



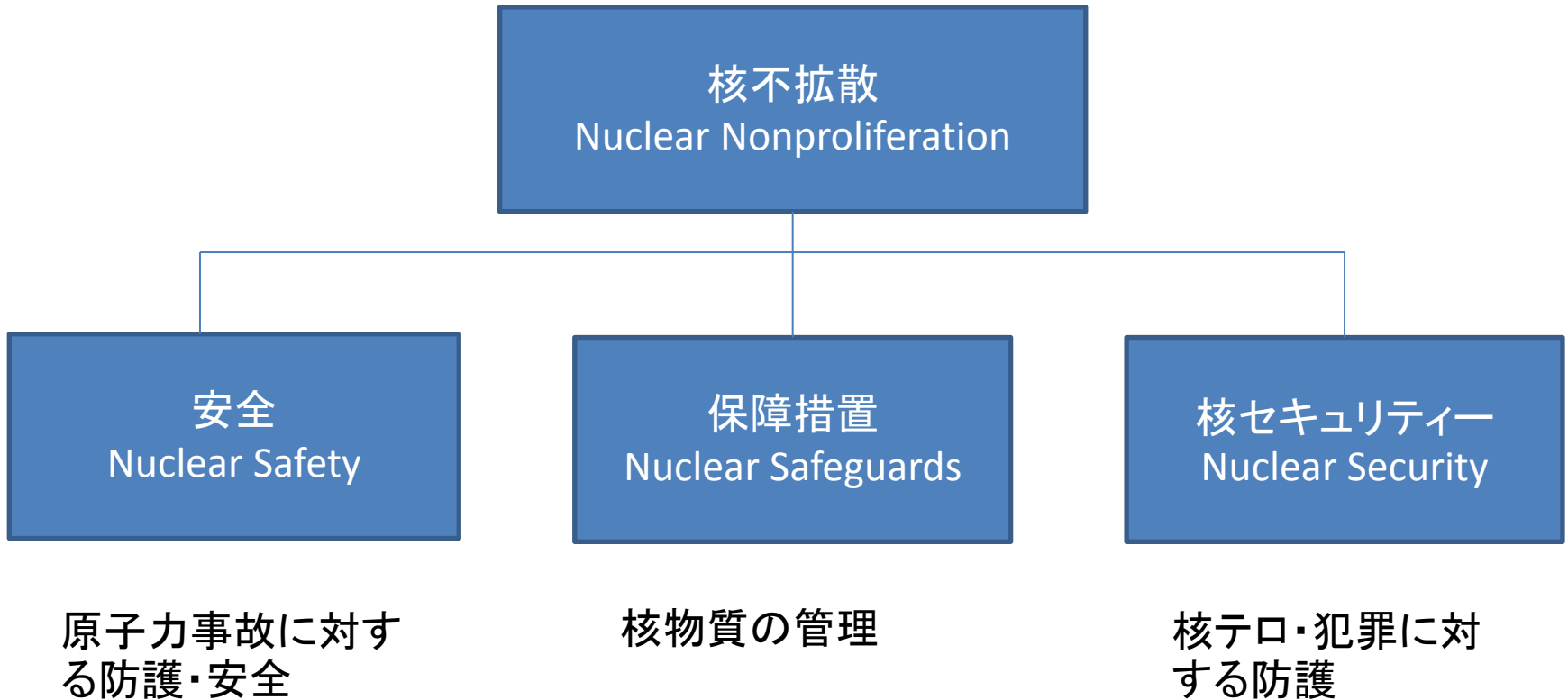
Nuclear physics for Nuclear Security and nonproliferation

Japan Atomic Energy Agency
Takehito Hayakawa

2014.4 Riken

Introduction

核不拡散: Nuclear Nonproliferation

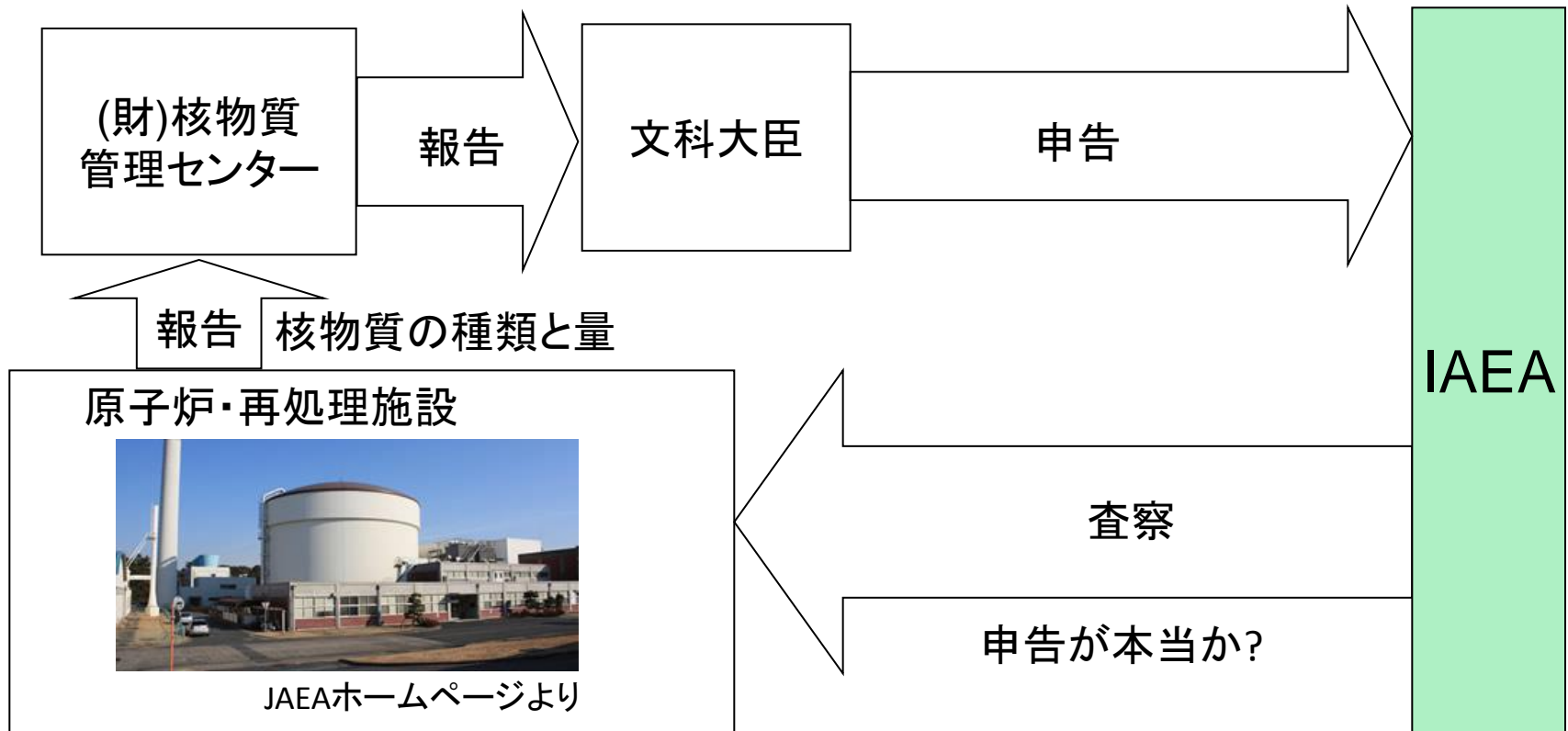


Nuclear Safeguards

日本は核不拡散条約(NPT)の締結国

日本は核物質を移動させる時にIEAEに申告する義務がある

IEAEの査察を受ける義務がある



日本は原子力を平和利用の堅持を証明するために積極的に新しい核物質探知技術を開発し、世界の核不拡散に寄与することが望まれている。

Nuclear Security

IAEAが想定する核テロリズム

- ① 原子爆弾、核ミサイルなど
核兵器そのものを盗む



- ② 高濃縮ウランやプルトニウムなど
核物質を盗んで核爆発装置を製造



- ③ 盗んだ放射性物質を発散させる装置
(汚い爆弾 = ダーティー・ボム)の製造

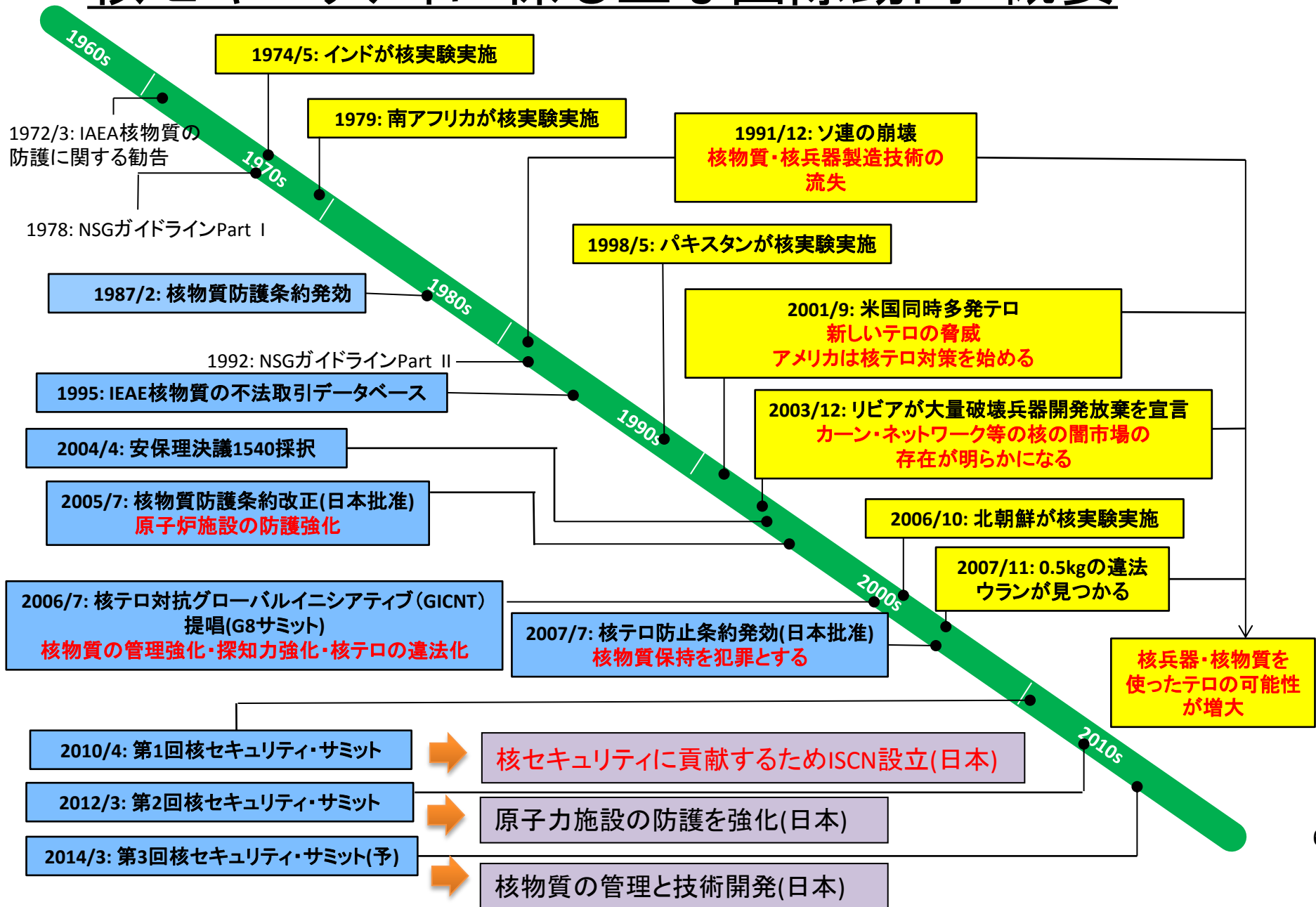


- ④ 原子力施設や放射性物質の輸送船など
に対する妨害破壊行為



出典:外務省HP「わかる！国際情勢 核セキュリティ・サミット～核テロ対策の強化に向けて」
<http://www.mofa.go.jp/mofaj/press/pr/wakaru/topics/vol56/>

核セキュリティに係る主な国際動向:概要



September 11, 2001

- March 2004 Madrid train bombings, 191 killed
- May 2005 London bombings, 56 killed
- July 2006 Mumbai train bombings, 190 killed



US government DOD and/or DOE photograph

Small -yield Nuclear weapon developed in US M-388, weight 23kg, can killed most of lives within 400m distance.

A nuclear attack by such weapon in Tokyo may cause 290,000 dead.

Risk Management Solutions reported that if a terrorist group detonates a small-yield nuclear bomb in the center of Tokyo, a quarter of a million people are killed in the blast, and 50,000 die from the effects of radiation over the coming years.

To secure the nuclear energy, management of special nuclear materials is crucial issue.

Requirement of scanning test for all ship cargo containers to US

Including special nuclear materials (SNMs)!!

However, it's postponed until 2014, and may extend further...

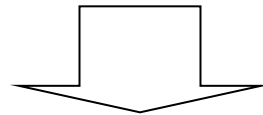


Photo s from Gunnar Ries

20 ft (6 m) cargo container(TEU)

From Yokohama to US

~12,000 cargo containers(TEU)/y ↔ 400 containers/day



Rapid inspection system is required (< 10 min)

Existing techniques for non-destructive inspection system

X-rays

AS&E



Short penetration depth => hidden by obstacles
Can not identify isotopes

D-T neutrons

Rapiscan co.(US)



- Tritium : radioactive
=> possible pollution by T itself
- very intense neutron
=> radioactive production, shielding problem

Bremsstrahlung gamma-rays



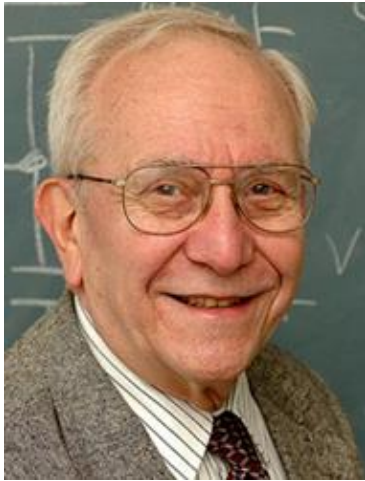
Passport Systems Inc(US)

- huge background => low S/N ratio, shielding problem



**•New SNM inspection system for cargo container is required.
*Short inspection time, easy to shield, radioactive free***

W. Bertozzi



Prof. William Bertozzi

マサチューセッツ工科大

http://web.mit.edu/physics/people/faculty/bertozzi_william.html

2011年国際核物質管理
学会の特別セッションで
第一トークを依頼した。

9.11の後、国防省に呼ばれ、米国の核物理学を代表して、核物質を非破壊で検知する方法を教えて欲しいと質問される。



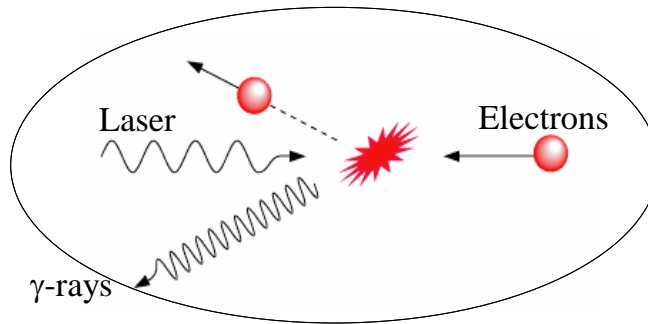
それは、核共鳴蛍光散乱である

New Non-destruction dotation
method with gamma-ray beam

Measurement of Nuclear Material Isotopes with NRF using LCS Gamma-rays

R. Hajima et al., J. Nuclear Science and Technology, 45, 441-451 (2008).

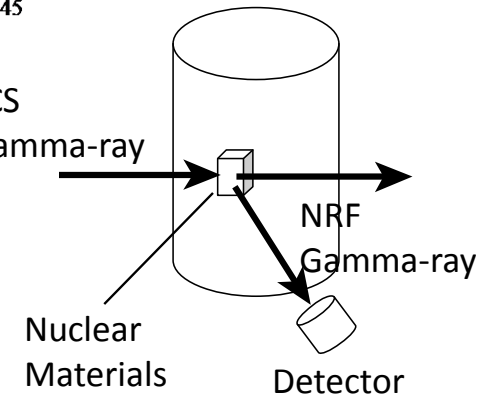
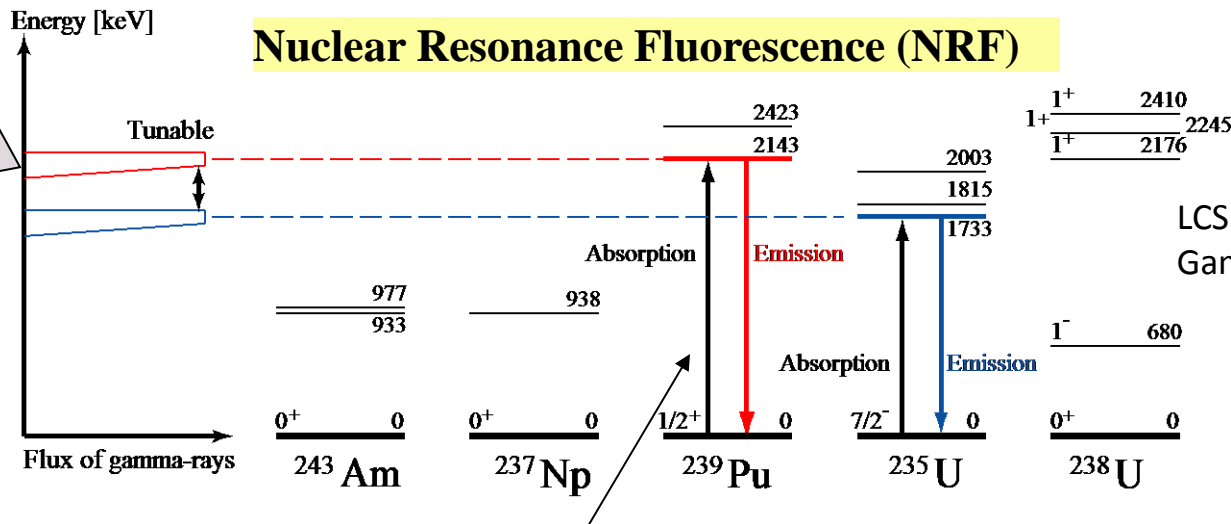
Laser Compton Scattering (LCS) gamma-ray beam



Mono-energetic & tunable g-ray beam

Gamma-ray beam is generated by Compton scattering of laser photon and high energy electron.

Nuclear Resonance Fluorescence (NRF)

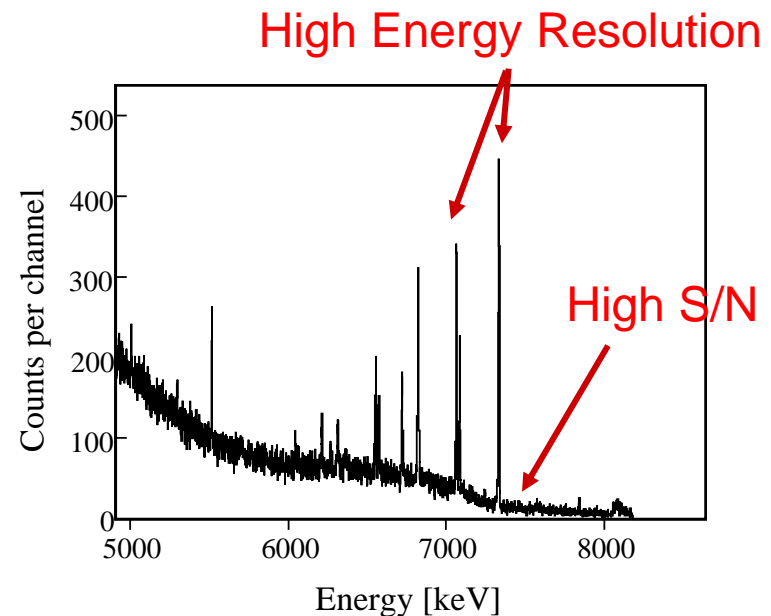


1. Incident gamma-rays are effectively absorbed.
2. Gamma-ray with the same energy is subsequently emitted.

What is advantage ?

