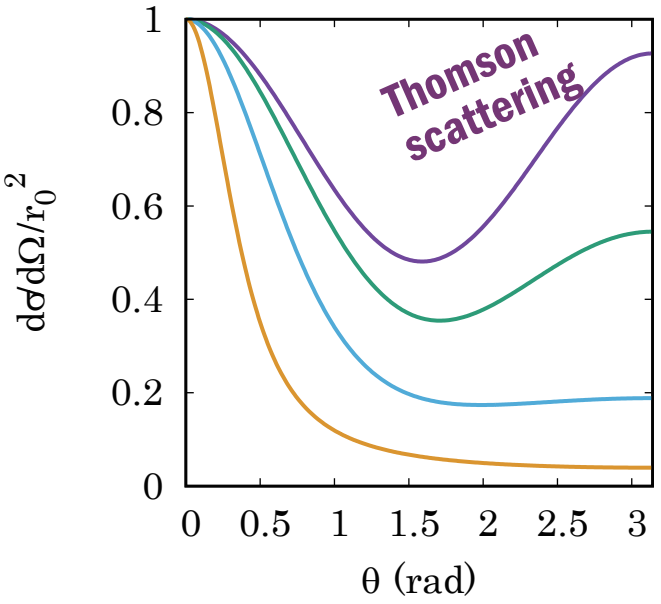
$$\omega' = \frac{\omega}{1 + \frac{\omega}{m_e c^2}(1 - \cos\theta)}$$

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{\omega'}{\omega}\right)^2\left(\frac{\omega'}{\omega} + \frac{\omega}{\omega'} - \sin^2\theta\right)$$

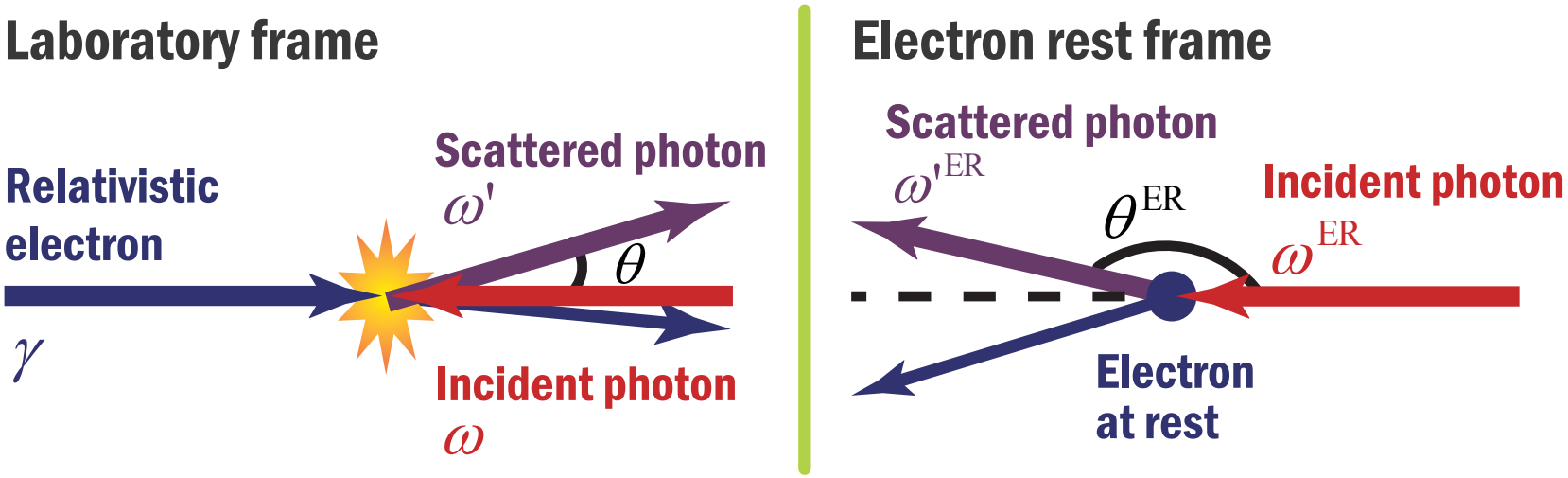
Photon energy



Cross section



Inverse Compton scattering (ICS)

