

Recent Progress in Generation and Application of AIST Laser-Compton Gamma-ray Beam

H. Toyokawa, R. Kuroda, N. Oshima, M. Tanaka, M. Koike, A. Kinomura, H. Ogawa, N. Sei, R. Suzuki, T. Ohdaira, S. Goko, S. Hohara, T. Kaihori, K. Yamada

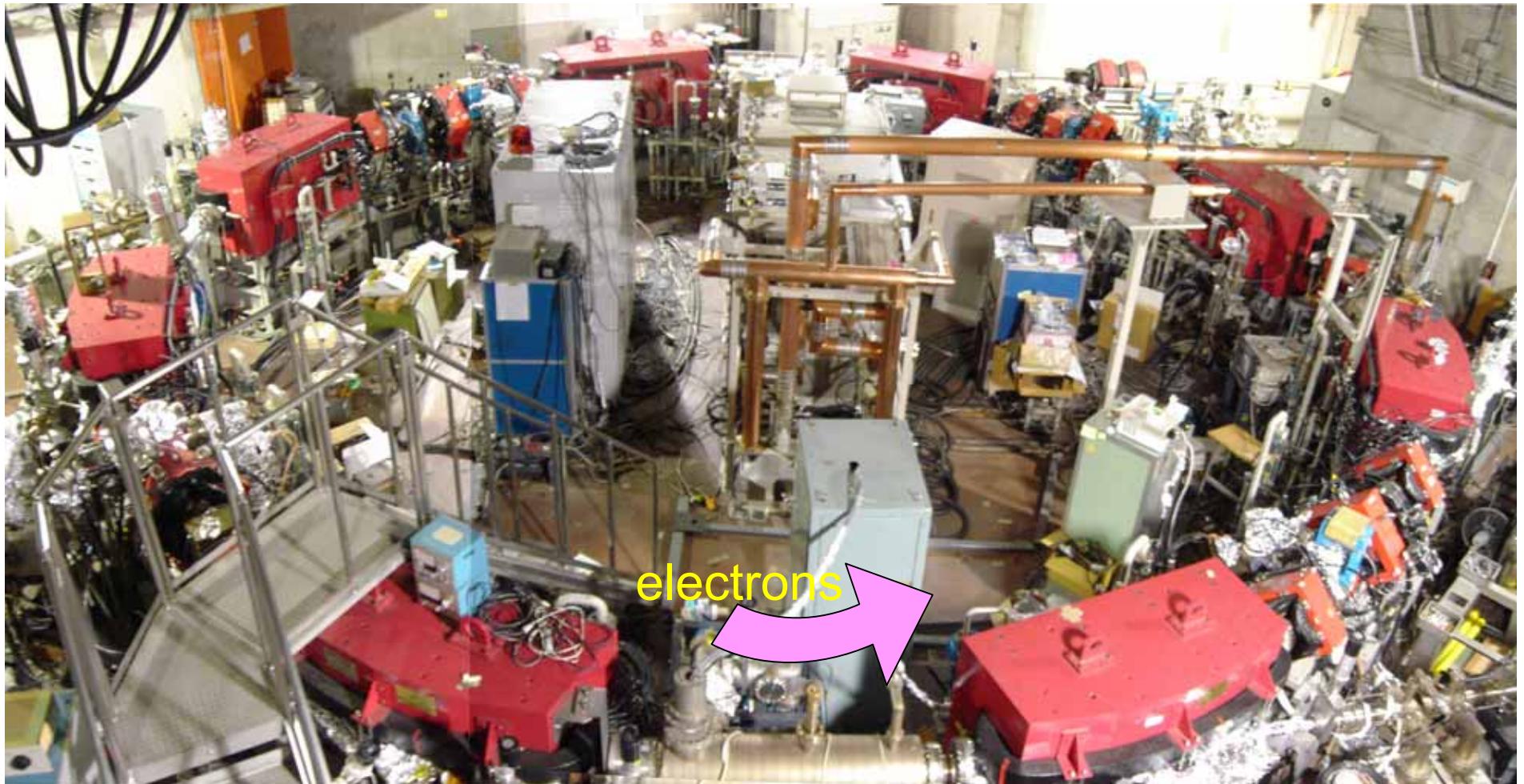
AIST electron accelerator team

Contents

- Introduction
- Basics: *Fundamental properties*
- Source development:
 - *Multi-pass laser-Compton scattering*
 - *Long-Axis Fabry-Perot Cavity*
 - *W-band (95 GHz) Electromagnetic-wave Undulator*
- Applications:
 - *Electron energy measurement*
 - *High-energy Gamma-ray CT*
 - *Detector development, calibration
(X-ray line sensor for Homeland security)*
 - *Nuclear and Astrophysics studies*

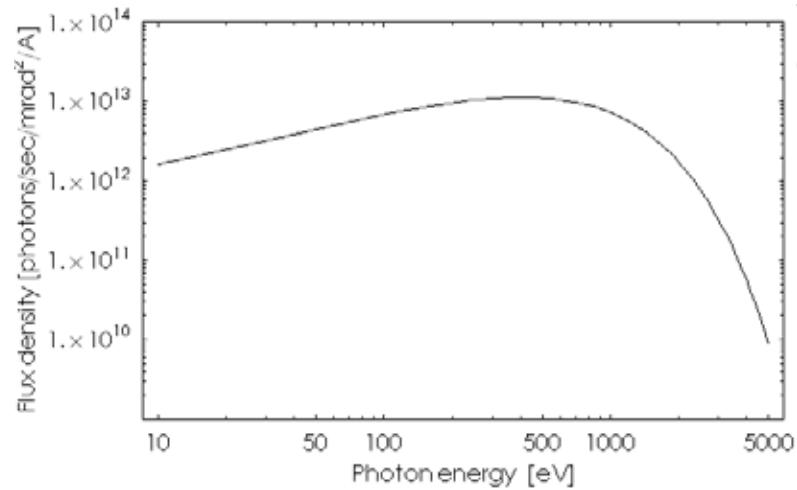
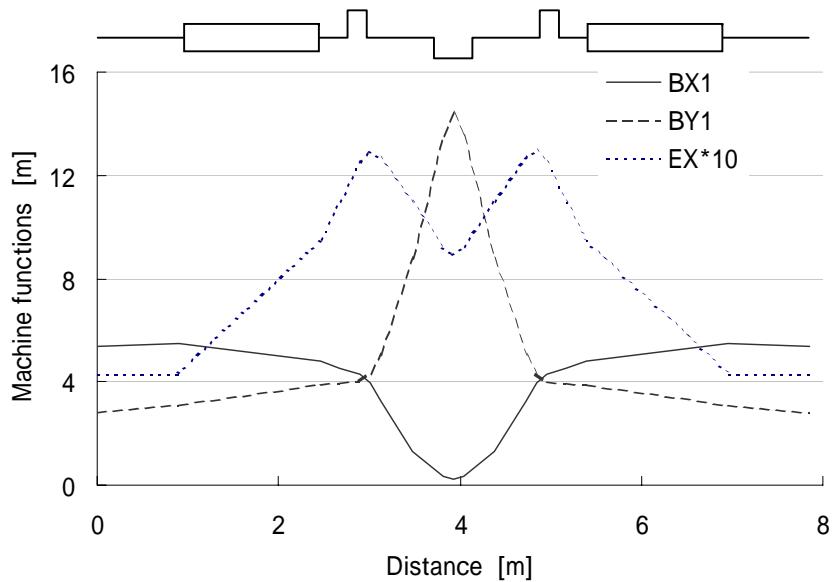
Introduction,

- *Facilities*
- *Laser-Compton photons*

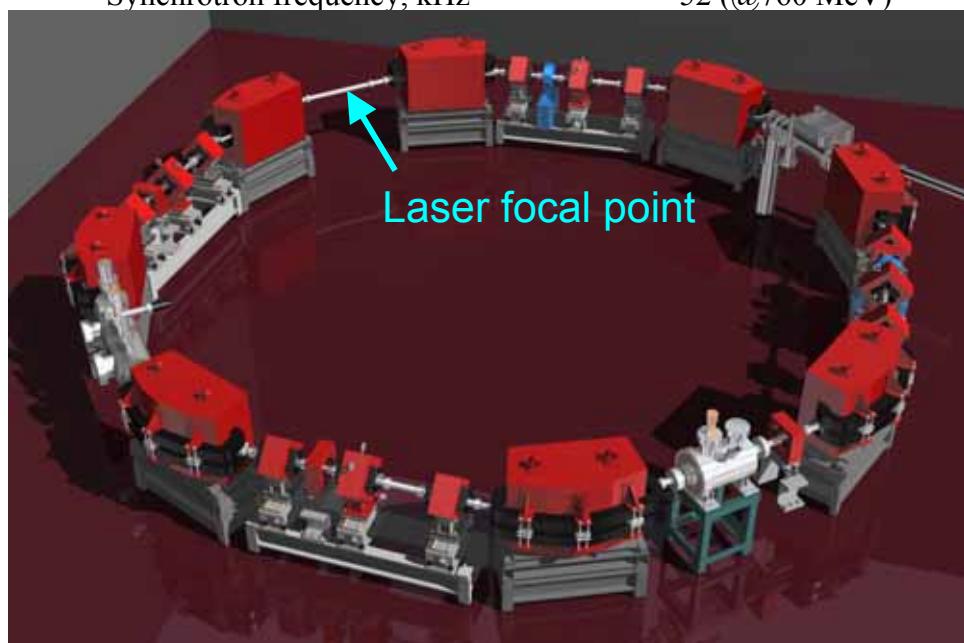


300 ~ 800 MeV, 300 mA

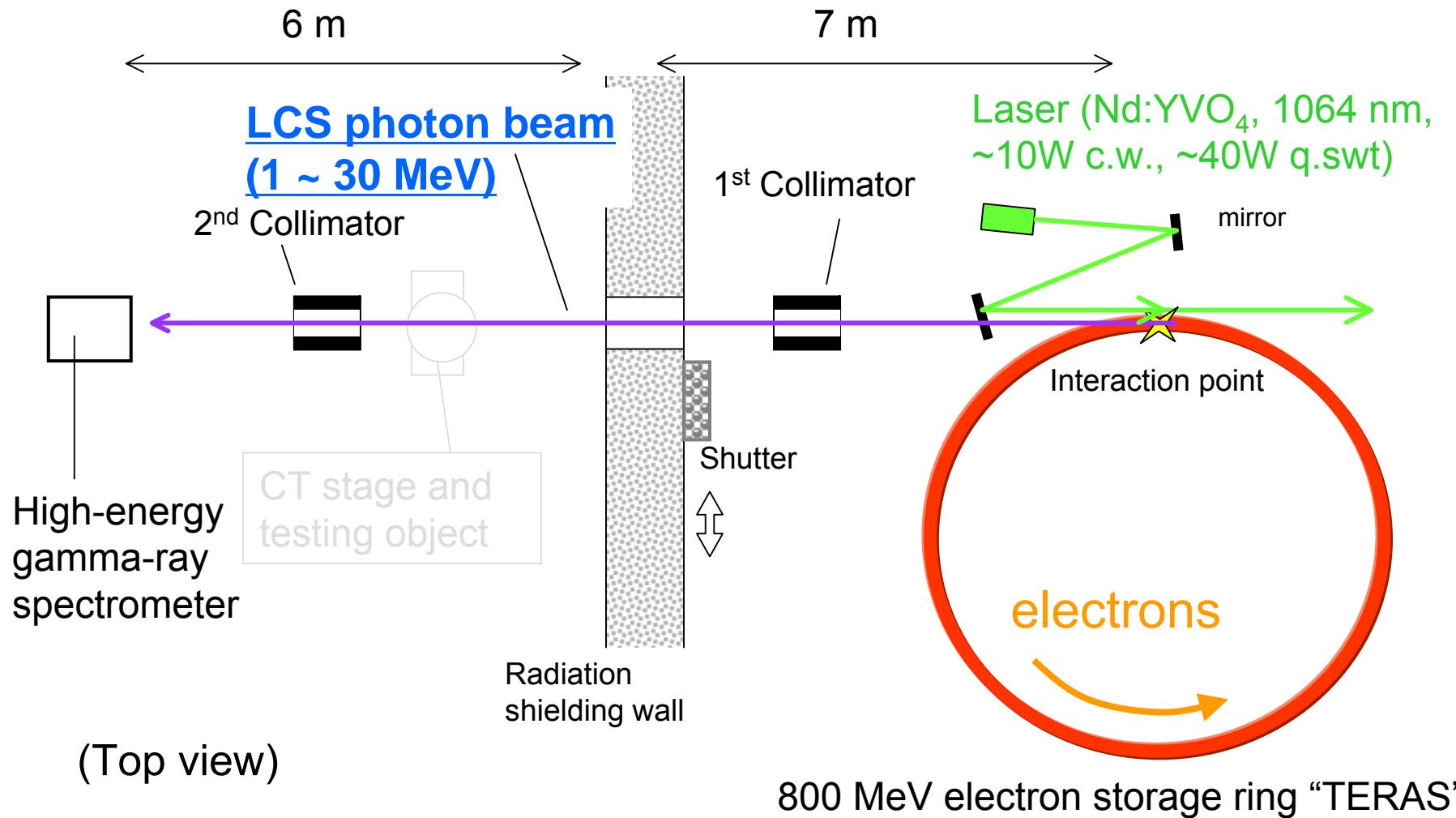
Electron storage ring “TERAS” of AIST Tsukuba, Japan



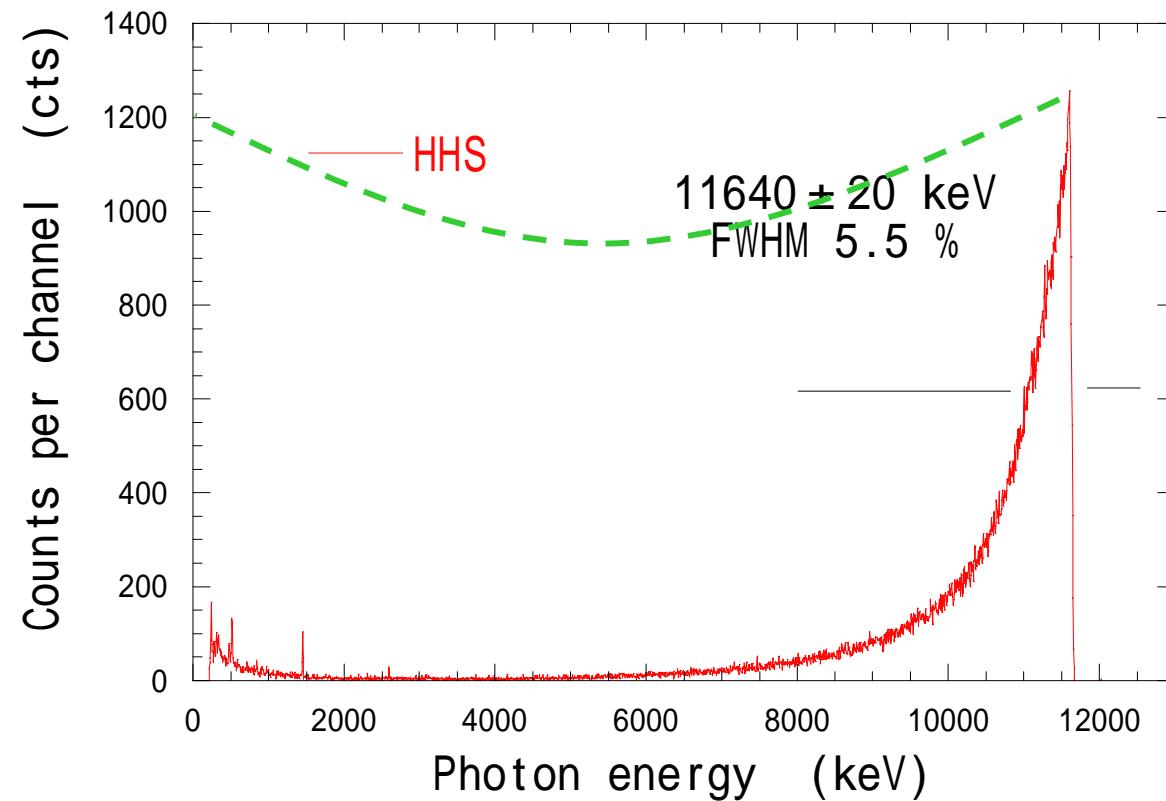
Injection energy, MeV	300
Max. operation energy, MeV	800
Lattice periodicity	4
Circumference, m	31.4
Horizontal betatron tune, x	2.258
Vertical betatron tune, y	1.311
Momentum compaction factor,	0.120
Horizontal chromaticity, x	-2.965
Vertical chromaticity, y	-2.891
Natural emittance, nm-rad	570 (@760 MeV)
)	
Operating frequency, MHz	171.7
RF voltage, kV	65
Synchrotron frequency, kHz	52 (@760 MeV)



