Laser Compton Sources:
Present and Envisioned

Ying K. Wu

Department of Physics, Duke University

Triangle Universities Nuclear Laboratory

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Acknowledgment:

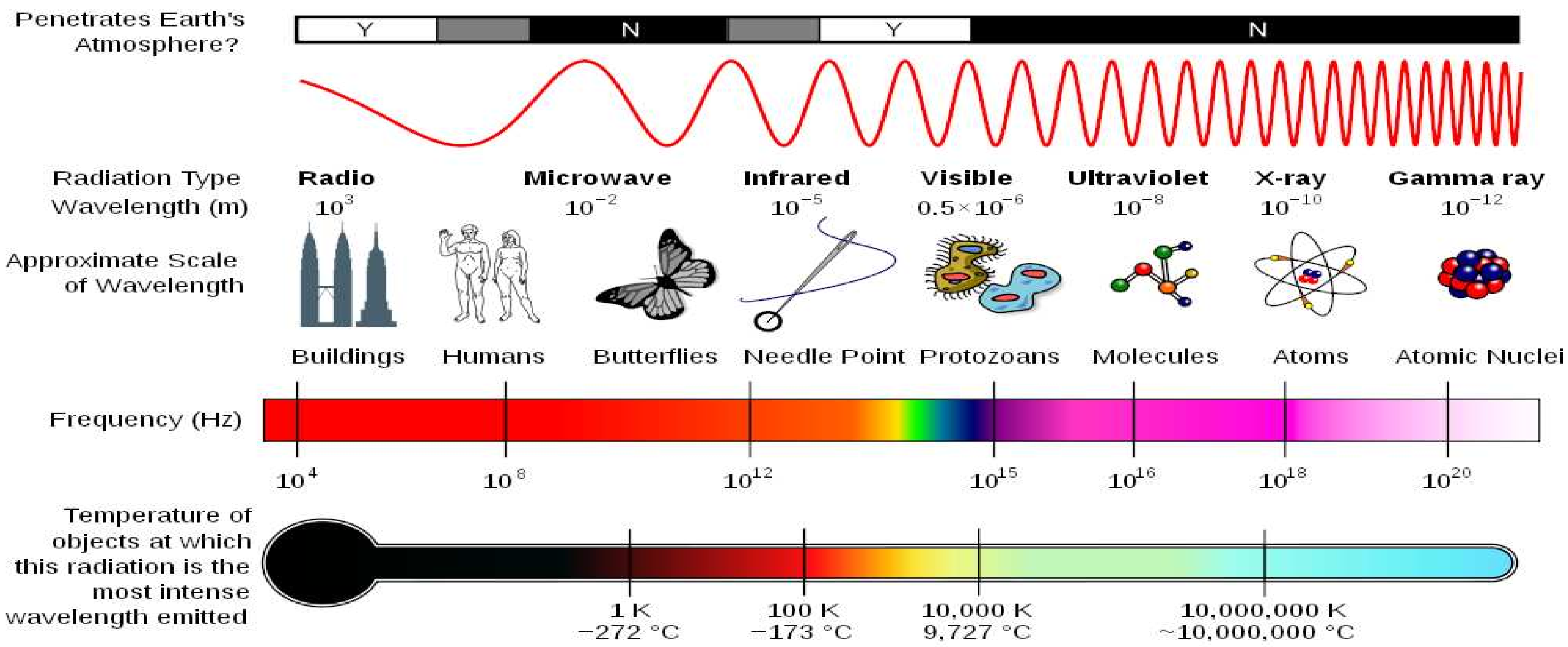
To researchers of the worldwide accelerator and laser communities who contributed to the development of Compton photon sources.

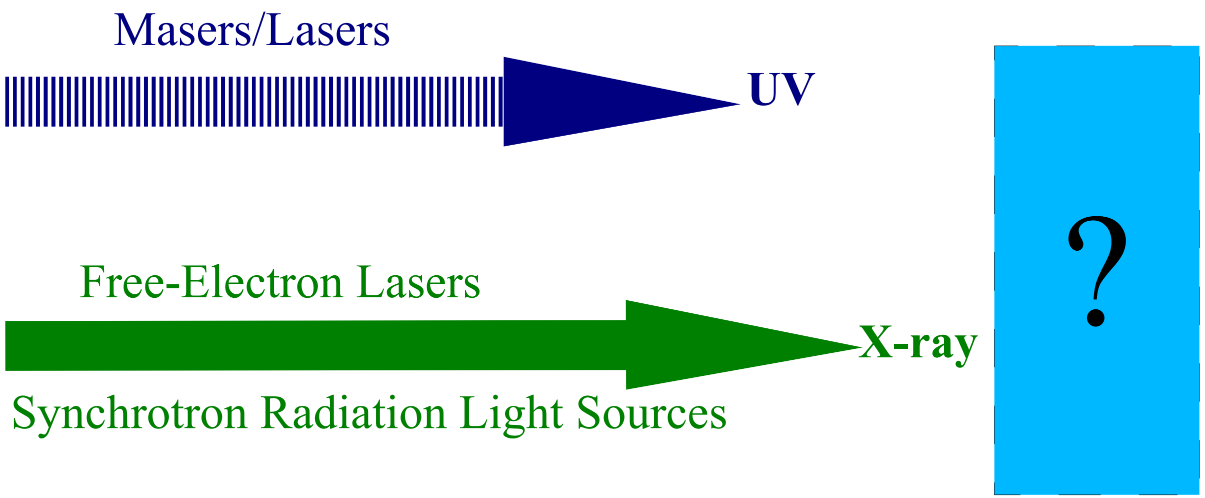
Credit will be given on individual slides.

Outline

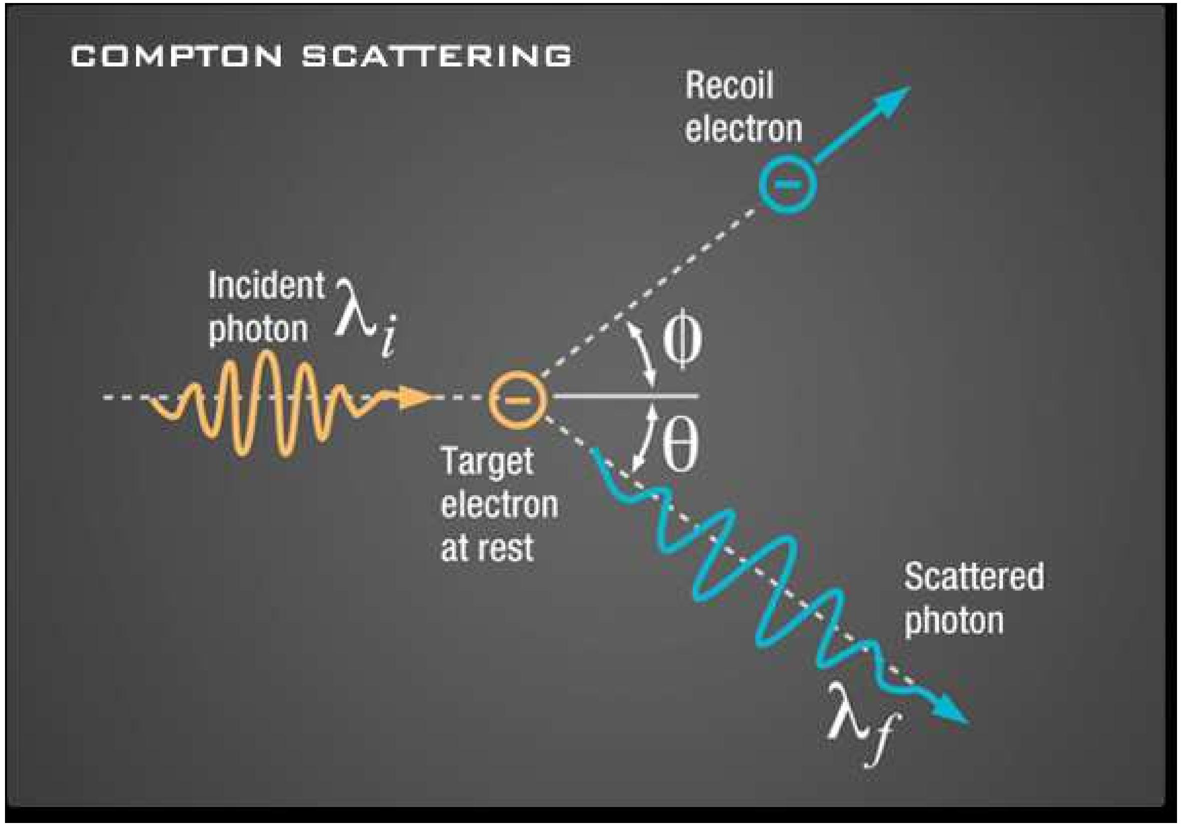
- Physics of Compton Photon Sources
- Recent Developments at HIGS
- Compton Photon Sources around the World
  - Operational Sources/Facilities
  - Projects under Development
  - Future Gamma-ray Sources for Nuclear Physics Research

Spectrum of Electromagnetic Radiation





Compton Scattering
Arthur H. Compton (1892 – 1962)
Discovery: 1923
Nobel Price for Physics: 1927

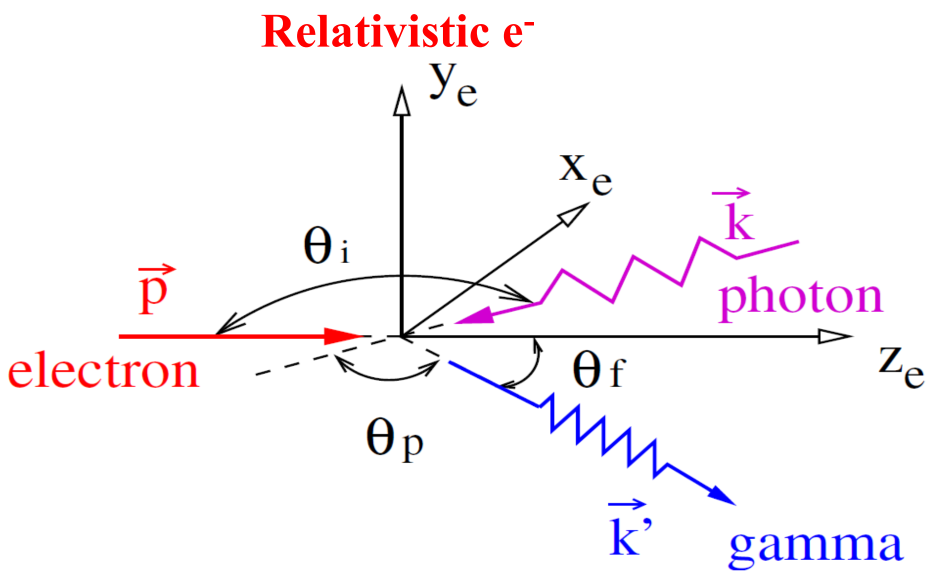


$$\lambda_f - \lambda_i = \frac{h}{m_e c}(1-\cos\theta)$$

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.

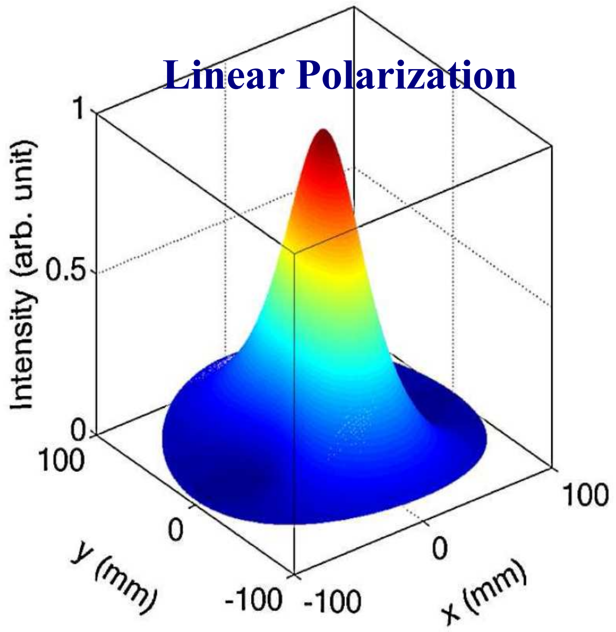
Photon Energy

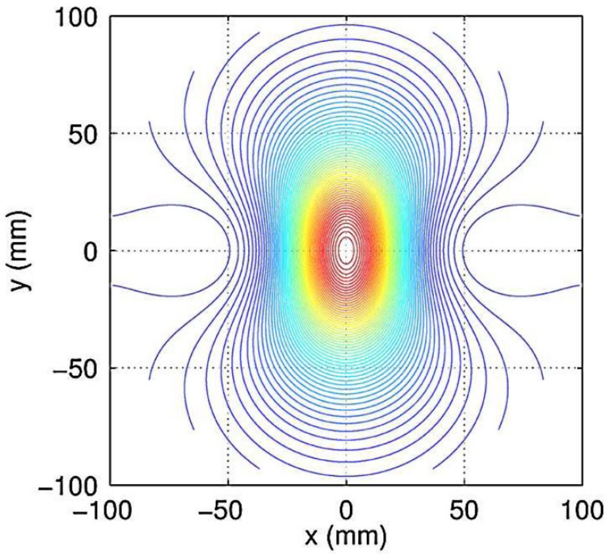


$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f + \frac{\hbar\omega}{\mathcal{E}_e}(1-\cos\theta_{ph})}$$

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

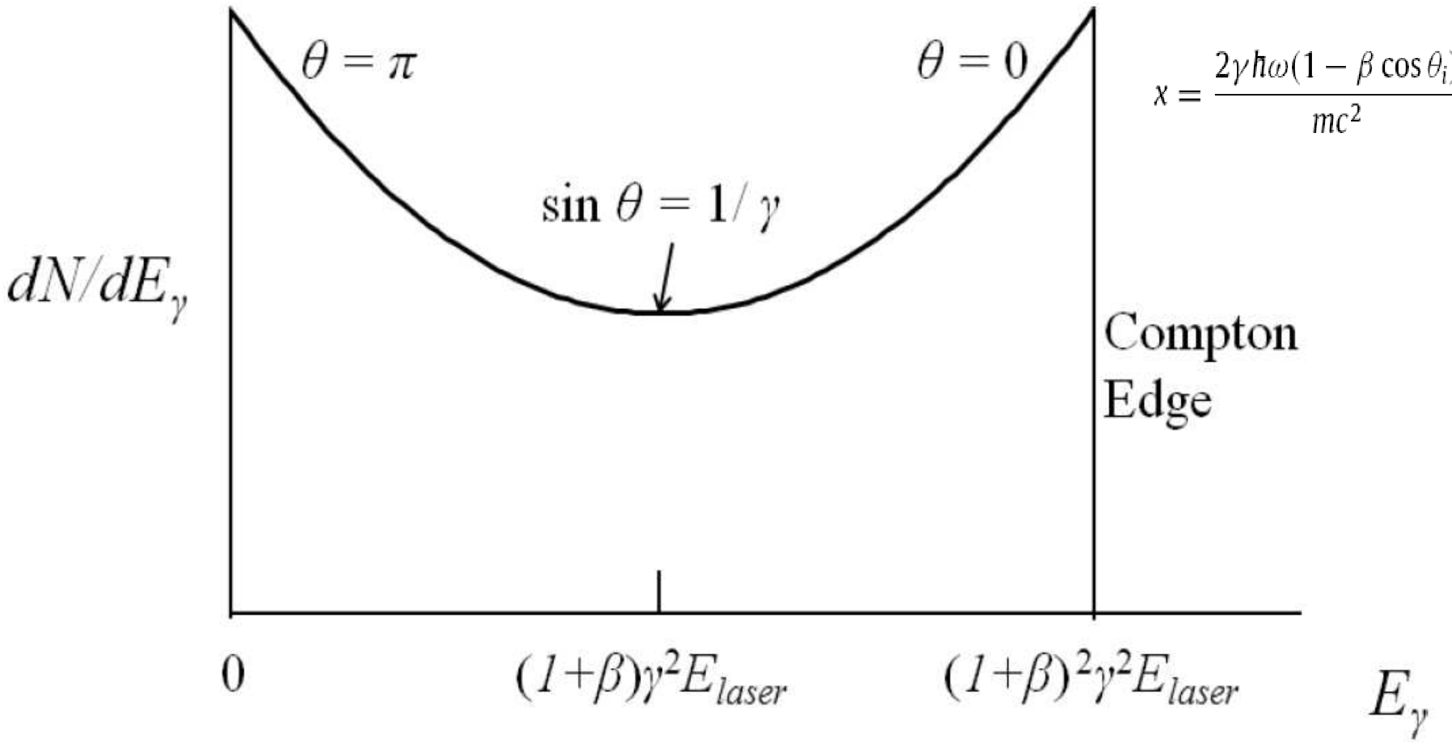
C. Sun and Y. K. Wu, Phys. Rev. ST Accel. Beams 14, 044701 (2011)





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:

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

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

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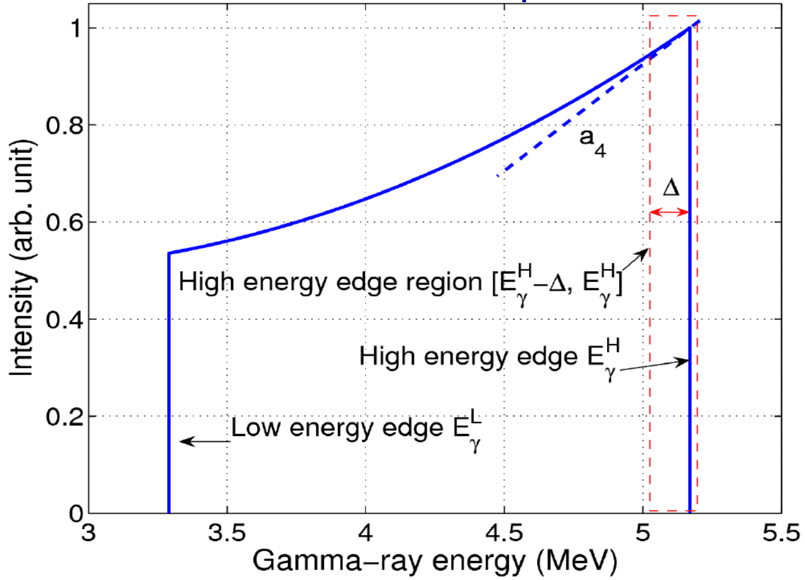
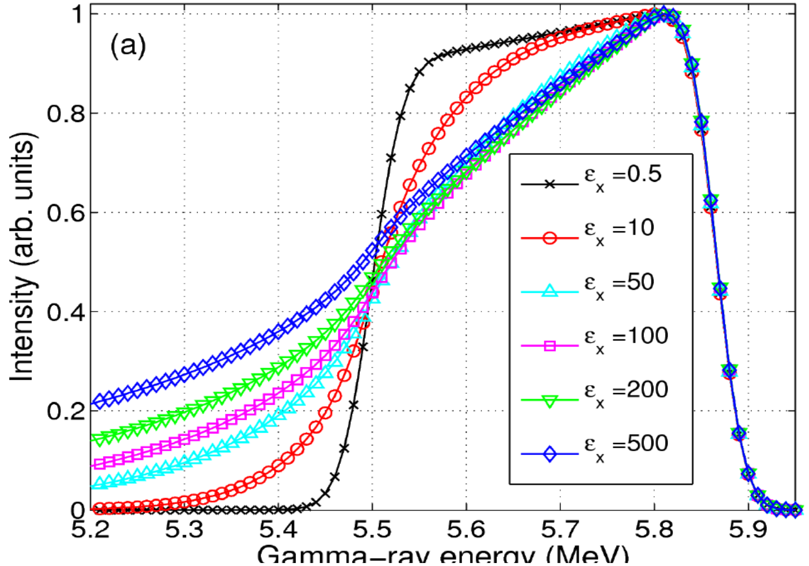
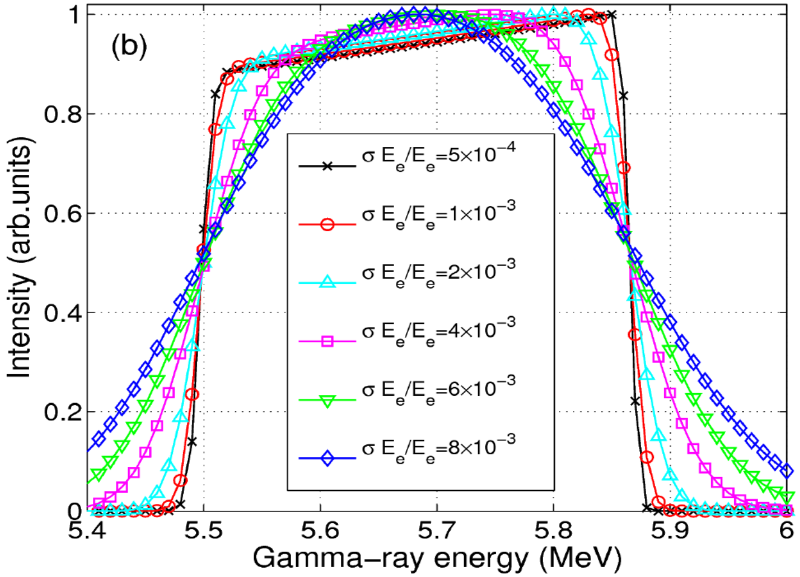
Monochromatic electron and photon beams



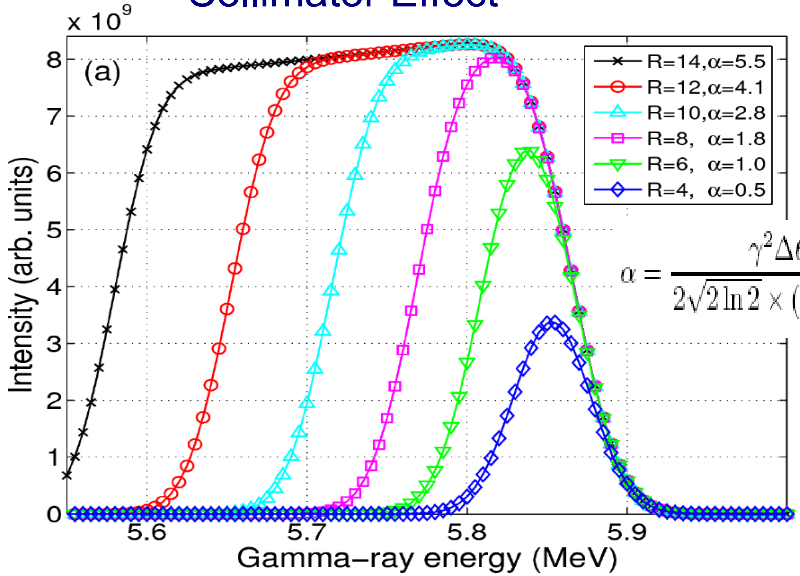
Emittance Effect (Scaled)



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).

