Overview of High Intensity Gamma-ray Source – Capabilities and Future Upgrades

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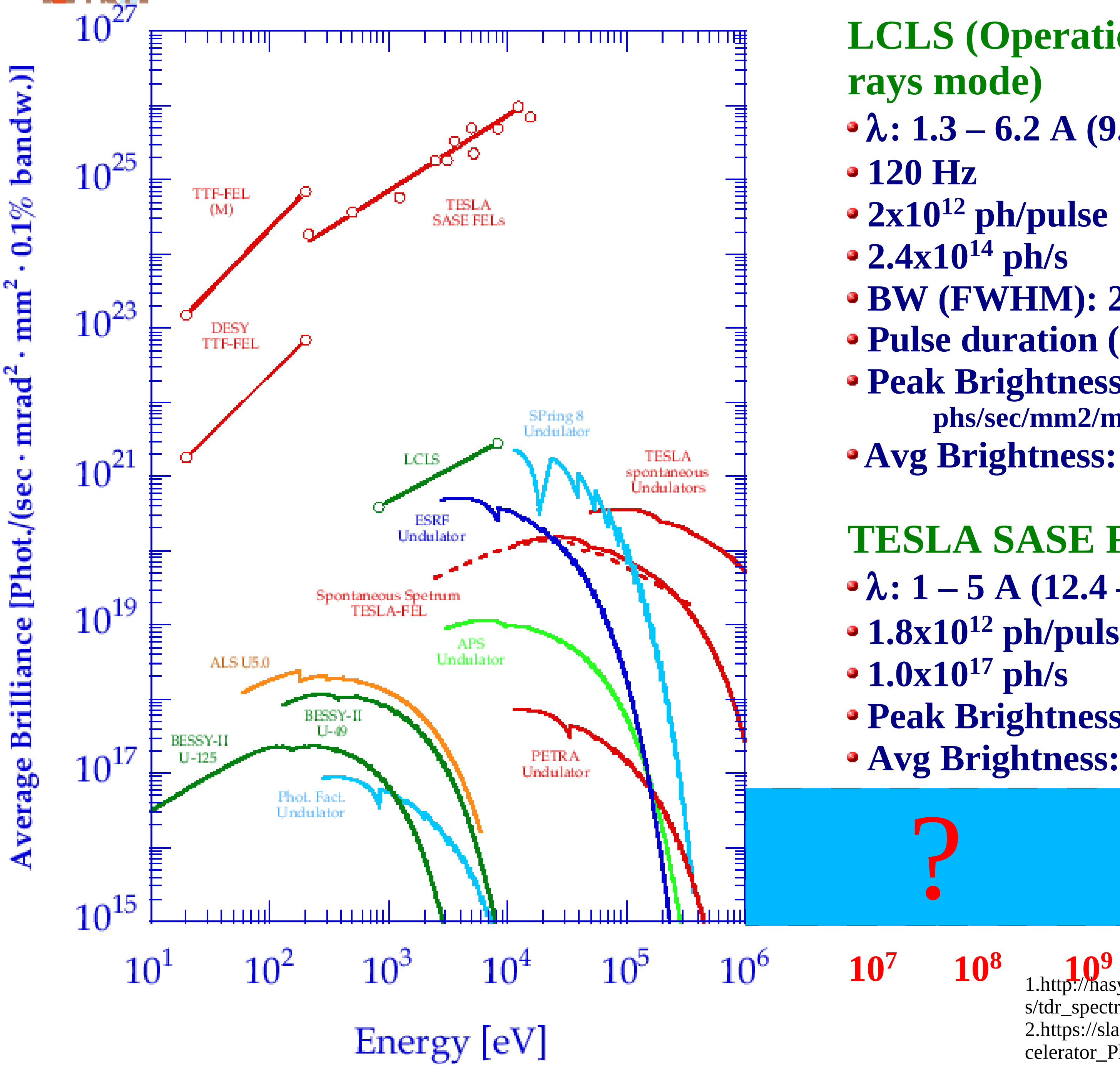
Outline

- **Overview of Compton Photon Sources**
- **High Intensity Gamma-ray Source Capabilities**
- **HIGS Development Projects**
- **Scientific Research at HIGS and Impact**

Gamma-rays

Energy and Average Brightness of Undulators and XFELs



LCLS (Operational, hard x-rays mode)

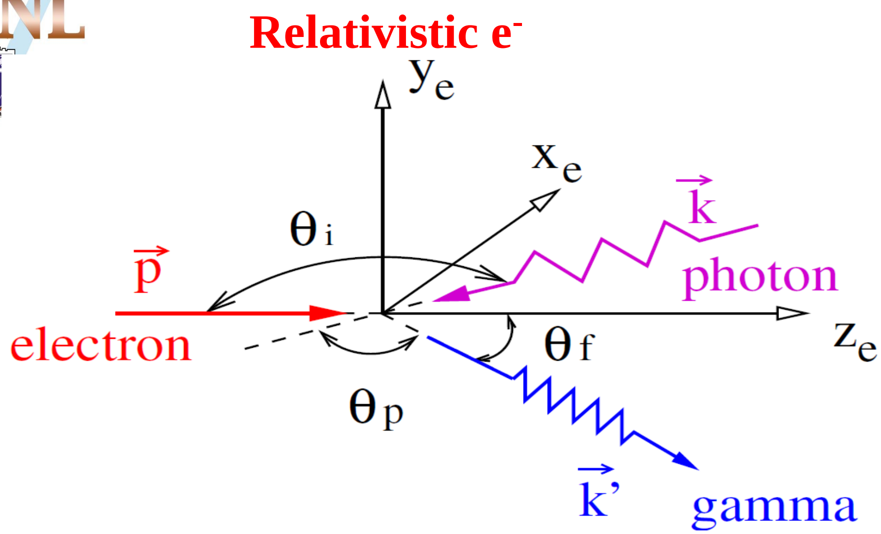
- λ: 1.3 – 6.2 A (9.6 – 2.0 keV)
- 120 Hz
- $2x10^{12}$ ph/pulse
- $2.4x10^{14}$ ph/s
- BW (FWHM): 2 – 5 $x10^{-3}$
- Pulse duration (rms): 23 fs
- Peak Brightness: 2.0 $x10^{33}$ phs/sec/mm2/mrad2/0.1%-BW
- Avg Brightness: 1.6 $x10^{22}$

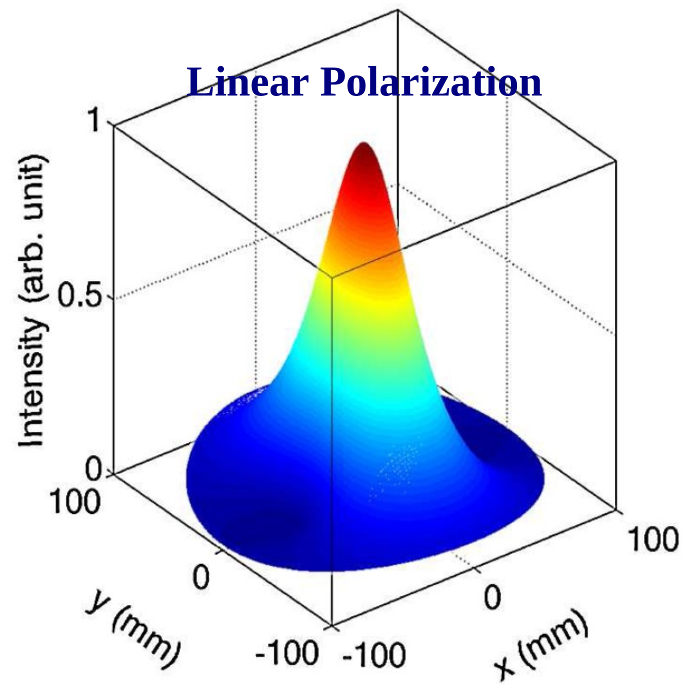
TESLA SASE FEL (Design)

- λ: 1 – 5 A (12.4 – 2.5 keV)
- $1.8x10^{12}$ ph/pulse
- $1.0x10^{17}$ ph/s
- Peak Brightness: 8.7 $x10^{33}$
- Avg Brightness: 4.9 $x10^{25}$

1.http://hasylab.desy.de/facilities/sr_and_fel_basics/fel_basics/tdr_spectral_characteristics/index_eng.html
2.https://slacportal.slac.stanford.edu/sites/lclscore_public/Accelerator_Physics_Published_Documents/LCLS-parameters.pdf

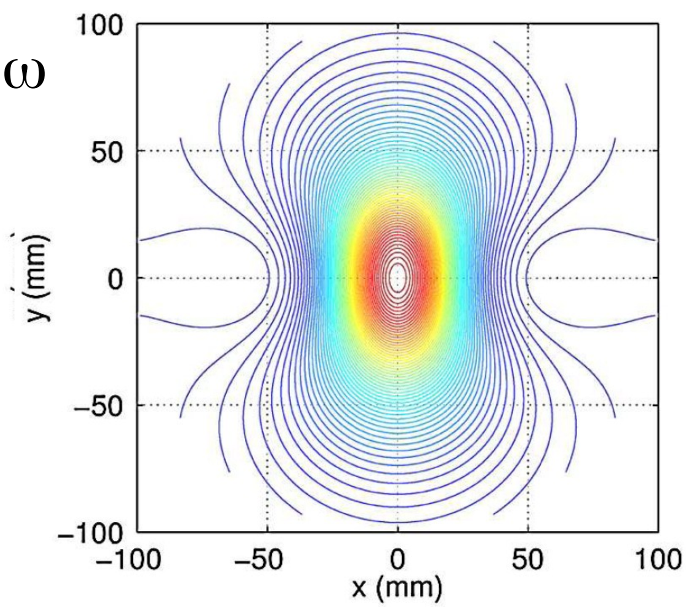
Compton Photon Energy





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

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)

