Beam Physics Issues in ERL γ-ray Sources

R. Hajima
Quantum Beam Science Directorate,
Japan Atomic Energy Agency

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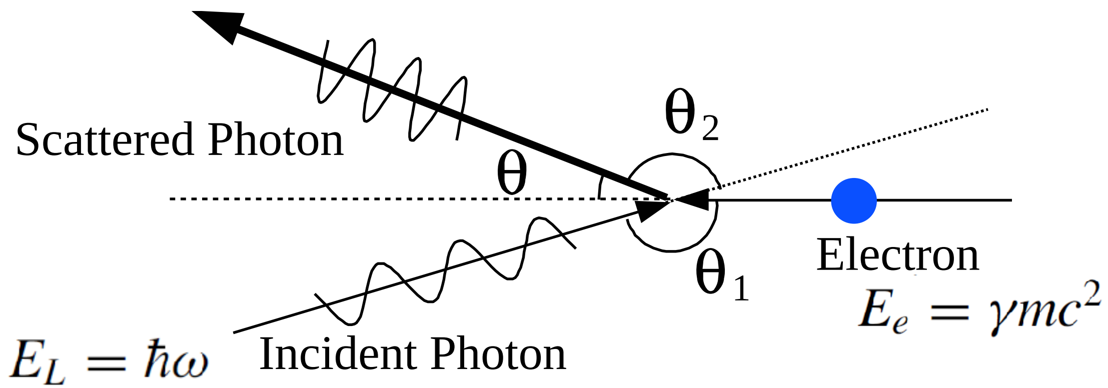
Laser Compton scattering γ-ray sources



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

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

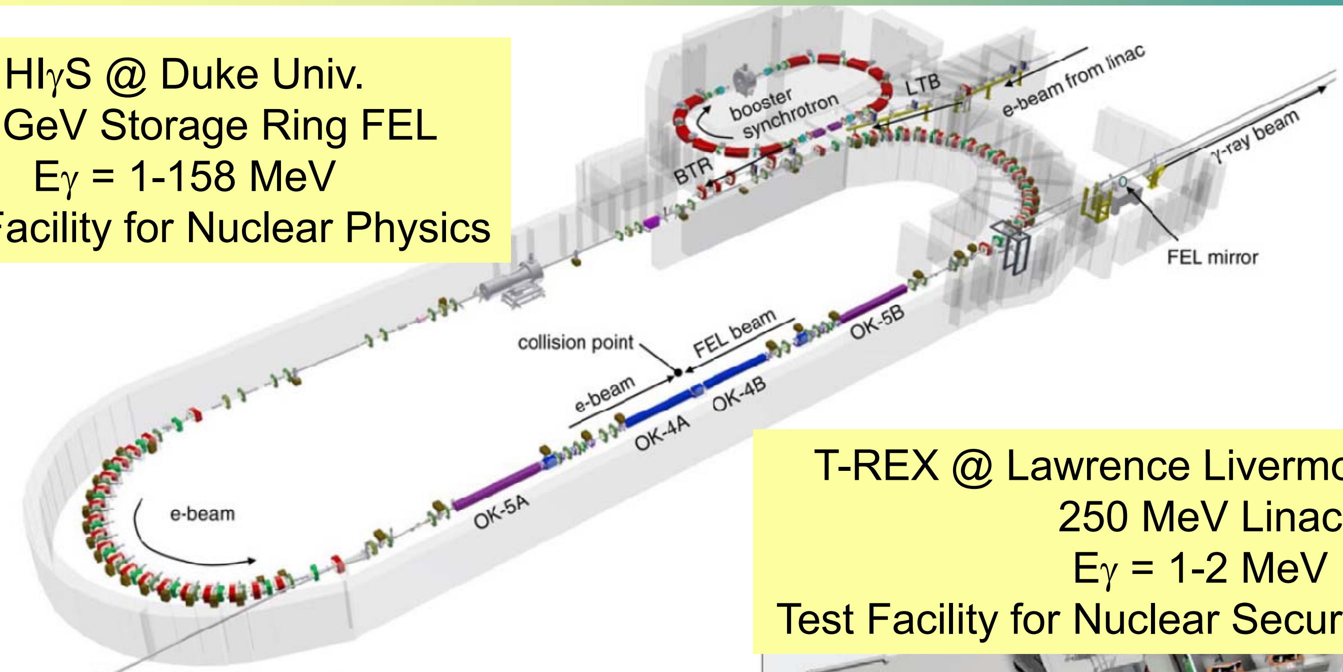
- Narrow bandwidth with a collimator
- Energy Turntable
- Sharp energy edge
- Pencil like beam

→ New generation of γ-ray source

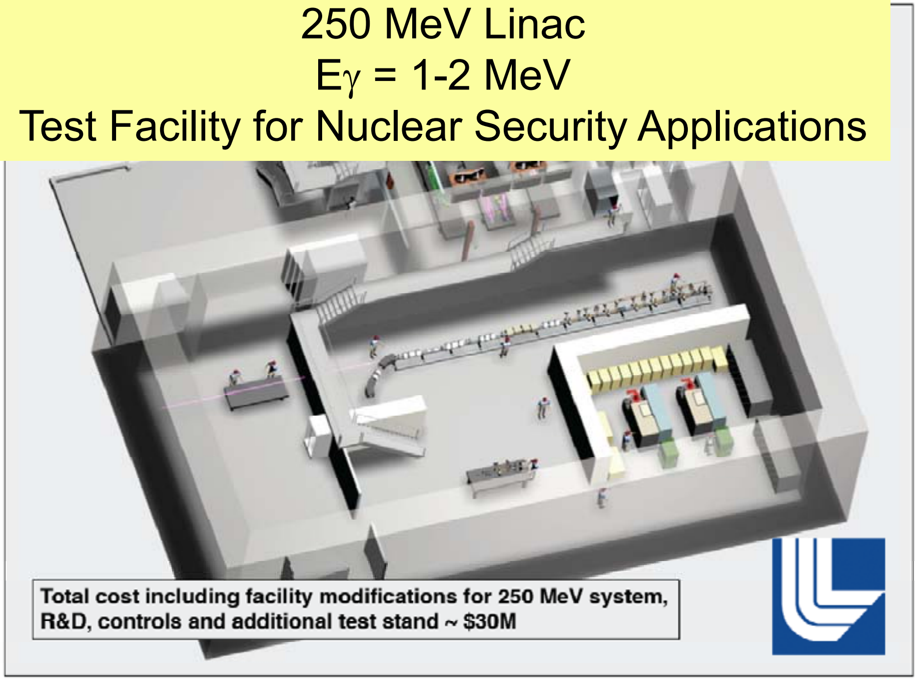
(c.f. Bremsstrhalung, isotopes)

LCS γ-ray Sources in the World

HIγS @ Duke Univ.
1.2 GeV Storage Ring FEL
Eγ = 1-158 MeV
User Facility for Nuclear Physics



T-REX @ Lawrence Livermore Natl. Lab.
250 MeV Linac
Eγ = 1-2 MeV
Test Facility for Nuclear Security Applications

