Linac-Based Laser Compton Scattering X-ray and γ-ray Sources

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XXVI Linear Accelerator Conference
Sep. 12, 2012

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   Principle and Features

2. LCS X-ray Sources
   applications
   R&D programs

3. LCS gamma-ray Sources
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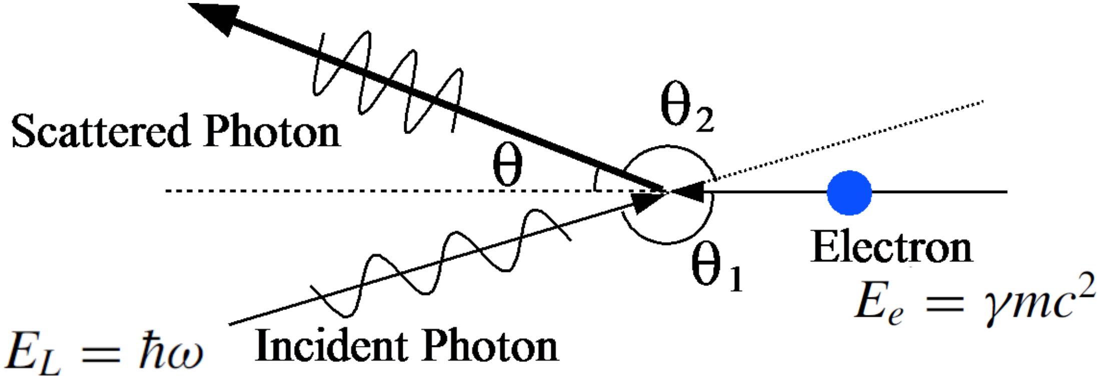
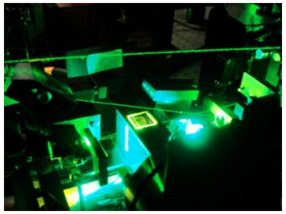
Laser Compton Scattering (LCS)





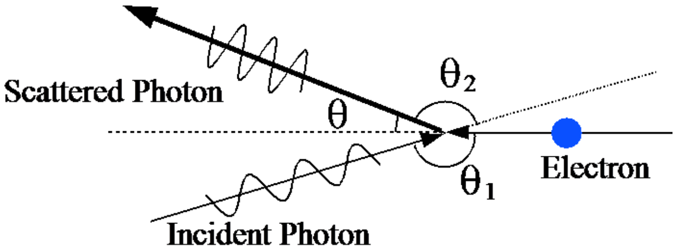
$$E_X = \frac{E_L(1 - \beta\cos\theta_1)}{1 - \beta\cos\theta + (E_L/E_e)(1 - \cos\theta_2)}$$

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

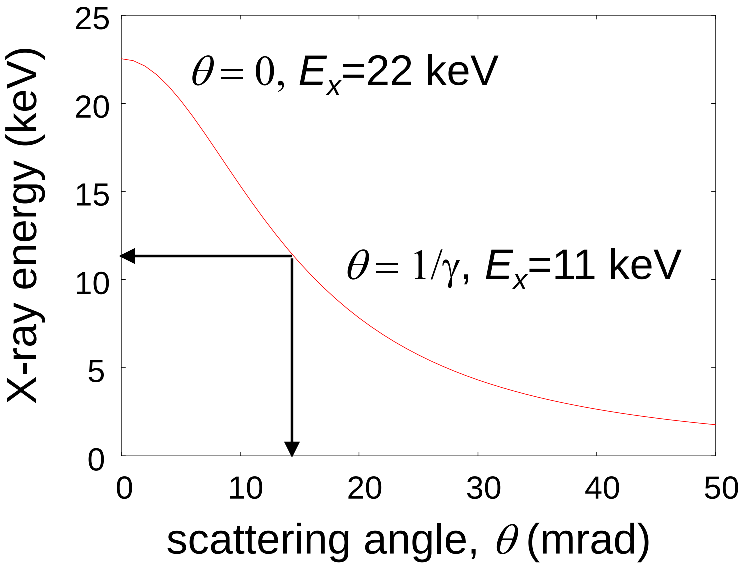
- ✓ Pencil like beam
- ✓ Energy Tunable
- ✓ Polarized (linear and circular)
- ✓ Correlation of E_X and θ

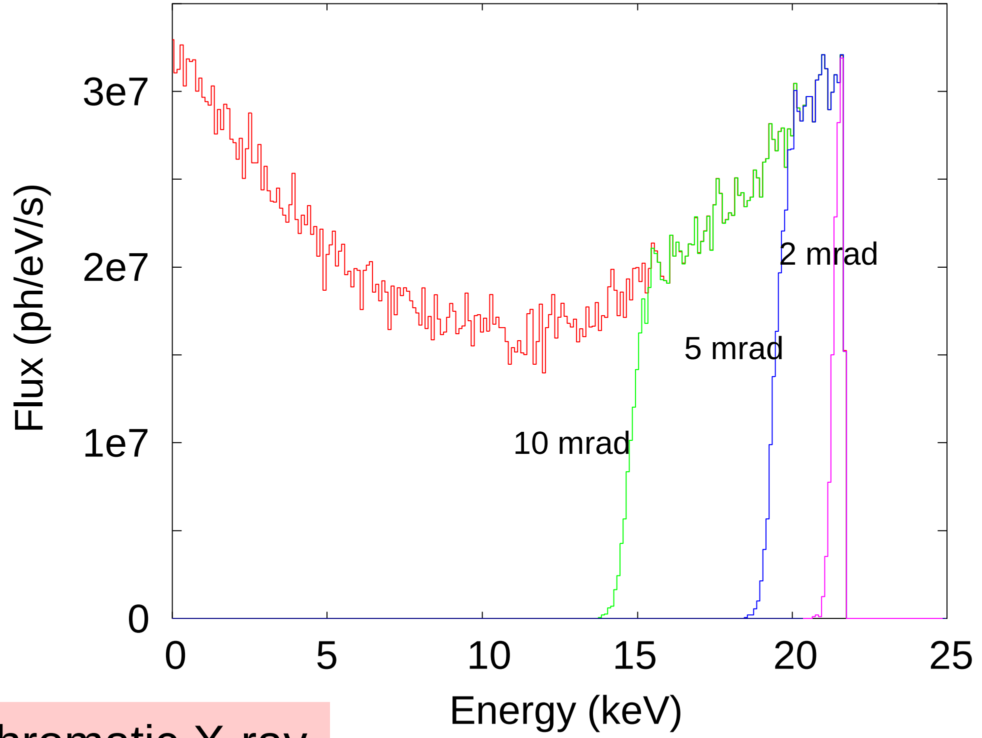
Quasi-monochromatic LCS photon beam

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



for example: E_e = 35 MeV, E_L = 1.2 eV





quasi-monochromatic X-ray
is obtained with a collimator

Flux and Brightness of LCS sources

Flux : photons/s

$$F_{total} = \frac{16}{3} N_e N_L f \frac{r_0^2}{w_0^2}$$

electron classical radius

collision spot size

electrons

laser photons

collision frequency

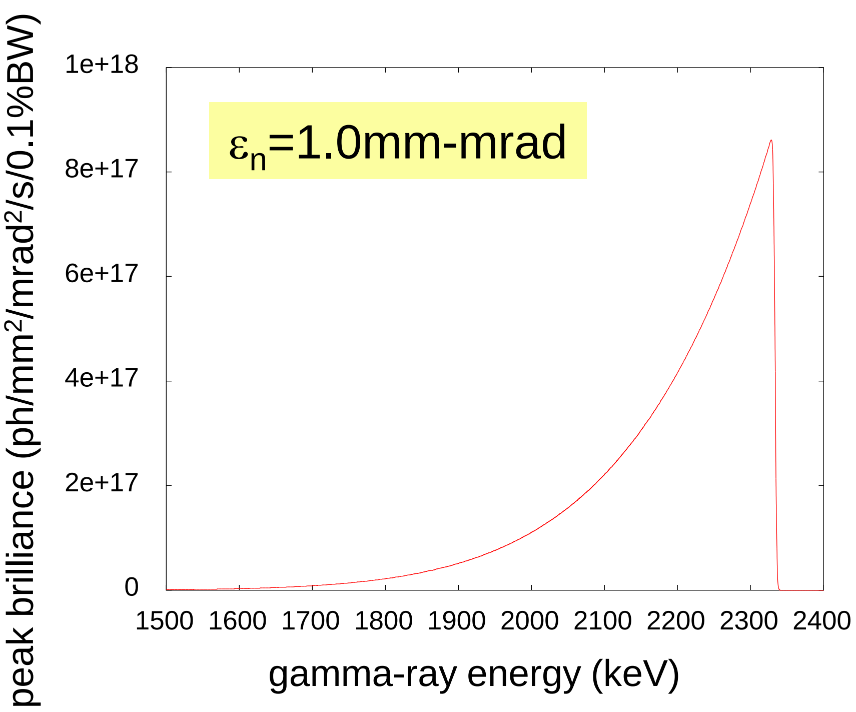
Spectral Brightness: photons/s/mm^2/mrad^2/0.1%BW