LCS gamma-ray beamline

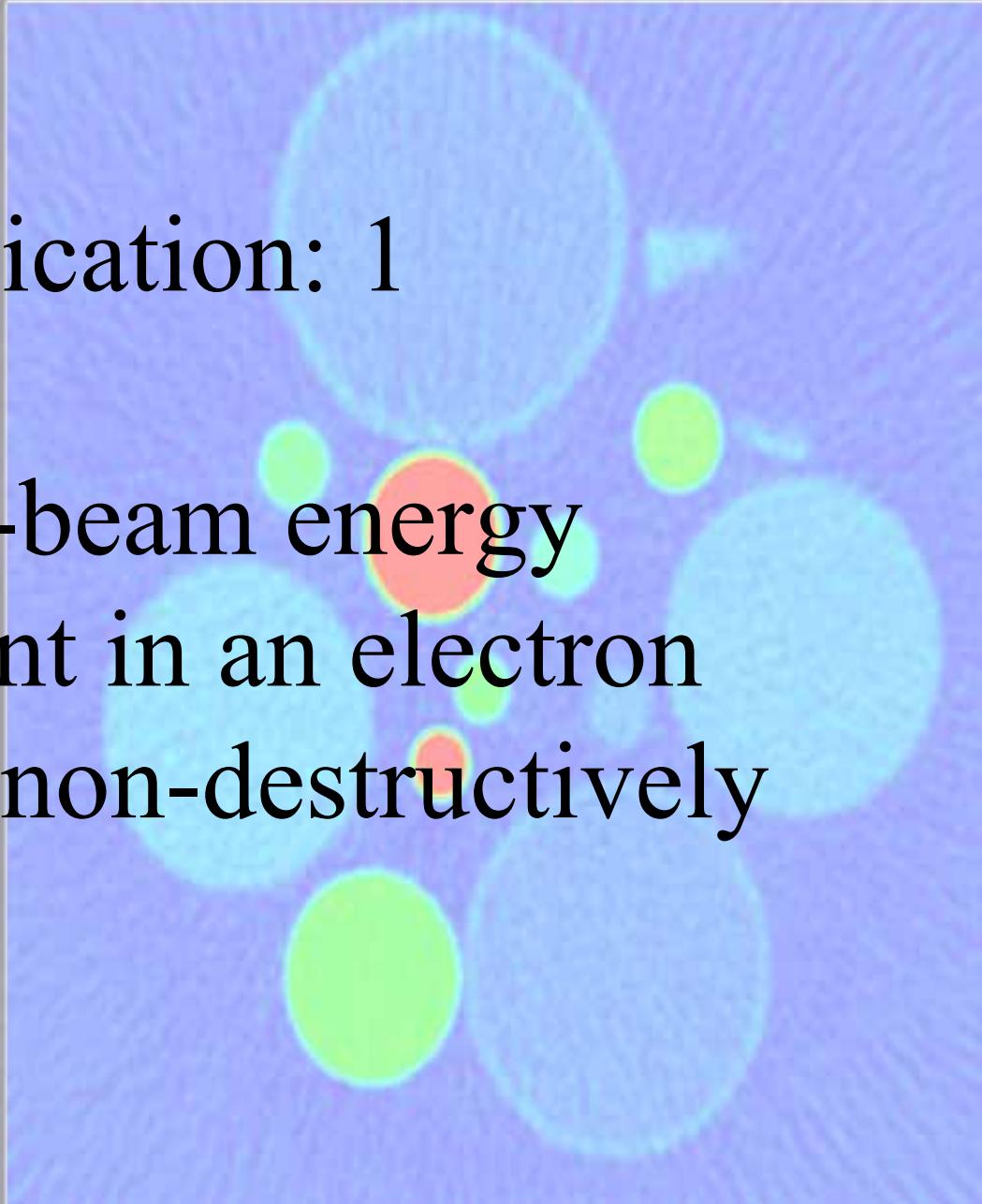


Energy spectrum of 11 MeV laser-Compton photon beam

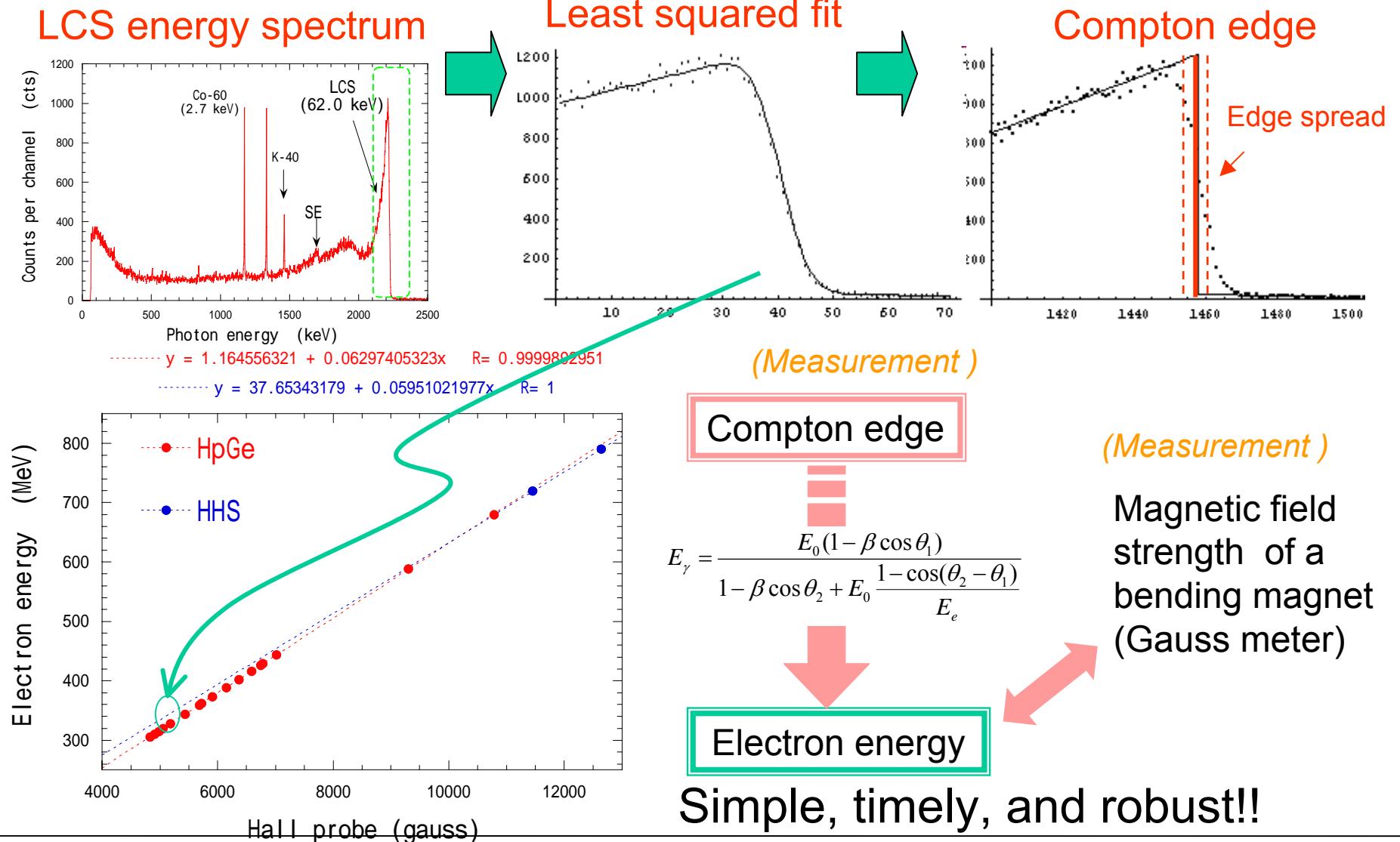


Application: 1

Electron-beam energy
measurement in an electron
storage ring, non-destructively



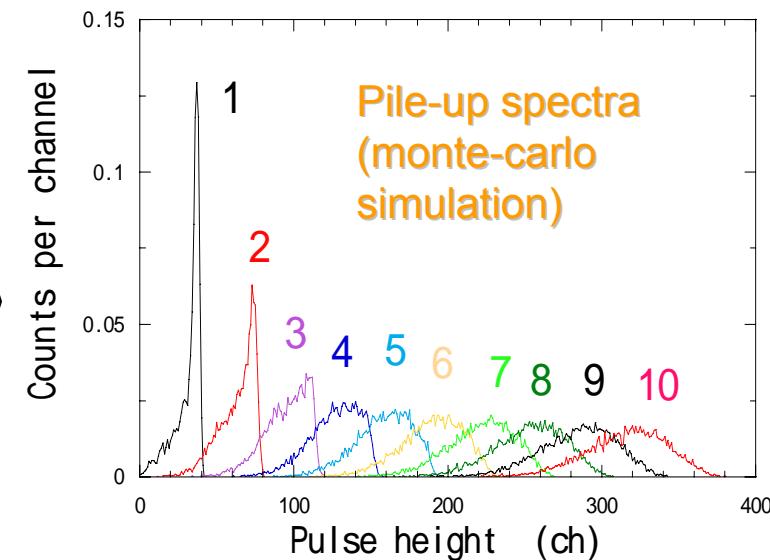
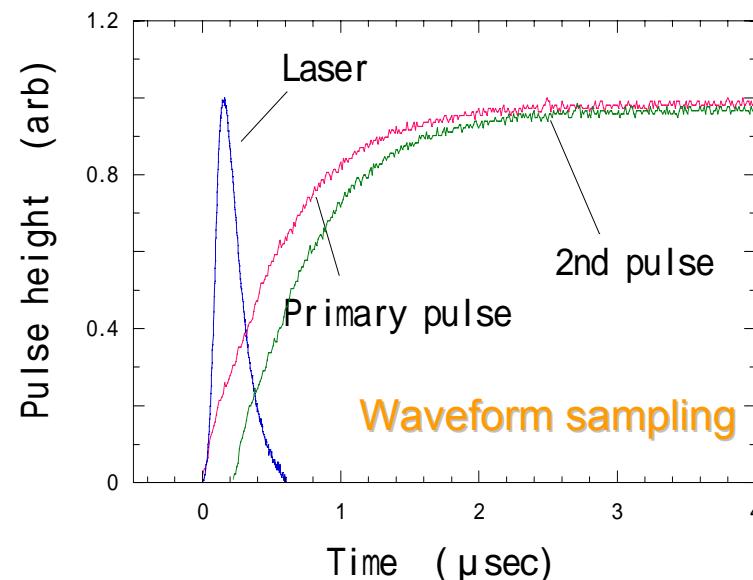
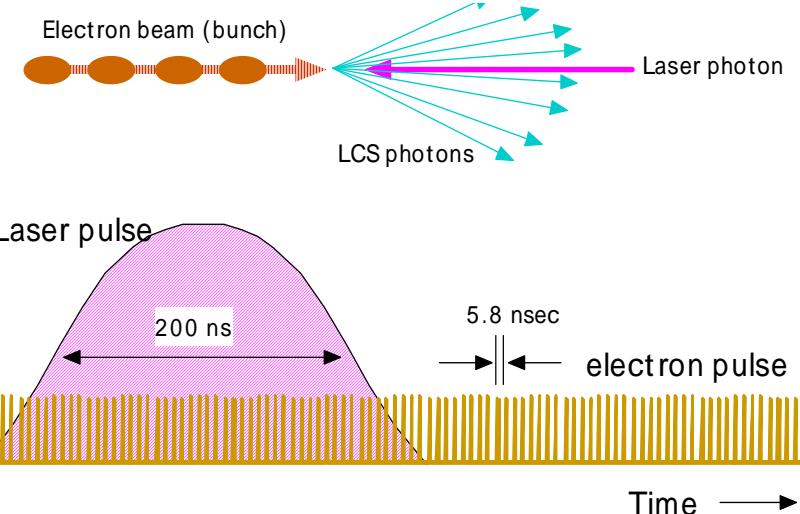
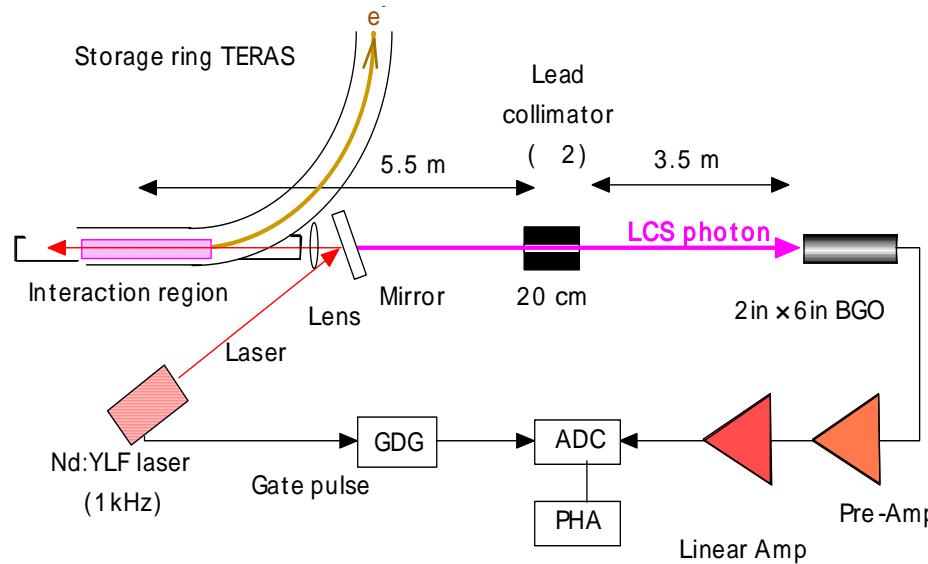
Non-destructive measurement of electron energy in an electron storage ring with laser- Compton scattering

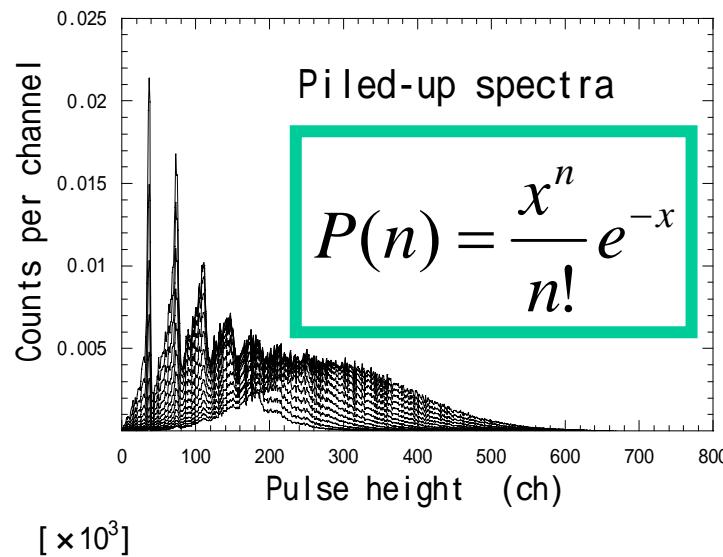


Basics: 1

Photon flux of pulsed gamma-ray
(Q-switched laser, pile-up event)

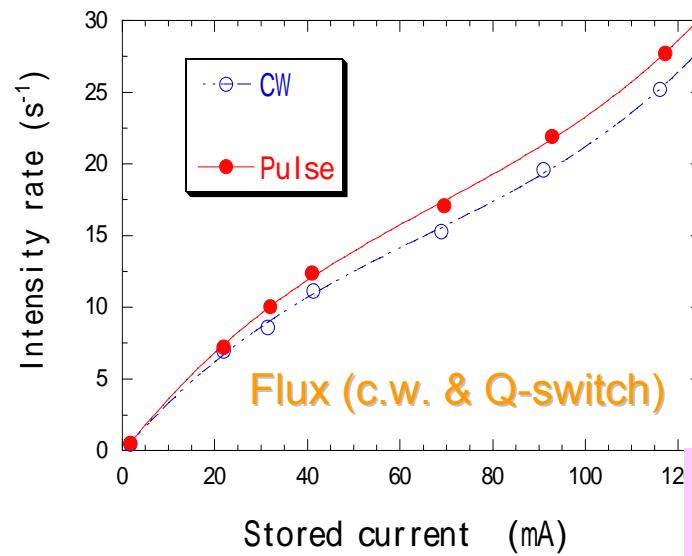
How to estimate photon flux of pulsed-LCS gamma-ray?