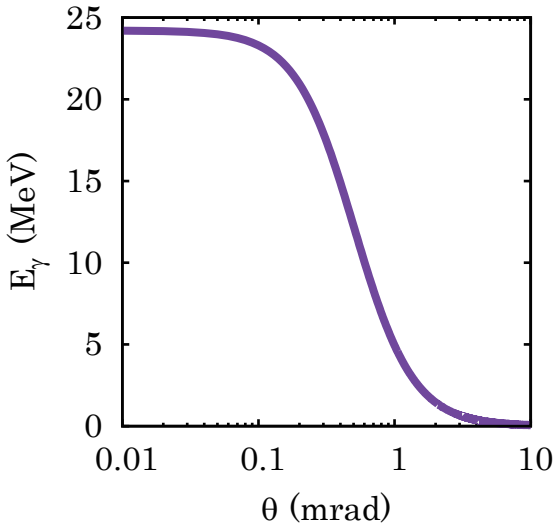


ICS can be derived by the Lorentz transformation of the Compton scattering.

$$\omega^{ER} = \gamma(1+\beta)\omega = 6.2\,\mathrm{keV} < m_e c^2 = 511\,\mathrm{keV}$$ **Thomson scattering**

when γ = 2000 and ω = 1.5 eV

Energy and spatial distribution

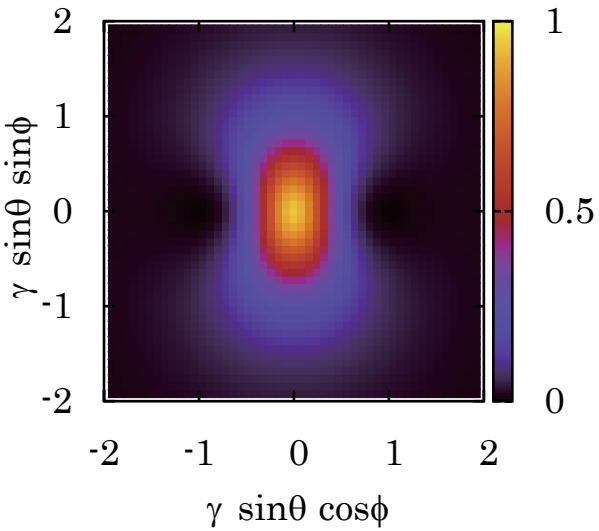


$$E_\gamma = \frac{4\gamma^2\hbar\omega}{\gamma^2\theta^2 + 1}$$

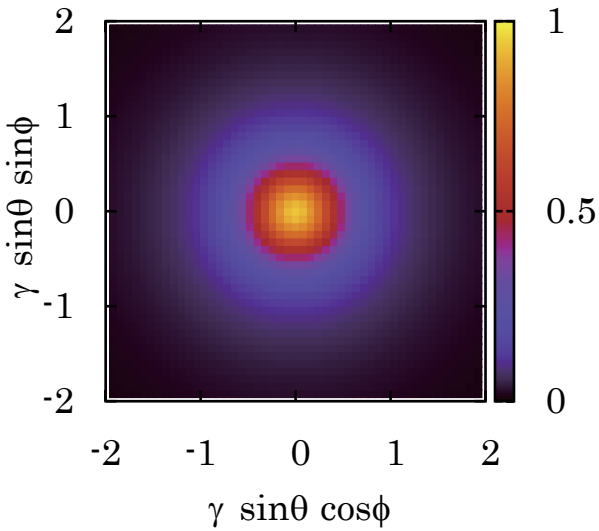
γ = 2000

ω = 1.55 eV (λ = 800 nm)

