Progress using an FEL Oscillator for Compton Scattering

Y. K. Wu

DFELL, Triangle Universities Nuclear Laboratory, and

Department of Physics, Duke University

August 27, 2014

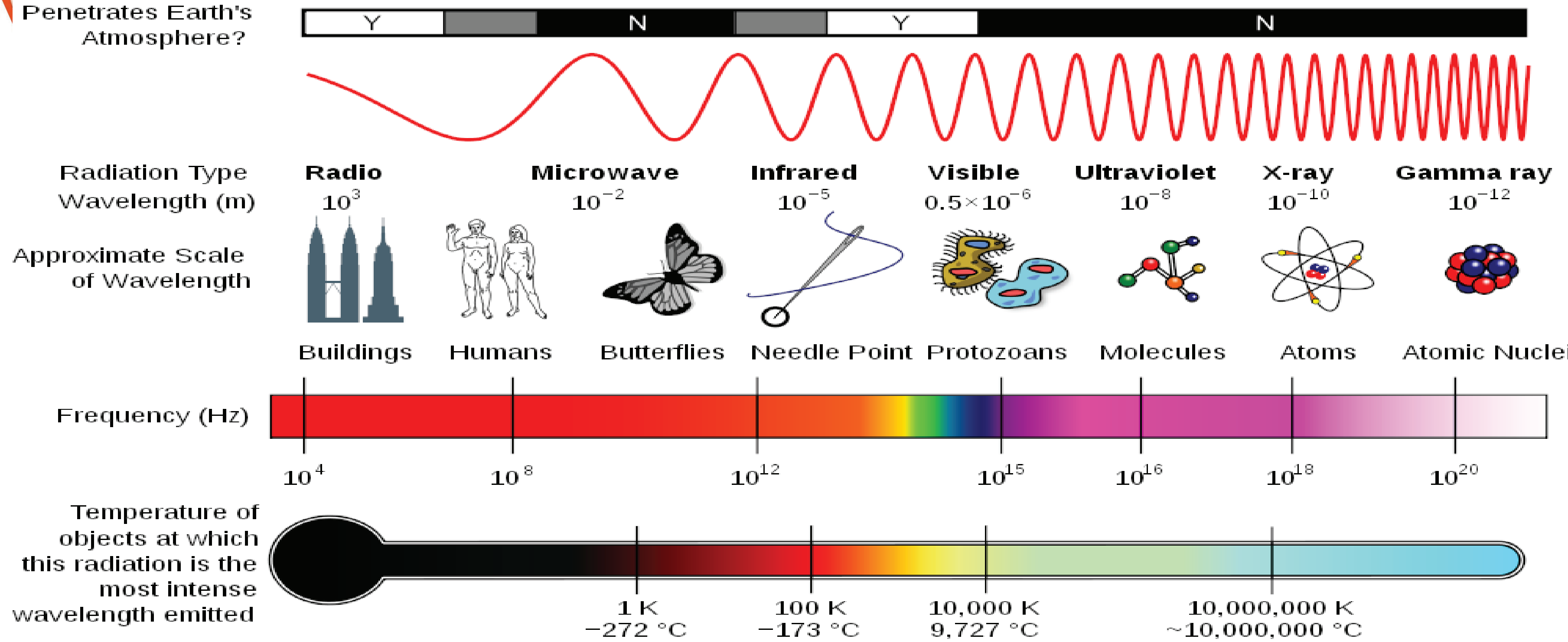
Work supported by U.S. DOE Grant: DE-FG02-97ER41033

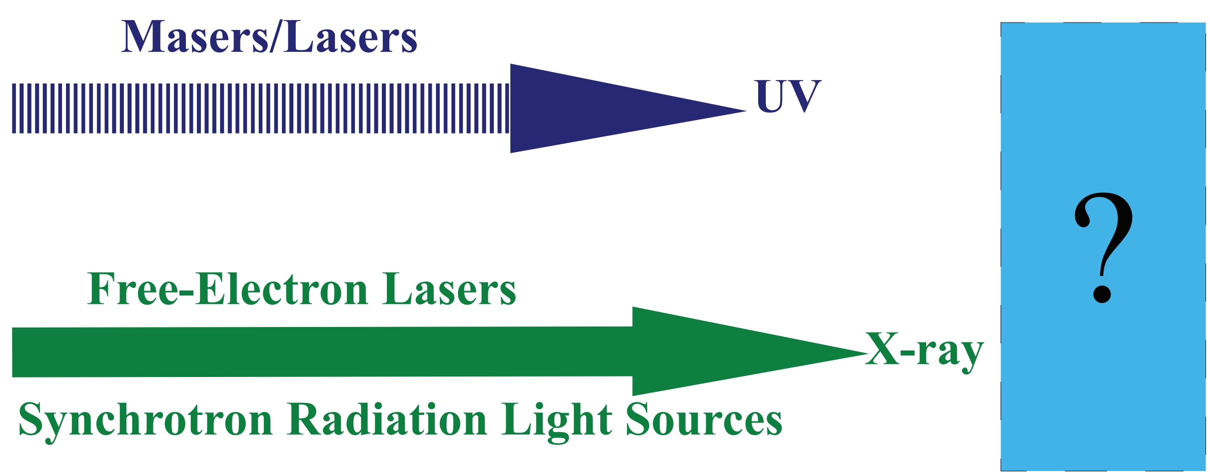
Outline

- Overview: High-energy Photon Generation via Compton Scattering
- A Review of Compton sources powered by FEL Oscillators
- High Intensity Gamma-ray Source (HIGS) at Duke University
- Basic and Applied Research Using Compton Gamma-ray Beams

Compton Scattering Effect and Physics of Compton Photon Beams

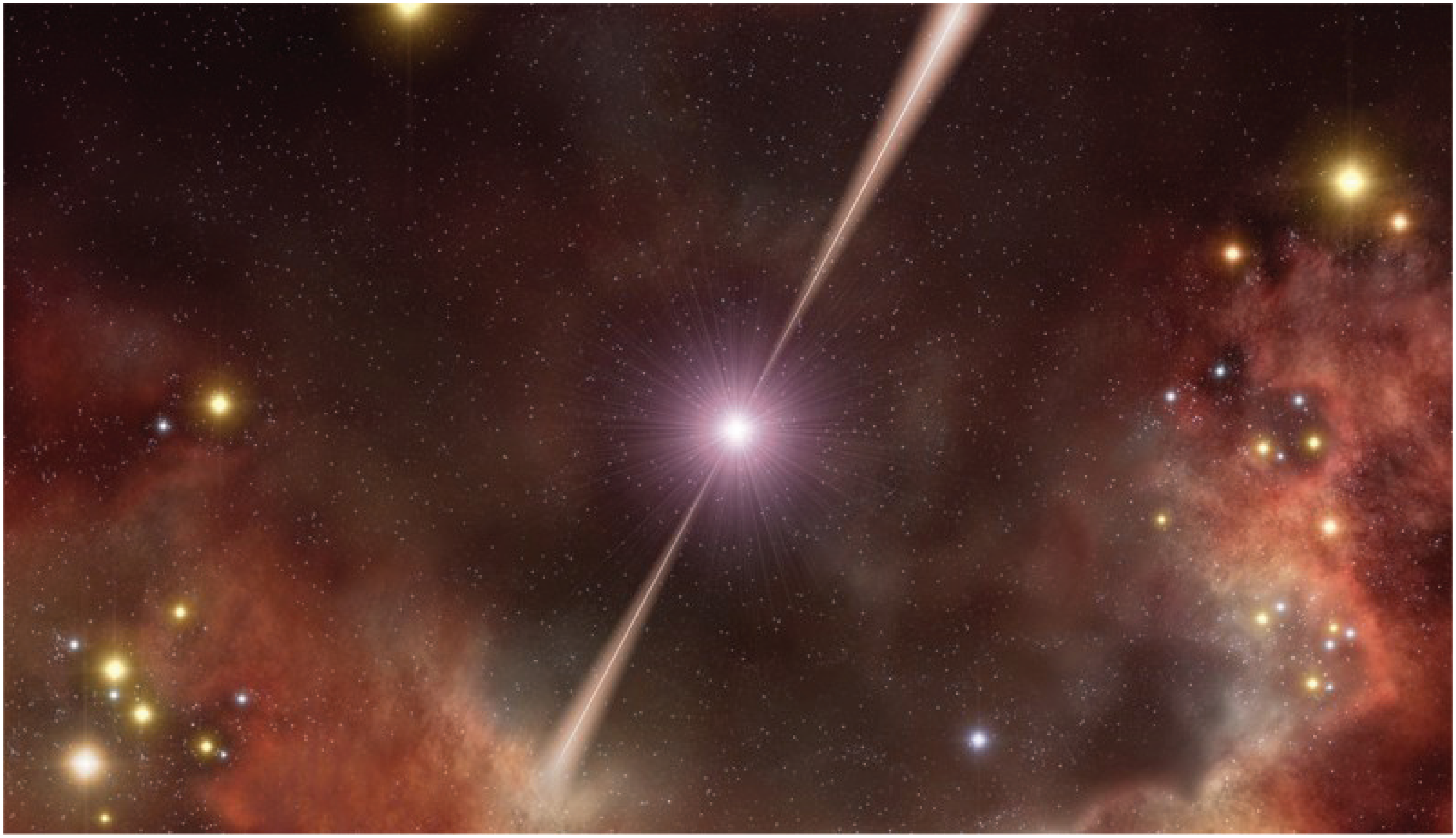
Spectrum of Electromagnetic Radiation





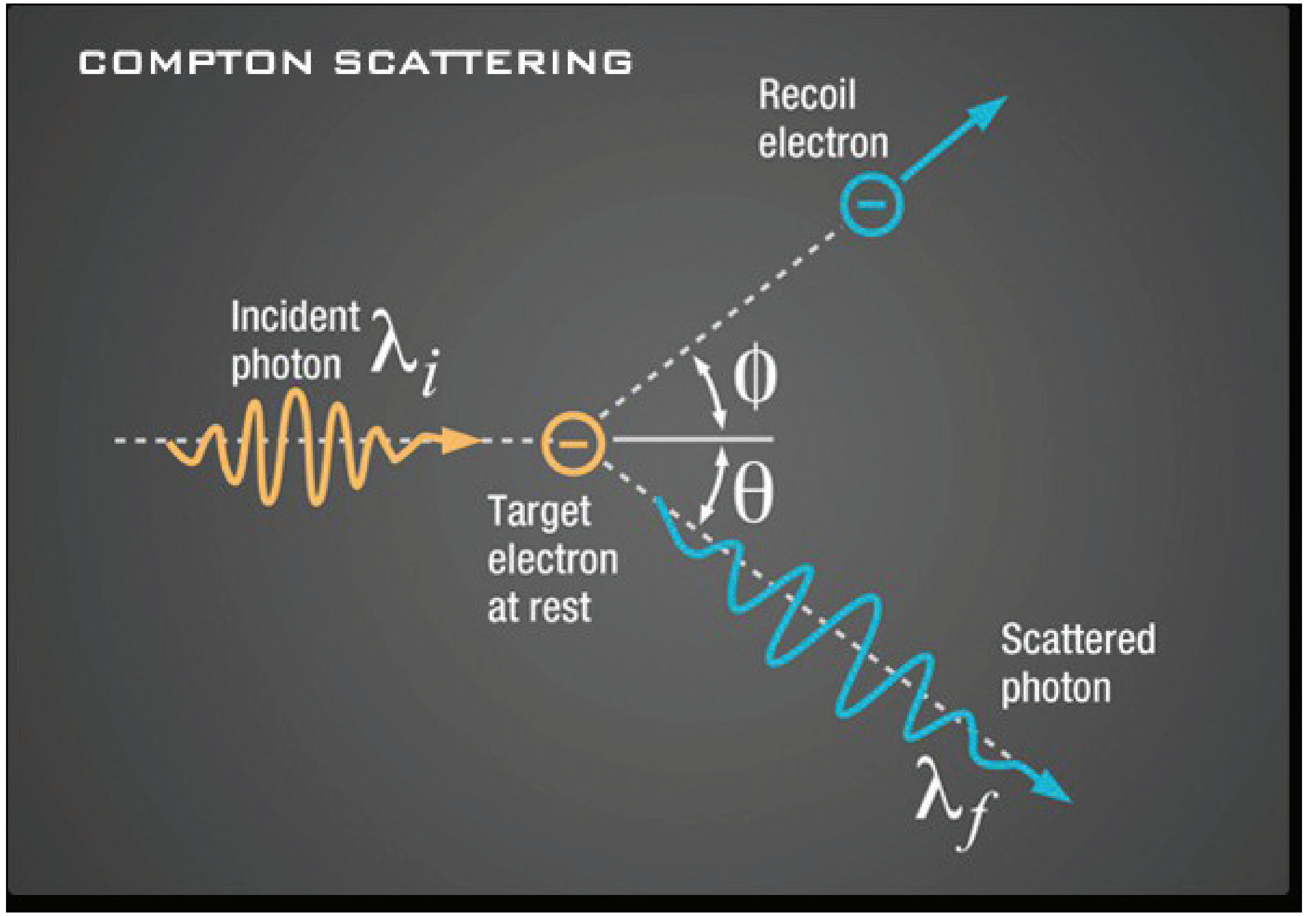
http://en.wikipedia.org/wiki/Electromagnetic_spectrum

Gamma-ray Bursts: GRB 080319B



1. http://en.wikipedia.org/wiki/GRB_080319B

Compton Scattering



Compton Scattering

Arthur H. Compton (1892 – 1962)

Discovery: 1923

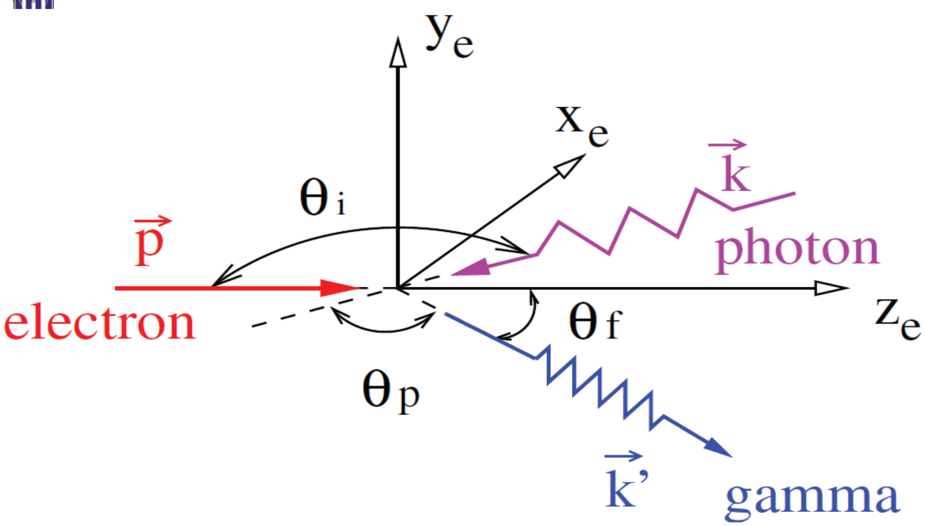
Nobel Price for Physics: 1927

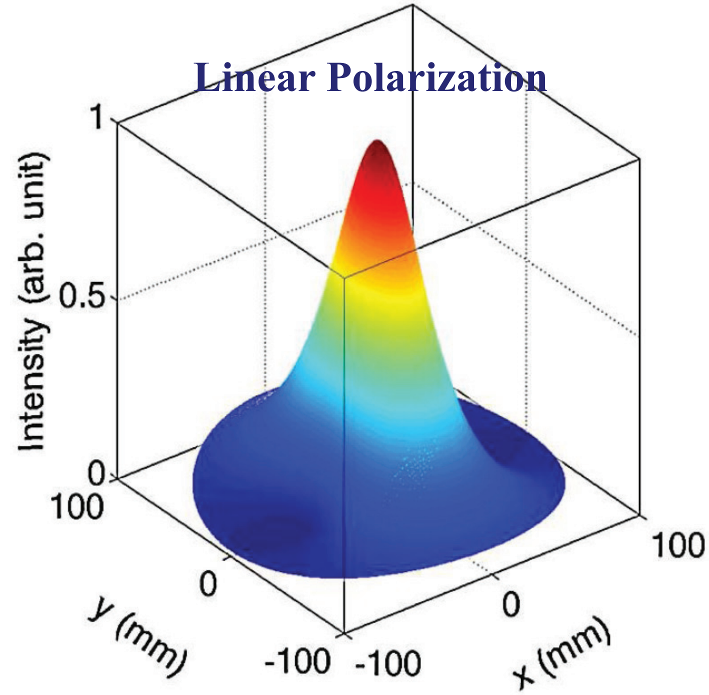
$$\lambda_f - \lambda_i = \frac{h}{m_e c}(1 - \cos\theta)$$

1. http://fishbein.uchicago.edu/courses.html
2. http://missionscience.nasa.gov/ems/12_gammarays.html

A.H. Compton, Bull. Nat. Res. Council (US) 20 (1922) 19; Phys. Rev. 21 (1923) 483.

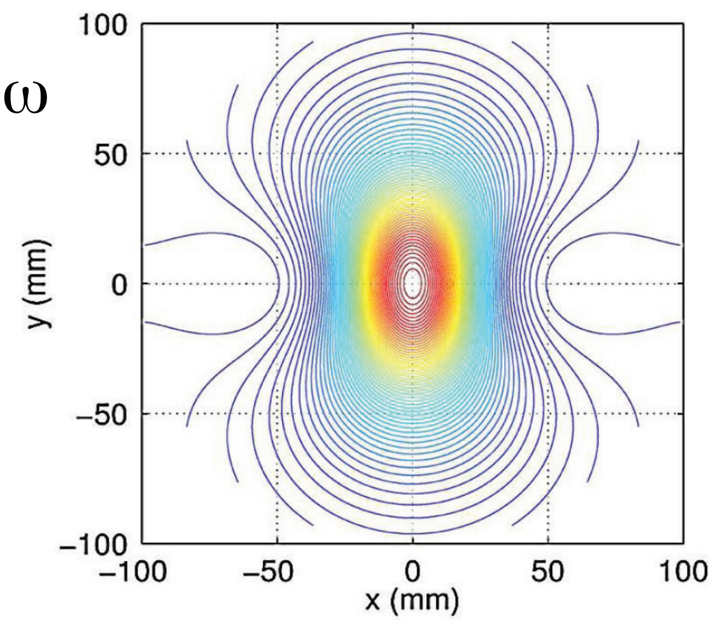
Photon Energy





$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f + \frac{\hbar\omega}{\mathcal{E}_e}(1-\cos\theta_{ph})}$$

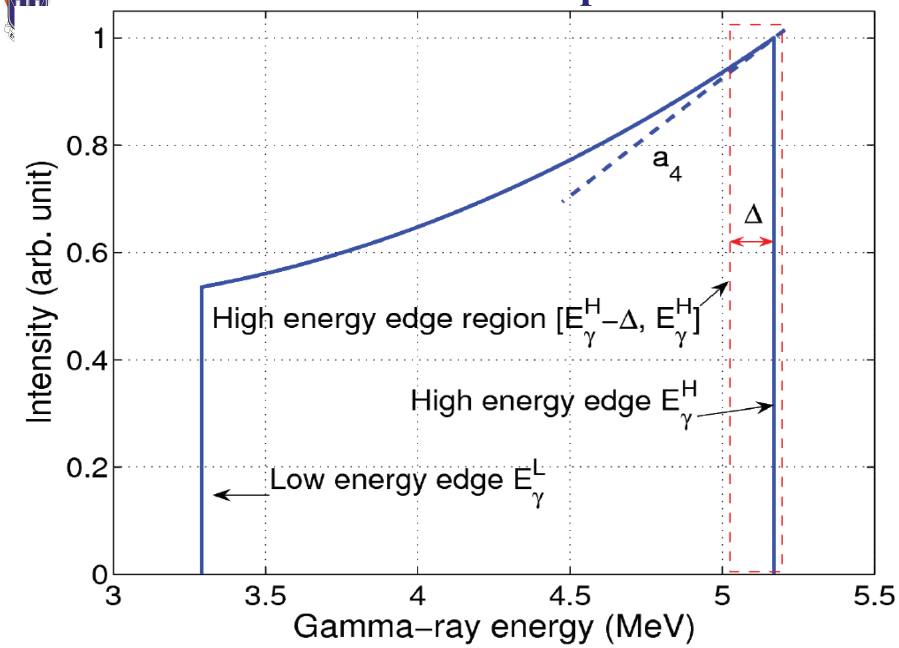
Head-on Collision: $E_\gamma^{max} \approx (\gamma(1+\beta))^2 \hbar\omega \approx 4\gamma^2\hbar\omega$



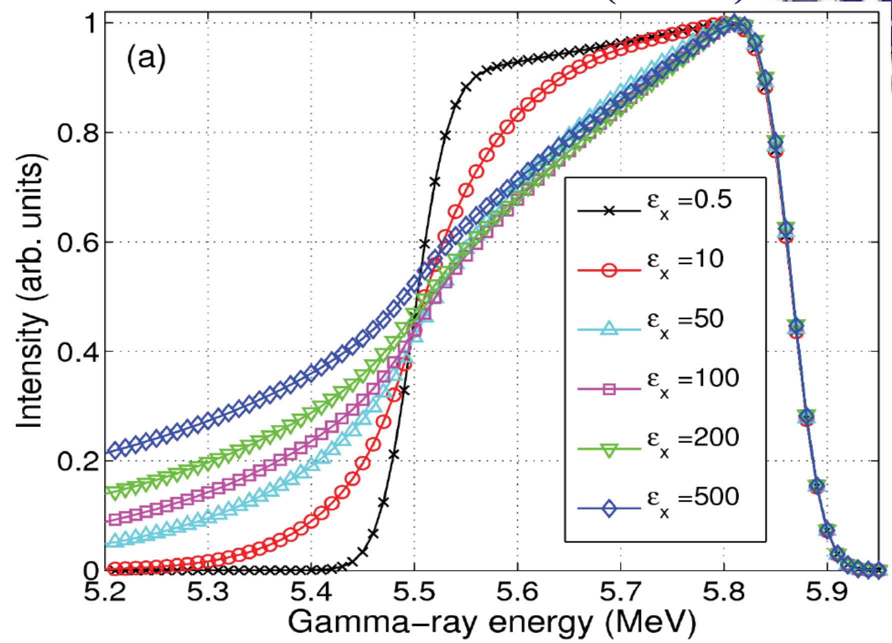
C. Sun and Y. K. Wu, Phys. Rev. ST Accel. Beams 14, 044701 (2011)

