Present and Future Compton Gamma-ray Sources

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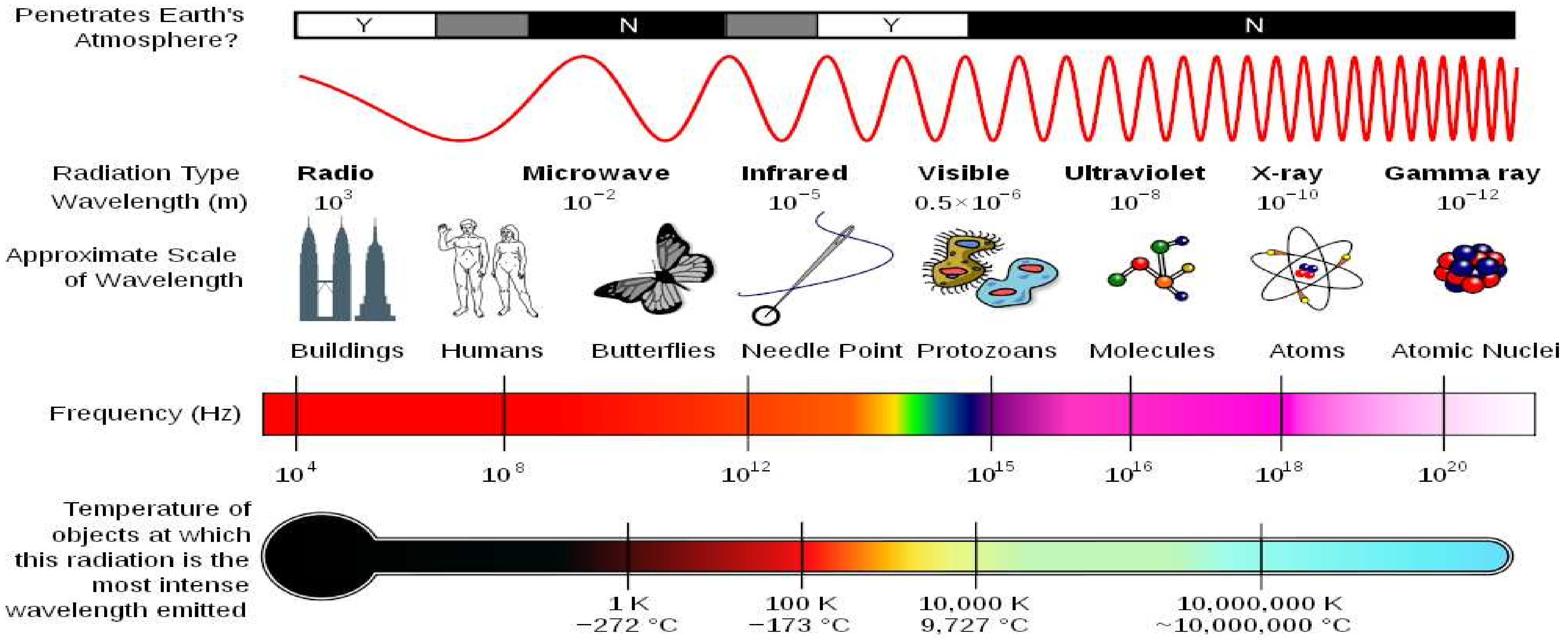
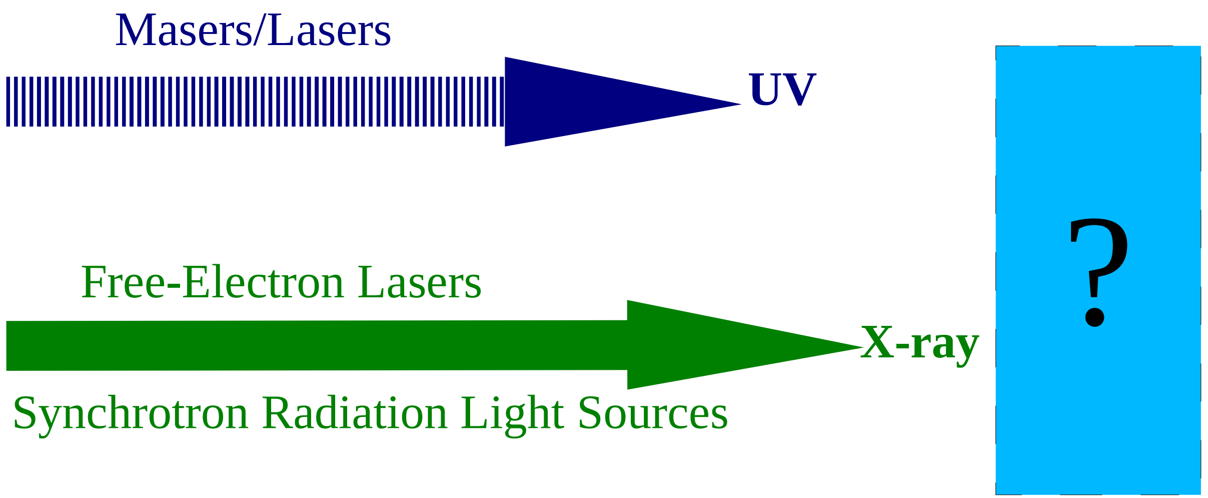
Outline

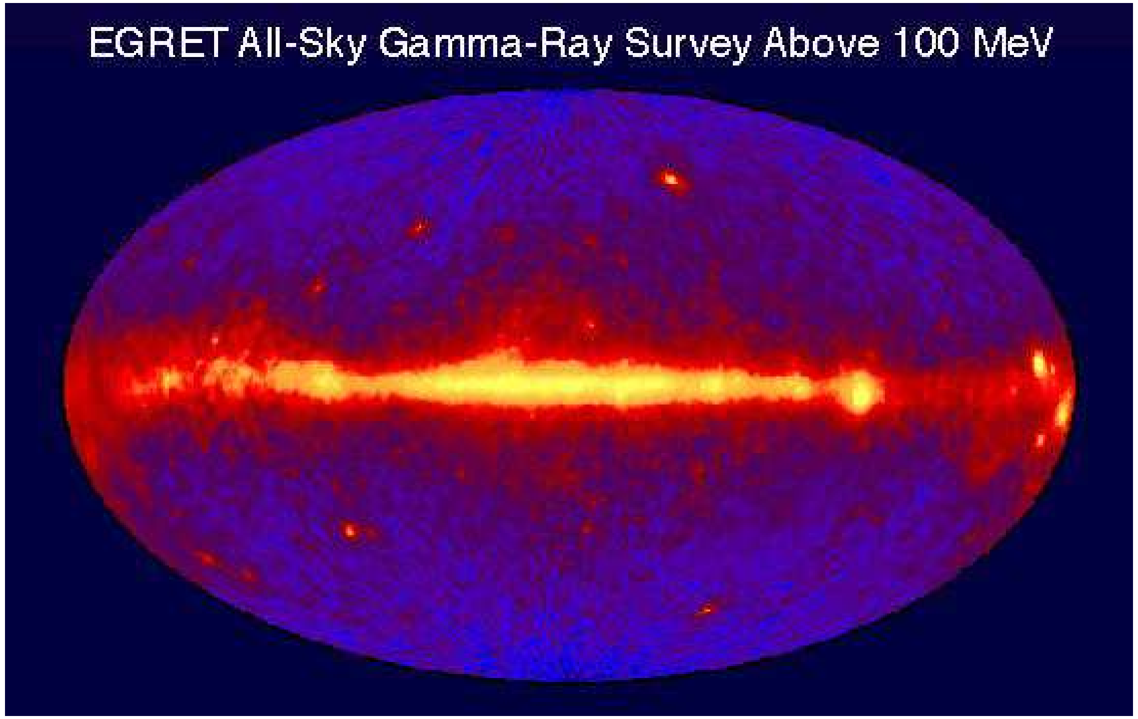
- Introduction: Light Sources
- Physics of Compton Photon Sources
- Examples of Compton Photon Sources
- HIGS — High Intensity Gamma-ray Source at TUNL, USA
- Toward Next-generation Sources: HIGS2; VEGA, ELI-NP
- Next Generation Compton Gamma-ray Sources

Spectrum of Electromagnetic Radiation

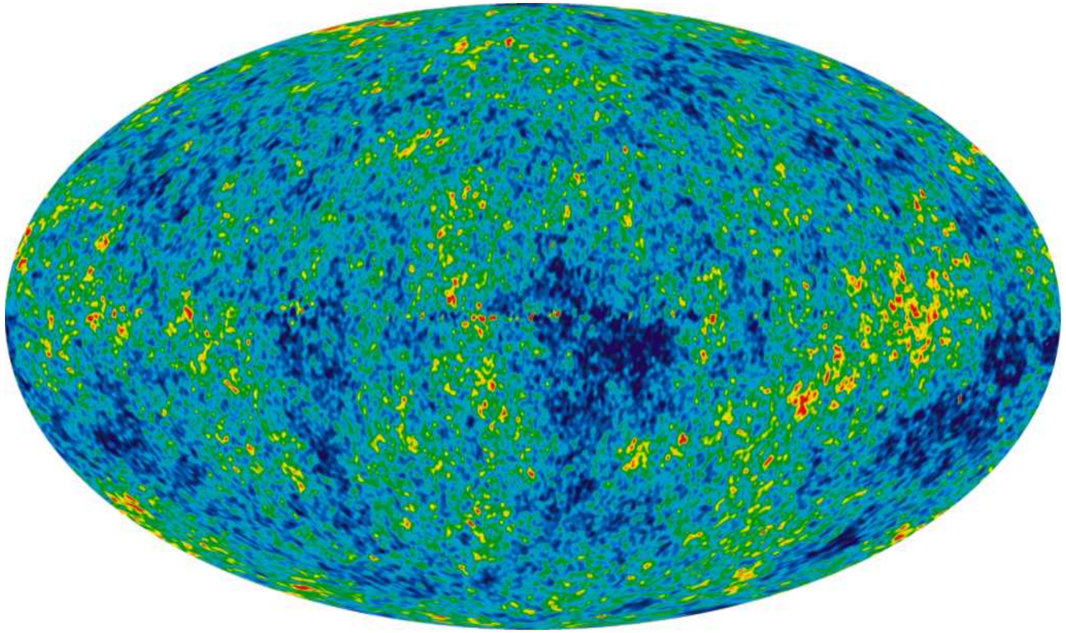




View of the Universe via Gamma-rays



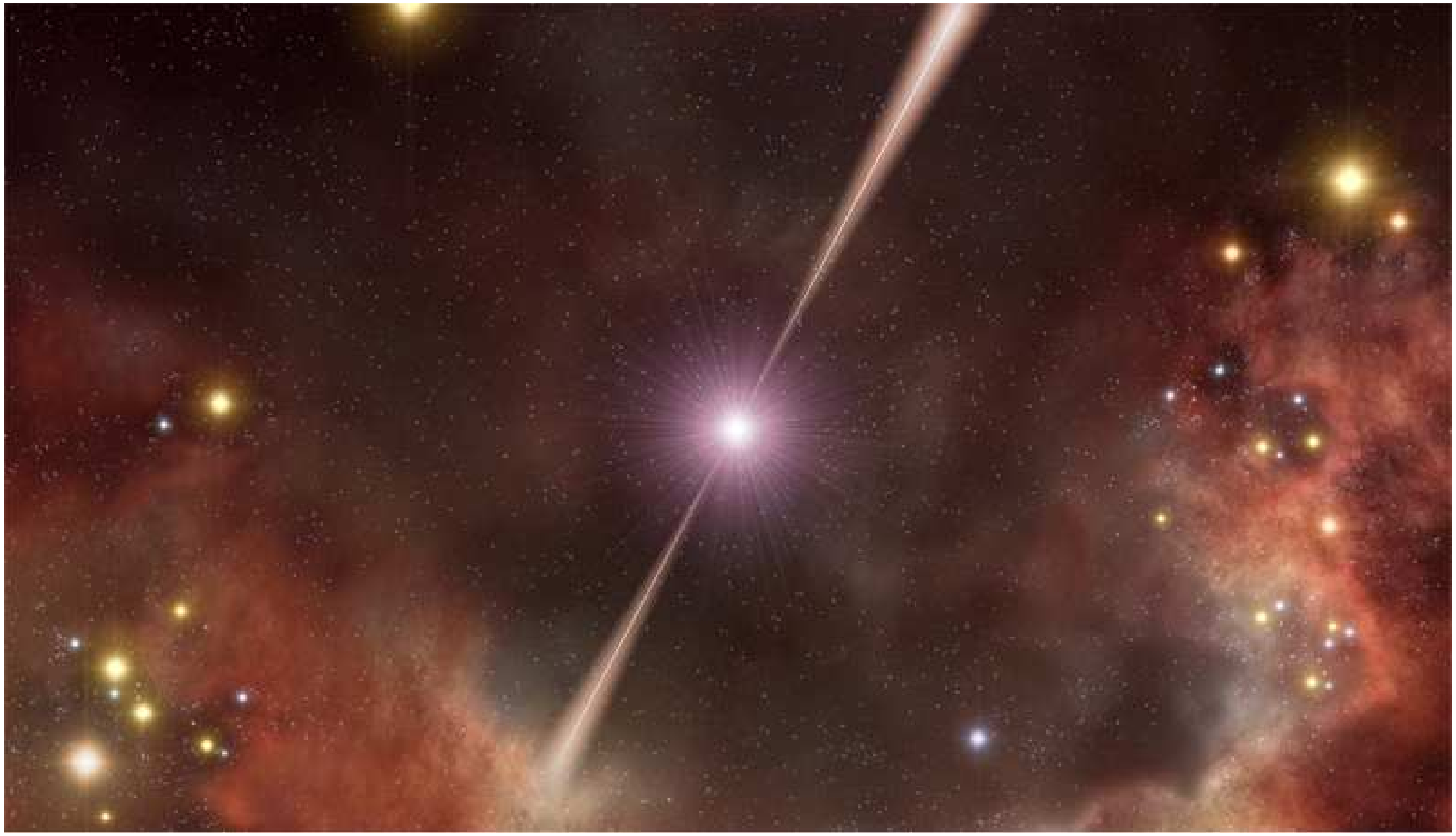
ERGET: Energetic Gamma Ray Experiment Telescope
(NASA's Compton Gamma Ray Observatory satellite 1991 – 2000)



CMB: Cosmic Microwave Background
Arno Penzias and Robert Wilson
Discovery: 1964; Nobel Price: 1978