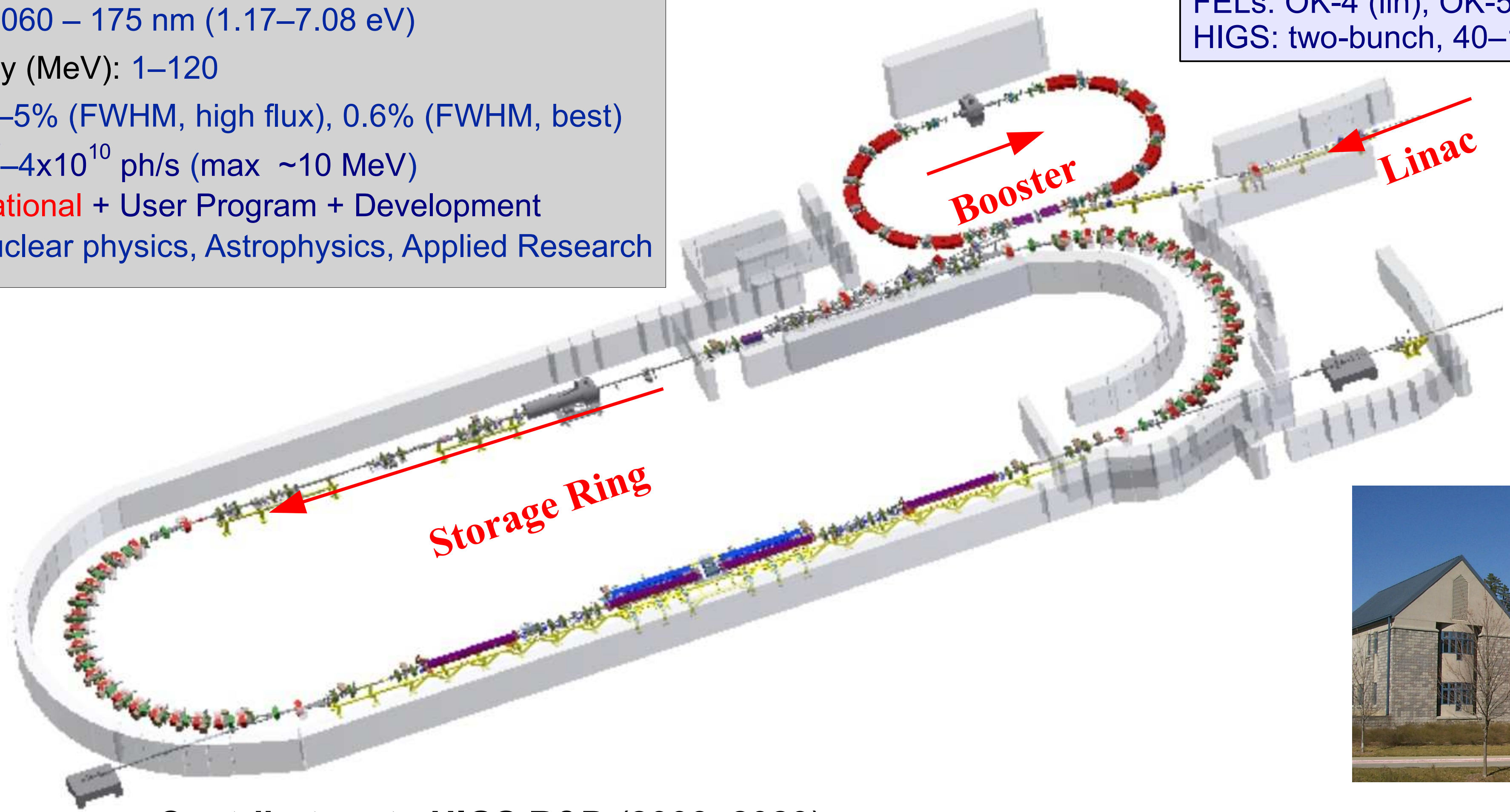
Recent Developments at HIGS

- Pulsed Mode Operation
- Two-color FEL
- Polarization Control
- High-energy Beam Development: 120 MeV
- Twisted Photon Beams

High Intensity Gamma-ray Source (HIGS)

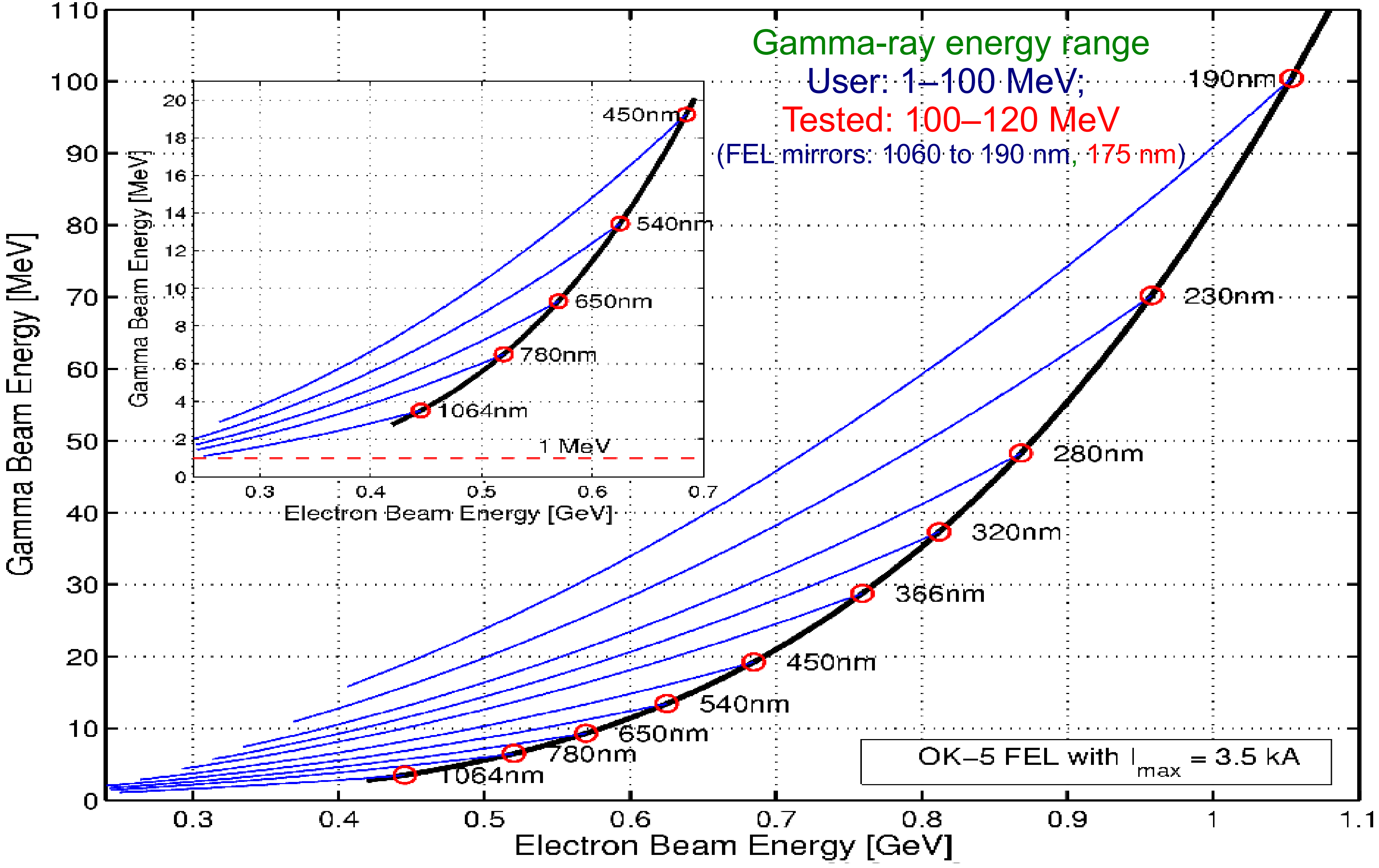
Facility/Project: High Intensity Gamma-ray Source (HIGS)
Institution: TUNL
Country: United States
Accelerator: Storage Ring, 0.24–1.2 GeV
Laser: FEL, 1060 – 175 nm (1.17–7.08 eV)
Photon energy (MeV): 1–120
Resolution: 2–5% (FWHM, high flux), 0.6% (FWHM, best)
Total flux: 10^7–$4x10^{10}$ ph/s (max ~10 MeV)
Status: Operational + User Program + Development
Research: Nuclear physics, Astrophysics, Applied Research

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)



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, E. Martin, S. Mikhailov, M. Pentico, V. Popov, C. Sun, G. Swift, B. Thomas, E. Vajzovic,P. Wang, P. Wallace, W. Wu, Y. K. Wu, W. Xu, J. Yan

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



HIGS Flux Summary

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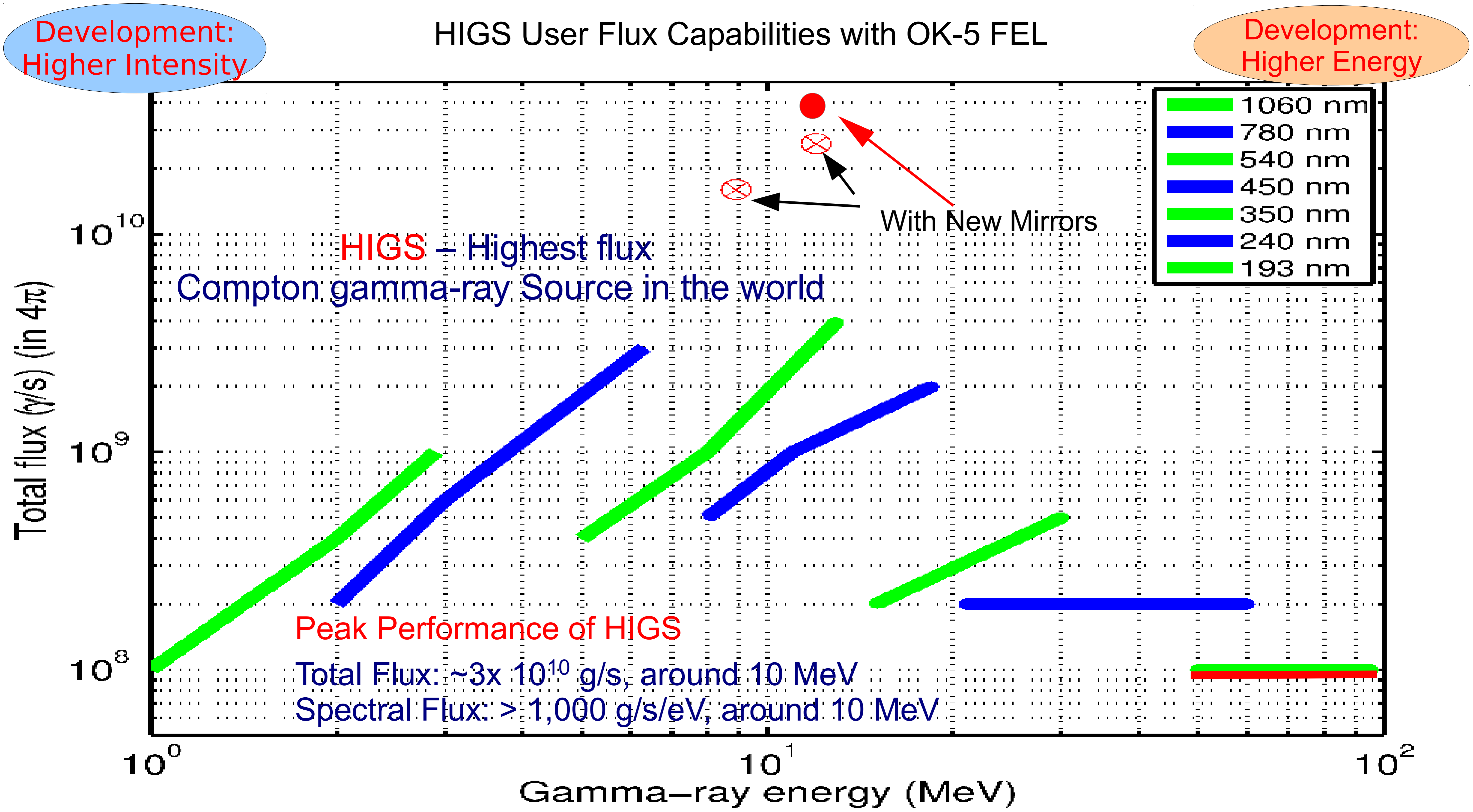
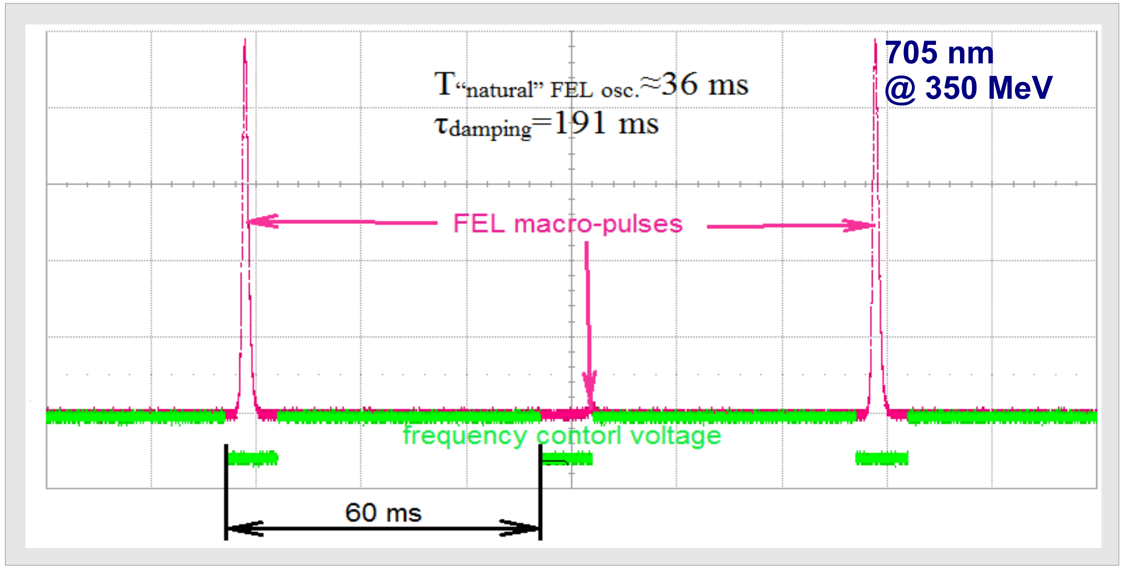
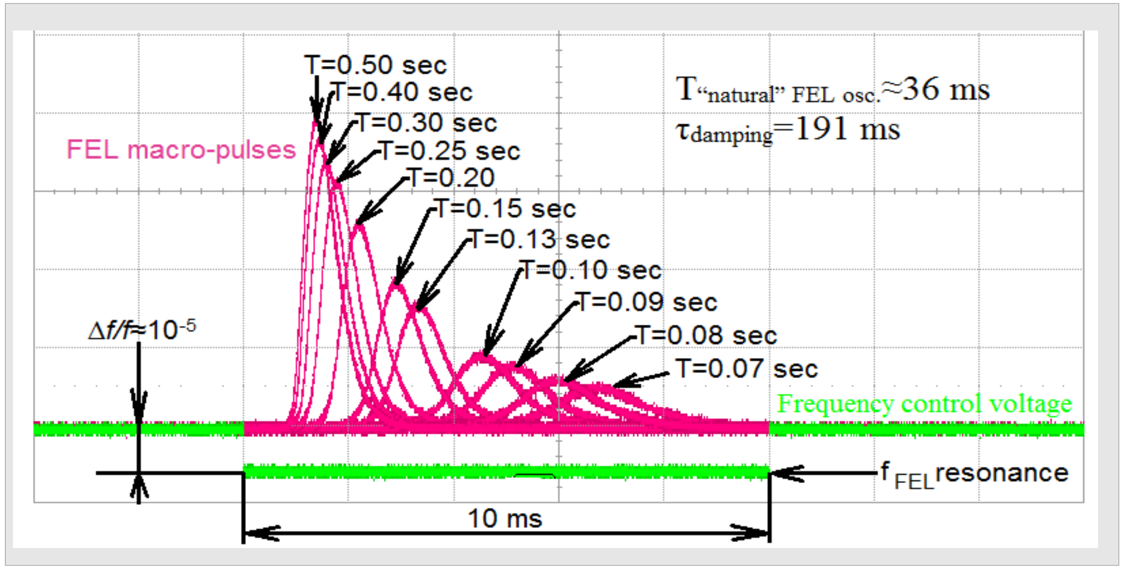


HIGS New Capabilities: Pulsed Beam for Low Background Experiments



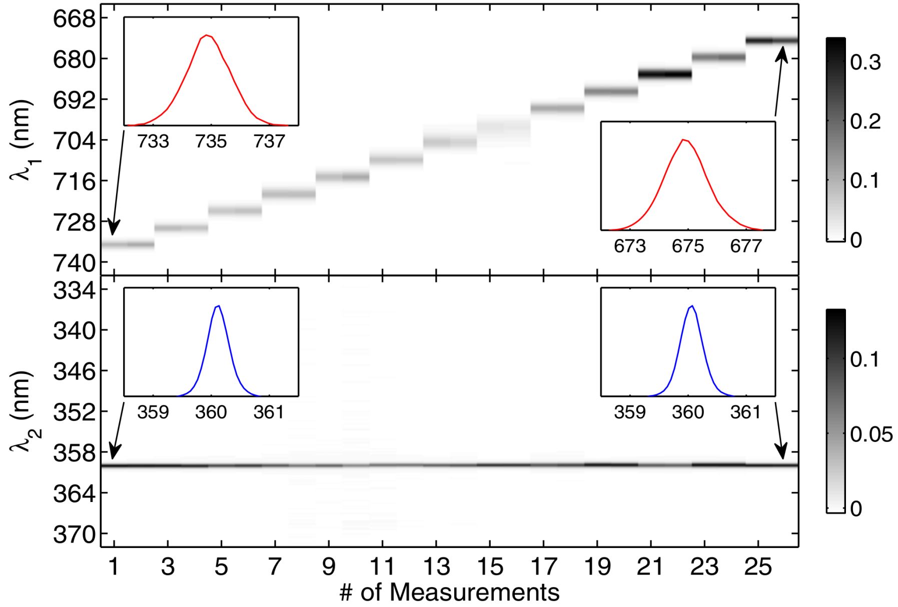


Gain Modulation with RF—FEL Macropulse Operation

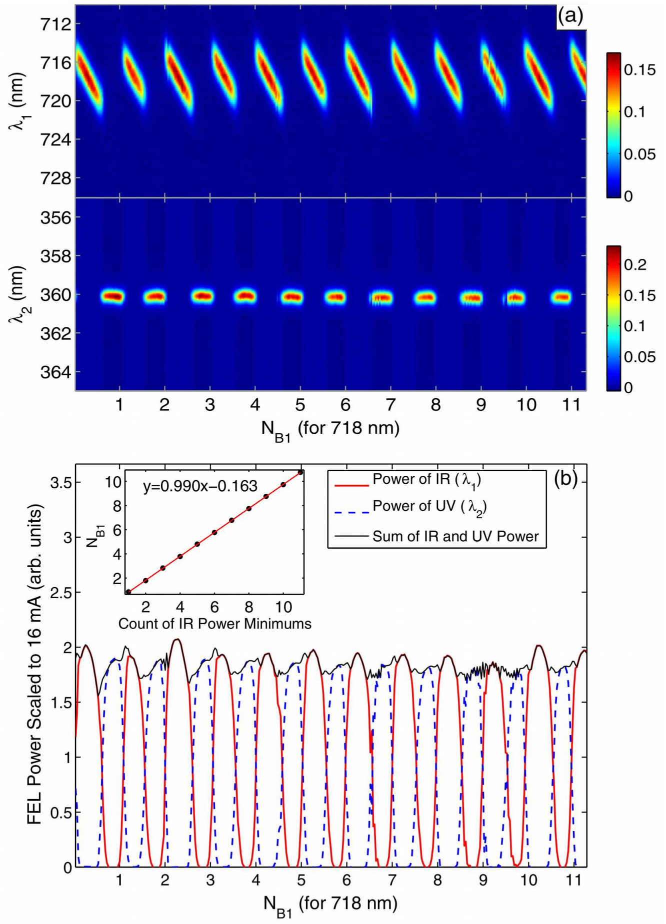
- Rapidly and periodically change f_{RF}
  - $Df_{RF}/f_{RF} \sim 10^{-5}$
  - Transition in 10s of microseconds
  - Duration for a few milliseconds
- Rep-rate: few to tens of Hz, depending on operational conditions
- About the same average FEL power
- Good beam stability and lifetime
- Type of user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

HIGS New Capabilities: 2-Color FEL

Wavelength Tuning



FEL Power Control



PRL 115, 184801 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

Widely Tunable Two-Color Free-Electron Laser on a Storage Ring

Y. K. Wu,* J. Yan, H. Hao, J. Y. Li, S. F. Mikhailov, and V. G. Popov
FEL Laboratory, TUNL and Department of Physics, Duke University, Durham, North Carolina 27708-0319, USA

N. A. Vinokurov
Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

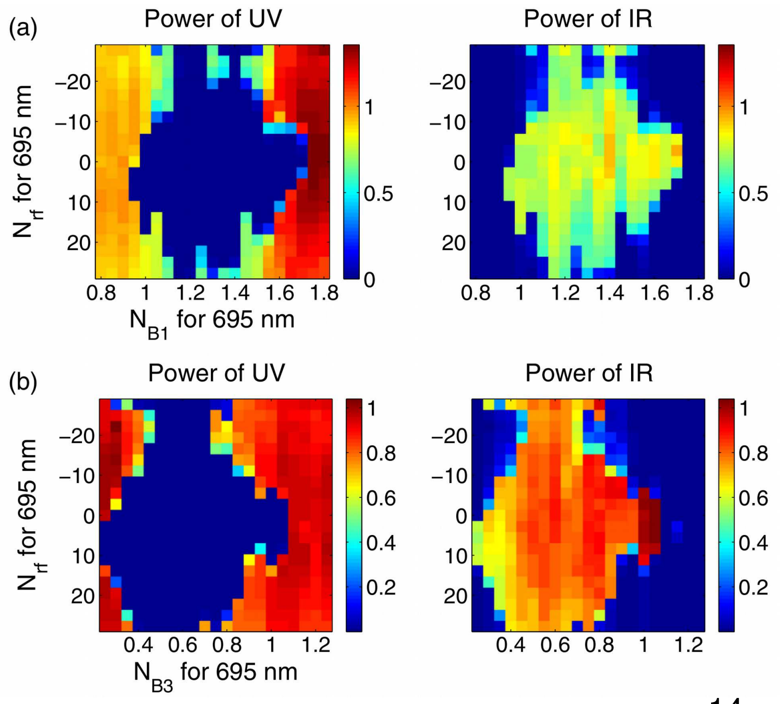
S. Huang
Institute of Heavy Ion Physics, School of Physics, Peking University, Beijing 100871, China

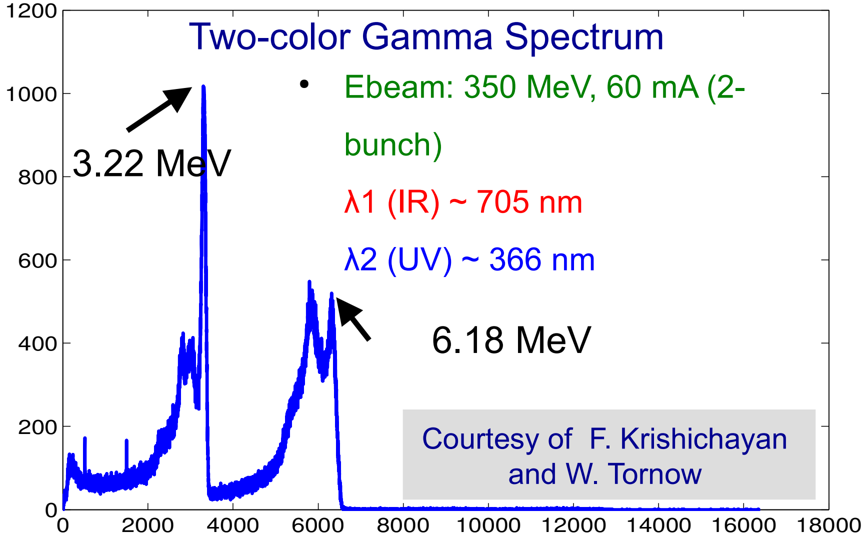
J. Wu
SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94309, USA

(Received 15 August 2015; published 26 October 2015)

