**Paper Number:** IAEA-CN-184/65

**Paper Title**

# Needs of Advanced Safeguards Technologies for Future Nuclear Fuel Cycle (FNFC) Facilities and a Trial Application of SBD Concept to Facility Design of a Hypothetical FNFC Facility

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## Abstract.

Some of **f**uture **n**uclear **f**uel **c**ycle (FNFC) facilities are supposed to have the characteristic features of very large throughput of plutonium, low decontamination reprocessing (no purification process; existence of certain amount of **f**ission **p**roducts (FP) in all process material), full **m**inor **a**ctinides (MA) recycle, and treatment of MOX with FP and MA in fuel fabrication. In addition, the following international safeguards requirements have to be taken into account for safeguards approaches of the FNFC facilities.
-Application of **i**ntegrated **s**afeguards (IS) approach
-Remote (unattended) verification
- "**S**afeguards **b**y **D**esign" (SBD) concept
These features and requirements compel us to develop advanced technologies, which are not emerged yet. In order to realize the SBD, facility designers have to know important parts of design information on advanced safeguards systems before starting the facility design. The SBD concept requires not only early start of R&D of advanced safeguards technologies (before starting preliminary design of the facility) but also interaction steps between researchers working on safeguards systems and nuclear facility designers. The interaction steps are follows. Step-1; researchers show images of advanced safeguards systems to facility designers based on their research. Step-2; facility designers take important design information on safeguards systems into process systems of demonstration (or test) facility. Step-3; demonstration and improvement of both systems based on the conceptual design. Step-4; Construction of a FNFC facility with the advanced safeguards systems
We present a trial application of the SBD concept to a hypothetical FNFC facility with an advanced hybrid K-edge densitometer and a Pu NDA system for spent nuclear fuel assembly using laser Compton scattering (LCS) X-rays and $\gamma$-rays and other advanced safeguards systems.

## 1. Introduction / Needs of advanced safeguards technologies for FNFC facilities

Some of FNFC facilities presently under study have the following characteristic features;

(1) Very large throughput of plutonium,
(2) Low decontamination reprocessing (No purification process),
(3) Full minor actinides (MAs) recycle,
(4) Treatment of MOX with fission products (FPs) and MAs in fuel fabrication.

In addition, the following requirements to the FNFC facilities for implementation of international safeguards are in prospect;

(1) Application of integrated safeguards (IS) approach,
  (Random interim inspections (RII) based on operator's frequent declarations),
(2) Application of "Safeguards by Design" (SBD),
(3) Further improvement of shipper/receiver difference (SRD) of reprocessing facilities.

Above mentioned characteristic features and requirements inspire us to new challenges in safeguards of the

FNFC facilities, and we need to develop advanced technologies not only for operator's material accounting and also for safeguards inspection of FNFC facilities [1]. Here we summarize the required issues and needs of advanced safeguards technologies for the FNFC facilities in Table 1.

Table 1. Safeguards issues and advanced safeguards technologies for FNFC facilities.

| characteristic features / requirements | | | challenges and needs of advanced technologies |
|---|---|---|---|
| characteristic features | (1) | Very large throughput of plutonium | Very fast accumulation of uncertainty of Pu quantity (i.e. need of very short interval of MUF（Material Un-accounted For）evaluation (a few days in very large throughput case))<br>→**Speedy measurement and analysis of Pu** |
| | (2) | Low decontamination reprocessing<br>(No purification process) | Pu is always accompanied by FPs and MAs.<br>Existence of FPs; making γ-ray spectroscopy for Pu isotopic compositions difficult (or impossible).<br>Existence of MAs; very strong neutron emissions from $^{244}$Cm makes neutron coincidence counting of Pu difficult (or impossible).<br>→**Alternative (or improved) NDA technologies to Pu NDA with γ-ray spectroscopy and neutron coincidence counting.** |
| | (3) | Full minor actinides (MAs) recycle | |
| | (4) | MOX fabrication with FPs and MAs in fuel | |
| prospected requirements | (1) | Application of IS approach | Frequent declarations of Pu of FNFC facilities with very short interval of MUF evaluation<br>→**Speedy measurement and analysis of Pu.** |
| | (2) | Application of SBD | Advanced safeguards systems need to be incorporated into designs of FNFC facilities.<br>→**Early realization of advanced safeguards and material accountancy systems for FNFC facilities.** |
| | (3) | Further improvement of SRD of reprocessing facilities | Direct measurement of Pu in spent fuel assemblies instead of burn-up calculations (see below).<br>→**New NDA technologies for direct measurement of Pu in spent fuel assemblies.** |

Table 1. shows that the following technologies are to be developed for safeguards and material accountancy of FNFC facilities,

1. Speedy measurement and analysis of Pu,
2. Alternative (or improved) NDA technologies to Pu-NDA with γ-ray spectroscopy and neutron coincidence counting,
3. New NDA technologies for direct measurement of Pu in spent fuel assemblies.