Energy Distribution of Compton Gamma-beam

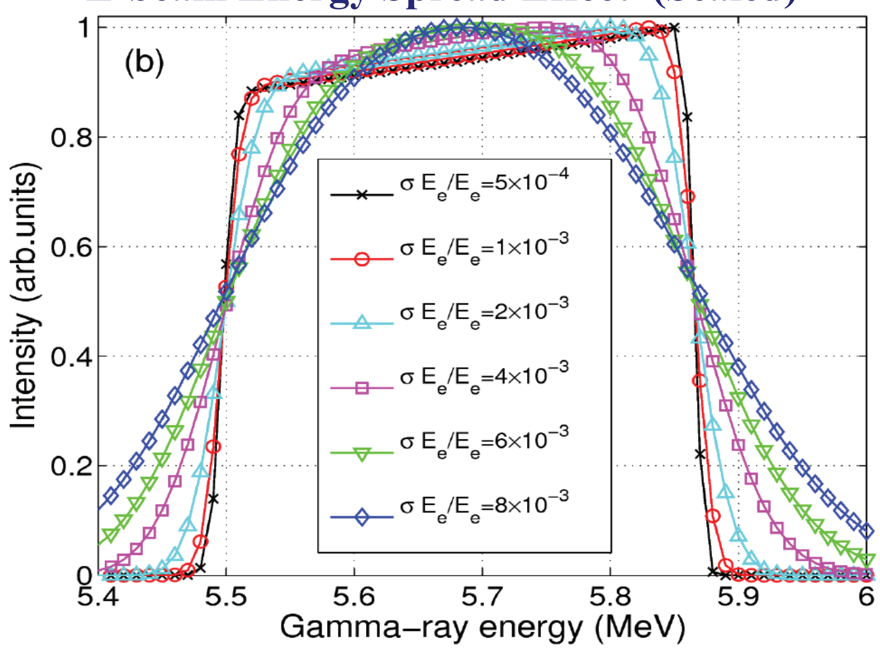
Monochromatic electron and photon beams



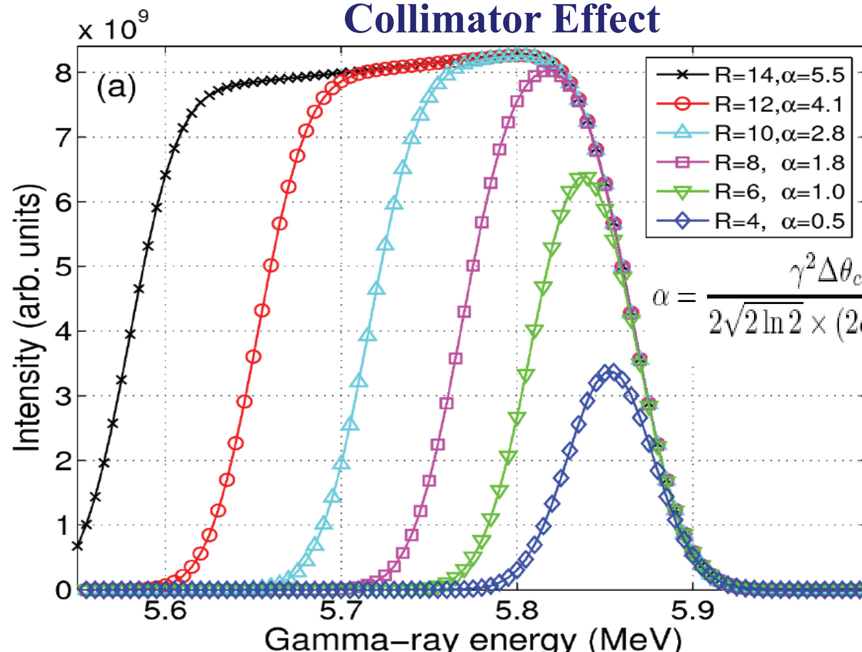
Emittance Effect (Scaled)



E-beam Energy Spread Effect (Scaled)



Collimator Effect



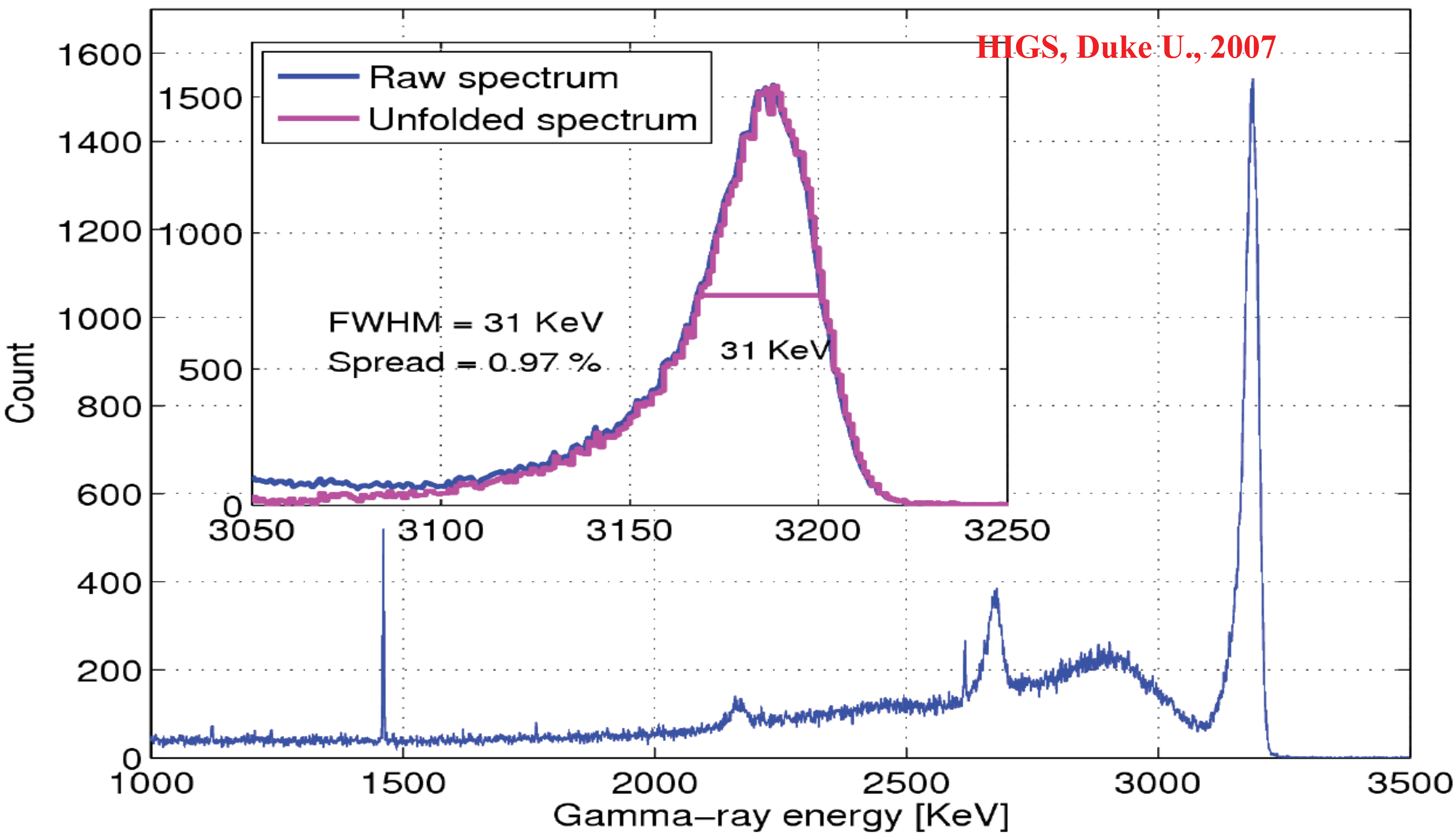
$$\alpha = \frac{\gamma^2 \Delta\theta_c^{\,2}}{2\sqrt{2\ln 2}\times(2\sigma_{E_e}/E_e)},$$

C. Sun *et al.* Phys. Rev. ST Accel. Beams 12, 062801 (2009).

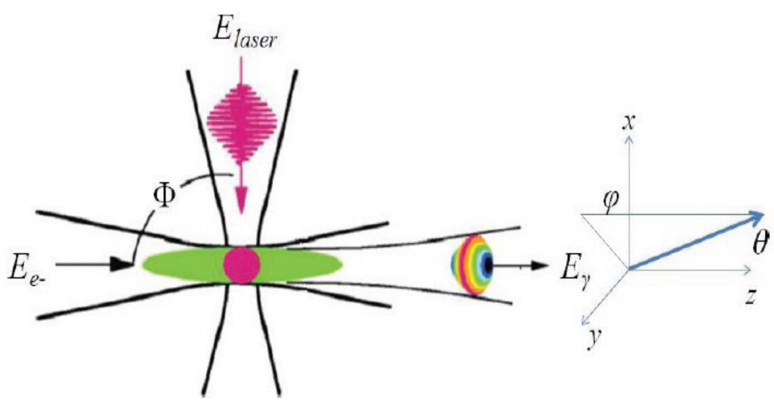
High Energy-Resolution

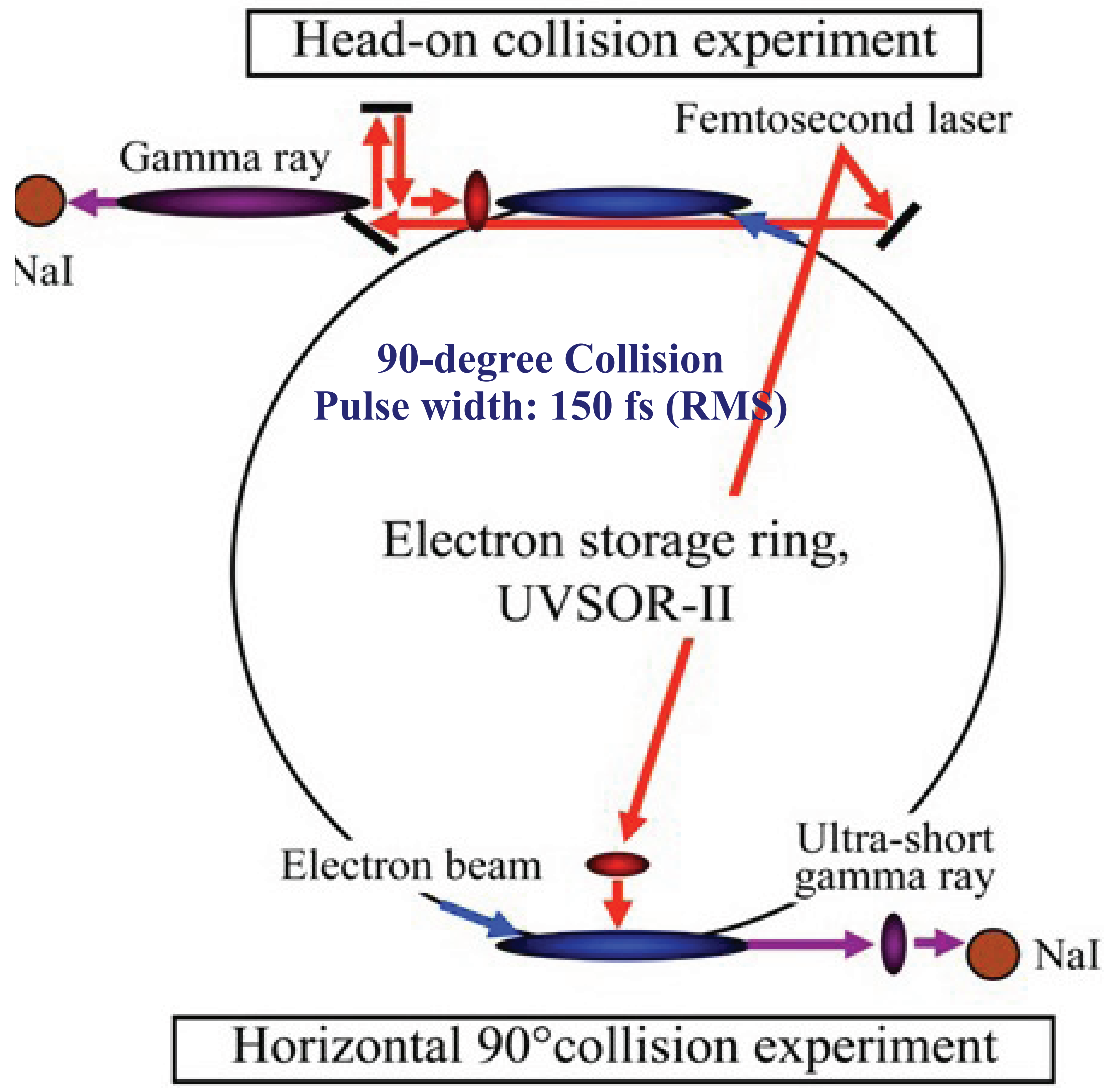
E-spread $\sigma/E \sim 5.7 \times 10^{-3}$ @ 3 MeV

356 MeV e–beam, Asymmetric bunch pattern #0 = 5 mA and #32 = 57 mA
738 nm OK4 lasing, 0.5" collimator, Run #55, 11–01–2007



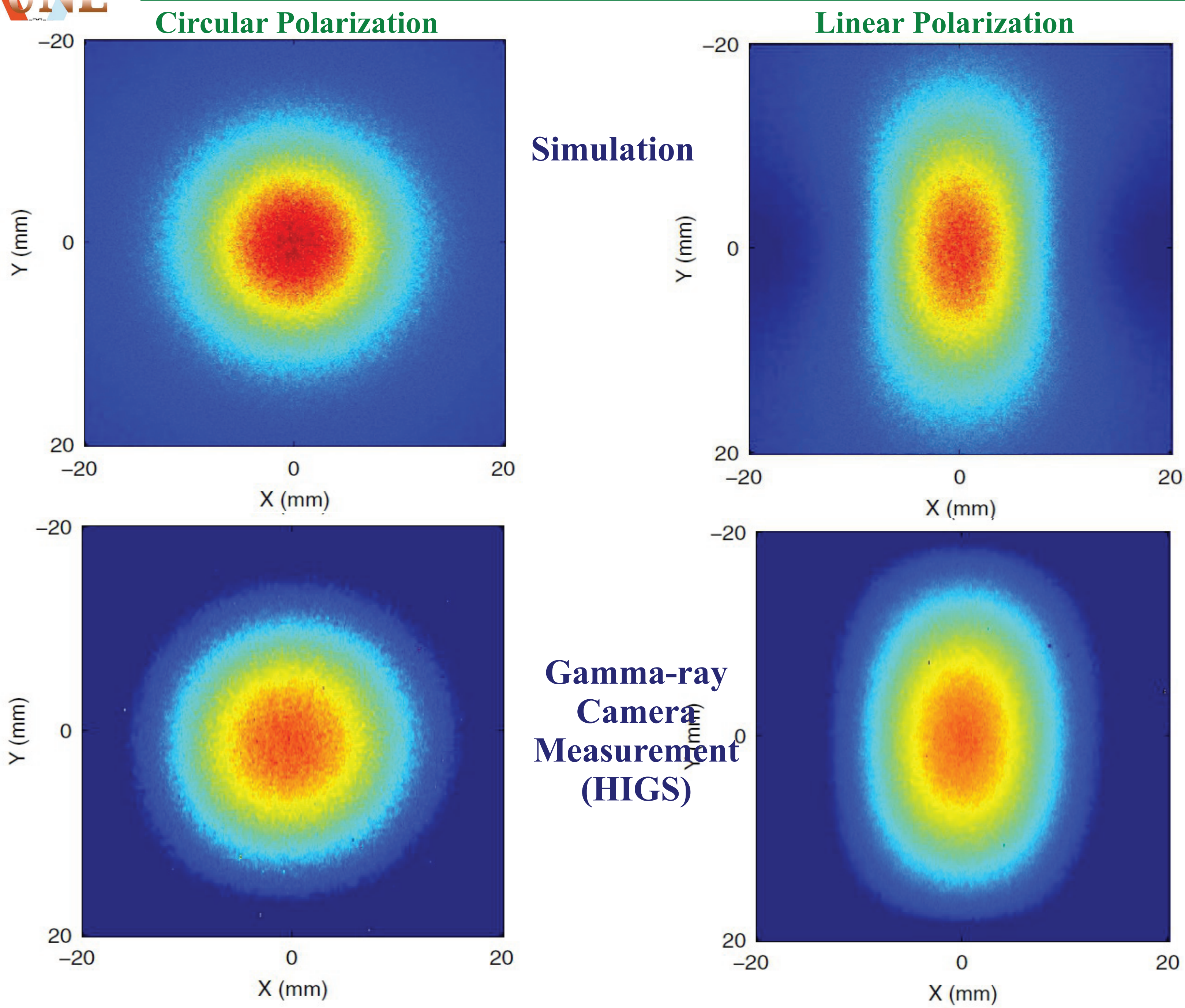
Pulse Duration





1. G. Kraff and G. Priebe, Rev. Acc. Sci. & Tech. V3, 147 (2010).
2. Y. Taira *et al.,* TUPD091, IPAC'10, Kyoto, Japan

Polarization Effect



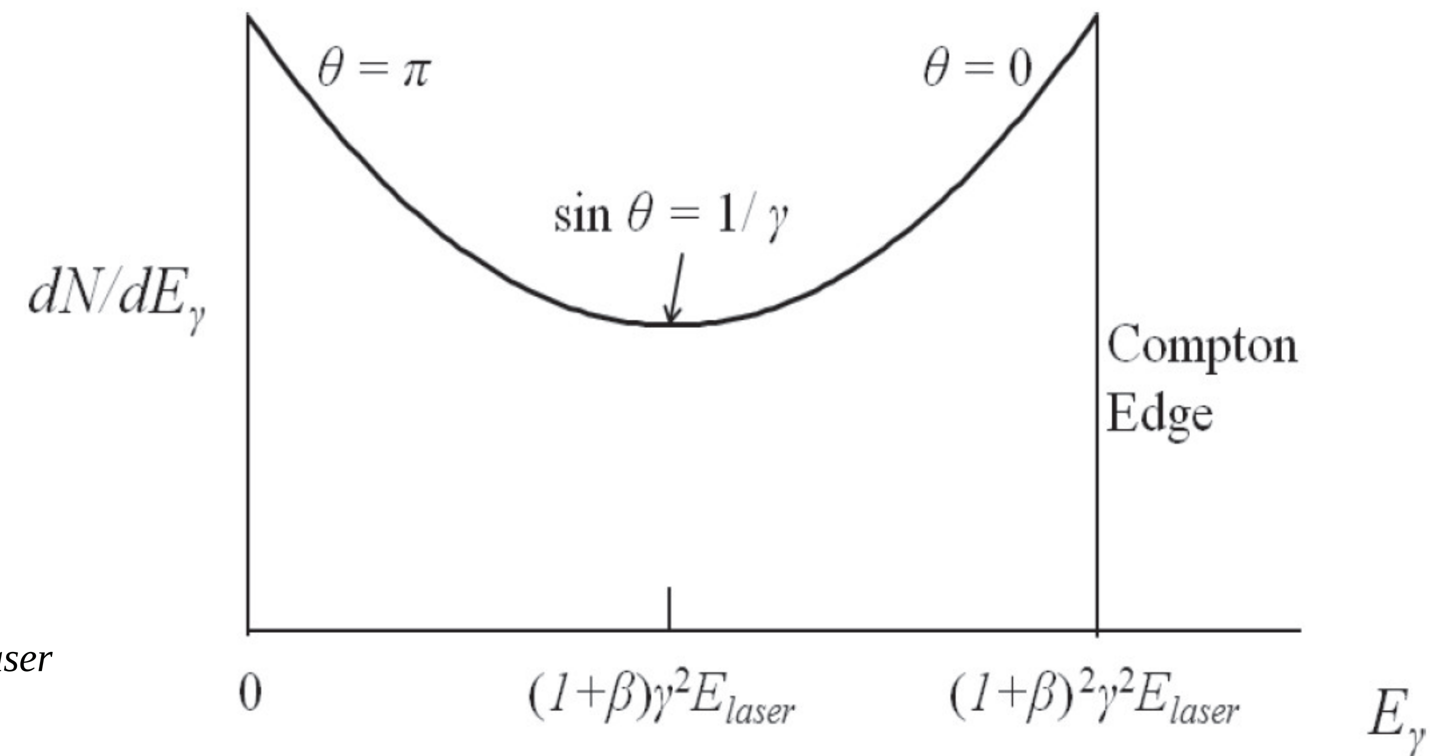
C. Sun and Y. K. Wu, Phys. Rev. ST Accel. Beams 14, 044701 (2011)

Compton Photon Beam Flux

Compton Photon Sources = Electron-Photon Colliders

$$d\sigma = 8\pi r_e^2 \frac{dy}{x^2}\left[\left(\frac{1}{x}-\frac{1}{y}\right)^2+\left(\frac{1}{x}-\frac{1}{y}\right)+\frac{1}{4}\left(\frac{x}{y}+\frac{y}{x}\right)\right]$$

$$x = \frac{2\gamma\hbar\omega(1-\beta\cos\theta_i)}{mc^2}, \qquad y = \frac{2\gamma\hbar\omega'(1-\beta\cos\theta_f)}{mc^2}$$



$$\frac{dN_\gamma}{dt} \sim \frac{\sigma}{A_{eff}} f N_e N_{laser}$$

Thomson cross-section:

$$\sigma_0 = 6.6524\times 10^{-29} m^2$$

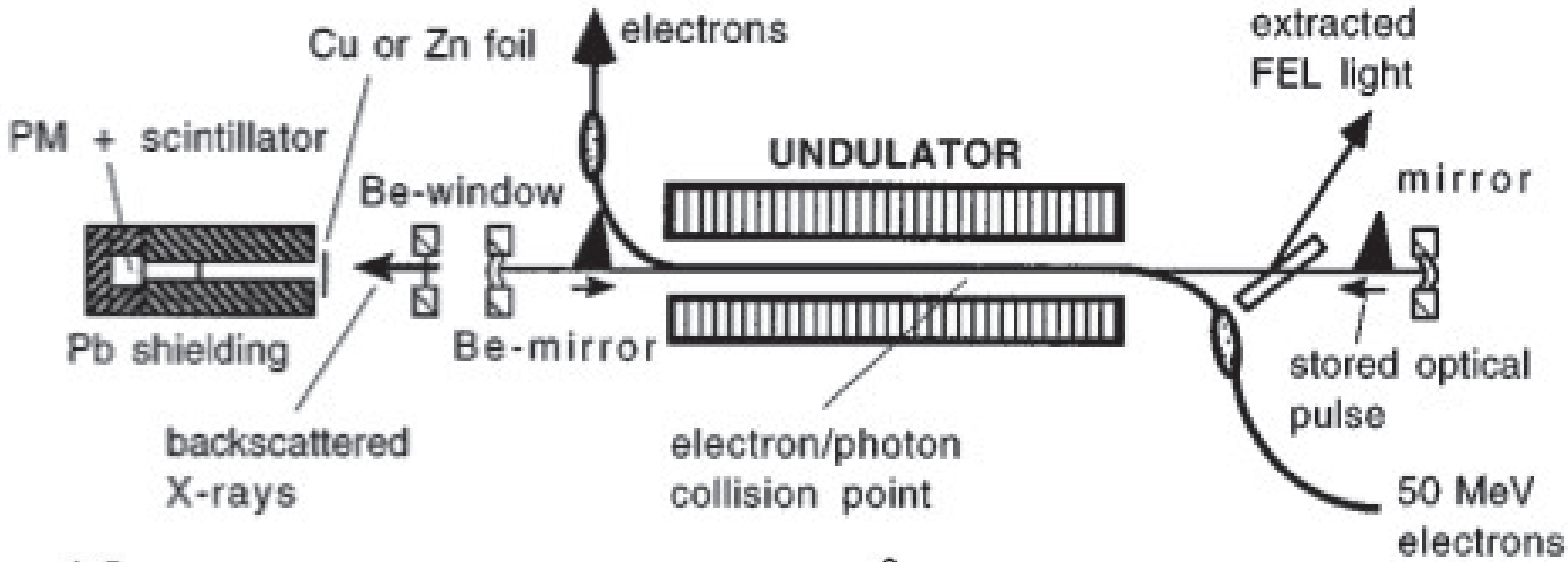
Figure: G. Kraff and G. Priebe, Rev. Acc. Sci. & Tech. V3, 147 (2010).

