Generation of High-flux High-energy Ultra-short Vortex Photon Beams at JLab

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[4]The College of Williams and Mary

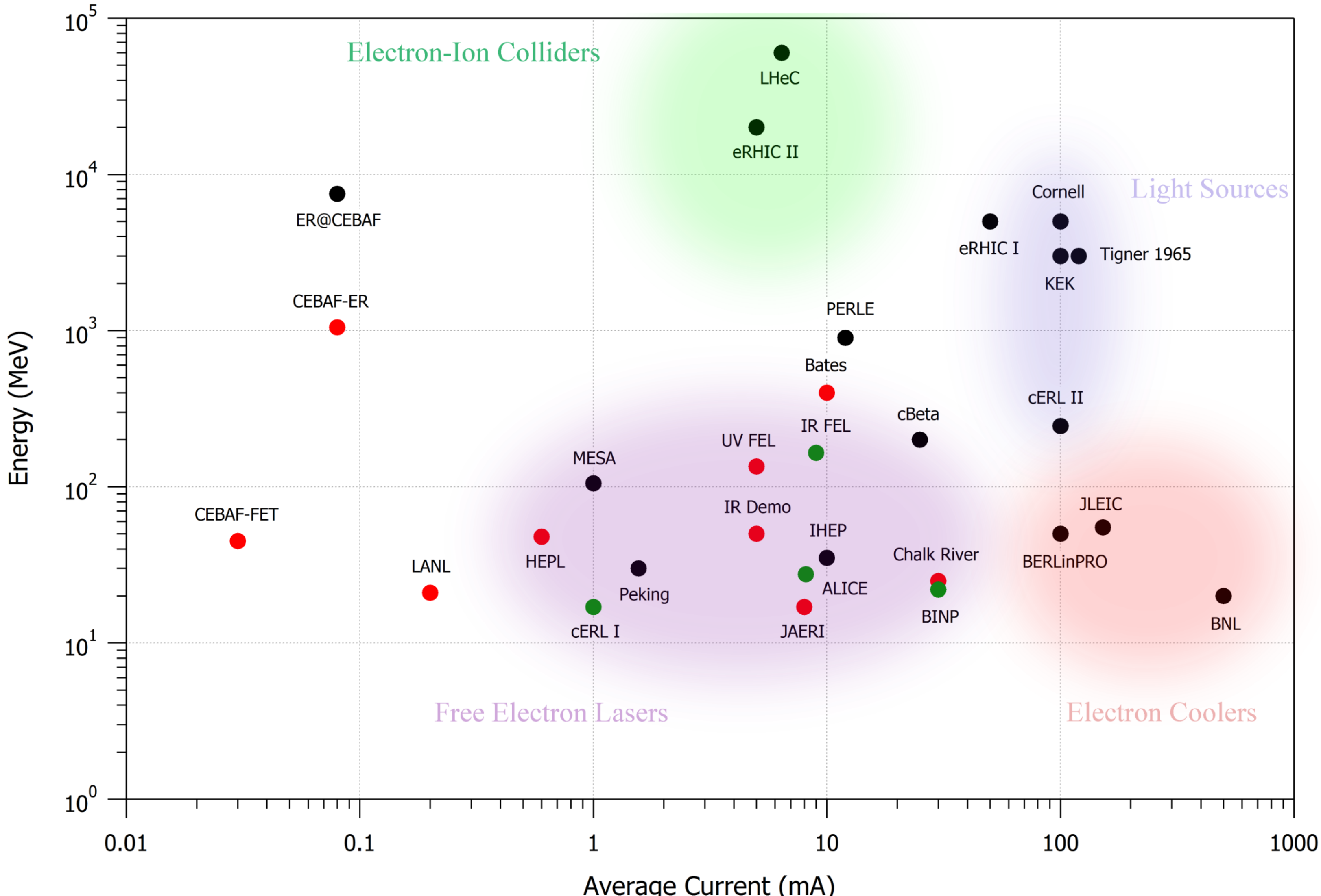
ERL Workshop 2017

June 23, 2017, CERN

Outline

- Review of Laser Compton Sources
- Vortex Beams
- High Energy Vortex Beams and Challenges
- Summary and Acknowledgement

World-wide ERLs



Courtesy C. T.

Applications of ERLs

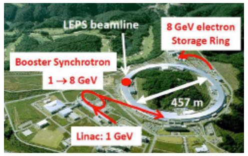
- High Power Photon Beams

  High average power FELs, tunable, covering EUV~THz
- Nuclear Physics: *DarkLight*
- High Current Accelerator Science & Technology

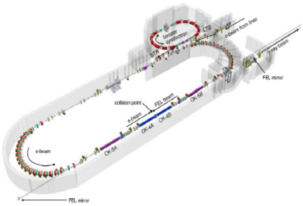
  Electron Cooling/ next generation colliders (JLEIC)
- Isotope Production
- *Laser Compton sources: x-rays/Gamma-rays*
- UED, LWFA,…

Benefit to many: JELIC, eRHIC, Perle, LHeC,…...

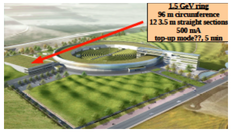
World-wide Effort on LCS (back in 2013)

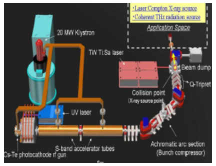


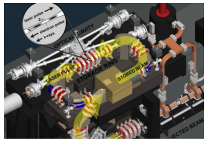
- **LEPS@Spring8 (Japan),** *operation & User Program*
  8GeV Storage Ring/UV laser, 2GeV/10^6 ph./s.

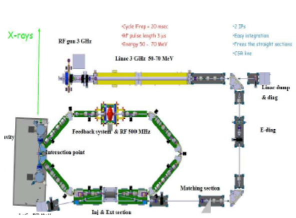


- **HIGS@Duke (US),** *operation & User Program*
  0.24~1.2GeV Storage Ring/FEL NIR~UV, 1~100MeV/10^{10} ph./s.
- **LBSF@M4, MAX-IV Lab, (Sweden),** *proposal*
  1.5GeV Storage Ring/299,244nm Laser, 100~170MeV/4x10^6 ph./s.







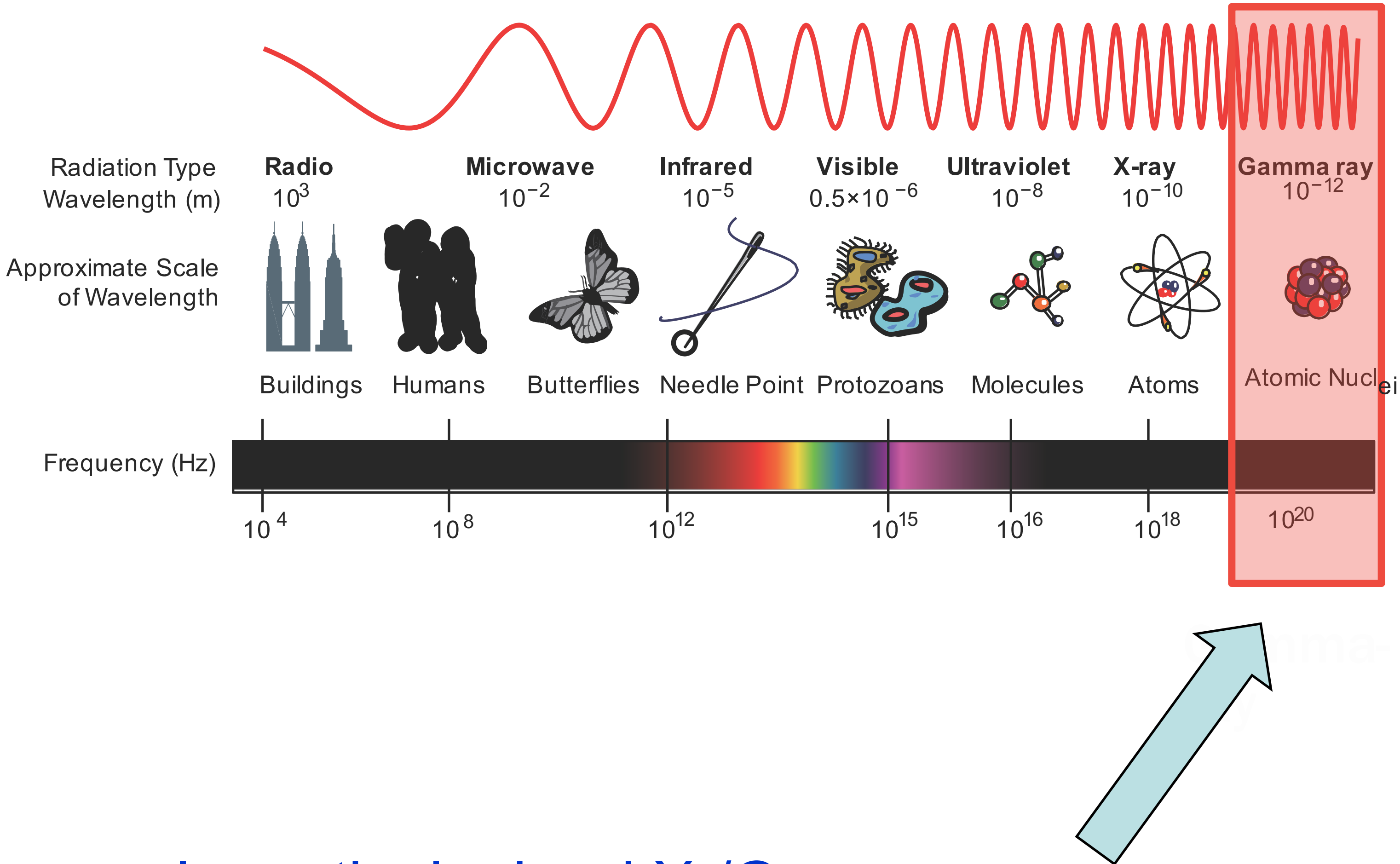


- **AIST (Japan),** *operation & development*
  40MeV Linac/TW 800nm Ti:S, 10~40keV/5x10^6 ph./s.
- **Lyncean Tech. (US),** *commercial product*
  40MeV Storage Ring/FP cavity Laser, 7~35keV/10^{11} ph./s.
- **ThomX, (France),** *under construction*
  50~70MeV Storage Ring/FP cavity, 7~35keV/$10^{11\sim13}$ ph./s.

And many: KEK (Japan), LLNL (US), MIT(US), ELI-NP (EU), SSRS (China),…

For more refer to Y. WU, talk at IPAC12.

Huge interests in Light Sources



In particular hard X-/Gamma-rays

Science, Research, and Applications

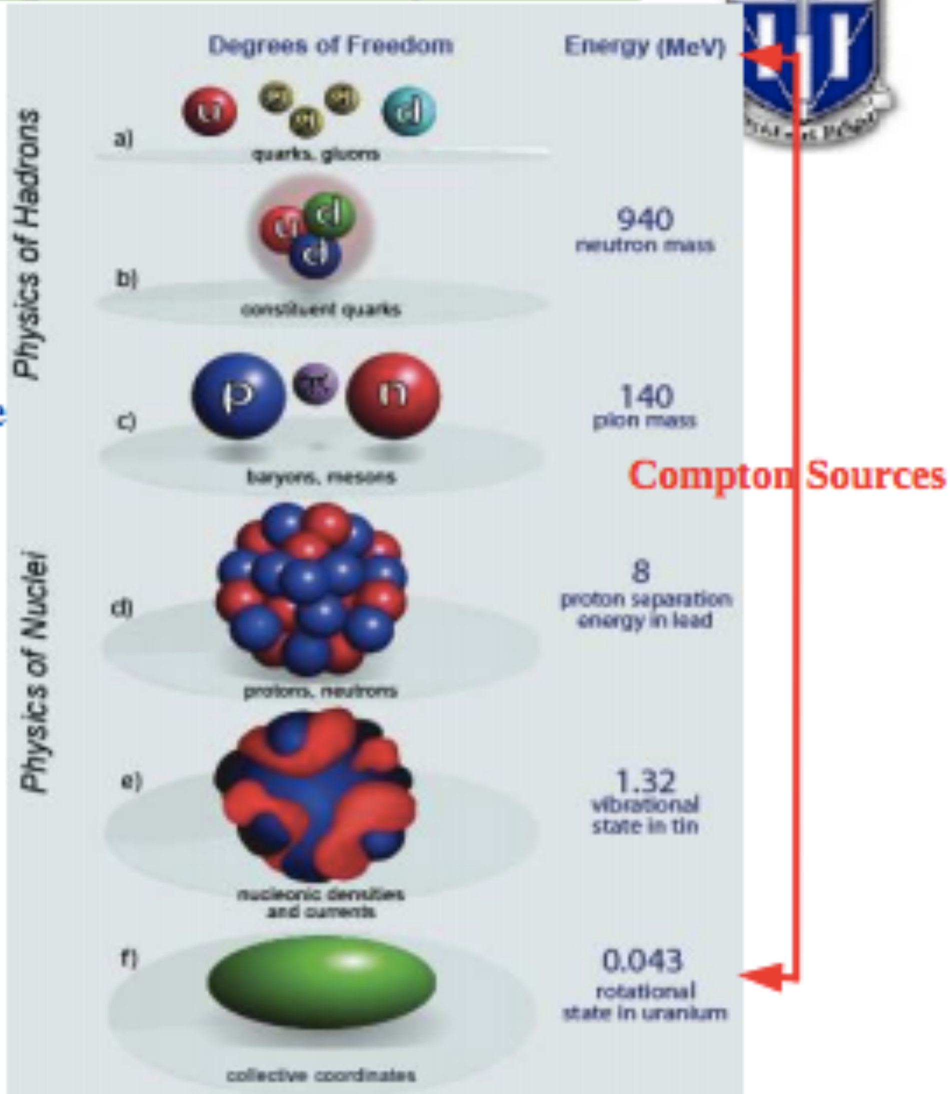
Basic Research Using Compton Gamma-ray Sources

Physics Research: Nuclear and HEP

- Nuclear Structure
- Few-Nucleon Physics
- Astrophysics
- Gerasimov-Drell-Hearn (GDH) Sum Rule
- Compton Scattering from Nucleons
- Photon-Pion Physics
- Hadron structure and quark interactions
- Hadronic parity violation
- Physics beyond the Standard Model

Complementary Sources

- CEBAF (Jlab)
- ELSA Bonn
- MAMI Mainz



H. R. Weller *et al.*, "Research Opportunities at the Upgraded HIγS Facility," Prog. Part. Nucl. Phys. Vol 62, Issue 1, p. 257-303 (2009).

