



Detection of Radioactive Isotopes by Laser Compton γ -rays

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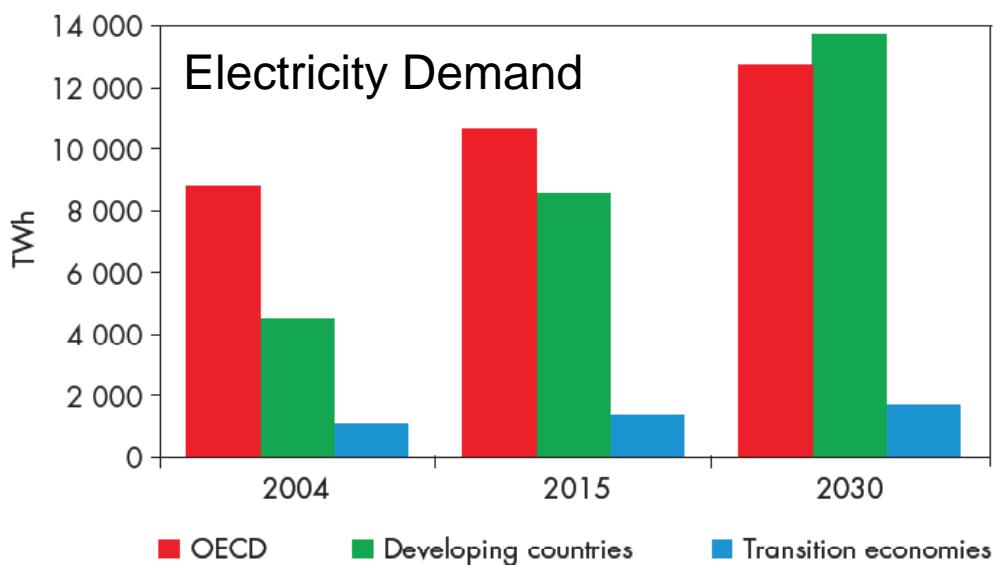
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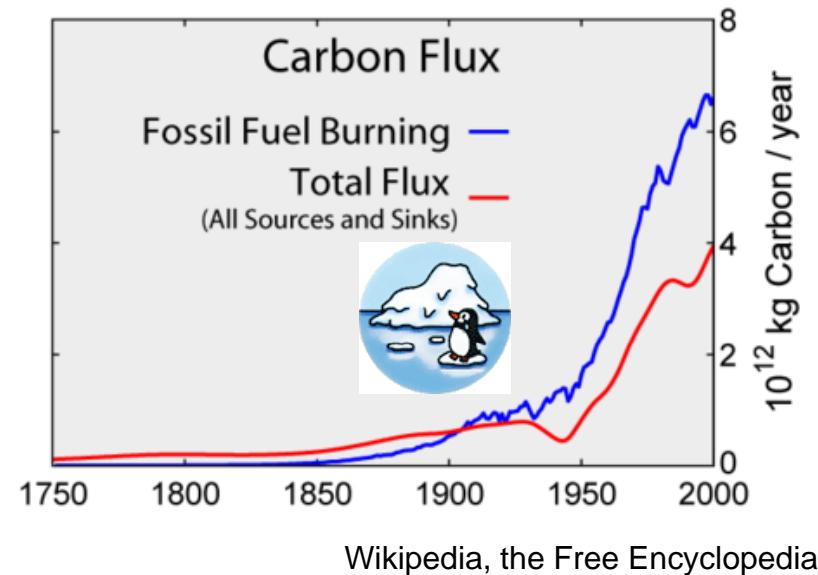
Thanks to

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J. Urakawa (KEK)
H. Kawata (KEK) and the ERL collaboration team

Role of Nuclear Power in the World Energy Demand



World Energy Outlook 2006, International Energy Agency



Nuclear Power

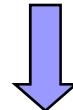
- a proven technology for baseload electricity generation
- curbing CO₂ emission & smaller dependence on imported gas
- world-wide efforts to promote peaceful use of nuclear power
 - IAEA, NPT
 - GNEP (Global Nuclear Energy Partnership)

Photon Science can resolves urgent issues of nuclear research and industry

Radioactive waste in JAEA



cleanup of all the waste in JAEA costs \$20 billion and 80 years.



the most urgent issue !

Physics Today, Sep. 2006.



Science-based cleanup of Rocky Flats

David L. Clark, David R. Janecky, and Leonard J. Lane

The chemical and physical interactions of radioactive compounds are key to understanding how they can contaminate the environment and, more importantly, how best to remove them.

A nuclear weapons plant



X-ray science has contributed to the cost saving of \$30 billion.

\$37B (70 years) → \$7B (10 years)

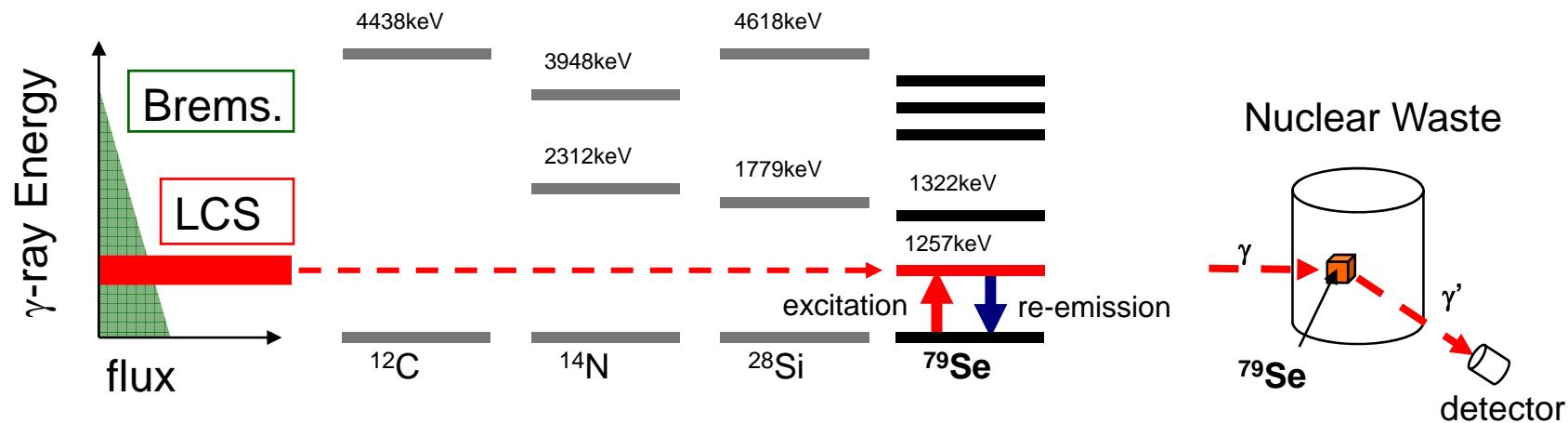
Outline

Applications of a high-flux γ -ray source to

- nondestructive assay of radioactive nuclides
- management of nuclear waste

1. Nuclear Resonance Fluorescence
2. Design of a High-flux γ -ray source
3. PoP Experiments
4. Source Development
5. Summary

Nondestructive Assay by Nuclear Resonant Fluorescence



- Irradiation of γ -rays tuned at a NRF energy of nuclide to detect
- Detection of scattered γ -rays by energy-resolved detectors
- NRF is a unique fingerprint of nuclides → radioactive and stable nuclides can be detected
- Using MeV γ -rays → applicable to thick objects

