Accelerator-driven Compton Gamma-ray Source: High Intensity Gamma-ray Source

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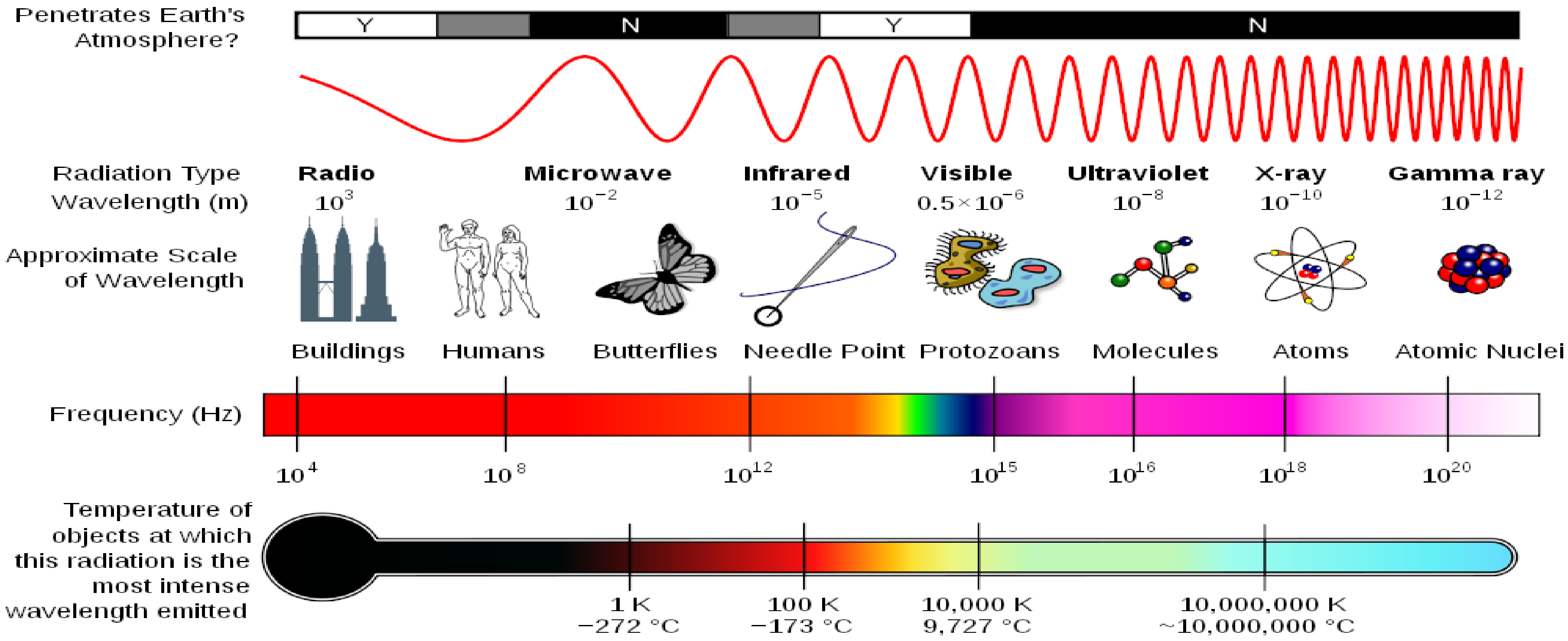
Outline

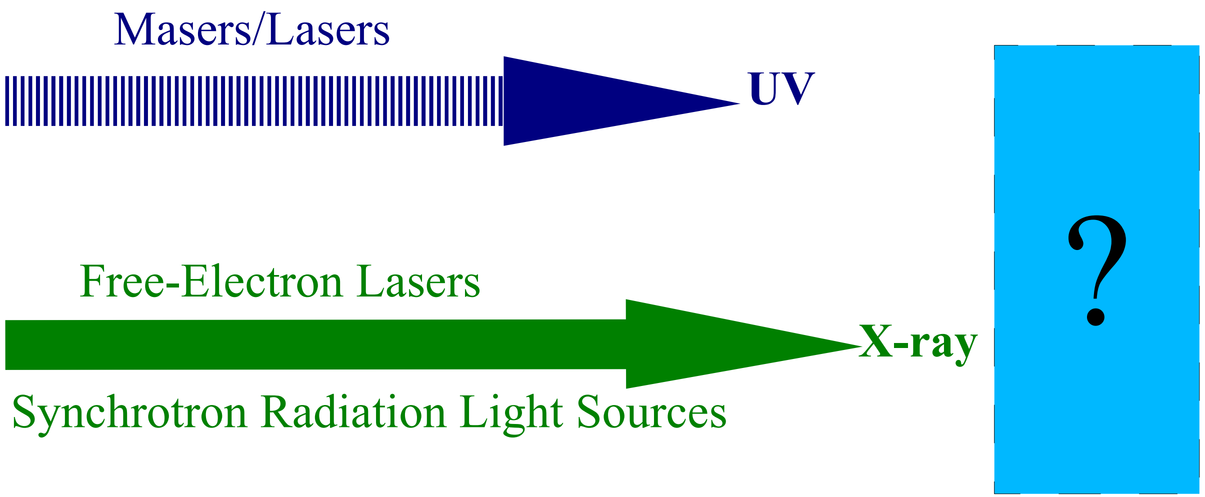
- **Accelerator Driven Light Sources**
  - Compton Gamma-ray Source and Characteristics

- **High Intensity Gamma-ray Source (HIGS) and New Capabilities**
  - Operation Principle of HIGS
  - Gamma-ray Beam Capabilities and Performance
  - Pulsed Beam, Two-color, Polarization Control
  - Summary of Nuclear Physics Program at HIGS

- **Future Compton Gamma-ray Sources**

Spectrum of Electromagnetic Radiation





Masers/Lasers

UV

Free-Electron Lasers

X-ray

Synchrotron Radiation Light Sources

?

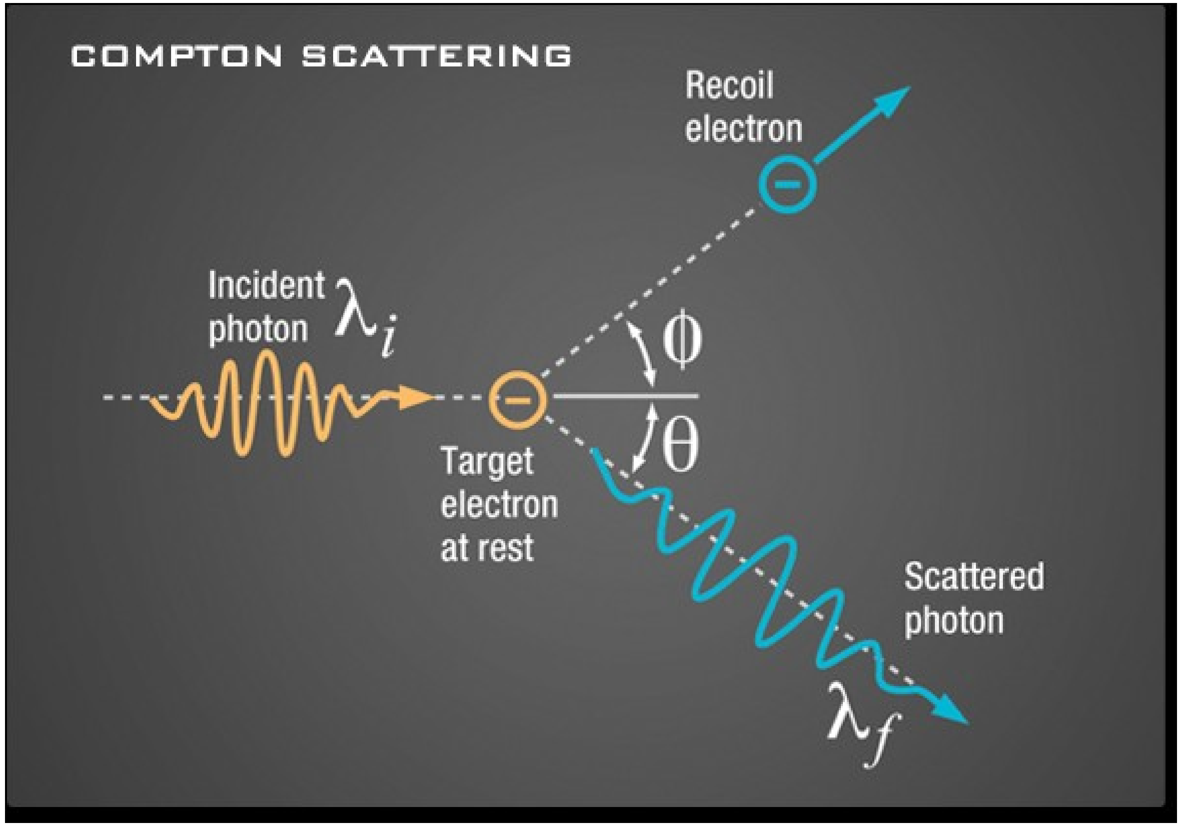
Compton Scattering

Compton Scattering

Arthur H. Compton (1892 – 1962)

Discovery: 1923

Nobel Price for Physics: 1927

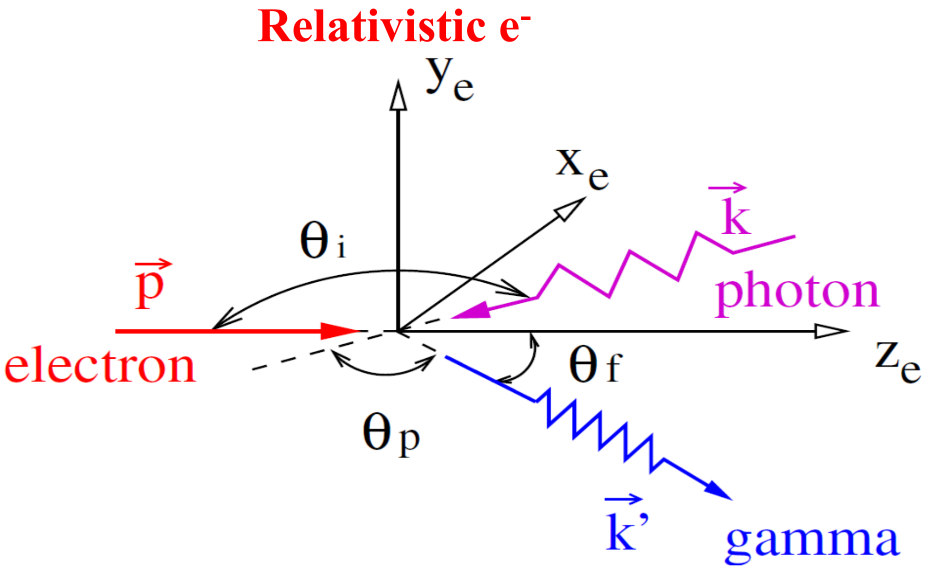


$$\lambda_f - \lambda_i = \frac{h}{m_e c}(1 - \cos\theta)$$

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.

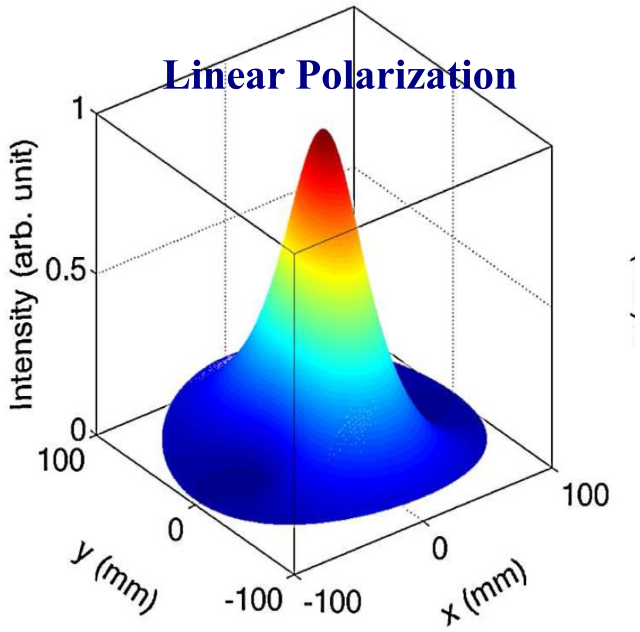
Photon Energy

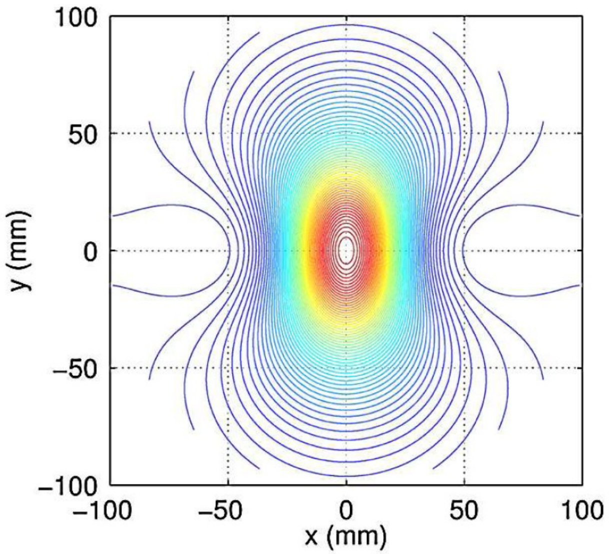


$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f + \frac{\hbar\omega}{\mathcal{E}_e}(1-\cos\theta_{ph})}$$