Compton Sources Powered by FEL Oscillators

FEL Oscillator Driven Compton Sources

Accelerator	FEL	Energy Range	Status
Linac	CLIO FEL, France	X-ray: 7 – 12 keV	No active research at present
Linac	Vanderbilt FEL, USA	X-ray: 14 – 18 keV	Shut Down
Linac (SRF)	JLab FEL, USA	X-ray: 3.5 – 18 keV	No active research at present
Storage Ring	UVSOR FEL, Japan	Gamma-ray: 14 – 25 MeV	No active research at present
Storage Ring	Duke FEL, USA	Gamma-ray: 1 – 100 MeV	Operational with User Program
Storage Ring	NIJI-VI FEL, Japan	Gamma-ray: 0.7 – 2.1 MeV	User program; Ready to resume operation
Storage Ring	Super- ACO FEL, France	Gamma-ray: ~35 MeV	Shut Down

CLIO FEL, France



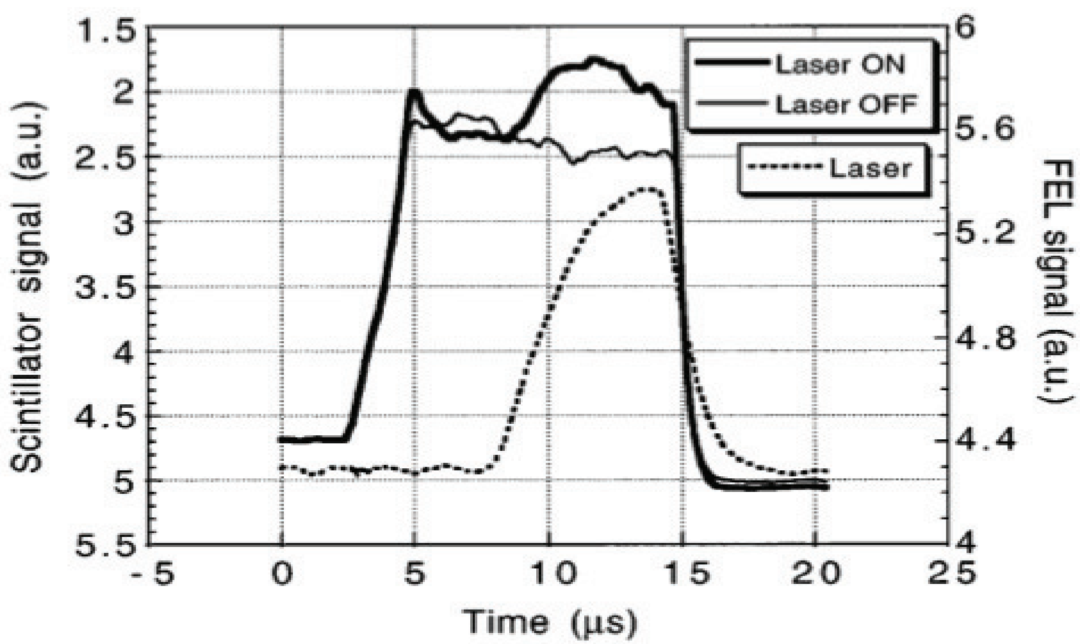


FIG. 2. X-ray detector signal with laser on and off. The background is due to lost electrons and has the time structure of the electron beam.

Energy: 14 – 18 keV
Flux: 5x10^{6} ph/s (2 mrad angle)

F. Glotin et al., PRL , v.77 n.15, p.3130 (1996).

FEL Center, Vanderbilt University

Project: Vanderbilt FEL Center
Institution: FEL Center, Vanderbilt University
Country: US
Energy: 14 – 18 keV
Accelerator: S-Band Linac
Initial work (1998 – 1999):

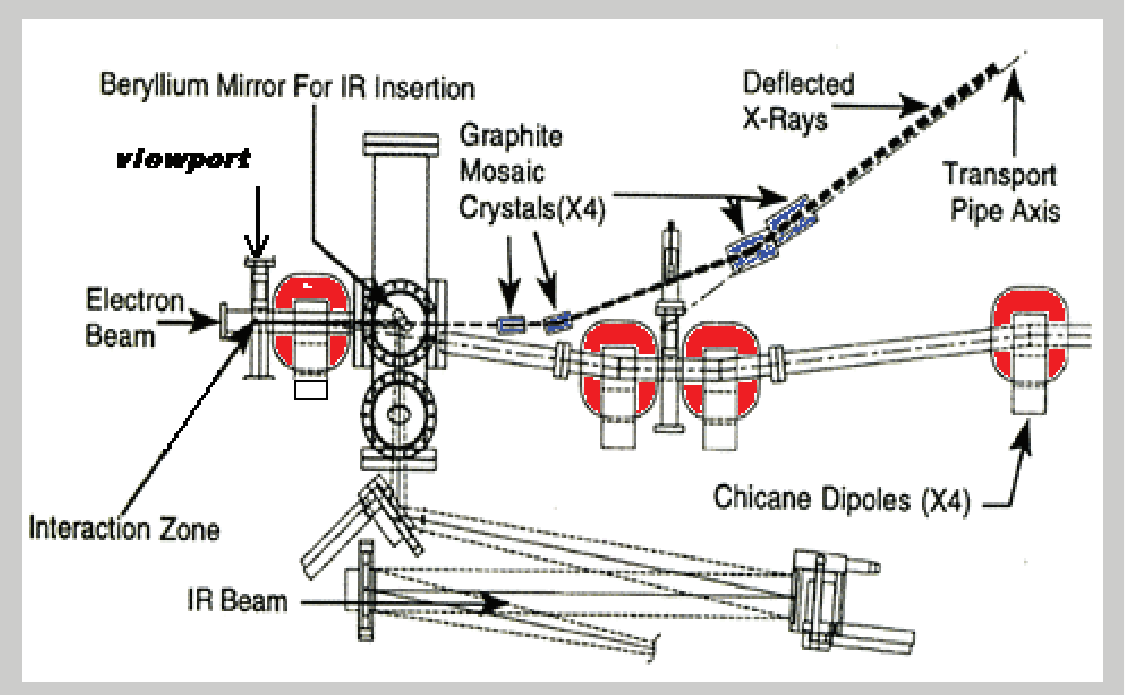
- **X-ray: 14.5 keV**
- **E-beam: 43 MeV**
- **Laser: FEL, 2.4 μm**
- **Flux: ~ 4×10^4 ph/s (exit window)**
- **Pol: linear**

Status;

- **1st light: Dec. 1998**
- **Current Status: shut down**

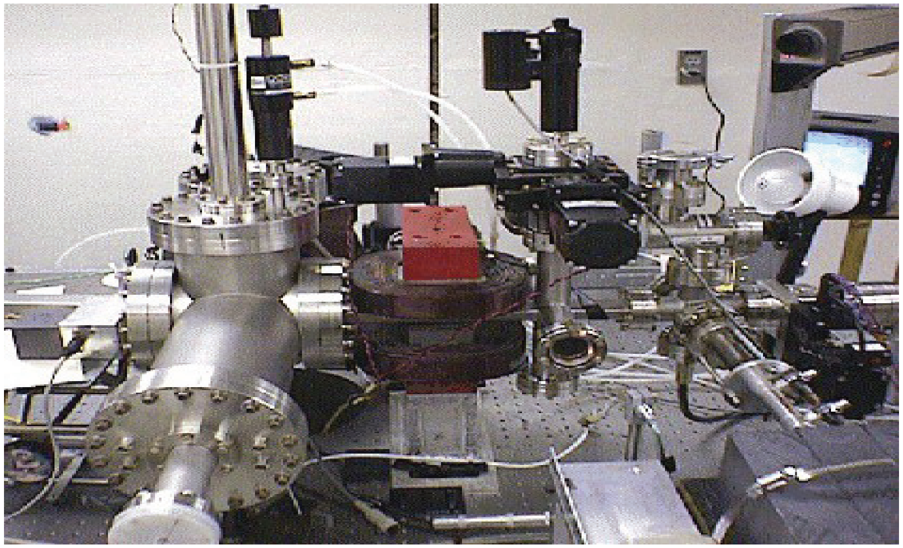
F. E. Carroll *et al*. SPIE Vol.3614, p. 139 – 146 (1999).

Pulsed, tunable, monochromatic X-rays



While it worked, it wasn't very Practical !

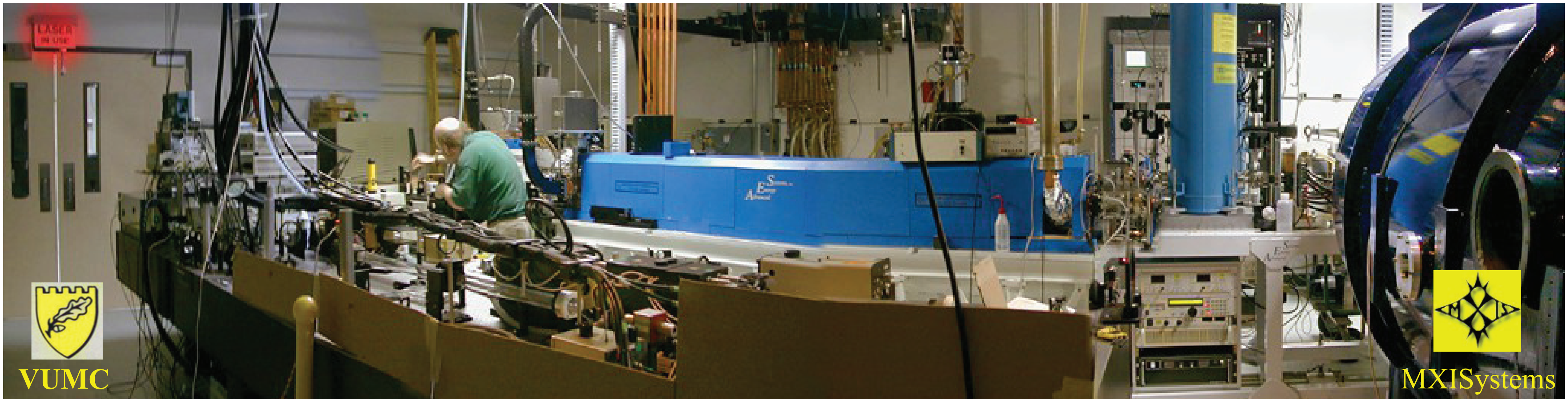
- **Few X-rays per pulse = long exposure times**
- **X-rays had to be deflected for use = low flux**
- **FEL performance fell as X-rays optimized = low flux**
- **Radiation environment high = need radiation vault**
- **Very large device = cumbersome and costly**



Courtesy of Frank E. Carroll, Vanderbilt Univ., US

Linac FEL Driven Compton Source

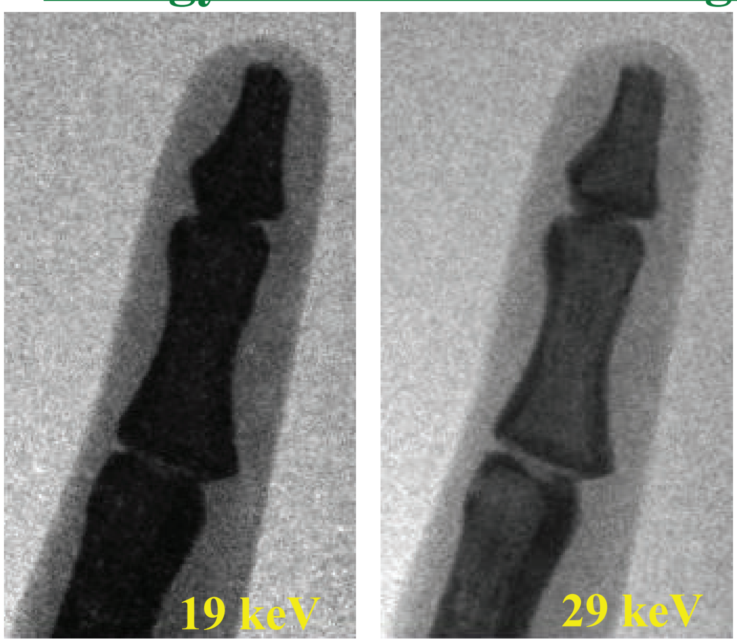
FEL Lab, Vanderbilt University



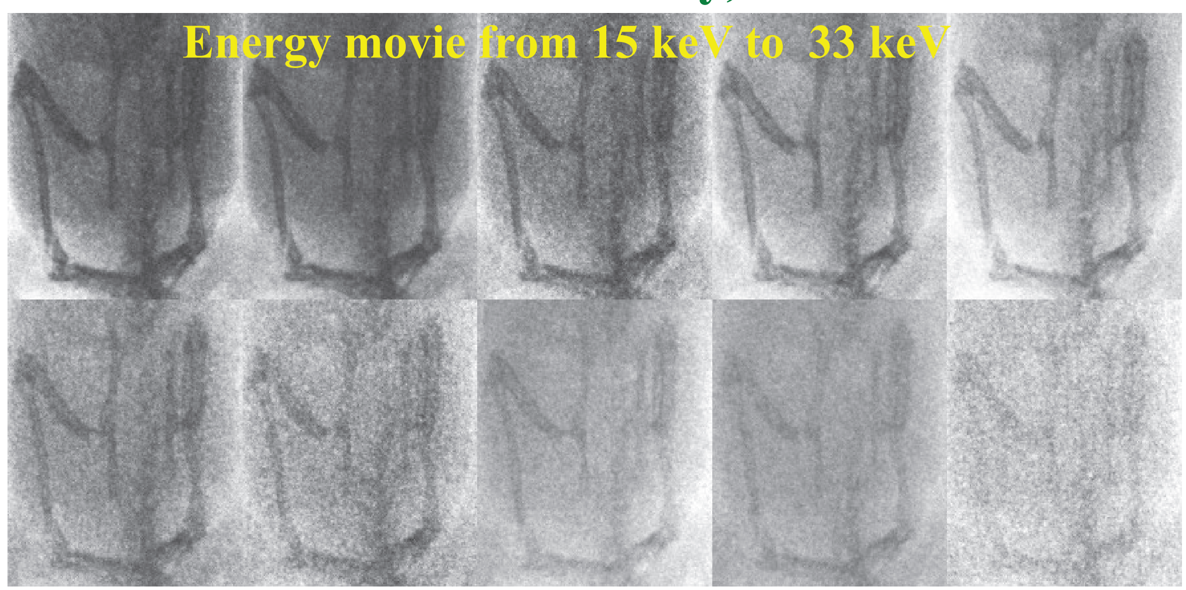
With a new laser, 1st X-rays produced April 2001. Typical performance:
10 – 50 keV, up to 10^{10} ph in an 8-psec pulse, few to 20 Hz (new design);
Laser: 1,052 nm, Nd glass amplifier seeded by a 200 fs Ti:Sapphire laser

Applications:
- **K-edge Imaging,**
- **Phase Contrast Imaging,**
- **Auger Cascade Radiotherapy**

Energy differences in a finger



or in a body, such as a mouse



•* F. E. Carroll *et al*. American Journal ofRoentgenology, 181, p.1197-1202 (2003).

Courtesy of Frank E. Carroll, Vanderbilt Univ., US

JLab FEL

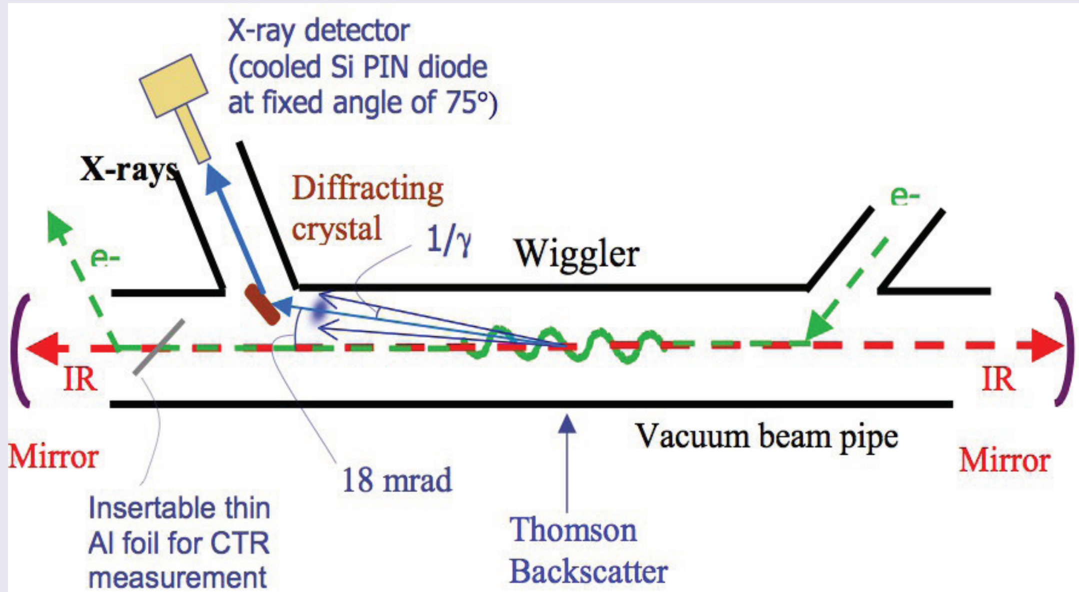
Project: JLab FEL
Institution: Jefferson Lab
Country: US
Energy: 3.5 – 18 keV
Accelerator: S-Band Linac (28 – 48 MeV)
Typical x-ray setup:

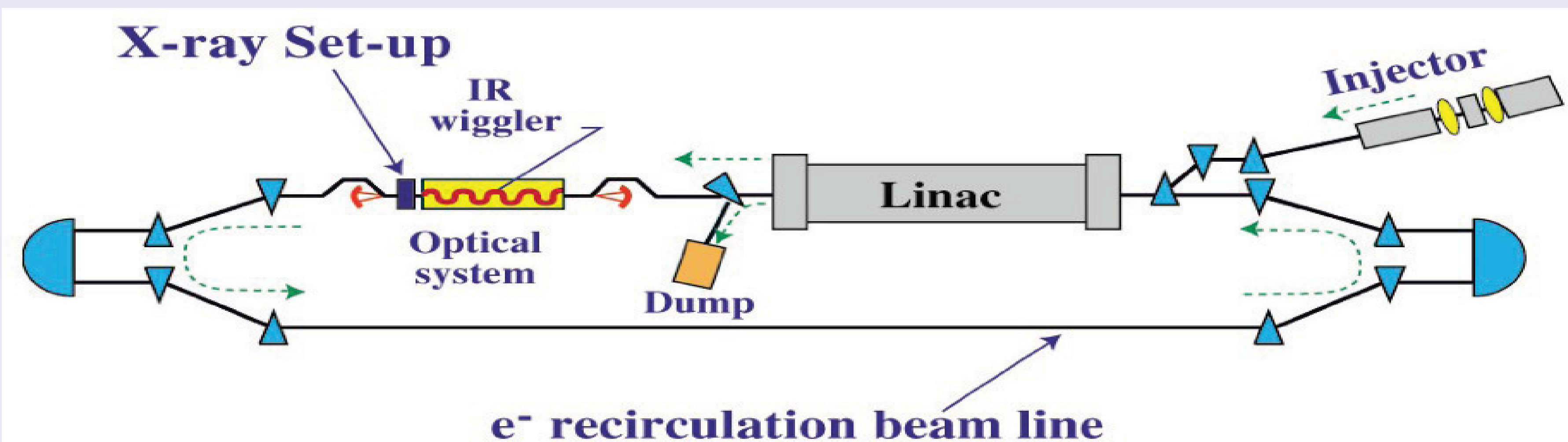
- **X-ray: 5.12 keV, 37.5 MHz**
- **E-beam: 36.7 MeV**
- **Laser: FEL, 5.18 µm**
- **Total Flux: ~ >2x10^9 ph/s**
- **Peak brightness: 10^{10} ph/(s mm^2 mr^2 0.1% BW)**
- **Pol: linear**

