National Institute of Advanced Industrial Science and Technology
AIST

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非線形逆トムソン散乱によるガンマ線渦の発生

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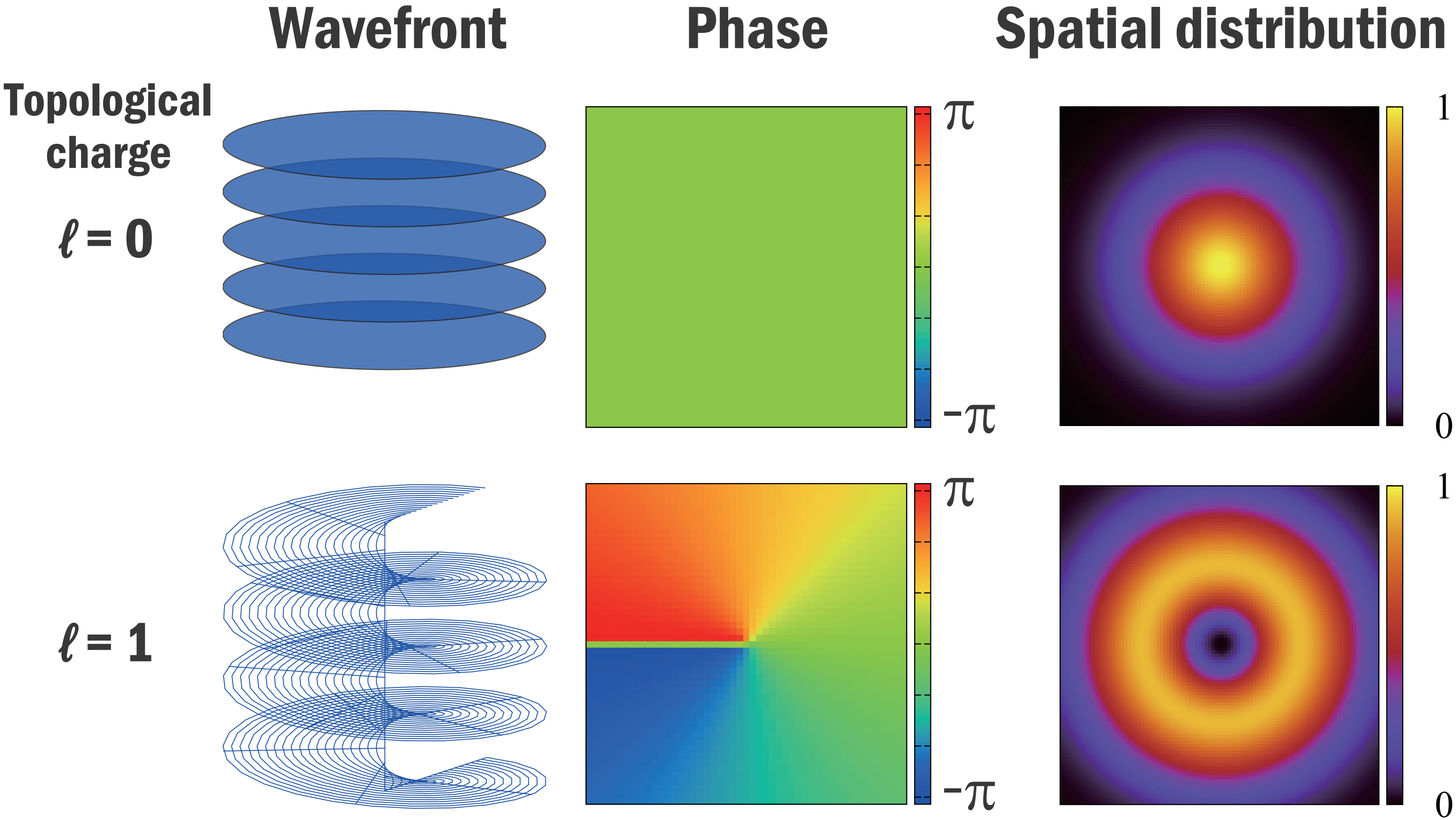
Optical vortices forming helical wavefronts



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

Carrying $\ell\hbar$ orbital angular momentum (OAM)

Representative optical vortex: Laguerre Gaussian mode

Poynting vector and total AM

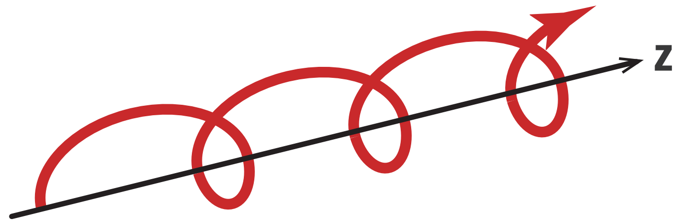
Poynting vector of Laguerre Gaussian mode

