National Institute of Advanced Industrial Science and Technology
AIST

20th ATF Users Meeting, BNL, 12/5/2017

Feasibility study for measurement of X-ray vortices at ATF

Yoshitaka Taira[1], Yusuke Sakai[2]

1:National Institute of Advanced Industrial Science and Technology (AIST), Japan
2: University of California at Los Angeles

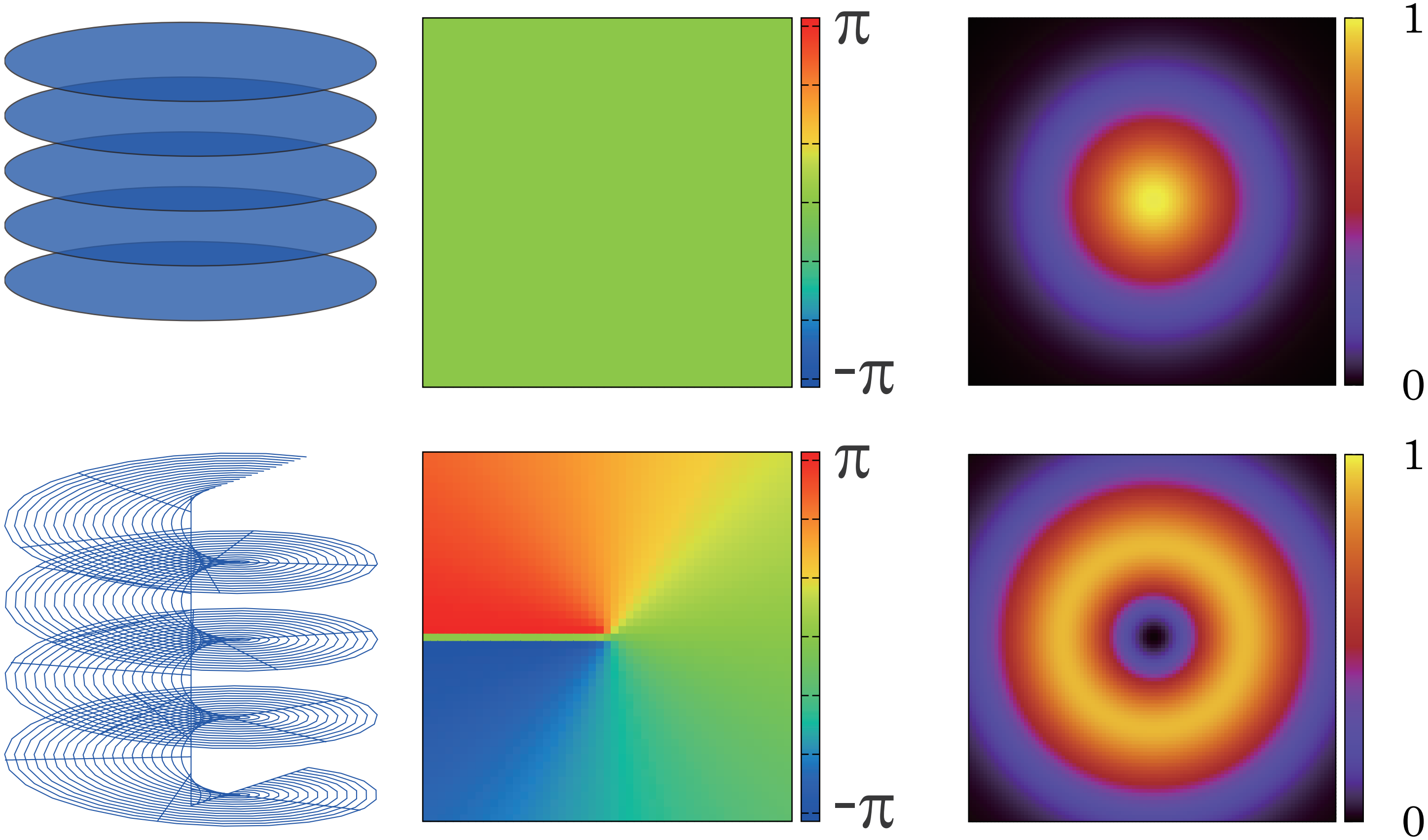
Vortex beams forming helical wavefront

Wavefront | **Phase** | **Spatial distribution**

Topological charge

$\ell = 0$

$\ell = 1$

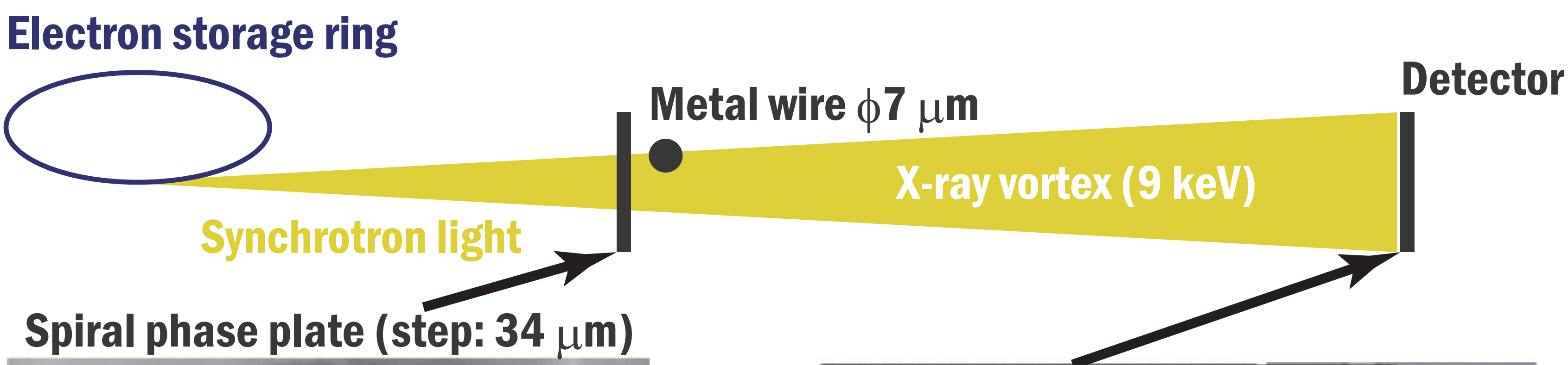


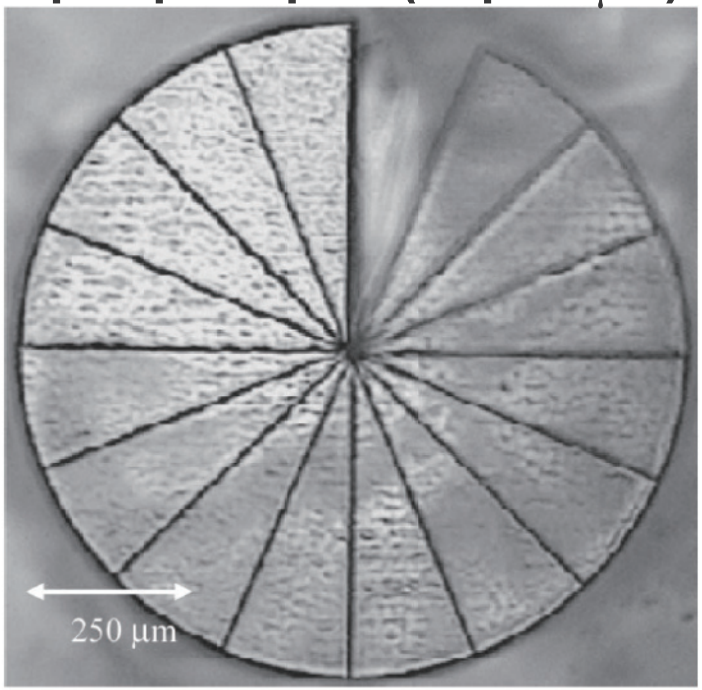
Electric field

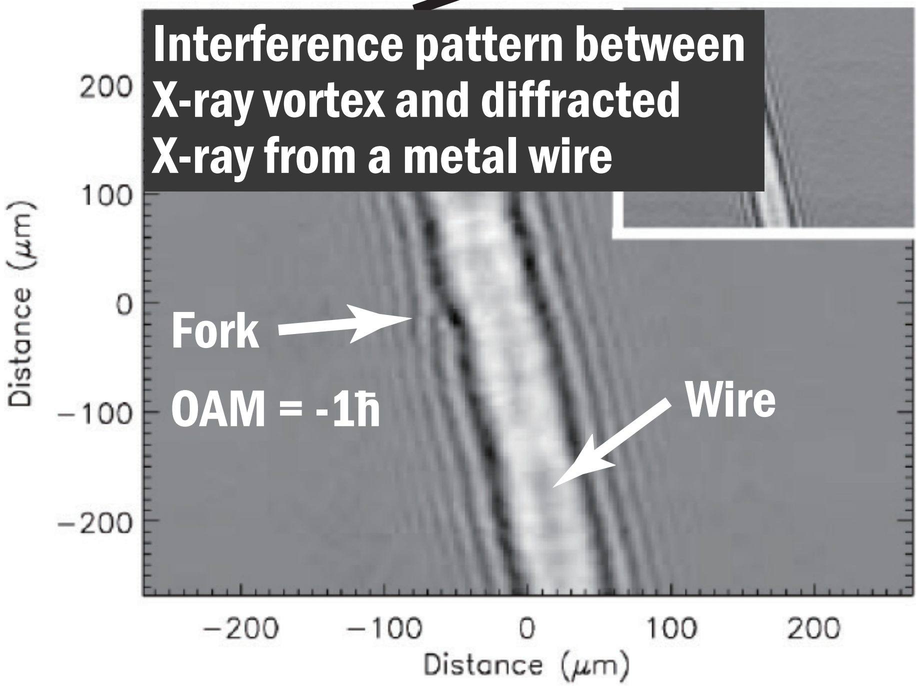
$$E \propto \exp\left(i\ell\phi\right)$$