Status:

- **1st light: Sep. 1999;**
- **Current Status (2014): No research activity**

High Reprate Compton X-ray Source Powered by Superconducting RF Driven FEL (37.5 MHz)



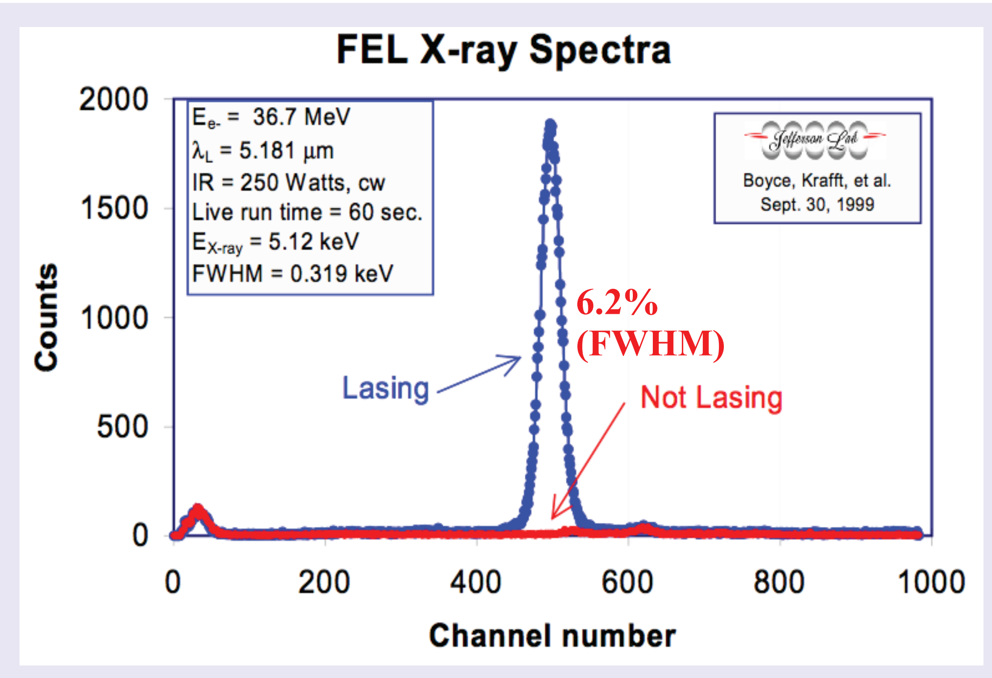


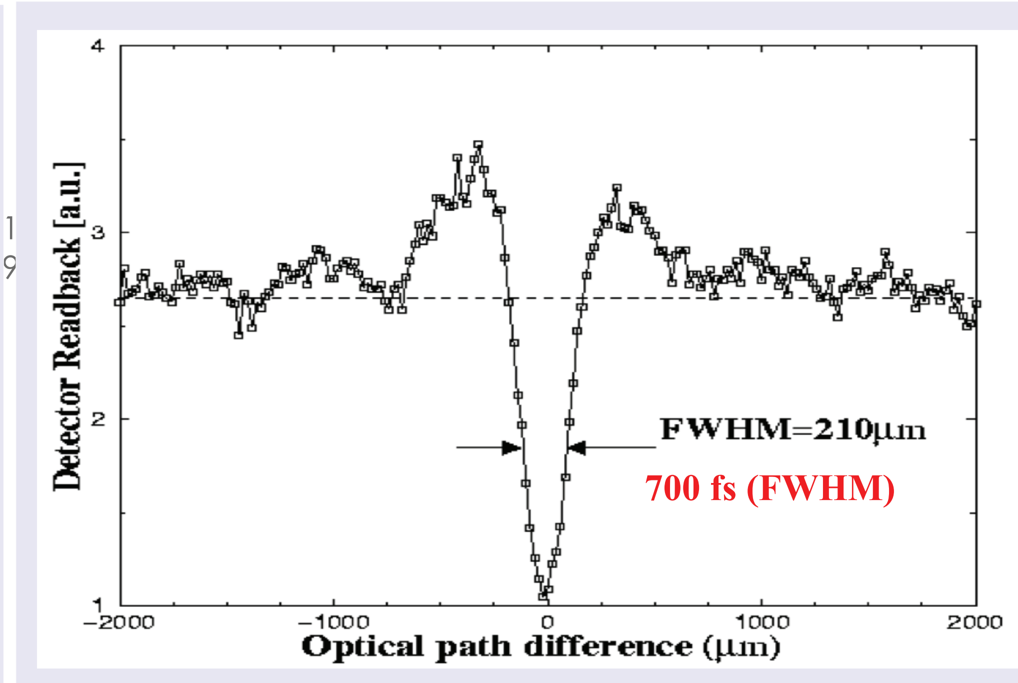
1. G. A. Krafft , G. Priebe, Reviews of Accelerator Science and Technology Vol. 3 (2010) 147–163.
2. R. Boyce *et al.*, The Jeffersåon Lab Sub-picosecond X-ray Program, in Proc. 17th Int. Conf. Applications of Accelerators in Research and Industry (2002), pp. 325–328.
3. R. Boyce *et al.*, High Flux Femtosecond X-rays Simultaneous with FEL Infrared Pulses (*unpublished*).

Courtesy of Stephen Benson, JLab, US

JLab FEL

Highly time-correlated IR and x-ray pulses with sub-ps time duration





Potential Applications

- Study dynamical processes in physics, chemistry and biology;
- Pump-probe using sub-picosecond IR pulses and ultra-fast synchronous x-rays;

JLab Team: J. R. Boyce, G. A. Krafft, U. Happek, S. V. Benson, C. L. Bohn, D. R. Douglas, H. F. Dylla, J. F. Gubeli, K. Jordan, L. Merminga, G. R. Neil, P. Piot, M. D. Shinn

Courtesy of Stephen Benson, JLab, US

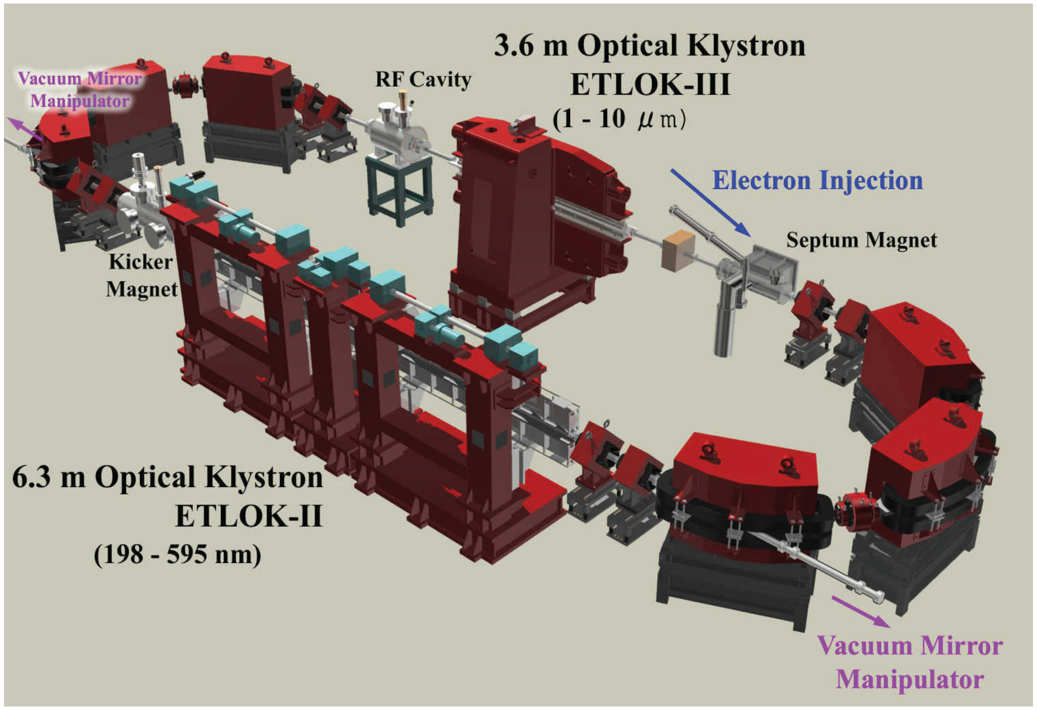
NIJI-IV, AIST, Japan

Project: FEL–X*
Institution: AIST
Country: Japan
Energy: 0.7 – 2.1 MeV
Accelerator: Storage ring, 310 MeV
Laser: FEL, 0.9 – 2.7 µm
Total flux: < 2 × 10^6 ph/s
Pol: linear
Status:

- **Current Status: Dormant**

User program: Nuclear Physics

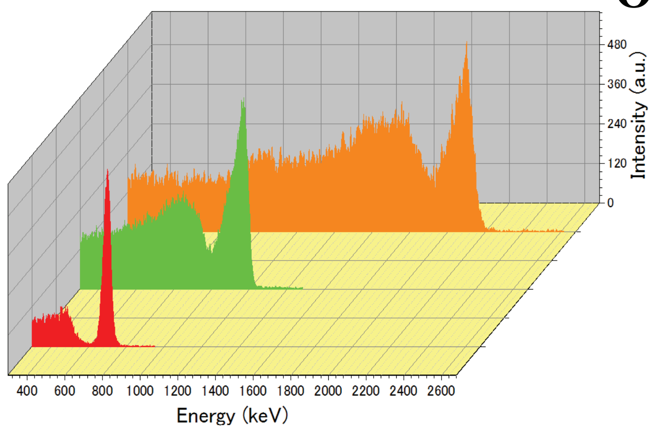
* T. Yamazaki et al. NIM B, **144** (1998) 83.

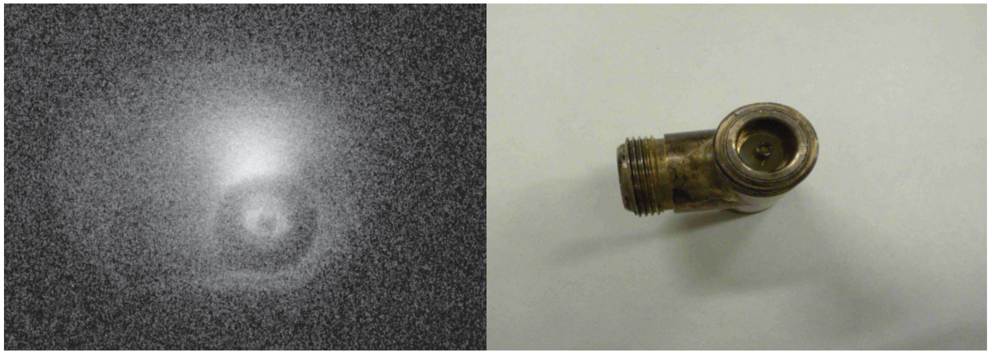


Research Object

- generation of low-energy LCS X-ray with using storage ring (< 1 MeV)
- Demonstration of Compton backscattering with multi FEL pulses to enhance the yield of the X-ray beam

Observation of Compton X-ray beam





Slide by courtesy of Norihiro Sei, AIST, Japan

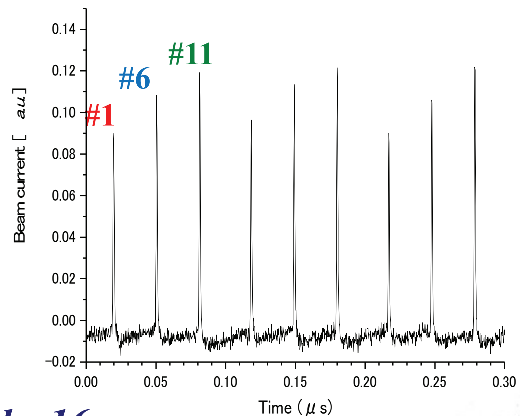
NIJI-IV, AIST, Japan

Enhancement of X-ray yield by increasing the FEL pulses

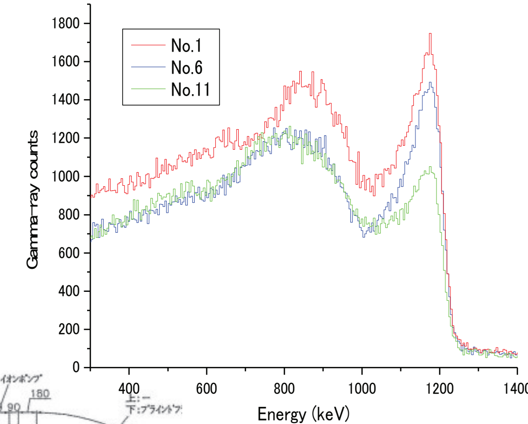
Number of FEL pulses	Collision points per revolution	Maximum collision points without magnetic filed	Yield of X-ray beam (a.u.)
1	–	–	–
2	2	2	1
3	6	5	2.5

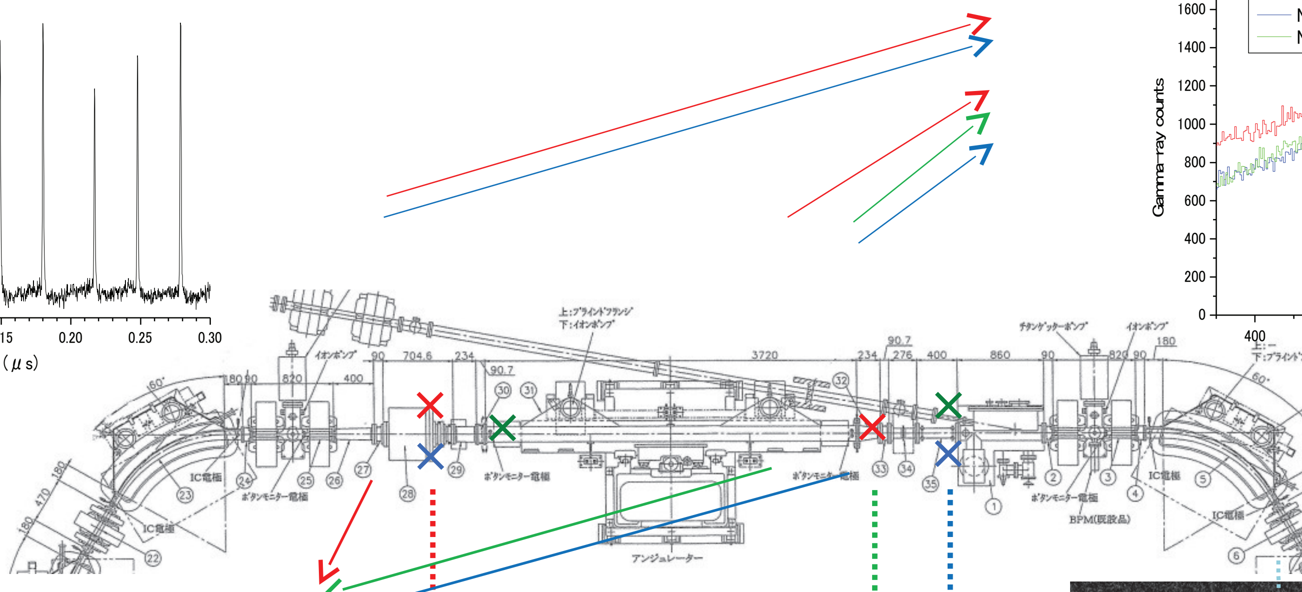
1.5 times

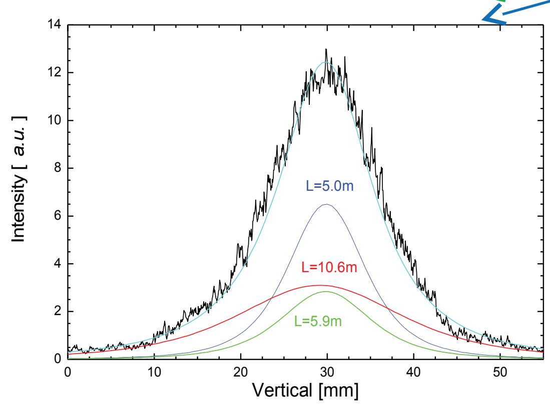
2.5 times

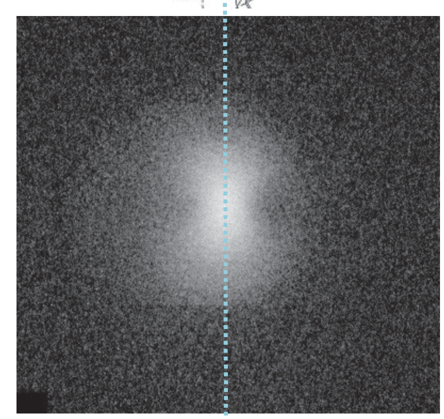


h=16







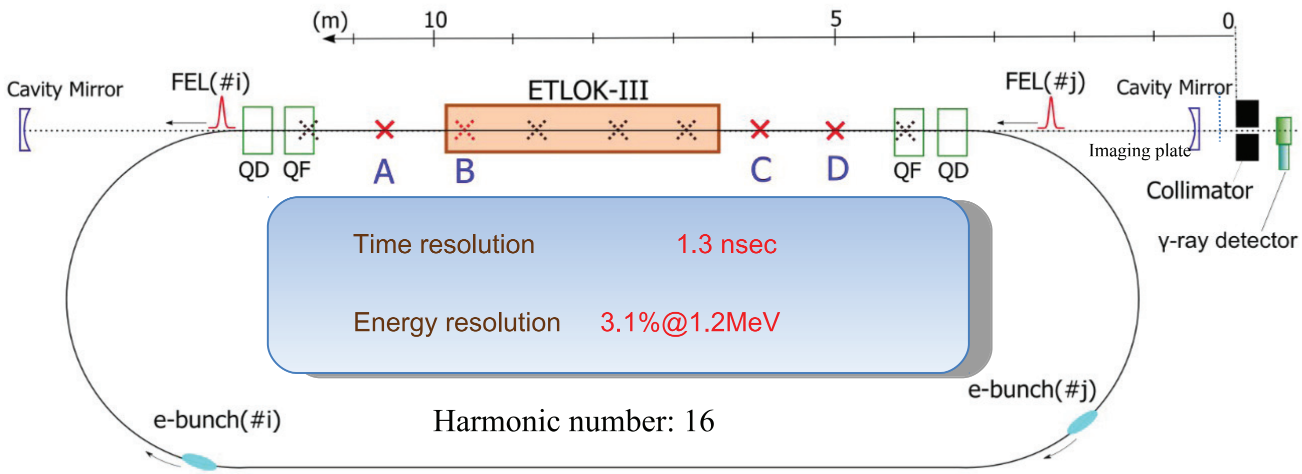


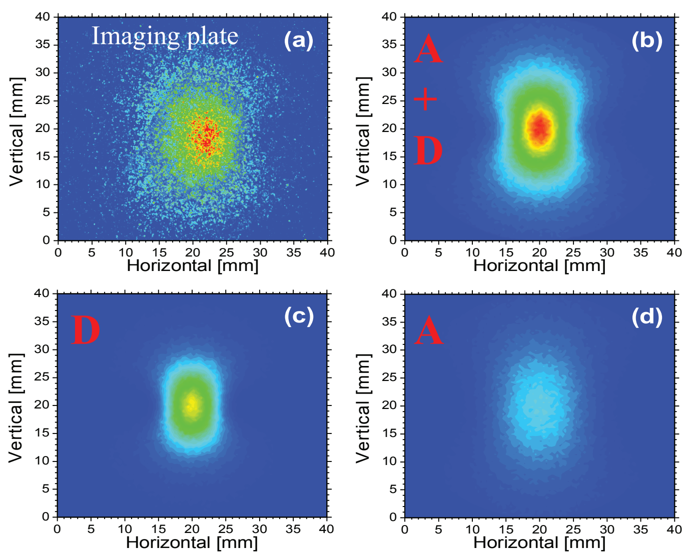
Slide by courtesy of Norihiro Sei, AIST, Japan

NIJI-IV, AIST, Japan

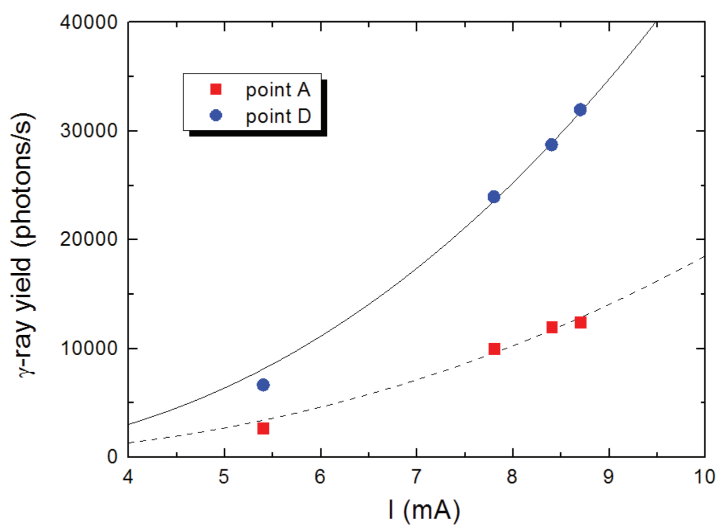
Relationship between the collision point and X-ray beam

In asymmetric two-bunch operation, we can select the collision point by changing the filling pattern of the electron bunches.