Courtesy Y. Wu

Other Applications

- Accelerators

  Polarized positron generation

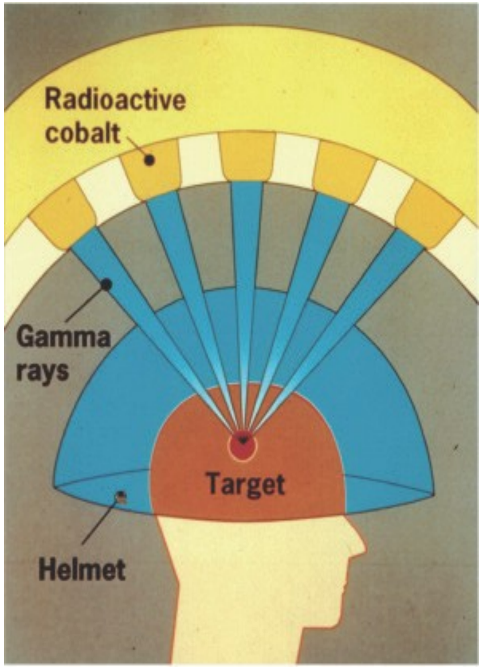
  E-beam diagnostics

- National Security

  Non-destructive nucl. materials detection

- Medical

  Medicine, Isotope production, Cancer diagnostics



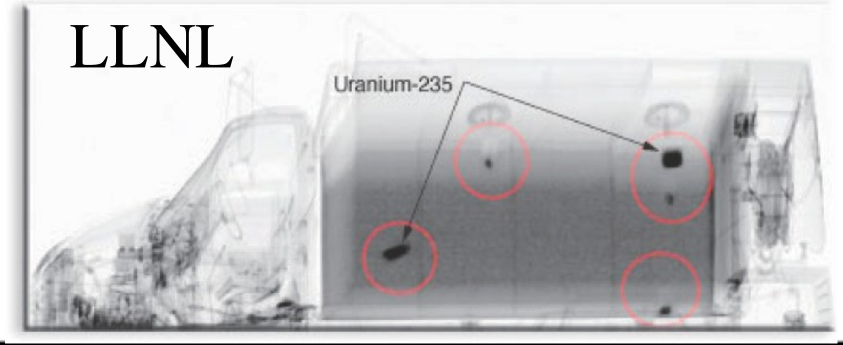
- Industriy

  Nucl. waste treatment, product inspection

- Materials Research

  Novel scintillators/detectors

- etc.



A Bit of Background

Topics for Compact Light Sources (2010 BES Workshop)

To develop:

- IR laser systems: kW avg power, fs pulses, kHz rep rates
- Laser storage cavities: 10-mJ, ps&fs pulses focused to um beam sizes
- High-brightness, high rep rate electron sources
- CW 4K superconducting RF linacs

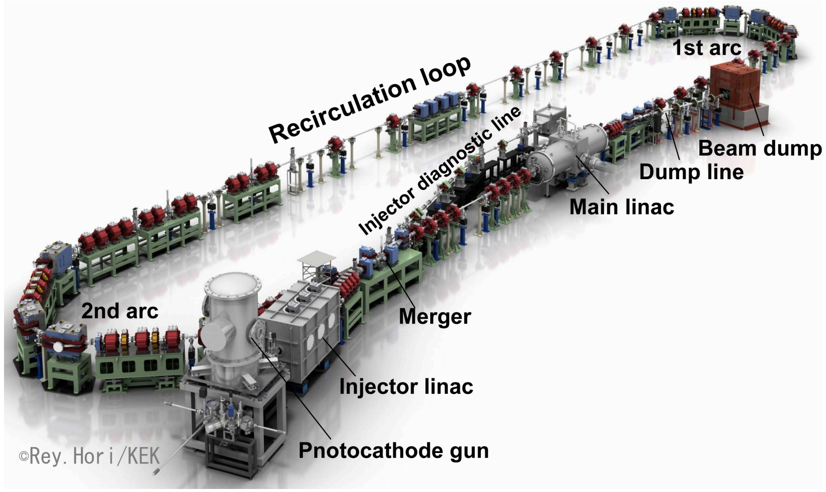
Other Topics Specific to Compton Sources

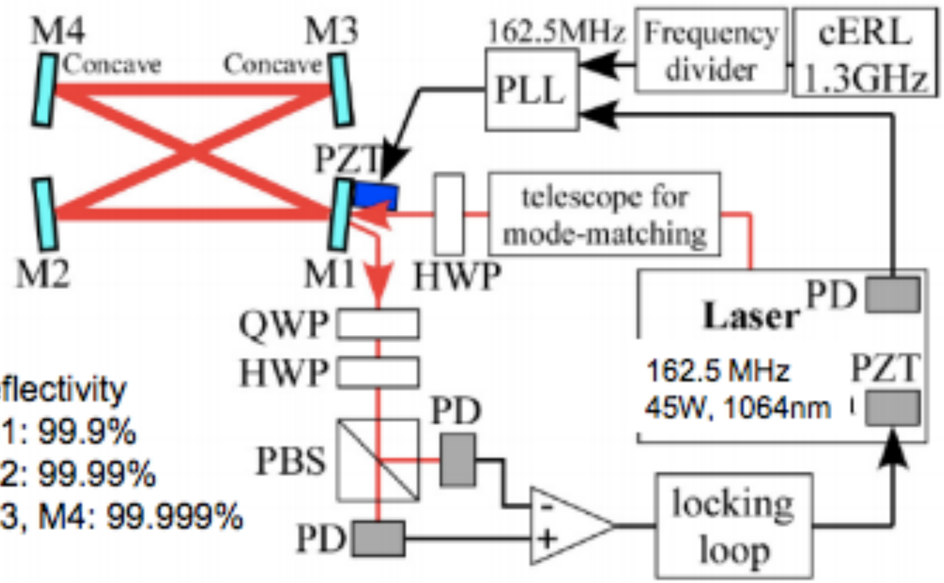
- Laser cavities tailored for specific Compton sources in terms of power, rep rate, beam size, polarization, and collision geometry (two-mirror & multi-mirror ring resonators, non-Gaussian mode cavities)
- Storage ring Compton sources:
    - Optimizing final focusing design and mitigate its impact on beam dynamics
    - General impact on beam dynamics at very high intensities
- ***Gamma-ray sources: Energy recovery consideration***

See "Report of BES Workshop on Compact Light Source", W. Barletta, M.Borland, May 2010

An ERL with LCS

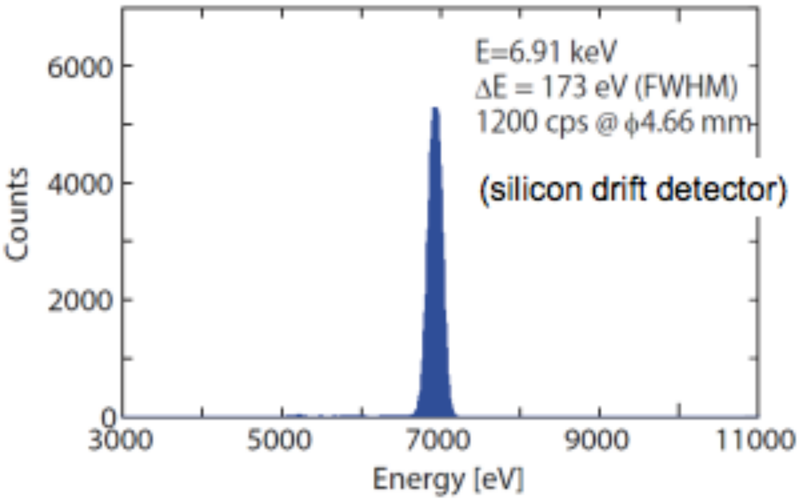
KEK cERL





reflectivity
M1: 99.9%
M2: 99.99%
M3, M4: 99.999%

waist size: σ=30μm

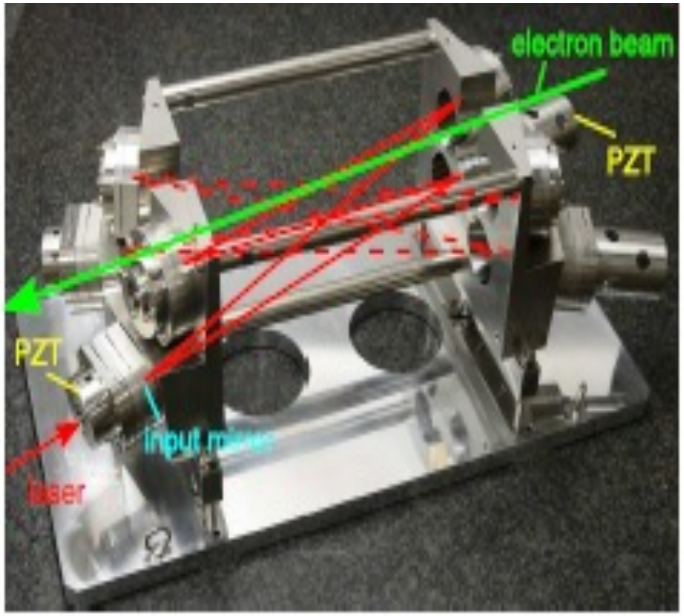


Results:

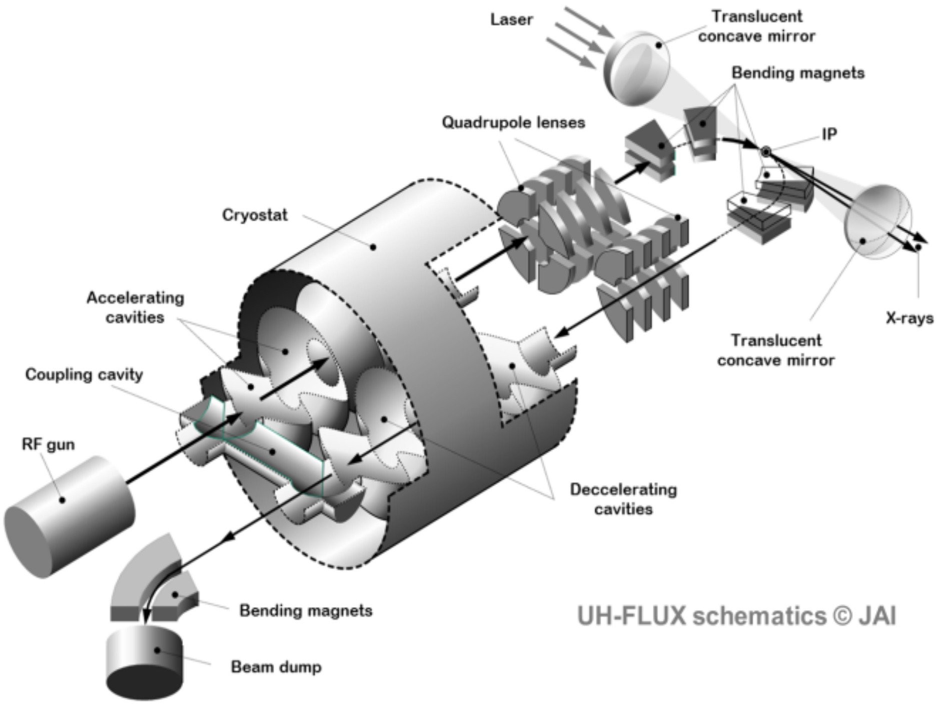
Photon energy = 6.9 keV
Detector count rate = 1200 cps @ϕ4.66mm (*)
Source flux = 4.3×10^7 ph/s (**)