- Detection of isotopes of all the elements of $Z > 2$
- Identification of unstable isotope as well as stable isotopes.
- With about 2-MeV gamma-rays, detection of Pu through several centimeter thick shields is feasible.
- Gamma-rays at 2 MeV penetrate water of several ten centimeters.
- High S/N ratio at peak because backgrounds appear in low energy part.

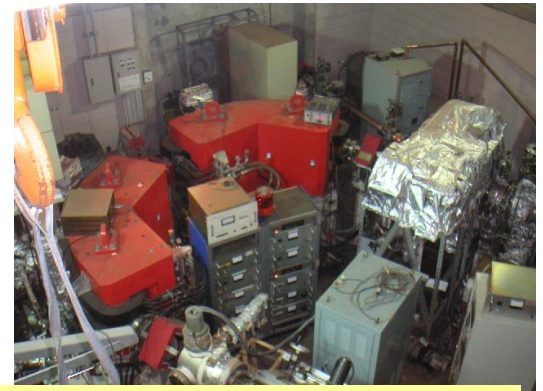
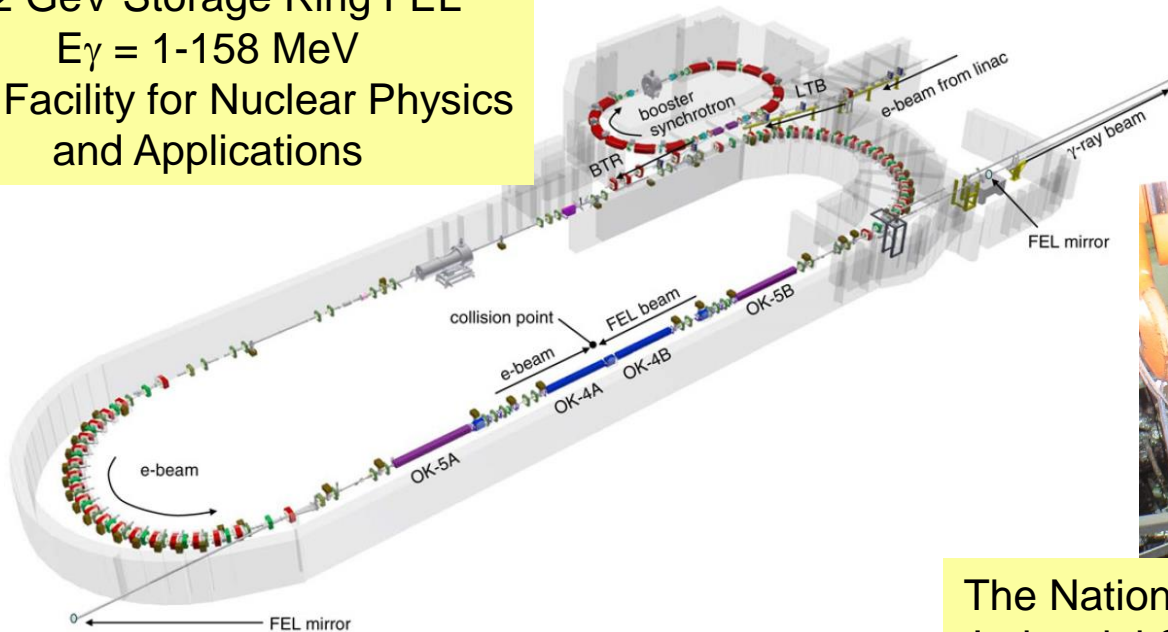
Example of detection of Pb-208 with a LCS gamma-rays in Japan.



T.Shizuma, et al., Phys. Rev. C 78, 061303(R) (2008)

LCS Gamma-ray Sources in the world

HIGS @ Duke Univ.
1.2 GeV Storage Ring FEL
 $E_\gamma = 1-158$ MeV
User Facility for Nuclear Physics
and Applications

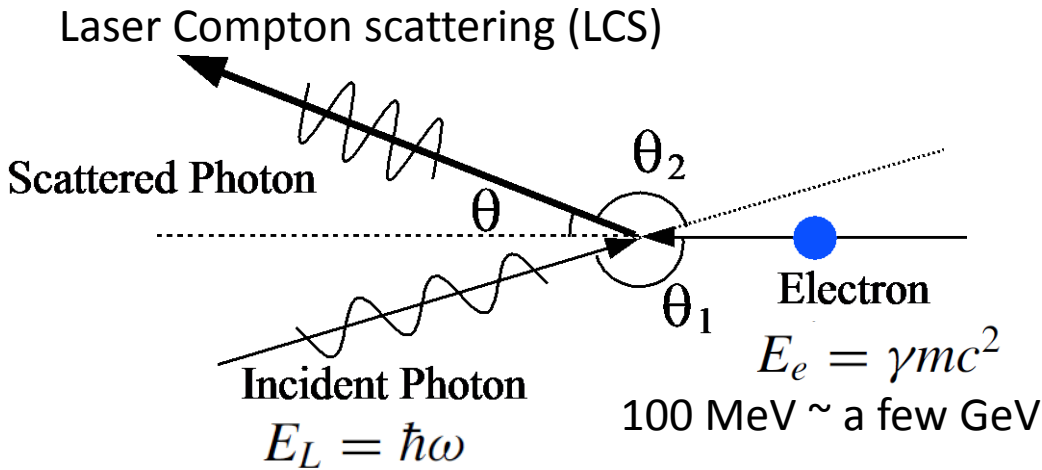


The National Institute of Advanced
Industrial Science and Technology
In Japan (AIST)
300-700 MeV Storage Ring
 $E_\gamma = 4-40$ MeV
User Facility



NewSUBARU in SPring-8: 1-1.5 GeV Storage Ring
 $E_\gamma = 1.7-40$ MeV
User Facility

Energy tunable monochromatic gamma-ray beam by laser Compton scattering



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

In case of head-on collision

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

We can obtain energy tunable monochromatic gamma-ray beam in this manner.



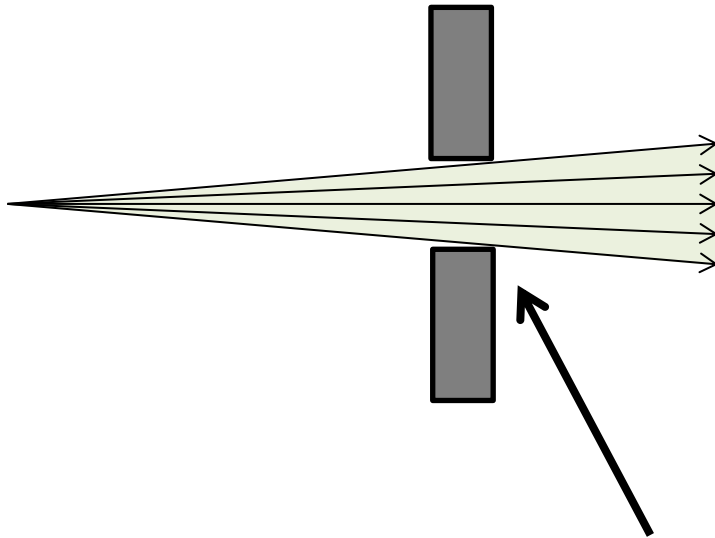
High current and small emittance electron accelerator is a key technology.

Energy distribution of gamma-rays

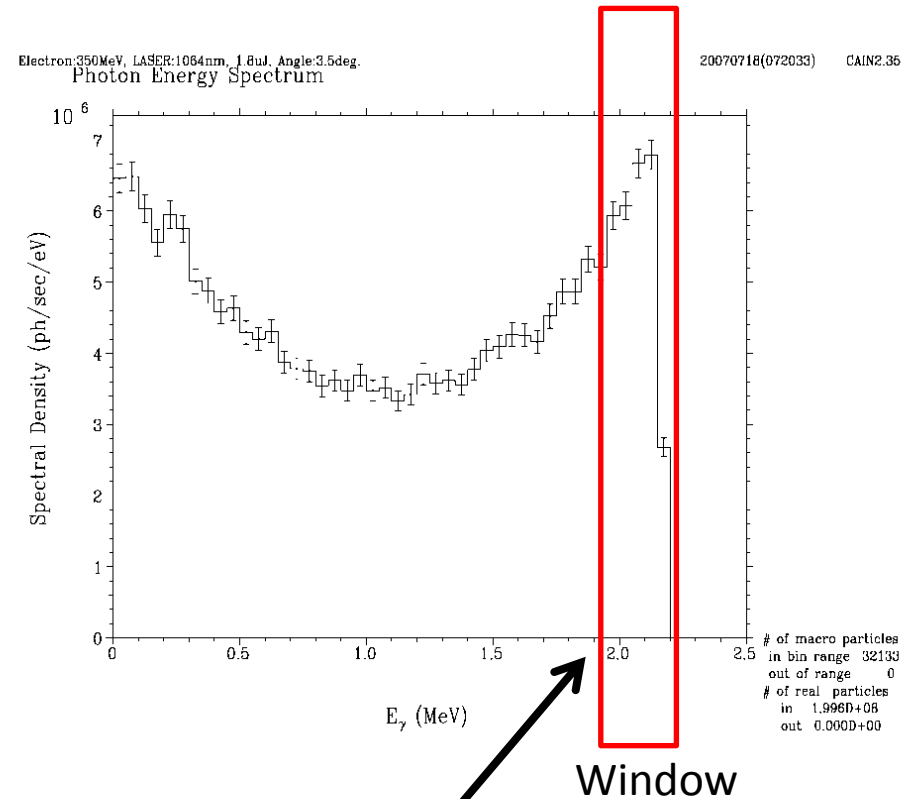
Gamma-ray beam includes many photons with various scattered angles.

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

Energy depends on scattering its angle

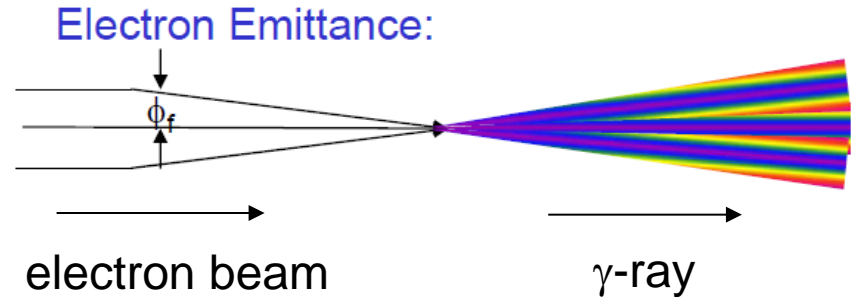
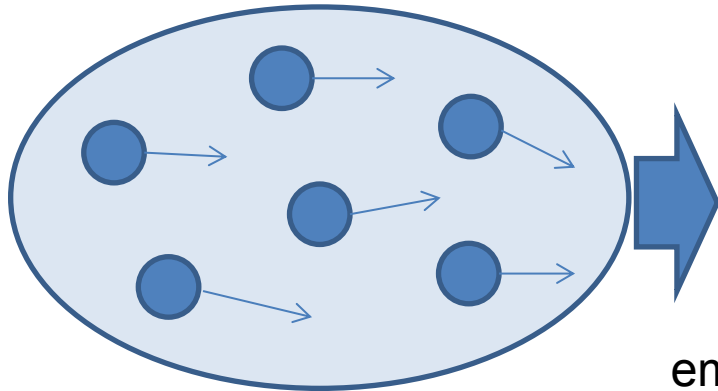


We determine energy spread using collimator which consternate the scattered angles



Small Emittance for Narrow-band γ -ray

Electron bunch



emittance smears “angle-energy correlation” of γ -ray

from a detail analysis:

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

normalized emittance $\varepsilon_n = 1 \text{ mm-mrad}$, collision spot $\sigma_x = 10 \mu\text{m}$ $\rightarrow \Delta E_\gamma / E_\gamma = 2\%$

normalized emittance $\varepsilon_n = 0.1 \text{ mm-mrad}$, collision spot $\sigma_x = 10 \mu\text{m}$ $\rightarrow \Delta E_\gamma / E_\gamma = 0.02\%$

Normalized emittance of 0.1mm-mrad is the key parameter.

Proposal for new gamma-ray source based Energy recovery Linac

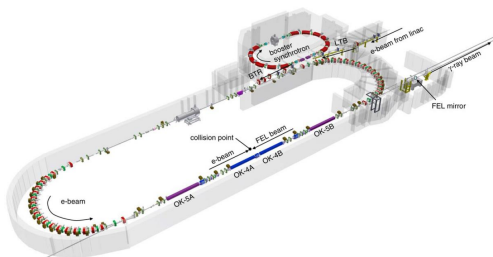
基礎科学・核セキュリティのため世界のLCS γ 線源 -新世代の高輝度 γ 線源の開発が開始された-

現在MeV領域では世界で2か所のみで稼働。基礎研究用。

ニュースバル(SPring-8)

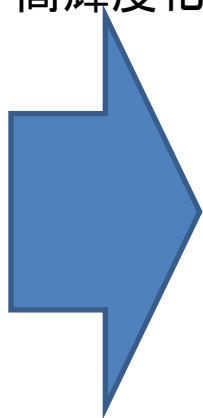


Duke大(米)

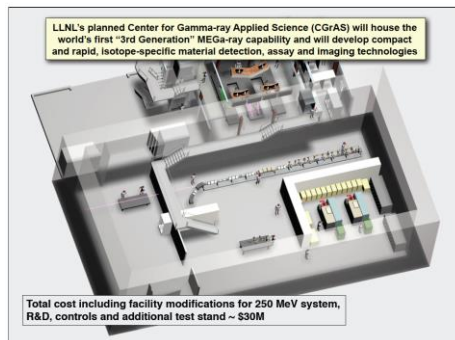


核セキュリティ技術研究を推進中

5~7桁
高輝度化



MEGArray(LLNL)



建設中

その他
・カナダ(基礎研究中)
C. Rangacharyulu

ELI-NP(ヨーロッパ)



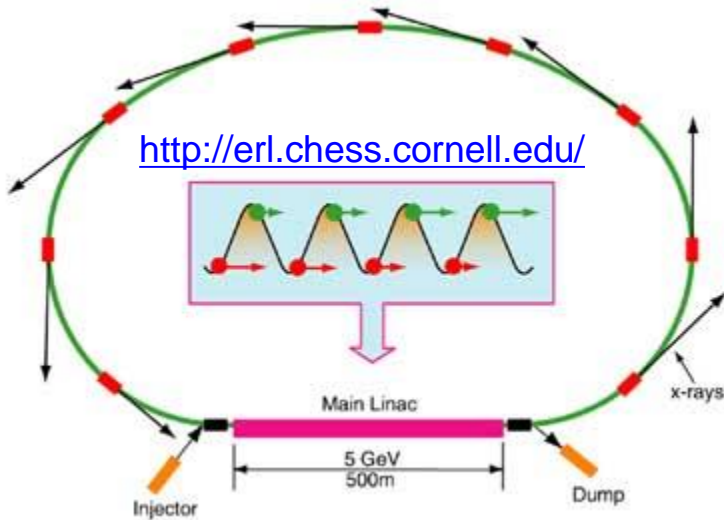
来年度建設開始

KEK-JAEA

原理実証機



Energy-Recovery Linac

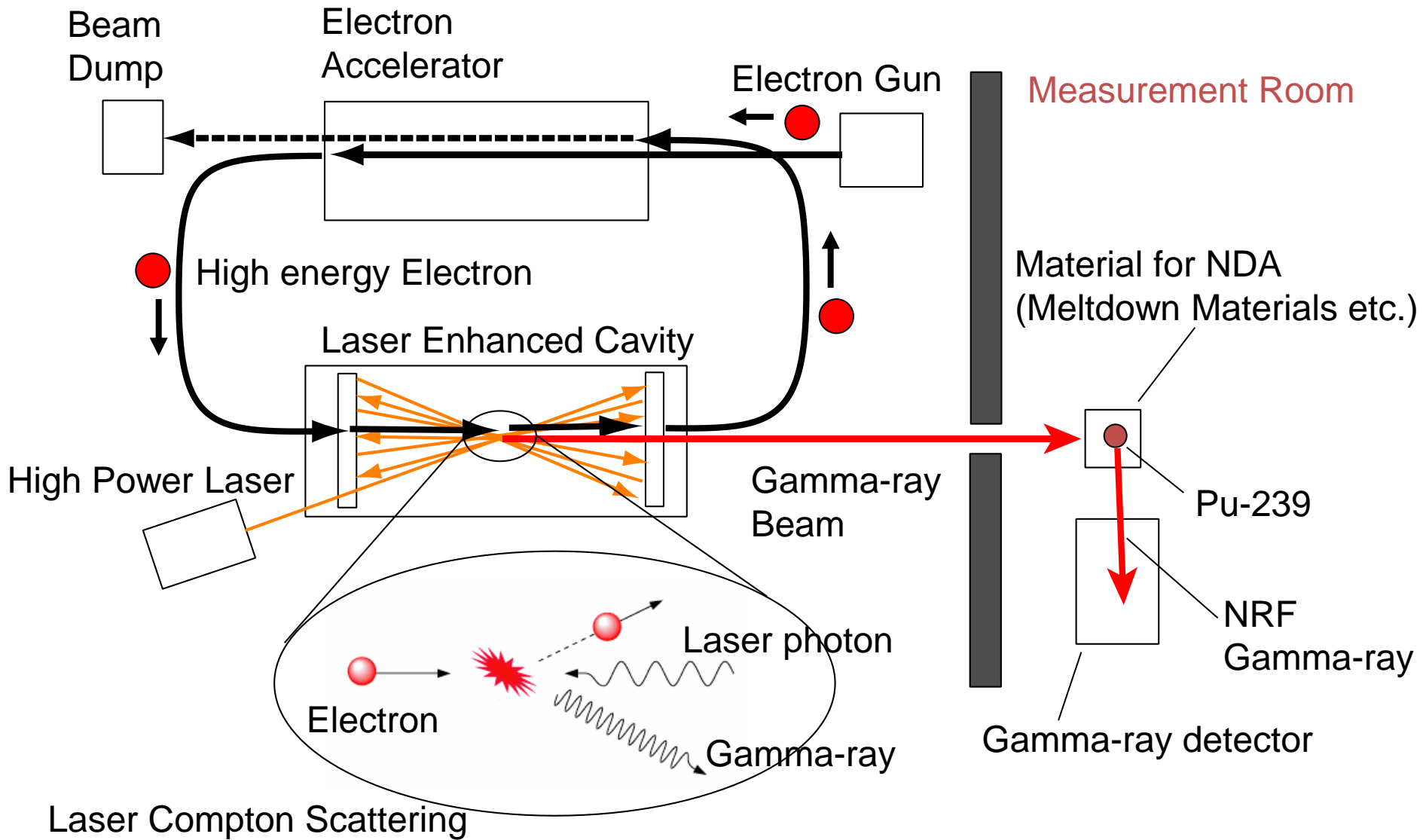


Energy Recovery Linac has been studied for the next generation of radiation source in the world.

