Overview of Present and Future Compton Photon Sources

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Acknowledgment:

To all members of the world's accelerator community who contributed to the development of Compton photon sources in the last five decades.

Credit will be given on individual slides.

Outline

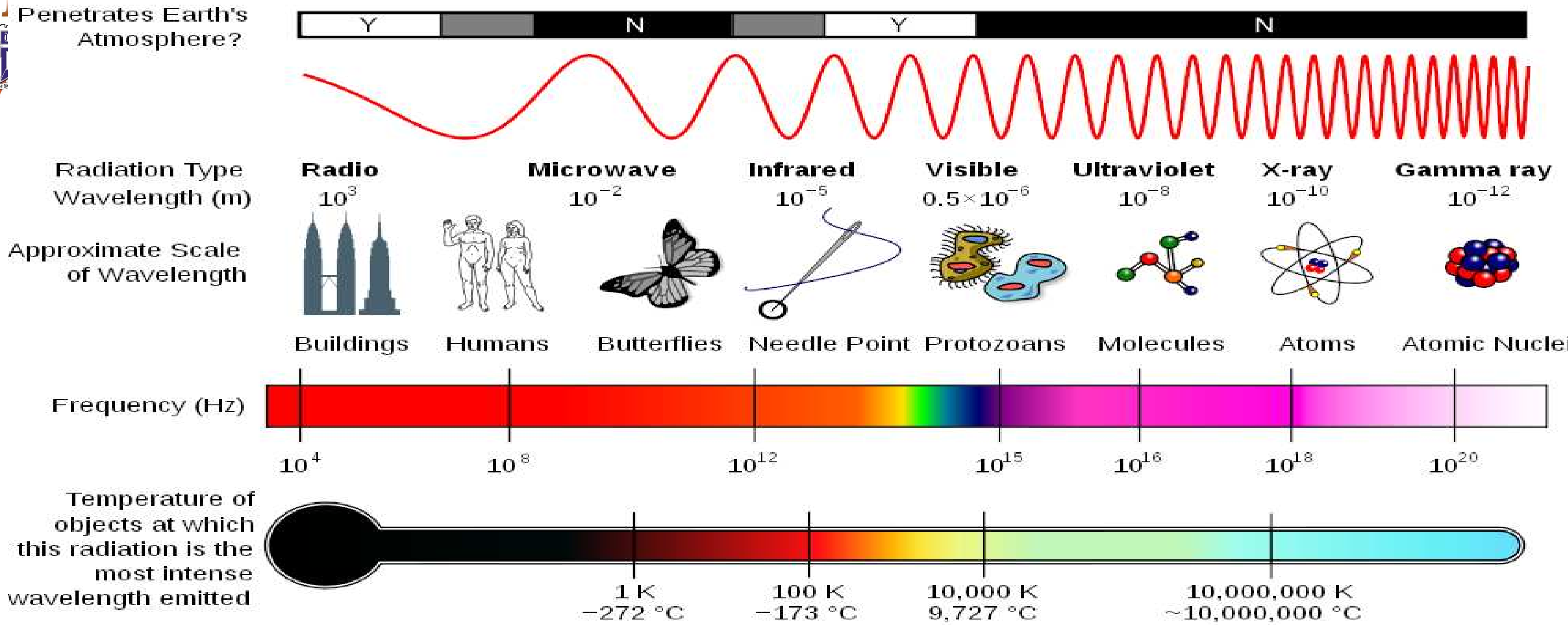
- **Compton Scattering Effect and Physics of Compton Photon Beams**
- **Compton Photon Sources around the World, Present and Future**
  - **Compton X-ray Sources: Facilities, Projects and Experiments**
  - **Compton Gamma-ray Sources: Facilities and Projects**
  - **New Technologies**
- **Fundamental and Applied Research Using Compton Photon Sources**
  - **Limitations and Prospects**
  - **R&D Topics**
- **Summary: World Wide Effort on Compton Photon Sources**

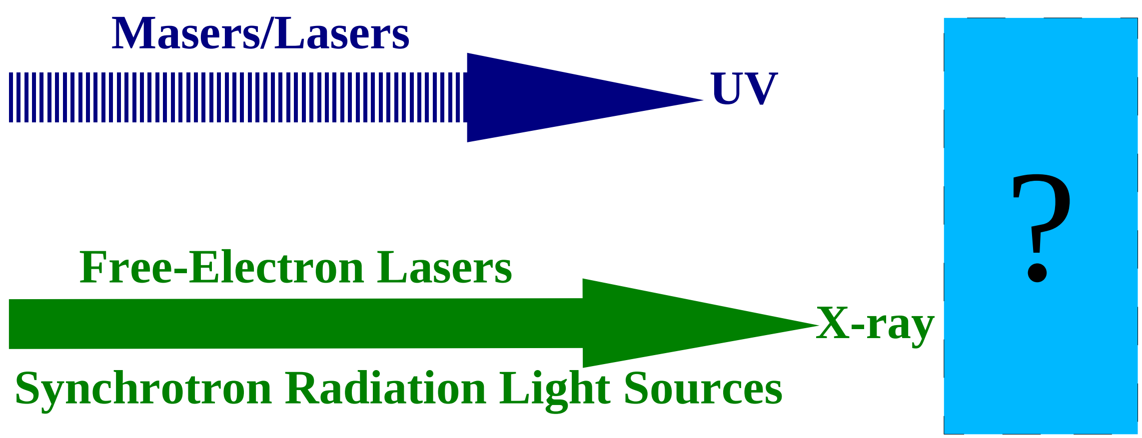
Compton Scattering Effect and

Physics of Compton Photon Beams

Gamma-rays

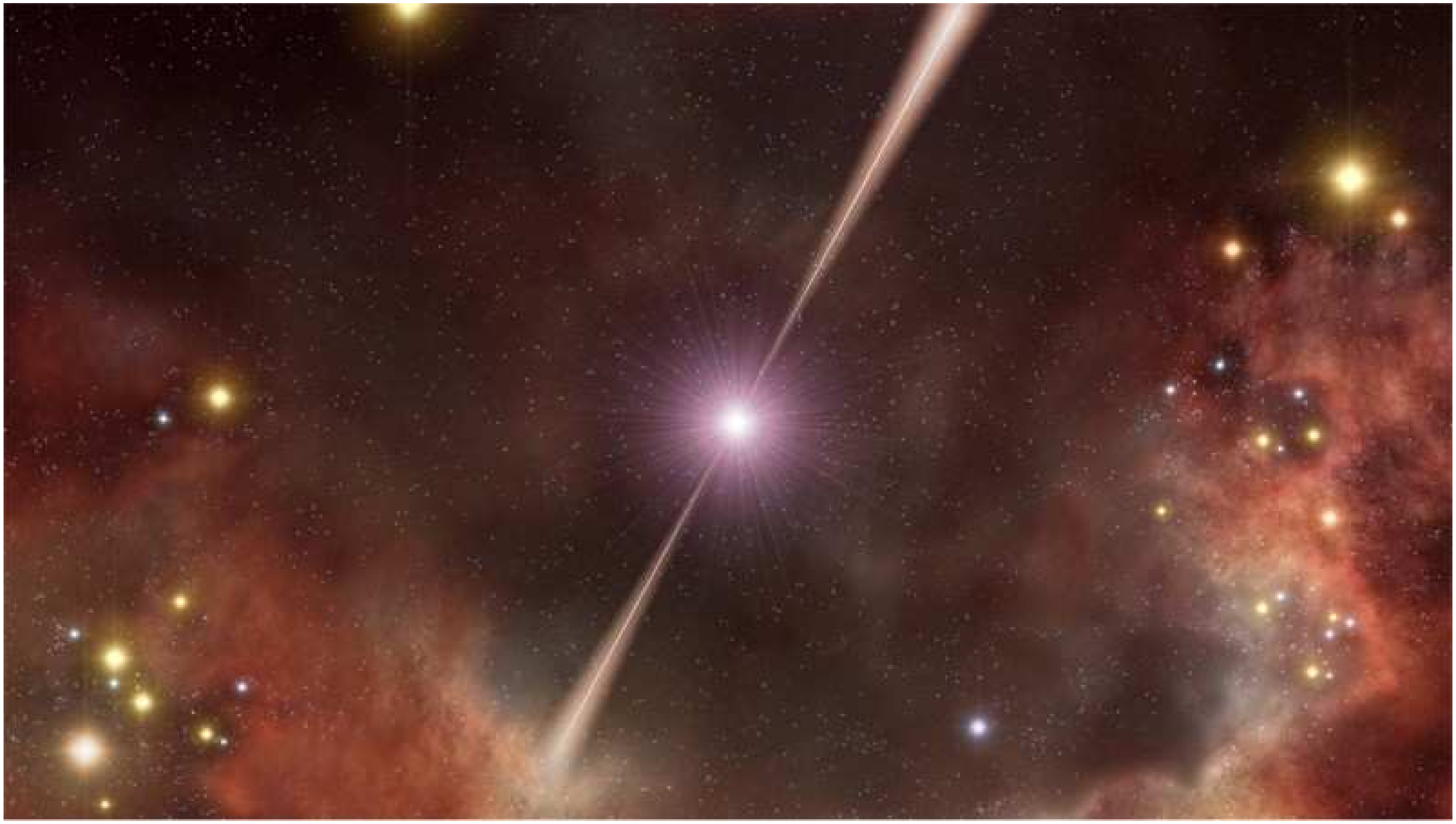
Spectrum of Electromagnetic Radiation





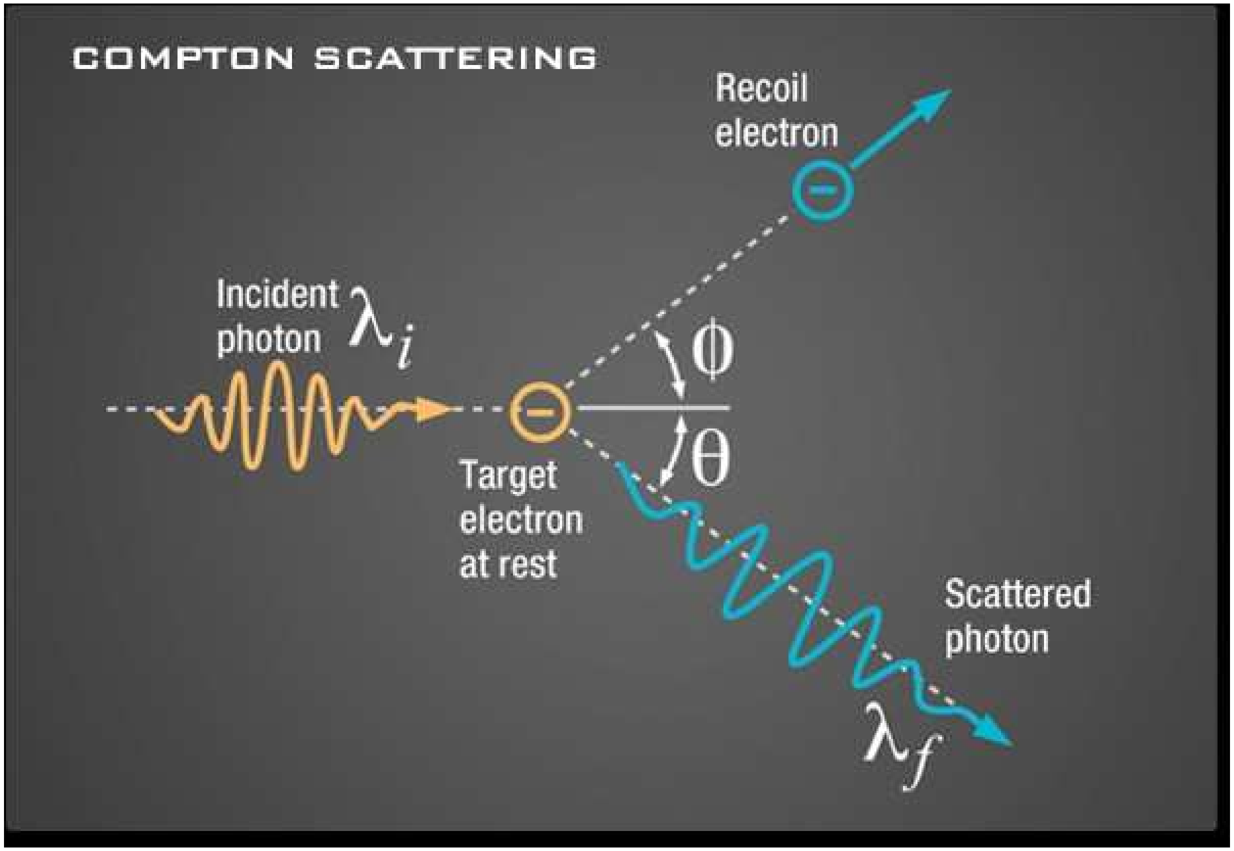
http://en.wikipedia.org/wiki/Electromagnetic_spectrum

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

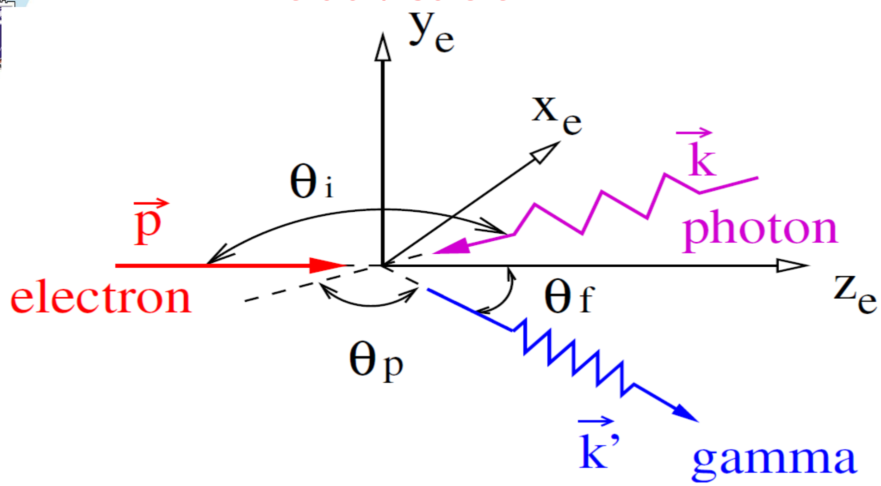
$$\lambda_f - \lambda_i = \frac{h}{m_e c}(1 - \cos\theta)$$

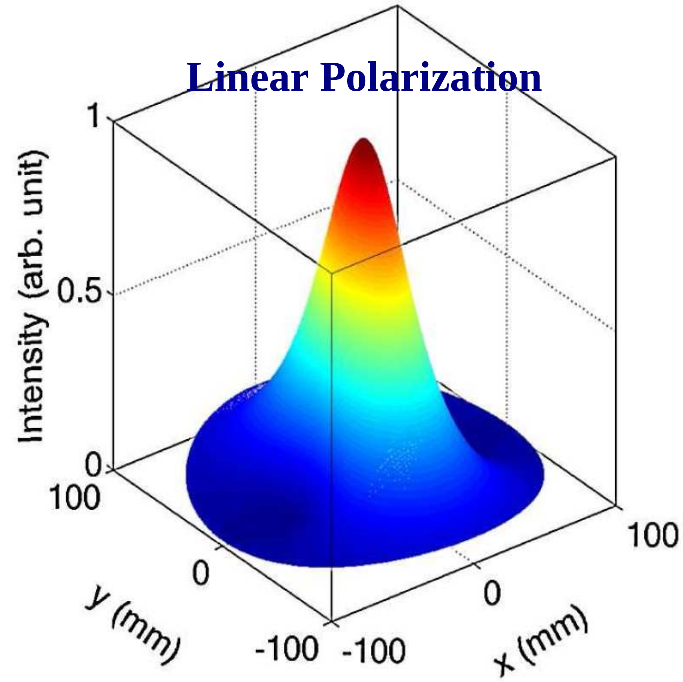
1. http://fishbein.uchicago.edu/courses.html
2. http://missionscience.nasa.gov/ems/12_gammarays.html

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

Photon Energy

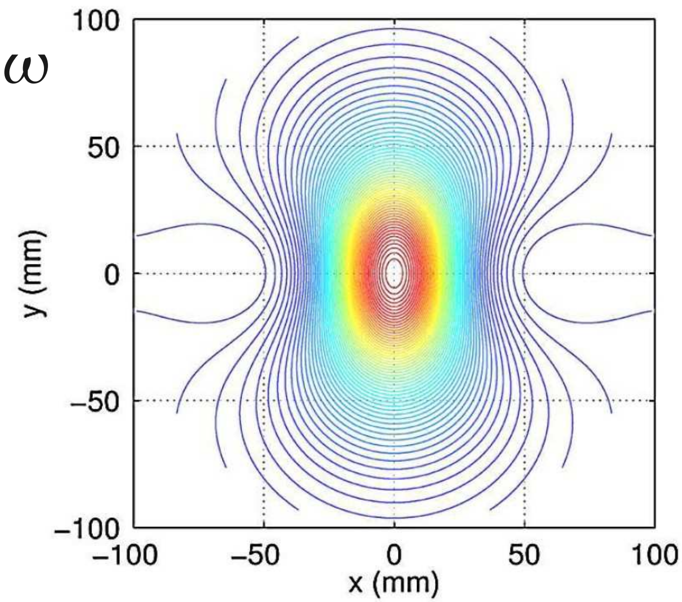
Relativistic e⁻





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

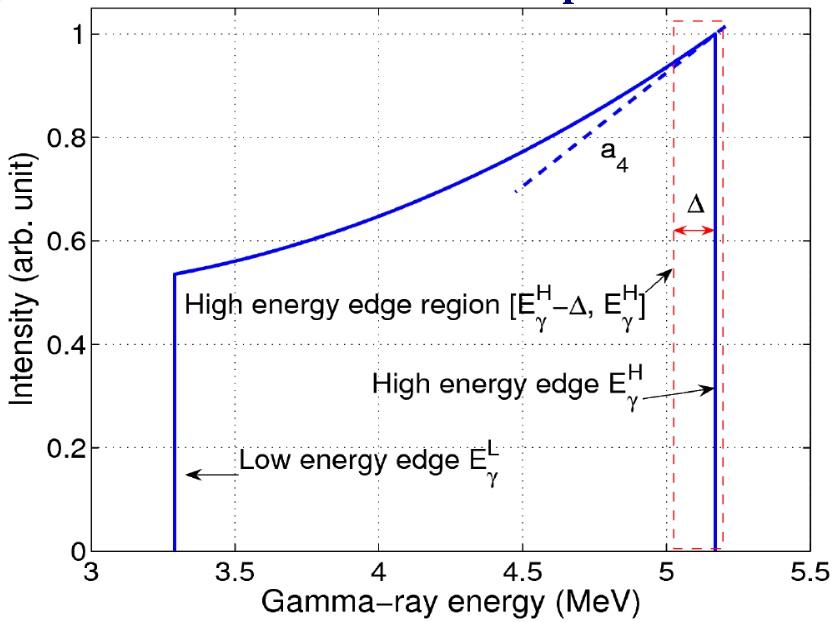
Head-on Collision: $E_\gamma^{max} \approx (\gamma(1+\beta))^2 \hbar\omega \approx 4\gamma^2 \hbar\omega$