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

Measurement of 9-keV X-ray vortex

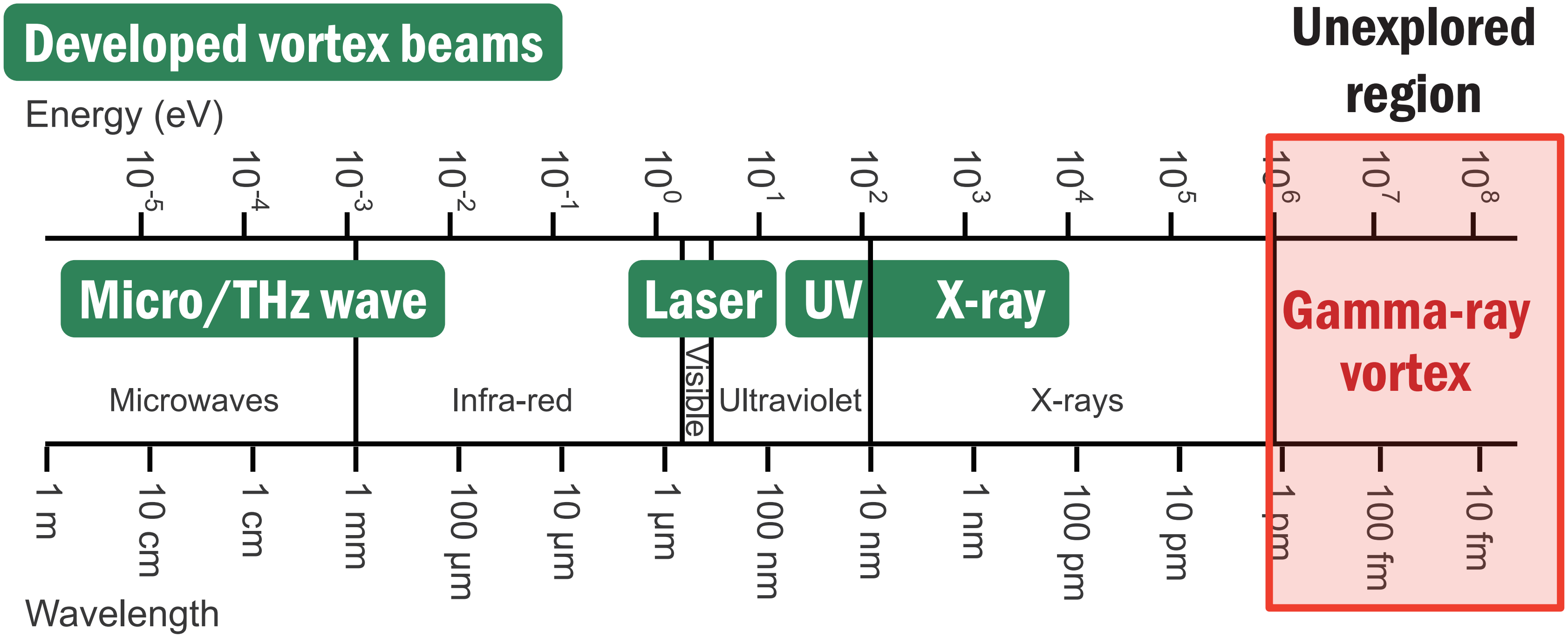






A. G. Peele et al., Opt. Lett. 27 (2002) 1752.

Vortex beams

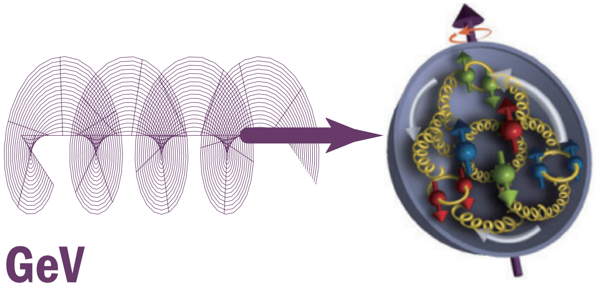


Except for the electromagnetic wave

- 300 kV electron
- Cold neutron

Possible applications of gamma-ray vortex

Insight into the proton structure



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