In section 2, we show some portion of the above needs can be covered by development of advanced technologies using laser Compton scattering (LCS) X/γ -ray sources (The LCS is a phenomenon of laser photons scattering by accelerated electrons.). These advanced technologies are needed to be realized in early stage for operator's incorporation of advanced safeguards systems into designs of FNFC facilities (for application of SBD concept). In section 3, we show an idea for deploying the advanced safeguards systems in a hypothetical FNFC facility.

## 2. Proposal of advanced safeguards technologies for FNFC facilities

### *2.1 Proposal of Pu-NDA systems using LCS X/γ-ray sources*

For analysis of nuclear material, X/γ-rays have been used as interrogation probes for a long time. These X/γ-rays with widely spread energy distribution are generated mainly by bremsstrahlung. However, along with progresses of energy recovery linac (ERL) technologies for high-energy, high-current electron, the new era that mono-energetic (monochromatic), energy-tunable, very high-intensity X/γ-rays can be generated on our demand by using LCS technologies has come. The characteristic features of above LCS X/γ-rays and advantages for measurement are summarized in Table 2. Here we propose to use LCSX/γ-ray sources for speedy measurement and new NDA for Pu and MAs.

Table 2. Characteristic features of LCS X/γ-rays and advantages for measurement.

| characteristic features | advantages for measurement |
|---|---|
| Mono-energetic (Monochromatic) | Interrogation within pin-point energy region<br>-Avoiding unnecessary excitation or absorption<br>-Useful for reduction of BGs and obtaining higher accuracy |
| Energy tunability | Interrogation with the tuned energies for the targets<br>-Successive and/or simultaneous measurements of targets<br>(-Making measurements easy and fast) |
| Very high intensity | Interrogation with very high intensity<br>-Higher probabilities of reactions to be interrogated<br>(-Making measurements faster with higher accuracy even for measurements of low concentration elements) |
| Good penetrability （for γ-rays with MeV class energy） | Deep penetration into heavy material reaching to the target isotopes<br>(-Making non-destructive assay of nuclear material in fuel assemblies / wastes possible) |
| Good directivity | Emission of LCS X /γ-rays within very limited direction<br>(-Giving measurements freedom for target distance from the source) |

Utilizing the above characteristic features and advantages, we introduce the following two advanced systems using LCS X/γ-ray source (explained in subsections 2.2 ‐ 2.4).

**AT1 Hybrid-K-edge (HKED) densitometry system using mono-energetic X-ray（A-HKED system)** for the technology 1.

**AT2 Pu-NDA system using LCS γ-ray and NRF reaction (LCSγ・NRF Pu-NDA system)** for the technologies 2 and 3.

AT1 is the advanced hybrid K-edge (A-HKED) densitometry system for measuring concentrations of U, Pu and MAs in solution with ~150 keV X-ray generated by using 85 MeV electrons. AT2 is the Pu-NDA system for direct measurement of Pu in spent fuels and high active wastes using nuclear resonance fluorescence (NRF) reaction with 1 ~ 3 MeV γ-rays produced by collisions of laser and 350 MeV electrons.

### *2.2 LCS mono-energetic X/γ-ray source based on energy recovery linac (ERL)*

Energy-tunable mono-energetic (monochromatic) X/γ-ray can be generated by laser Compton scattering (LCS), which is laser-photon scattering by high-energy electron as shown in Fig. 1. The energy of scattered X/γ-ray photons, $E_X$, is expressed as a function of incident photon energy, $E_L=hc/\lambda$, electron's Lorentz factor $\gamma = E_e/mc^2$, and scattering geometry, and approximated for a head-on collision by:

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

This equation shows that the X/γ-ray energy depends on the scattered angle. Thus, monochromatic X/γ-ray can be obtained by putting a collimator to restrict the X/γ-ray divergence at the downstream.