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

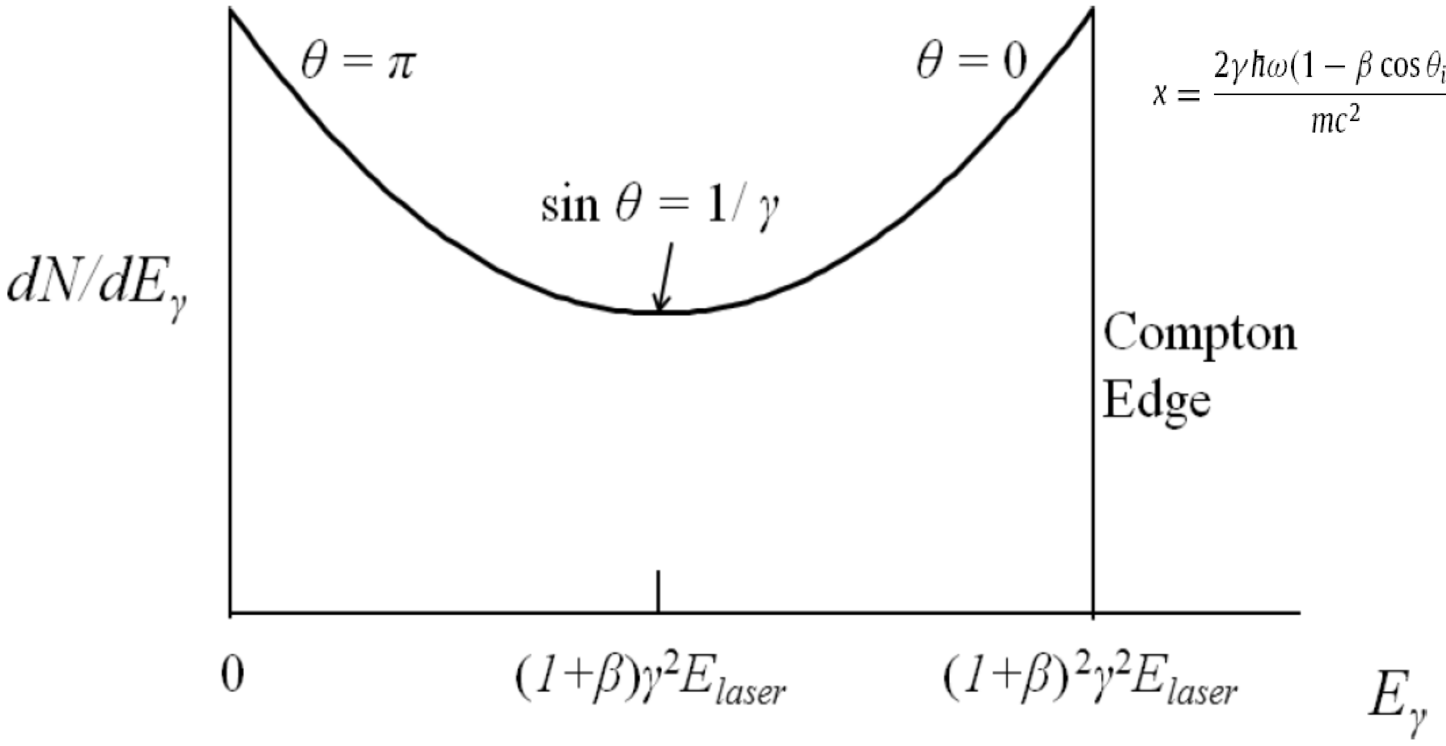
C. Sun and Y. K. Wu, Phys. Rev. ST Accel. Beams 14, 044701 (2011)





Compton Photon Beam Flux

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



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

Thomson cross-section:

$$\sigma_0 = 6.6524\times10^{-29}\,m^2$$

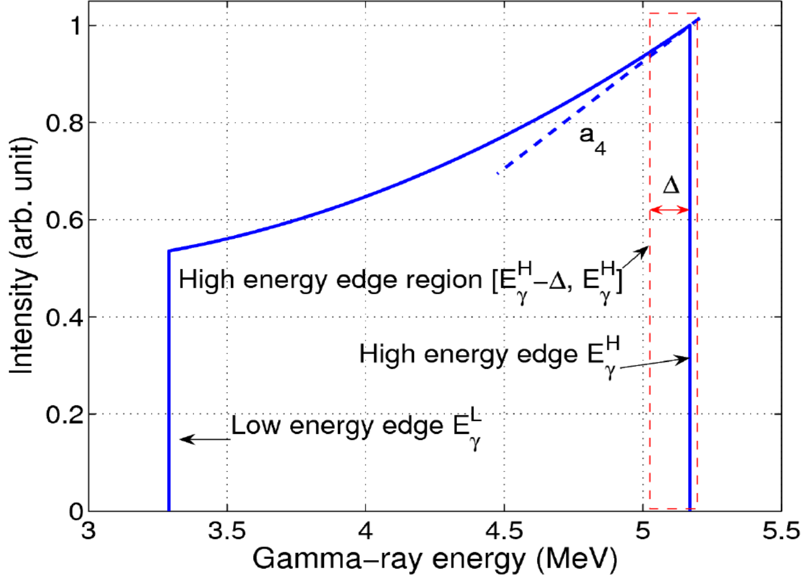
Compton Photon Sources = Electron-Photon Colliders

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

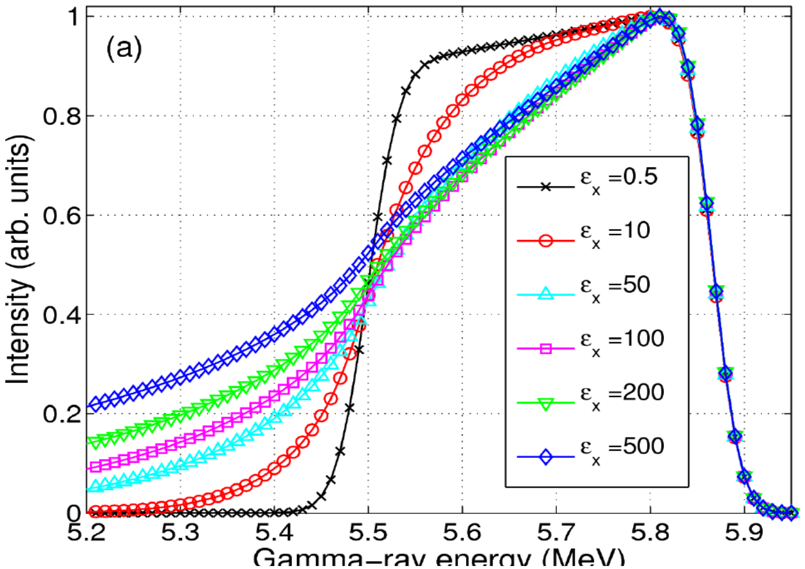
Figure: G. Kraff and G. Priebe, Rev. Acc. Sci. & Tech. V3, 147 (2010).

Energy Distribution of Compton Gamma-beam

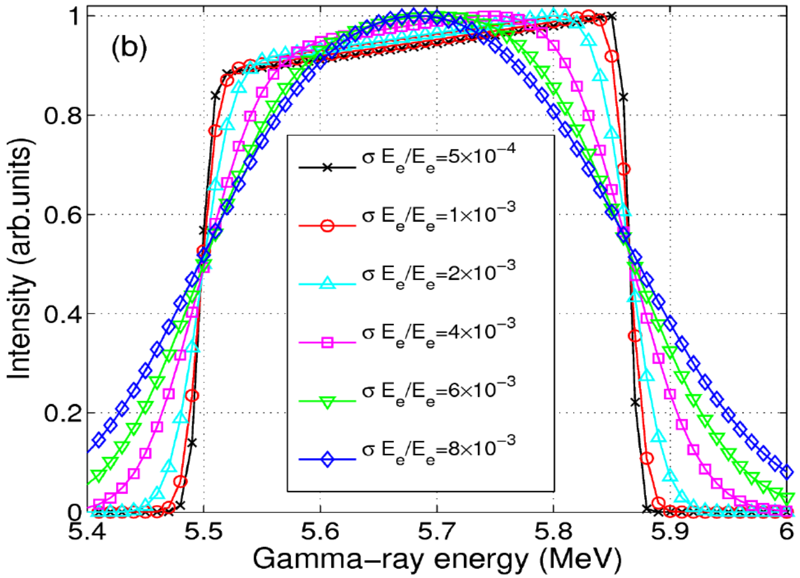
Monochromatic electron and photon beams



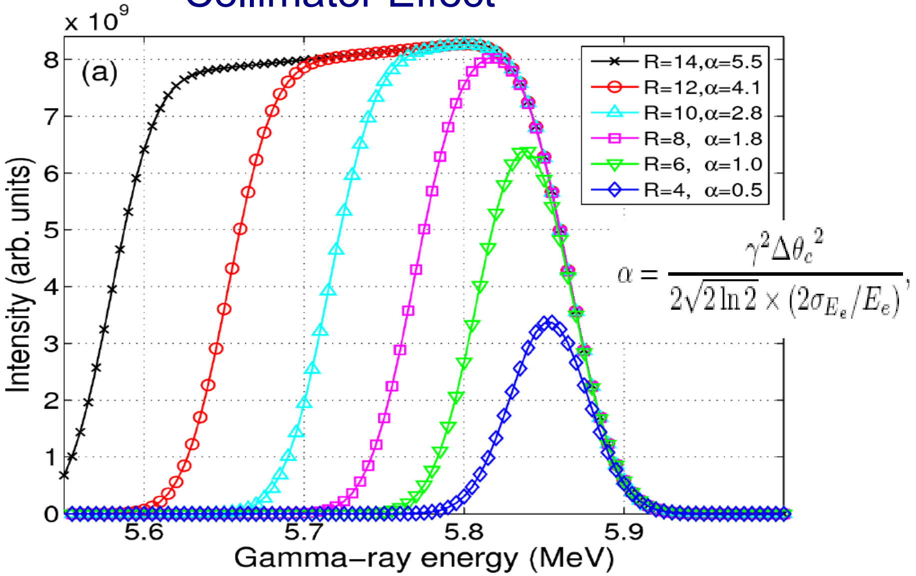
Emittance Effect (Scaled)



E-beam Energy Spread Effect (Scaled)



Collimator Effect



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

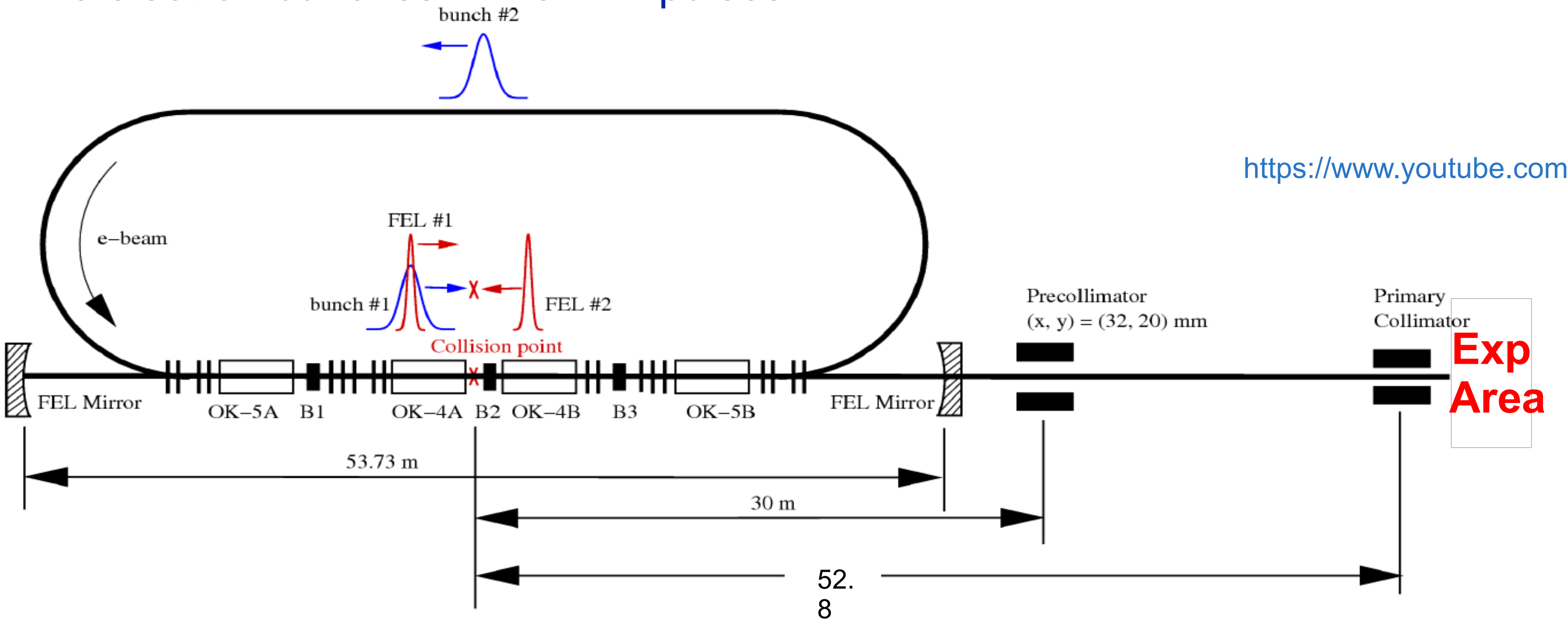
C. Sun *et al.* Phys. Rev. ST Accel. Beams 12, 062801 (2009).