R. Nagai, IPAC-2015, TUPJE002

Proposed LCS Sources



CBETA Application



Oxford Design: AERL

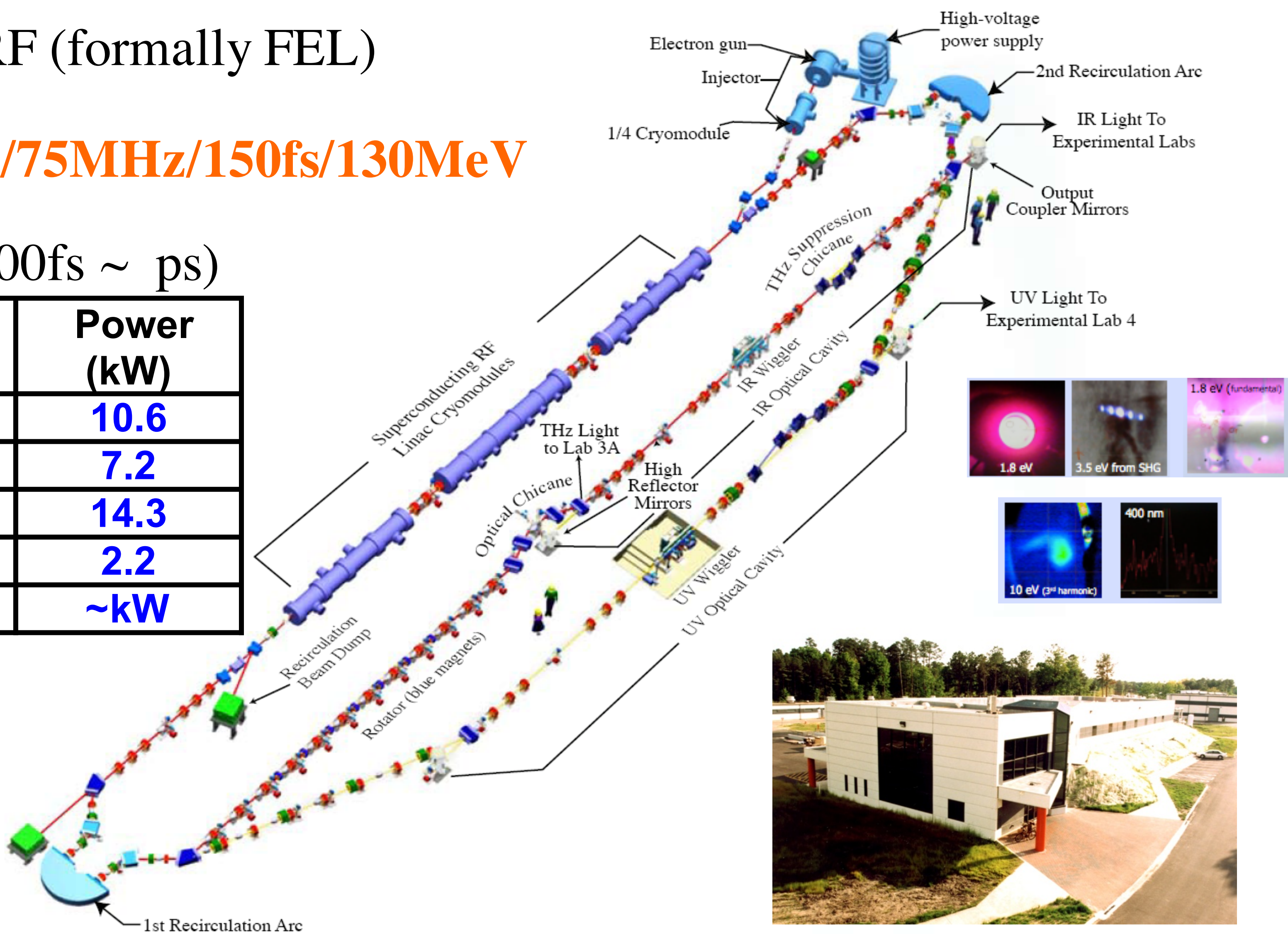
JLAB ERL

JLAB LERF (formally FEL)

ERL:10mA/75MHz/150fs/130MeV

FEL (sub-100fs ~ ps)

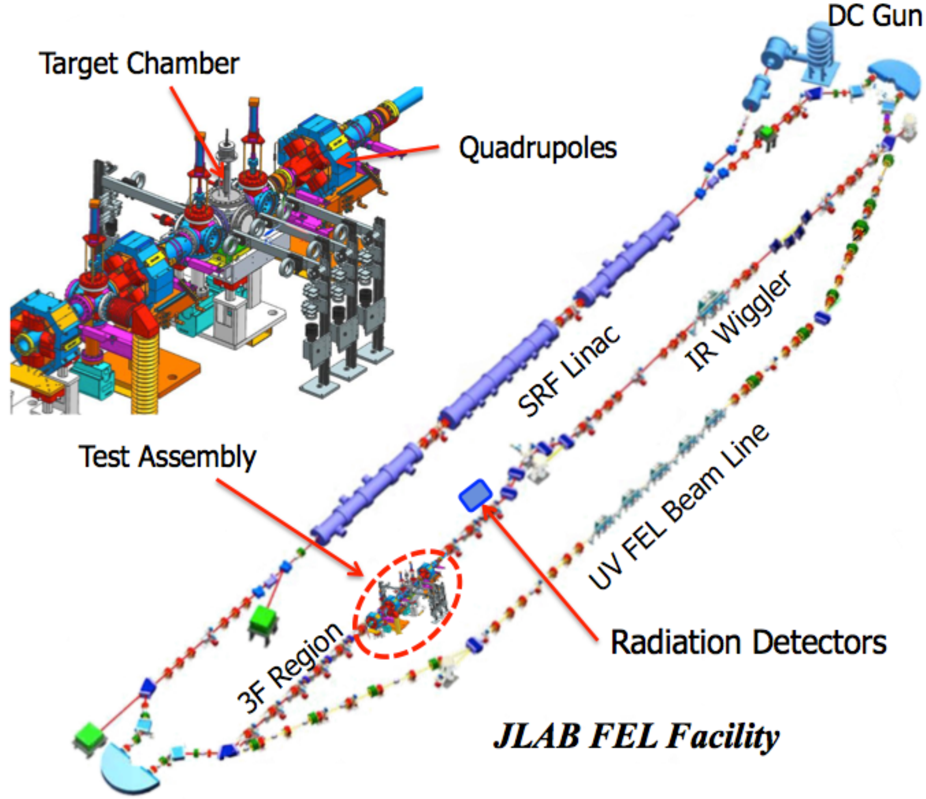
Wavelength (μm)	Power (kW)
6	10.6
2.8	7.2
1.6	14.3
1.0	2.2
THz	~kW

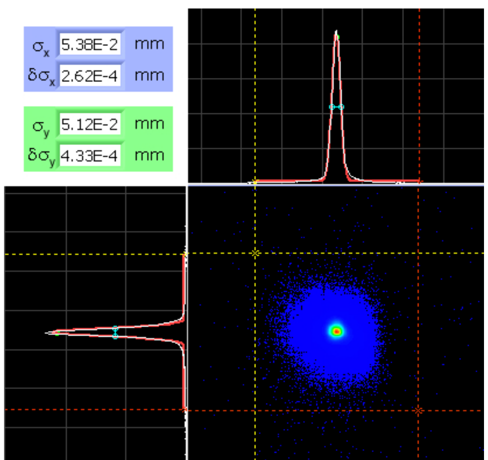


A Facility for NP Research

DarkLight: Aperture Test For Internal Target

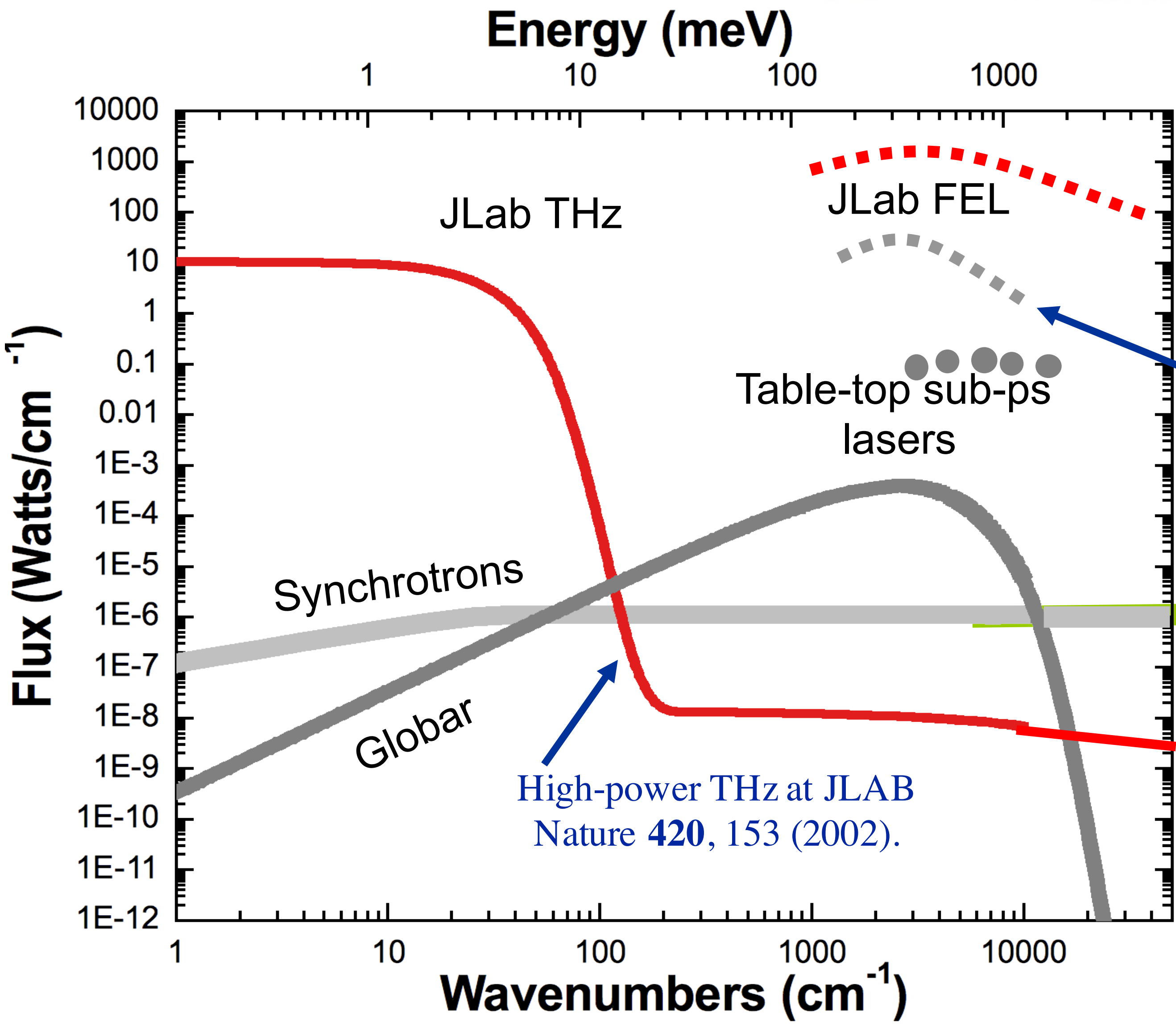
- **Sustained 8-hr high current beam transmission through a 2 mm aperture**
  - **Beam size: 50 um (rms)**
  - **Beam loss: a few ppm**
  - **Nearly 0.5 MW CW beam power**
- **Surpassed the users' initial expectation**
- **Demonstrated JLAB ERL unique capability**





PRL. **111**, 164801 (2013)
NIM. **A729** 223 (2013)

JLAB FEL Photon Source Spectral Characteristic



High-power THz at JLAB
Nature **420**, 153 (2002).

ERL-based High-power FEL
PRL **84**, 662 (2000).

