Status and Perspectives of Compton Sources

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National Institutes of Quantum and Radiological Sciences and Technology

High Energy Accelerator Research Organization

SFR-2016

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Budker Institute of Nuclear Physics, SB, RAS

Work supported by:

- A government (MEXT) subsidy for strengthening nuclear security,
- Photon and Quantum Basic Research Coordinated Development Program from the MEXT

QST: a New Research Inst.

Japan Atomic Energy Agency (JAEA)

3,700 staffs

National Institute of Radiological Sciences (NIRS)

455 staffs

Apr. 1, 2016

JAEA

- research reactors
- nuclear fuel cycle
- safety research
- R&D's for Fukushima
- nuclear waste
- FBR: Monju
- J-PARC

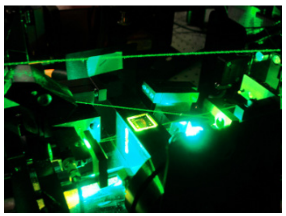
QST

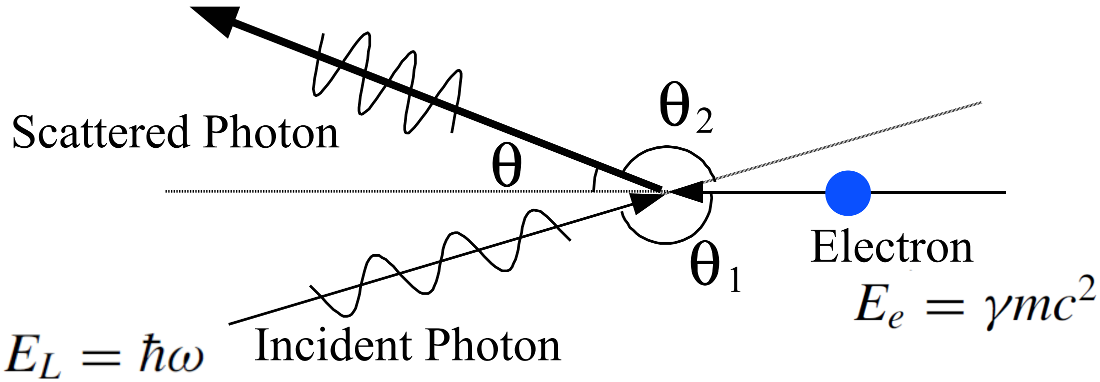
National Institutes for Quantum and Radiological Science and Technology (QST)

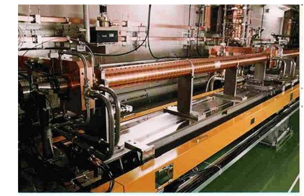
- beam science
- fusion
- heavy ion cancer therapy

1,220 staffs

Laser Compton Scattering (LCS)



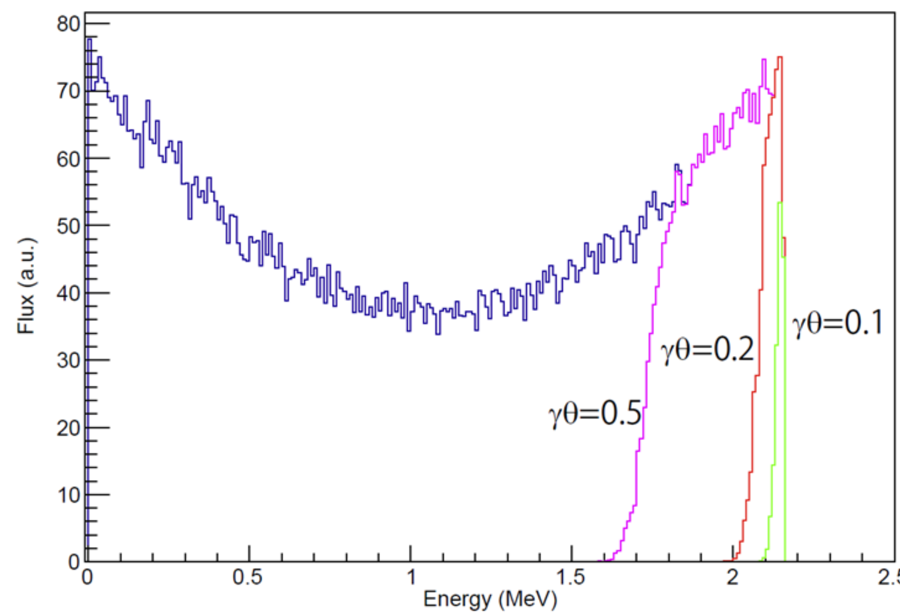




$$E_X \simeq \frac{4\gamma^2 E_L}{1 + (\gamma\theta)^2 + 4\gamma E_L/(mc^2)}$$

for head-on collision

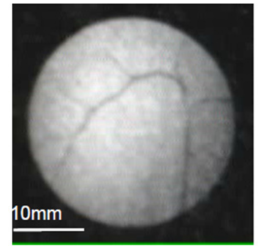
- ✓ Pencil like beam
- ✓ Energy Tunable
- ✓ Polarized (linear and circular)
- ✓ Correlation of E_X and θ

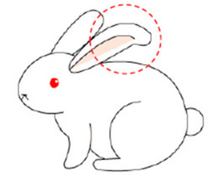


Applications of LCS

keV

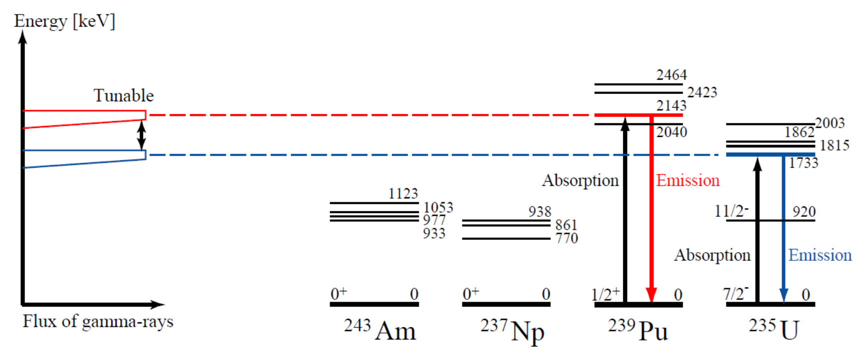
biomedical imaging
XRF analysis





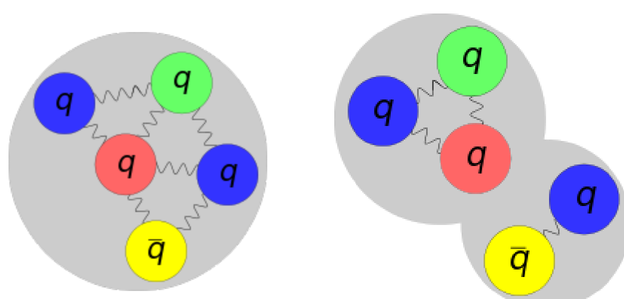
MeV

photo-nuclear reaction (γ,γ') (γ,n)
non-destructive detection/assay of nuclear material
polarized positron generation