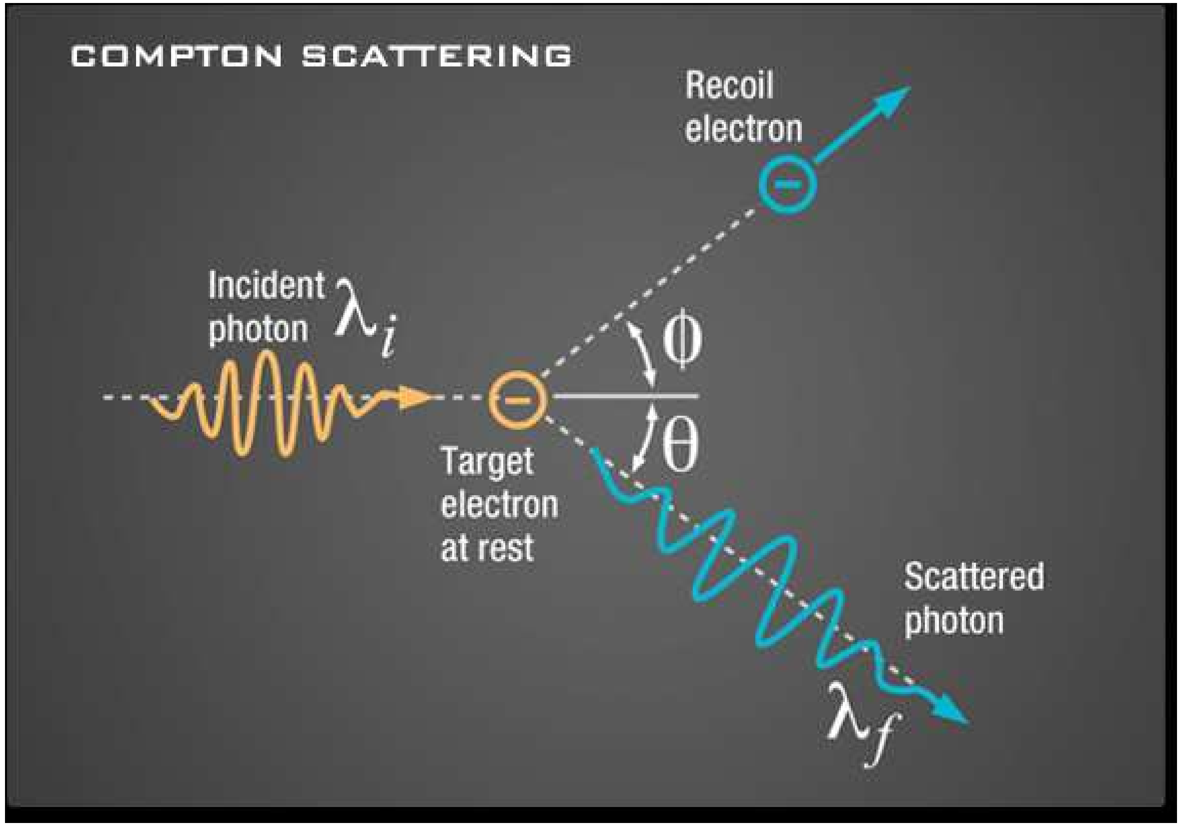
1. http://heasarc.gsfc.nasa.gov/docs/cgro/egret/
2. http://en.wikipedia.org/wiki/Cosmic_microwave_background_radiation

Gamma-ray Bursts: GRB 080319B



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

Compton Scattering



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

Compton Scattering

Arthur H. Compton (1892 – 1962)

Discovery: 1923

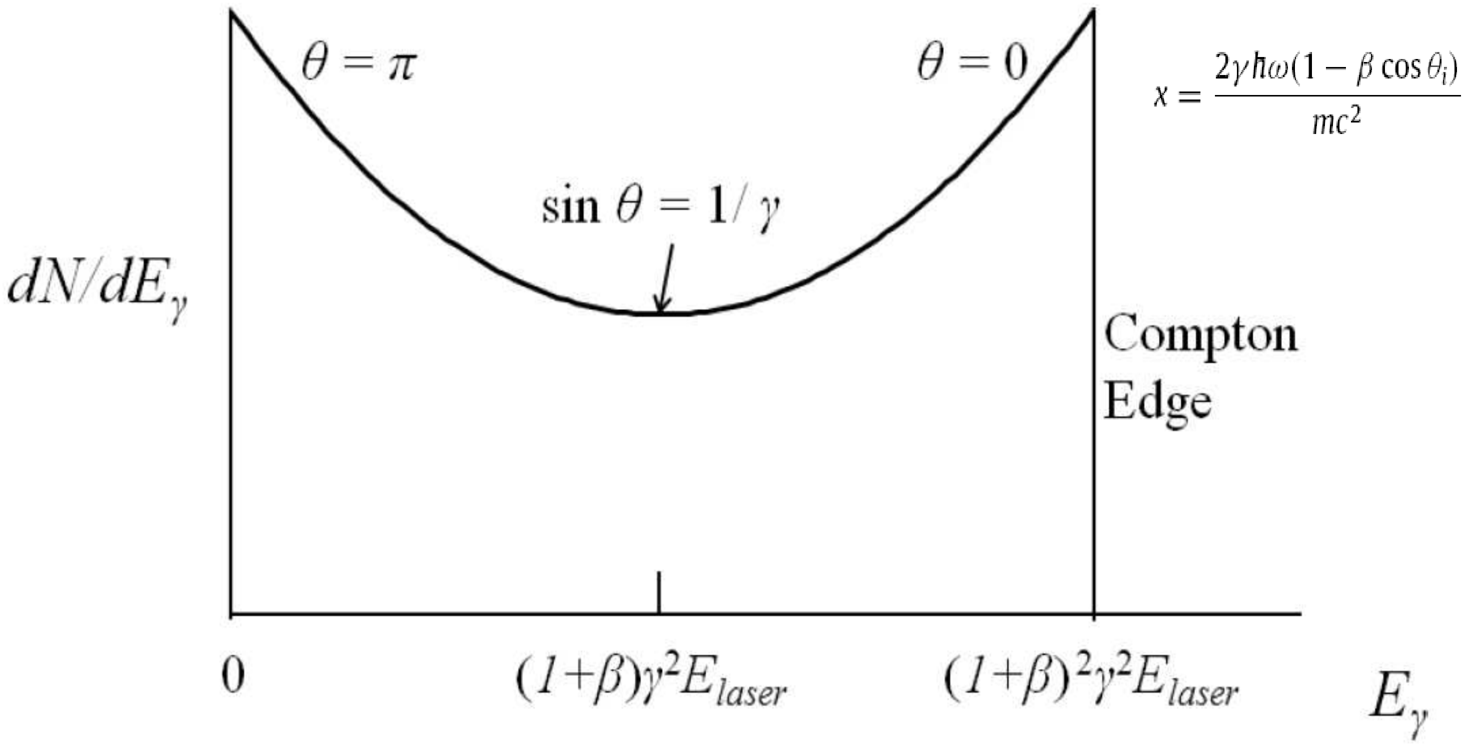
Nobel Price for Physics: 1927

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.

Compton Photon Sources = Electron-Photon Colliders

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



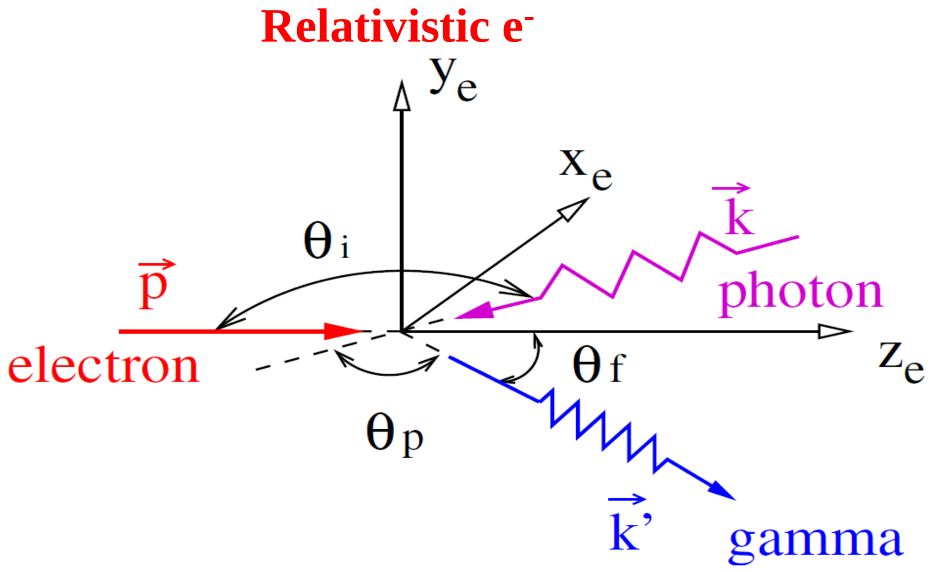
$$x = \frac{2\gamma\hbar\omega(1-\beta\cos\theta_i)}{mc^2}, \qquad y = \frac{2\gamma\hbar\omega'(1-\beta\cos\theta_f)}{mc^2}$$

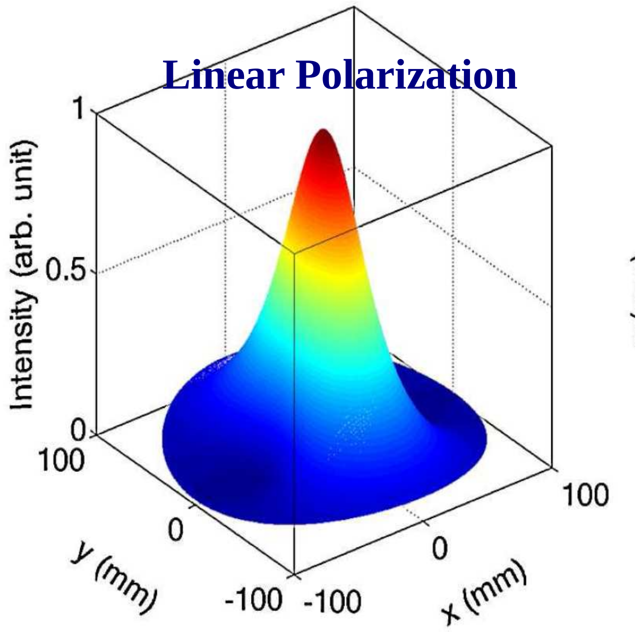
$$\frac{dN_\gamma}{dt} \sim \frac{\sigma}{A_{eff}} f\, N_e N_{laser}$$

Thomson cross-section: $\sigma_0 = 6.6524\times10^{-29} m^2$

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

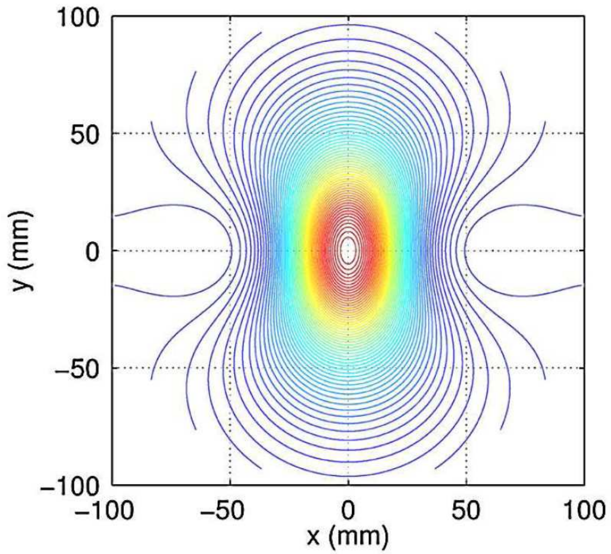
Photon Energy





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

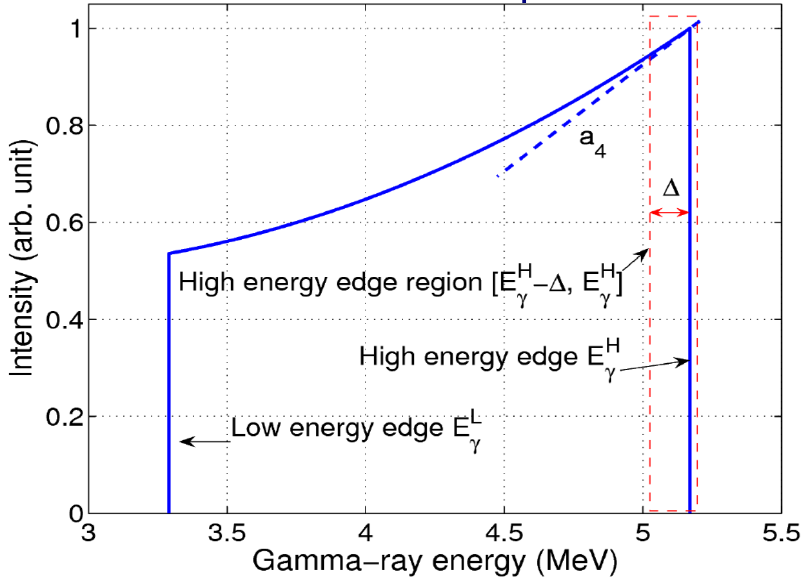
Head-on Collision: $E_\gamma^{max} \approx (\gamma(1+\beta))^2\hbar\omega \approx 4\gamma^2\hbar\omega$



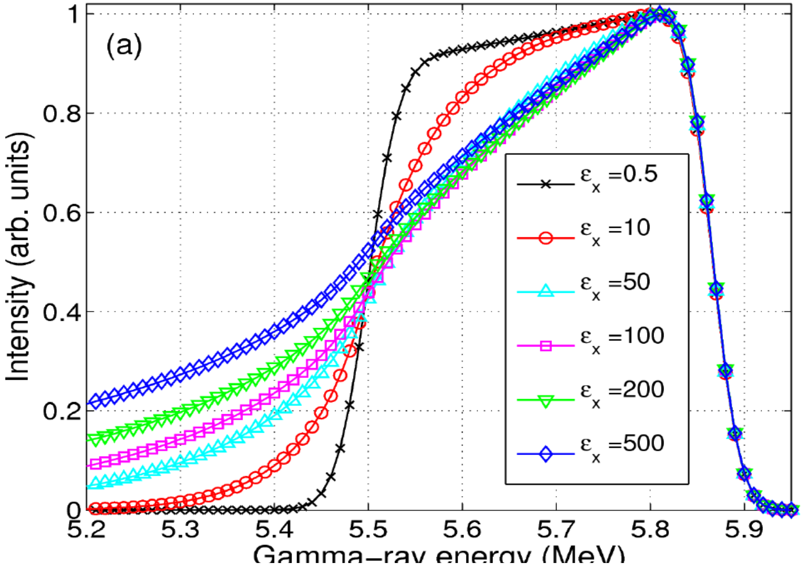
C. Sun and Y. K. Wu, Phys. Rev. ST Accel. Beams 14, 044701 (2011)

Energy Distribution of Compton Gamma-beam

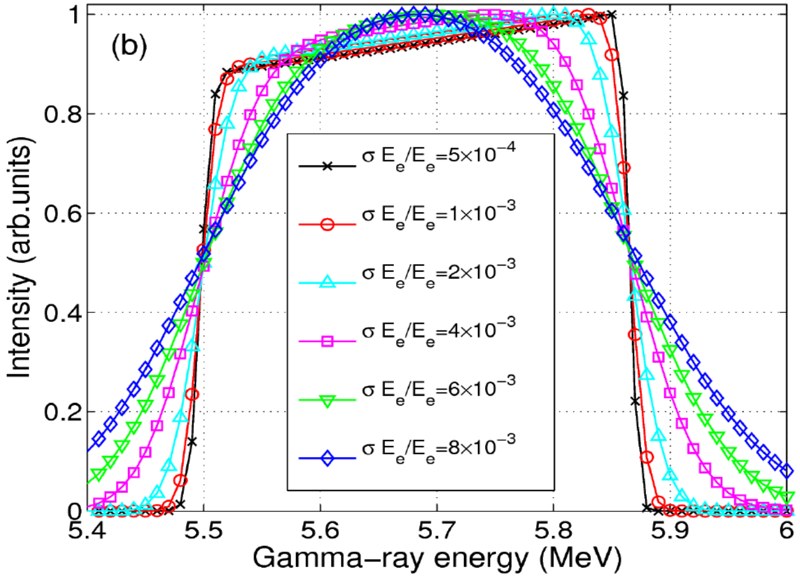
Monochromatic electron and photon beams



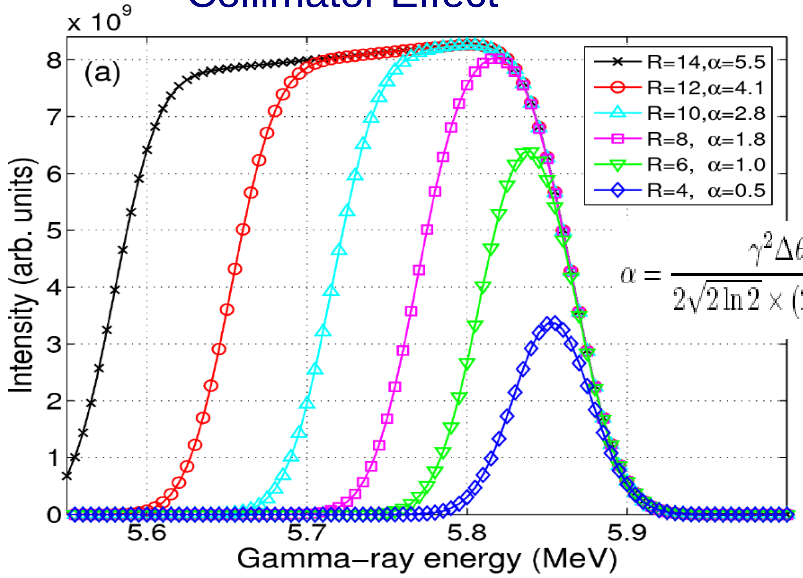
Emittance Effect (Scaled)



