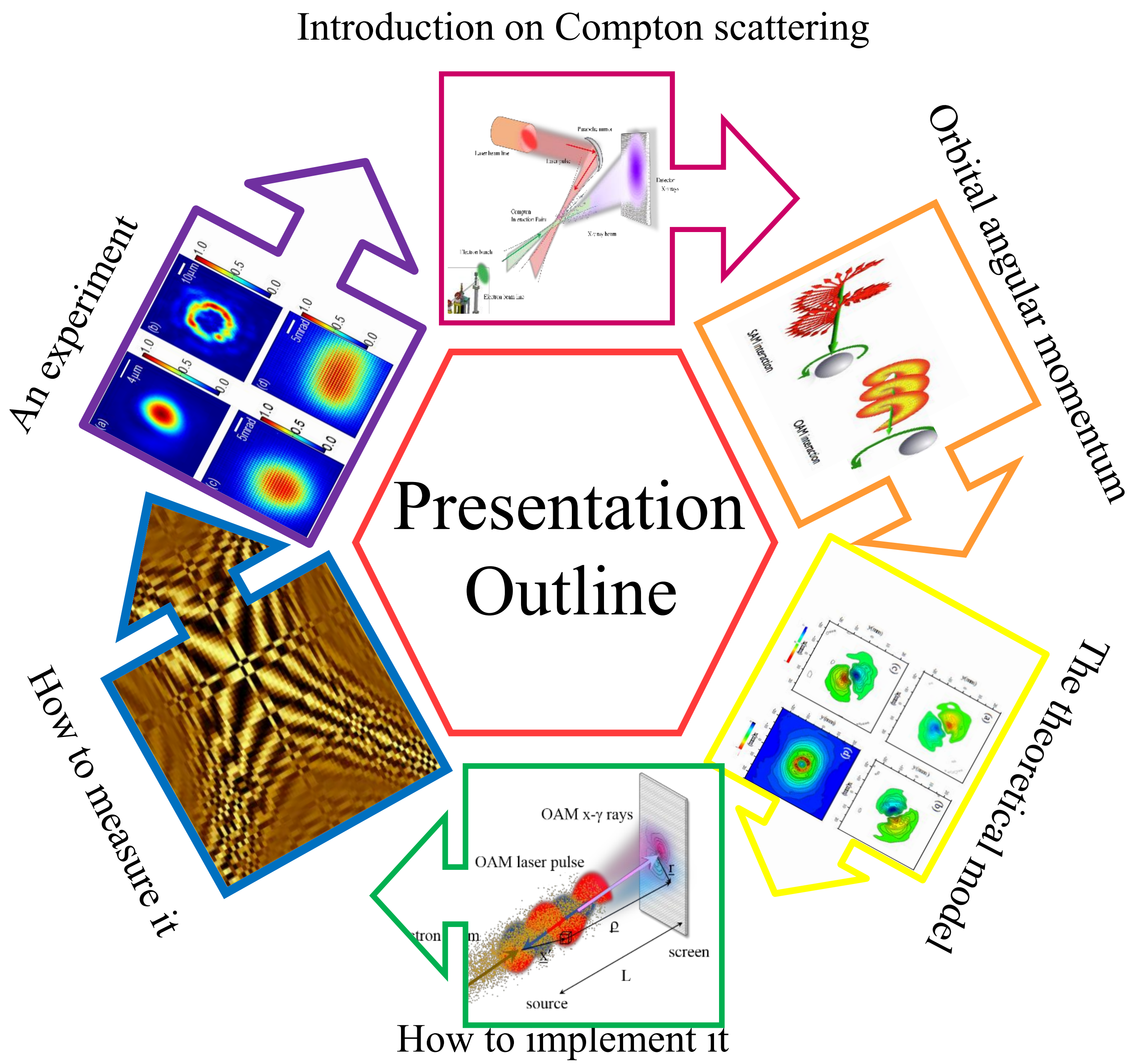
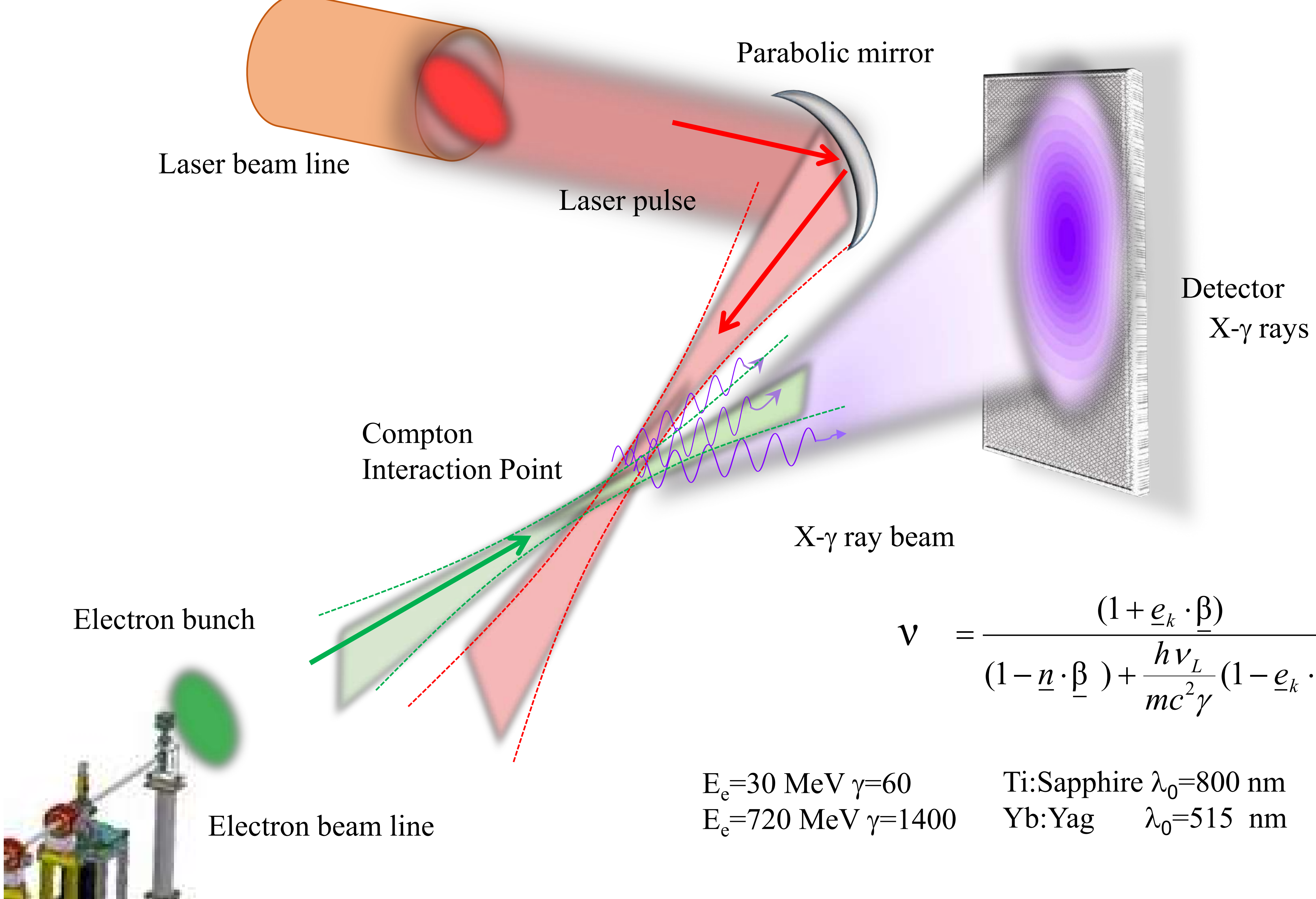
Compton sources with orbital angular momentum

V. Petrillo, I. Drebot, L. Serafini
B. Paroli, M. Siano, A. Cirella, M. Potenza

Thanks to: C. Maroli, A. Bacci, C. Vaccarezza, A. Rossi, C. Curatolo, M. Rossetti, P. Dattoli

and also to all the SPARC LAB and ELI-NP groups


Presentation Outline
Introduction on Compton scattering
Orbital angular momentum
The theoretical model
How to implement it
How to measure it
An experiment
OAM x-γ rays
OAM laser pulse
screen
source
L



$$\nu = \frac{(1+\underline{e}_k\cdot\underline{\beta})}{(1-\underline{n}\cdot\underline{\beta}) + \frac{h\nu_L}{mc^2\gamma}(1-\underline{e}_k\cdot\underline{n})}\nu_L \approx 4\gamma^2\nu_L$$

E_e=30 MeV γ=60	Ti:Sapphire λ_0=800 nm	E_{ph}=22 keV
E_e=720 MeV γ=1400	Yb:Yag λ_0=515 nm	E_{ph}= 19 MeV