Quest for the remaining ~70% is a major enterprise in nuclear physics

quark OAM
gluon spin, OAM

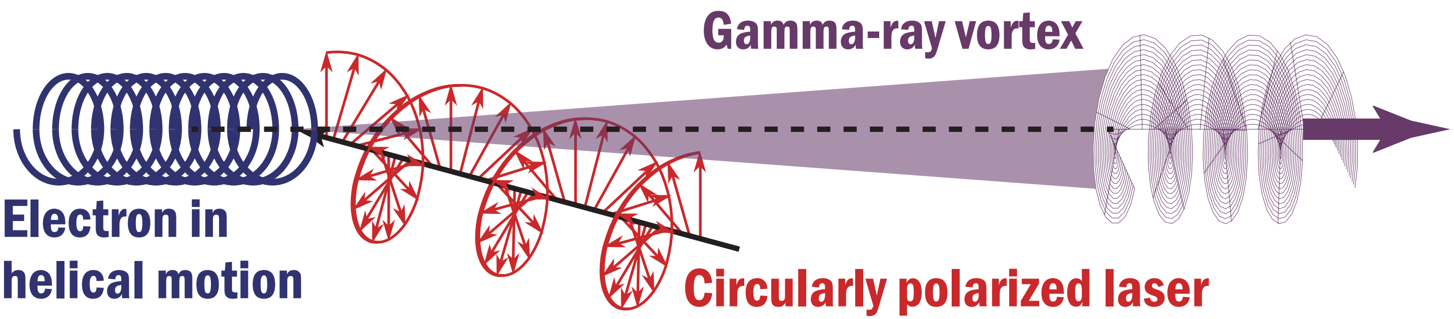
If the OAM of gamma ray affects to the OAM of quark or gluon, it becomes novel probe of the proton spin.

Other potential application

Excitation of nucleus
Generation of positron vortices via pair production.
Astrophysics (gamma-ray burst)
Solid state physics (magnetic Compton scattering)