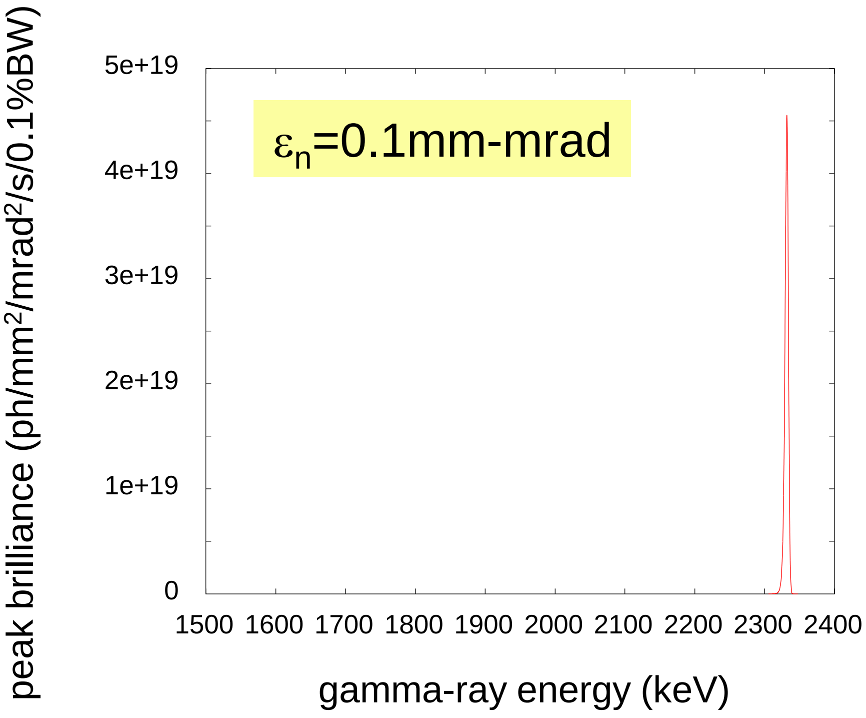
$$B \approx F_{total} \frac{\gamma^2}{\varepsilon_n^2} \times 0.1\%$$

for the higher brightness

- higher collision density
- higher repetition rate
- smaller emittance

Analytical evaluation of on-axis brightness





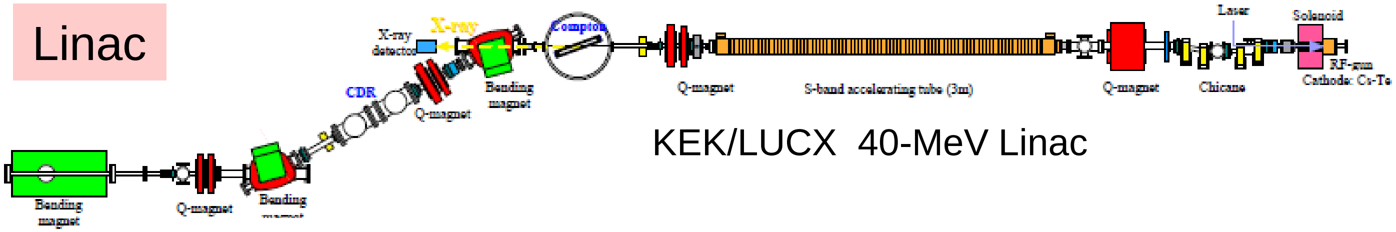
$$\hat{B}_x = \frac{4\times 10^{-15}}{\pi^2}\frac{\gamma_0^2}{\varepsilon^2}\frac{N_e N_\lambda}{\Delta\tau}\frac{r_0^2}{w_0^2}\exp\left\{\frac{\chi-1}{2\chi\Delta u_\perp^2}\left[2+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right\}\left[1-\Phi\left\{\frac{\chi-1}{\sqrt{\delta\omega^2+\delta\gamma^2\chi^2}}\left[1+\frac{\delta\omega^2+\delta\gamma^2\chi^2}{2\chi(\chi-1)\Delta u_\perp^2}\right]\right\}\right] \times \frac{\eta e^{1/\mu^2}[\Phi(1/\eta)-1]-\mu e^{1/\mu^2}[\Phi(1/\mu)-1]}{\mu^2-\eta^2}, \quad (50)$$

calculation by using a formula in [1].

[1] F.V. Hartemann et at. Phys. Rev. ST AB 8, 100702 (2005).

Various types of LCS Sources

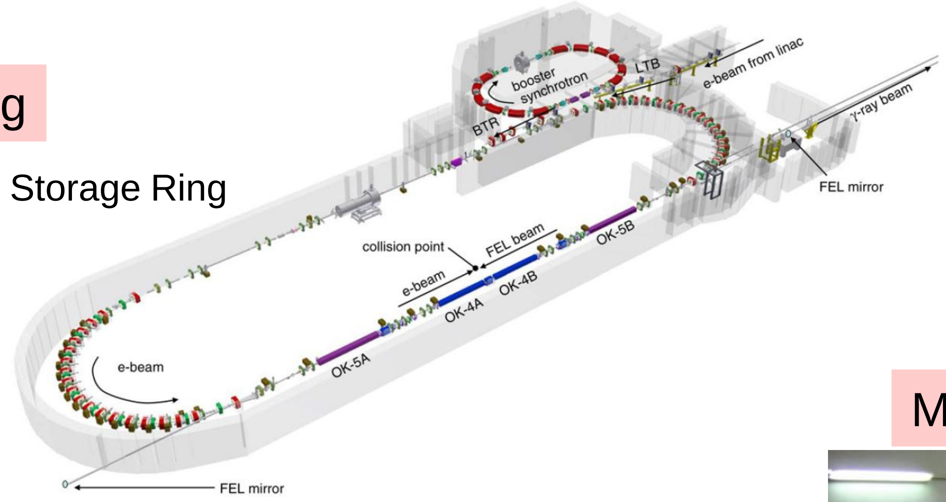
Linac



KEK/LUCX 40-MeV Linac

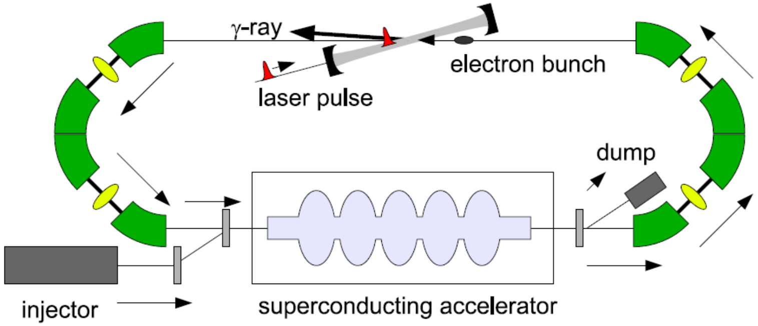
Storage Ring

Duke/HIGS 1-GeV Storage Ring



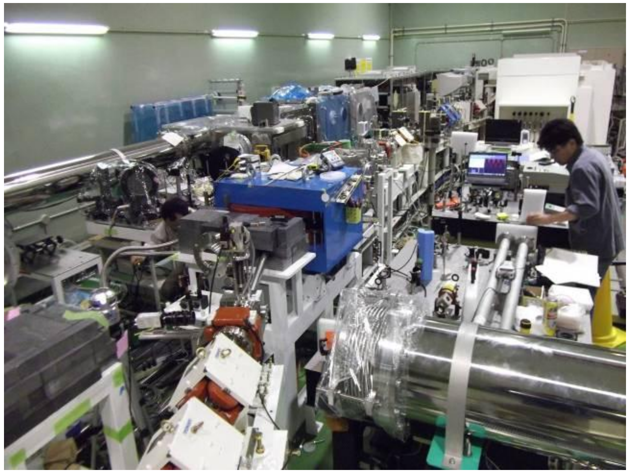
Energy Recovery Linac

JAEA 350-MeV ERL (proposal)



Microtron

JAEA 150-MeV RTM



Linac-based LCS Sources

Advantages of Linac

in combination with modern acc. technologies

small emittance → high spectral brightness

short electron bunch → short pulse X-ray

free from quantum excitation

scattering of high-energy photons
→ large energy spread in e-beam especially for γ-ray

Drawbacks of Linac

low repetition rate → small flux

can be compensated by multi bunch operation

or energy recovery linac

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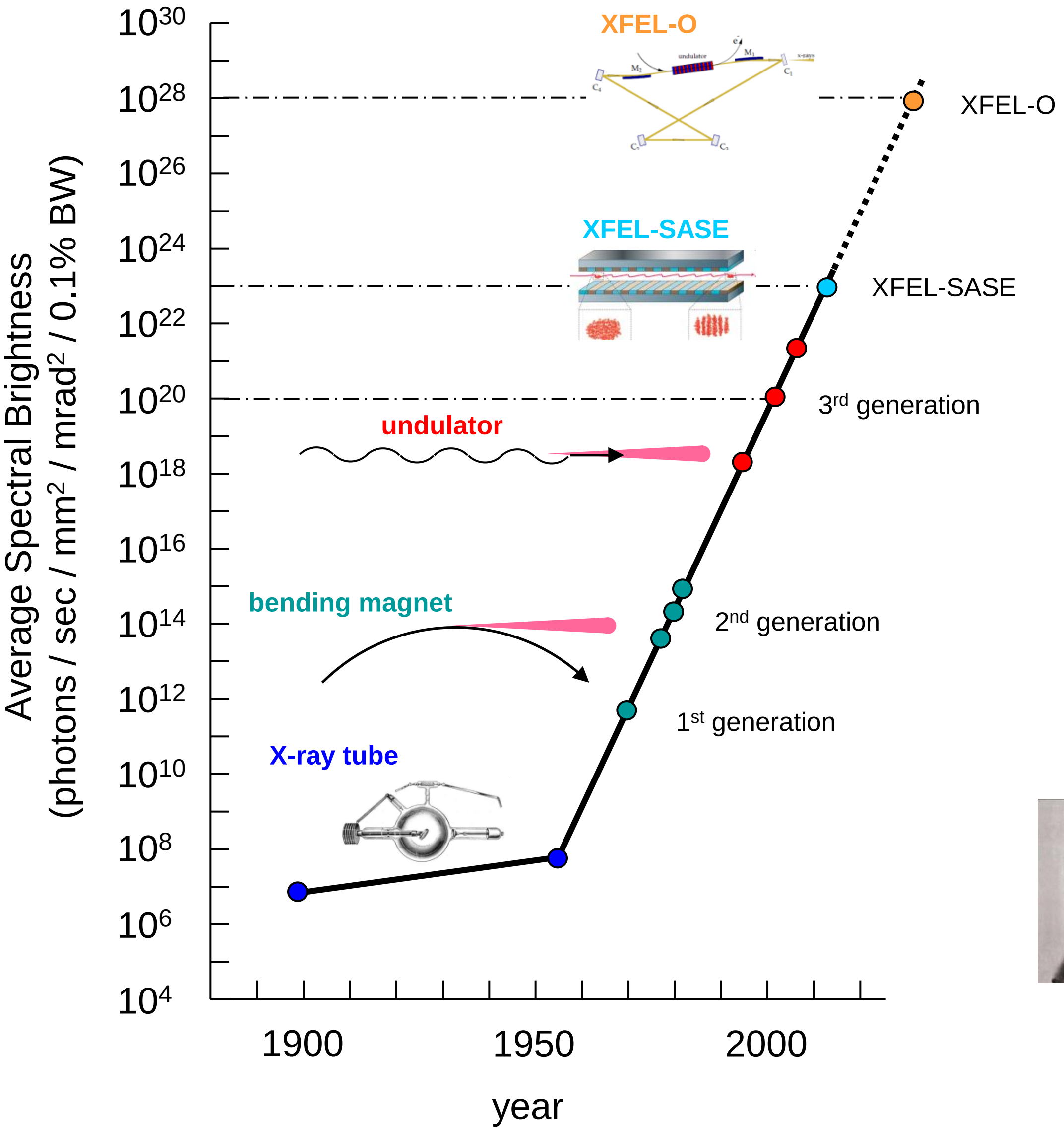
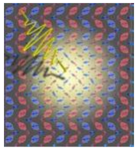
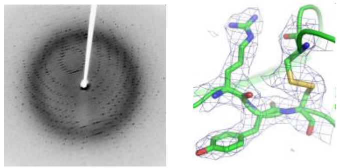
Applications of X-ray Sources