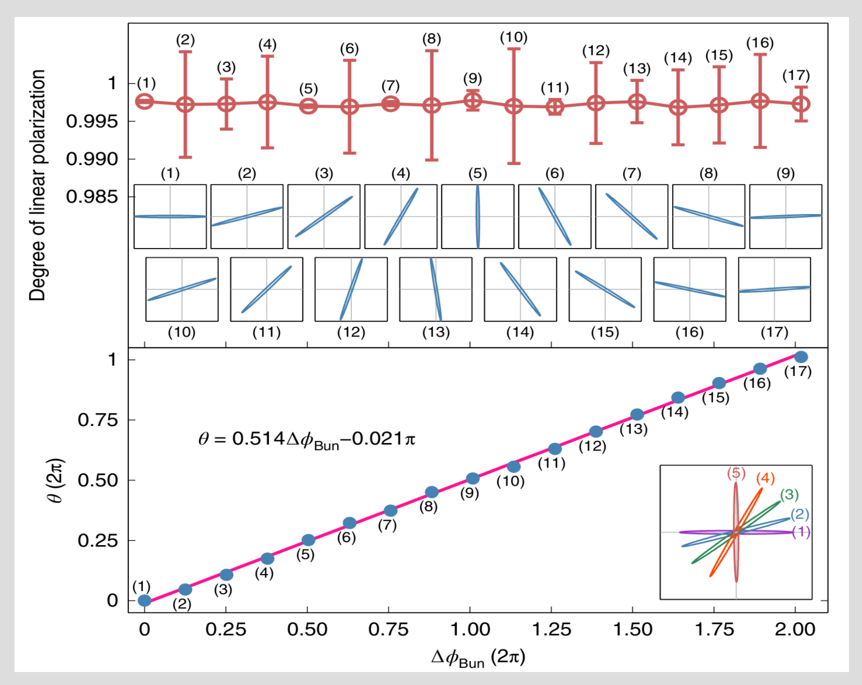
Y.K. Wu *et al*. PRL 115, 184801(2015)
J. Yan *et al*. PRAB 19, 070701 (2016)

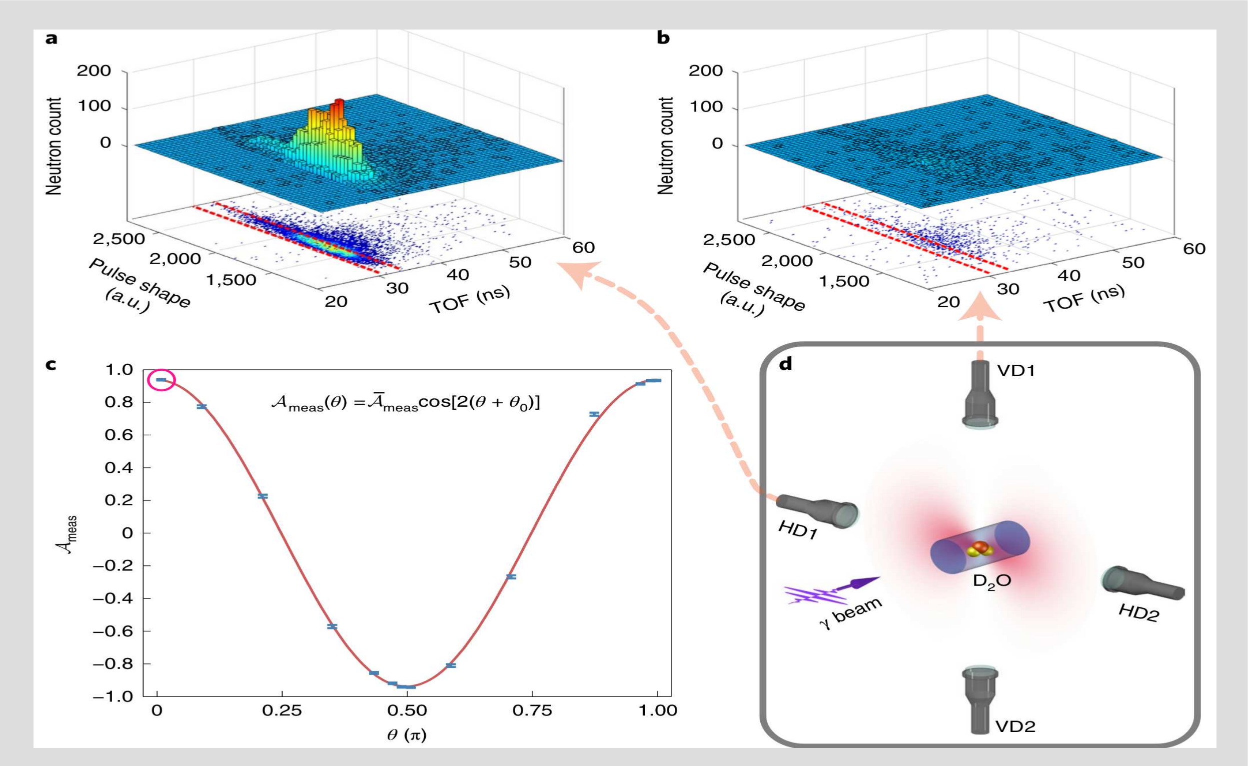
Lasing Phasespace

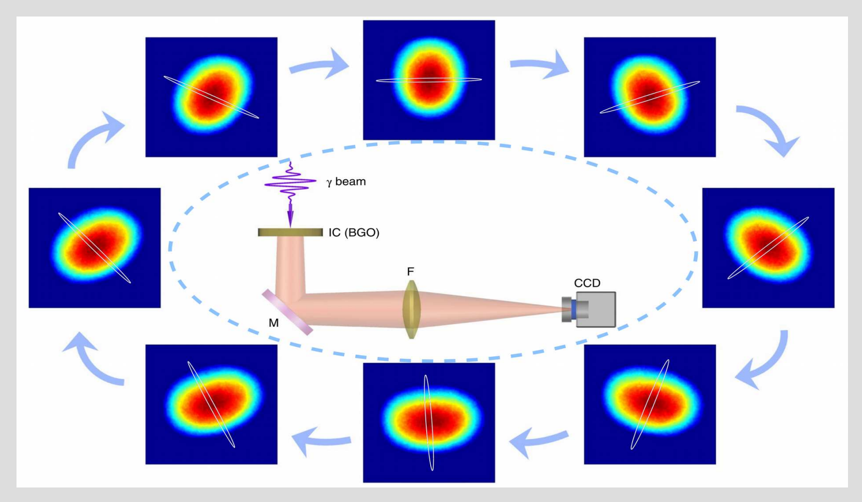




HIGS New Capabilities: Precision Polarization Control



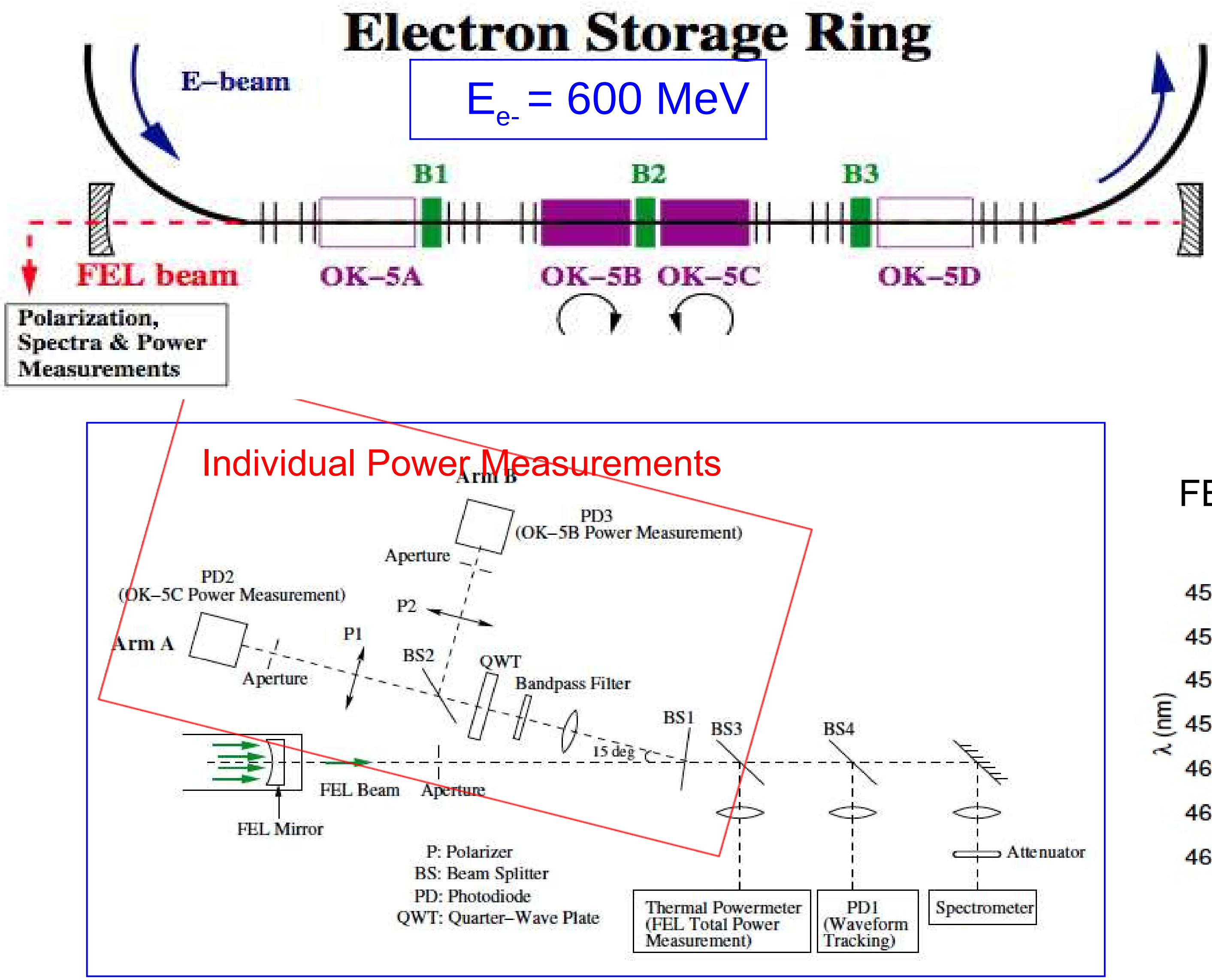


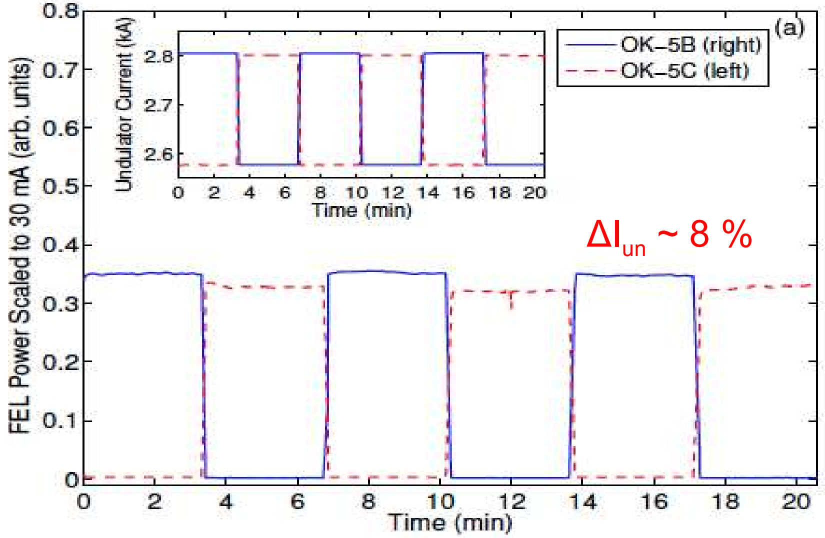


New Gamma-ray Capability in Polarization Control

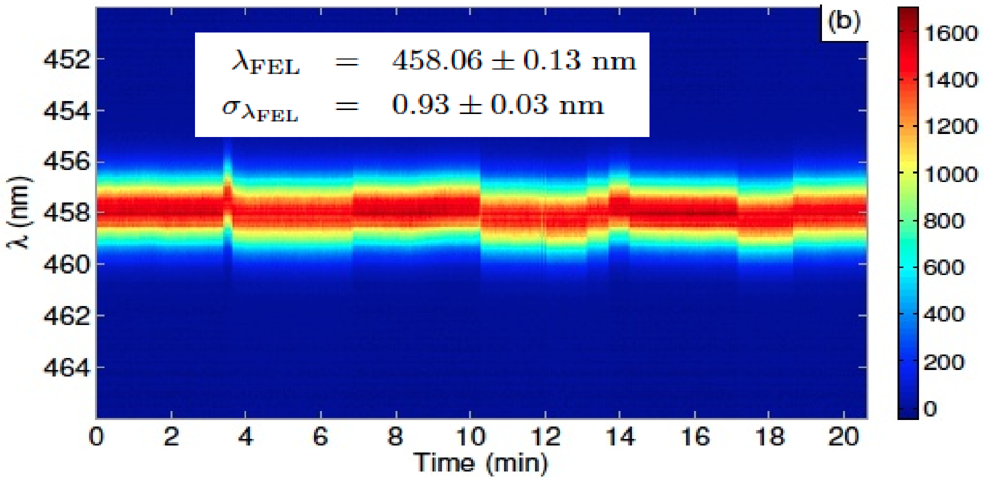
- Precision control of gamma-ray polarization:
  two crossed helical undulators ==> FEL and gamma-ray beams with linear polarization in any direction
  - Linear polarization, P_{Lin} > 0.97 for gamma-ray (P_{Lin} > 0.99 for FEL)
  - Available: 3 – 30 MeV
- Impact on nuclear physics research:
  - Experiment 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.

HIGS New Capabilities: Helicity Switch





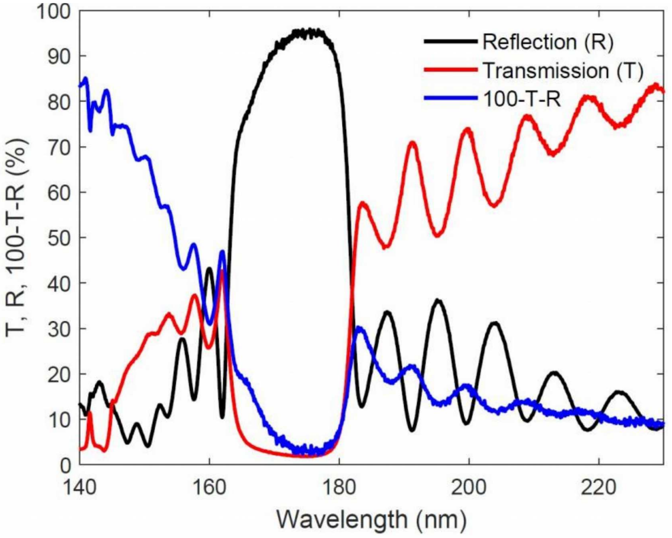
FEL Power (rms): OK-5B, 0.8%; OK-5C, 0.9%



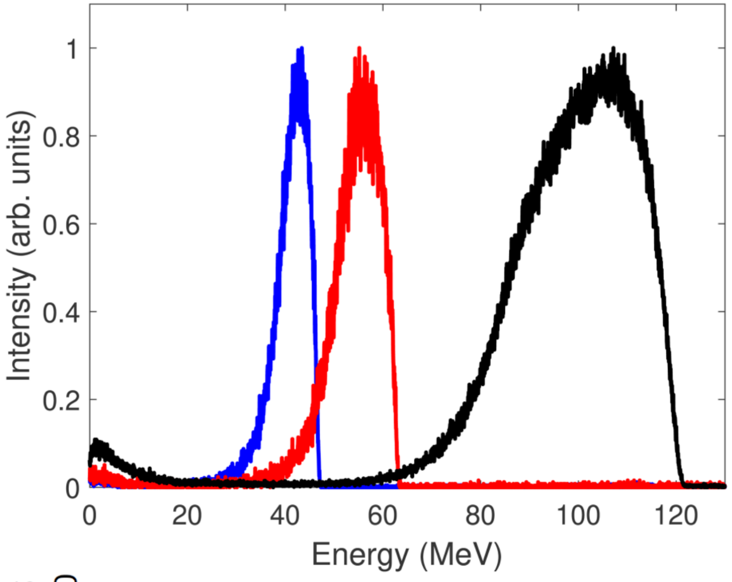
From Jun Yan's dissertation (2016)

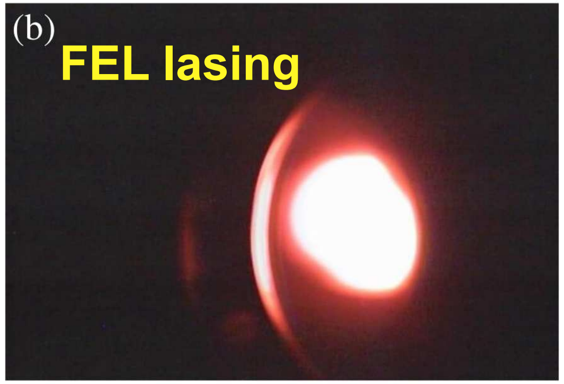
HIGS New Capabilities: 120 MeV Production with VUV FEL

Fluoride multilayer w. SiO2 top layer

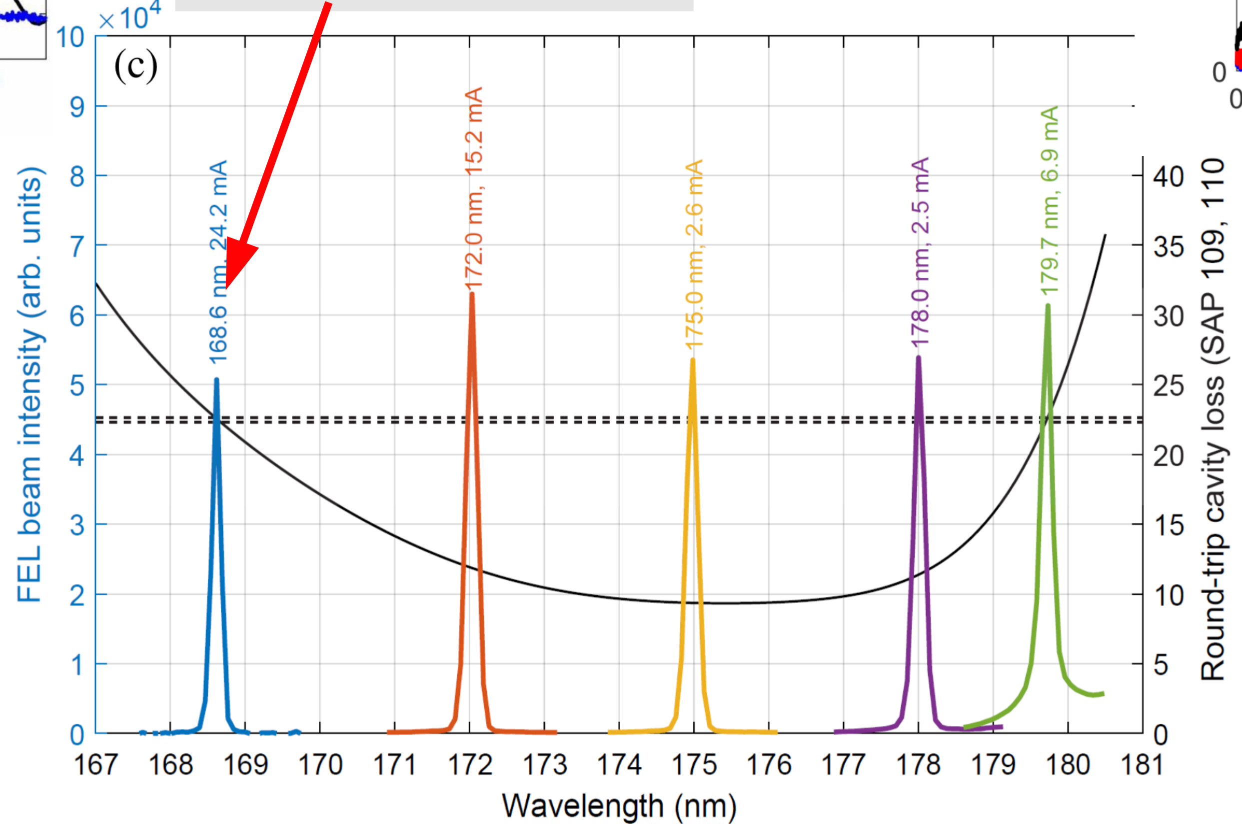


Gamma Spectra, Max E_γ = 45, 60, 120 MeV



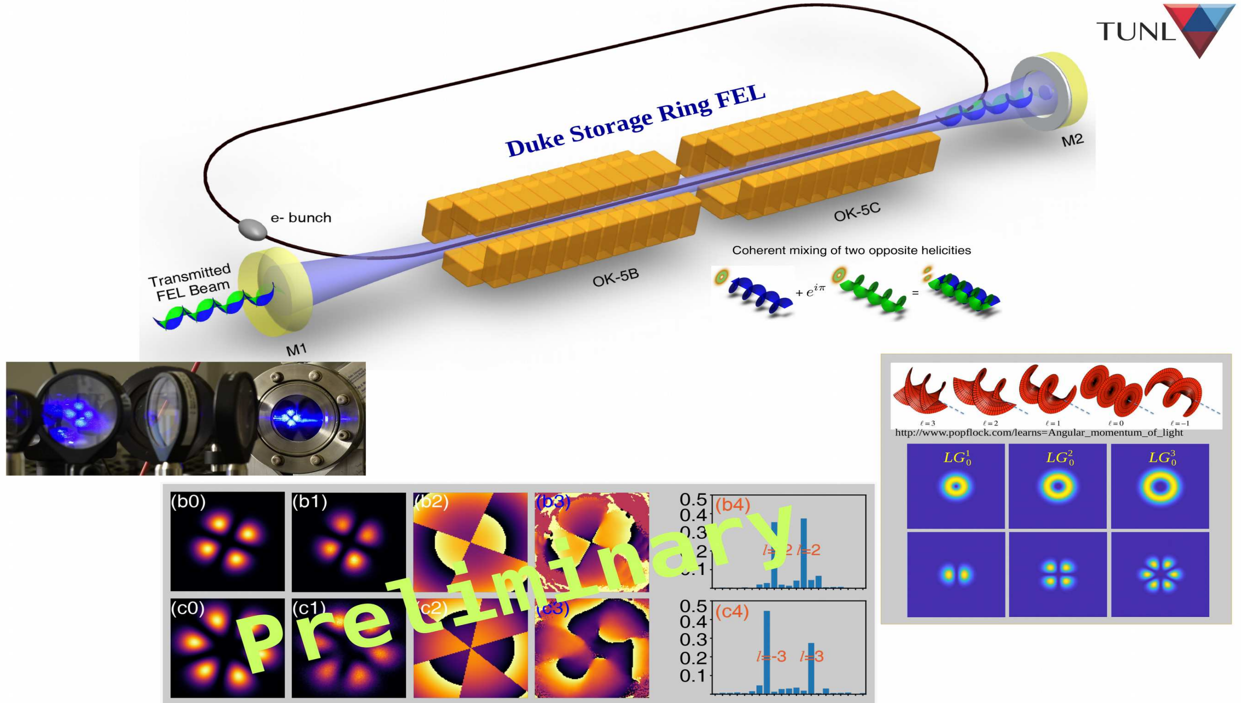


Shortest wavelength for Oscillator FEL: 168.6 nm



HIGS: FEL/CGS Research: Orbital Angular Momentum Beam

OAM Beam Generation Using FEL Oscillator

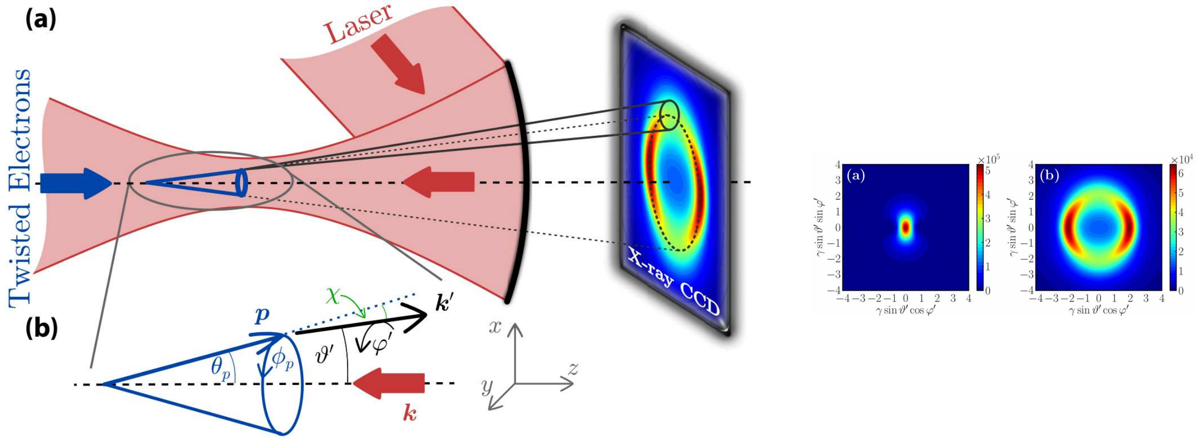


OAM FEL Research Collaboration:
Y.K. Wu, P. Liu, J. Yan, H. Hao, S.F. Mikhailov, V.G. Popov (Duke/TUNL); S. Benson (JLab), A. Afanasev (GW)

This work is partially supported by U.S. DOE Grant: DE-FG02-97ER41033.