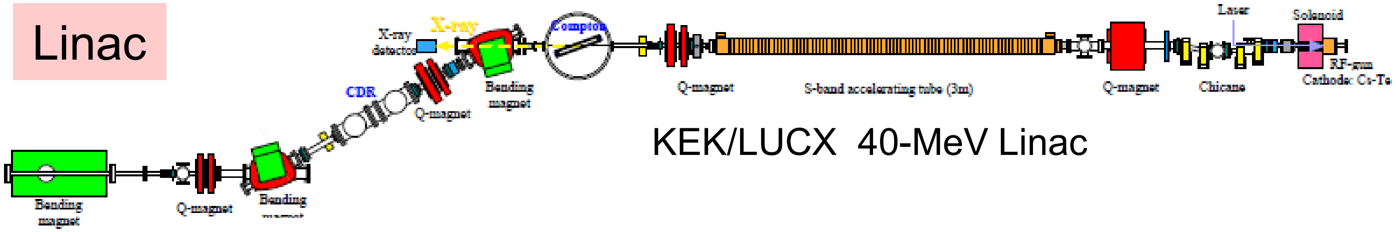
GeV

hadron physics



Various types of LCS Sources

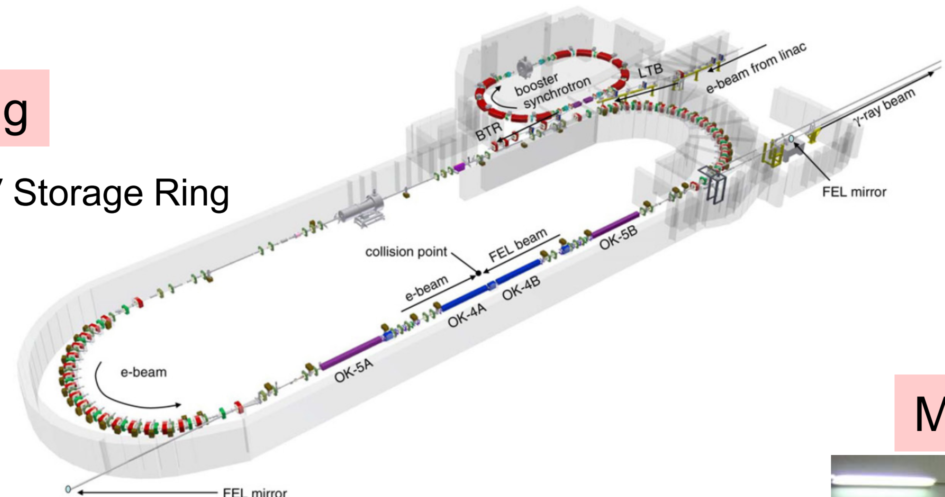
Linac



KEK/LUCX 40-MeV Linac

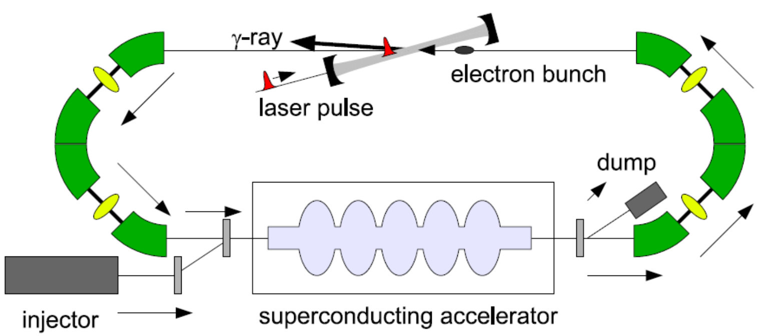
Storage Ring

Duke/HIGS 1-GeV Storage Ring



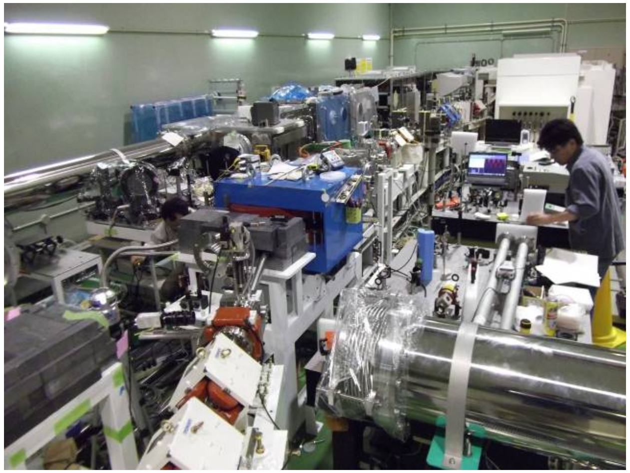
Energy Recovery Linac

JAEA 350-MeV ERL (proposal)



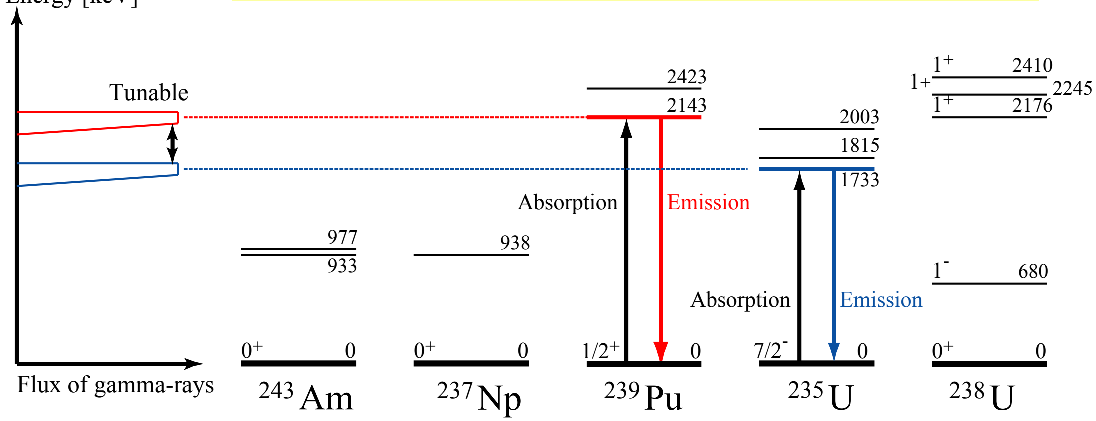
Microtron

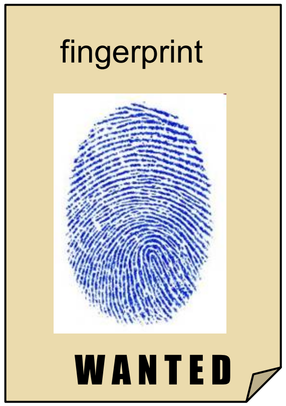
JAEA 150-MeV RTM



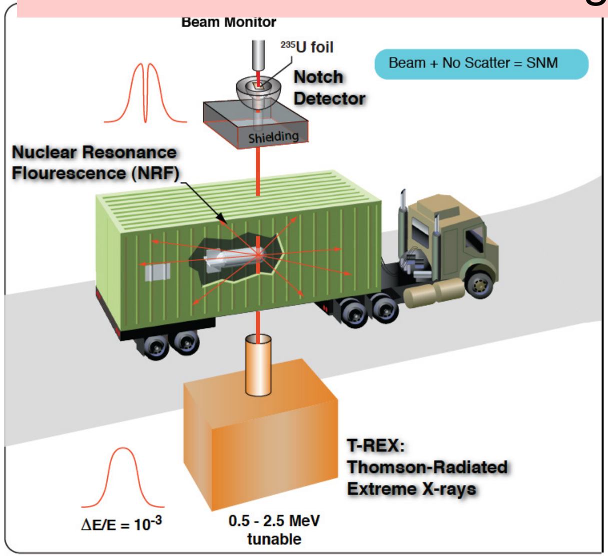
Nondestructive Detection & Measurement of Nuclear Material

Nuclear Resonance Fluorescence (NRF)



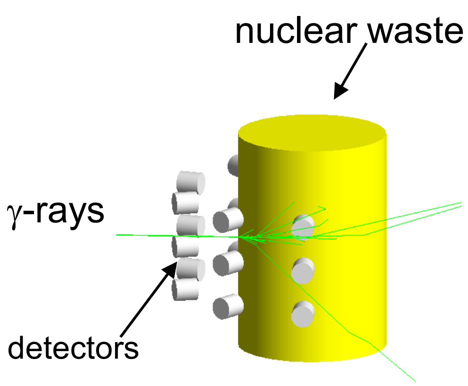


Detection of SNM in a cargo



SNM: special nuclear material

Management of nuclear material



detection and assay of isotopes
-- U, Pu, and Minor Actinides
-- alpha emitter
-- difficult to measure by passive assay

R. Hajima et al., J. Nucl. Sci. Tech. 45, 441 (2008)
J. Pruet et al., J. App. Phys. 99, 123102 (2006)

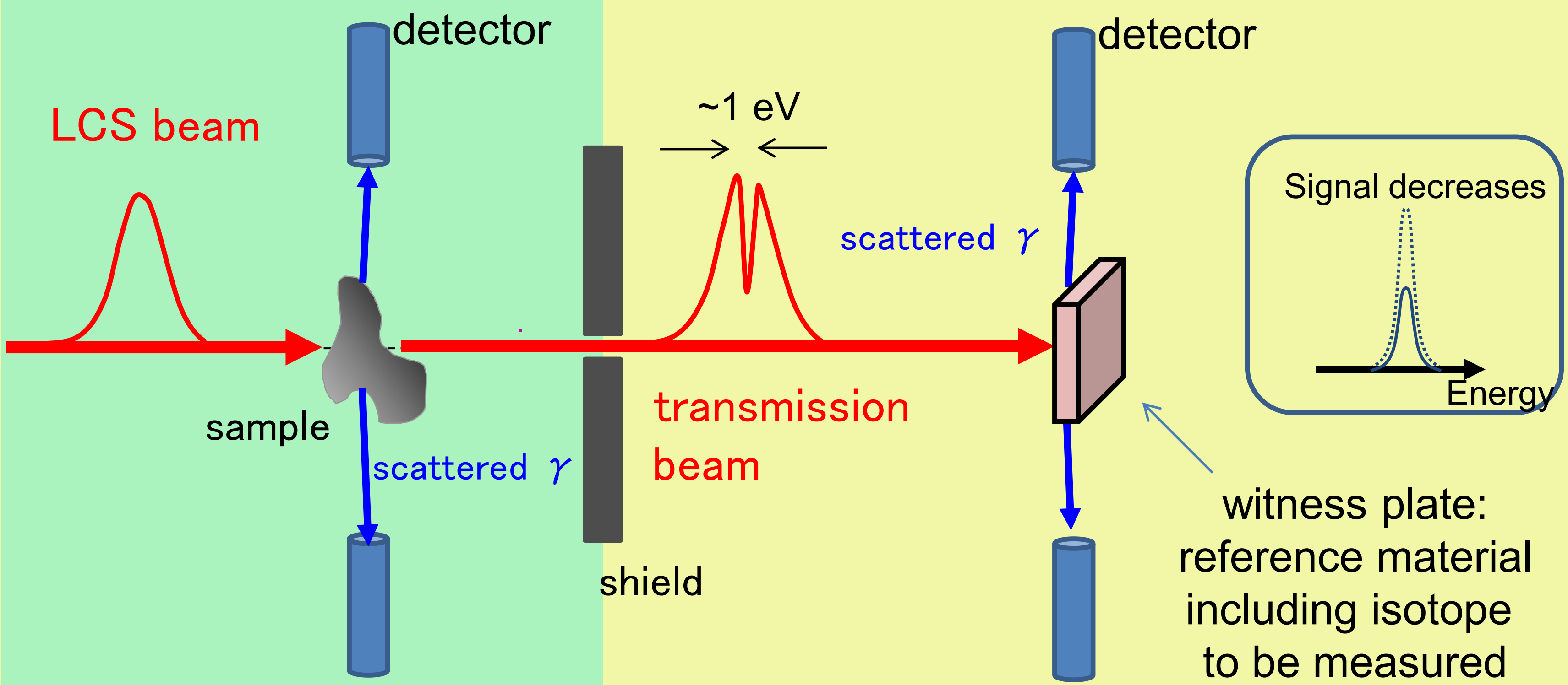
Two Measurement Methods

Scattering

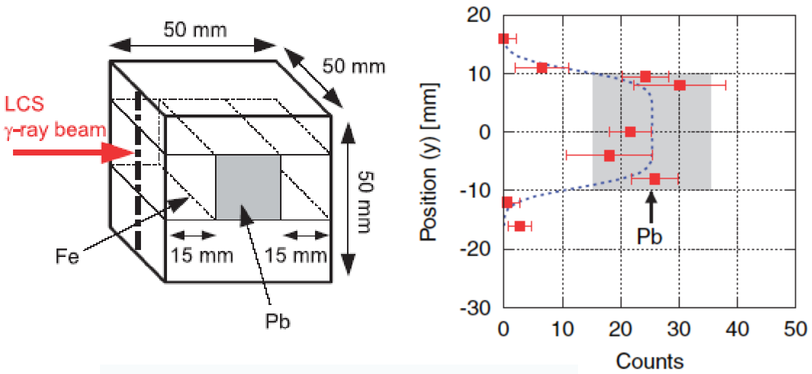
detect resonantly scattered γ

Transmission

detect resonantly absorbed portion of γ by "witness plate"