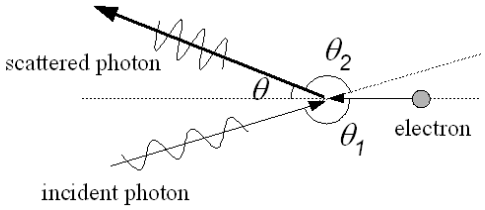
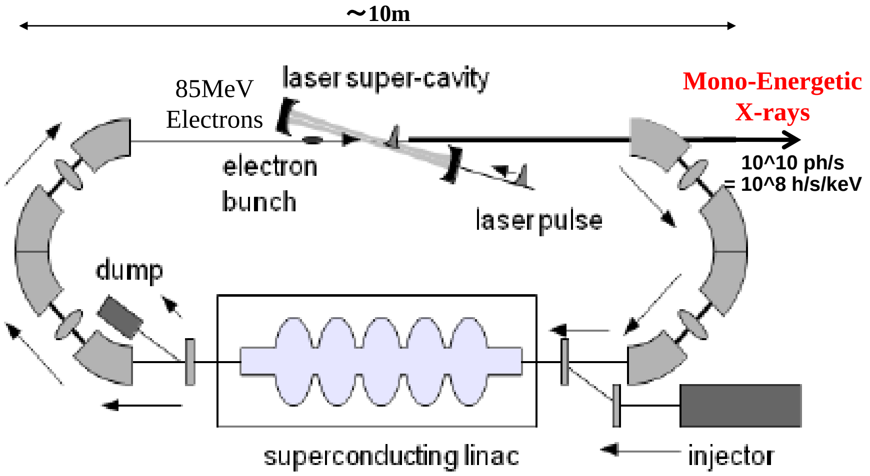


Figure 1. A schematic view of laser Compton scattering.

An X-ray beam of 100-150 keV for HKED is available from a 1 μm laser and an 85 MeV electron beam (Fig. 2(a) and Fig. 2(b).) and a γ-ray beam of 1-3 MeV for NRF application is obtained from a 0.5-1 μm laser and a 350 MeV electron beam (Fig.3(a) and Fig.3(b).). The flux of LCS X/γ-rays is proportional to a product of photon density and electron density at the collision. Thus, a tightly-focused, i.e. small-emittance, and high-current electron beam is necessary for high-flux LCS X/γ-rays.



ERL: Energy Recovering Linac
Acceleration / Deceleration
( for producing high-quality, high-intensity electron beams)

Figure 2(a). A laser Compton scattering X-ray (100-150keV) source based on an ERL [2] .

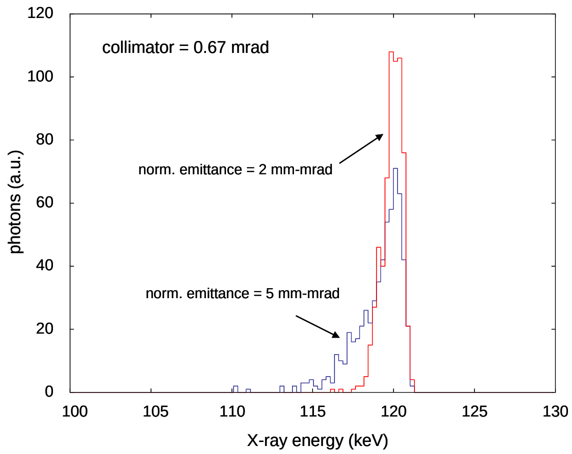
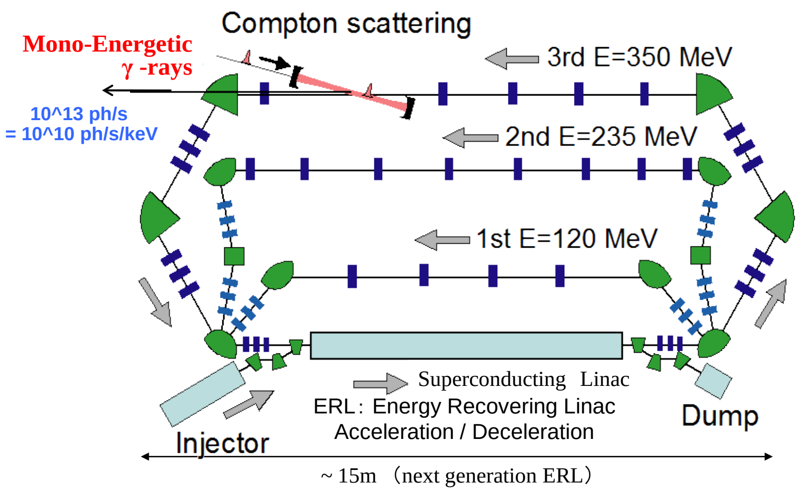