Generalities on Compton scattering, frequency-angle correlation

Compton radiation is frequency-angle correlated

Frequency of the radiation in a direction n

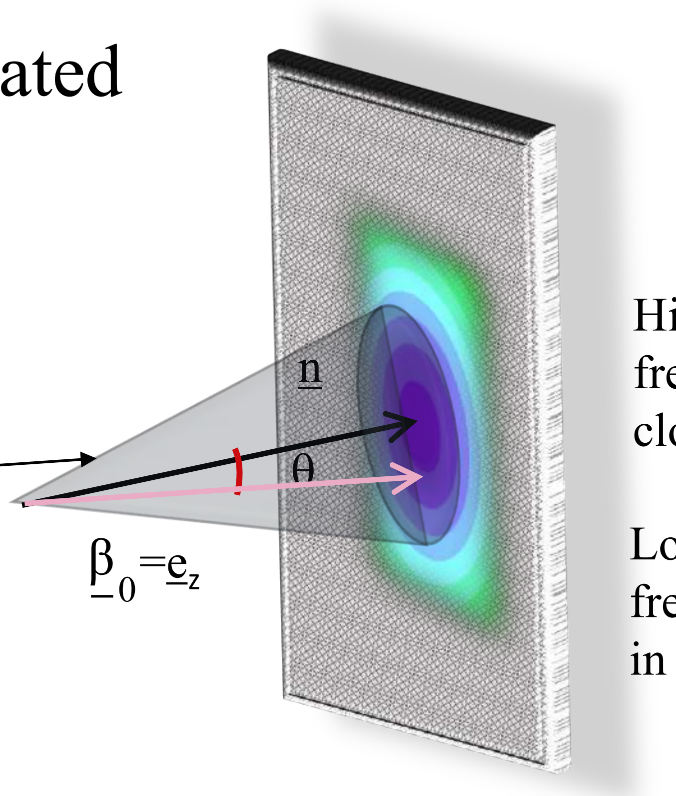
$$\nu = \nu_L \frac{1-\underline{e}_k \cdot \underline{\beta}_0}{1-\underline{n}\cdot\underline{\beta}_0} \approx 4\gamma_0^{\,2}\nu_L$$

$1-\beta\cos\theta$

Total acceptance

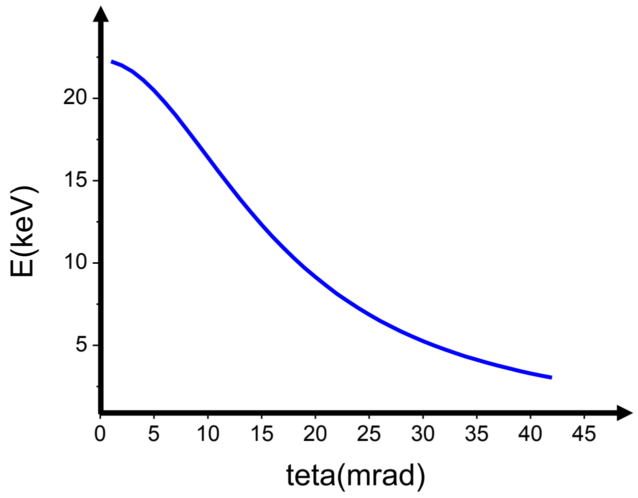
$\Psi_{max}=\gamma\theta_{max}=1$

$\theta_{max}=1/\gamma$

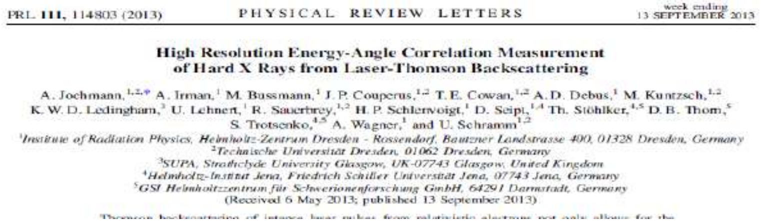


Higher frequencies close to axis

Lower frequencies in the outer part



Frequency-angle correlation


PRL 111, 114803 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

High Resolution Energy-Angle Correlation Measurement of Hard X Rays from Laser-Thomson Backscattering

A. Jochmann,[1,2,*] A. Irman,[1] M. Bussmann,[1] J. P. Couperus,[1,2] T. E. Cowan,[1,2] A. D. Debus,[1] M. Kuntzsch,[1,2] K. W. D. Ledingham,[3] U. Lehnert,[1] R. Sauerbrey,[1,2] H. P. Schlenvoigt,[1] D. Seipt,[1,4] Th. Stöhlker,[4,5] D. B. Thom,[5] S. Trotsenko,[4,5] A. Wagner,[1] and U. Schramm[1,2]

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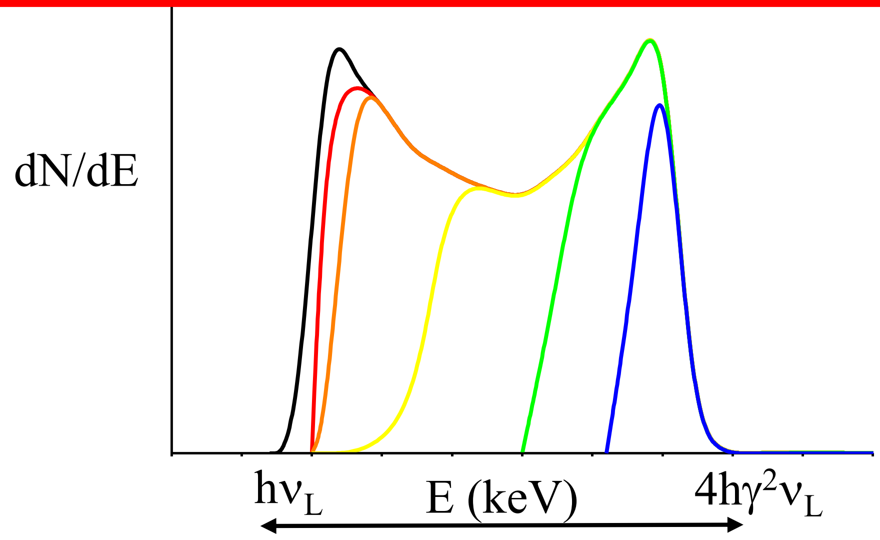
(Received 6 May 2013; published 13 September 2013)

Generalities on Compton scattering, collimation



Large natural spectrum

The energy-angle correlation permits the control of bandwidth and divergence

Nuclear Instruments and Methods in Physics Research A

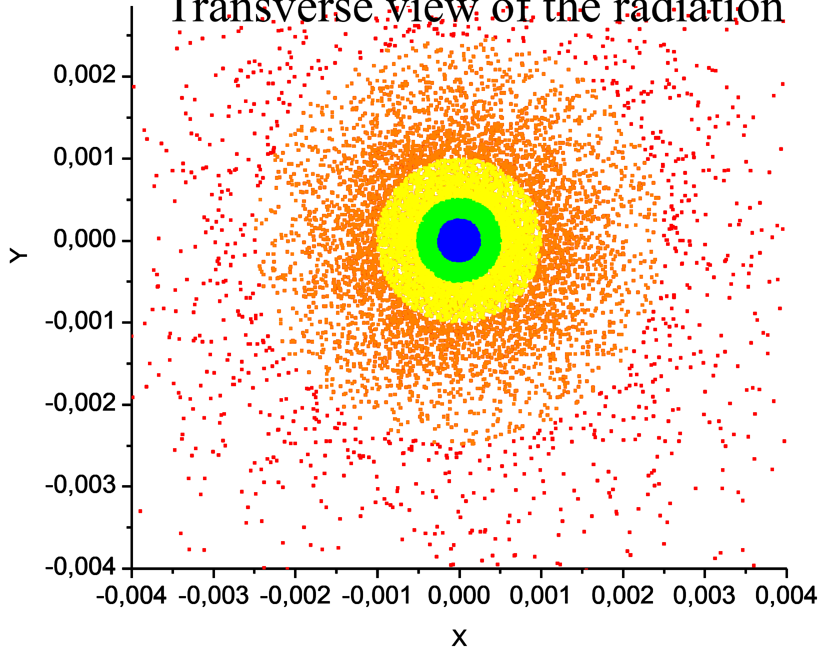
journal homepage: www.elsevier.com/locate/nima

Characterization results of the BNL ATF Compton X-ray source using K-edge absorbing foils

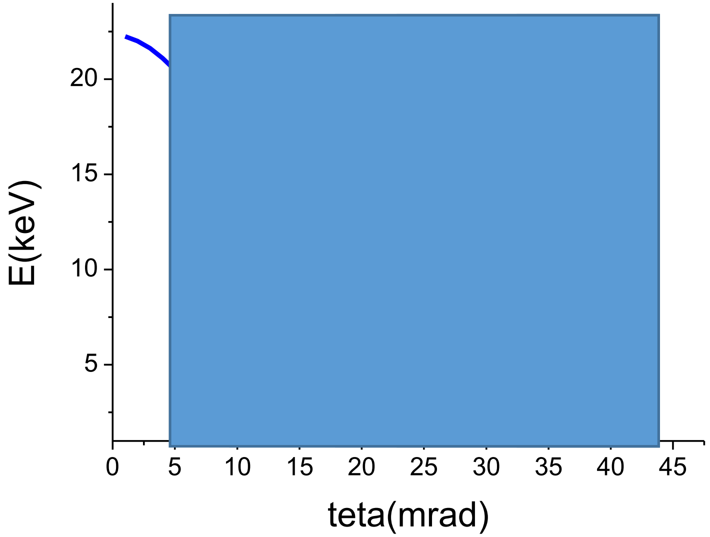
O. Williams[a,*], G. Andonian[a], M. Babzien[b], E. Hemsing[a], K. Kusche[b], J. Park[b], I. Pogorelsky[b], G. Priebe[c], J. Rosenzweig[a], V. Yakimenko[b]