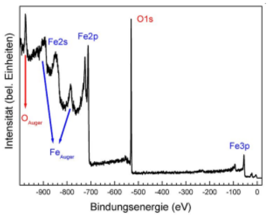




dynamic structure



crystallography



spectroscopy

imaging

Phase Contrast Imaging

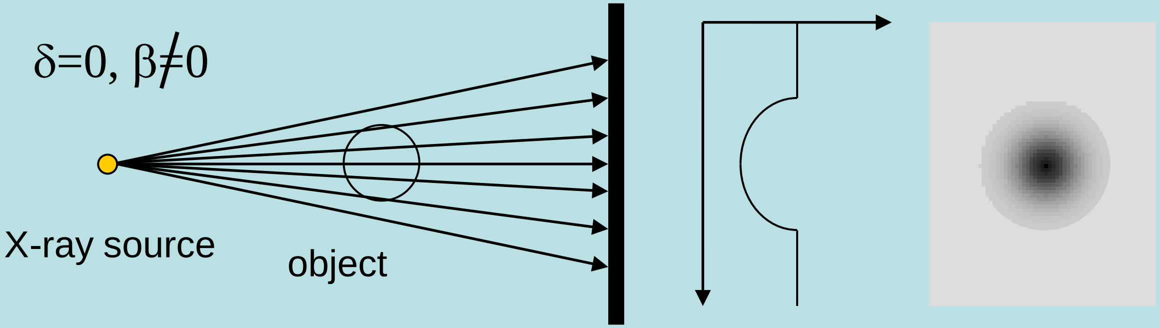
complex refractive index of X-ray

$$n = 1 - \delta - i\beta$$

phase shift ← δ absorption ← β

absorption imaging

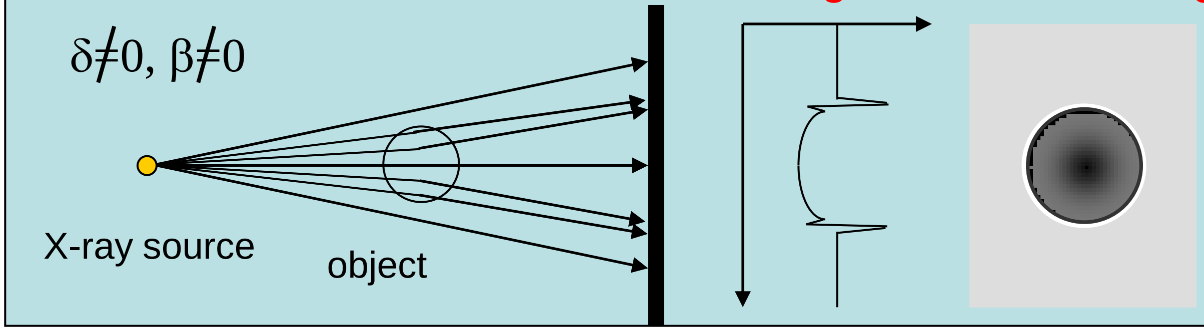
$\delta=0,\ \beta\neq0$



phase contrast imaging

$\delta\neq0,\ \beta\neq0$

edge-enhanced image



✓small source is essential

✓no need monochro X-ray

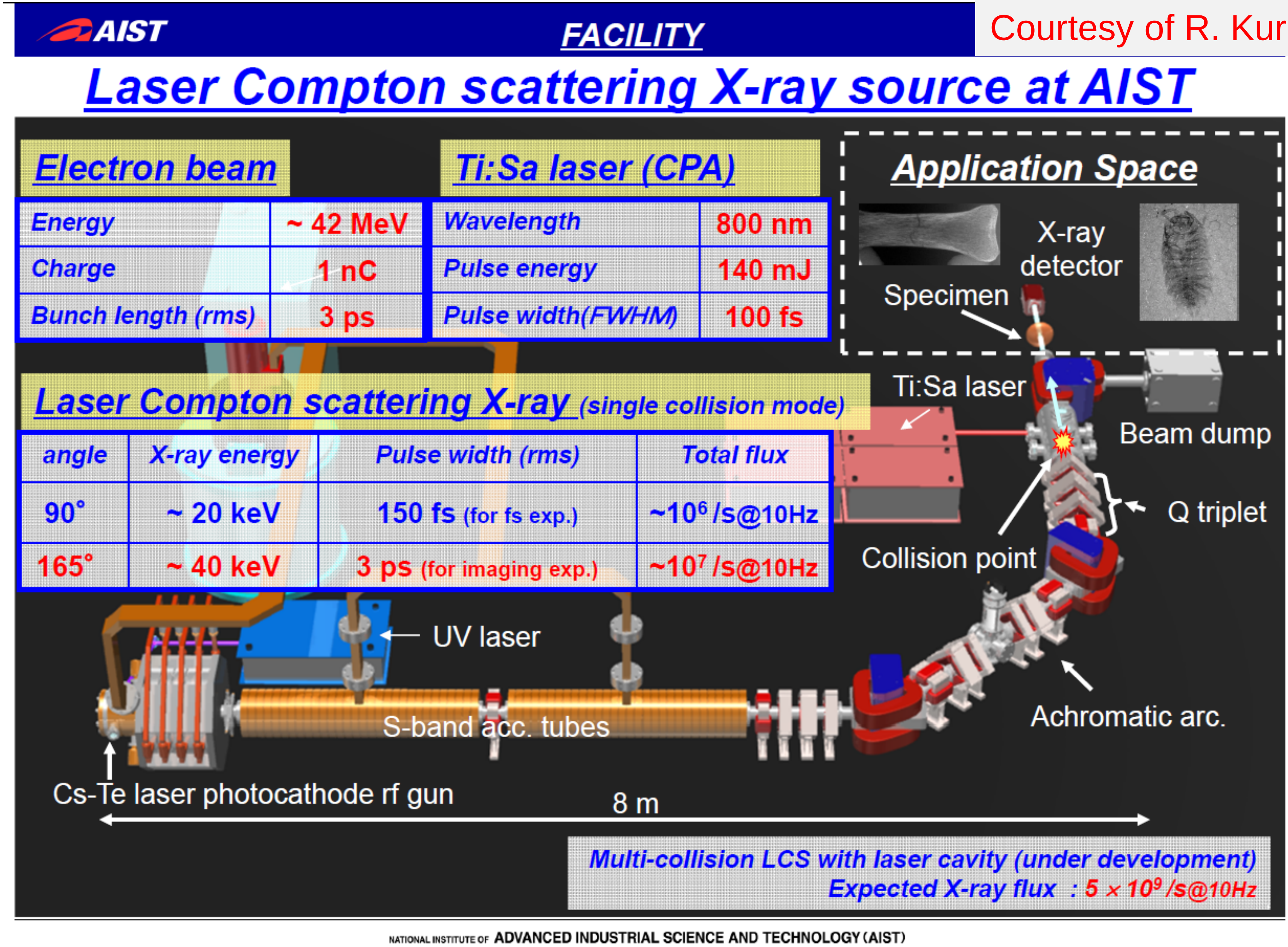
good matching with LCS

In biomedical tissues, $\delta \gg \beta$

10^3 1

LCS X-ray Source at AIST

Courtesy of R. Kuroda



AIST FACILITY

Laser Compton scattering X-ray source at AIST

Electron beam

Energy	~ 42 MeV
Charge	1 nC
Bunch length (rms)	3 ps

Ti:Sa laser (CPA)

Wavelength	800 nm
Pulse energy	140 mJ
Pulse width(FWHM)	100 fs

Application Space

Laser Compton scattering X-ray (single collision mode)

angle	X-ray energy	Pulse width (rms)	Total flux
90°	~ 20 keV	150 fs (for fs exp.)	~10^6 /s@10Hz
165°	~ 40 keV	3 ps (for imaging exp.)	~10^7 /s@10Hz

Multi-collision LCS with laser cavity (under development)
Expected X-ray flux : 5 × 10^9 /s@10Hz

NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE AND TECHNOLOGY (AIST)