Figure2(b). An example of calculated energy spectrum of LCS X-rays.



(ERL; for producing high-quality, high-intensity electron beams)

Figure 3(a). A laser Compton scattering γ-ray (1-3 MeV) source based on an ERL [3].

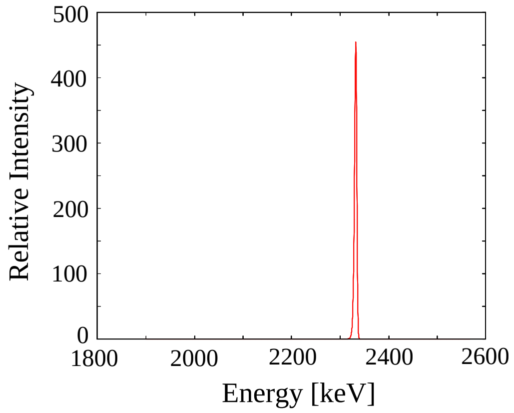


Figure 3(b). An example of calculated energy spectrum of LCS γ-rays.

The ERL accelerator is a novel type of accelerator to generate a high-quality and high-intensity electron beam. An electron beam from an injector (up to 2 MeV) is accelerated up to 85 MeV by time-varying rf field stored in a superconducting linear accelerator, and the beam is transported to a recirculation loop for the LCS X-ray generation. After the recirculation, the electron beam is injected again to the superconducting accelerator so that the electrons are decelerated. This deceleration can be accomplished by putting the electrons at the opposite phase to the acceleration. The energy of accelerated electrons is, thus, converted back into rf energy and is recycled to accelerate succeeding electrons. In an ERL equipped with a small-emittance injector, it is possible to accelerate an electron beam with a small-emittance and high-average current.

ERL-based LCS X/γ-ray sources show outstanding performance when it is equipped with a laser super-cavity for the colliding laser. The super-cavity consists of mirrors with high reflectivity, and optical pulses from an external mode-locked laser are stacked in the super-cavity to be a high-average power. Super-cavities having an enhancement factor of $10^3$-$10^4$ are under development. In the Compton scattering, only a small fraction of electrons and photons contributes to the generation of high-energy photons, because the cross section of Compton scattering is very small. Thus, recycling of electrons and photons unused for the Compton scattering is essential to obtain a high-flux LCS X/γ-ray source. The combination of an ERL and a laser super-cavity is an ideal device for such recycling of electrons and photons.

### *2.3 Advanced HKED (A-HKED) system*

A hybrid K-edge method (HKED) has been used for measuring concentrations of U and other actinide in solutions used in nuclear recycle plants. The concentrations are measured by transmission of X-rays with energies around the K-edge and X-ray fluorescence (XRF). Bremsstrahlung X-rays from X-tubes have been used as the X-ray source. Since the energy spread of bremsstrahlung X-rays is wide, the sensitivity for measuring low concentration elements is low. We have proposed an advanced hybrid K-edge method (A-HKED) using a monochromatic X-ray beam generated by the Compton scattering [2]. With the high flux monochromatic X-ray beams, we can measure the concentration of Pu in solutions faster than those available in the presently existing HKED systems. A new accelerator is a key technology to obtain a high-flux LCS X-ray beam. We have proposed an energy-recovery linac (ERL) to generate such a X-ray beam as shown in Fig. 4.