For increasing the γ -ray flux

$$F = \frac{f N_e N_L \sigma_c}{A}$$

f collision frequency

N_e number of electrons

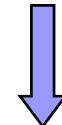
N_L number of laser photons

σ_c scattering cross-section

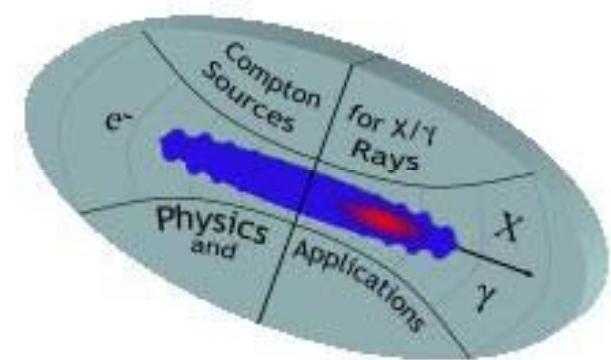
A effective sectional area

In order to obtain a high-flux γ -ray beam

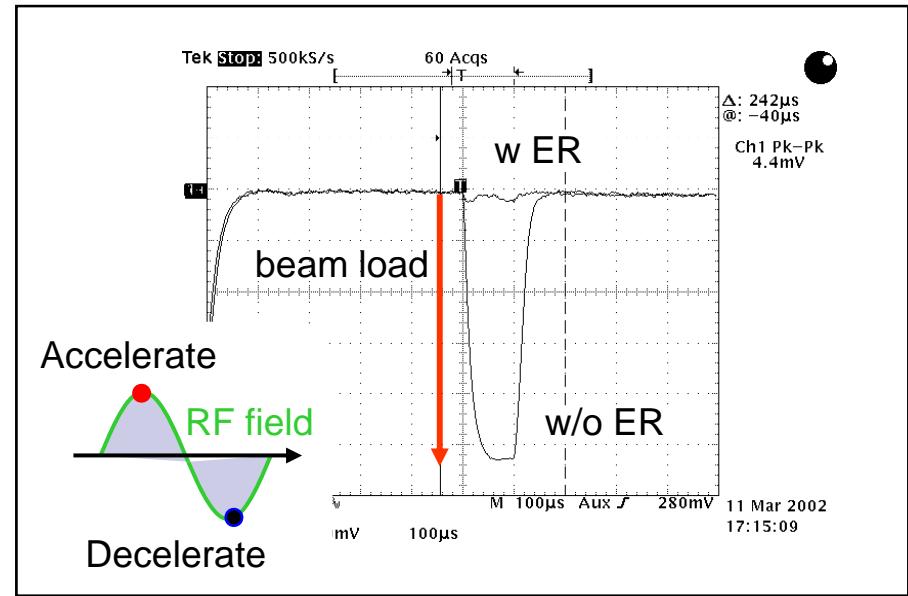
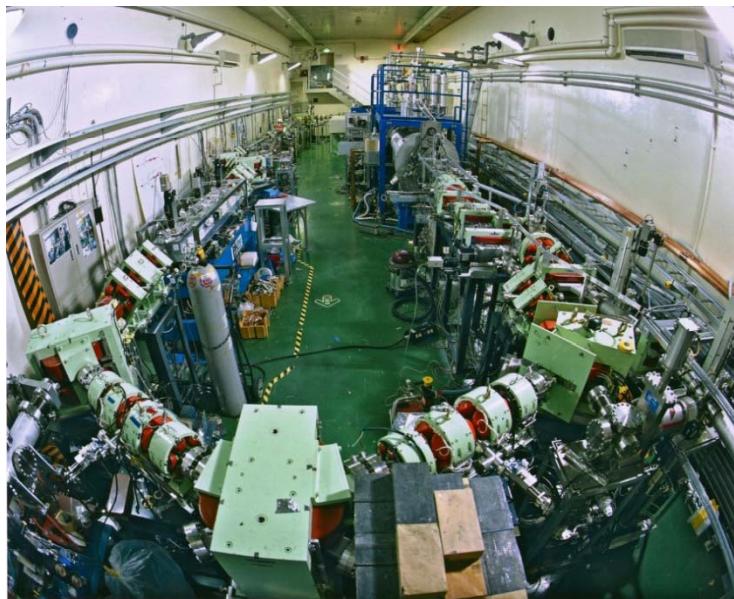
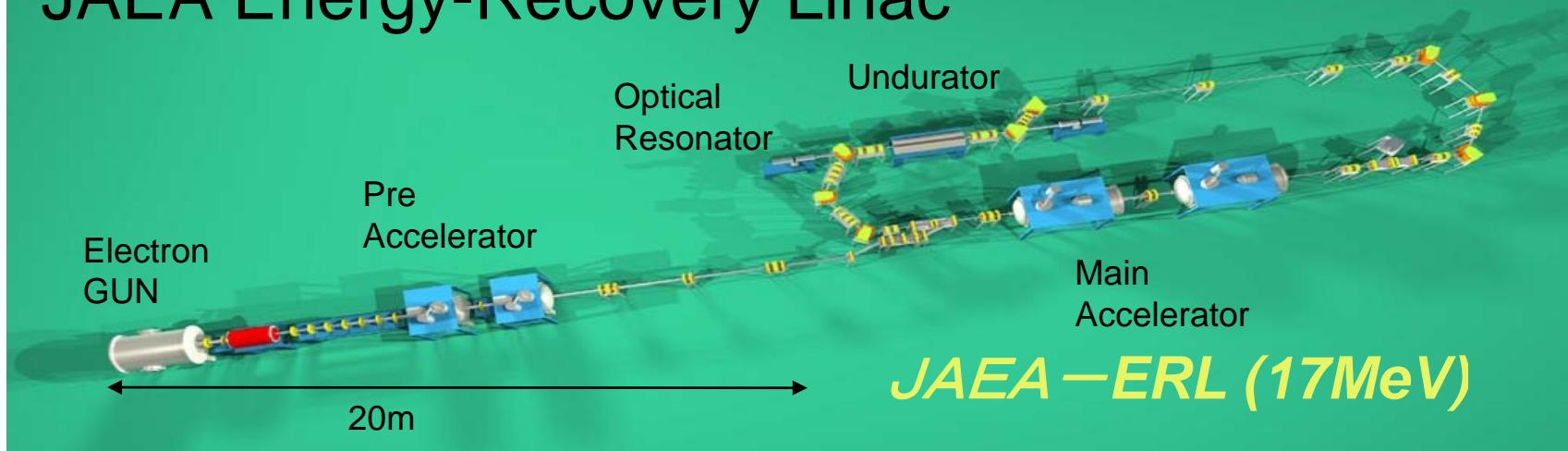
- high-average current
- small emittance
- short pulse (for oblique collision)