Monday afternoon talk: Peifan Liu, *et al*, *Experimental study of orbital angular momentum beams using a free-electron laser oscillator*

OAM laser beam + relativistic electrons



OAM x-ray/gamma rays via Compton backscattering

New selection rules, strong dichroism, etc.

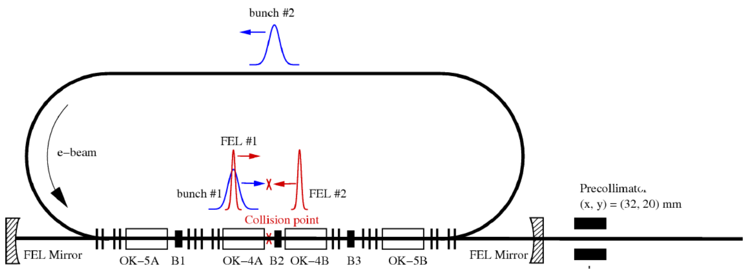
- X-ray spectroscopy in orbital physics and magnetism
- Nuclear spectroscopy
- Nuclear resonance fluorescence
- Nuclear photoionization
- Probe for hadron structures

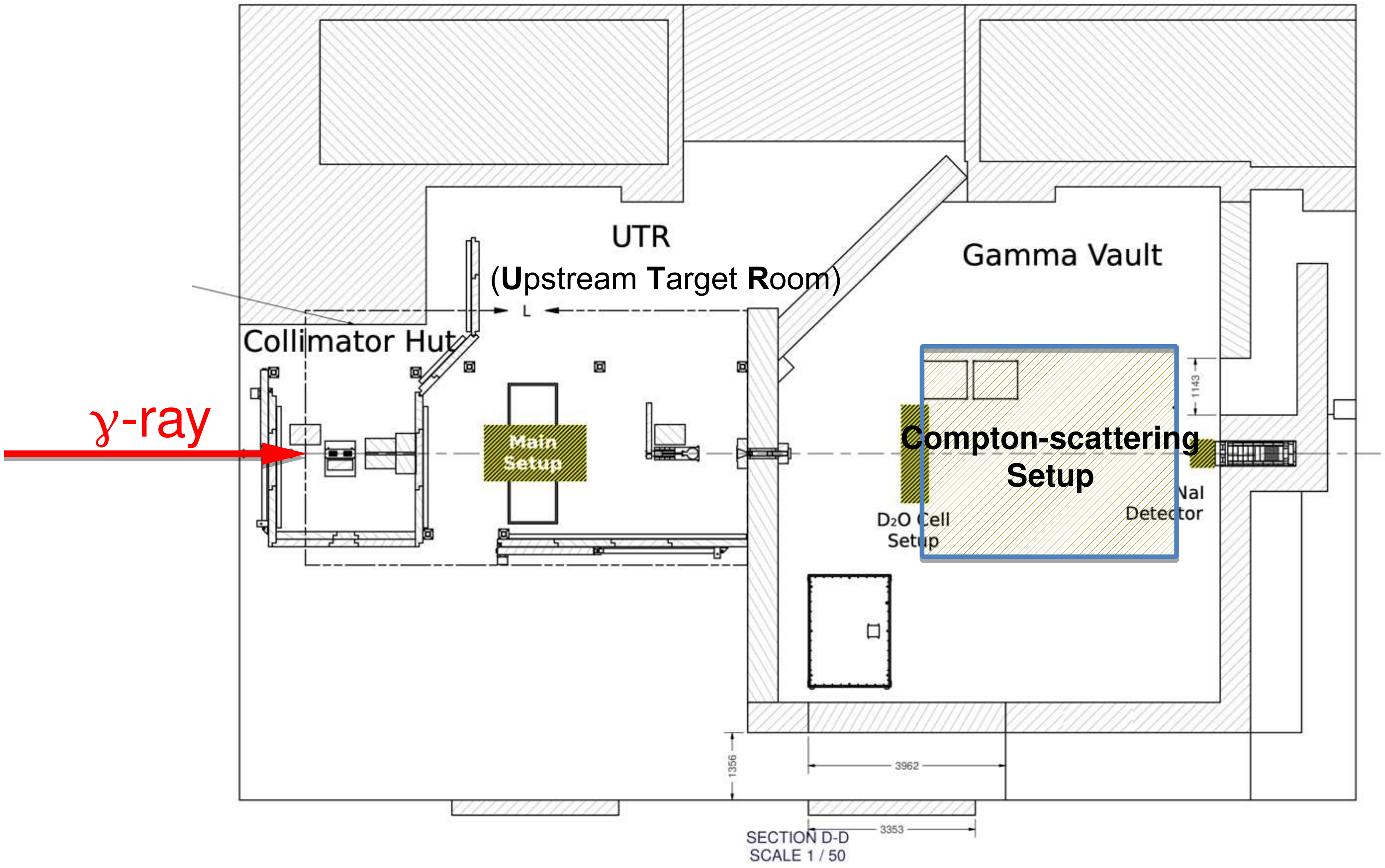
Challenges remain:

- Can Compton scattering produce OAM gamma rays efficiently?
- How to improve the production rate of OAM gamma rays?

D. Seipt *et al*. "Structured x-ray beams from twisted electrons by inverse Compton scattering of laser light," PRA 90, 012118 (2014).

HIGS Target Room Layout





HIGS User Research Programs

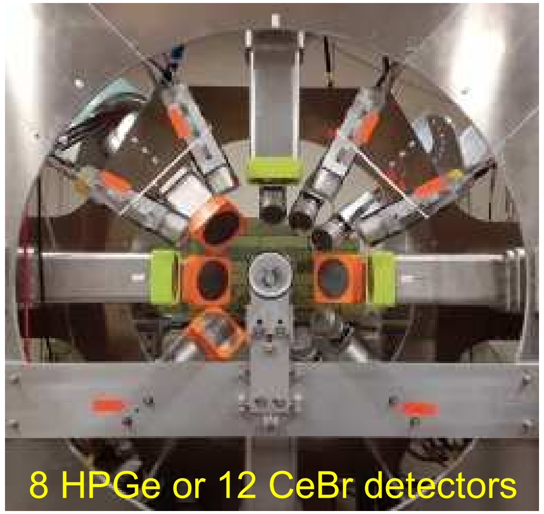
Nuclear Structure and Nuclear Astrophysics

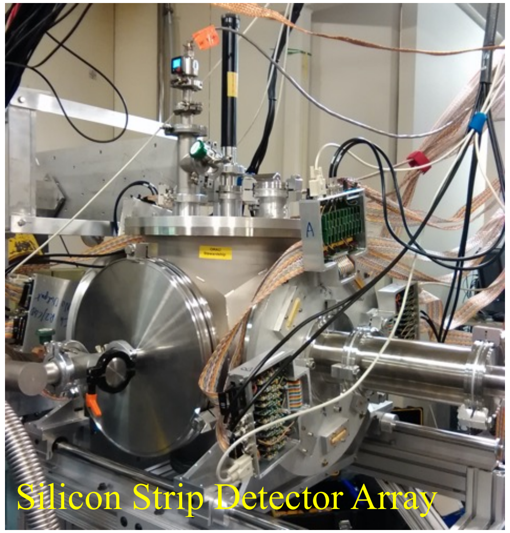
TUNL Groups:

(a) M. Ahmed, NCCU
(b) C. Howell, W. Tornow, Y. Wu, Duke Univ.
(c) A. Ayangeakaa, A. Champagne, C. Iliadis, R. Janssens, H. Karwowski, UNC

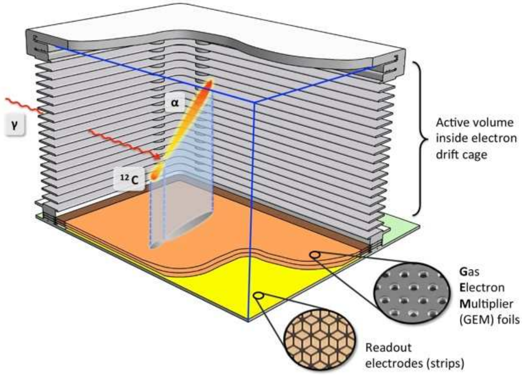
External Researchers: 32 institutions: 11 USA + 21 International

- Clover-Share Collaboration:
  17 institutions = 7 USA + 10 International
- Photon-induced Nuclear Reactions: 20 institutions + TUNL
- Other smaller collaborations





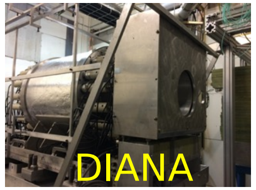
Time Projection Chamber (TPC)

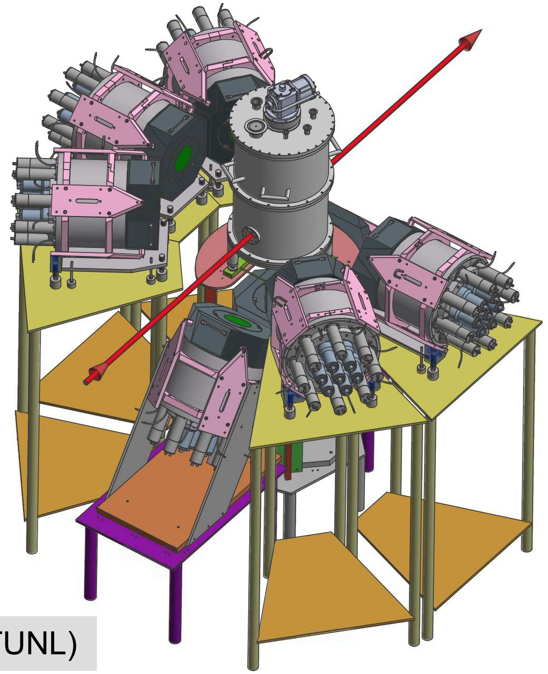


Low Energy QCD

TUNL Groups:

(a) M. Ahmed, B. Crowe, D. Markoff, NCCU
(b) H. Gao, C. Howell, W. Tornow, Y. Wu, Duke Univ.
(c) H. Karwowski, UNC
(d) A. Young, NC State Univ.





External Researchers: 14 institutions: 9 USA + 5 International

Courtesy of C. Howell (Duke/TUNL)

Compton Photon Sources around the World

Operational Sources/Facilities

Projects under Development

Future Gamma-ray Sources for Nuclear Physics Research

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

Institution: Tsinghua University

Country: China

Accelerator: S-band linac w. photoinjector, 20–50 MeV. 500 pC

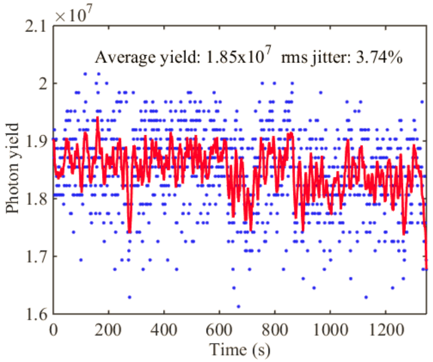
Laser: Ti:Sapphire, 800 nm, 500 mJ/50fs/10 Hz

Photon energy (keV): 20–55 keV

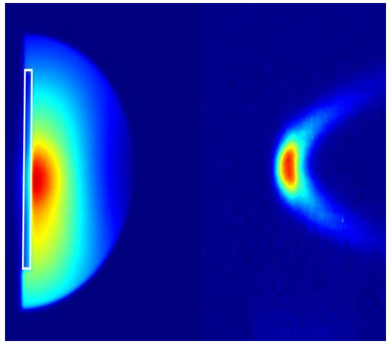
Total flux (measured): > $3x10^8$ ph/s, Lin/Cir/Elliptical

Best resolution: ~ 5% (FWHM)

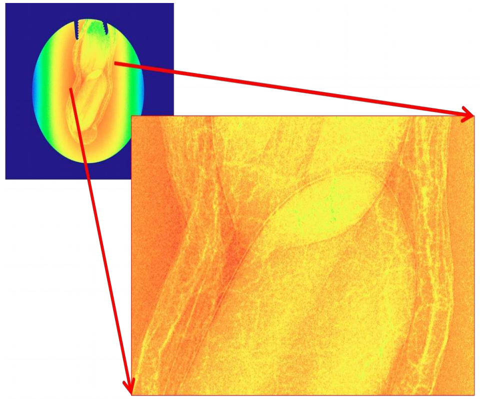
Status: Operational + Development



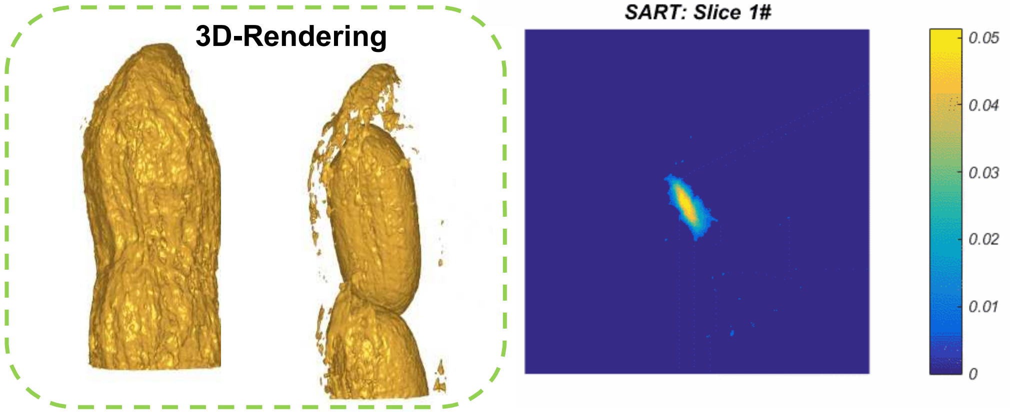
Pulse flux for 20 &50keV in 20 min.



Direct X-ray beam pattern and diffraction pattern with HOPG crystal



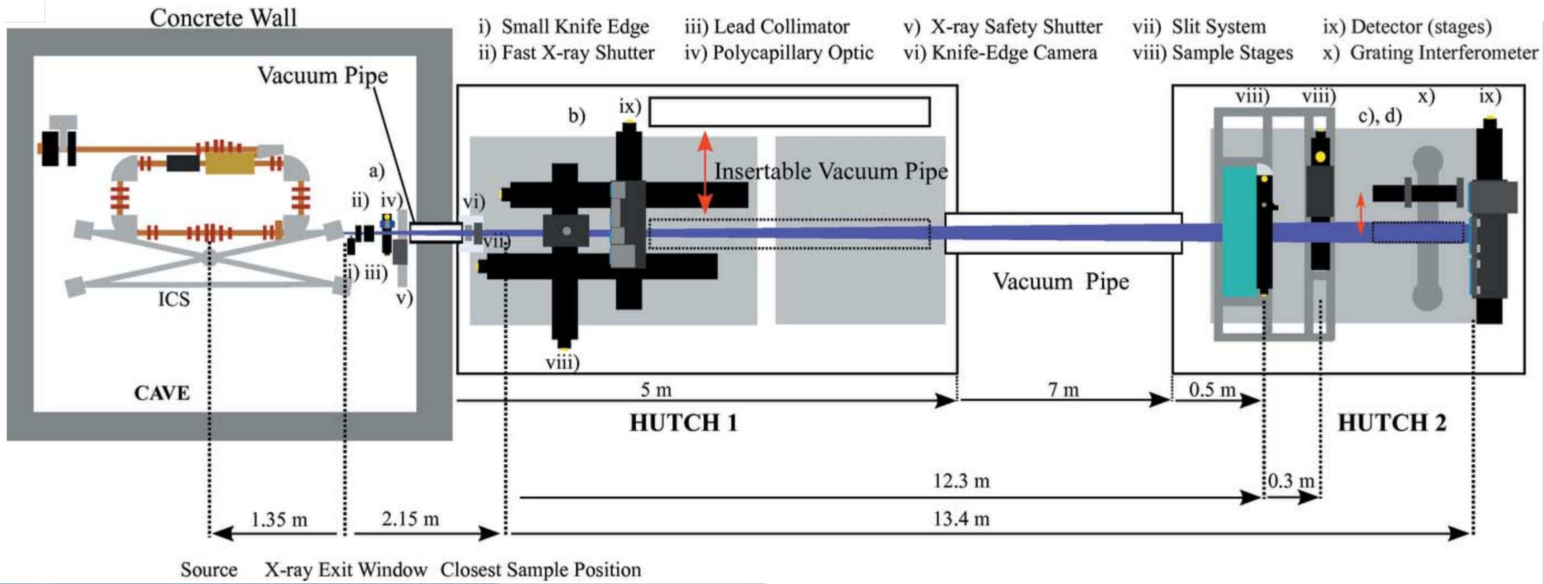
In-line phase contrast imaging with TTX (24keV)

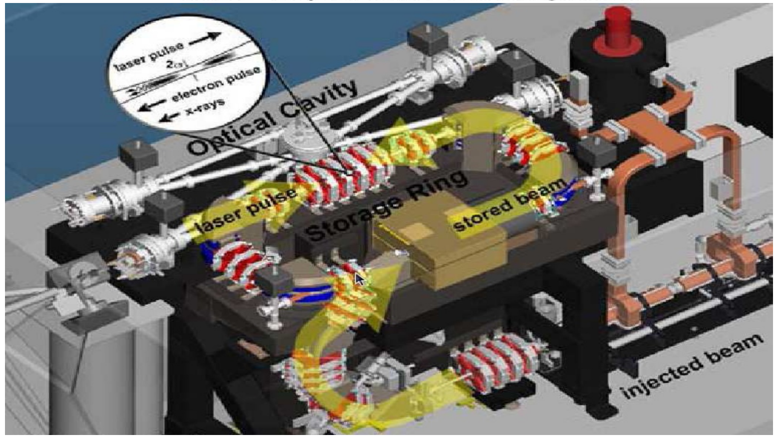


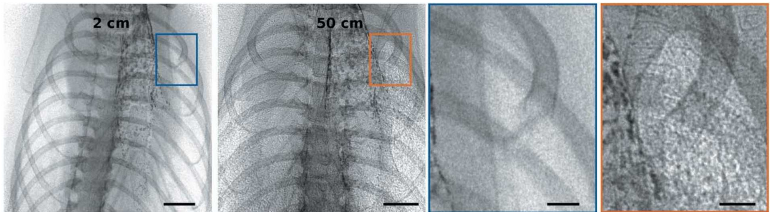
Mono-energetic X-ray CT imaging with TTX (24keV)

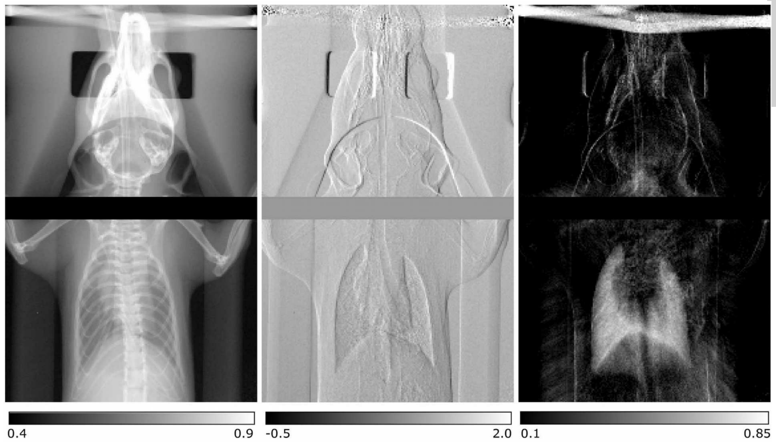
Courtesy of Chuanxiang Tang and Yingchao Du, Tsinghua U.

Munich Compact Light Source (MuCLS)









Facility/Project: Munich Compact Light Source (MuCLS)

Institution: Technical University of Munich

Country: Germany

Commercial product: Lyncean Technologies Inc.