LCS X-ray Source at AIST

AIST **APPLICATIONS**

Courtesy of R. Kuroda

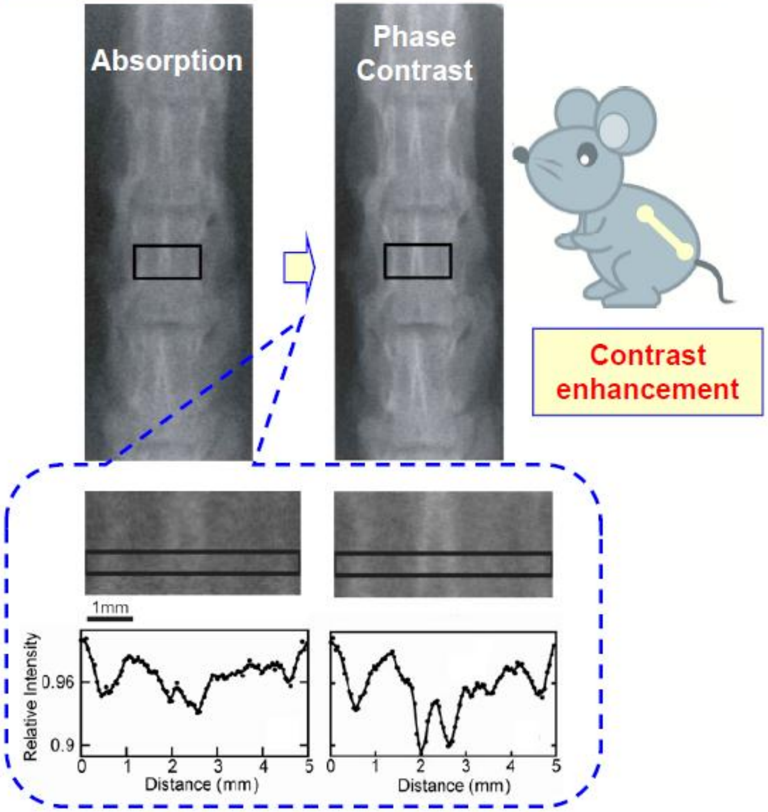
In-line phase contrast imaging

Purpose: Investigation of Initial bone disease *(Osteoporosis)*

In collaborating with
Ibaraki Prefectural University of Health Sciences

Sample : Rat's lumbar vertebra
X-ray energy : 30 keV

For example



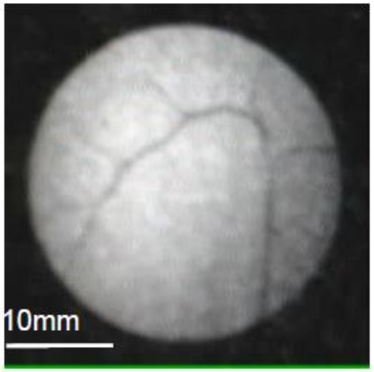
K-shell absorption edge imaging

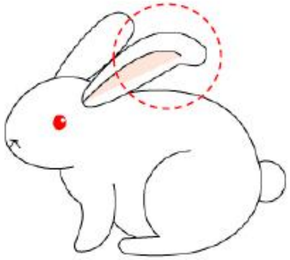
Purpose: Investigation of initial symptom of the blood vessel disease *(Diabetes)*

In collaborating with
National Cerebral and Cardiovascular Center
& Tokai University School of Medicine

For example

Sample:
Rabbit's ear with iodinated contrast media
X-ray energy:
33.17 keV (K-edge of Iodine)





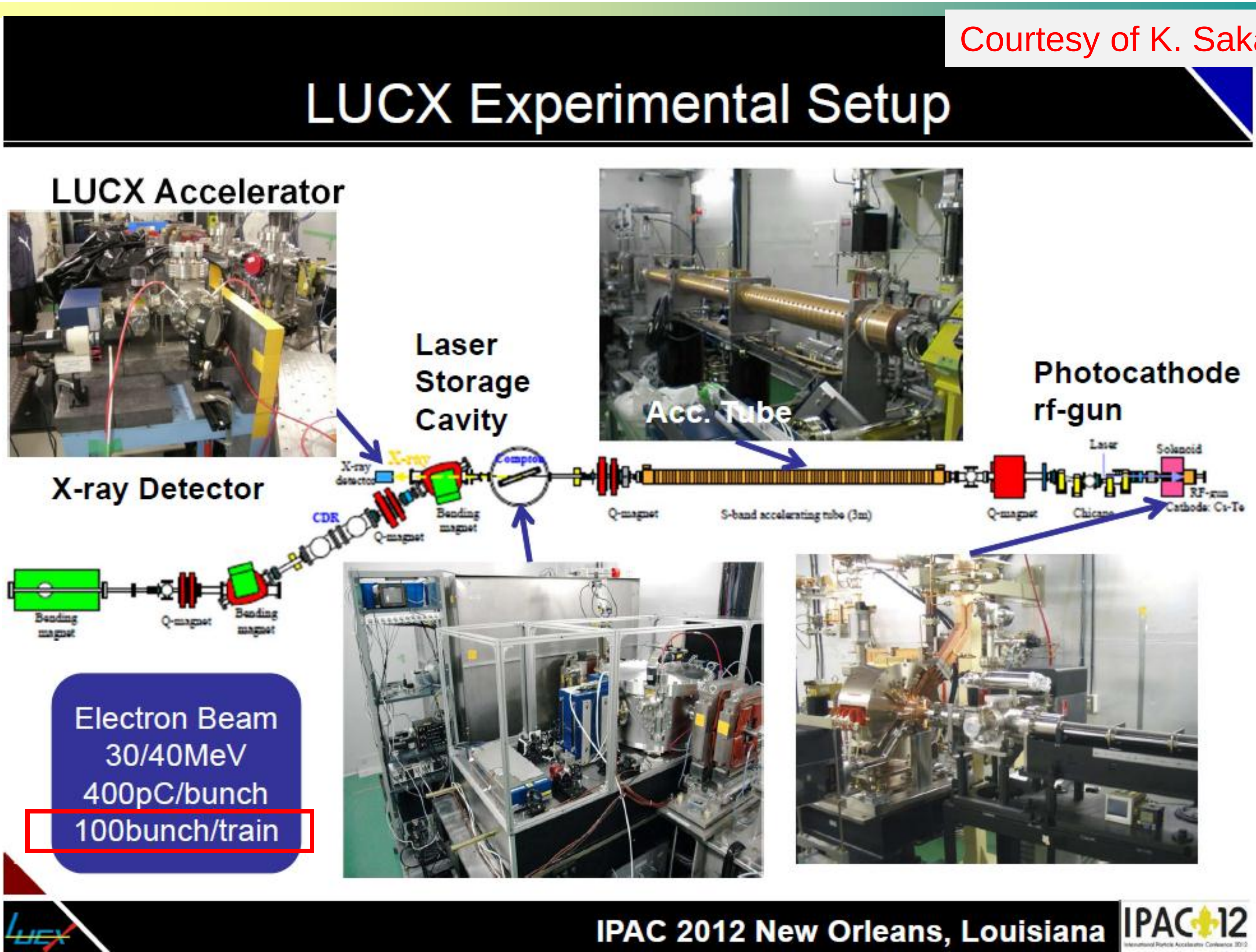
Real time imaging (1 or 10 frame/sec)

REFERENCES

H. Ikeura-Sekiguchi et al., APL 92,131107 (2008)
K. Yamada et al., NIM A 608, S7 (2009)
R. Kuroda et al., NIM A 637, S183 (2011)