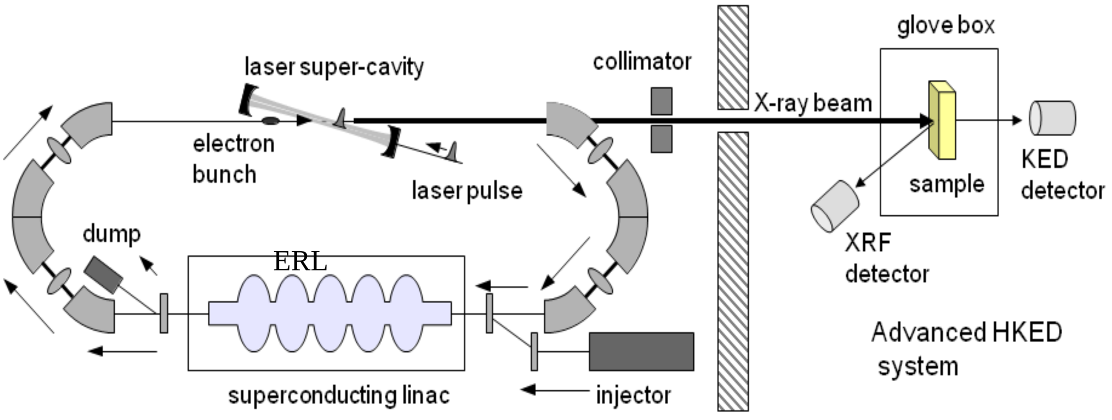
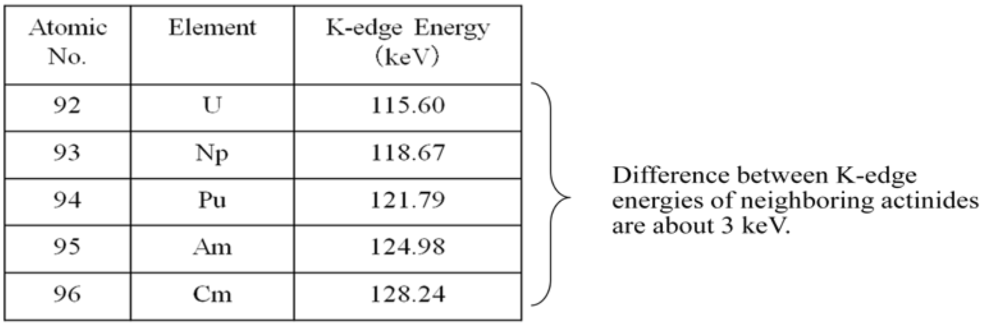


Figure 4. An advanced hybrid K-edge densitometry system using mono-energetic X-ray source.

Utilizing an ERL and a laser super-cavity, we can build a high-flux X-ray source for HKED, which has spectral intensity of $10^7$-$10^8$/s/keV at 100-150 keV. The X-ray beam with a 1% energy spread is transported to the HKED system to measure U, Pu and MA concentrations in solution samples. Table 3 shows K-edge energies of actinide elements, indicating that the differences between K-edge energies of neighbouring actinides are about 3 keV.

Table 3. K-edge energies of actinides



| Atomic No. | Element | K-edge Energy (keV) |
|---|---|---|
| 92 | U | 115.60 |
| 93 | Np | 118.67 |
| 94 | Pu | 121.79 |
| 95 | Am | 124.98 |
| 96 | Cm | 128.24 |

Difference between K-edge energies of neighboring actinides are about 3 keV.

With monochromatic LCS X-rays with a 1% energy spread, we are able to measure Pu concentration in solution by K-edge absorption method using two different X-rays (for an example, 120.6 keV and 123.0 keV) sandwiching Pu K-edge energy (121.79keV) as shown in Fig. 5. Simulation calculations with EGS5 of K-edge absorptions (Fig. 6(a)) and XRF reactions (Fig. 6(b)) of injected mono-energetic X-rays show a possibility of speedy measurement of Pu in solution and also a possibility of measurement of Np concentration (Fig. 6(c)), which is the lowest concentration among the actinides in the fast reactor cycle.

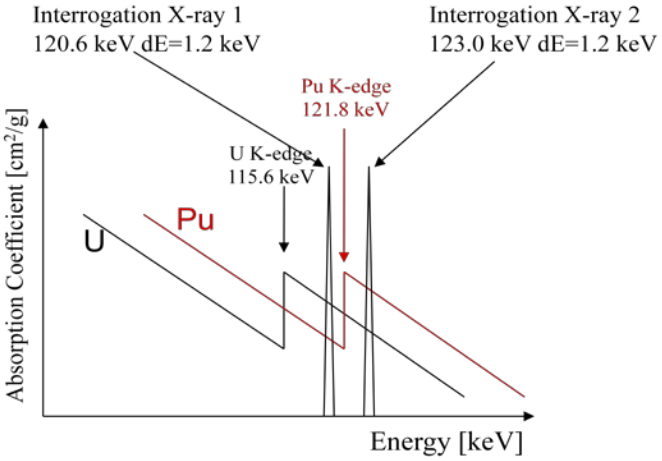


Figure 5. Interrogation of 2 X-rays between Pu K-edge energy.