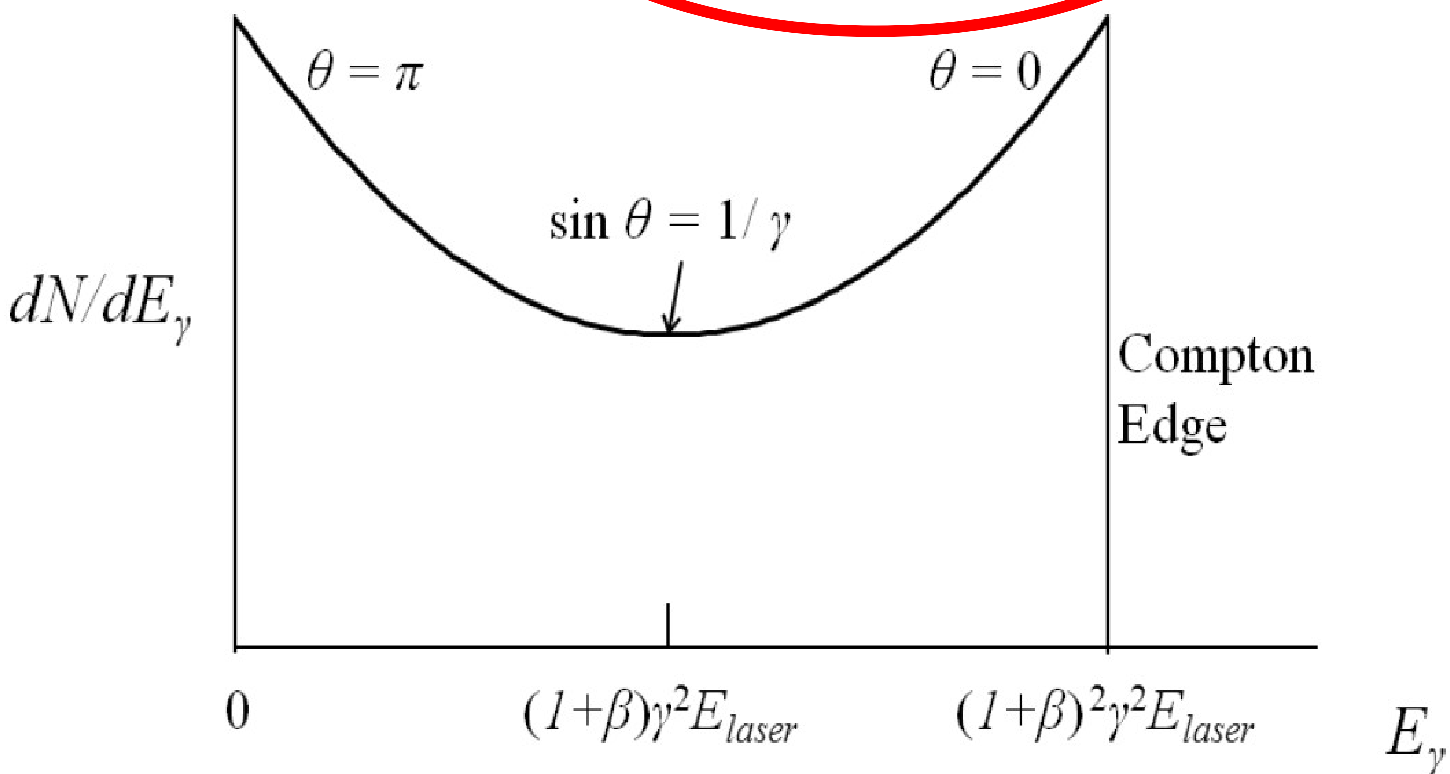
Compton Photon Beam Flux

Compton Photon Sources = Electron-Photon Colliders

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

Thomson cross-section:

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



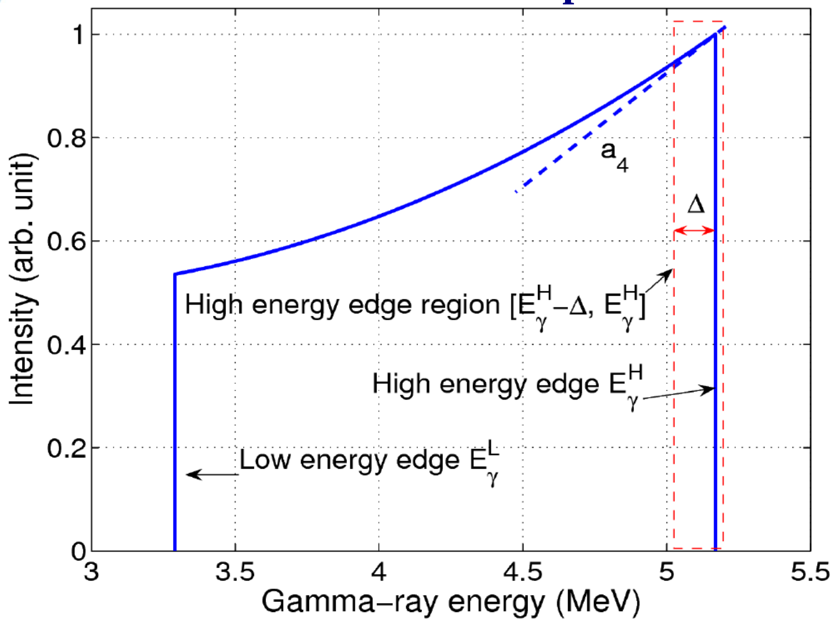
$$d\sigma = 8\pi r_e^2 \frac{dy}{x^2}\left[\left(\frac{1}{x}-\frac{1}{y}\right)^2 + \left(\frac{1}{x}-\frac{1}{y}\right) + \frac{1}{4}\left(\frac{x}{y}+\frac{y}{x}\right)\right]$$

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

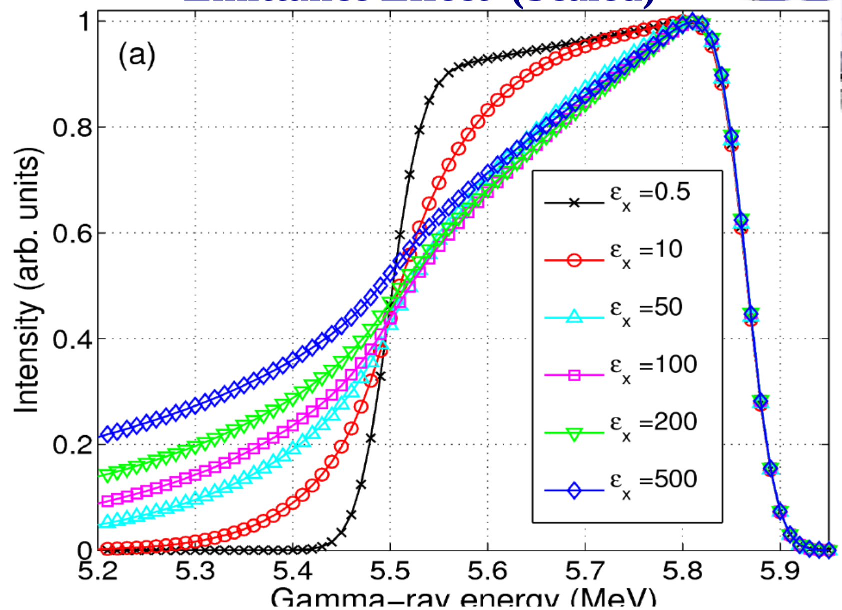
Figure: G. Kraff and G. Priebe, Rev. Acc. Sci. & Tech. V3, 147 (2010).

Energy Distribution of Compton Gamma-beam

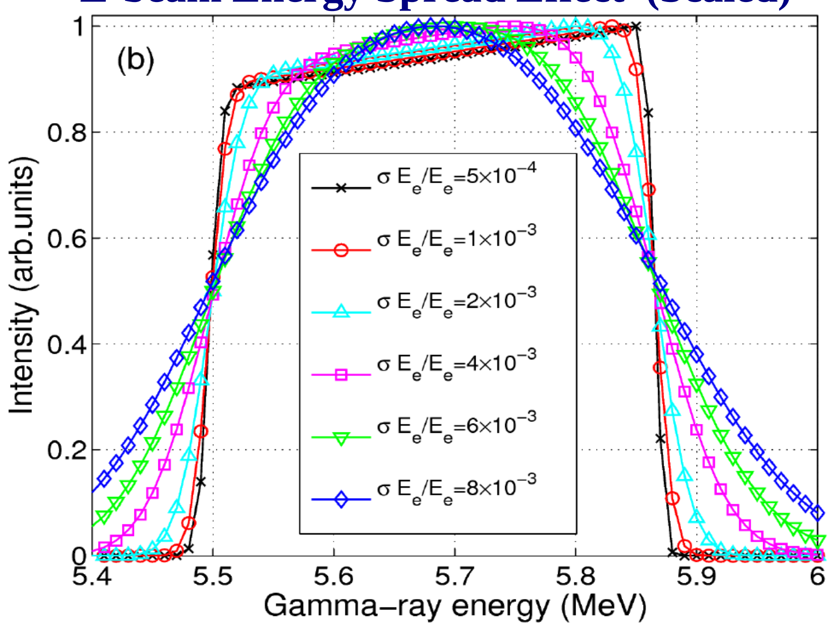
Monochromatic electron and photon beams



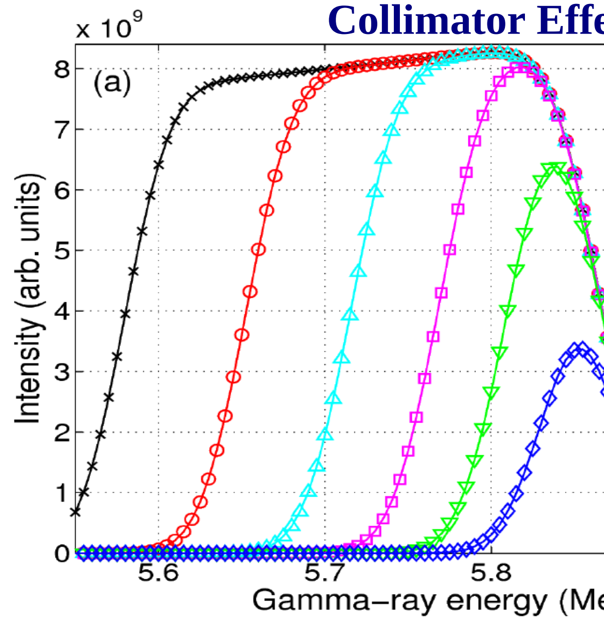
Emittance Effect (Scaled)