LCS X-ray Source at KEK / LUCX

Courtesy of K. Sakaue



LUCX Experimental Setup

LUCX Accelerator

X-ray Detector

Laser Storage Cavity

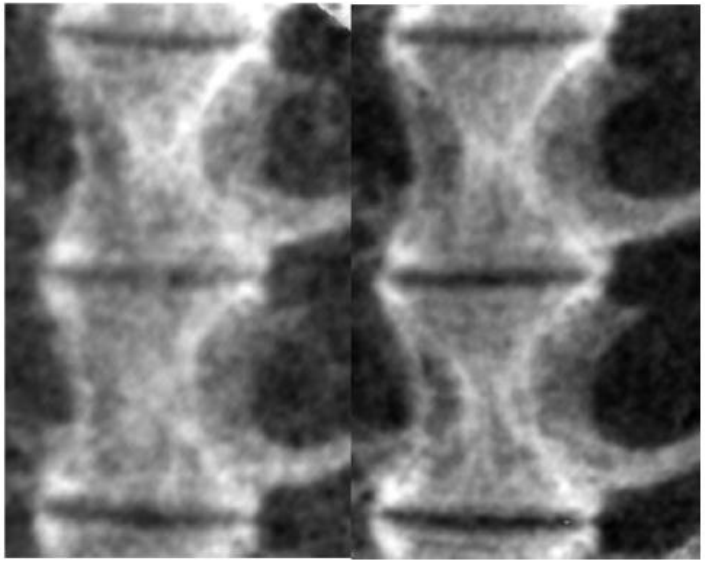
Photocathode rf-gun

Electron Beam
30/40MeV
400pC/bunch
100bunch/train

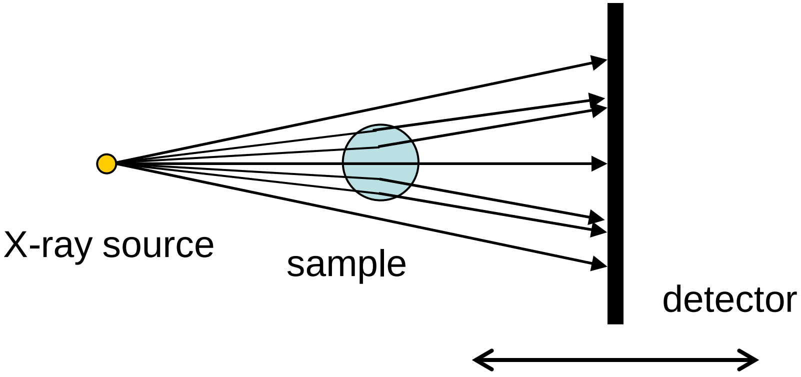
IPAC 2012 New Orleans, Louisiana

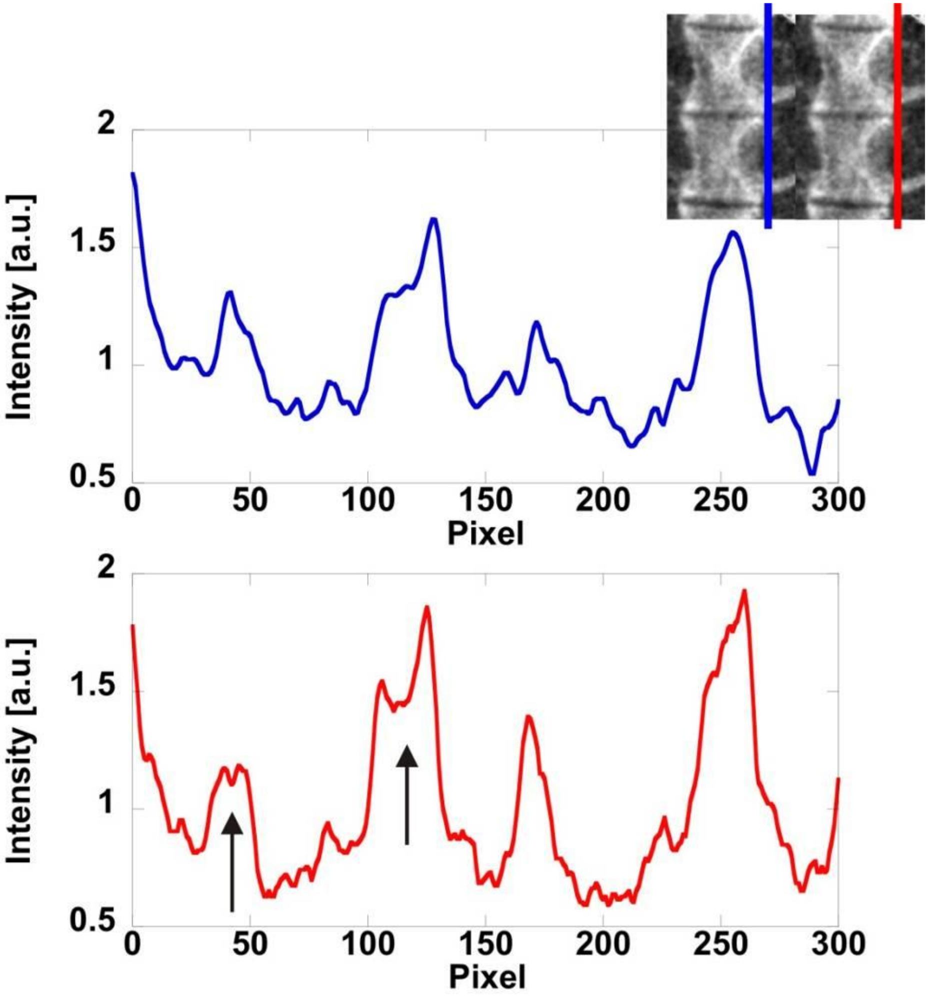
LCS X-ray Source at KEK / LUCX

Courtesy of K. Sakaue



distance from the sample
to the detector

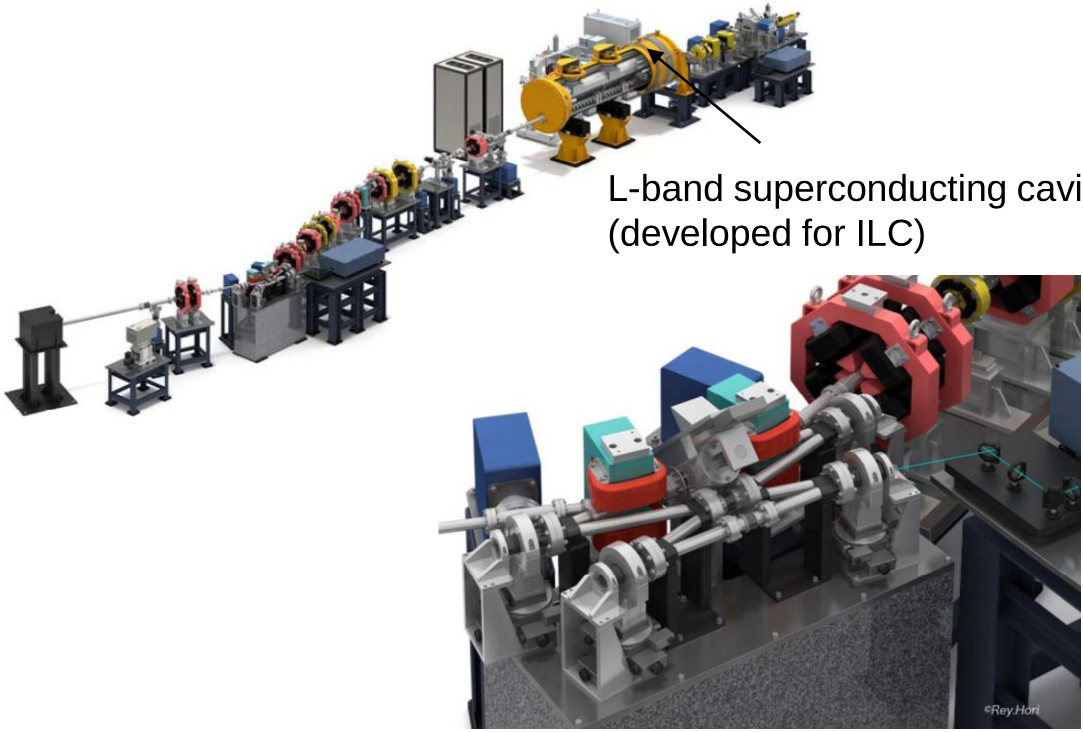




edge enhancement

LCS X-ray Source at KEK / STF

Courtesy of J. Urakawa



L-band superconducting cavities (developed for ILC)

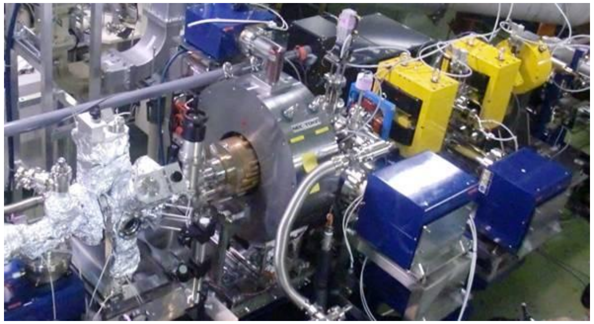
electron beam	laser pulse	collision spot (μm)	X-ray flux (10% BW)
40 MeV 62 pC, σ_t = 8.7 ps 162.5k bunch/pulse 5Hz	30 mJ /pulse 162.5 MHz σ_t = 4.3 ps	head on σ_{ex} / σ_{ey} = 10 / 10 σ_{lx} / σ_{ly} = 20 / 20	1.4 x 10^{11}

Supported by MEXT Quantum Beam Technology Program

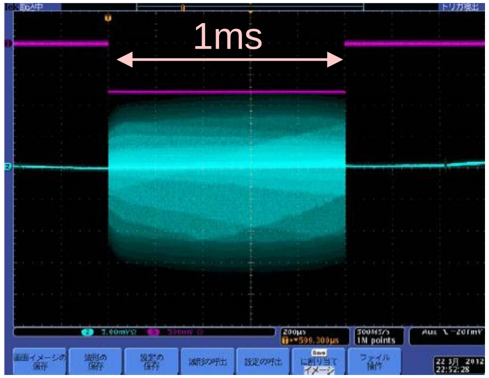
Multi-collision operation of LCS sources

For the higher flux !

