Current Status and Perspectives of ERL-based Compton Sources

Ryoichi Hajima

National Inst. Quantum and Radiological Sci. and Tech. (QST)

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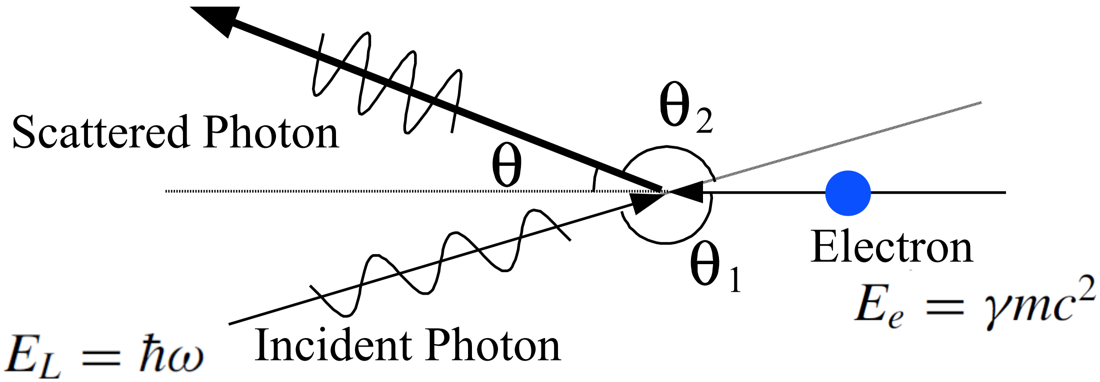
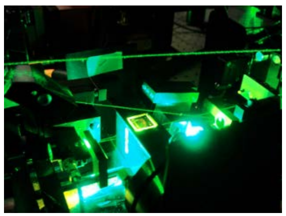
Work supported by:

- A government (MEXT) subsidy for strengthening nuclear security
- Photon and Quantum Basic Research Coordinated Development Program from the MEXT
- JSPS KAKENHI 17H02818.

Laser Compton Scattering (LCS)





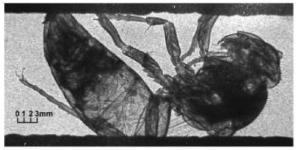
$$E_X \simeq \frac{4\gamma^2 E_L}{1 + (\gamma\theta)^2 + 4\gamma E_L/(mc^2)}$$ for head-on collision

- ✓ Pencil like beam
- ✓ Energy Tunable
- ✓ Polarized (linear and circular)
- ✓ Correlation of E_X and θ

Applications and Advantages of LCS

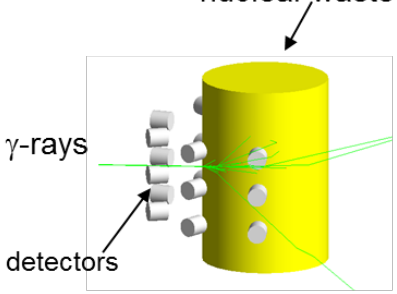
keV

Imaging
Element assay by XRF



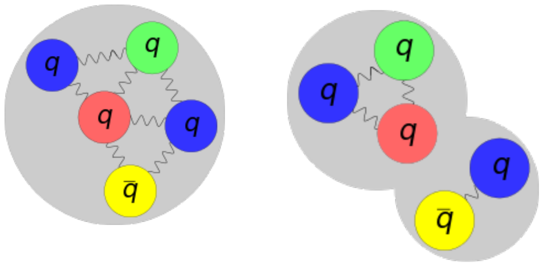
MeV

Photo-nuclear reaction (γ,γ') (γ,n)
Isotope assay by NRF
Polarized gamma and positron



GeV

Hadron physics
γ-γ collider

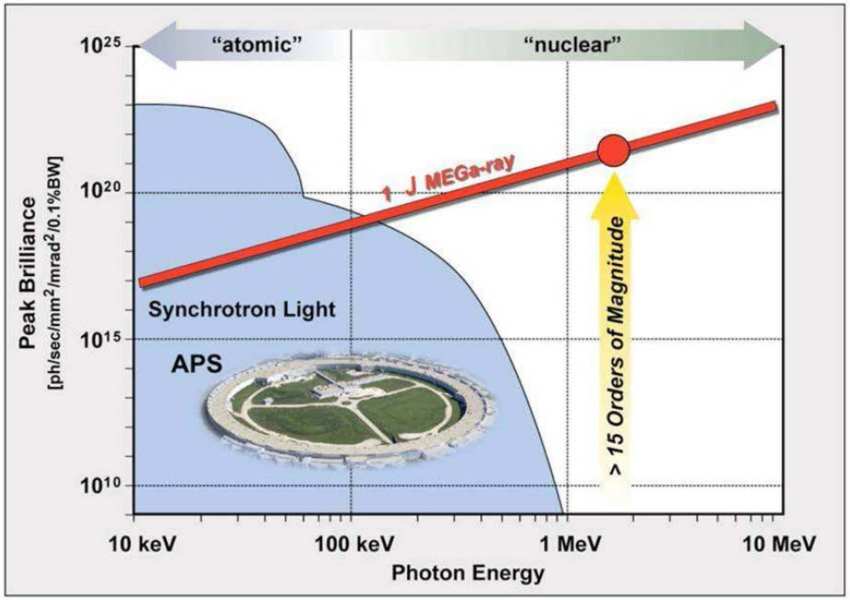


Advantage

Compactness

25 MeV x 1 μm → 10 keV

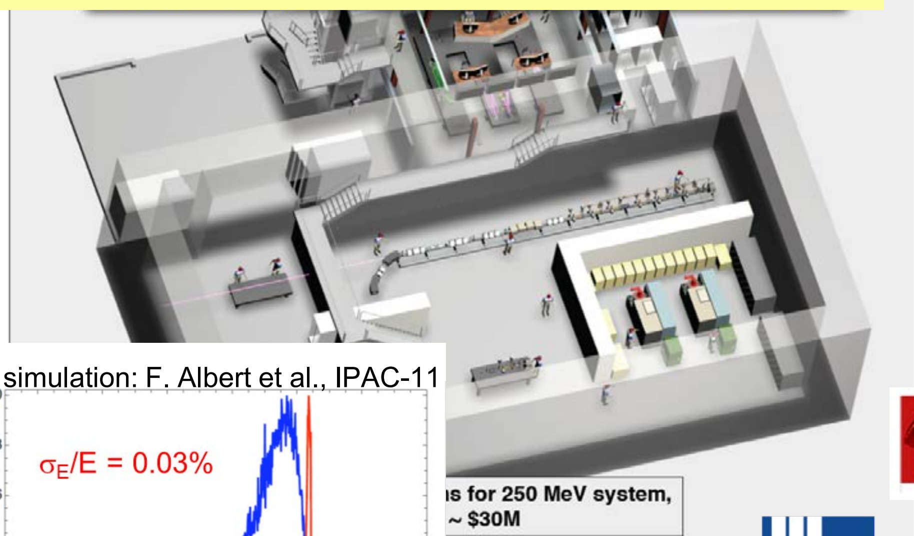
Unparalleled Brightness > MeV

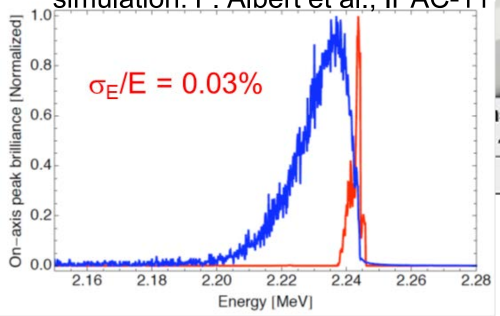


C.P.J. Barty, "White Book of ELI-NP"