ERL is suitable for a high-flux γ -ray source

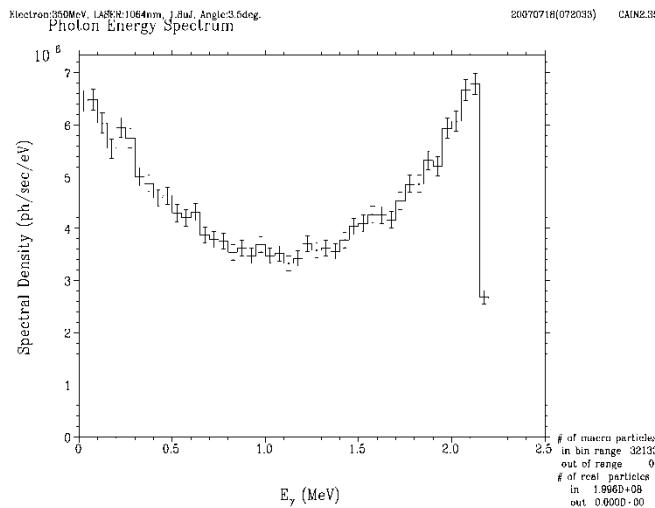


JAEA Energy-Recovery Linac

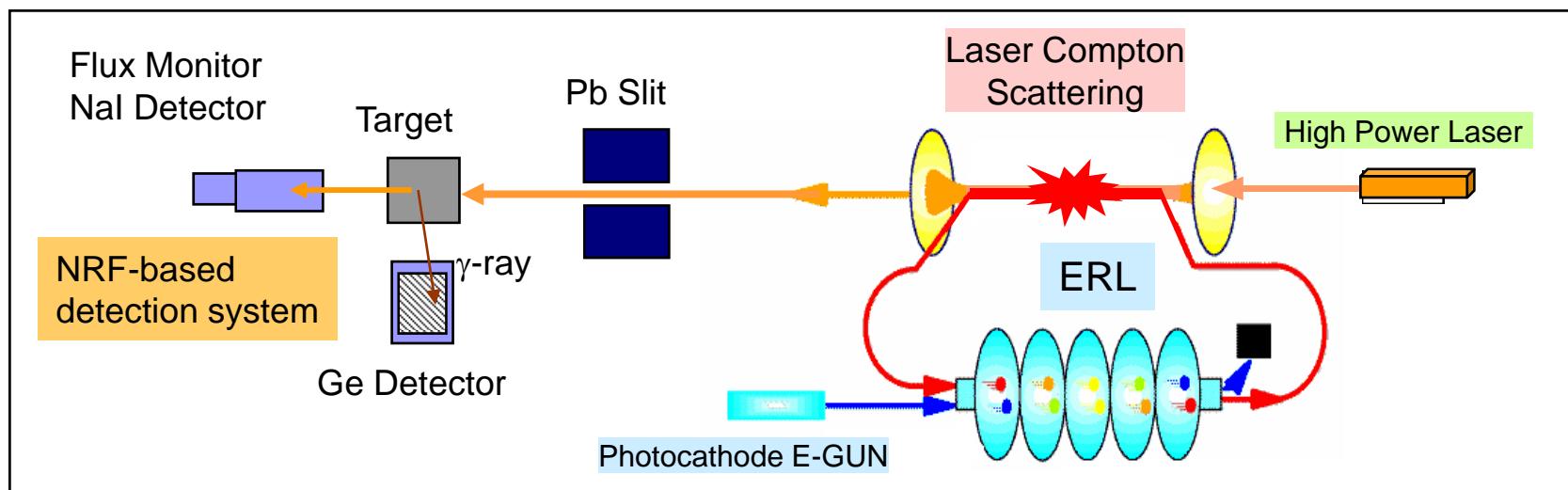
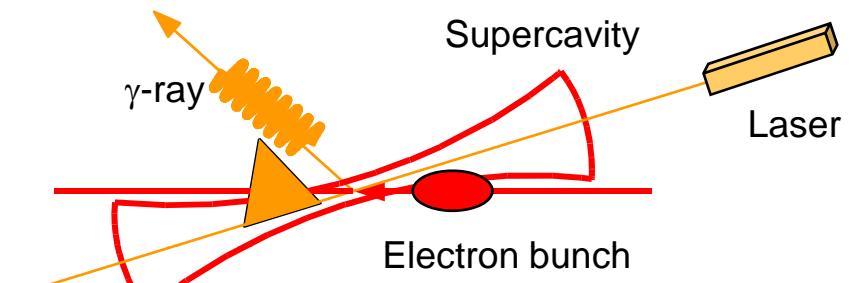


R. Hajima, et. al., Nucl. Instr. Meth. A507 (2003) 115-119.

Concept of a high-flux γ -ray source

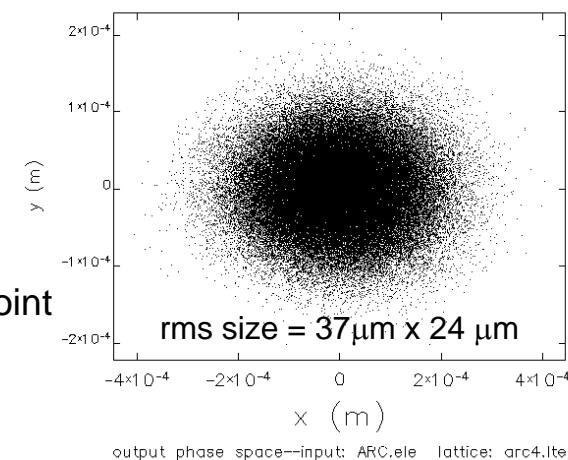
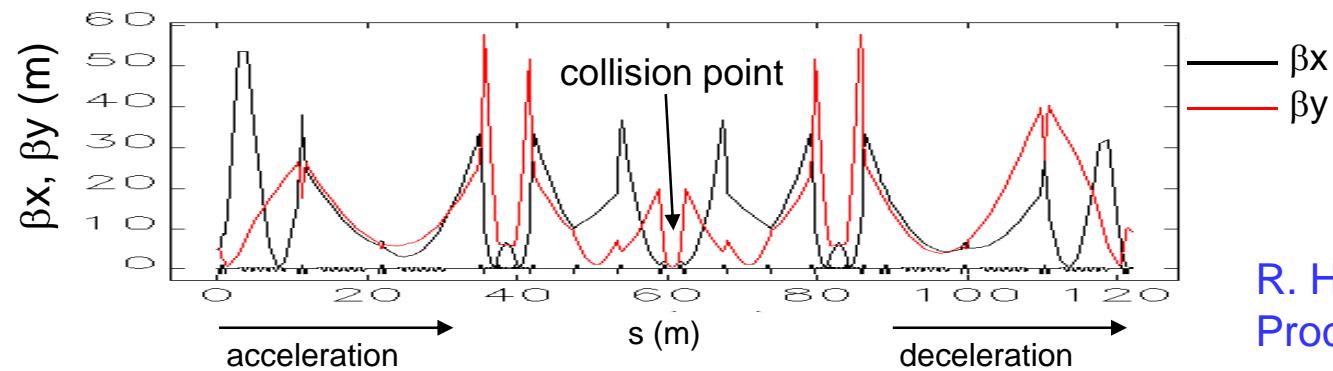
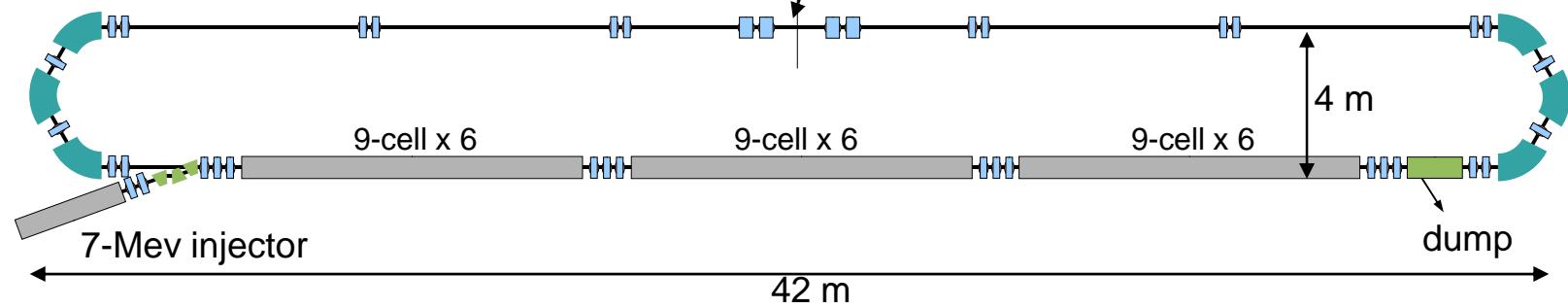


Laser Compton Scattering (LCS)