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

k: wave number of LG light
ρ: distance from the z-axis

spread of the beam

Spiral Poynting vector gives OAM



Total angular momentum

Spin AM + OAM = ± ħ + ℓ ħ or ℓ ħ

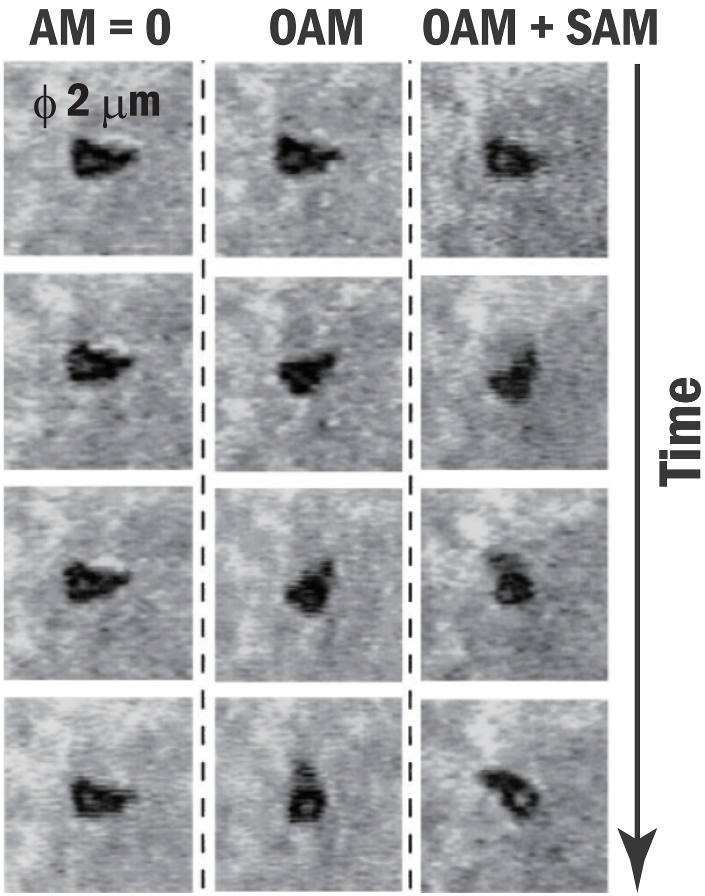
Circularly polarized optical vortex

Linearly polarized optical vortex

L. Allen et al., Phys. Rev. A 45 (1992) 8185.
L. Allen et al., Prog. Opt. 39 (1999) 291.

Transfer of OAM using optical vortex lasers

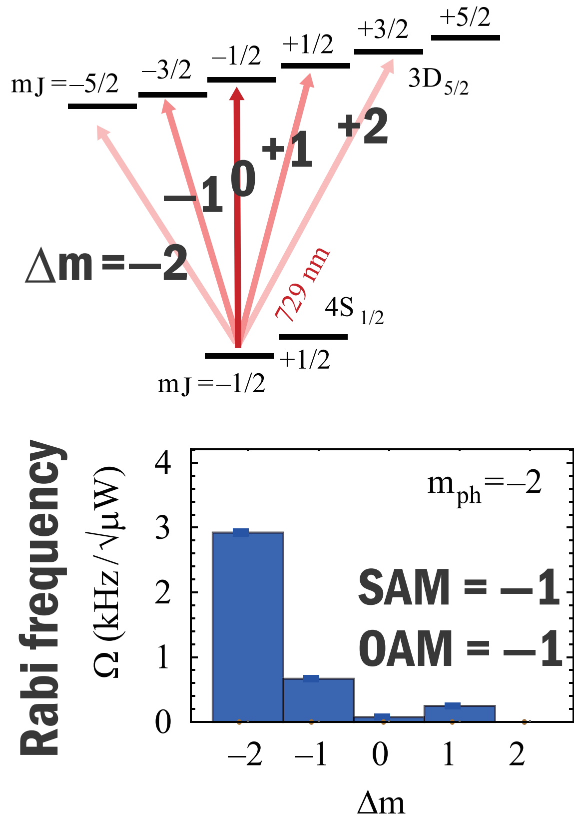
To a micro particle



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

To a valence electron

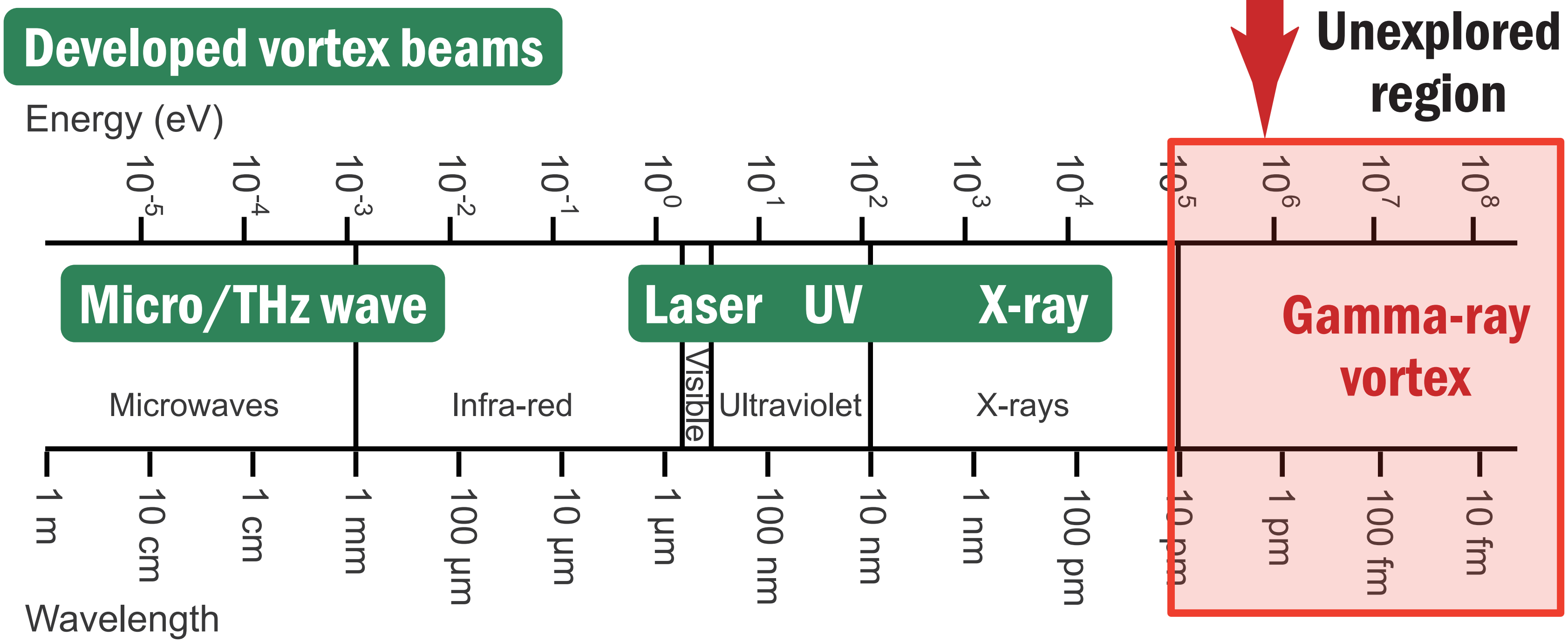
Quadruple transition at 729 nm of $^{40}Ca^{+}$ ion.



C. T. Schmiegelow et al., Nat. Comm. 7 (2016) 12998.

Purpose

Generation of gamma-ray vortices (more than sub-MeV energy) and development of their application.