New-generation LCS Gamma-ray Sources

MEGA-Ray @ Lawrence Livermore Natl. Lab.
250 MeV Linac, Eγ = 1-2 MeV

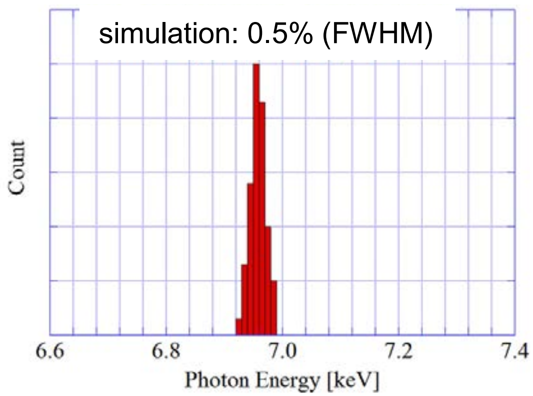




ELI-NP : Complex of PW lasers and LCS

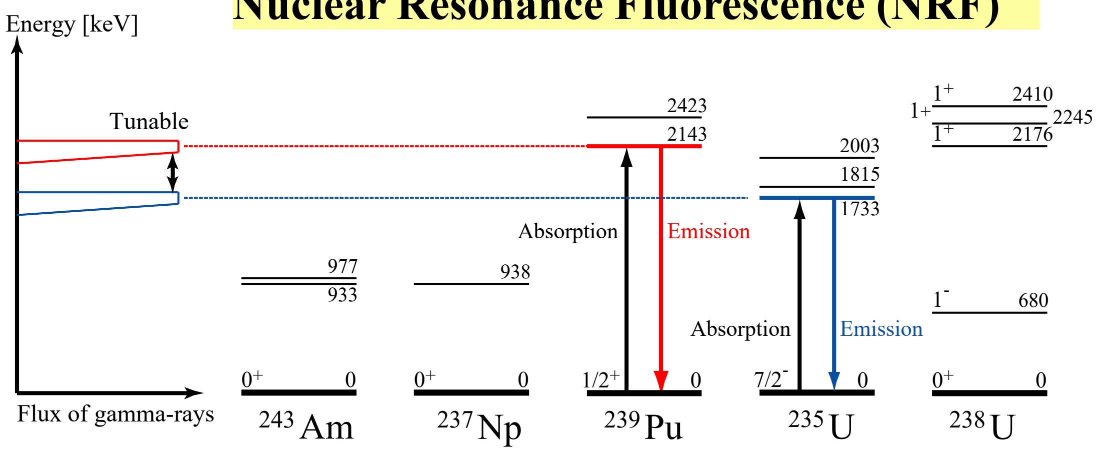
The Extreme Light Infrastructure
European Project

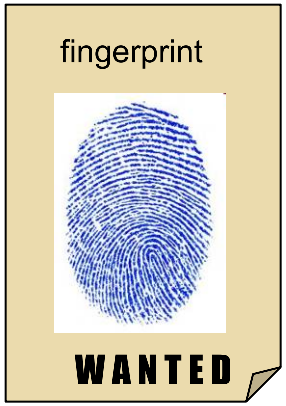
ERL-based LCS gamma-ray @ KEK-JAEA Test Facility



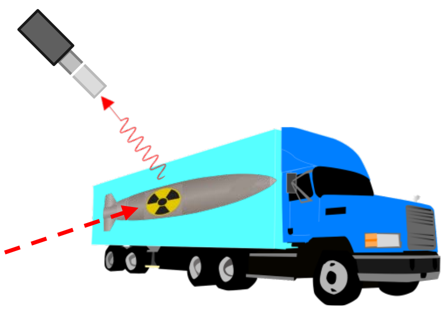
Nondestructive Detection & Measurement of Nuclear Material

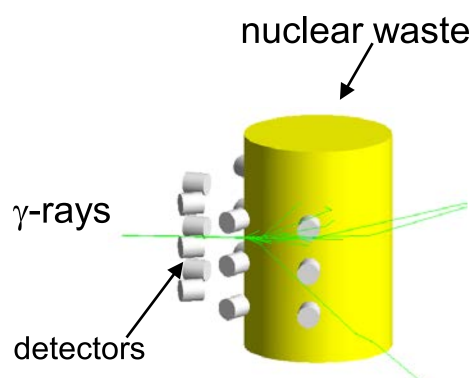
Nuclear Resonance Fluorescence (NRF)



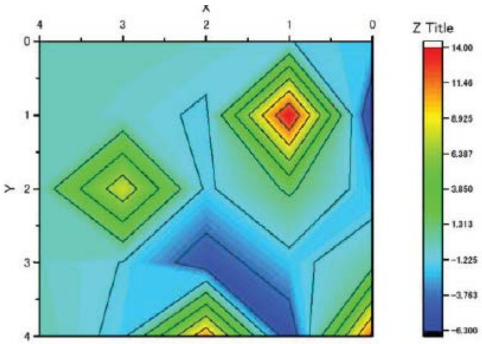


Detection and measurement of specific isotopes





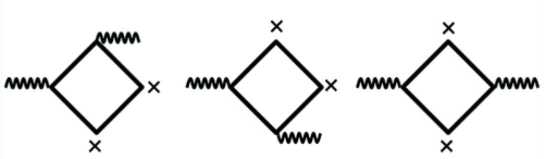
Isotope specific NRF-CT



J. Pruet et al., J. App. Phys. 99, 123102 (2006)
R. Hajima et al., J. Nucl. Sci. Tech. 45, 441 (2008)
H. Ohgaki et al., IPAC-2016, 2007 (2016)

Applications on Fundamental Science

QED predicts two photon collision



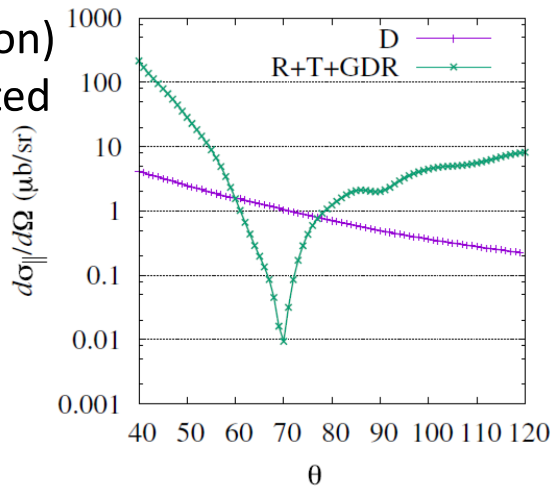
Many experiments for testing the QED.