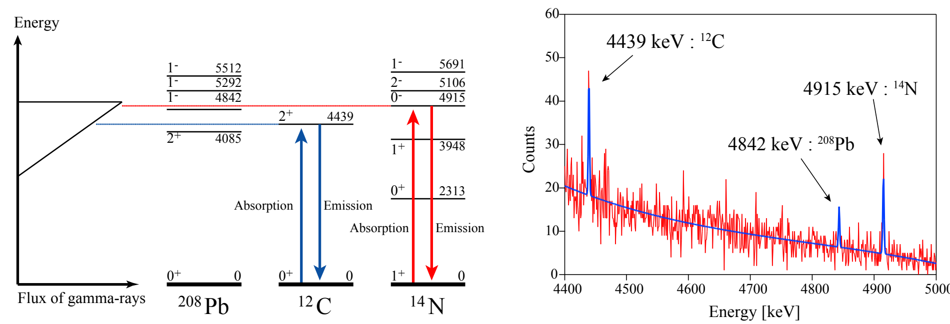


Experimental Demonstration – nondestructive detection of isotope



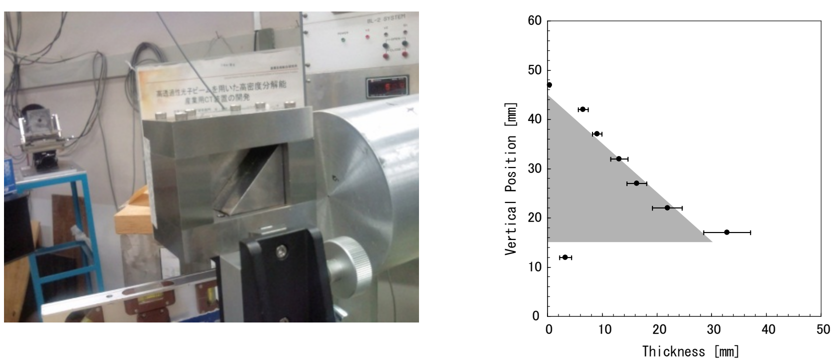
1-d isotope mapping

N. Kikuzawa et al., APEX 2, 036502 (2009).



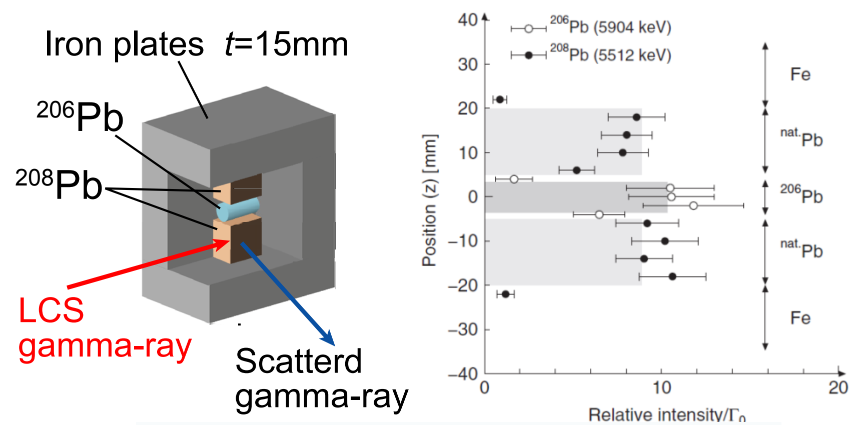
Detection of two isotopes

T. Hayakawa et al., RST 80, 045110 (2009).



2-d isotope mapping

H. Toyokawa et al., JJAP 50, 100209 (2011).



1-d mapping of two isotopes

T. Shizuma et al., RSI 83, 015103 (2011).

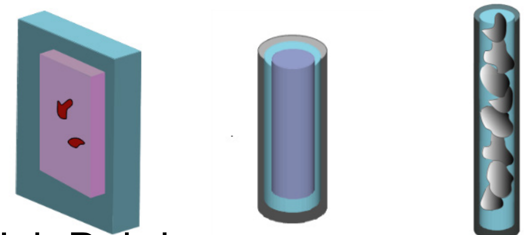
Demonstration for TMI-2 containers

C.T. Angell et al.,
“Demonstration of a transmission nuclear resonance fluorescence measurement for a realistic radioactive waste canister scenario”
NIM-B 347, 11 (2015)

LCS γ-ray for Fukushima

Measurement of Pu in the melted fuel → necessary for nuclear nonproliferation!

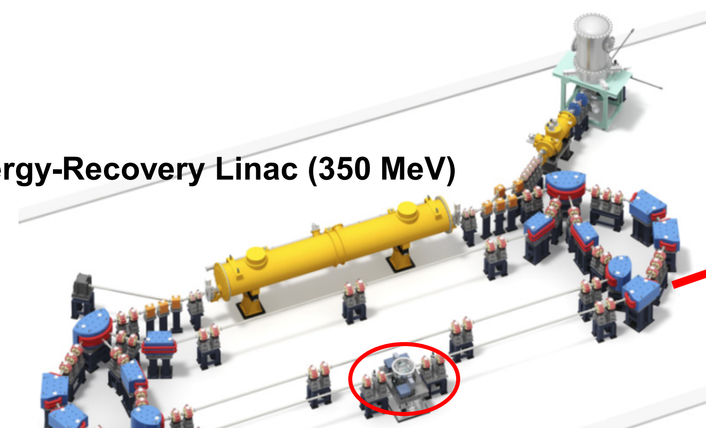
removal of debris
from the core ~2022

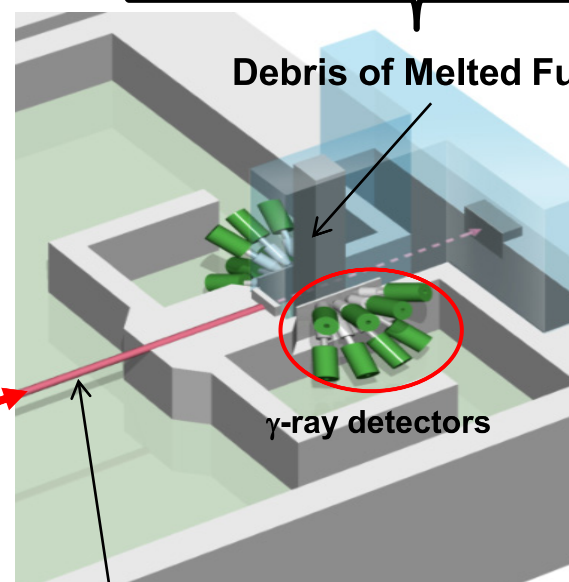


Slab Debris   Small Rock-Debris

Debris of Melted Fuel

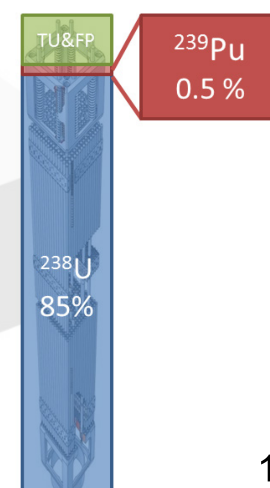
Energy-Recovery Linac (350 MeV)





γ-ray beam pipe

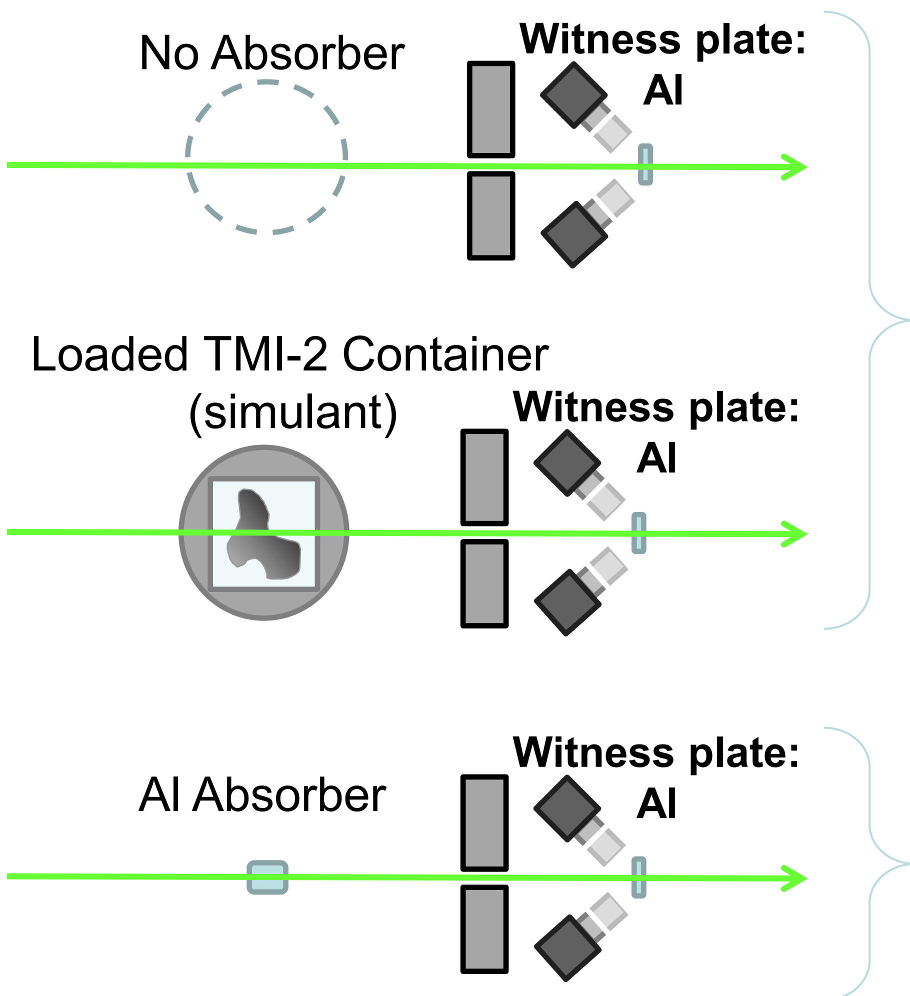
^{239}Pu Small Fraction of Spent Fuel



Demonstration for Debris in a TMI-2 container

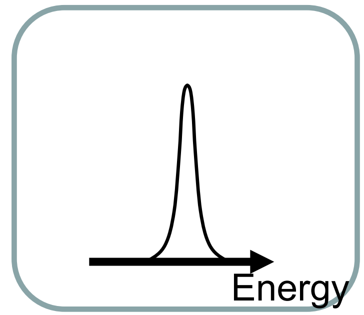
Experiment at Duke/HIγS
(LCS γ facility)