Accelerator: Storage ring, 29–45 MeV, 16 mA

Laser: Nd:YAG 1064 nm, 350 kW (intracavity)

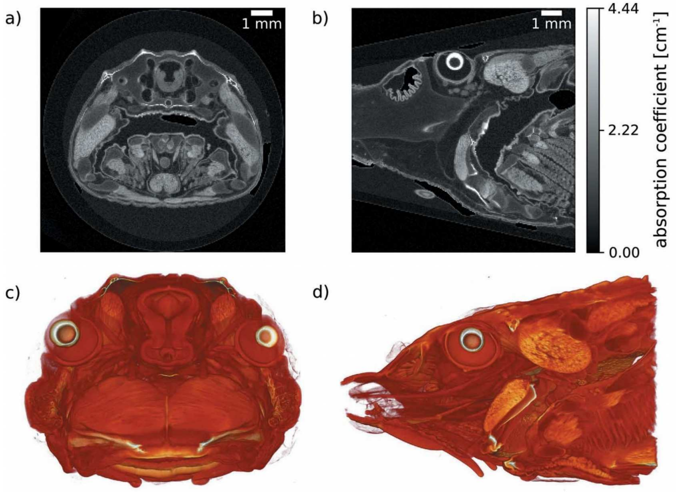
Photon energy (keV): 15–35

Total flux (measured): $1.5\text{x}10^{10}$ ph/s (15 keV), $4.5\text{x}10^{9}$ (35 keV)

Resolution: 3% (15 keV) to 5% (35keV) (FWHM)

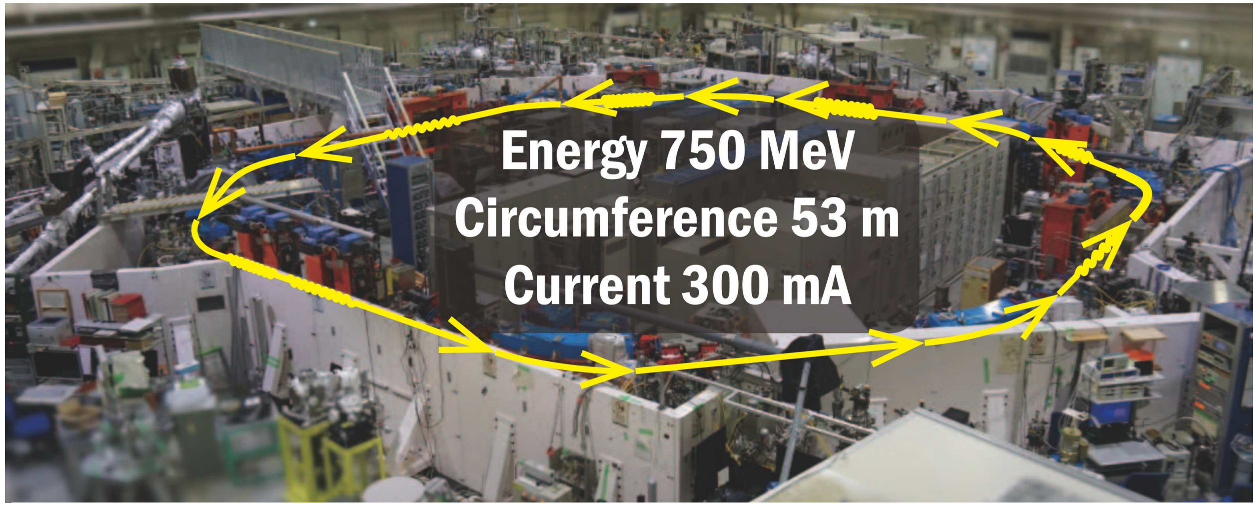
Status: Operational + User Program

Research: Imaging, X-ray absorption spectroscopy (XAS), Microbeam radiation therapy



Sources:
B. Gunther *et al.* J. Syn. Rad, 27, p. 1395 (2020)
G. Kraff and G. Priebe, Rev. Acc. Sci. & Tech. V3, 147 (2010).
R. Ruth, http://www.eurekalert.org/pub_releases/2009-01/lti-fsf010609.php

UVSOR Synchrotron Facility

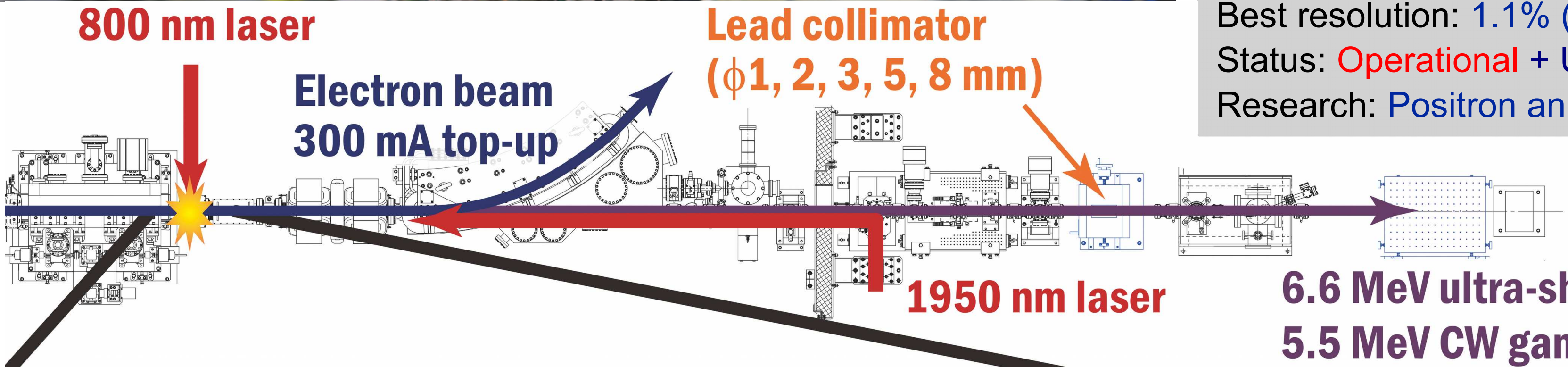


Facility/Project: UVSOR Synchrotron Facility
Institution: Institute for Molecular Science
Country: Japan
Accelerator: Storage ring, 750 MeV
Laser: 800 nm (pulse, 90 deg), 1950 nm (CW, head-on)

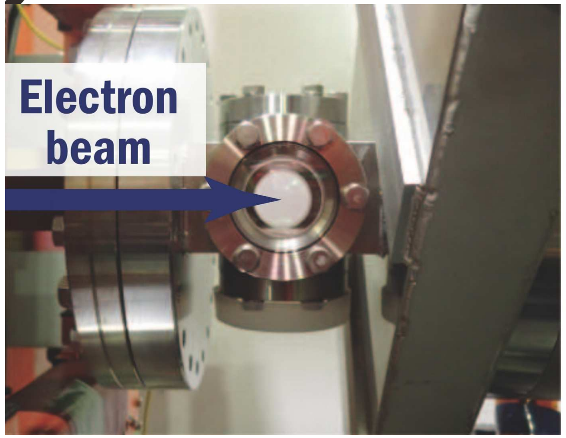
Photon energy (MeV): 5.5, 6.6

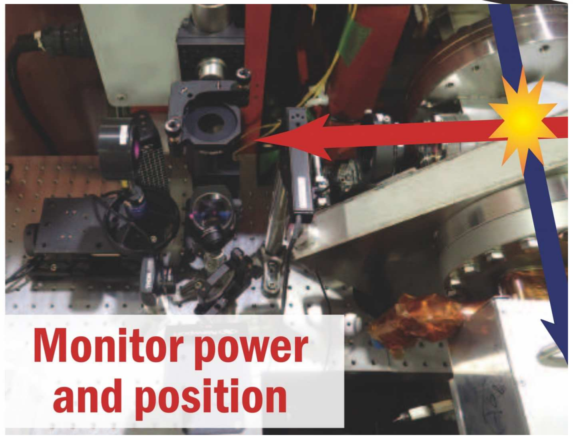
Total flux (measured): few 10^5 ph/s (6.6 MeV, 90-deg)
10^8 ph/s (5.5 MeV, head-on)

Best resolution: 1.1% (FWHM)
Status: Operational + User Program
Research: Positron annihilation spectroscopy, Nuclear physics (NRF)



6.6 MeV ultra-short pulsed gamma rays,
5.5 MeV CW gamma rays





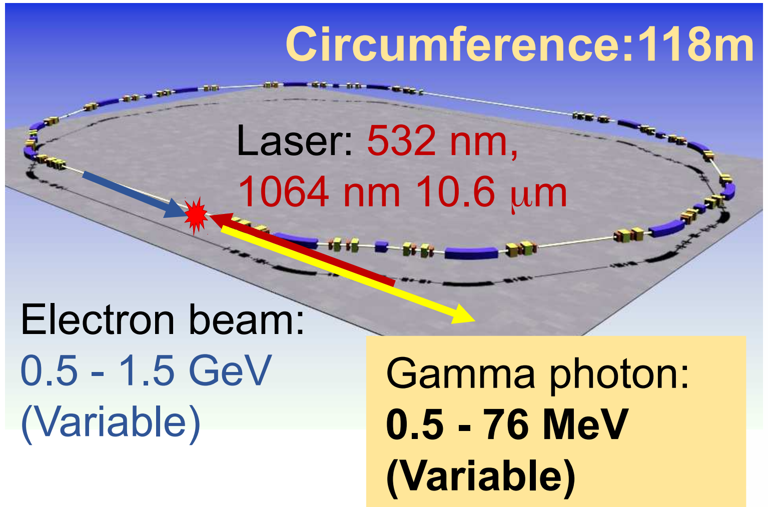
Stability of laser at the collision point:

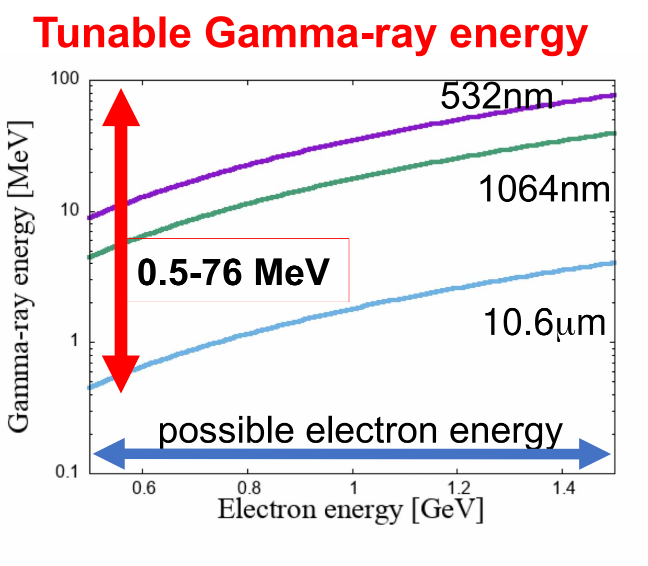
Average power for 10 hours: < 0.1% (RMS)

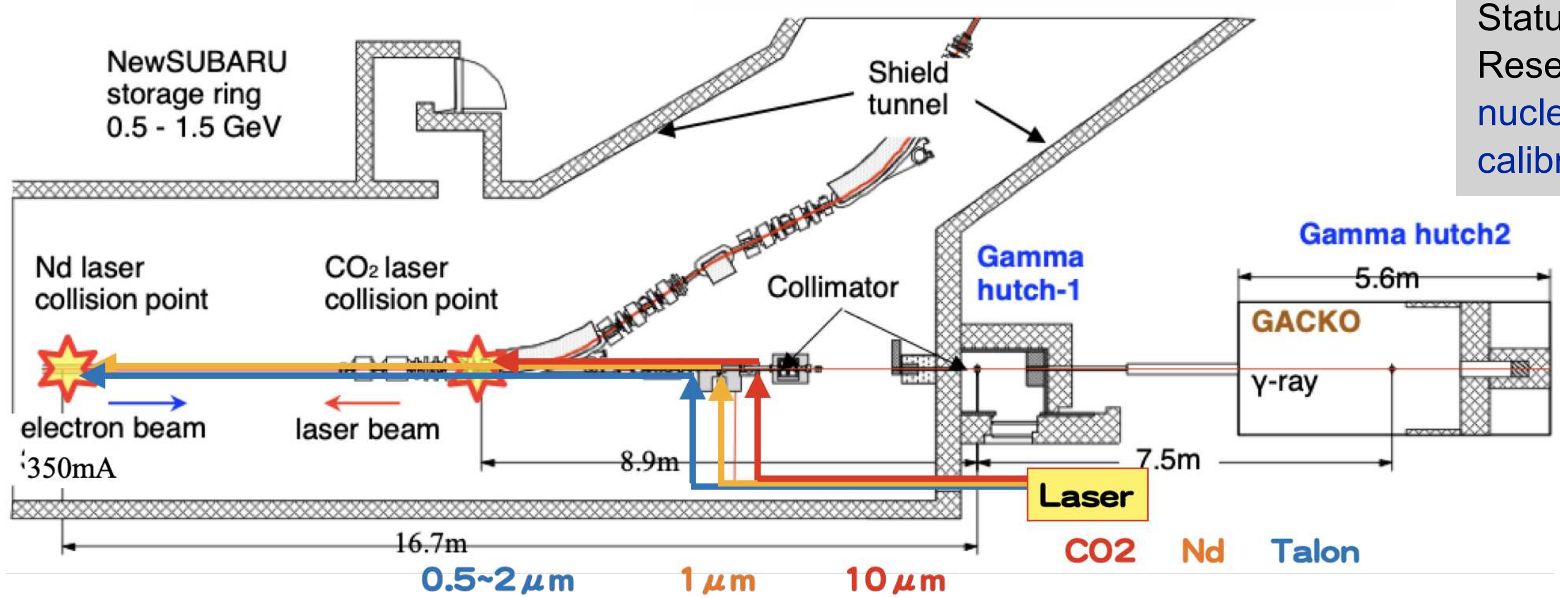
Position for few tens of seconds: 1.3 μm (H), 2.0 μm (V)

Courtesy of Yoshitaka Taira, Institute for Molecular Science

NewSUBARU Synchrotron Light Facility







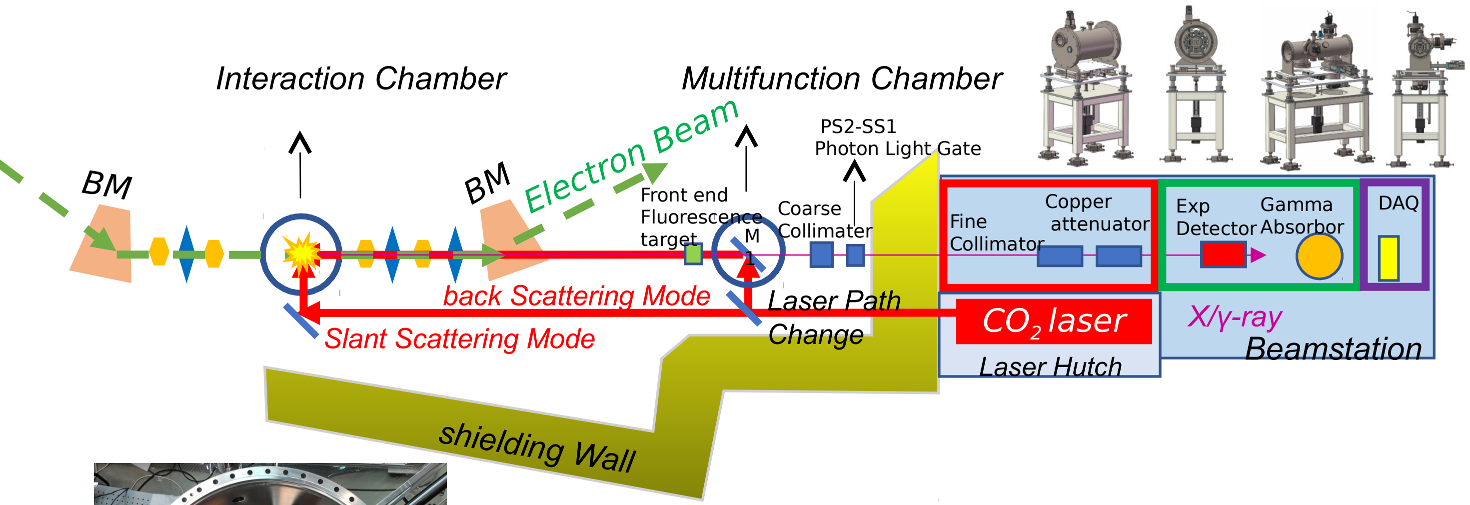
Facility/Project: NewSUBARU, BL01
Institution: Laboratory of Advanced Science and Technology for Industry (LASTI), University of Hyogo
Country: Japan
Accelerator: NewSUBARU Storage ring, 0.5–1.5 GeV, 400mA
Laser: 532 nm, 1064 nm, 10.6 μm, etc.
Photon energy (MeV): 0.5 – 76 MeV
Total flux (measured): 10^6 – 10^9 ph/s
Best resolution: 1.4% (FWHM)
Status: Operational + User Program
Research: Gamma source R&D, photonuclear reactions, nuclear transmutation, positron generation, detector calibration, and materials research

- Variable stored electron energy (0.5–1.5 GeV). Arbitrary gamma ray energy desired by the user.
- Top-up operation at various energy (0.5–1.0 GeV). The intensity of gamma rays remains constant overtime.

Courtesy of Satoshi Hashimoto, LASTI, Univ. of Hyogo

SLEGS, Shanghai Advanced Research Institute (SARI)

TUNL Duke UNIVERSITY



Facility/Project: Shanghai Laser Electron Gamma Source (SLEGS)

Institution: Shanghai Advanced Research Institute (SARI)

Country: China

Accelerator: Storage Ring, 3.5 GeV, 200 mA

Laser: CO_2, 10.6 um, 5–20 W

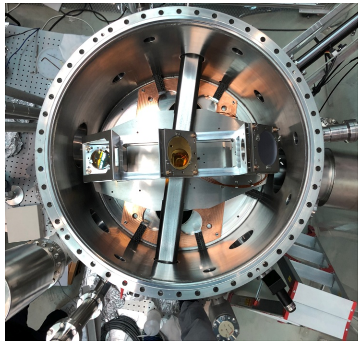
Photon energy (MeV): 0.6 – 21.7

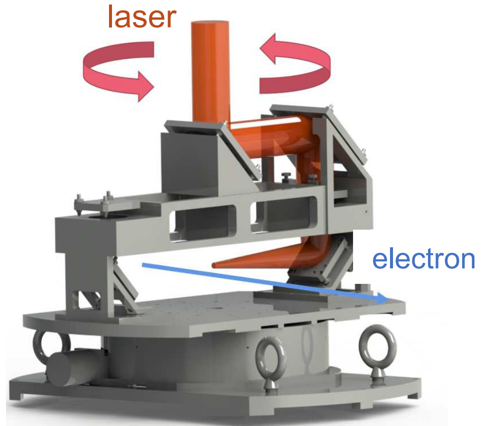
Total flux (measured): 2×10^4 (20-deg), 2×10^6 (180-deg)

Resolution: ~2–15% (FWHM)

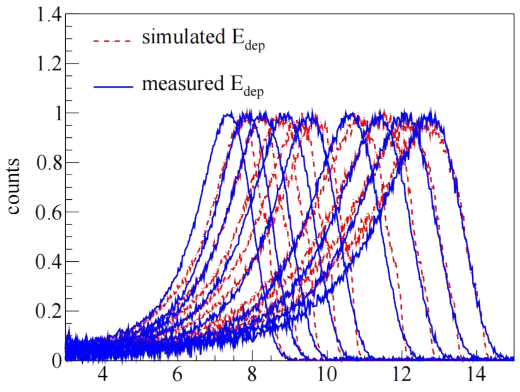
Status: Operational + Development

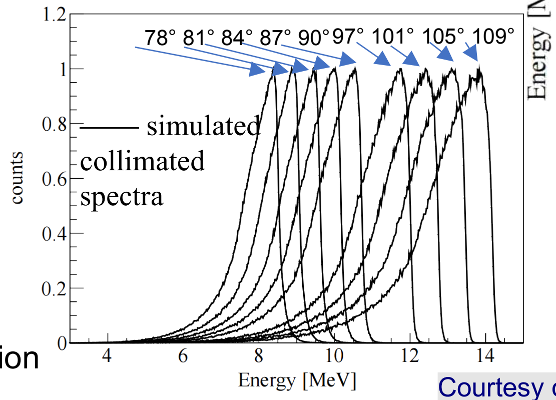
Research: Nuclear structure (GDR,PDR,cluster), Nuclear Data (Photoneutron cross-section measurement), Nuclear astrophysics



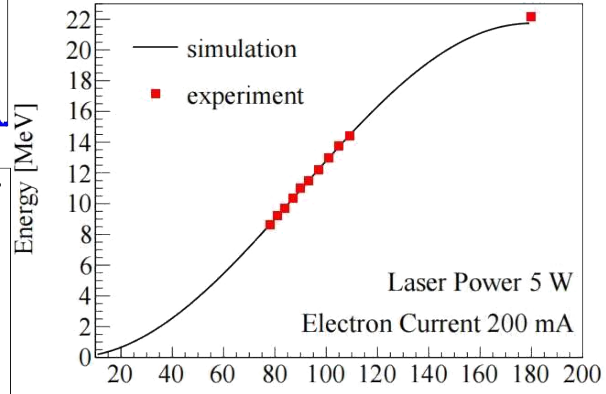


Rotatable optics inside the interaction chamber to vary incident angle

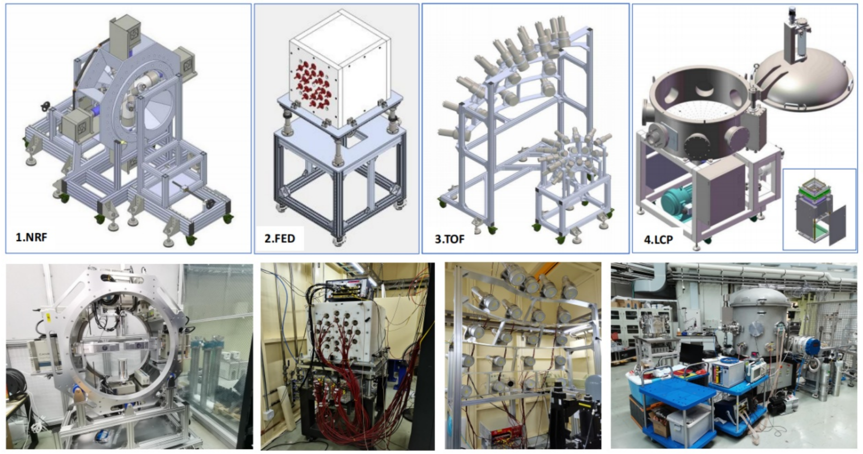




High energy end of the spectra



Neutron flattening efficiency spectrometer | Nuclear resonance fluorescence spectrometer | Photoneutron time-of-flight spectrometer | Charged particle spectrometer

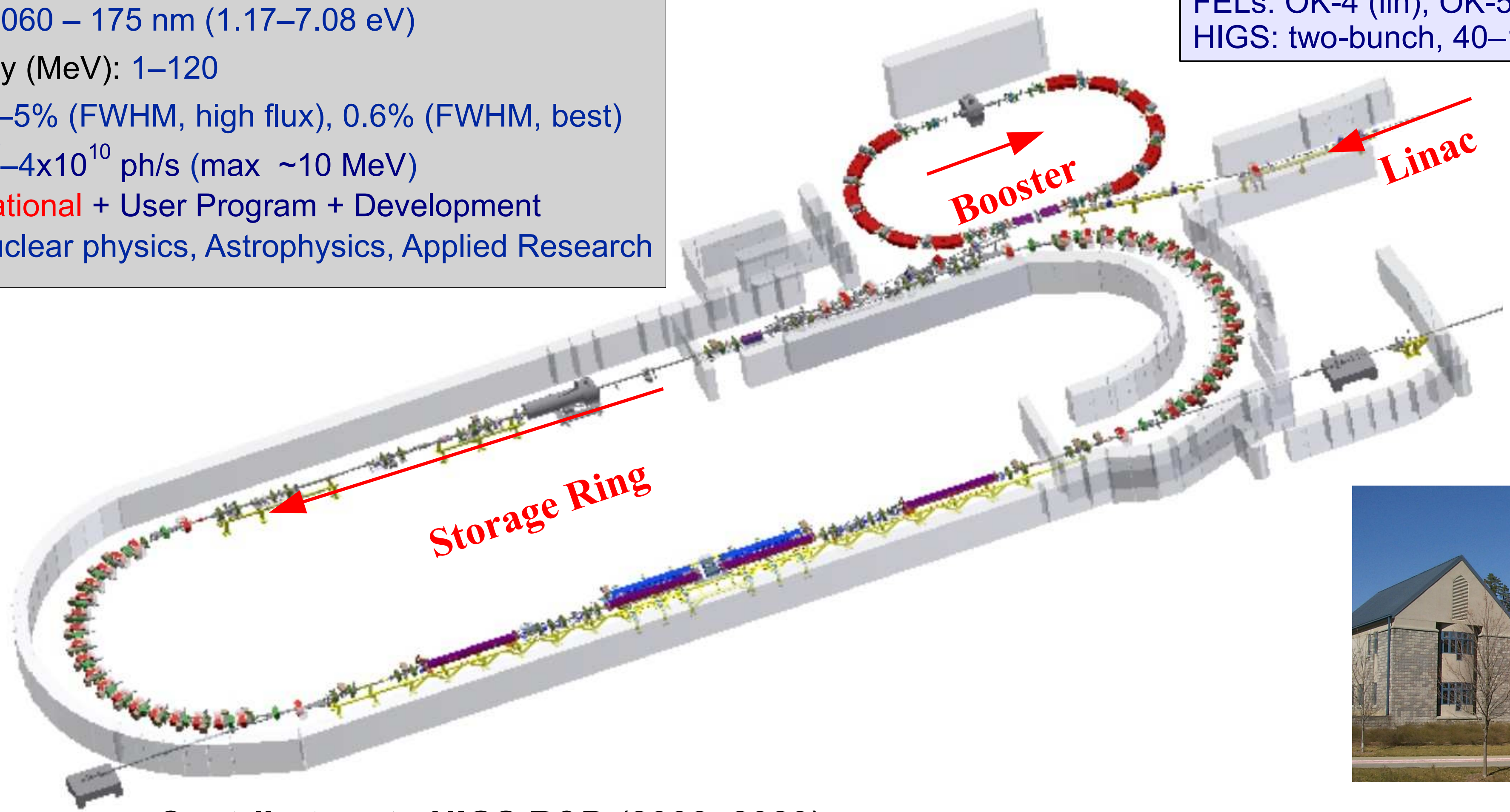


Courtesy of Hongwei Wang, Gongtao Fan, Hanghua Xu, SLEGS

High Intensity Gamma-ray Source (HIGS)