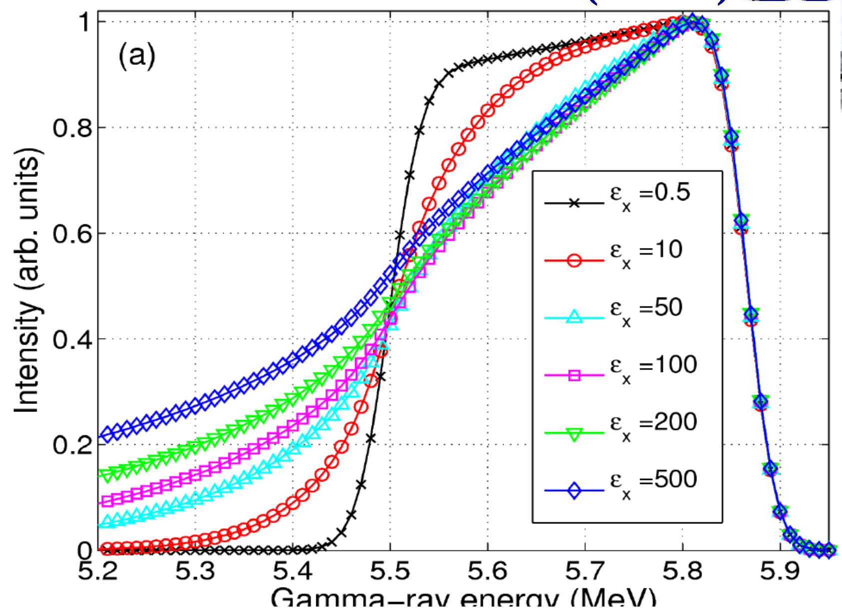
C. Sun and Y. K. Wu, Phys. Rev. ST Accel. Beams 14, 044701 (2011)

Energy Distribution of Compton Gamma-beam

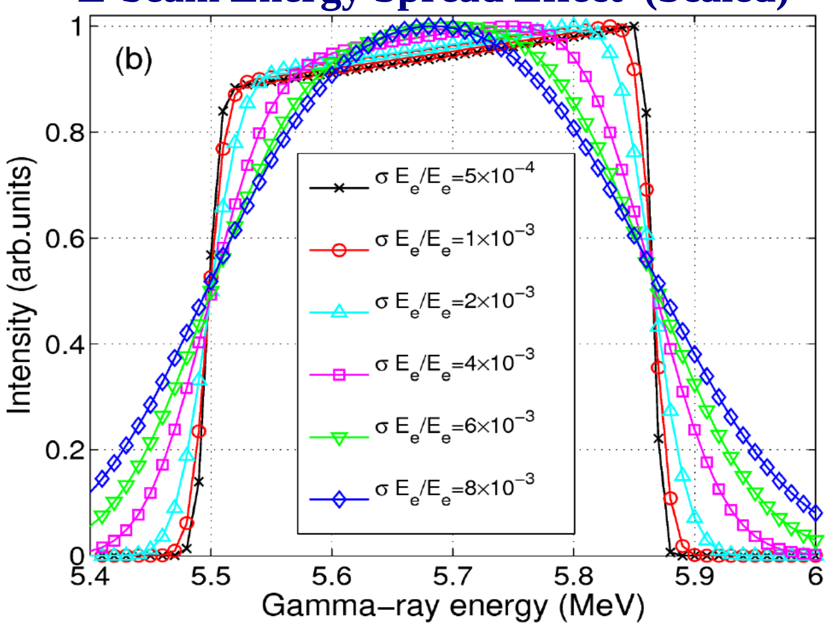
Monochromatic electron and photon beams



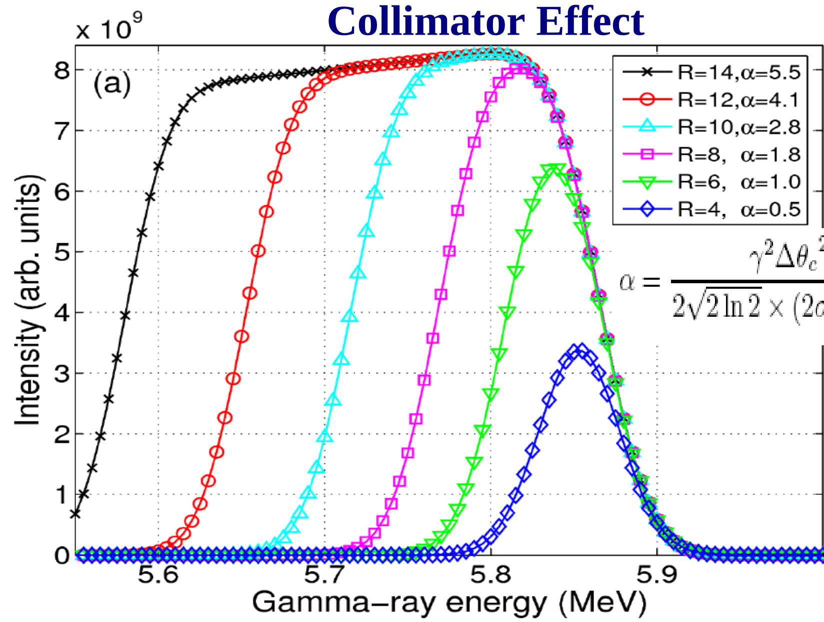
Emittance Effect (Scaled)



E-beam Energy Spread Effect (Scaled)



Collimator Effect

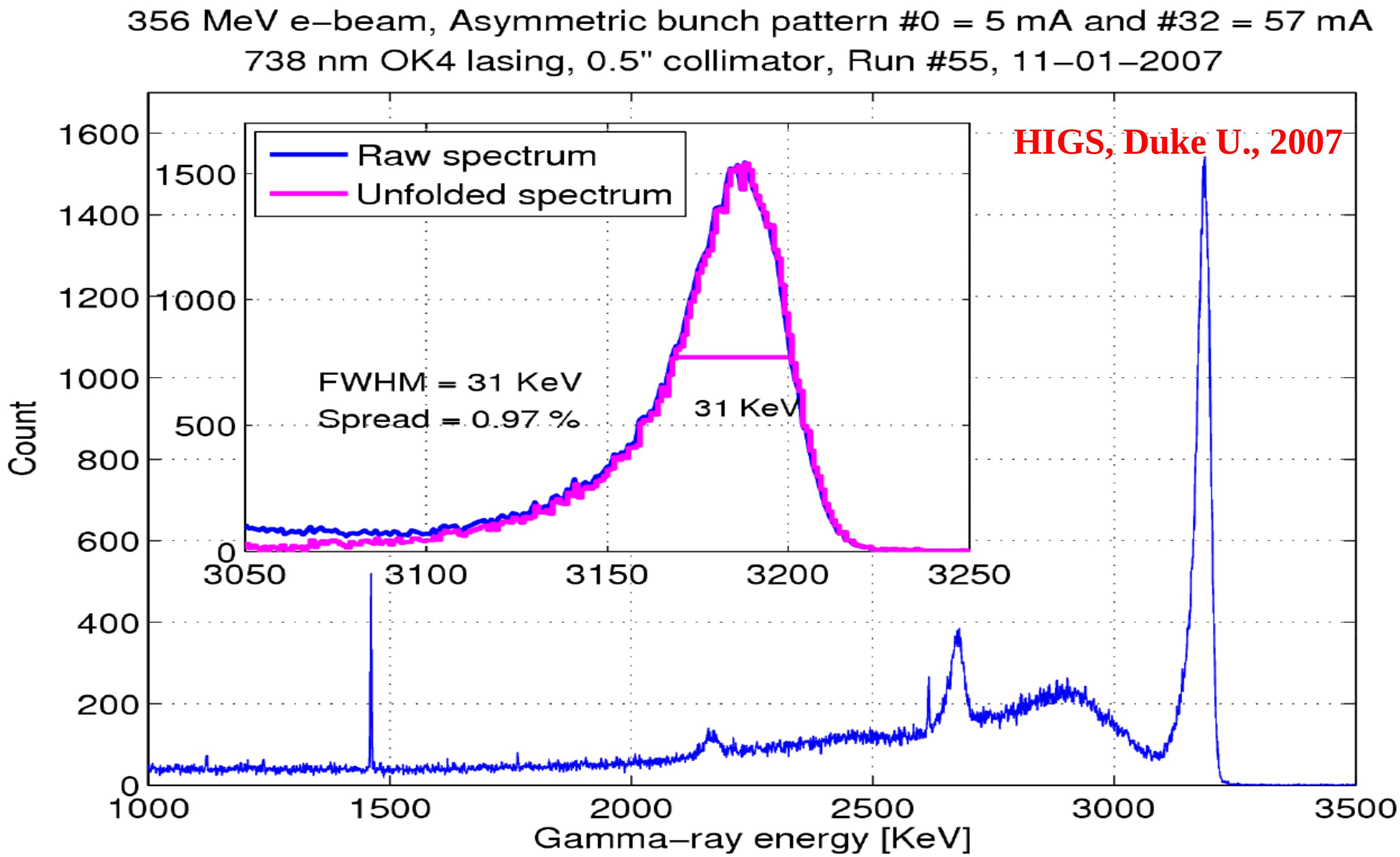


$$\alpha = \frac{\gamma^2 \Delta\theta_c^{\,2}}{2\sqrt{2\ln 2} \times (2\sigma_{E_e}/E_e)},$$

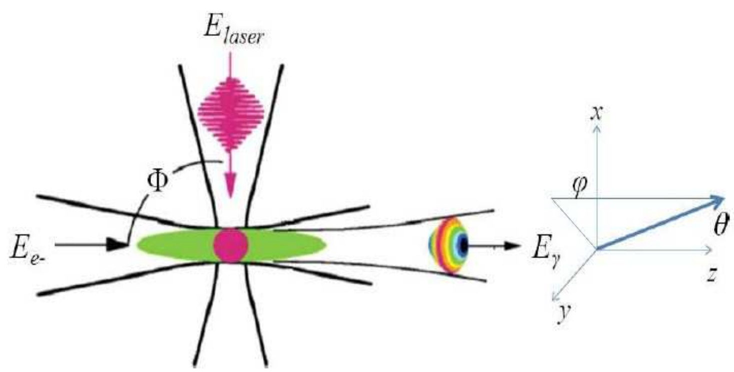
C. Sun *et al.* Phys. Rev. ST Accel. Beams 12, 062801 (2009).

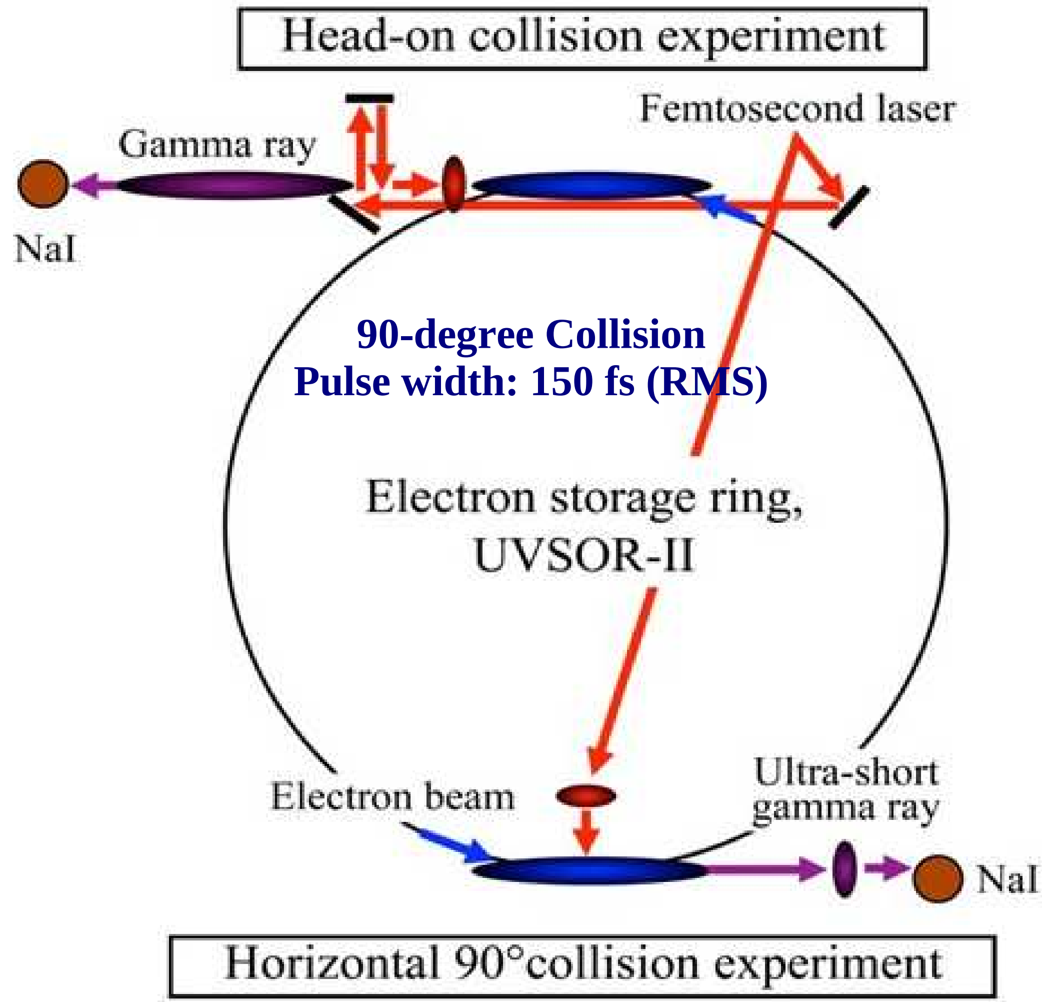
High Energy-Resolution

FWHM ~ 0.97%, 3 MeV



Pulse Duration



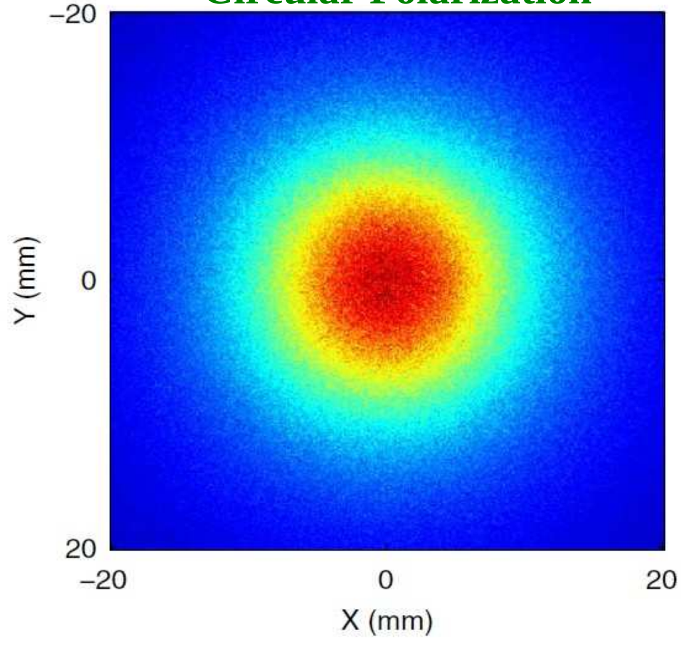


90-degree Collision
Pulse width: 150 fs (RMS)

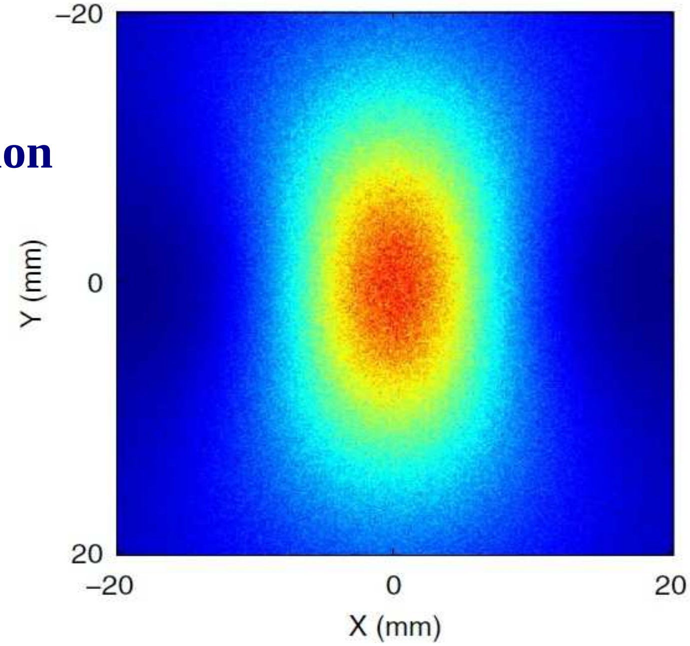
1. G. Kraff and G. Priebe, Rev. Acc. Sci. & Tech. V3, 147 (2010).
2. Y. Taira *et al.*, TUPD091, IPAC'10, Kyoto, Japan