13 events were observed at 2015 run.

ATLAS Collaboration, Nat. Phys. (2017).

MeV gamma provides an efficient way.

Delbrück (photon-photon) Scattering can be selected from other scattering by linearly-pol. MeV γ.

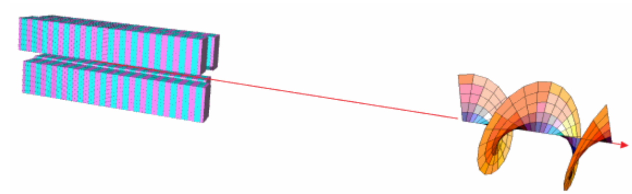


10^4 events in 76-day exp. at ELI-NP.

J. Koga and T. Hayakawa, PRL (2017)

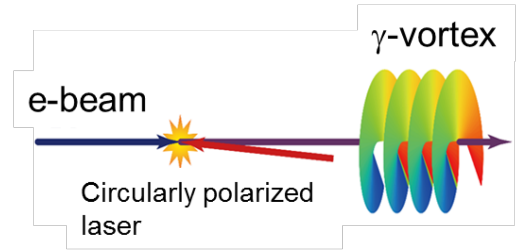
Photon Vortex beams carrying orbital angular momentum.

X-ray vortex



S. Sasaki et al., PRL100, 124801 (2008).

γ-ray vortex



γ-ray vortex from nonlinear LCS

Y. Taira et al. Sci. Rep. 7, 5018(2017)

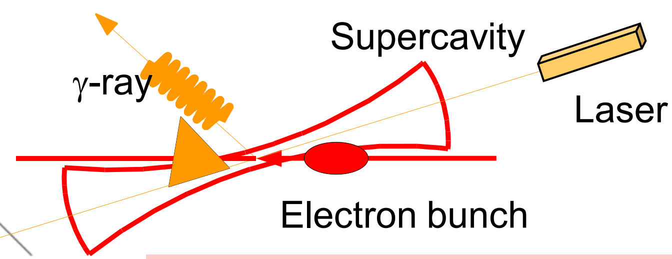
γ-ray vortex with Laguerre Gaussian wave function

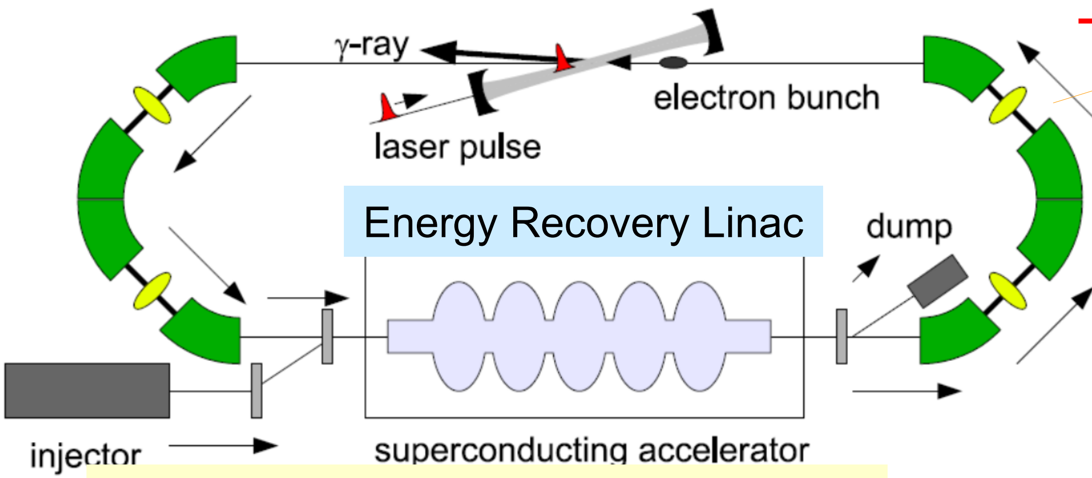
T. Maruyama et al., arXiv:1710.09369 (2017)

ERL-based Compton Source

high-average current & small emittance
→ high-flux and narrow-band LCS

laser enhancement cavity





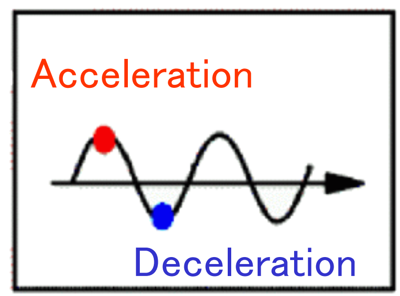
laser photons are recycled

↓

high-flux γ-ray

↑

electron energy is recycled



- Electron beam = 350 MeV, 13 mA
- Laser intracavity = 700 kW
- **LCS ~2MeV, 1×10^{13} ph/s**