E-beam Energy Spread Effect (Scaled)



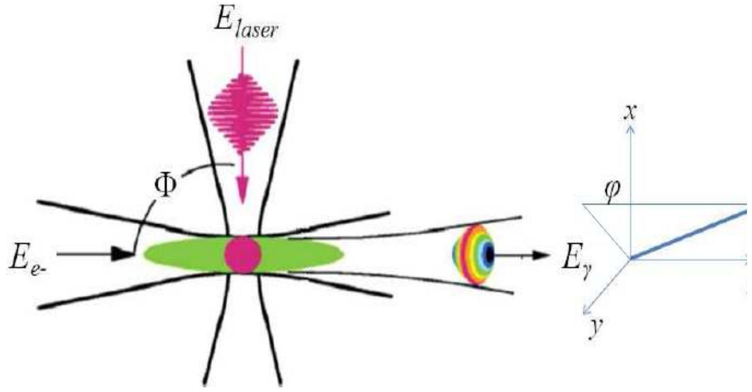
Collimator Effect

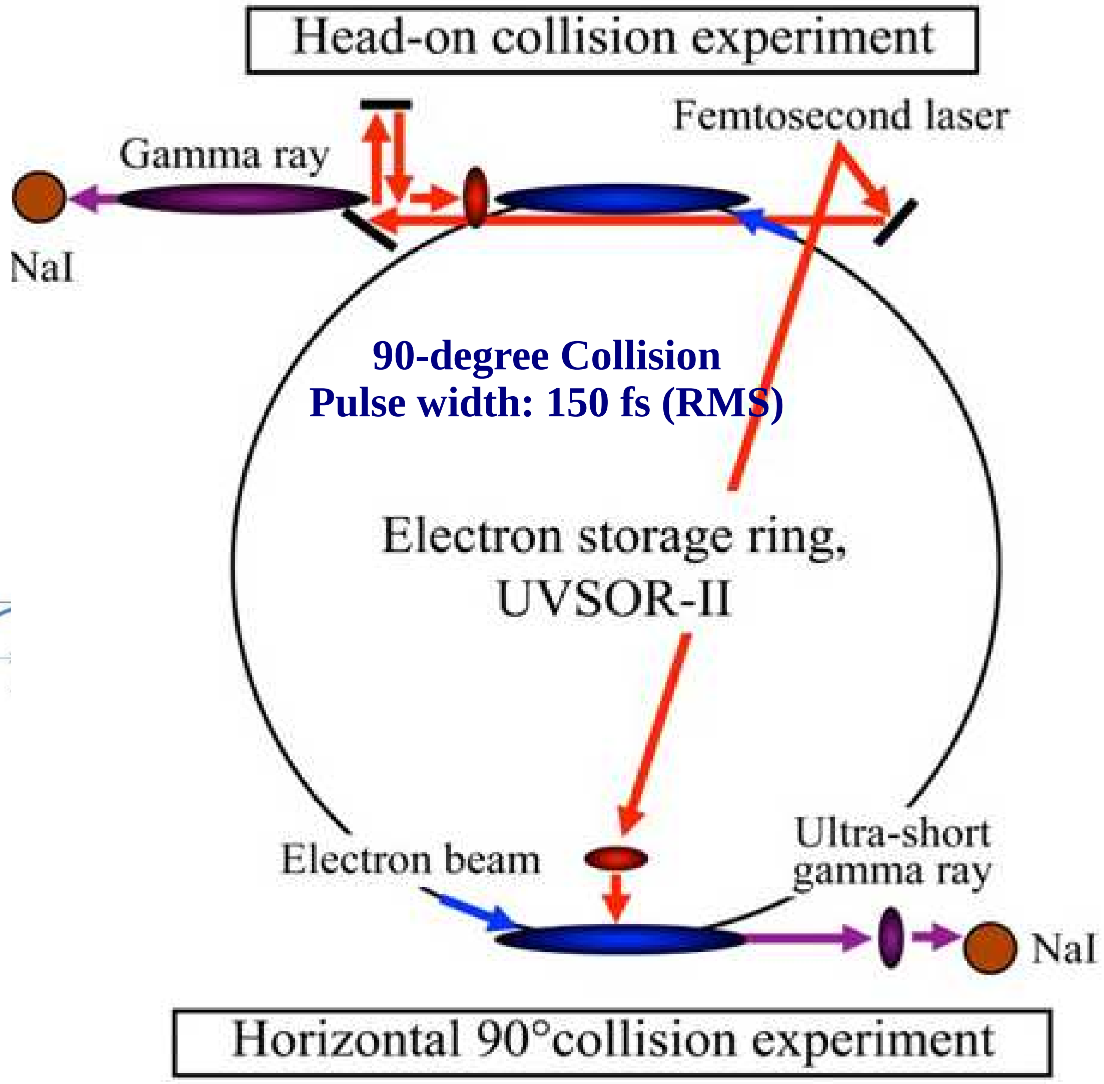


$$\alpha = \frac{\gamma^2 \Delta\theta_c^2}{2\sqrt{2\ln 2} \times (2\sigma_{E_e}/E_e)},$$

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

Pulse Duration





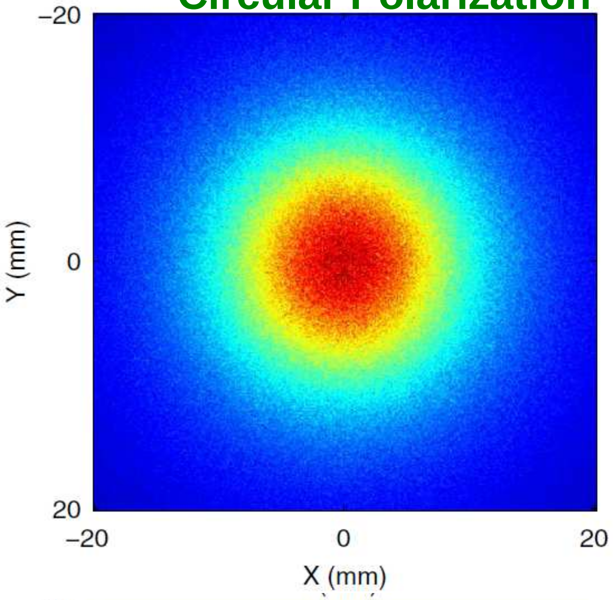
90-degree Collision
Pulse width: 150 fs (RMS)

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

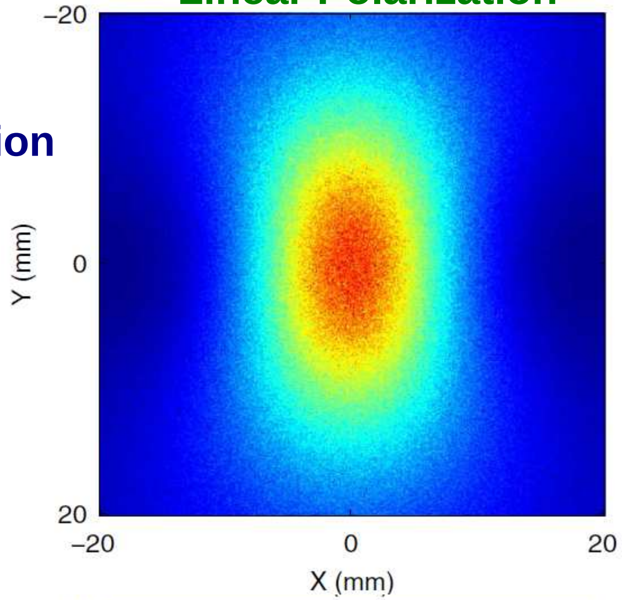
Polarization Effect

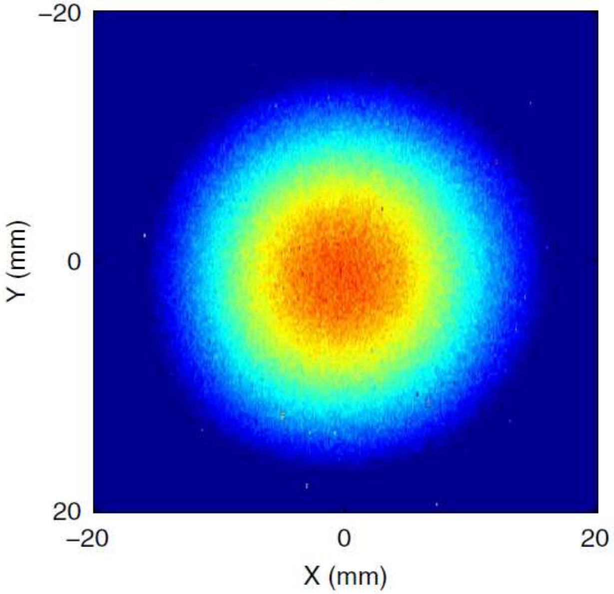
Circular Polarization

Linear Polarization

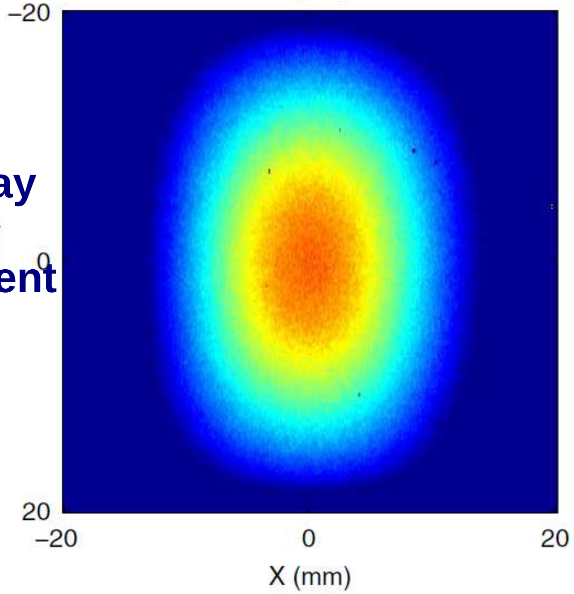


Simulation





Gamma-ray Camera Measurement (HIGS)



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

Electron Beam and Photon Beam Sources

E-beam Sources	X-ray	Gamma-ray	Comments
Storage Ring	Several	Common	High reprate Gamma-ray: large charge in a bunch, good emittance, expensive
Linac	Common	Several	Low reprate X-ray: need to improve charge & emittance
SC Linac	JLab (Early 2000s), and KAERI (2009)		High reprate, short pulses, good emitance
ERL	Proposed	Proposed	Expensive; New tech

Photon Beam Sources	X-ray	Gamma-ray	Comment
Cavity: FEL	Several	Several	High reprate; Medium to high avg power Large beam size
Cavity: Fabry-Perot	Several	Several	High reprate; Medium to high avg power Small beam size possible
External Lasers	Common	Common	Low reprate; Low avg power; Very high peak power possible Small beam size possible

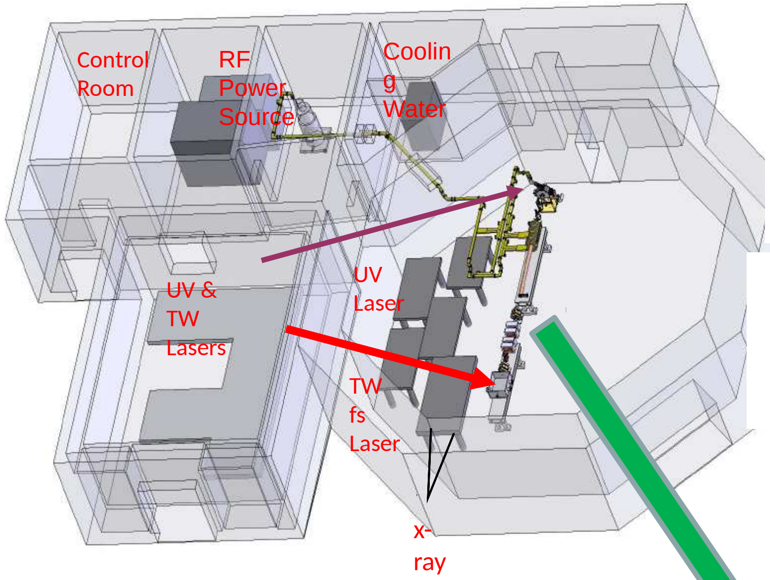
Compton Photon Sources around the World

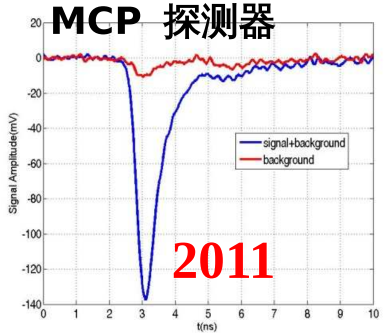
Examples

First Compton Gamma-ray Source for Nuclear Physics Research

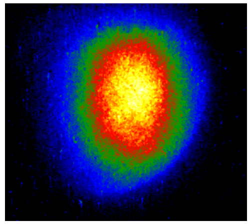
- LADON Project on Adone storage ring at Frascati, Italy
- 5–80 MeV, 5×10^5 ph/s (max, total flux) (1978–1993)

Compton X-ray Sources: TTX, Tsinghua University, China





脉冲光子产额：~ 10 ^{6}，能量 ~50keV



Facility/Project: Tsinghua Thomson Scattering X-ray Source (TTX)

Institution: Tsinghua University

Country: China

Energy (keV): 24 , 48 (90, 180 deg)