By introducing irides or collimators one can diminish the bandwidth, by selecting the photons close to the axis

Transverse view of the radiation

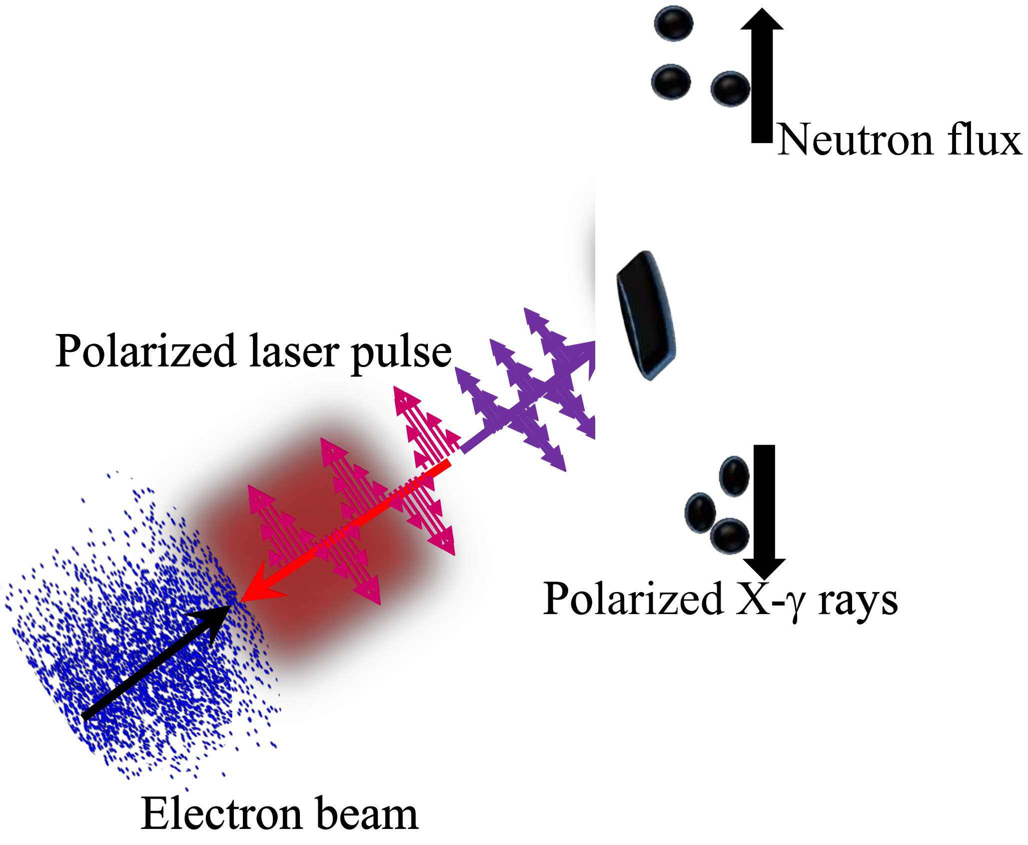


Effect of the collimator



Generalities on Compton scattering, polarization

In nuclear photonics experiments, the kinematics of neutrons is strongly influenced by the polarization of the gamma rays



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 044701 (2011)

Theoretical and simulation studies of characteristics of a Compton light source

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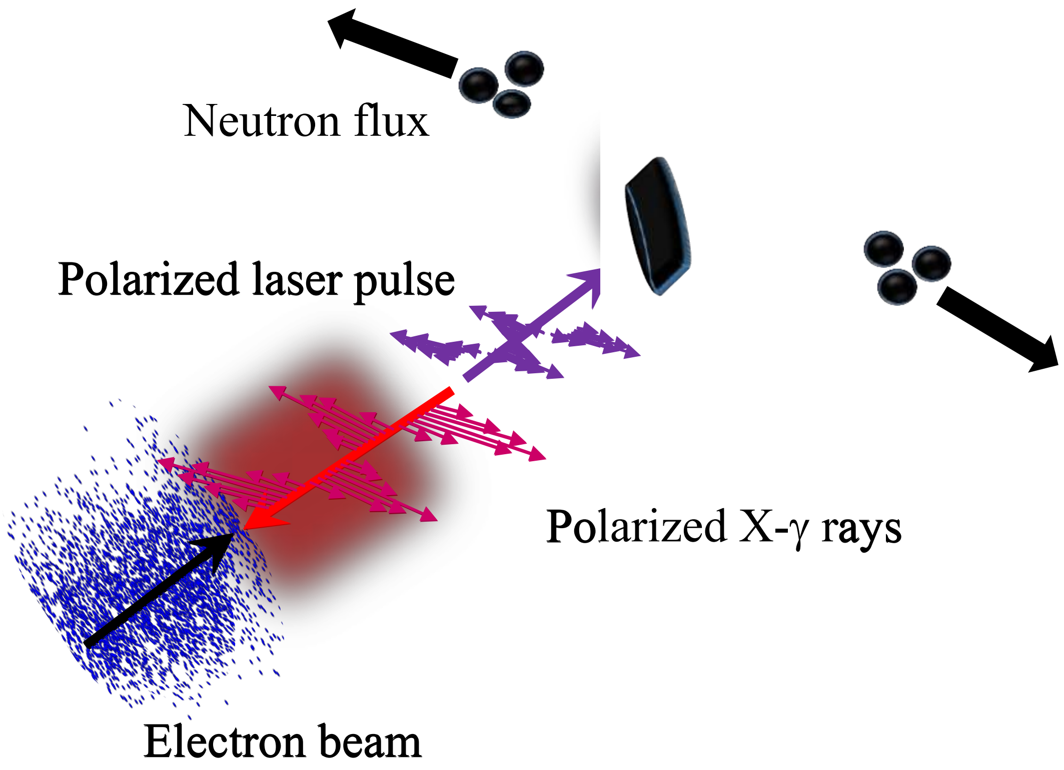
Department of Physics, Duke University, Durham, North Carolina 27708-0305, USA
and DFELL, Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308, USA
(Received 25 January 2011; published 21 April 2011)



Polarization: ELI-NP case

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS 18, 110701 (2015)

Polarization of x-gamma radiation produced by a Thomson and Compton inverse scattering

V. Petrillo,[1,2] A. Bacci,[2] C. Curatolo,[1,2] I. Drebot,[2] A. Giribono,[4] C. Maroli,[1] A. R. Rossi,[2] L. Serafini,[2] P. Tomassini,[1] C. Vaccarezza,[3] and A. Variola[2]
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[4]Università La Sapienza, Via Antonio Scarpa, 14 00161 Roma, Italy
and INFN-Roma1, Piazzale Aldo Moro, 2 00161 Rome, Italy
(Received 24 June 2015; published 19 November 2015)

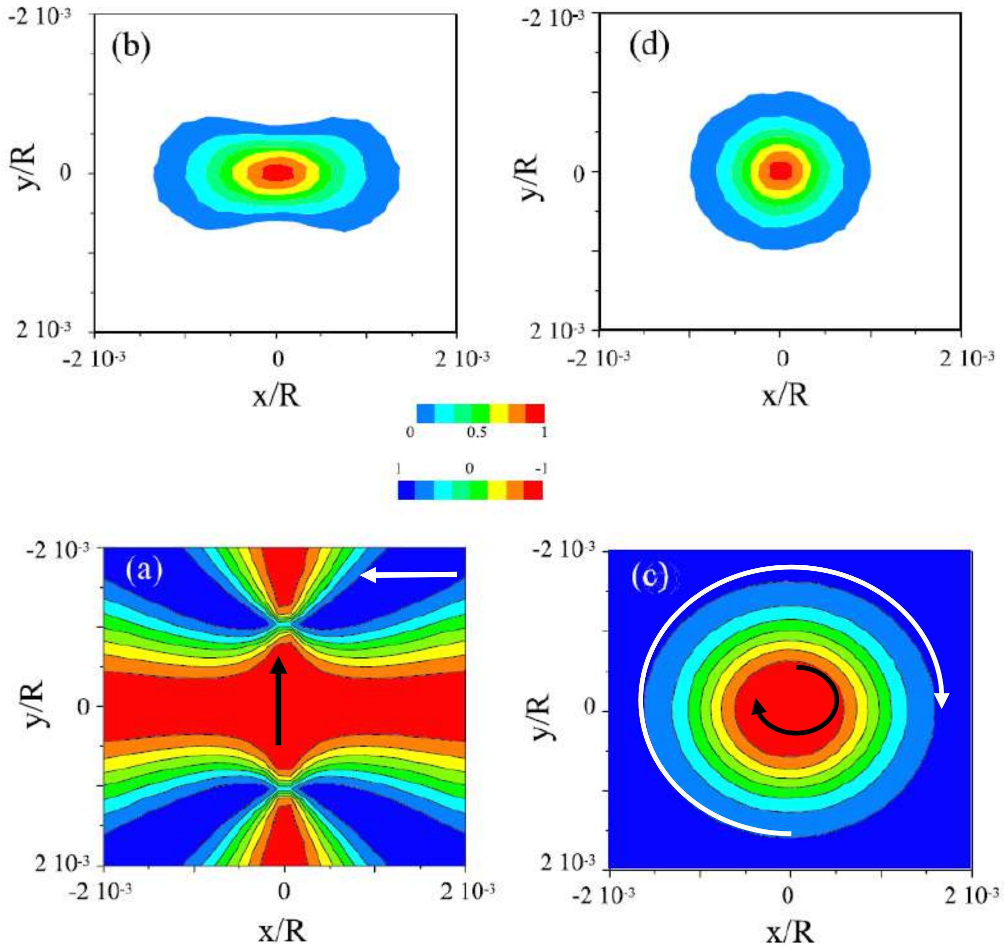
ELI-NP Parameters

E=234-529 MeV
Q=250 pC
ε=0.5 mm mrad
$\Delta E/E = 7\ 10^{-4}$
λ=520 nm
E_L=0.2-0.4 J
δ=8°
w_0=28 μm
E_{ph}=2-10 MeV