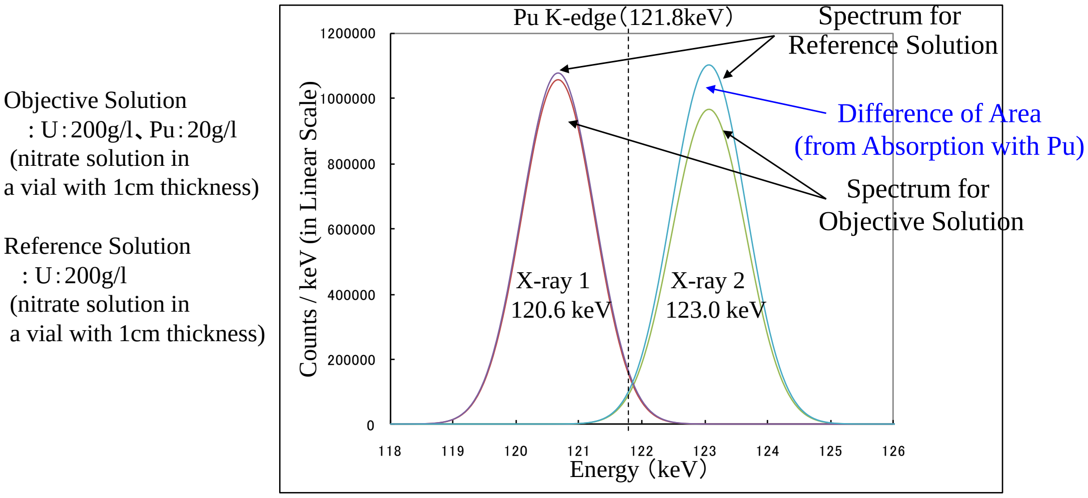
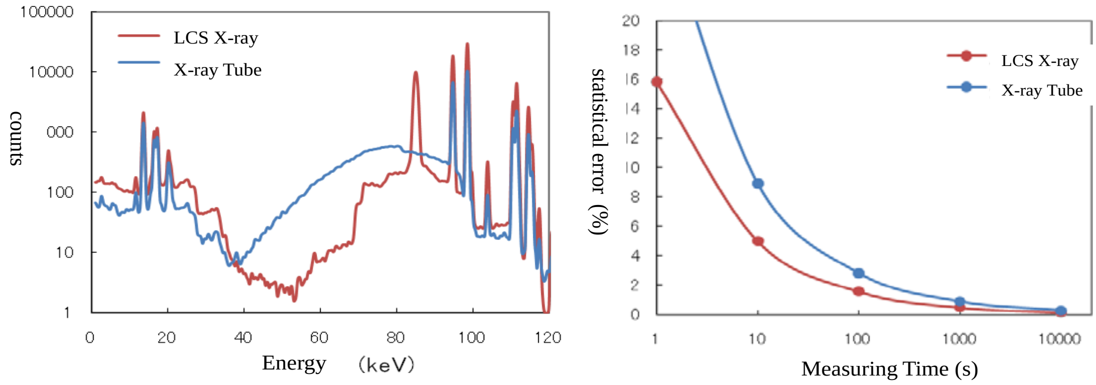


Figure 6(a). Result of simulation calculations for Pu K-edge absorption with two X-rays with different energies.