Accelerator: Linac, 45 MeV

Laser: Ti: Sapphire TW, 800 nm

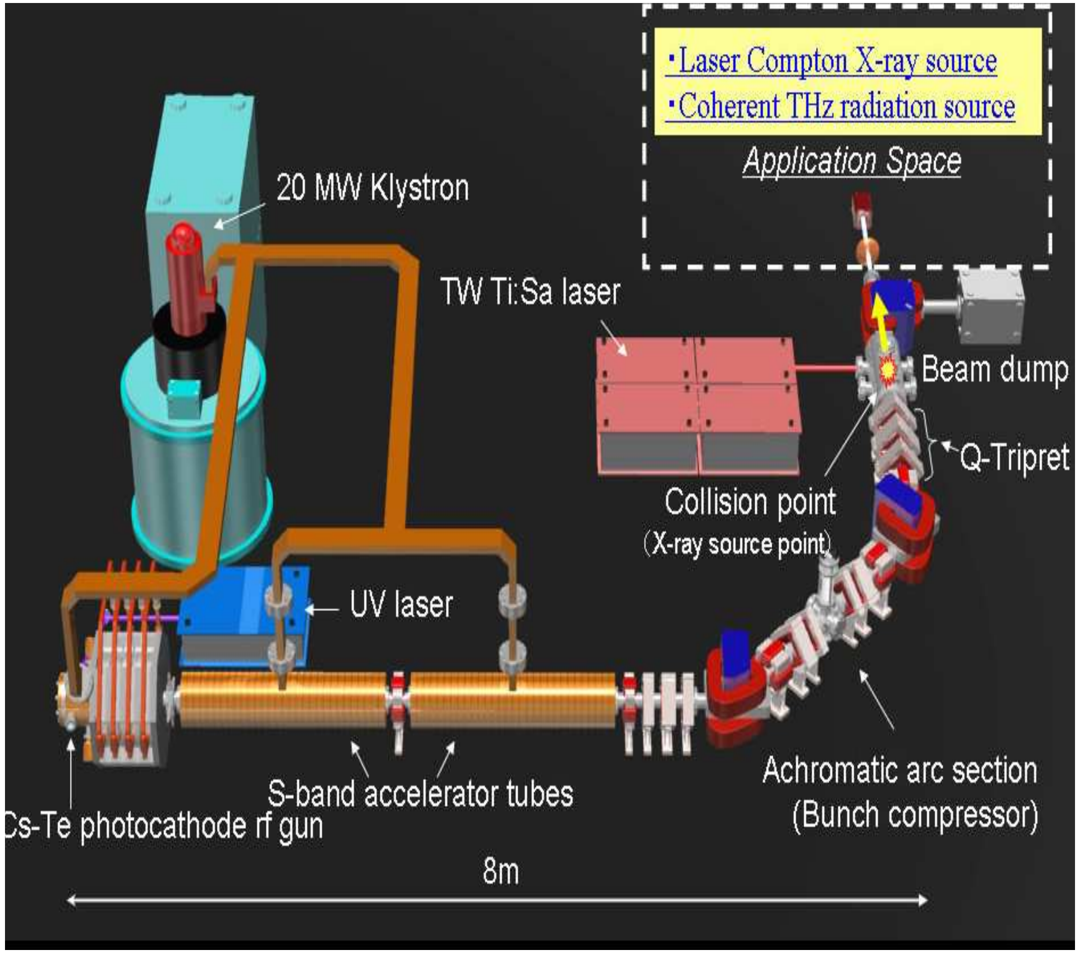
Total flux (@300mA): $8.4\text{x}10^{6}$ – $5.5\text{x}10^{7}$ ph/s (design)

Status: Operational + Development

Last update: 2012

Courtesy of Chuanxiang Tang, Tsinghua U.

Compton X-ray Sources: AIST, Japan



Facility/Project: (hard x-ray project)

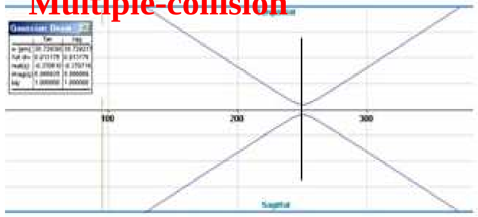
Institution: AIST

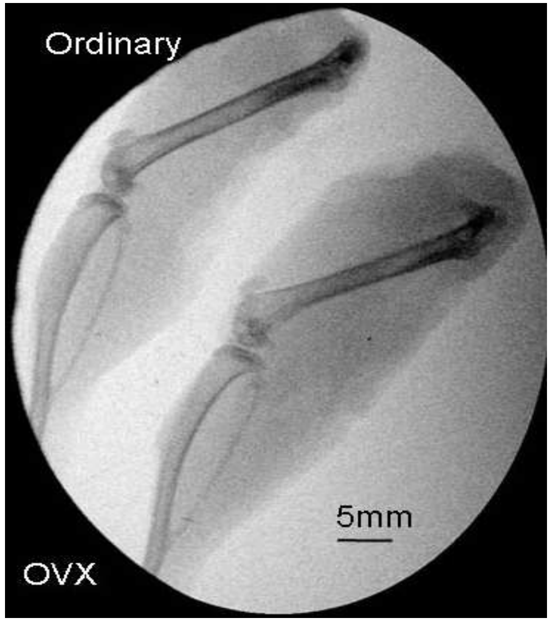
Country: Japan

Energy (kev): 10 – 40

Accelerator: Linac, 40 MeV
Laser: Ti:Sapphire (800 nm)
Flux: 5×10^6 ph/pulse (10 Hz)
(5×10^9 ph/s, est with multiple collisions)

Status: Operational + Development
Applications: Medical and industrial imaging

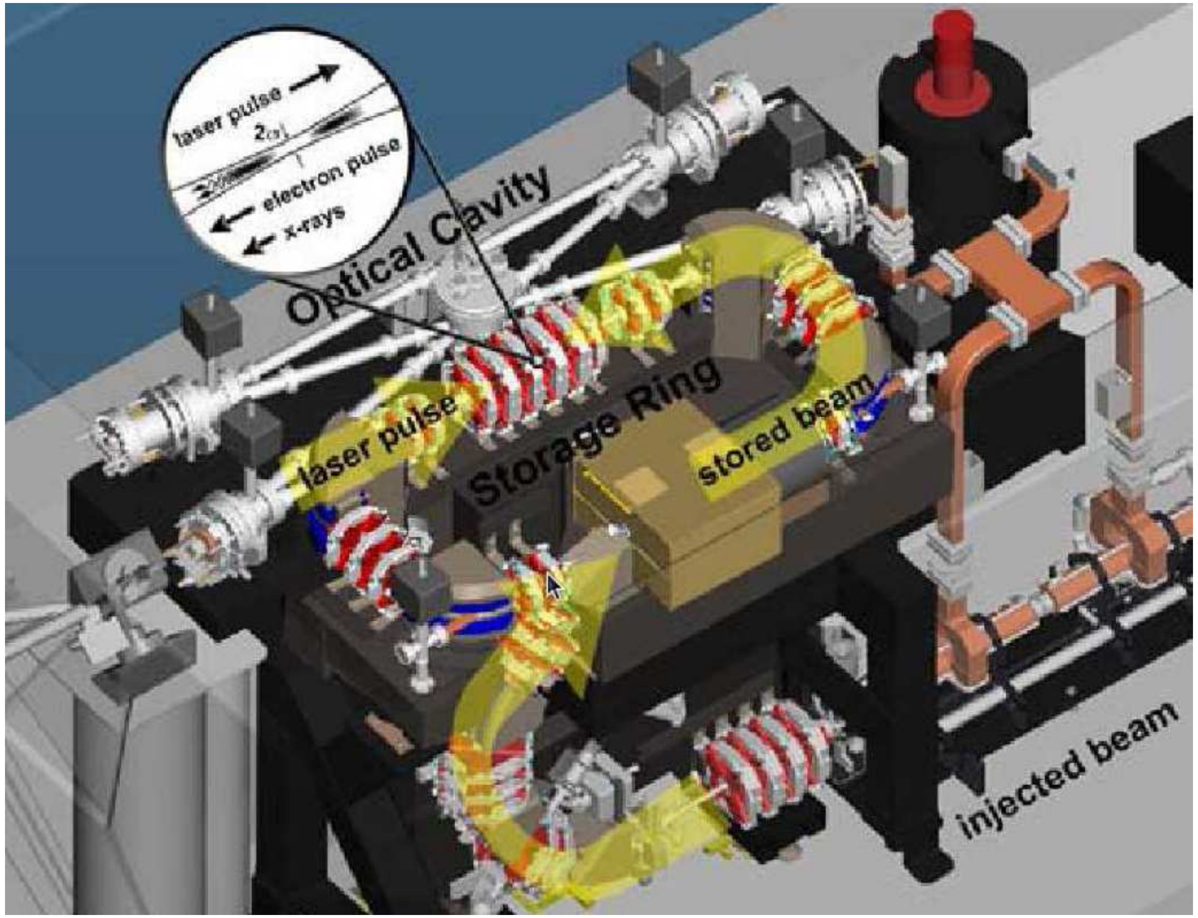




Sources:
R. Kuroda *et al.* THP038, PAC'11, New York, 2011

Last update: 2012

Compton X-ray Sources: Compact Light Source, Lyncean Tech., Inc.



Facility/Project: Compact Light Source

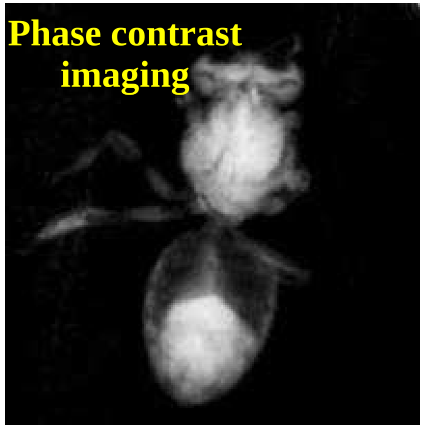
Company: Lyncean Technologies, Inc

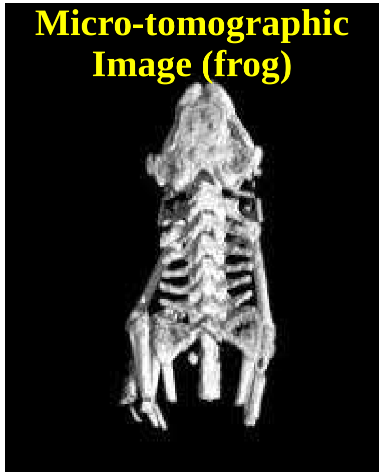
Country: USA

Energy (keV): 7 to 35

Accelerator: Storage Ring
Laser: FP cavity

Total flux: about 10^{11} ph/s
Status: Commercial product

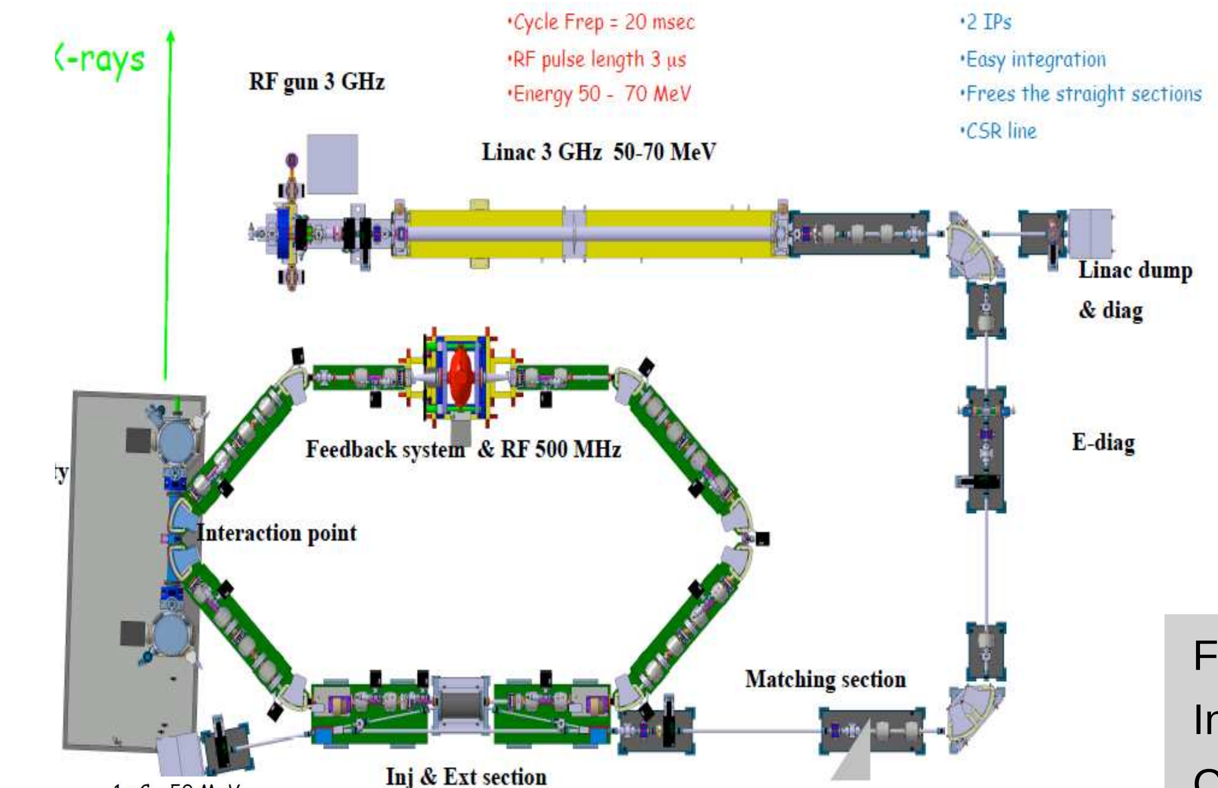


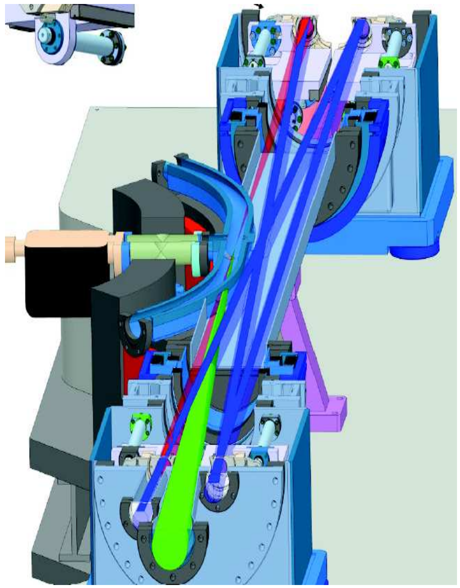


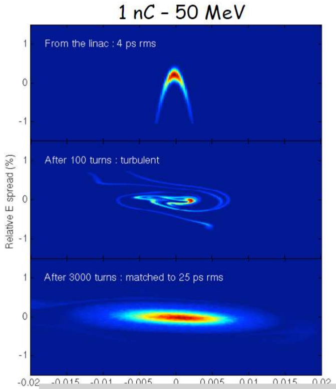
Sources:
1. www.lynceantech.com
2. G. Kraff and G. Priebe, Rev. Acc. Sci. & Tech. V3, 147 (2010).
3. R. Ruth, http://www.eurekalert.org/pub_releases/2009-01/lti-fsf010609.php

Last update: 2012

Compton X-ray Sources: Compact Light Source, Lyncean Tech., Inc.







Sources:
1. A. Variola et al. “The ThomX Project,” FLS2012, Jlab, Mar. 2012.