Total intensity I
on the screen at 1 m
E_{ph}=10 MeV

Linear polarization of the laser

Circular polarization of the laser

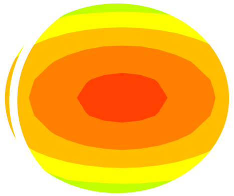


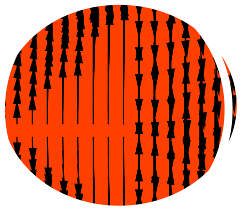
Stokes parameter

$$\frac{(|E_x|^2-|E_y|^2)}{(|E_x|^2+|E_y|^2)}$$

Polarization: ELI-NP case

With a **linear polarization** of the laser:





Total intensity

on the screen at 1 m,
the circle is $1/\gamma$

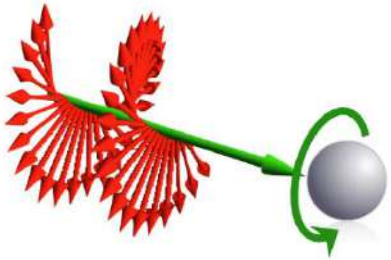
Stokes parameter
$(|E_x|^2-|E_y|^2)/(|E_x|^2-|E_y|^2)$

Orbital Angular Momentum (OAM)

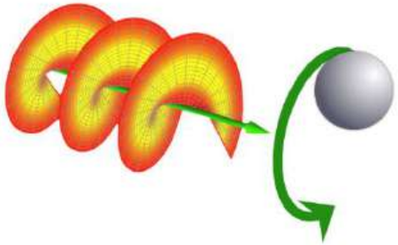
Why studying radiation with orbital angular momentum?

Additional degree of freedom

In exp. of photoinization forbidden decays can be excited, molecules in rotational states can resonate in vortex,dipolar and quadrupolar transition can be distinguished.



Spin Ang Mom interaction



Orb Ang Mom interaction

s= ½ħ   j=s+ mħ

Pilot experiment with FEL in infrared

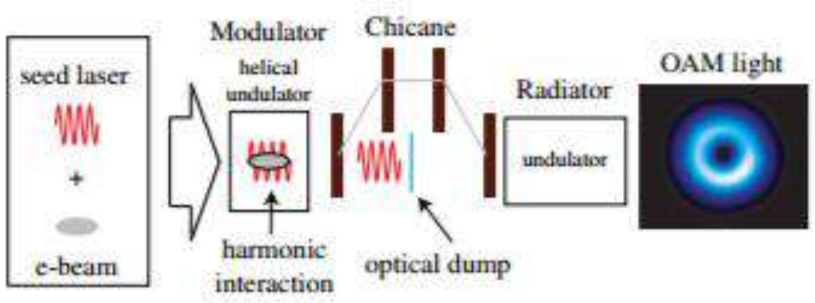


FIG. 1 (color online). Arrangement for generating OAM light in an FEL.

Hemsing, E.; Dunning, M.; Hast, C.; Raubenheimer, T.; Xiang, D. First Characterization of Coherent Optical Vortices from Harmonic Undulator Radiation. Phys. Rev. Lett. **2014**, 113, 134803.

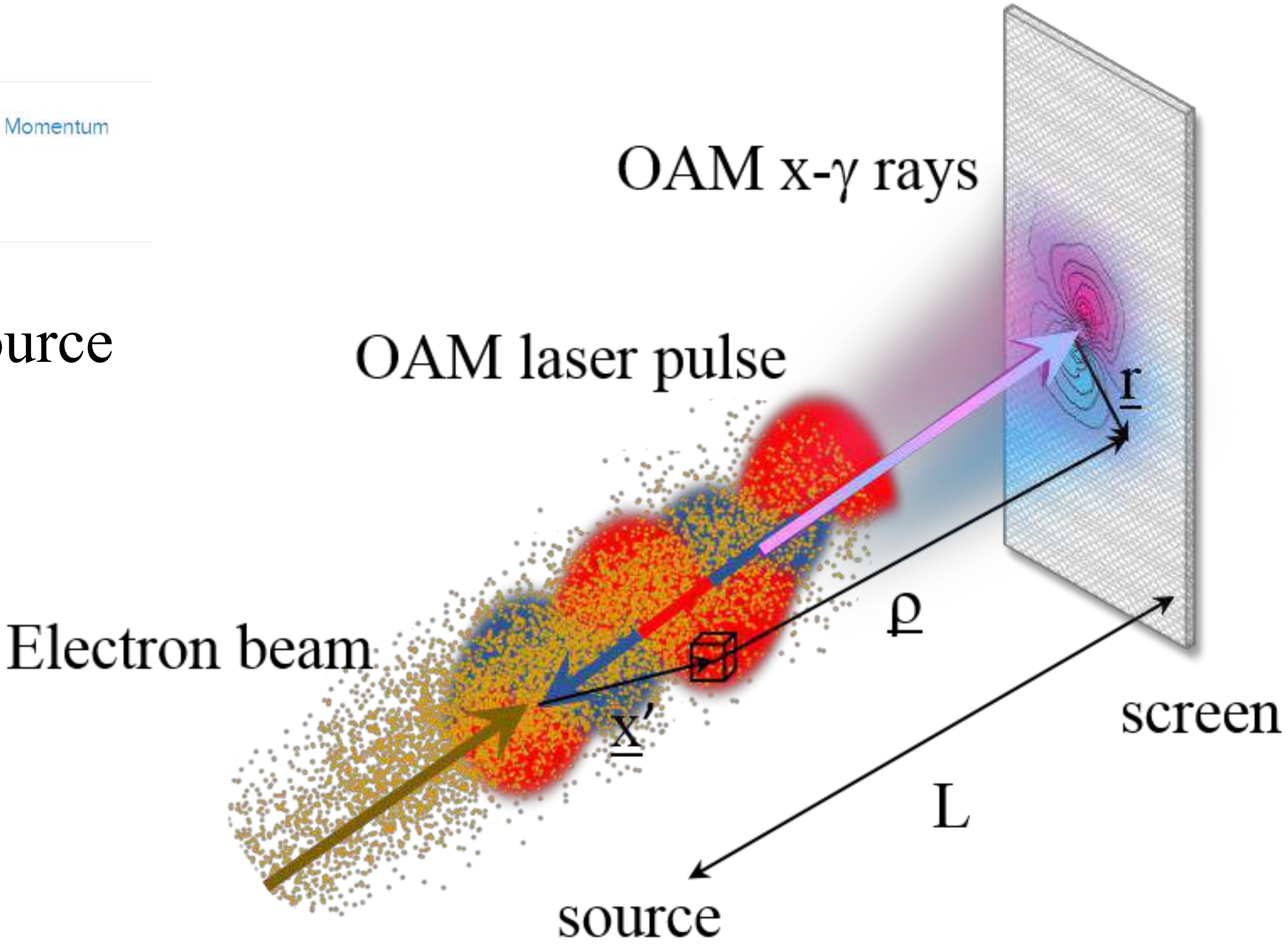
How to approach the X/gamma range?

Proposals for OAM X-beams are based on manipulation of electrons in FEL emission. The electrons are treated in such a way that they carry OAM and tranfer it to the radiation.