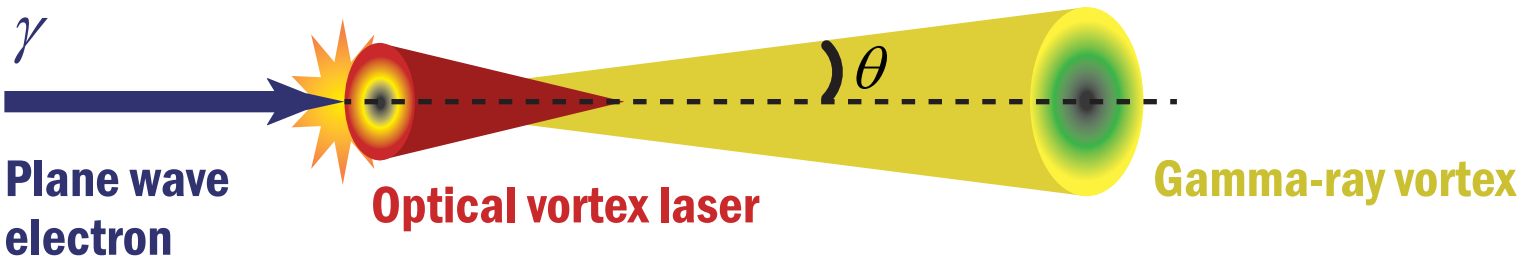
Linear polarization



Circular polarization



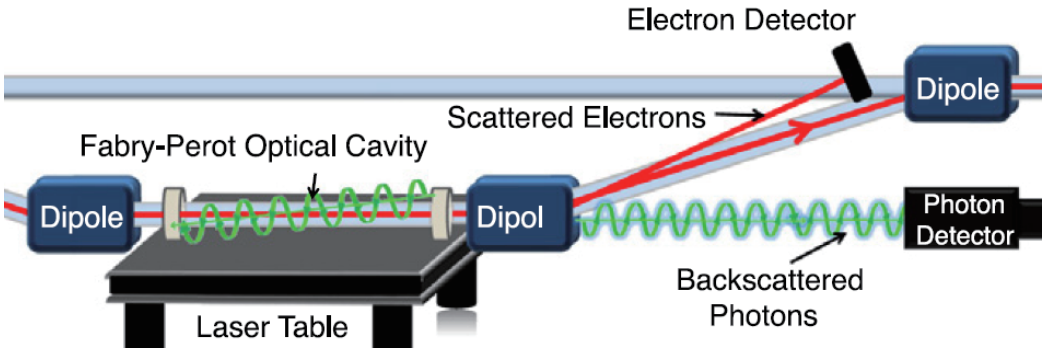
1. ICS of an optical vortex laser



It was predicted that OAM of the gamma-ray preserved the OAM of the laser at the very small angle $\theta < 1/\gamma^2$.

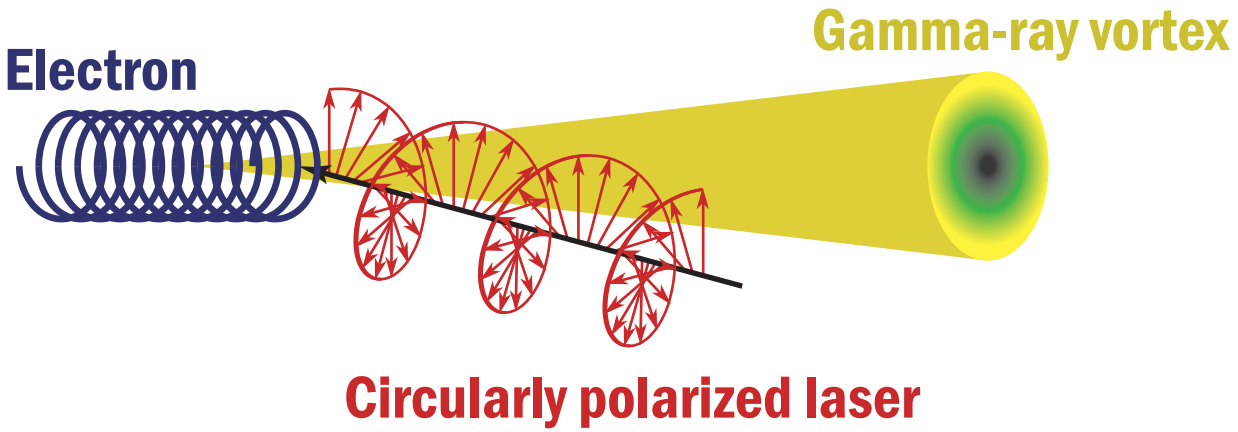
U. D. Jentchura et al., PRL 106 (2011) 013001.