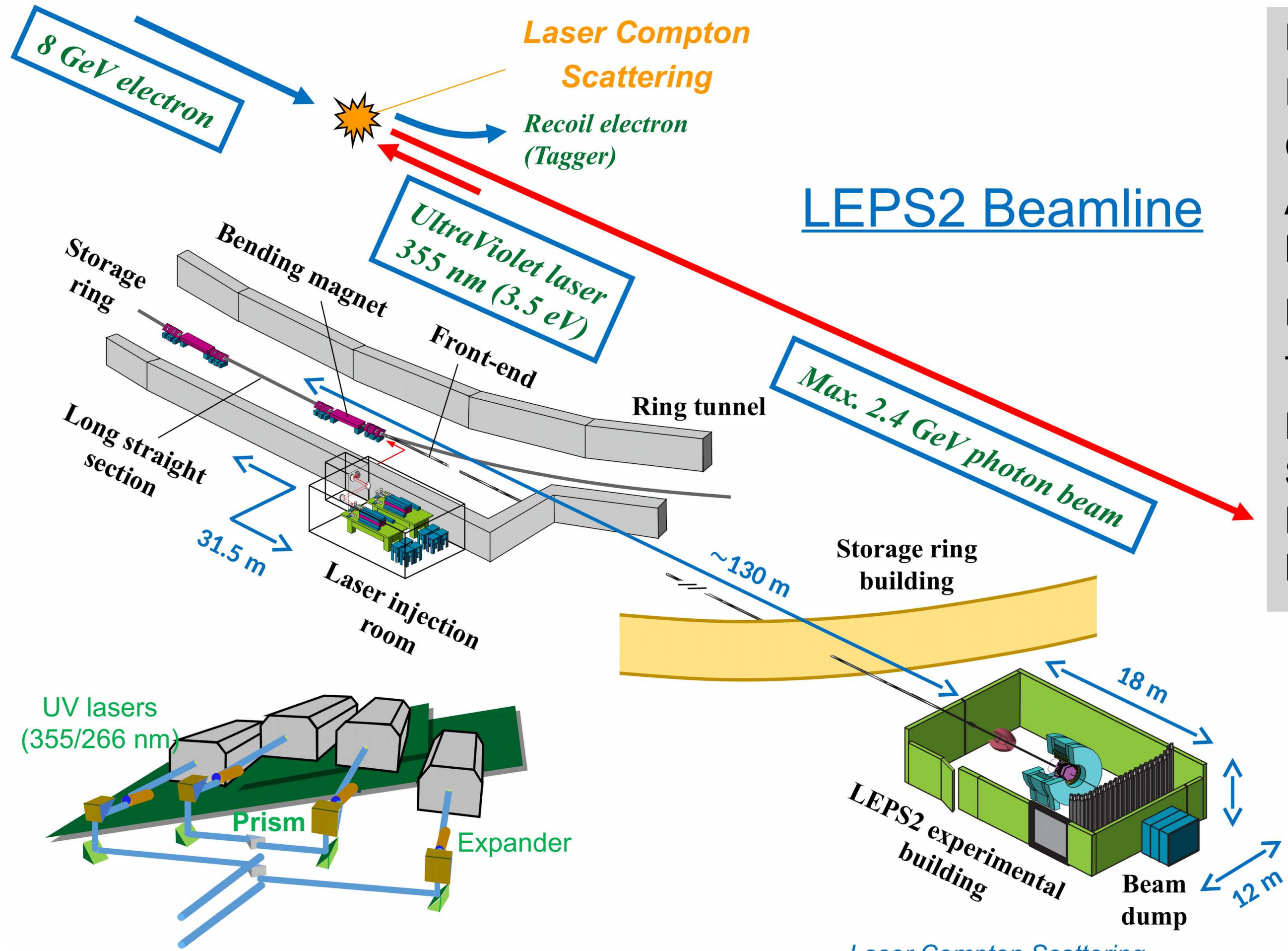
Facility/Project: High Intensity Gamma-ray Source (HIGS)
Institution: TUNL
Country: United States
Accelerator: Storage Ring, 0.24–1.2 GeV
Laser: FEL, 1060 – 175 nm (1.17–7.08 eV)
Photon energy (MeV): 1–120
Resolution: 2–5% (FWHM, high flux), 0.6% (FWHM, best)
Total flux: 10^7–$4x10^{10}$ ph/s (max ~10 MeV)
Status: Operational + User Program + Development
Research: Nuclear physics, Astrophysics, Applied Research

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)



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, E. Martin, S. Mikhailov, M. Pentico, V. Popov, C. Sun, G. Swift, B. Thomas, E. Vajzovic, P. Wang, P. Wallace, W. Wu, Y. K. Wu, W. Xu, J. Yan

LEPS2, SPring-8



Facility/Project: LEPS2

Institution: SPring-8

Country: Japan

Accelerator: Storage Ring, 7.975 GeV

Laser: 355 nm (3.49 eV), 266nm (4.66 eV)

Photon energy (GeV): 2.39 (355 nm), 2.89 (266 nm), lowest: 1.3 GeV

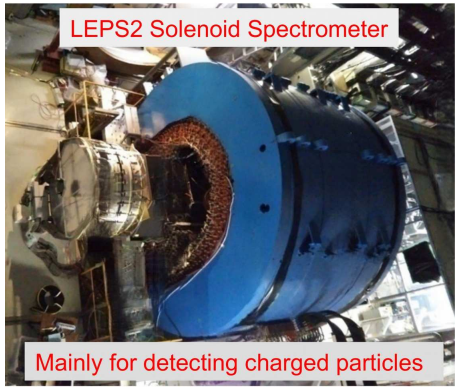
Total flux (measured): a few 10^6 ph/s (~ 2 10^6 tagged)

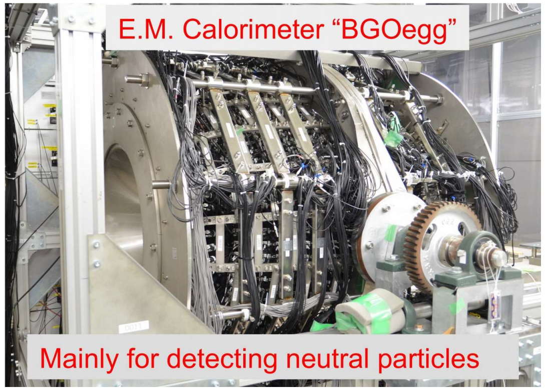
Resolution: 12.1 MeV (RMS, tagging)

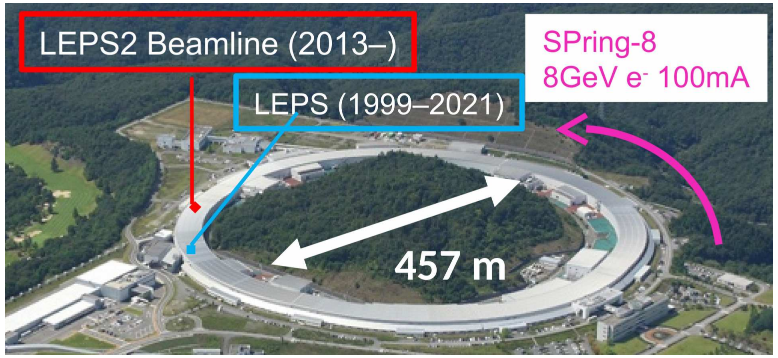
Status: Operational + User Program

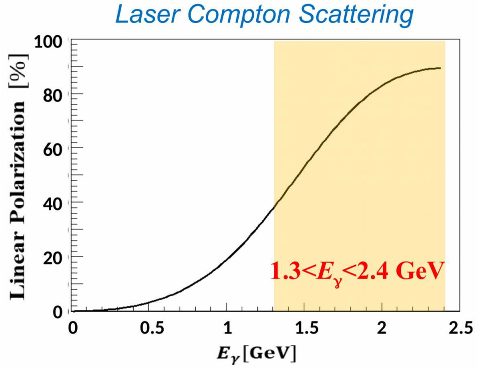
Research: Hadron structure and interactions

Note: LEPS2 supersedes LEPS (1999–2021)









Courtesy of Norihito Muramatsu and Takatsugu Ishikawa, SPring-8
Ref: N. Muramatsu *et al.*, NIMA 1033, 166677(2022).

Compton Photon Sources around the World

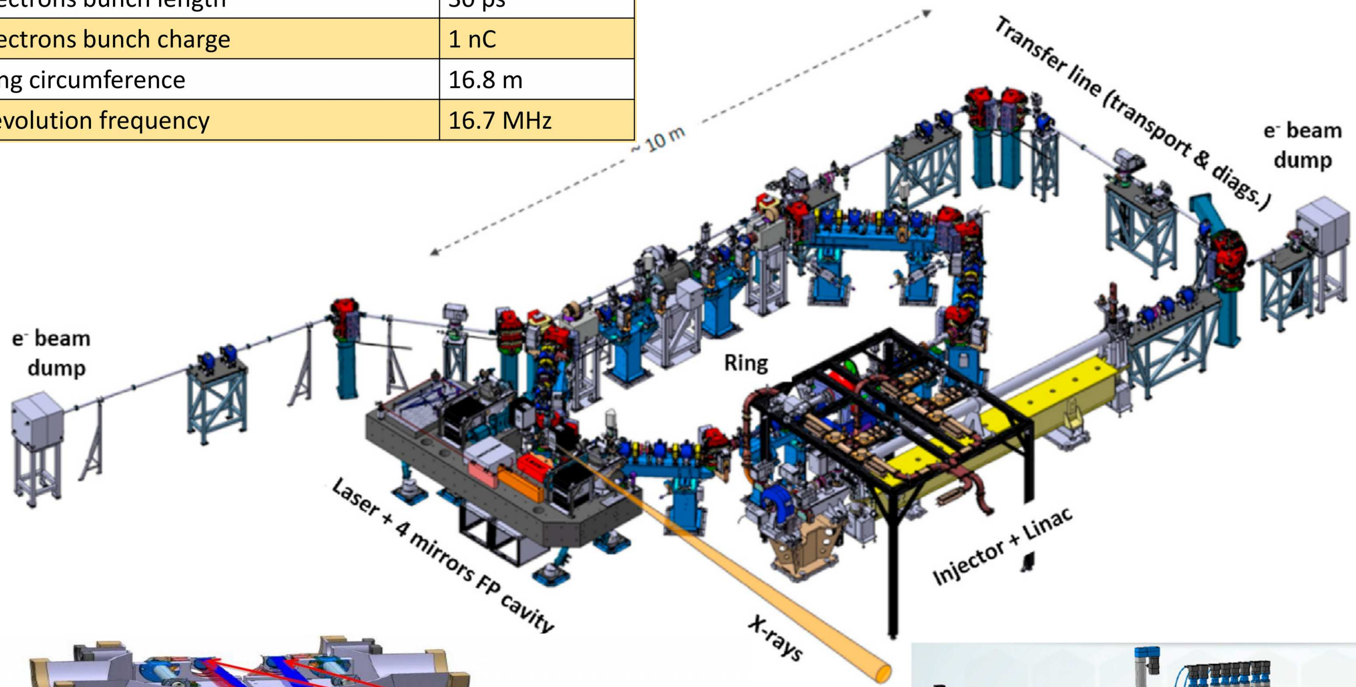
Operational Sources/Facilities

Projects under Development

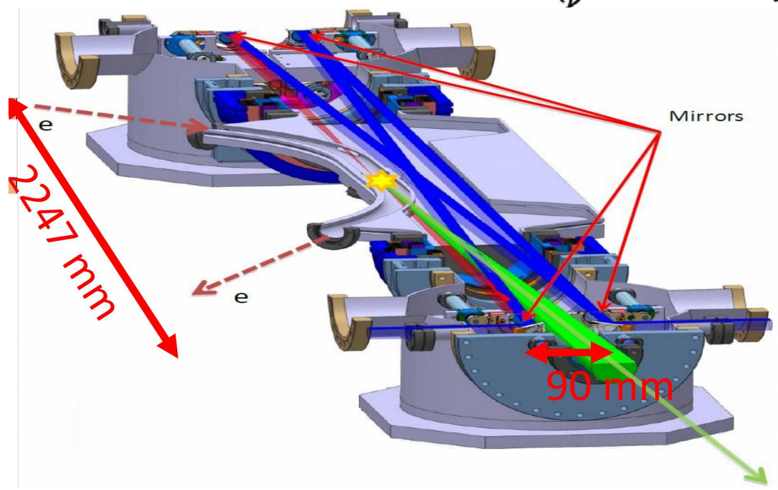
Future Gamma-ray Sources for Nuclear Physics Research

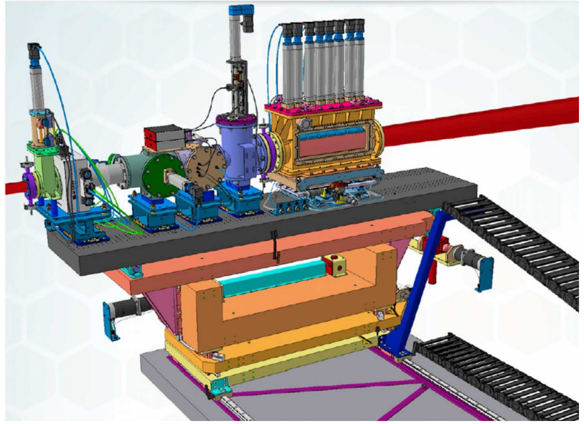
ThomX

Storage ring parameters	Values
Electrons bunch energy	50 – 70 MeV
Electrons bunch length	30 ps
Electrons bunch charge	1 nC
Ring circumference	16.8 m
Revolution frequency	16.7 MHz



Facility/Project: ThomX
Institution: ThomX Consortium
Site: Irene Joliot-Curie Laboratory (IJCLab), Paris-Saclay University
Country: France
Accelerator: Storage ring, 50 – 70 MeV
Energy (keV): 45 – 90
Laser: FB-Cavity (1030 nm), 1 MW (F~3x10^4)
Total flux: 10^{12} – 10^{13} ph/s (design)
Phase I: 100 kW, 10^{10} ph/s (design), 45 keV (design)
Status: Under construction
Applications: imaging, mammography, microtomography



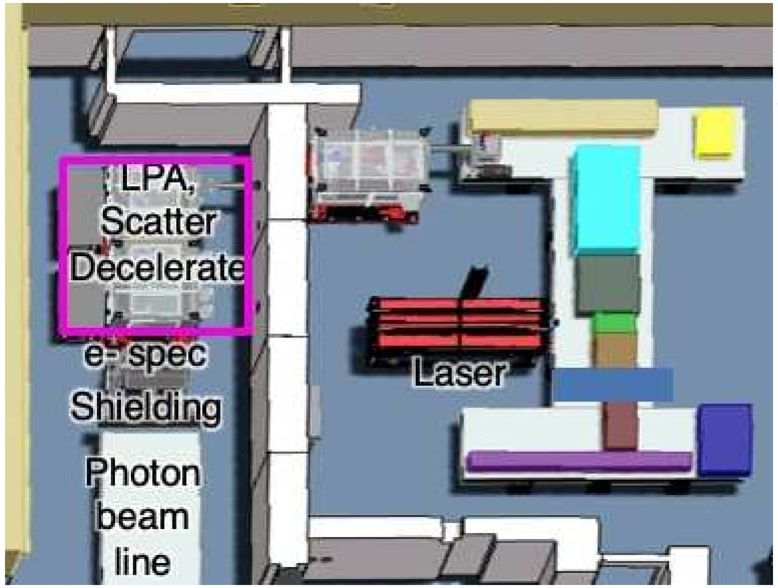


Parameters	Typical values
Laser repetition frequency	33.3 MHz
Laser wavelength	1031 nm
Laser pulse temporal length	50 ps rms
Cavity optical length	8.994 m
Cavity finesse	30 000
Cavity waist size	80 μm
Injected power	100 W
Circulating power	600 kW
X-rays flux	10^{13} photons/s

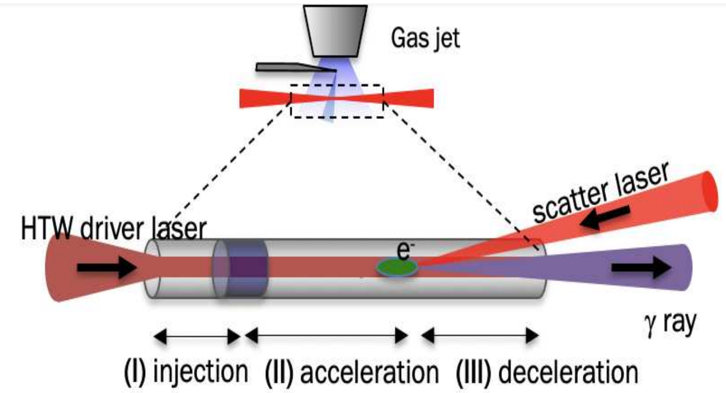
Sources: 1. K. Dupraz *et al.* "The ThomX ICS source," Physics Open 5, 100051 (2020).
2. F. Pierre (2015)
https://thomx.ijclab.in2p3.fr/wp-content/uploads/sites/21/2021/02/2015_Study-and-conception-of-a-high-finesse-Fabry-Perot-cavity-for-the-compact-X-ray-source-ThomX.pdf

Laser-plasma Compact MeV Compton Photon Source, LBNL

Laser currently at Room/truck scale



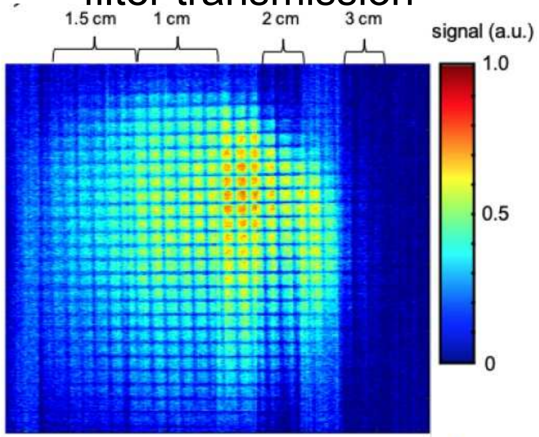
Acceleration to 0.4 GeV class in centimeter distance



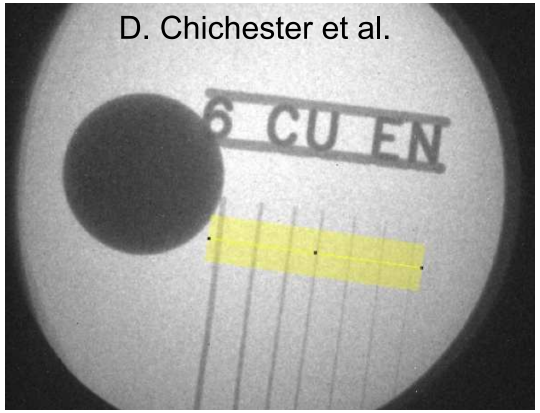
Facility/Project:
Institution: Lawrence Berkeley National Lab
Country: United States
Accelerator: Laser-plasma acccel. 50–400 MeV, 10s pC
Laser: (scatter) Ti:sapphire 800 nm, 500 mJ, 50 fs, 5 Hz
Photon energy (GeV): 0.1–2 MeV, with 9 MeV in progress
Total flux (measured): 10^7 ph/shot
Resolution: 10%–50% (FWHM)
Status: Development + Test experiments
Research: Path to 1% energy spread, higher flux, deceleration to reduce shielding requirements

- kHz fiber laser in development for even smaller sizes
- cm-scale accelerator enables
  - compact system at high photon energies
  - deceleration after scattering for applications

Photon energy via filter transmission



High resolution radiography



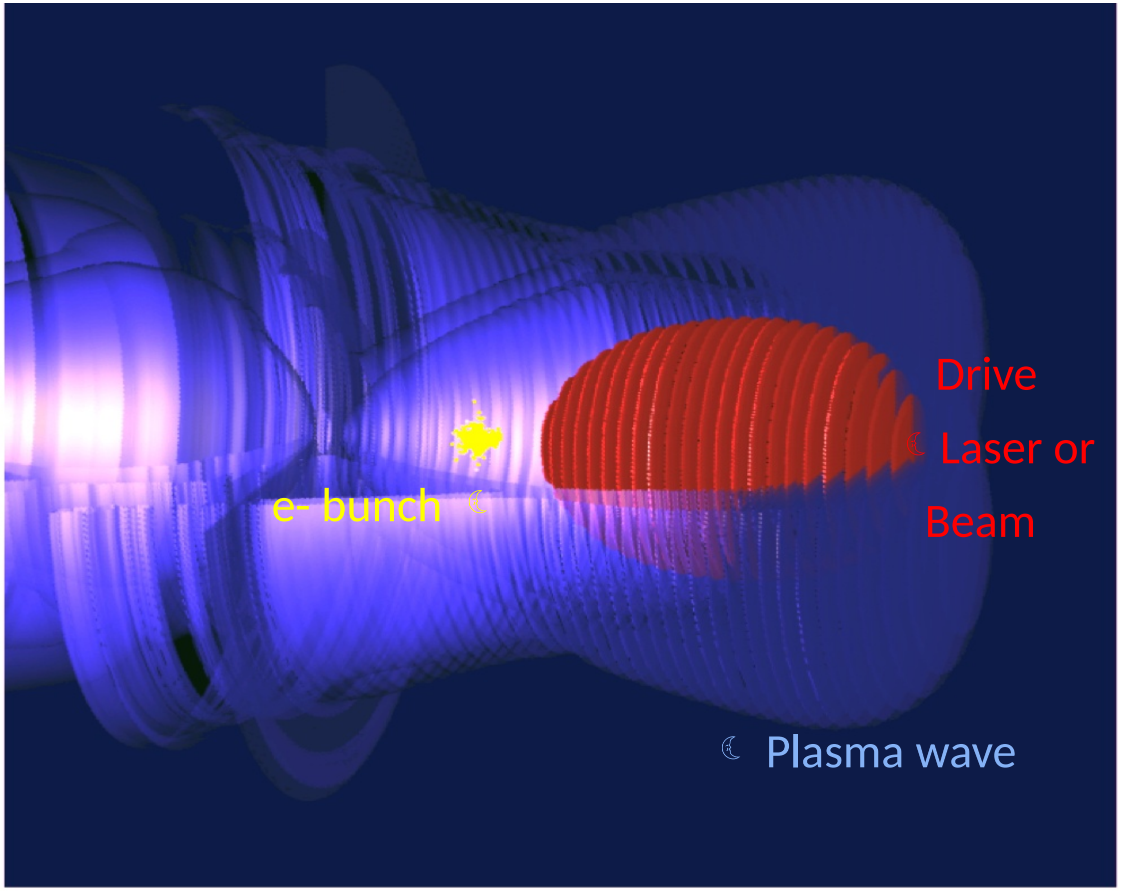
Other research areas

- Sub-mm 3D MeV tomography
- Time of flight backscatter single-view 3d imaging

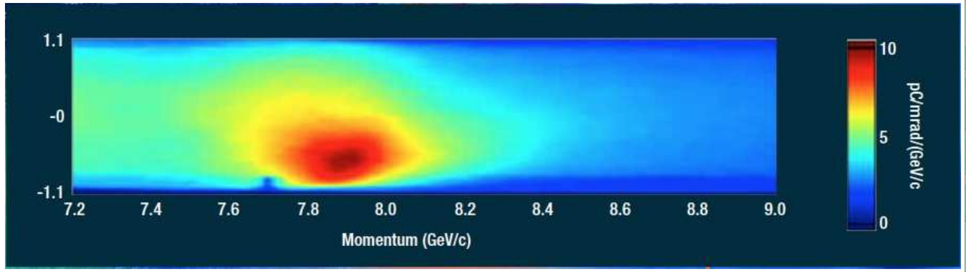
Courtesy of Cameron Geddes, Qiang Chen, Jeroen van Tilborg, LBNL

1: Final report of project "Impact of Monoenergetic Photon Sources on Nonproliferation Applications ," C. Geddes, B. Ludewigt, J. Valentine, B. Quiter, M.-A. Descalle, G. Warren, M. Kinlaw, S. Thompson, D. Chichester, C. Miller, S. Pozzi (2017)