E-beam Energy Spread Effect (Scaled)



Collimator Effect

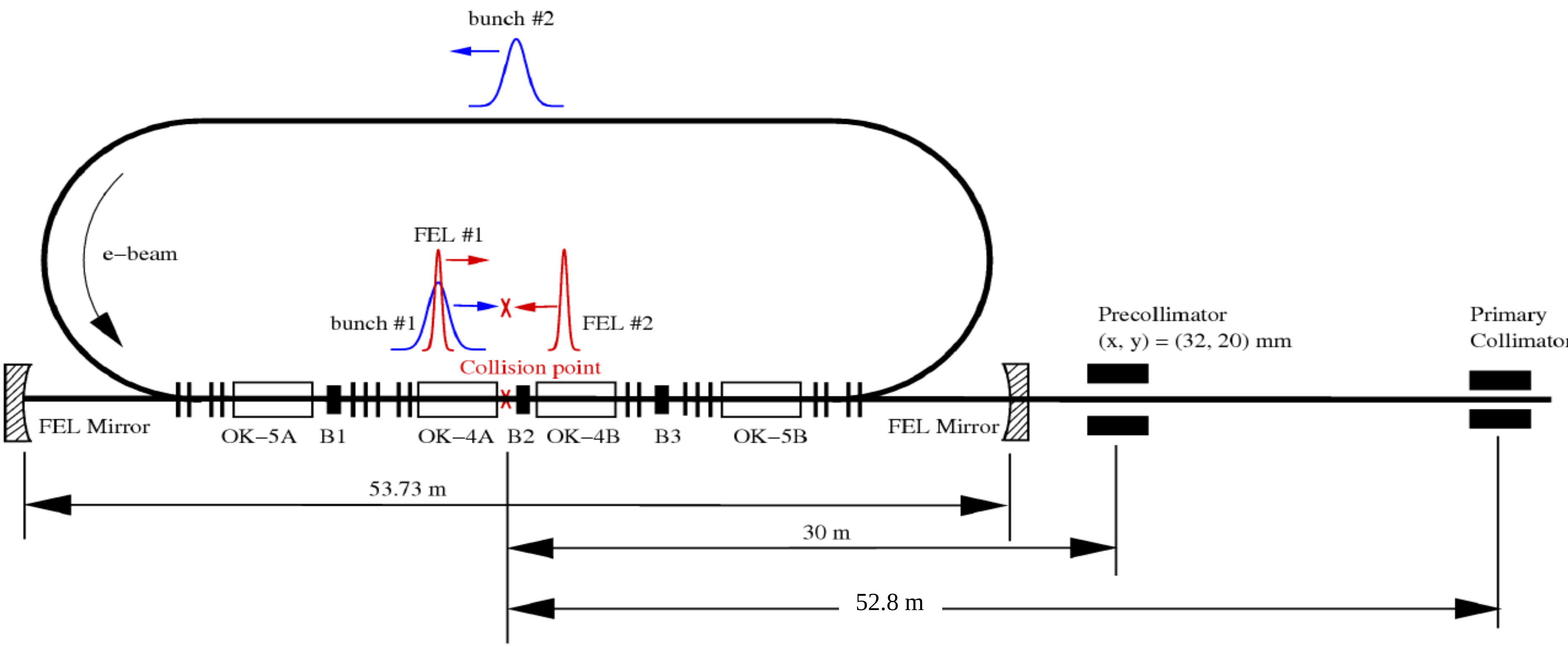


$$\alpha = \frac{\gamma^2 \Delta\theta_c^2}{2\sqrt{2\ln 2} \times (2\sigma_{E_e}/E_e)},$$

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

Operation Principle of HIGS

Two electron bunches + two FEL pulses



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

HIGS Capabilities

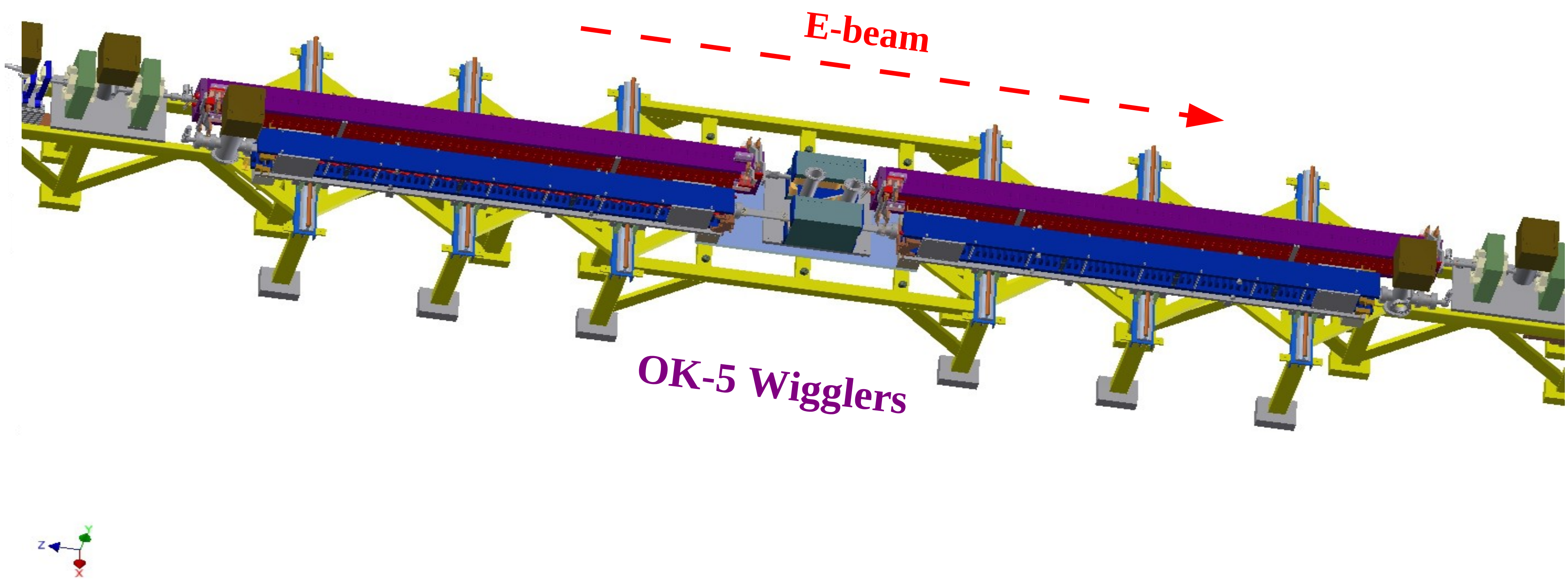
1. **HIGS Accelerator Facility Overview**

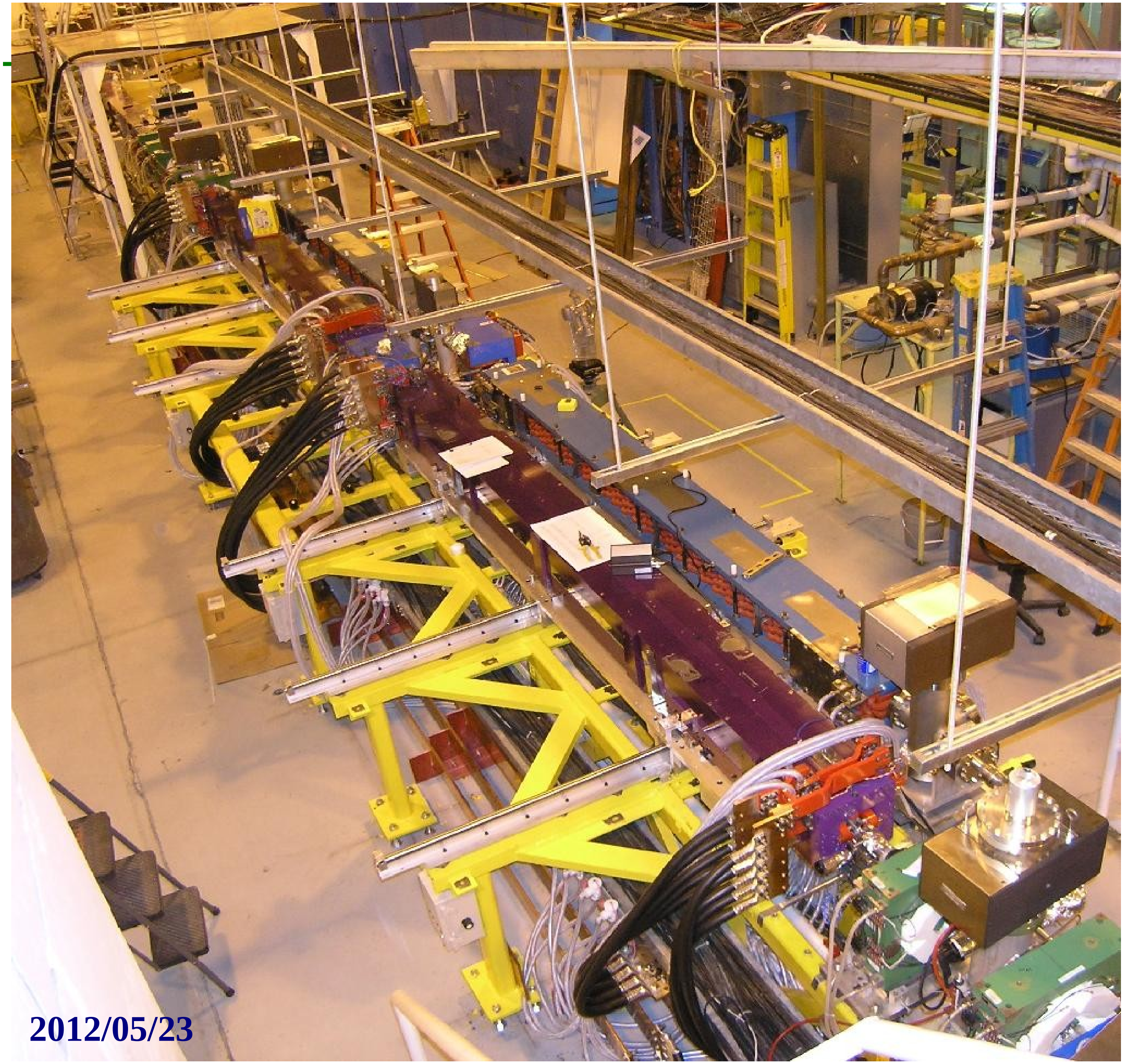
2. **HIGS Capabilities**

   - **Energy Range and Tuning**
   - **Gamma-ray Intensity**
   - **Energy Resolution**
   - **Gamma-ray Beam Stability**
   - **Helicity Switch**