multi-bunch electron beam

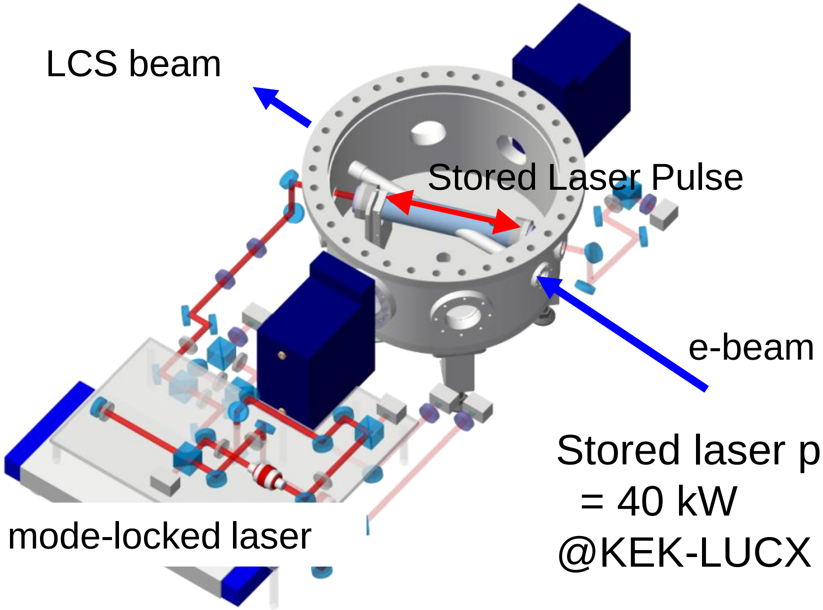


KEK/STF
L-band RF gun with CsTe photocathode



BPM signal --- 162,500 bunch / 1ms

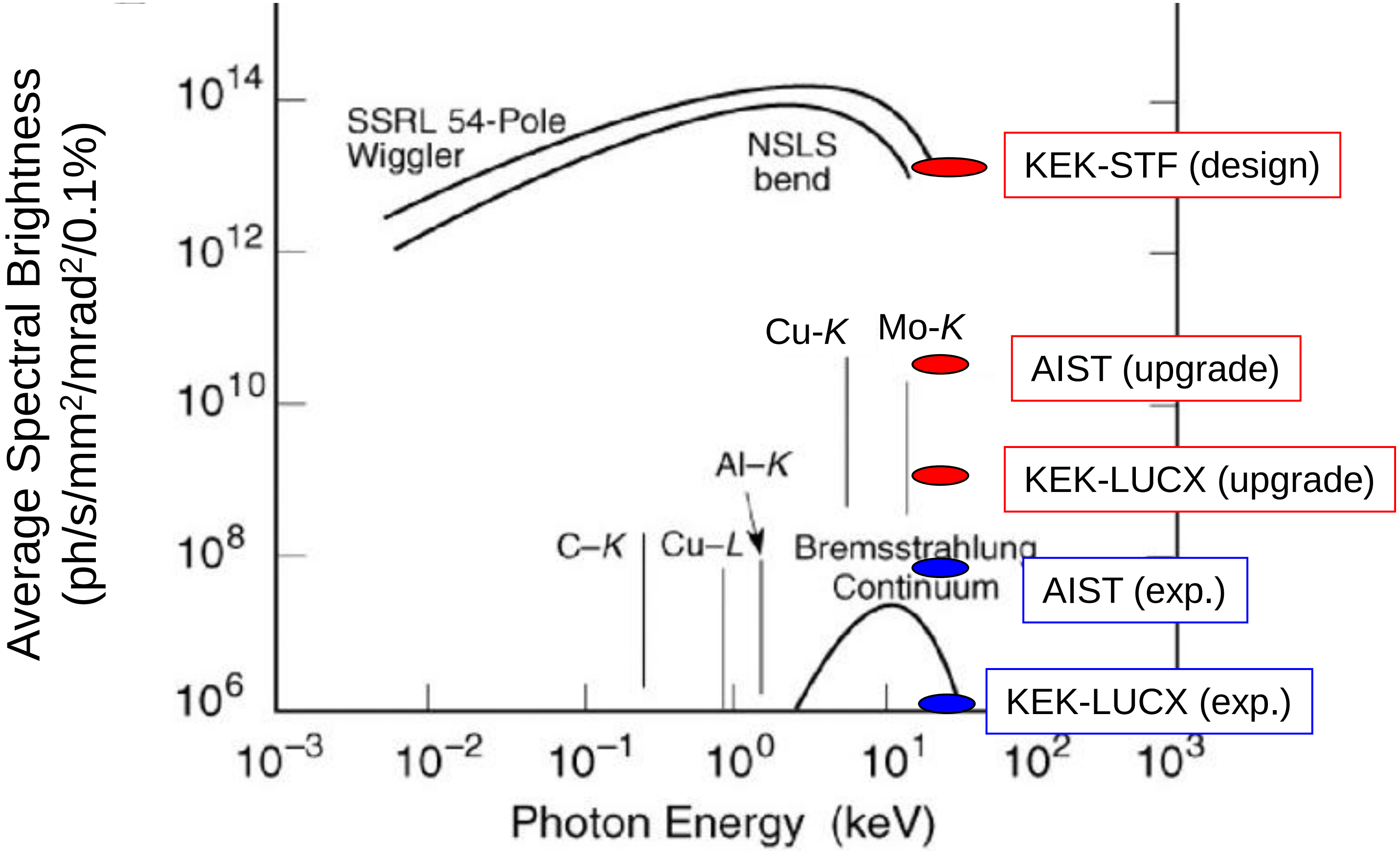
laser storage cavity



Stored laser power
= 40 kW
@KEK-LUCX

laser pulses from a mode-locked laser are coherently stacked in a high-finesse Fabry-Perót cavity.

Spectral Brightness of LCS sources



(assumed ε_n = 1mm-mrad)

LCS sources are surpassing X-ray tubes and approaching 2nd gen. SR.

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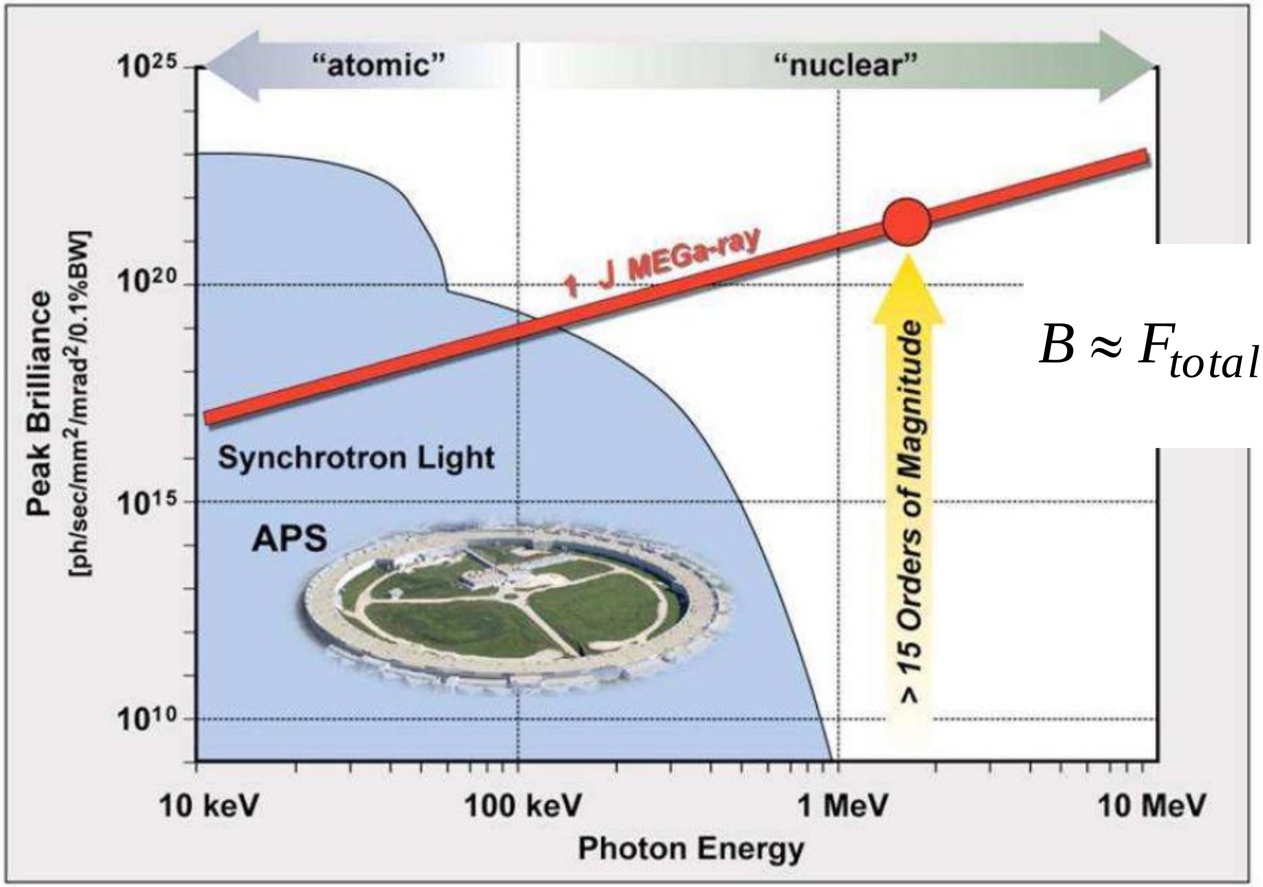
LCS sources above 1 MeV



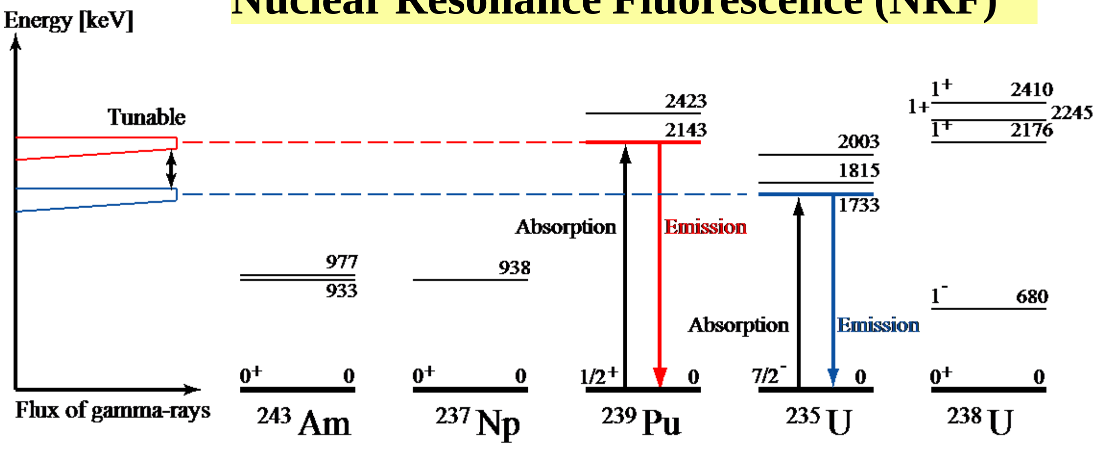
$$B \approx F_{total} \frac{\gamma^2}{\varepsilon_n^2} \times 0.1\%$$

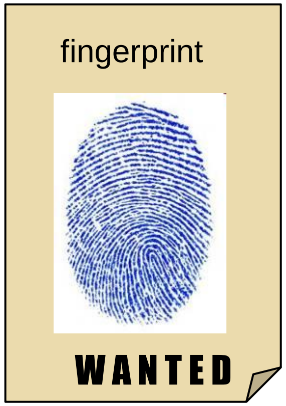
C.P.J. Barty, "White Book of ELI Nuclear Physics"

LCS is unparalleled photon source above 1 MeV.

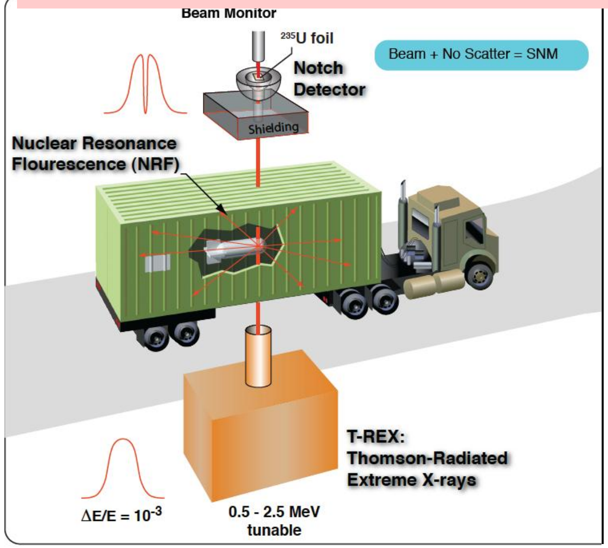
Applications of LCS γ-ray sources

Nuclear Resonance Fluorescence (NRF)