High-Intensity Gamma-ray Source (HIGS) and New Capabilities with Accelerator Research

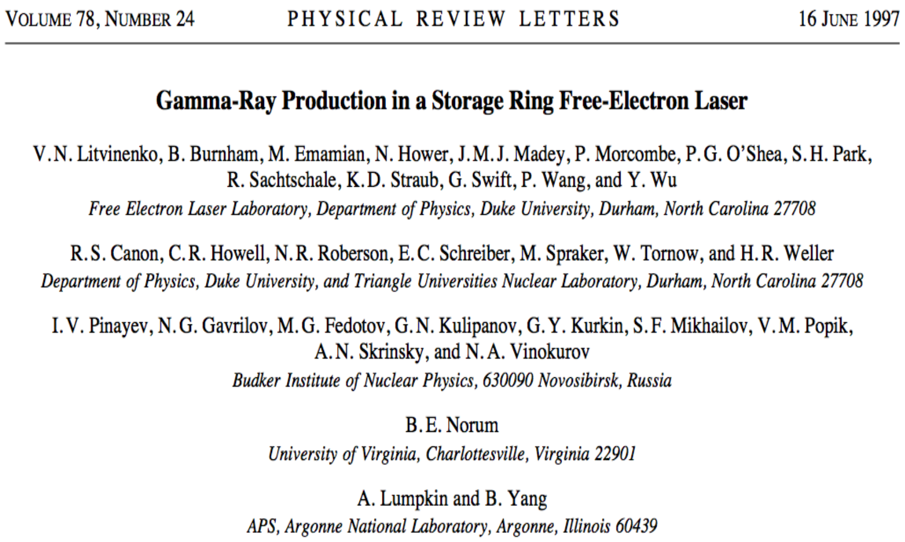
- HIGS Facility: Compton Gamma-ray Source and Characteristics
- Pulsed Mode Operation
- Two-color FEL
- Polarization Control

Operation Principle of HIGS

Two electron bunches + two FEL pulses



https://www.youtube.com/watch?v=JoIXGPNGEOc



VOLUME 78, NUMBER 24 PHYSICAL REVIEW LETTERS 16 JUNE 1997

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

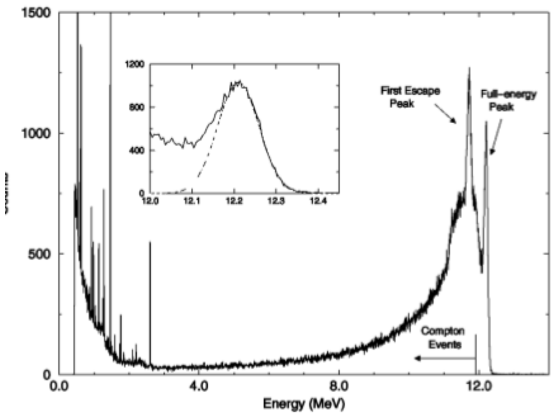
V.N. Litvinenko, B. Burnham, M. Emamian, N. Hower, J.M.J. Madey, P. Morcombe, P.G. O'Shea, S.H. Park,
R. Sachtschale, K.D. Straub, G. Swift, P. Wang, and Y. Wu
Free Electron Laser Laboratory, Department of Physics, Duke University, Durham, North Carolina 27708

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

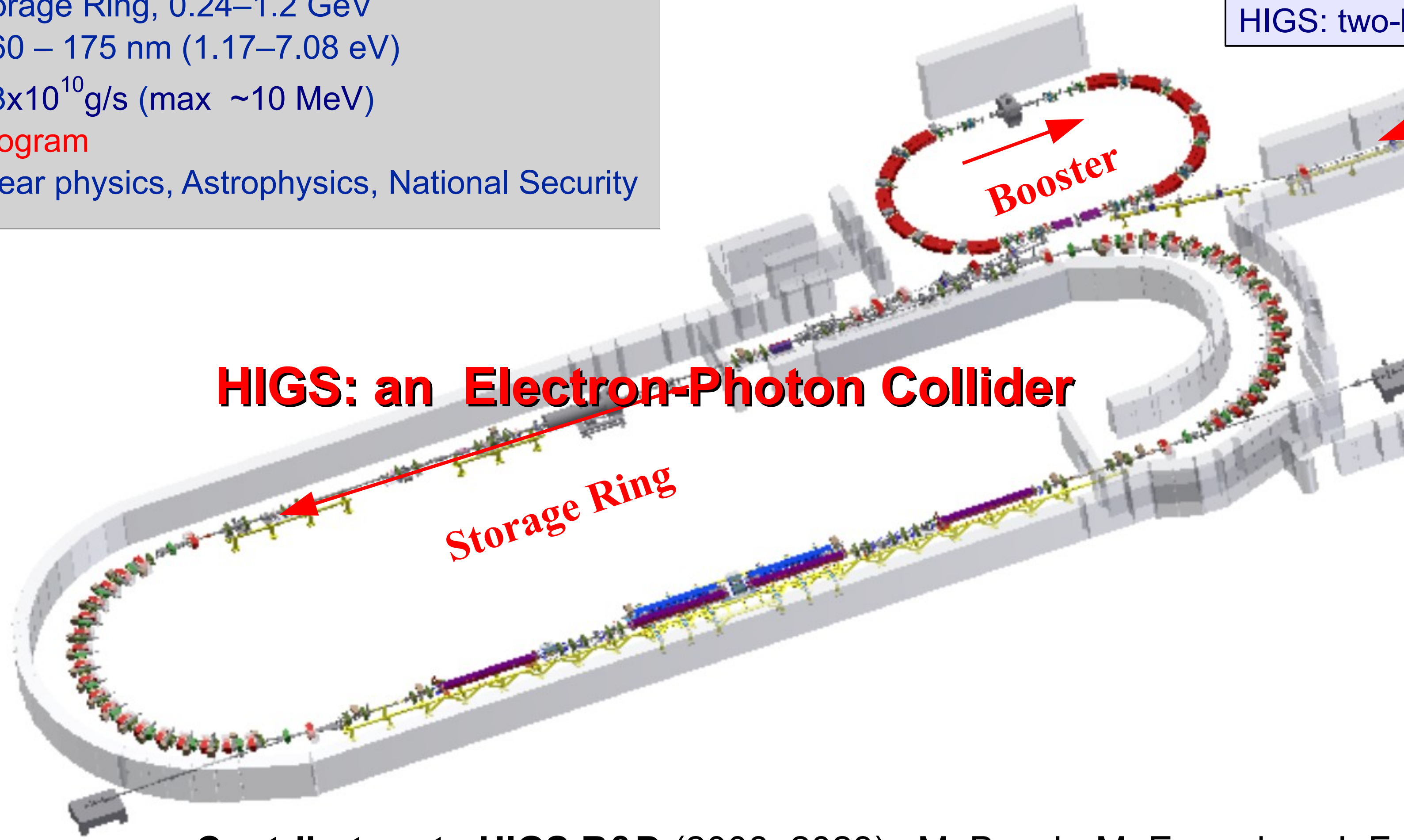
A. Lumpkin and B. Yang
APS, Argonne National Laboratory, Argonne, Illinois 60439



HIGS/TUNL: Accelerator Facility

Facility/Project: High Intensity Gamma-ray Source (HIGS)
Institution: TUNL
Country: US
Energy (MeV): 1–120
Accelerator: Storage Ring, 0.24–1.2 GeV
Laser: FEL, 1060 – 175 nm (1.17–7.08 eV)
Total flux: 10^7–$3\text{x}10^{10}$g/s (max ~10 MeV)
Status: User Program
Research: Nuclear physics, Astrophysics, National Security

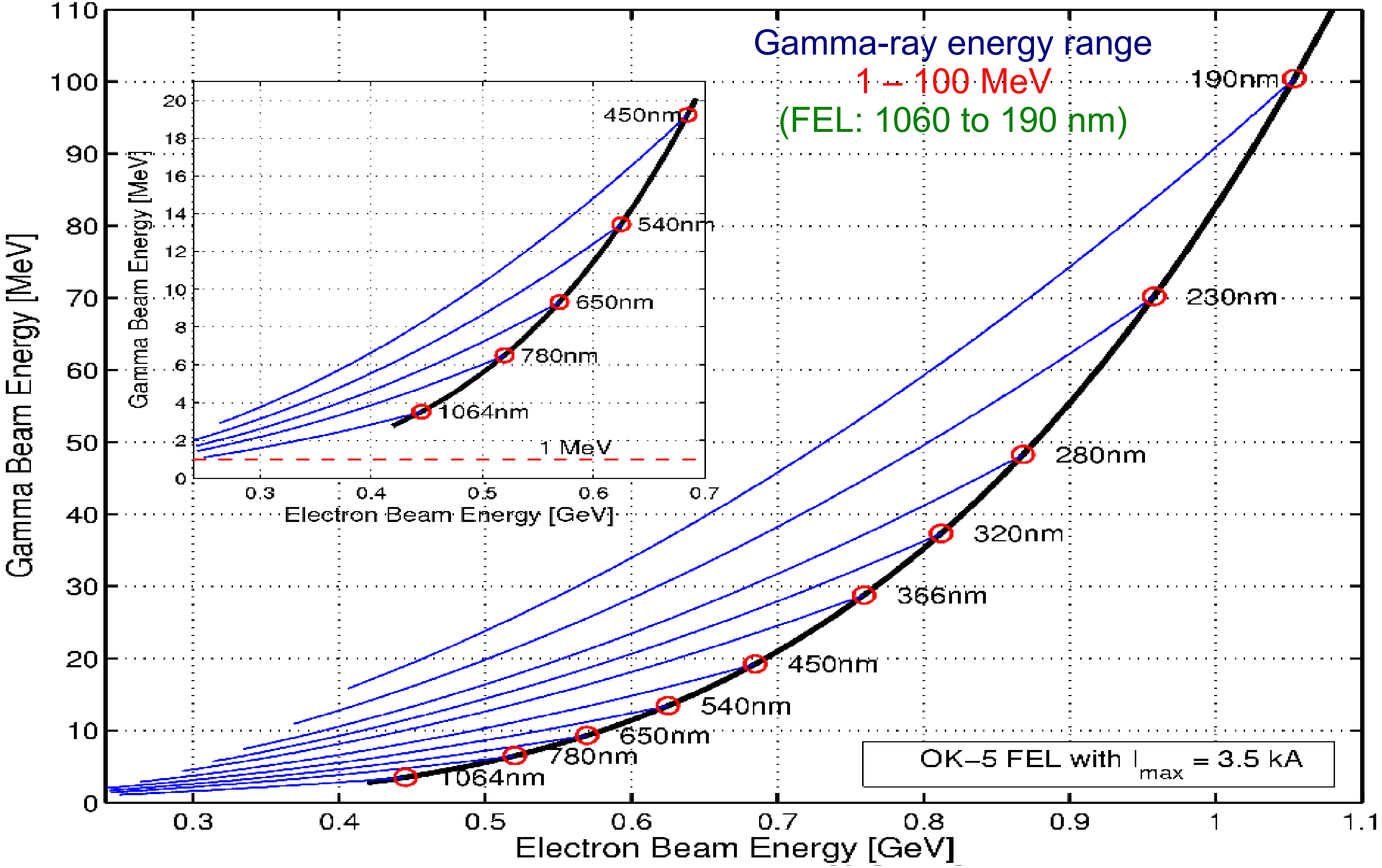
Accelerator Facility
160 MeV Linac pre-injector
160 MeV–1.2 GeV Booster injector
240 MeV–1.2 GeV Storage ring
FELs: OK-4 (lin), OK-5 (cir)
HIGS: two-bunch, 40–120 mA (typ)



HIGS: an Electron-Photon Collider

Contributors to HIGS R&D (2008–2023): 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