- Each electron bunch is used only once
- Energy of used electron is recycled

- ✓ energy-recovery for high-average current beams
- ✓ Small emittance of electron bunch

Concept of LCS Gamma-ray NDA system

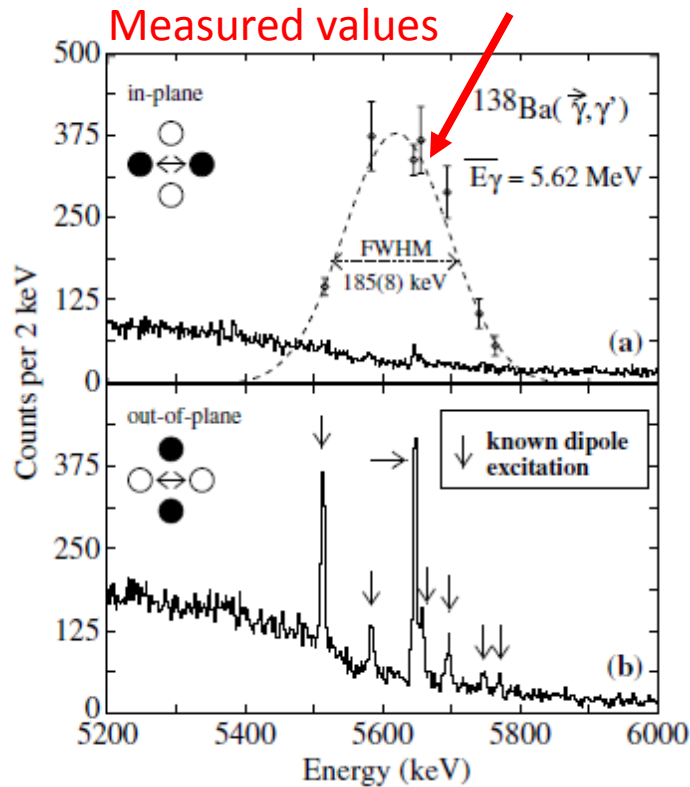


Spec of LCS gamma-ray sources

Duke University

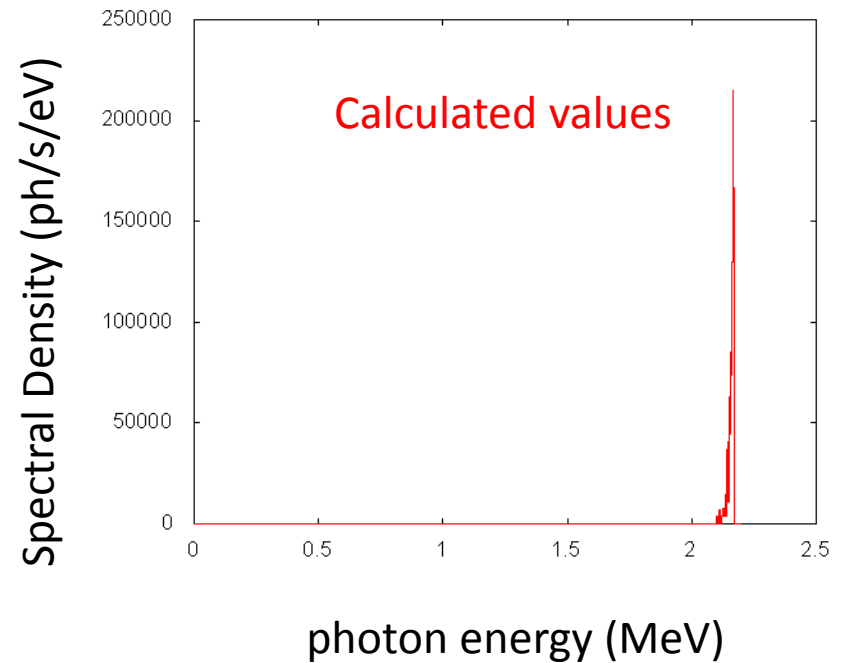
Flux is 10^8 photons/s
 $dE/E = \text{about } 3\%$

Spread of Incident LCS gamma-rays



ERL-LCS gamma-rays

Flux is 10^{13} photons/s
 $dE/E = 0.5\%$
 with a collimator of 0.05 mrad



Proposal for nuclear safeguards

Development of a simulation code

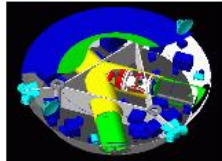
The GEANT4 is widely used in the particle physics and nuclear physics.

Applications



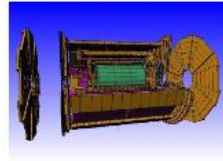
A sampling of applications, technology transfer and other uses of Geant4

User Support



Getting started, guides and information for users and developers

Results & Publications



Validation of Geant4, results from experiments and publications

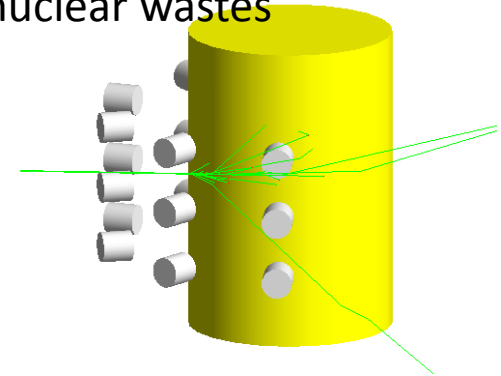
Collaboration



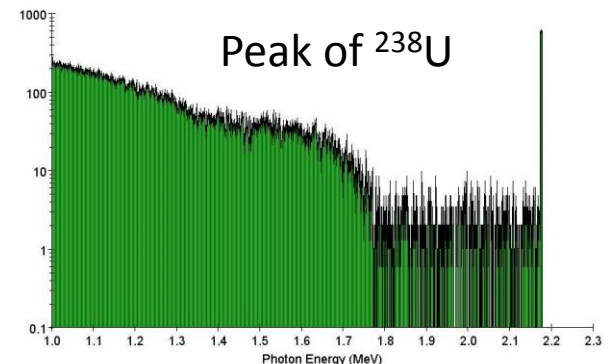
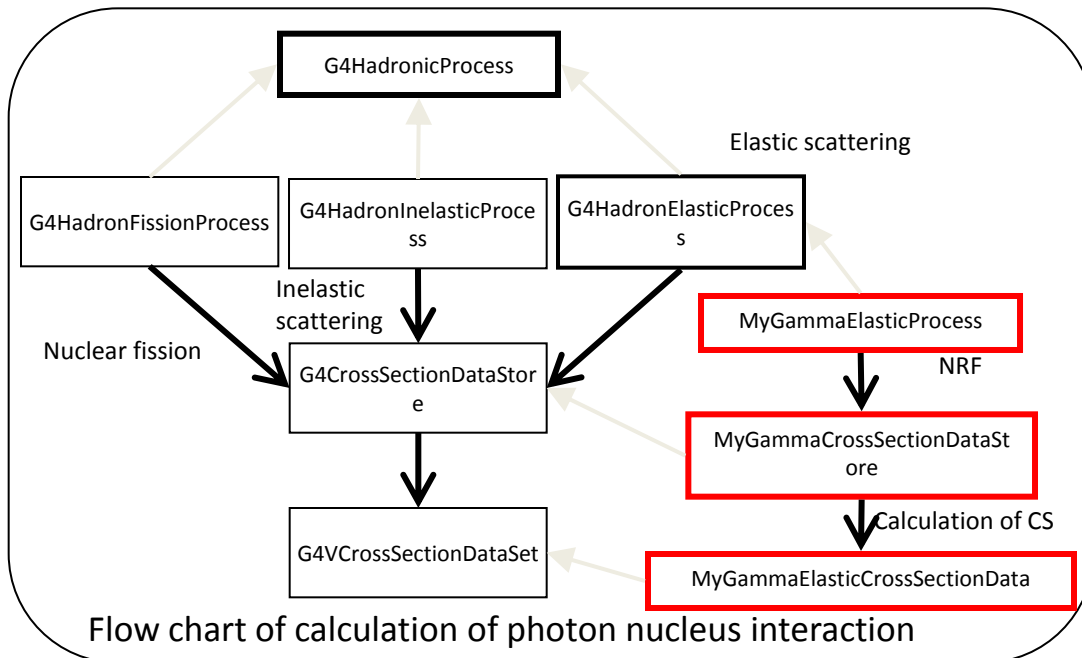
Who we are: collaborating institutions, members, organization and legal information

<http://geant4.cern.ch/>

Calculation example:
Detection of U in nuclear wastes

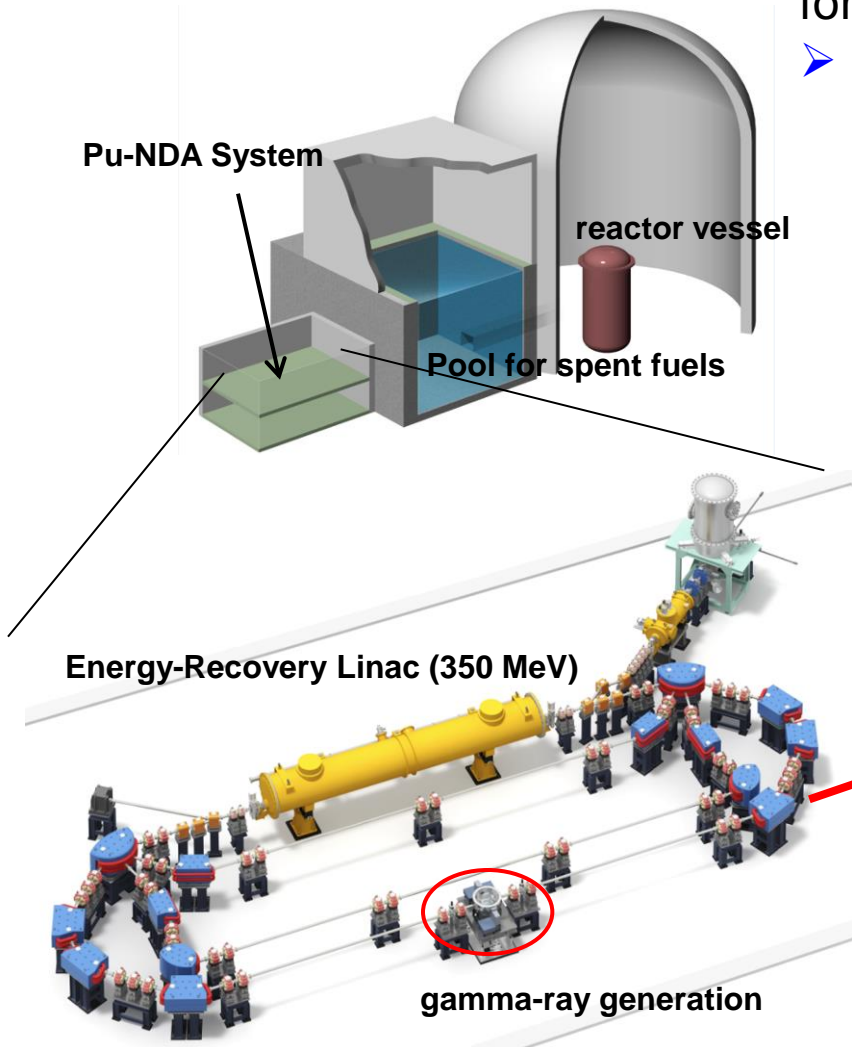


We added new packages to calculate NRF.



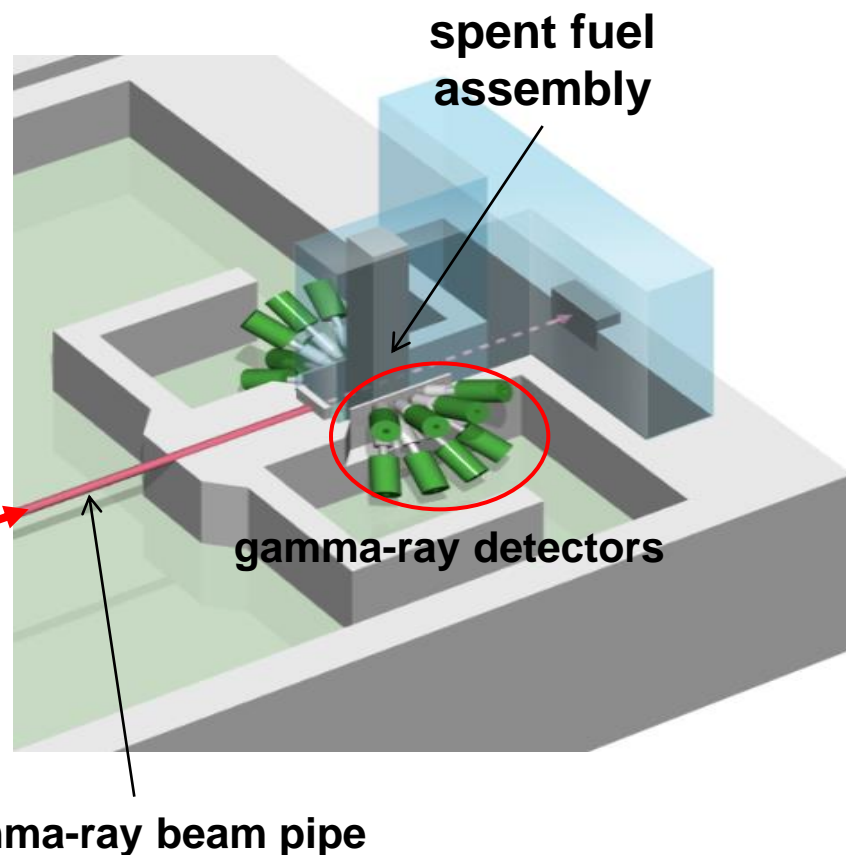
A Proposal of Spent Fuel (Pu-239) NDA System with NRF using LCS Gamma-rays

Nuclear Power Plant

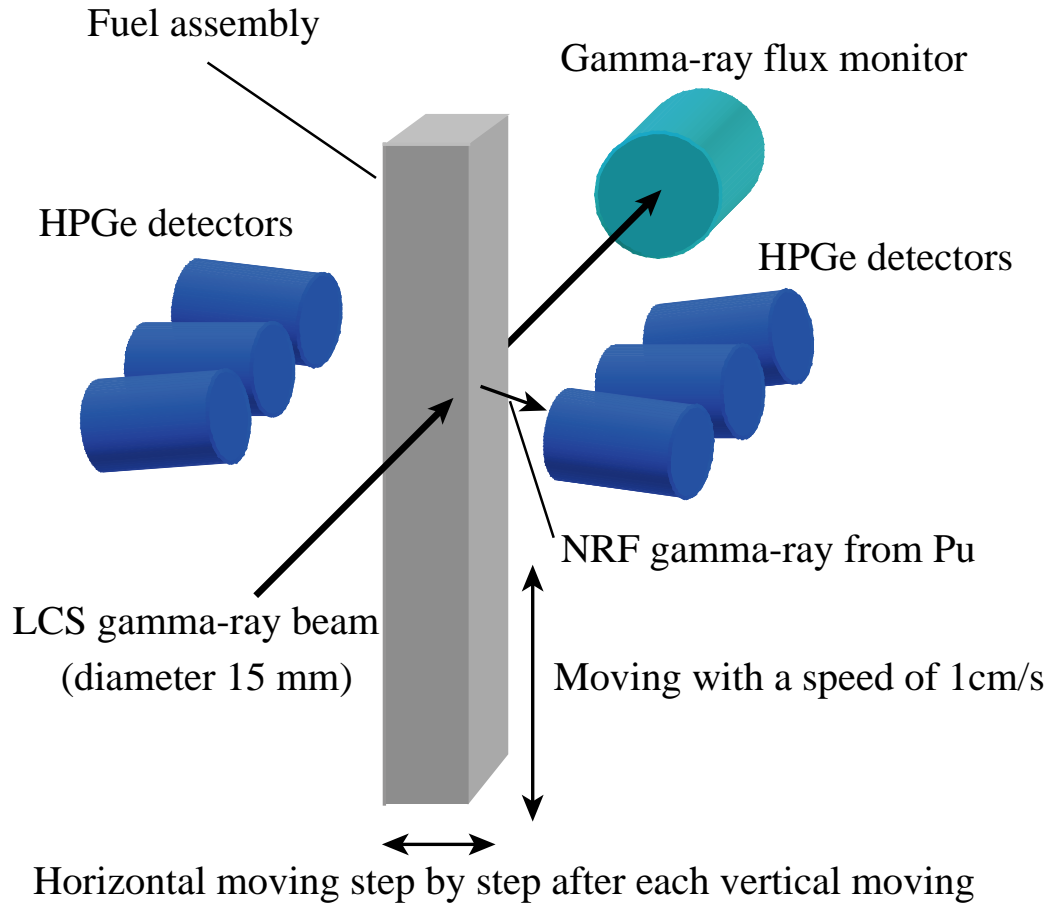


Non-Destructive Assay of plutonium (Pu-NDA) for spent fuel assemblies

- Detection of diversion of fuel rods from fuel assemblies stored in a reactor pool.



Analysis of Fuel assembly



This system can measure a spent fuel assembly per the measurement time of 4000 s.

The position of gamma-ray beam is fixed and the assembly is moved with a speed of 1cm/s.

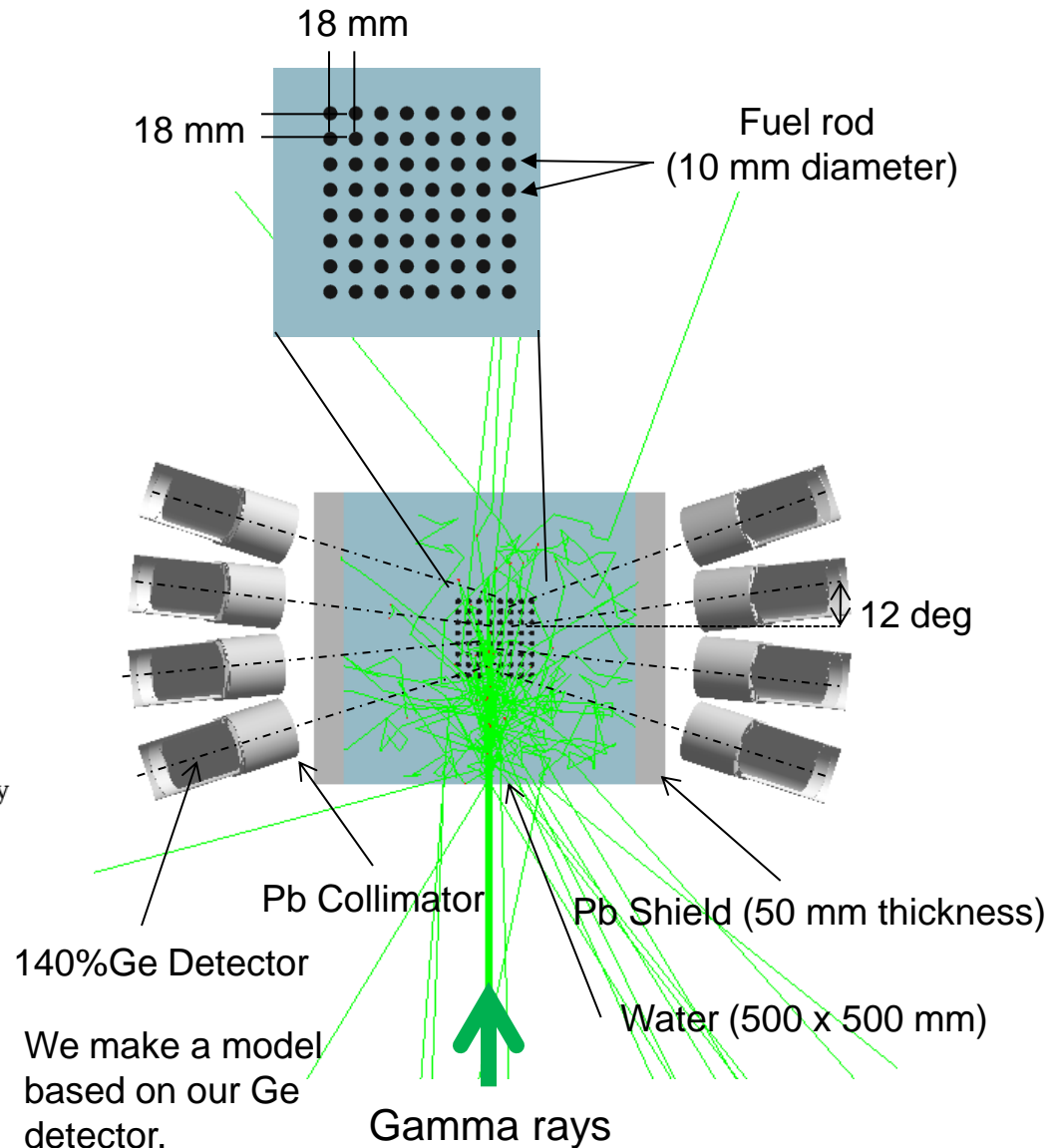
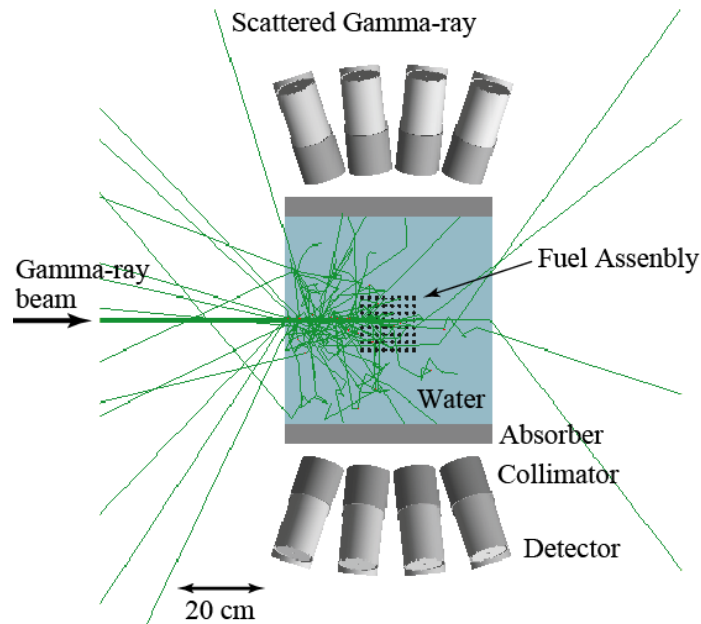
Each Ge detector measure NRF gamma-rays from only one fuel rod.