Switchyard for OK-4 and OK-5 Wigglers

1. Preserve existing HIGS capabilities
2. Enable high-energy operation (>100 MeV)

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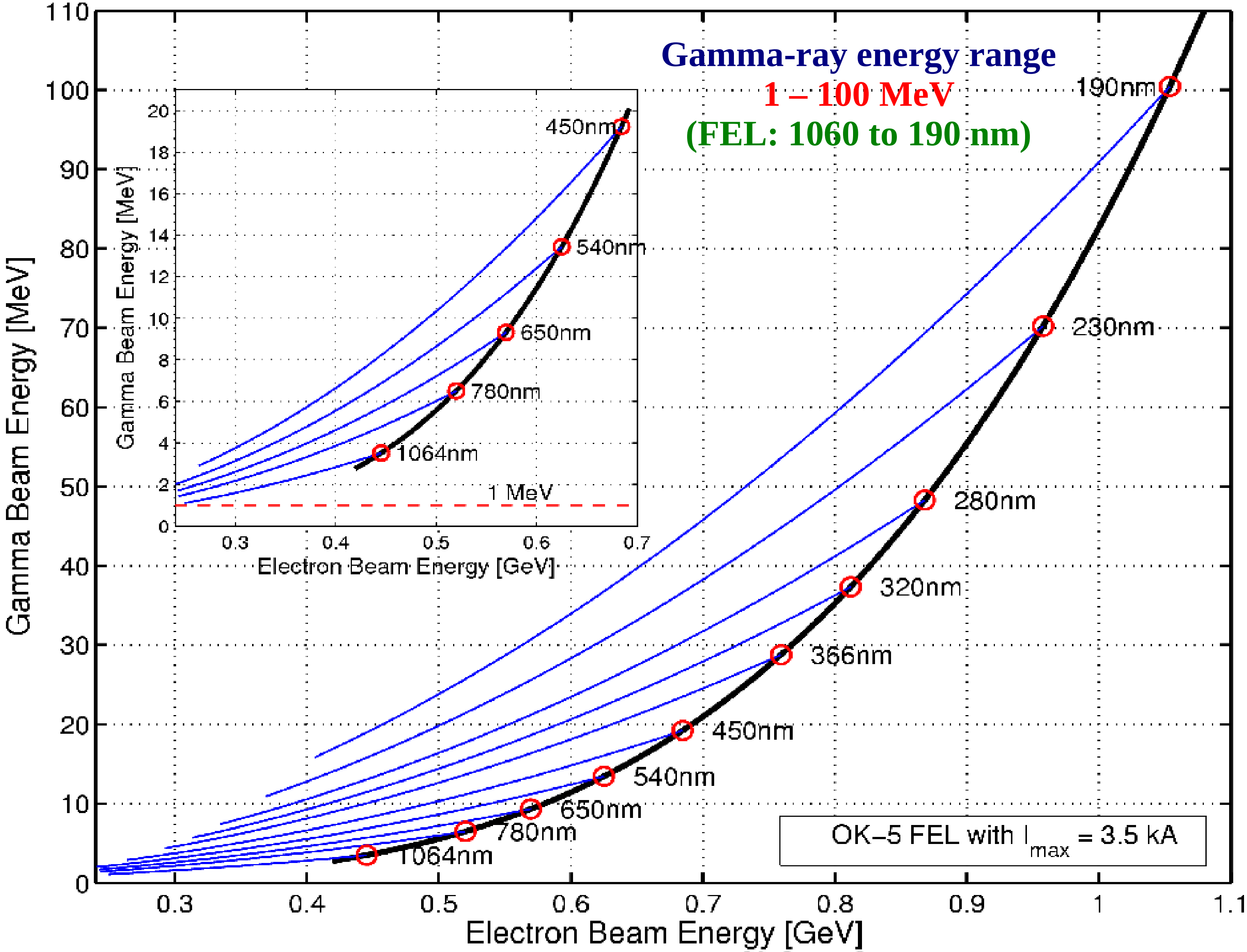
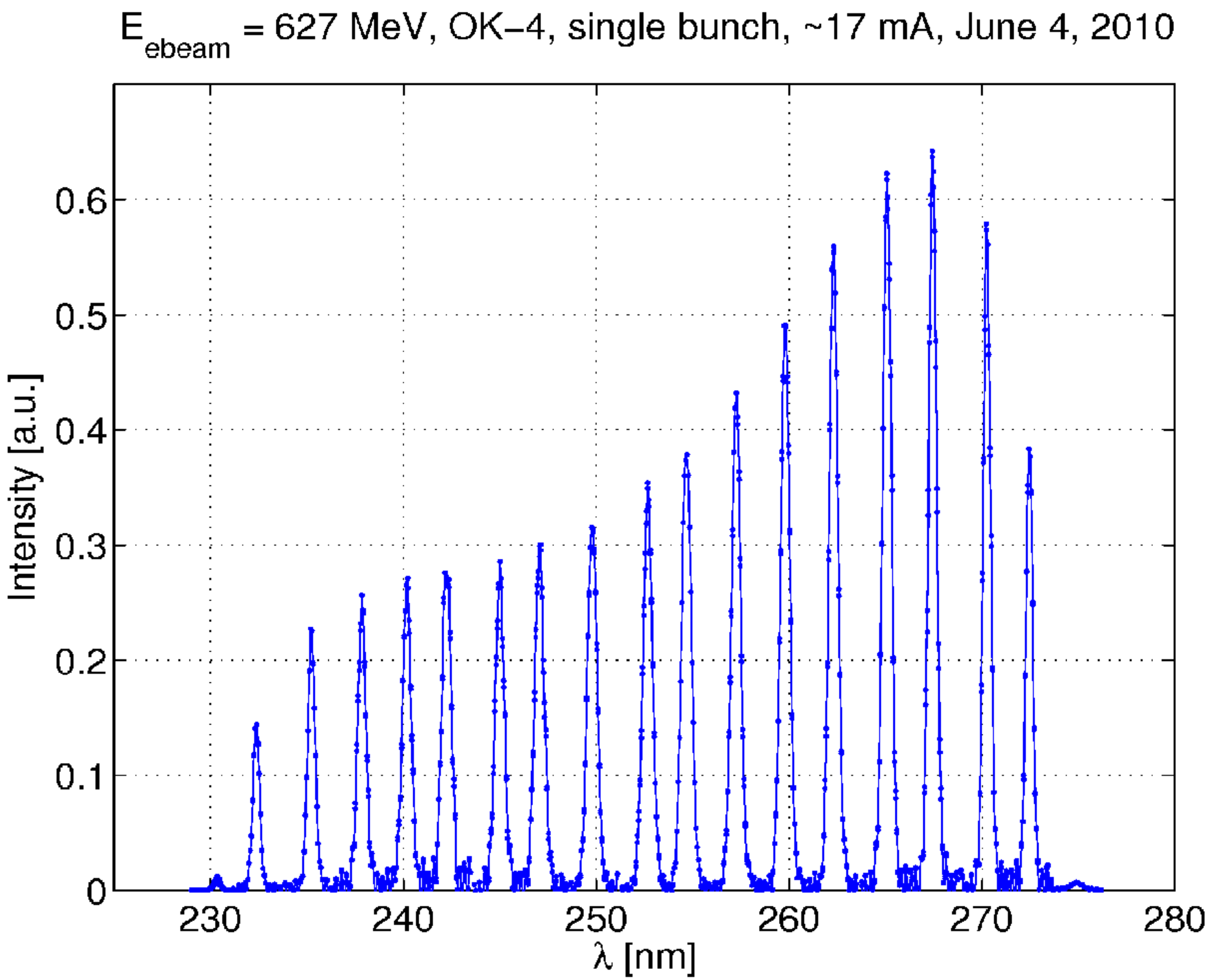
Gamma Energy Tuning Range with OK-5 FEL (3.5 kA)