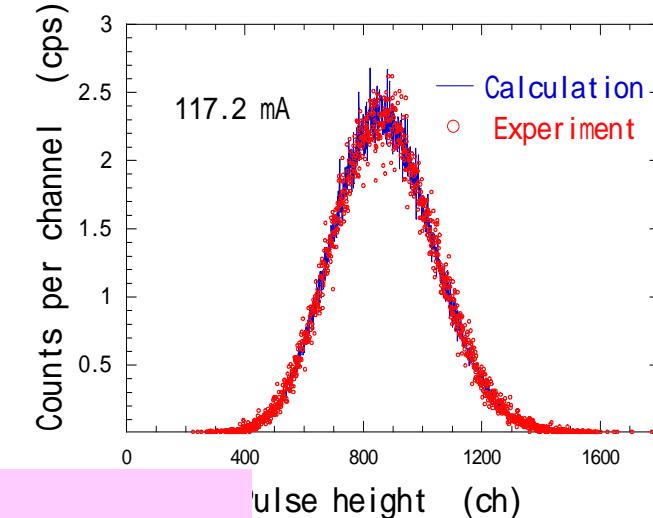
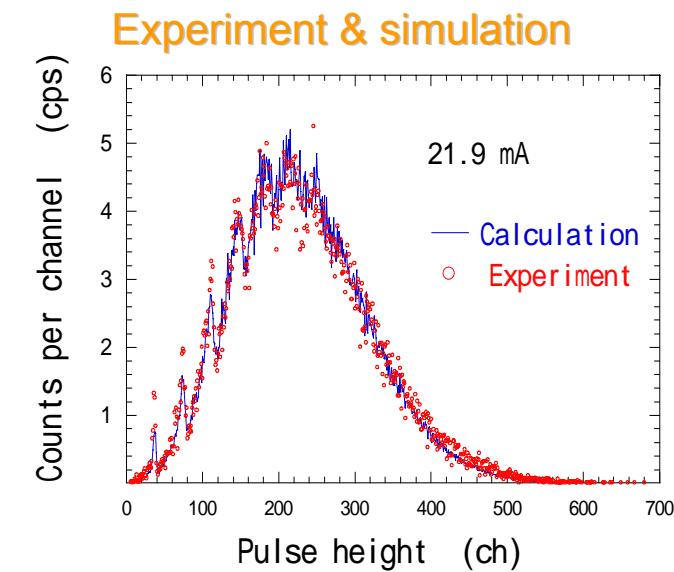


Response function
Poisson distribution

Least squared fit



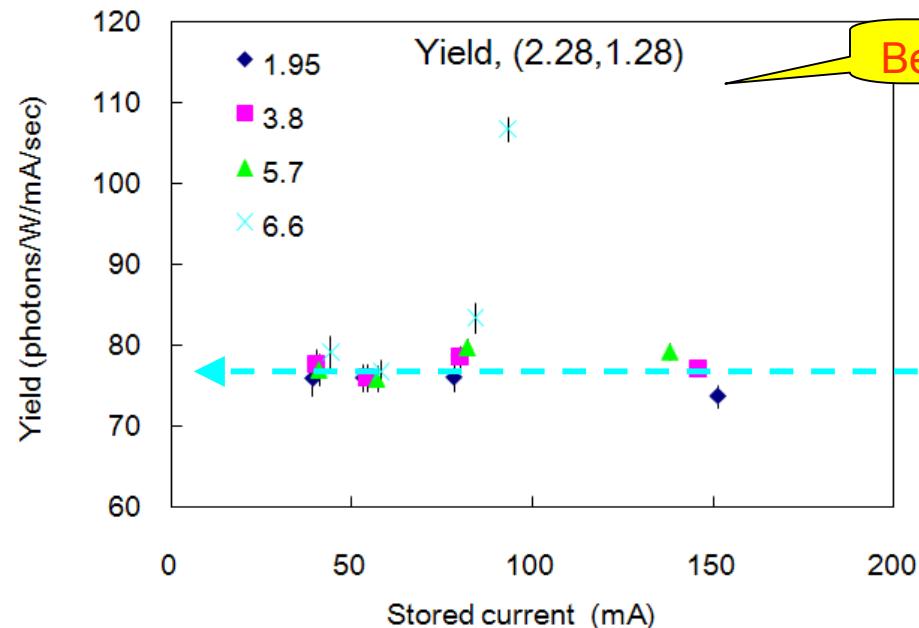
Intensity rate
= laser rep. Rate × pile-up number



H. Toyokawa et al., "Flux Measurement of the Laser-Compton-Backscattered Photons With a Poisson Fitting Method", IEEE Trans. Nucl. Sci., Vol. 47, No. 6, pp. 1954-1957, 2000

Basics: 2

Photon yield and beam life time

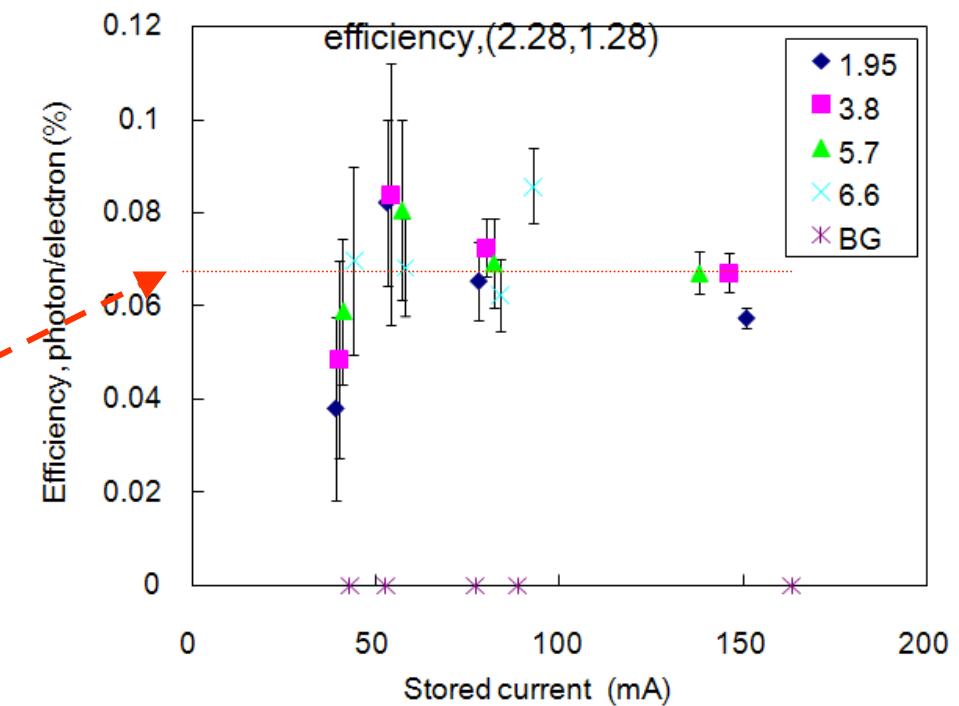


Photon yield normalized to
the same laser power and
storage current.