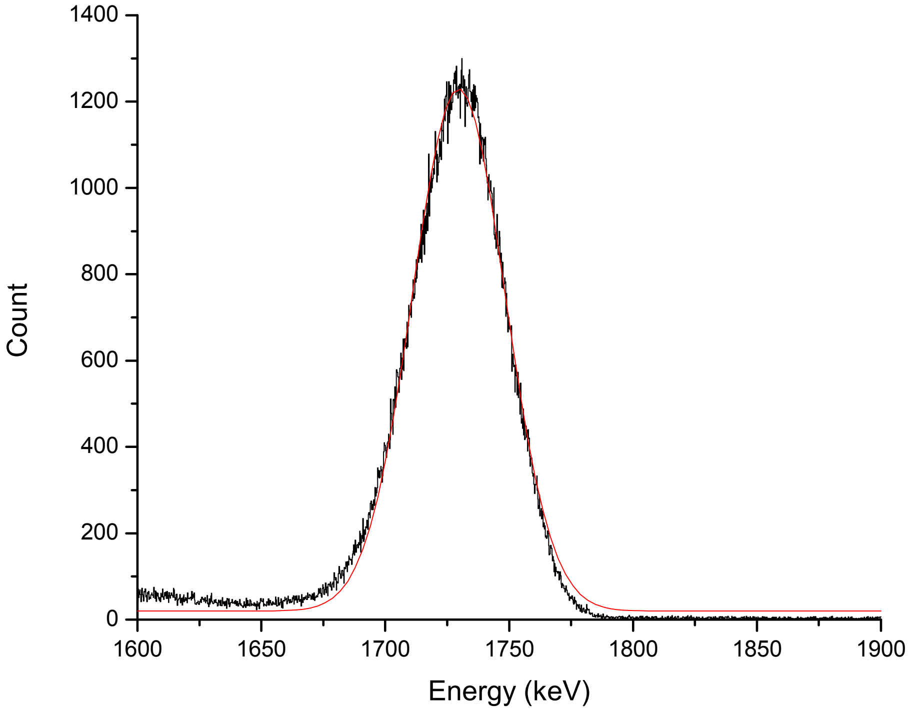


ELI-NP : Complex of PW lasers and LCS

The Extreme Light Infrastructure European Project

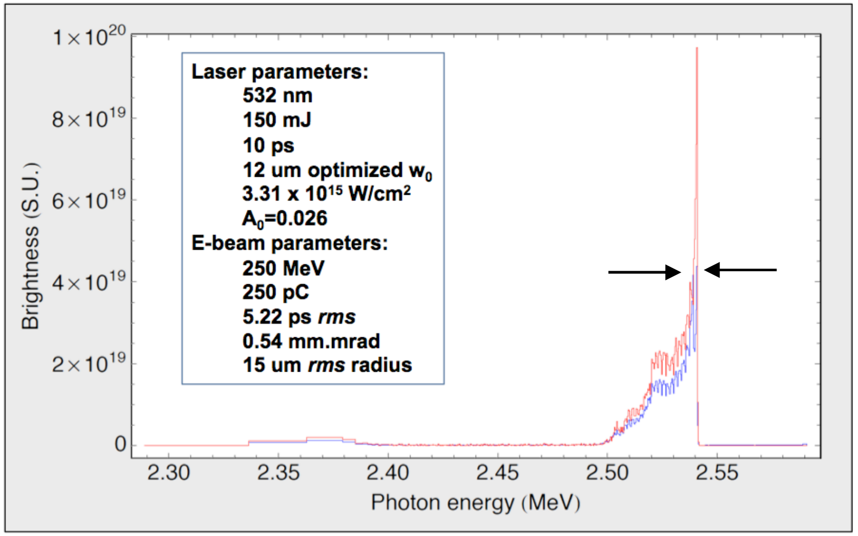
Example of LCS γ-ray spectrum

Storage Ring-based LCS



HIγS @ Duke Univ.
measured spectrum
ΔE/E ~ 5% (FWHM)

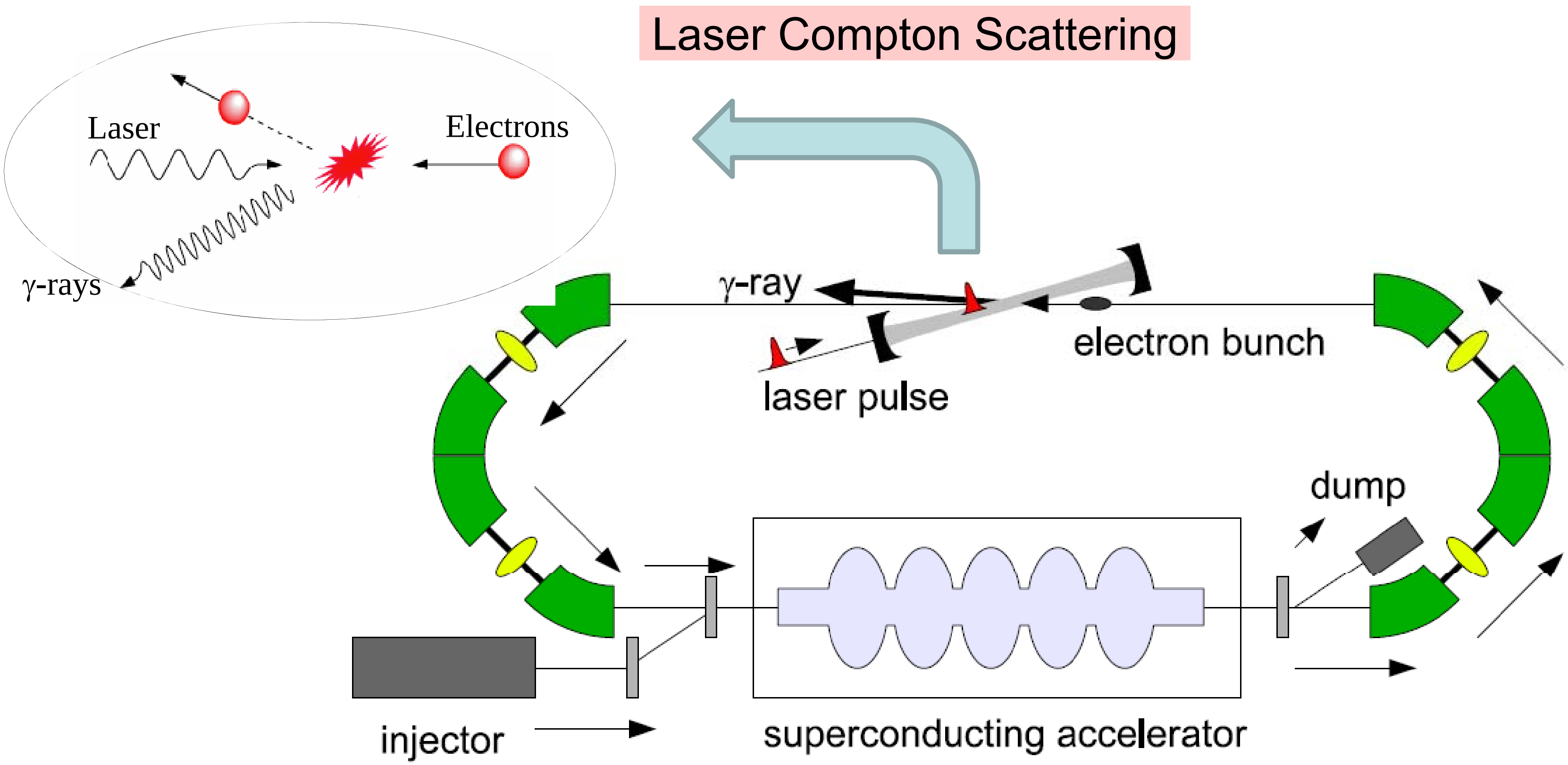
Linac-based LCS



ELI-NP Whitebook (2010)