Example of a 350 MeV ERL

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

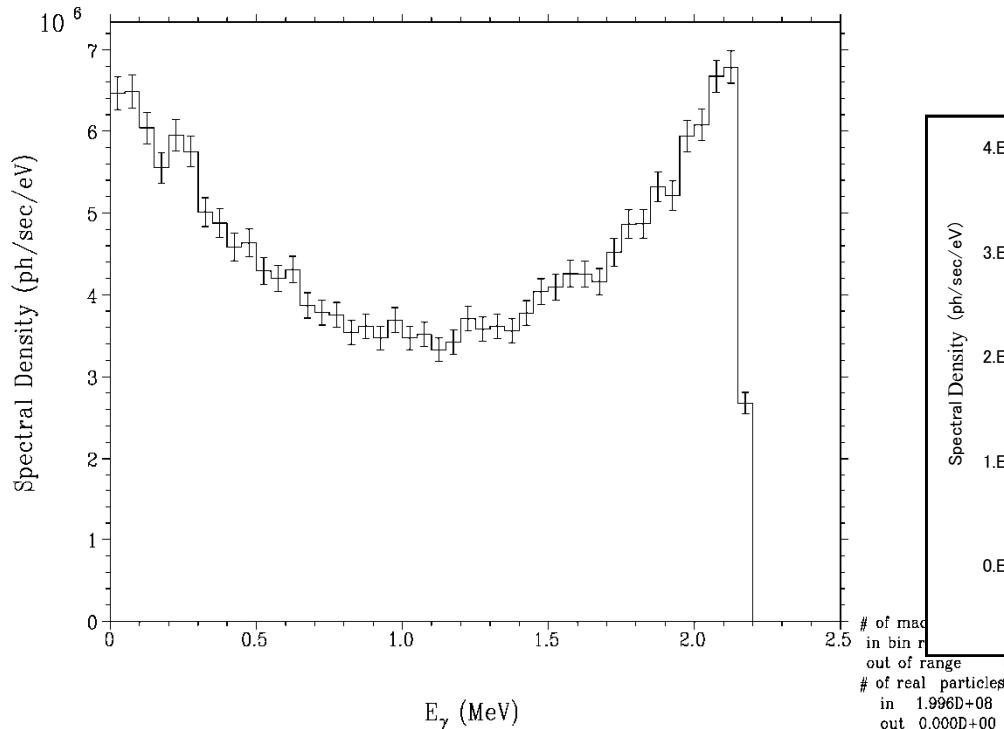


R. Hajima et al.,
Proc. AccApp'07

γ -ray flux calculation for the 350-MeV ERL

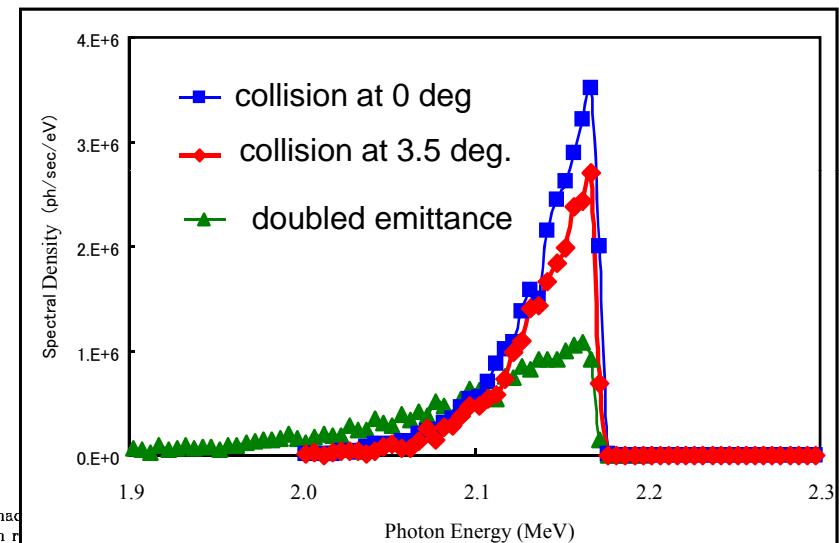
Electron:350MeV, LASER:1064nm, 1.8uJ, Angle:3.5deg.
Photon Energy Spectrum

20070718(072033) CAIN2.36



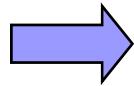
R. Hajima et al.,
Proc. AccApp'07

with a collimator of 0.1mrad



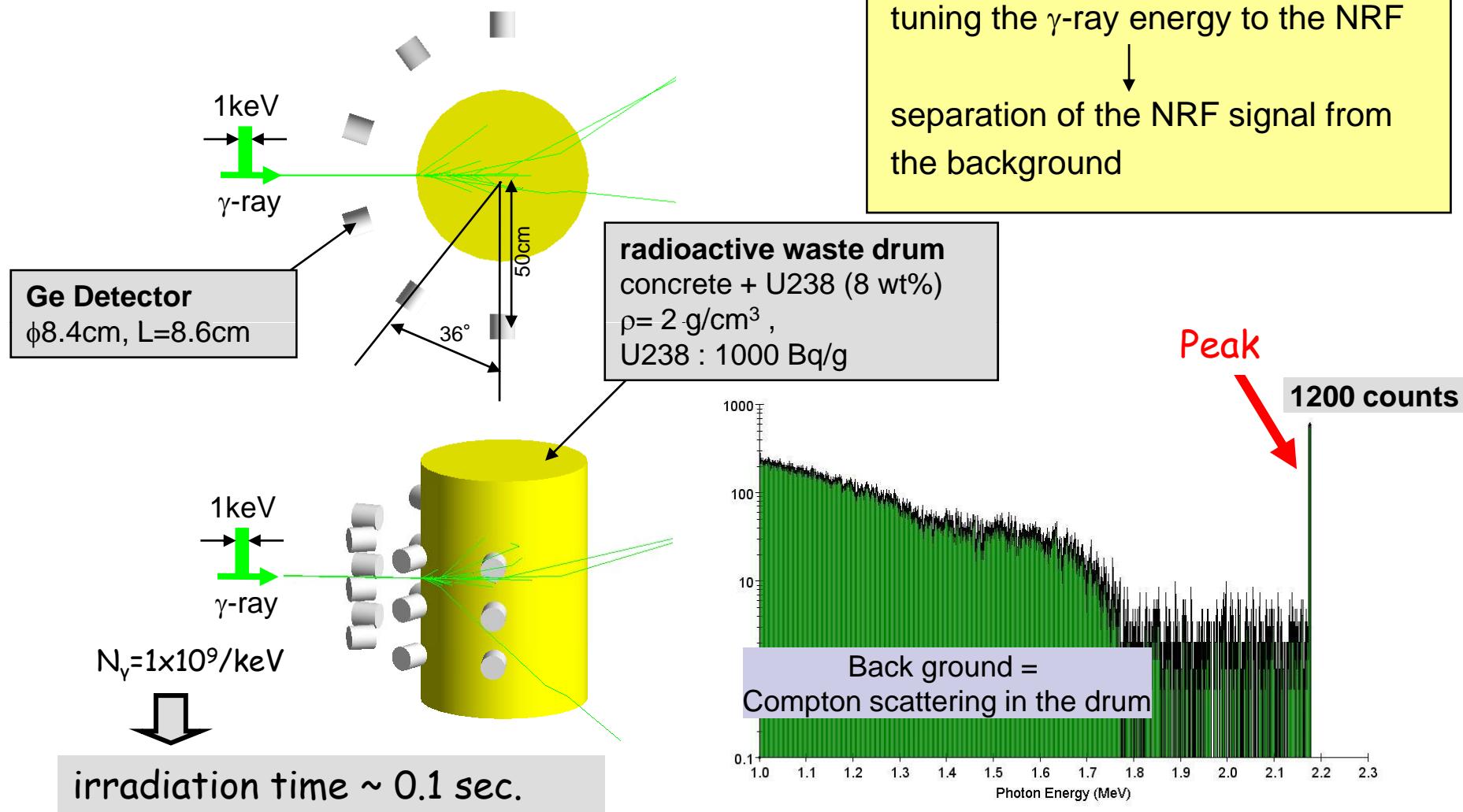
$$F_{total} = 1.0 \times 10^{13} \text{ ph/sec}$$