0.1 ph/eV/s → 10^7 ph/eV/s

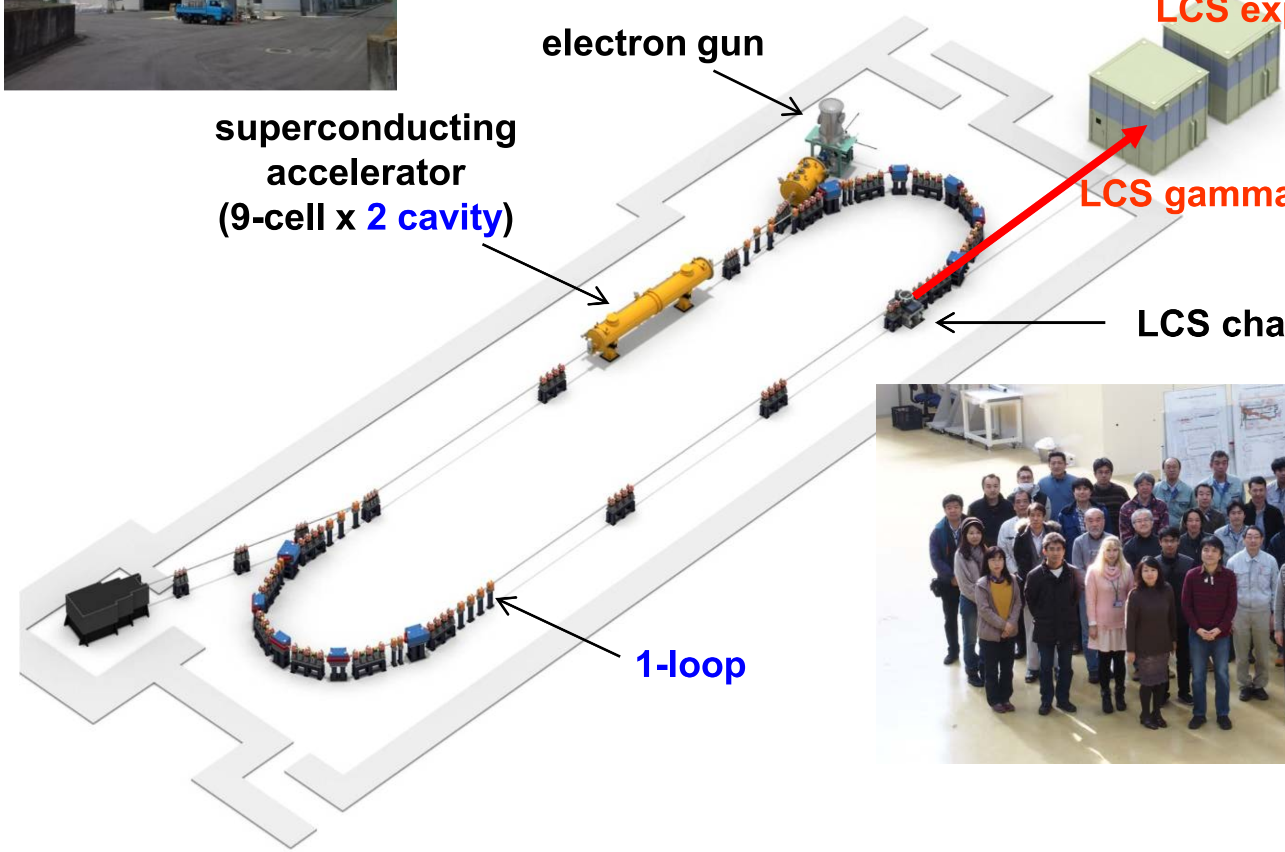
AIST (1st-generation LCS) ERL

R. Hajima et al., NIM-A608 (2009)

LCS Experiment at the Compact ERL

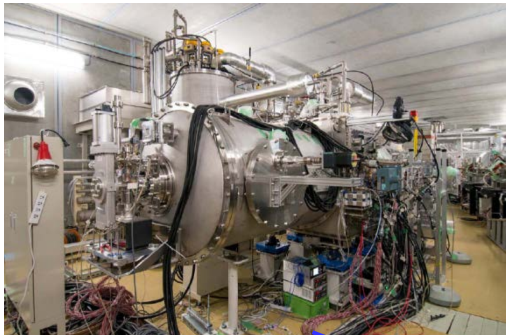
4-year R&D program funded from MEXT (2011-2014)

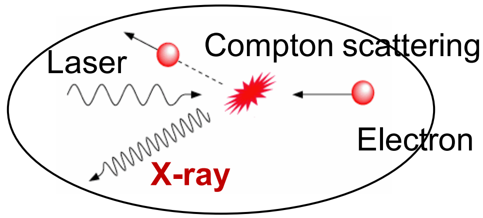
ERL-LCS technologies towards high-flux and narrow-bandwidth γ-rays.

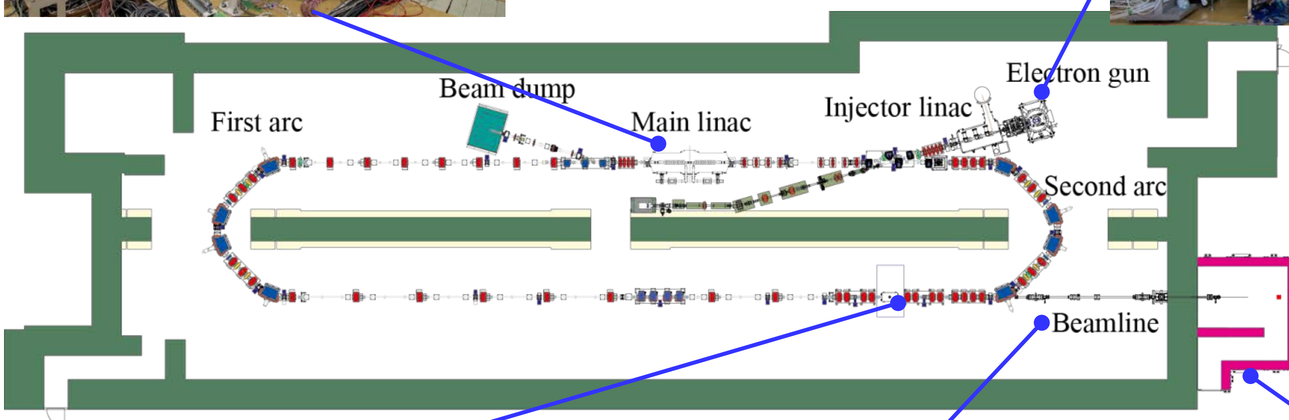


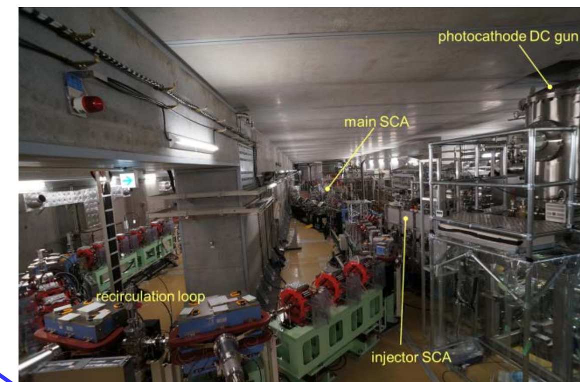
Installation of Equipment for LCS Experiment