3N $HNO_3$ Solution; U 200g/L、Pu 2g/L

LCS X-ray ; monochromatic (120 keV, Gaussian (FWHM= 1%))
X-ray tube ; continuous (110 keV, Gaussian (FWHM=55%))

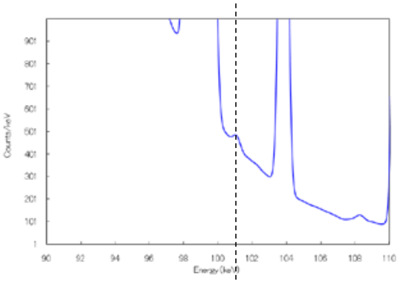


Large reduction of backgrounds by using LCS X-rays contributes improvement of P/B ratio and P/T ratio. [ P/B : peak-to-background, P/T : peak-to-total ]

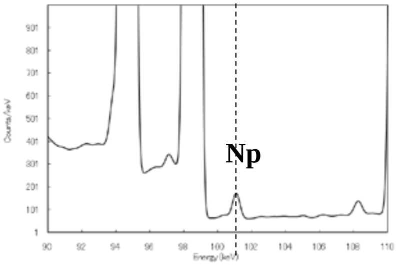
Ge detector ; 200mm$^2$ × 10mm (100mm from the target, scattering angle 150 degrees)
; FWHM 0.6keV@100keV

Figure 6(b). Results of simulation calculations for XRF of Pu/U solution.

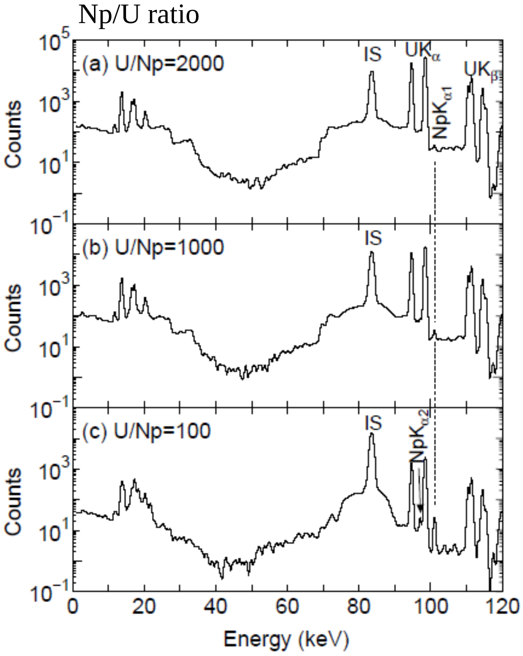
X-ray tube case



LCSX-ray case with
interrogation X-rays of 121keV



Np/U ratio



121keV X-rays are not absorbed by Pu
which makes BGs around 100 keV area
low. This is an advantage of Np measurement.

Np: 0.1g/l
Pu: 20g/l

U: 10-200g/l

Figure 6(c). Result of simulation calculations for XRF of Np in solution.

### *2.4 LCSγ ・NRF Pu-NDA system*

Using the same machine configuration as the X-ray source for HKED, we can construct a γ-ray source for an NRF Pu-NDA system (LCSγ･NRF Pu-NDA system). The NRF method for measuring specific isotope (for example $^{239}$Pu) is shown in Fig. 7.