(TMI: Three Mile Island)



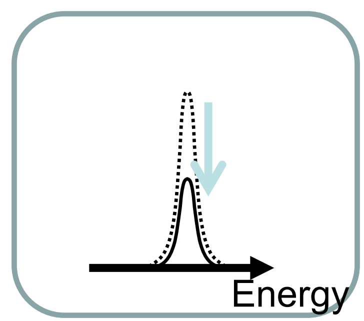
Al witness target chosen as it has strong resonance at similar energies to ^{239}Pu

No change expected!



Since witness target is Al, no absorption expected from simulant container

Signal decrease expected



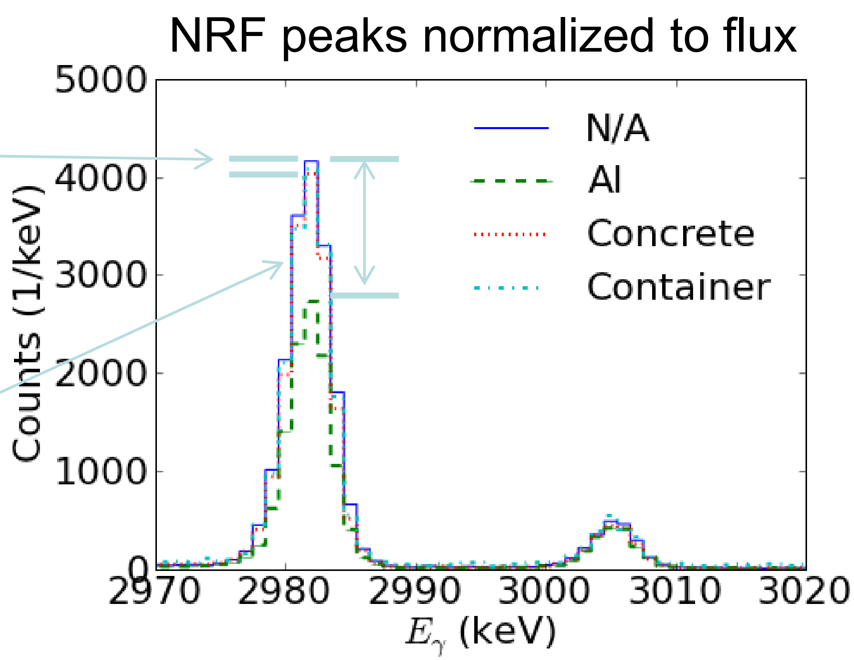
Using Al absorber can verify that experiment was done correctly.

Demonstration for Debris in a TMI-2 container

Verified NRF transmission feasible for TMI-2 container!

Small difference with concrete and container verified – concrete has small amount of Al

Large difference with Al absorber verified



Absorber	Expected	Measured
Concrete	0.96±0.01	0.95±0.02
Container	0.96±0.01	0.97±0.03
Al	0.66±0.01	0.65±0.02

C.T. Angell et al., Nucl. Instr. Meth. B 347, 11 (2015)

Analytical study shows
3.7h – 22h measurement for ^{239}Pu in melted fuel with 3% accuracy by using a future ERL-LCS

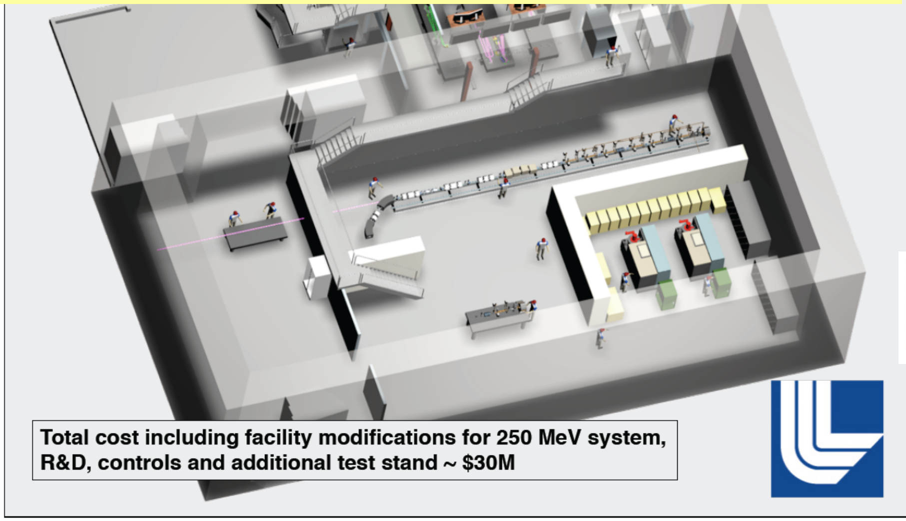
C.T. Angell et al., to be published

Demonstration of ERL-LCS

T. Akagi et al., Proc. IPAC-2014, p.2072
A. Kosuge et al., Proc. IPAC-2015, TUPWA-66
R. Nagai et al., Proc. IPAC-2015, TUPJE002
S. Sakanaka et al., Proc. IPAC-2015, TUBC1

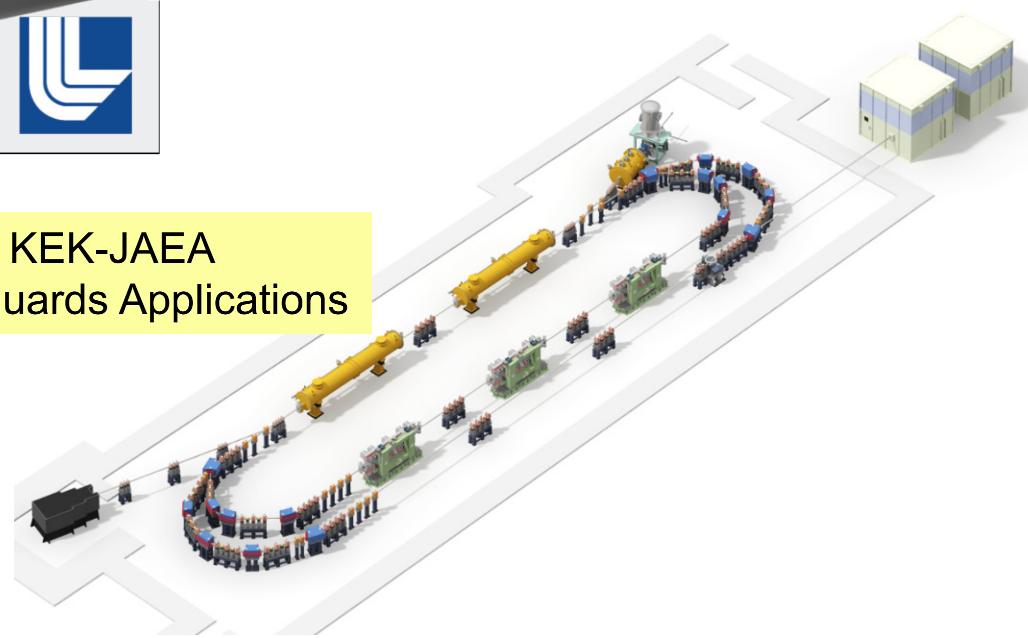
New generation of MeV Gamma-ray Sources

MEGA-RAY @ Lawrence Livermore Natl. Lab.
250 MeV Linac
$E\gamma$ = 1-2 MeV
Test Facility for Nuclear Security Applications



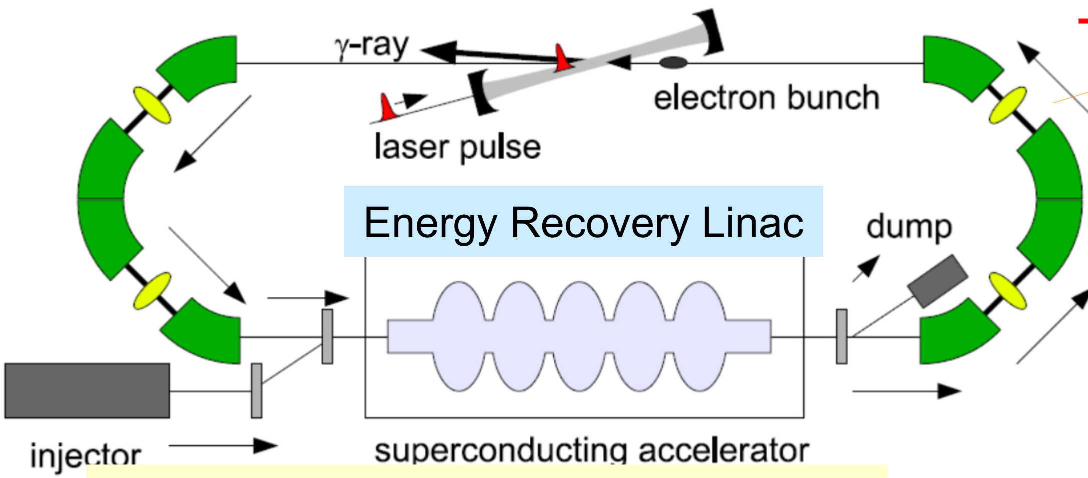
ELI-NP : Complex of PW lasers and LCS

ERL-based LCS gamma-ray @ KEK-JAEA
Test Facility for Nuclear Material Safeguards Applications