Ultrahigh Laser-plasma Fields (>10 GV/m) Enable Compact Accelerators – GeV in cm



2019: 8 GeV record



Gonsalves et al., PRL 2019

in a 20 cm plasma

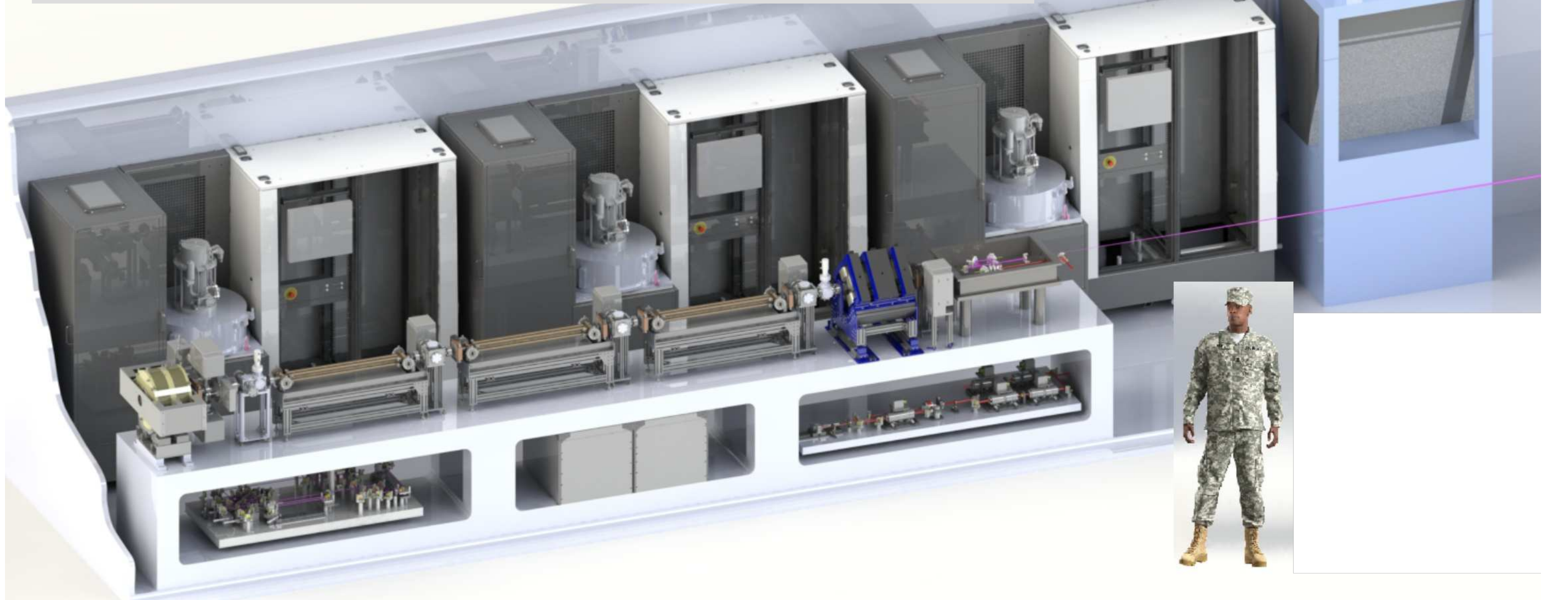
vs. 300-500m conventional

Courtesy of Cameron Geddes, Qiang Chen, Jeroen van Tilborg, LBNL

TUNL Duke UNIVERSITY

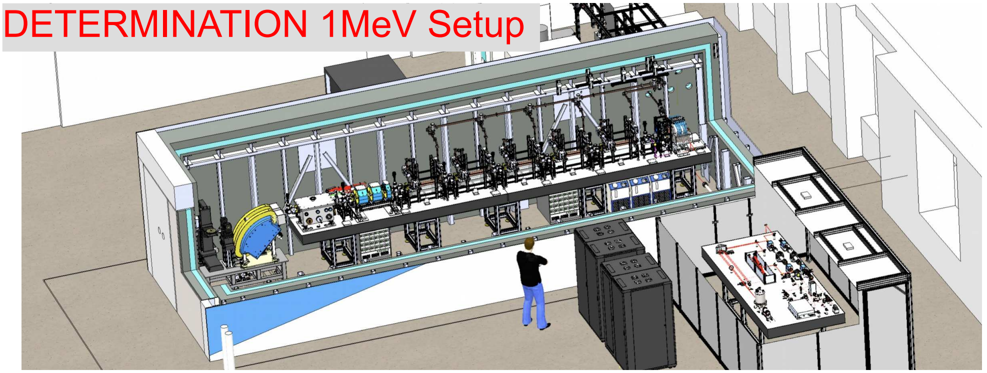
DETERMINATION:

Development of **E**quipment and **T**echnologies for **E**lemental **R**adiography, **M**icron-scale **I**maging, **N**uclear **A**ssessments & **T**ransportable **I**nterrogation of **O**bjects **N**ondestructively



Performance Targets and SWaP Goals
Tunable from 10 keV to 3 MeV
>10^{12} photons/second & < 0.1% bandwidth
Must fit within a standard 40 ft container
Must be compatible with air transport
Must operate with on less than 300 kW

DETERMINATION 1MeV Setup



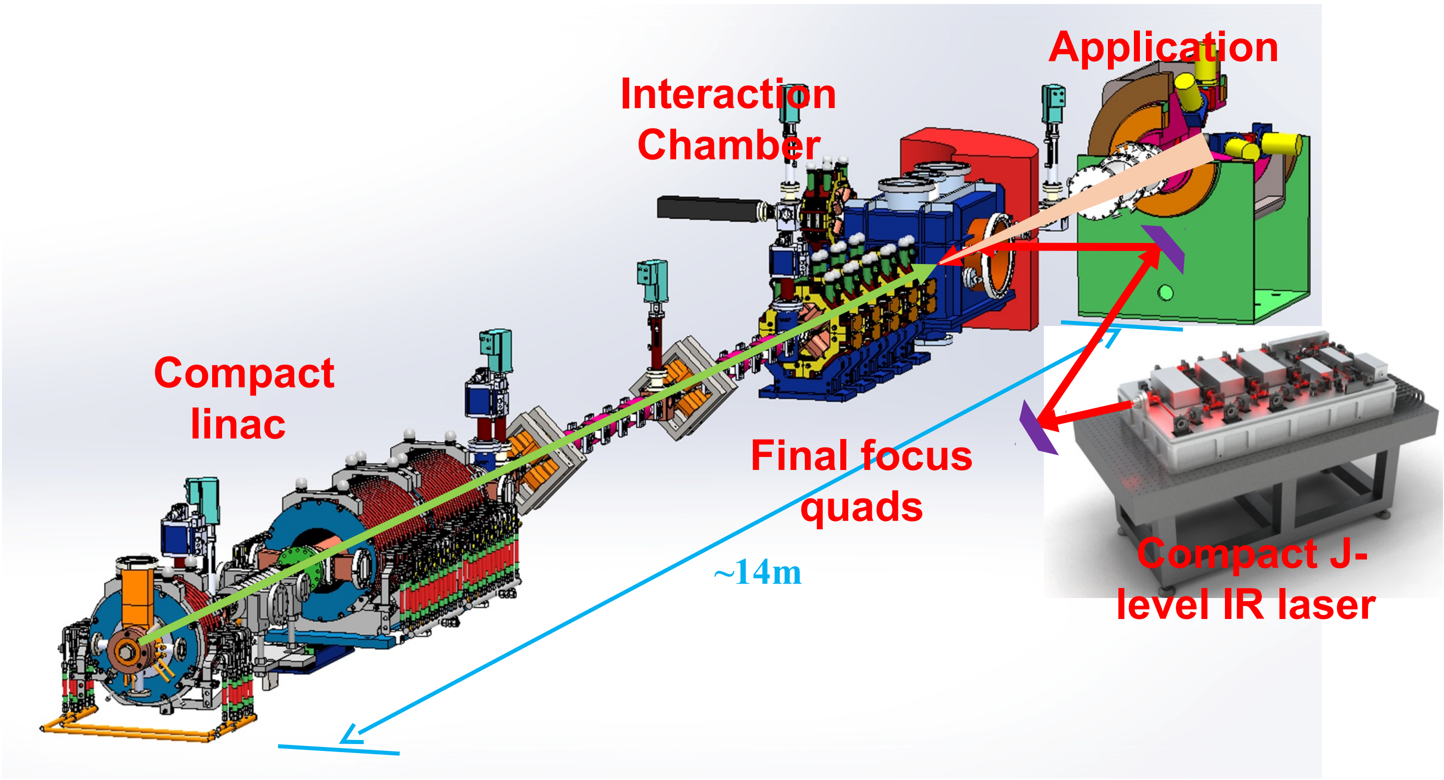
In 2020, DARPA's Gamma-Ray Inspection Technologies (GRIT) program: to create the world's 1st compact, high-brilliance, MeV capability - Performance well beyond the needs of commercial markets

Keys to Lumitron's approach

- High-gradient, x-band (11.424 GHz) linacs
- High-power, compact x-band klystrons
- RF pulse compression of klystron output
- RF pulse synthesis of laser pulse trains
- High-current & brightness photo-guns
- High-average power, UV interaction lasers
- Imaged recirculation of UV laser pulses
- Source-matched, diffraction-based filters

Courtesy of C. P. J. Barty, University of California, Irvine and Lumitron Technologies, Inc.

VIGAS, Tsinghua University



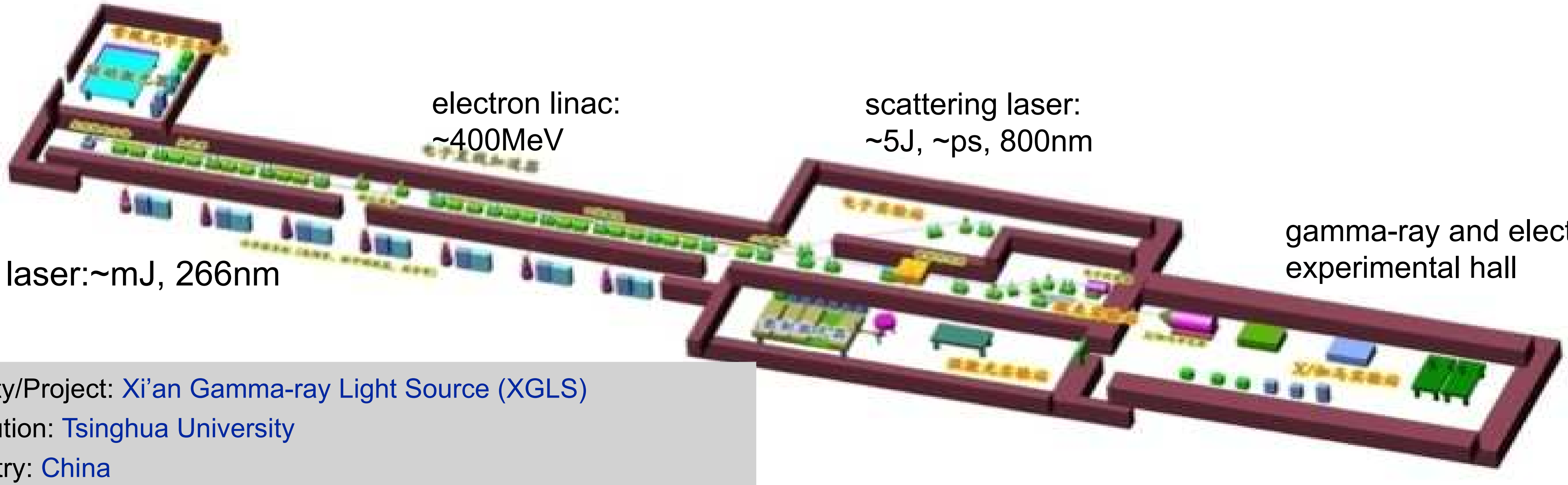
Facility/Project: Very Compact ICS Gamma-ray Source (VIGAS)
Institution: Tsinghua University
Country: China
Accelerator: S-band photoinjector + X-band linac (~14 m)
90–350 MeV, 200 pC, 10 Hz
Laser: Ti:Sapphire, ~1.5J@800nm, 0.8J@400 nm, BW 10 nm, 10 Hz

Photon energy (MeV): 0.2–4.8 MeV
Total flux (design): > 4x10^8 ph/s (0.2–2.4 MeV), > 1x10^8 ph/s (2.4–4.8 MeV), controllable Pol
Best resolution: ~3 % (FWHM)
Status: Under construction (2021–2025)

γ-ray energy: 0.2-4.8MeV
Bandwidth with collimator : <1.5%
Total photon flux(ph/s): >4×10^8@0.2-2.4MeV; >1×10^8@2.4-4.8MeV
Photon flux with 1.5% Bandwidth(ph/s): >4×10^6@0.2-2.4MeV; >1×10^6@2.4-4.8MeV
controllable polarization from linear to circle

Courtesy of Chuanxiang Tang and Yingchao Du, Tsinghua U.

XGLS, Tsinghua University



Facility/Project: Xi'an Gamma-ray Light Source (XGLS)

Institution: Tsinghua University

Country: China

Accelerator: S-band injector and linac, 100–400 MeV, 500 pC, 10 Hz

Laser: Ti:Sapphire, 800 nm, ~5J, 10 Hz

Normal Operation:

- Energy (MeV): 0.1–3 MeV tuneable
- Total flux (design): > 1×10^{8} ph/pulse, ~3 ps
- Best resolution: < 3 %

Ultra-short Pulse:

- Energy (MeV): 0.5–3 MeV tuneable
- Total flux (design): > 1×10^{7} ph/pulse, < 250 fs
- Best resolution: ~ 6–7% (FWHM)

Status: Under construction

Courtesy of Chuanxiang Tang and Yingchao Du, Tsinghua U.

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

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

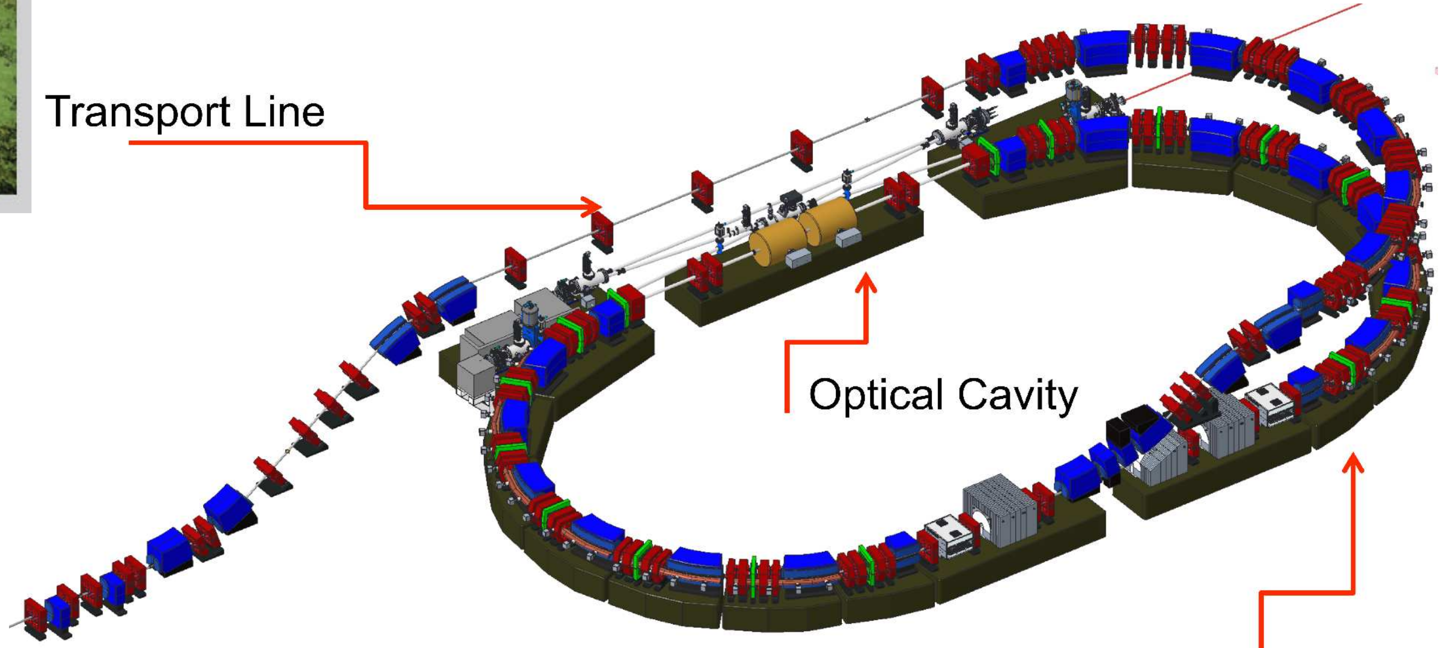


Image by Lyncean Technologies

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

Last update: 2020

Compton Photon Sources around the World

Operational Sources/Facilities

Projects under Development

Future Gamma-ray Sources for Nuclear Physics Research

Conventional Accelerators: 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

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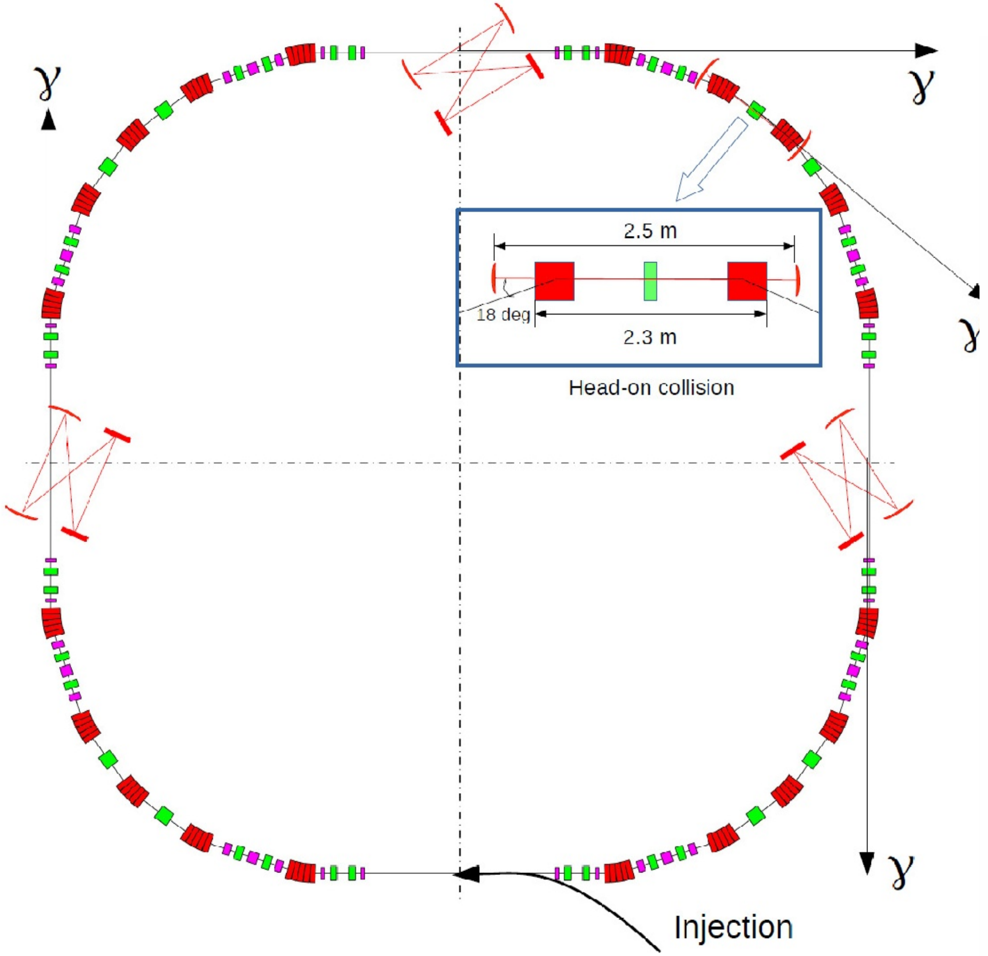
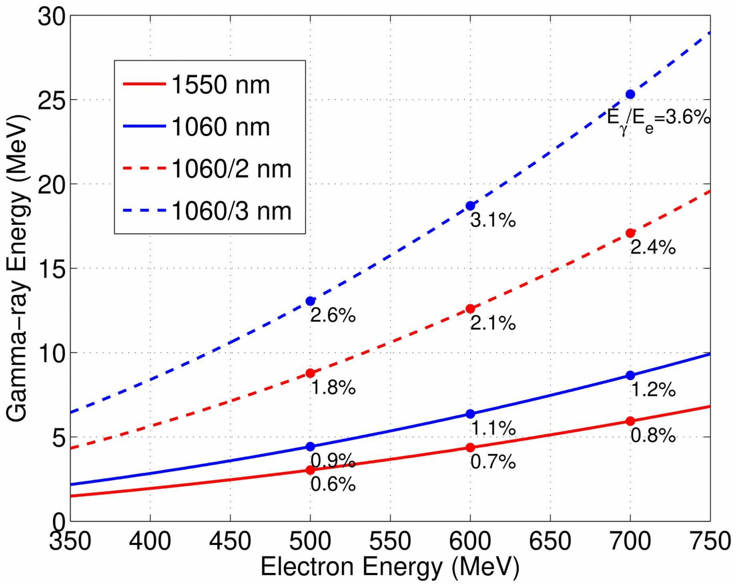
Low-Energy CGS: Storage Ring





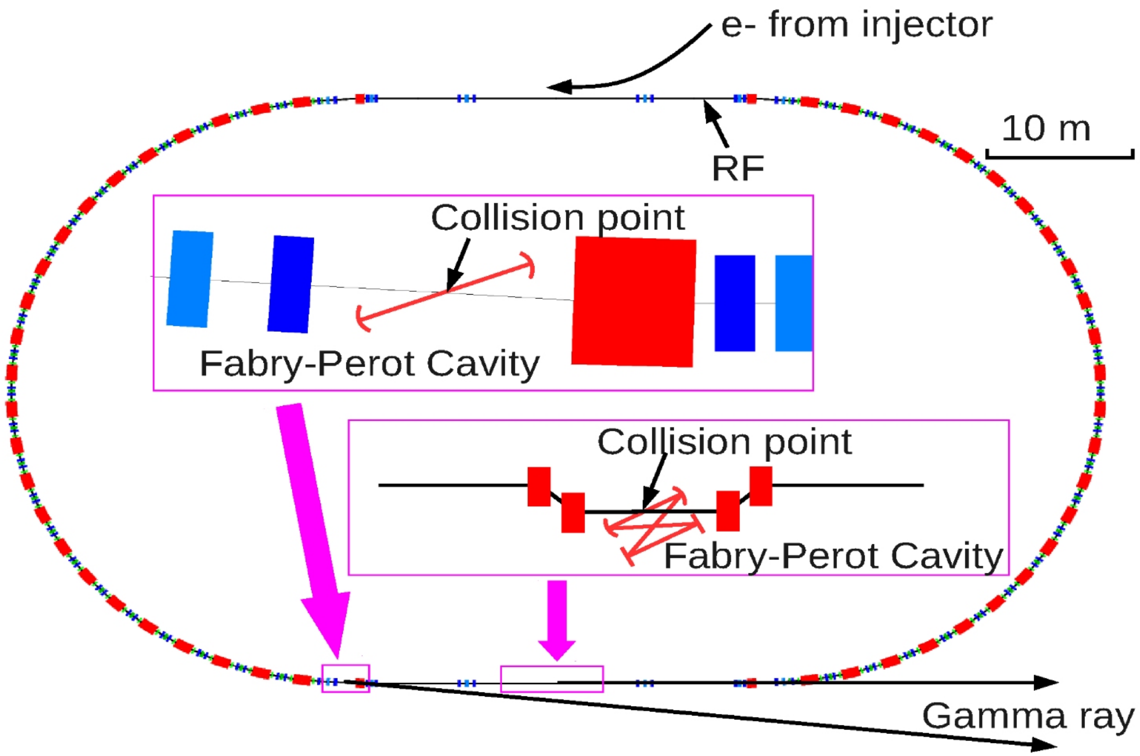
E-beam (MeV)	E_γ (MeV)	λ_1 (nm) 1064	$\lambda_1/3$ 355	λ_2 (nm) 1550	$\lambda_2/3$ 517
350	$E_{\gamma,\mathrm{min}}$	2.2	6.4	1.5	4.4
750	$E_{\gamma,\mathrm{max}}$	9.9	29	6.8	20

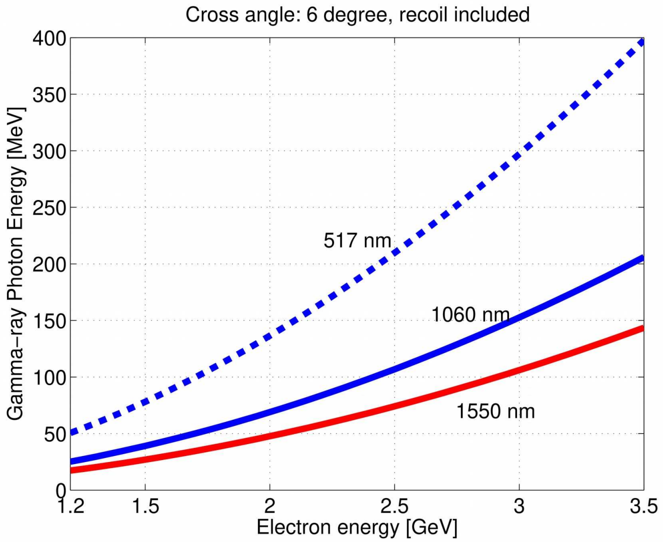
Electron beam	
Beam energy	500 MeV
Stored currents	1000 mA
Bunch filled	24
Hori./Vert. emittance	7.5/0.75 nm-rad
Hori./Vert. size (rms)	212/39 μm
Bunch length (rms)	150 ps
Laser beam	
Wavelength	1064 nm
Intracavity power	100 kW
Pulse length (rms)	20 ps
Hori./Vert. size (rms)	40/40 μm
Gamma-ray beam	
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.*, J. Phys. G: Nucl. Part. Phys. 49, 010502 (2022).