240 nm Mirror Wavelength Tuning



HIGS/TUNL, Duke University, US

Facility/Project: HIGS

Institution: TUNL and Duke University

Country: US

Energy (MeV): 1 – 100

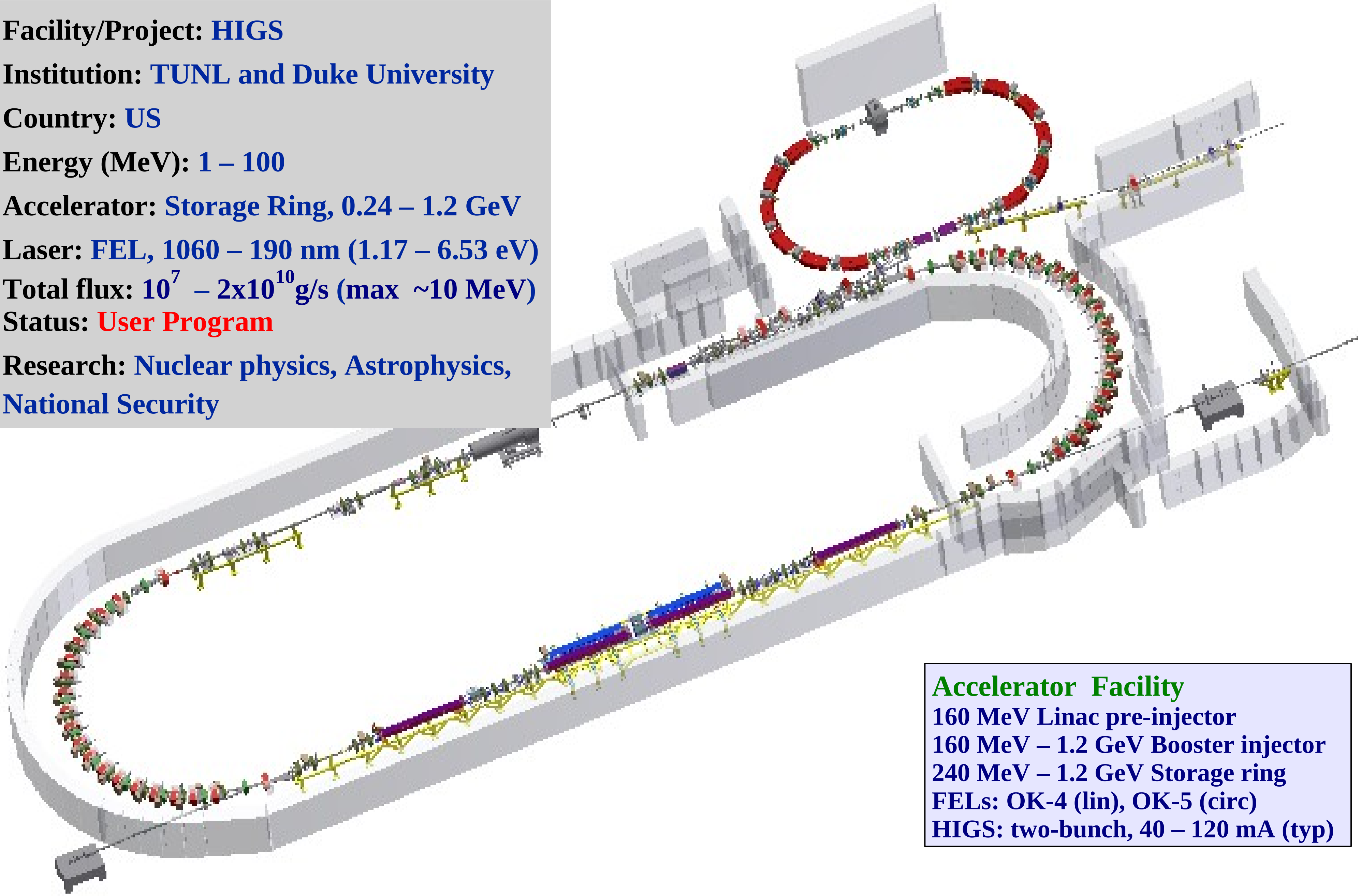
Accelerator: Storage Ring, 0.24 – 1.2 GeV

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

Total flux: 10^{7} – $2x10^{10}$g/s (max ~10 MeV)

Status: User Program

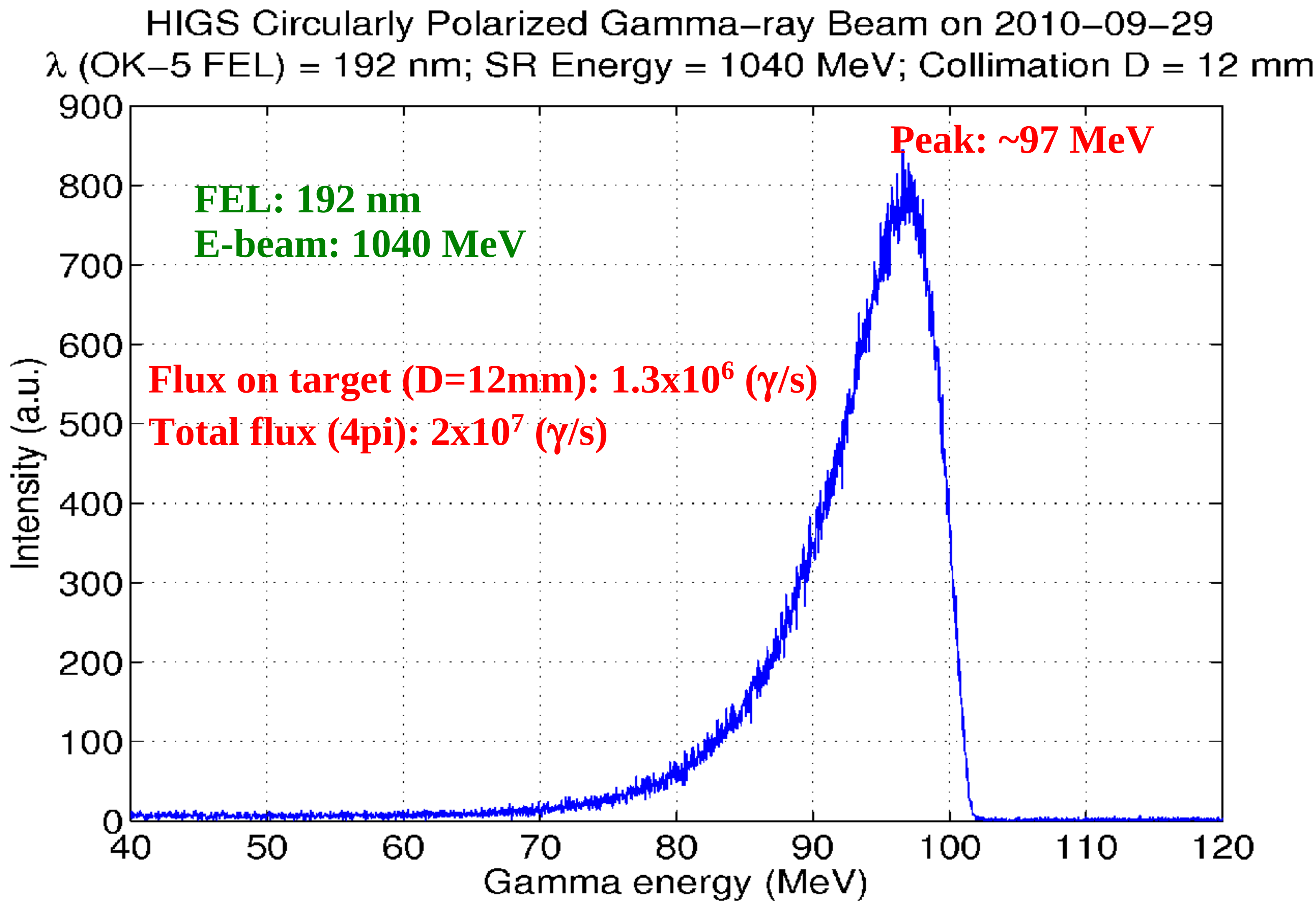
Research: Nuclear physics, Astrophysics, National Security



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)

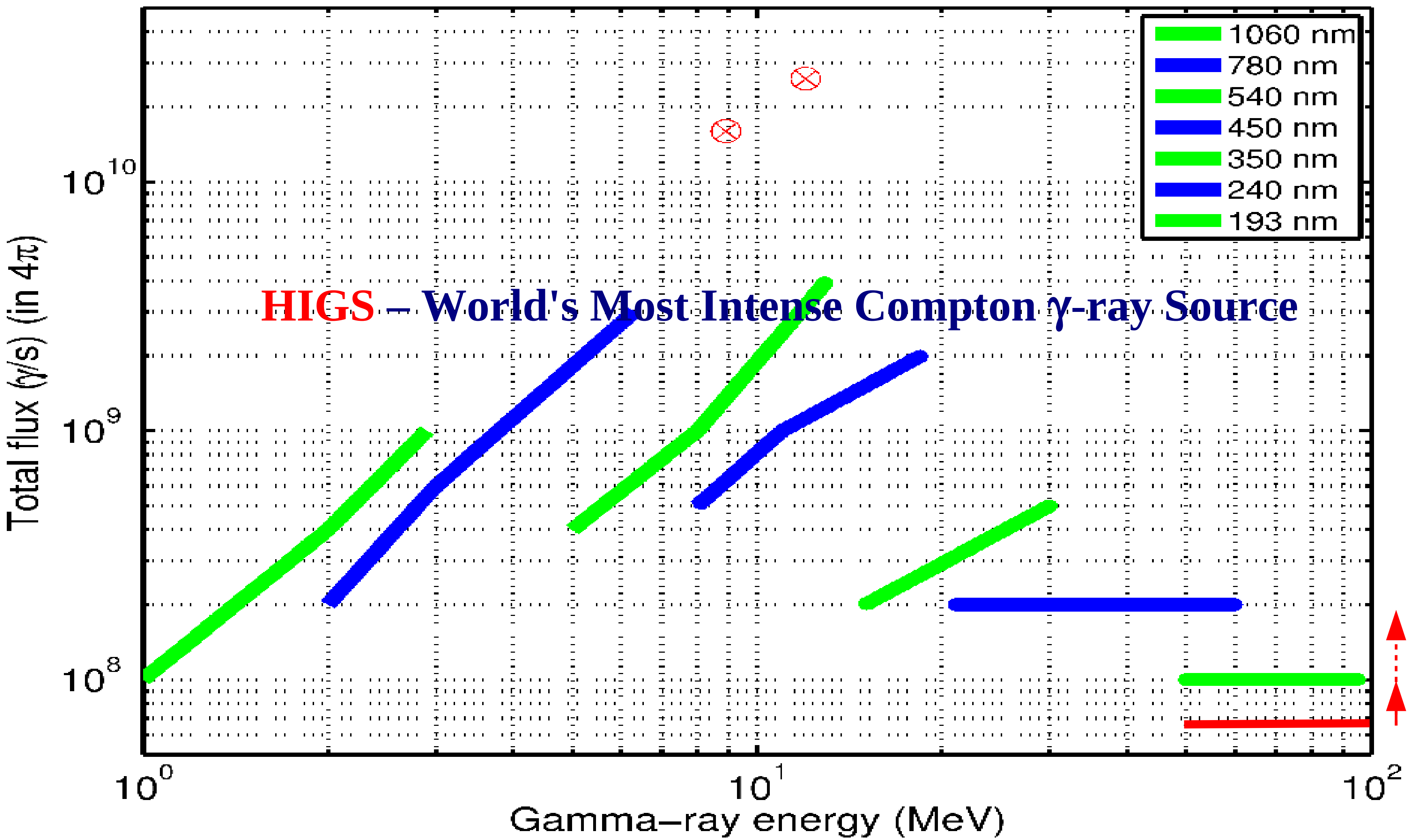
New Gamma-ray Energy Region: 70 – 100 MeV