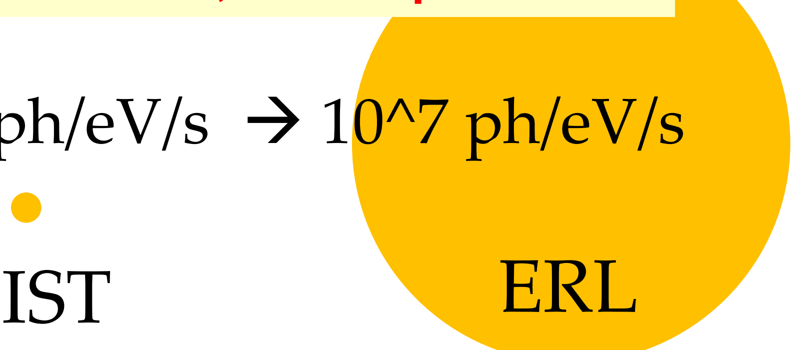
Proposal of ERL-based LCS γ-ray source

Low emittance & high-average current
→ high flux and narrow bandwidth γ-ray

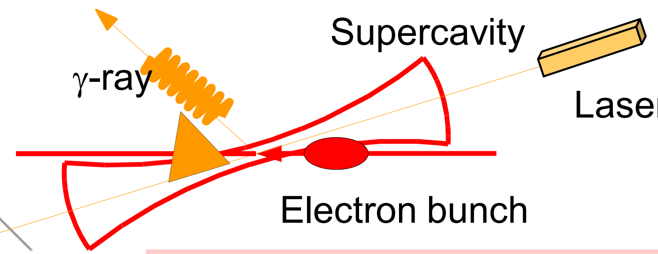


- Electron beam = 350 MeV, 13 mA
- Laser intracavity = 700 kW
- **LCS ~2MeV, 1×10^{13} ph/s**

0.1 ph/eV/s → 10^7 ph/eV/s



laser enhancement cavity



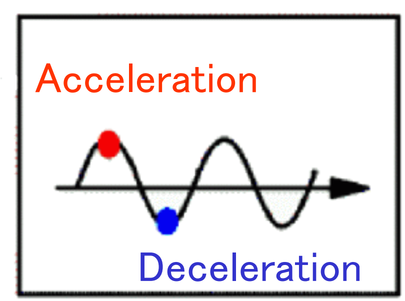
laser photons are recycled

↓

high-flux γ-ray

↑

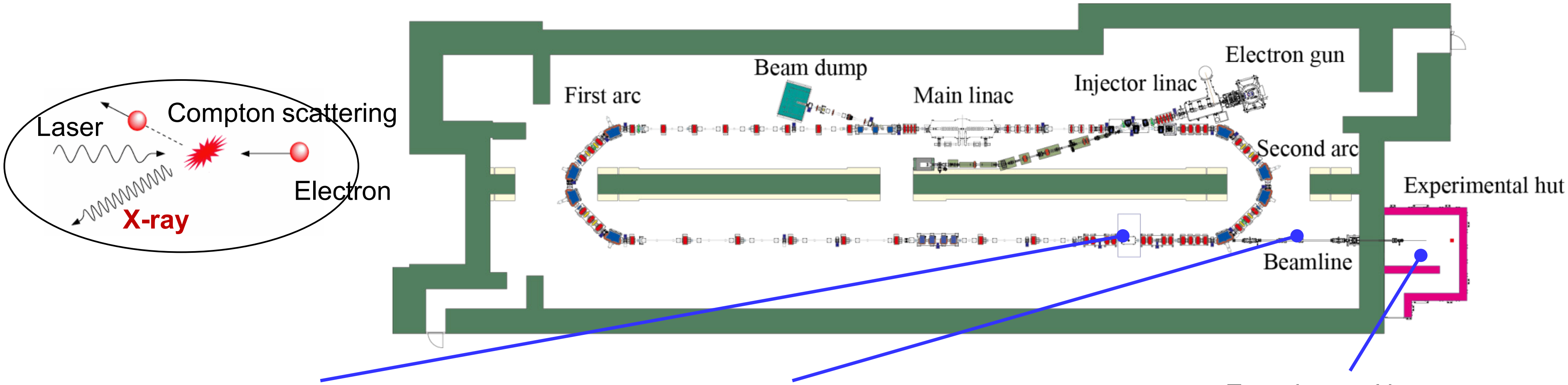
electron energy is recycled



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

LCS Experiment at the Compact ERL

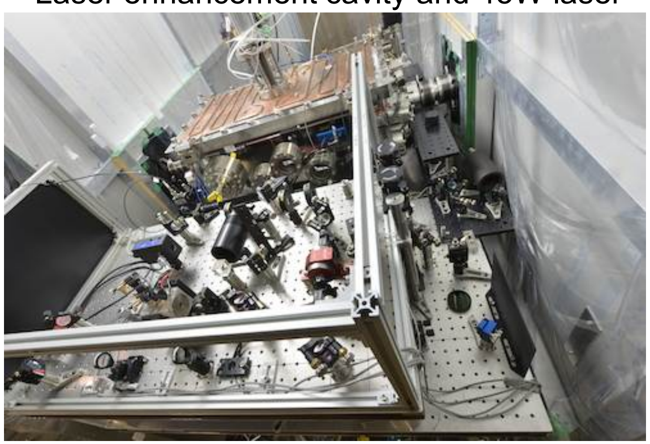
Demonstration of technologies relevant to future ERL-based LCS sources



Laser enhancement cavity and 45W laser

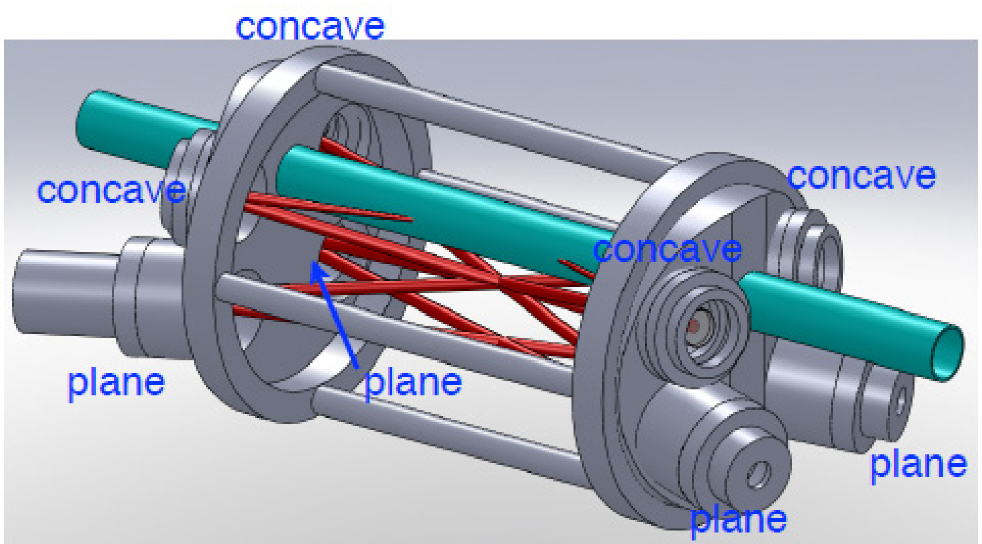
Beam line

Experimental hut



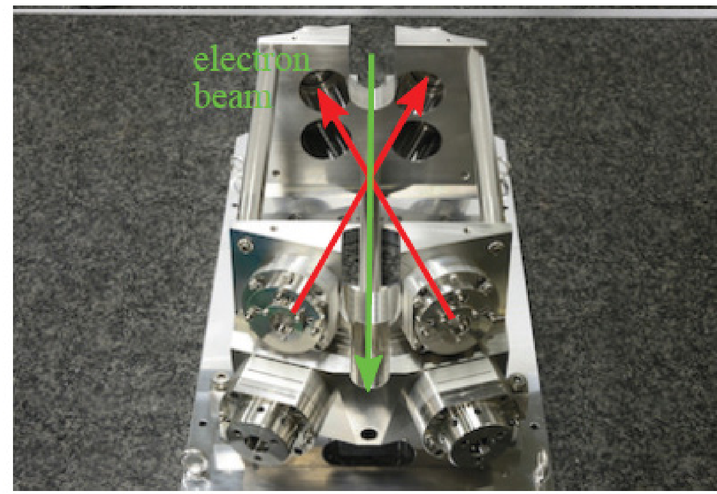
Work supported by:
A government (MEXT) subsidy for strengthening nuclear security (R. Hajima, JAEA), and
Photon and Quantum Basic Research Coordinated Development Program from the MEXT (N. Terunuma, KEK)