ELI-NP
calculated spectrum
ΔE/E < 1%

Energy-Recovery Linac as a γ-ray Source



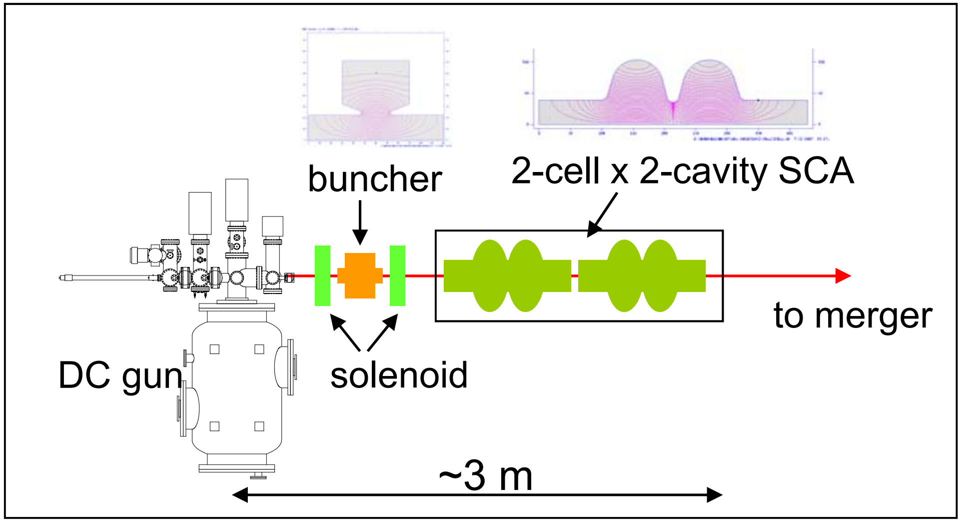
R. Hajima et al., AccApp'07 (2007).

✓ energy-recovery for high-average current beams

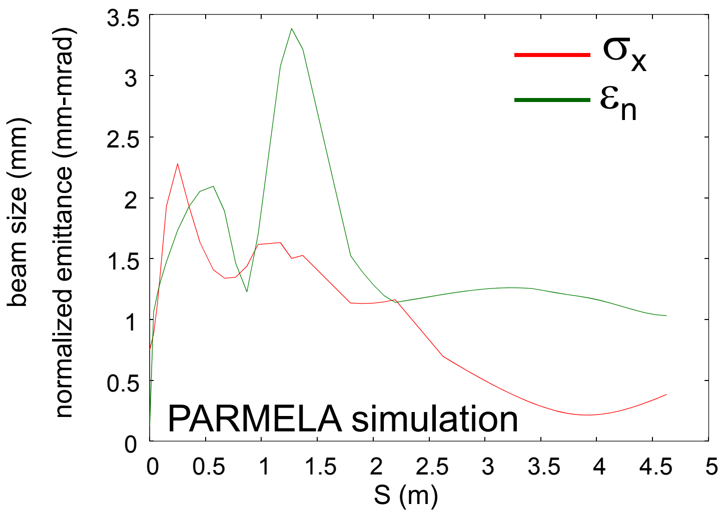
✓ always fresh electron beam

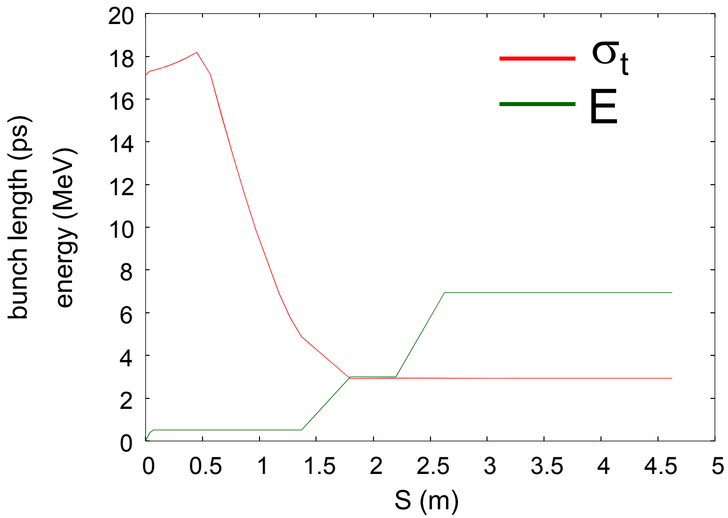
γ-ray beam with high-flux and narrow bandwidth

Design of an Injector for an ERL γ-ray source (7 MeV, 13 mA injector)



gun voltage	500 kV
buncher field	1.25 MV/m
1st cavity field	10 MV/m
2nd cavity field	15 MV/m
bunch charge	100 pC
norm. emittance	1.0 mm-mrad
bunch length	3 ps (rms)
energy	7 MeV
energy spread	0.1 %
repetition	130 MHz
average current	13 mA