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

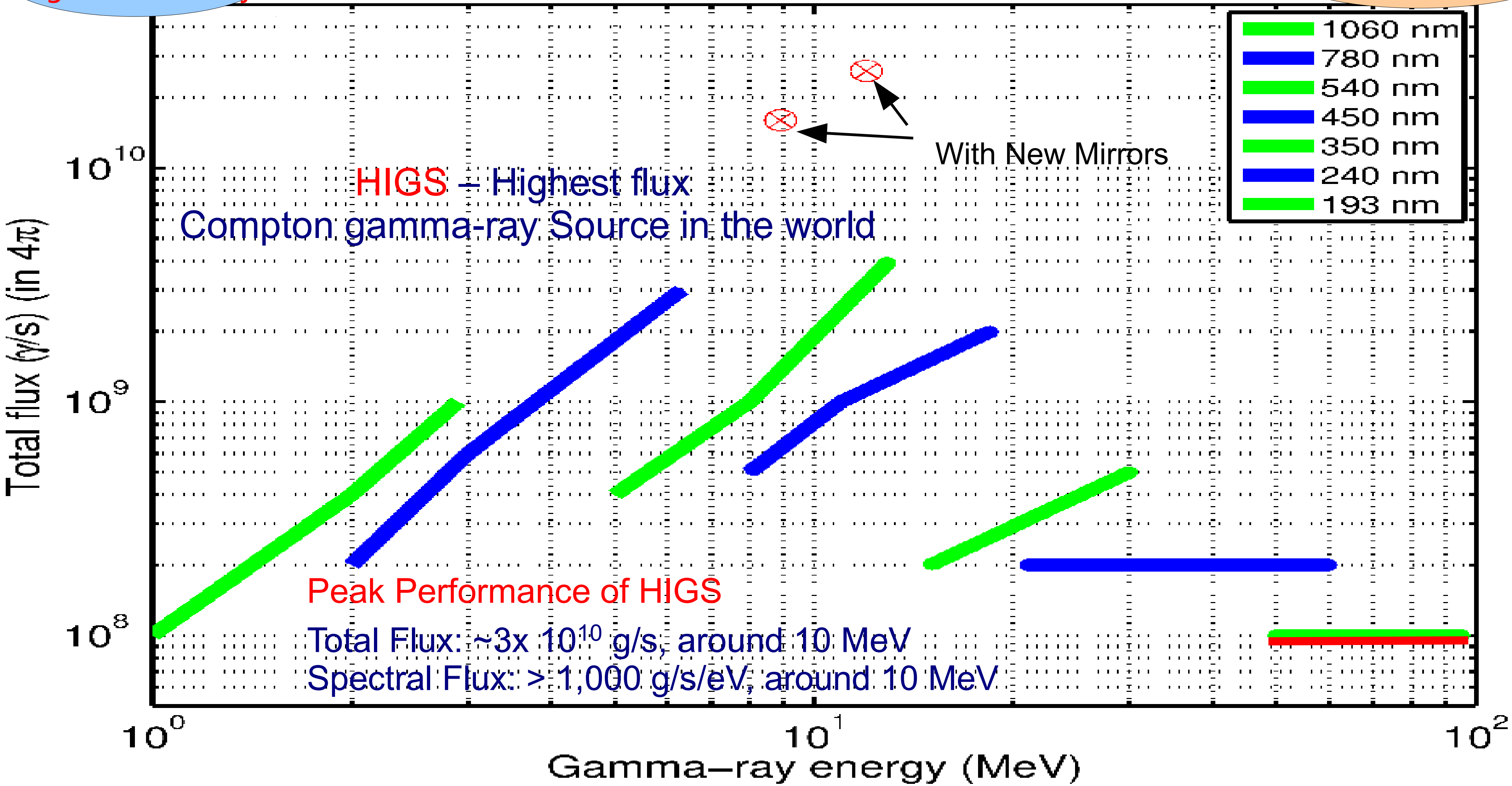


HIGS Flux Summary

Development:
Higher Intensity

HIGS User Flux Capabilities with OK-5 FEL

Development:
Higher Energy



HIGS – Highest flux
Compton gamma-ray Source in the world

Peak Performance of HIGS

Total Flux: ~3x 10^{10} g/s, around 10 MeV
Spectral Flux: > 1,000 g/s/eV, around 10 MeV

Electron/Photon Collision Angle Monitor

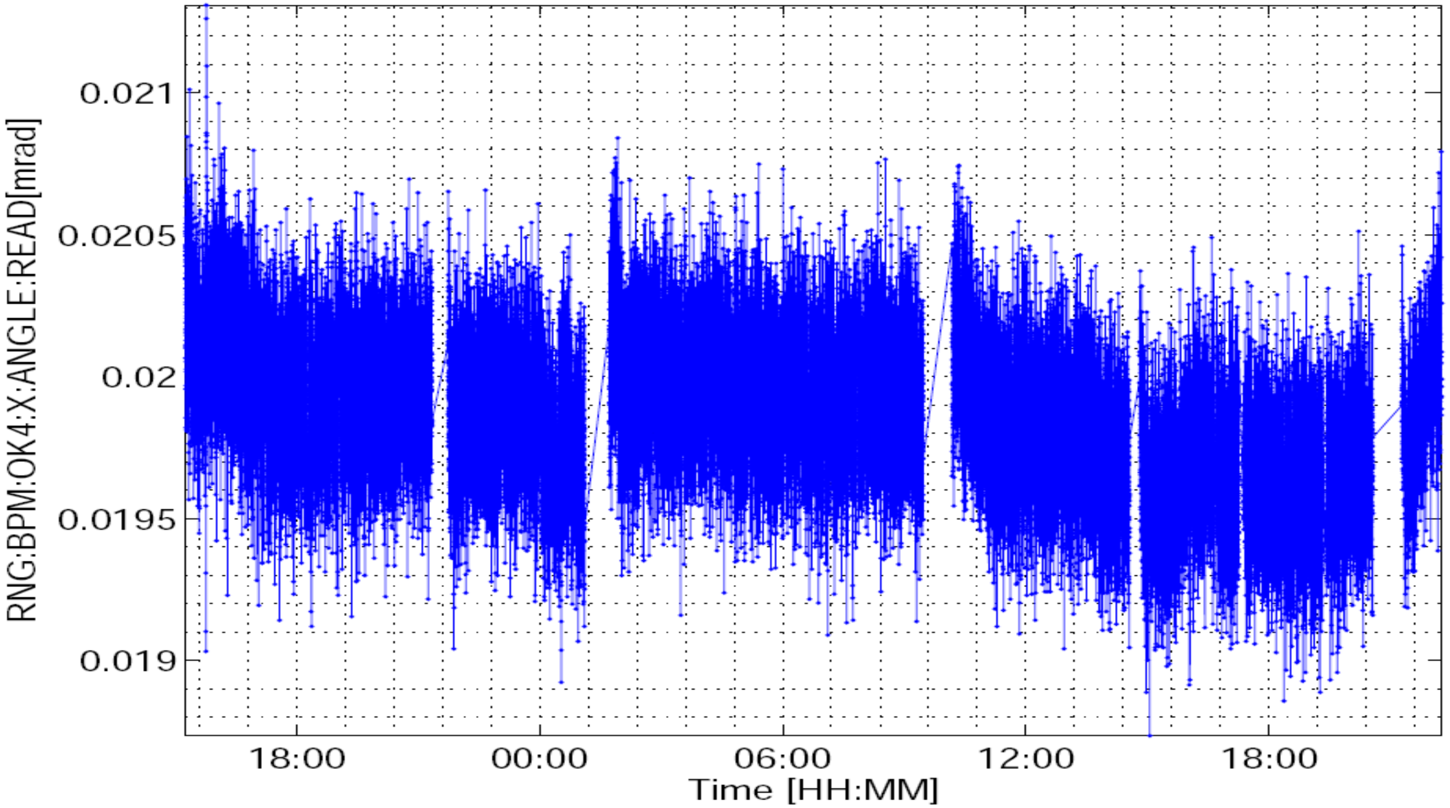
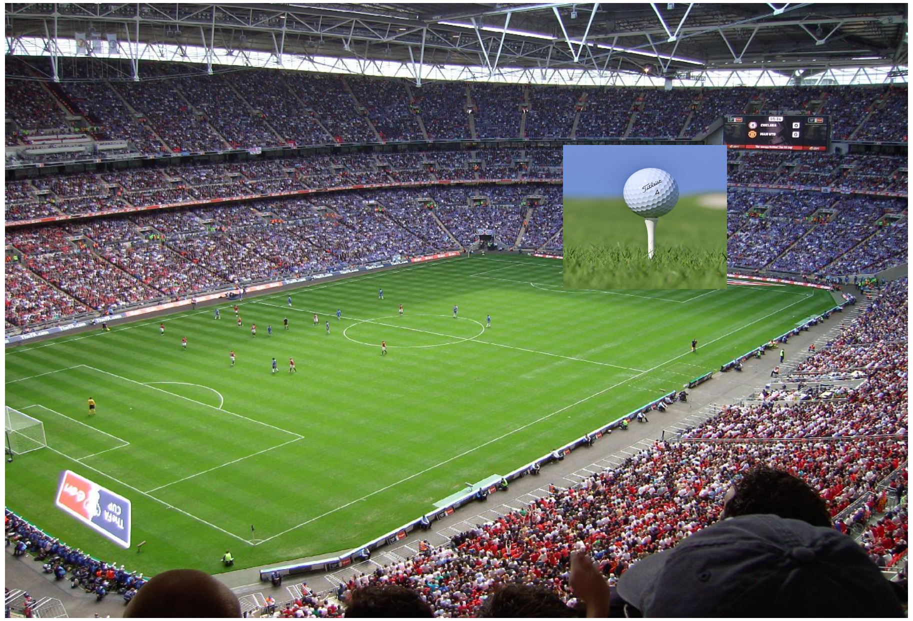
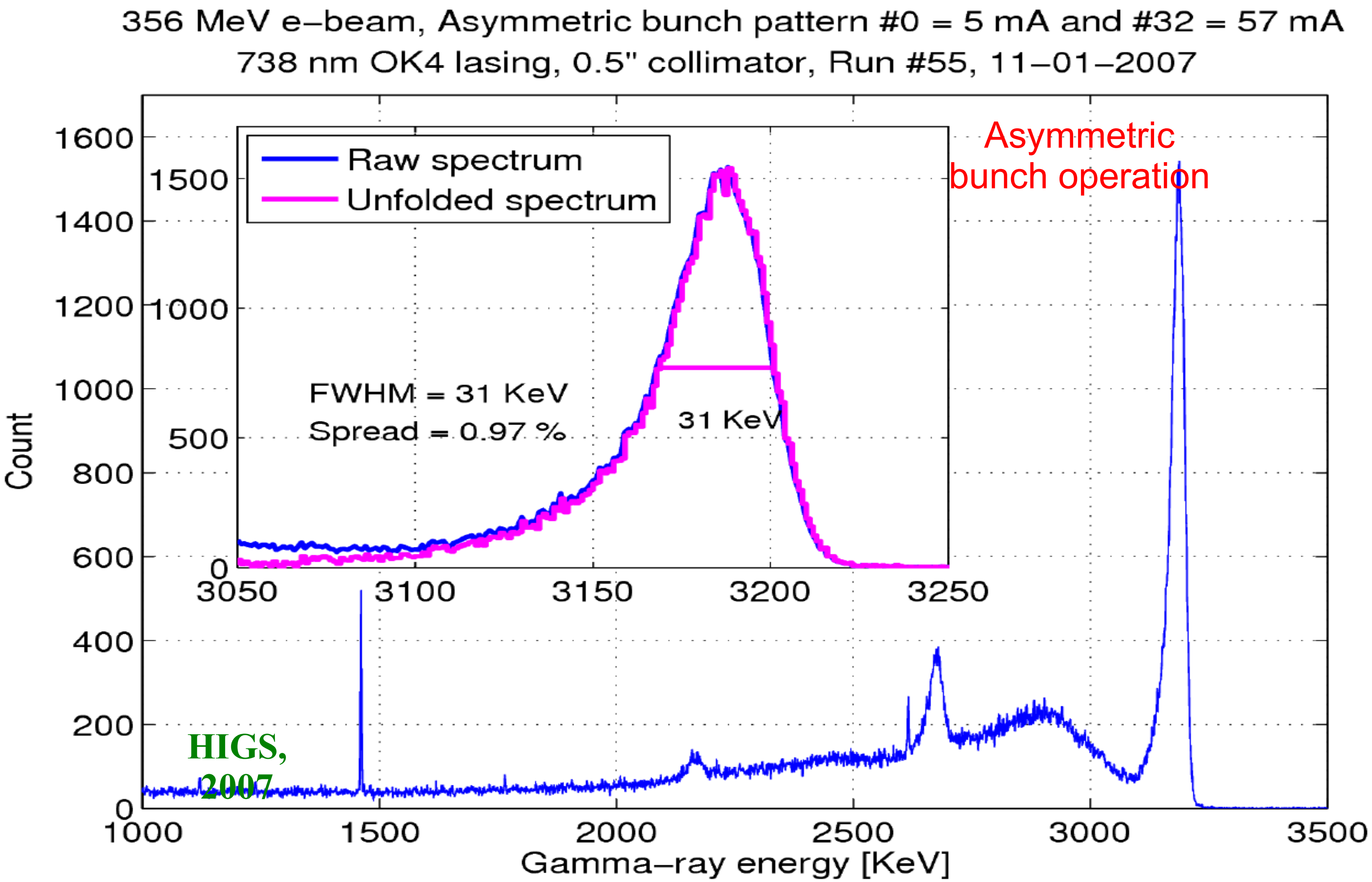


Figure 15: Horizontal beam angle at OK4 for about 36 hours operation from Aug. 20 to Aug. 21, 2009. The angle varied 2.5μrad (peak to peak) during this operation, this value corresponds to 150μm variation of gamma ray beam position at the gamma vault which is located 60 m downstream of the collision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