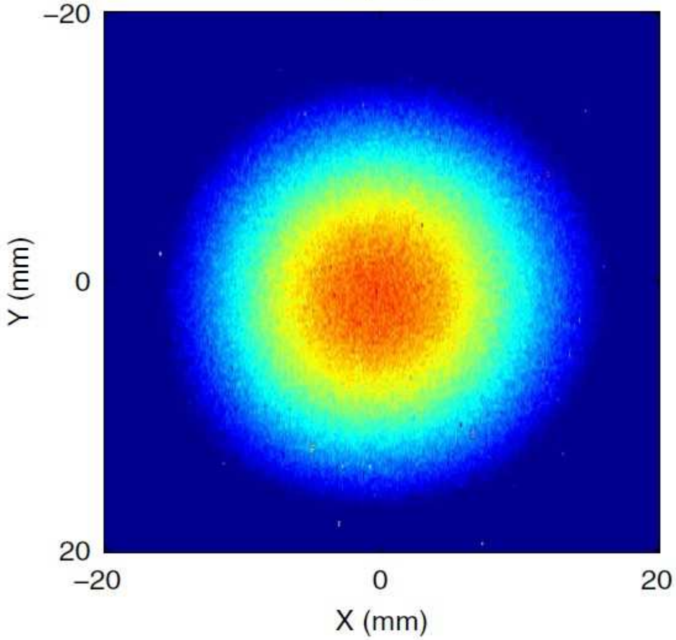
Polarization Effect

Circular Polarization | **Linear Polarization**

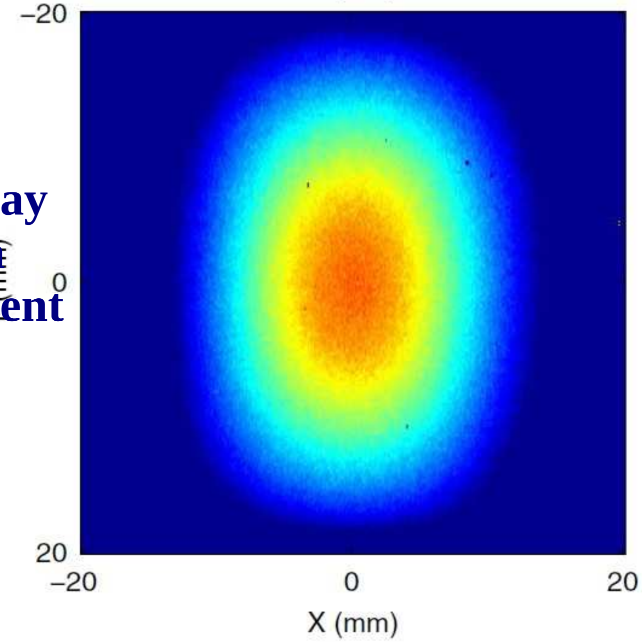


Simulation





Gamma-ray Camera Measurement (HIGS)

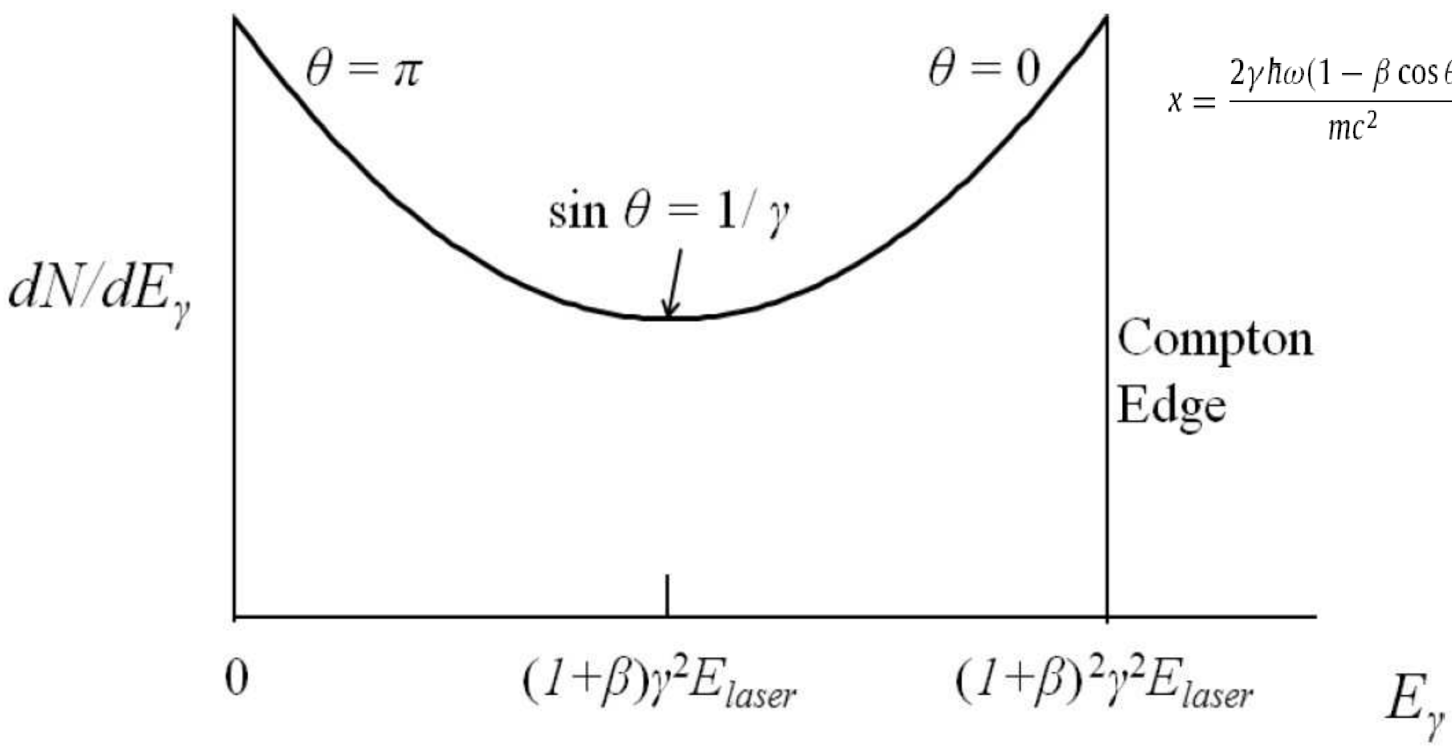


C. Sun and Y. K. Wu, Phys. Rev. ST Accel. Beams 14, 044701 (2011)

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).

Electron Beam and Photon Beam Sources

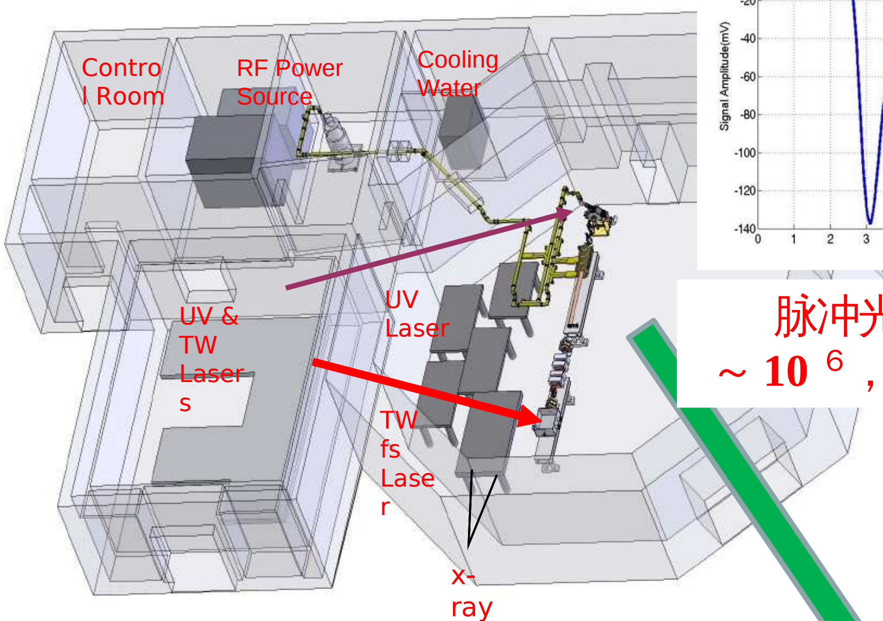
E-beam Sources	X-ray	Gamma-ray	Comments
Storage Ring	Several	Common	High reprate G-ray: large charge in a bunch, good emittance, expensive
Linac	Common	Several	Low reprate X-ray: need to improve charge & emittance
SC Linac	JLab (Early 2000s), and KAERI (2009)		High reprate, short pulses, good emitance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

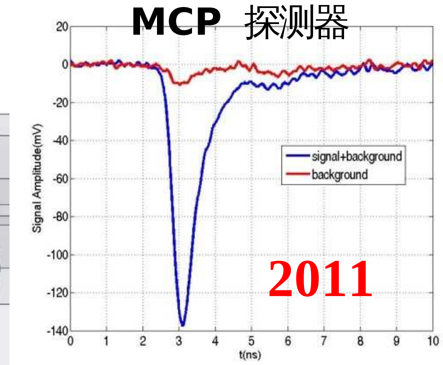
Photon Beam Sources	X-ray	Gamma-ray	Comment
Cavity: FEL	Several	Several	High reprate; Medium to high avg power Large beam size
Cavity: Fabry-Perot	Several	Several	High reprate; Medium to high avg power Small beam size possible
External Lasers	Common	Common	Low reprate; Low avg power; Very high peak power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

Compton Photon Sources around the World, Present and Future

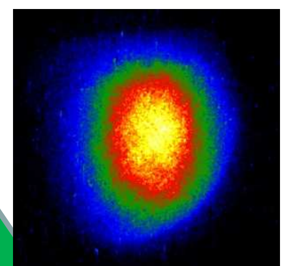
Compton X-ray Sources: Facilities, Projects and Experiments

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

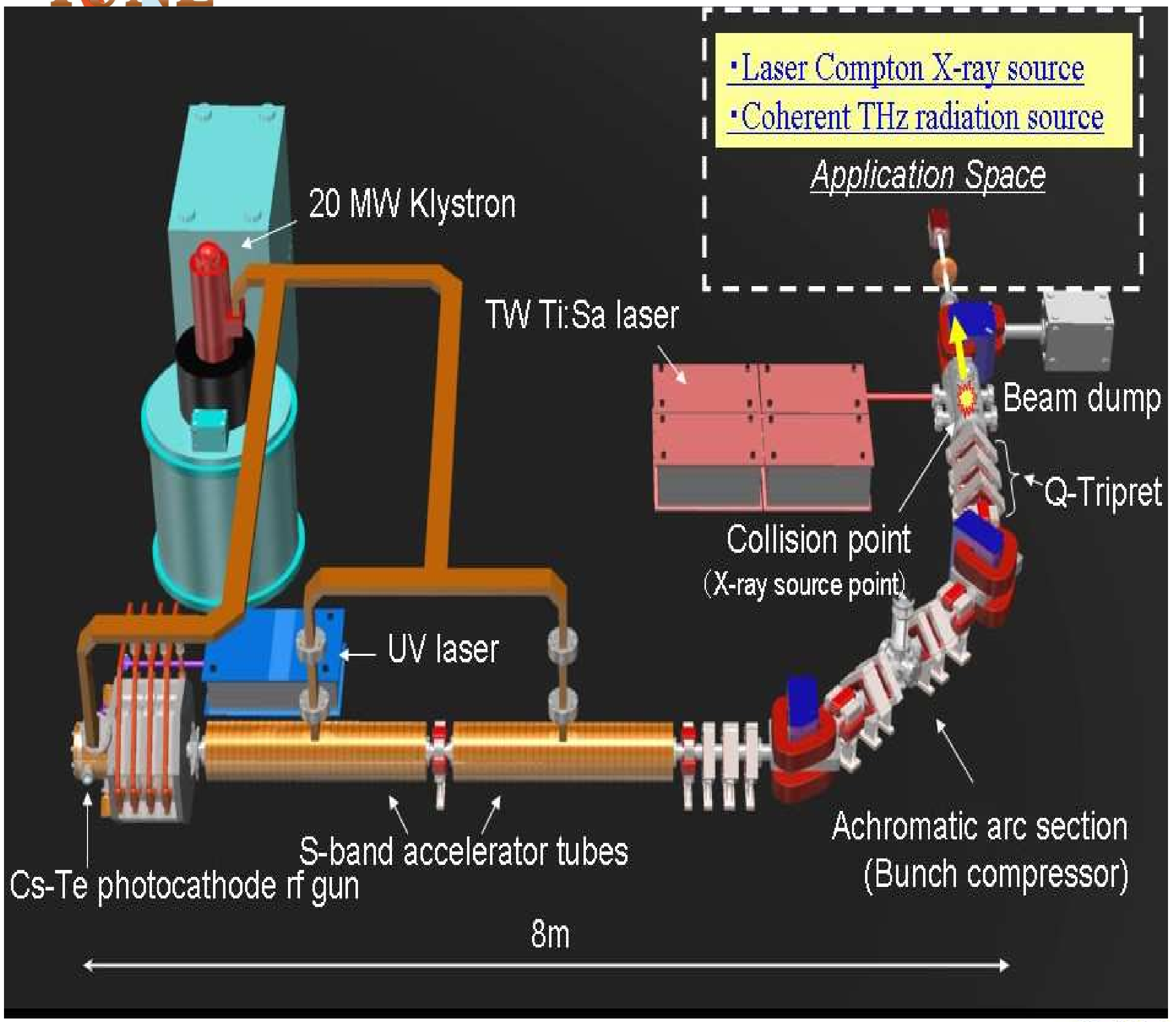
Laser: Ti: Sapphire TW, 800 nm

Total flux (@300mA): 8.4×10^6 – 5.5×10^7 ph/s (design)

Status: Operational + Development

Courtesy of Chuanxiang Tang, Tsinghua U.

AIST, Japan



Facility/Project: **(hard x-ray project)**

Institution: **AIST**

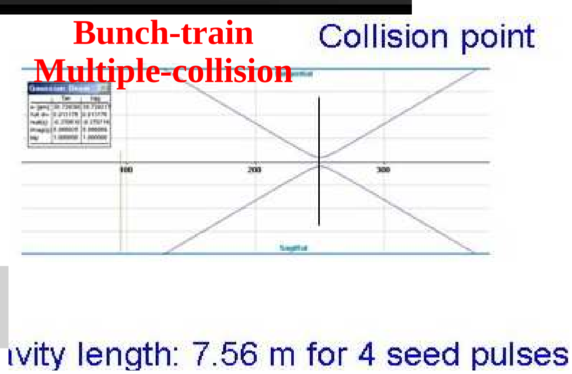
Country: **Japan**

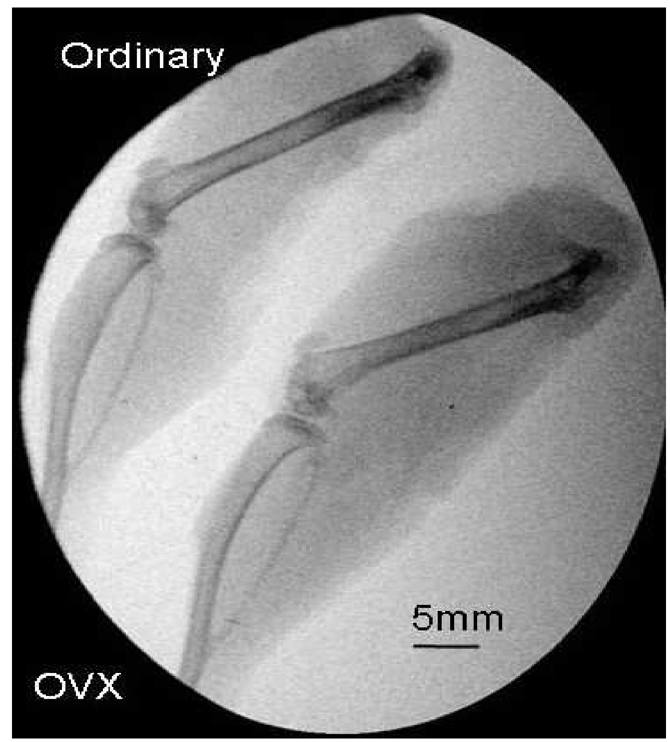
Energy (kev): **10 – 40**

Accelerator: **Linac, 40 MeV**
Laser: **Ti:Sapphire (800 nm)**

Flux: **5x10^{6} ph/pulse (10 Hz)**
(5x10^{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

Compact Light Source, Lyncean Tech., Inc.