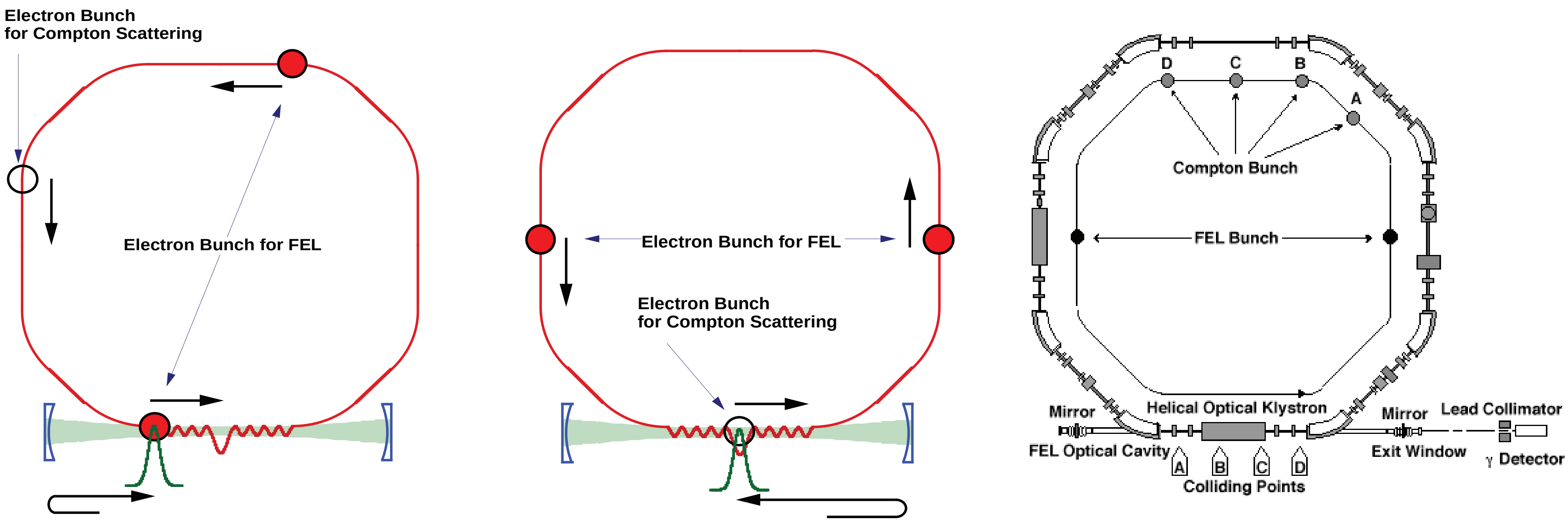
N. Sei et al., Opt. Lett. **36** (2011) 3645.

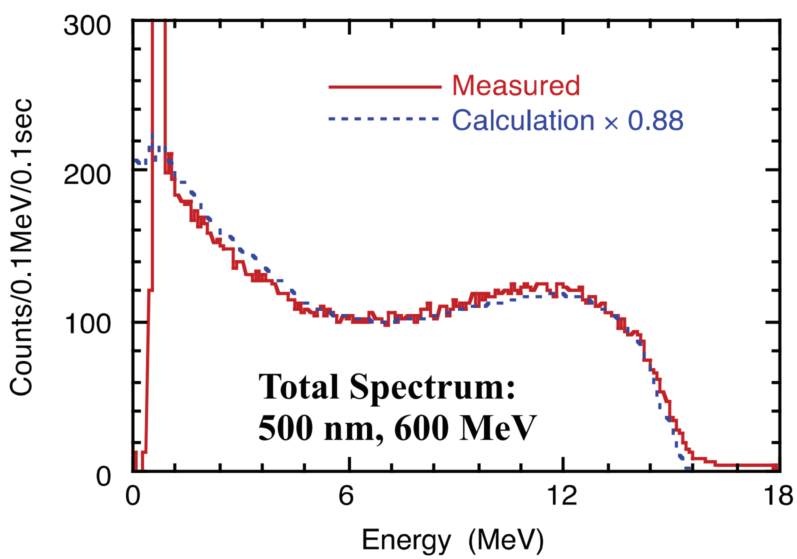


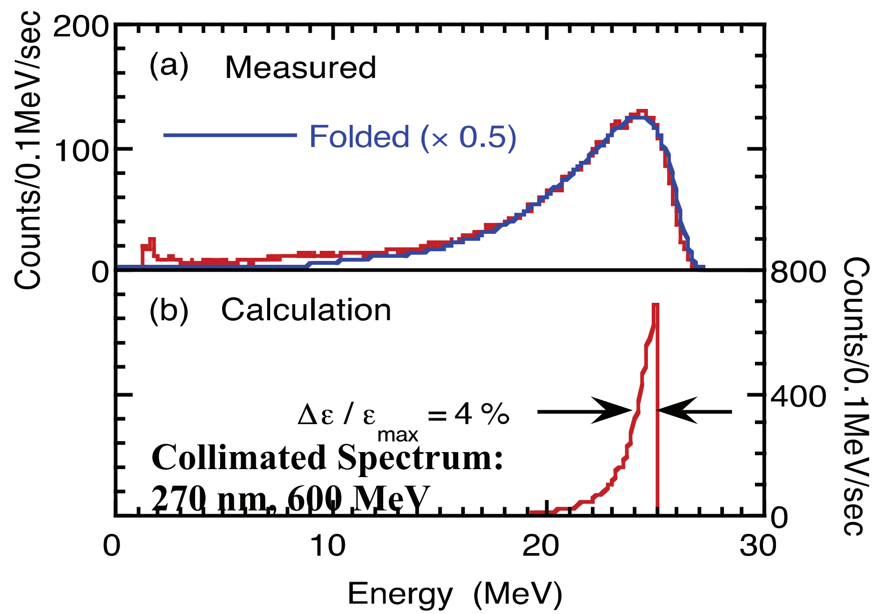
H. Ogawa et al., Phys. Lett. A, **376** (2012) 1171.

Slide by courtesy of Norihiro Sei, AIST, Japan

UVSOR FEL, Japan



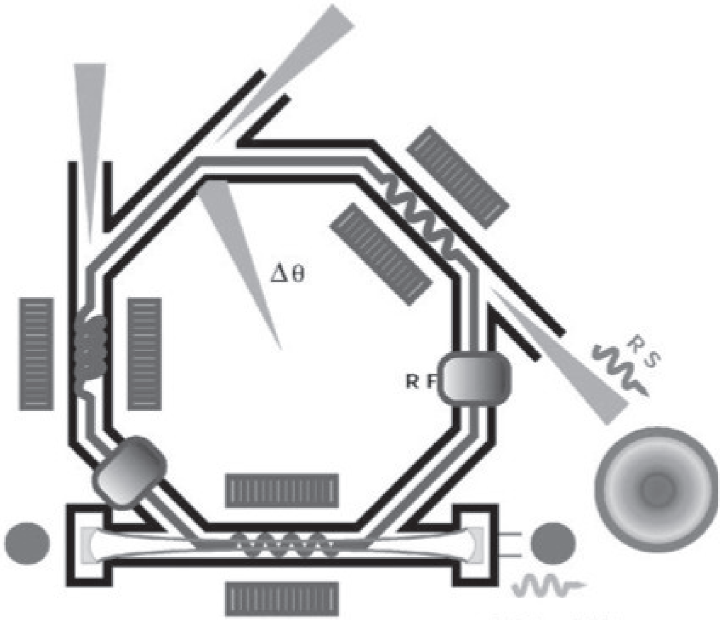


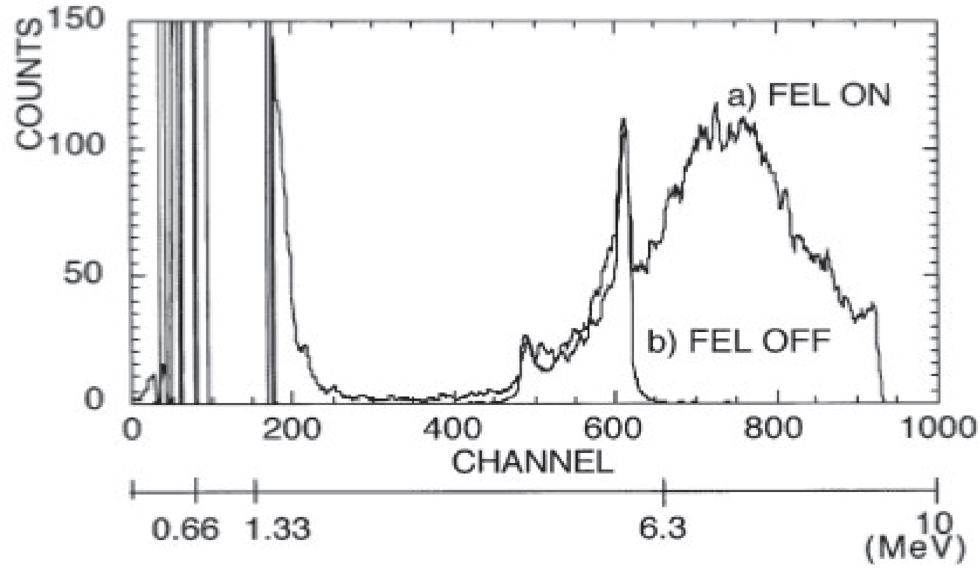


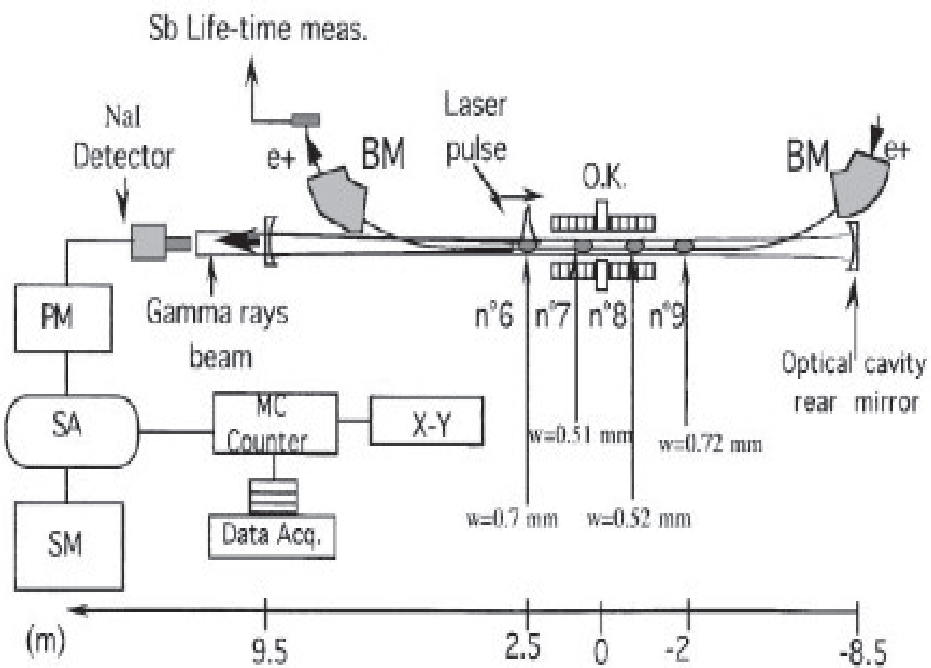
Hosaka et al., NIM-A 393, p.525 (1997)

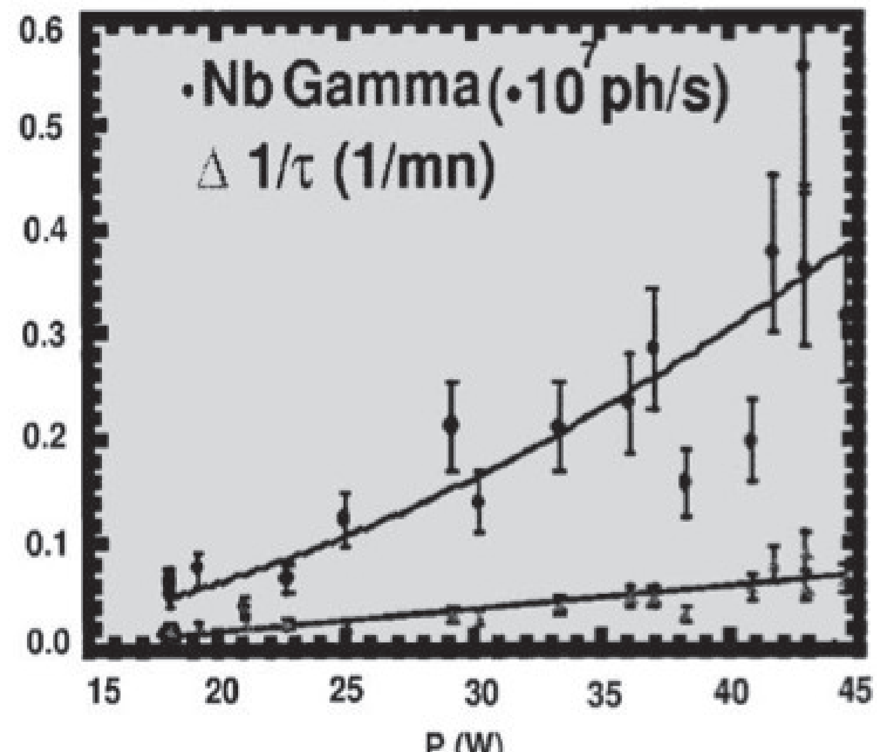
Courtesy of Hiroyuki Hama, Tohoku, Japan

Super-ACO FEL, France







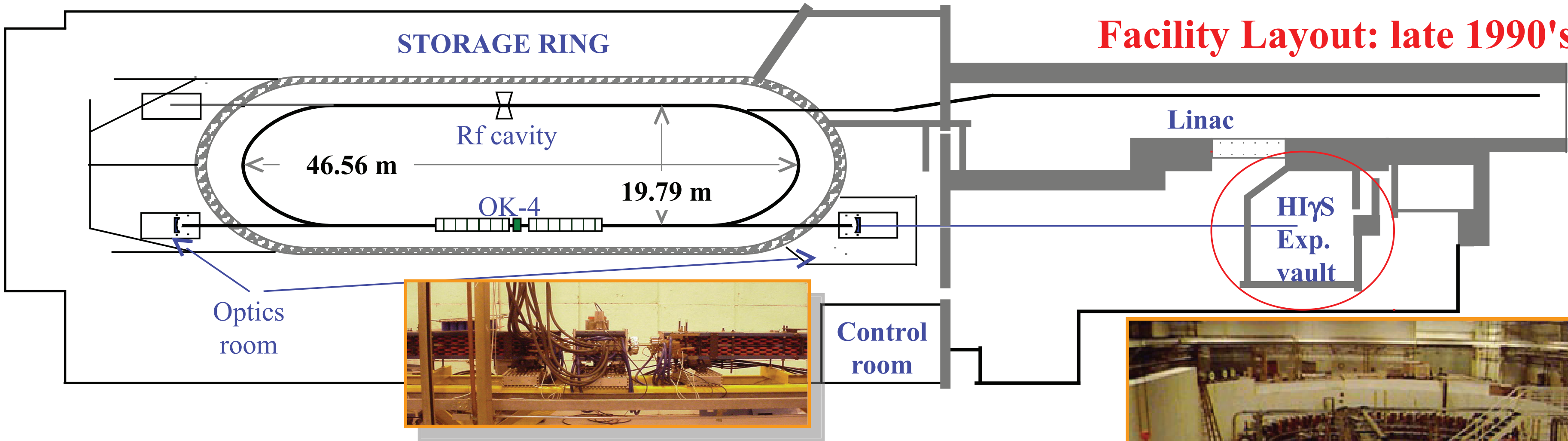


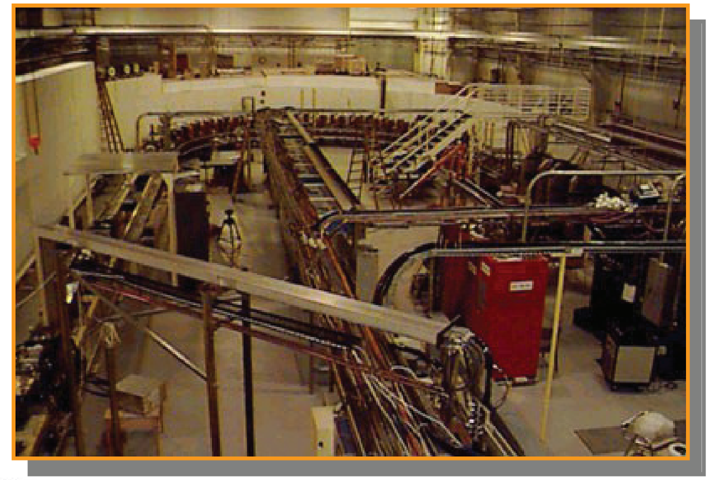
Num. Of gamma-rays (>14 MeV) and inverse of lifetime of the small bunches vs intra-cavity powers

D. Nutarelli et al., NIM-A 407, p.459 (1998).
G. De Ninno, Rad. Phys. and Chem. 61, p.351 (2001)

High Intensity Gamma-ray Source (HIGS) at Duke University

HIGS, Duke FEL Laboratory, US in 1990s





VOLUME 78, NUMBER 24 PHYSICAL REVIEW LETTERS 16 JUNE 1997

Gamma-Ray Production in a Storage Ring Free-Electron Laser

V.N. Litvinenko, B. Burnham, M. Emamian, N. Hower, J.M.J. Madey, P. Morcombe, P.G. O'Shea, S.H. Park, R. Sachtschale, K.D. Straub, G. Swift, P. Wang, and Y. Wu

Free Electron Laser Laboratory, Department of Physics, Duke University, Durham, North Carolina 27708

R.S. Canon, C.R. Howell, N.R. Roberson, E.C. Schreiber, M. Spraker, W. Tornow, and H.R. Weller

Department of Physics, Duke University, and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708

I.V. Pinayev, N.G. Gavrilov, M.G. Fedotov, G.N. Kulipanov, G.Y. Kurkin, S.F. Mikhailov, V.M. Popik, A.N. Skrinsky, and N.A. Vinokurov

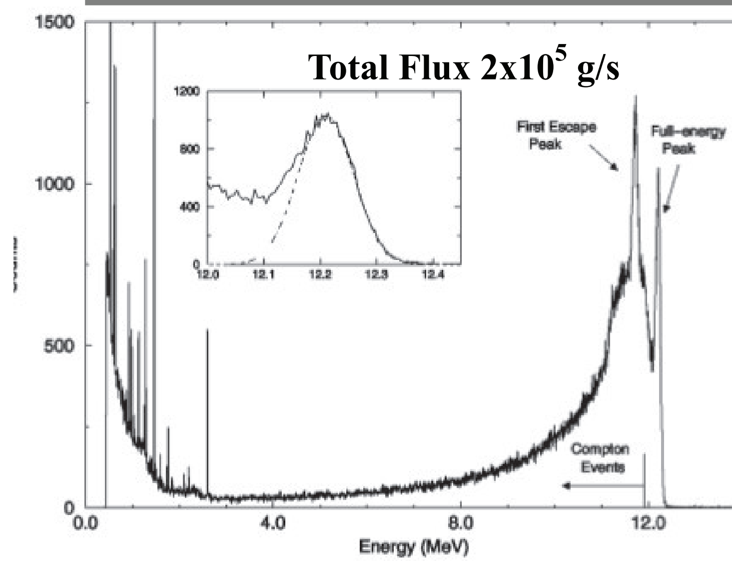
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

B.E. Norum

University of Virginia, Charlottesville, Virginia 22901

A. Lumpkin and B. Yang

APS, Argonne National Laboratory, Argonne, Illinois 60439



Courtesy of S.H. Park and V.N. Litvinenko

Development of HIGS

History of HIGS

- 1993, HIGS first proposed
- Nov. 1994, Duke Storage Ring Commissioning
- Nov. 1996, Duke FEL 1st Lasing, and 1st gamma-rays at HIGS;

  V.N. Litvinenko, et al. PRL v. 78, n. 24, p.4569 (1997).
- 1997 – starting gamma-ray user experiments
- 2000 – 2007, Accelerator upgrades
  - Storage ring lattice upgrade: new straight sections
  - New top-off booster injector
  - OK-5 helical FELs
- 2012, a new FEL wiggler switchyard system
- 2008 – present, Acc. Facility of Triangle Universities Nuclear Laboratory (TUNL), User-mode Operation for Nuclear Physics Research

HIGS Project leaders:
V. N. Litvinenko (inception – 2003)
Y. K. Wu (2003 – present)

Accelerator/FEL Upgrades ===> New and Improved Capabilities

- Before Upgrades: Energy 0.7 – 58 MeV; Total Flux 10^5 – 5x 10^8 g/s; Pol. Linear only;
- After Upgrades: Energy 1 – 100 MeV; Total Flux 10^8 – 3x10^{10} g/s; Pol. Linear and Circular

HIGS, Duke University, US

Facility/Project: HIGS

Institution: TUNL and Duke University

Country: US

Energy (MeV): 1 – 100

Accelerator: Storage Ring, 0.24 – 1.2 GeV

Laser: FEL, 1060 – 190 nm (1.17 – 6.53 eV)