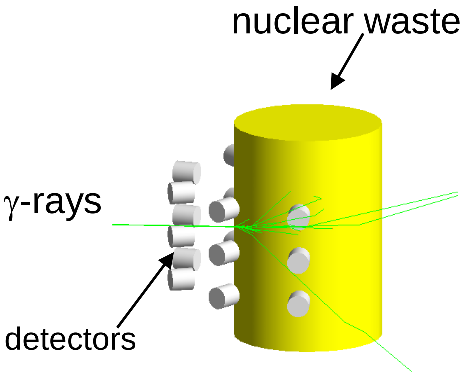


Detection of SNM in a cargo



SNM: special nuclear material

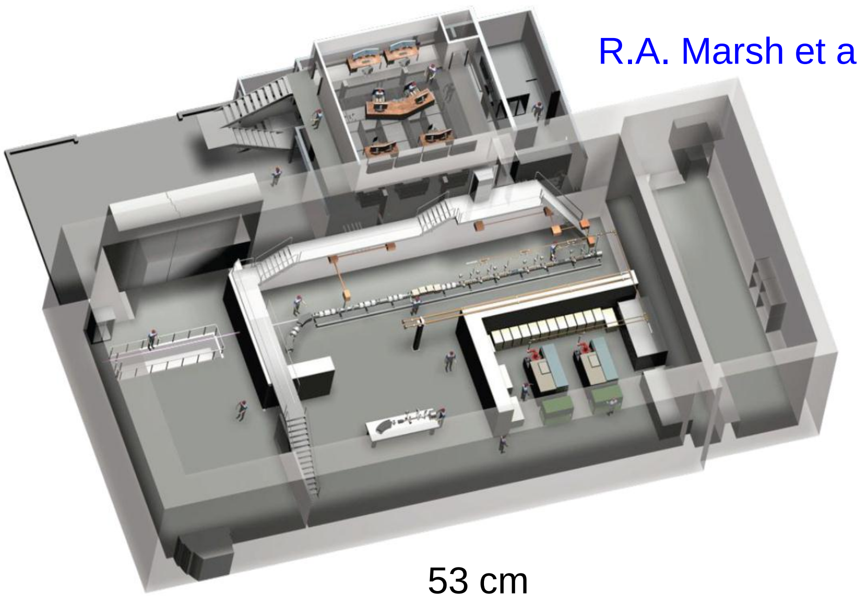
Management of nuclear material



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

LCS γ-ray source at Lawrence Livermore

VELOCIRAPTOR @ Lawrence Livermore Natl. Lab.
250 MeV Linac
$E\gamma = 1\text{-}2$ MeV
Test Facility for Nuclear Security Applications

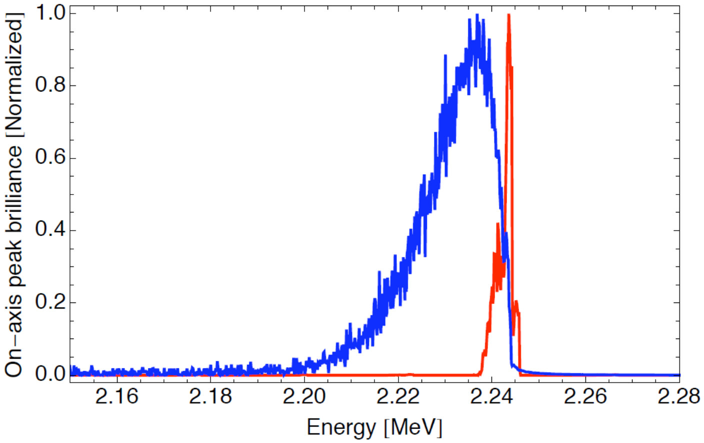


R.A. Marsh et al., IPAC-12

optimization of e-beam

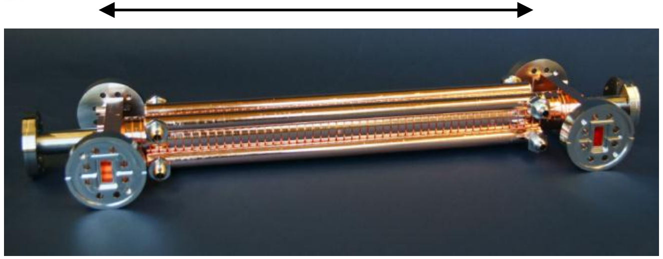
250 pC, $\varepsilon_n = 0.35$mm-mrad, $\sigma_E/E = 0.17\%$

25 pC, $\varepsilon_n = 0.1$mm-mrad, $\sigma_E/E = 0.03\%$



F. Albert et al., IPAC-11

53 cm



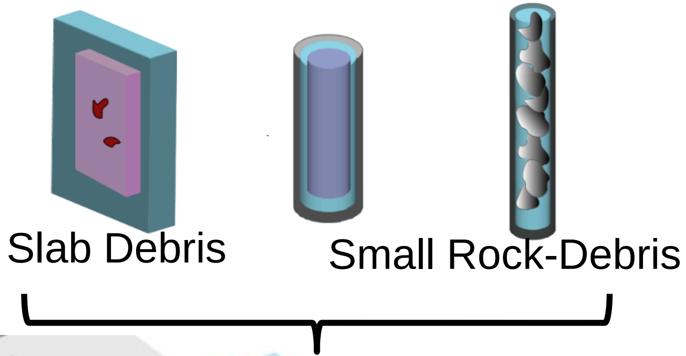
X-band linac, SLAC T53 (~ 70MV/m)

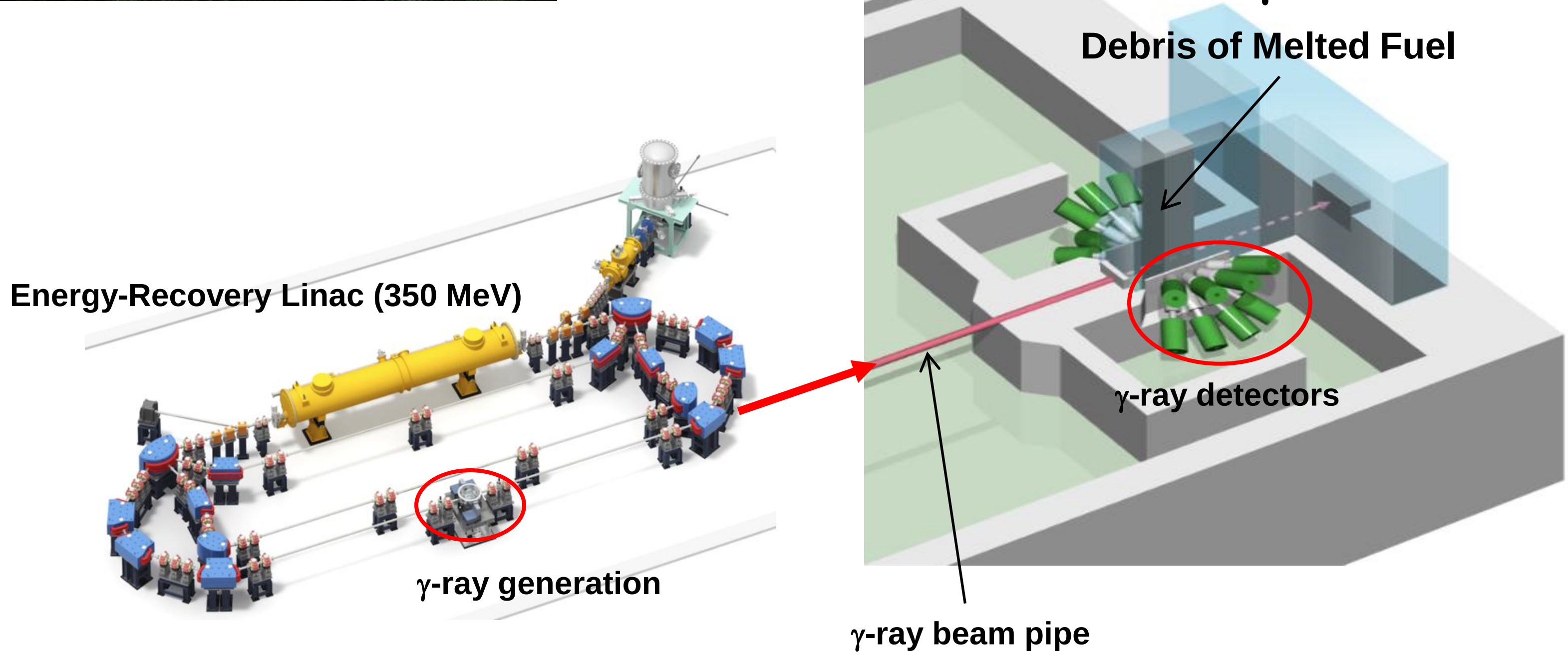
Flux = 1×10^{10} ph/s
$B_{peak} = 1\times10^{20}$

LCS γ-ray for Fukushima

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

removal of debris
from the core ~2022



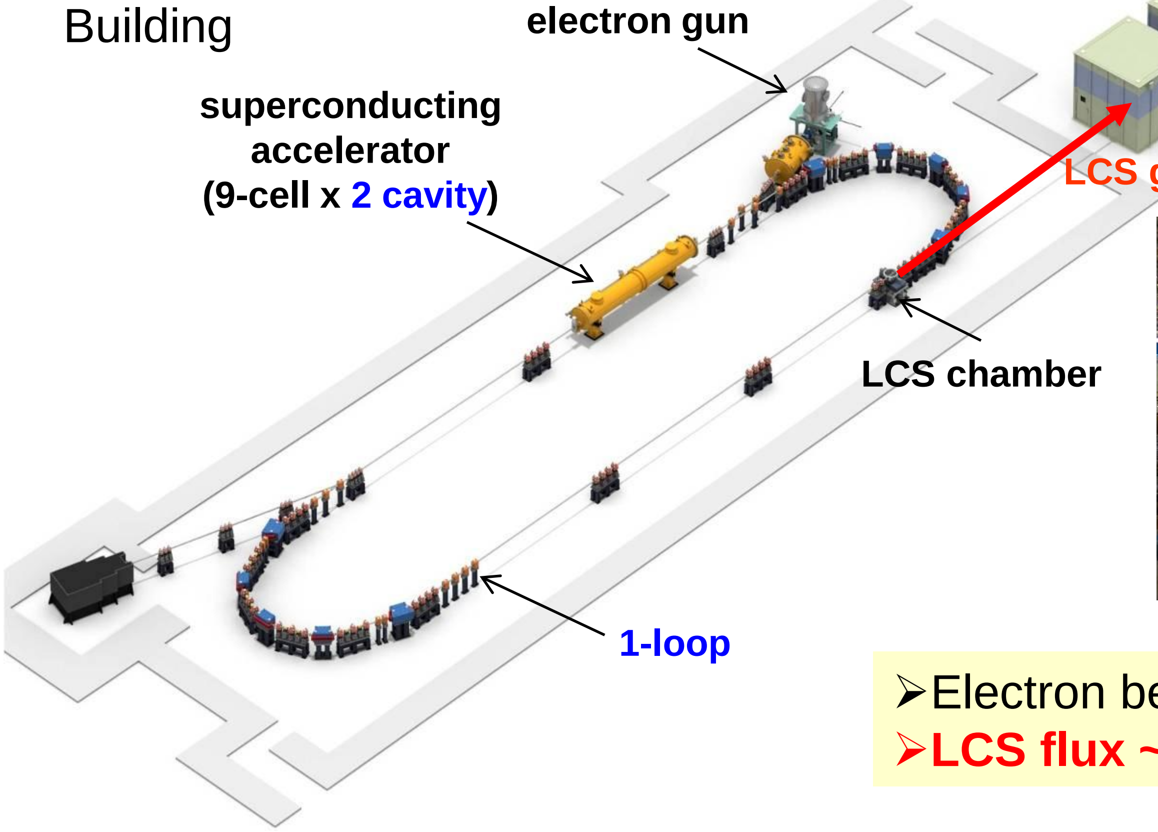


LCS Experiment at the Compact ERL

3-year R&D program funded from MEXT (2011-2013)