Experimental demonstration using JLab Compton polarimeter



2. Nonlinear ICS

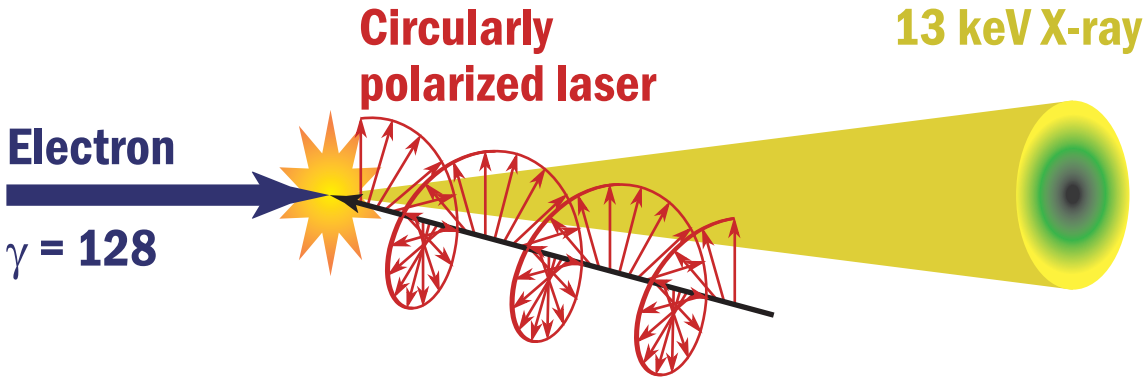
Nonlinear effect of the laser (a laser strength parameter, $a_0 \approx 1$) induces helical motion of the electron.



Scaling of the emitted wavelength

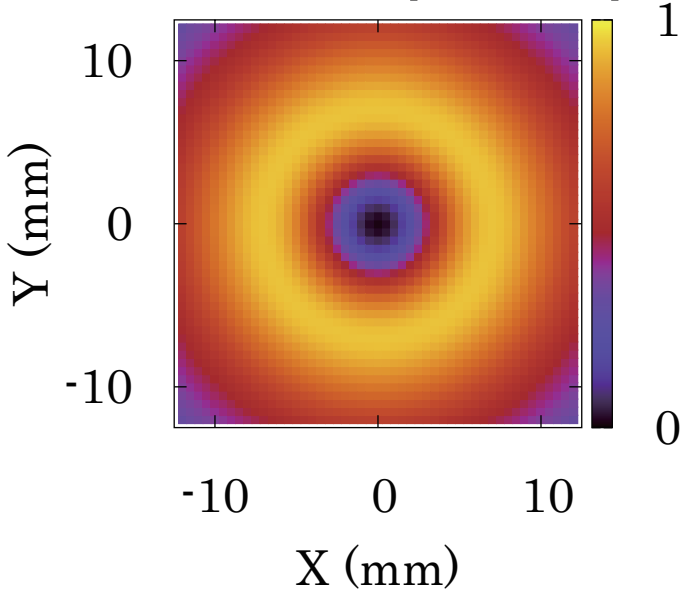
	Helical undulator	Nonlinear ICS
Period of helical motion	cm	10^{-4} → μm
Wavelength of emitted photon	Visible to soft X-ray	Hard X-ray to Gamma-ray

Second harmonic X-rays at BNL (a_0=0.6)

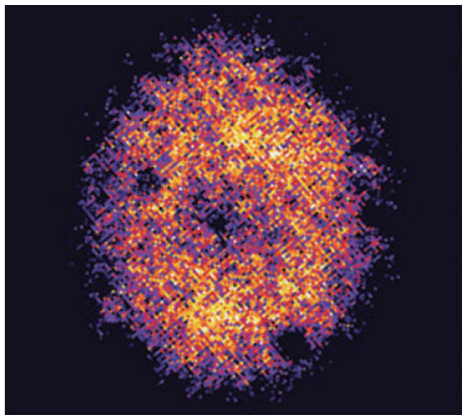


λ_0 = 10.6 μm, pulse energy = 2 J,
$2\omega_0$ = 100 μm, pulse width = 5 ps (FWHM)

Calculation (Y. Taira)



Measurement (BNL)



E = 13 keV (λ = 0.095 nm)

This will be the X-ray vortex.

Y. Sakai et al., PRSTAB 18 060702 (2015).

Review articles

Journal papers

M. Padgett, J. Courtial, and L. Allen, Phys. Today 57 (2004) 35.

G. M. Terriza, J. P. Torres, and L. Torner, Nat. Phys. 3 (2007) 305.

S. F. Arnold, L. Allen, and M. Padgett, Laser & Photon. Rev. 2 (2008) 299.

A. M. Yao and M. J. Padgett, Adv. Opt. Phot., 3 (2011) 161.

Books

L. Allen et al., "Optical Angular Momentum" IoP publishing, 2003.

A. Bekshaev et al., "Paraxial Light Beams with Angular Momentum" Nova Science Publishers, 2008.

D.L. Andrews, "Structured Light and its Applications" Academic Press, 2008.

J. P. Torres and L. Torner, "Twisted Photons" Wiley-VCH, 2011.

D.L. Andrews and M. Babiker, "The Angular Momentum of Light" Cambridge University Press, 2013.