Except for the electromagnetic wave

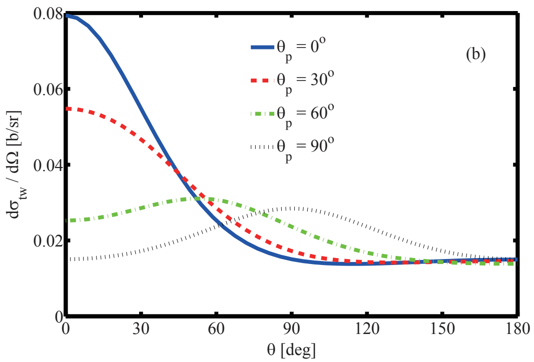
300 kV electron

Cold neutron

Applications of gamma-ray vortices

Compton scattering

J. A. Sherwin, Phys. Rev. A 96 062120 (2017).

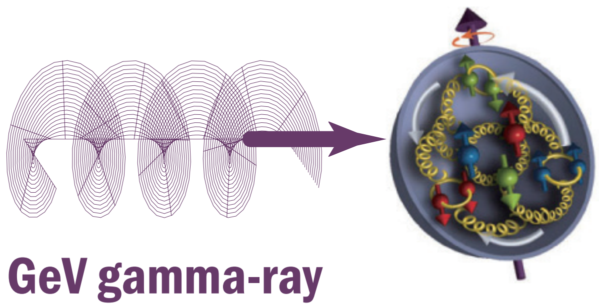


Cross section (E_0 = 500 keV)

θ_p: Momentum ratio between transverse and longitudinal component

They may be applied to solid state physics by being expanded to magnetic Compton scattering.

Insight into the proton structure



Proton spin puzzle: Only 30% of the proton spin is carried by the quark spin.

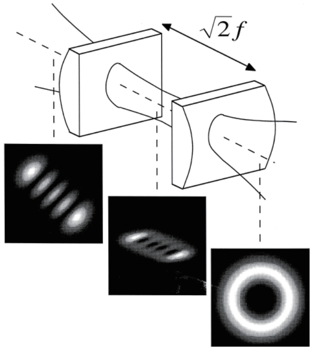
If OAM of gamma-rays affects to OAM of quark or gluon, it becomes novel probe of the proton spin.

Other potential application

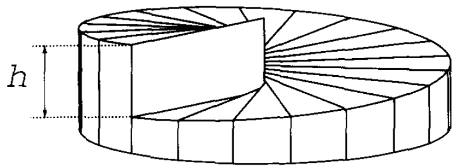
Excitation of nucleus, Generation of positron vortices, Astrophysics, etc.

Generation of optical vortices

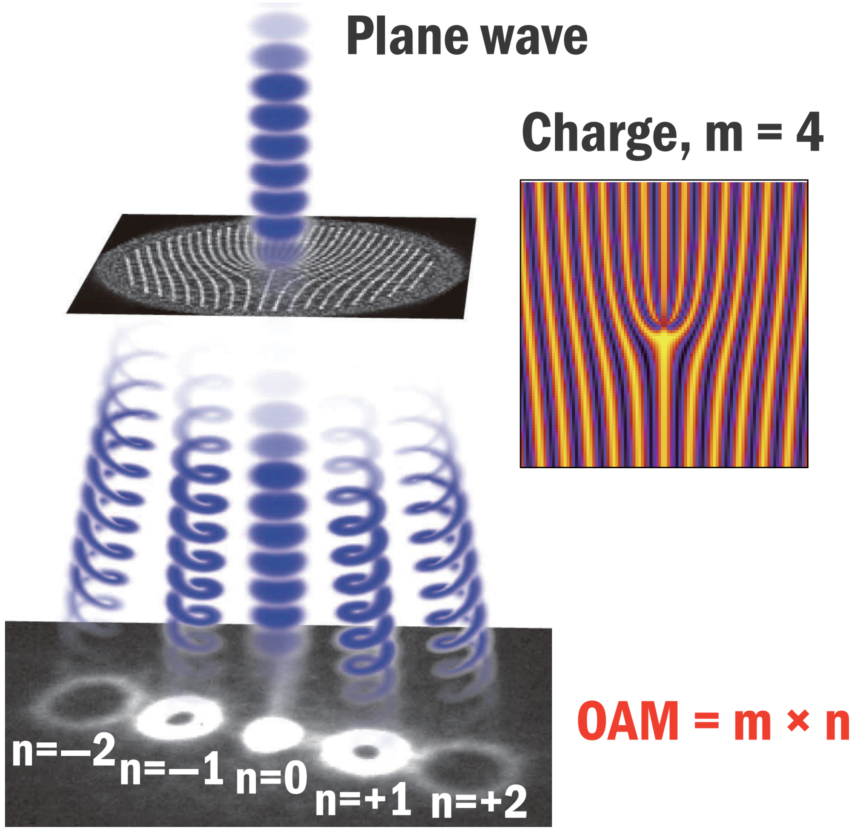
Cylindrical lens



Spiral phase plate



Fork grating

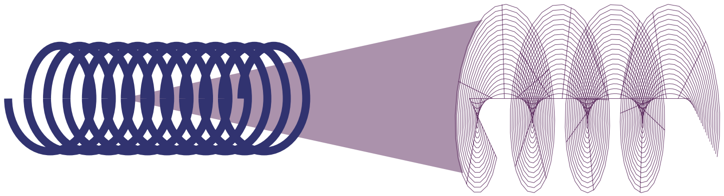


J. Courtial et al., Opt. Comm. 159 (1999) 13.
M. W. Beijersbergen et al., Opt. Comm. 112 (1994) 321.
B. J. McMorran et al., Science 331 (2011) 192.