Building

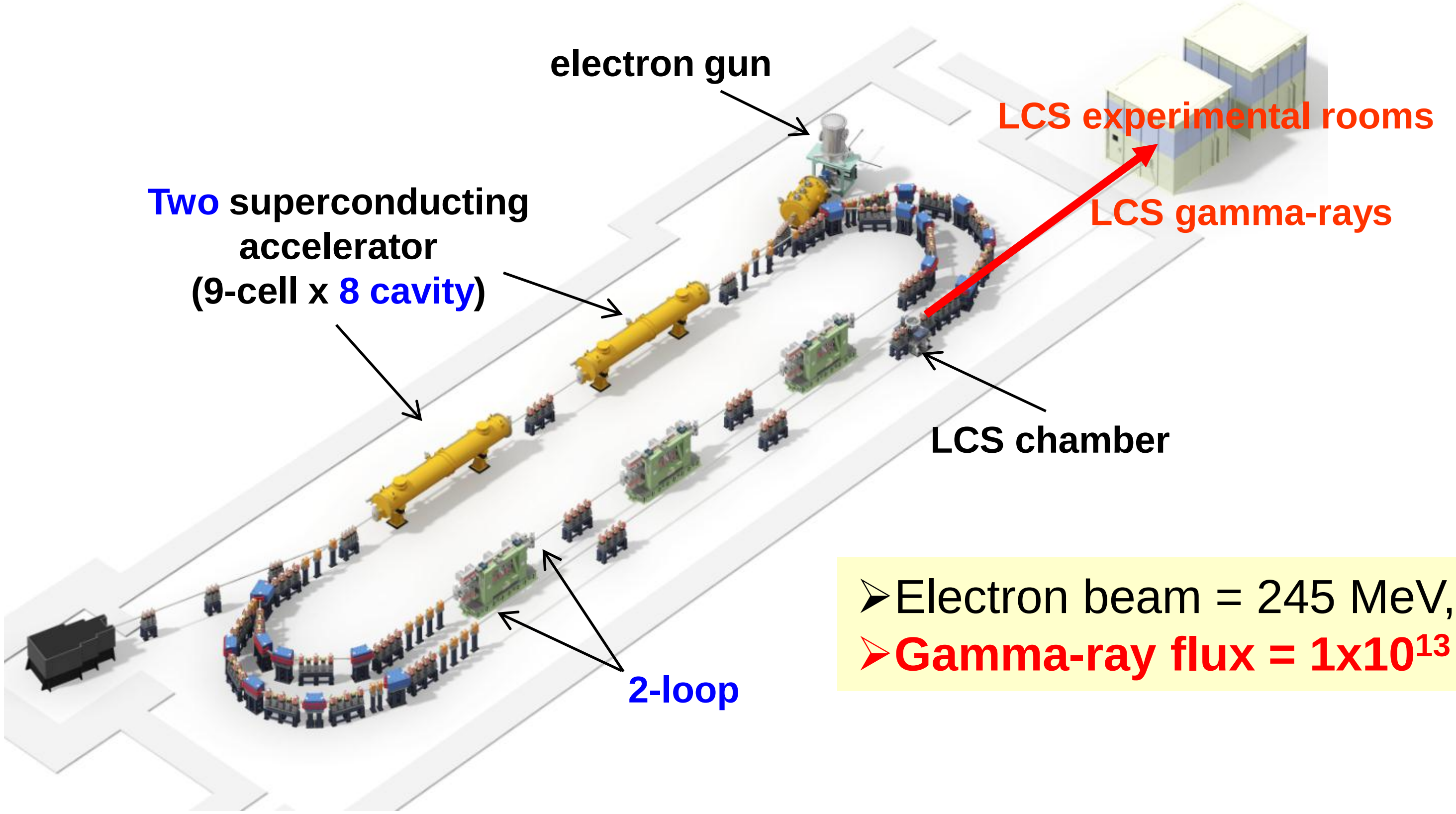
- Installation of a LCS chamber
- Generation of LCS gamma-rays
- Demo-Experiment of NRF measurement



- Electron beam = 35 MeV, 10 mA
- **LCS flux ~ 1×10^{11} ph/s**

Upgrade for U-238 measurement (Just a Plan)

- Reinforcement of superconducting accelerator
- Addition of the 2nd loop



electron gun

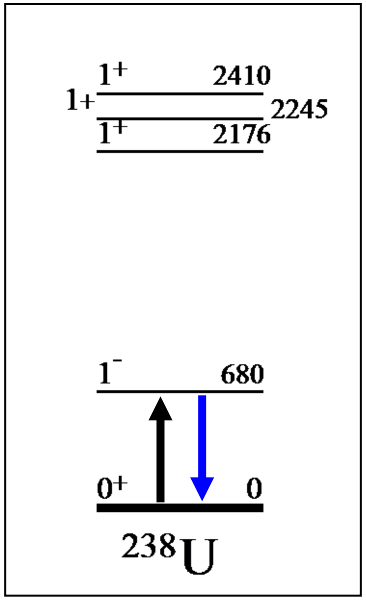
LCS experimental rooms

LCS gamma-rays

Two superconducting accelerator (9-cell x 8 cavity)

LCS chamber

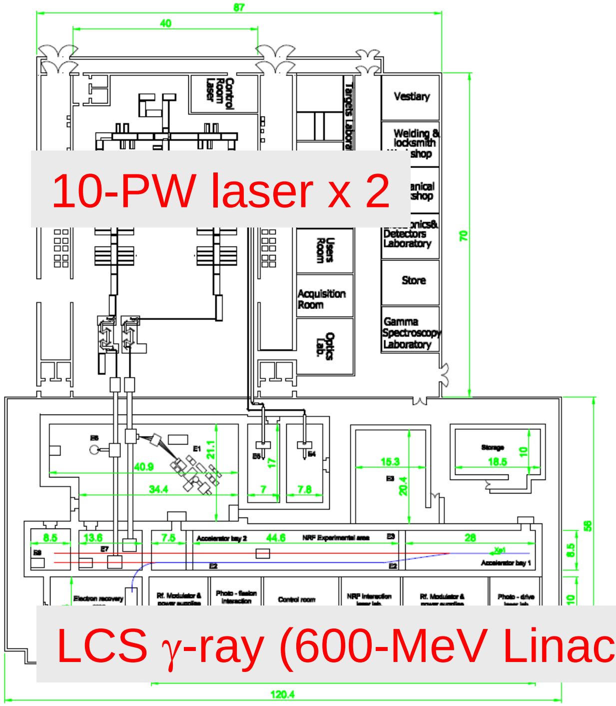
2-loop



- Electron beam = 245 MeV, 10 mA
- **Gamma-ray flux = 1x10^{13} ph/s**

LCS γ-ray source at ELI-NP

ELI-Nuclear Physics : Complex of PW lasers and LCS at Bucharest, Romania



10-PW laser x 2

LCS γ-ray (600-MeV Linac)

#PW laser stand alone
Production of Neutron-Rich Nuclei
Radiation Pressure Acceleration
.....

#LCS-γ / e^- stand alone
Mapping of nuclear potential landscape
Deformed nuclear shape
Parity violation in (e, e') process
Production of medical isotopes
....

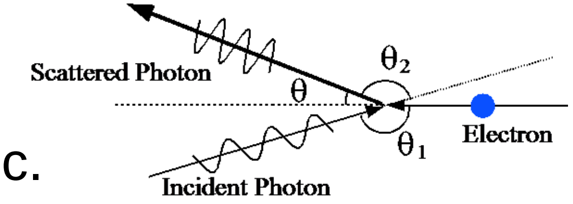
#PW laser + LCS-γ / e^-
Pair creation from the vacuum
Vacuum Birefringence
.....

http://www.eli-np.ro/

Summary

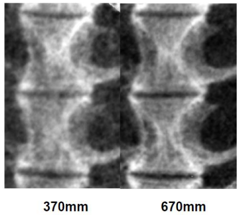
LCS photon sources is evolving

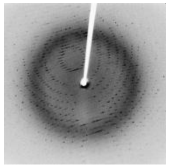
in cooperation with advanced Laser and Acc.

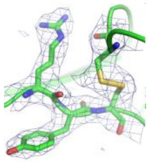


LCS X-ray is approaching 2nd-gen. SR

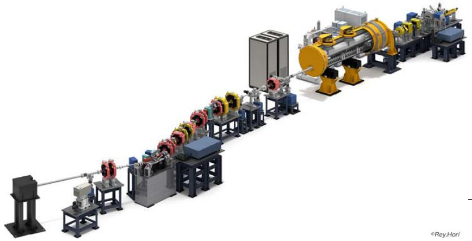
in terms of Spectral Brightness.





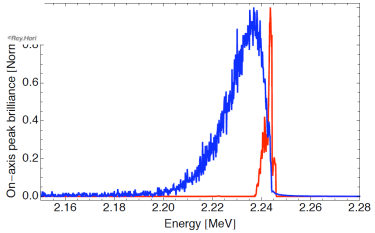


2nd-gen. SR in "laboratory size"



LCS γ-ray is an unparalleled source in terms of

its flux, brightness, narrow bandwidth.



Innovative science and applications