Facility/Project: ThomX

Institution: ThomX Collaboration

Country: France

Energy (keV): 40 – 90

Accelerator: Storage ring, 50 – 70 MeV, trans. and long. feedbacks for damping

Laser: FB-Cavity (1032 nm), F~30,000

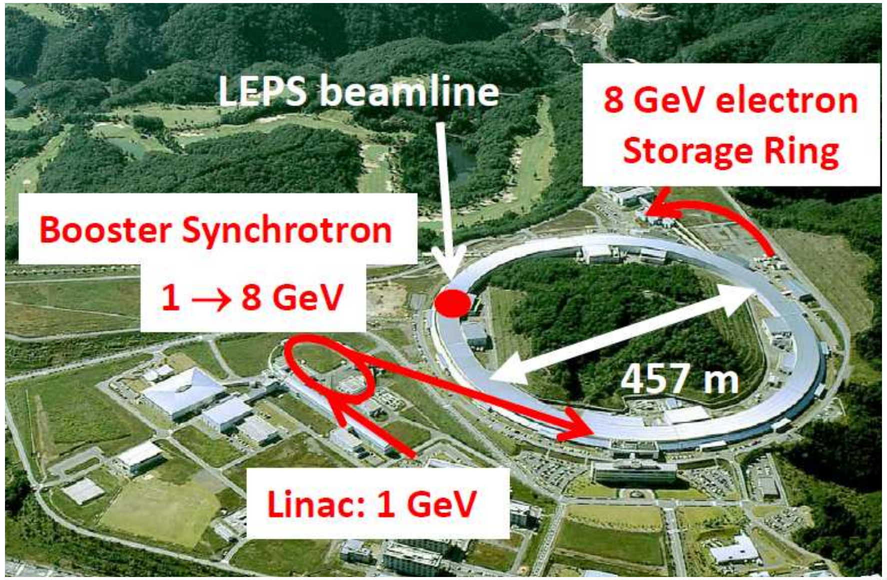
Total flux: 10^{11} – 10^{13} ph/s (design)

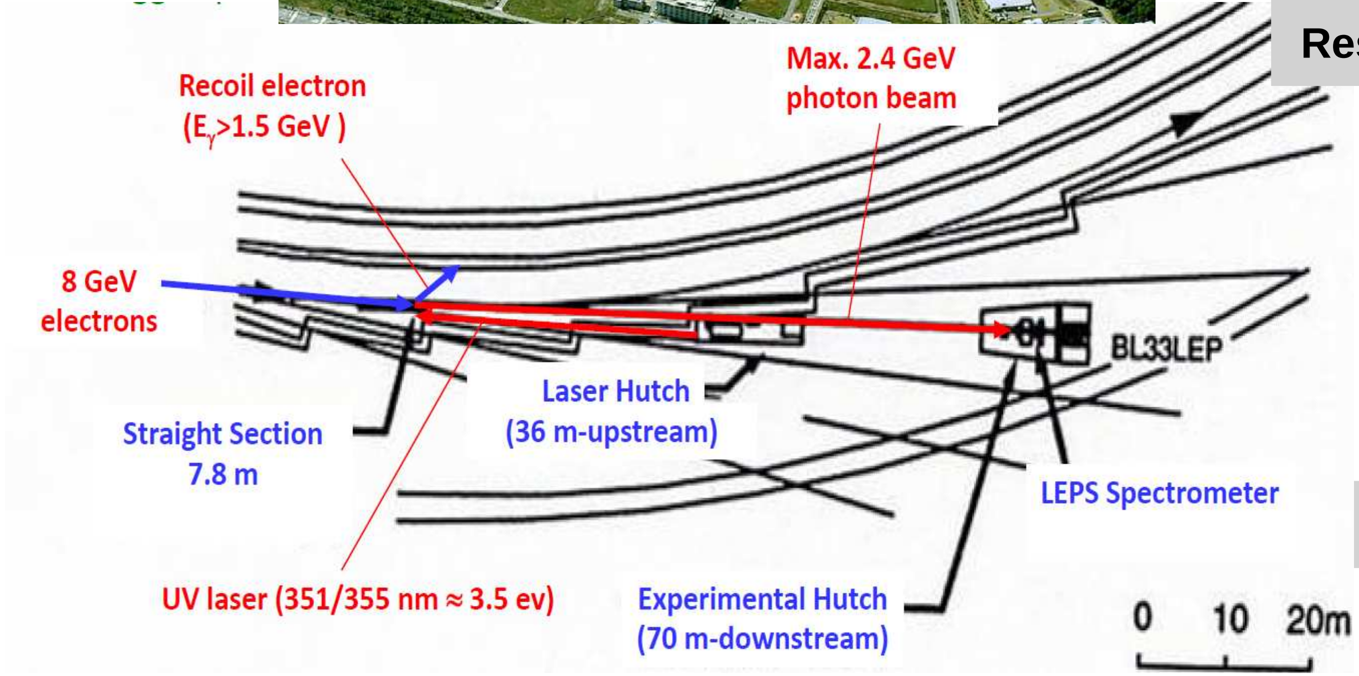
Status: Under construction

Applications: imaging, mammography, microtomography

Last update: 2012

Compton Gamma-ray Sources: **LEPS, SPring-8, Japan**





Facility/Project: LEPS

Institution: SPring-8

Country: Japan

Energy (MeV): 2,380 (2960, LEPS2)

Accelerator: Storage Ring, 8 GeV

Laser: 351 – 355 nm (3.5 eV); (LEPS2, 257 nm ,4.83 eV)

Total flux: few 10^6 g/s (10^6 tagged)

Status: Operational/User Program

Research: hadron structure and interactions

1. N. Muramatsu, “The LEPS Facility,” MAX-lab User Meeting, Nov. 2009.

Last update: 2012

TUNL

Access to various basic and applied studies

- **Basic physics** (nuclear structure, nuclear astrophysics, etc.)
- **National strategic demands** (nuclear power, aerospace, etc.)
- **Industry or Medicine** (NMR-CT, SPE-CT, etc.)

Facility/Project: SLEGS

Institution: Shanghai Syn. Rad. Fac. (SSRF)

Country: China

Energy (MeV): 2 – 20, 300 – 550

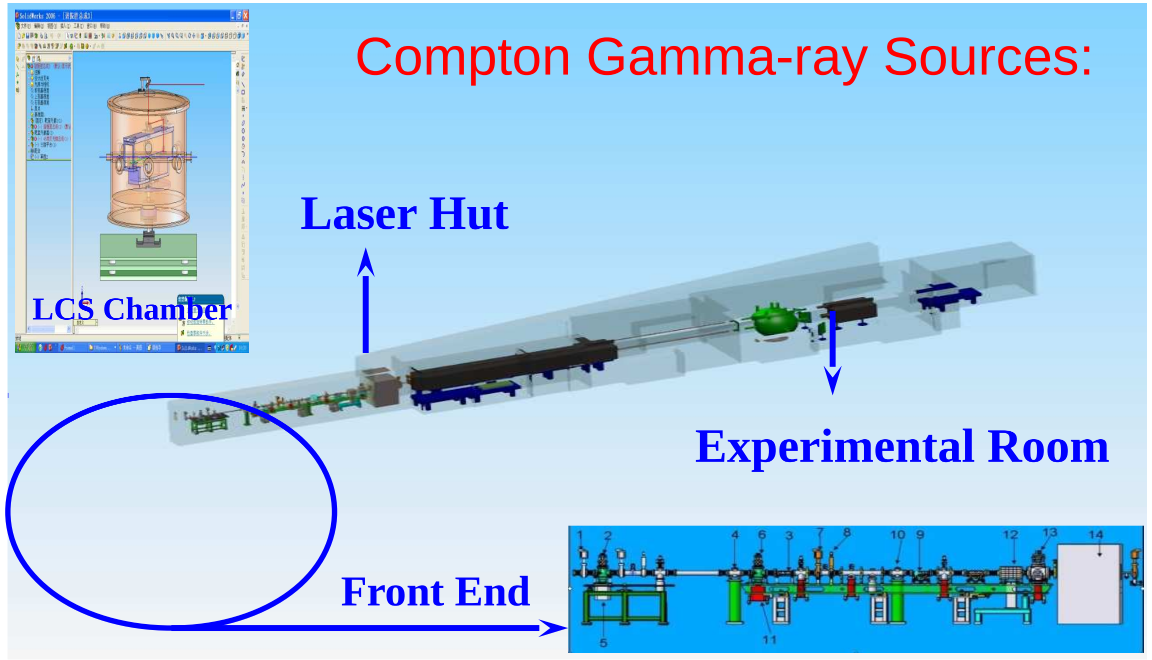
Accelerator: Storage Ring, 3.5 GeV

Laser: CO_2 ,or YAG

Total flux (@300mA): 10^5 – 10^7 g/s (low eng)
$6X10^6$ g/s (high eng)

Status: Under Development

SSRF Shanghai Synchrotron Radiation Facility



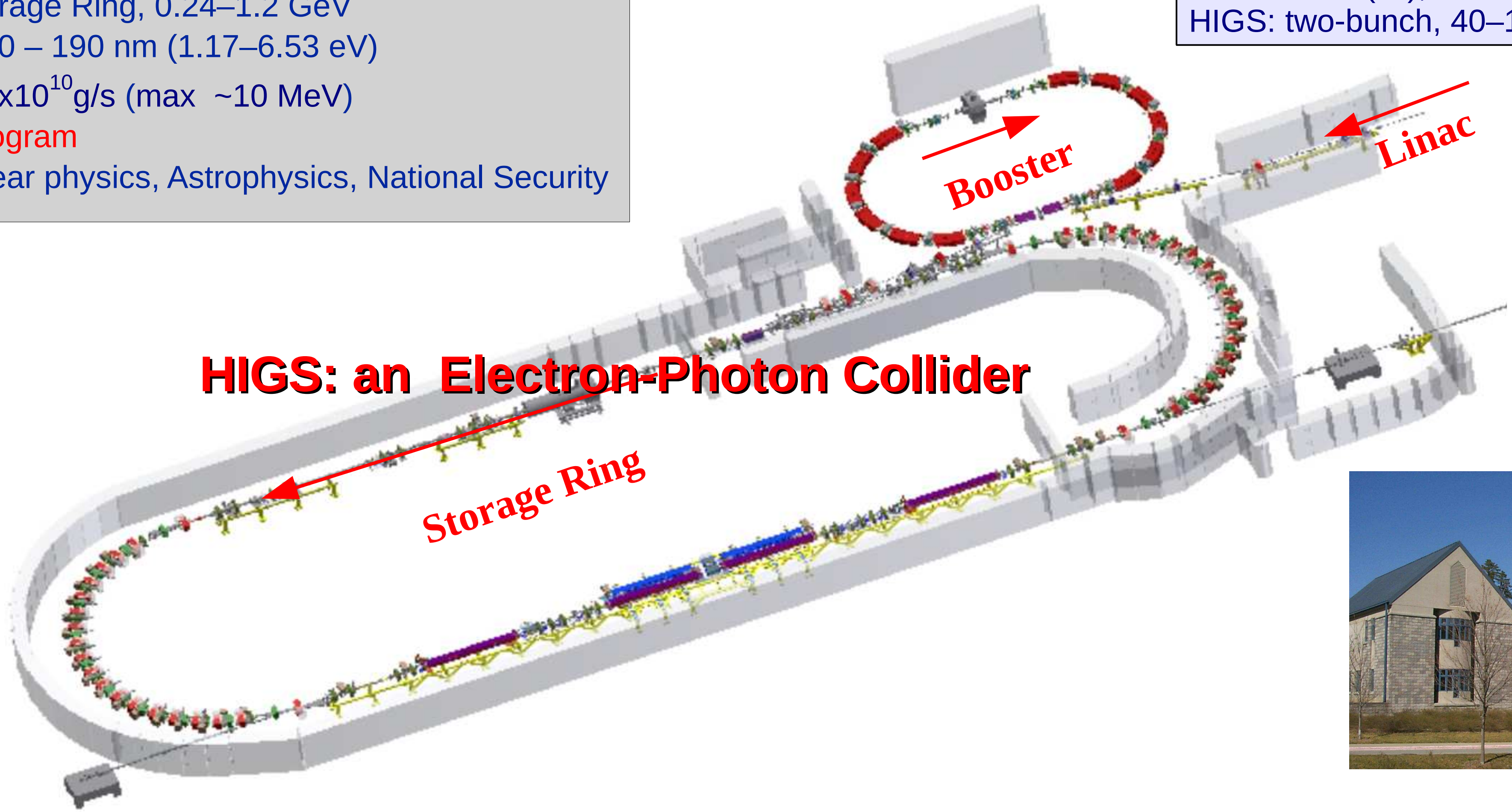
Last update: 2012

Courtesy of Wang Xu, SSRF

HIGS/TUNL: Accelerator Facility

Facility/Project: HIGS
Institution: TUNL
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–$3x10^{10}$ g/s (max ~10 MeV)
Status: User Program
Research: Nuclear physics, Astrophysics, National Security

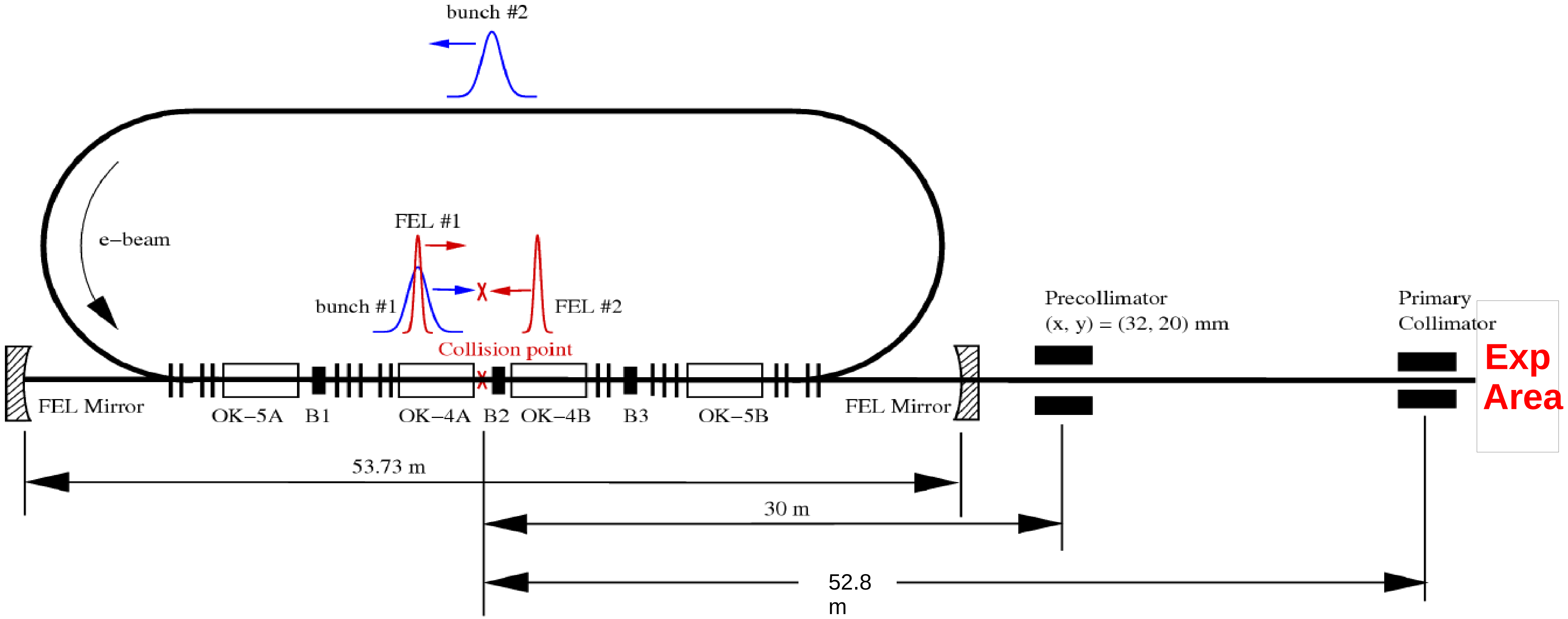
Accelerator Facility
160 MeV Linac pre-injector
160 MeV–1.2 GeV Booster injector
240 MeV–1.2 GeV Storage ring
FELs: OK-4 (lin), OK-5 (cir)
HIGS: two-bunch, 40–120 mA (typ)



HIGS R&D Team (2008–2020): M. Busch, M. Emamian, J. Faircloth, B. Jia, H. Hao, S. Hartman, C. Howell, S. Huang, B. Li, J. Li, W. Li, P. Liu, S. Mikhailov, M. Pentico, V. Popov, C. Sun, G. Swift, B. Thomas, P. Wang, P. Wallace, W. Wu, Y.K. Wu, W. Xu, J. Yan