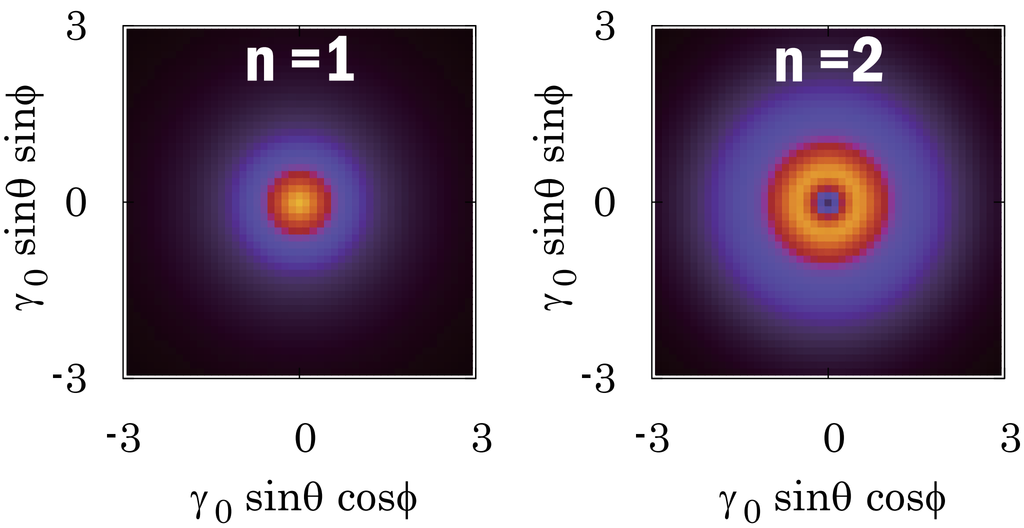
How to generate gamma-ray vortices?

Nonlinear inverse Thomson scattering



Electric field of emitted gamma-rays

$$\vec{E} \propto C \exp\{i(n-1)\phi\} e_{+}$$



n^{th} higher harmonics carry $(n-1)\hbar$ OAM and higher harmonics show annular intensity distribution.

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

Research objectives

Final goal

We will demonstrate that higher harmonic gamma-rays form helical wavefronts and apply them to nuclear physics.

Problem

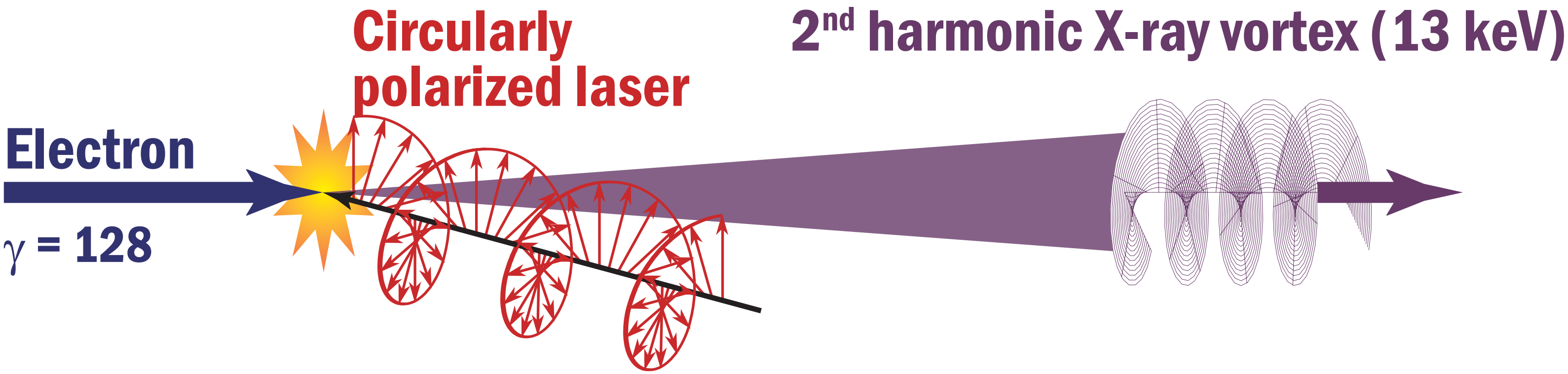
The measurement of a helical wavefront in the gamma-ray frequency range is difficult using current technology.

In the 10 keV energy range, diffraction and interference methods can be used to measure the helical wavefronts.