Facility/Project: Compact Light Source

Company: Lyncean Technologies, Inc

Country: USA

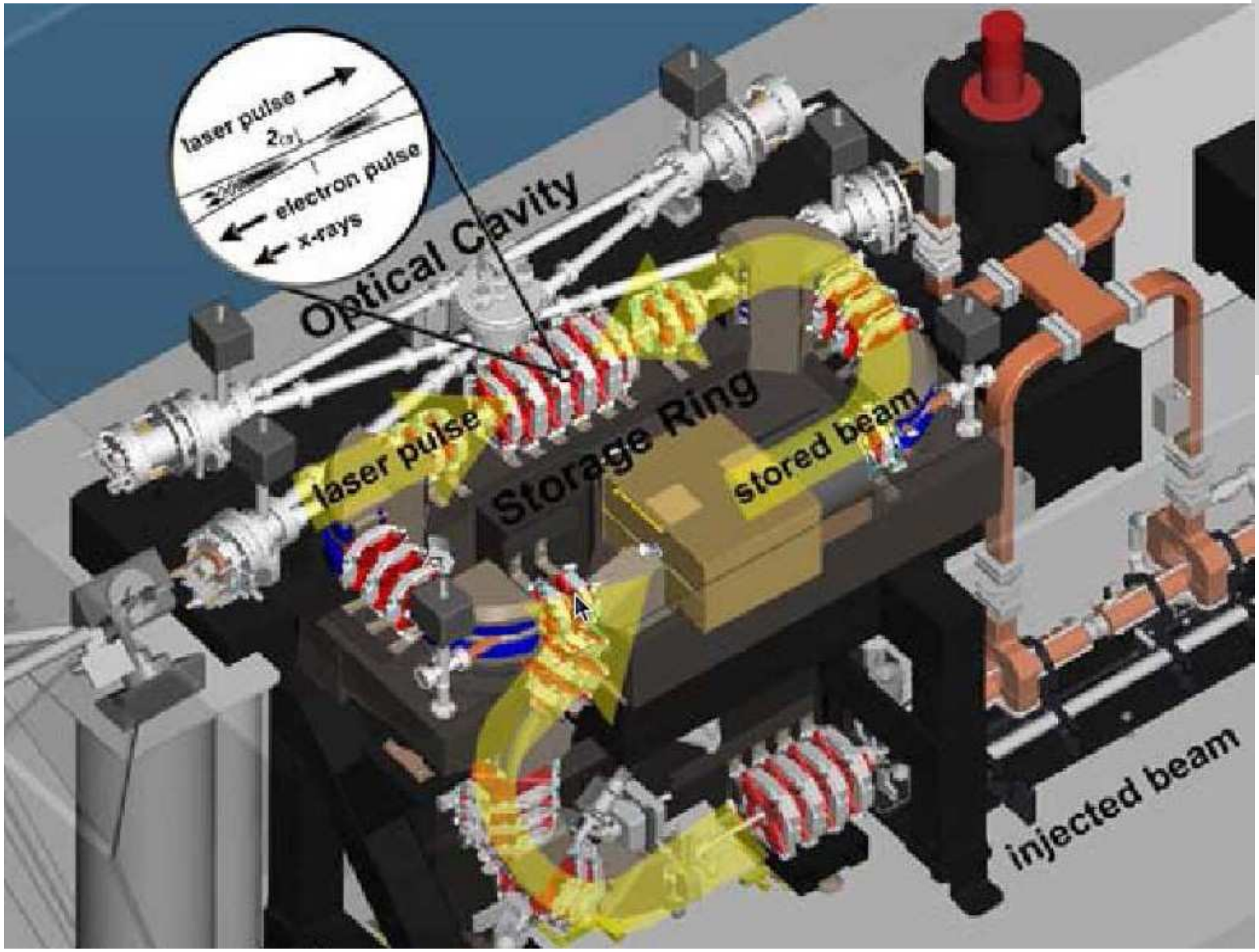
Energy (keV): 7 to 35

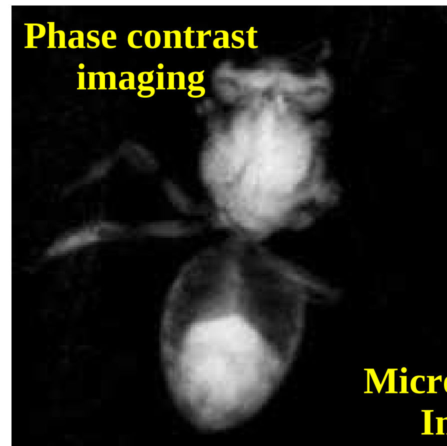
Accelerator: Storage Ring

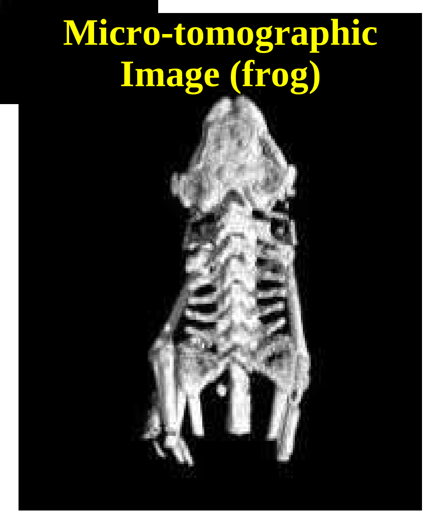
Laser: FP cavity

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

Status: Commercial product

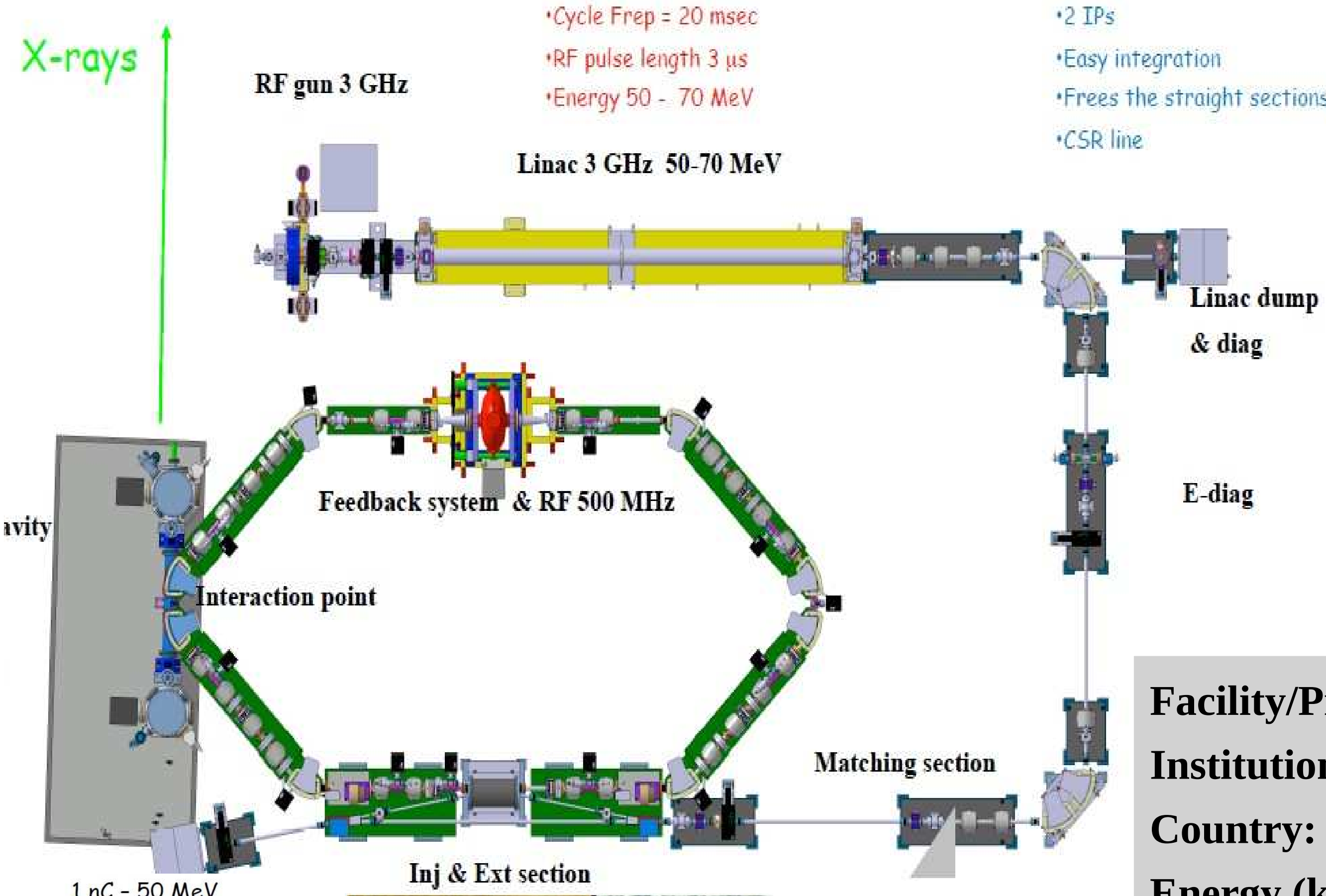


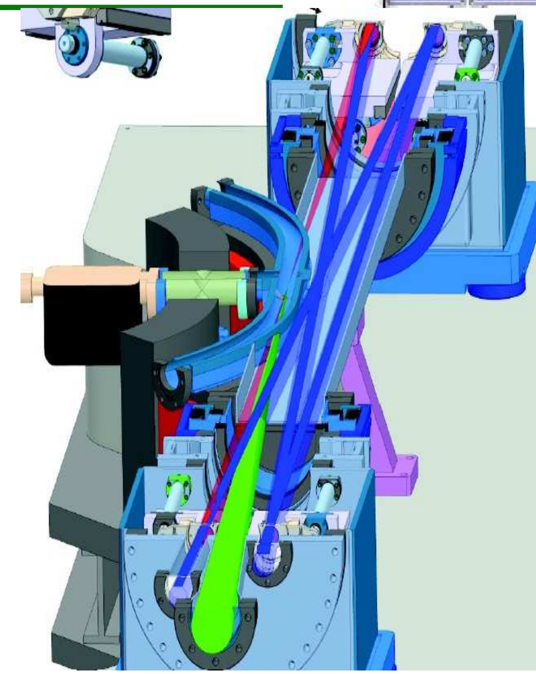


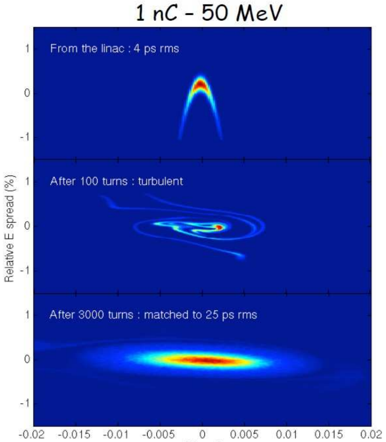


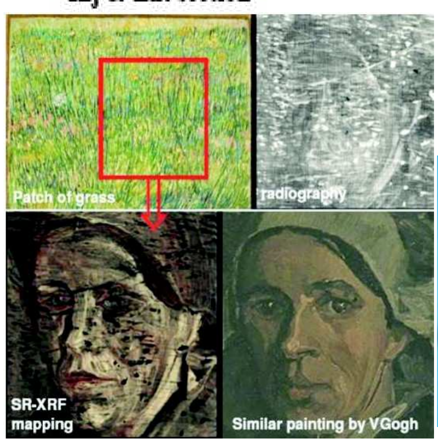
Sources:
1. www.lynceantech.com
2. G. Kraff and G. Priebe, Rev. Acc. Sci. & Tech. V3, 147 (2010).
3. R. Ruth, http://www.eurekalert.org/pub_releases/2009-01/lti-fsf010609.php

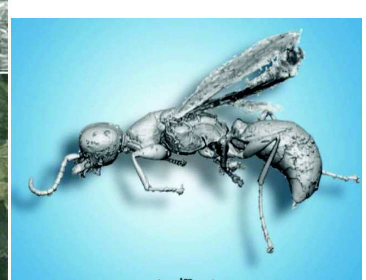
ThomX, France











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

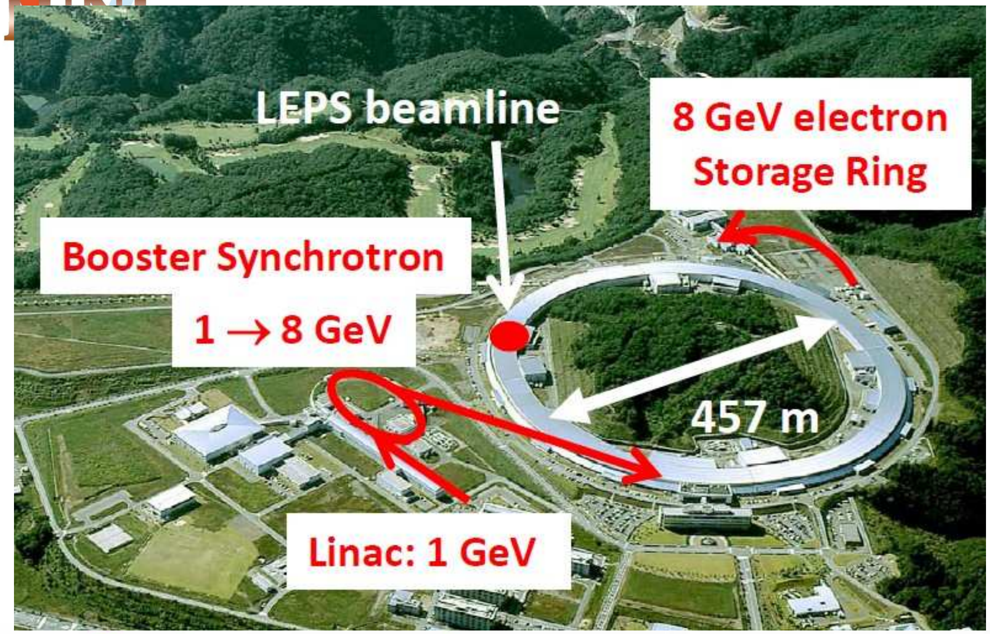
Applications: imaging, mammography, microtomography

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

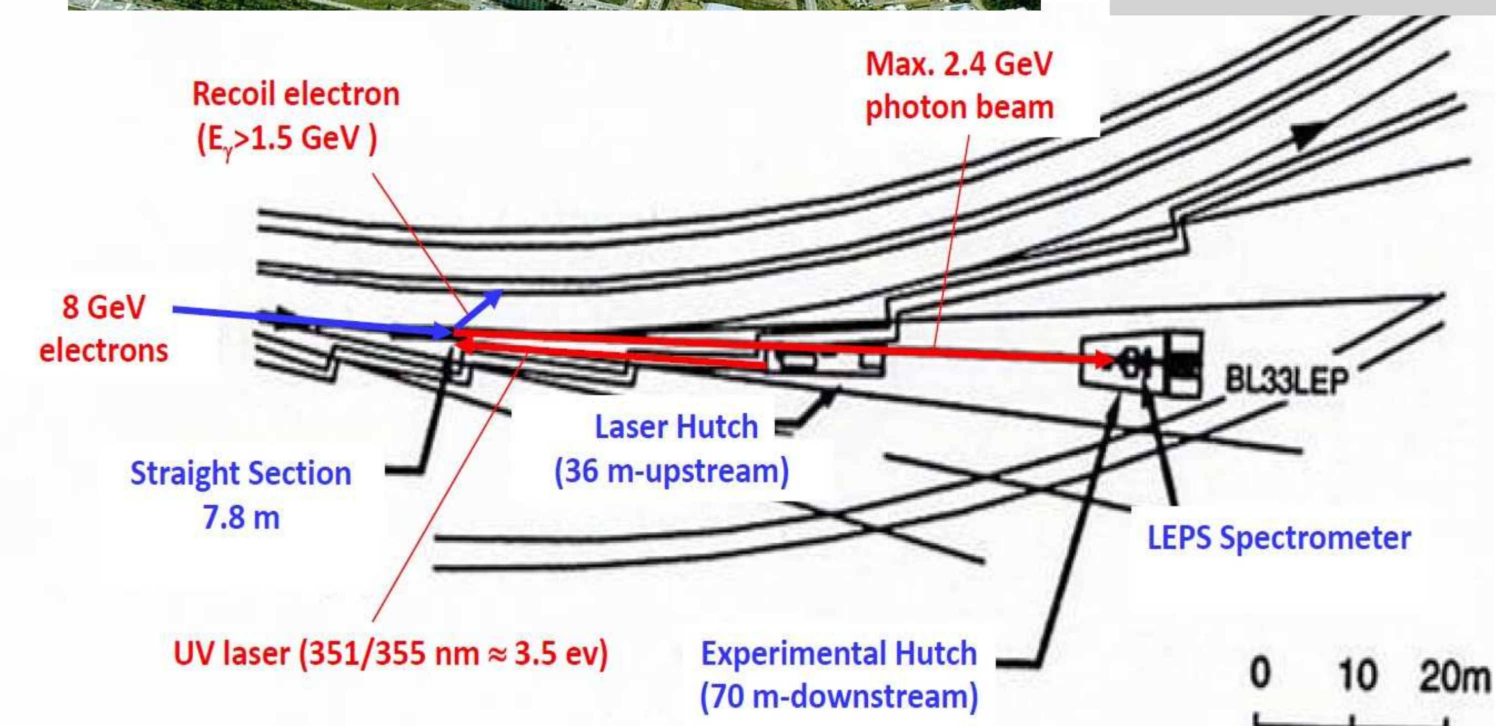
Compton Photon Sources around the World, Present and Future

Compton Gamma-ray Sources: Facilities and Projects

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

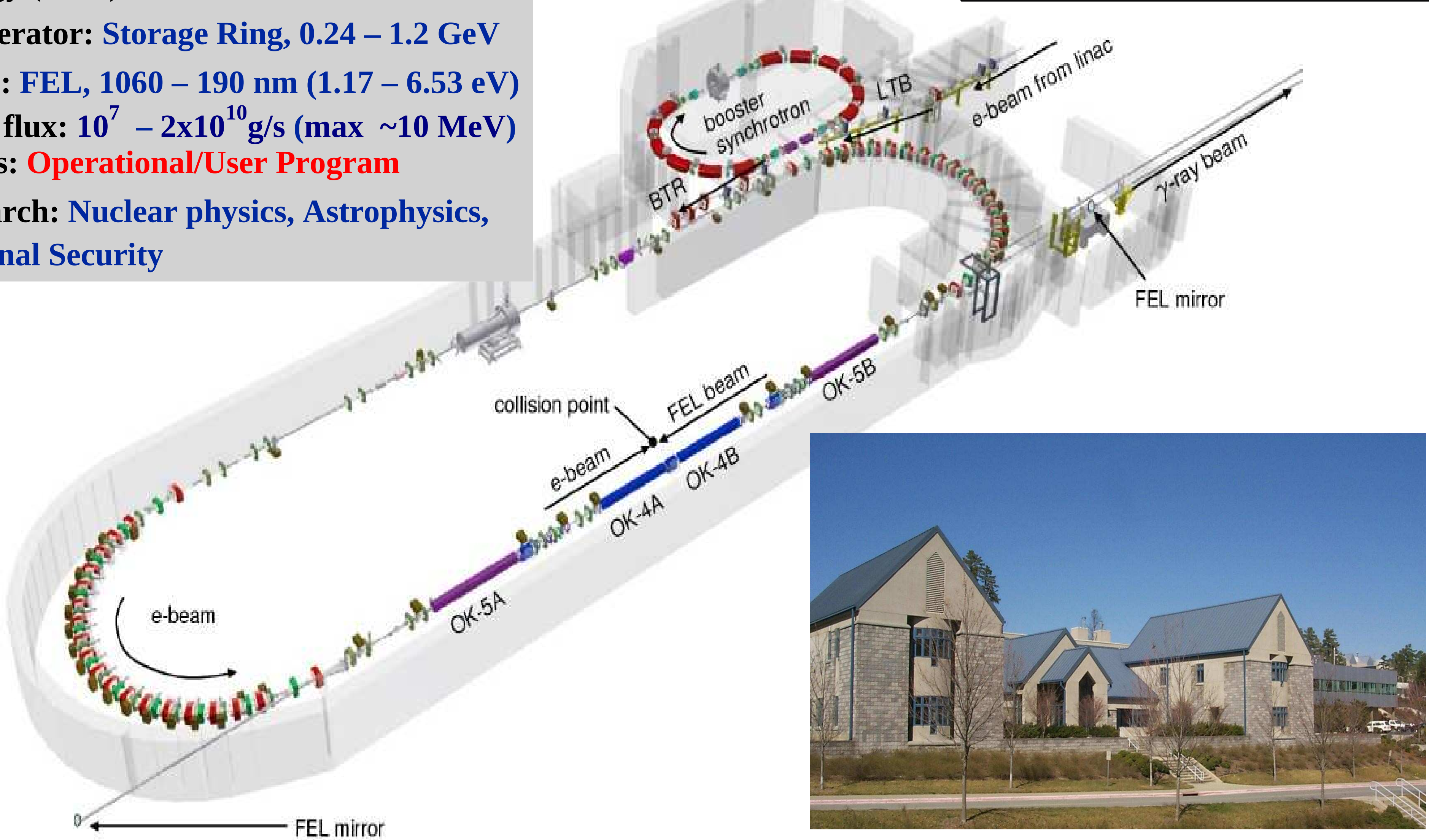


Sources:
1. N. Muramatsu, "The LEPS Facility," MAX-lab User Meeting, Nov. 2009.