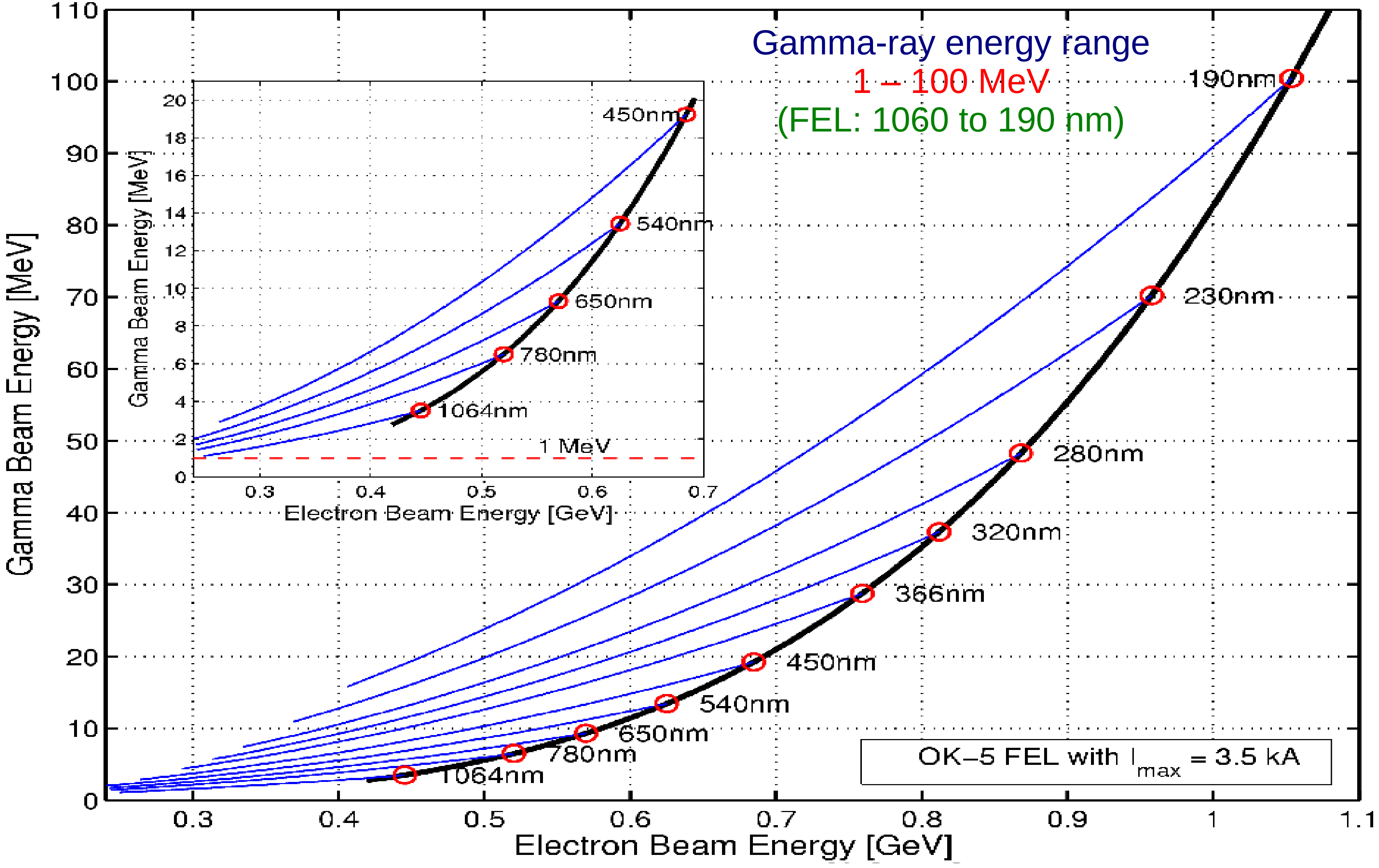
Operation Principle of HIGS

Two electron bunches + two FEL pulses



V.N. Litvinenko *et al*. PRL v. 78, n. 24, p. 4569 (1997)

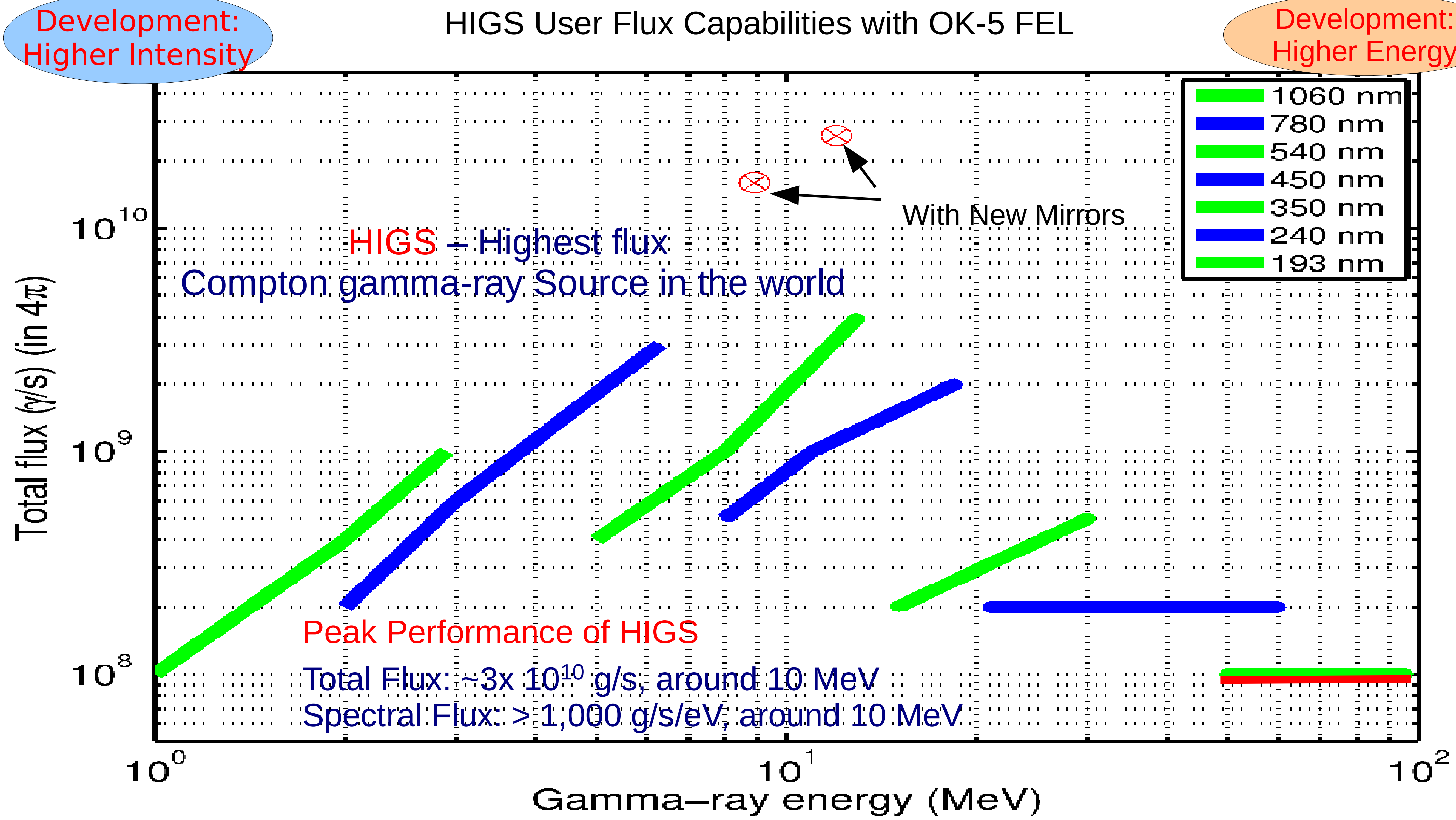
Gamma Energy Tuning Range with OK-5 FEL (3.5 kA)



HIGS Flux Summary

Development: Higher Intensity

Development: Higher Energy



Electron/Photon Collision Angle Monitor

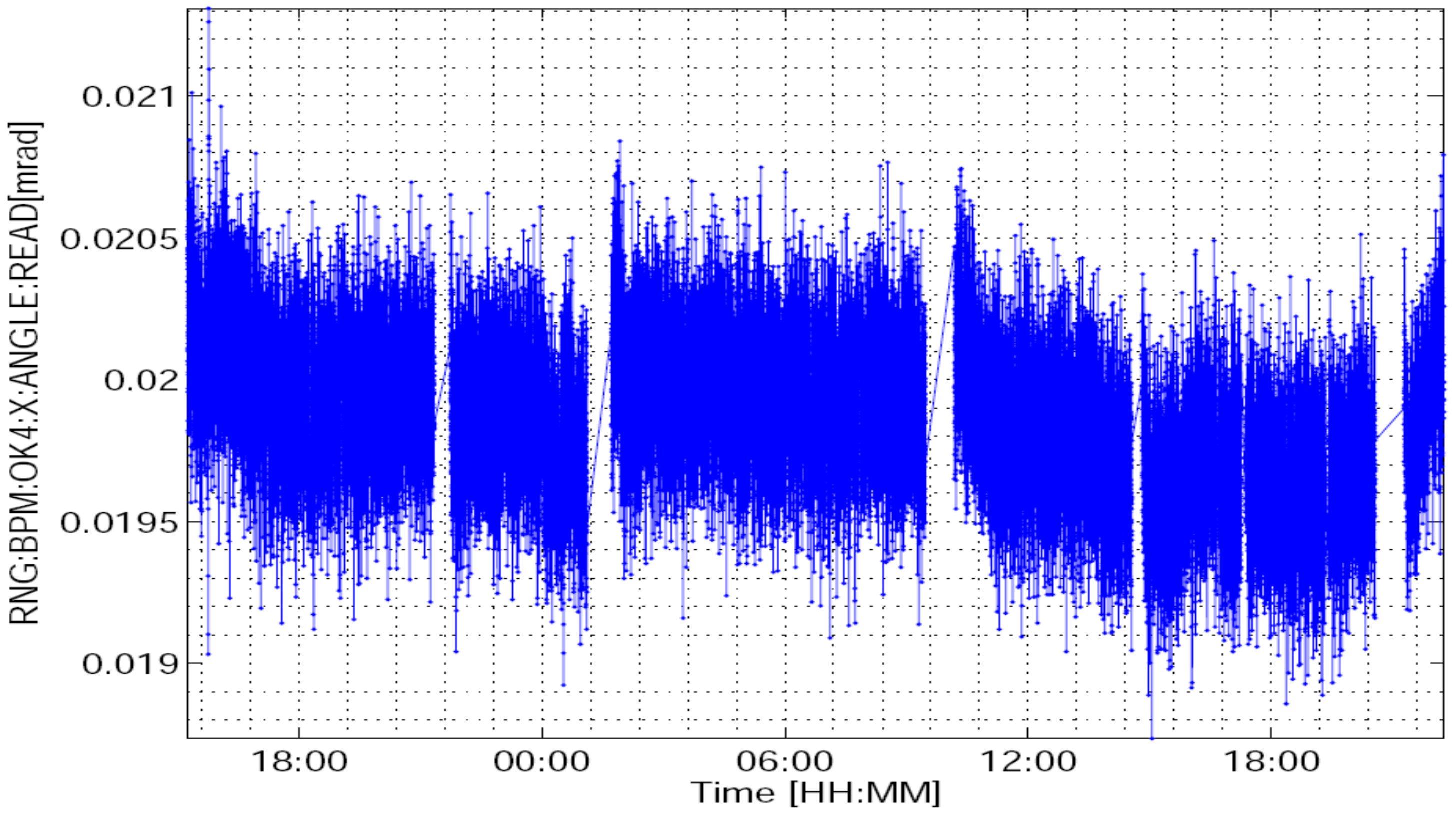
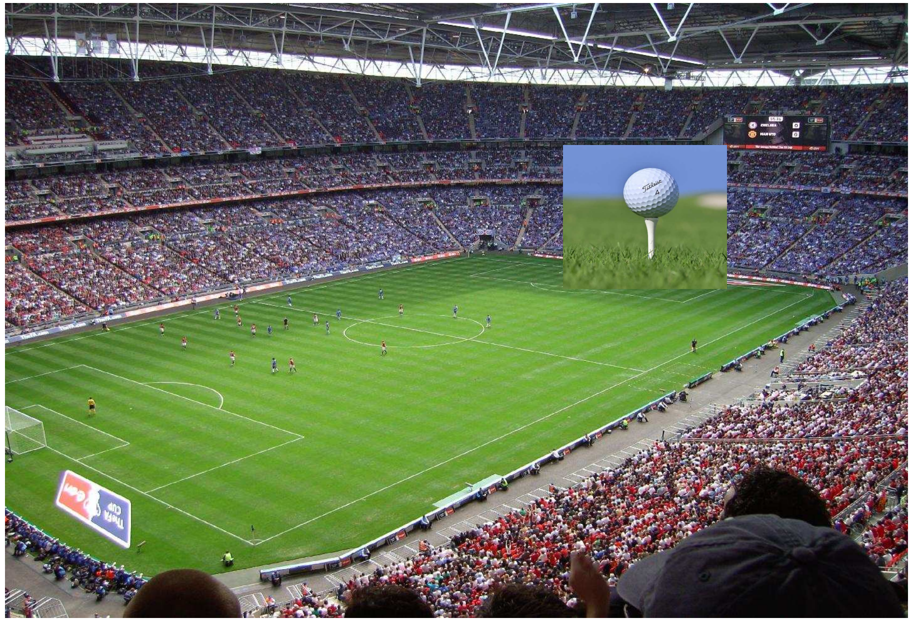
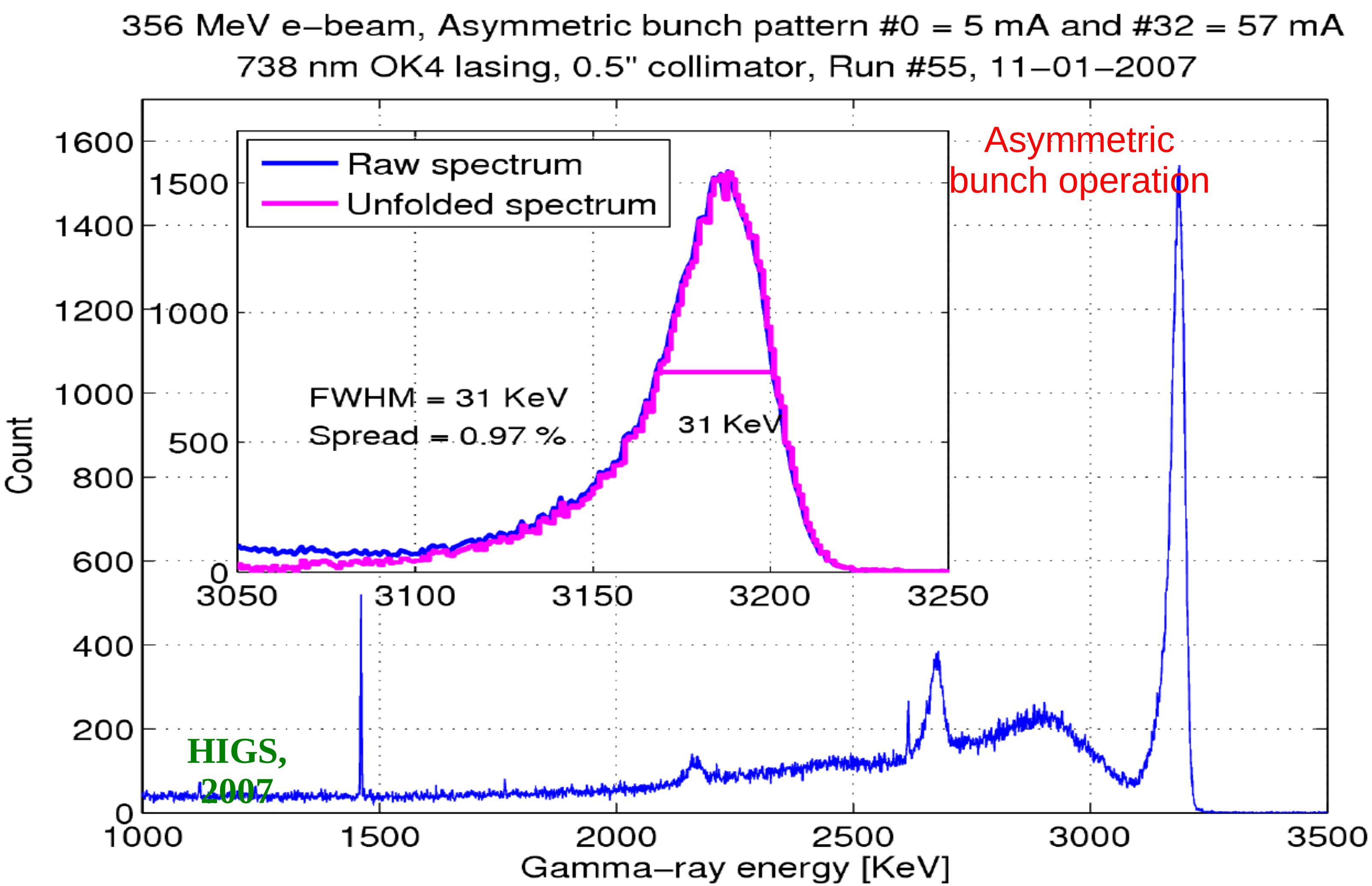


Figure 15: Horizontal beam angle at OK4 for about 36 hours operation from Aug. 20 to Aug. 21, 2009. The angle varied 2.5μrad (peak to peak) during this operation, this value corresponds to 150μm variation of gamma ray beam position at the gamma vault which is located 60 m downstream of the collision 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.