Significance

- **Opened new research frontiers: precise measurements of electric and magnetic polarizabilities, and spin polarizabilities of nucleons**

HIGS User Flux Capabilities with OK-5 FEL



Peak Performance of HIGS

Total Flux: >2x 10^{10} γ /s, around 10 MeV
Spectral Flux: > 1,000 γ /s/eV, around 10 MeV

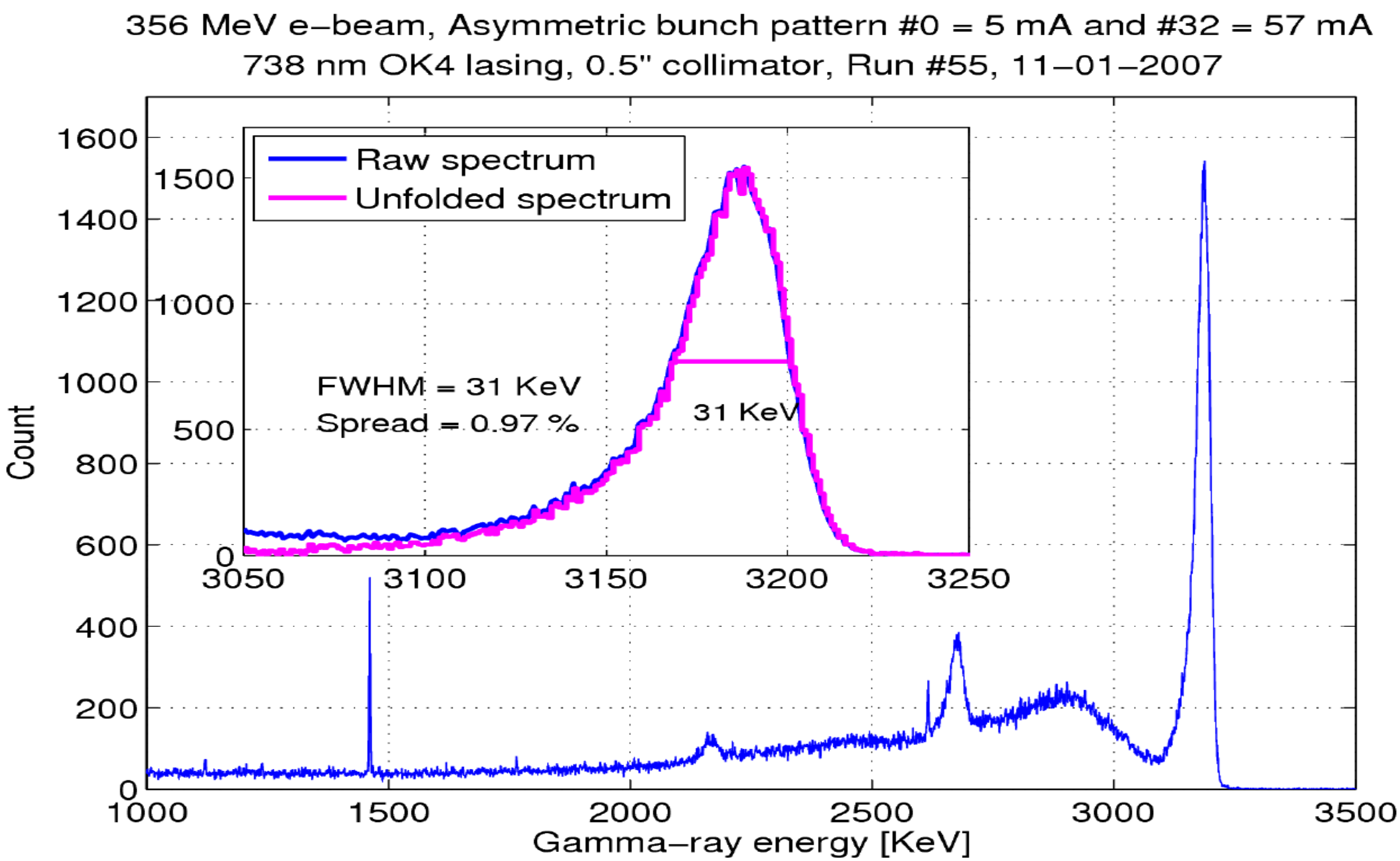
HIGS Capabilities for User Programs in 2013

Parameter	Value		Comments
E-beam Configuration E-beam current [mA]	Symmetric two-bunch beam 50 - 120		High flux configuration
Gamma-ray Energy [MeV]	1 – 100		with mirrors 1064 to 190 nm Available with existing hardware Extending wiggler current to 3.5 kA
(a) No-loss mode	Total flux [γ/s]	Collimated flux ($\Delta E/E$~5%) [γ/s]	Both Horizontal and Circular Polarizations
1 – 3 MeV[a]	$1 \times 10^8 – 1 \times 10^9$	$6 \times 10^6 – 6 \times 10^7$	
3 – 5 MeV	$6 \times 10^8 – 2 \times 10^9$	$3.6 \times 10^7 – 1.2 \times 10^8$	
5 – 13 MeV	$4 \times 10^8 – 4 \times 10^9$	$2.4 \times 10^7 – 2.4 \times 10^8$	
13 – 20 MeV	$1 \times 10^9 – 2 \times 10^9$	$6 \times 10^7 – 1.2 \times 10^8$	
(b) Loss mode	Total flux [γ/s]	Collimated flux ($\Delta E/E$~5%) [γ/s]	To extend mirror lifetime, circular polarization is preferred
21 – 54 MeV	> 2×10^8 [b]	> 1×10^7	1st user experiment: March, 2011
55 – 65 MeV	~ 2×10^8 [b]	~ 1×10^7	
66 – 100 MeV	~ 0.7×10^8 [b] [c]	~ 0.4×10^7	190 nm, 1st user experiment in 2013

[a] With present configuration of OK-5 wigglers separated by 21 m, the circular polarization is about ½ the values here.
[b] The flux in loss mode is mainly limited by injection rate.
[c] Thermal stability of FEL mirror may limit the maximum amount of current can be used in producing FEL lasing, thus flux.

Highest Total Flux: >2×10^{10} γ/s @ 9 – 11 MeV

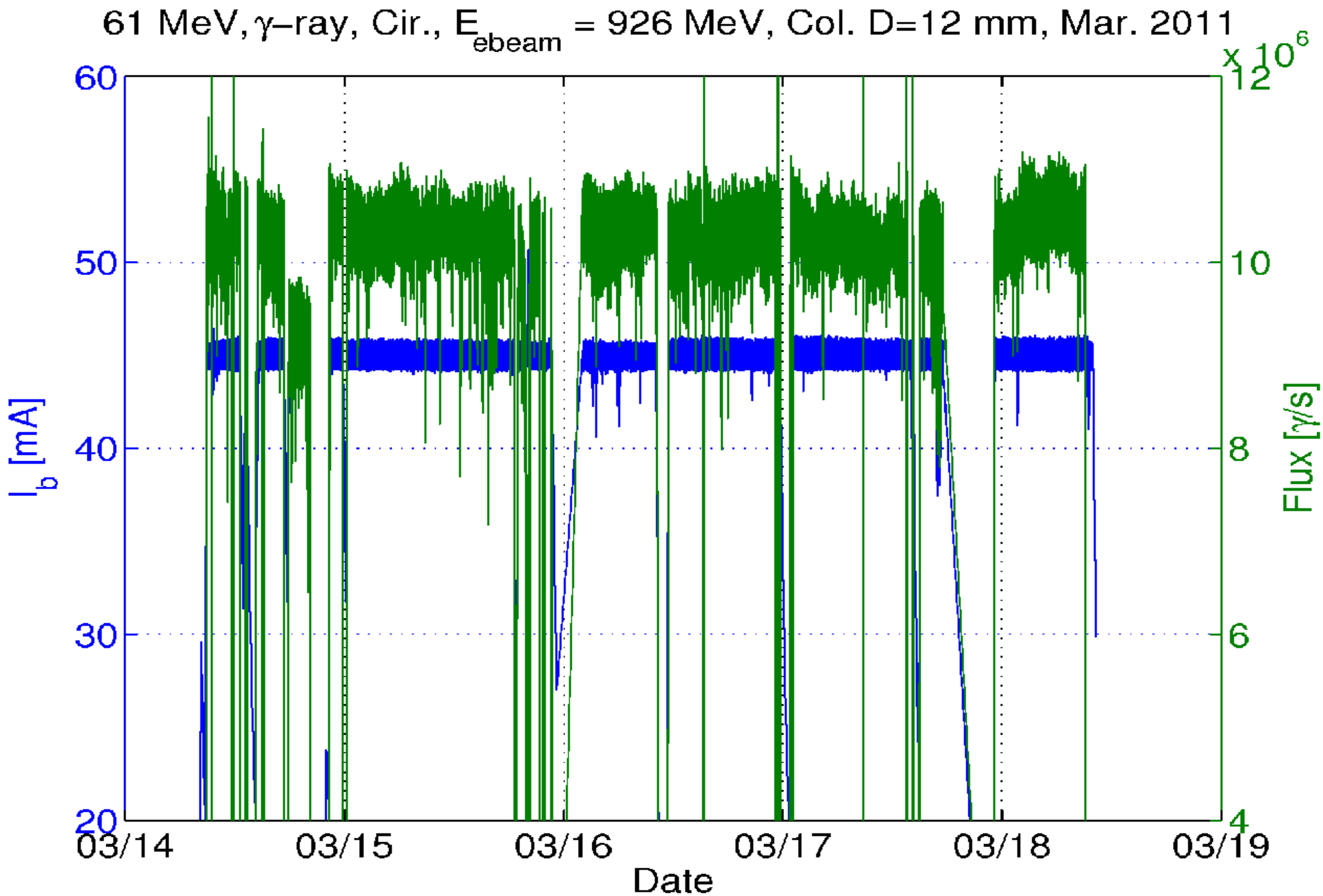
High Energy-Resolution Operation



Gamma-ray Beam Energy Resolution

- **High-resolution operation: asymmetric electron bunches, lower flux**
- **High-flux operation: typical 3 – 5% (or larger), selected by collimation**