Asymmetric bunch operation

HIGS, 2007

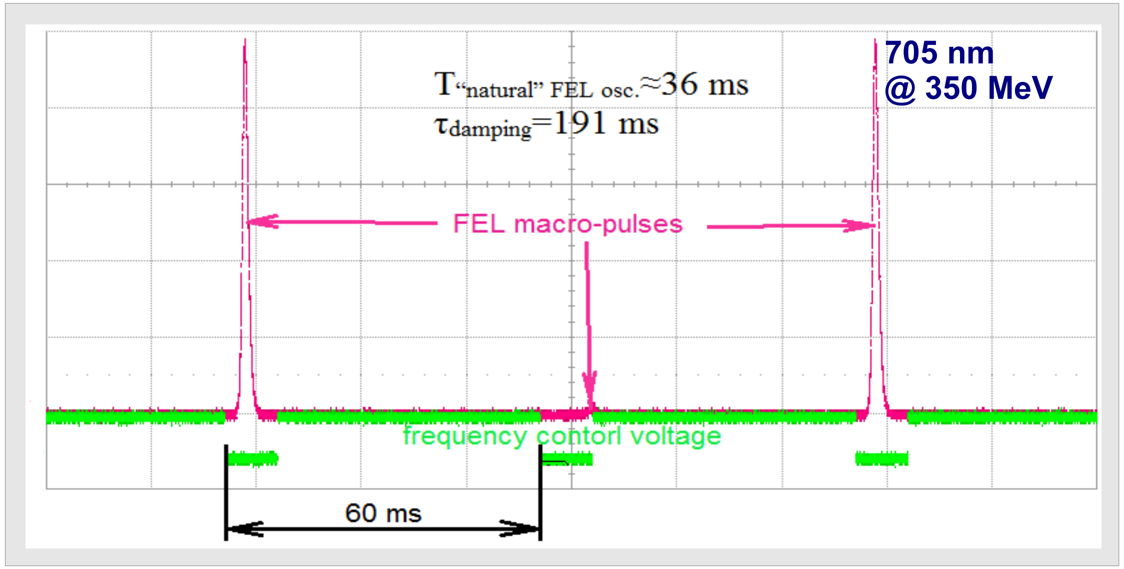
FWHM: 0.97%

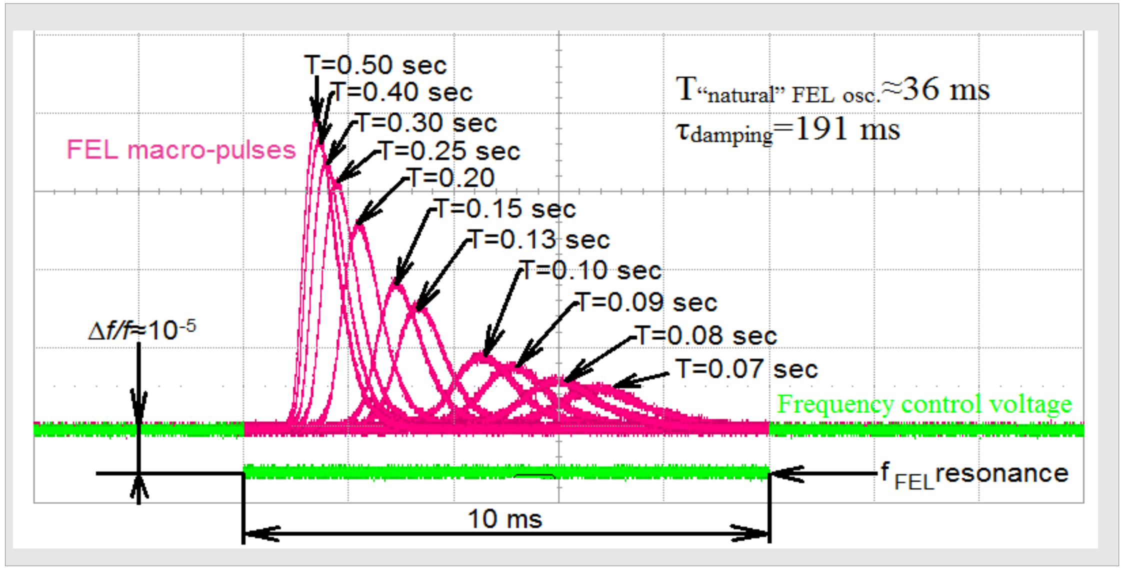
RMS: 0.41%

Gamma beam energy resolution in high-flux operation:

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

New Capabilities: Pulsed Beam for Low Background Experiments





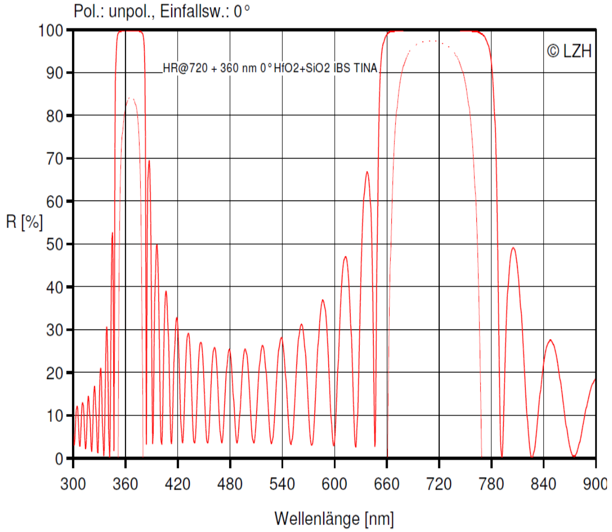
Gain Modulation with RF—FEL Macropulse Operation

- Rapidly and periodically change f_{RF}
  - $Df_{RF/}/f_{RF}$ ~ 10^{-5}
  - Transition in 10s of microseconds
  - Duration for a few milliseconds
- Rep-rate: few to tens of Hz, depending on operational conditions
- About the same average FEL power
- Good beam stability and lifetime
- Type of user experiments

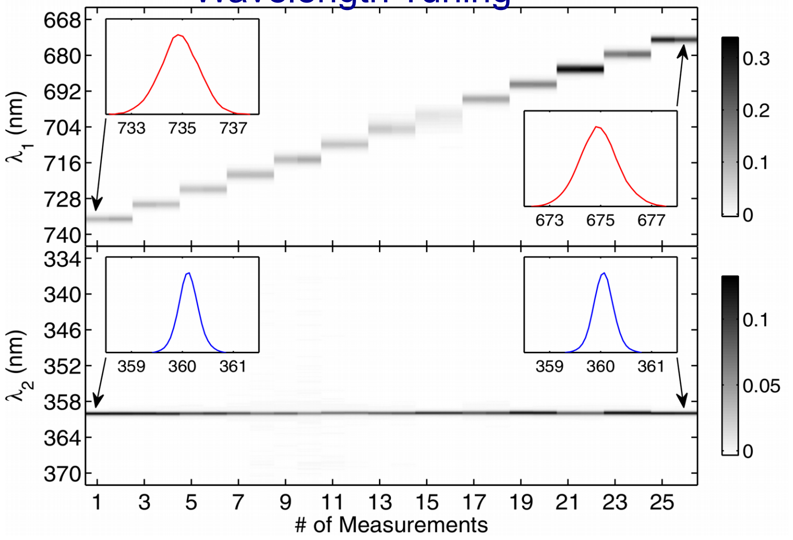
  Detector calibration with low background

New Capabilities: 2-Color FEL

Dual-band: 720/360nm



Wavelength Tuning

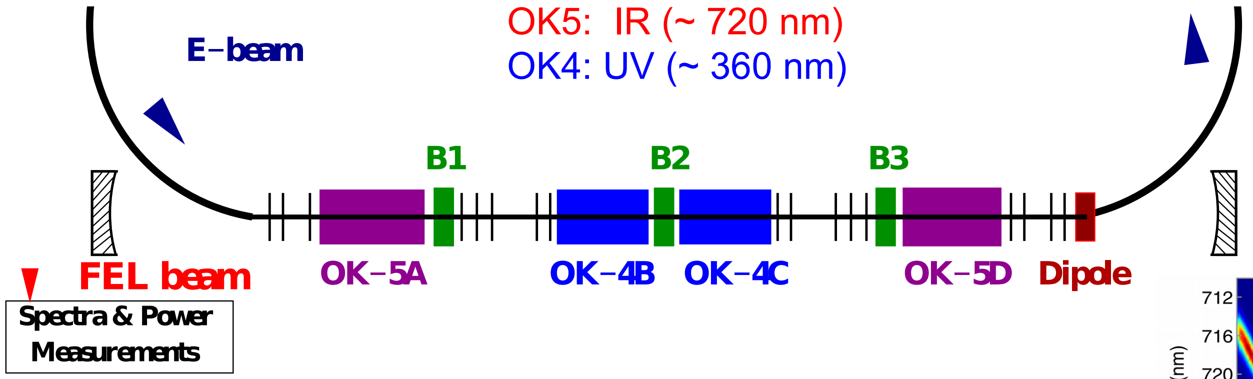


Y.K. Wu *et al*. PRL 115, 184801(2015); J. Yan *et al*. PRAB 19, 070701 (201

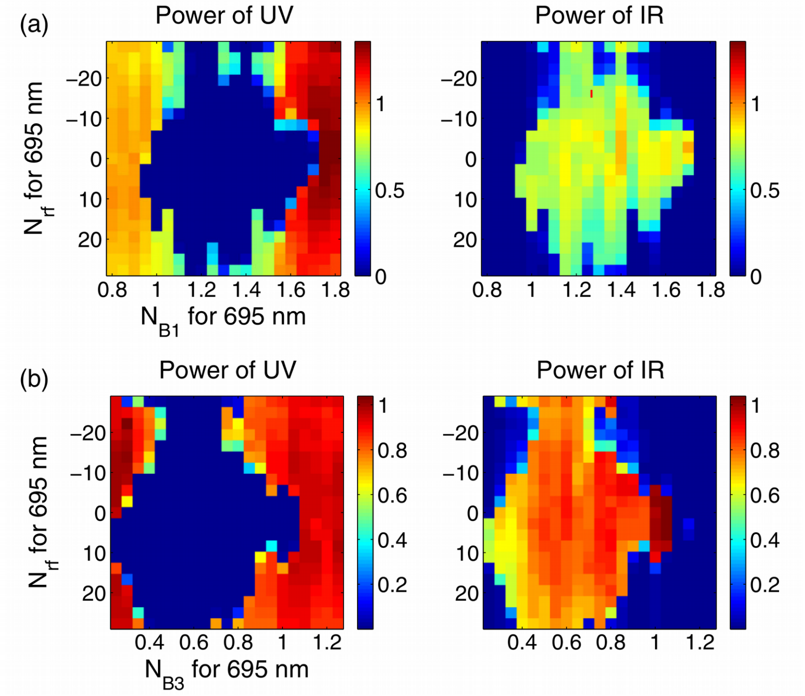
Gain Matching

OK5: IR (~ 720 nm)

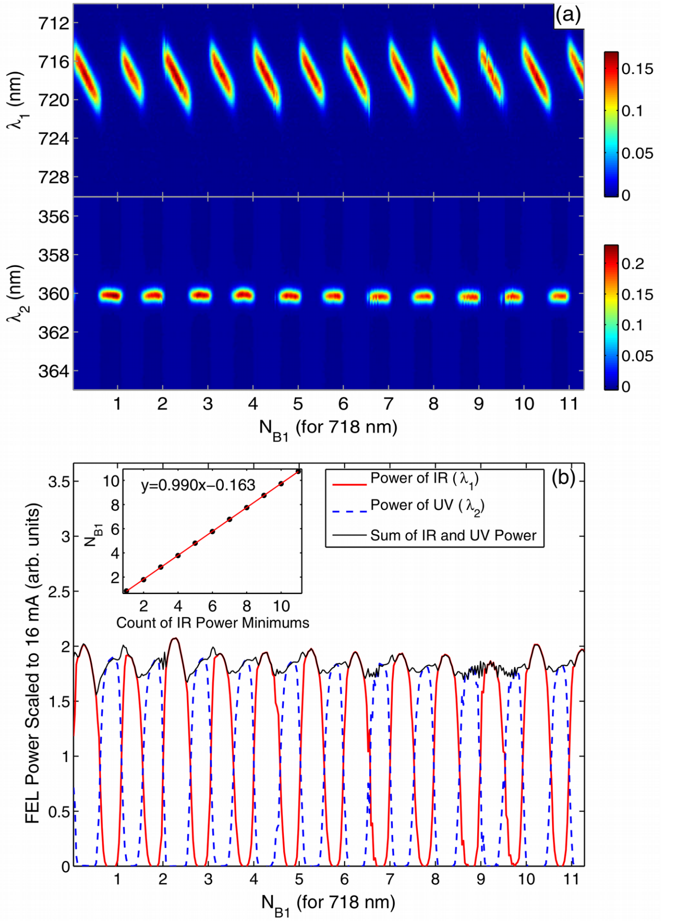
OK4: UV (~ 360 nm)