Demonstration of technologies relevant to future ERL-based LCS sources







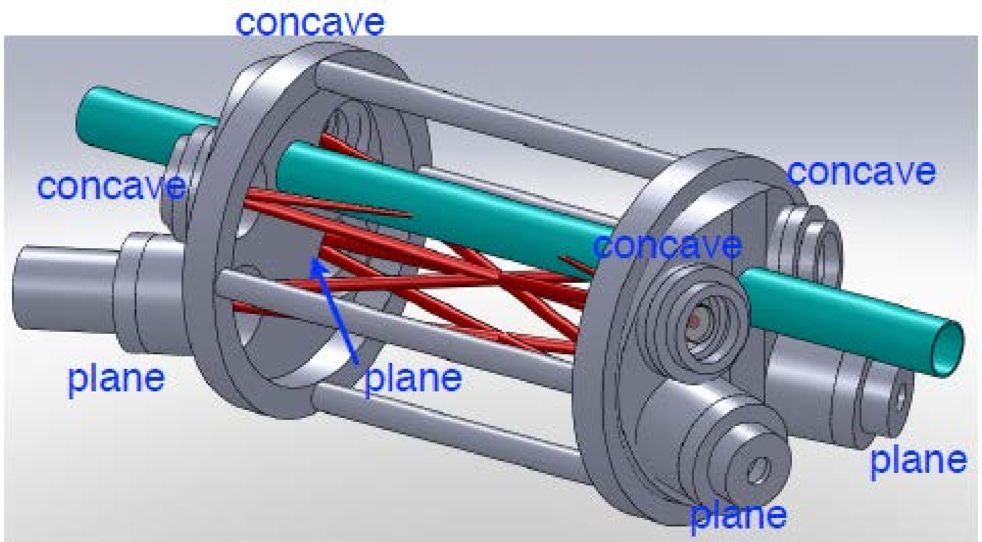


Laser enhancement cavity and 45W laser

Beam line

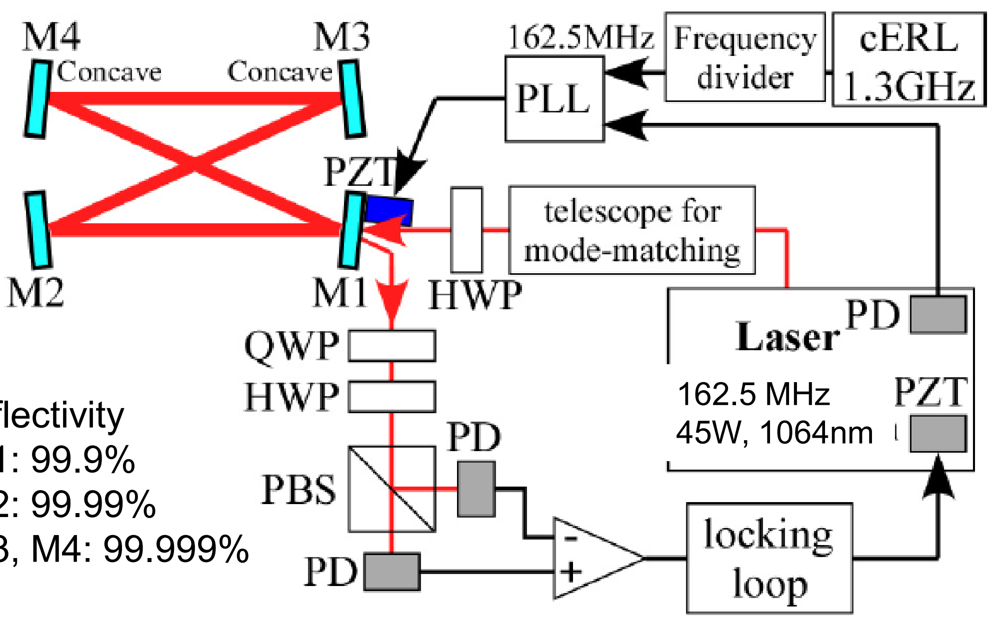
Experimental hut

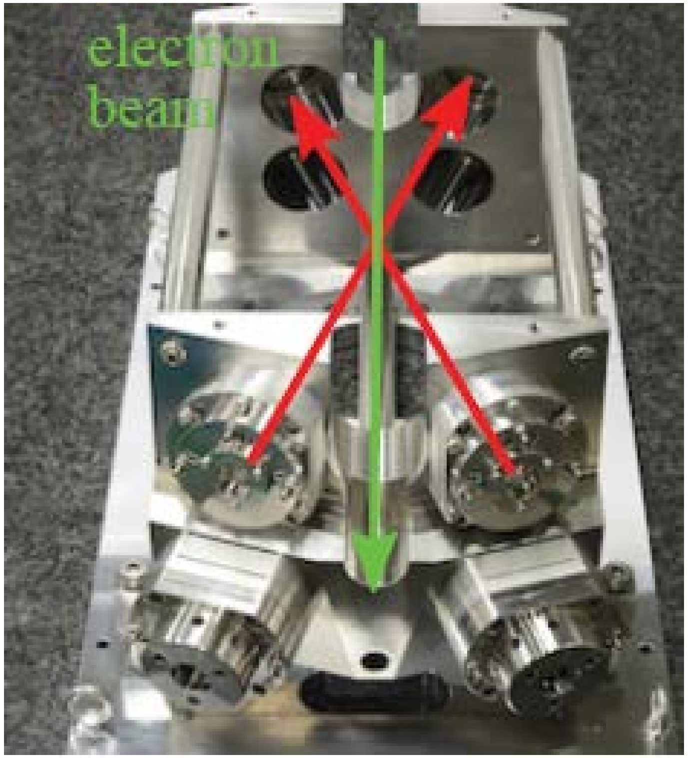
Laser Enhancement Cavity



Developed by KEK group

T. Akagi et al., Proc. IPAC-2014, p.2072
A. Kosuge et al., Proc. IPAC-2015, TUPWA-66





reflectivity
M1: 99.9%
M2: 99.99%
M3, M4: 99.999%

Spot size: σ=30μm

Electron beam tunings for the LCS

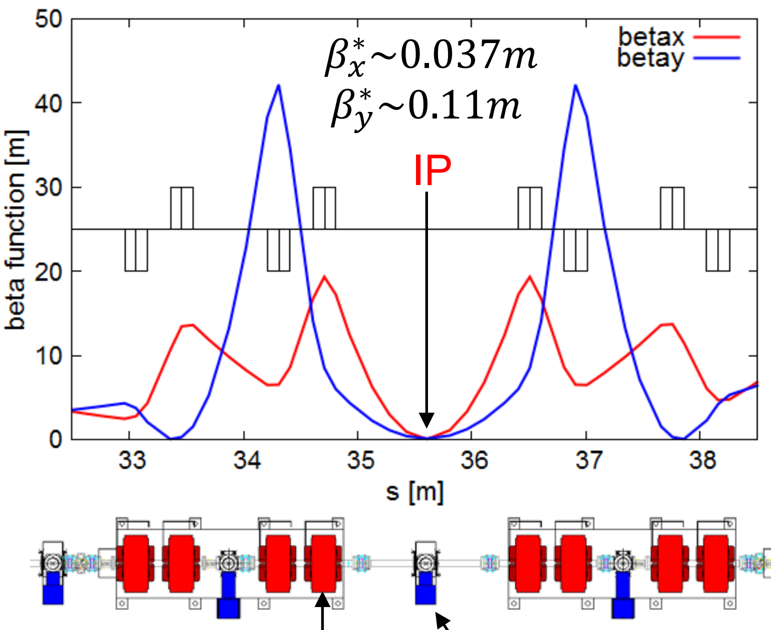
- Low-beta insertion for small beam sizes at IP
- Transport beams to the dump with small beam losses

Beam optics was established

IP: interaction point

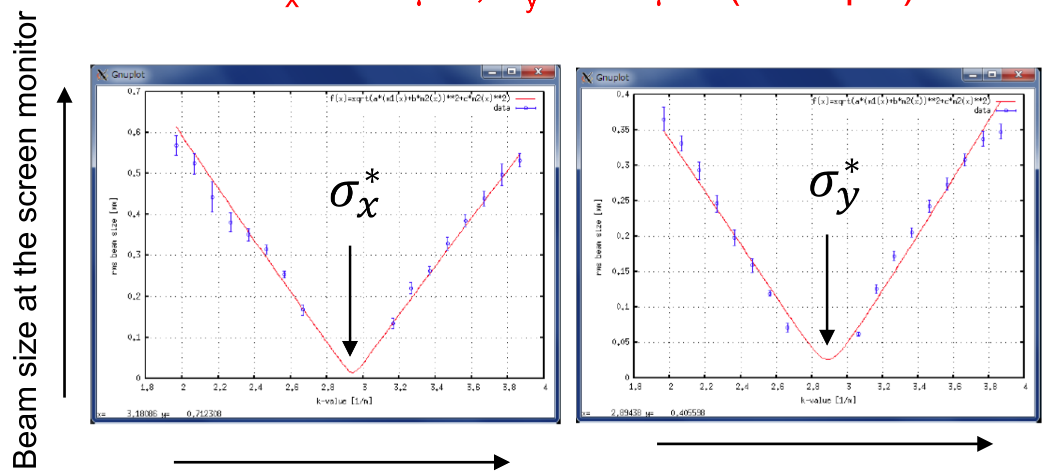
Design optics (example: “70% middle” optics)