240 nm Mirror: 61 MeV γ-Beam Production



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

Stability of Electron/Photon Collision Angle

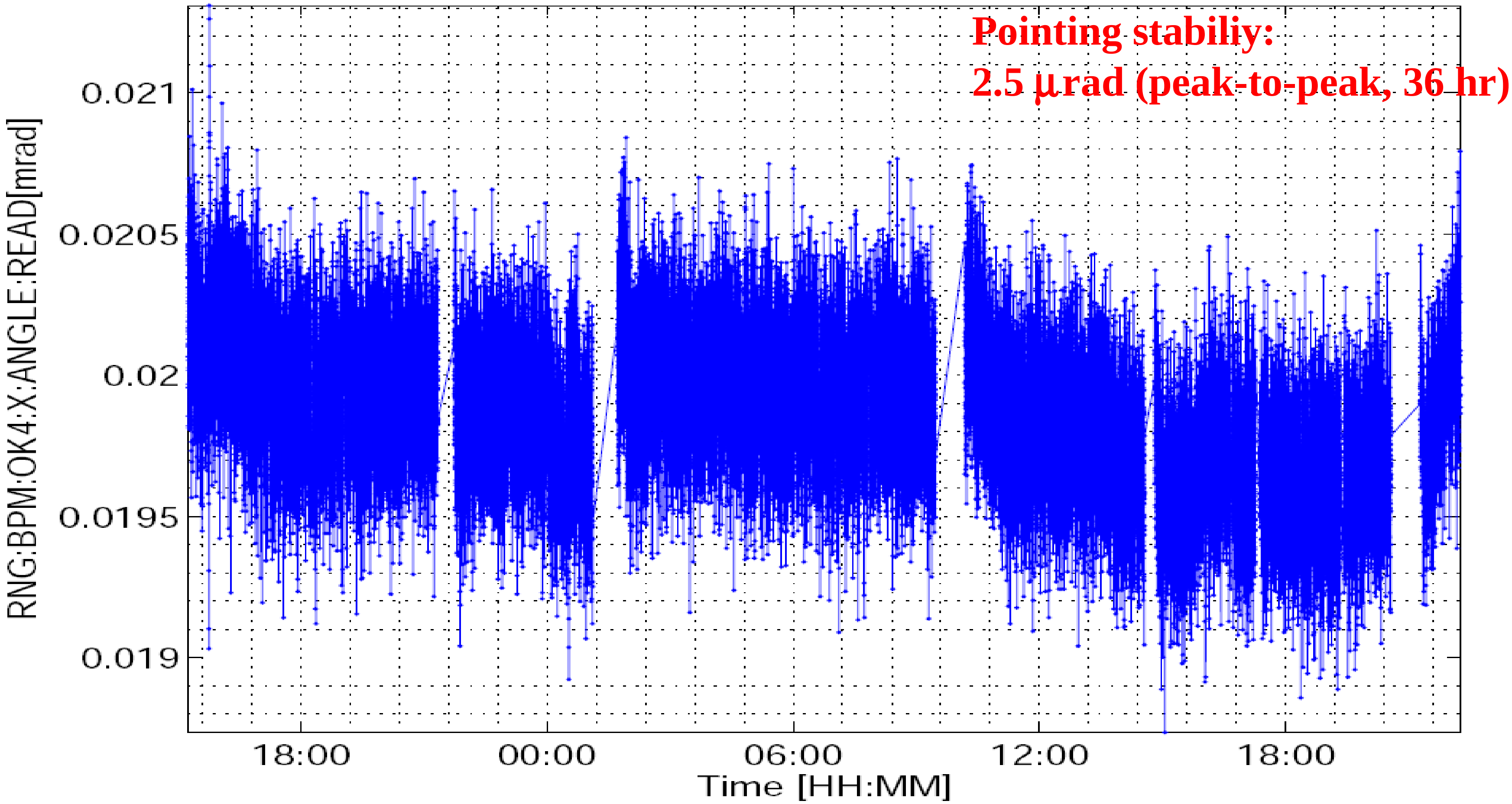
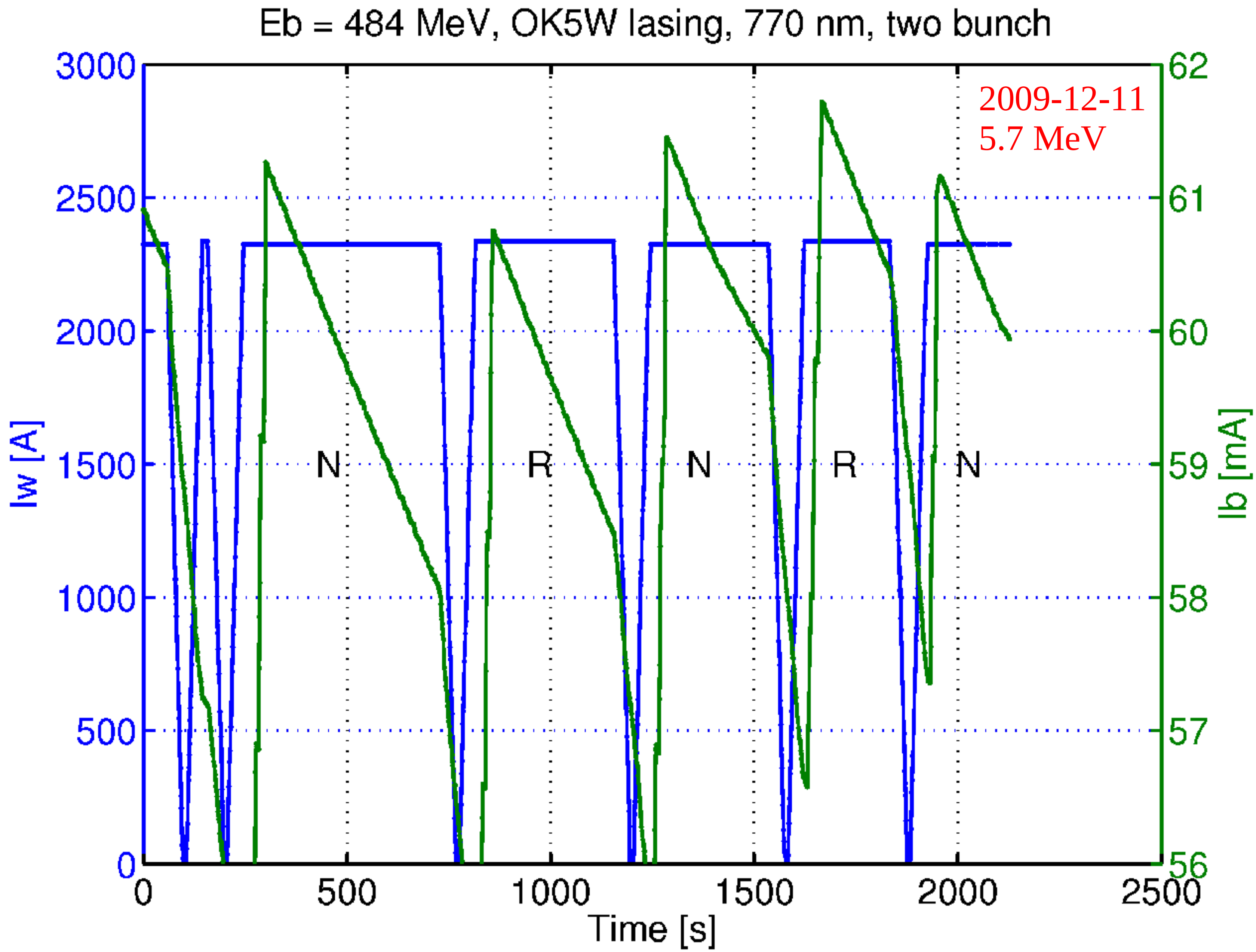
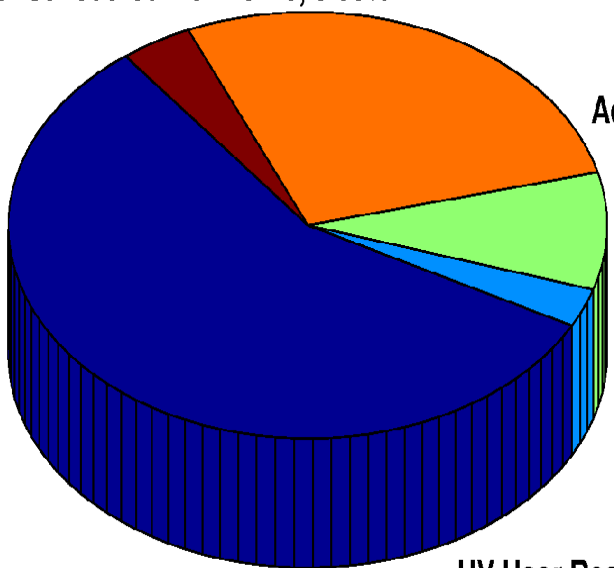


Figure 15: Horizontal beam angle at OK4 for about 36 hours operation from Aug. 20 to Aug. 21, 2009. The angle varied 2.5μrad (peak to peak) during this operation, this value corresponds to 150μm variation of gamma ray beam position at the gamma vault which is located 60 m downstream of the collision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