This system can distribution of Pu as a function of position and rod.

Model for Simulation (BWR:8 by 8)

(Spent Fuel (Pu-239) NDA System with NRF using LCS Gamma-rays)

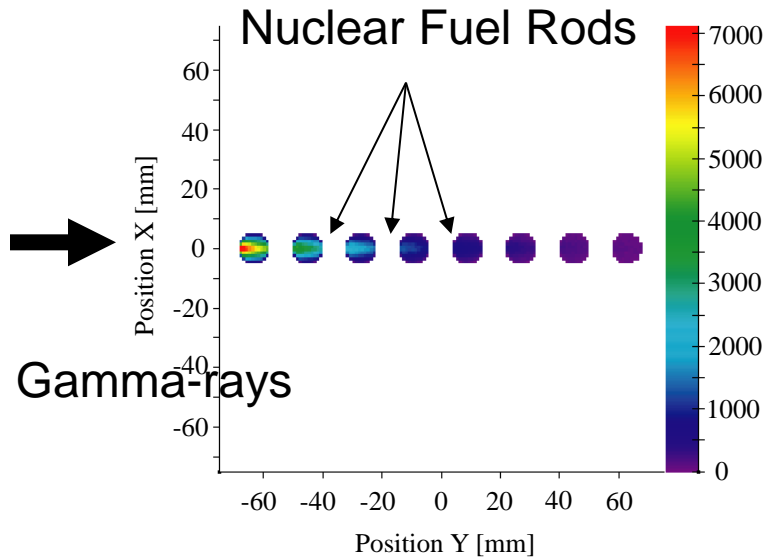
Composition	
Density	11.0g/cm ³
UO ₂	90 % (U-238 100 %)
PuO ₂	10 % (Pu-239 52 %) (Pu-240 48 %)



Expected Spectrum and Statistical Error

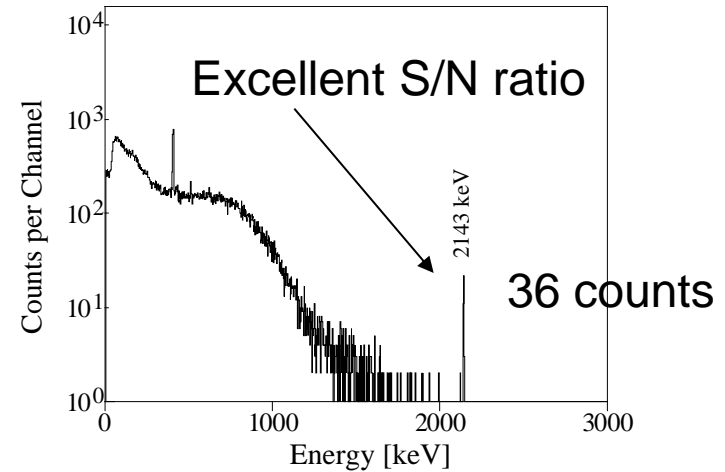
(Spent Fuel (Pu-239) NDA System with NRF using LCS Gamma-rays)

NRF event rates



Our designed system can observe ^{239}Pu in all rods.

A sum spectrum for 5 seconds



For **10%** PuO_2 with 4000 s,
 2.8×10^4 events for ^{239}Pu .



For **1%** PuO_2 with 4000 s,
 2.8×10^3 events for ^{239}Pu .

Statistical Error is 2%.

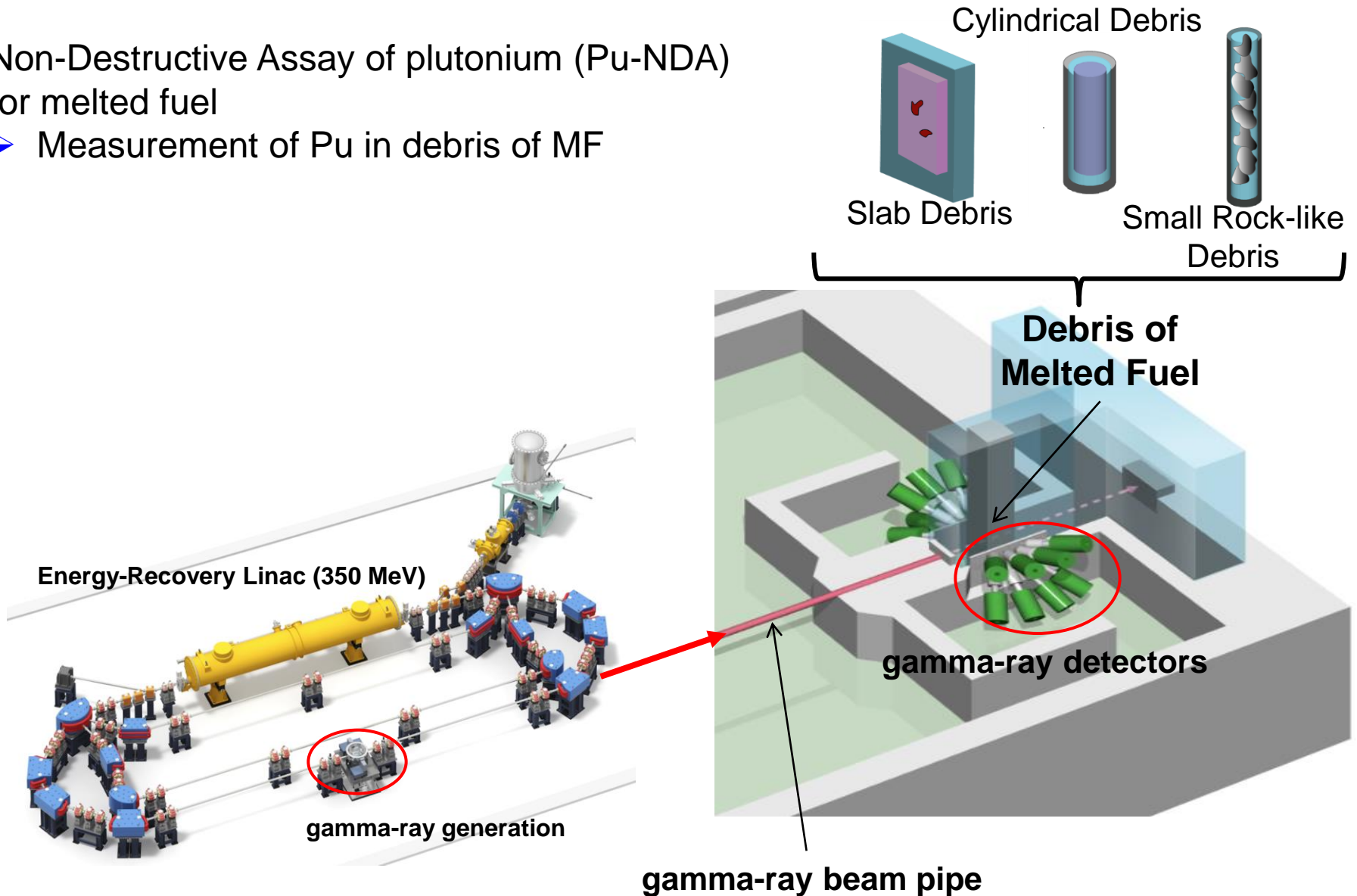
Measurement by the SF Pu-NDA System with statistical error of 2%.

T. Hayakawa, et al. NIMA, 621, 695 (2010).

A Proposal of LCS Gamma-ray Melted Fuel (Pu) NDA System

Non-Destructive Assay of plutonium (Pu-NDA)
for melted fuel

- Measurement of Pu in debris of MF



Demonstration of ERL-LCS gamma-ray source

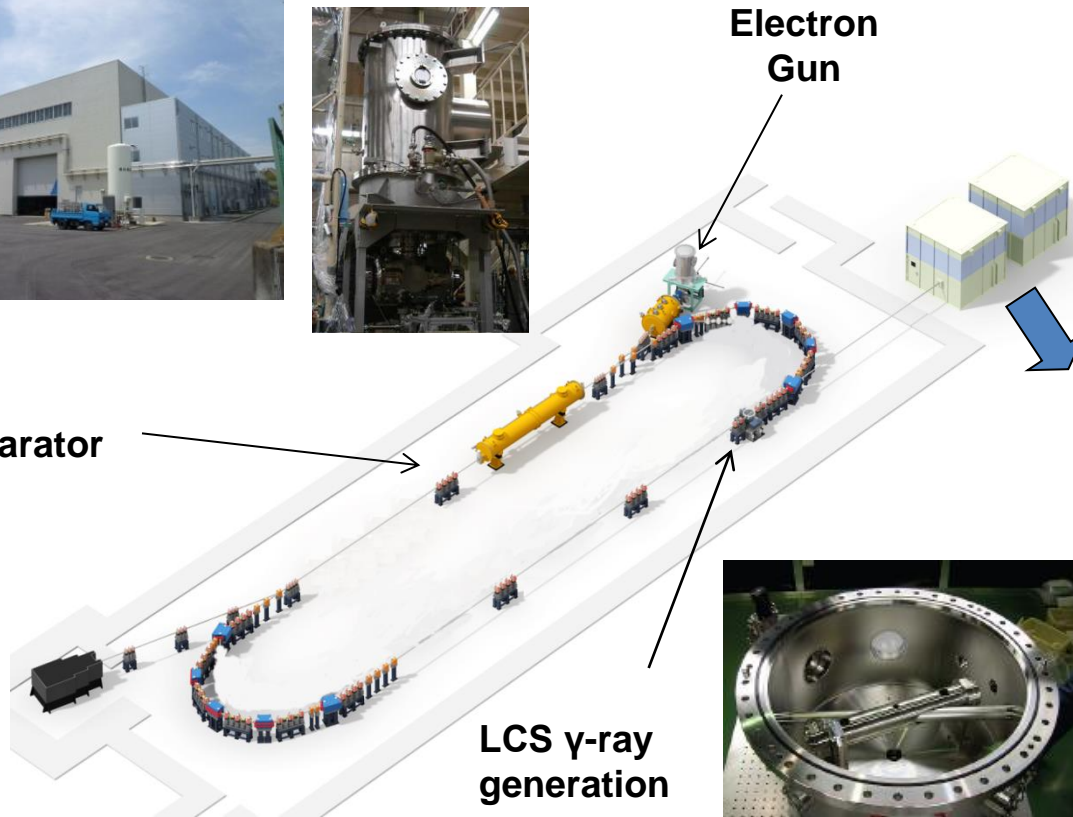
Test facility of ERL-LCS gamma-ray source at KEK (2011~2014 March): **Demonstration of generation of intense LCS gamma-ray**

KEK-JAEA collaboration



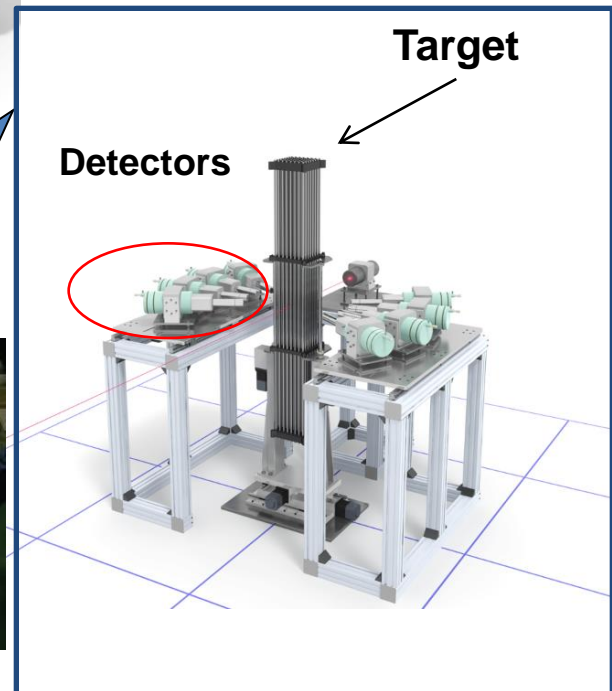
Electron
Gun

Accelerator



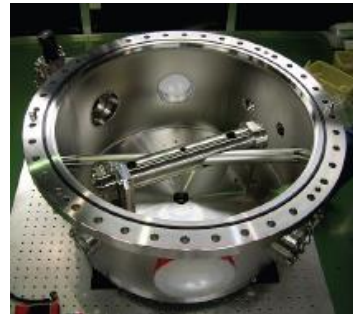
LCS γ -ray
generation

Experimental Room
X-ray with 10 keV

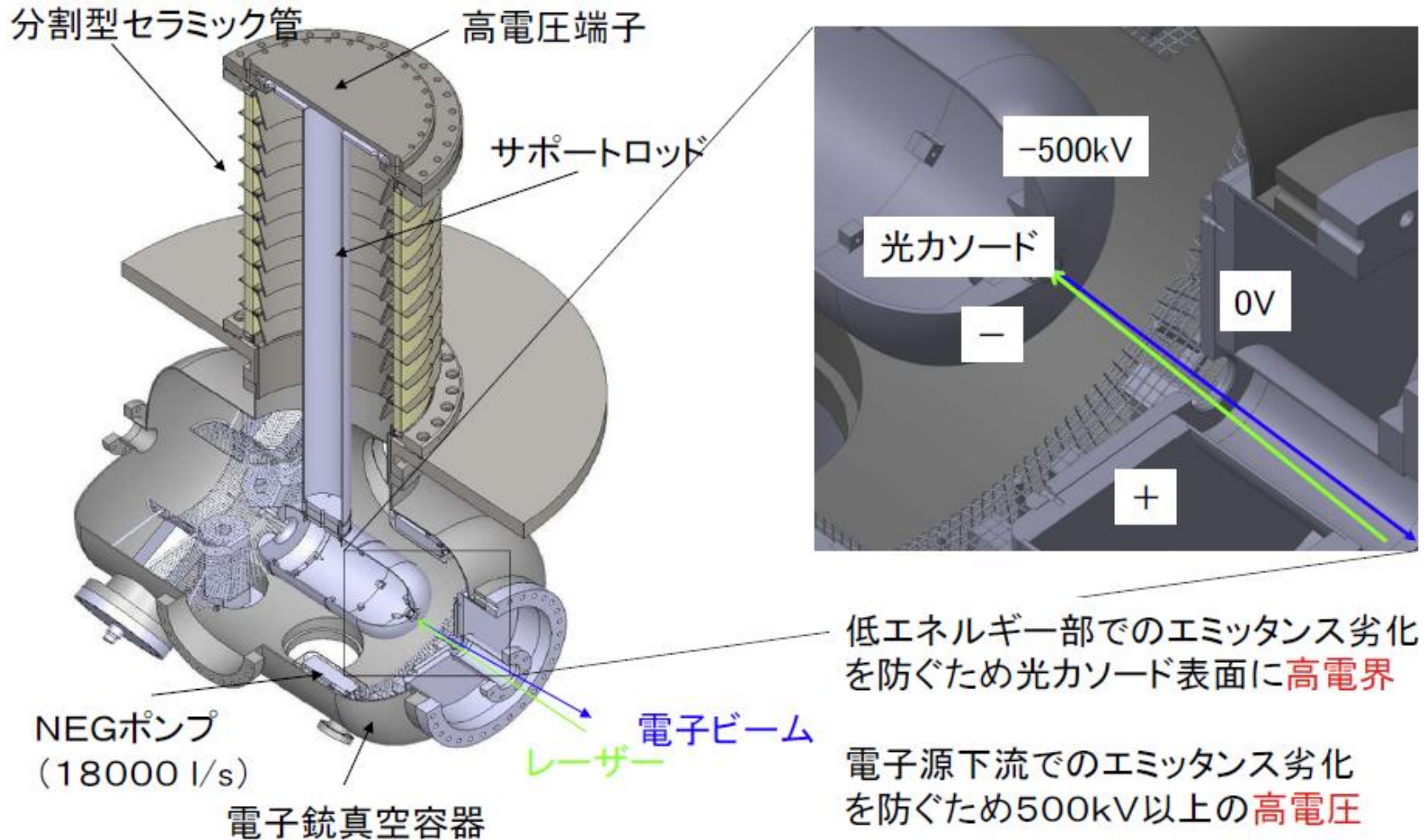


Target

Detectors



要素技術(1) 電子銃



500 kV での電子ビーム発生に成功、コンパクトERLに移設(2012年10月)

要素技術(2) 超伝導加速空洞

- リニアコライダー用の技術を転用
- 大電流加速に最適化
- KEK、JAEA、東京大学の共同チーム
- 2つの装置(入射器、主加速器)を完成



9-セル空洞
(ニオブ製)