$\sigma_x^* = 21\ \mu$m, $\sigma_y^* = 33\ \mu$m at IP



Beam sizes at IP were estimated from Q-scan data

$\sigma_x^* \sim 13\ \mu$m, $\sigma_y^* \sim 25\ \mu$m (example)



σ_x^*, σ_y^* < (resolution of the screen monitor)

Bunch charge: 0.5 pC/bunch,
Normalized emittances : $(\varepsilon_{nx},\varepsilon_{ny})$=(0.47, 0.39) mm·mrad

S. Sakanaka et al., Proc. IPAC-2015, TUBC1

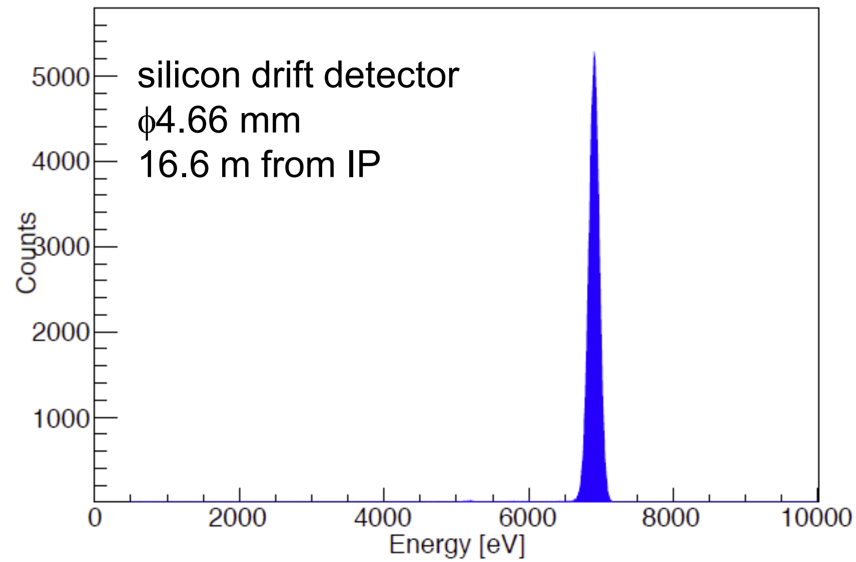
First LCS photon (Mar. 2015)

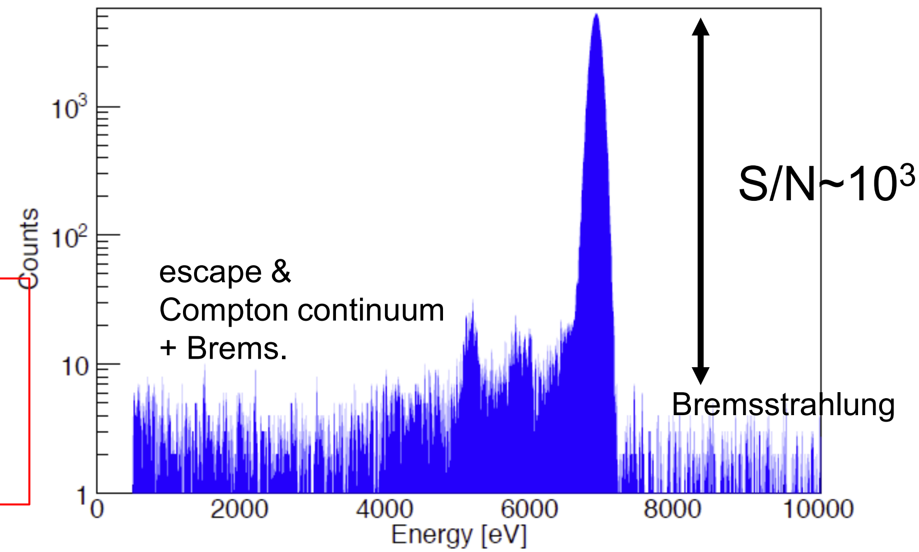
Parameters of electron beams:

Energy [MeV]	20
Bunch charge [pC]	0.36
Bunch length [ps, rms]	2
Spot size [μm, rms]	30
Emittance [mm mrad, rms]	0.4
Repetition Rate [MHz]	162.5
Beam current [μA]	58

Parameters of laser (enhanced by cavity):

Center wavelength [nm]	1064
Pulse energy [μJ]	64
Pulse length [ps, rms]	5.65
Spot size [μm, rms]	30
Collision angle [deg]	18
Repetition rate [MHz]	162.5
Intracavity power [kW]	10.4





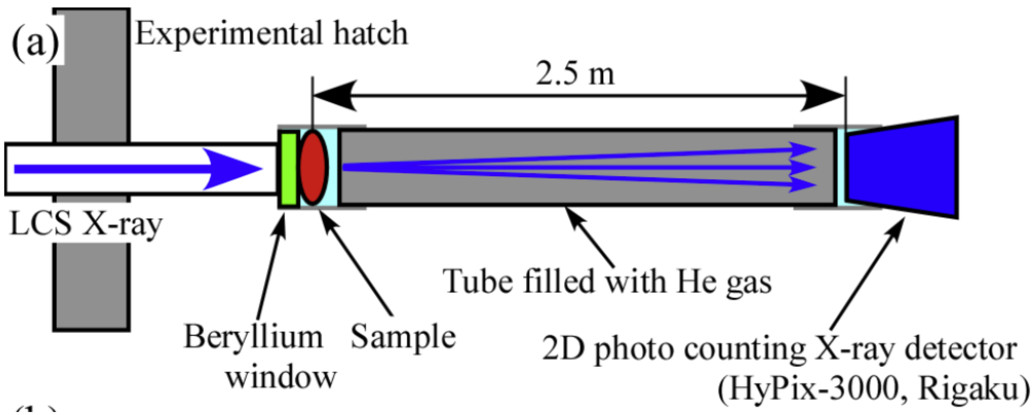
Results:

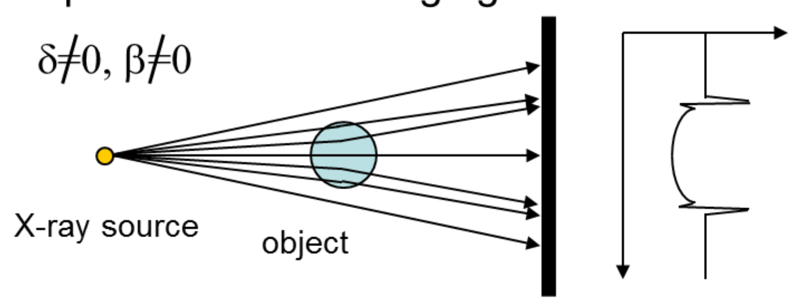
Photon energy = 6.95 keV
Detector count rate = 1370 cps @ϕ4.66mm (*)
Energy bandwidth = 30 eV(0.4%)@ϕ4.66mm (**)
Source flux = 2.6 x 10^7 ph/s (***)