80 photons/W/mA/sec

LCS photon number per
net electron decay

7×10^{-4}



Basics: 3

Beam profiles and source size

LCS gamma-ray
beam source size

Horizontal: 40 µm

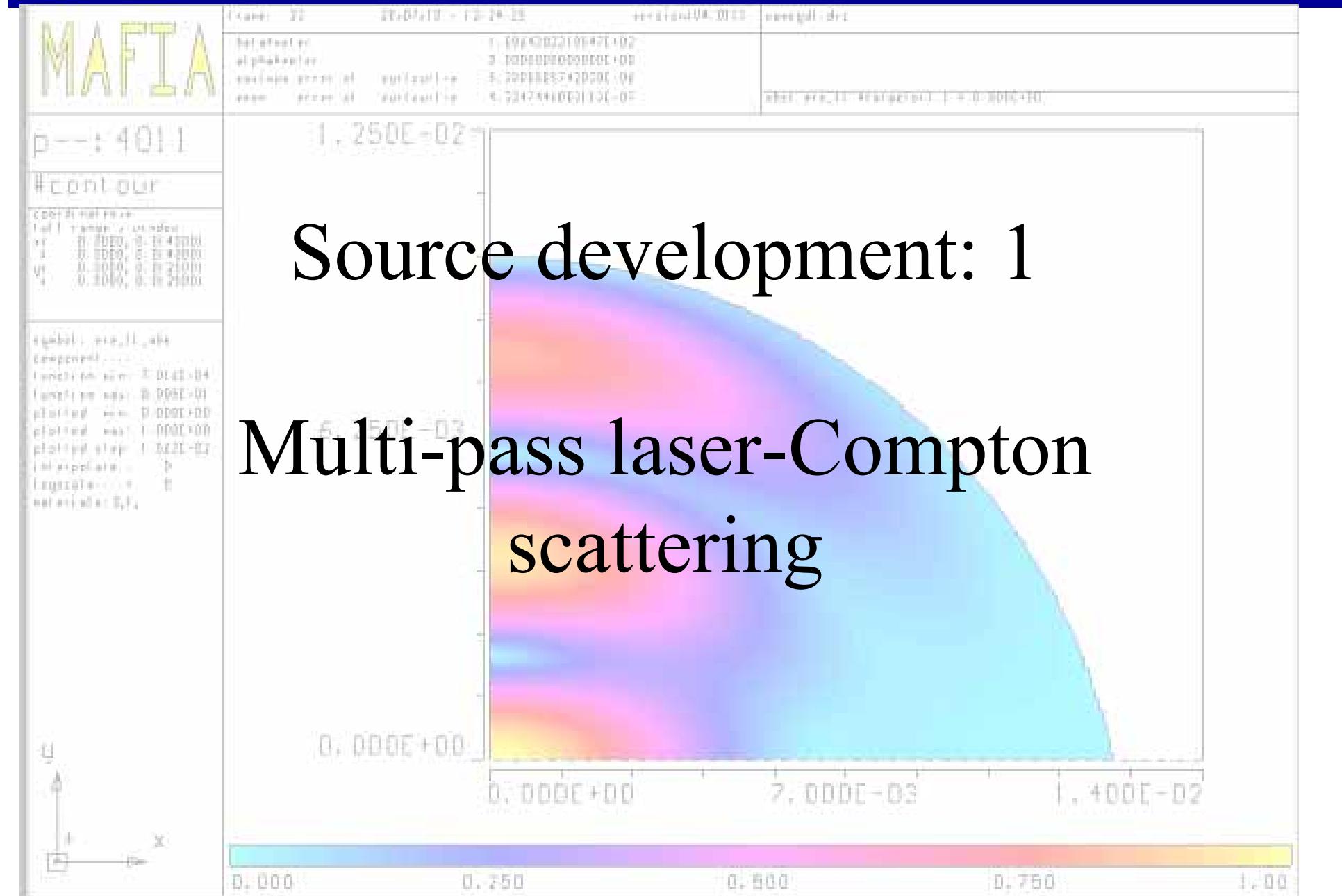
Vertical: 180 µm

Longitudinal size: 40 cm

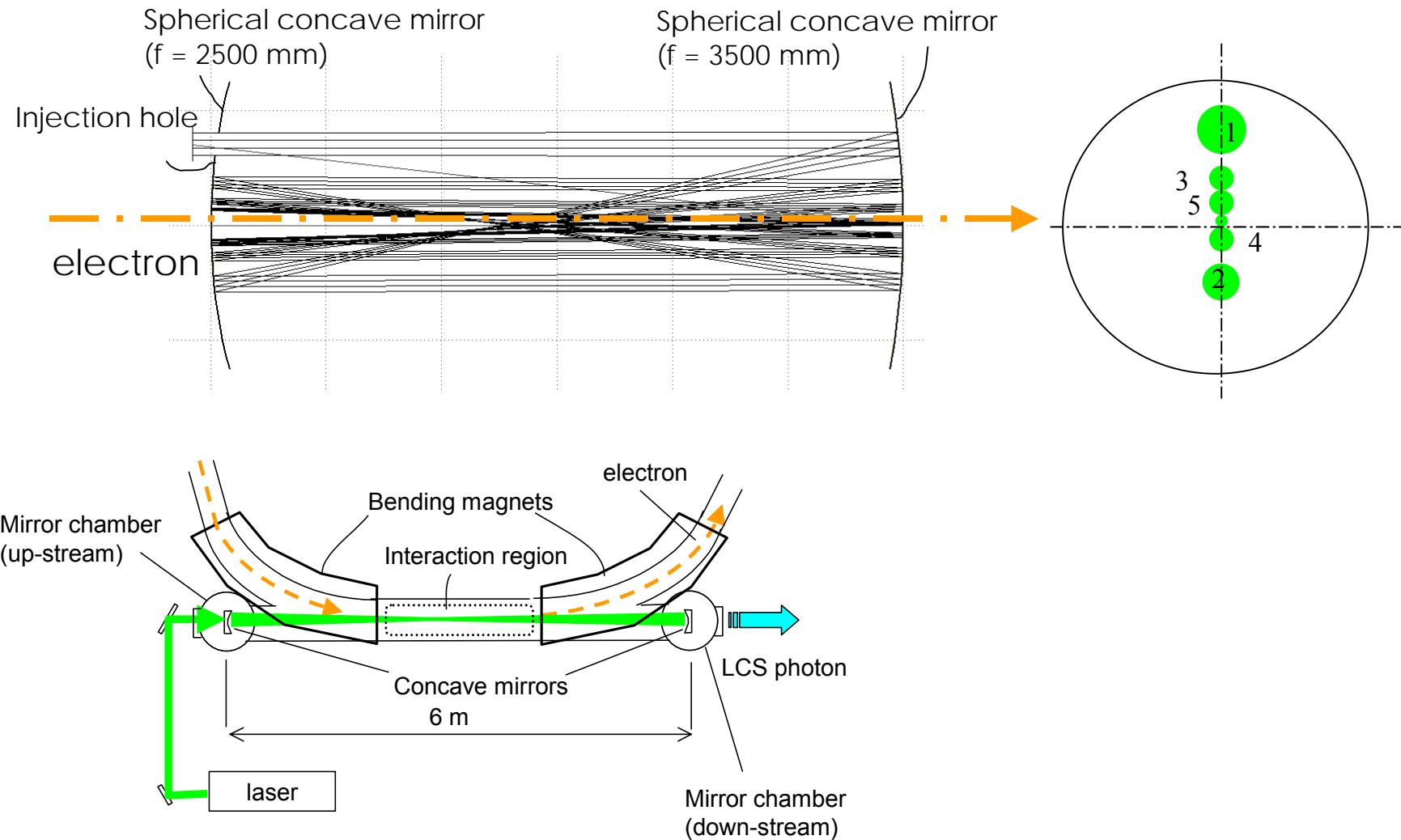
Beam divergence

Horizontal: 299 µrad

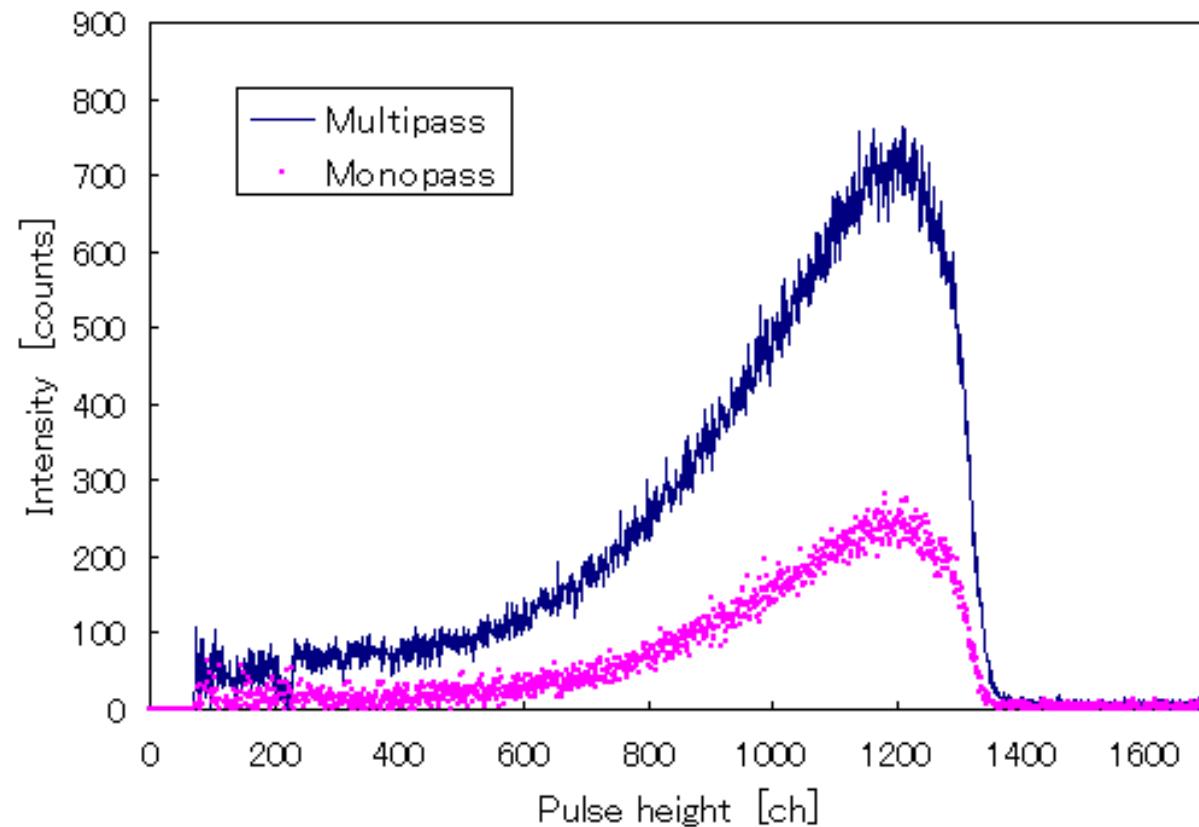
Vertical: 277 µrad



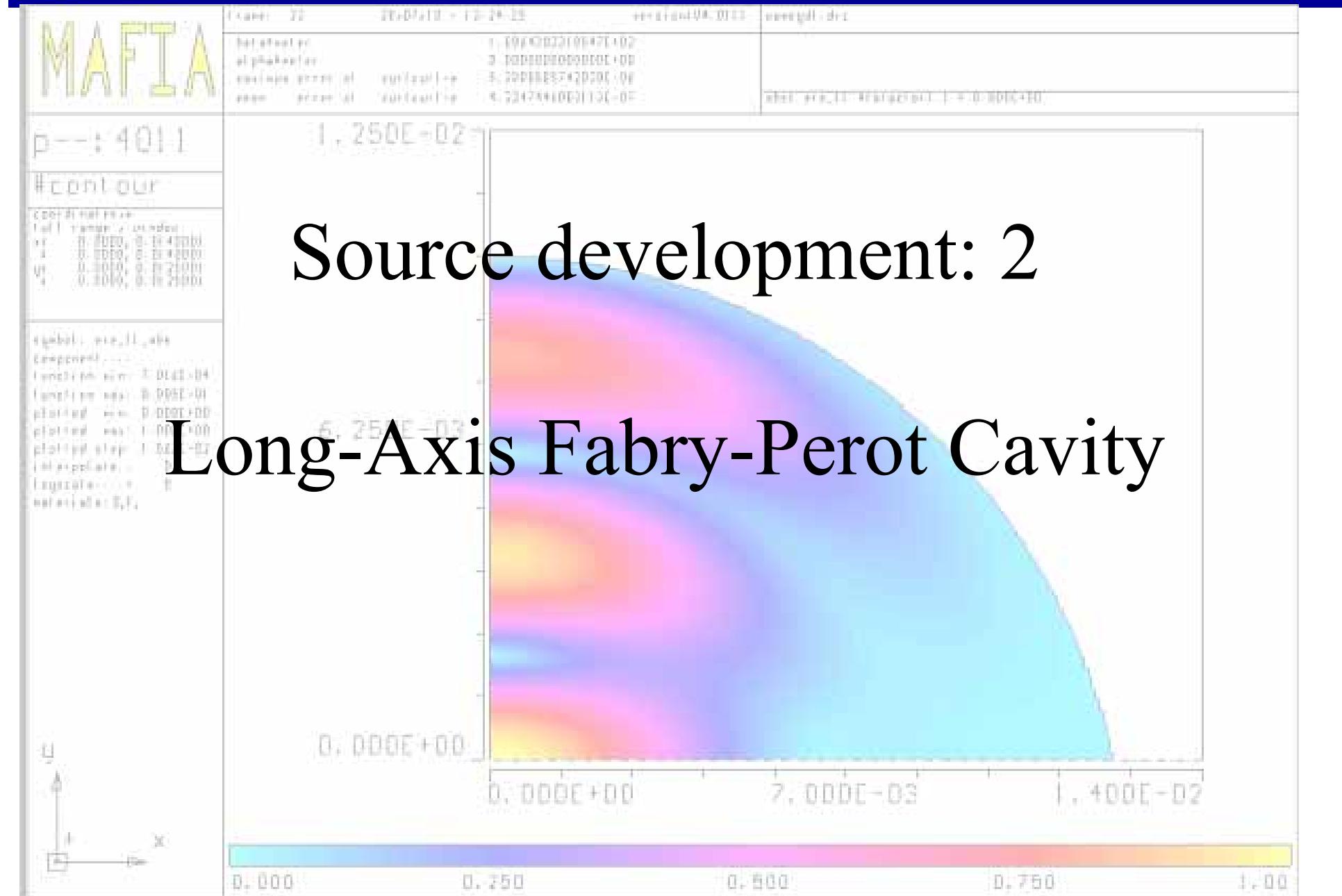
Multi-pass laser-Compton scattering with circulating electrons



Multi-pass laser-Compton scattering with circulating electrons

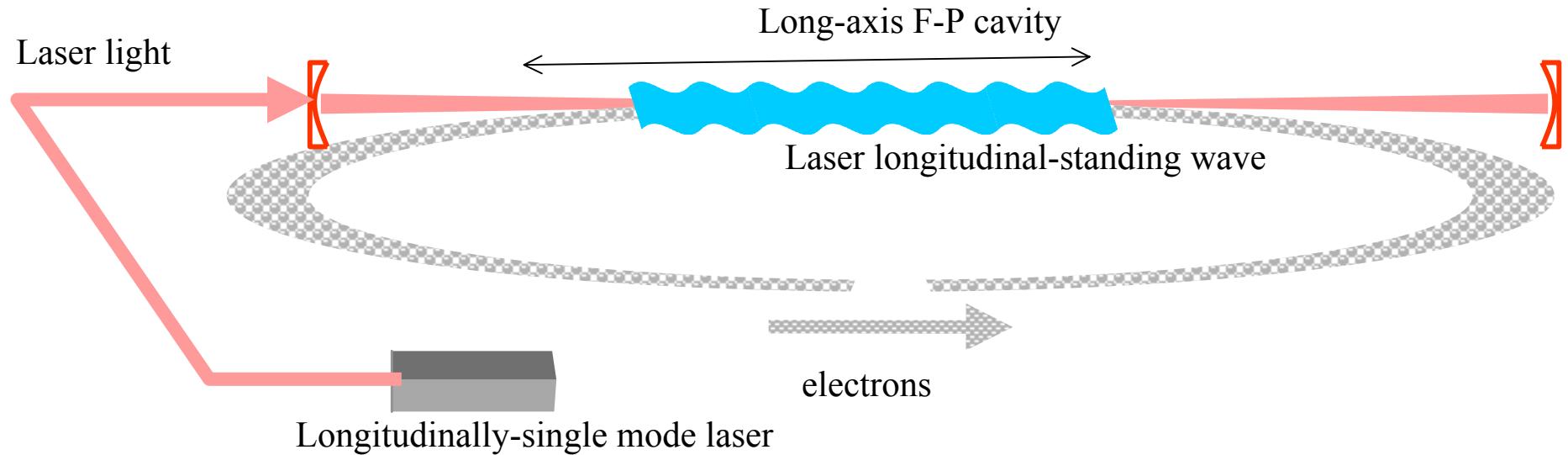


Intensity gain of 3.3 was achieved with method-A!!

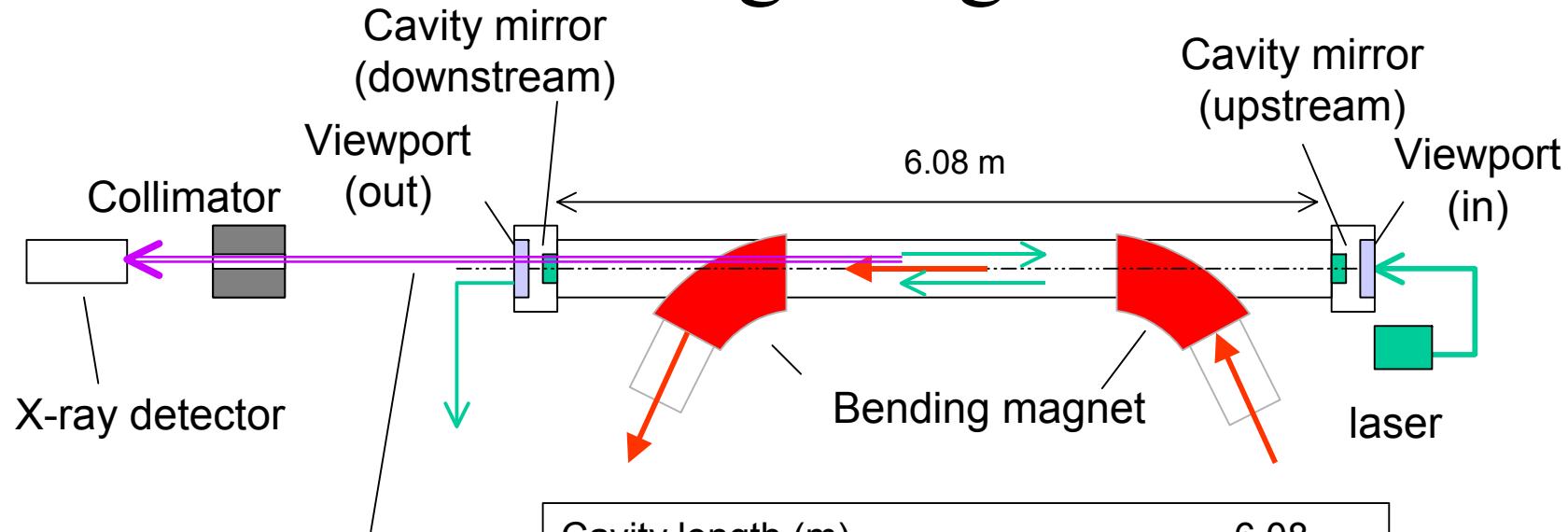


Fabry-Perot cavity in electron storage ring

Enhancement of an effective laser power for LCS up to a few decades using a F-P cavity.

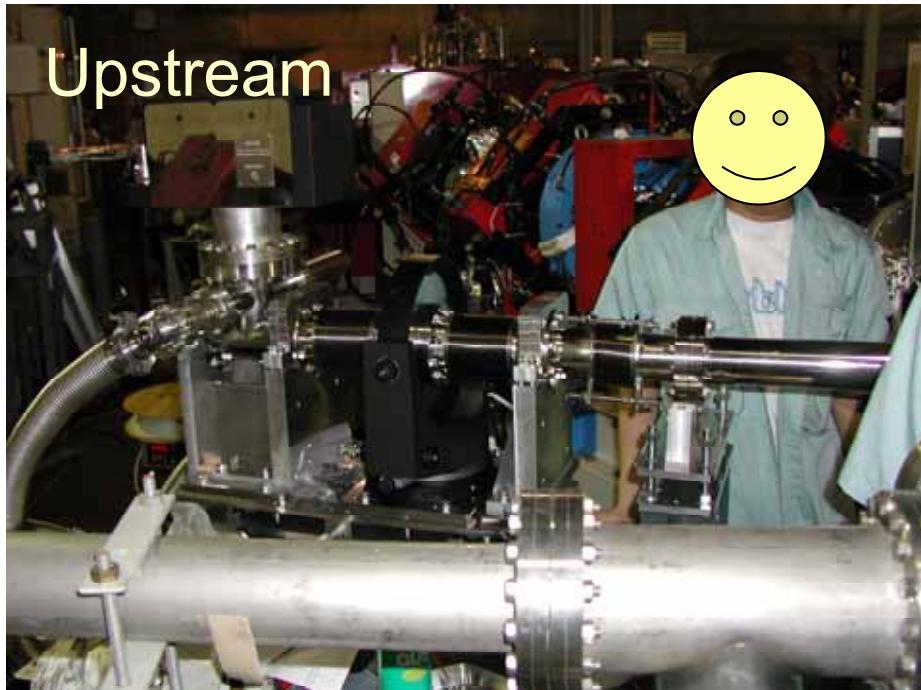


6-m F-P cavity, installed in the storage ring



Cavity length (m)	6.08
g-parameter	-0.216
Mirror r.o.c (m)	5.0
Rayleigh range (cm)	244.1
Beam waist size at focal point (mm)	0.909
Beam waist size at mirror (mm)	1.452
Power density (kW/cm ²)	60.4