クリーンルームでの組み立て作業



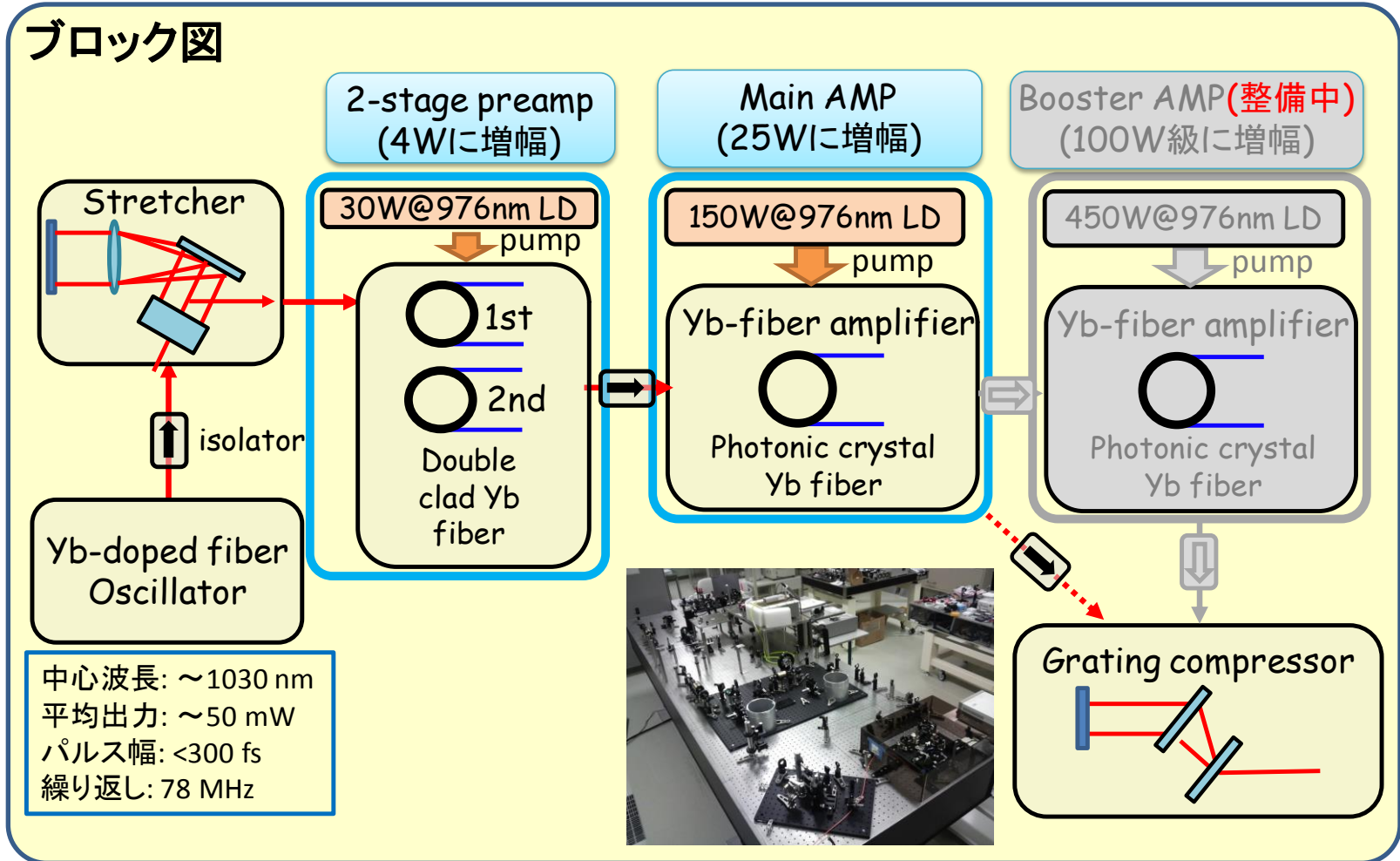
超伝導入射器の据え付け(2012年7月)



超伝導主加速器の据え付け(2012年10月)

要素技術(3) 高出力レーザー

Yb ファイバーレーザー、4段増幅方式 → 平均出力100W級

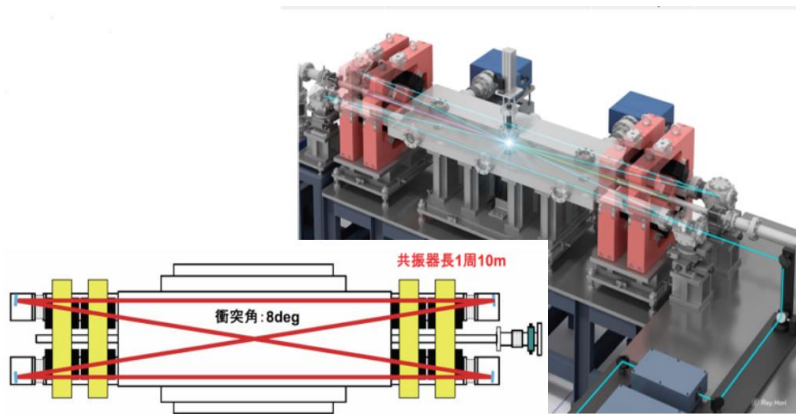


**Main AMPまでの構築で平均出力 20W(パルス圧縮後)
パルス幅 330fs(FWHM)を達成**

小菅淳氏提供

光蓄積共振器

現在、KEKと原子力機構の2つのグループで開発中



光蓄積共振器
=4枚のミラーで構成、
電子ビーム収束用の磁石との干渉
を防ぎつつ、浅い角度で衝突させる
設計（図は KEK-LUCXIにて
製作中の装置）

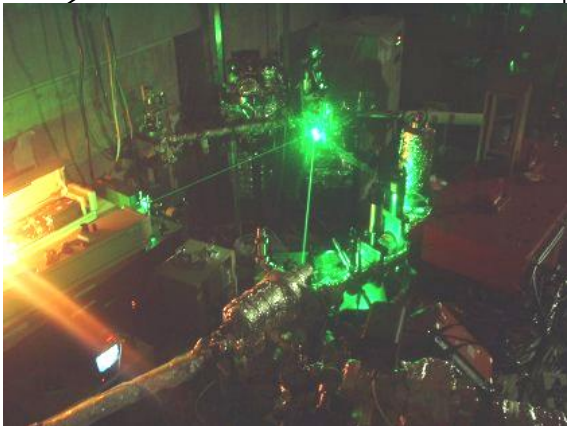
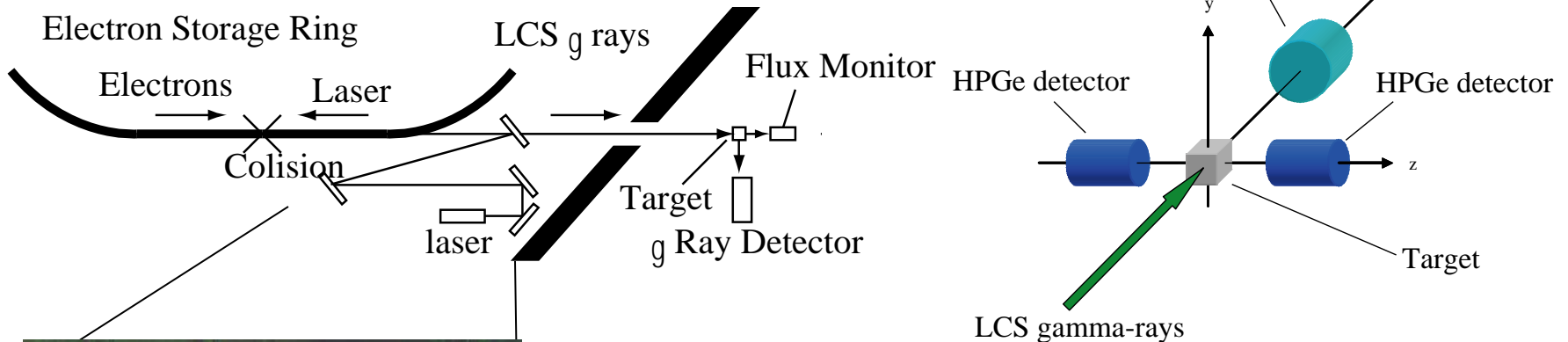


関西研でレーザーの専門家が独立に開
発中（2012年から）

Proofs-of-principle experiments

Demonstration of detection

We use a LCS gamma-ray source at synchrotron TERAS in Advanced Industrial Science and Technology (AIST)

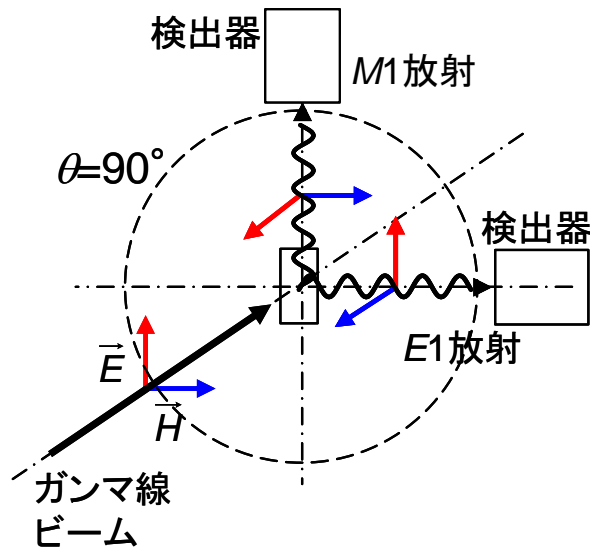


- Nd:YVO₄ Q-switched laser
1064 nm, ~40W
- 570 MeV electrons
200 mA
- 1-40 MeV LCS gamma-rays
- 10⁵ photons/s

M1 strength of Pb-208

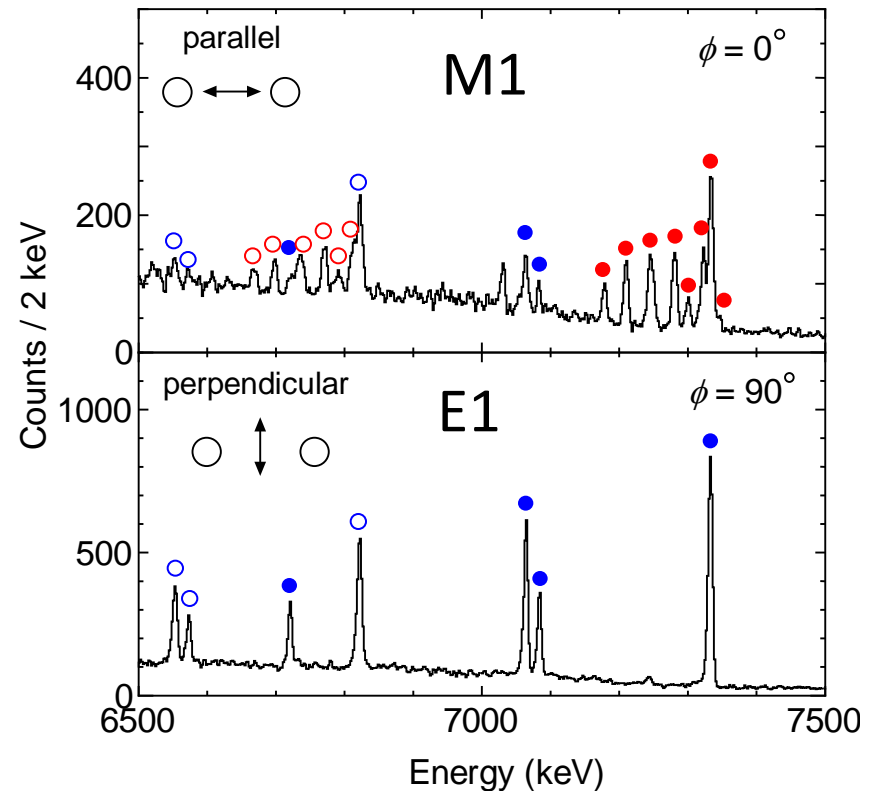
NRF experiments of a double magic nucleus Pb-208

Nuclear Resonance Fluorescence with polarized gamma-ray beam.



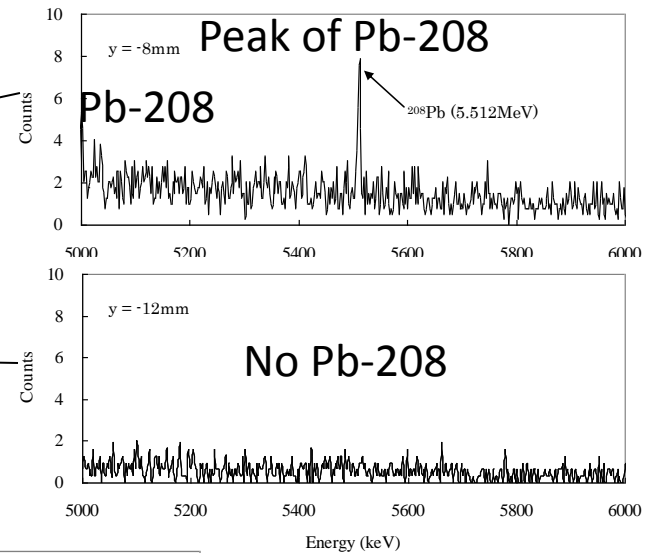
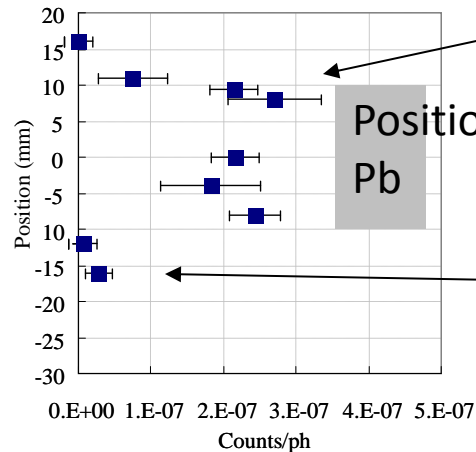
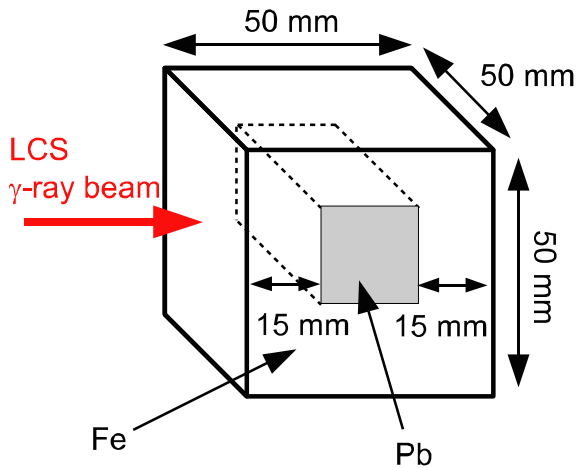
Angular distribution of NRF gamma-ray is strongly sensitive to angle of the beam.

Measured spectra at AIST

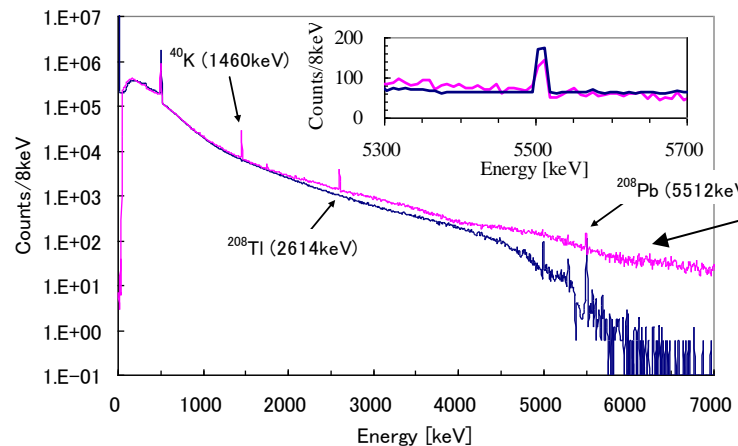


Detection of a hidden isotope

We used Pb-208 instead of U-238, since we cannot use it at AIST.

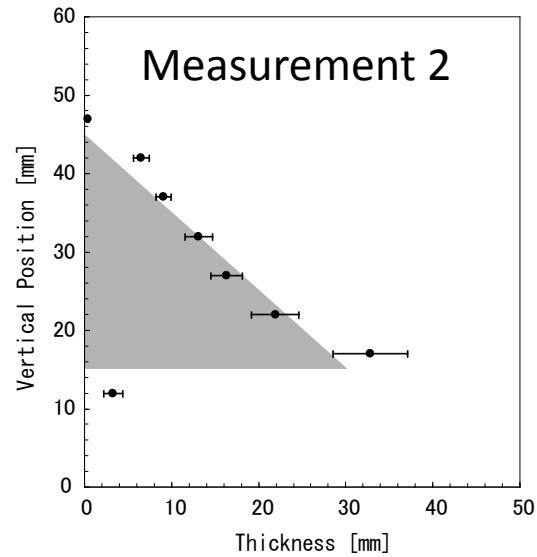
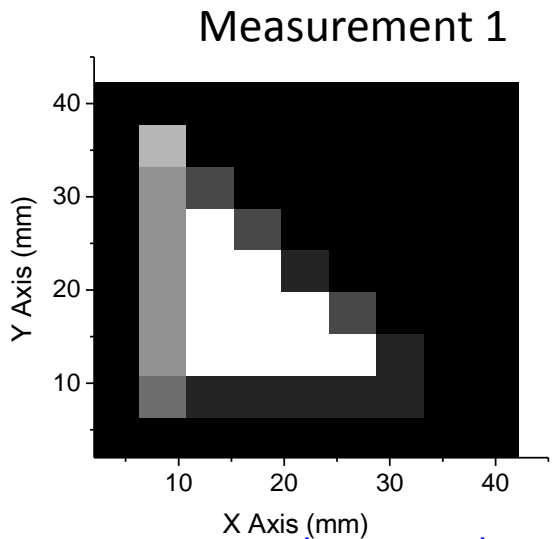
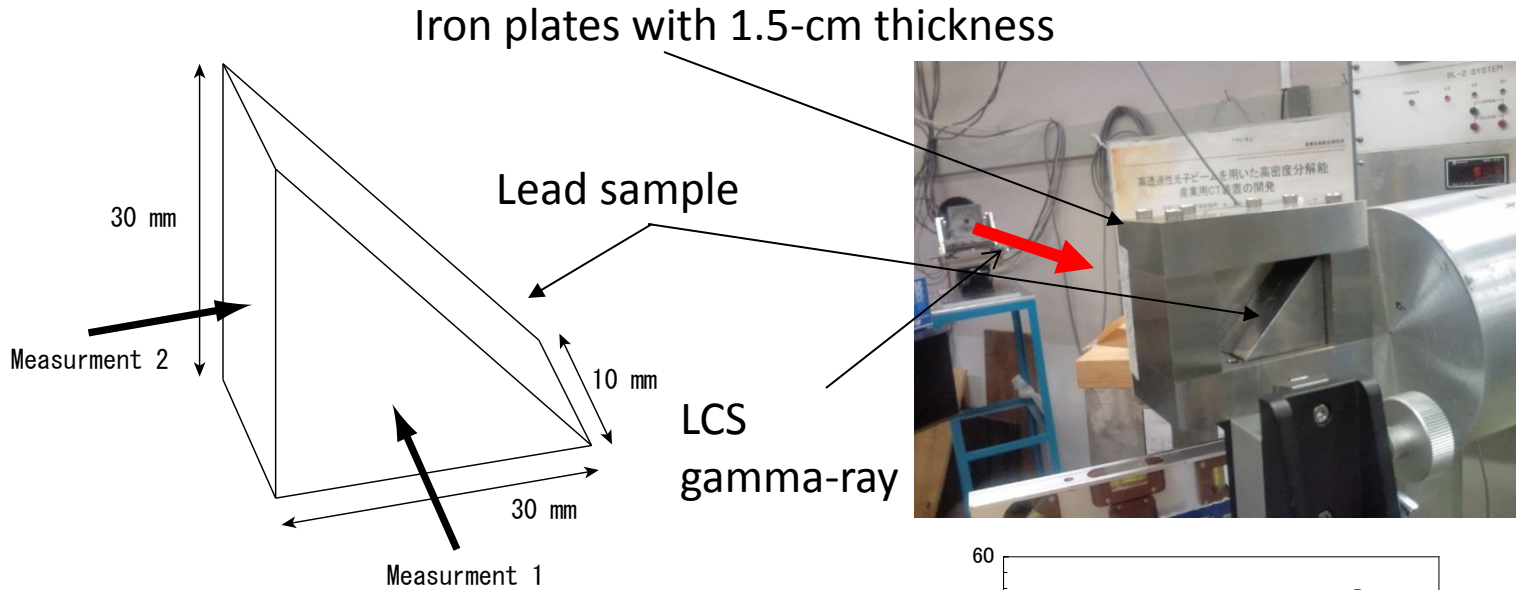


We detected Pb-208 hidden by 15mm iron plate.