Optical vortices from free electrons

An electron moving on a circular trajectory emits optical vortices

Electron



S. Sasaki et al., PRL. 100 124801 (2008).
M. Katoh et al., PRL. 118 094801 (2017).

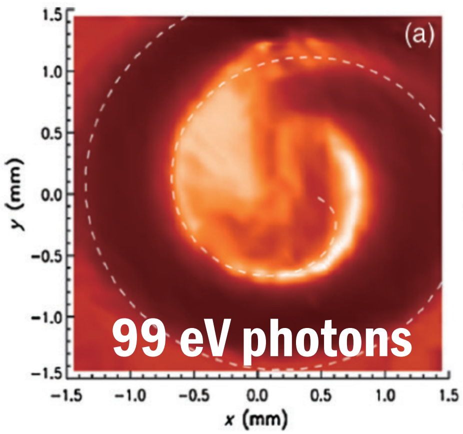
Electric field emitted by a helical undulator

$$\mathbf{E} \propto C \exp\{i(n-1)\phi\} \mathbf{e}_+$$

n^{th} higher harmonics carry (n—1)ħ OAM

This was demonstrated in ultraviolet and soft X-ray regions.

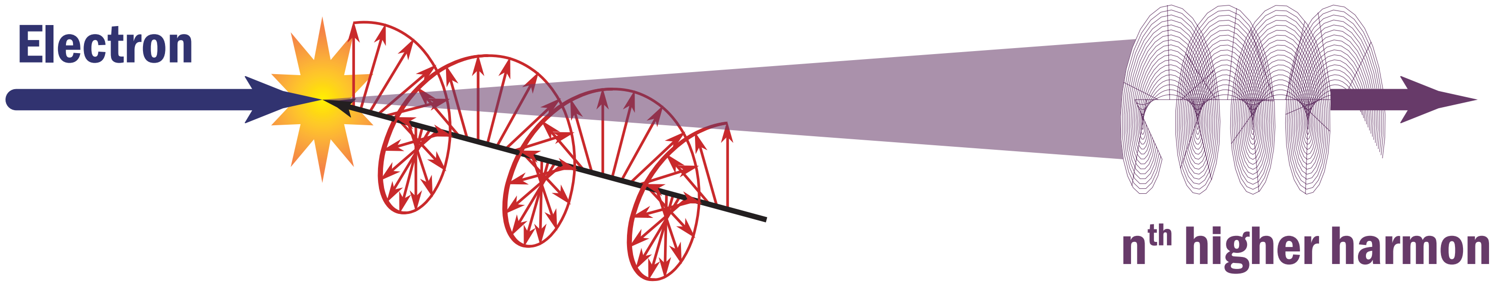
2nd harmonics (1ħ OAM) → 1 spiral interference fringe (Helical + Spherical)



J. Bahrdt et al., PRL 111 034801 (2013).
M. Katoh et al., Sci. Rep. 7 6130 (2017).

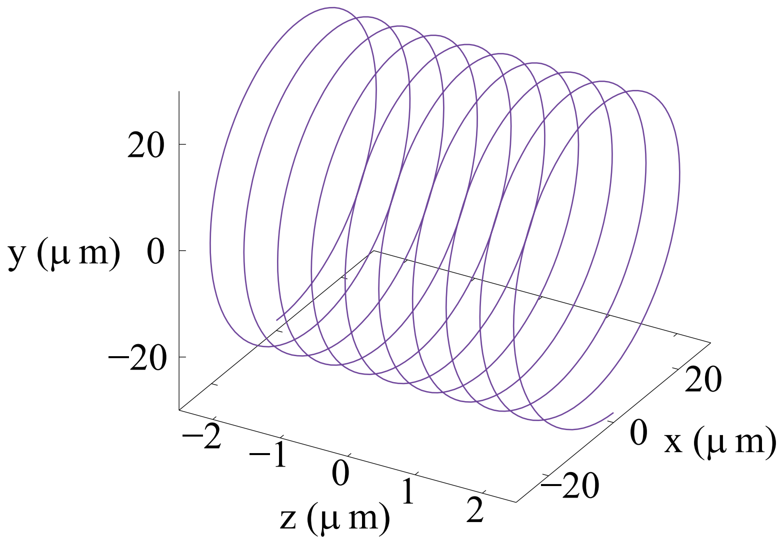
Gamma-ray vortices via NITS

Nonlinear inverse Thomson scattering (NITS)