Goal of the first step

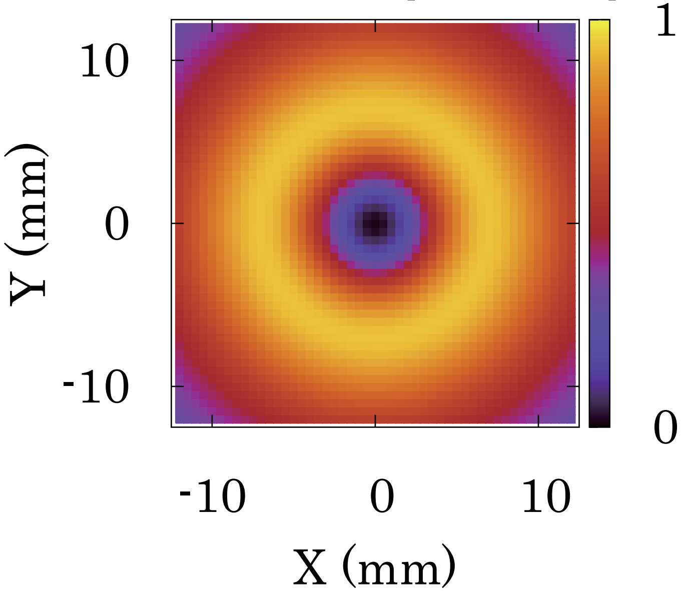
We will demonstrate that 2nd harmonic X-rays generated by nonlinear inverse Thomson scattering form a helical wavefront.

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

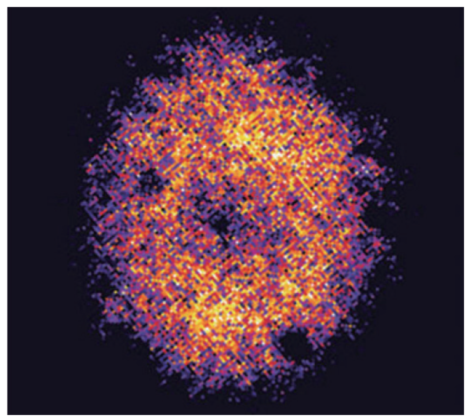


λ_0 = 10.6 μm, pulse energy = 2 J,
$2\omega_0$ = 100 μm, pulse width = 5 ps (FWHM)

Calculation (Y. Taira)



Measurement (BNL)



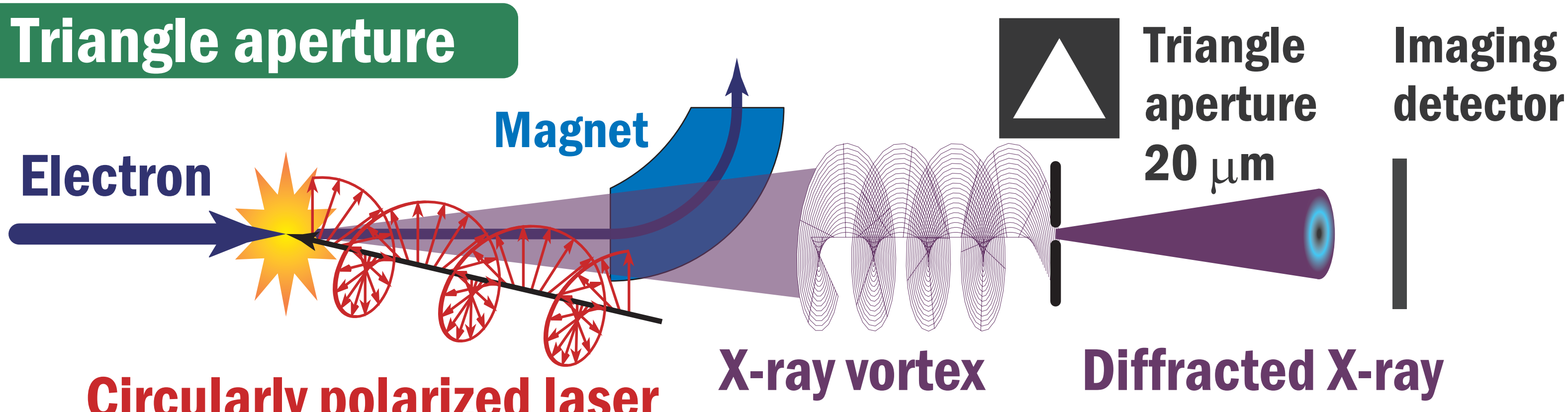
E = 13 keV (λ = 0.095 nm)

This result implies that second harmonic X-rays form a helical wavefront.