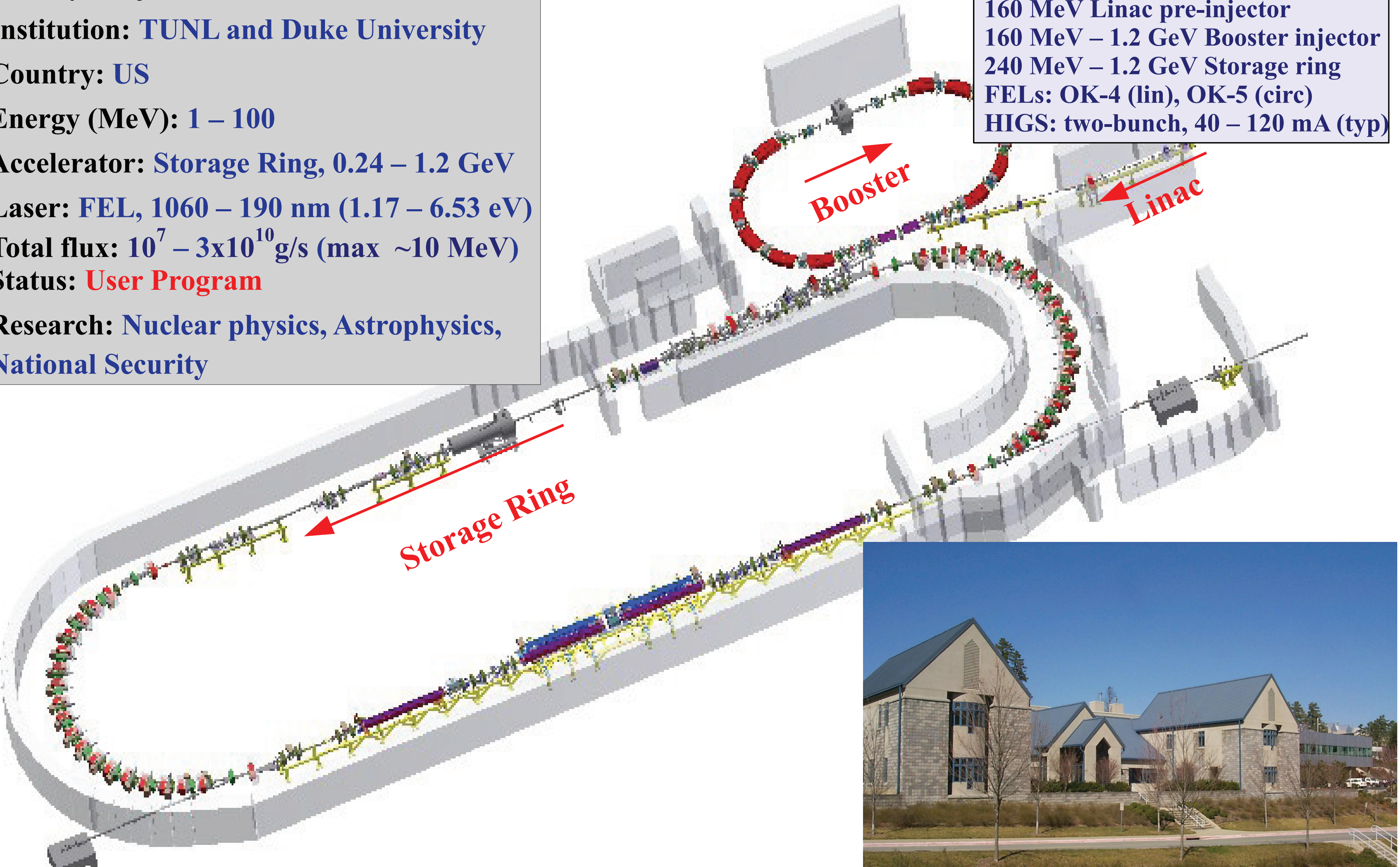
Total flux: 10^7 – 3×10^{10} g/s (max ~10 MeV)

Status: User Program

Research: Nuclear physics, Astrophysics, National Security

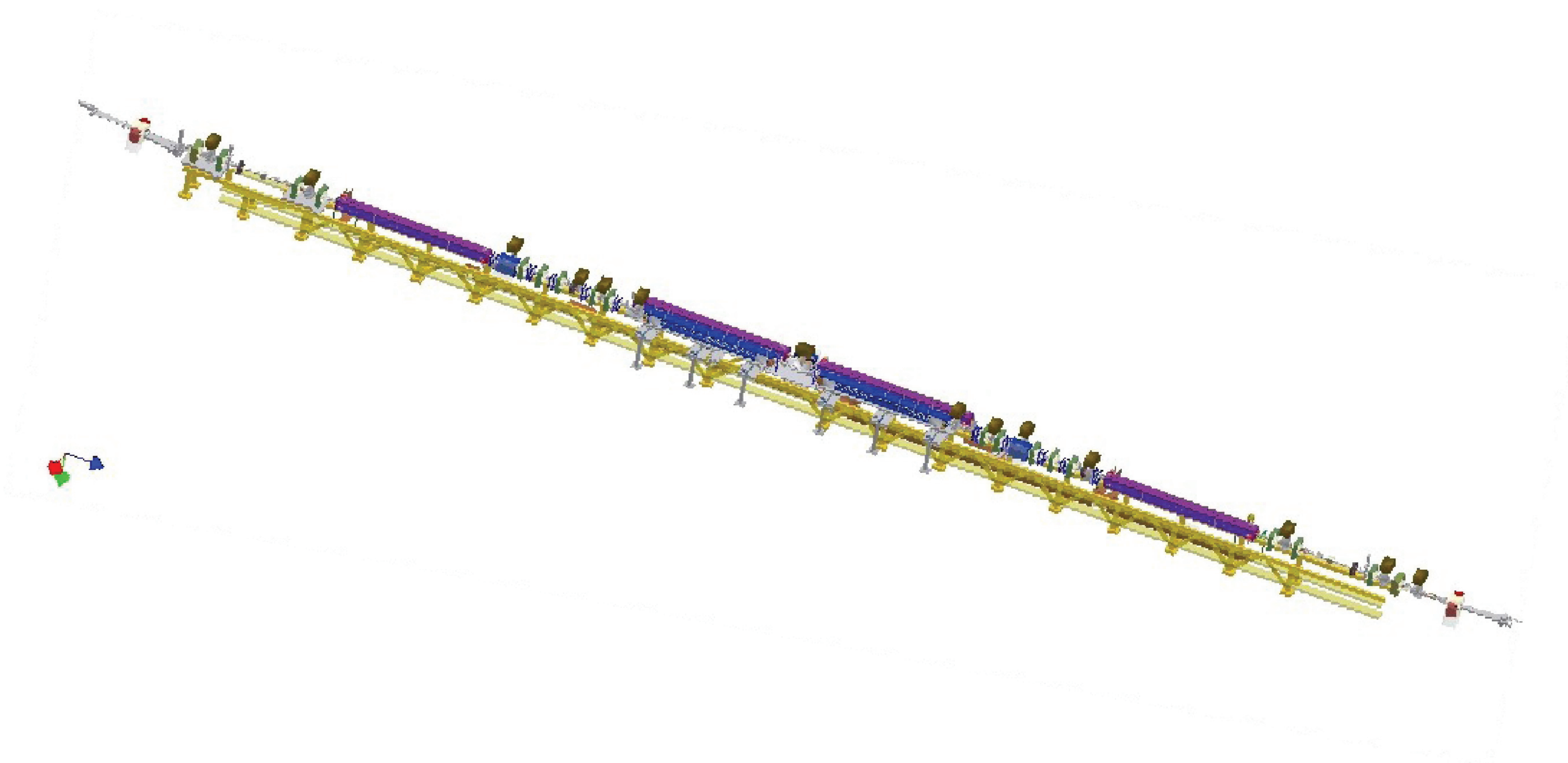
Accelerator Facility

- 160 MeV Linac pre-injector
- 160 MeV – 1.2 GeV Booster injector
- 240 MeV – 1.2 GeV Storage ring
- FELs: OK-4 (lin), OK-5 (circ)
- HIGS: two-bunch, 40 – 120 mA (typ)

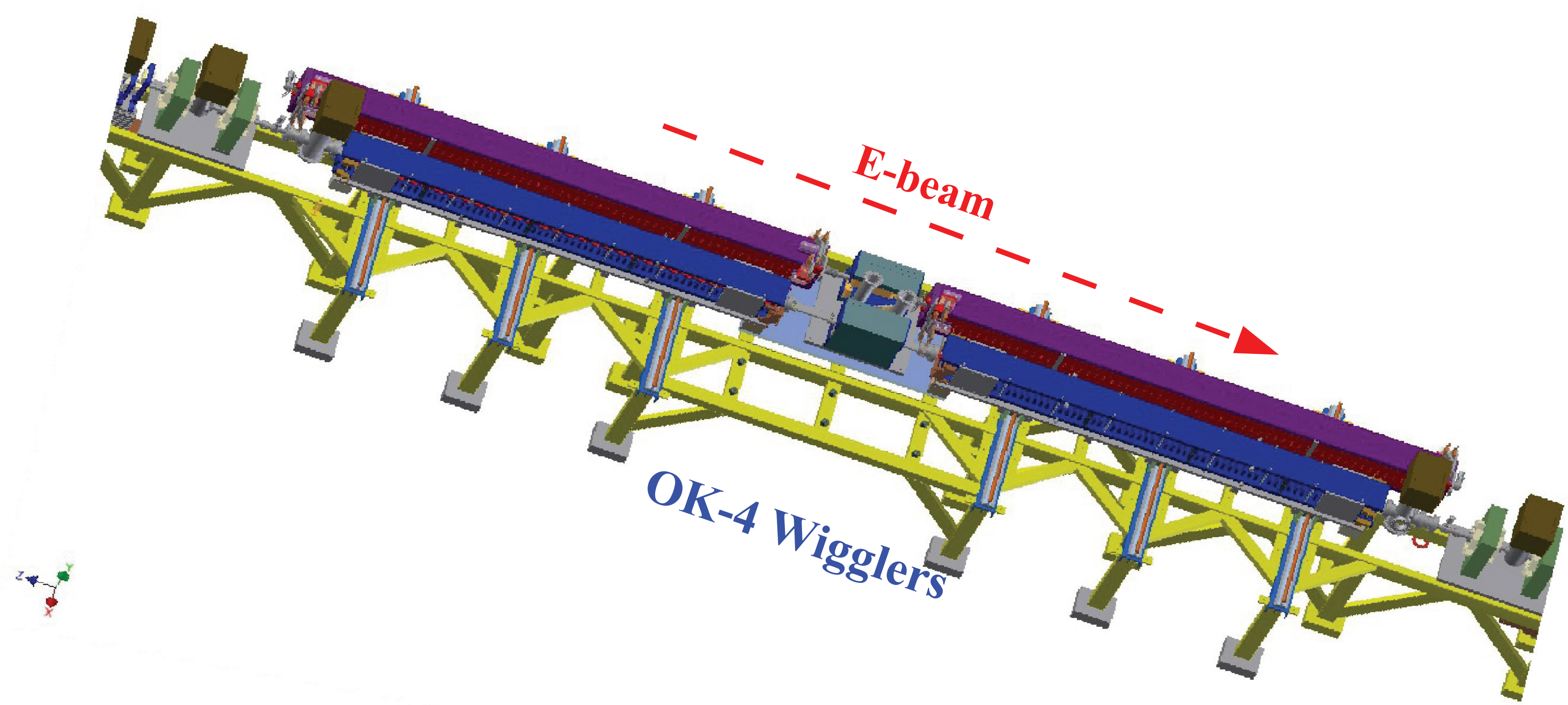


HIGS R&D Team (2004 – 2014): M. Busch, M. Emanian, J. Faircloth, B. Jia, H. Hao, S. Hartman, C. Howell, S. Huang, J. Li, S. Mikhailov, V. Popov, C. Sun, G. Swift, P. Wang, P. Wallace, W. Wu, Y.K. Wu, W. Xu

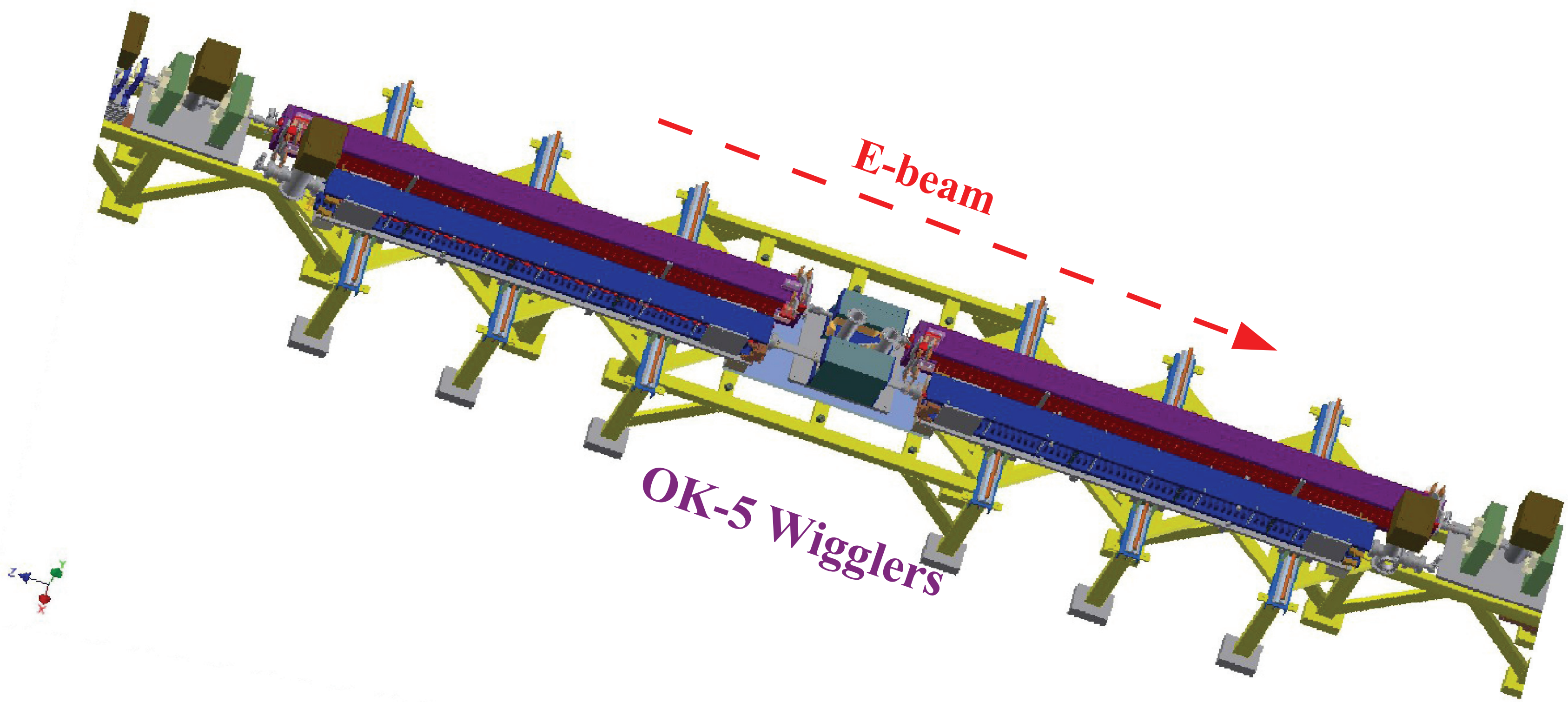
Wiggle Switchyard: Two helical OK-5 <==> Two linear OK-4



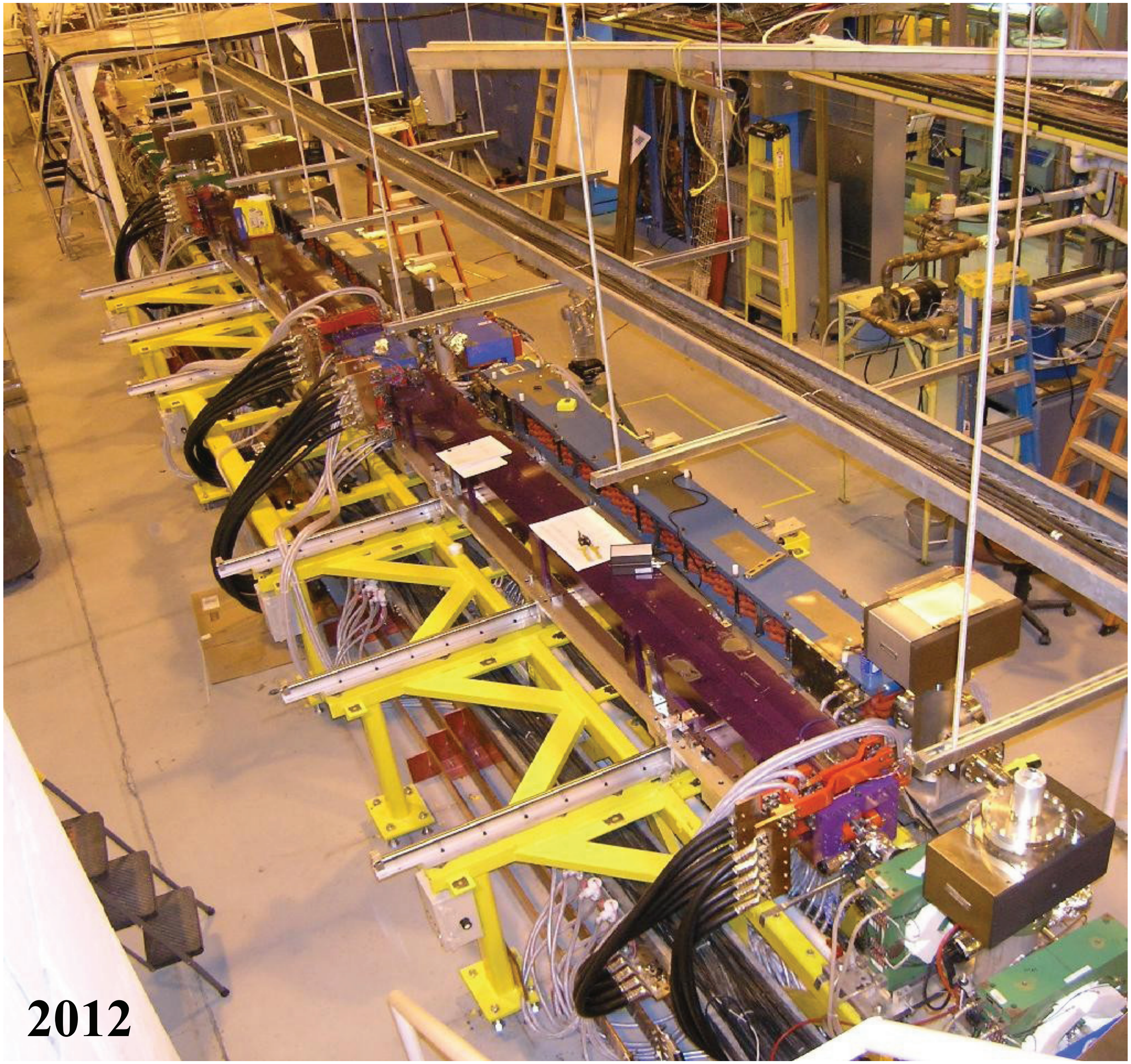
Wiggle Switchyard: Two helical OK-5 <==> Two linear OK-4



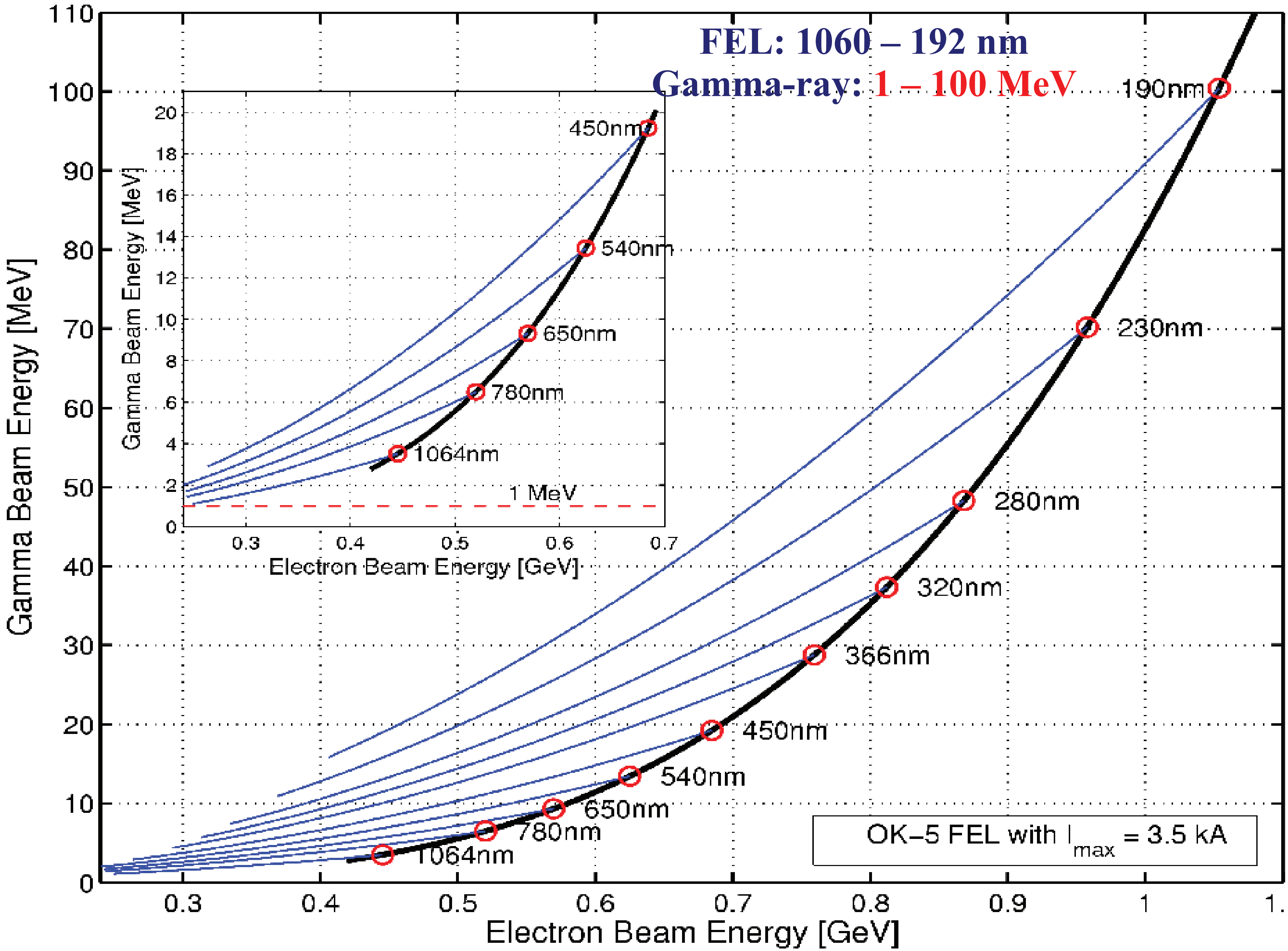
Wiggle Switchyard: Two helical OK-5 <==> Two linear OK-4