n^th higher harmonics carry (n−1)ħ OAM

Electron trajectory inside a laser



Gamma-ray energy

$$E_\gamma = \frac{4n\gamma_0^2 E_L}{1 + a_0^2/2}$$

γ_0: Lorentz factor of an electron

E_L: Energy of laser photon

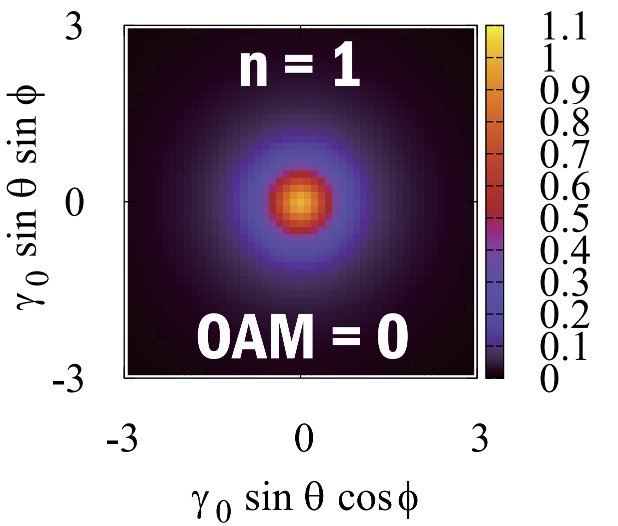
a_0: Laser strength parameter

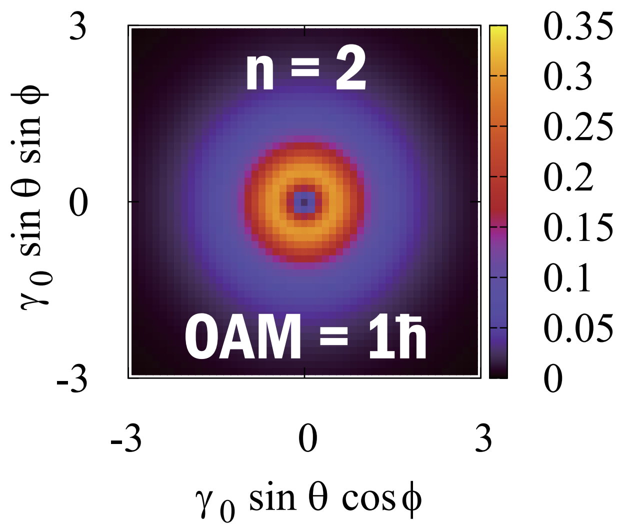
10^{18} W/cm^2 reaches $a_0 \simeq 1$

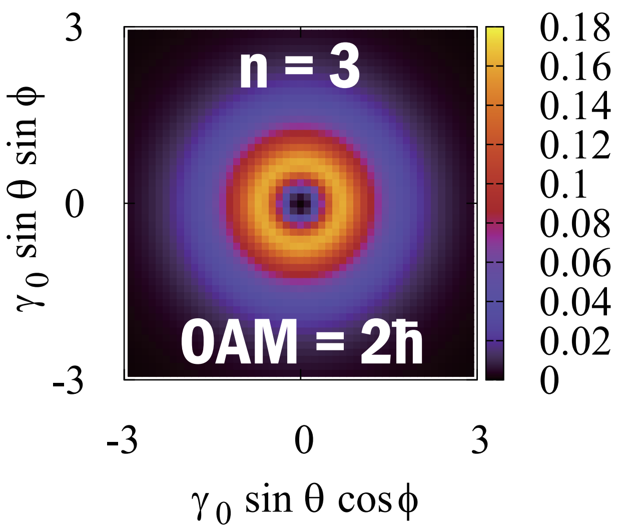
Y. Taira et al., Sci. Rep. 7 5018 (2017).

Y. Taira et al., The Astrophysical Journal 860 45 (2018).

Spatial distributions of NITS gamma-rays





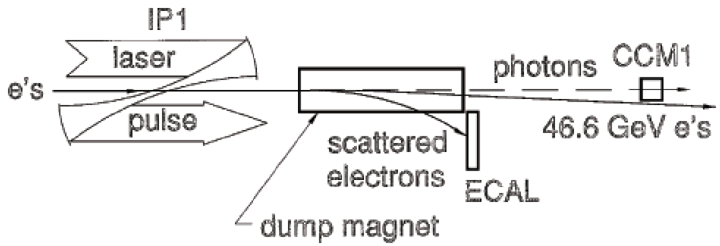


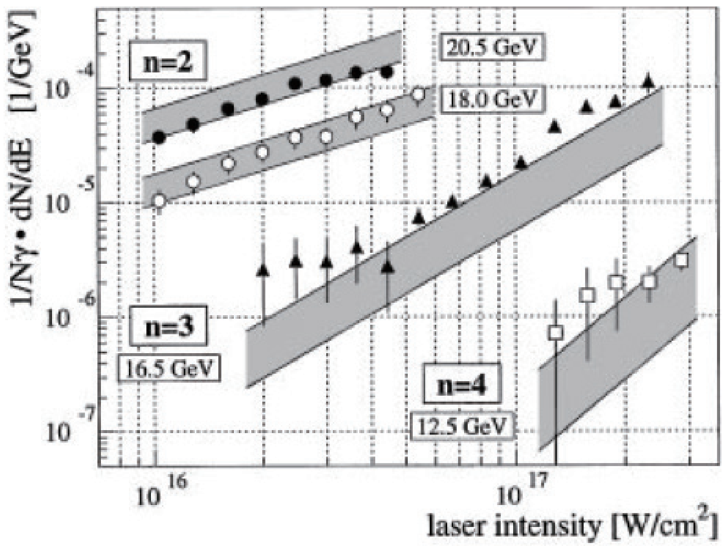
Only higher harmonic gamma-rays show annular intensity distribution, which is consistent with the characteristics of an optical vortex.

Y. Taira et al., Sci. Rep. 7 5018 (2017).

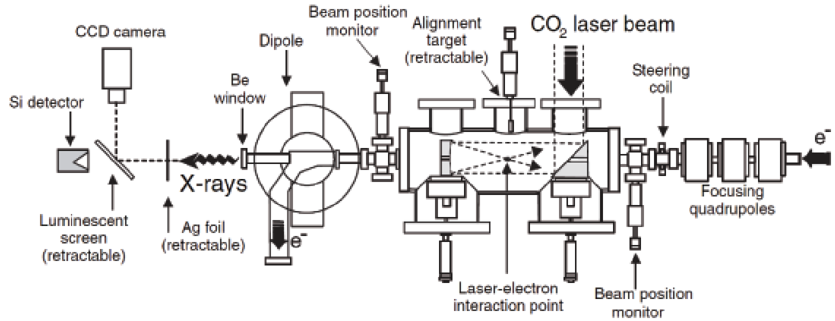
NITS using RF accelerated electrons

SLAC C. Bula et al., PRL 76 3116 (1996).

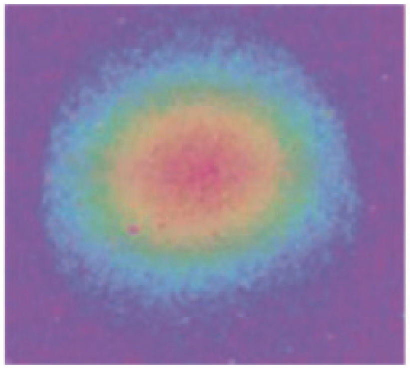


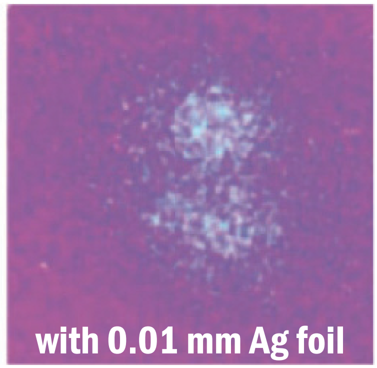


BNL M. Babzien et al., PRL 96 054802 (2006).