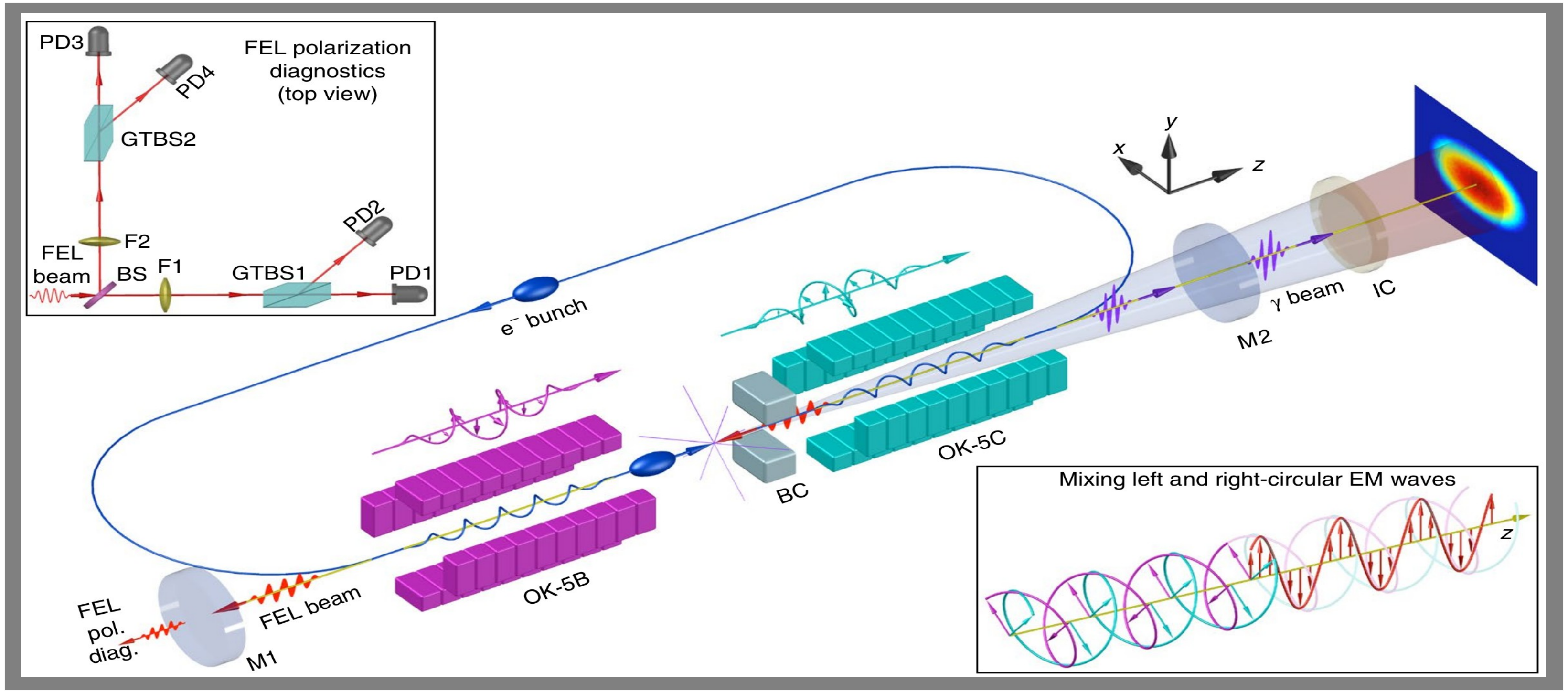
Lasing Phasespace

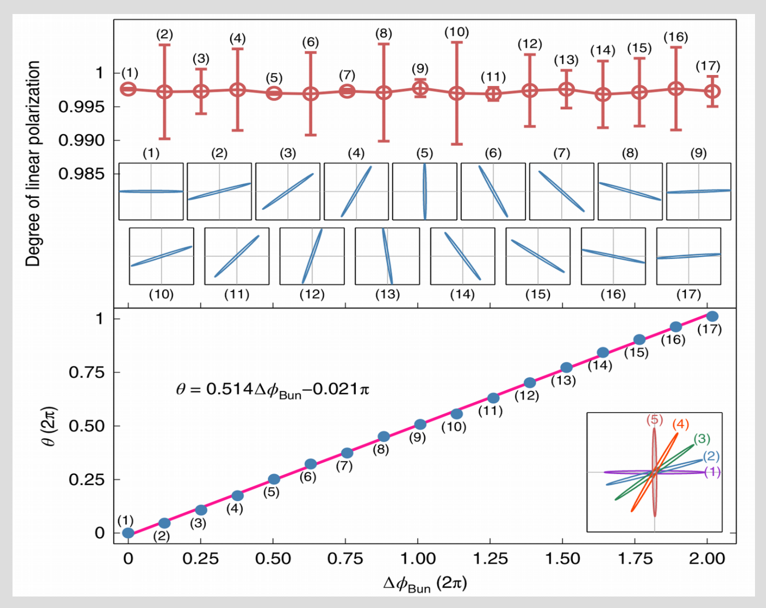


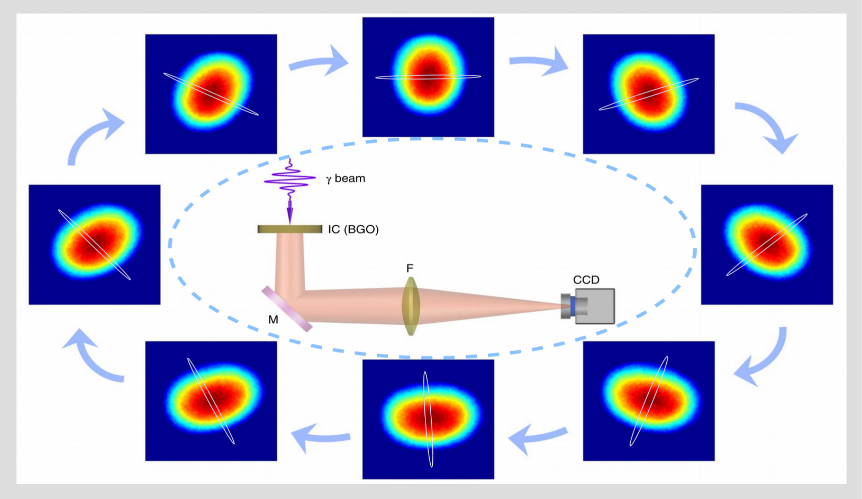
FEL Power Control



New Capabilities: Precision Polarization Control

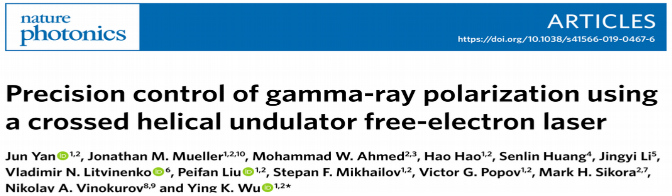






New Gamma-ray Capability in Polarization Control

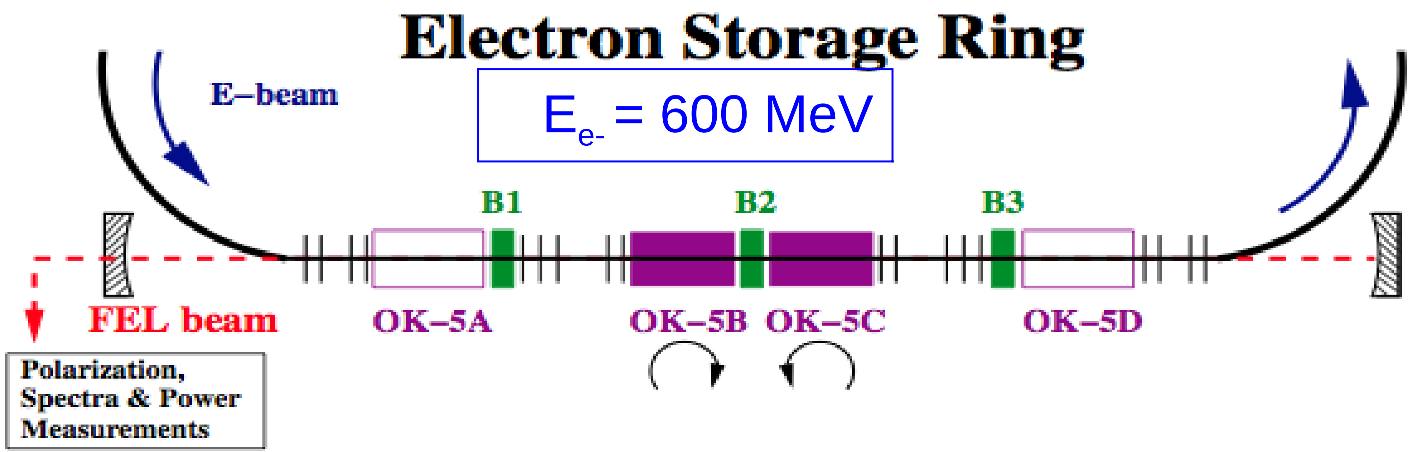
- Precision control of gamma-ray polarization:
  two crossed helical undulators ==> FEL and gamma-ray beams with linear polarization in any direction
  - Linear polarization, $P_{Lin} > 0.97$ for gamma-ray ($P_{Lin} > 0.99$ for FEL)
  - Available: 3 – 30 MeV
- Impact on nuclear physics research:
  - Experiment can rapidly access gamma-ray beams with variable polarization: left- and right-circular, linear with changeable direction
  - Allow for the exploration of polarization-dependent nuclear observables
  - Significantly reduce systematic errors in measurements.


nature photonics ARTICLES
https://doi.org/10.1038/s41566-019-0467-6

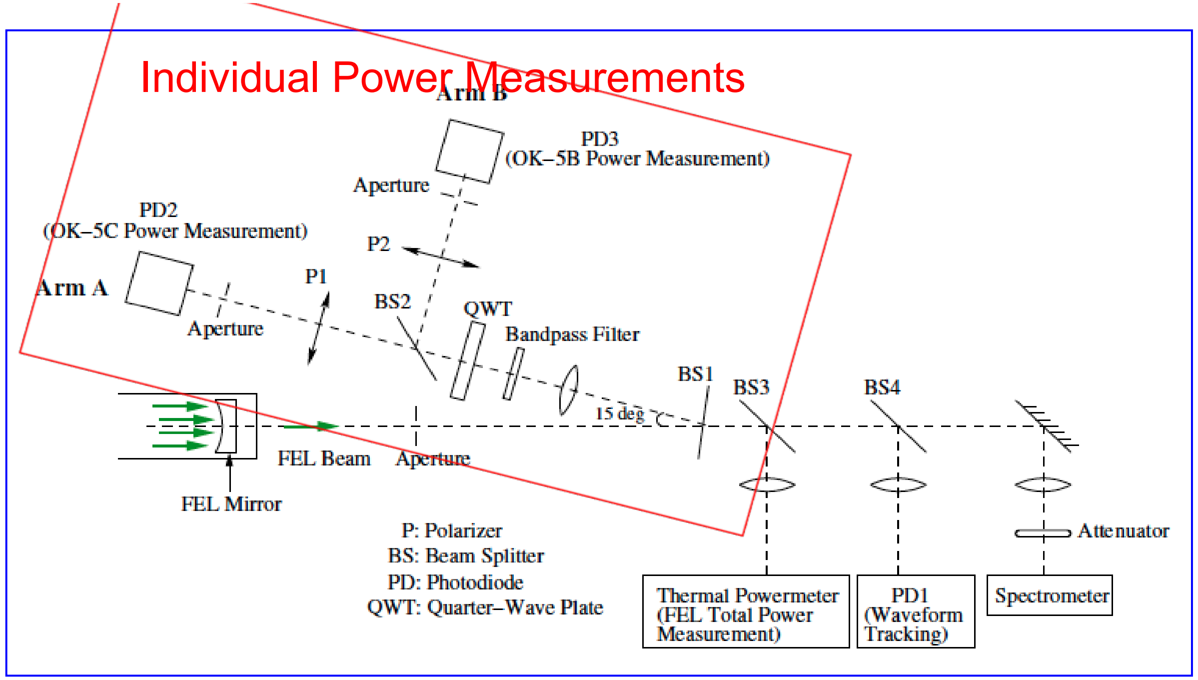
Precision control of gamma-ray polarization using a crossed helical undulator free-electron laser

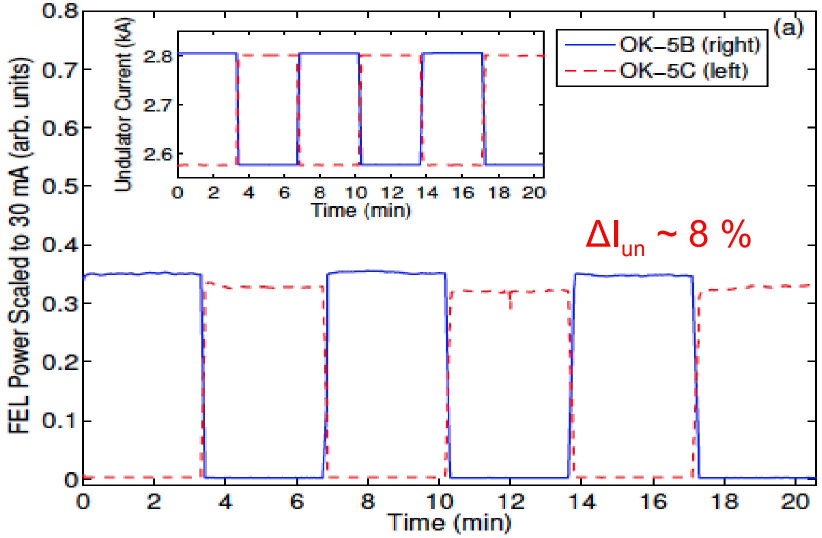
Jun Yan[1,2], Jonathan M. Mueller[1,2,10], Mohammad W. Ahmed[2,3], Hao Hao[1,2], Senlin Huang[4], Jingyi Li[5], Vladimir N. Litvinenko[6], Peifan Liu[1,2], Stepan F. Mikhailov[1,2], Victor G. Popov[1,2], Mark H. Sikora[2,7], Nikolay A. Vinokurov[8,9] and Ying K. Wu[1,2*]