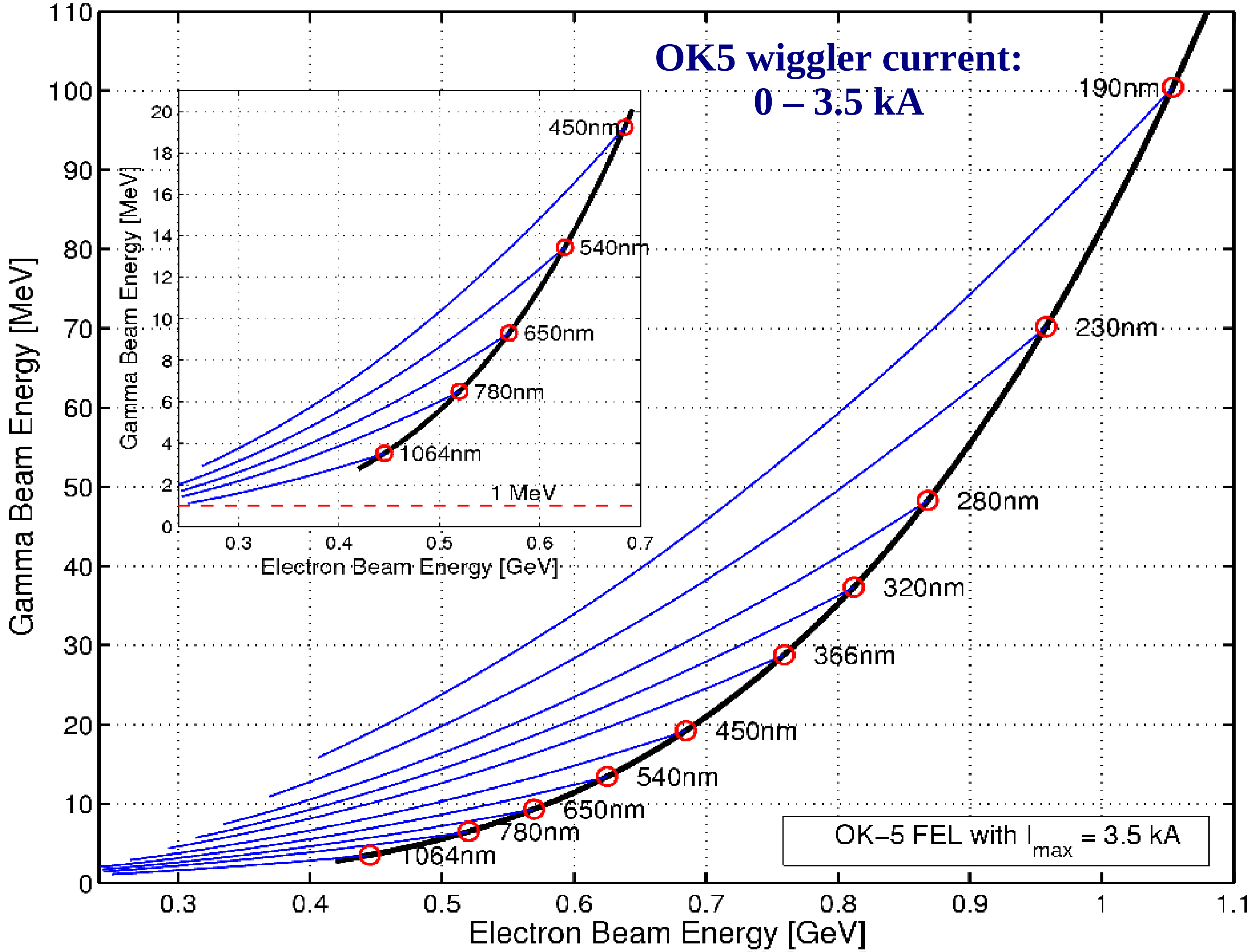
HIGS, Duke University, US

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 – 2×10^{10} g/s (max ~10 MeV)
Status: Operational/User Program
Research: Nuclear physics, Astrophysics, National Security

Accelerator Facility
180 MeV Linac pre-injector
180 MeV – 1.15 GeV Booster injector
240 MeV – 1.15 GeV Storage ring
FELs: OK-4 (lin), OK-5 (circ)
HIGS: two-bunch, 40 – 110 mA (typ)

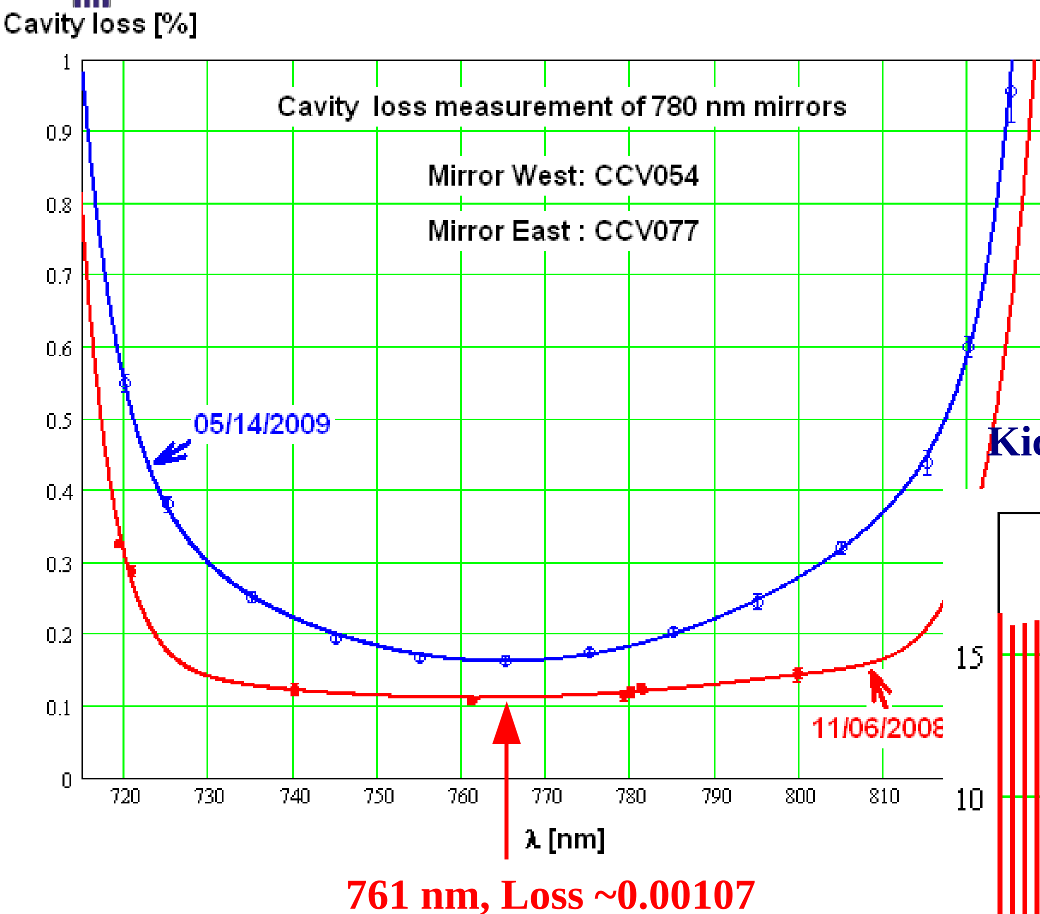


Gamma Energy Tuning Range with OK-5 FEL (3.5 kA)



High-Q FEL Optical Cavity

High Reflectivity FEL Mirrors

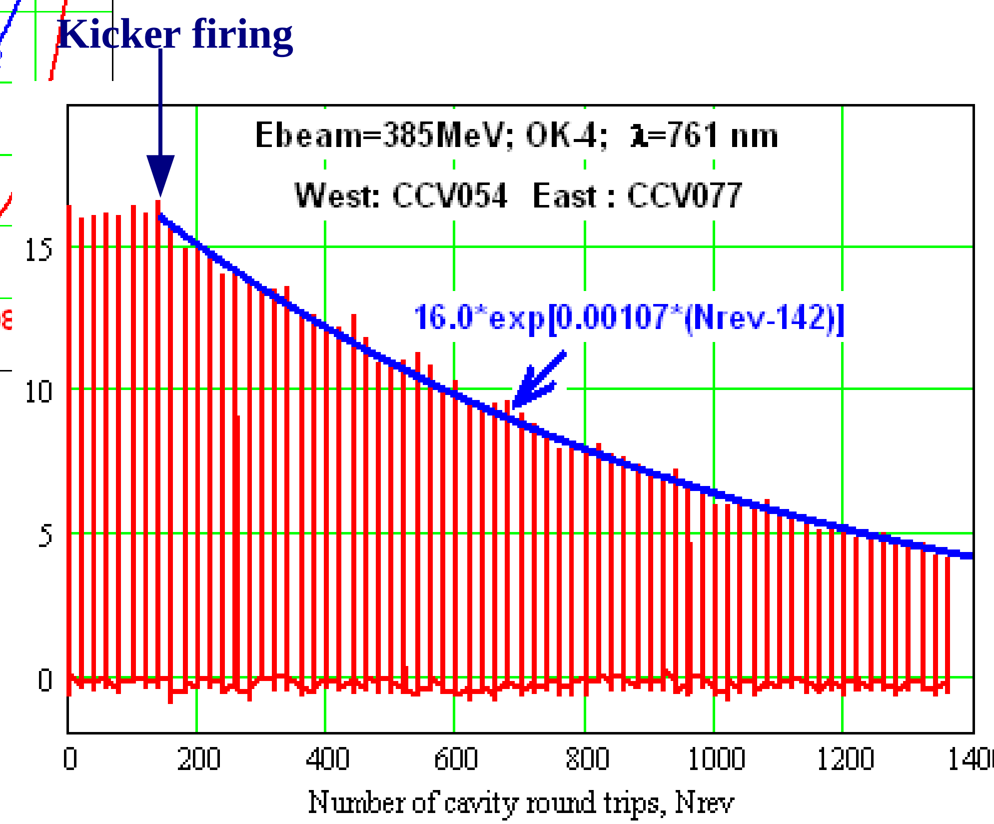


780 nm Mirrors

Minimal round-trip loss: ~ 0.107%

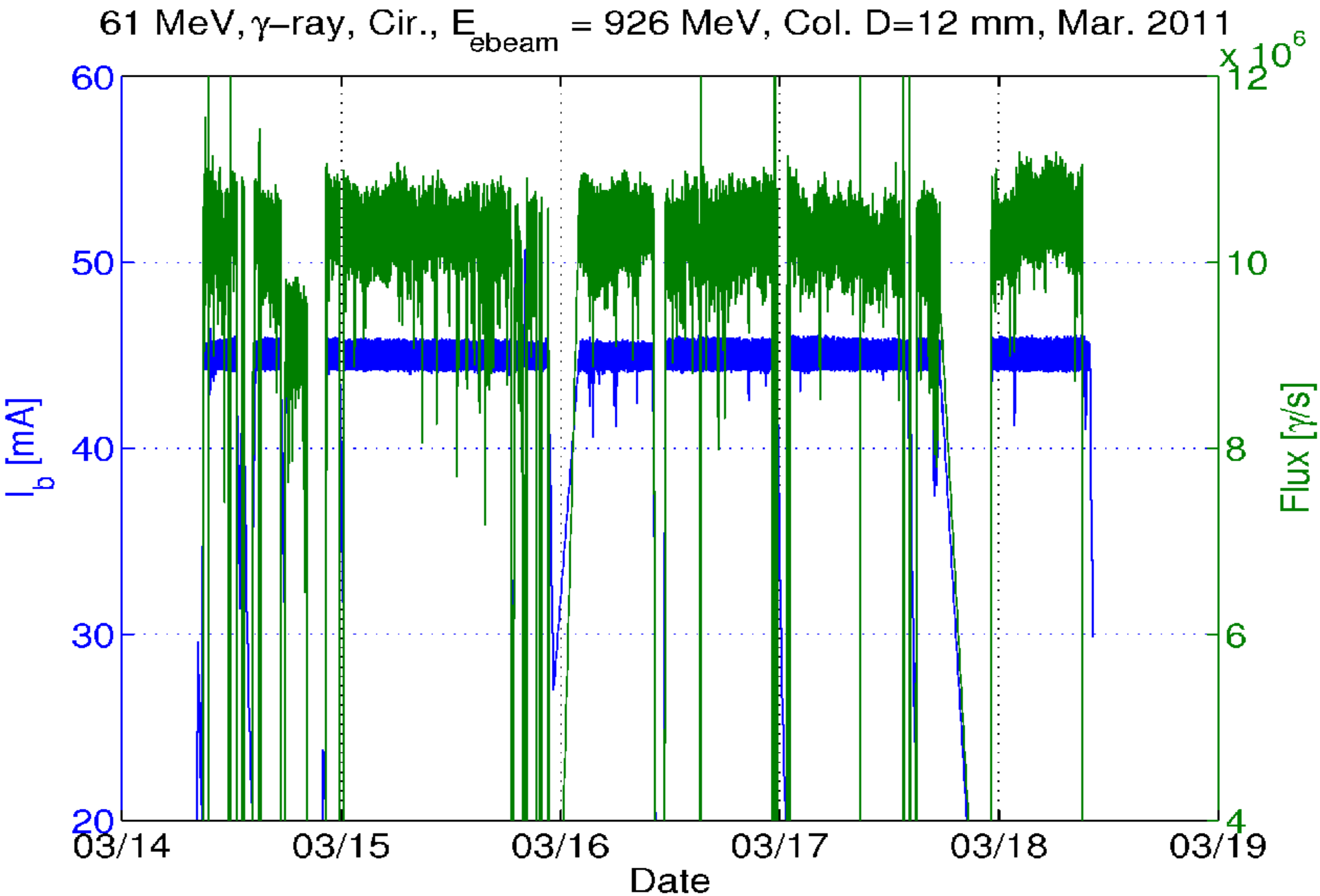
Finesse ~ 3,000

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

Electron/Photon Collision Angle Monitor

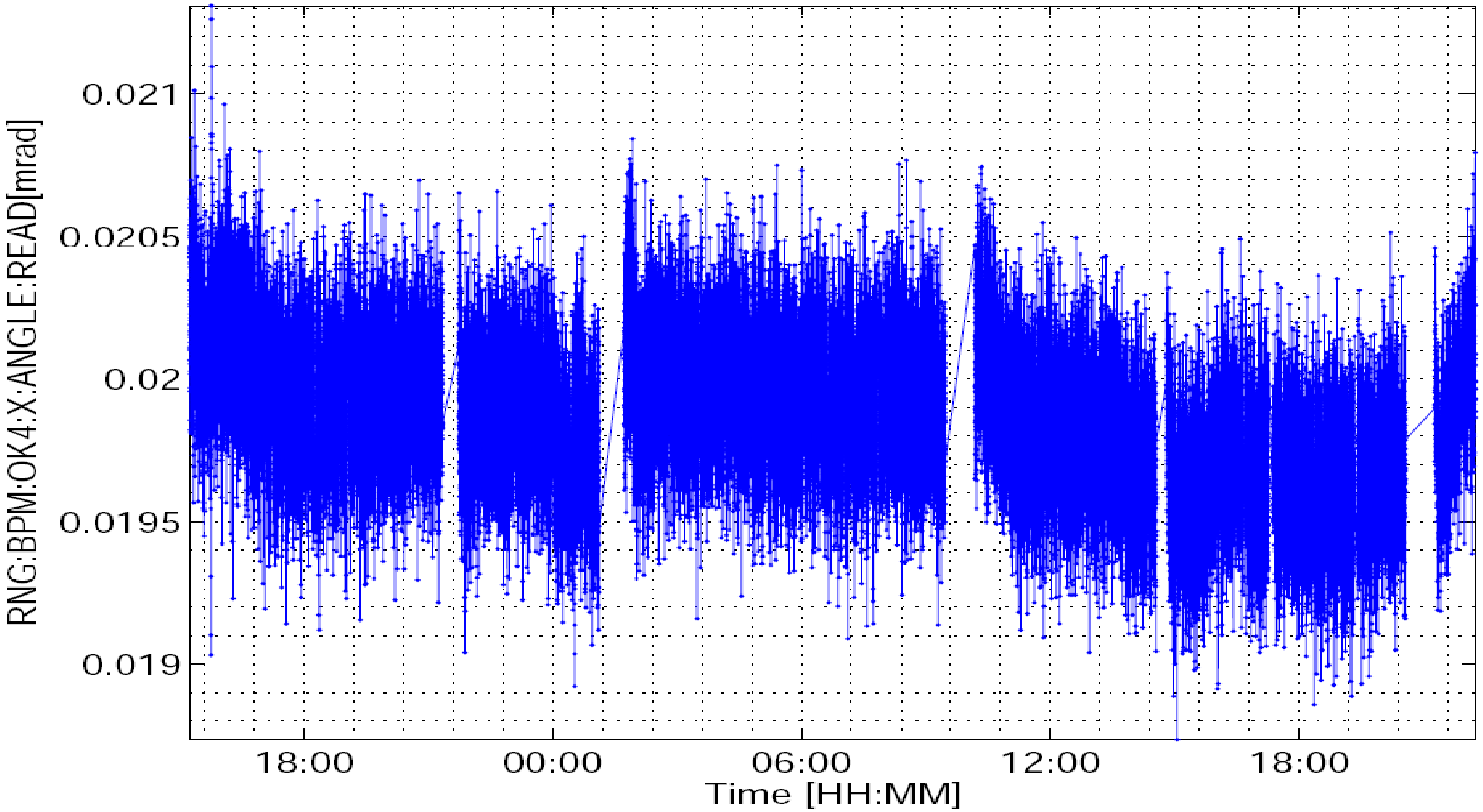
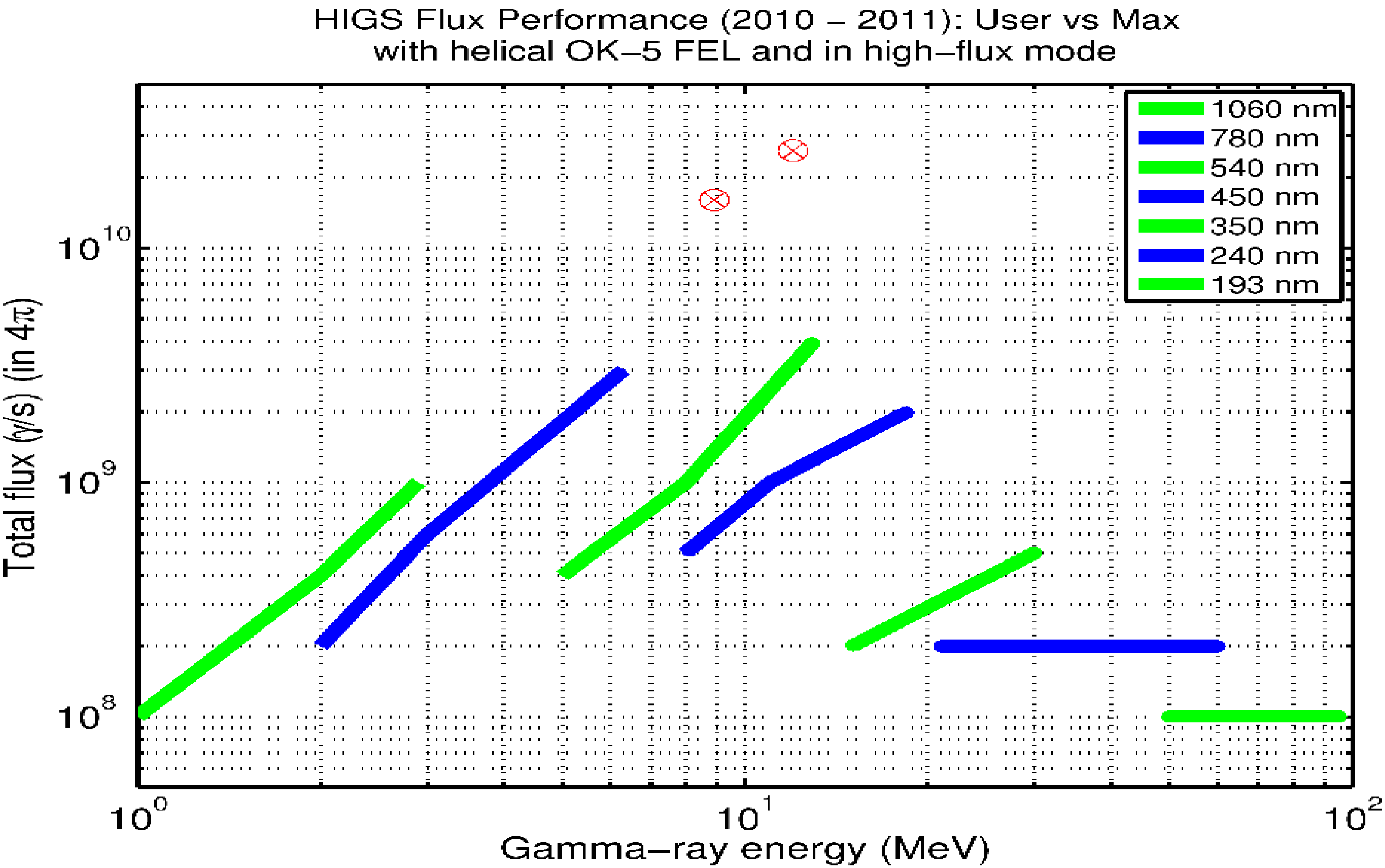