Spatial distributions of linearly polarized X-rays

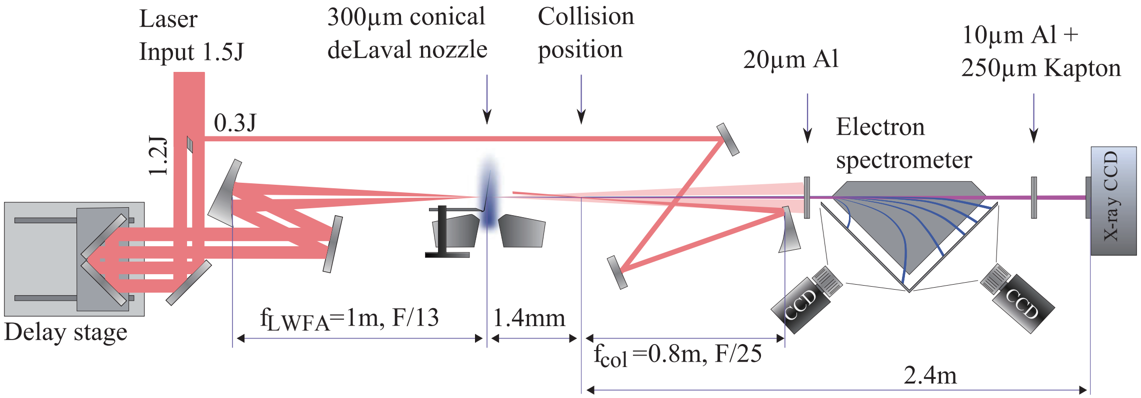


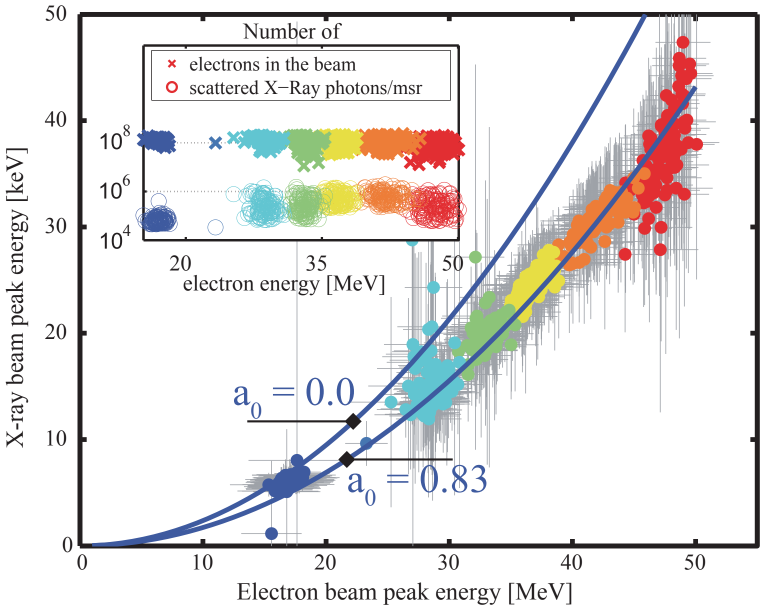


NITS using laser wakefield accelerated e-

Ludwig-Maximilians-Universität München

K. Khrennikov et al., PRL 114 195003 (2015).





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E. Miura et al., APEX 7 046701 (2014).

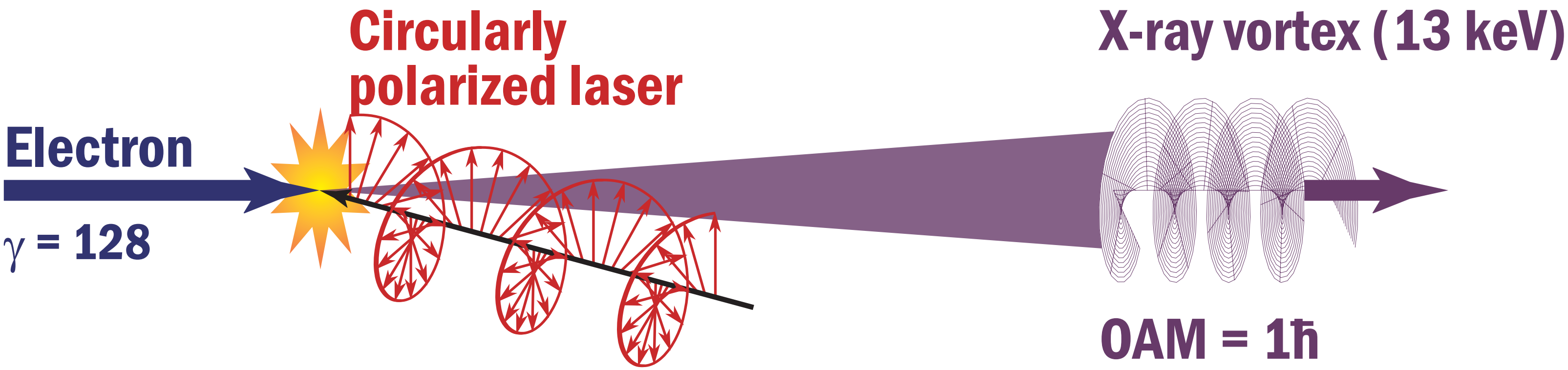
U of Nebraska-Lincoln

W. Yan et al., Nat. Phot. 11 514 (2017).

Rutherford Appleton Laboratory

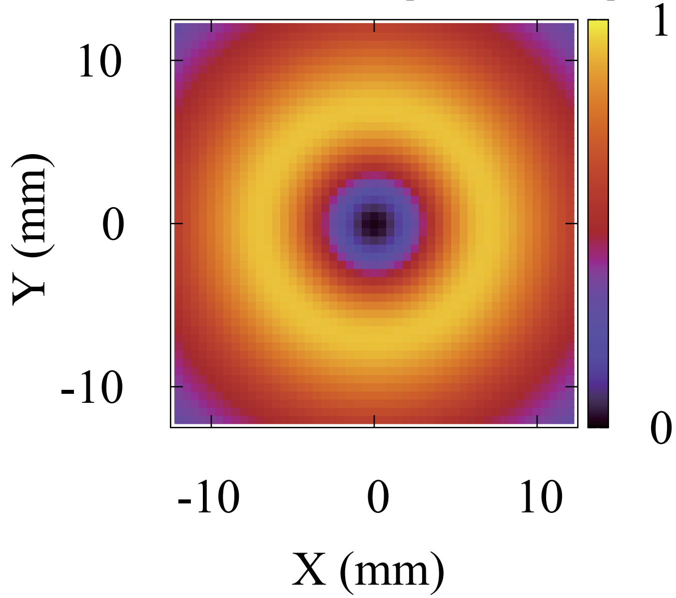
G. Sarri et al., PRL 113 224801 (2014).
J. M. Cole et al., PRX 8 011020 (2018).