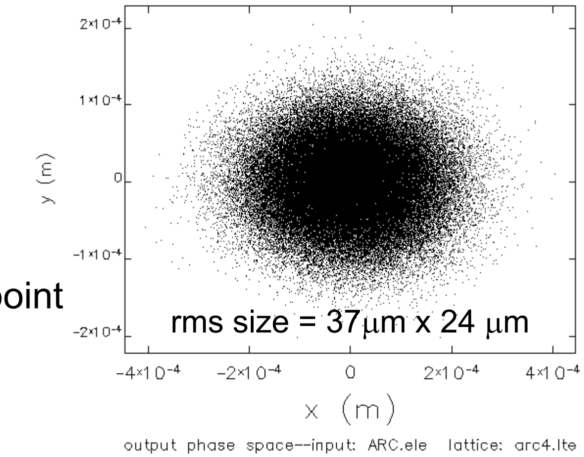


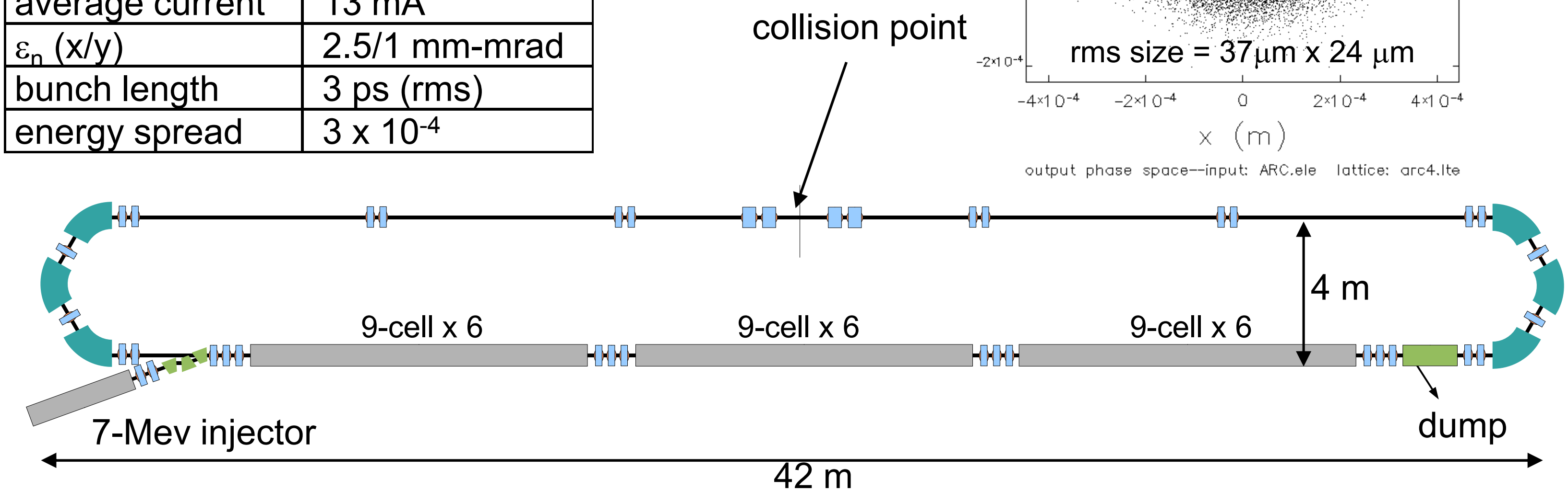


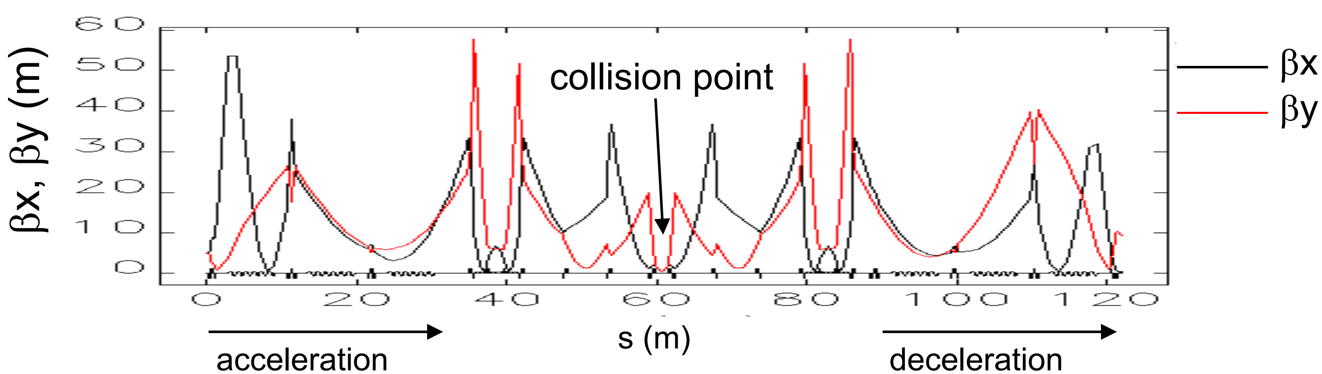
R. Hajima et al., NIM A (2009).

Design of a 350 MeV ERL for γ-ray source

full energy	350 MeV
injection energy	7 MeV
bunch charge	100 pC
repetition	130 MHz
average current	13 mA
ε_n (x/y)	2.5/1 mm-mrad
bunch length	3 ps (rms)
energy spread	3 x 10^{-4}



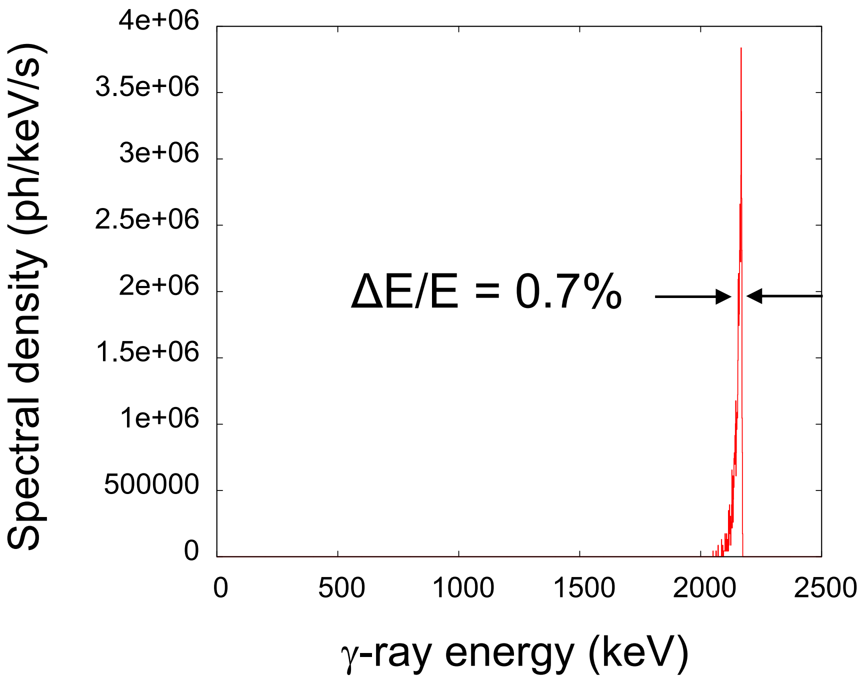




R. Hajima et al., NIM A (2009).

Design Performance of 350-MeV ERL LCS γ-ray Source

electron beam		laser	
Energy	350 MeV	wavelength	1064 nm
Bunch Charge	100 pC	pulse energy	1.8 μJ
Bunch Length (rms)	3 ps	rms pulse length	2 ps
Bunch Repetition	130 MHz	pulse repetition	130 MHz
Norm. emittance (x/y)	2.5/1 mm-mrad	enhancement cavity	3000
rms collision spot (x/y)	38/24 μm	rms collision spot	29 μm
rms energy spread	0.03%	collision angle	3.5 deg.
γ-ray flux	1.0 x 10^{13} /s		



total flux
= 1 x 10^{13} ph/s

Exceeds existing facilities
by order of 10^5-10^8

with a collimator of 0.1mrad
ΔE/E = 0.7% (FWHM)

Spent beam

Electron beam degradation due to LCS is summarized in [1]

[1] Z. Huang and R. Ruth, PRL 80, 976 (1998).