$$F_{peak} = 7 \times 10^9 \text{ ph/sec/keV}$$



exceeds the existing facilities
by several orders of magnitude

Nondestructive Detection of Isotopes

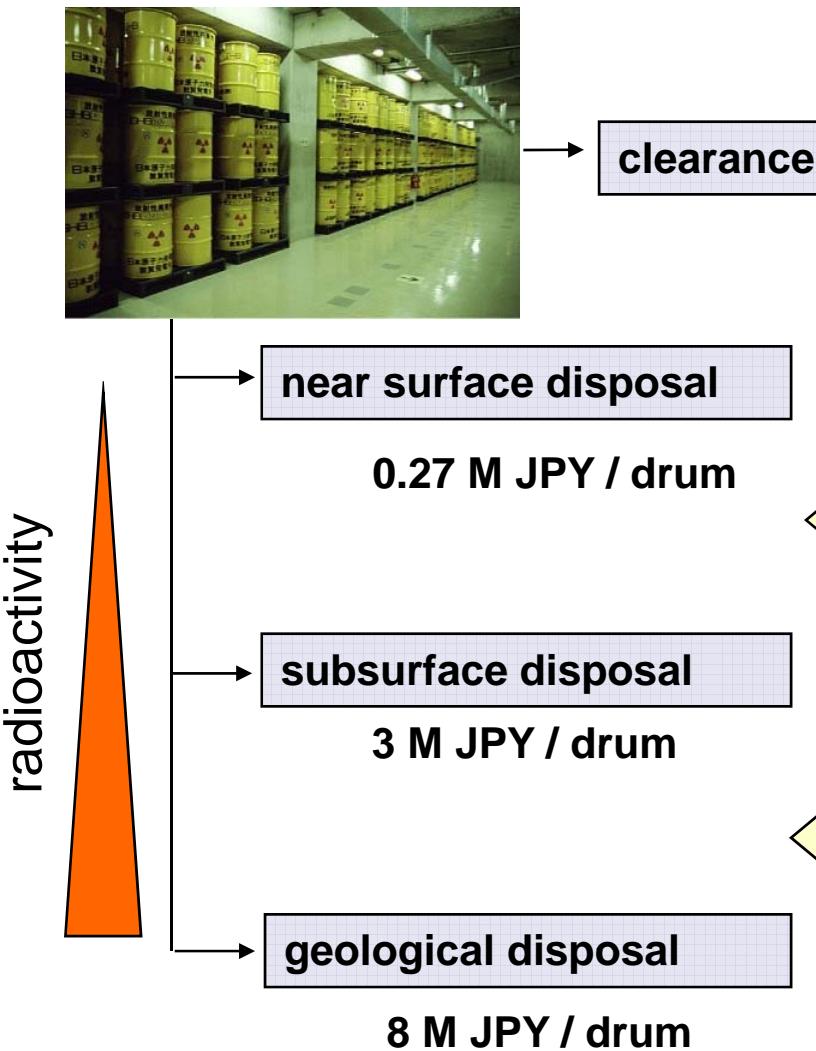


Simulation by GEANT4 (with NRF routine)

Segregation of Nuclear Wastes

68,900 drums stored in JAEA

R. Hajima et al., J. Nucl. Sci. Tech. 45 (2008)



Upper level for concrete pit disposal

C-14,	3.4E10 (Bq/ t),	230 sec
Co-60,	4.1E13 (Bq/ t),	210 sec
Ni-63,	8.9E11 (Bq/ t),	500 sec
Sr-90,	6.5E10 (Bq/ t),	24000 sec
Nb-94,	1.1E10 (Bq/ t),	200 sec
I-129,	1.4E8 (Bq/ t),	20 sec
Cs-137,	1.0E12 (Bq/ t),	1500 sec

Upper level for subsurface disposal

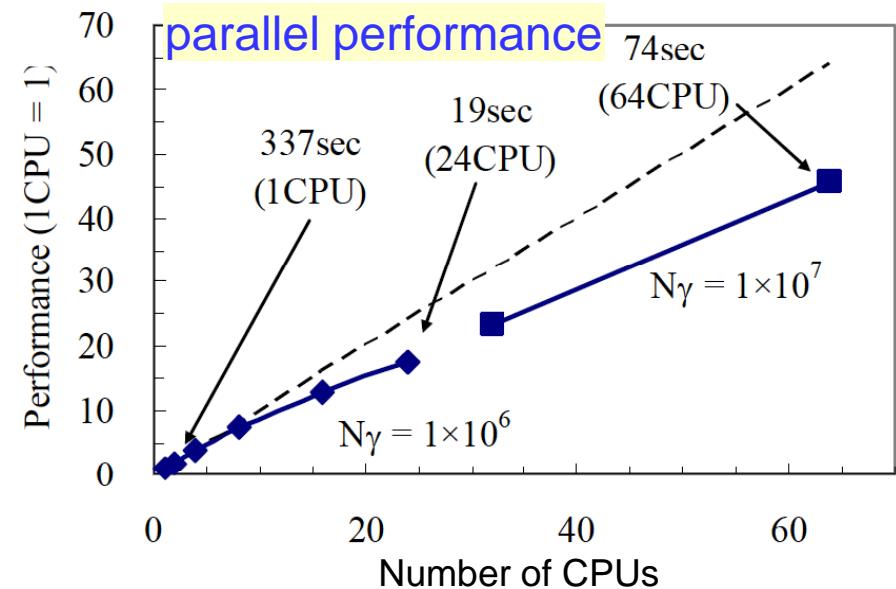
Cl-36,	9.3E10 (Bq/ t),	1.6 sec
Tc-99,	4.4E11 (Bq/ t),	0.48 sec
I-129,	2.2E10 (Bq/ t),	0.13 sec
Pu-238,	1.6E14 (Bq/ t),	3.2 sec
Am-241,	1.8E14 (Bq/ t),	0.57 sec

Simulation Code Development

We are developing a GEANT4-based code for the NRF simulations.

Geant 4

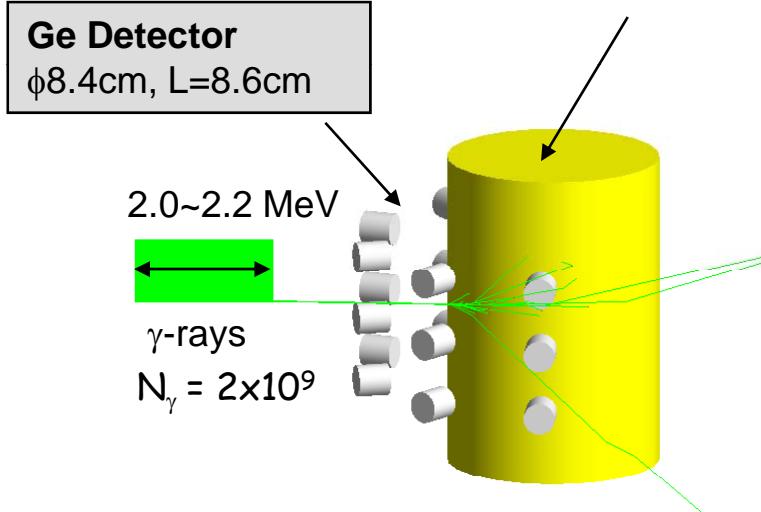
Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science. The two main reference papers for Geant4 are published in *Nuclear Instruments and Methods in Physics Research A* 506 (2003) 250-303, and *IEEE Transactions on Nuclear Science* 53 No. 1 (2006) 270-278.