Mirror chamber



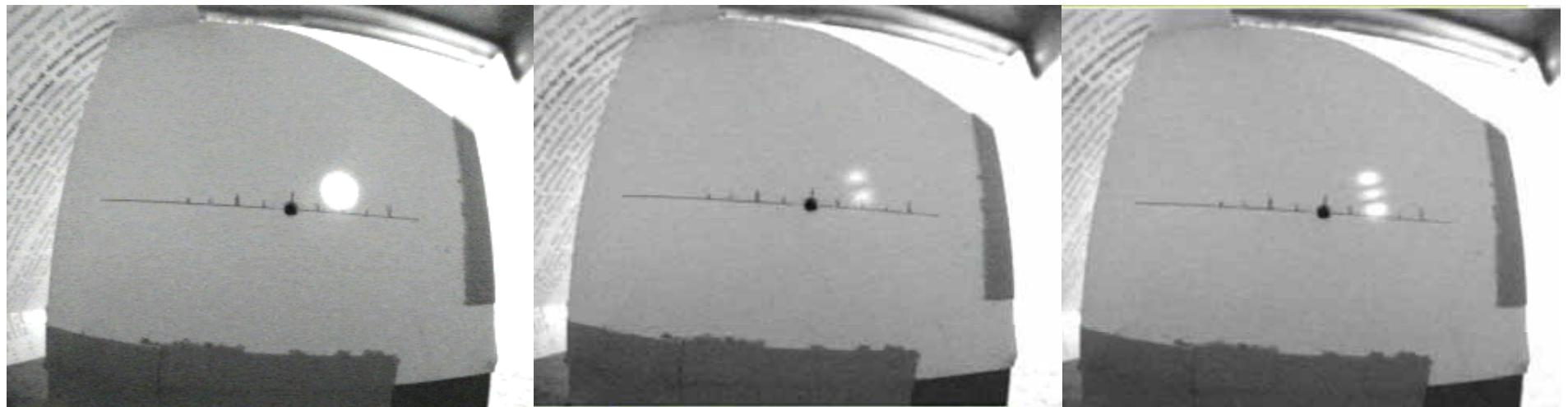
Upstream



Downstream

Long-Axis Fabry-Pérot Cavity for Intense Laser-Compton Photon Beam

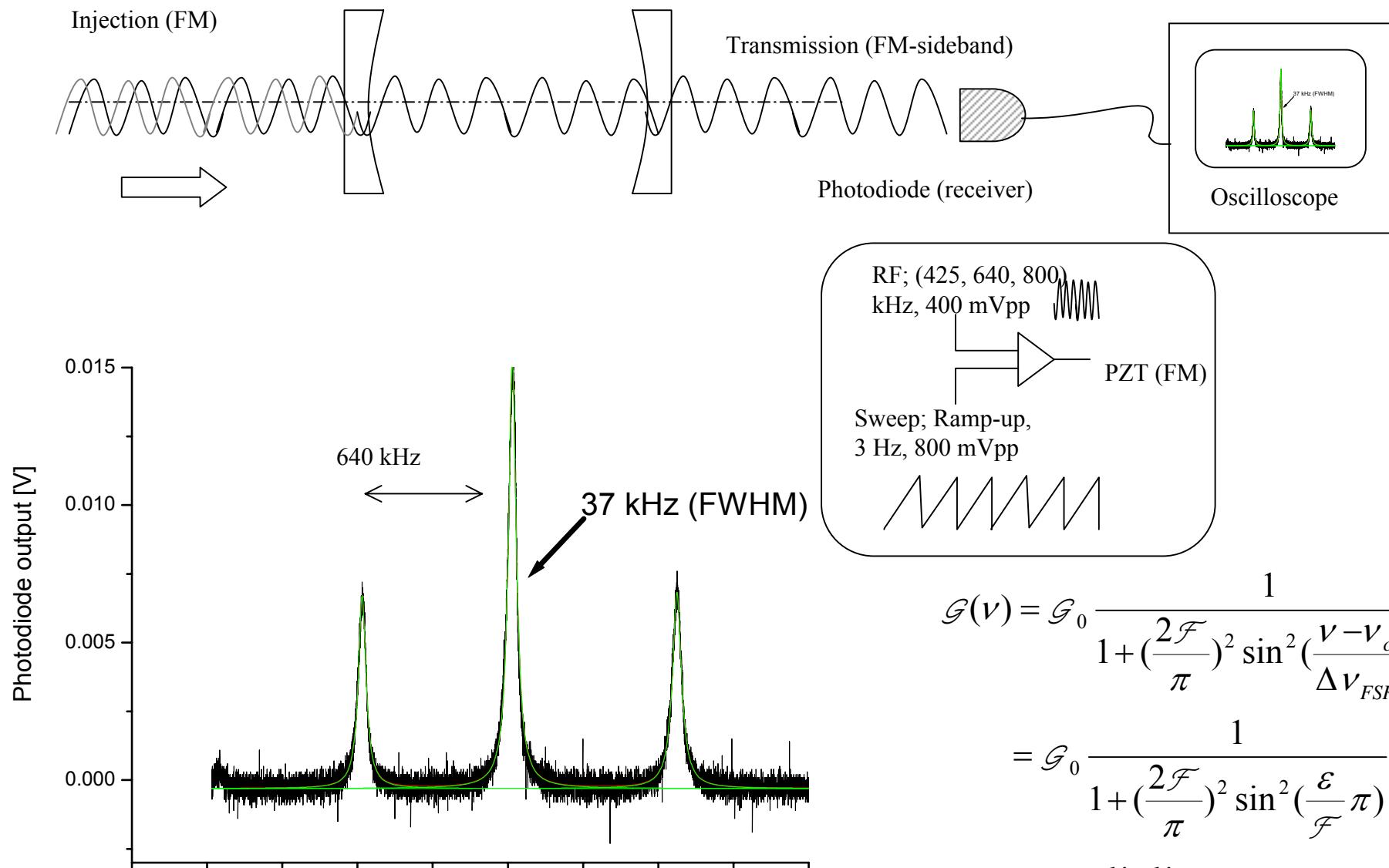
H. Toyokawa et al., Jpn. J. Appl. Phys. 44[10] (2005)7671.



TEM_{00}

TEM_{01}

TEM_{02}



$$\text{where } \varepsilon \equiv \frac{\nu - \nu_c}{\Delta\nu_{cav}}$$

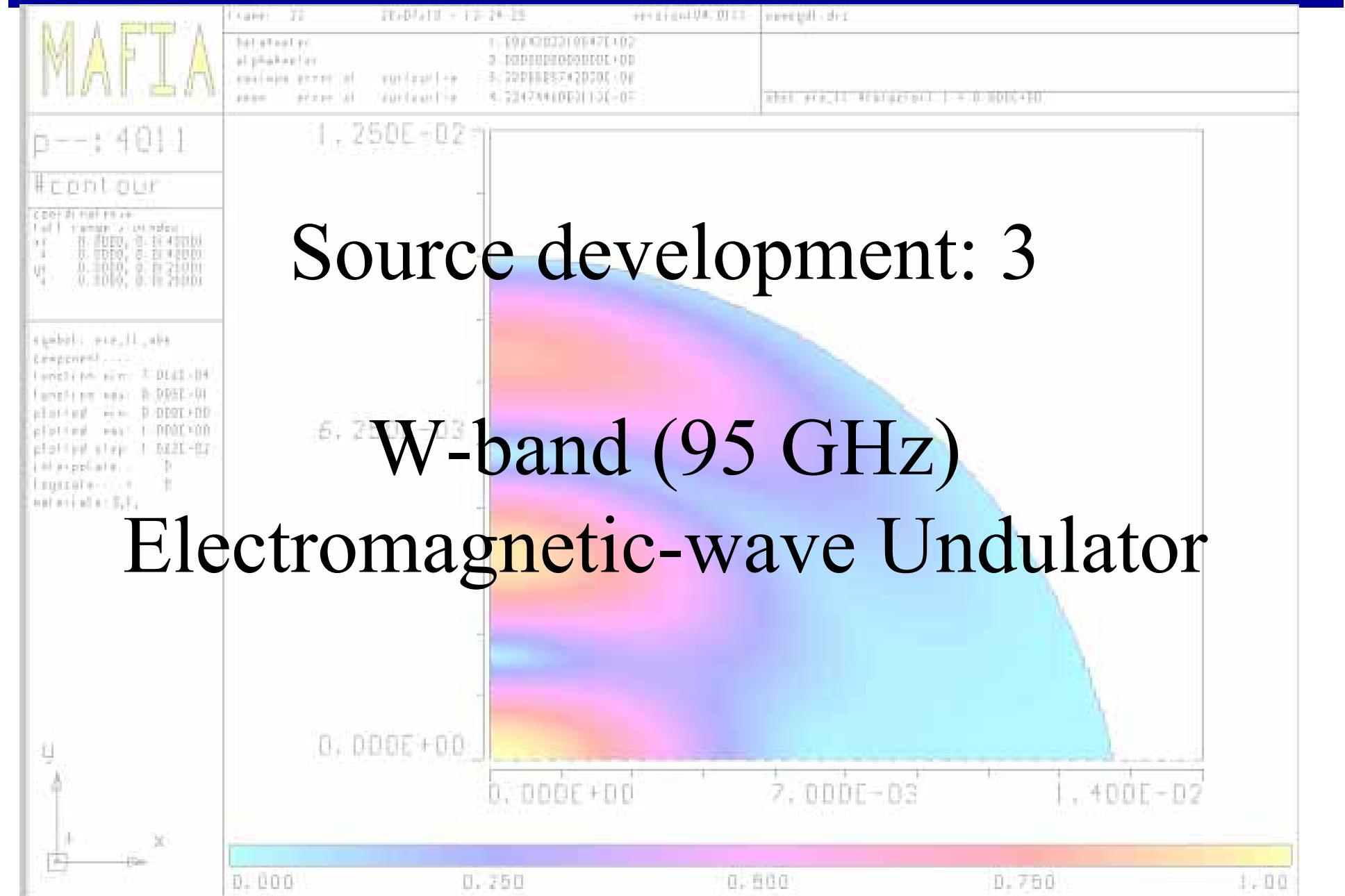
Photon yield enhancement of 75.3!!

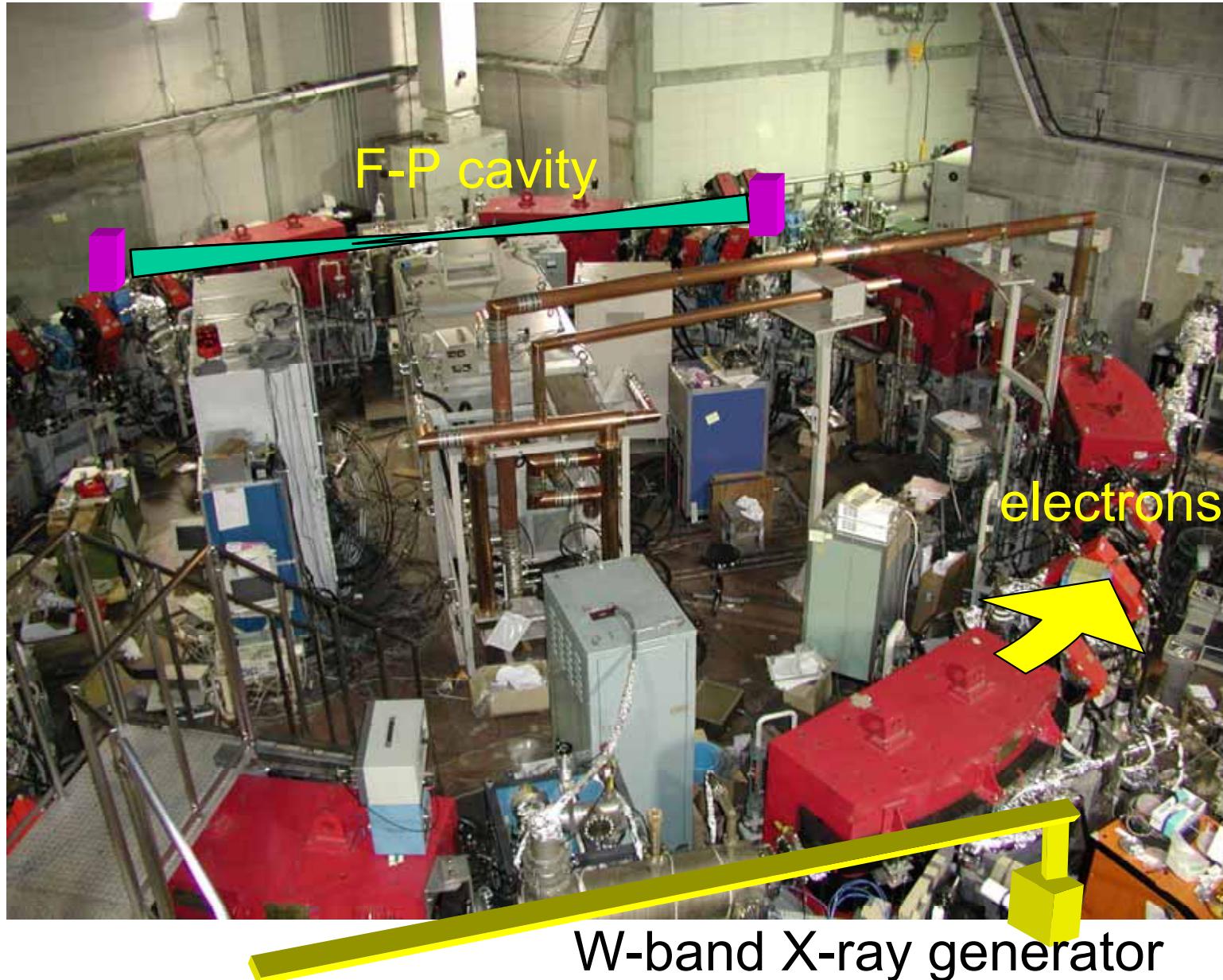
Nominal values

▫ Reflectivity; R	99.83 % (catalogue)
▫ Transmissivity; T	0.17% (catalogue)
▫ Total loss; P	? (ppm)
▫ Finesse; \mathcal{F}	1850
▫ <i>Ring down time</i>	12.1 μ sec

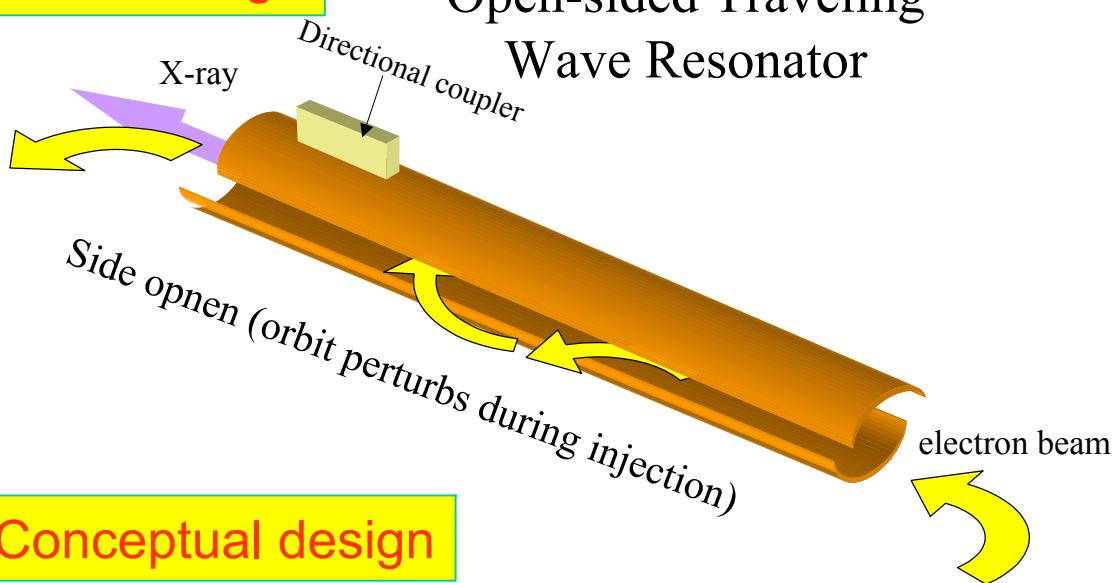
Measured values

✓ Cavity length; L	6.08 ± 0.05 m
✓ FSR; $\Delta\nu_{\text{FSR}}$	24.7 MHz
✓ Bandwidth; $\Delta\nu_{\text{cav}}$)	37 kHz
✓ Finesse ; \mathcal{F}	~ 660
✓ Reflectivity with round trip loss	99.53 %
✓ Round trip energy absorption; δ_0	0.612 %
✓ Maximum gain; G_0	<u>75.3</u>
✓ Cold cavity Q; Q_c	1.17×10^{10}
✓ PZT tuning coefficient	0.550 MHz/V