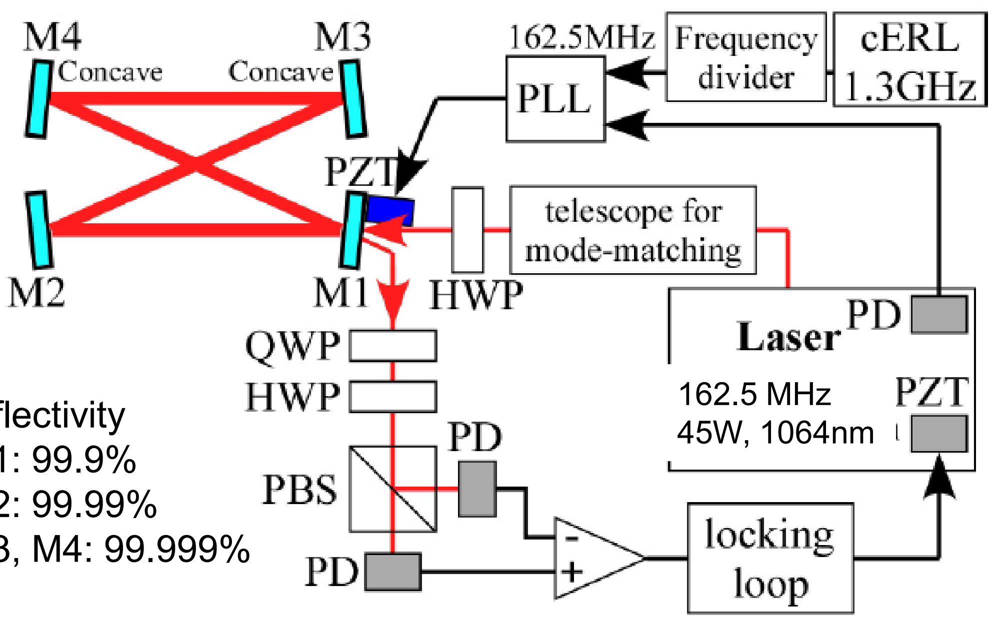
Laser Enhancement Cavity



Developed by T. Akagi (KEK)

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

Can store two beams independently

⇩

Fast polarization switch at 325 MHz
or
Double the laser power at LCS

(Single laser for the first experiment)

E-Beam tunings for the LCS

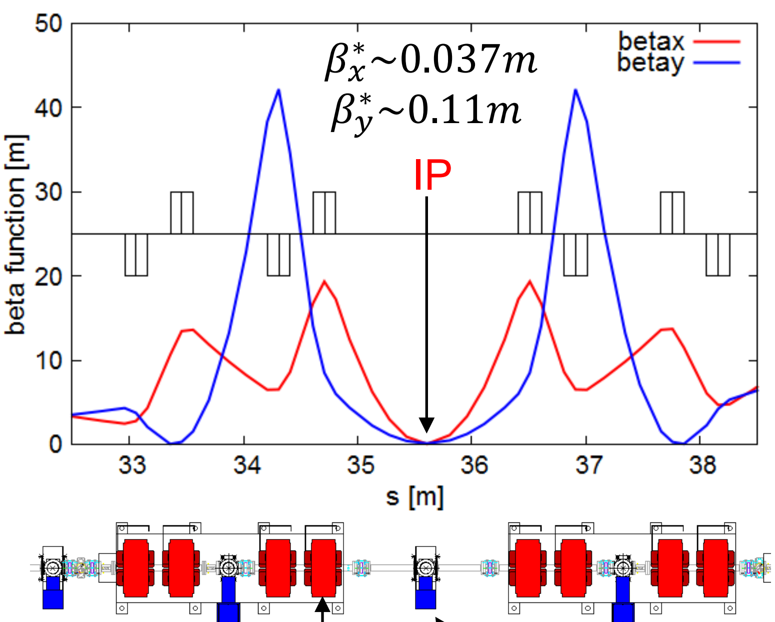
- Low-beta insertion for small beam sizes at IP
- Transport beams to the dump with small beam losses

Beam optics was established

IP: interaction point

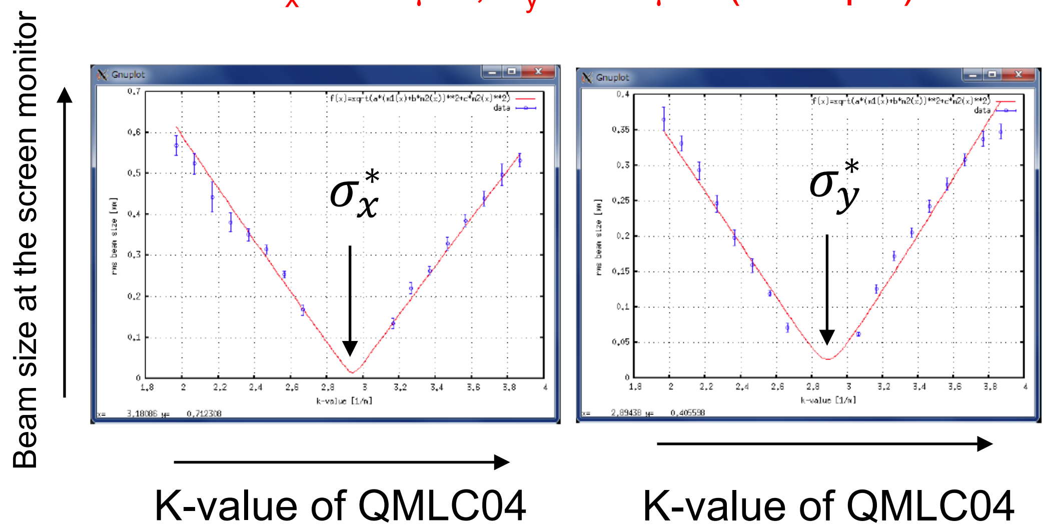
Design optics (example: “70% middle” optics)

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



$\sigma_x^*,\ \sigma_y^*$ < (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

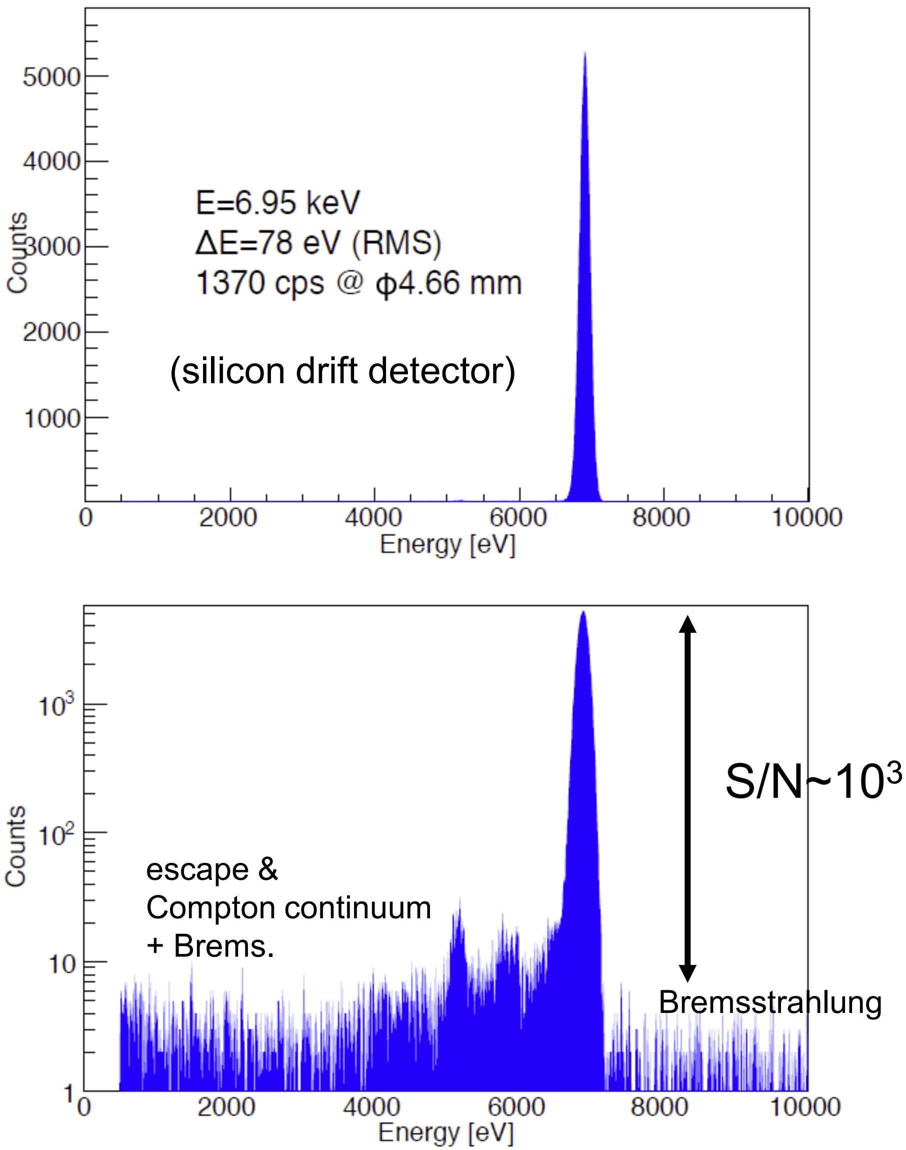
X-ray Produced by LCS

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



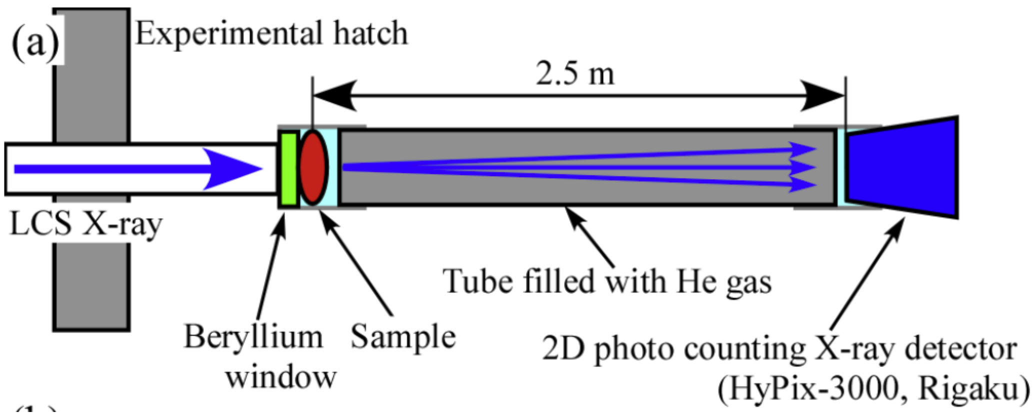
Results:

Photon energy = 6.95 keV
Detector count rate = 1370 cps @ϕ4.66mm (*)
Source flux = 2.6×10^7 ph/s (**)

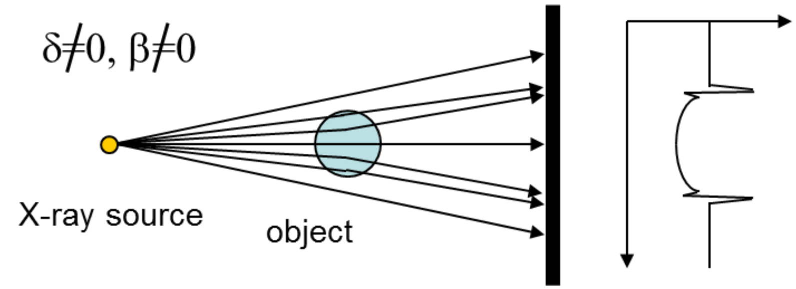
(*) Detector collecting angle is 4.66mm/16.6m = 0.281 mrad
(**) CAIN/EGS simulations with the detector count rate

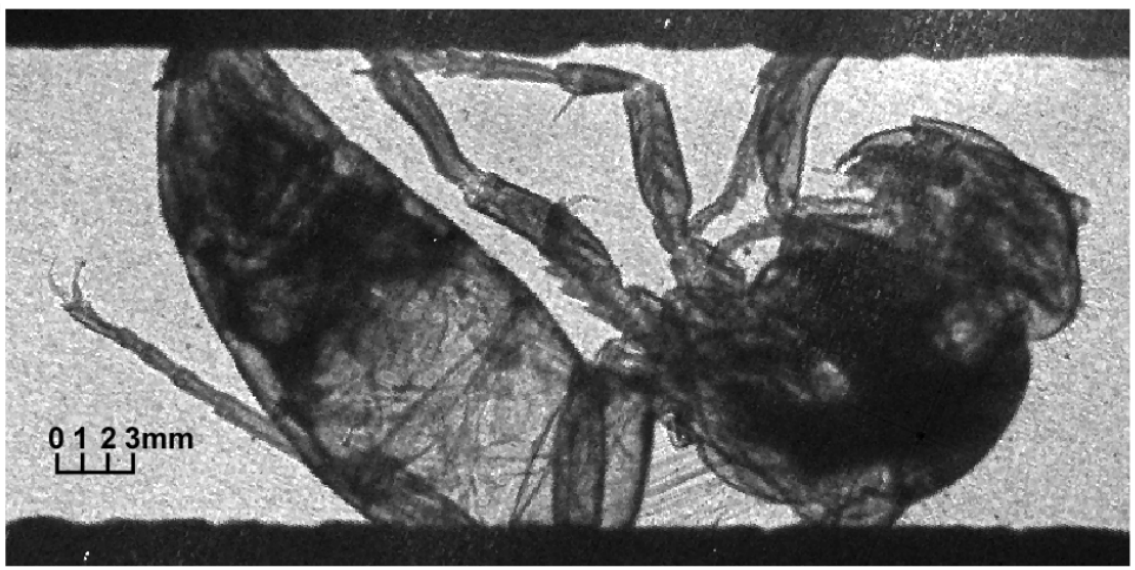
T. Akagi et al. submitted

X-ray imaging with a LCS beam



phase contrast imaging





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.

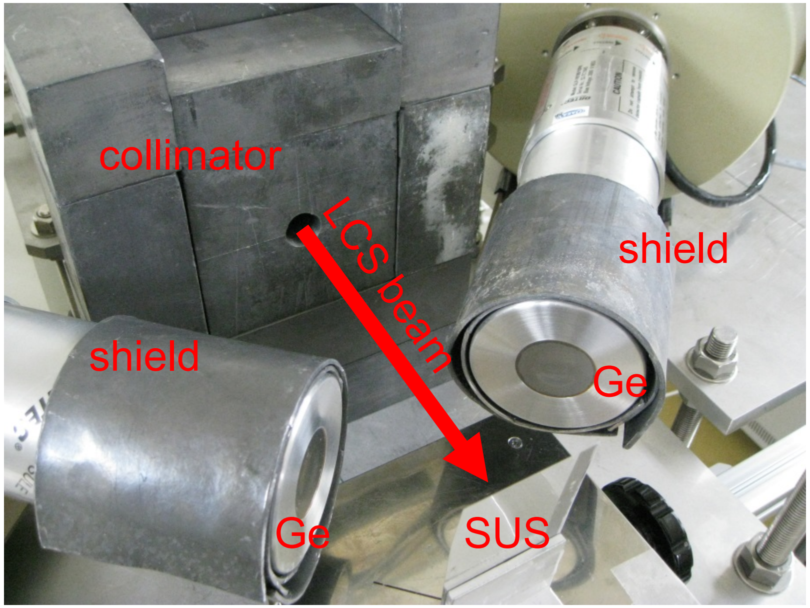
A. Kosuge et al., Proc. IPAC-2015, TUPWA066

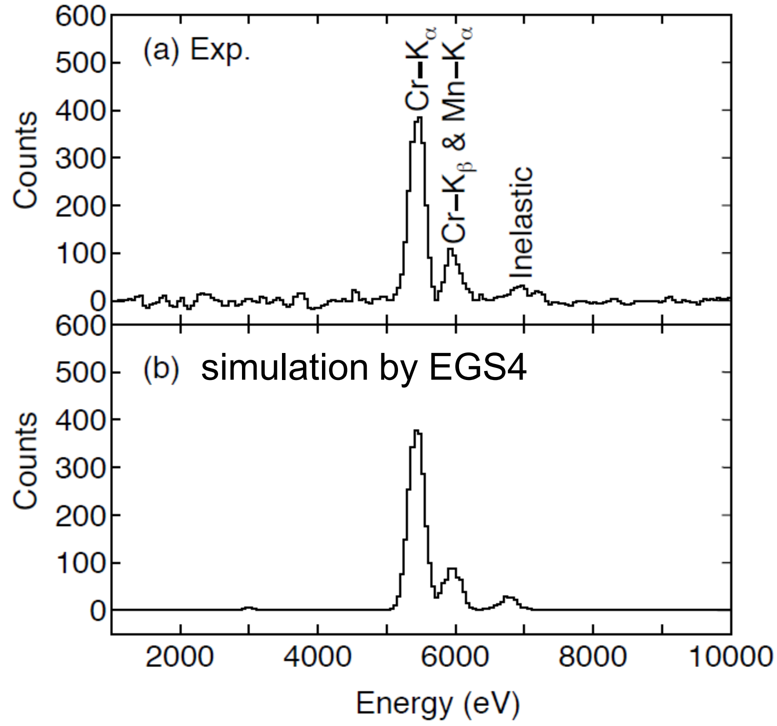
X-ray resonance fluorescence with a LCS beam

7 keV X-ray is between
K absorption edge of Mn and Fe

Elements	K edge [keV]	K_α [keV]
Cr	5.989	5.4, 5.9
Mn	6.539	5.9, 6.5
Fe	7.112	6.4, 7.1

minor composition (Cr, Mn) in SUS can be assayed with XRF

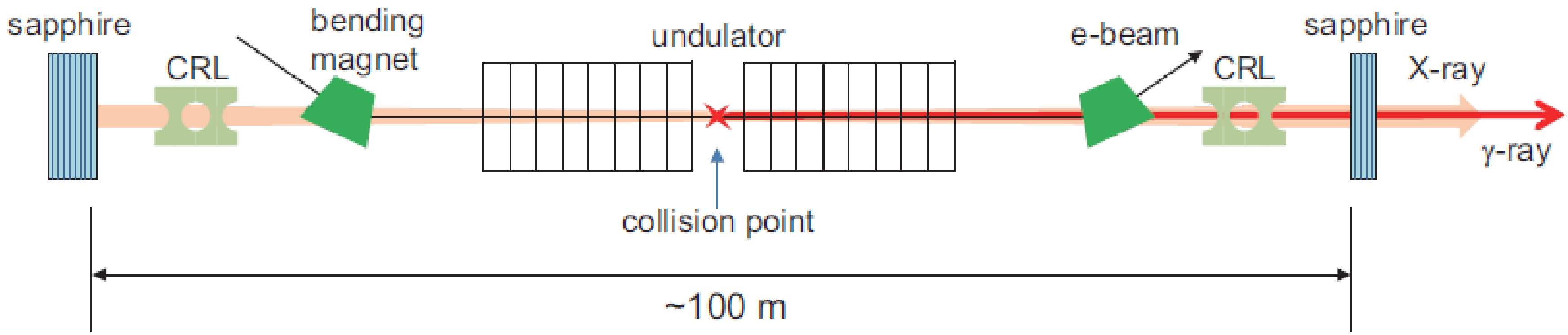




Narrow-band GeV photon generation from XFELO

R. Hajima and M. Fujiwara, Phys. Rev. Accel. Beams 19, 020702 (2016).

XFELO-γ = XFEL Oscillator + LCS



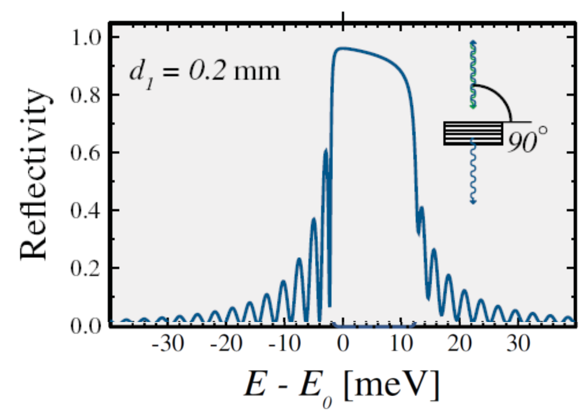
X-ray oscillator with Bragg mirrors (perfect crystals)