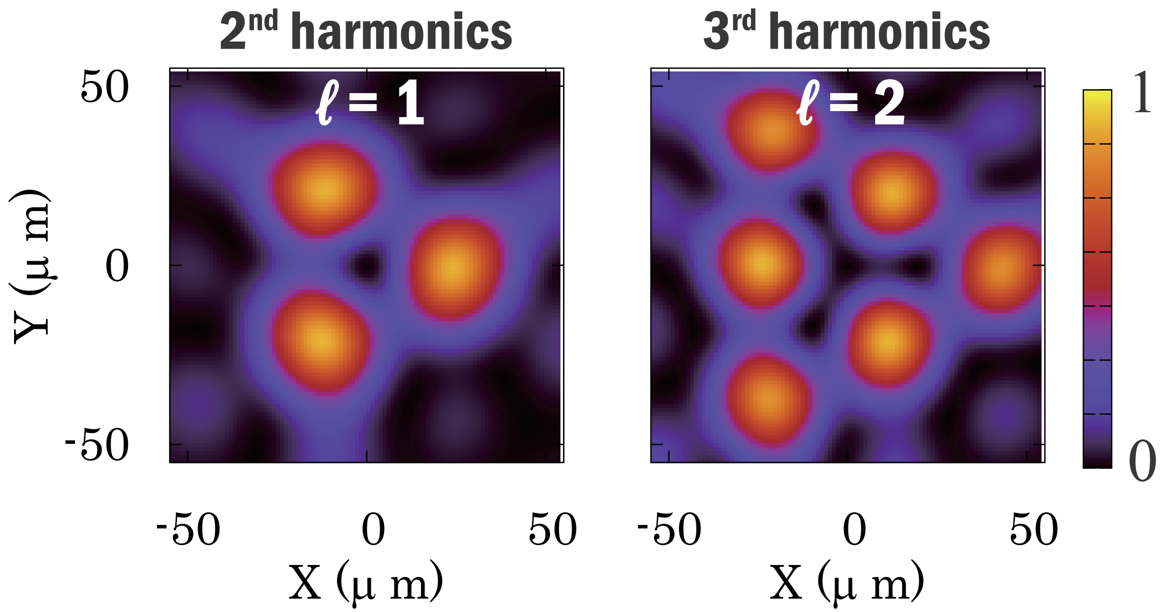
Y. Sakai et al., PRSTAB 18 060702 (2015).

Measurement of a helical wavefront

Triangle aperture



Calculated diffraction pattern



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

Coherence length and number of photons

Coherence length and angle

$$L_c = \frac{\lambda R}{2\pi\sigma} \qquad \theta_c = \frac{\lambda}{2\pi\sigma}$$

λ: wavelength of X-ray
R: distance from source to aperture plane
σ: X-ray source size (rms)

When λ = 0.17 nm, R = 2 m, and σ = 2 μm, L_c = 28 μm and θ_c = 14 μrad .

Cohenrence length is larger than a dimension of a triangle aperture.

The number of photons

Electron: γ_0 = 100, charge = 0.16 nC/pulse, pencile beam

Laser: λ_0 = 9.3 μm, a_0 = 1.0, pulse width = 3.5 ps (FWHM)

X-ray: Maximum energy = 7.1 keV (λ = 0.17 nm)
The number of photons = 10^{-3}~10^{-2} photons/pulse (θ_c = 14 μrad)

Single shot measurement is difficult.

Research plan in FY2018

What is important? - Please give us any ideas -

Small X-ray source size to get large transverse coherence length

Is the minimum electron beam size 5 μm (rms)?
Is it possible to obtain < 2 μm electron souce size?
Can an electron beam size along the one axis be reduced?

Using short wavelength laser ($\lambda_0 \sim 1$ μm)?

Intense X-ray source to measure at a single or few shots

Is a high current electron source avairable?

Is $a_0 \sim 1$ laser with the long pulse width possible?

Calculation of other detection methods

Using a double slit and interference of 1st and 2nd harmonics.

Summary

- Gamma-ray and X-ray vortices are generated by nonlinear inverse Thomson scattering.
- A triangle aperture can be used to measure the helical wavefront.
- However, it is very difficult to achieve the required coherence length of X-rays and the single shot measurement.
- In FY2018, we continue to do theoretical investigation using a double slit and an interference method for a future experiment.

Thank you for your attention!