Laser Compton Scattering

$$E_\gamma = \frac{E_l(1+\beta\cos\alpha)}{1-\beta\cos\theta + E_l(1+\cos(\alpha-\beta))/E_e}$$

$$E_\gamma \sim \frac{4\gamma^2 E_l}{1+\gamma^2\theta^2 + 4E_l E_e/m^2c^4}$$ ($\alpha\sim0$, head-on collision)

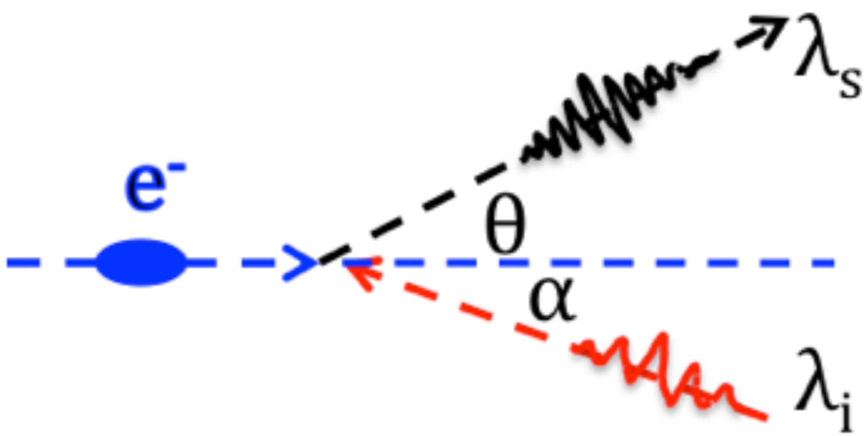
Back-scattering $\alpha\sim0°, \theta\sim0°$,

$E_\gamma \sim 4\gamma^2 E_l$

Crossed-angle $\alpha\sim90°, \theta\sim0°$,

$E_\gamma \sim 2\gamma^2 E_l$

E_l: *initial photon energy*
E_e: *e-beam energy*
E_γ: *scattered photon energy*



Laser-Compton-Scattering

More About Compton Scattering

Assuming Gaussian beams, in *linear interaction* regime, total scattered photons

$$N_\gamma = \frac{N_e N_l \sigma_t}{2\pi\sqrt{\sigma_{ey}^2 + \sigma_{ly}^2}\sqrt{(\sigma_{ex}^2 + \sigma_{lx}^2)\cos^2(\alpha/2) + (\sigma_{ez}^2 + \sigma_{lz}^2)\sin^2(\alpha/2)}} F\zeta$$

head-on collision with matched beams,

$$N_\gamma = \frac{N_e N_l \sigma_t}{2\pi\sqrt{(\sigma_{ex}^2 + \sigma_{lx}^2)(\sigma_{ey}^2 + \sigma_{ly}^2)}} F$$

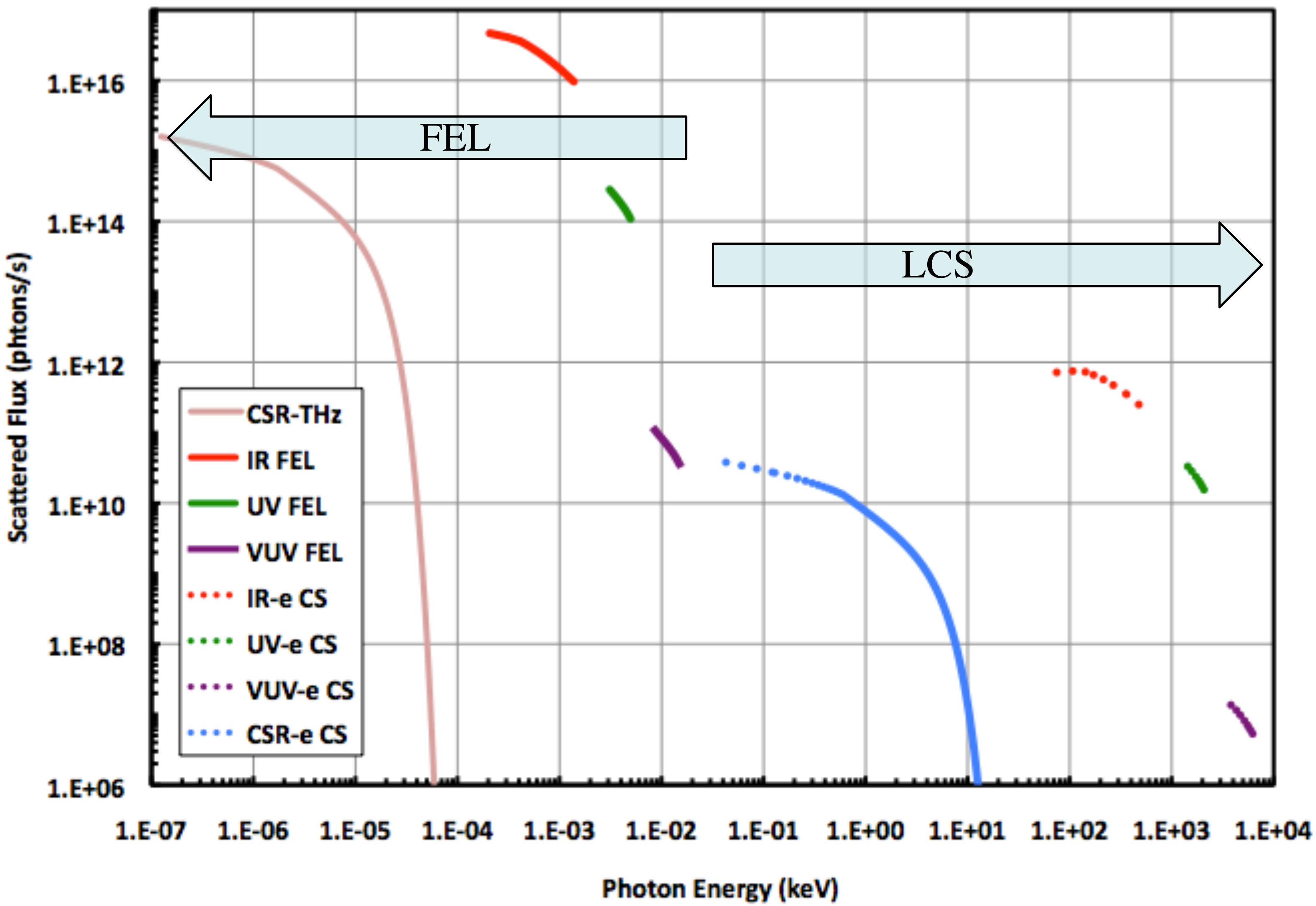
Brightness (ph. /A s Ω 0.1%BW)

$$B_\gamma \approx 1.5 \times 10^{-3} \frac{N_e N_l \sigma_t \gamma^2}{(2\pi)^3 \varepsilon_e^2 \sigma_l^2} F$$

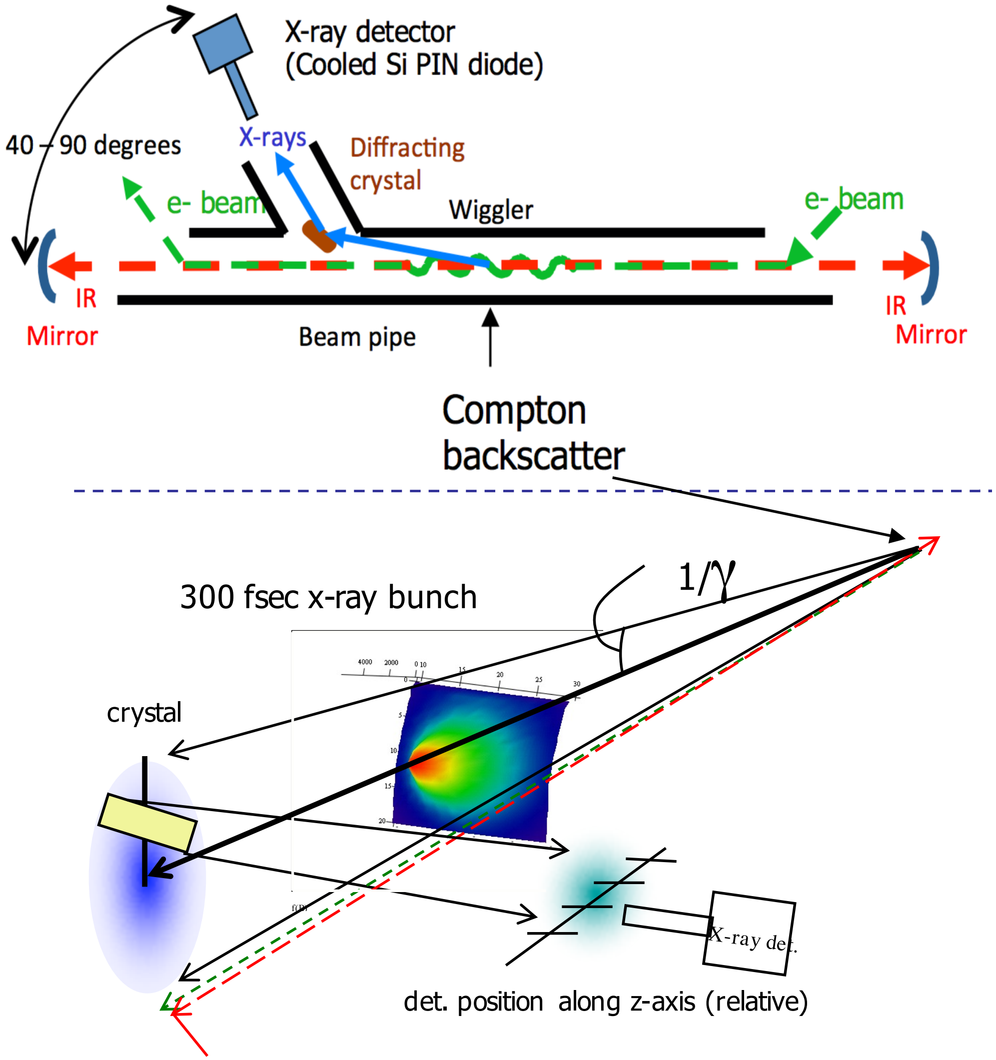
N_l: # of initial photon
N_e : # of e-beam energy
N_γ: scattered photon flux
γ : e-beam energy
ζ: efficiency factor
F: rep rate,
ε_e: normalized e-beam emittance
σ_e: e-beam size
σ_l: laser beam size
σ_t: CS cross section

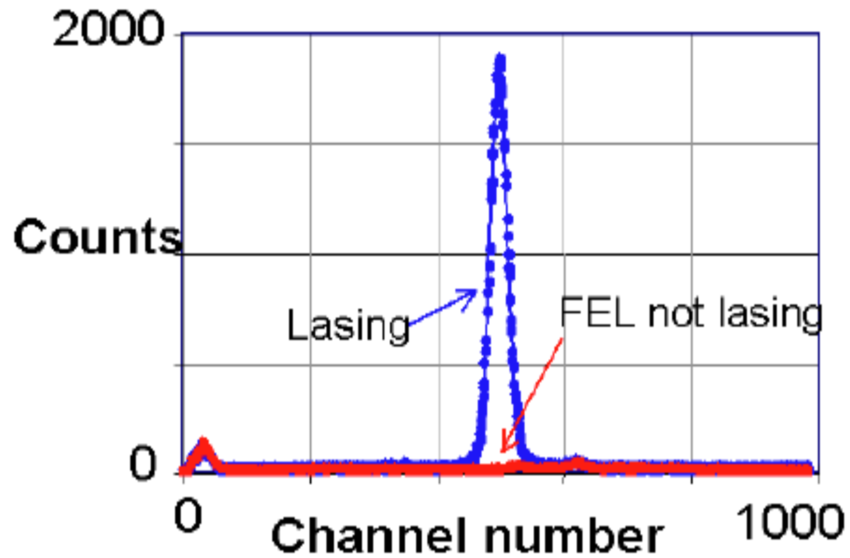
Ref: J. Yang, NIMA 428 (1999). W.J. Brown,, PRST 7 (2004).