- Add “NRF Process” as a sub-class of *G4HadronElasticProcess*
- Ready for parallel computation
- Benchmarking with experimental results are underway

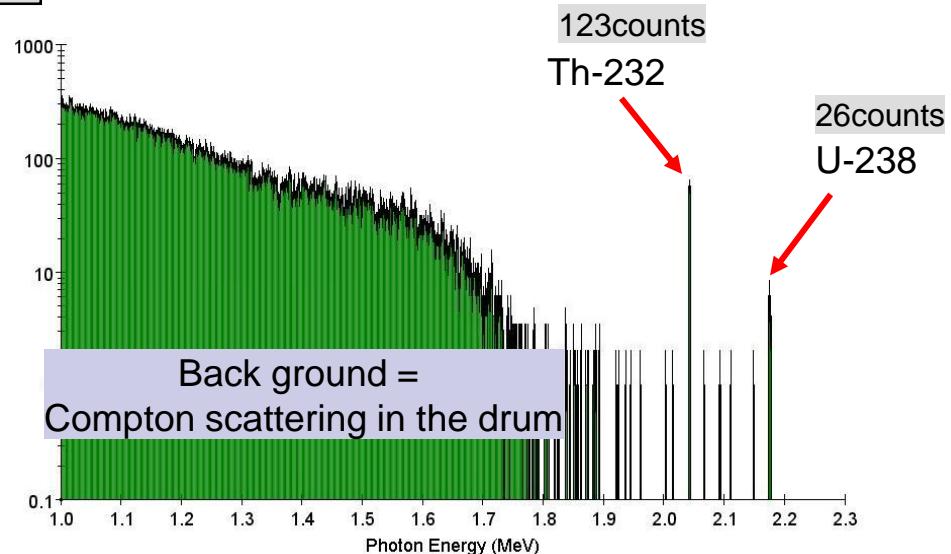
Simulation 1 : Detection of multiple isotopes

radioactive waste drum
concrete + U238 + Th232,
 $\rho = 2 \text{ g/cm}^3$,
U238 : 1000 Bq/g (8 wt%)
Th232 : 1000 Bq/g (25 wt%)



irradiation time $\sim 1 \text{ msec.}$

Detection of two kinds of isotopes at once.

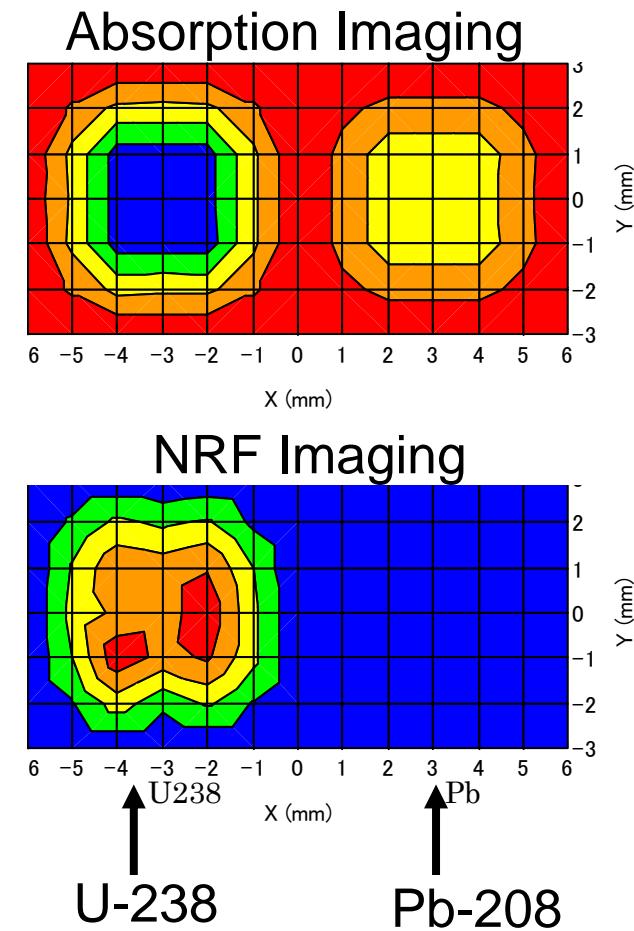
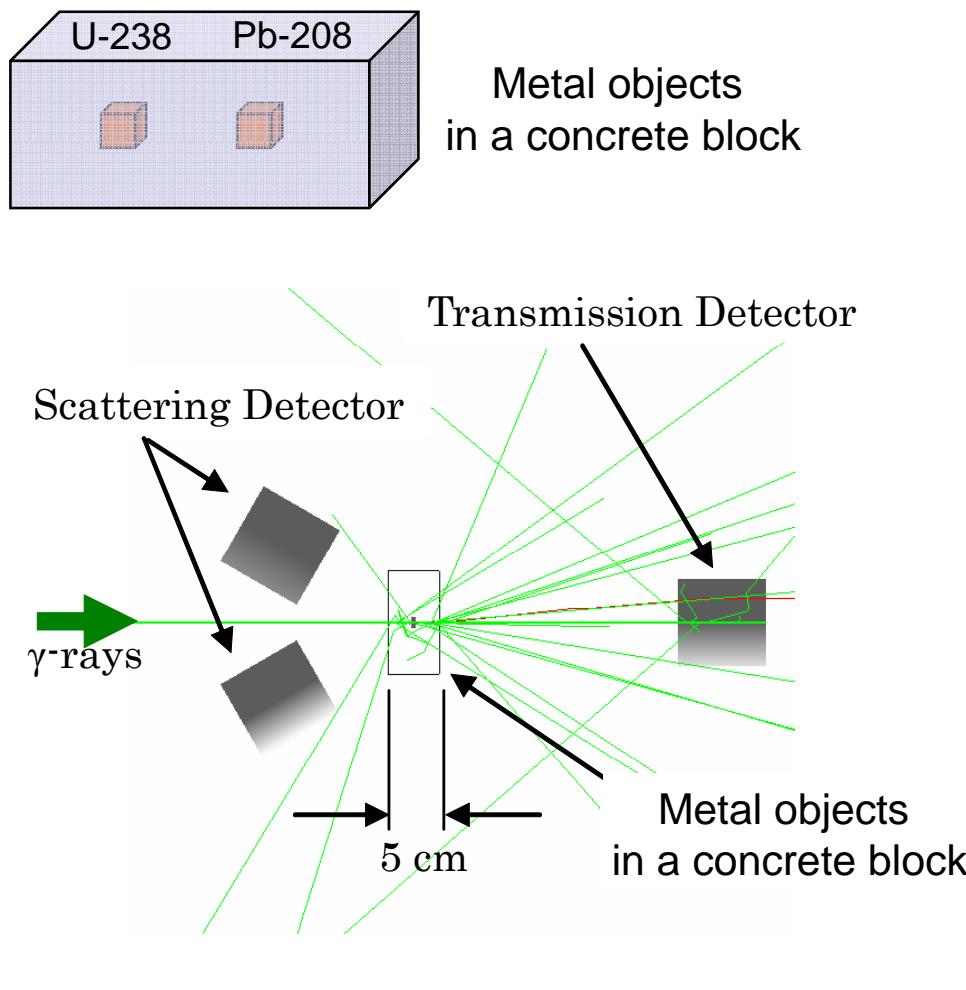


Th-232 : $\sigma_{NRF} = 100 \text{ mbarn}\cdot\text{keV}$ @ 2.043 MeV
U-238 : $\sigma_{NRF} = 100 \text{ mbarn}\cdot\text{keV}$ @ 2.176 MeV

Simulation by GEANT4 (with NRF extension)

N. Kikuzawa et al.,
Proc. AccApp'07

Simulation 2: 2-D Mapping of Shielded Isotopes





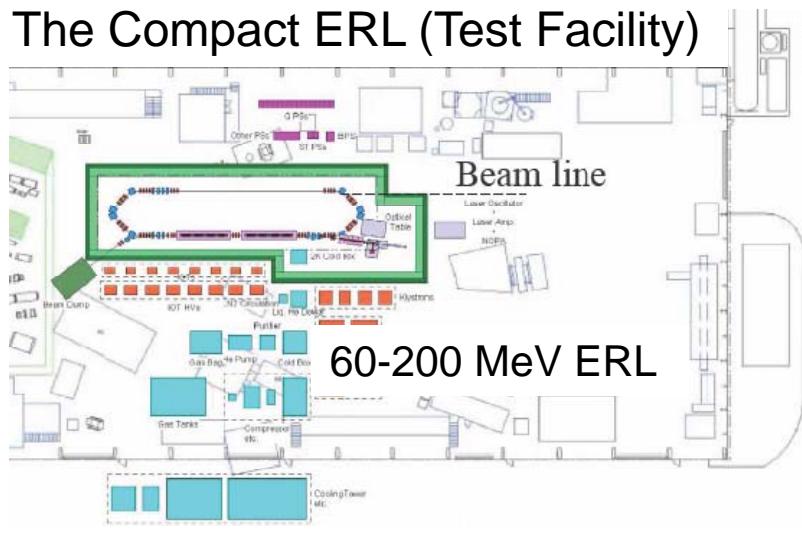
Source Development

The ERL Project in Japan

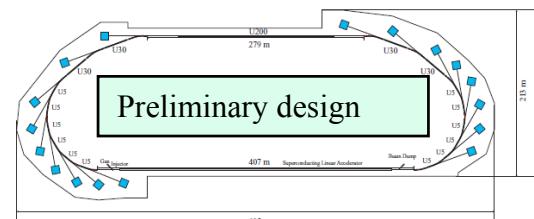
A collaborative project has launched towards a future ERL light source in Japan.