Orbital Angular Momentum (OAM), scheme of the source

Compton Scattered X-Gamma Rays with Orbital Momentum
V. Petrillo, G. Dattoli, I. Drebot, and F. Nguyen
Phys. Rev. Lett. **117**, 123903 (2016) – Published 16 September 2016
Show Abstract

Scheme of the source



'Wild type' electron beam generated by linac

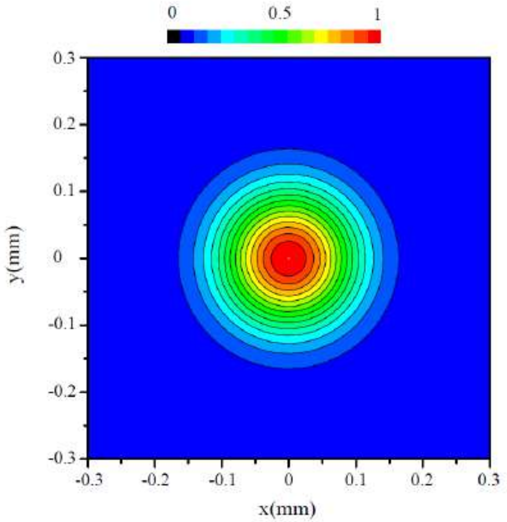
Orbital Angular Momentum, laser structure

Expression and propagation of an OAM laser mode

L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Phys. Rev. A **45**, 8185 (1992).

$$\underline{\tilde{E}}_L(x,y,z,t) = \underline{\varepsilon}_y f(z+ct) E_m(x,y,z) e^{i(\omega t + k_z z)}$$

$$E_m(x,y,z) = \pi \left(\frac{w_0}{w_z}\right)^2 H_m(\xi,\alpha) e^{-\frac{x^2+y^2}{2w_z^2}}$$



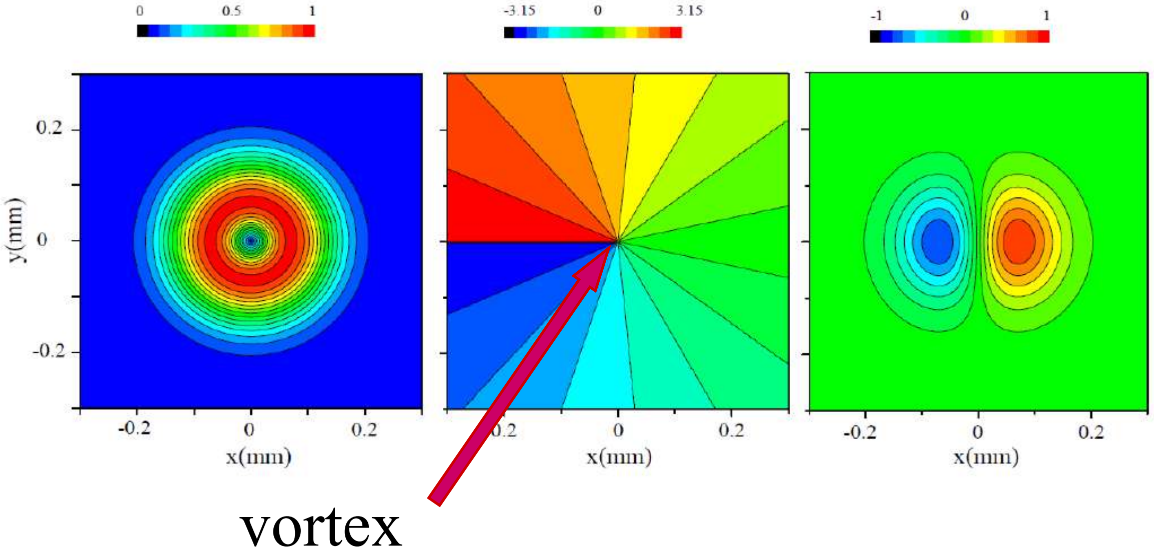
Gaussian mode

$$H_m(\xi,\alpha) = m! \sum_{r=0}^{[m/2]} \frac{\alpha^r \xi^{m-2r}}{r!(m-2r)!}$$

$$\xi = \frac{1}{w_0}\left[\left(\frac{w_0}{w_z}\right)^2 (x + i\varepsilon y) - (x_0 + i\varepsilon y_0)\right]$$

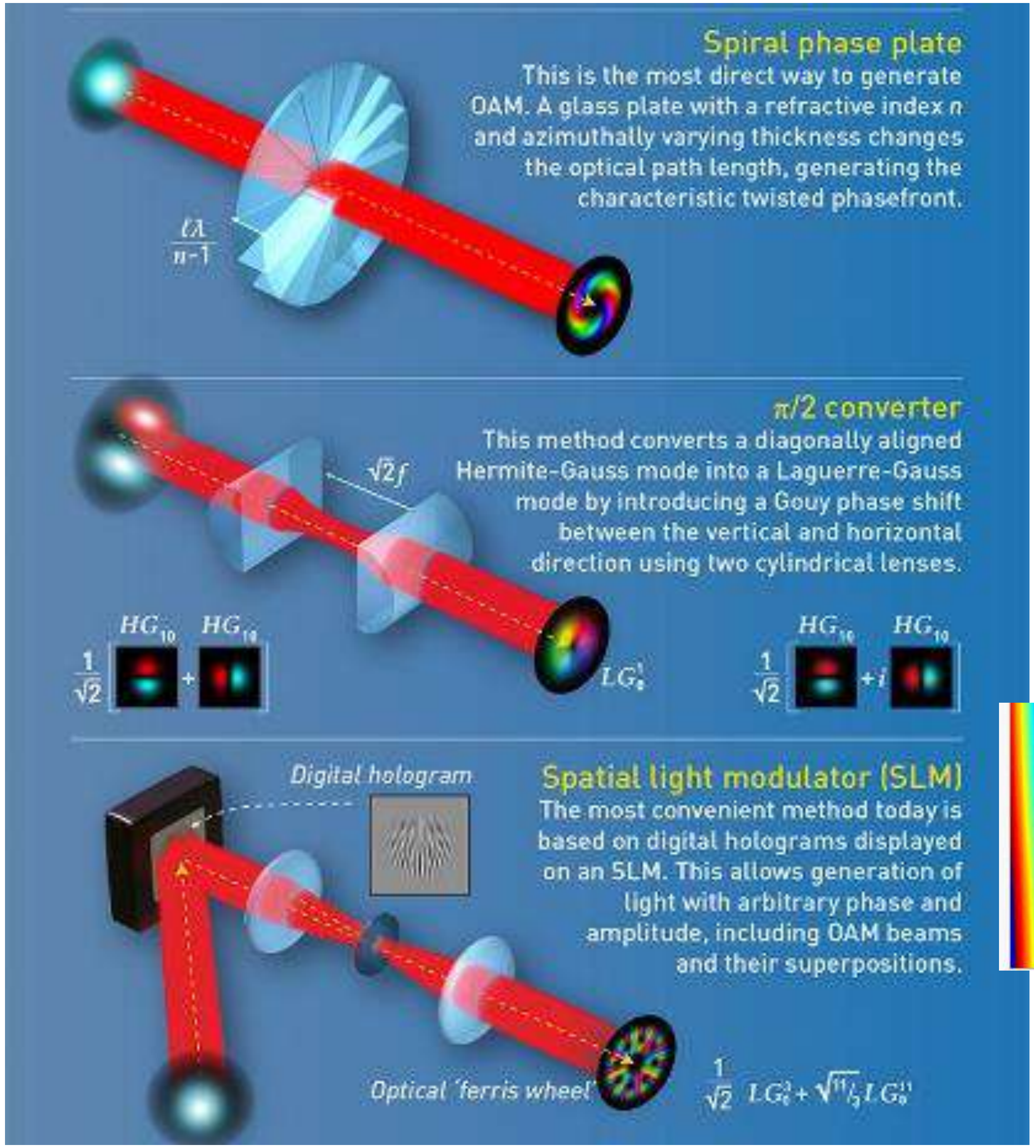
$$\alpha = \frac{i}{2}(1-\varepsilon^2)\frac{\lambda z}{w_z^2}.$$

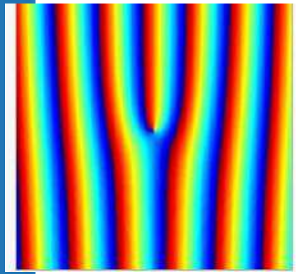
Transverse shape of a laser with OAM, intensity, phase and real part $m=1$, $x_0=y_0=0$