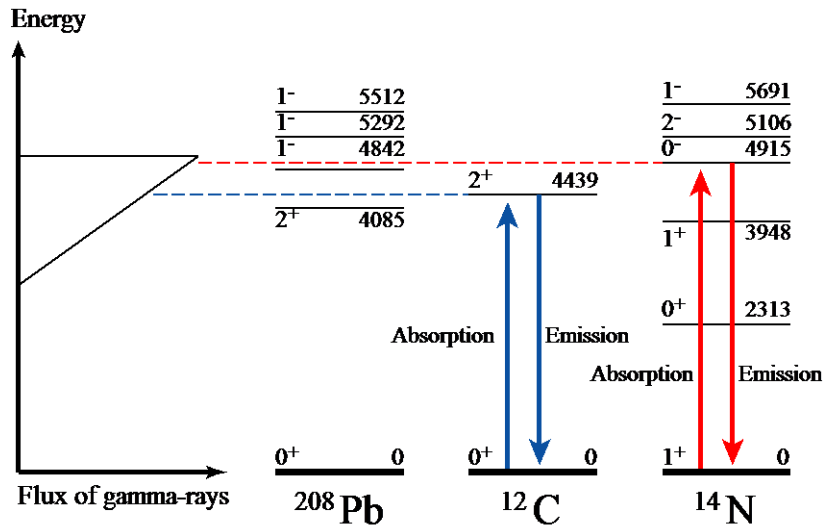


Background at high energy region originated from bremsstrahlung of the electron beam.

Demonstration of 2D-imaging



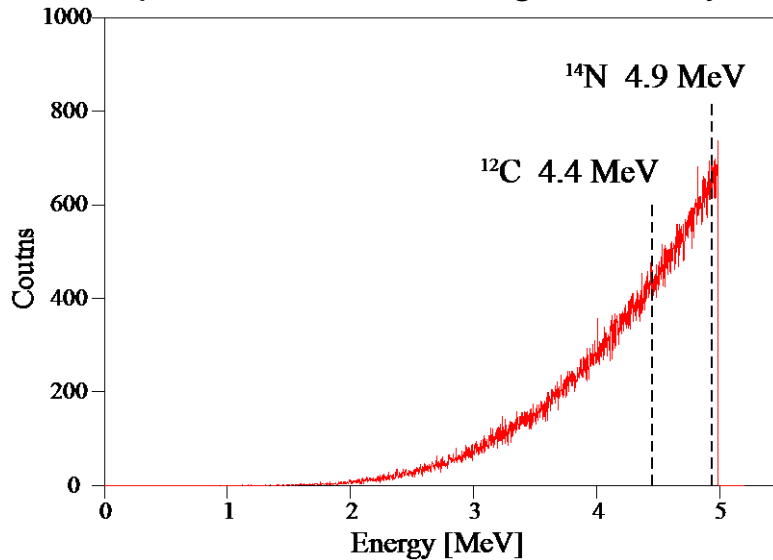
Demonstration of Detection of Two Elements



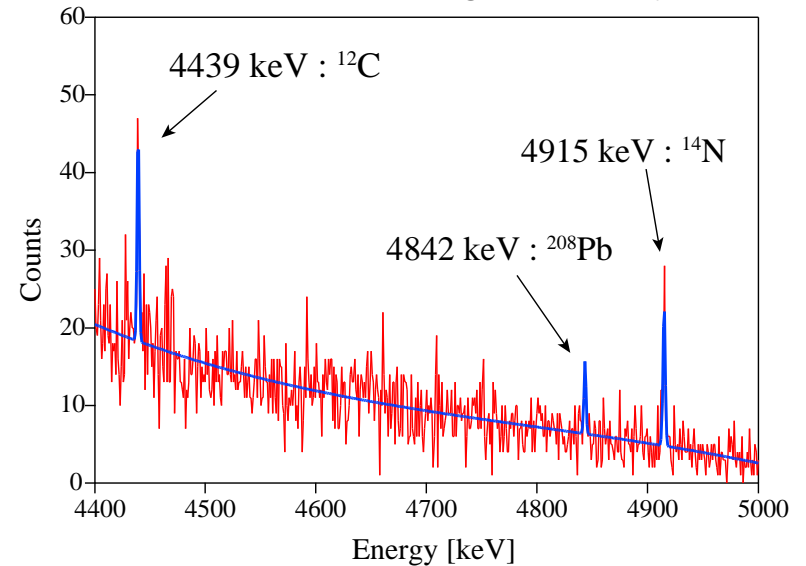
The NRF method can be extended to detect several isotopes at the same time with a selected energy width gamma-rays.

We have demonstrated to detect ^{12}C and ^{14}N of the melamine hidden by 15-mm thickness iron plate.

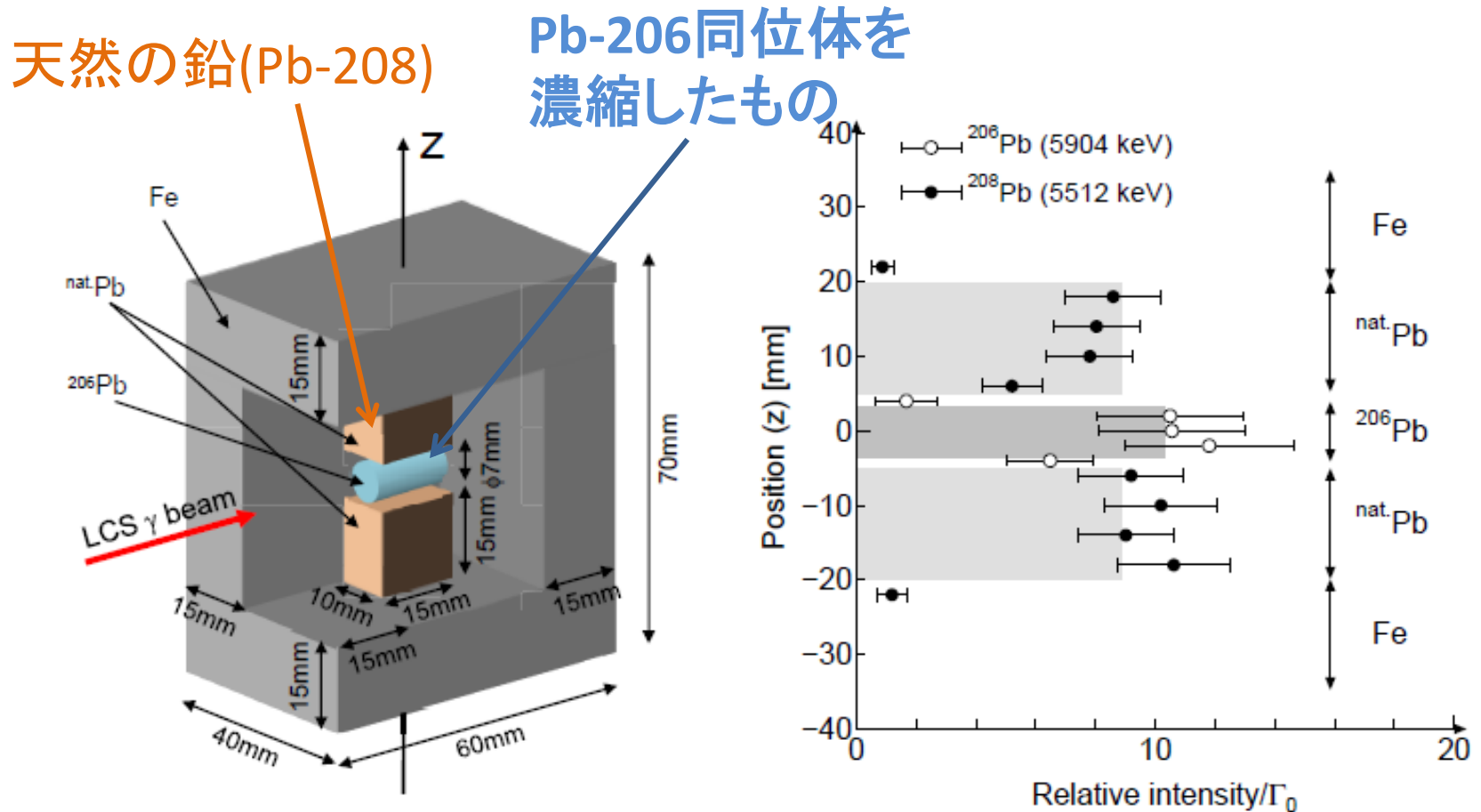
Spectrum of incident gamma-rays



Spectrum of NRF gamma-rays



Pb-206とPb-208の識別



T. Shizuma et al. Rev. Sci. Instr. 83, 015103 (2012).

Background

1. Decay gamma-rays from radioactivities
2. NRF of other materials whose energy is near the NRF energy of Pu-239.
3. Coherent scattering of the incident gamma-rays

Gamma-ray spectra of RI

Y. Lee, J. Korean Nucl. Soc. (1992)

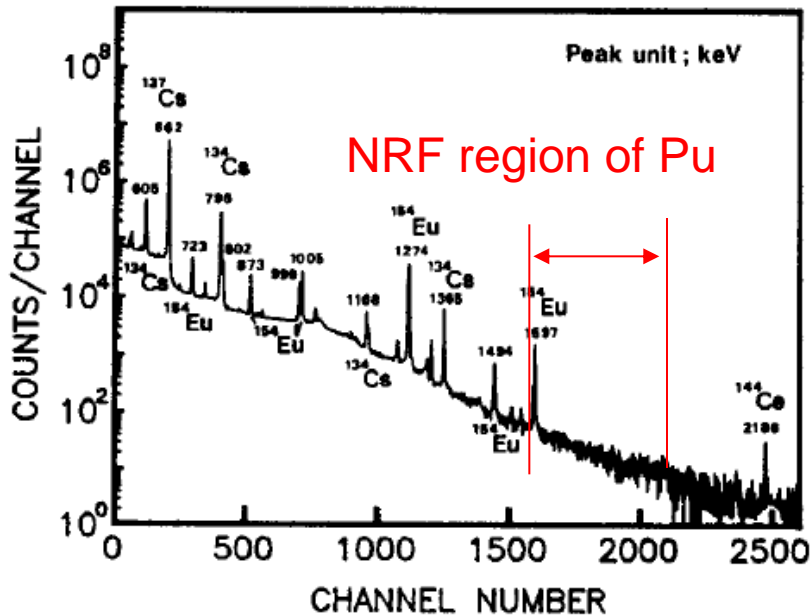


Fig. 2. Gamma-ray Spectrum Obtained from Spent PWR Fuel with a Cooling Time of about 8 Years.

C. Willman, Ann. Nucl. Energy. (2006)

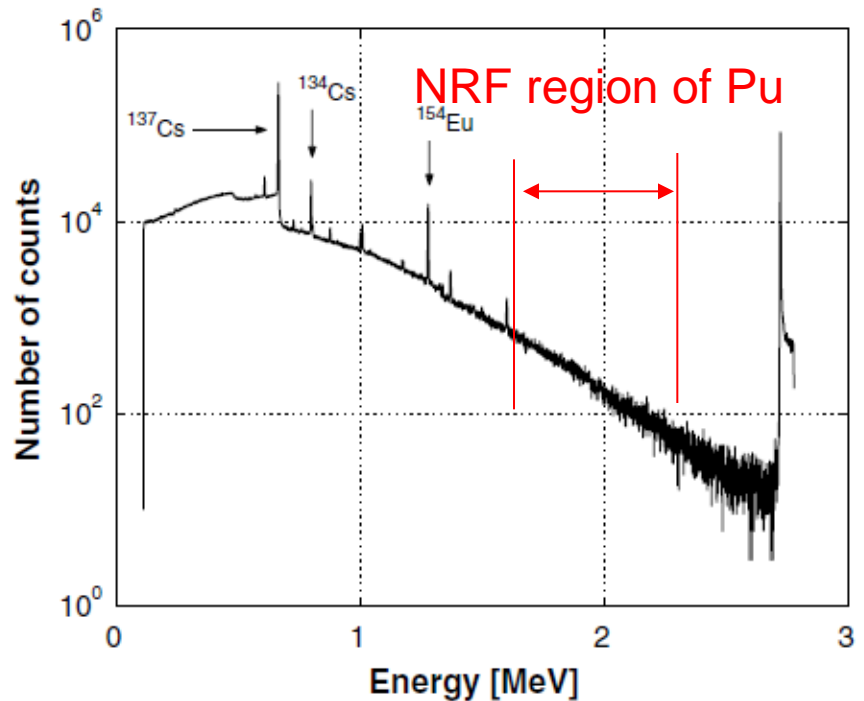


Fig. 6. A typical spectrum of one corner of a fuel assembly with a burnup of 47 GWd/tU and a cooling time of 12 years. The peak around 2.7 MeV is the pulser peak used for dead-time correction.

There is no gamma-rays around 2 MeV

Gamma-rays of other materials

Nd-146 17.2% E2 2143.86 keV
This is not observed in (g,g') experiment.

Kr-85 $T_{1/2}=10.77$ y M1 2144.9 keV $T_{1/2}=0.31$ ps
The energy difference is about 1.3 keV and thus we can distinguish them.

Some gamma-ray may become the background BUT
their abundances in nuclear fuels is rare.

2423.48 keV

Sb-123 42.8% 2423 keV This is not observed by (g,g') experiment.

Nd-145 8.3% E2 2423 keV

This is observed only (d,p) reaction and there is no data for gamma-ray

Sm-144 3.1% E2 2423.21 keV $T_{1/2}=0.037$ ps

This is not produced by beta-decay after fission

Cd-112 24.1% 2424 keV

This is observed only (d,p) reaction and is not observed in (g,g') reaction

Cd-113 12.2% 2424.1 keV

This is observed only (d,p) reaction and is not observed in (g,g') reaction

Ca-42 0.647% E2 2424.17 keV $T_{1/2}=0.14$ ps

The isotopic abundance is only 0.6%

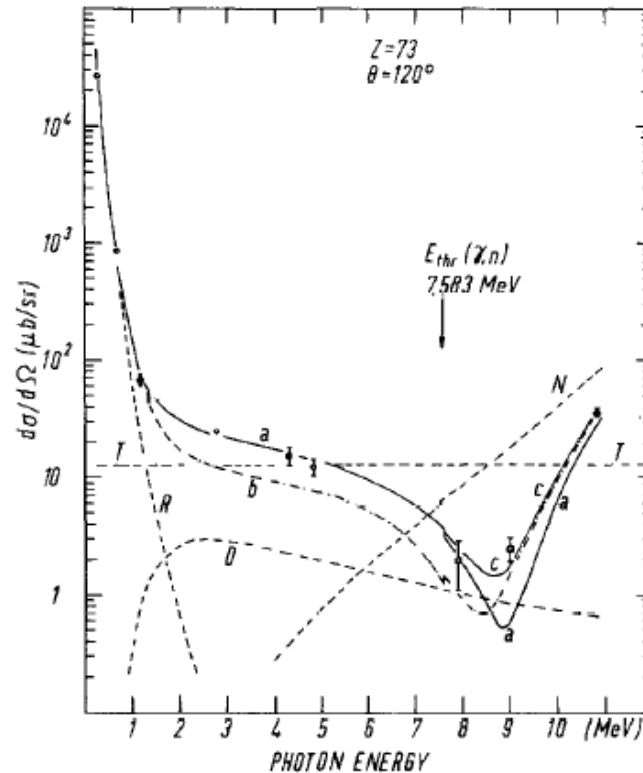
Tc-99 $T_{1/2}=2 \times 10^5$ y 2424.34 keV

This state is only observed high-spin state (Zell, 1983). The spin probably is larger than $J=10$ and this state cannot be populated

Sm-152 22.8% 2425 keV

This is observed only (p,t) reaction and there is no data for gamma-ray

Coherent Scattering gamma-rays



Reighly Scattering

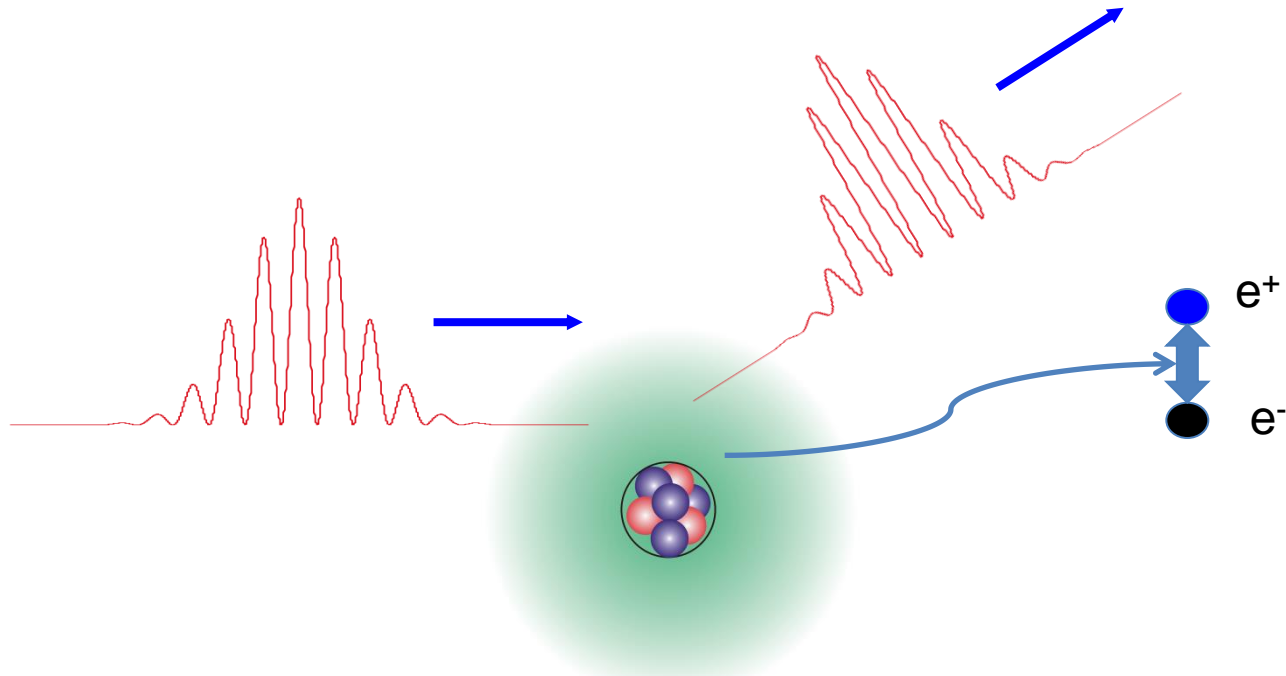
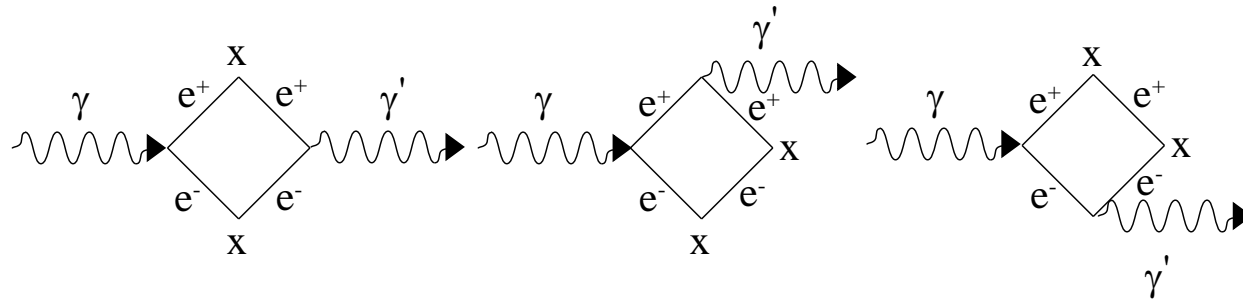
Derbuck scattering

nuclear Tomson Scattering

nuclear resonance scattering

Fig. 4. Differential cross sections for elastic scattering vs photon energy for $Z = 73$. Experimental data: \circ present authors [refs. ^{2,23}] and present work; \bullet P. P. Kane ²²; \square Kahane and Moreh ⁷; \blacktriangle Jackson *et al.* ⁸. Theoretical curves: (a) calculated including Rayleigh (R), nuclear Thomson (T), lowest-order Delbrück (D), and coherent nuclear resonance (N) scattering, (b) calculated including R-, T-, and N-scattering, but excluding D-scattering, (c) calculated including incoherent nuclear resonance scattering in addition to the processes included in curve (a). R, T, D, N differential cross sections calculated for the single processes.