New Capabilities: Helicity Switch

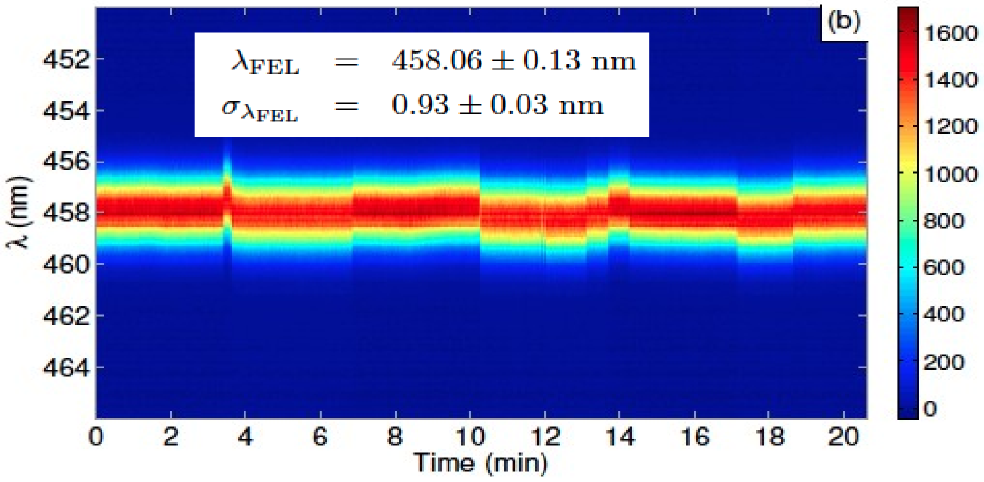


$E_{e-} = 600$ MeV


Individual Power Measurements

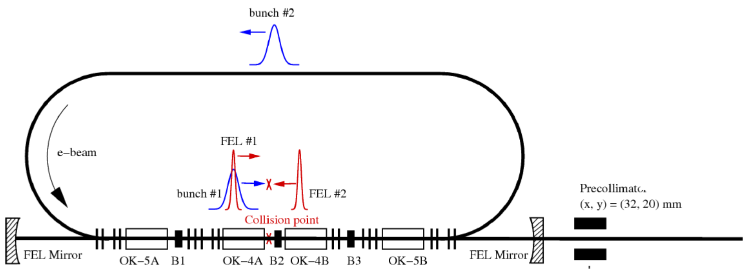

$\Delta I_{un} \sim 8$ %

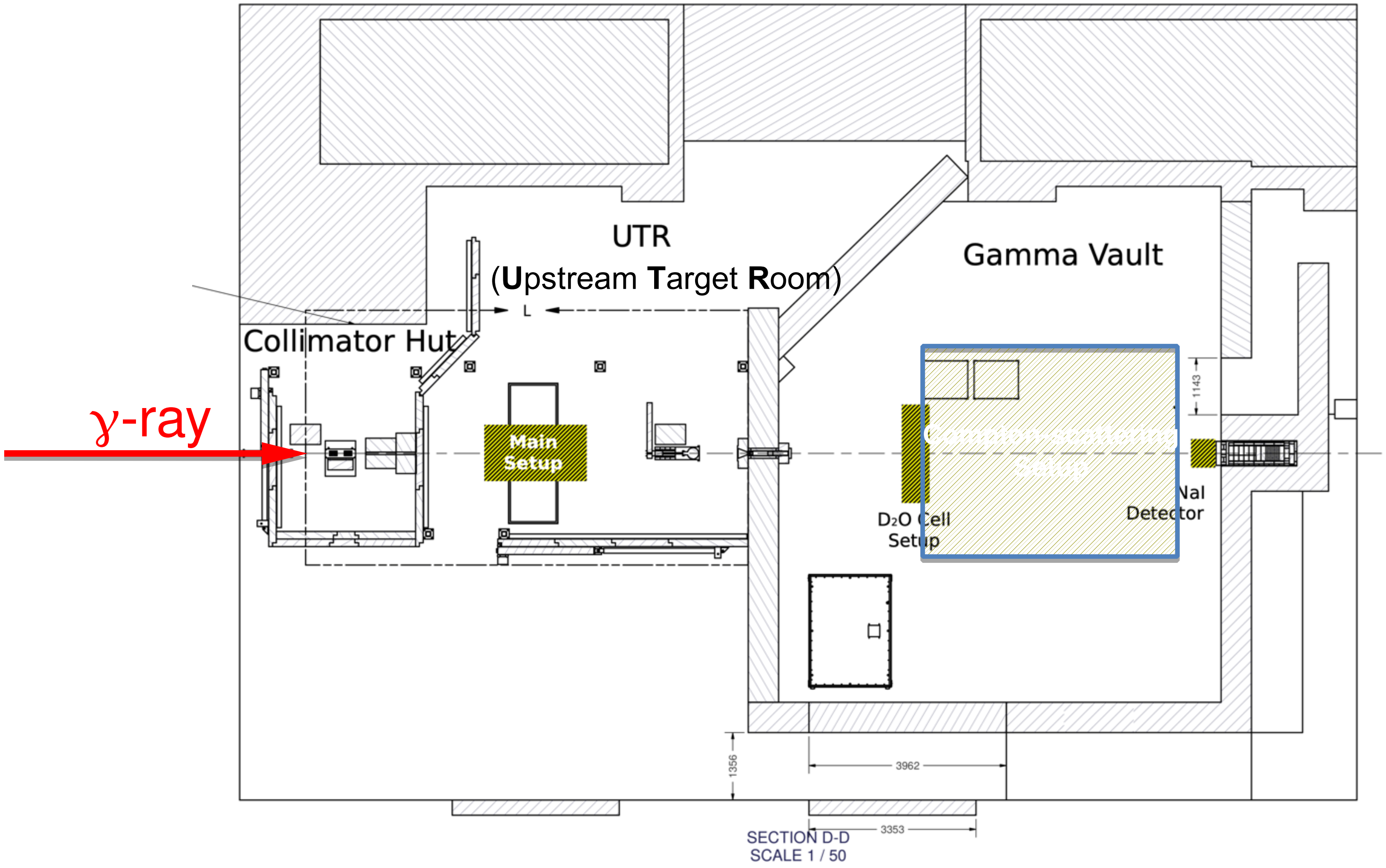
FEL Power (rms): OK-5B, 0.8%; OK-5C, 0.9%


$$\lambda_{\rm FEL} = 458.06 \pm 0.13 \text{ nm}$$
$$\sigma_{\lambda_{\rm FEL}} = 0.93 \pm 0.03 \text{ nm}$$

From Jun Yan's dissertation (2016)

Target Room Layout at HIγS





Zoomed Out View of Research at HIγS

HIγS operates about 1600 hours/year for nuclear physics research

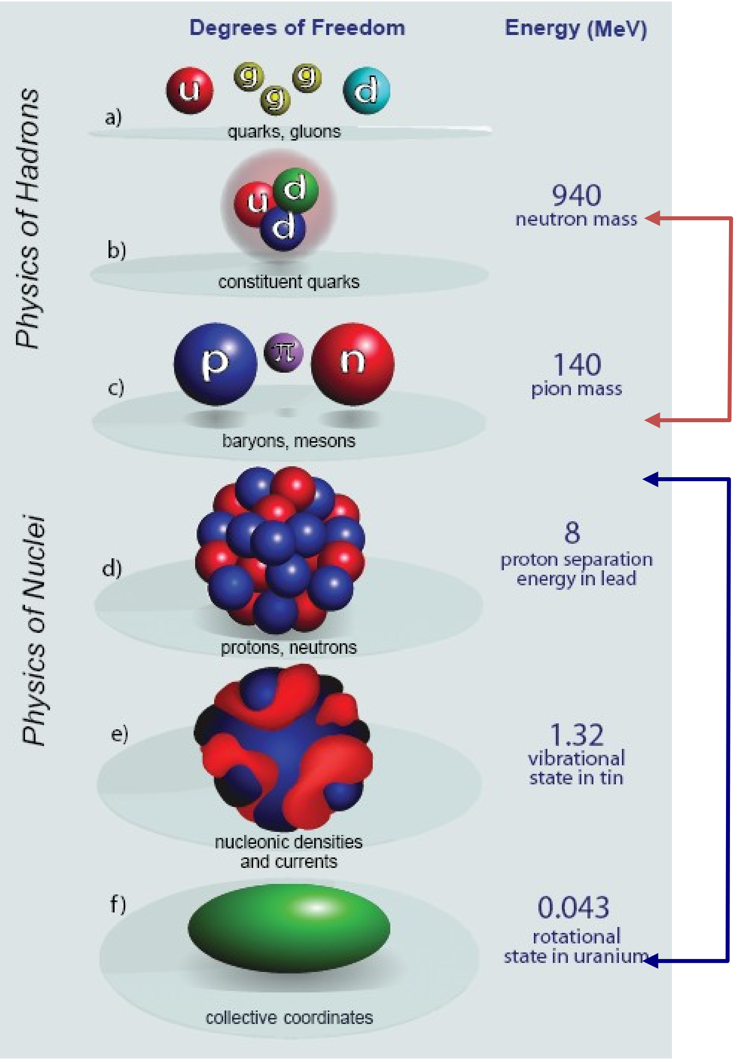


Figure from 2007 USA Nuclear Science LRP

Low-Energy QCD:

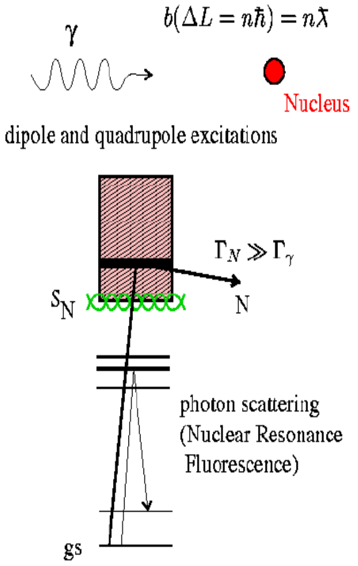
Nucleons

Compton Scattering: nucleon electric and magnetic polarizabilities
nucleon spin polarizabilities

Few-nucleon Systems

Photodisintegration of ^{2}H, ^{3}He and ^{3}H (cross sections, target-beam helicity dependent cross sections, polarization transfer)

Nuclear Structure and Nuclear Astrophysics



Many-body strongly interacting systems

NRF, (γ,γ’)
(γ,n), (γ,p), (γ,α) and (γ, fission) reactions

Applied Research:

- Nuclear Security
- Medical Isotope R&D
- Particle Detector R&D

Courtesy of C. Howell (Duke/TUNL)