What Can Be Expected From JLAB FEL



LCS Exp. at JLAB IR FEL DEMO (2000)



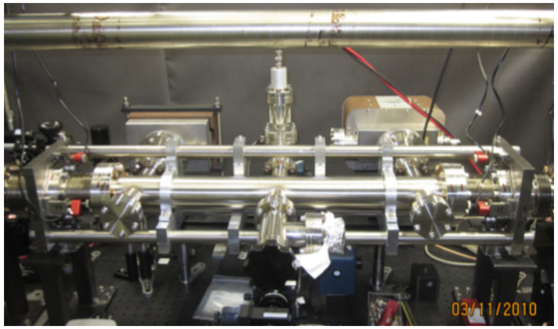


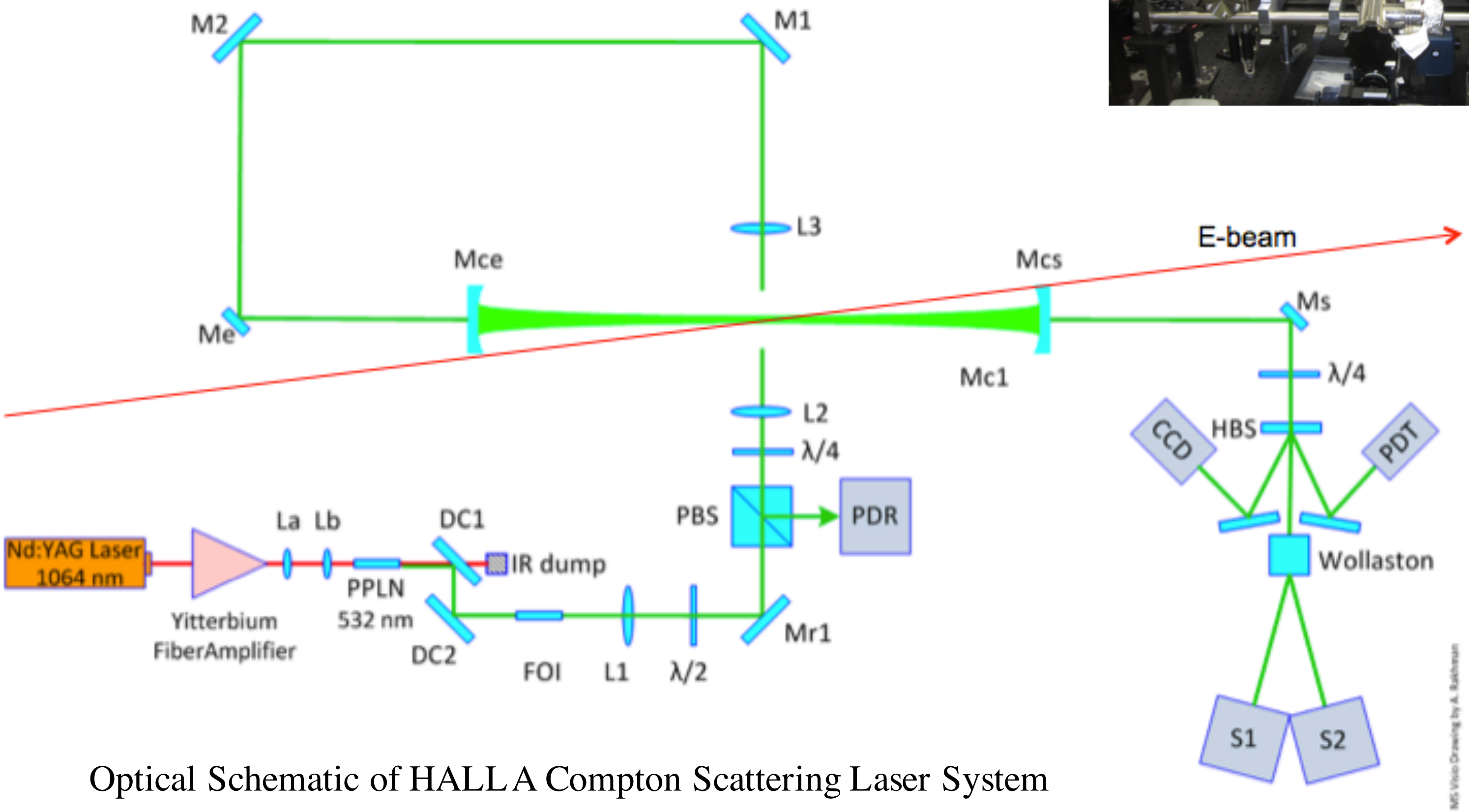
Measured 5.12 keV X-ray Spectrum (Tunable from 3.5 to 18keV)

J. Boyce et, al, IPAC'03

Laser Polarimeter

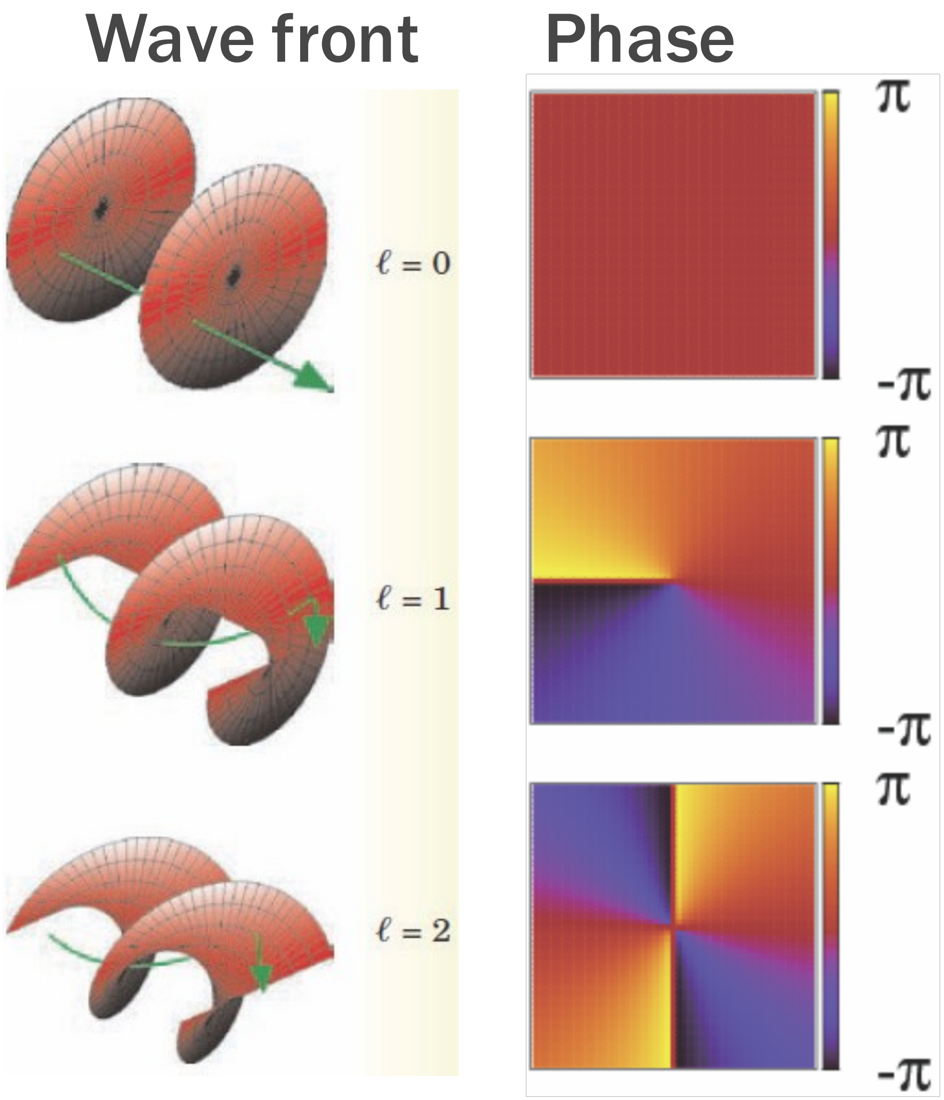
- Hall A Compton Polarimeter, 1~5kW/532nm
- Cavity power enhancement: up to 5000
- ***Much more efficient with ps laser***





Optical Schematic of HALL A Compton Scattering Laser System

Vortex Beams: Helical wave front



ℓ :Topological Charge (TC)

- Forming a helical wave front.

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

- Carrying orbital angular momentum (OAM)

  $$\ell\hbar$$

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

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

Vortex Beam Porpagation

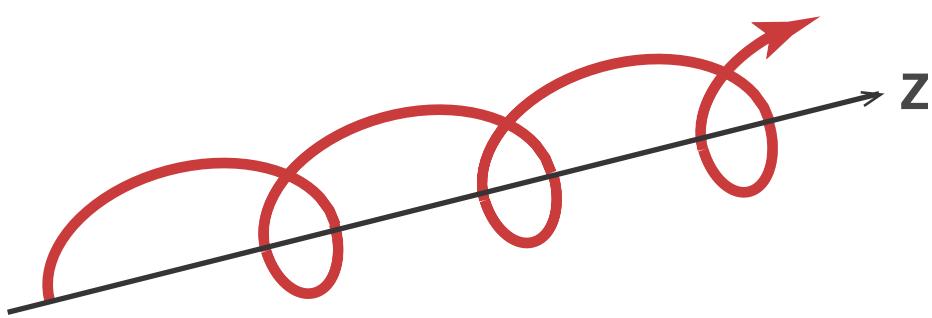
Poynting vector of Laguerre-Gaussian mode

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

spread of the beam

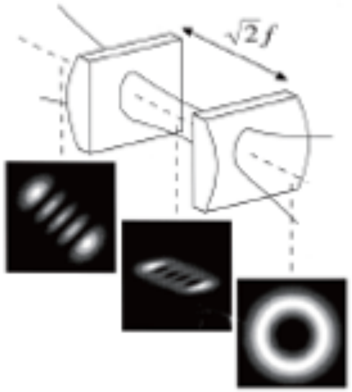
Spiral Poynting vector leads to Obital Angular Momentum (OAM)

Electric and magnetic field is slightly against the z-axis

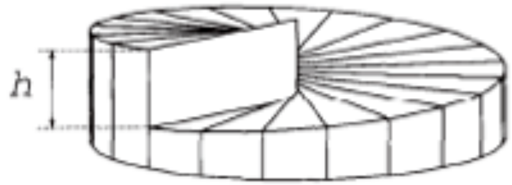


Generation of Vortex & OAM

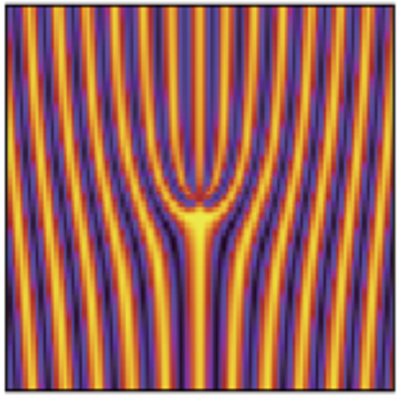
Cylindrical lens

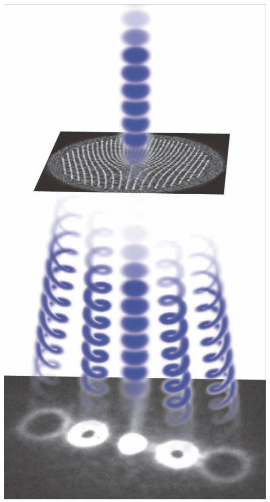


Spiral phase plate



Hologram





Without filters

Electron **Vortex beam**

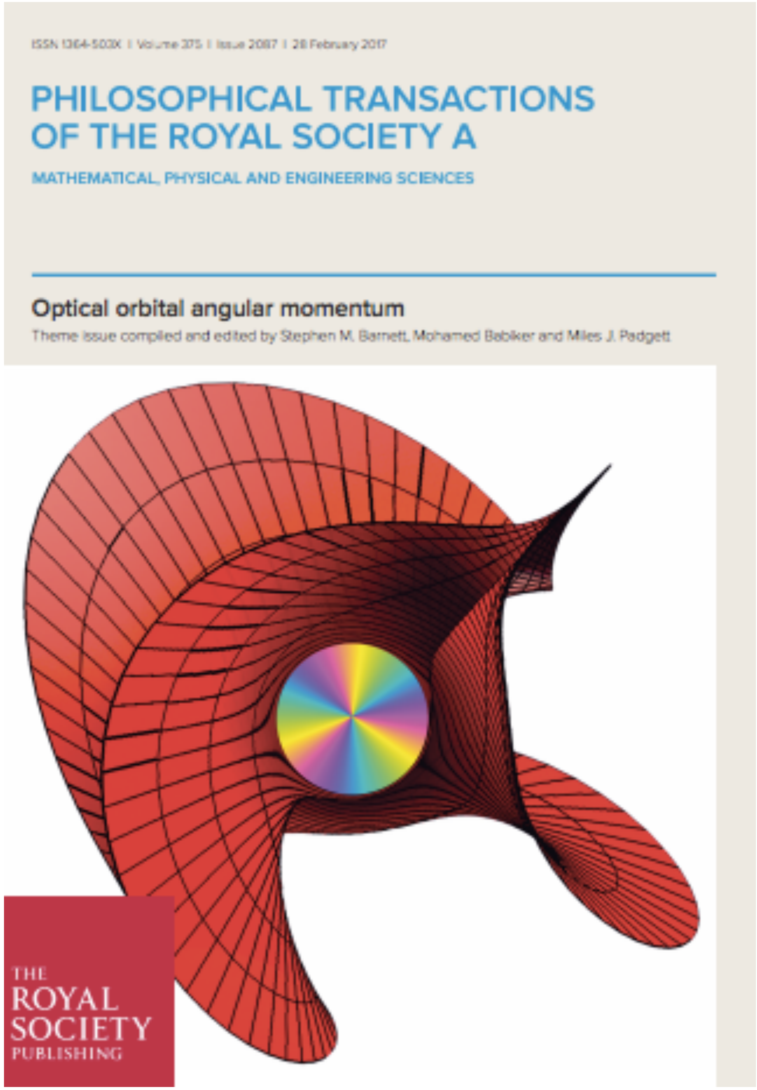
Electromagnetic radiation from an electron

J. Courtial et al., Opt. Comm. 159 (1999) 13.
M. W. Beijersbergen et al., Opt. Comm. 112 (1994) 321.
B. M. Kincaid et al., J Appl Phys 48 (1977) 2684.