Delbrück scattetring



Scattering Amplitude

We write the total coherent elastic scattering amplitude in the form

$$A = A^R + A^T + A^D + B^D + A^N \quad (1)$$

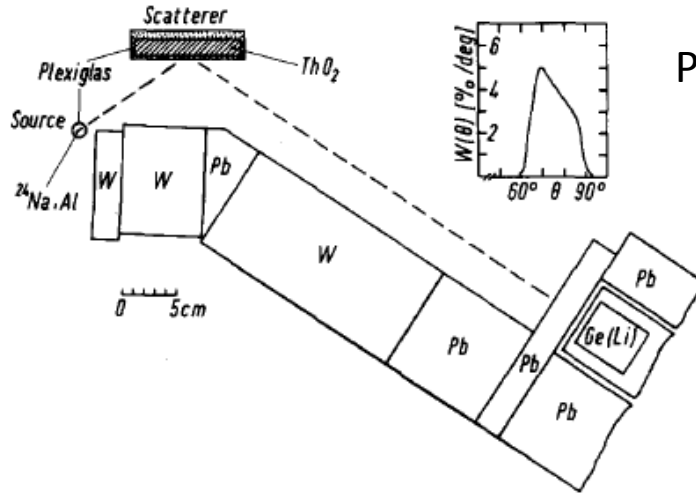
and the differential cross section either as

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} (|A_{\parallel}|^2 + |A_{\perp}|^2) \quad (2)$$

TABLE IX. Scattering amplitudes and differential cross sections for elastic scattering of 2.754 and 3.253 MeV photons from Pb and U through $\theta = 15^\circ$. The notations are the same as in Table IV.

E (MeV)	Z	$A_{R\perp}$ ($10^{-3} r_0$)	$A_{D\perp}$ ($10^{-3} r_0$)	$B_{D\perp}$ ($10^{-3} r_0$)	$A_{T\perp}$ ($10^{-3} r_0$)	$A_{N\perp}$ ($10^{-3} r_0$)	$d\sigma/d\Omega_{LO}$ (mb/sr)	$d\sigma/d\Omega$ (mb/sr)	$d\sigma/d\Omega_{\text{expt}}$ (mb/sr)
2.754	92	$-409.8 + 11.45i$	$171.3 + 87.89i$	$-34.03 + 37.25i$	-18.83	1.833	7.401	9.438	10.00(2.00)
		$-433.8 + 24.11i$	$130.7 + 67.60i$	$-26.46 + 29.57i$	-19.49	1.898			
	82	$-319.8 + 7.016i$	$136.1 + 69.82i$	$-21.48 + 23.51i$	-17.12	1.569	4.514	5.364	4.700(0.700)
		$-339.5 + 14.63i$	$103.8 + 53.71i$	$-16.70 + 18.67i$	-17.72	1.624			
3.253	92	$-289.3 + 7.372i$	$193.5 + 128.0i$	$-60.89 + 37.97i$	-18.83	2.460	3.015	5.180	5.450(0.400)
		$-307.1 + 18.81i$	$144.2 + 93.81i$	$-45.38 + 27.83i$	-19.49	2.547			
	82	$-212.9 + 4.779i$	$153.7 + 101.7i$	$-38.43 + 23.96i$	-17.12	2.281	1.604	2.566	2.486(0.377)
		$-226.1 + 11.61i$	$114.5 + 74.53i$	$-28.64 + 17.56i$	-17.72	2.361			

過去の実験(ドイツグループ)



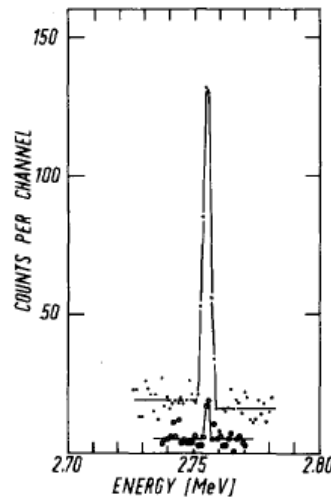
P. Rullhusen, Nucl. Phys. A 313, 307 (1979).

^{24}Na (半減期は15.02時間) 150mCi

500gのTh(酸化物)とBi

76ccの大きさのGe検出器

Fig. 1. Experimental set-up used for the $Z = 90, \theta = 75^\circ, E = 2.754 \text{ MeV}$ experiment. The inset shows the distribution of scattering angles admitted by the geometry.



散乱角度は60、75、90、120度

Fig. 2. Spectra of elastically scattered photons: measured with ThO_2 scatterer (dots), and measured without scatterer (open circles).

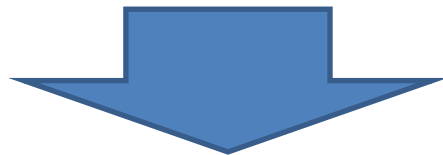
理論研究

レーリー散乱が怪しいため、1980年代以降に研究が進展

P. Papatzacos , Phys. Rev. D. 12, 206 (1975)

the lowest-order Born approximationで
Delbrück散乱

real part とimaginary part が寄与する。imaginary partについては、この時点での実験データをある程度再現できたが、real partについては問題を残していた

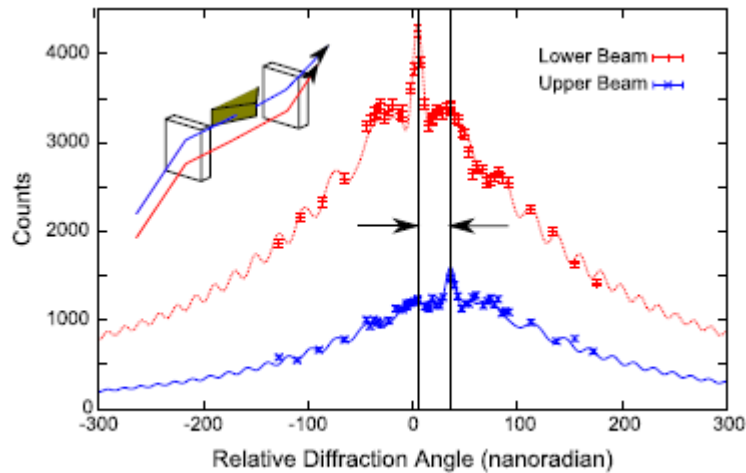


H. Falkenberg, Atom. Nucl. Data Tables 50, 1 (1992).
計算結果をテーブルとしてまとめる

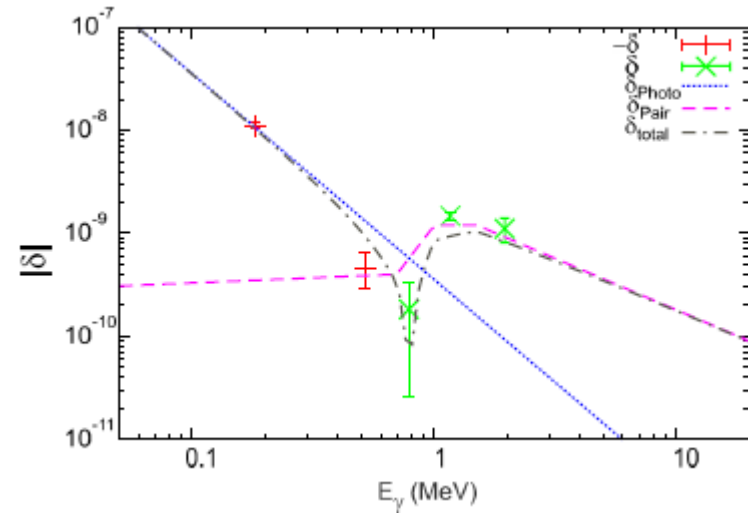
1970年代から本質的な進歩なし！

REVIVAL

D. Habs, Phys. Rev. Lett. 108, 18402 (2012)



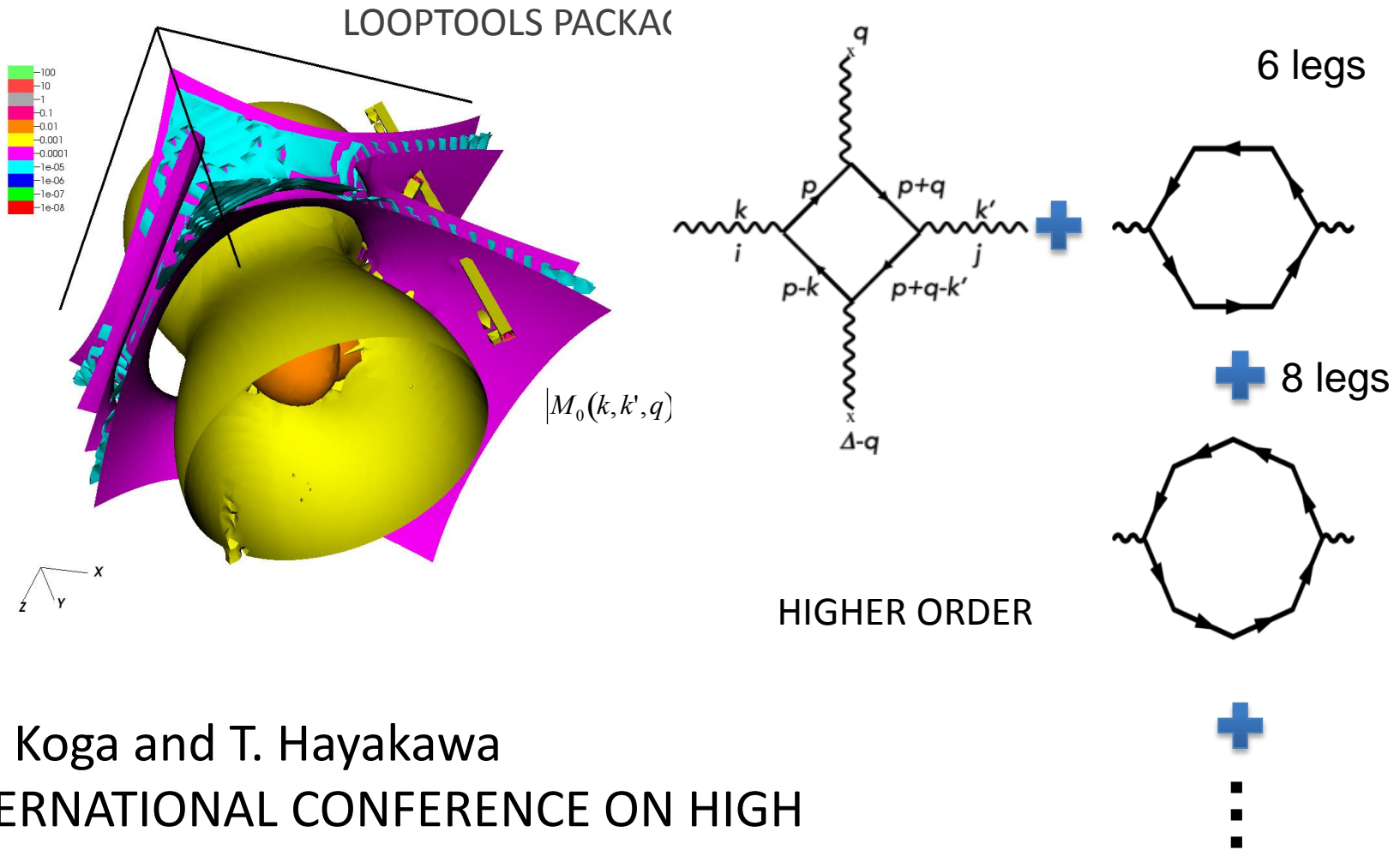
Index of refraction



$$n(E_\gamma) = 1 + \delta(E_\gamma) + i\beta(E_\gamma)$$

High intensity LCS γ -ray sources + γ -ray spectroscopy leads to precision measurement

NEW RESULTS WITH LOOPTOOLS



J. K. Koga and T. Hayakawa
 INTERNATIONAL CONFERENCE ON HIGH
 ENERGY DENSITY SCIENCES 2014, 4/22-
 4/24/2014, Pacifico Yokohama, Japan

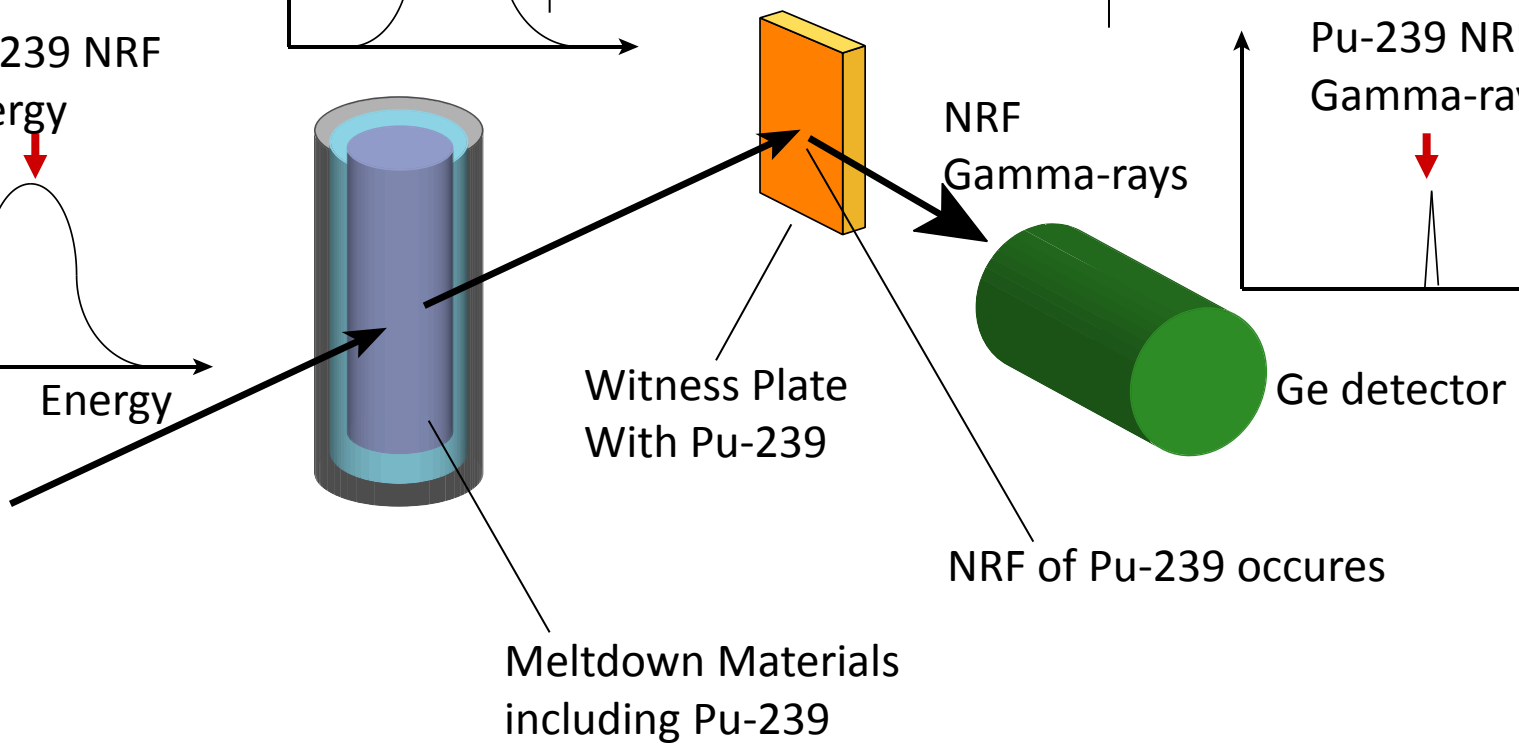
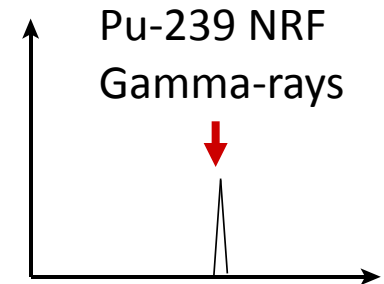
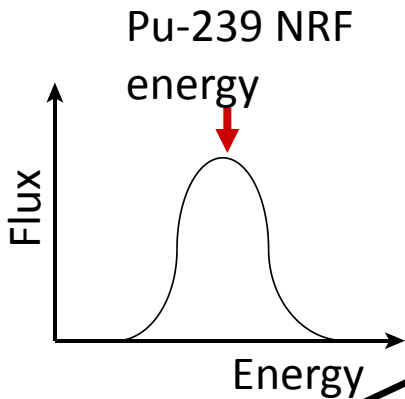
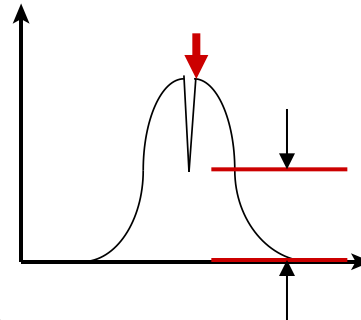
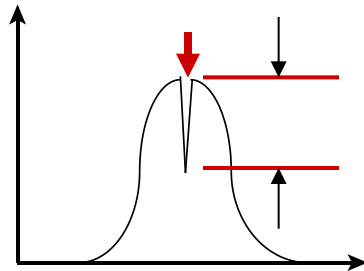
Other Detection methods

Witness Plate method

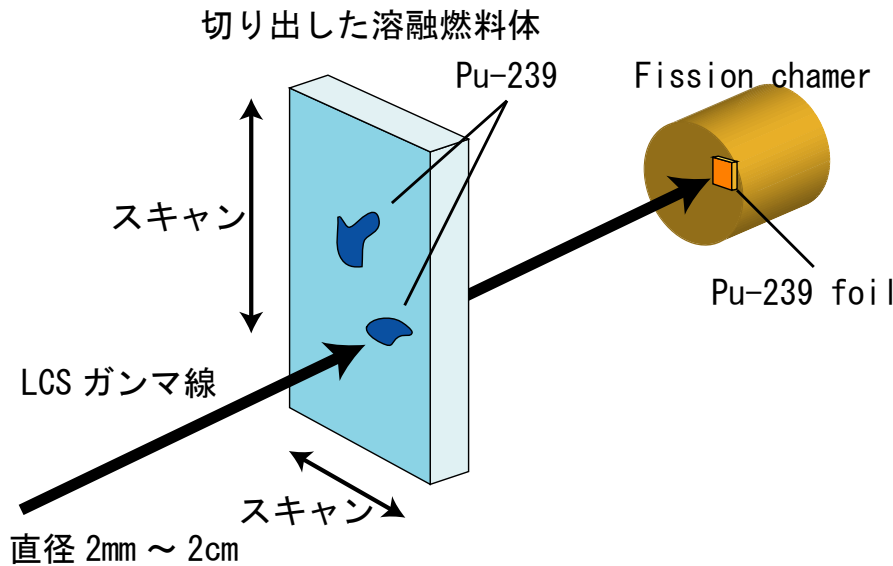
Absorption is proportional to amount of Pu-239

NRF rate is proportional to Amount of flux at Pu-239 energy

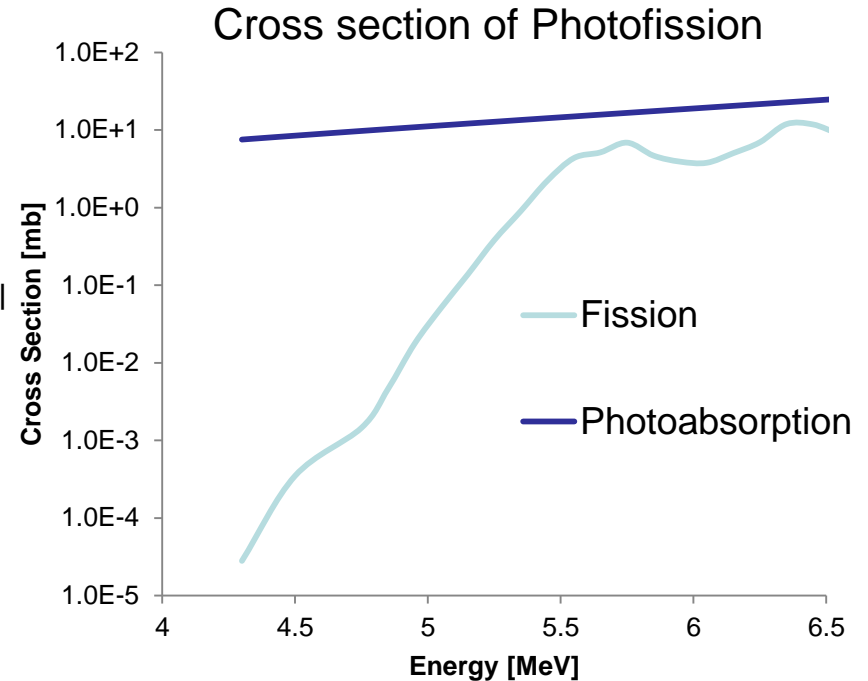
Energy Spectrum of LCS gamma-ray



Photofission



We use about 5 MeV gamma-ray as the probe. We measure the absorption of the target using a fission chamber.