High-Energy CGS: Storage Ring





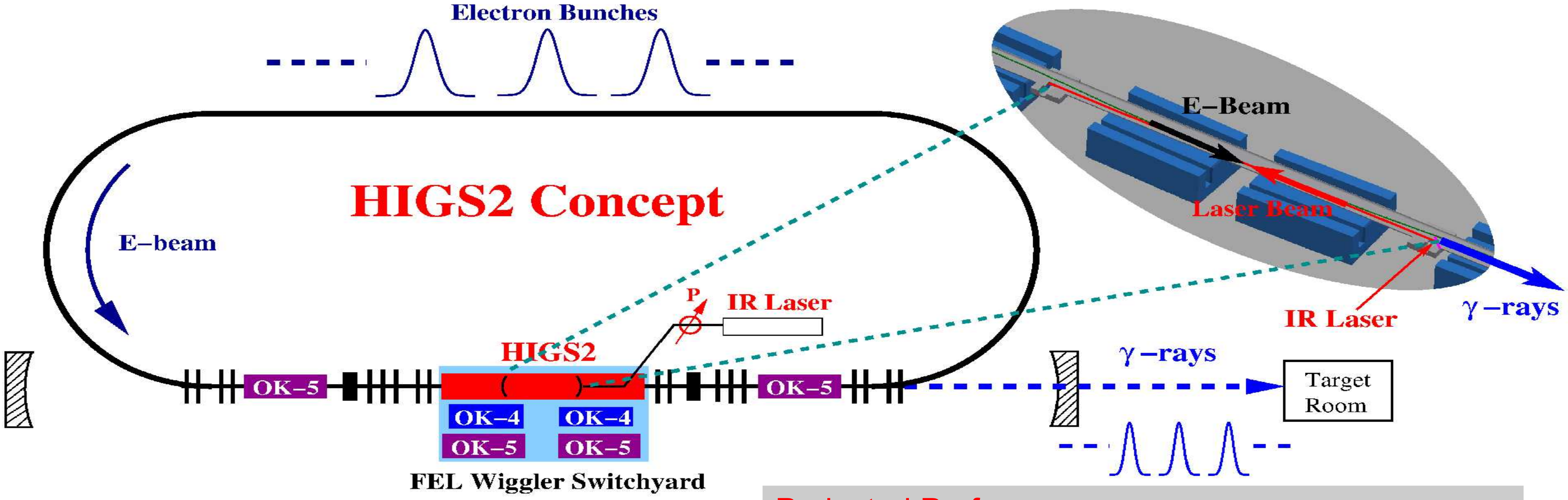
E-beam (GeV)	E_γ (MeV)	λ_1 (nm) 1064	λ_2 (nm) 1550	$\lambda_2/3$ 517
1.2	$E_{\gamma,\text{min}}$	25	17	51
3.5	$E_{\gamma,\text{max}}$	205	144	398

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.,* J. Phys. G: Nucl. Part. Phys. 49, 010502 (2022).

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)

The Gamma Factory proposal for CERN †

† An Executive Summary of the proposal addressed to the CERN management.

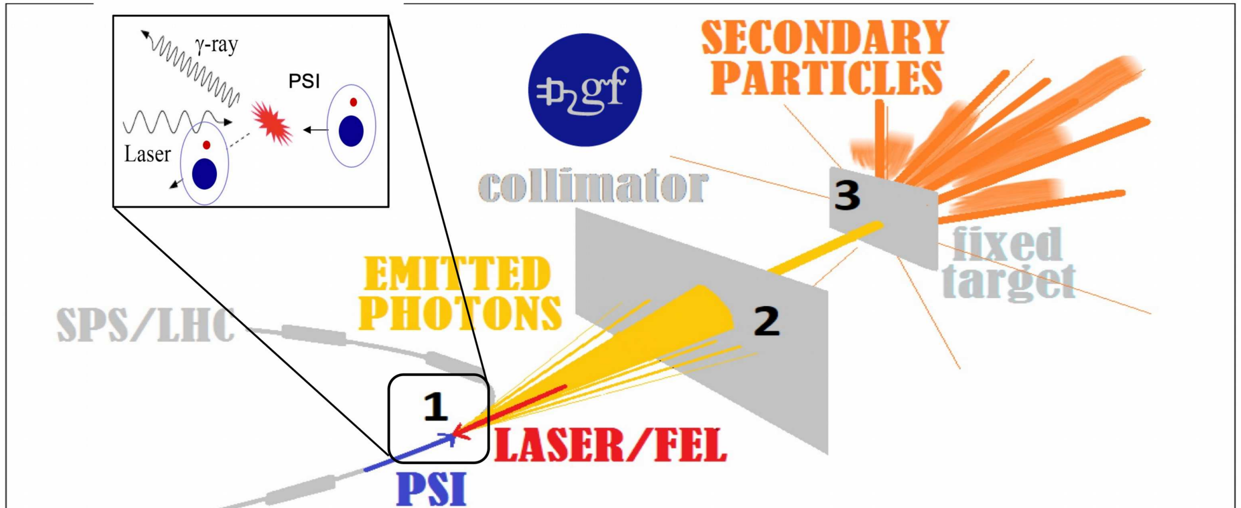
Mieczyslaw Witold Krasny*

LPNHE, Universités Paris VI et VII and CNRS–IN2P3, Paris, France

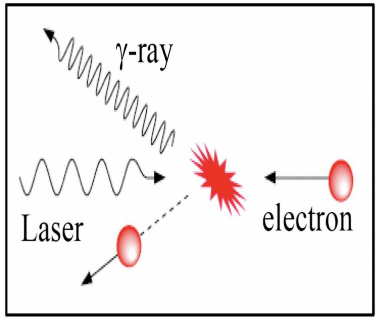
e-Print: 1511.07794 [hep-ex]

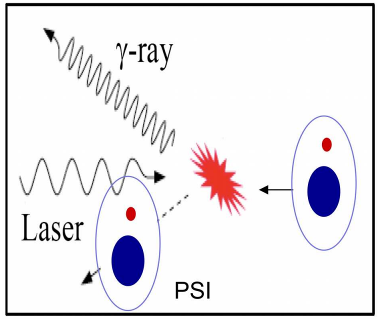
~100 physicists form 40 institutions have contributed so far to the Gamma Factory studies

A. Abramov[1], A. Afanasev[37], S.E. Alden[1], R. Alemany Fernandez[2], P.S. Antsiferov[3], A. Apyan[4], G. Arduini[2], D. Balabanski[34], R. Balkin[32], H. Bartosik[2], J. Berengut[5], E.G. Bessonov[6], N. Biancacci[2], J. Bieroń[7], A. Bogacz[8], A. Bosco[1], T. Brydges[36], R. Bruce[2], D. Budker[9,10], M. Bussmann[38], P. Constantin[34], K. Cassou[11], F. Castelli[12], I. Chaikovska[11], C. Curatolo[13], C. Curceanu[35], P. Czodrowski[2], A. Derevianko[14], K. Dupraz[11], Y. Dutheil[2], K. Dzierżęga[7], V. Fedosseev[2], V. Flambaum[25], S. Fritzsche[17], N. Fuster Martinez[2], S.M. Gibson[1], B. Goddard[2], M. Gorshteyn[20], A. Gorzawski[15,2], M.E. Granados[2], R. Hajima[26], T. Hayakawa[26], S. Hirlander[2], J. Jin[33], J.M. Jowett[2], F. Karbstein[39], R. Kersevan[2], M. Kowalska[2], M.W. Krasny[16,2], F. Kroeger[17], D. Kuchler[2], M. Lamont[2], T. Lefevre[2], T. Ma[32], D. Manglunki[2], B. Marsh[2], A. Martens[12], C. Michel[40] S. Miyamoto[31] J. Molson[2], D. Nichita[34], D. Nutarelli[11], L.J. Nevay[1], V. Pascalutsa[28], Y. Papaphilippou[2], A. Petrenko[18,2], V. Petrillo[12], L. Pinard[40] W. Płaczek[7], R.L. Ramjiawan[2], S. Redaelli[2], Y. Peinaud[11], S. Pustelny[7], S. Rochester[19], M. Safronova[29,30], D. Samoilenko[17], M. Sapinski[20], M. Schaumann[2] R. Scrivens[2], L. Serafini[12], V.P. Shevelko[6], Y. Soreq[32], T. Stoehlker[17], A. Surzhykov[21], I. Tolstikhina[6], F. Velotti[2], A. Viatkina[9] A.V. Volotka[17], G. Weber[17], W. Weiqiang[27] D. Winters[20], Y.K. Wu[22], C. Yin-Vallgren[2], M. Zanetti[23,13], F. Zimmermann[2], M.S. Zolotorev[24] and F. Zomer[11]



PSI – atomic beams of Partially Stripped Ions





Electrons:

$\sigma_e = 8\pi/3 \times r_e^2$

r_e - classical electron radius

Partially Stripped Ions (PSIs):

$\sigma_{peak} = \lambda_{res}^2/2\pi$

λ_{res} - photon wavelength in the ion rest frame

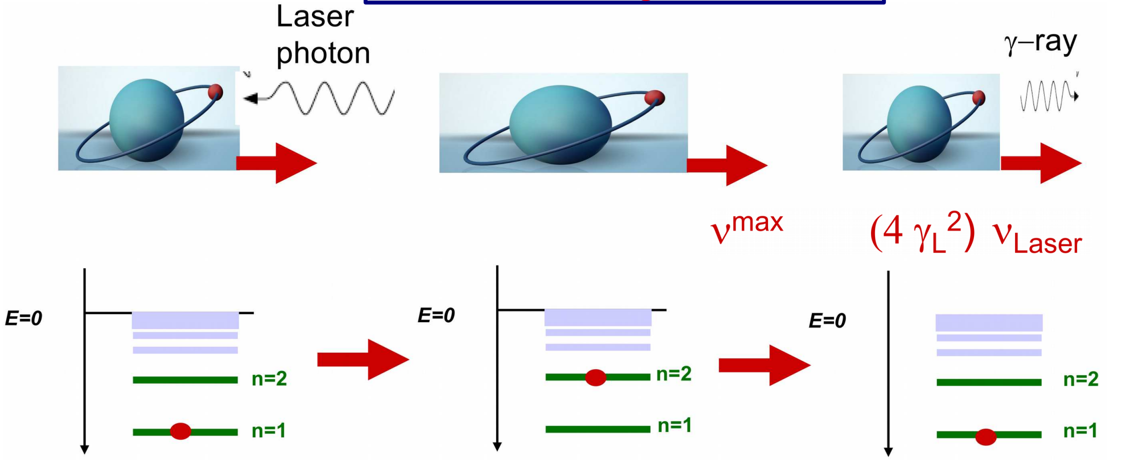
Electrons:

$\sigma_e = 6.6 \times 10^{-25}$ cm^2

PSIs:

$\sigma_{peak} = 1.7 \times 10^{-15}$ cm^2

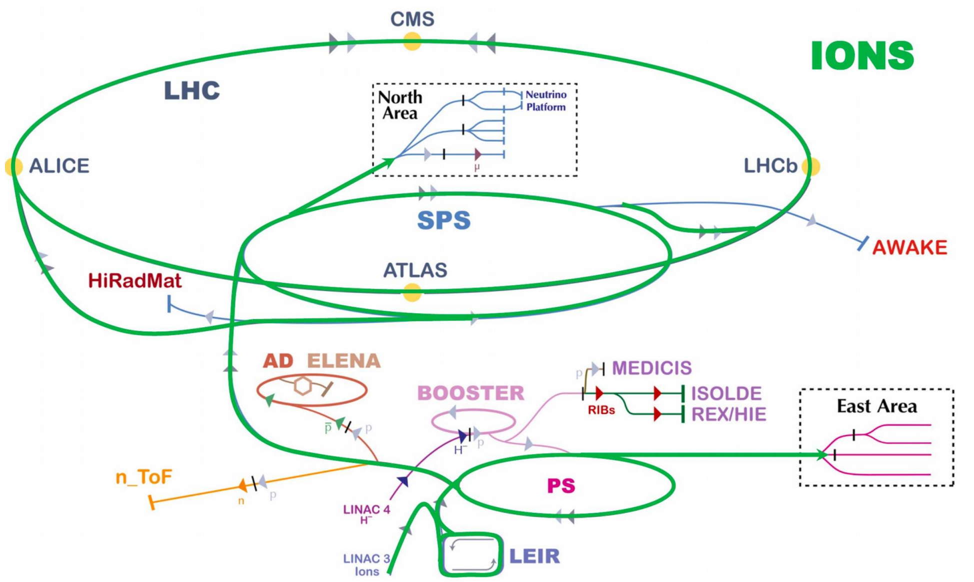
Flux increase by as much as 9 orders of magnitude: x10^9



Courtesy of Mieczyslaw Witold Krasny LPNHE, CNRS and University Paris Sorbonne and CERN, BE-ABPb

Gamma Factory for CERN

Gamma Factory requirement:
Production, acceleration, and storage of atomic beams in the LHC rings



Extraordinary properties of the CERN-based GF photon source

1. Point-like, small divergence

- $\Delta z \sim l_{PSI\text{-}bunch}$, $\Delta x, \Delta y \sim \sigma^{PSI}_{x}, {}^{PSI}_{y}$, $\Delta(\theta_x)$, $\Delta(\theta_y) \sim 1/\gamma_L < 1$ mrad

2. Huge jump in intensity:

- ***6–8 orders of magnitude*** *w.r.t. existing (being constructed) γ-sources >* ***10^{18} photons/sec***

3.Very wide range of tuneable energy photon beam :

- ***40 keV – 400 MeV*** *- extending, by a factor of* ***~10000****, the energy range of the FEL photon sources*

4. Tuneable polarisation:

- *γ–**polarisation transmission** from laser photons to the GF γ-beams of **up to 99%***

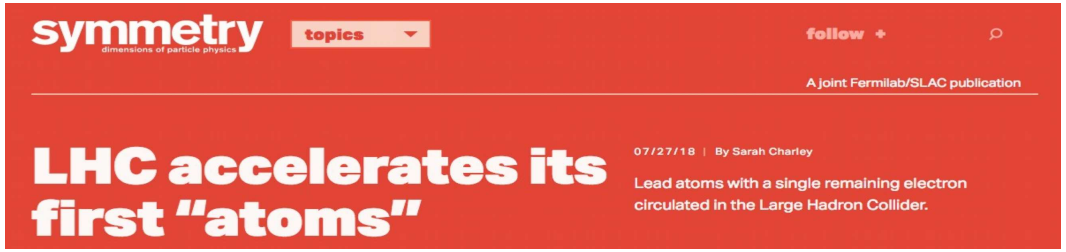
5. Unprecedented plug power efficiency (energy footprint):

- ***LHC RF power can be converted to the photon beam power.*** *Wall-plug power efficiency of the* ***GF photon source is*** *by a factor of* ***~300 better than that of the DESY-XFEL!***
  (assuming power consumption of 200 MW - CERN and 19 MW - DESY)

- ***particle physics*** *(precision QED and EW studies, vacuum birefringence, Higgs physics in $\gamma\gamma$ collision mode, rare muon decays, precision neutrino physics, QCD-confinement studies, …);*
- ***nuclear physics*** *(nuclear spectroscopy, cross-talk of nuclear and atomic processes, GDR, nuclear photo-physics, photo-fission research, gamma polarimetry, physics of rare radioactive nuclides,…);*
- ***atomic physics*** *(highly charged atoms, electronic and muonic atoms, pionic and kaonic atoms);*
- ***astrophysics*** *(dark matter searches, gravitational waves detection, gravitational effects of cold particle beams, $^{16}O(\gamma,\alpha)^{12}C$ reaction and S-factors…);*
- ***fundamental physics*** *(studies of the basic symmetries of the universe, atomic interferometry,…);*
- ***accelerator physics*** *(beam cooling techniques, low emittance hadronic beams, plasma wake field acceleration, high intensity polarised positron and muon sources, beams of radioactive ions and neutrons, very narrow band, and flavour-tagged neutrino beams, neutron sources…);*
- ***applied physics*** *(**accelerator driven energy sources**, medical isotopes' and isomers' production).*

Courtesy of Mieczyslaw Witold Krasny LPNHE, CNRS and University Paris Sorbonne and CERN, BE-ABP

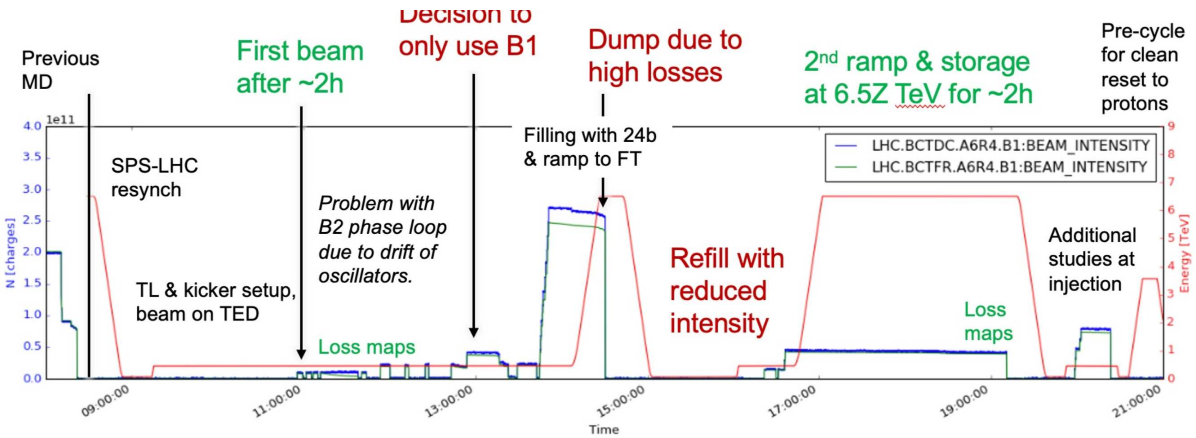
Gamma Factory for CERN

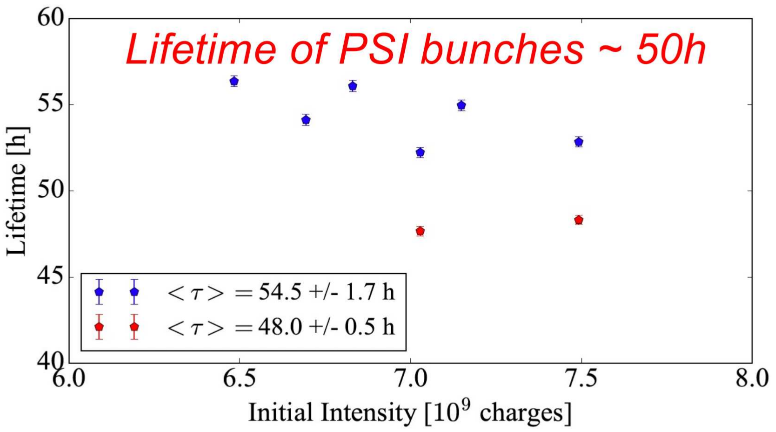

symmetry
dimensions of particle physics
topics
follow +
A joint Fermilab/SLAC publication

LHC accelerates its first "atoms"

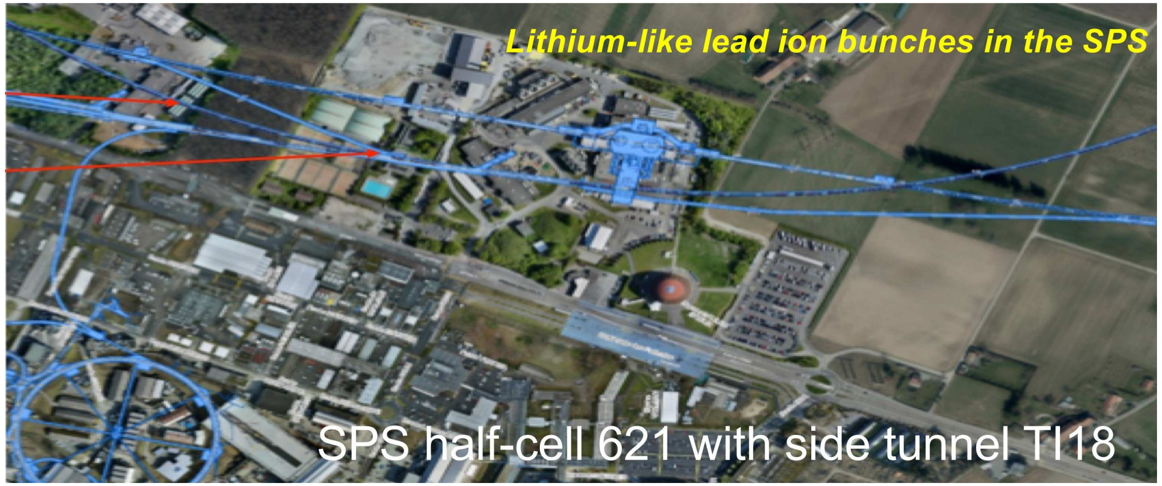
07/27/18 | By Sarah Charley

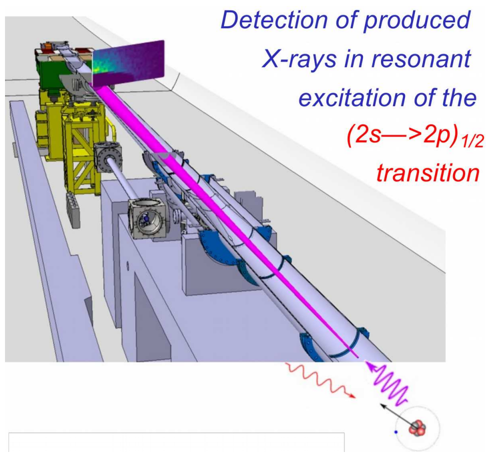
Lead atoms with a single remaining electron circulated in the Large Hadron Collider.



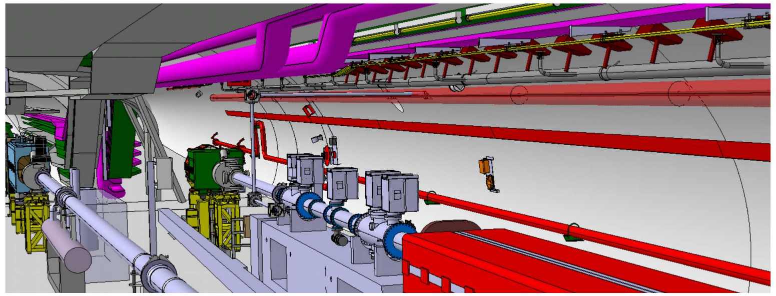


Gamma Factory Proof-of-Principle (PoP) SPS Experiment





F-P cavity – "in beam" position



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