Wiggle Switchyard: Two helical OK-5 <==> Two linear OK-4

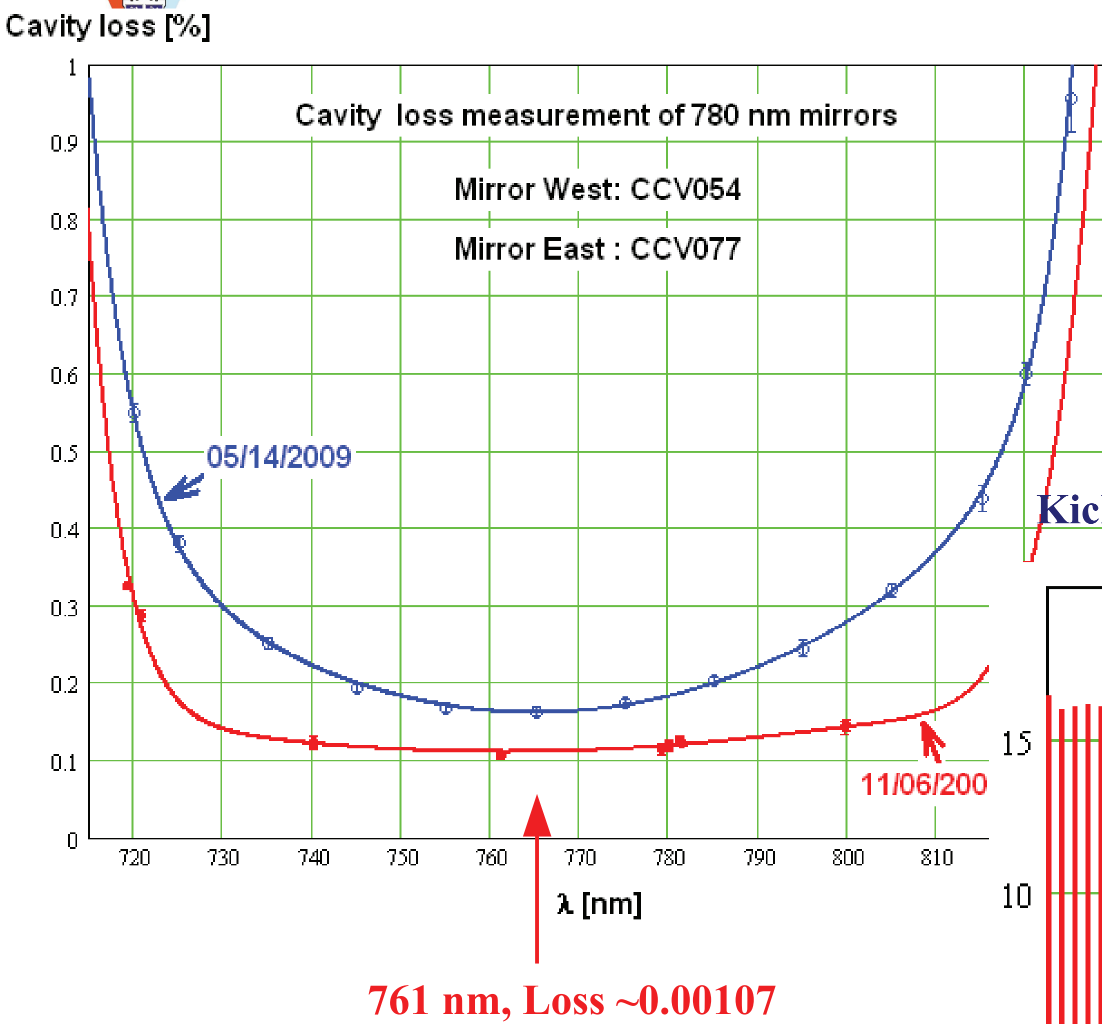


Gamma Energy Tuning Range with OK-5 FEL (3.5 kA)



High-Q FEL Optical Cavity

High Reflectivity FEL Mirrors

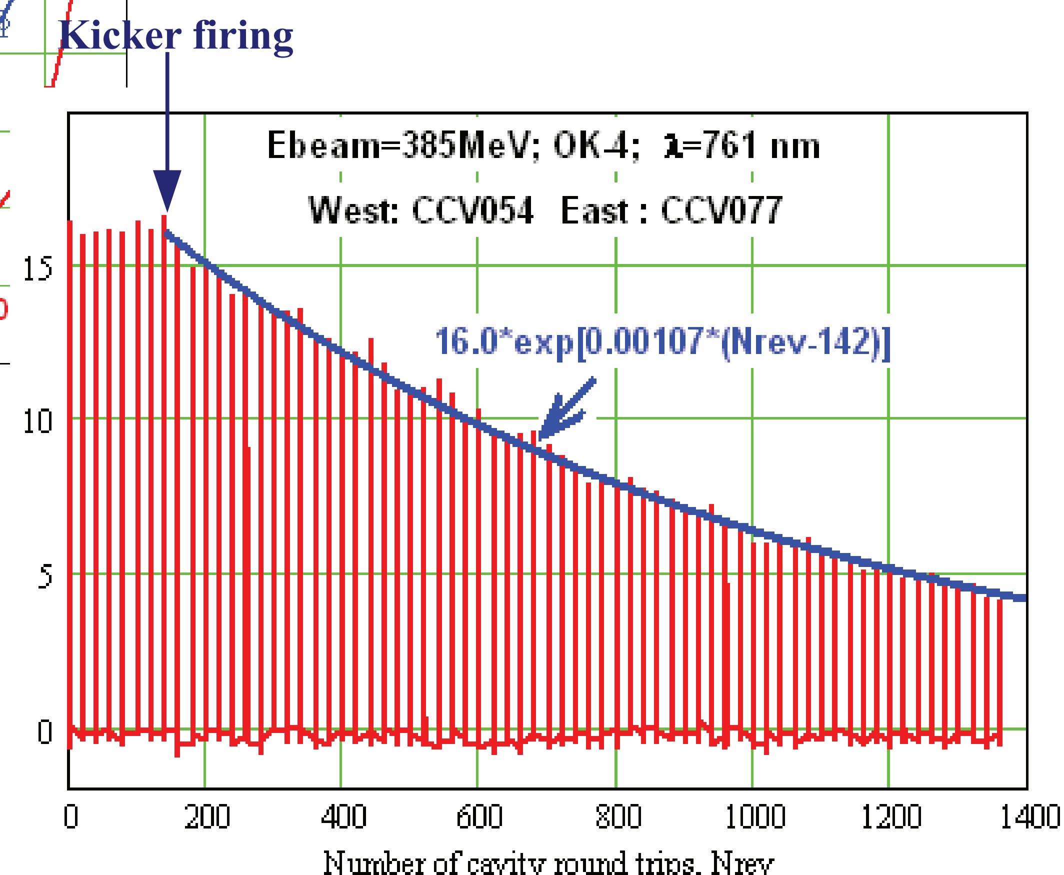


780 nm Mirrors

Minimal round-trip loss: ~ 0.107%

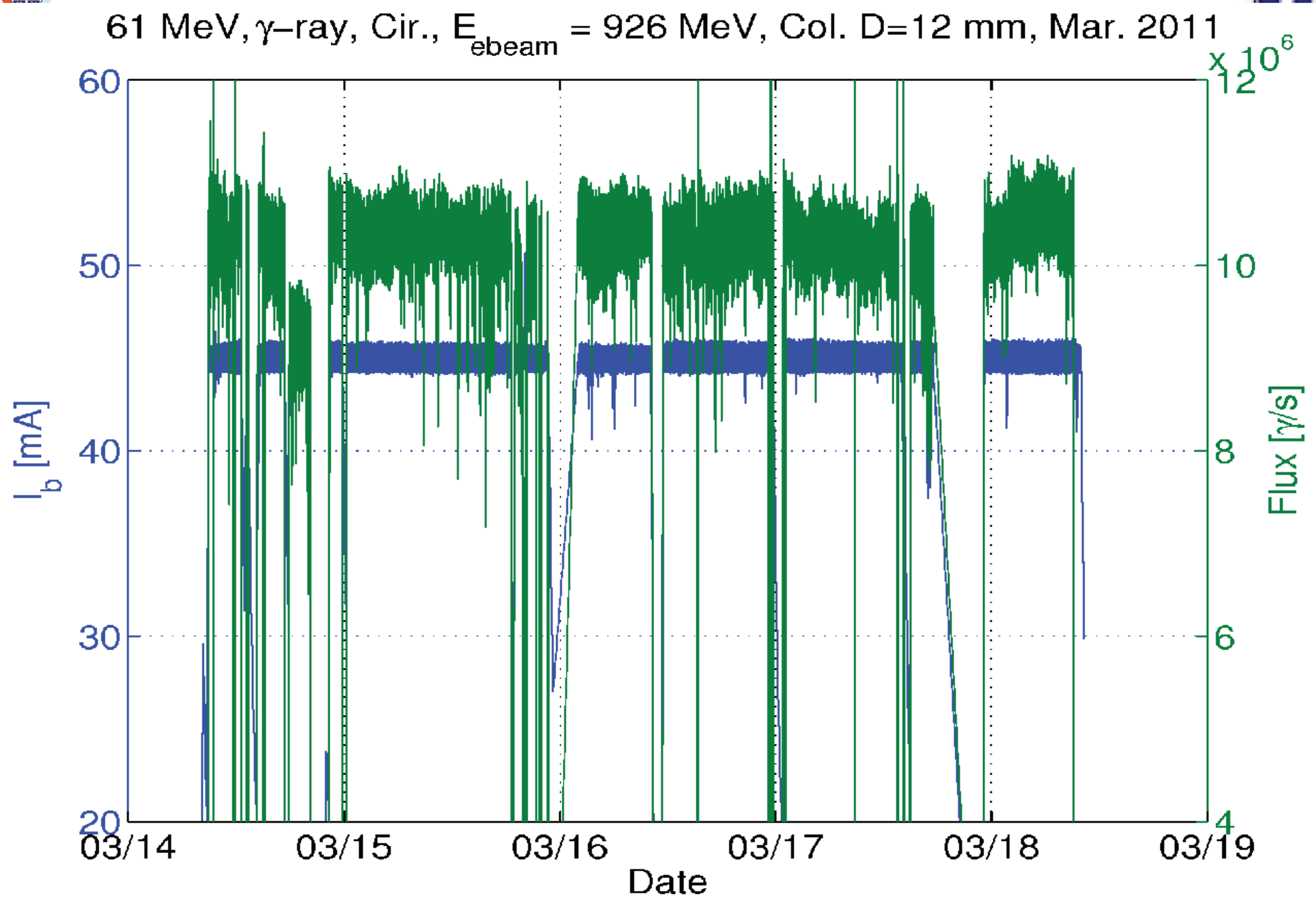
Finesse ~ 3,000

Effective: R ~ 99.95%



Top-off Injection

240 nm Mirror: 61 MeV γ-Beam Production



Highest energy gamma-ray beam delivered for experiments: 61 MeV, ^{6}Li Compton Scattering

Aiming Stability of Electron Beam/Gamma-ray Beam

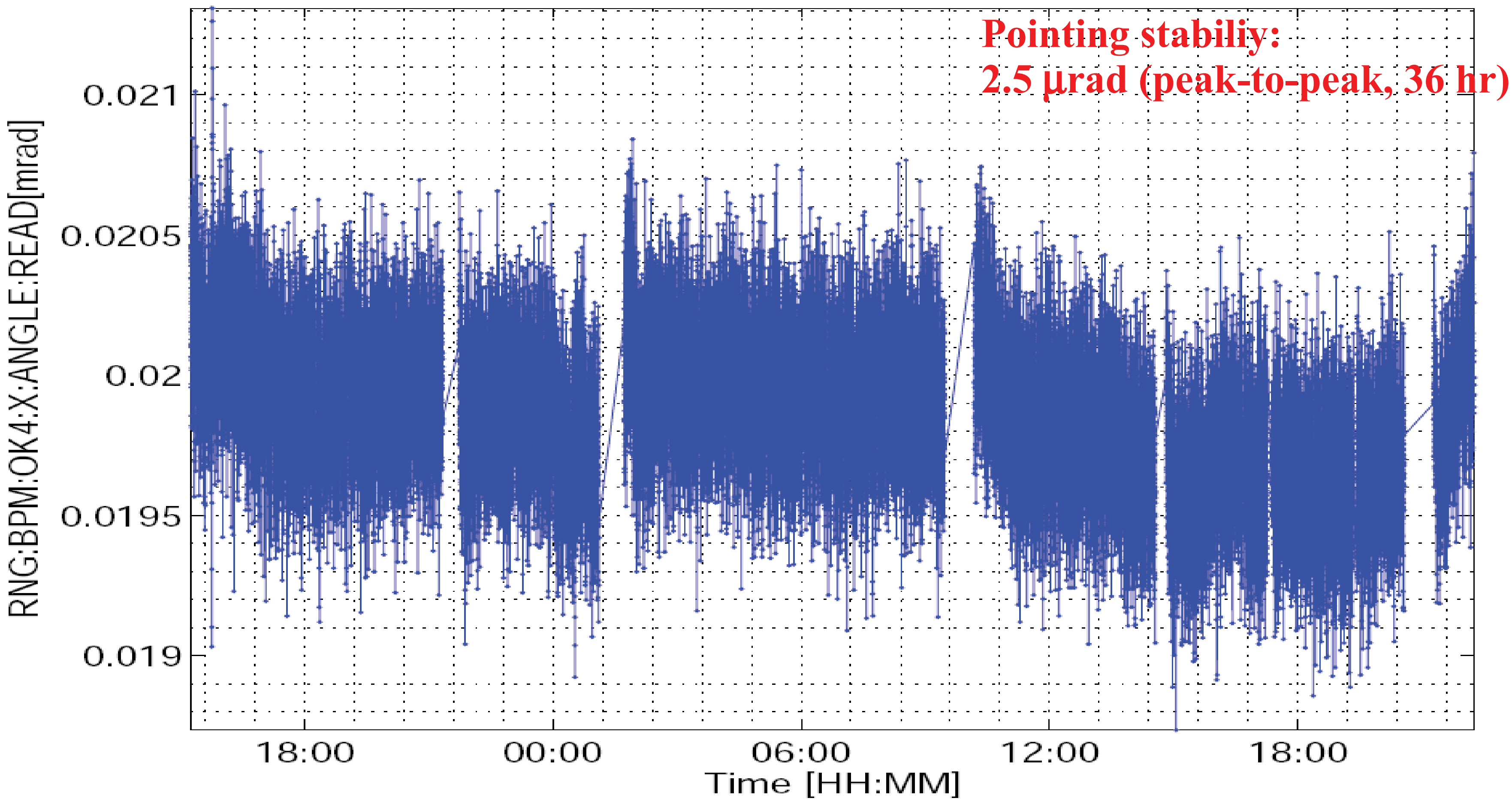
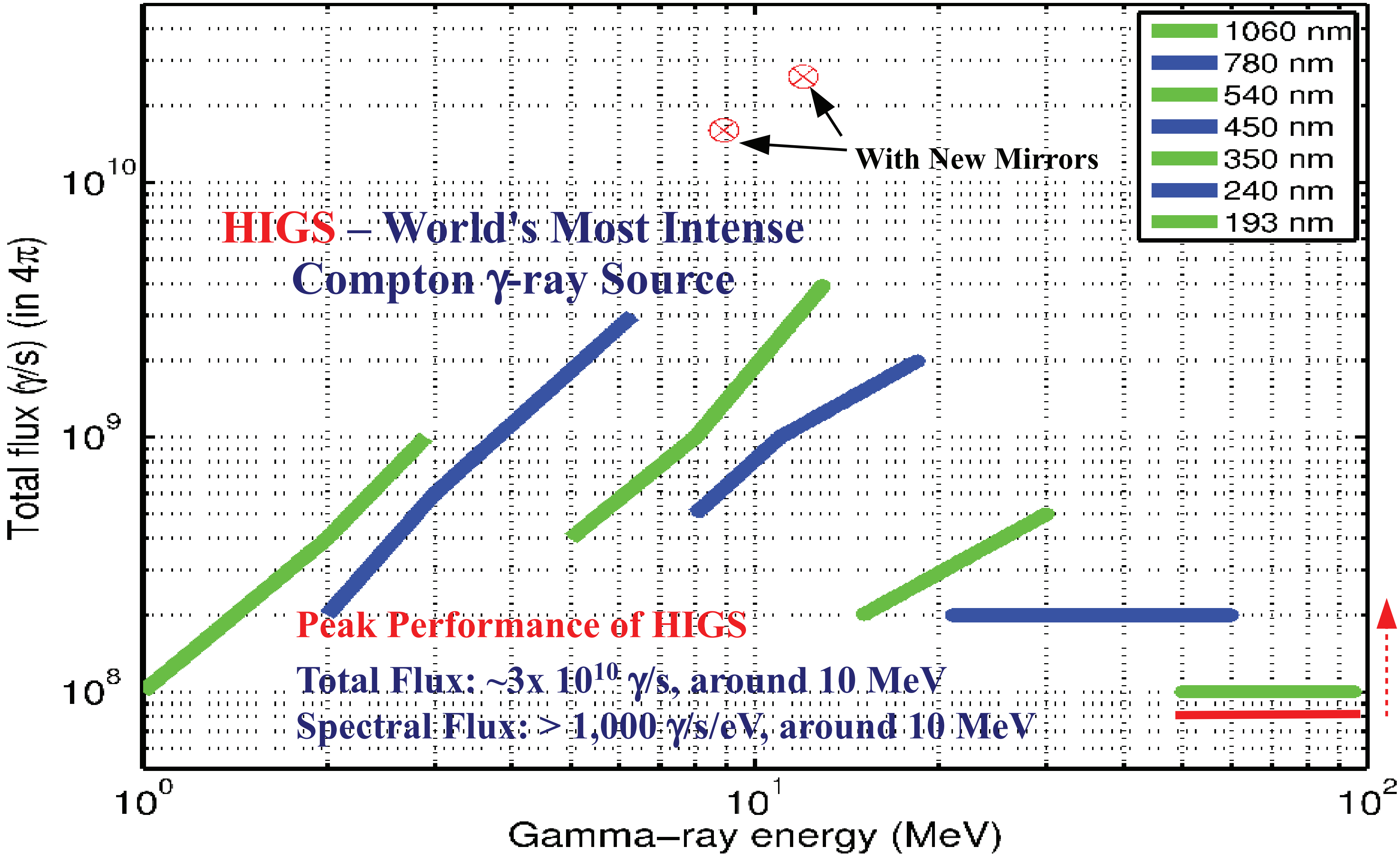


Figure 15: Horizontal beam angle at OK4 for about 36 hours operation from Aug. 20 to Aug. 21, 2009. The angle varied 2.5μrad (peak to peak) during this operation, this value corresponds to 150μm variation of gamma ray beam position at the gamma vault which is located 60 m downstream of the collision point. Typically, the collimator radius of the γ ray beam is 6 mm to 15 mm, therefor the misalignment caused by the beam orbit is about 2.5% to 1.0% of radius of the beam.