About Vortex & OAM

Journal papers

- Phys. Today 57 (2004) 35.
- Nat. Phys. 3 (2007) 305.
- Laser & Photon. Rev. 2 (2008) 299.
- 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, “Twisted Photons” Wiley-VCH, 2011.
- D.L. Andrews, “The Angular Momentum of Light” Cambridge University Press, 2013.

Application with Vortex Beams

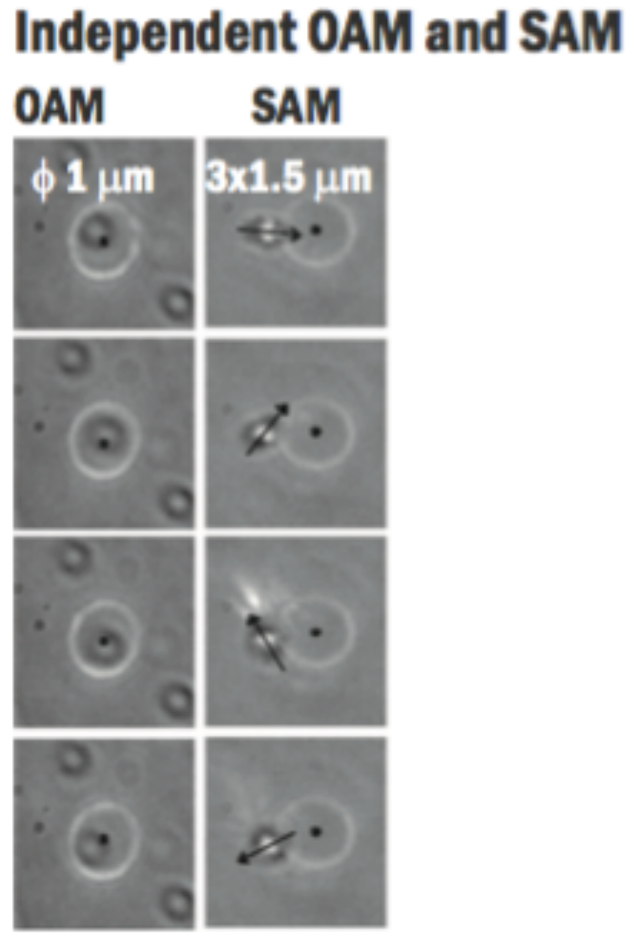
Demonstrated

- OAM transfer to micro particle
- Quantum entanglement
- Creation of metal nano needle
- Terabit data transmission

Proposed

- X-ray dichroism
- Magnetic mapping using electron vortex
- Direct observation of rotating black hole
- Excitation of atom

Optical Tweezers
(OAM to micro particles)



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

Why Bother with Gamma Vortex Beams?

The **proton spin crisis** (sometimes called the "proton spin puzzle") is a theoretical crisis precipitated by an experiment in **1987**[1] which tried to determine the spin configuration of the proton. The experiment was carried out by the European Muon Collaboration (EMC).[2]

Physicists expected that the quarks carry all the proton spin. However, not only was the total proton spin carried by quarks far smaller than 100%, these results were consistent with almost zero (4–24%[3]) proton spin being carried by quarks. This surprising and puzzling result was termed the "proton spin crisis".[4] ***The problem is considered one of the important unsolved problems in physics.***[5]

from Wikipedia

Gamma Vortex Beams May Bring Hope

- The lack of more effective tools to probe the OAM contribution of quarks and gluons to nucleon's spin has kept us from completely resolving the "**proton spin puzzle**".
- Even with JLab 12GeV/EIC physics program, it is still a challenge to understand the hadron spin, such a fundamental emerging phenomenon of QCD dynamics, without a firm determination of the OAM contribution of quarks and gluons.
- High energy and high luminosity photon vortex beams carrying quantized OAM maybe *sensitive in measuring the transverse motion of the hadron's constituents*, and potentially a very effective probe into the proton substructure, providing us with an *additional capability to explore the partons' OAM* and *to find the answer to the long-standing and mysterious "spin-puzzle".*

Gamma Vortex Beams May Bring Surprise

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Gamma Vortex Beams May Bring A Big-PRIZE

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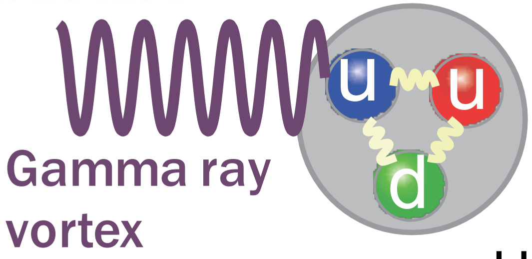
Potential Applications in NP

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.

High angular momentum excited baryons?

Nuclear physics

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

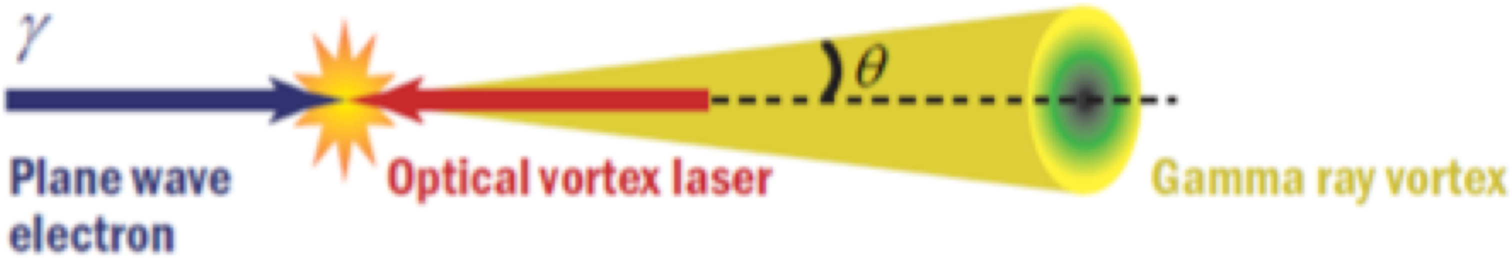
Excited states can be populated by high order transition.
Photon-induced reaction cross section will change.

Generation of positron vortex via pair production

As a new particle source for high energy physics.

MeV~GeV Vortex Beams

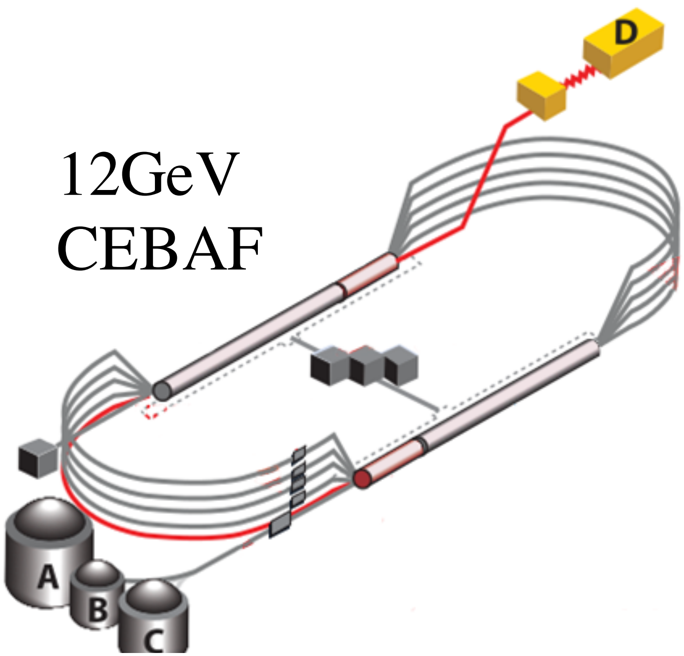
- Vortex γ-rays can be generated by Compton Scattering (LC): either ***Linear LCS*** or ***Nonlinear LC***.

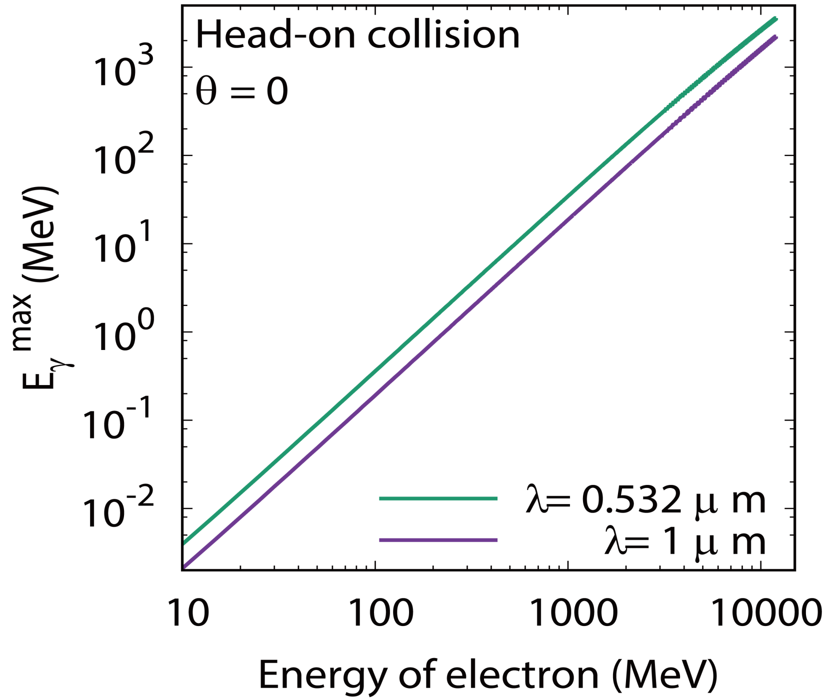


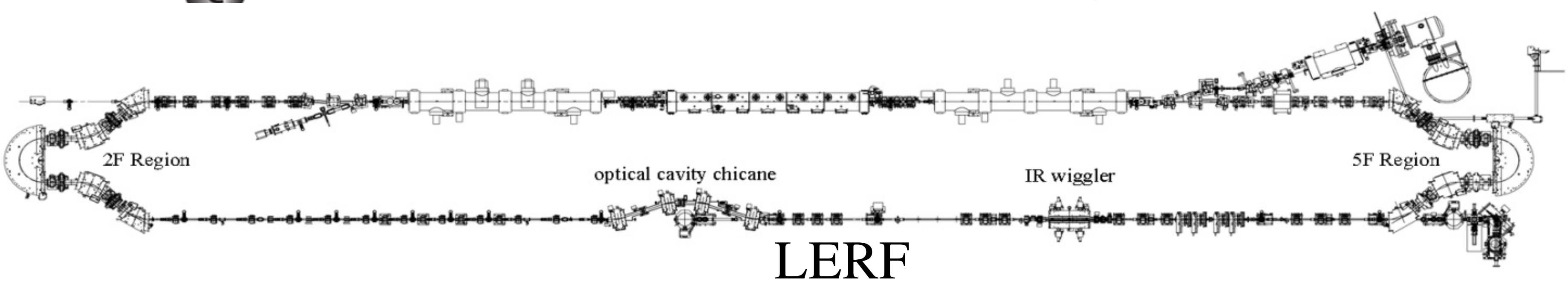
- **Two imperative elements**
  - **High energy electron beams**
  - **High power vortex laser (>1k W) needed**
    - ✓Low power vortex laser with external enhancement cavity
  - **And above all: funding**