Figure 15: Horizontal beam angle at OK4 for about 36 hours operation from Aug. 20 to Aug. 21, 2009. The angle varied 2.5μrad (peak to peak) during this operation, this value corresponds to 150μm variation of gamma ray beam position at the gamma vault which is located 60 m downstream of the collision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



2011 Perfomance of High Intensity Gamma-ray Source (HIGS)

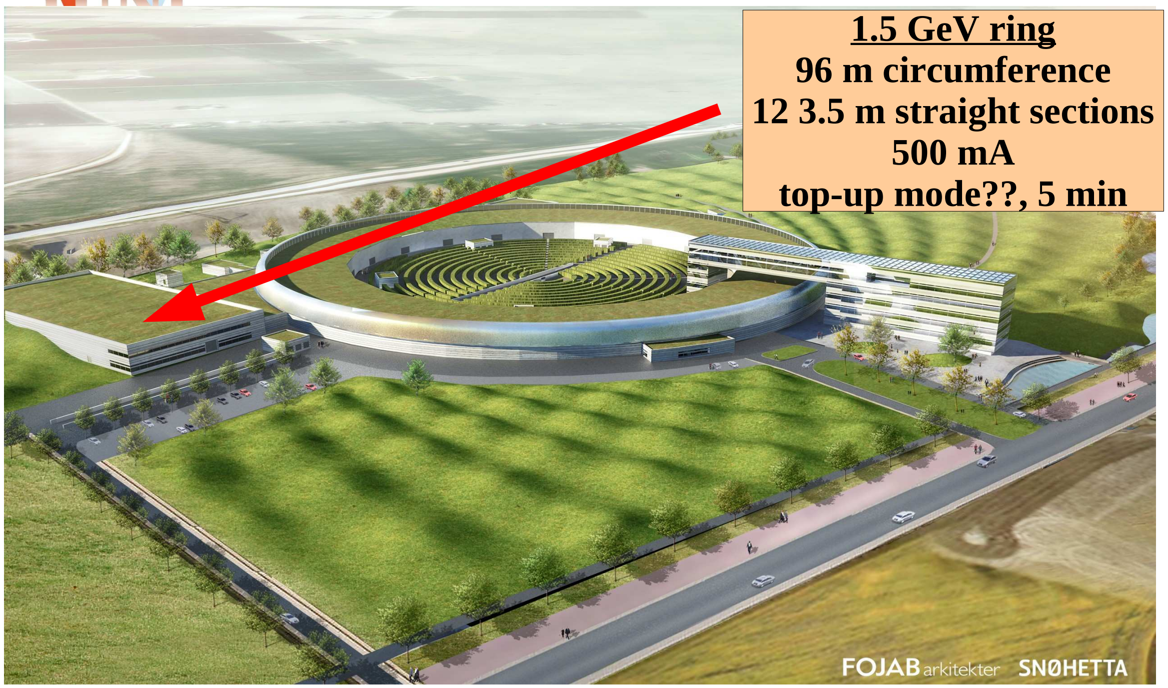
1 – 100 MeV

Max Total Intensity > 2x10^{10} (g/s) (around 10 MeV)

Operation reliability: ~ 96%

Proposed HIGS2: 2 – 12 MeV, Total Intensity: few 10^{11} - few 10^{12}(g/s)

LBSF@M4 MAX-IV Laboratory, Sweden

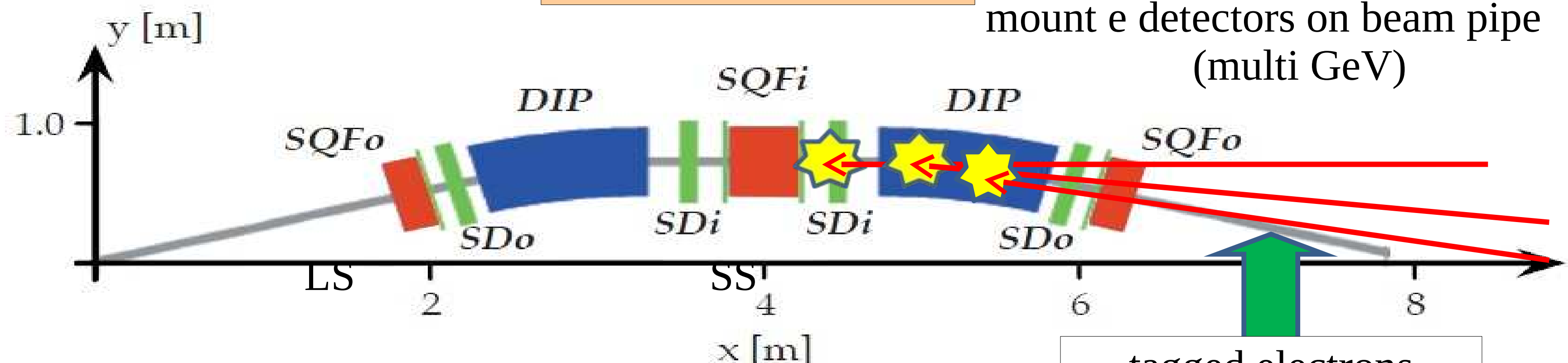


Facility/Project: LBSF@M4
Institution: MAX-IV Lab
Country: Sweden
Energy (MeV): 100 – 170
Accelerator: Storage Ring, 1.5 GeV
Laser: 229 nm (5.42 ev); 244 nm (5.80 eV)
Total flux: 4x10[6] g/s (10% of ebeam lifetime)
Status: White paper/CDR in preparation

Use synchrotron light port for laser

interact in the dipole

mount e detectors on beam pipe (multi GeV)



tagged electrons

Figure 3.1: Schematic of one of

Laser Backscattering

Courtesy of K. Fissum, U. Lund, MAXLAB

SLEGS, Shanghai Synchrotron Radiation Facility, China

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

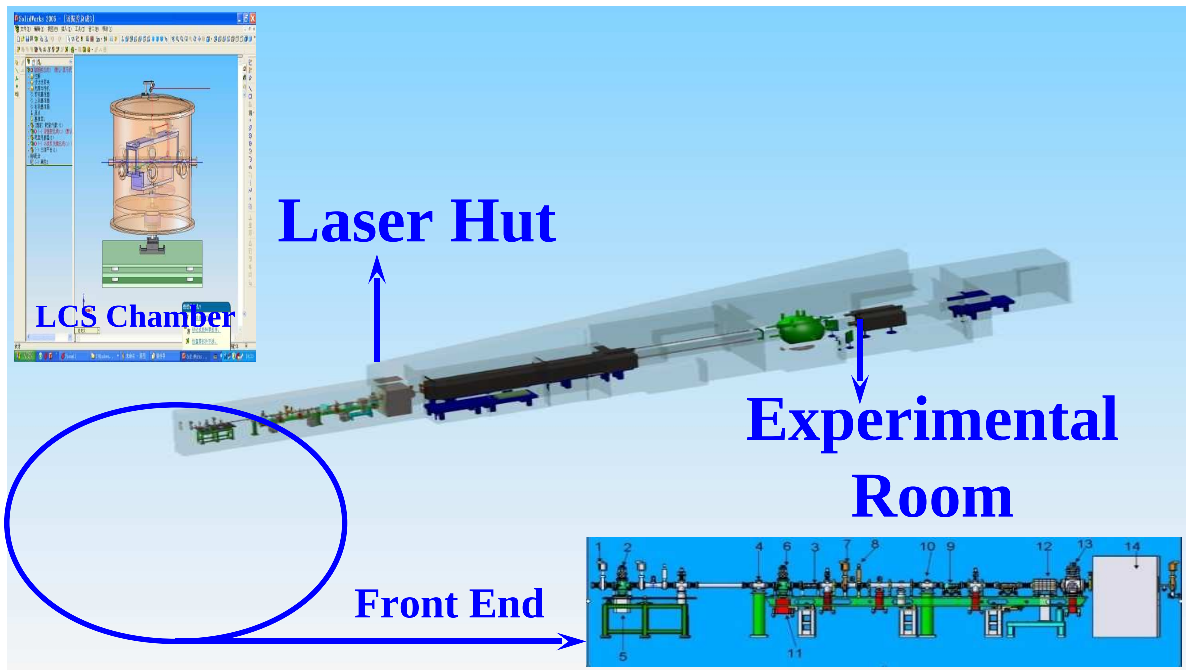
Total flux (@300mA): $10^5 – 10^7$ g/s (low eng)
$6X10^6$ g/s (high eng)

Status: Under Development

Access to various basic and applied studies

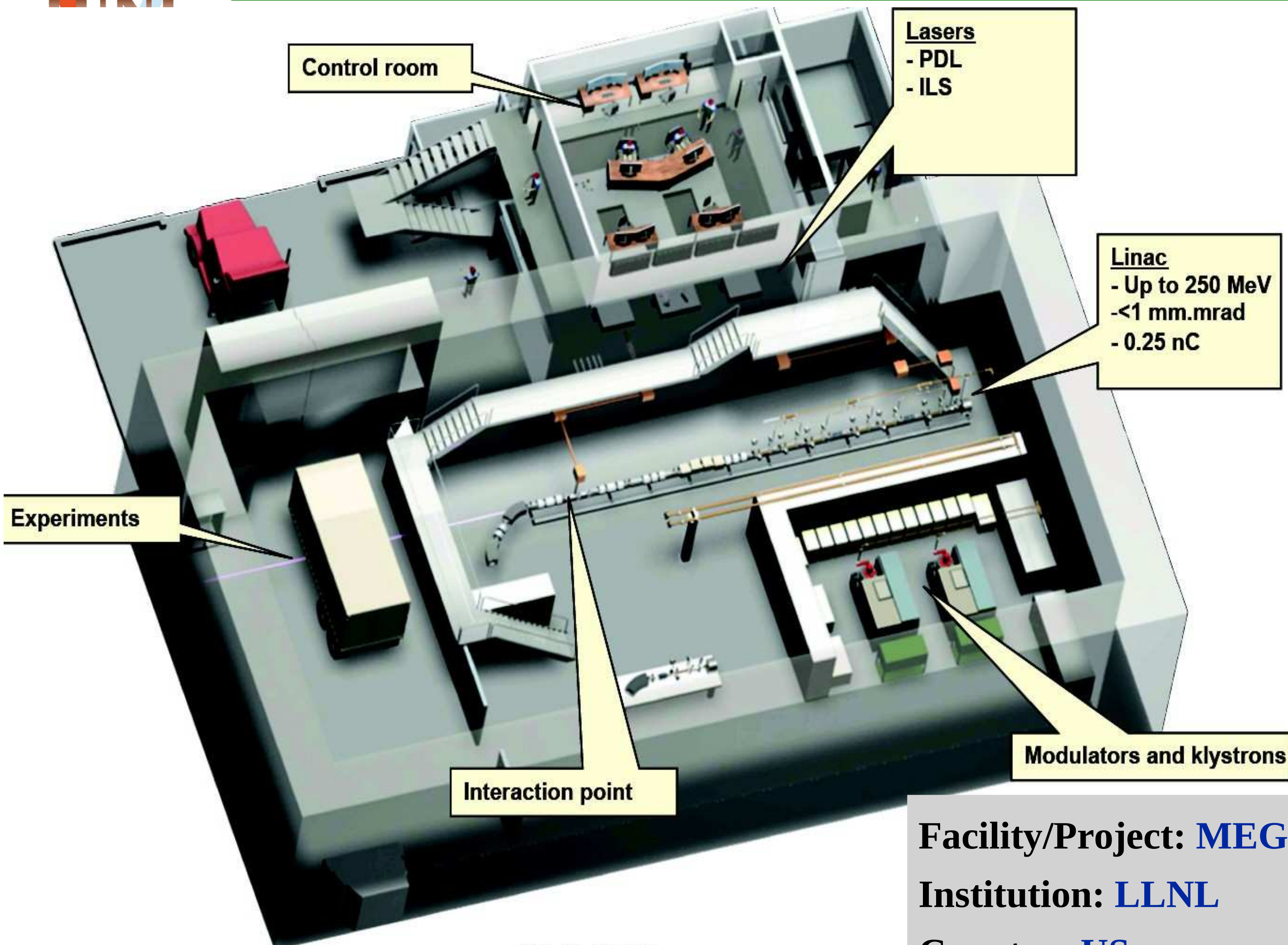
- **Basic physics** (nuclear structure, nuclear astrophysics, etc.)
- **National strategic demands** (nuclear power, aerospace, etc.)
- **Industry or Medicine** (NMR-CT, SPE-CT, etc.)

SSRF **Shanghai Synchrotron Radiation Facility**

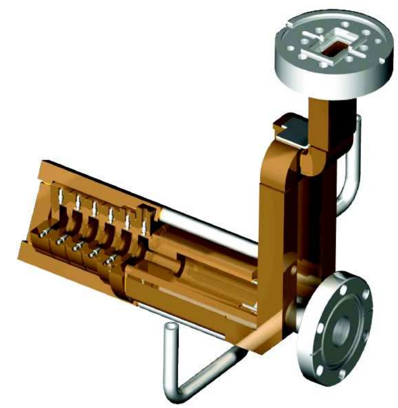


Courtesy of Wang Xu, SSRF

MEGa-ray, LLNL, US



Félicie Albert FLS-2012



Facility/Project: MEGa-ray

Institution: LLNL

Country: US

Energy (MeV): 0.5 – 2.3

Accelerator: x-band Linac, 250 MeV, 250 pC, 70MV/m, 120 Hz, high reprate: 12,000 (100 micro-bunches)

Laser: Ring-down cavity (12 kHz)

Total flux: $8x10^{7}$ (ph/pulse), 10^{12} ph/s (design)

Status: Under Development

Sources:
1.”The White Book of ELI Nuclear Physics Bucharest-Magurele, Romania,” the ELI-Nuclear Physics working group,
2. F. Albert *et al.* “Design Considerations for a Tunable, Laser-based, Compact Mono-energetic Gamma-ray source,” FLS2012, Jlab, Mar. 2012.