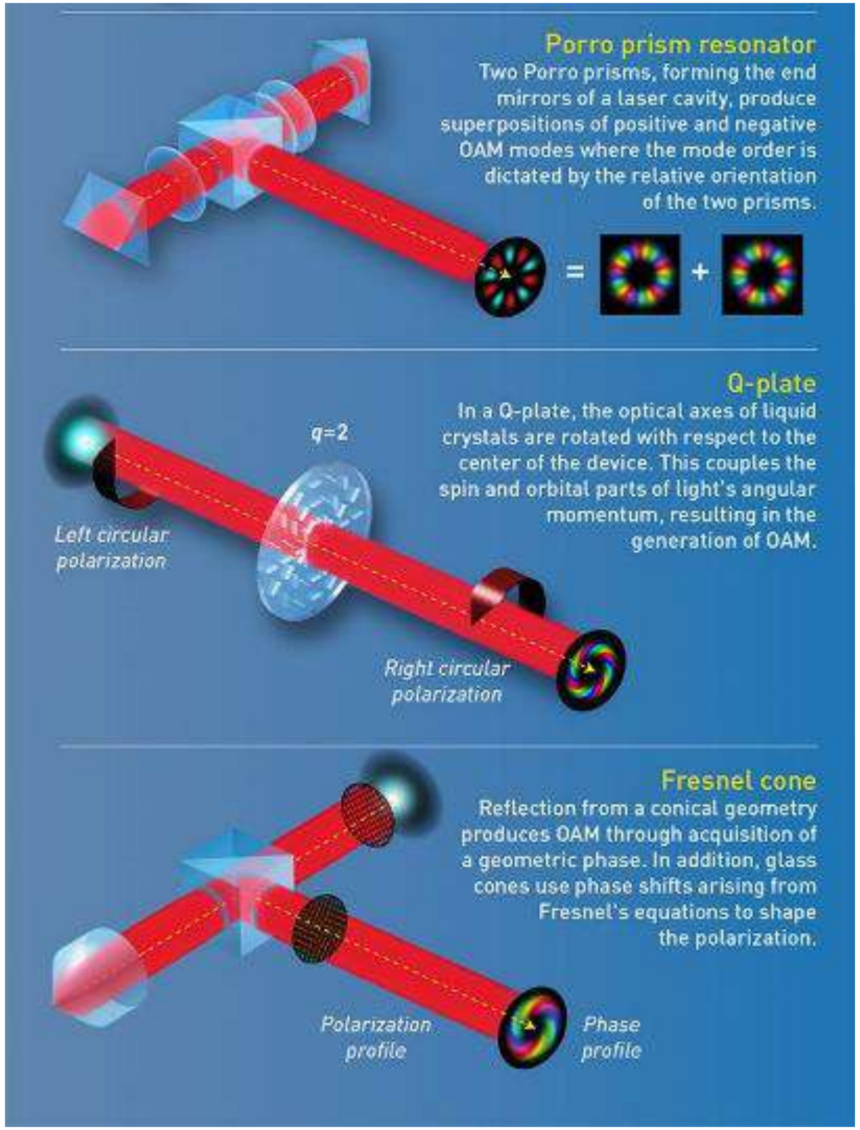
OAM laser modes are generated with fork holograms or phase masks

Orbital Angular Momentum, laser structure



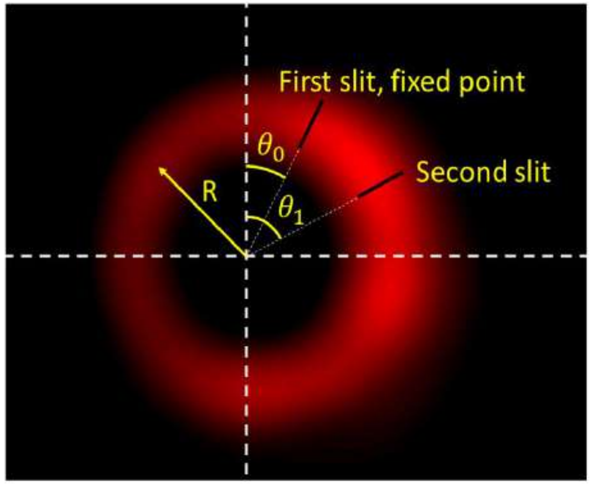


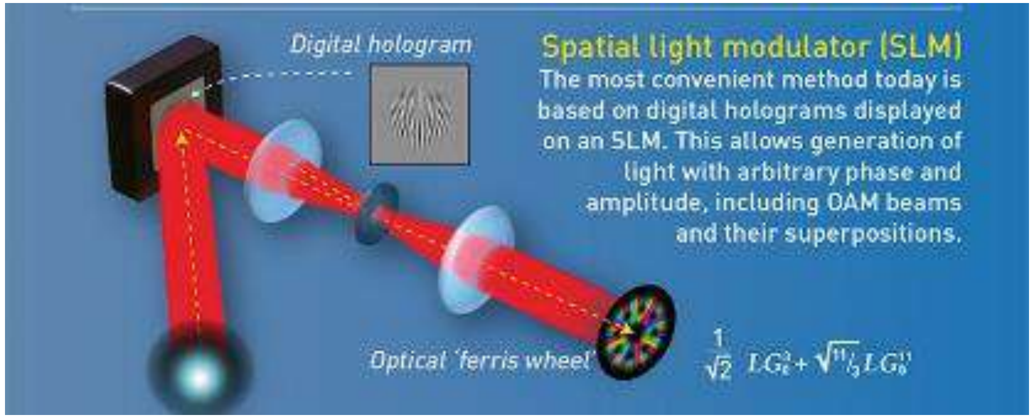
OAM laser modes
are generated
with fork holograms
or phase masks

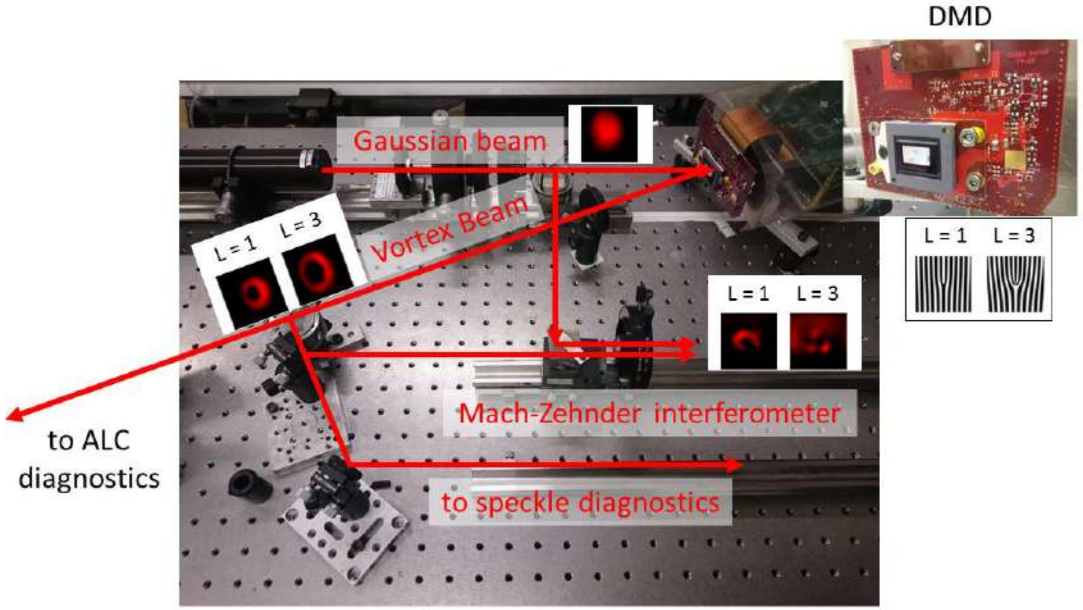


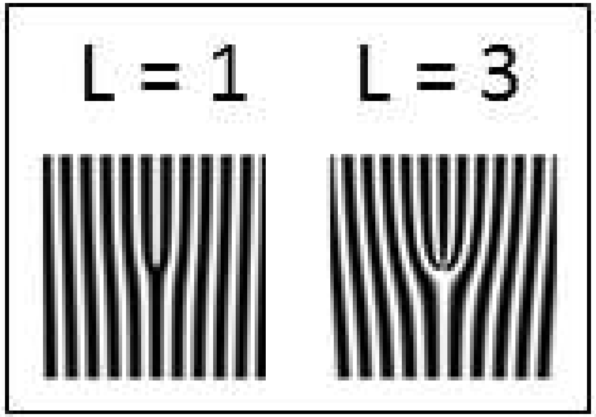
OAM Laser pulse, Milan Optics Laboratory, M. Potenza, B. Paroli et al.