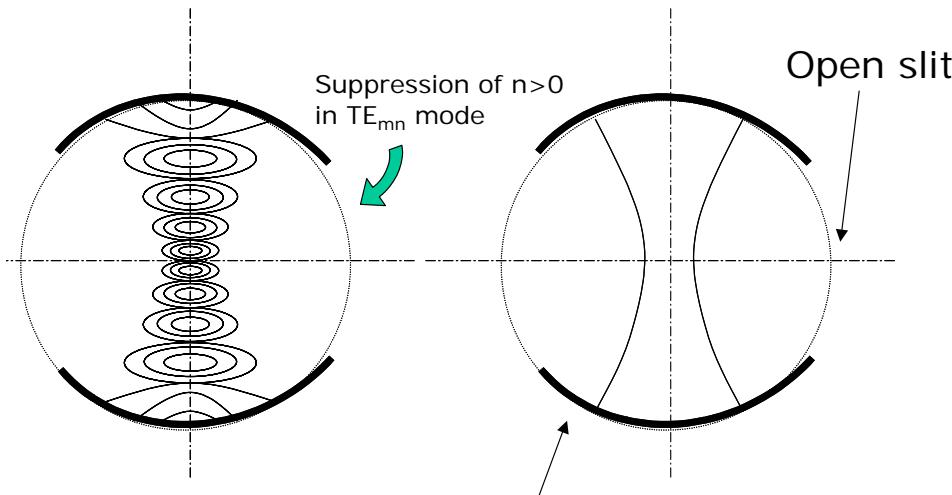


Device image

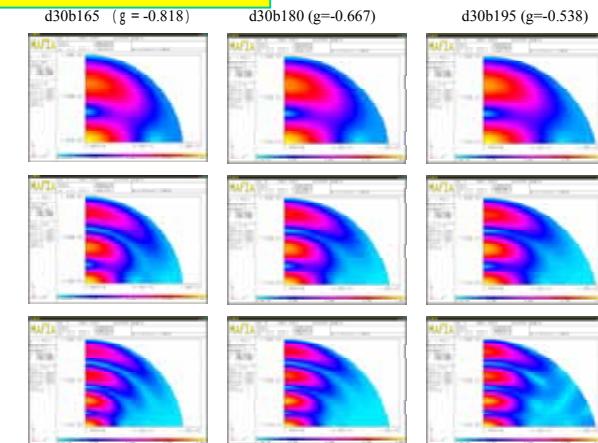


Conceptual design

TE_{mn} Mode. In this example, $m=9$, $n=0$

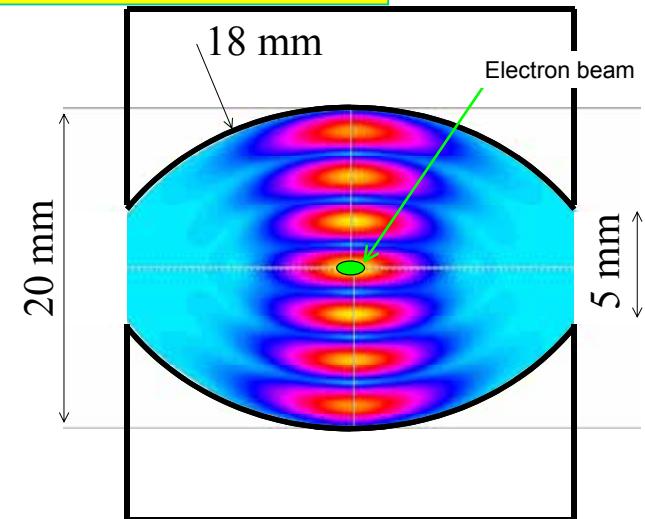


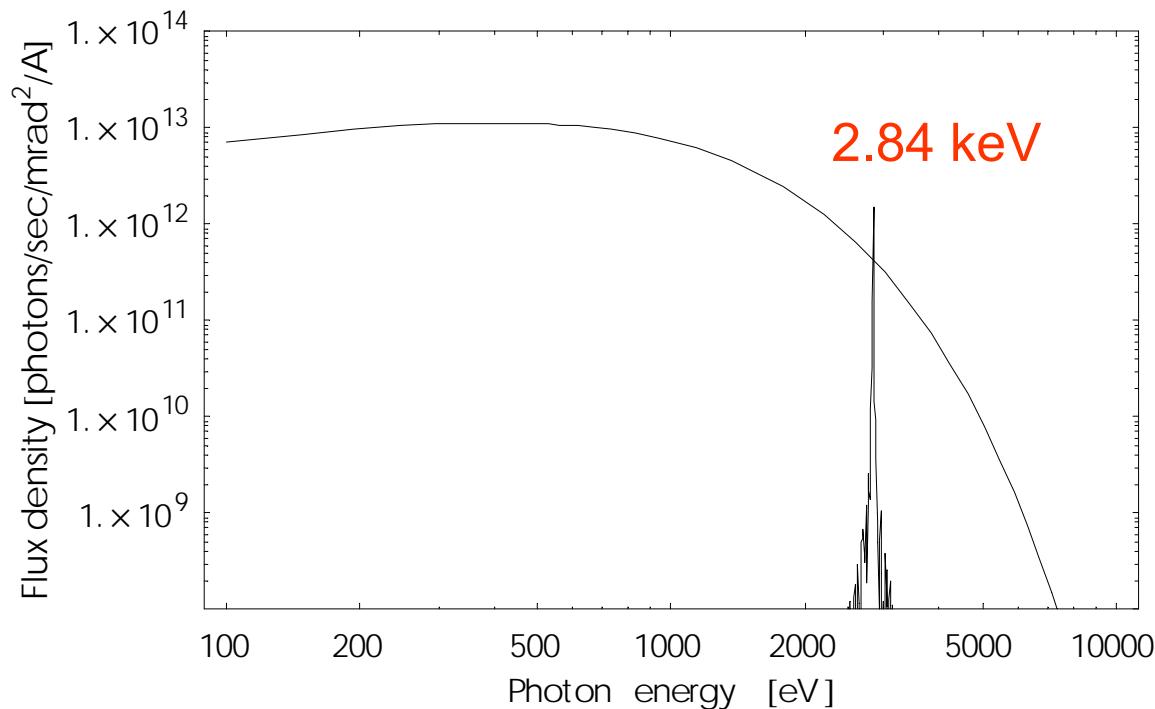
Simulation



TE mode simulation by MAFIA

Practical solution





$$K = \frac{eB\lambda}{2\pi mc} = 0.934B[T]\lambda[cm]$$

$$= 6.04 \times 10^{-6} \frac{\sqrt{I}\lambda}{\beta}$$

$$\text{where } \beta = \frac{v}{c}, \quad I = \frac{EB}{\mu_0},$$

(I; Power density of electromagnetic wave,

μ_0 ; permeability in vacuum)

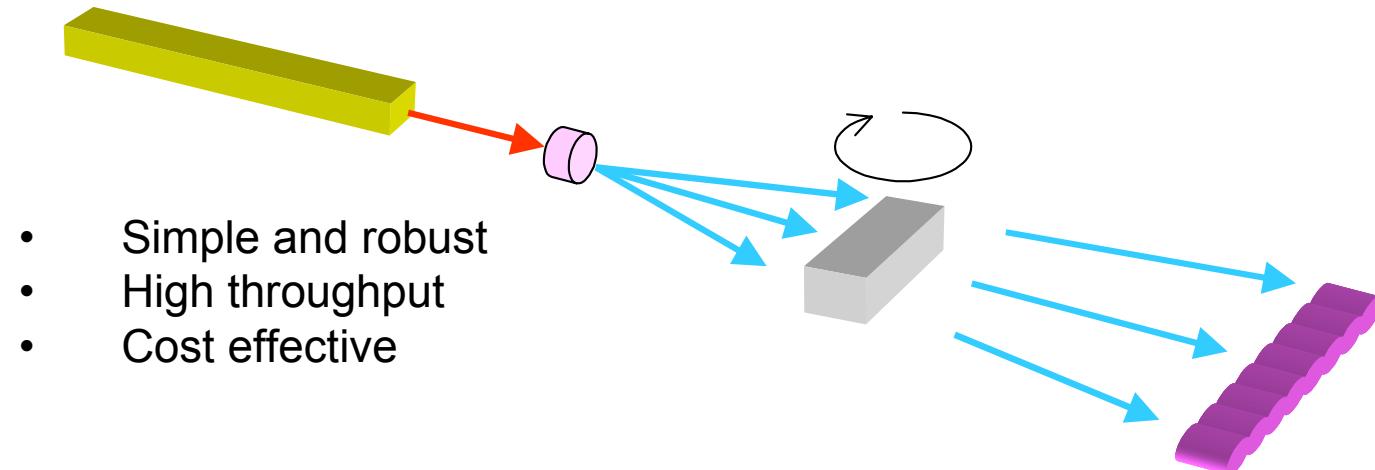
$$\lambda_k = \frac{\lambda}{2n\gamma^2} \left(1 + \frac{K^2}{2}\right), \quad (\text{on axis radiation})$$

H. Toyokawa, R. Kuroda, H. Ohgaki, Proc. 22nd Particle Accelerator Conference , pp.1025-1027, June 2007, Albuquerque.

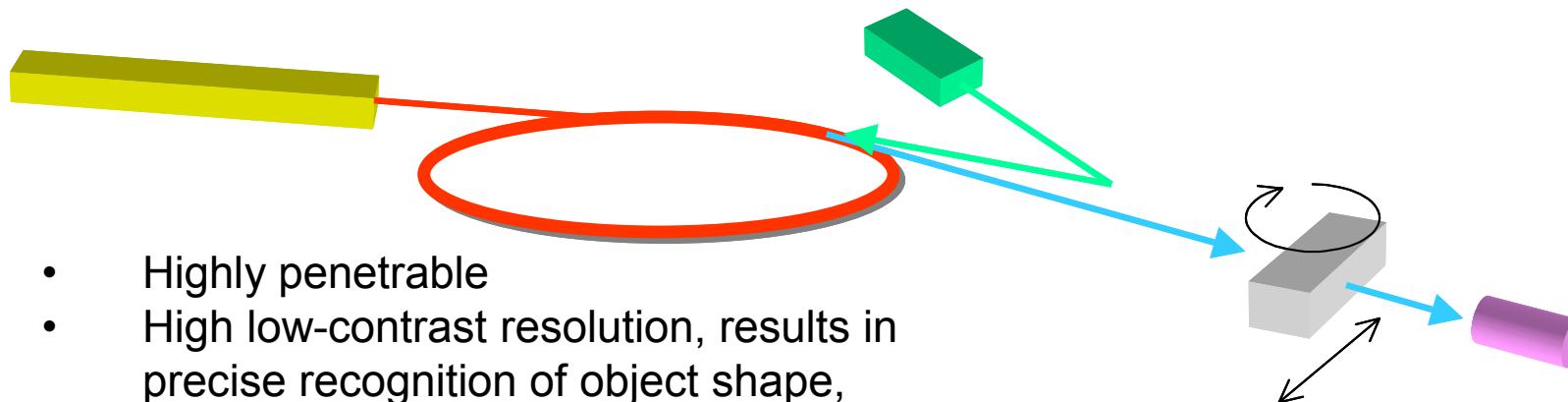
Application: 2

High-energy Gamma-ray CT

Linac-based X-ray scanner



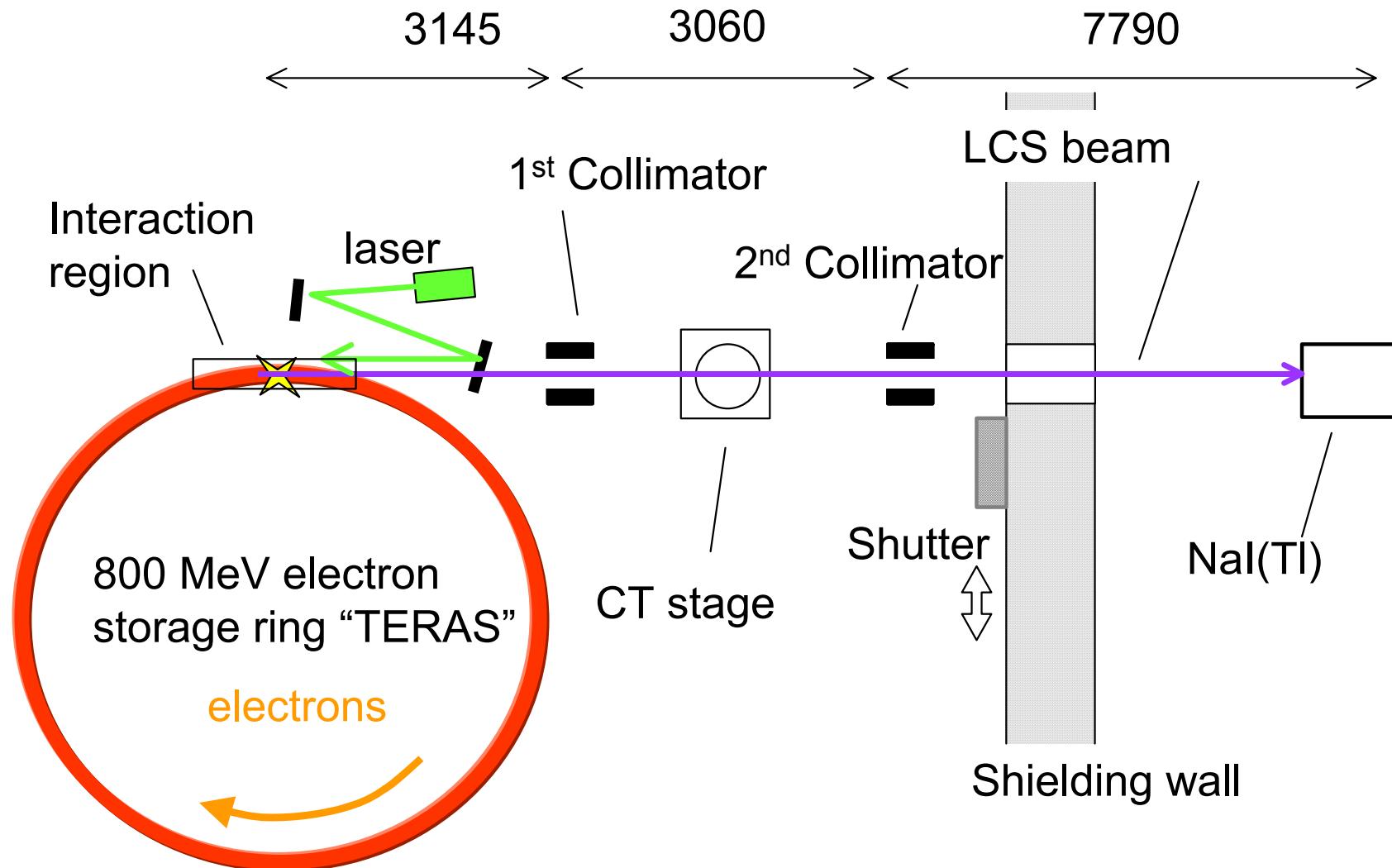
LCS γ -ray CT system using electron storage ring



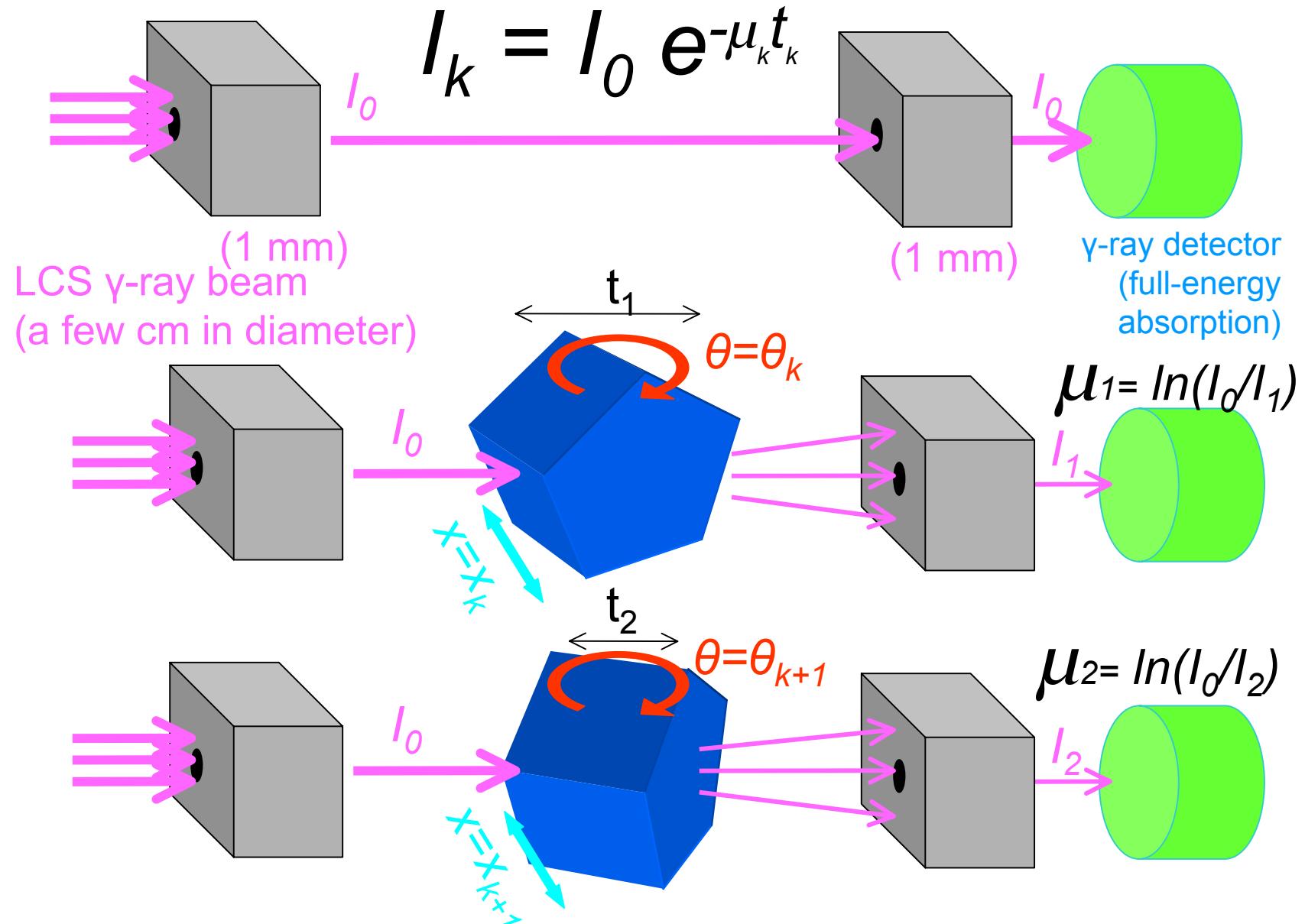
Why CT using high-energy monochromatic photon beam is required?