Possible Approach twd. Gamma Vortex Beams at JLAB

- LCS by a high energy relativistic electron beam & a laser beam

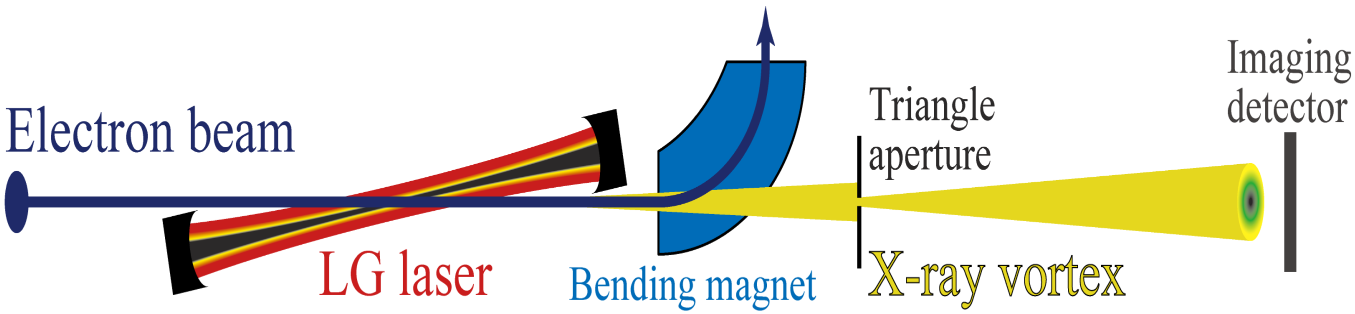


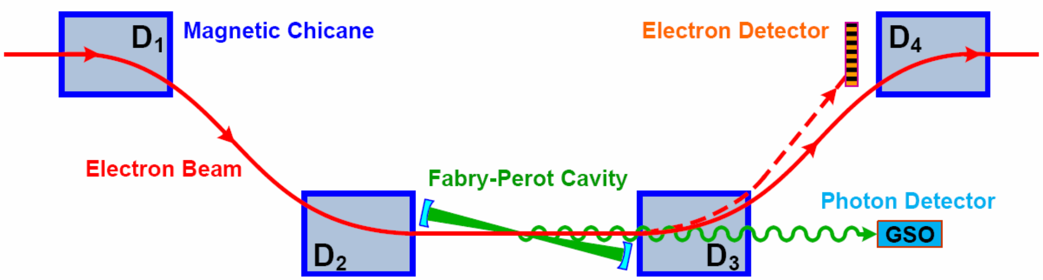


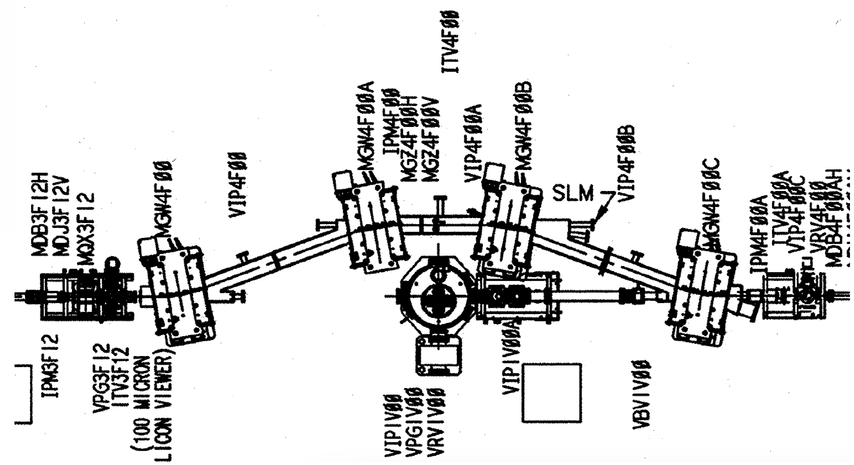


Possible Experimental Locations

- Accelerator - eBeams







Vortex Photon Flux

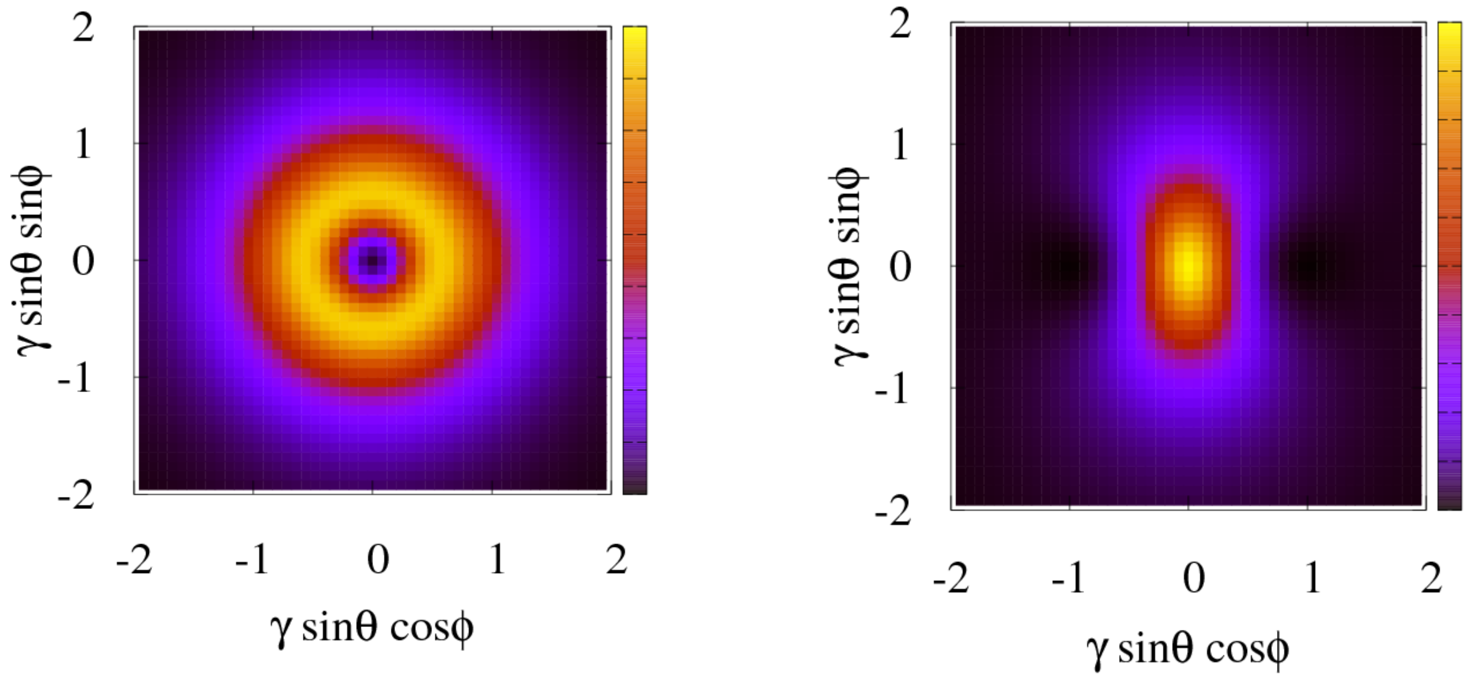
- Estimate from JLAB Facilities

Facility	CEBAF		LERF
Gamma-ray			
Maximum energy	360 keV	3.6 GeV	360 keV
Number of photons*	10^6 (/sec/0.1mA/2kW)		10^8 (/sec/1mA/2kW)
Electron			
Energy	100 MeV	12 GeV	100 MeV
Current	0.1 mA	0.07 mA	1.0 mA
Transverse size (rms)	0.1 mm		0.5 mm
Bunch length (rms)	43 fs		2 ps
Repetition rate	499 MHz		75 MHz
Repetition rate	499 MHz		75 MHz

LG laser	
OAM	3
Power	2,000 W
Energy	2.33 eV (532 nm)
Cavity length	0.85 m
Transverse size (rms)	0.09 mm
Pulse width (rms)	10 ps
Crossing angle	23.5 mrad

Vortex Beams by LCS

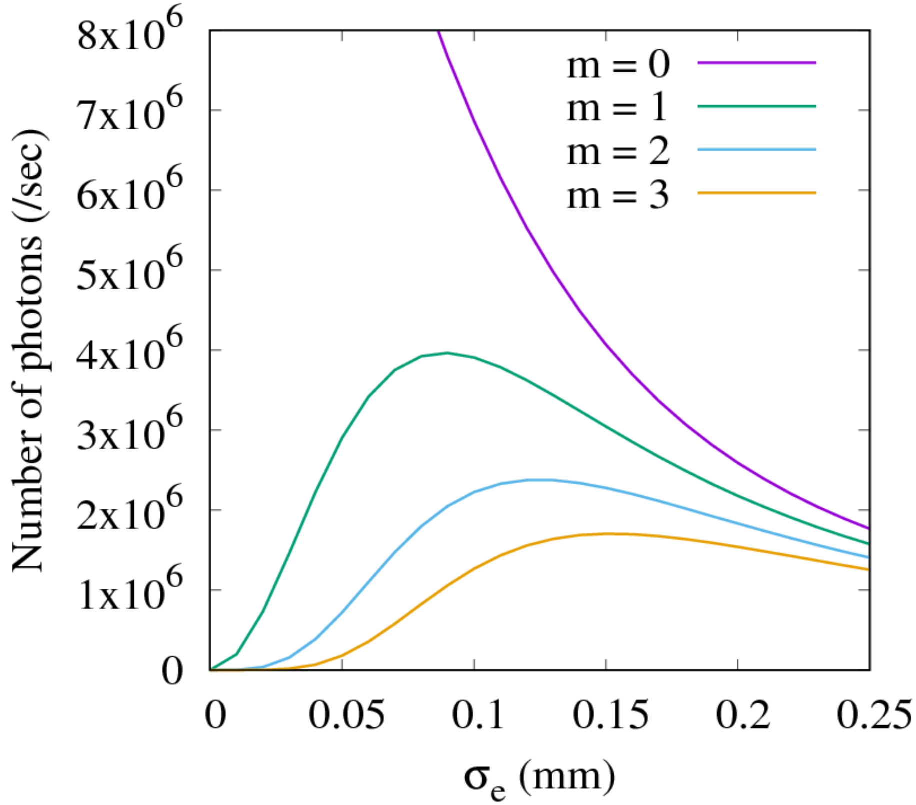
- Spatial property



Calculated spatial distributions of radiation power of ICS gamma-rays when $m/(k'x)$ is (a) 20 and (b) 0.02, respectively (m: OAM of the incident photon, $k' = 2\gamma k$)

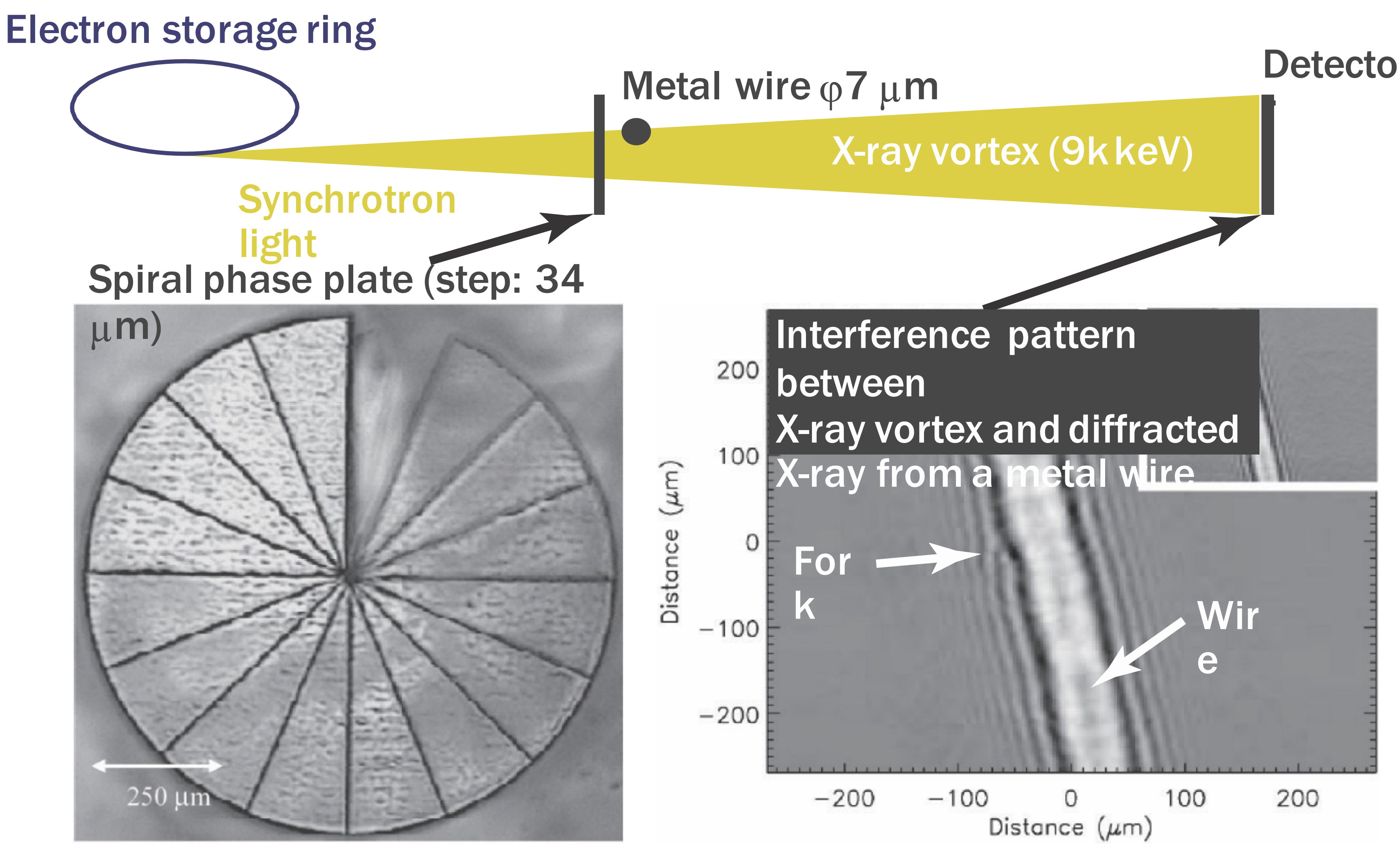
Vortex Photon Flux

- Dependent on both beam size & OAM (TC)



Calculated number of photons vs. the transverse size of an electron beam ($\boldsymbol{\sigma_e}$), for each OAM value (*m*), of a LG laser. The waist size of the laser is w = 0.17 mm.