See poster section



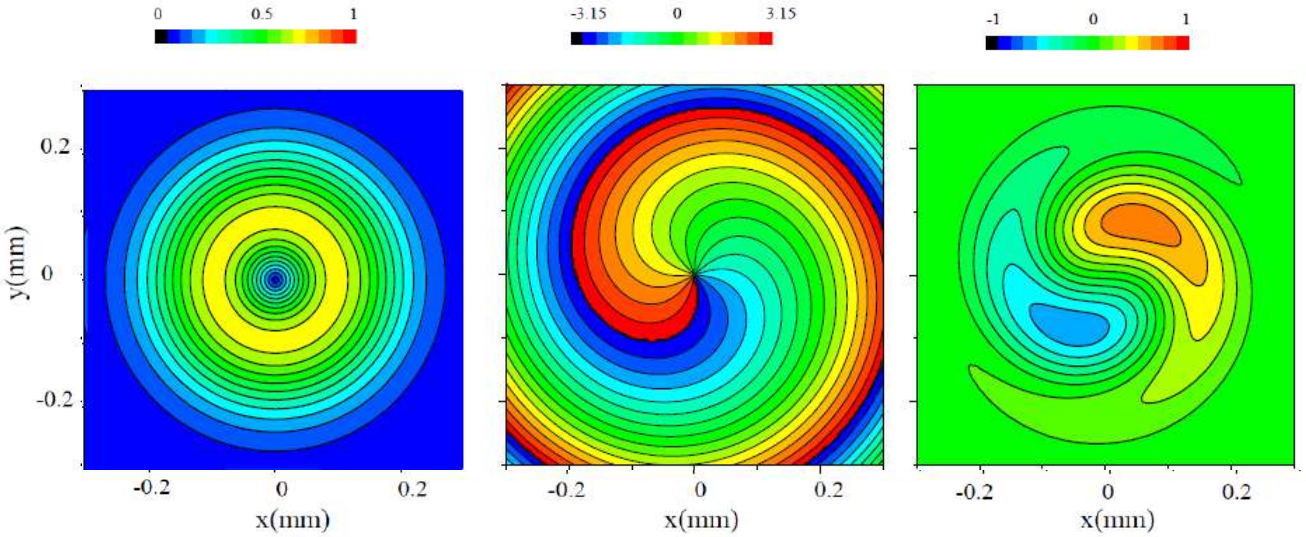






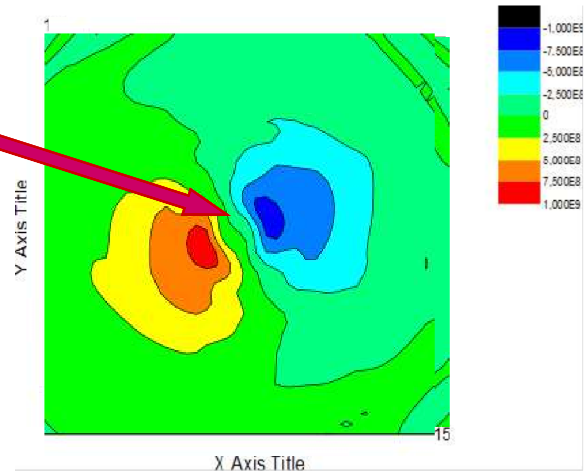
Orbital Angular Momentum, radiation calculation

Propagation of the laser:



X radiation the screen, classical treatment:

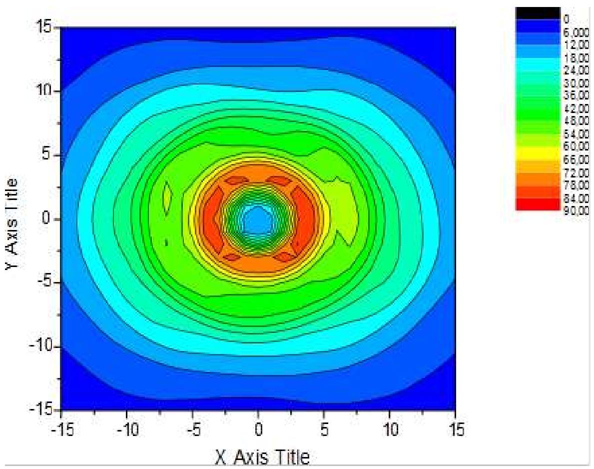
vortex



Lienard-Wiechert electric field:

$$\underline{E} = \frac{e}{c}\sum_j \left[\frac{\underline{n} \times ((\underline{n} - \underline{\beta}_j) \times \dot{\underline{\beta}}_j)}{(1 - \underline{\beta}_j \cdot \underline{n})^3 R} \right]_{ret}$$

$$\dot{\underline{\beta}}_j = -\frac{e}{mc\gamma_j} \left[\underline{E}_L (1 - \underline{\beta}_j \cdot \underline{e}_k) + \underline{\beta}_j \, \underline{E}_L (\underline{e}_k - \underline{\beta}_j) \right]$$



Quantum treatment:

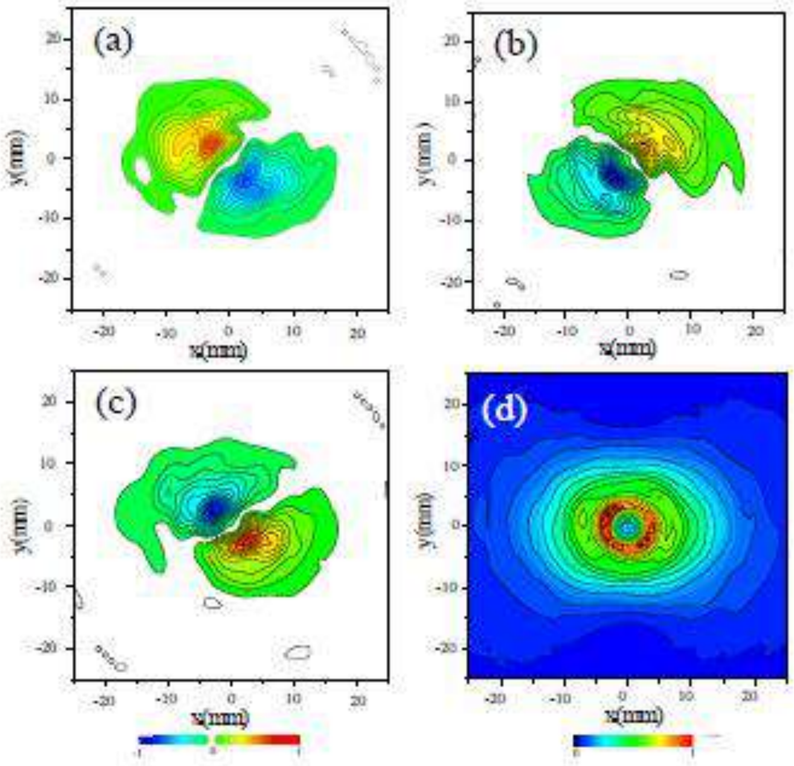
Generation of High-Energy Photons with Large Orbital Angular Momentum by Compton Backscattering

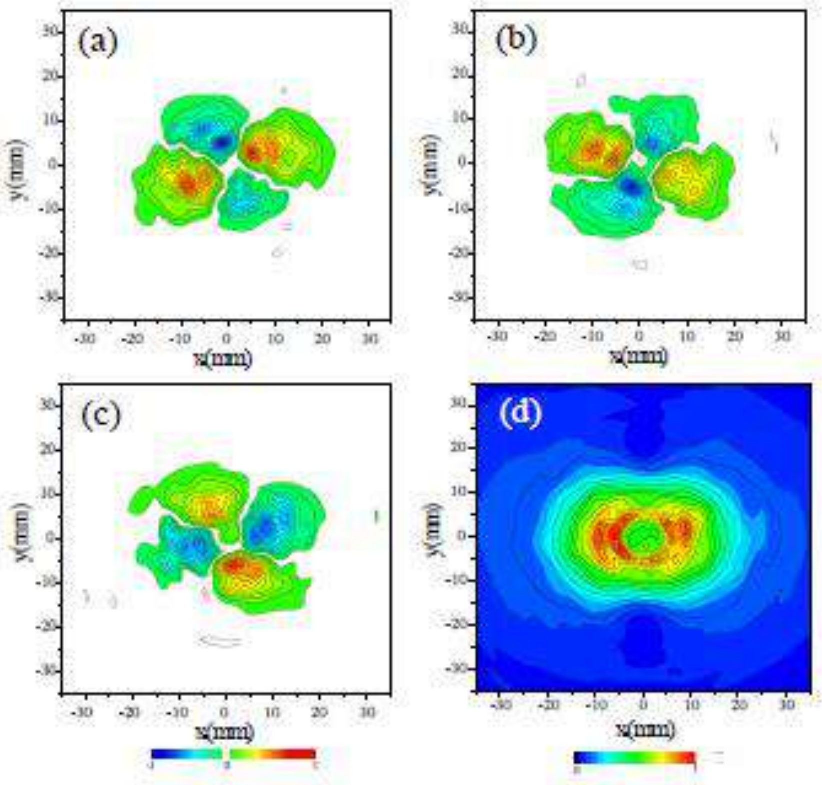
U. D. Jentschura and V. G. Serbo

Scattering of twisted light: angular distribution and polarization of scattered photons