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

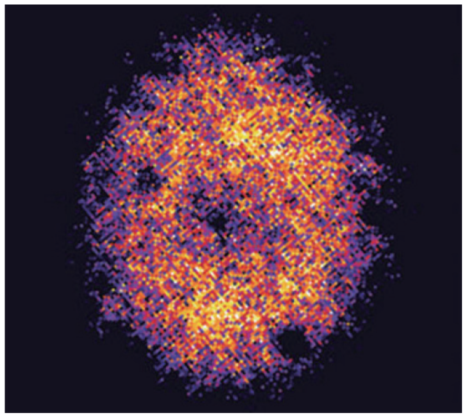


λ_0 = 10.6 μm, pulse energy = 2 J,
$2\omega_0$ = 100 μm, pulse width = 5 ps (FWHM)

Calculation (Y. Taira)



Measurement (BNL)



E = 13 keV (λ = 0.095 nm)

This will be a X-ray vortex.

Next step

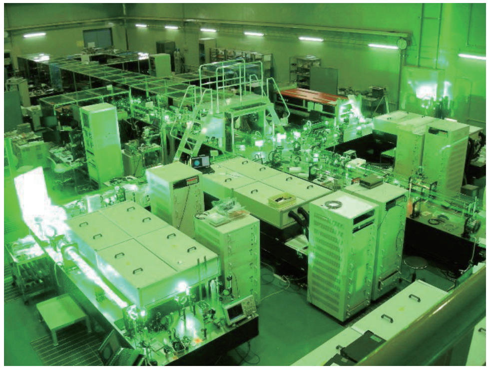
Measurement of a herical wavefront.

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

Experimental plans at KPSI and UVSOR-III

KPSI of QST

Microtron + J-KAREN-P PW laser (800 nm)



γ_0 = 300
a_0 < 3

→ **0.4 MeV gamma-ray vortices.**
$N_\gamma = 10^3 \sim 10^5$ photons/sec

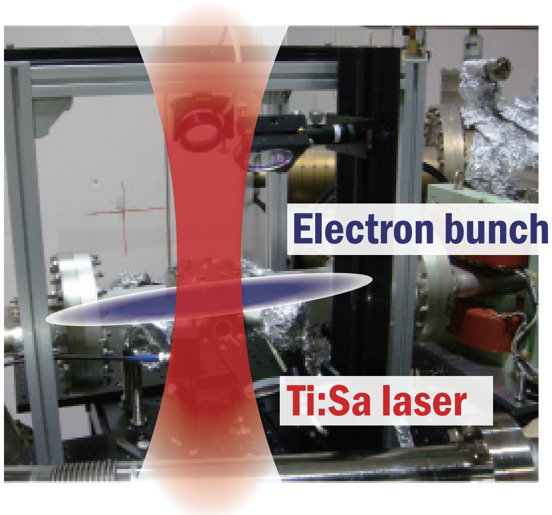
Purpose:

Measurement of annular distribution and helical wavefront.

Study of Compton scattering.

UVSOR-III

90-degree collision



γ_0 = 1470
$a_0 \sim 0.6$

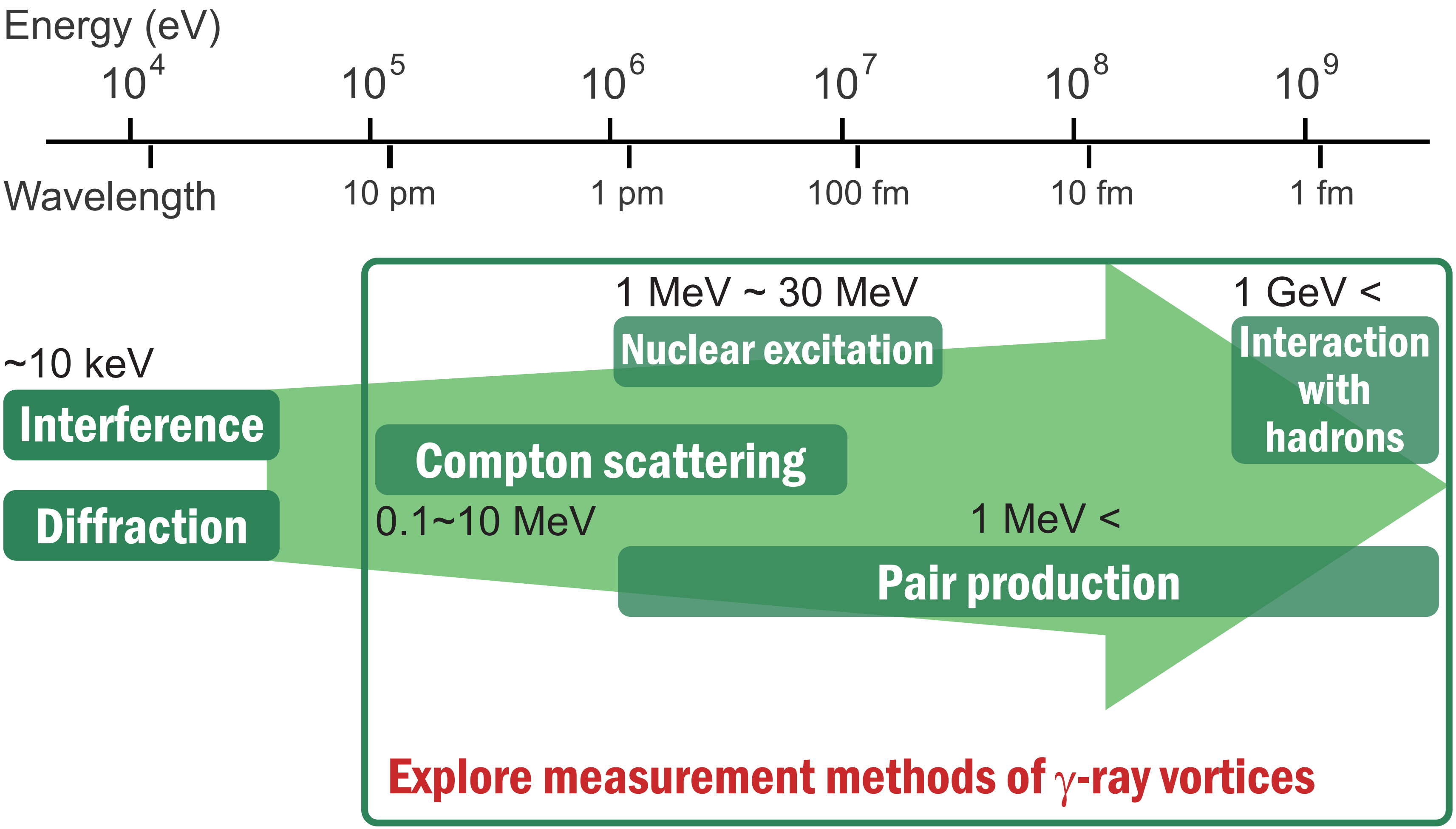
→ **10 MeV gamma-ray vortices.**
$N_\gamma \sim 800$ photons/sec