C. Angel et al. to be submitted (2012).

International Symposium

“Nuclear Physics and Gamma-ray sources for Nuclear Security and Nonproliferation”

講演者: 合計46名

口頭発表者: 38名

ポスター発表者: 8名

参加者総数: 63名

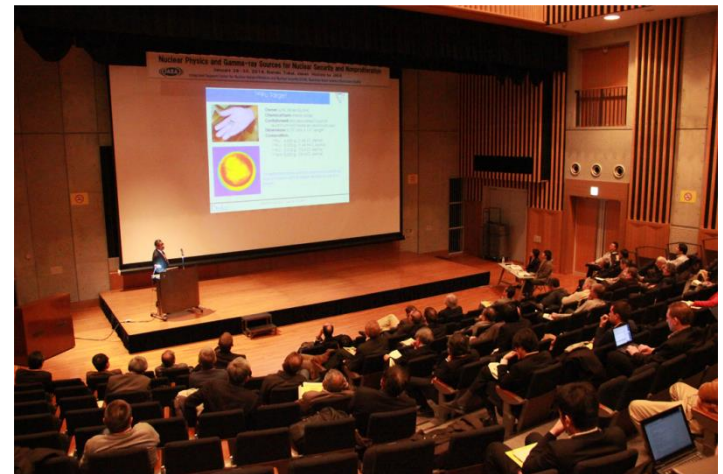
World Scientific社から報告書
を出版予定

企業から3件の講演 Passport System Inc. 東芝(株) 清水建設(株)

旅費、滞在費、参加費は全て自己負担

海外からは約20名が趣旨に賛同してくれ、自己負担での参加

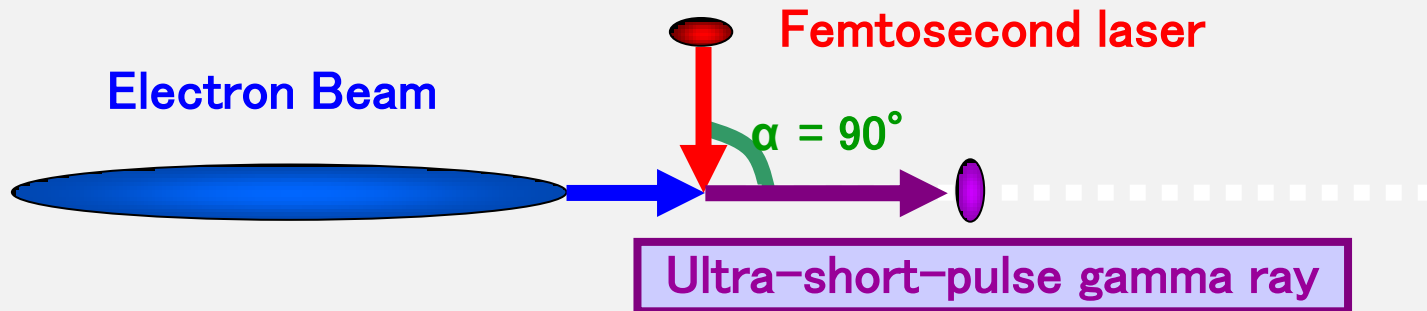
主な参加者の勤務国: アメリカ、フランス、カナダ、ウクライナ、ルーマニア、ドイツ、イギリス、イタリア、ロシア、エジプト、ベトナム



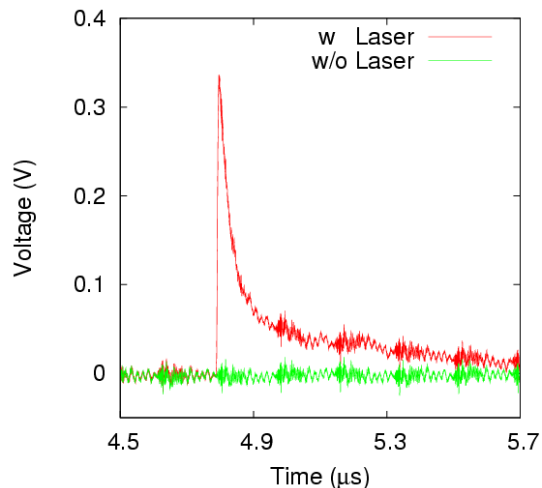
Proposal of New facility

極短(fs)パルスγ線

Vertical collision $\alpha = 90^\circ$



チェレンコフ光による確認



平 義隆 ビーム物理研究会2010

UVSORIIIによる実験

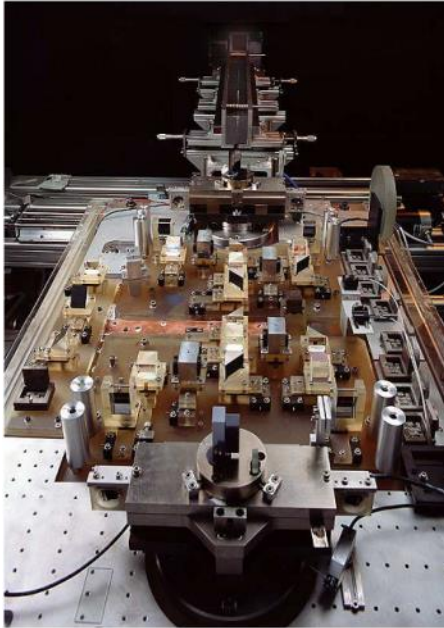
150 fsの幅のLCSγ線を生成可能

Y. Taira, et al., NIMA, A 652 (2011) 696



fsのレーザーを使うことでfsのパルス幅を生成可能

極単色(数十eV)パルスγ線

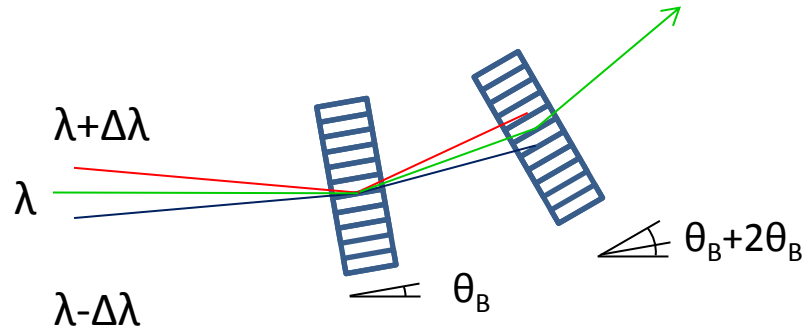


ラウエランジェバン研究所の
ガンマ線分光器
M.Jentschel, ISINN-20

$dE/E \sim 10^{-6}$



γ線分光器を応用して切り出せるはず

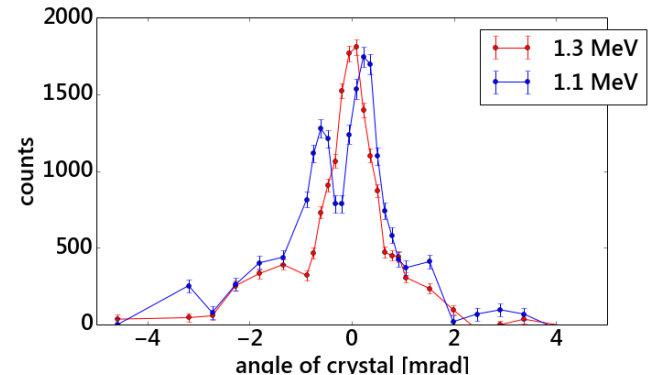


LCSγ線の場合には角度アクセプタンスを広くとれる

60Co照射施設を
使って極単色γ線装
置の基礎研究中

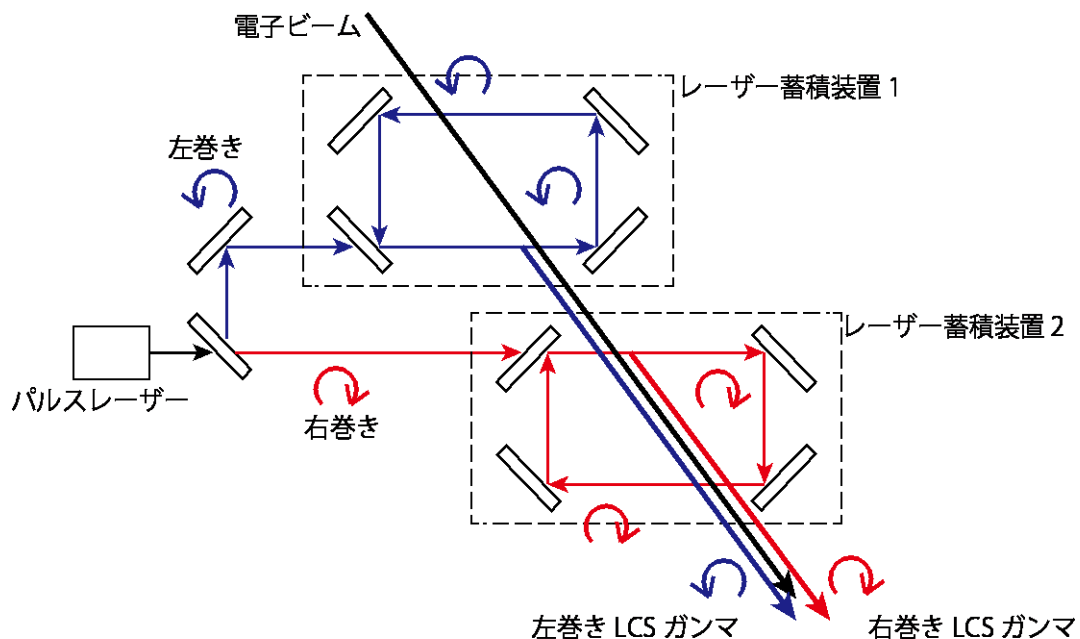
↓
1.1MeVと1.3MeVの2本
のγ線があるので評価
に適している

測定結果



松葉俊哉他、原子力学会2014年春

高速円偏光切り替え γ 線ビーム



2つのレーザー蓄積装置に右巻きと左巻きのレーザーを蓄積する。

交互に電子ビームと衝突させることで、高速に右巻き、左巻きを切り替える

100MHzに切り替え可能

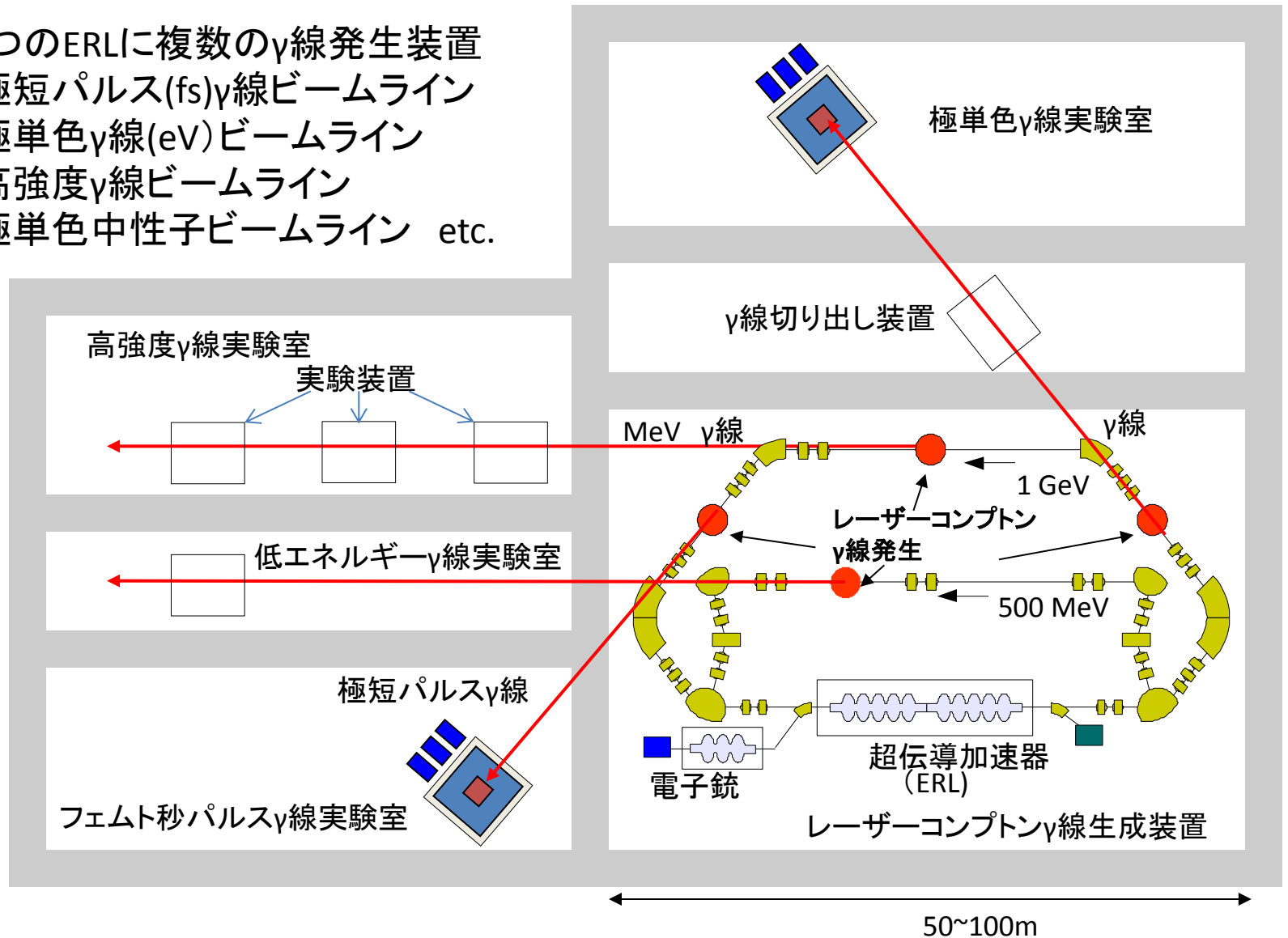
磁気コンプトン散乱による磁性物性の研究
従来は不可能な動的磁性の研究が可能に

パリティの破れの研究
中性ボゾンによるパリティの破れ

「次世代レーザーコンプトン散乱ガンマ線源とその利用」
大垣英明他、京大エネルギー理工学
研究所レポートより

レーザーコンプトン散乱ガンマ線施設イメージ図

一つのERLに複数の γ 線発生装置
極短パルス(fs) γ 線ビームライン
極単色 γ 線(eV)ビームライン
高強度 γ 線ビームライン
極単色中性子ビームライン etc.



京都大学 大垣英明他

ISSN 1342-3185
IAE-RR-2013 No.101



Institute of Advanced Energy
Kyoto University

基礎科学

ローレンス不変性の検証
余剰次元の測定
パリティの破れの測定
シザーズモードの研究

次世代レーザーコンプトン散乱
ガンマ線源とその利用

産業利用

特定元素の γ 線CT
深部陽電子族低法
磁気コンプトン散乱

IAE

福島原発の処理



石棺化

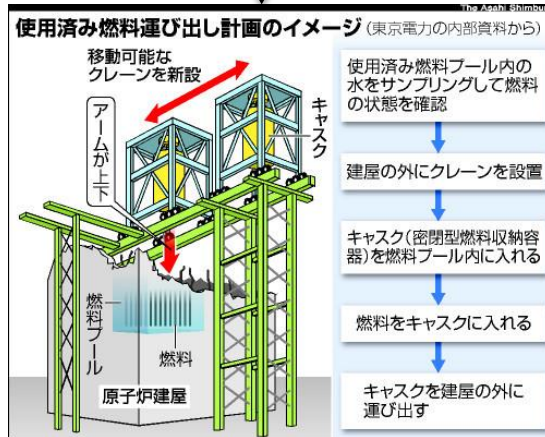


チェルノブイリ

溶融燃料の処理工場(分析、分離)



更地にするには



ピット、トレンチ、地層処分など

asahi.com・ニュース
(2011年4月13日3時2分)

産業への応用

深部陽電子分析法

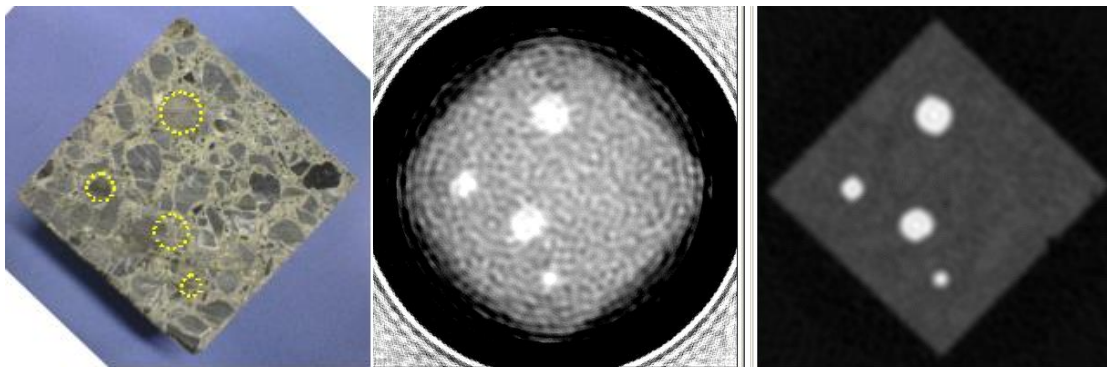


図1 産業技術総合研究所のガンマ線施設（東日本大地震のために施設は閉鎖）において進められていた基礎研究の一部。コンクリート角柱(左)、ガンマ線の対生成陽電子による陽電子消滅CT像(中)、透過ガンマ線CT像(右)。白く見えるのが鉄筋である。

次世代コンプトン散乱ガンマ線源
とその応用より

高速円偏光切り替え磁気コンプトン散乱

100MHzの高速で、右巻きと左巻きの円偏光を切り替えることができる。



磁性物質の動的分析へ

まとめ

2010年以降、2年ごとに核安全保障サミットが開催され、日本も技術開発・教育等で貢献している。

ウラン235等の核物質の非破壊測定技術の開発が世界的に望まれている。

日本では、エネルギー回収型リニアックによるレーザーコンプトン散乱ガンマ線ビームを用いた核共鳴蛍光散乱による測定技術を提案し、原理実証機をKEKで開発中である。

実機を、港湾や空港に設置して海外から密輸出入する核物質を非破壊測定することが可能である。

実機は、 10^{13} photon/sの強度が可能であり、極短パルス(fs)モード、極単色(eV)モード、高速円偏光切り替えビームなどのバリエーションが可能である。

将来、MeV領域のガンマ線装置が開発されたら、基礎科学や産業応用などにも貢献する。