spatial and temporal coherence

next-generation X-ray source

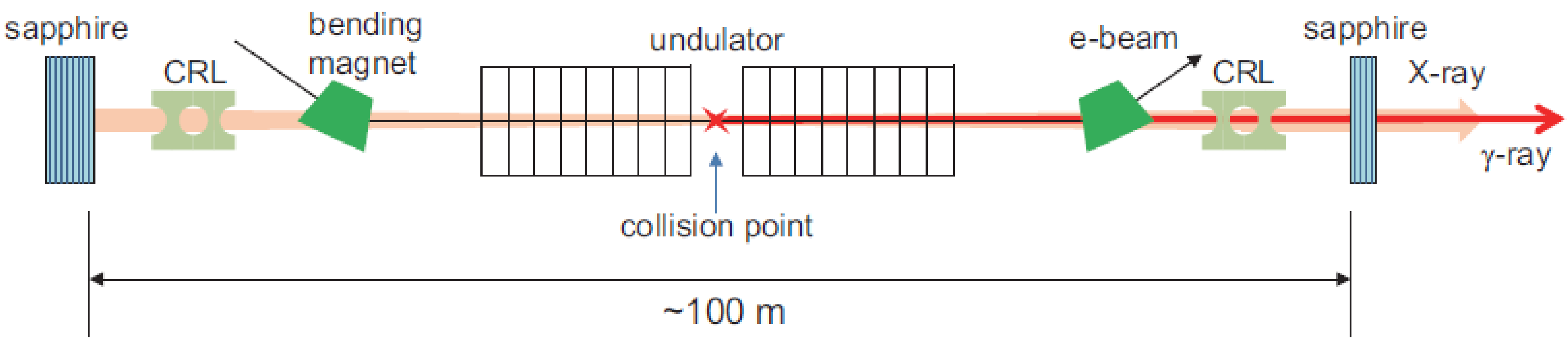
K-J. Kim et al. ERL-2007 WS
PRL 100, 244802 (2008)

Bragg reflection at Al2O3 (14.3keV)



Compton scattering occurs as well as VUV-FEL
Compton photons have "GeV" energy

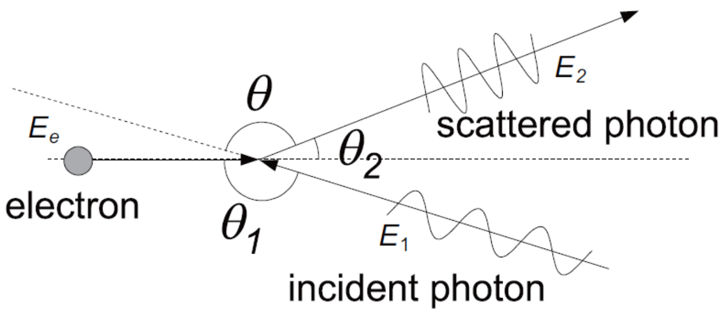
Design parameters 7-GeV XFELO-γ

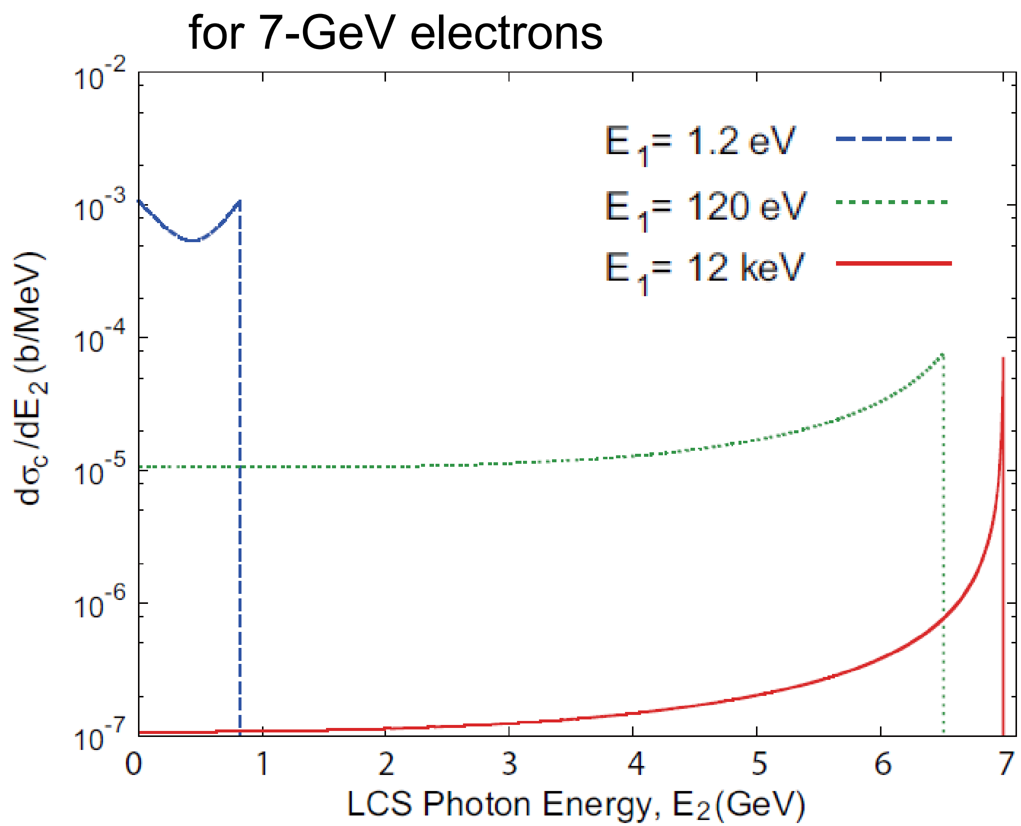


E_e (GeV)	Q (pC)	σ_E (MeV)	ε_n (mm-mrad)	τ_e (ps)
7	40	1.4	0.082	2
f (MHz)	K	λ_u (cm)	N_u	Z_R (m)
3	1.414	1.88	3000	10
λ (Å)	gain (%)	loss (%)	out couple (%)	N_X
1.0	50	17	4	2.0×10^{10}

Repetition of 3 MHz → 2 FEL pulses in the oscillator
→ Compton scattering at the undulator center

Energy differential cross section of Compton scattering





$$\gamma_e = E_e/mc^2,$$

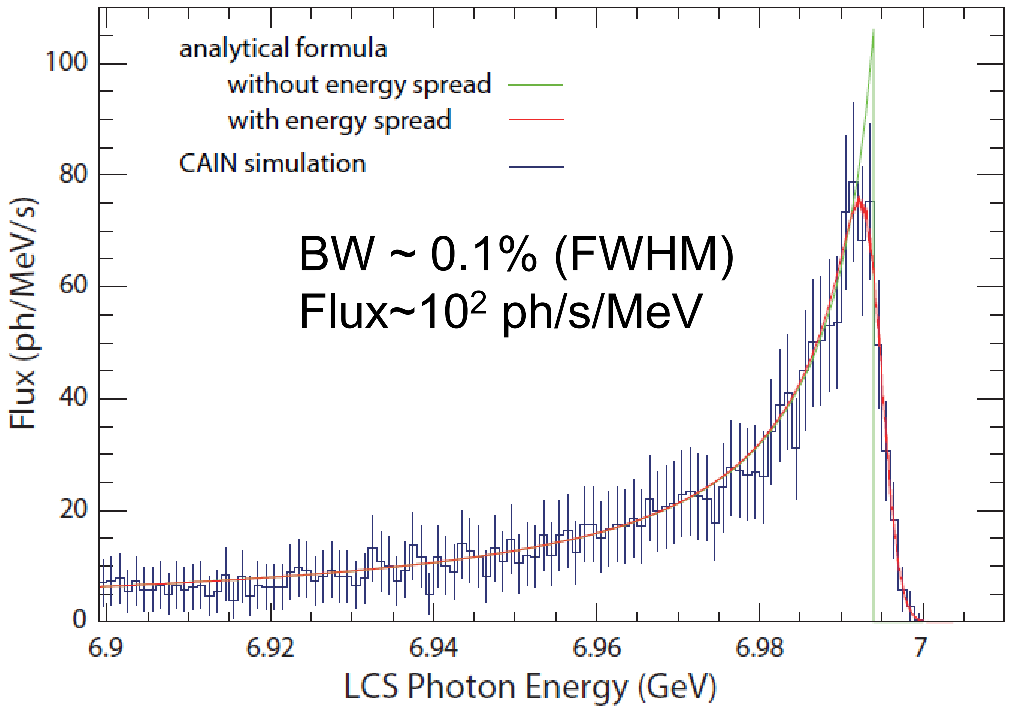
$$\epsilon_1 = E_1/mc^2$$

$$\epsilon_2 = E_2/mc^2$$

$$\frac{d\sigma_c}{d\epsilon_2} = \frac{\pi r_0^2}{2}\frac{1}{\gamma_e^2\epsilon_1}\left[\frac{1}{4\gamma_e^2\epsilon_1^2}\left(\frac{\epsilon_2}{\gamma_e-\epsilon_2}\right)^2 - \frac{1}{\gamma_e\epsilon_1}\left(\frac{\epsilon_2}{\gamma_e-\epsilon_2}\right) + \frac{\gamma_e-\epsilon_2}{\gamma_e} + \frac{\gamma_e}{\gamma_e-\epsilon_2}\right]$$

F. R. Arutyunian and V.A. Tumanian, Phys. Lett. 4, 176 (1963)

GeV photon spectrum of XFELO-γ



Energy is tunable by changing e-beam energy with keeping X-ray oscillation.

XFELO-γ provides a new opportunity for studying the charmed quark (c-quark) production dynamics from proton and neutron which mainly consist of u- and d-quarks.

Summary

- Compton sources have been developed and utilized in a wide range of photon energy from keV to GeV.
- CS is the only practical energy-tunable source in MeV and GeV. There are many demands such as isotope-specific non-destructive detection and assay.
- Flux, spectral density and bandwidth have been improved according to a progress of laser and e-beam technologies.
- ERL-based Compton source demonstrated at the cERL is a promising path towards a high-flux and narrow-bandwidth CS.

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