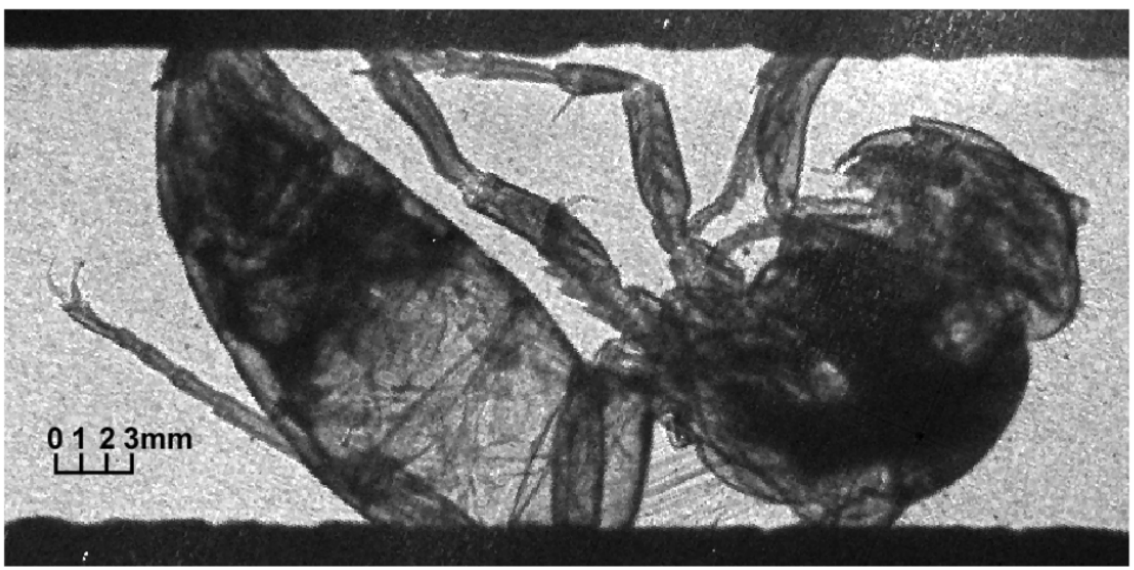
(*) Detector collecting angle is 4.66mm/16.6m = 0.281 mrad
(**) Detector resolution subtracted
(***) CAIN/EGS simulations with the detector count rate

T. Akagi et al. PR-AB 19, 114701 (2016)

X-ray imaging with a LCS beam







An X-ray image of a hornet taken with LCS-produced X-ray.
Detector: HyPix-3000 from RIGAKU. Detector was apart from the sample by approx. 2.5 m.

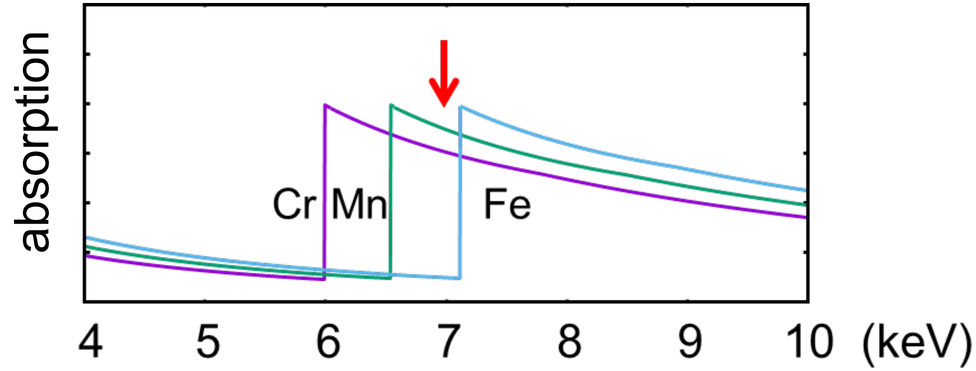
A. Kosuge et al., Proc. IPAC-2015, TUPWA066

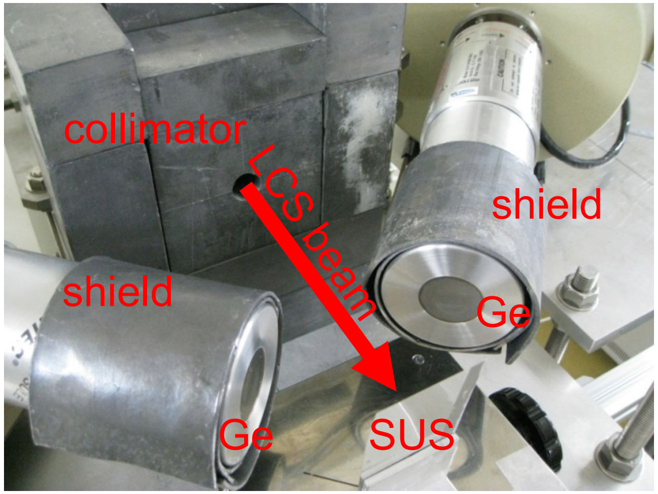
X-ray resonance fluorescence with a LCS beam