Quantum excitation by laser Compton scattering

$$\Delta(\varepsilon_n) = \frac{3}{10}\frac{\lambda_c}{\lambda_L}\frac{(\Delta E)_\gamma}{E}\beta^*$$

$$\Delta(\sigma_E) = \sqrt{\frac{7}{10}\hbar\omega\Delta E_\gamma}$$

For the designed 350-MeV ERL, 2-MeV γ-ray source,

$$\Delta(\varepsilon_n) = 5\times10^{-13}\,\mathrm{m-rad}$$

$$\Delta(\sigma_E) = 40\,\mathrm{keV}$$ ~10^{-4}

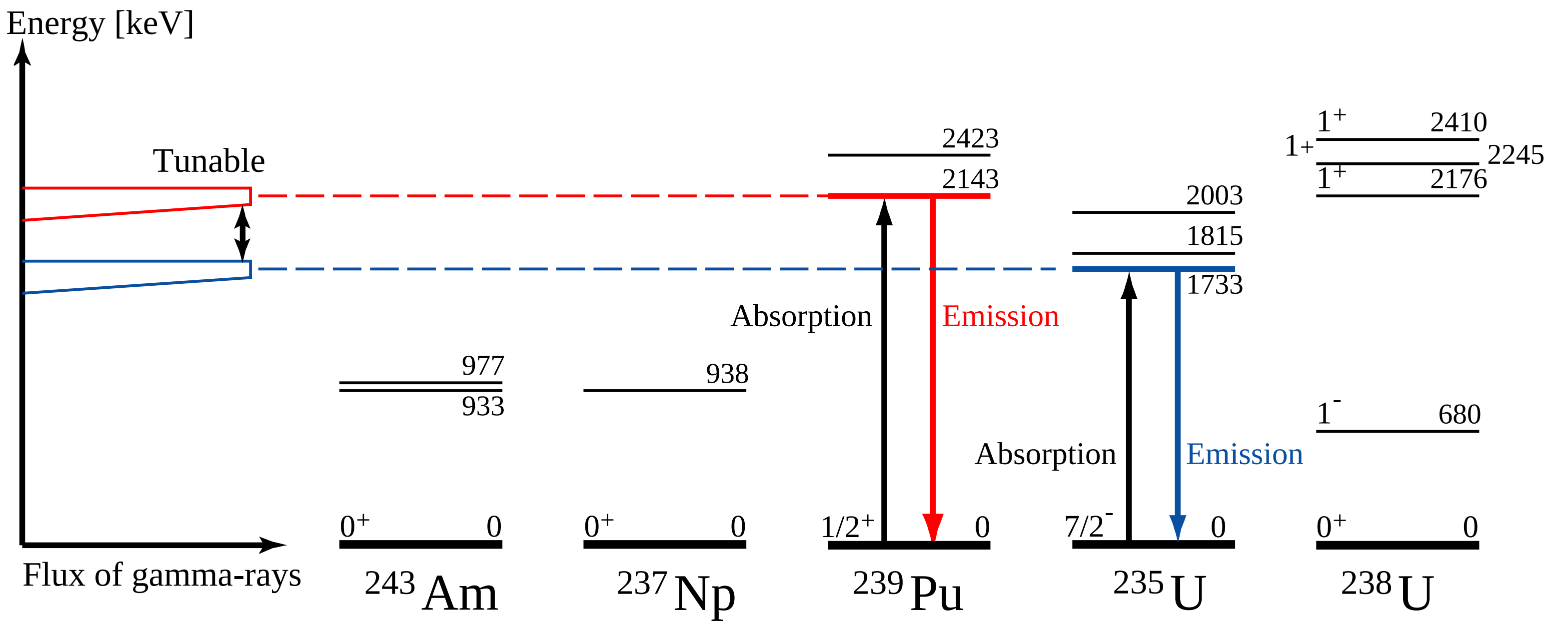
$$\frac{\Delta E_\gamma}{E} = 0.6\%$$ maximum energy loss

Multiple LCS in the ERL loop is possible with keeping the γ-ray quality

Requirement from nuclear physics experiments

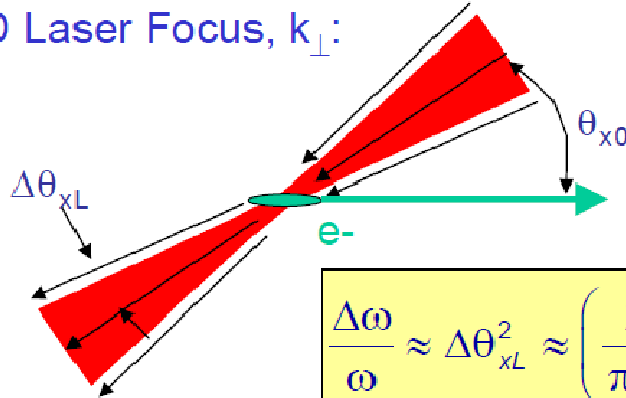
In Nuclear Resonance Fluorescence experiment

- energy width of resonance level is very small
  typically ΔE_{NRF}~ 30meV for 2MeV excitation level
- incident γ-ray out of ΔE_{NRF} results in background noise



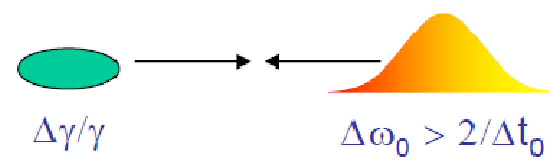
Bandwidth and Divergence Effects

3D Laser Focus, $k_\perp$:



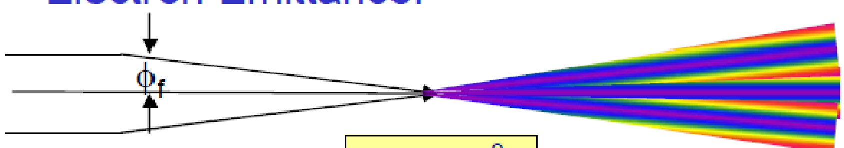
$$\frac{\Delta\omega}{\omega} \approx \Delta\theta_{xL}^2 \approx \left(\frac{\lambda_0}{\pi W_0}\right)^2$$

Laser Bandwidth/Electron Energy Spread:

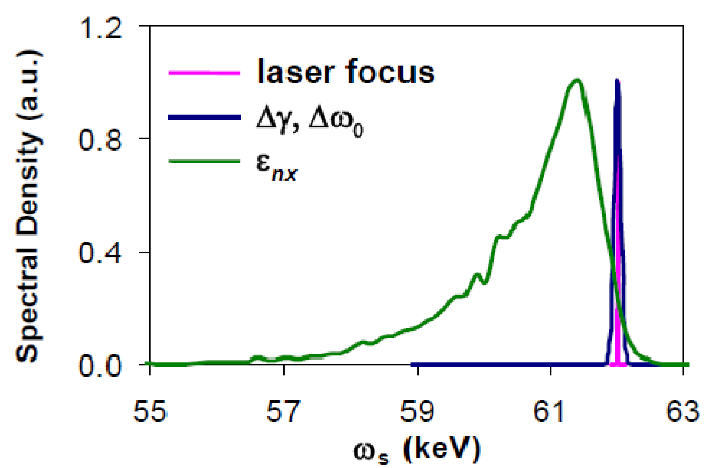


$$\frac{\Delta\omega}{\omega} \approx 2\sqrt{\frac{\Delta\omega_0^2}{\omega_0^2} + \frac{\Delta\gamma^2}{\gamma^2}}$$