ELI-NP, Extreme Light Infrastructure, Europe

Facility/Project: ELI-NP

Institution: Extreme Light Infrastructure (up to 4 facilities)

Country: Europe

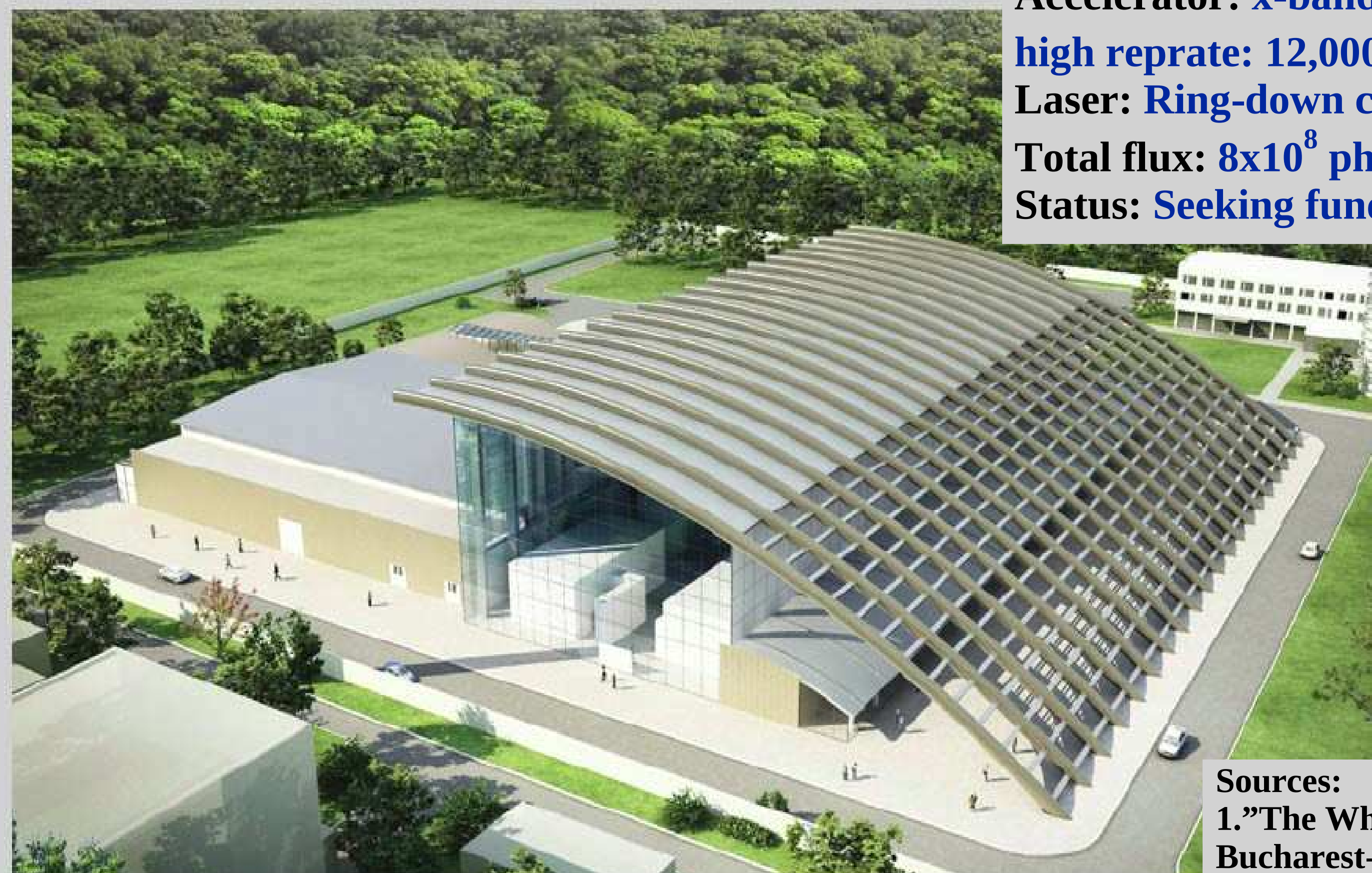
Energy (MeV): 1 – 13

Accelerator: x-band Linac, 600 MeV, 250 pC, 120 Hz, high reprate: 12,000 (100 micro-bunches)

Laser: Ring-down cavity (12 kHz)

Total flux: $8x10^8$ ph/pulse, 10^{13} ph/s (design)

Status: Seeking funding



Sources:

1. "The White Book of ELI Nuclear Physics Bucharest-Magurele, Romania," the ELI-Nuclear Physics working group,
2. www.extreme-light-infrastructure.eu

Highest Average Intensity Compton Sources (2012)

- **X-ray: Compact Light Source, Lyncean Tech (10^{11} ph/s)**
- **Gamma-ray: High Intensity Gamma-ray Source, Duke U. (>$2x10^{10}$ g/s, ~10 MeV)**

Compton Photon Sources around the World,

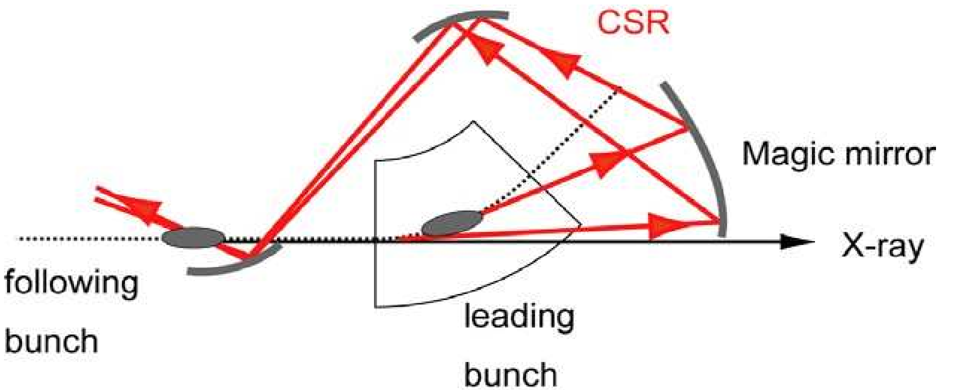
Present and Future

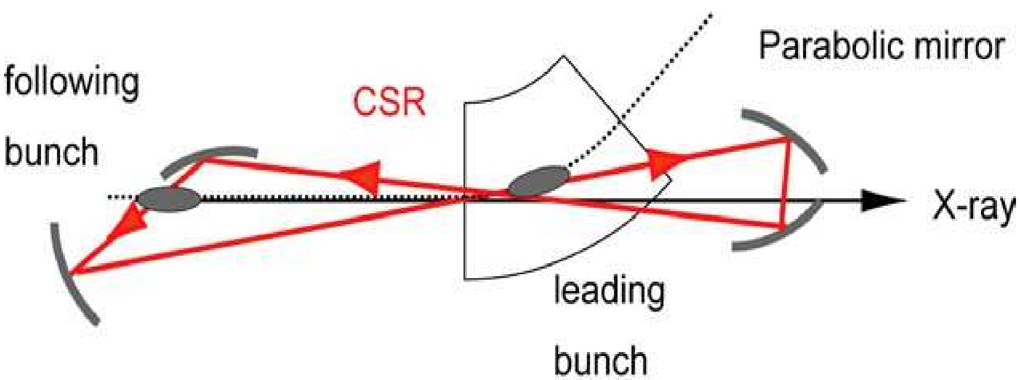
New Technologies

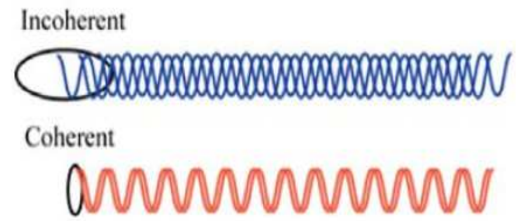
ERL Based Sources

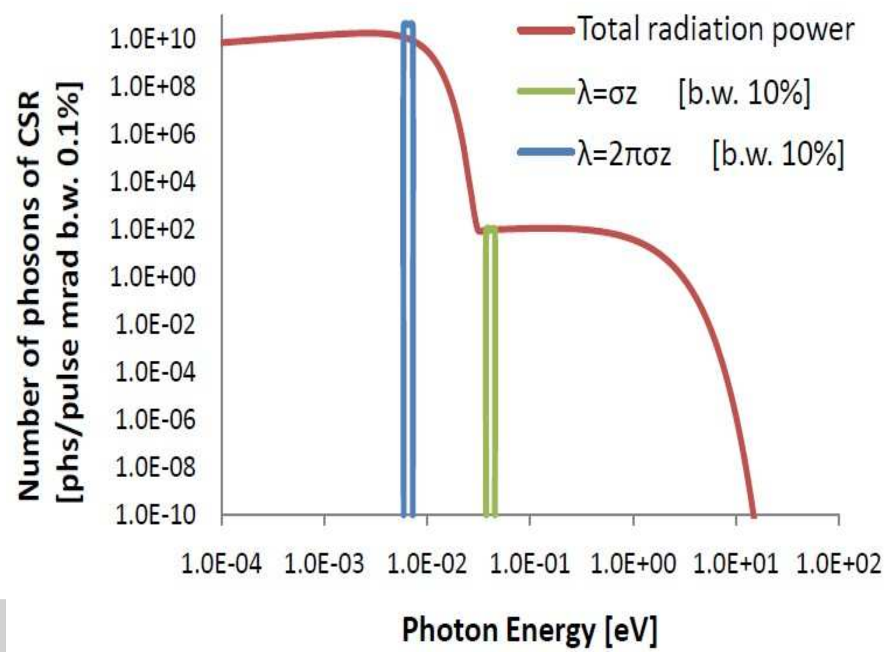
KEK, Japan (Proposed)

- **ERL + coherent synchrotron radiation**
- **X-ray: 200 MeV ERL, 0.04 to 4 keV, total flux: ~10^{13-14} ph/s**
- **Gamma-ray: 5 GeV ERL, 8 – 25 MeV, total flux: ~10^{17} g/s**





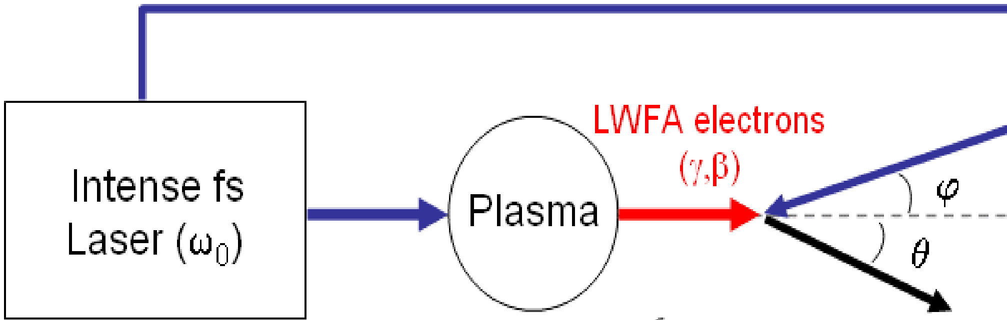




Sources:
1. M. Shimada and R. Hajima, eev. Phys. ST, 1, 100701 (2010).
2. M. Shimada, "X and gamma-ray due to inverse Compton scattering of CSR," CSR mini-workshop 2010.

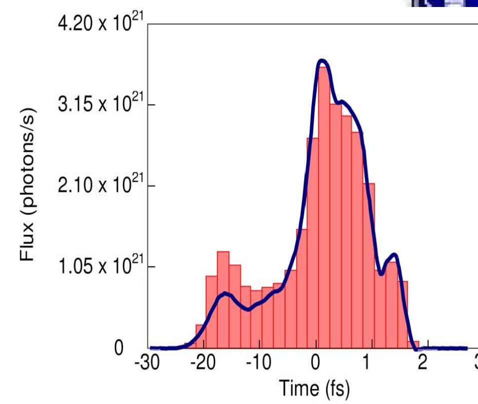
Laser Wakefield Acceleration

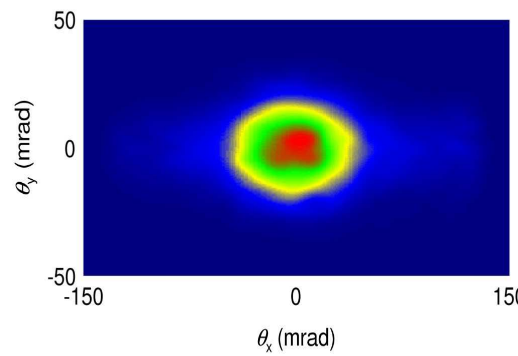
F. Hartemann *et al.*, LLNL

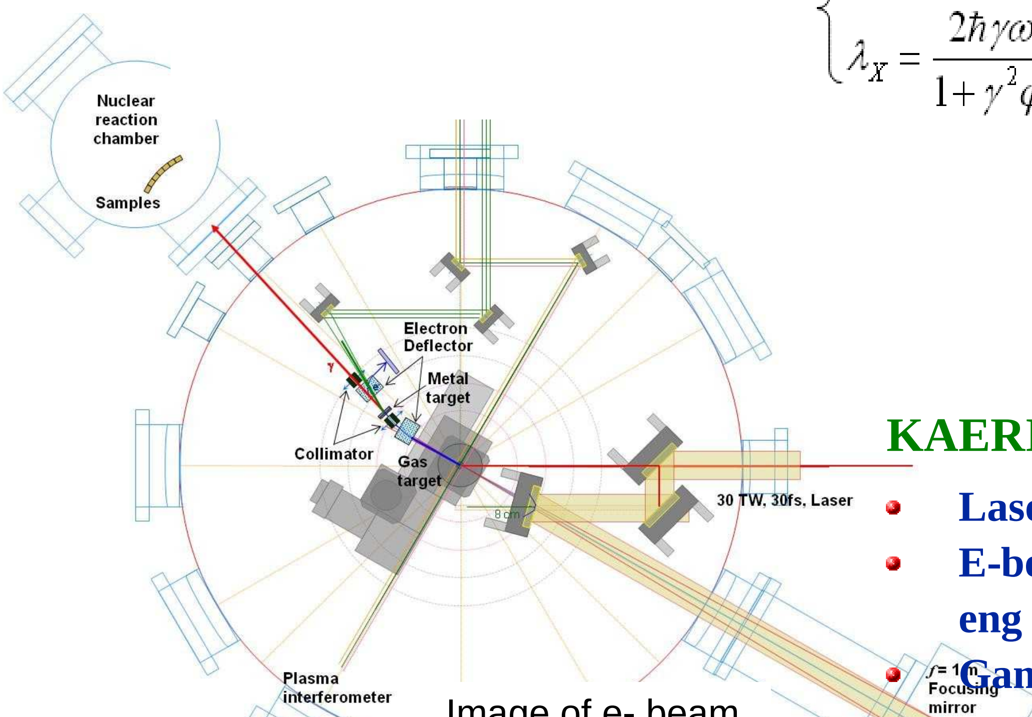


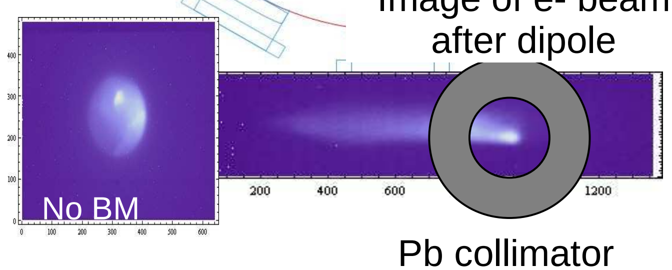
X-ray beam

$$\lambda_X = \frac{2\hbar\gamma\omega_0}{1+\gamma^2\varphi^2}\left[1+\beta\cos(\theta)\right]$$







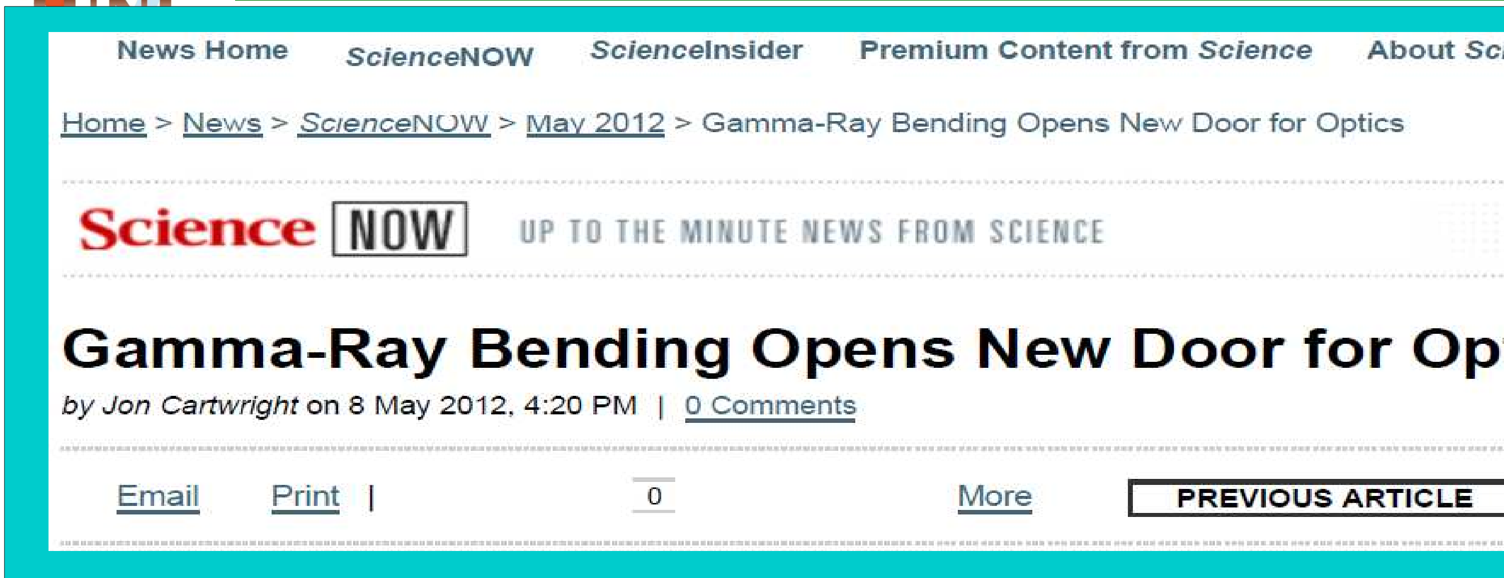


KAERI, Korea (Exp planned for 2013)

- **Laser: 532 nm, 1W (avg), 10 Hz, 3 cm Rayleigh range**
- **E-beam: 200 – 300 MeV, 10 Hz, ~100 pC/pulse, eng sprd <5%, norm-emittance, 5pi mm-mrad,**
- **Gamma-ray: 1.4 – 3.2 MeV, >10^6 g/pulse, eng sprd <10%**

Sources:
1. Courtesy of S. Park, KAERI, Korea
2. F. Hartemann *et al.*, Phys. Rev. ST-AB 10, 011301 (2007)

Gamma-ray Optics: focusing gamma-ray beams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Gamma-Ray Bending Opens New Door for Optics

by Jon Cartwright on 8 May 2012, 4:20 PM | 0 Comments

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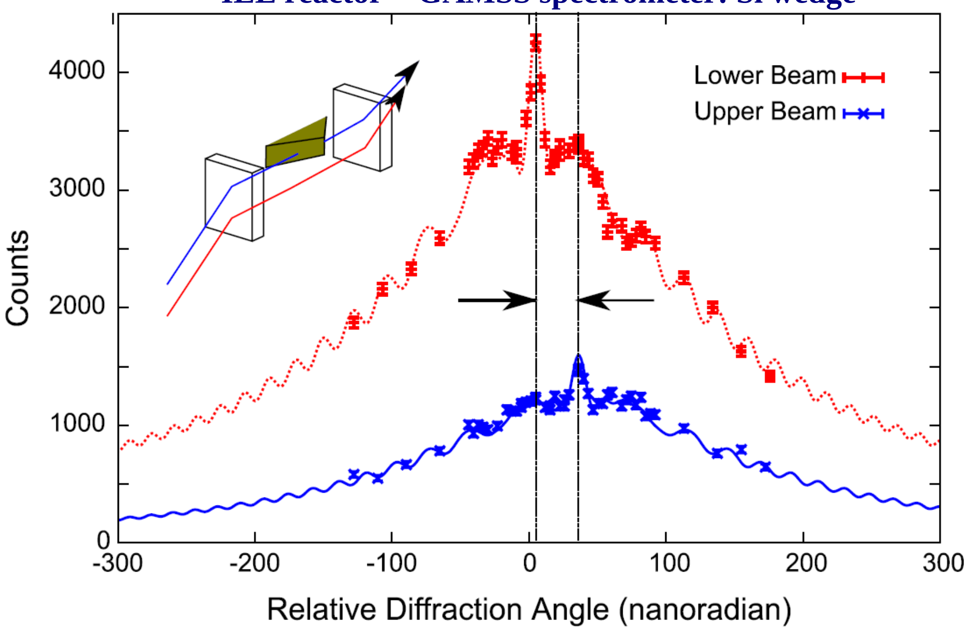
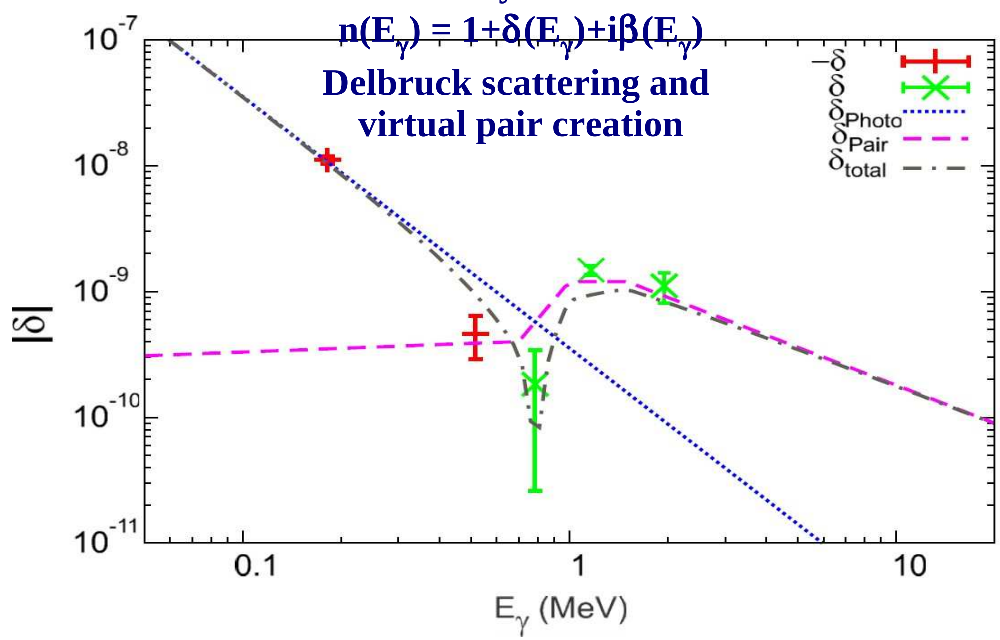
ILL reactor + GAMSS spectrometer: Si wedge