Future Compton Gamma-ray Sources

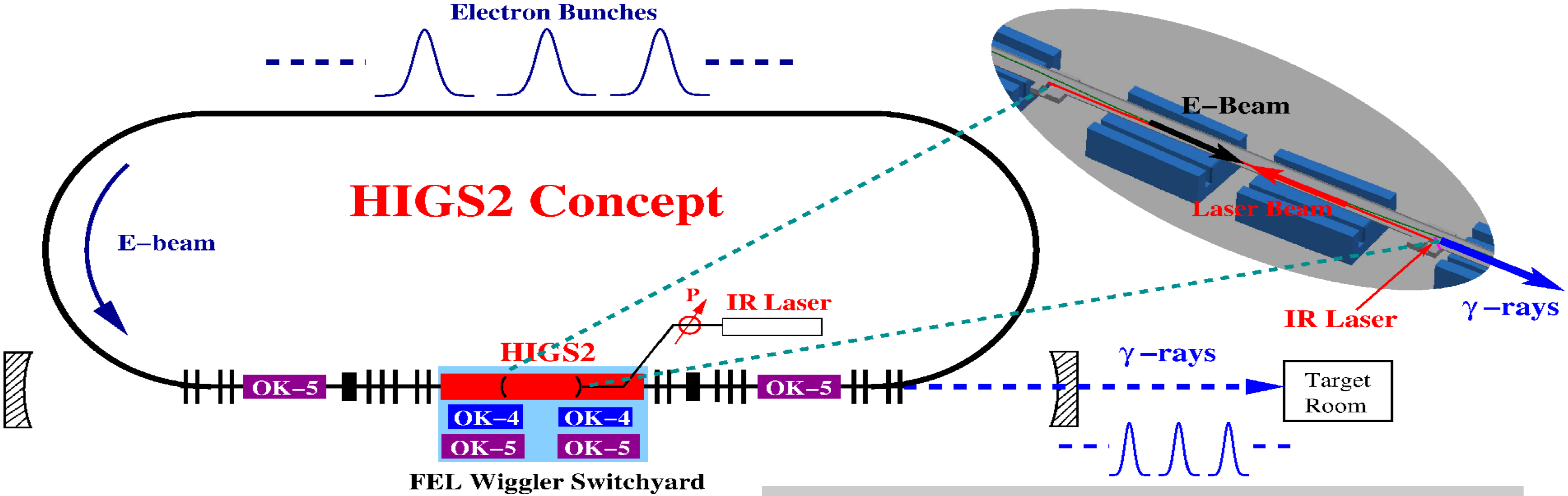
Unconventional Approaches

- 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

HIGS2: Next-Generation Gamma-ray Source



Research Programs

- Nuclear Structure
- Nuclear Astrophysics
- Hadronic Parity Violation

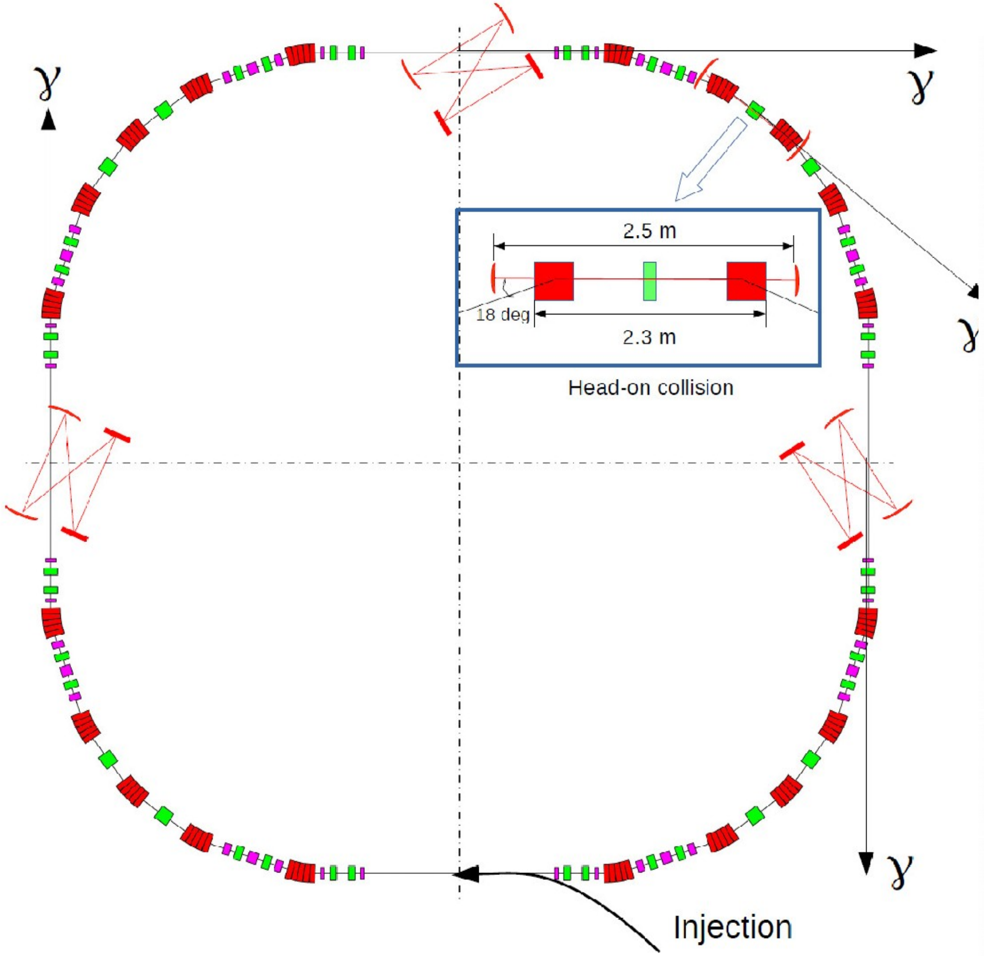
Status: Seeking funding

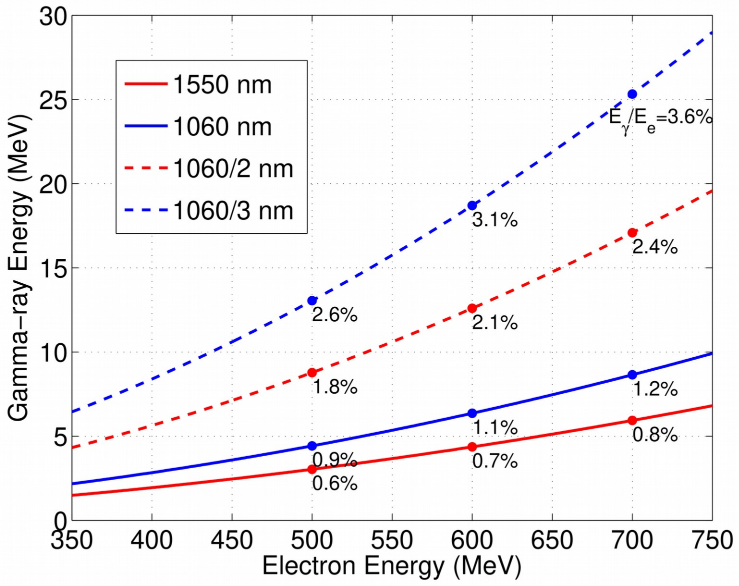
Projected Performance

- 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)

Next-generation CGS: Storage Ring Based Low Energy CGS

Low-Energy CGS: Storage Ring





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

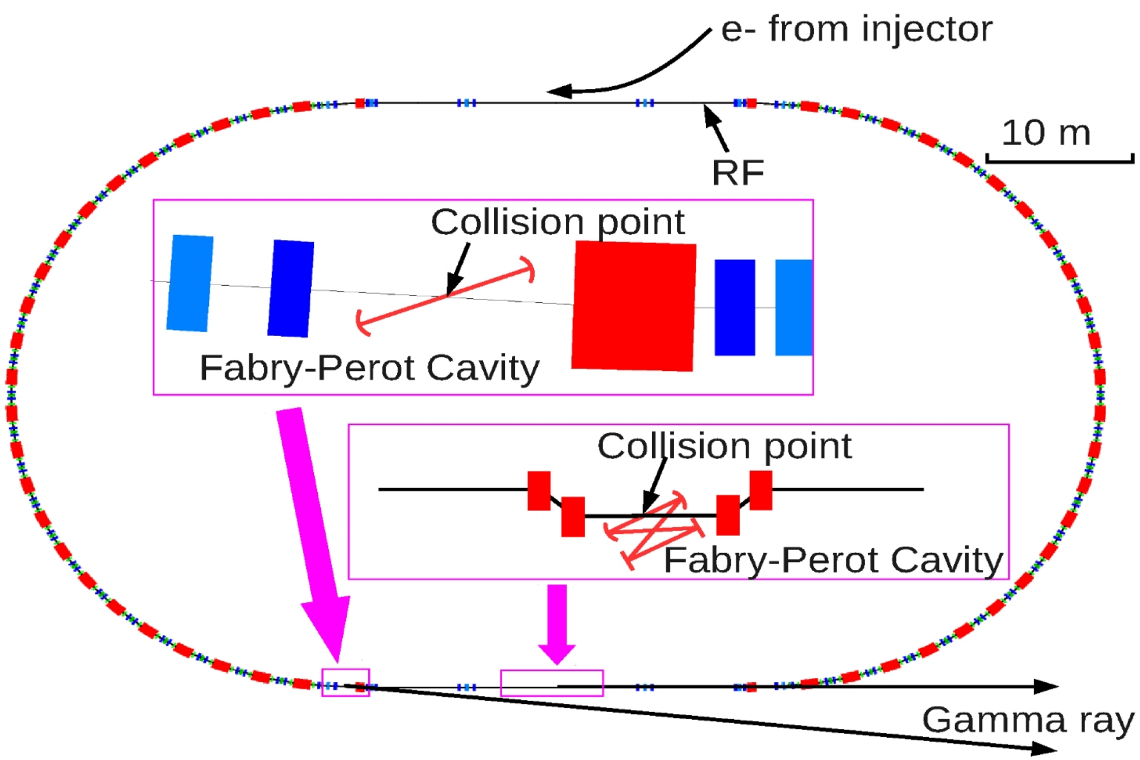
Electron beam	
Beam energy	500 MeV
Stored currents	1000 mA
Bunch filled	24
Hori./Vert. emittance	7.5/0.75 nm-rad
Hori./Vert. size (rms)	212/39 μm
Bunch length (rms)	150 ps
Laser beam	
Wavelength	1064 nm
Intracavity power	100 kW
Pulse length (rms)	20 ps
Hori./Vert. size (rms)	40/40 μm
Gamma-ray beam	
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

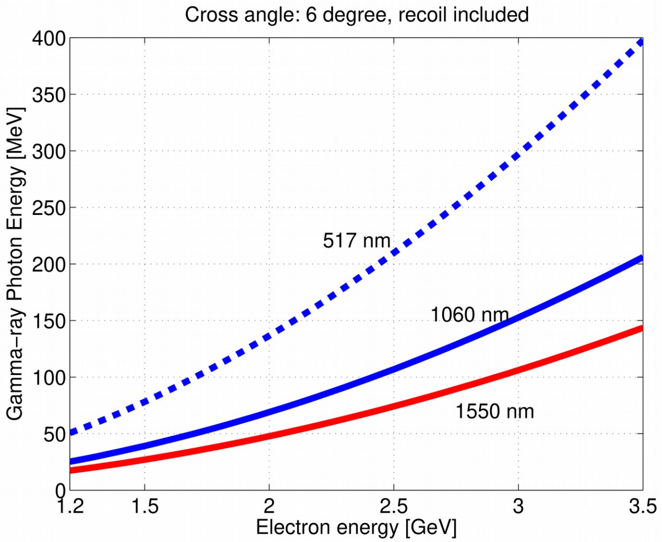
E-beam: $E = 500$ MeV, $I = 1$ A	FP cavity: 100 kW Beam size: 40/40 μm	
Laser wavelength (nm)	$\lambda_1 = 1064$	$\lambda_2 = 1550$
Tot. flux (γ/s): θ=6°	2.2×10^{12}	2.8×10^{12}
Tot. flux (γ/s): head-on	2.4×10^{13}	3.1×10^{13}

Whitepaper: “International Workshop on Next Generation Gamma-Ray Source,”
C.R. Howell *et al.*, arXiv:2012.10843 (2020)

Next-generation CGS: Storage Ring Based High Energy CGS

High-Energy CGS: Storage Ring





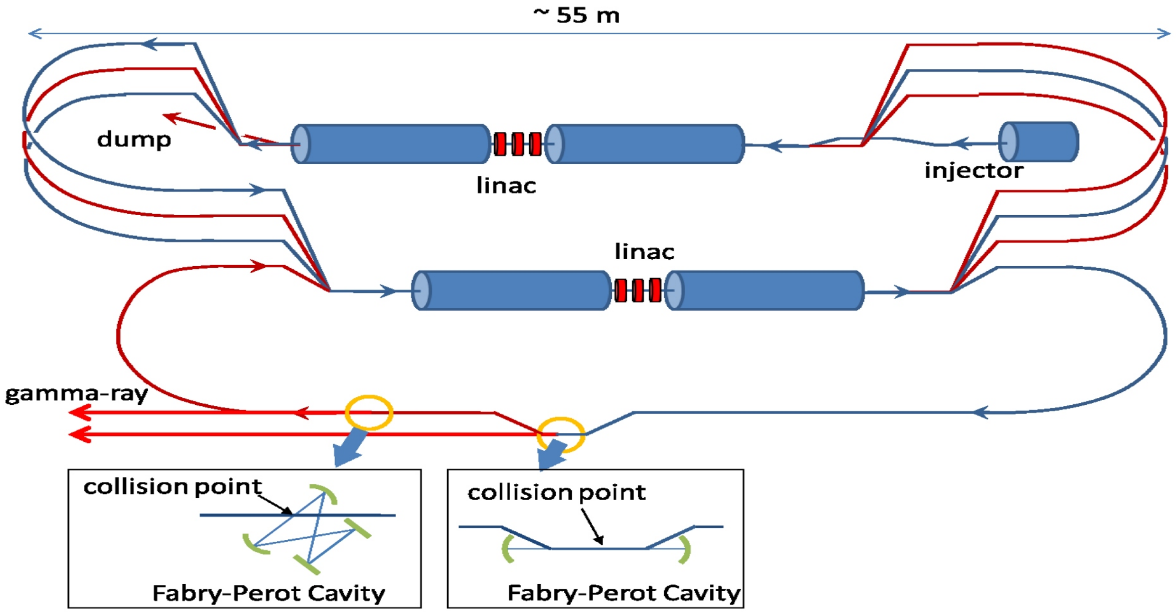
E-beam (GeV)	E_γ (MeV)	λ_1 (nm) 1064	λ_2 (nm) 1550	$\lambda_2/3$ 517
1.2	$E_{\gamma,\text{min}}$	25	17	51
3.5	$E_{\gamma,\text{max}}$	205	144	398

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

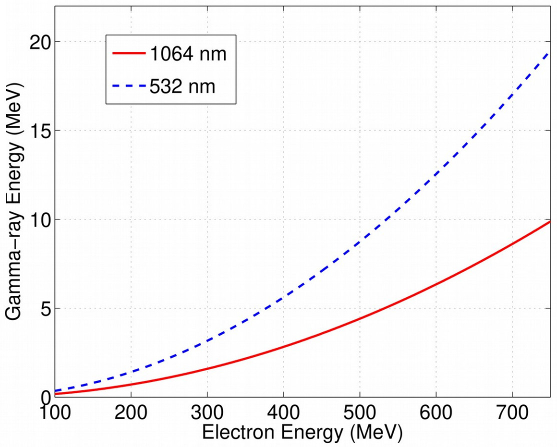
E-beam: $E = 3.27$ GeV, $I = 0.5$ A	Laser beam: λ =517 nm; Beam size: 40/40 μm	
FP cavity power (kW)	20 (kW)	100 (kW)
Tot. flux (γ/s): θ=6°	3.4×10^{11}	1.7×10^{12}

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



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

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 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.*, arXiv:2012.10843 (2020)

Thank you for your attention!