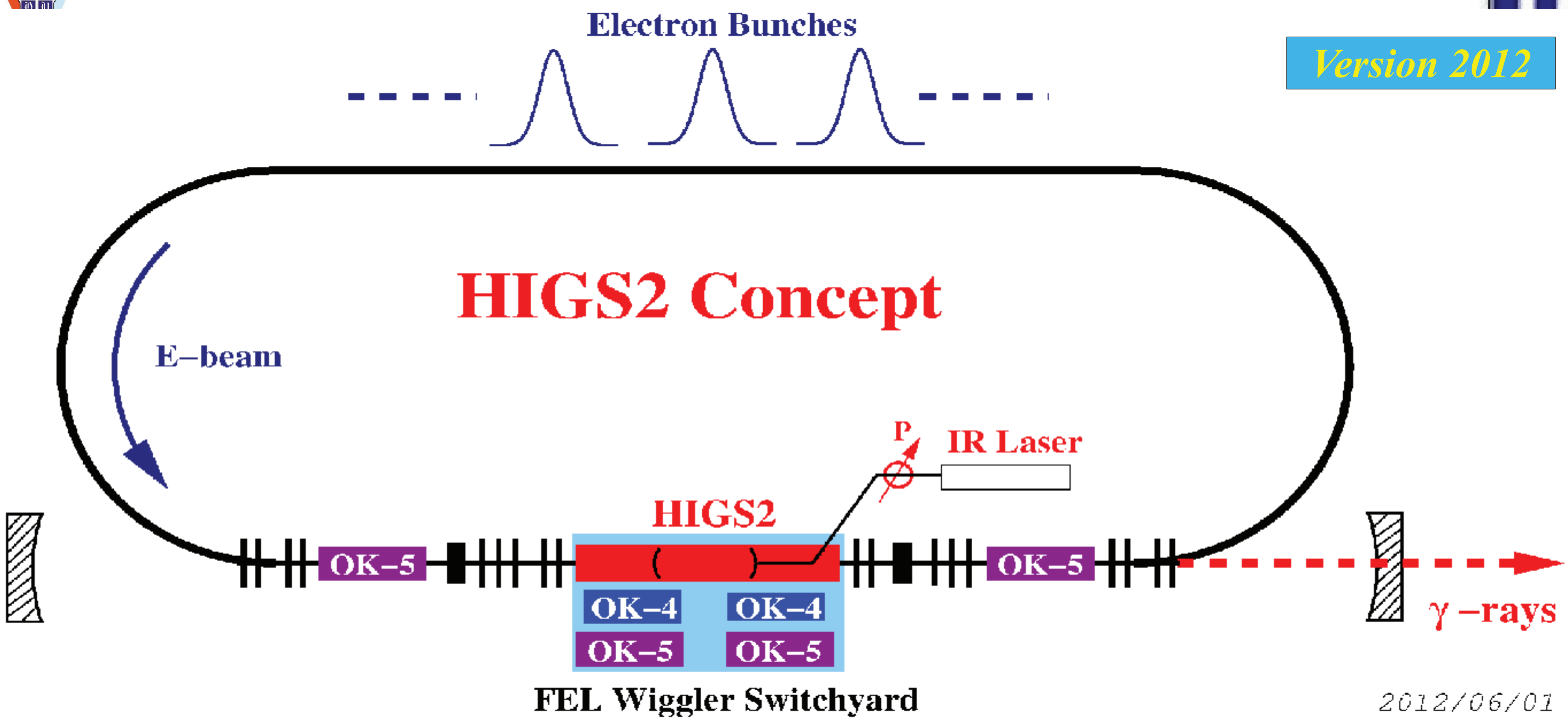
HIGS User Flux Capabilities with OK-5 FEL



On-Going and Future R&D Projects at HIGS

- New Gamma-ray Capabilities (short-term)
  - Two-color FEL and two-color gamma-ray beams
  - Fast gamma-ray helicity switch
  - Gamma-ray beam polarization manipulation and control
- Energy Front (3 – 5 years)
  - High-energy gamma-ray beam generation: 100 – 160 MeV
- Intensity Front (long-term)
  - HIGS2 – Fabry-Perot laser driven Compton gamma-ray beams

Version 2012



Research Programs

- Hadronic Parity Violation
- Nuclear Astrophysics
- Dark-matter Search

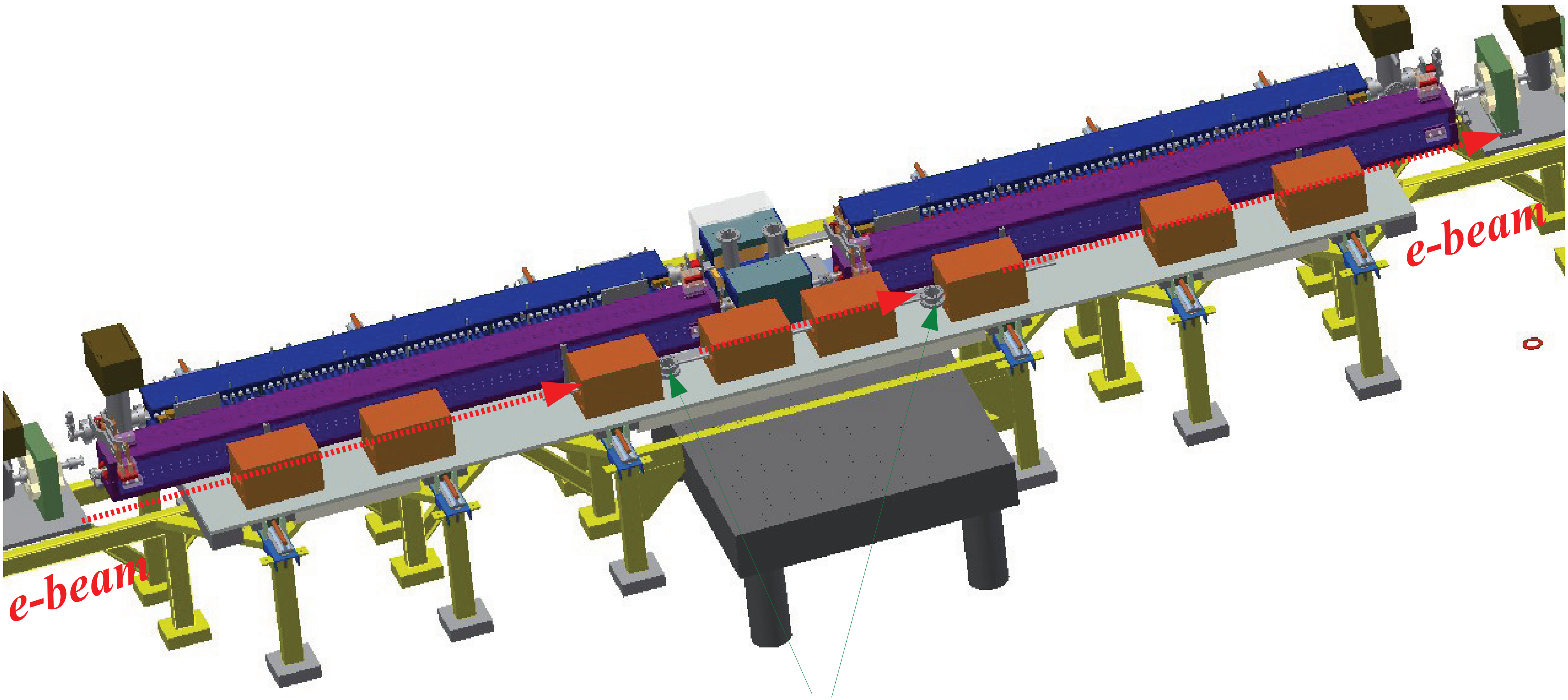
Projected Performance

- ~2 micron FP cavity: 2 – 12 MeV
- Total Flux: few 10^{11} – 10^{12} gamma/s
- Pol: Linear, or Circular (rapid switch)
- Energy resolution (FWHM): < 0.5%

A Prospectus Document for NSAC (Aug. 2012)

"*HIGS2: The Next Generation Compton g-ray Source*", M. W. Ahmed, A. E. Champagne, C. R. Howell, W. M. Snow, R. P. Springer, Y. Wu

HIGS2 Layout (Concept Only)



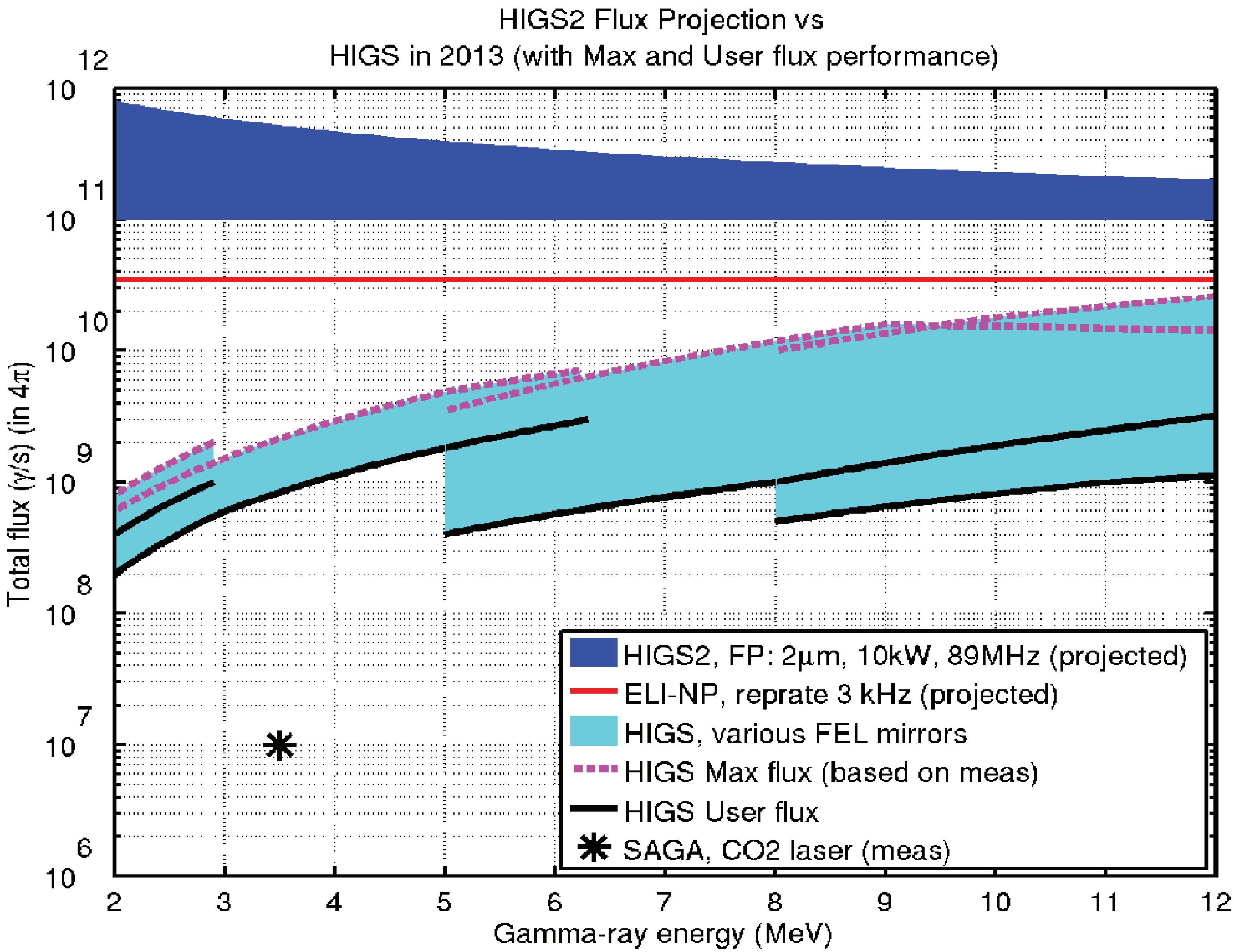
Mirrors of FB cavity

L_{cav} = 1.679 m

P_{FB} (avg) > 10 kW, 90 MHz, fiber laser

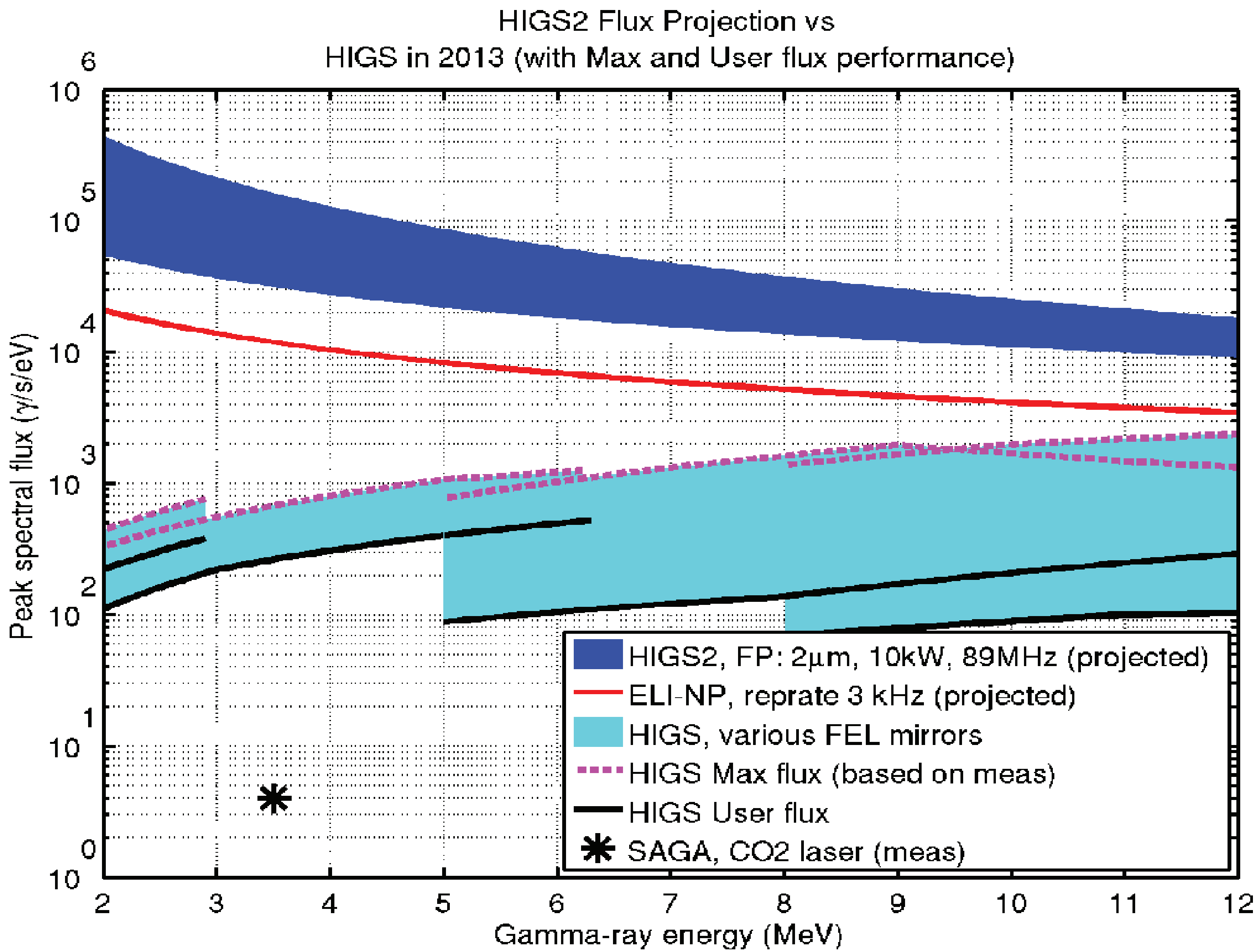
Collaborator: Jun Ye, JILA and U. of Colorado at Boulder

Projected HIGS2 Performance



ELI-NP: A. Bacci et al. J. Appl. Phys. 113, 194508 (2013)

Projected HIGS2 Performance



ELI-NP: A. Bacci et al. J. Appl. Phys. 113, 194508 (2013)

Fundamental and Applied Research Using Compton Gamma-ray Sources

Research Using Compton Gamma-ray Sources

Areas of Applications of Compton Gamma-ray Beams

- Accelerator Physics
  - Polarized positron generation
  - E-beam diagnostics (beam size, energy, and polarization)
- National Security
  - Special nuclear materials detection (non-destructive assay)
- Energy Industry
  - Nuclear waste management and treatment
- Medical Applications
  - Isotope production
  - Cancer diagnostics
- Industrial Applications
  - Industrial product inspection
- Materials Research
  - Novel scintillators and detectors
  - Applications in fundamental research, space program, industry, and medicine

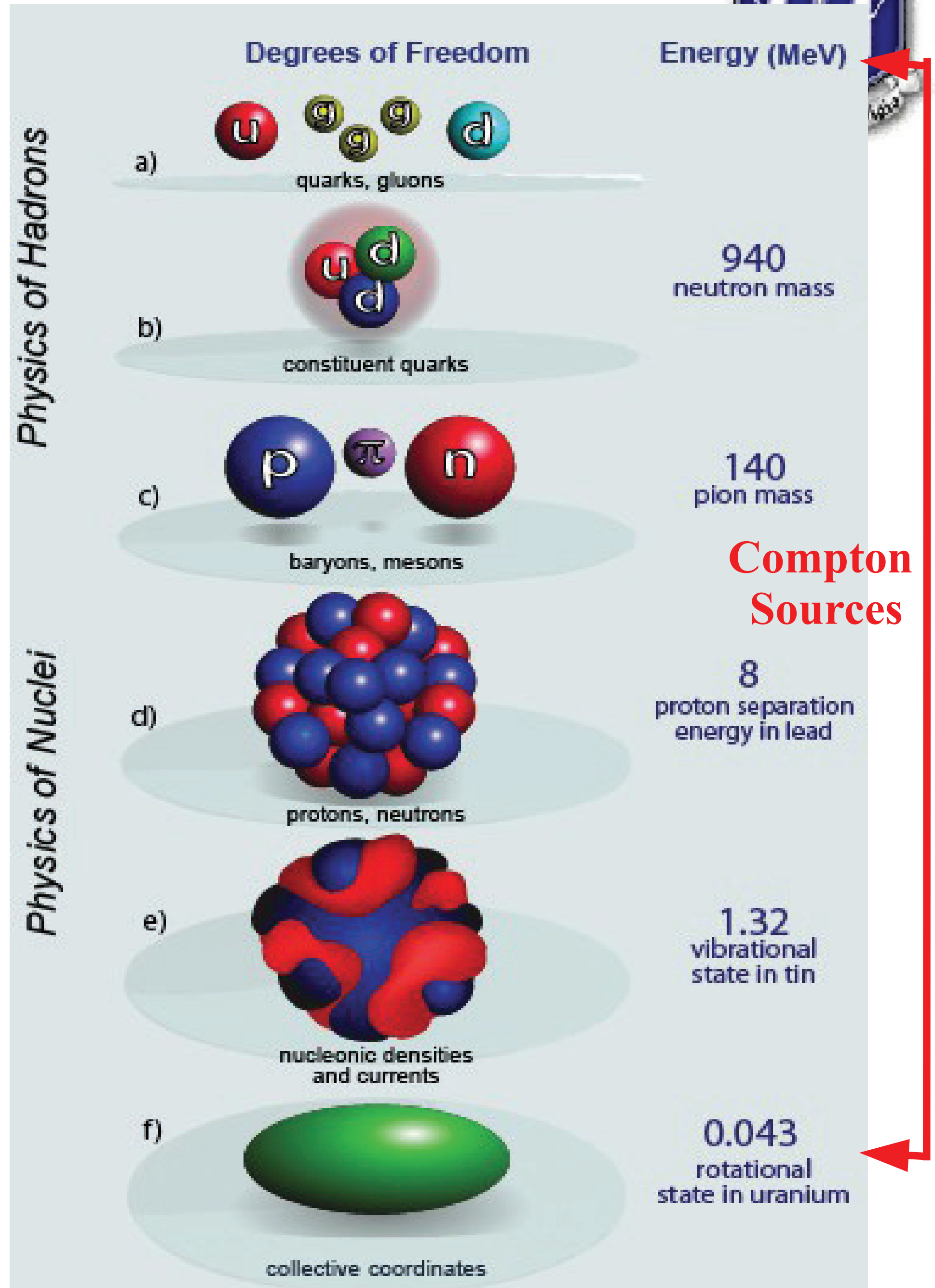
Basic Research Using Compton Gamma-ray Sources

Physics Research Using Compton Gamma-ray Beams: 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).

HIGS Target Room

HIFROST – HIGS Frozen Spin Target System

Courtesy of M. Ahmed, TUNL/Duke U.

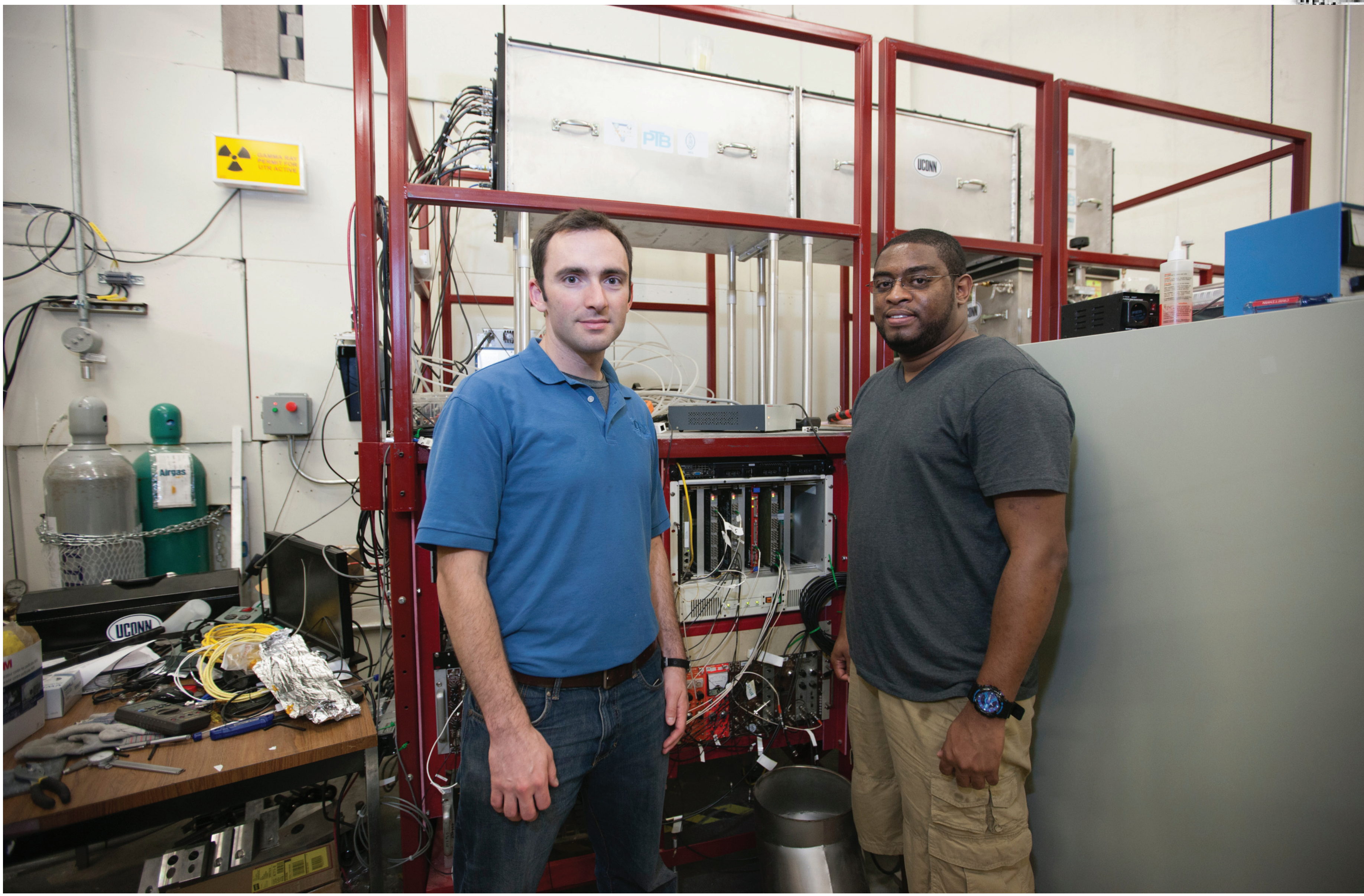
HIGS Target Room

HINDA – HIGS NaI Detector Array

Courtesy of M. Ahmed, TUNL/Duke U.

HIGS Target Room

OTPC – Optical Time Projection Chamber



Courtesy of M. Ahmed, TUNL/Duke U.

Thank You