Electron Emittance:



$$\frac{\Delta\omega}{\omega} \approx \frac{\varepsilon_{nx}^2}{X_f^2}$$



emittance for the ultimate LCS γ-ray source

diffraction limited electron beam

(energy spread from emittance becomes comparable to that from the laser diffraction)

$$\varepsilon_n \approx \frac{\lambda}{4\pi}$$

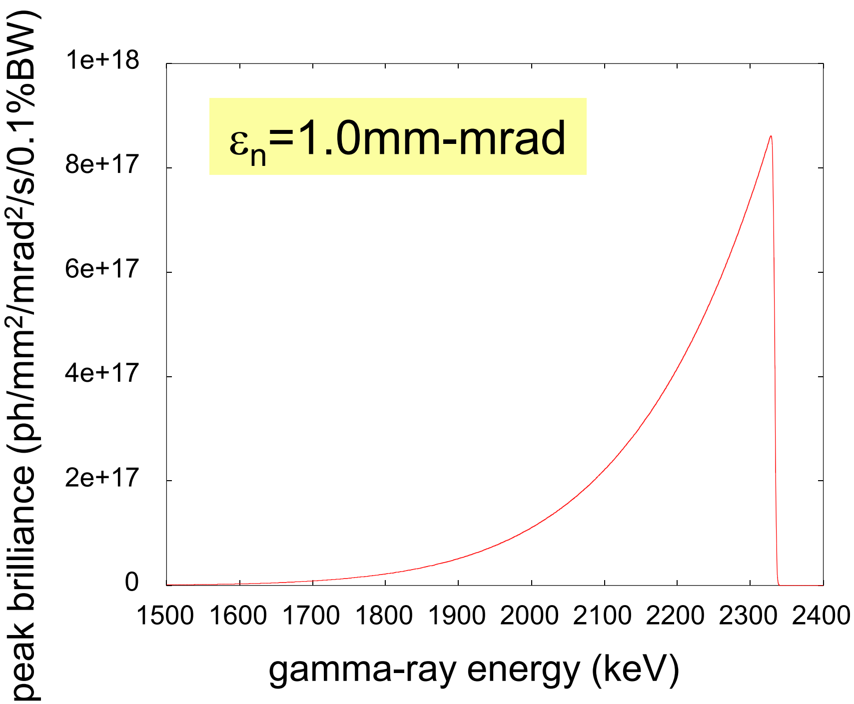
"normalized emittance"

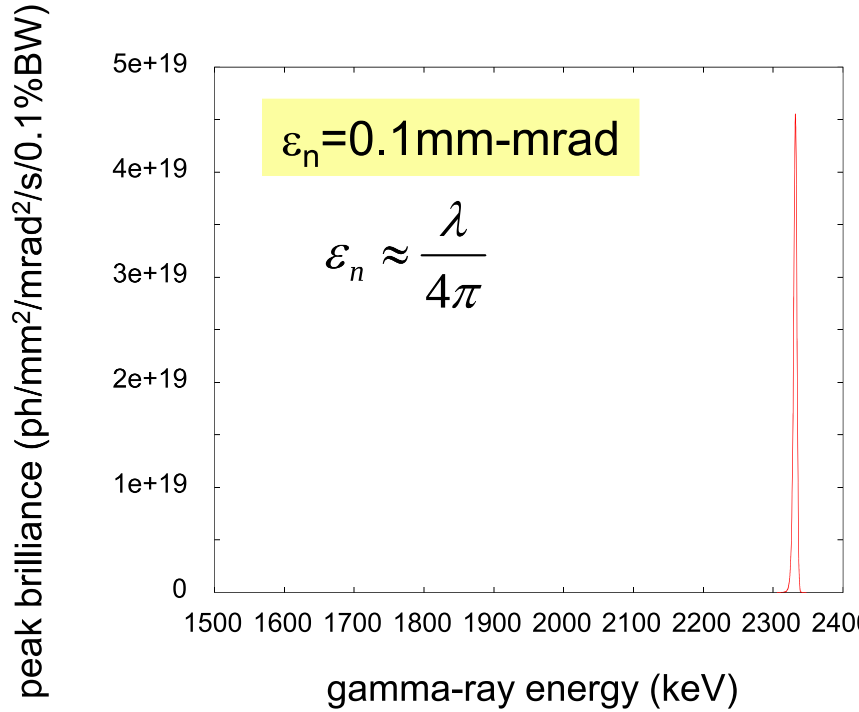
$$E_\gamma \simeq \frac{4\gamma^2 E_L}{1 + (\gamma\theta)^2 + 4\gamma E_L/(mc^2)}$$

λ=1 μm laser → ε_n ~ 0.08 mm-mrad

The target value is same as ERL X-ray sources and XFELO

On-axis Spectral Brightness (analytical estimation)





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

calculation by using a formula in [1].

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

e-beam energy spread for the ultimate LCS γ-ray source

contribution of emittance

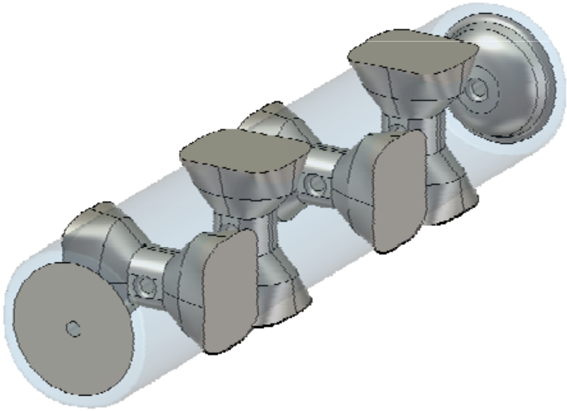
$$\left(\frac{\Delta E_\gamma}{E_\gamma}\right)_{rms} = 2\left(\frac{\varepsilon_n}{\sigma_x}\right)^2$$

normalized emittance ε_n = 0.1mm-mrad, collision spot σ_x = 10μm → ΔEγ/Eγ = 0.02%

contribution of electron energy spread

$$\left(\frac{\Delta E_\gamma}{E_\gamma}\right)_{rms} = \left(\frac{2\sigma_E}{E}\right)$$