The Compact ERL (Test Facility)



ERL Light Source



5-GeV X-ray light source

Components relevant to the ERL light source are under development.

electron gun, superconducting cavity ...

These components are common to the γ -ray source

Kick-off Meeting at Oct. 26, 2005

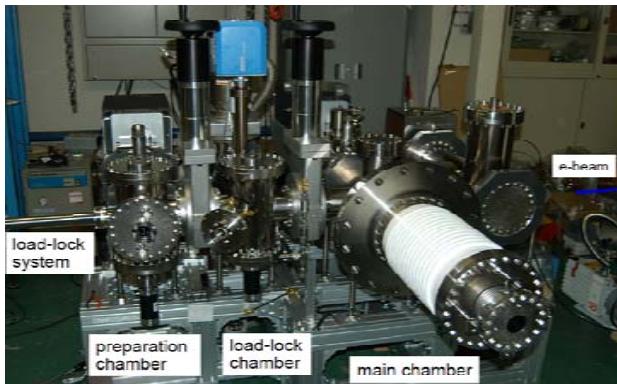
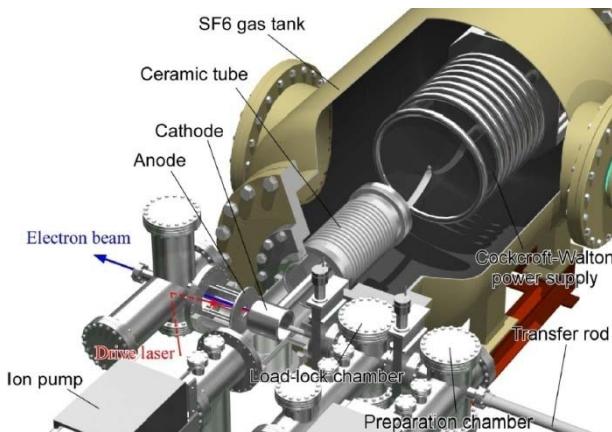


Development of ERL components



DC Photocathode Electron Gun

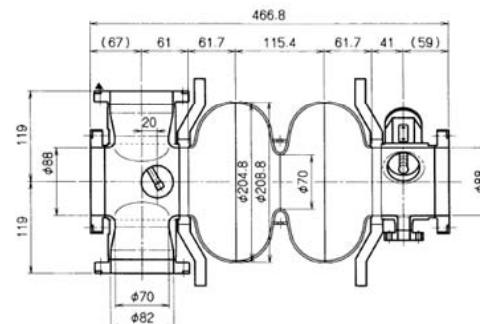
10-100 mA, $\varepsilon=0.1\text{-}1 \text{ mm-mrad}$



Superconducting Accelerator



L-band 9-cell cavity for the main linac



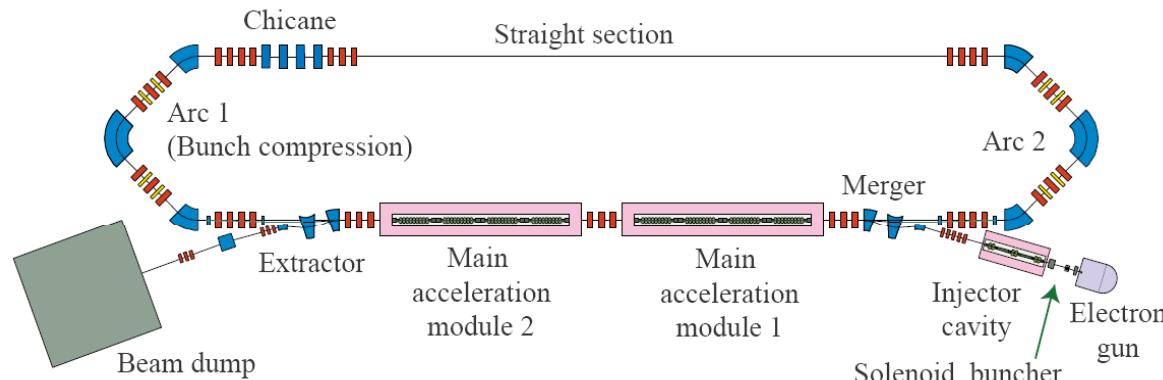
L-band 2-cell cavity for the injector

The Compact ERL (Test Facility)



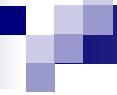
The Compact ERL will be constructed at the 12-GeV PS counter hall.

The first beam is scheduled in 2012.



beam energy	60 – 85 MeV (max 200 MeV)
beam current	10 – 100 mA
normalized emittance $\epsilon_n = \epsilon / (\gamma \beta)$	1 mm·mrad (77 pC/bunch) 0.1 mm·mrad (7.7 pC/bunch)
energy spread (rms)	$< 3 \times 10^{-4}$
bunch length (rms)	1 – 3 ps (w/o bunch compression) ~100 fs (bunch compression)

Conceptual Design Report,
R. Hajima et al. (Edit), KEK Report 2007-7 / JAEA-Research 2008-032



Compton X-rays at the Compact ERL



ultrafast mode

collision with a 50 fs, 1 kHz laser

laser		electron	
wavelength	800 nm	energy	30-60 MeV
energy	10 mJ	charge	100 pC
rep. rate	1 kHz	emittance	1 mm-mrad
length	50 fs (rms)	length	1 ps (rms)
size	20 μm (rms)	size	20 μm (rms)