S. Stock, A. Surzhykov, S. Fritzsche, and D. Seipt

Orbital Angular Momentum, radiation structure

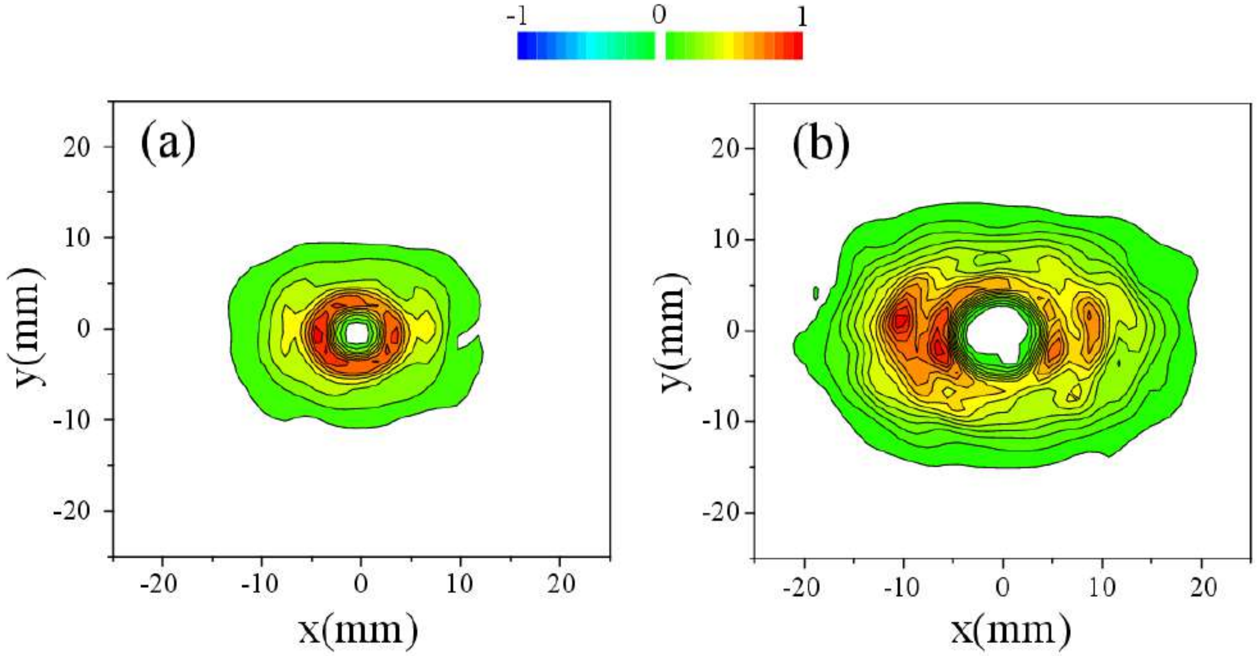




Electric field at different time and averaged intensity on the screen

m=1 m=2

Orbital Angular Momentum



Orbital Angular Momentum on the screen

m=1 m=2

N_{ph}= 6 10^6
E_{ph}= 8 keV

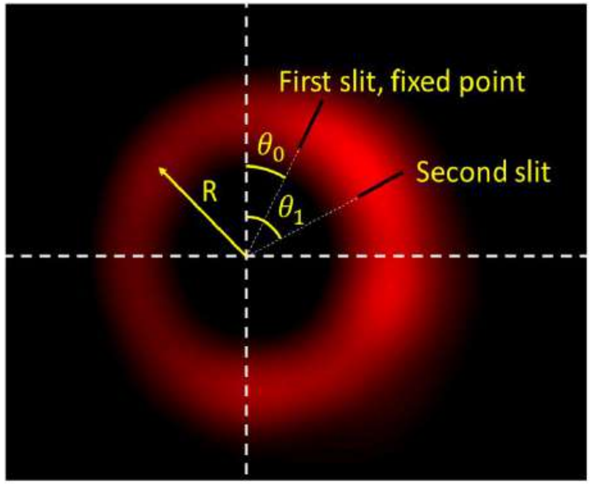
$$\frac{dL_z^{OM,rad}}{dV} \approx \frac{m}{4\pi\omega}\left|E_y\right|^2$$

$$L_z^{OM,rad} = 1.7 \times 10^{-27}\ \mathrm{J\cdot s}$$

Electron Energy	25 MeV
Electron Charge	1 nC
Electron Radius	0.1 mm
Electron Length	1 mm
Laser wavelength	800 nm
Laser energy	1 J
Laser waist	0.02 mm
Laser duration	1 ps
Repetition rate	10 Hz

Diagnostics of radiation with Orbital Angular Momentum

DIAGNOSTICS

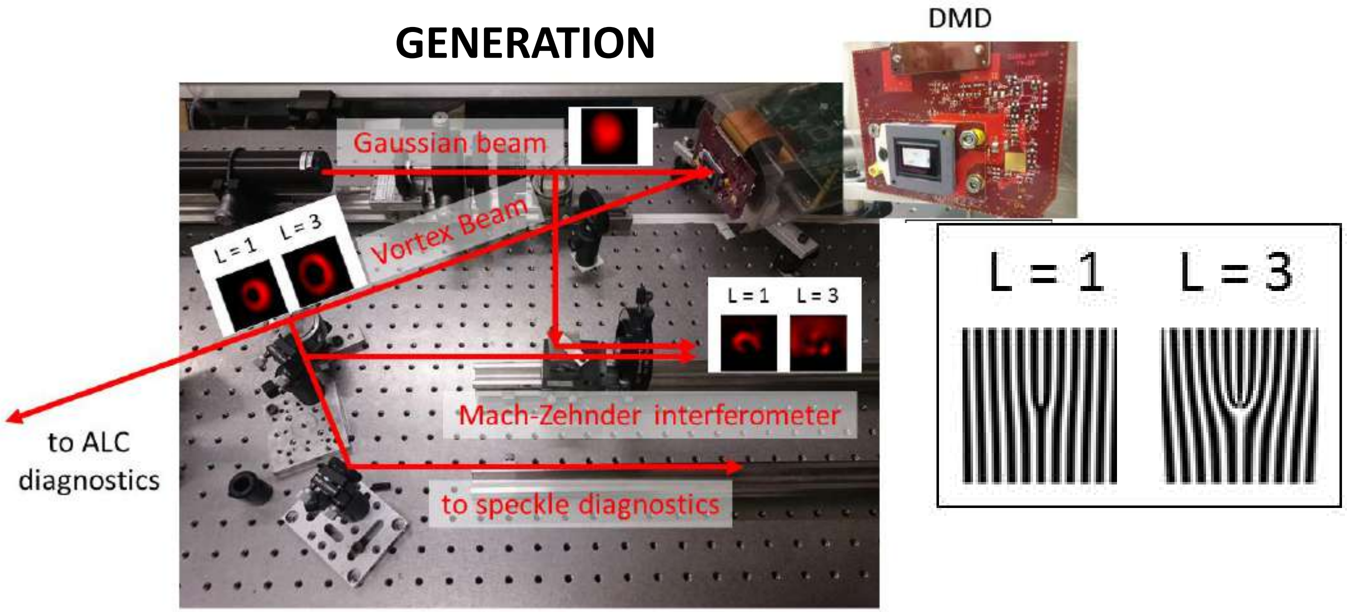


Topological charge and parity are obtained from the **Asymmetric Lateral Coherence (ALC)** of radiation, which is a measurement of the real part of the complex degree of coherence Υc with a fixed reference field ***E(R,ϑ₀)***:

$$\gamma_c(R,\theta_0,\theta_1) = \frac{\langle E(R,\theta_0)E^*(R,\theta_1)\rangle}{\mathcal{N}}$$

Azimuthally-arranged pairs of double slits or pinholes allow measurements of the asymmetric lateral coherence.

GENERATION

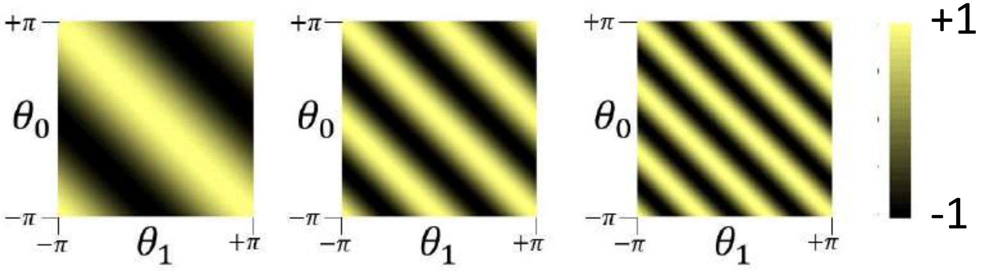


Generation and characterization of optical vortex beams with a Digital Micromirror Device (DMD). Vortices are generated by encoding a corkscrew-like phase modulation on a Gaussian laser beam with computer generated holograms.

Experimental apparatus is used for developments and test of novel diagnostics by scaling from visible light to X-rays.

Simulations of the Asymmetric Lateral Coherence of OAM radiation

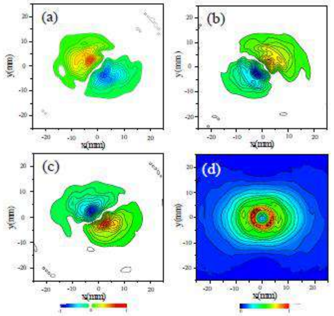
- Azimuthal coordinates



OPTICAL BEAMS

TOPOLOGICAL PROPERTIES:

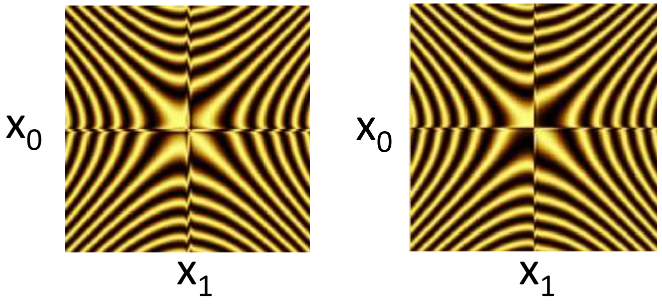
PARITY ✓
CHARGE ✓
CURVATURE ✗



- Cartesian coordinates

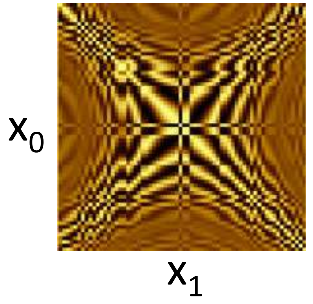
even

odd



OPTICAL BEAMS

First result: Inverse-Compton



X-RAY BEAM

TOPOLOGICAL PROPERTIES:

PARITY ✓
CHARGE ✗
CURVATURE ✓