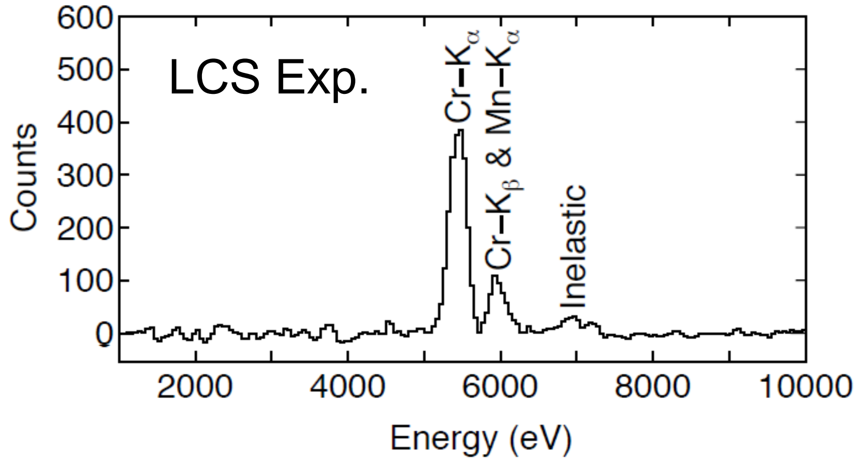
Assay of a SUS plate

6.95-keV X-ray is between
K absorption edges of Mn and Fe

minor composition (Cr, Mn)
can be assayed with LCS-XRF







	LCS	Rigaku, ZSX100e
Cr	18.0±0.5%	17.9%
Mn	0.95±0.06%	1.0%

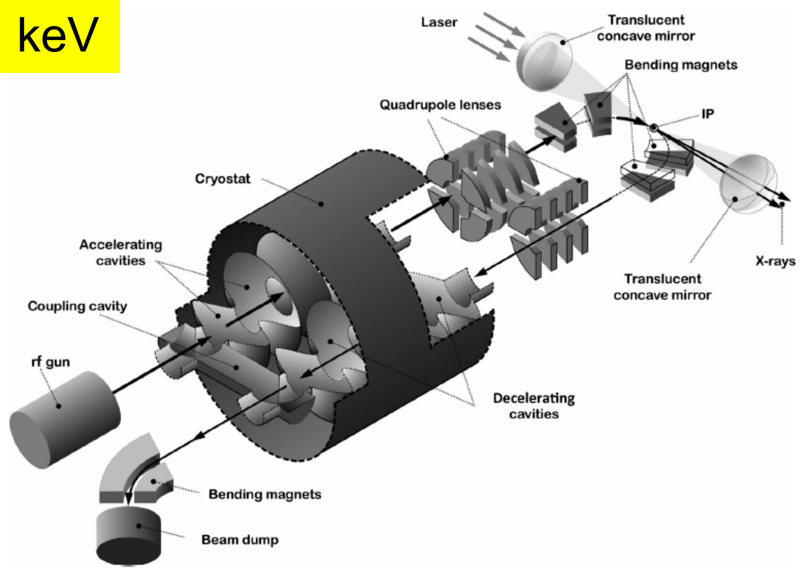
LCS-XRF is applicable to assay of U/Np/Pu in HNO_3 aqueous solution with ~100 keV LCS X-ray.

T. Shizuma et al. NIM-A 654, 597 (2011).

T. Akagi et al. PR-AB 19, 114701 (2016).

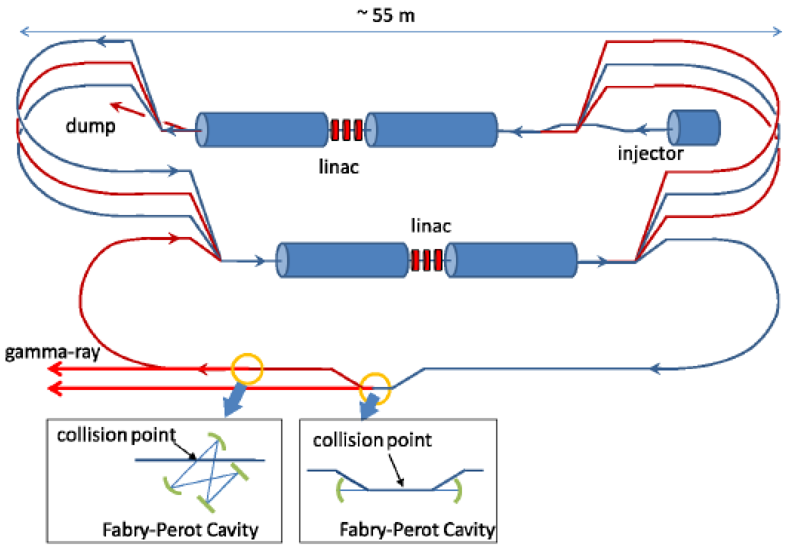
ERL-based LCS sources form keV to GeV

keV



R. Ainsworth et al., PR-AB 19, 083502 (2016)

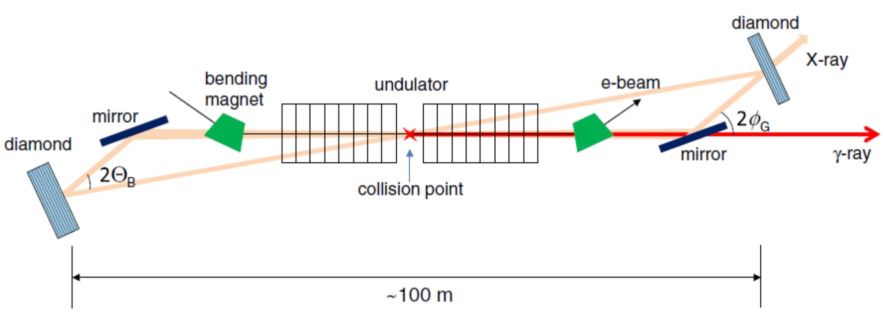
MeV

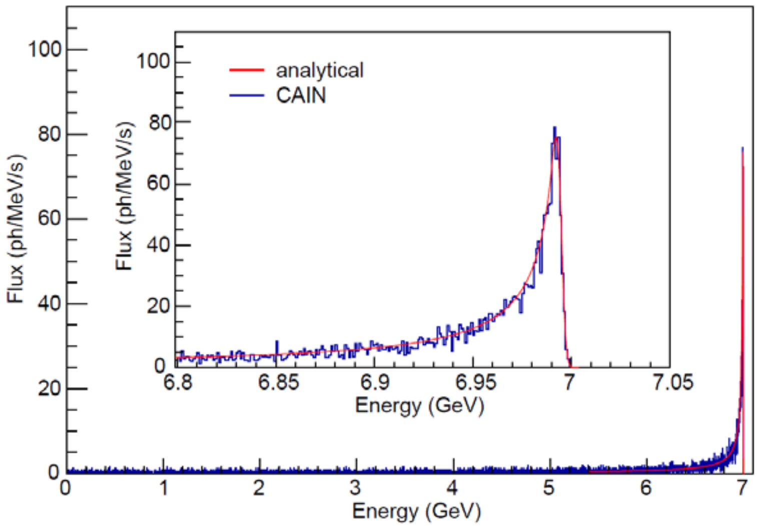


R. Hajima, S. Benson, Next-gamma WS (2016).

GeV

R. Hajima, M. Fujiwara,
PR-AB 19, 020702 (2016)





Summary

- Laser Compton Scattering sources have many advantages
  - pencil-like beam, energy tunability, polarization, narrow bandwidth, short pulse, vortex
- Applications of LCS sources cover
  - nondestructive detection, measurement and imaging of isotopes
  - QED, photon vortex, nuclear physics, hadron physics …
- ERL is one of the promising platforms for the next-gen LCS
  - small emittance, high repetition, high average current, compatible with a laser enhancement cavity
- We established technologies necessary for ERL-based Compton sources and demonstrated X-ray generation at the cERL.

Collaborators

- Quantum Beam Science Research Division, QST
  - Laser Compton Scattered Gamma-ray Research Project
    T. Hayakawa, T. Shizuma, C.T. Angell, M. Sawamura, R. Nagai
  - High-Intensity Laser Science Group
    M. Mori, J. Koga
- Integrated Support Center for Nuclear Nonproliferation and Nuclear Security, JAEA
  - M. Seya, M. Koizumi, M. Omer
- KEK
  - H. Kawata, Y. Kobayashi and cERL team
  - N. Terunuma, A. Kosuge, T. Akagi
- Kyoto Univ.
  - H. Ohgaki, H. Zen, T. Kii
- Osaka Univ.
  - M. Fujiwara
- Tohoku Univ.
  - N. Nishimori
- Hiroshima U.
  - S. Matsuba
- AIST.
  - Y. Taira, H. Toyokawa
- U. Hyogo
  - S. Miyamoto
- National Astronomical Observatory of Japan
  - T. Kajino
- Nihon U.
  - T. Maruyama