1. High-energy photons penetrate large sample objects (MeV photons are the best).
2. Only **monochromatic photon beam** tells us **linear attenuation coefficient** of the sample correctly (not polychromatic photons).

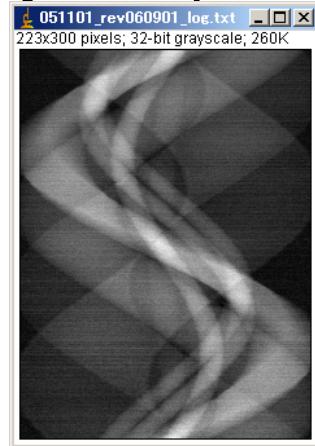
CT beam line



(Unit in mm, top view)

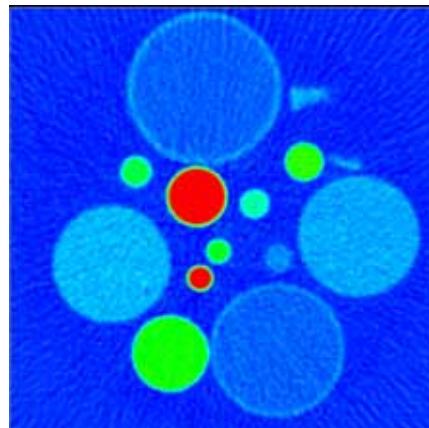


1. Measurement of μ_k at $x=x_k, \theta=\theta_k$
2. Survey every line-phase space (x, θ) , then obtain a sinogram



2-D image of $\mu(x, \theta)$

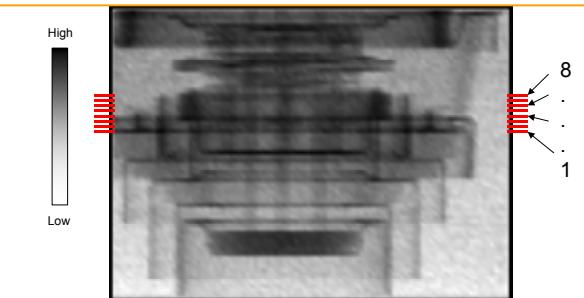
3. Tomographic image reconstruction (filtered back projection, algebraic reconstruction technique, maximum likelihood expectation maximization, etc.)



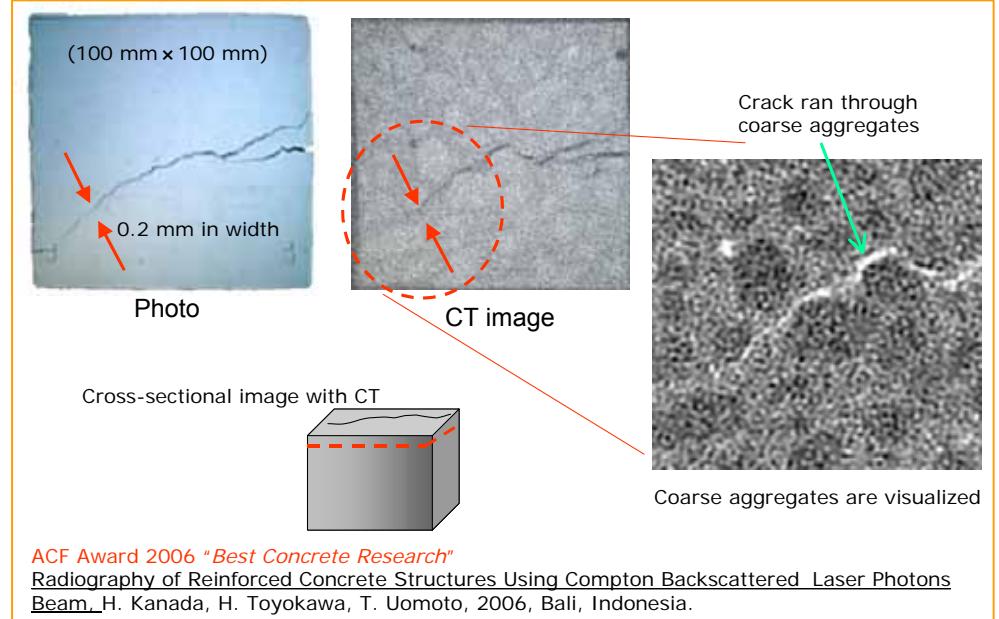
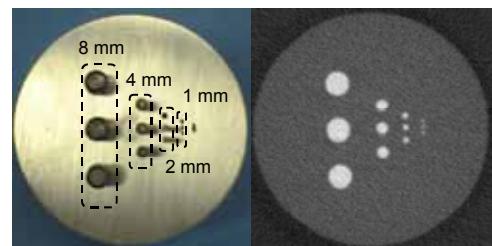
2-D image of $\mu(x, y)$



Aluminum phantom,
(high-contrast, and spatial
resolutions)



H. Toyokawa et al., Review of Scientific Instruments, 73(9), 3358(2002).

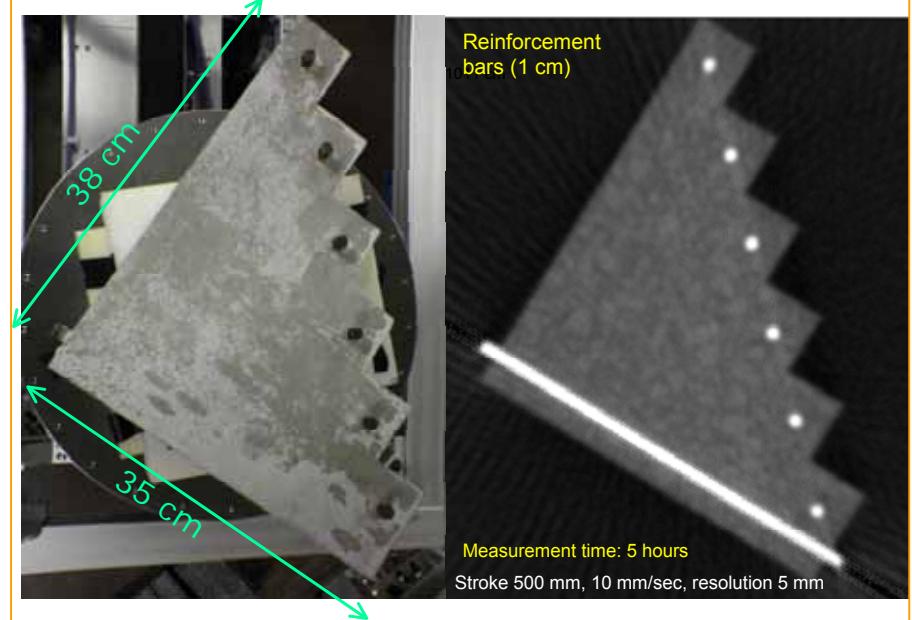


Photograph of specimen (from bottom)

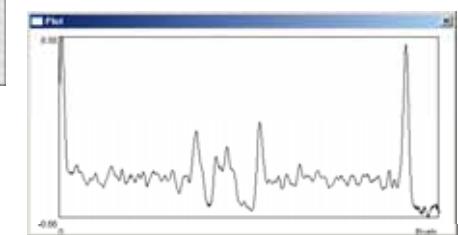
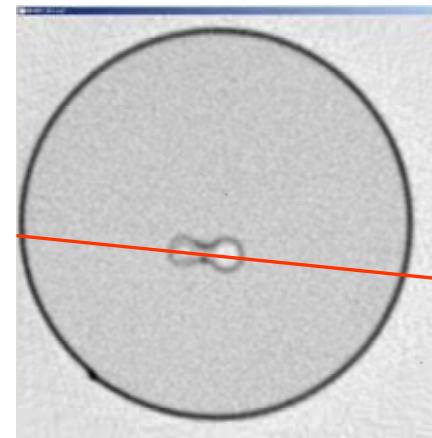


CT image on photo

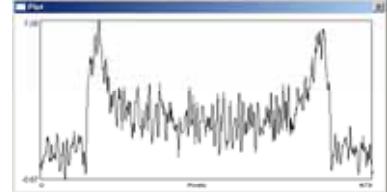
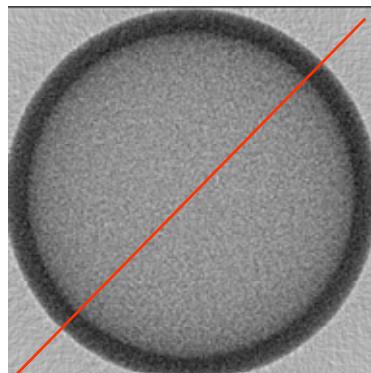
(Specimen: Concrete block with iron ores, 100 mm × 100 mm)



Fire extinguisher



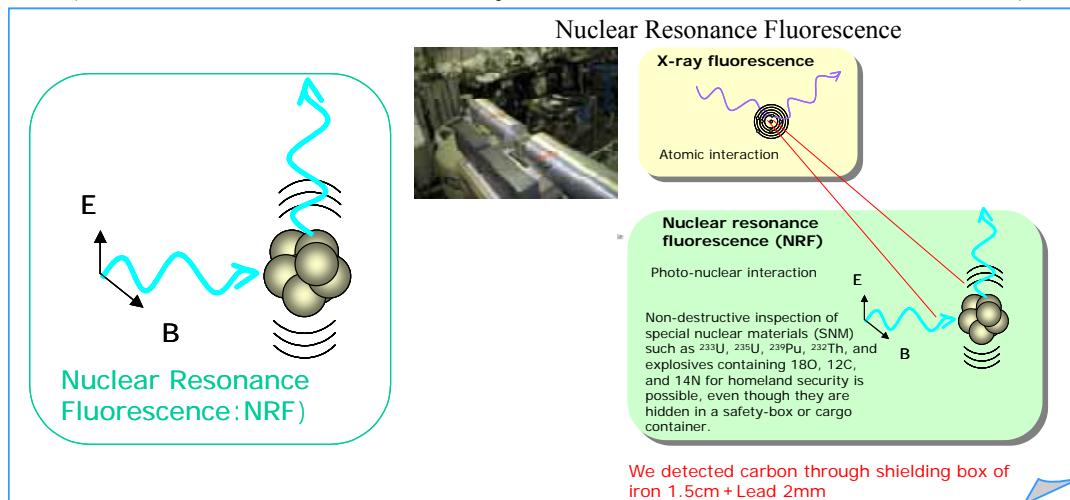
Wood (mulberry tree)



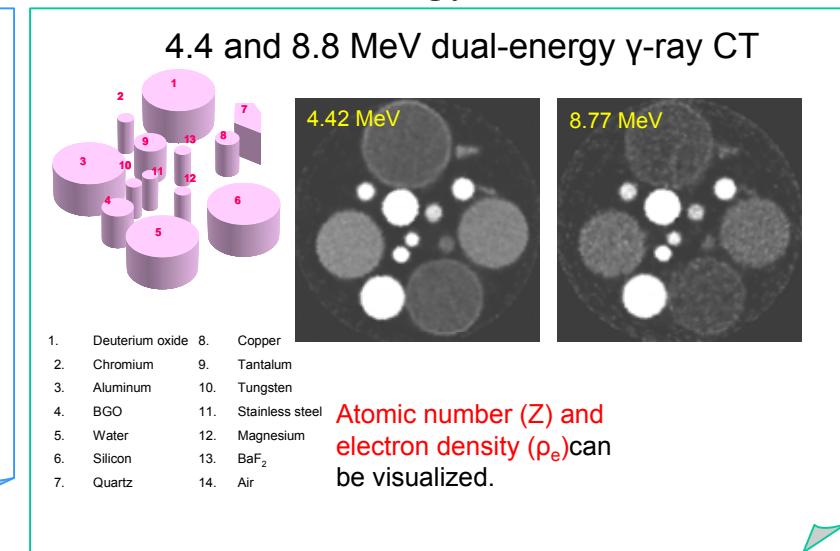
1. H. Toyokawa et al., Rev. Sci. Instrum, 73(2002)3358.
2. H. Toyokawa, Nucl. Instrum. and Methods in Phys. Res., A545(2005)469.
3. H. Toyokawa et al., Proc. of The Eighth International Topical Meeting on Nuclear Applications and Utilization of Accelerators, pp.331-335, 2008.

Novel methods under development

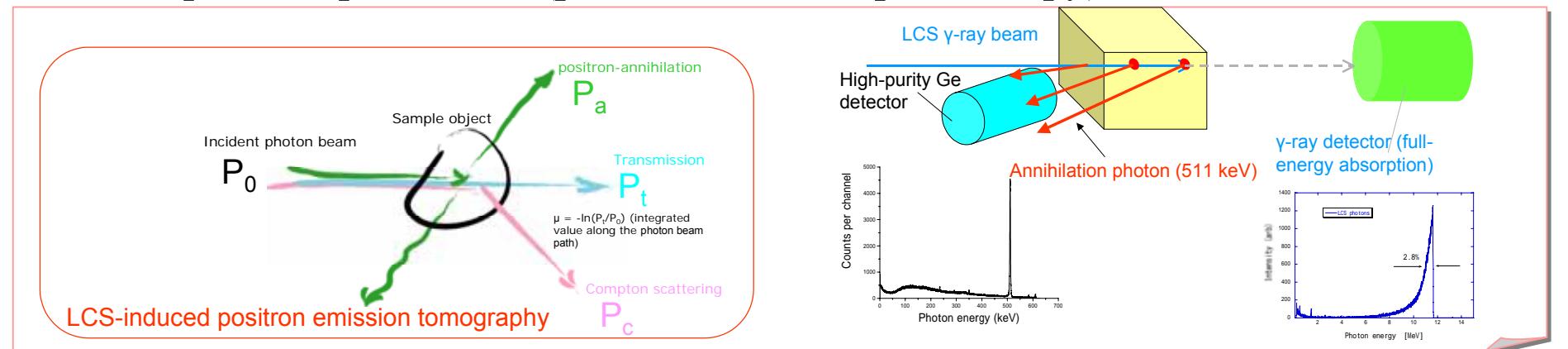
Nuclear Resonance Fluorescence (nondestructive assay of radioactive nuclides)