Physics:

$n(E_\gamma) = 1+\delta(E_\gamma)+i\beta(E_\gamma)$

Delbruck scattering and virtual pair creation



Sources:

1. Courtesy of D. Habs, Ludwig-Maximilians U., Munich

2. D. Habs, "Refractive Index of Silicon at g Ray Energies," PRL, 184802 (2012).

3. news.sciencemag.org/sciencenow/2012/05/gamma-ray-bending-opens-new-door.html

Fundamental and Applied Research Using Compton Photon Sources

Research Using Compton X-ray Sources

Research Using Compton X-ray Sources

Small-scale synchrotron x-ray sources:

all research typically conducted using x-ray beams from storage ring light sources, in particular in imaging, including phase-contrast imaging, micro-tomographic imaging, imaging using a single-pulse

Limitations and and Prospects of Compton X-ray Sources

- Average flux & brightness cannot compete with 3rd-gen storage ring light sources
- Peak flux & brightness cannot compete with x-ray FEL (also incoherent)

- Comparable cost to a complex, state-of-the-art undulator beamline at a major light source
- Increase x-ray accessibility:
  Making x-ray capabilities available where x-ray science takes place

Sources:
1. "Report of BEC Workshop on Compact Light Source, " Organizers:W. Barletta, M. Borland, May 2010.

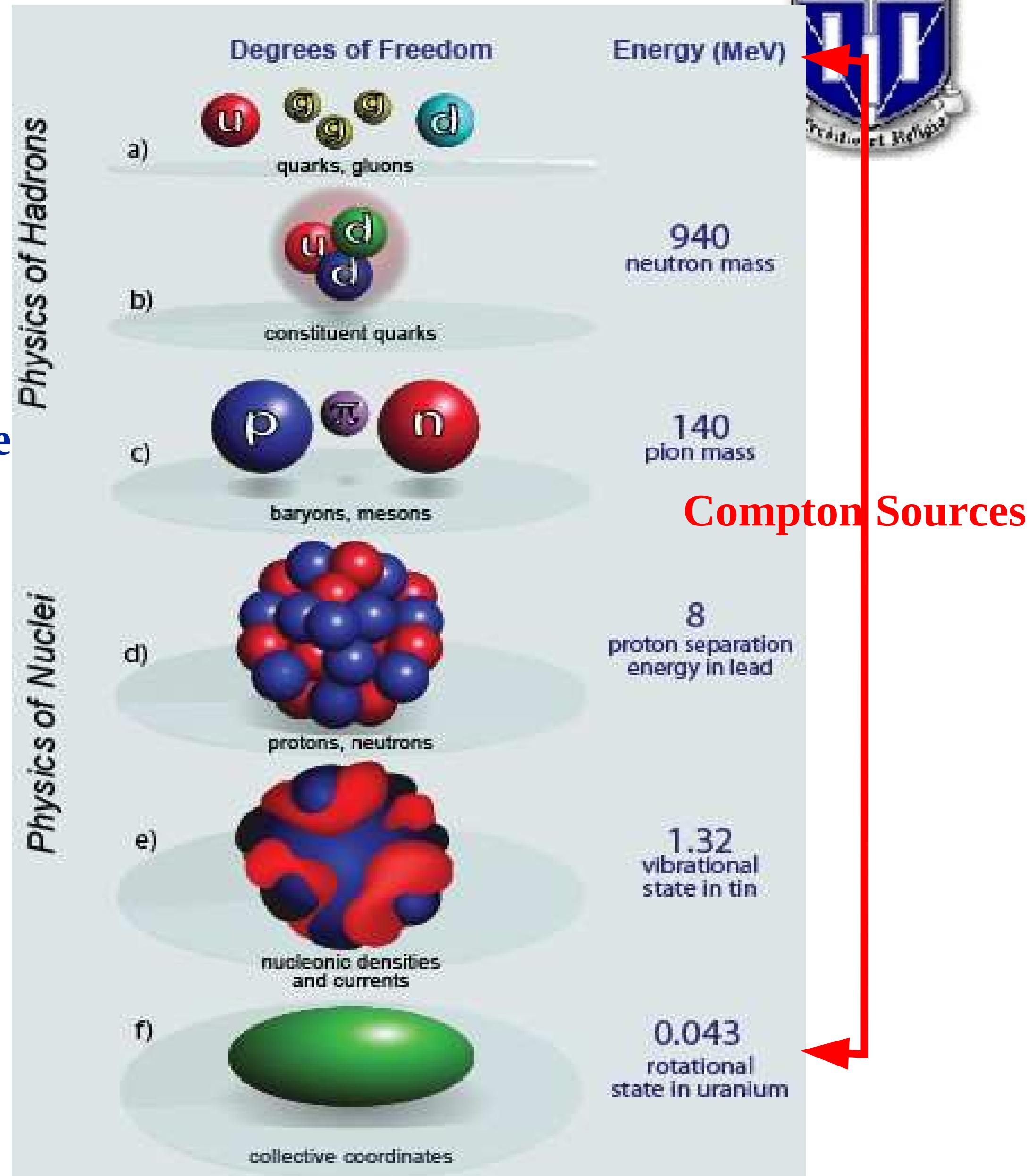
Basic Research Using Compton Gamma-ray Sources

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).

Basic Research Using Compton Gamma-ray Sources

Some 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

R&D Topics

R&D Topics for Compact Light Sources (2010 BES Workshop)

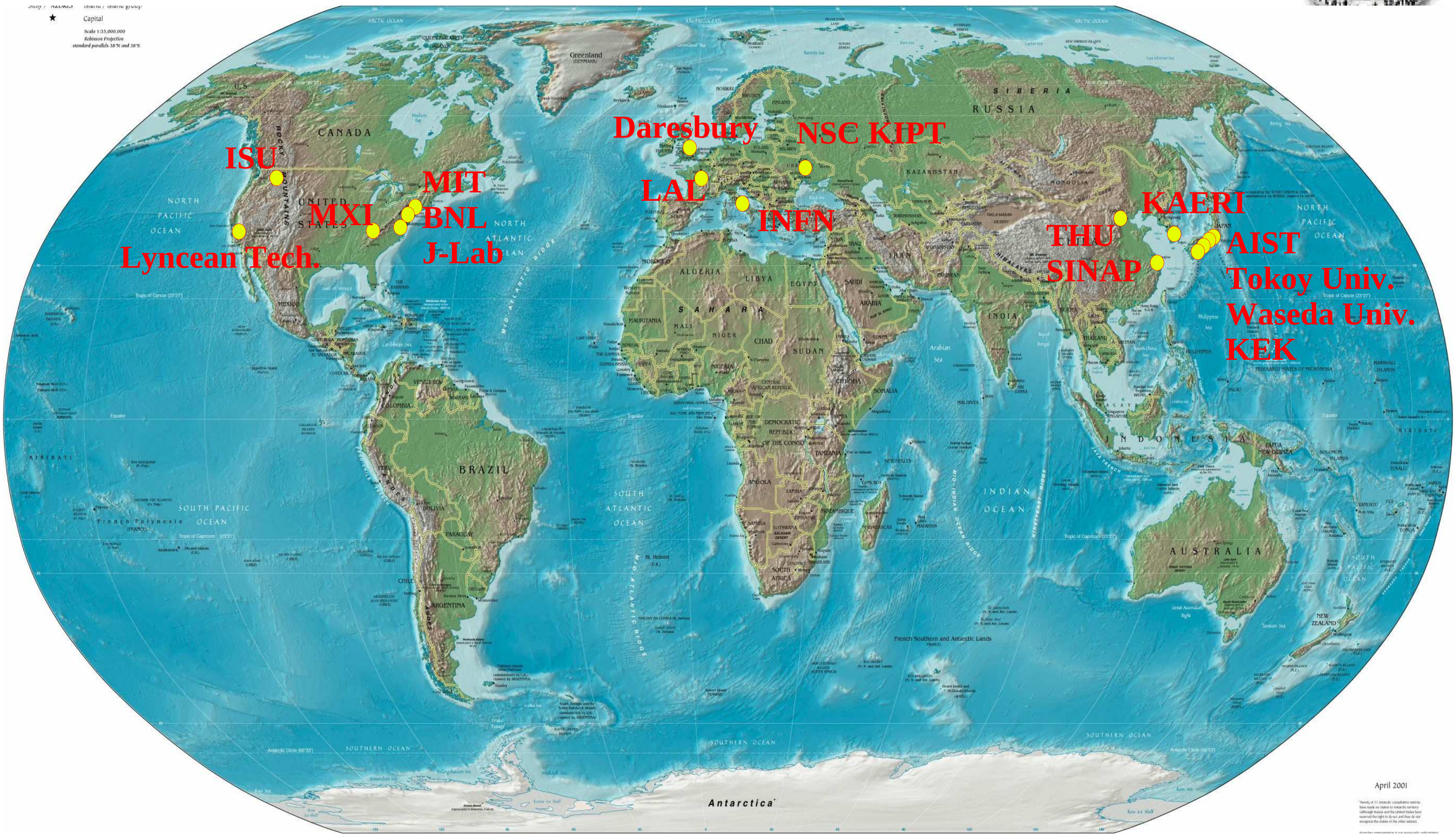
- Develop IR laser systems: kW avg power, fs pulses, kHz reprates
- Develop laser storage cavities: 10-mJ, ps and fs pulses focused to micron beam sizes
- Develop high-brightness, high reprate electron sources
- Develop CW 4K superconducting RF linacs

Other R&D Topics Specific to Compton Sources

- Laser cavities tailored for specific Compton sources in terms of power, reprate, beam size, polarization, and collision geometry (two-mirror resonators, multi-mirror ring resonators, and 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

Sources:
1. "Report of BEC Workshop on Compact Light Source, " Organizers:W. Barletta, M. Borland, May 2010.

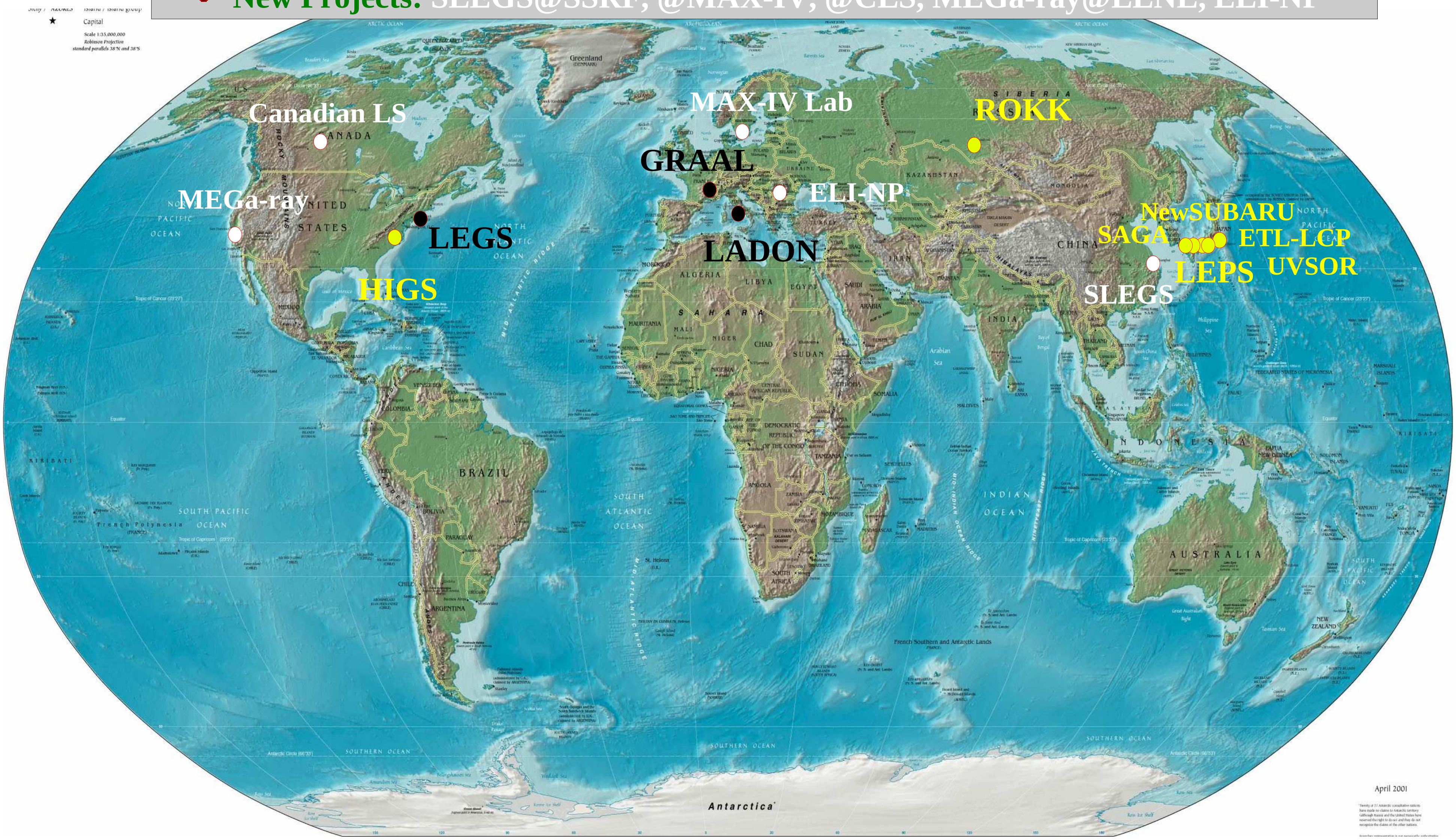
Compton X-ray Facilities, Projects, Experiments Around the World



Credit: H. Hao, Duke University

Compton Gamma-ray Facilities and Projects Around the World – Past, Present, and Future

- **Past Facilities:** LADON, LEGS, GRAAL
- **Operational Facilities and Development Projects:**
  HIGS, LEPS, ROKK, ETL-LCP, @UVSOR, @newSUBARU, @SAGA
- **New Projects:** SLEGS@SSRF, @MAX-IV, @CLS, MEGa-ray@LLNL, ELI-NP



Thank You

History of Storage Ring Based Compton Gamma Facilities

H.R. Weller *et al*. Progress in Particle and Nuclear Physics 62, p. 257-303 (2009).

Table 1

Parameters of major Compton gamma source facilities around the world

Project name	LADON[a]	LEGS	ROKK-1M[b]	GRAAL	LEPS	HIγS[c]
Location	Frascati Italy	Brookhaven US	Novosibirsk Russia	Grenoble France	Harima Japan	Durham US
Storage ring	Adone	NSLS	VEPP-4M	ESRF	SPring-8	Duke-SR
Electron energy (GeV)	1.5	2.5–2.8	1.4–6.0	6	8	0.24–1.2
Laser energy (eV)	2.45	2.41–4.68	1.17–4.68	2.41–3.53	2.41–4.68	1.17–6.53
γ-beam energy (MeV)	5–80	110–450	100–1600	550–1500	1500–2400	1–100 (158)[d]
Energy selection	Internal tagging	External tagging	(Int or Ext?) tagging	Internal tagging	Internal tagging	Collimation
γ-energy resolution (FWHM)						
ΔE (MeV)	2–4	5	10–20	16	30	0.008–8.5
$\frac{\Delta E}{E}$ (%)	5	1.1	1–3	1.1	1.25	0.8–10
E-beam current (A)	0.1	0.2	0.1	0.2	0.1–0.2	0.01–0.1
Max on-target flux (γ/s)	5×10^5	5×10^6	10^6	3×10^6	5×10^6	10^4–5×10^8
Max total flux (γ/s)						10^6–3×10^9[e]
Years of operation	1978–1993	1987–2006	1993–	1995–	1998–	1996–

For performance of facilities other than HIγS, see review articles: (1) A. D'Angelo et al., Nuclear Instrum. Methods A **455**, 1 (2000); and (2) C. Schaerf, Physics Today, August 2005, 44 (2005).

[a] The LADON facility used both collimation and internal tagging. The tagging operation is listed.

[b] ROKK-1 (1982) and ROKK-2 (1987) are two older Compton gamma source facilities at Novosibirsk.

[c] HIγS has the highest flux performance between 5 and 20 MeV.

[d] HIγS covers the gamma energy range of 1–100 MeV by using commercially available FEL mirrors from 1064 to 190 nm. The planned vacuum ultraviolet (VUV) FEL mirror development will extend its operation up to about 158 MeV.

[e] The HIγS flux performance is expected to increase by at least one order of magnitude by 2010 with further development.

From SALC 1st ncul.. exp (Ballam et al) in 1964 to LADON in 1978 to HIGS in 2012

- **Total flux: 10^3 to 10^6 to >2×10^{10} gamma/sec;**
- **Flux increment: ~30 times/decade**