σ_E /E = 0.01 % → ΔEγ/Eγ = 0.02%



for a fixed bunch length
energy spread due to the RF curvature

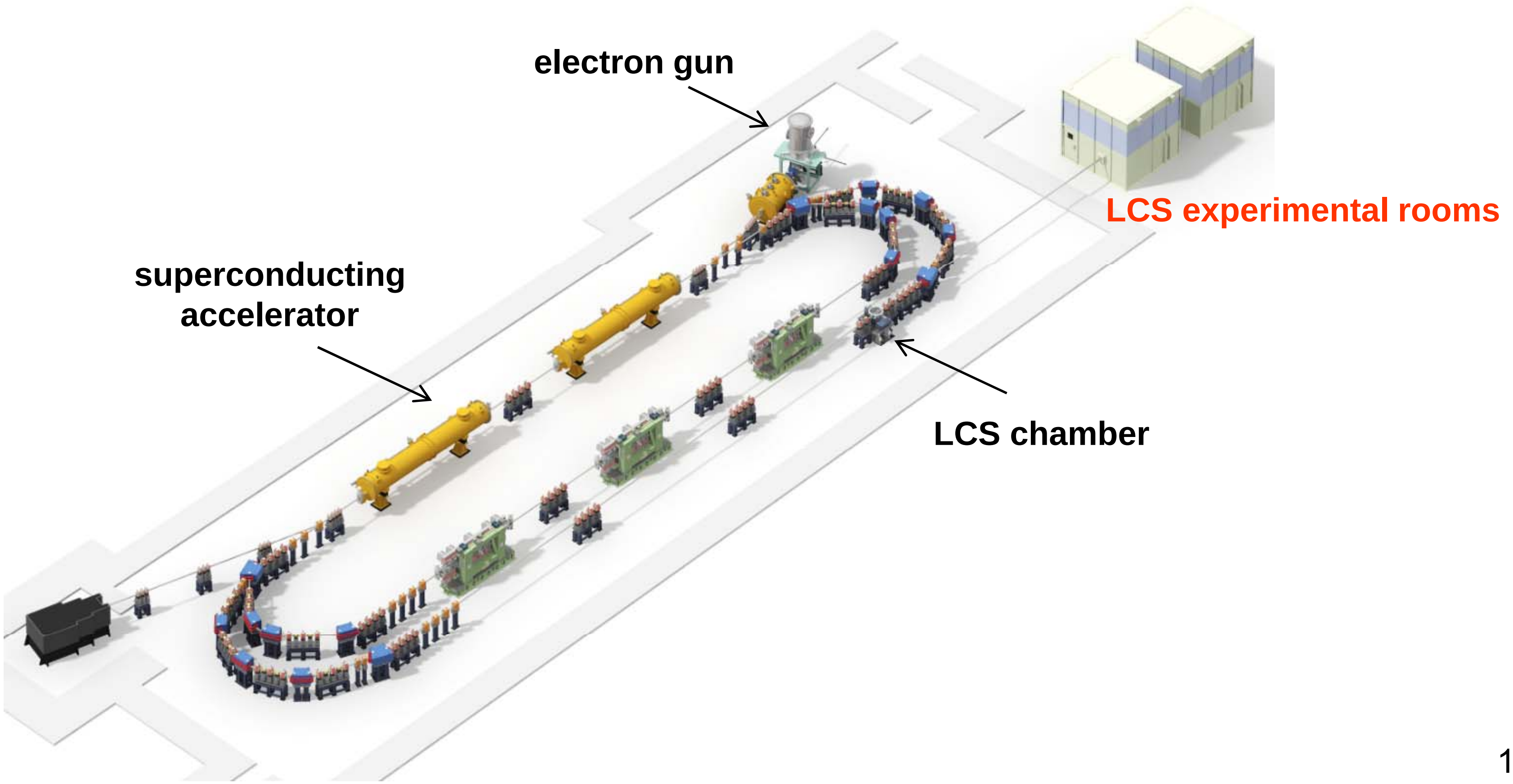
$\sigma_E \propto f^2$ ⇨ possible use of a low-frequency spoke cavity

M. Sawamura et al., Proc. SRF-2011 and ERL-2011 Poster

LCS-γ experiment at the Compact ERL

3-year R&D program funded from MEXT

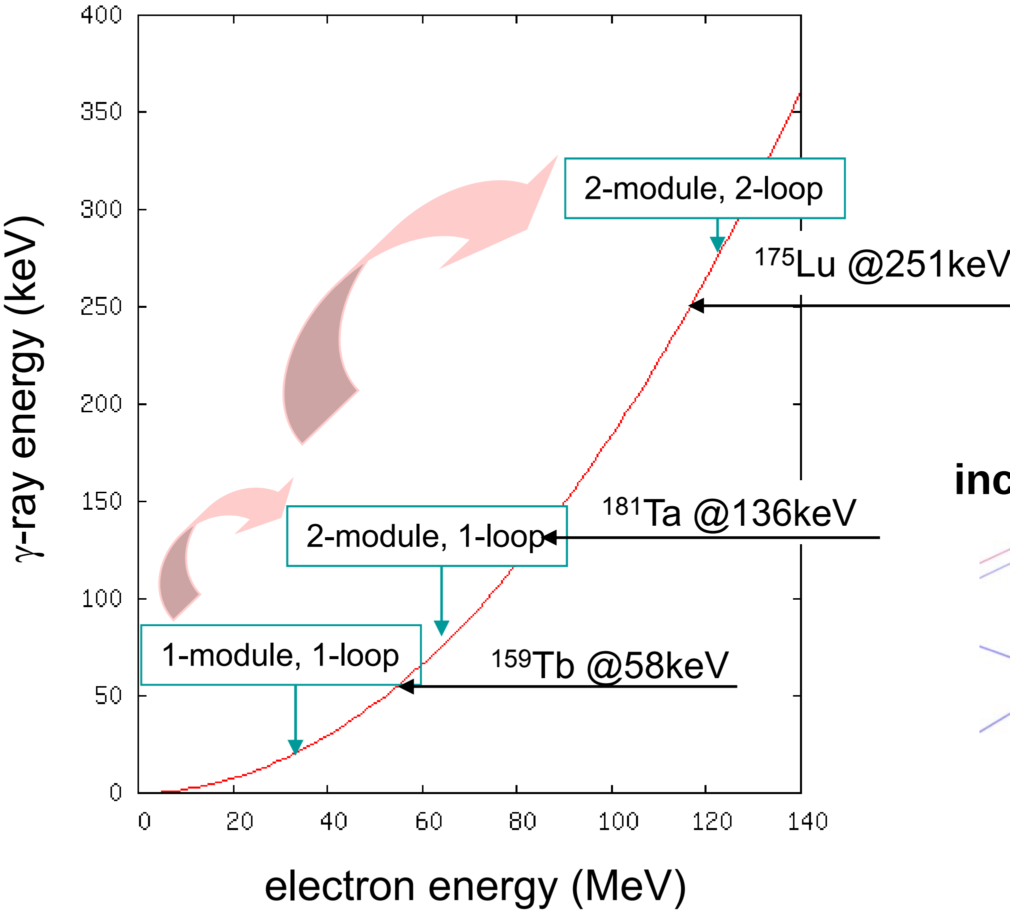
- Installation of a LCS chamber
- Generation of LCS γ-rays
- Demo-Experiment of NRF measurement