Aiming at a golf ball at the end of 150 football fields

High Energy Resolution



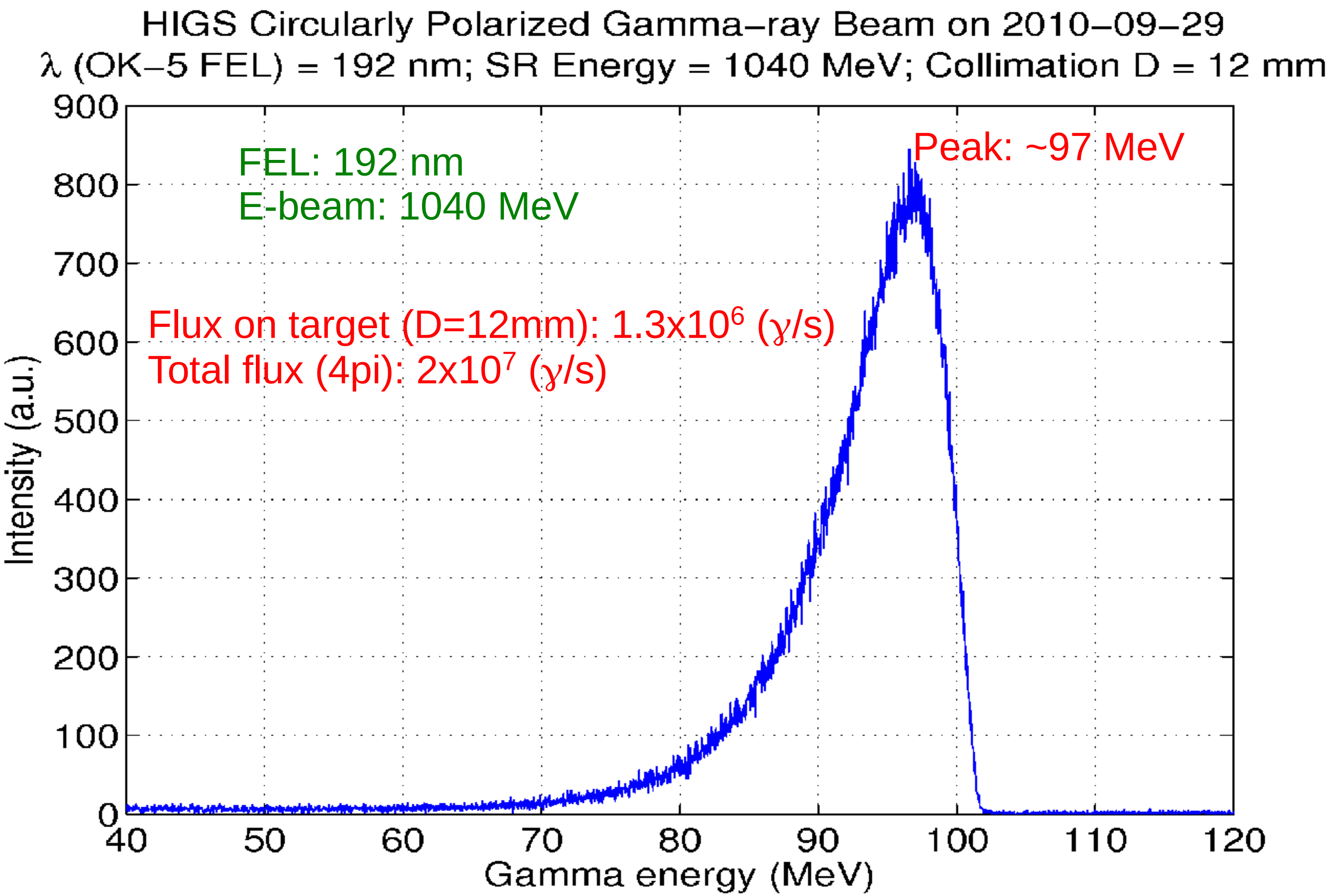
FWHM: 0.97%

RMS: 0.41%

Gamma beam energy resolution in high-flux operation:

Typically 3 – 5% (FWHM), or larger, selected by collimation

Electron/Photon Collision Angle Monitor



New research frontiers: nucleons structure

- Electric and magnetic polarizabilities
- Spin polarizabilities

Operational Compton Gamma-ray Sources for Nuclear Physics

TUNL
Duke UNIVERSITY

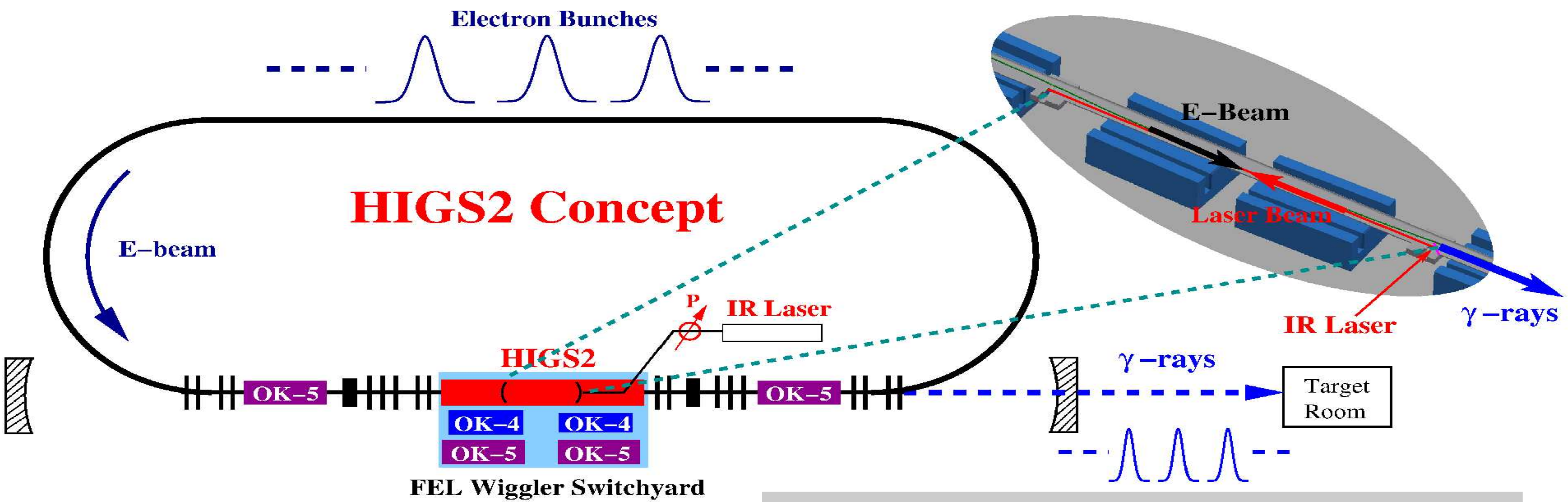
Table 1: A list of major laser Compton gamma-ray sources around the world which are being operated for nuclear physics research.

Project Name Parameters	HIGS	LEPS/LEPS2	NewSUBARU	UVSOR-III
Location	Durham, U.S.	Hyogo, Japan	Hyogo, Japan	Okazaki, Japan
Accelerator technology	Storage Ring	Storage ring	Storage ring	Storage ring
Laser technology	FEL	Solid state laser	Solid state or gas laser	Fiber laser or gas laser
Collision technology	Intra-cavity, head-on	External laser, head-on	External laser, head-on	External laser, head-on
Electron energy [MeV]	240–1,200	8,000	500–1,500	750
Laser wavelength [nm]	1,060–190	266 and 355	532–10,600	1,940&10,600
Charge and pulse CW: Avg. current [mA] Q [nC] @ reprate [MHz]	 10–120 1.8–22 @5.58	 100 0.2–2 @50–500	 300 0.6 @ 500	 300 3 @ 90
γ-beam energy [MeV]	1–100	1,300–2,900	1–40	1–5.4
Polarization	Lin, Cir	Lin, Cir	Lin, Cir	Lin, Cir
γ-beam energy resolution (FWHM)	0.8% –10% collimation	$< 15\%$ tagging	10% ($\phi = 3$ mm) collimation	2.9% ($\phi = 2$ mm) collimation
γ-beam pulse structure a. CW operation [MHz] b. Pulsed operation	 5.58 (typical) 0.5–1.5 ms (FW) 2–100 Hz Gain modulated	 50–500	 500 8 ns pulse, 10–100 kHz, Q-switched	 90
On-target flux [avg, γ/s]	10^3– 3×10^9	10^6–10^7	10^5–3×10^6 ($\phi = 3$ mm)	4×10^5 ($\phi = 2$ mm)
Total flux [avg, γ/s]	10^6– 3×10^{10}	10^6–10^7	10^7–4×10^7	10^7
Operation date	Since 1996	Since 1999	Since 2005	Since 2015

TUNL

Duke UNIVERSITY

HIGS2: Next-Generation Gamma-ray Source



Research Programs

- Nuclear Structure
- Nuclear Astrophysics
- Hadronic Parity Violation

Status: Seeking funding

Projected Performance

- 2–3 orders of higher flux than HIGS (2–8 MeV)
- 1064 nm FP cavity: 2 – 12 MeV
- Total Flux: 10^{10} – $2x10^{12}$ g/s
- Pol: Linear, or Circular (rapid switch)
- High-res capability: 0.6% (FWHM)

Compton Gamma-ray Sources: VEGA System, ELI-NP, Europe

Facility/Project: Variable Energy Gamma-Ray (VEGA) System

Institution: Extreme Light Infrastructure, Nuclear Physics

Country: Romania

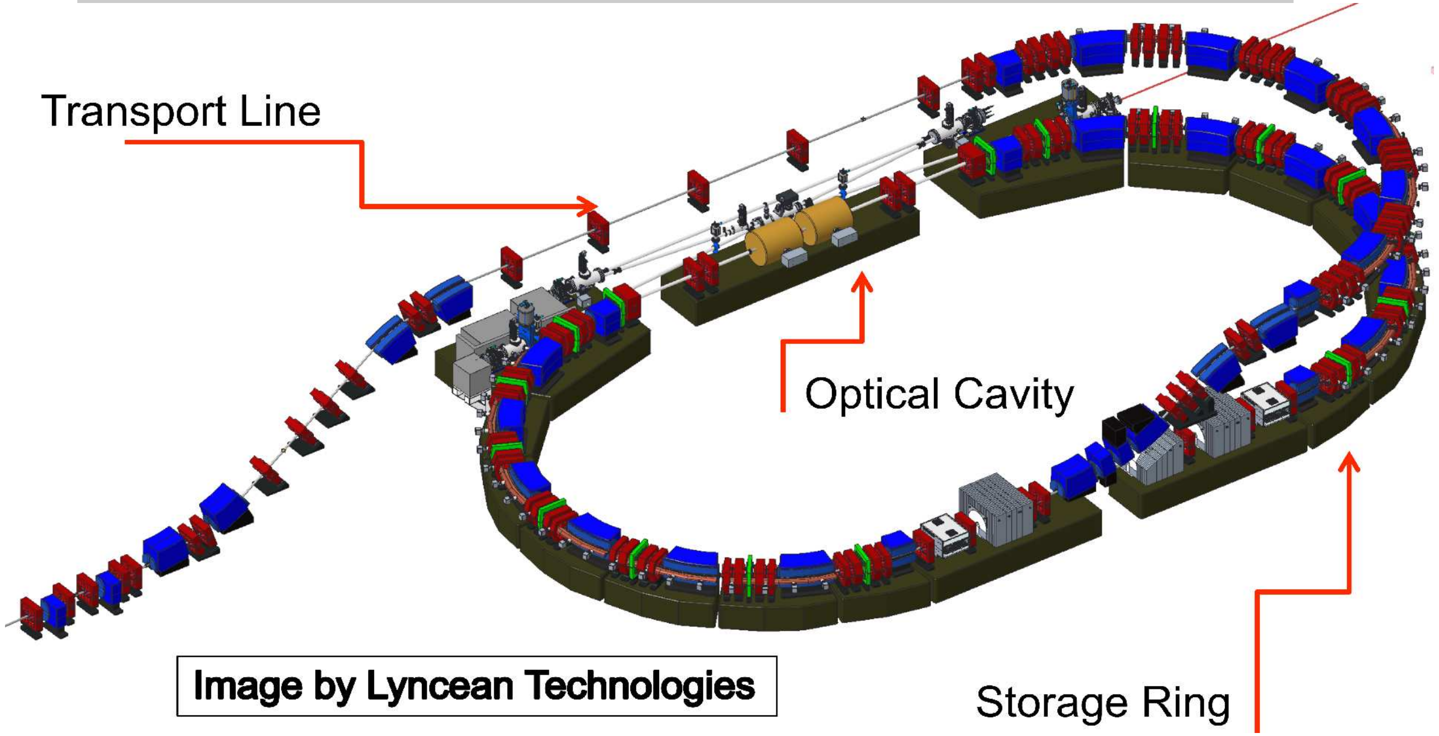
Energy (MeV): 1 – 10 (1030 nm); 2 – 19.5 (515 nm)

Accelerator: Storage ring

Laser: IR laser: 1030 nm; Green laser: 515 nm

Total flux: > 1.1 x 10^{11} ph/s, > 5.0 x 10^{3} ph/s/eV

Status: Under development



Courtesy: Catalin Matei (ELI-NP),
Benjamin Hornberger and Ronald Ruth (Lyncean Tech.)