OK-5 Helicity Switch



HIGS Operation Summary (Aug. 2008 – Jul. 2011)



Activities	Beamtime (hrs)	%
HIγS user research	4859	56.8%
UV research	251	2.9%
Acc. R&D	760	8.9%
Acc./FEL/HIγS setup and tune	2356	27.5%
Unscheduled downtime	332	3.9%
Total scheduled beamtime	8558	100%

Accelerator Operation Reliability: ~96%
(Aug. 2008 – Jul. 2011)

HIGS Development (2013 –)

New Capabilities Development in Two Fronts

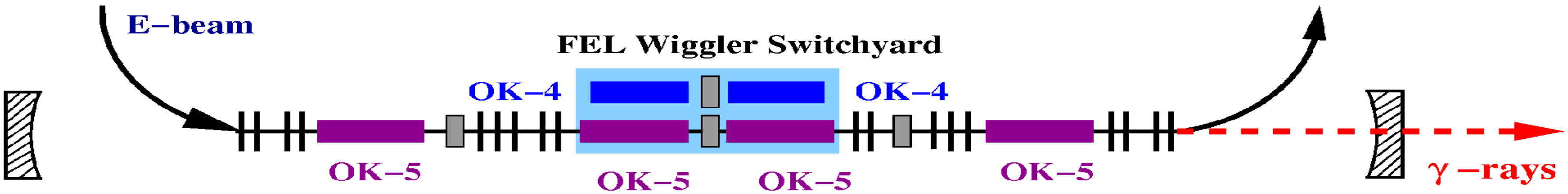
- **Energy Front**

  FEL ~175 nm => 100 – 120 MeV gamma-ray beams

  FEL ~150 nm => 120 – 158 MeV gamma-ray beams

- **Intensity Front: *Next Generation Compton Source at HIGS:* HIGS2**
  - **Hadronic parity violation**
  - **Nuclear astrophysics**
  - **Dark-matter search**

High Energy Gamma-ray Operation

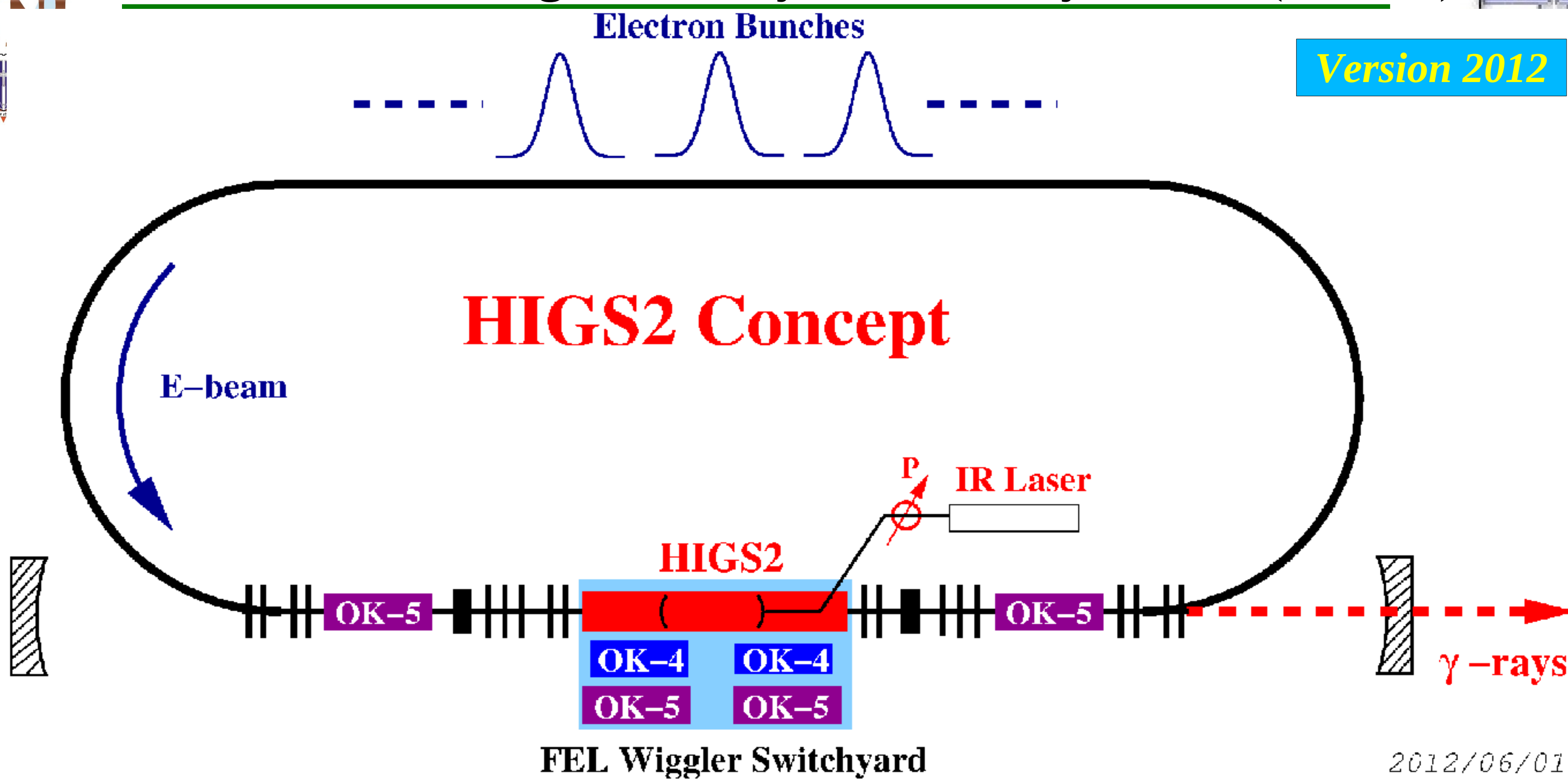


HIGS with VUV FEL Operation

1. 66 – 100 MeV, 190 nm FEL: two OK-5 wigglers
2. 100 – 120 MeV, 175 nm FEL: two OK-5 wigglers
3. 120 – 158 MeV, 150 nm FEL: three OK-5 wigglers

Next Generation High Intensity Gamma-ray Source (HIGS2)

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**

HIGS Capabilities vs Nuclear Physics Programs

To be developed
100 – 158 MeV

HIGS
1 – 100 MeV

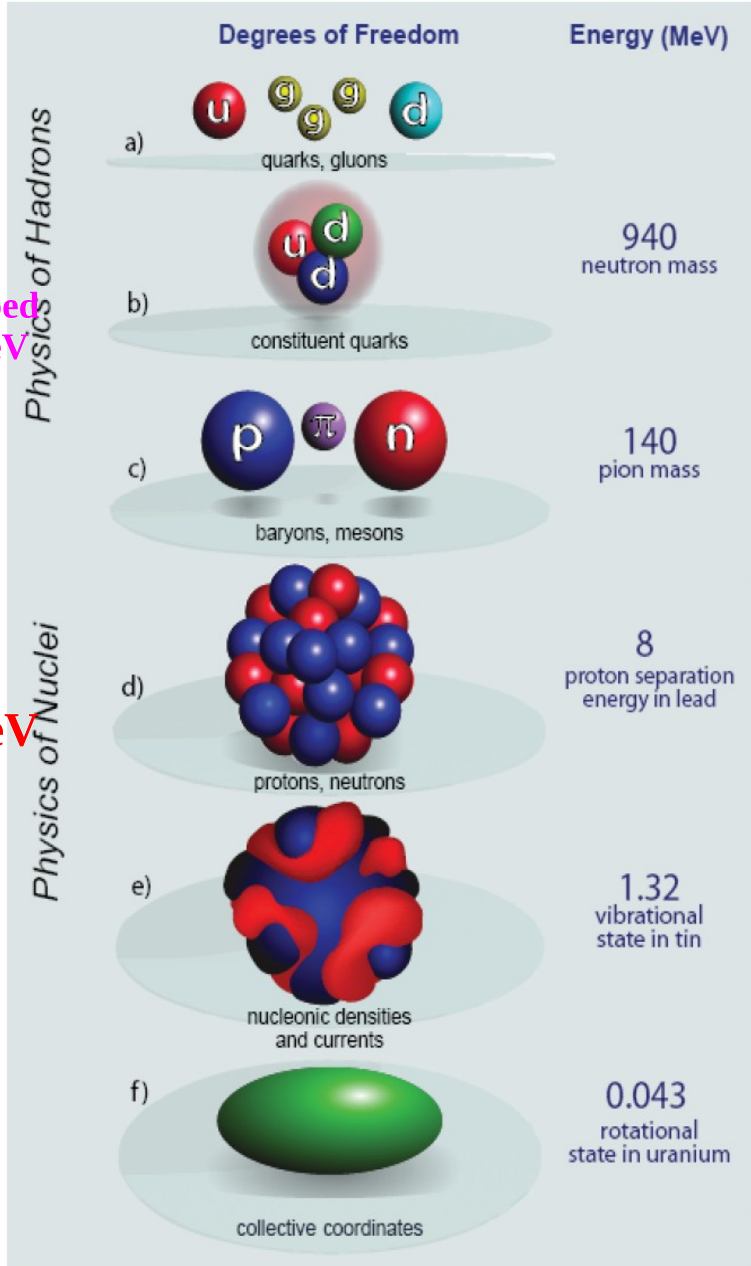


Photo-pion Production

Compton Scattering
nucleon electric and
magnetic polarizabilities
nucleon spin polarizabilities

GDH Sum Rule
D, ^{3}He

Few-nucleon Systems
photodisintegration

Nuclear Structure and Nuclear Astrophysics
NRF, (γ,γ')
(γ,n) reactions

Areas of Applications Research

- **National Security: SNM detection**
- **Materials: Novel scintillators**
- Energy: Nuclear waste
- Medical: Isotope production
- Industrial: product inspection

1. 2007 Long-Range Plan for Nuclear Science in the USA (NSAC);
2. Courtesy of C. Howell, TUNL