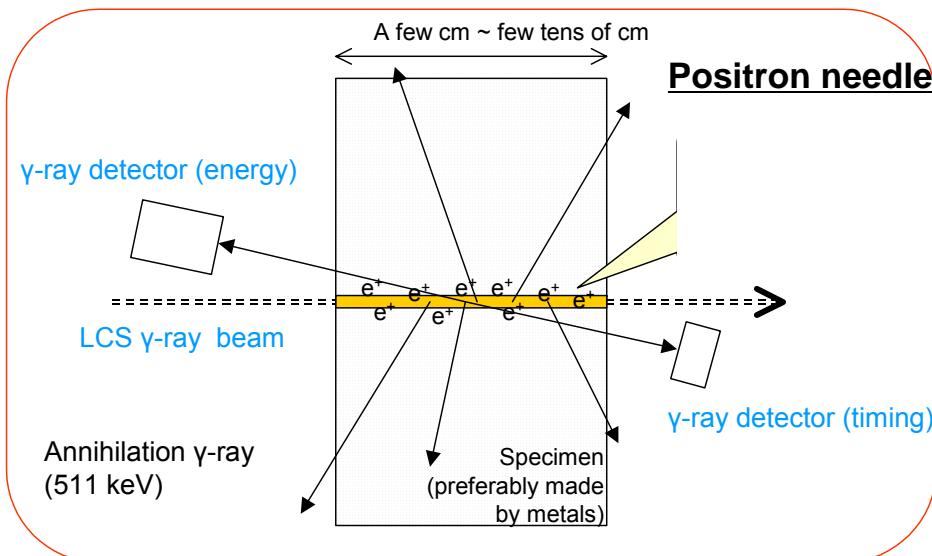
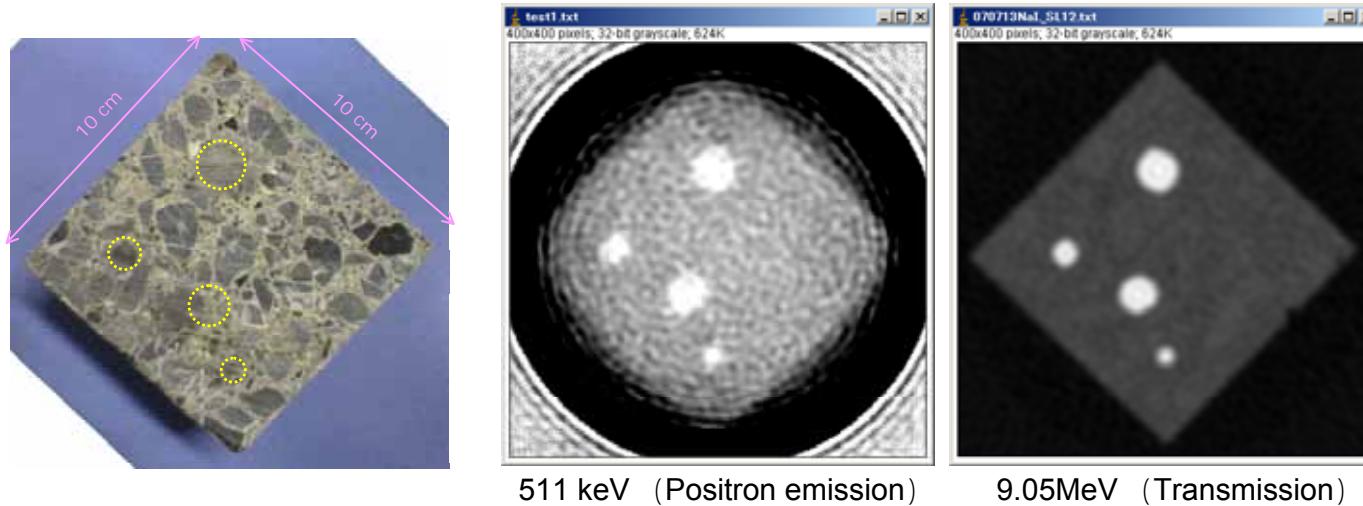


Dual-energy LCS-CT



Industrial PET/CT (material science) Pulsed positron production (positron lifetime spectroscopy)





Defect
Interstitial atom
Impurity
Vacancy
Void
Dislocation

We need intense short-pulse MeV gamma-rays (ERL)

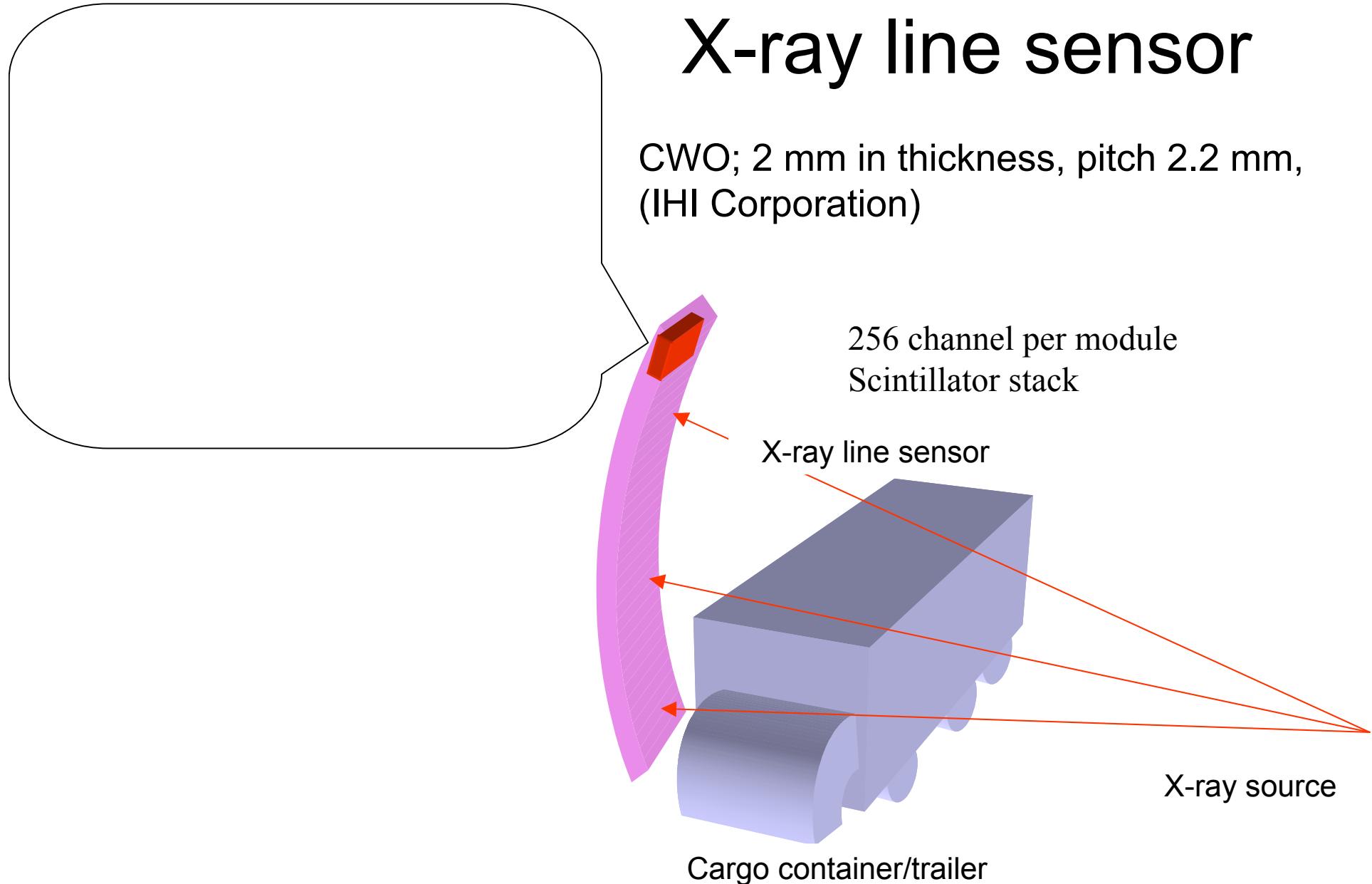
Application: 3

Detector development, calibration
(X-ray line sensor for Homeland security)



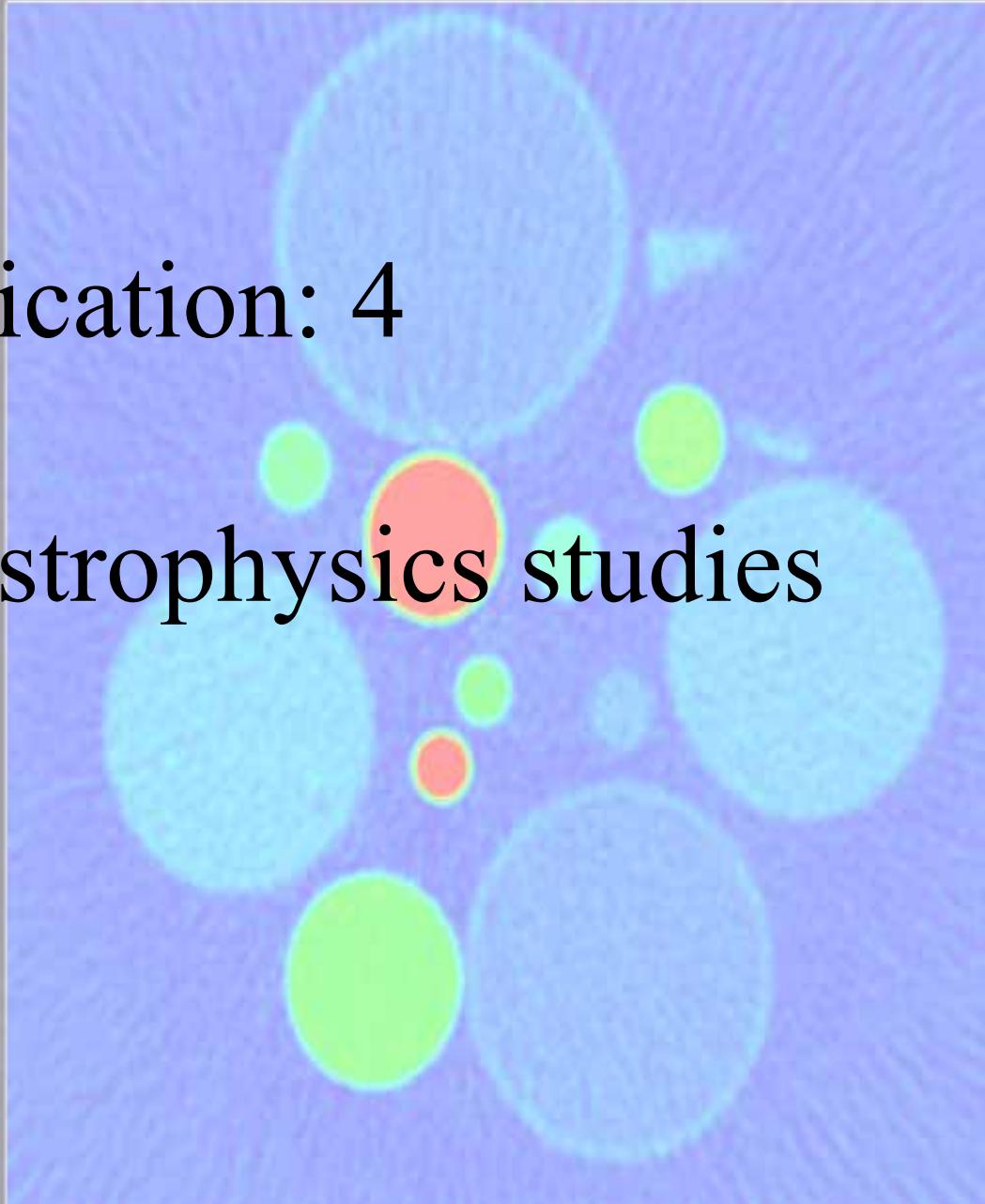
X-ray line sensor

CWO; 2 mm in thickness, pitch 2.2 mm,
(IHI Corporation)



Application: 4

Nuclear and Astrophysics studies

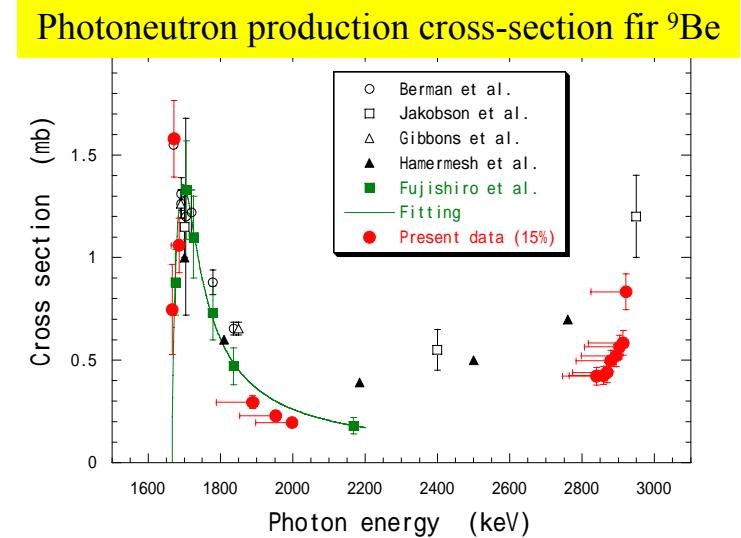
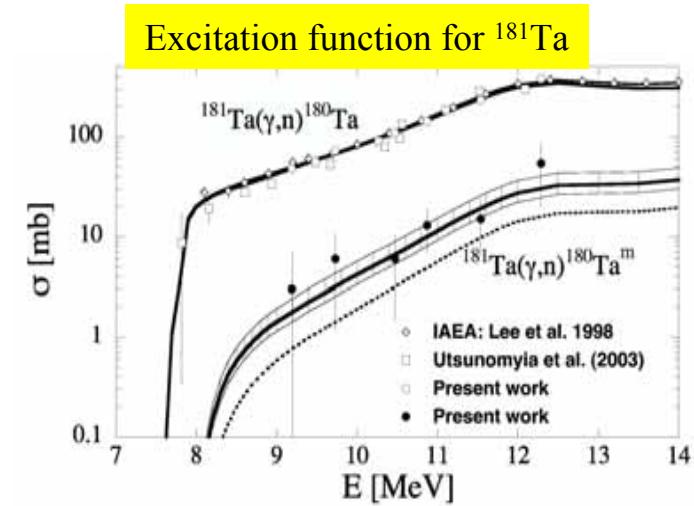


(γ,γ) , (γ,n) , $(\gamma,p$ or $d)$ etc.

Recent publication list of our team.

- H. Ohgaki et al., Nucl.Phys.A, 649, pp.73c-76c, 1999.
- H. Utsunomiya et al., Phys. Rev. C, 63, pp.018801-018804, 2000.
- T. Shima et al., Nucl.Phys.A, 687, pp.127-131, 2001.
- H. Utsunomiya et al., Phys. Rev. C, 67-1, pp.0158071-0158079, 2003.
- H. Utsunomiya et al., Nucl.Phys.A, 718, pp.199-206, 2003.
- T. Shima, Phys. Scrip., 104, pp.164-166, 2003.
- T. Shima et al., Nucl.Phys.A, 718, pp.23-26, 2003.
- K. Y. Hara et al., Phys. Rev. D, 68-7, pp.072001-1-072001-6, 2003.
- H. Utsunomiya et al., Nucl.Phys.A, 738, pp.136-142, 2004.
- T. Shima et al., Phys. Rev. C, 72-4, pp.044004-1-044004-16, 2005
- H. Utsunomiya et al., Eur. Phys. J. A, 27-1, pp.153-158, 2006
- S. Goko et al., Phys. Rev. Lett., 96-192501, pp.1-4, 2006
- H. Utsunomiya et al., Phys. Rev. C, 74, pp.025806-1-025806-6, 2006
- H. Utsunomiya et al., Phys. Rev. LETTERS, 100-162502, pp.1-4, 2008.

And many others...



Summary

- Basics: 1
 - *Measurement of photon flux of pulsed gamma-rays*
- Basics: 2
 - *Beam life time and photon yield*
- Basics: 3
 - *Beam source size*
- Source development: 1
 - *Multi-pass laser-Compton scattering*
- Source development: 2
 - *Long-Axis Fabry-Perot Cavity*
- Source development: 3
 - *W-band (95 GHz) Electromagnetic-wave Undulator*
- Application: 1
 - *Electron-beam energy measurement in the storage ring*
- Application: 2
 - *High-energy Gamma-ray CT*
- Application: 3
 - *Radiation detector development, calibration
(X-ray line sensor for Homeland security)*
- Application: 4
 - *Nuclear and Astrophysics studies*

International collaboration of laser-Compton photon facilities and users will be beneficial to all of us.

Hopefully, we can make loose but friendly partnership.

Keywords:

- Short term:

Short-pulse, high-intensity, small and compact

- Middle term:

Utility, stability, running cost

- Long term:

Uniqueness, robustness, simplicity