Last update: 2020

Next Generation

Compton Gamma-ray Sources

Unconventional Approaches

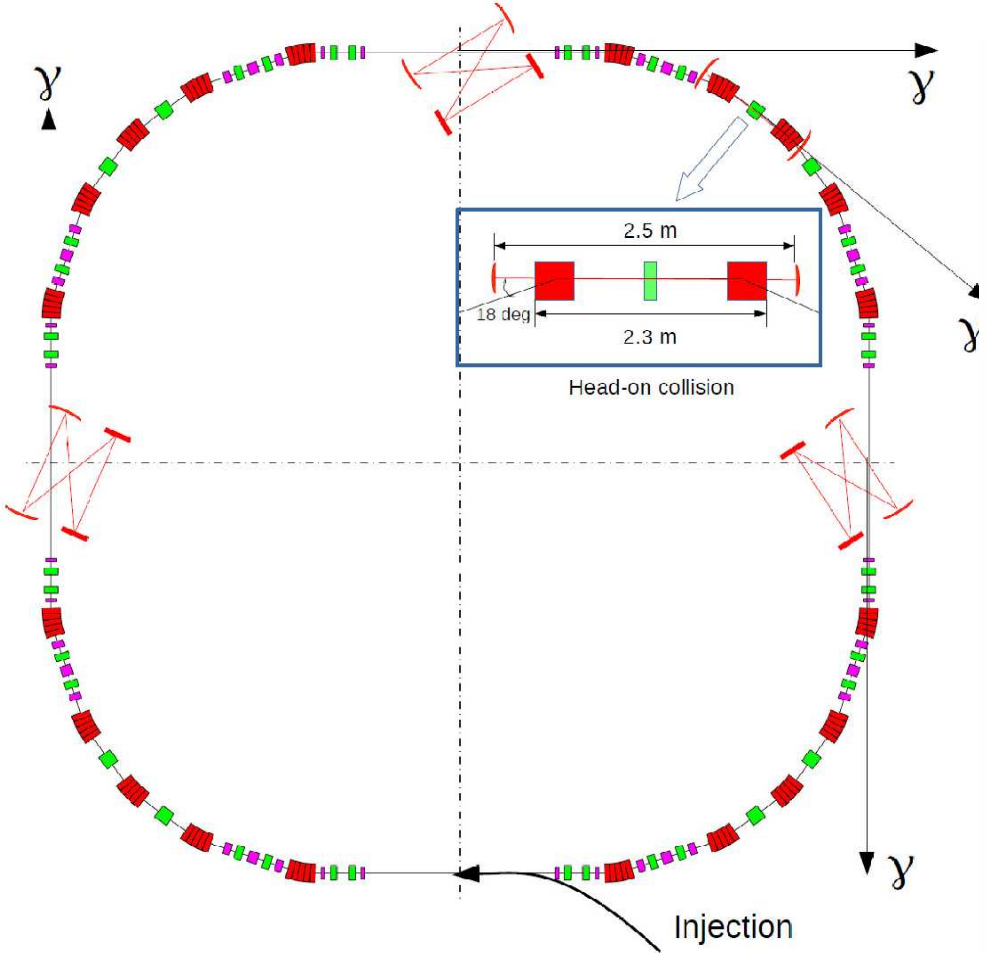
- Laser-plasma Accelerator Based Compton Sources

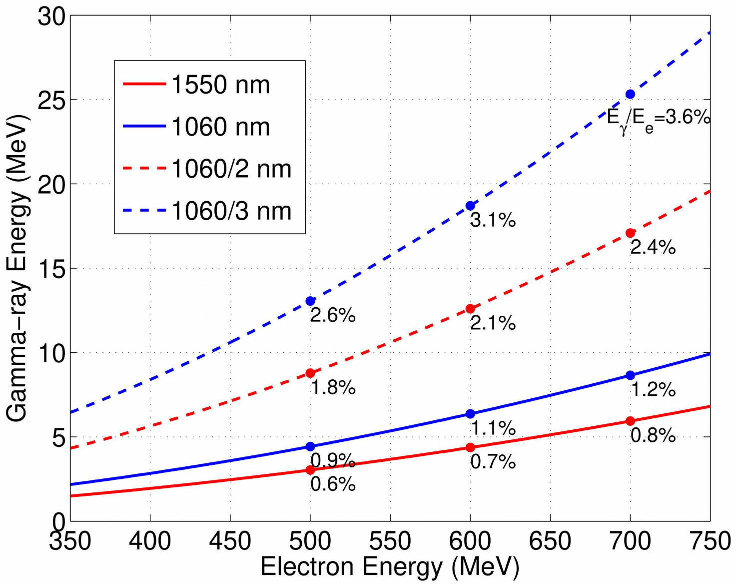
- Gamma Factory at Large Hadron Collider (LHC), CERN

Atomic-beam-driven light source using resonant photon absorption to reach several orders of magnitude higher flux than conventional Compton gamma-ray sources

Next-generation CGS: Storage Ring Based Low Energy CGS

Low-Energy CGS: Storage Ring





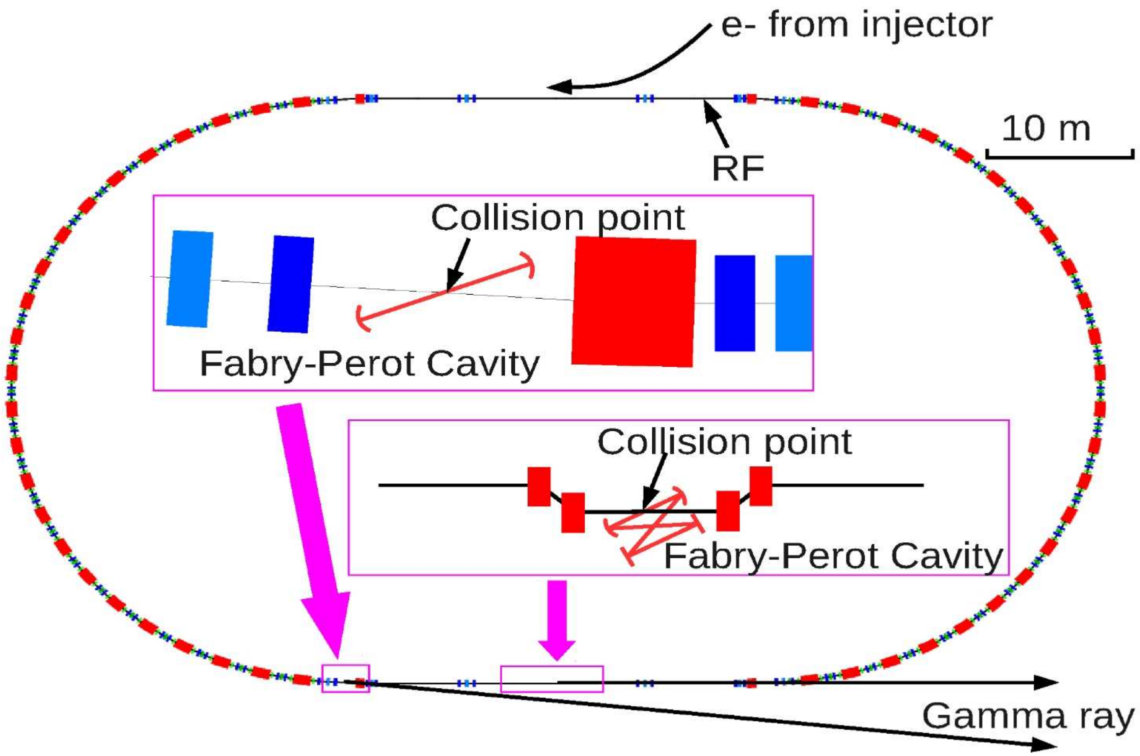
E-beam (MeV)	E_γ (MeV)	λ_1 (nm) 1064	$\lambda_1/3$ 355	λ_2 (nm) 1550	$\lambda_2/3$ 517
350	$E_{\gamma,\min}$	2.2	6.4	1.5	4.4
750	$E_{\gamma,\max}$	9.9	29	6.8	20

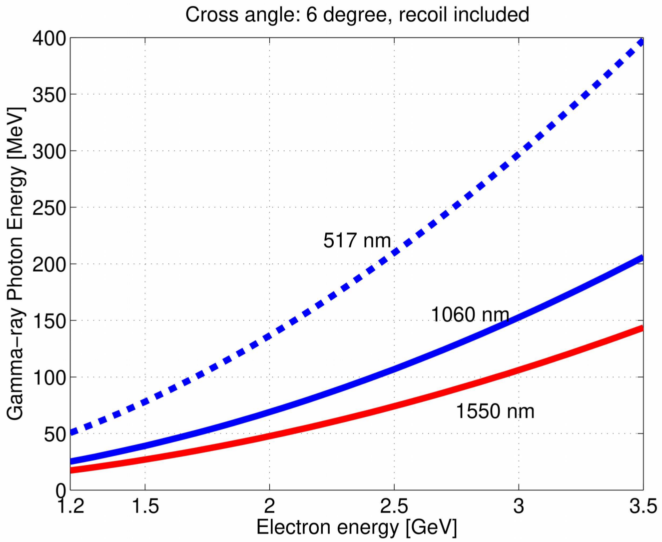
Electron beam	
Beam energy	500 MeV
Stored currents	1000 mA
Bunch filled	24
Hori./Vert. emittance	7.5/0.75 nm-rad
Hori./Vert. size (rms)	212/39 μm
Bunch length (rms)	150 ps
Laser beam	
Wavelength	1064 nm
Intracavity power	100 kW
Pulse length (rms)	20 ps
Hori./Vert. size (rms)	40/40 μm
Gamma-ray beam	
Max. energy	4.43 MeV
Collision rate	121.66 MHz
Collision angle	6°
Luminosity	3.3×10^{36} cm^{-2}s^{-1}
Total flux (in 4π solid angle)	2.2×10^{12} γ/s

E-beam: $E = 500$ MeV, $I = 1$ A	FP cavity: 100 kW Beam size: 40/40 μm	
Laser wavelength (nm)	$\lambda_1 = 1064$	$\lambda_2 = 1550$
Tot. flux (γ/s): θ=6°	2.2×10^{12}	2.8×10^{12}
Tot. flux (γ/s): head-on	2.4×10^{13}	3.1×10^{13}

Whitepaper: "International Workshop on Next Generation Gamma-Ray Source," C.R. Howell *et al*., 2020

High-Energy CGS: Storage Ring





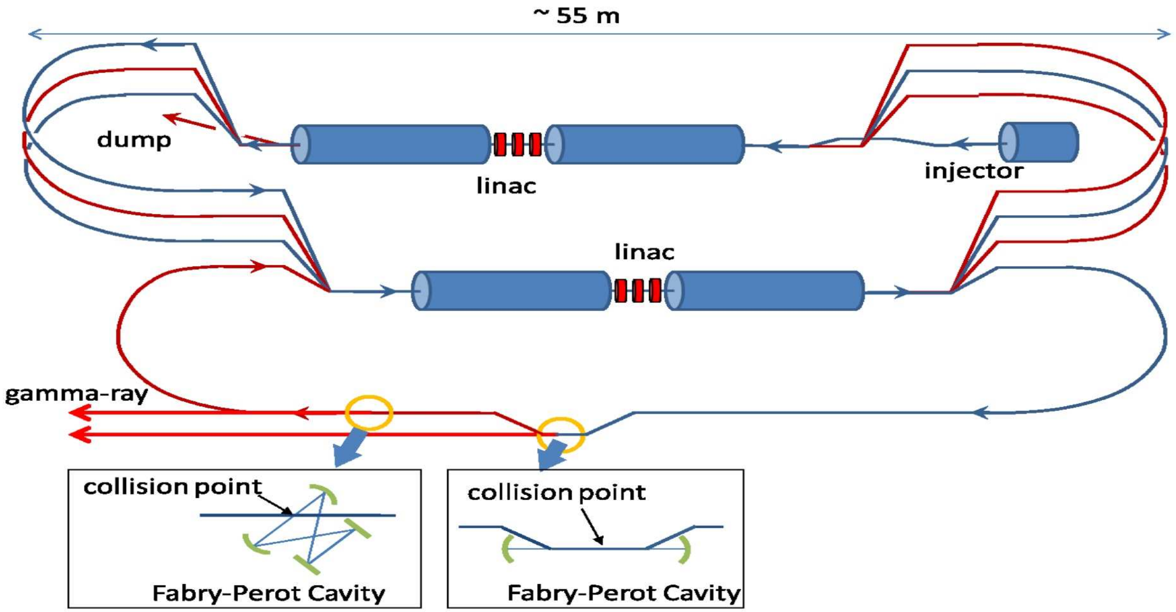
E-beam (GeV)	E_γ (MeV)	λ_1 (nm) 1064	λ_2 (nm) 1550	$\lambda_2/3$ 517
1.2	$E_{\gamma,\min}$	25	17	51
3.5	$E_{\gamma,\max}$	205	144	398

Electron beam	
Beam energy	3.27 GeV
Stored currents	500 mA
Bunch filled	64
Hori./Vert. emittance	1.94/0.16 nm-rad
Hori./Vert. size (rms)	100/26 μm
Bunch length (rms)	60 ps
Laser beam	
Wavelength	517 nm
Intracavity power	20 kW
Pulse length (rms)	20 ps
Hori./Vert. size (rms)	40/40 μm
Gamma-ray beam	
Max. energy	350 MeV
Collision rate	95.42 MHz
Collision angle	6°
Luminosity	5.7×10^{35} cm^{-2}s^{-1}
Total flux (in 4π solid angle)	3.4×10^{11} γ/s

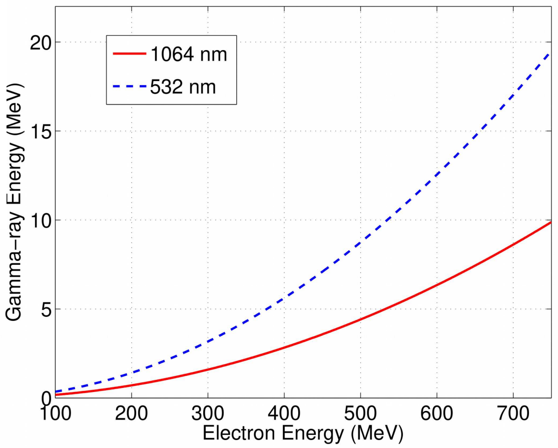
E-beam: $E = 3.27$ GeV, $I = 0.5$ A	Laser beam: λ =517 nm; Beam size: 40/40 μm	
FP cavity power (kW)	20 (kW)	100 (kW)
Tot. flux (γ/s): θ=6°	3.4×10^{11}	1.7×10^{12}

Whitepaper: "International Workshop on Next Generation Gamma-Ray Source,"
C.R. Howell *et al*., 2020

Next-generation CGS: ERL Based Low Energy CGS



Low-Energy CGS: Energy-Recovery Linac



Electron beam	
Beam energy	500 MeV
Average current	20 mA
Hori./Vert. emittance (norm.)	1mm-mrad
Hori./Vert. size (rms)	15 μm
Bunch length (rms)	3 ps
Laser beam	
Wavelength	1064 nm
Intracavity power	70 kW
Pulse length (rms)	10 ps
Hori./Vert. size (rms)	15/15 μm
Gamma-ray beam	
Max. energy	4.41 MeV
Collision rate	81.25 MHz
Collision angle	6°
Luminosity	2.6×10^{36} cm^{-2}s^{-1}
Total flux (in 4π solid angle)	1.7×10^{12} γ/s

E-beam (MeV)	E_γ (MeV)	λ_1 (nm) 1064	$\lambda_1/2$ 532
100	$E_{\gamma,\min}$	0.18	0.36
750	$E_{\gamma,\max}$	9.9	19.5

E-beam current (mA)	20	20	40
FP cavity power (kW)	70	70	70
Laser beam size (μm)	30/30	15/15	15/15
Tot. flux (γ/s): θ=6°	1.1×10^{12}	1.7×10^{12}	3.4×10^{12}
Tot. flux (γ/s): head-on	5.4×10^{12}	1.3×10^{13}	2.7×10^{13}

Whitepaper: "International Workshop on Next Generation Gamma-Ray Source," C.R. Howell *et al.*, 2020