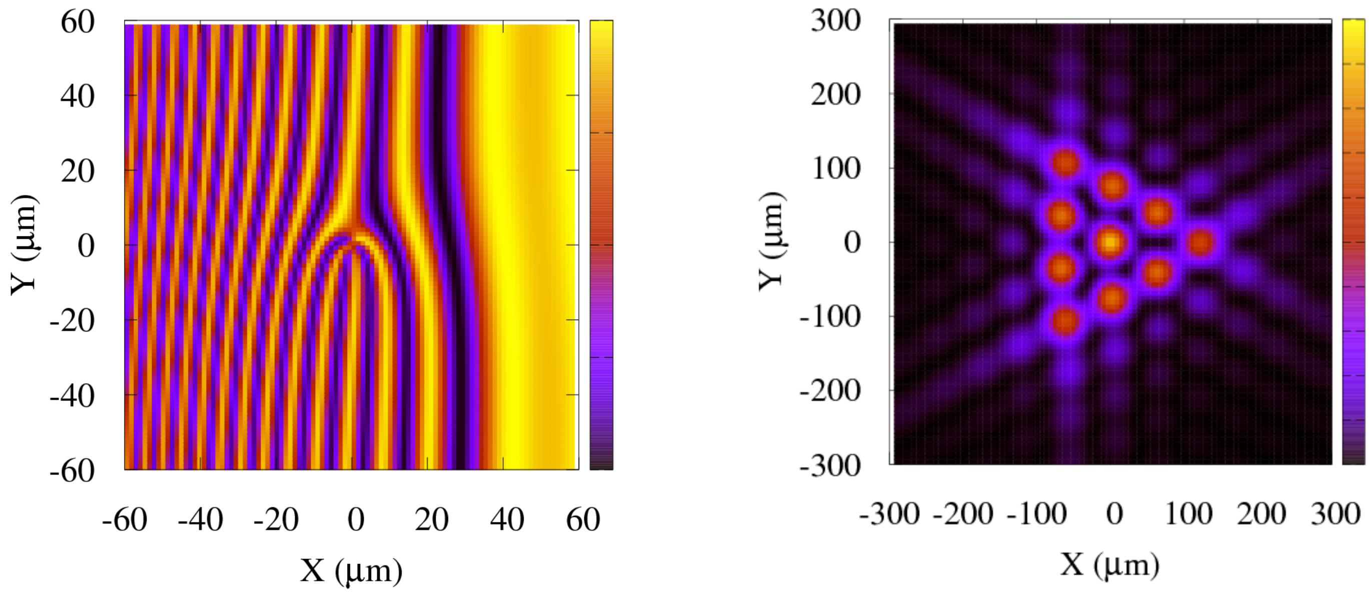
OAM Characterization: Another Challenge



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

LCS Vortex Characterization

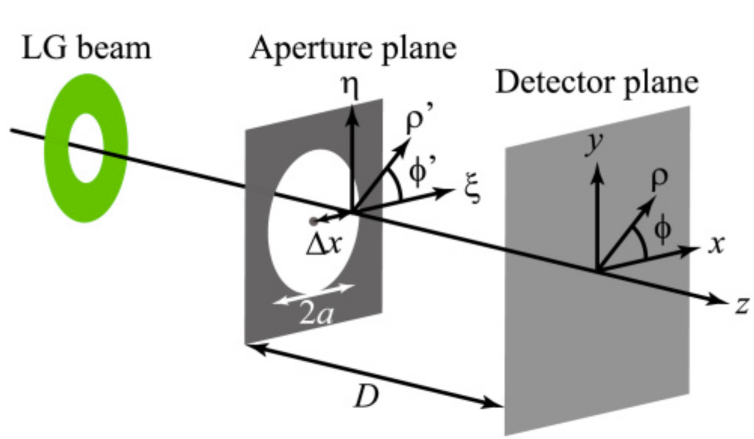
- How to measure Hard X-ray/Gamma OAM?

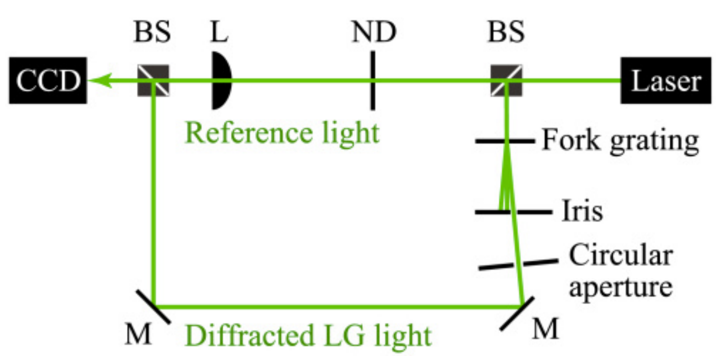


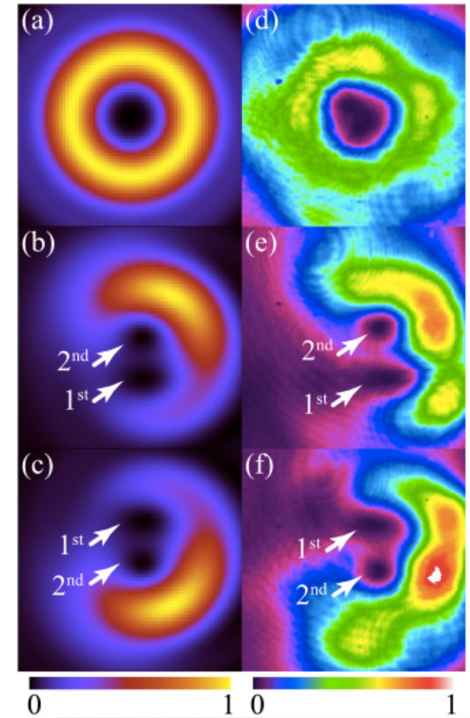
(a) Calculated interference pattern between a 10 keV X-ray vortex carrying m = 3ħ OAM and a diffracted X-ray from a metal wire. (b) Calculated diffraction pattern from a triangle aperture of a 10 keV X-ray vortex carrying m = 3ħ OAM.

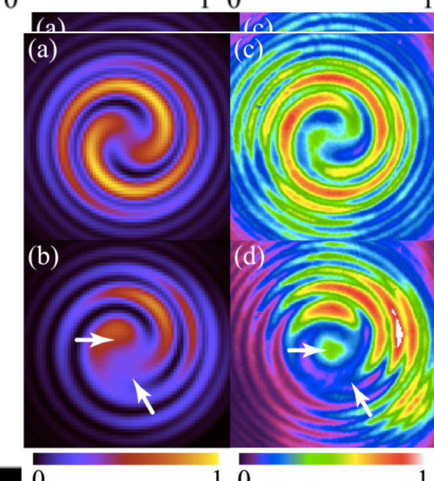
Explore New Characterization Method

- Diffraction properties of optical vortex beam through various apertures have been actively investigated to measure OAM(TC)
- For the first time, demonstrated that off-axis diffraction of the LG beam through a simple circular aperture can be used to determine both the magnitude and the sign of the TC.









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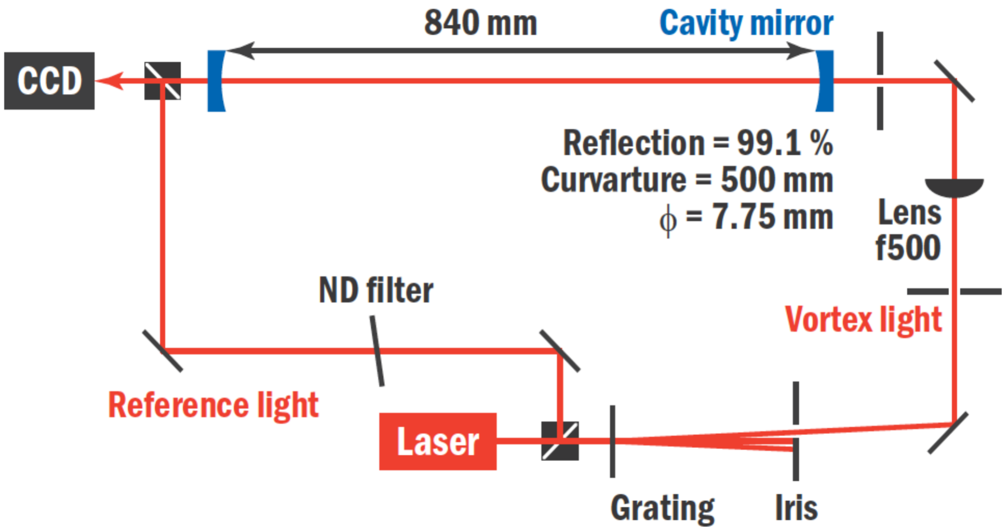
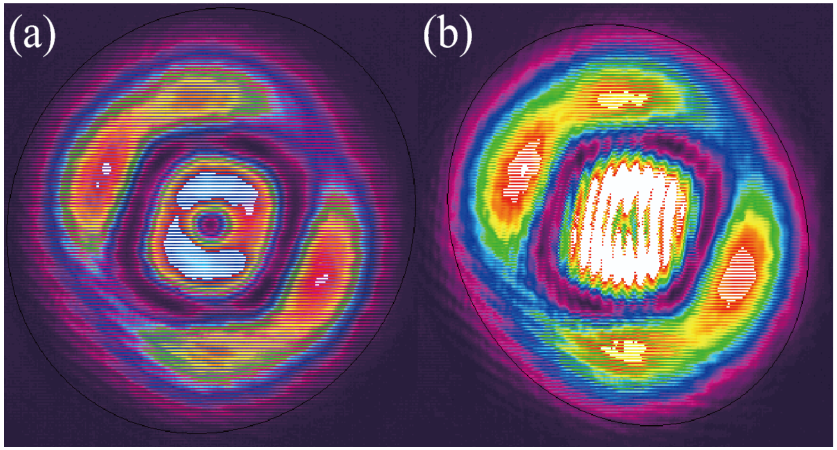
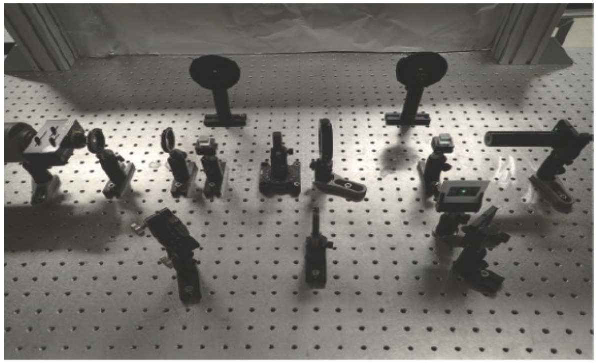
OAM Laser Study

- Preservation of Vortex in an Enhancement Cavity







(a) Profile of a LG beam (m=1) after passing through two cavity mirrors and being amplified. (b) Interference pattern between a plane wave reference beam and the amplified LG beam (m=1) through two cavity mirrors.

Summary

- Reviewed existing LCSs
- Explored basic properties of vortex beams and applications to new frontier physics
- Identified an unique opportunity at JLAB for X-ray and Gamma-ray vortex beam research
- Reported our recent effort on high power vortex laser and characterization

Acknowledgement: We'd like to thank S. Benson, C. Tennant, T. Satogata, and M. Tiefenback for very helpful discussions.

Your kind attention:

We have been encouraged to consider a workshop on the subjects about

X-/Gamma-ray Vortex beams and their applications to frontier sciences including nuclear/high energy physics.

You are welcome to show ideas and help!