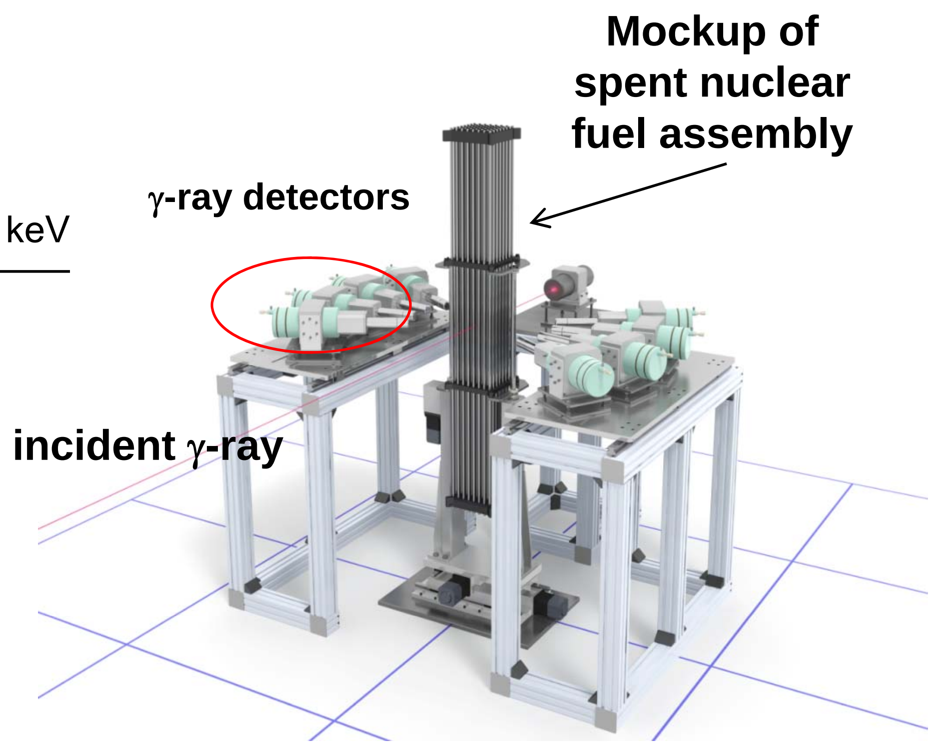


Demo-Experiment at the Compact ERL

Electron Energy Upgrade
35 MeV → 65 MeV → 125 MeV

Non-destructive measurement of "substitute" isotope (^{159}Tb for example)



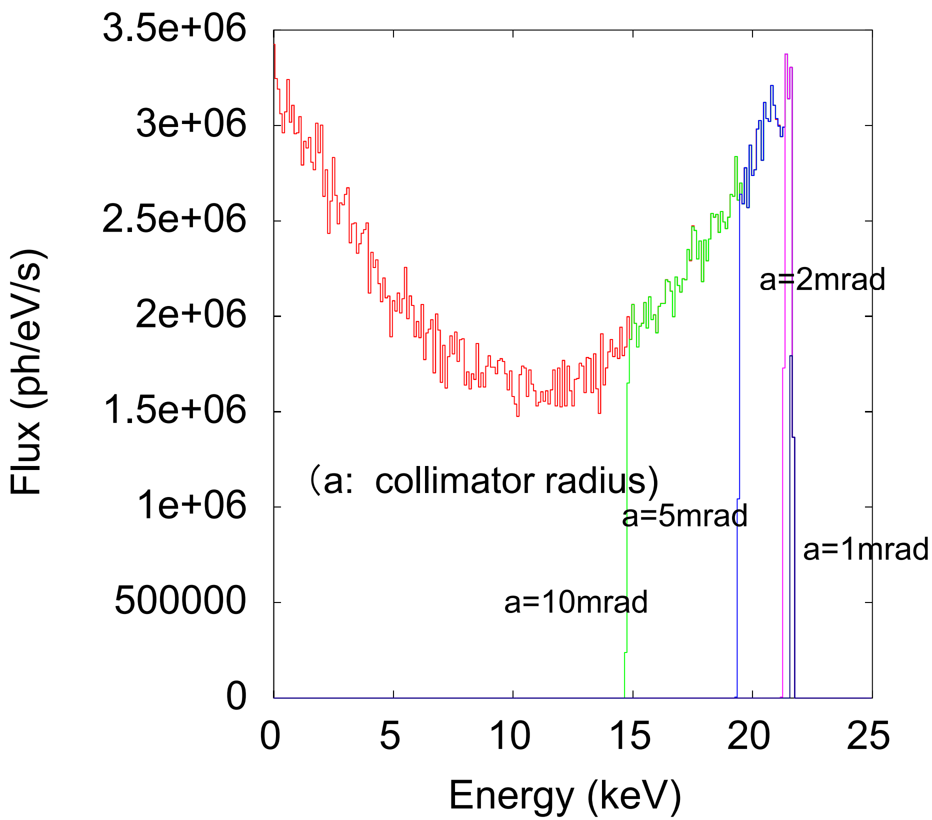


LCS photon flux expected in 35-MeV cERL

rep. rate 130 MHz, laser intracavity power = 100kW, collision spot = 40μm

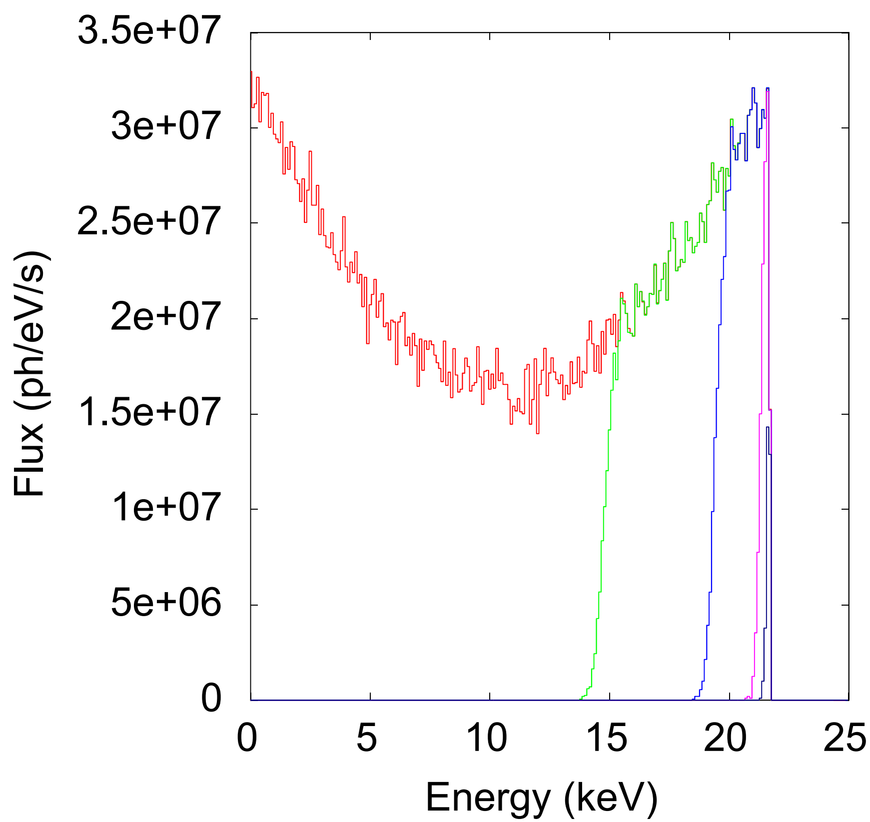
8pC, 0.1mm-mrad

total flux = 4.8E10/s
ΔE/E (rms) = 100eV for a=1.8 mrad



80pC, 1mm-mrad

total flux = 4.8E11/s
ΔE/E(rms)=100eV for a=1.4 mrad



Summary

- ERL is an ideal driver for laser Compton γ-ray sources.
  - no accumulation of quantum excitation by hard photon emission
- High-flux and narrow-bandwidth γ-rays are available.
- There are many scientific and industrial applications. (See Hayakawa's talk)
- Acc. technologies for "diffraction limited" electron beams can be shared with ERL X-ray sources and XFELO.
- Beam dynamics issues such as emittance growth, BBU, multi-loop design are also common to other ERLs.
- For the further reduction of γ-ray bandwidth, we need some developments: spoke cavity, precise LLRF, energy-width compensation …