X-ray = 10^4 - 10^5 photons/pulse

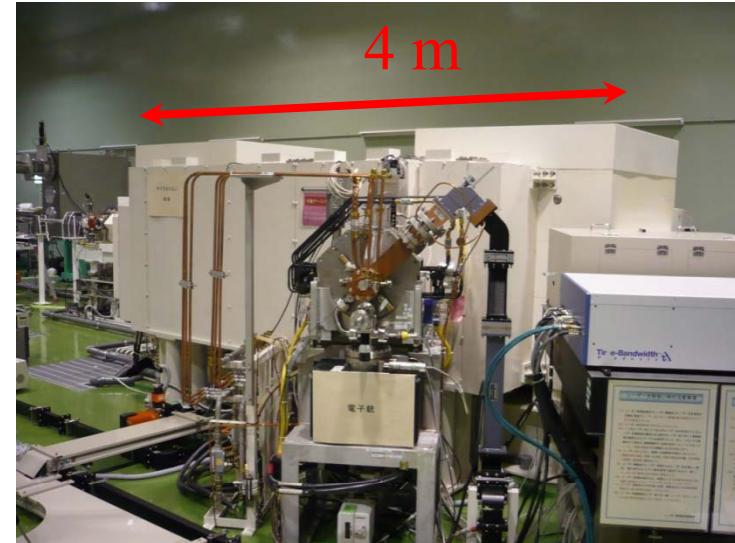
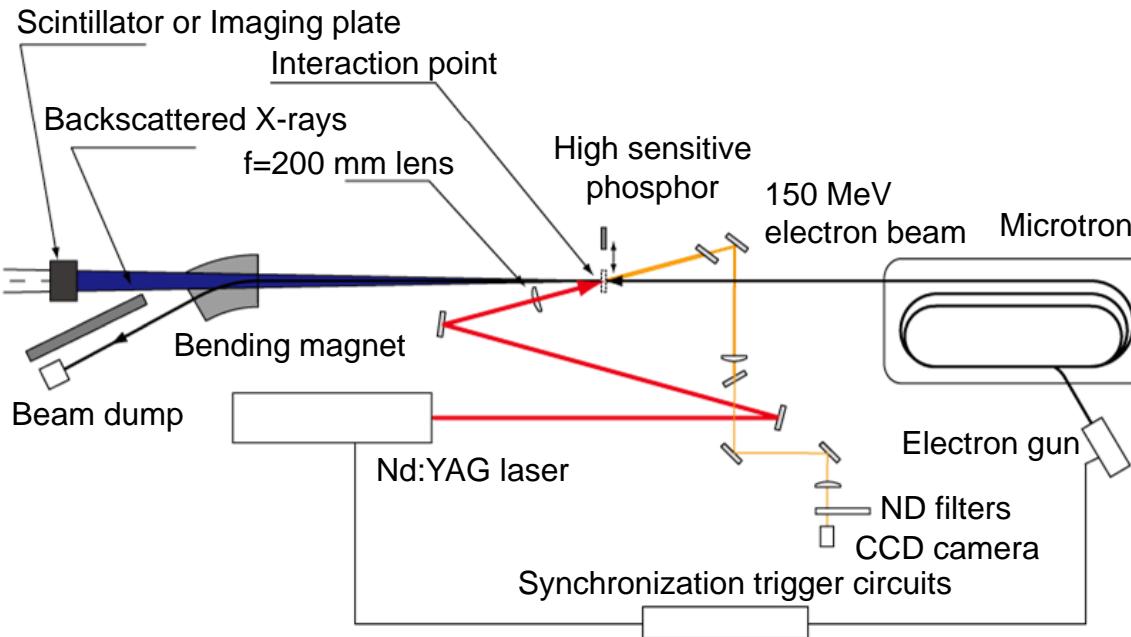
X-ray (10-40keV)	180-deg	90-deg
photons/pulse (100%bw)	6.7×10^5	3.9×10^4
photons/pulse (3%bw)	6.0×10^4	3.5×10^3
peak flux (3%bw)	2.4×10^{16}	1.3×10^{16}
pulse length (rms)	1 ps	110 fs

high-flux mode

collision in a supercavity (130 MHz)

intra cavity laser power = 100-700 kW \longrightarrow X-ray = 10^{12} - 10^{13} photons/sec

Sub-MeV Compton Source at JAEA



Microtron accelerator

Parameters of the laser and microtron

Nd:YAG laser

Pulse duration

23 ns (FWHM)

Output

1 J (1064 nm)

Repetition

10 Hz

Microtron

Energy

150 MeV

Pulse duration

10 ps (rms)

Charge

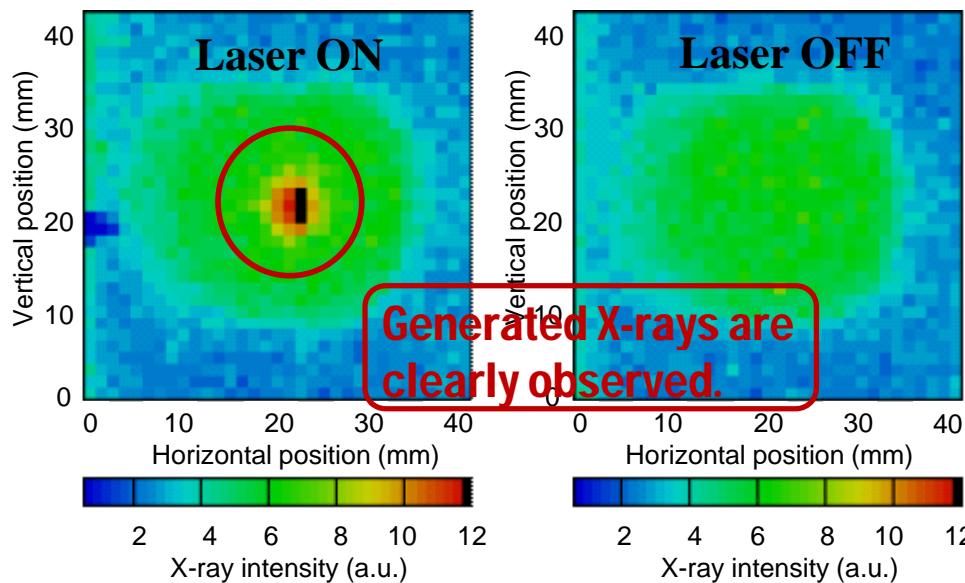
60 pC/pulse

Repetition

10 Hz

Sub-MeV Compton Source at JAEA

X-ray detection with Imaging plates

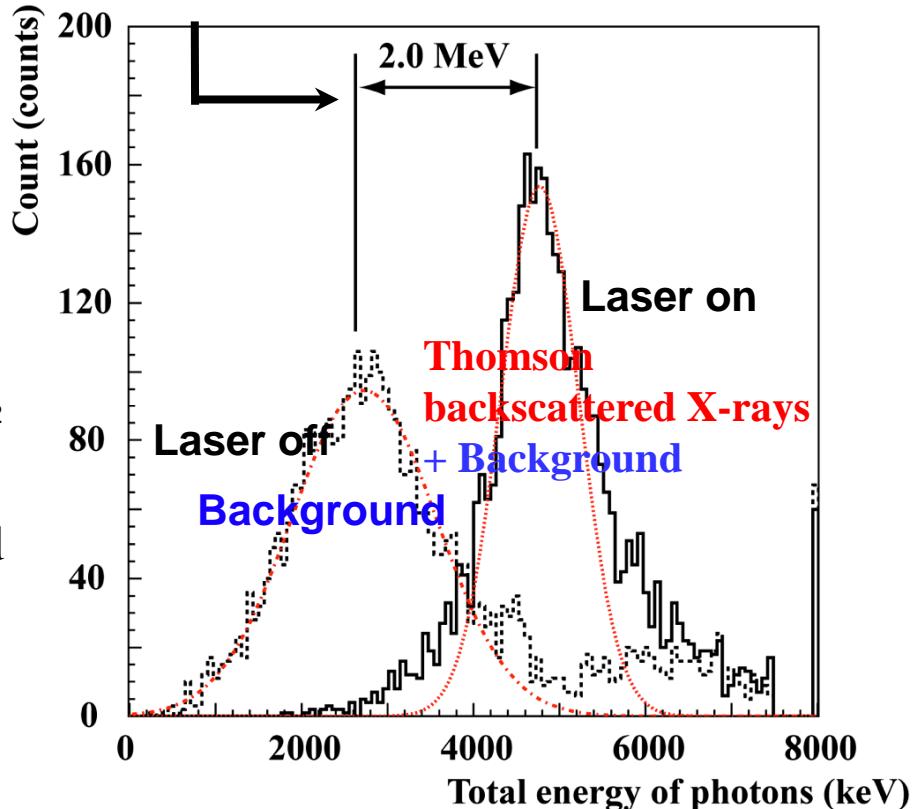


Assuming the calculated Compton backscattered spectrum and the detector efficiency evaluated with EGS4 simulation code, we conclude this experimental result as follows;

- Thomson backscattered X-rays with the energy **up to 400 keV** are generated.
- Total generated X-ray flux is estimated to be 20 photons/pulse.

Photon energy measured by scintillator

Total net energy of the backscattered X-rays in one-pulse (Mean energy x number of photons)



Summary

- We have proposed nondestructive assay of radioisotopes by laser Compton γ -ray and nuclear resonance fluorescence.
- LCS (quasi-monochromatic, tunable energy) is an ideal γ -ray source for the NRF measurements.
- A high-flux γ -ray source can be realized by using components under development in the ERL project.
- PoP experiments have been done.
- Source development and simulation studies are underway.