Purpose:

Measurement of annular distribution.

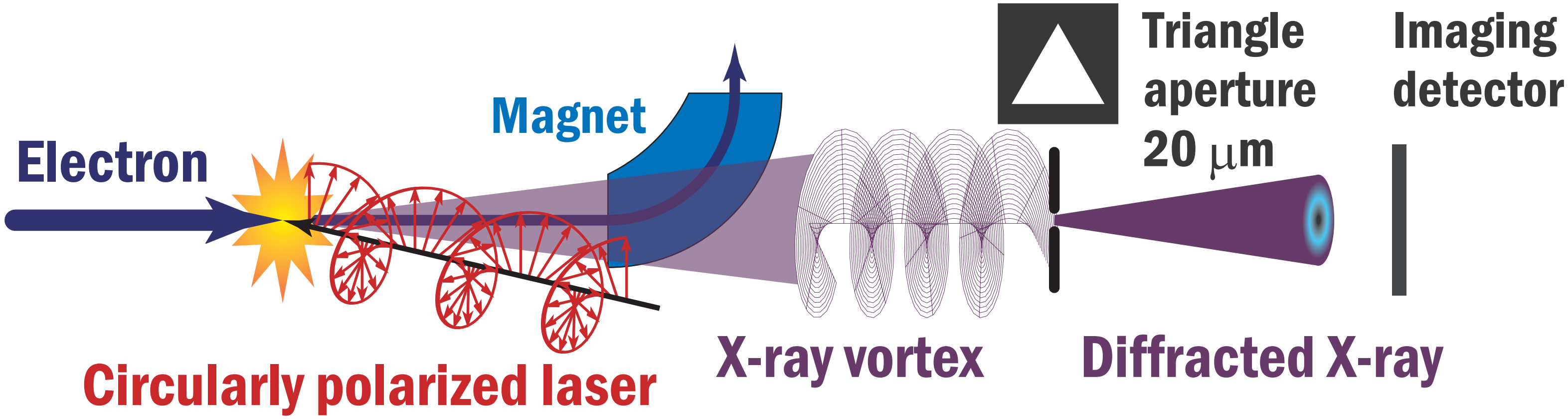
Study of Compton scattering and nuclear excitation.

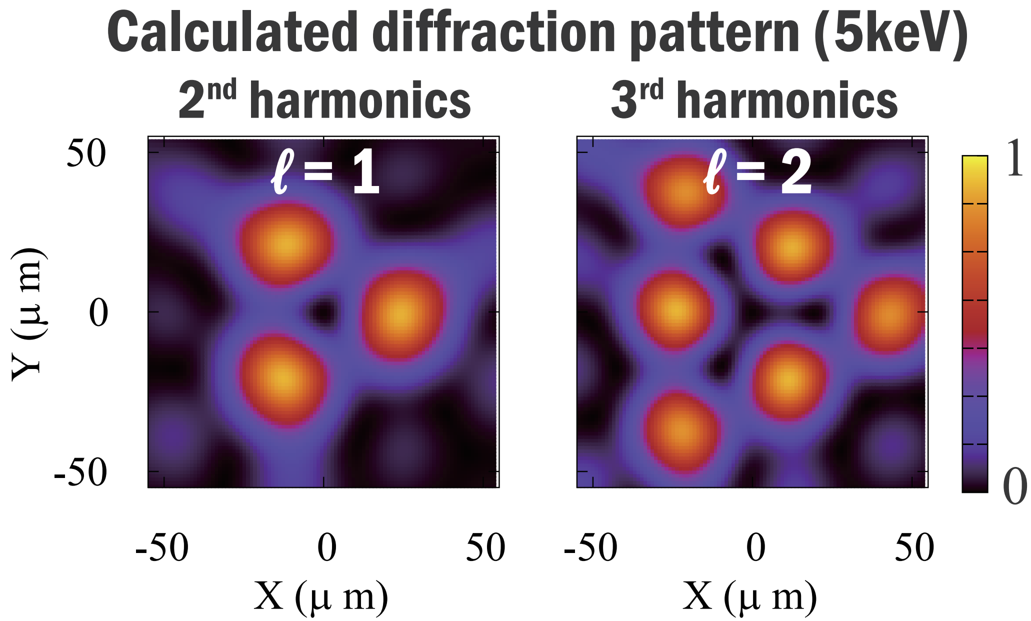
Measurement of γ-ray vortex is challenging



Diffraction method

Triangle aperture





A triangle aperture can be used to measure the helical wavefronts.

R&D is carried out at SPring-8.

Acknowledgment

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Summary

- Gamma-ray vortices can be generated by nonlinear inverse Thomson scattering.

  n-th higher harmonic gamma-rays carry $(n-1)\hbar$ OAM.

- Measurement of gamma-ray vortices is a big issue.

  In the low energy region, diffraction and interference methods must work.

  Compton scattering may work around MeV energy region.

Thank you for your attention!