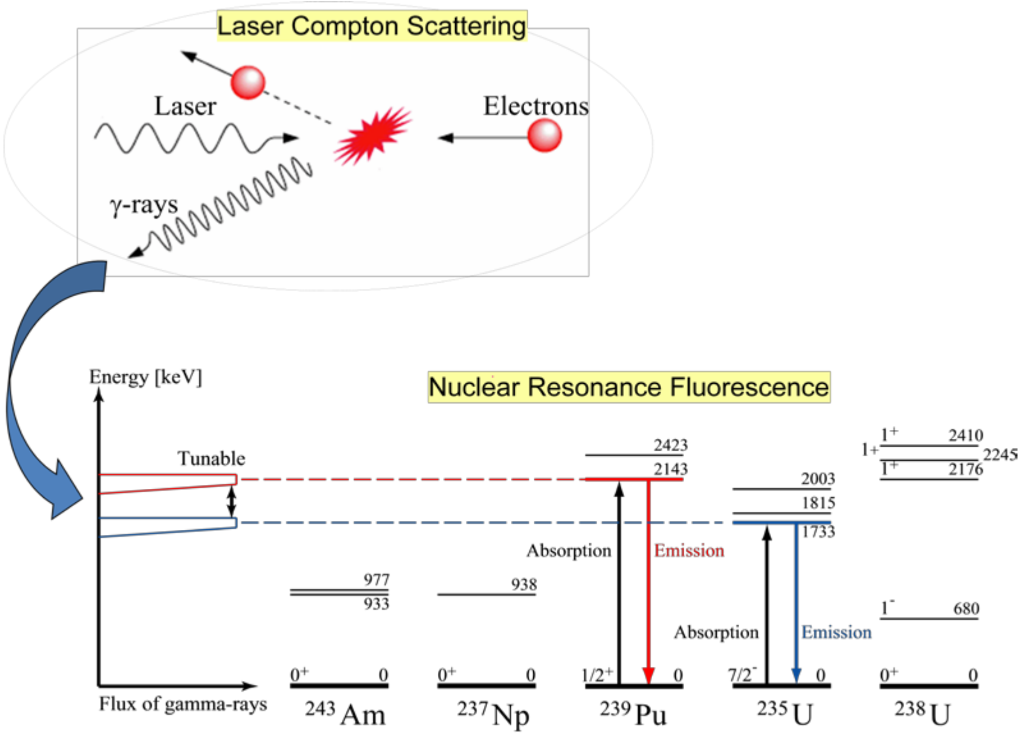


Figure 7. Explanation of NRF method for measuring $^{239}$Pu using 2.143 MeV LCS γ -ray.

The γ-ray source under proposal consists of a 350-MeV ERL and a laser super-cavity as shown in Fig. 8(a). In order to save a footprint of the ERL, we adopt a multi-loop design, in which an electron beam is accelerated three times by a superconducting linac. The spectral intensity of ~$10^{10}$/s/keV at 1-3 MeV will be obtained with parameters of ERL and laser available in near future (in 3-5 years) [4]. The flux of the ERL γ-ray source exceeds that of existing facilities by 6-8 orders of magnitude. The γ-ray is transported to a measurement area of the NRF Pu-NDA system. By injecting γ-rays with a specific resonance energy (for an example, 2.143 MeV of $^{239}$Pu) produced by this source on to spent fuel assemblies, and by detecting NRF γ-rays from $^{239}$Pu in the spent fuel assemblies, we are able to measure Pu in the spent fuel assemblies. Because of strong penetrability into material of 2 MeV γ-rays, we can measure Pu in spent fuel assemblies in water as shown in Fig. 8(b) [3].

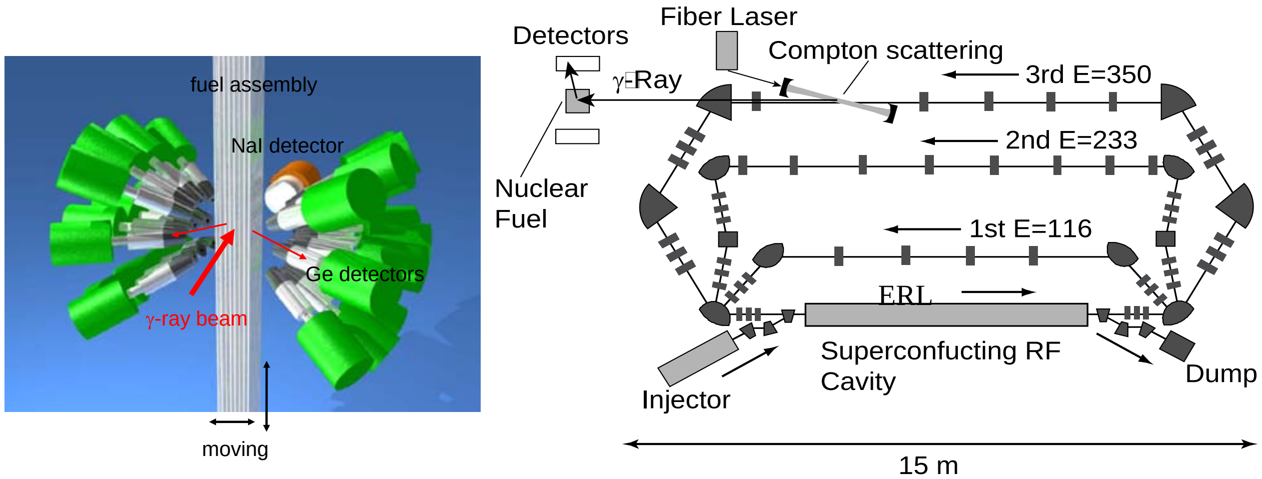


Figure 8(a). A LCSγ・NRF Pu-NDA system of spent fuel.

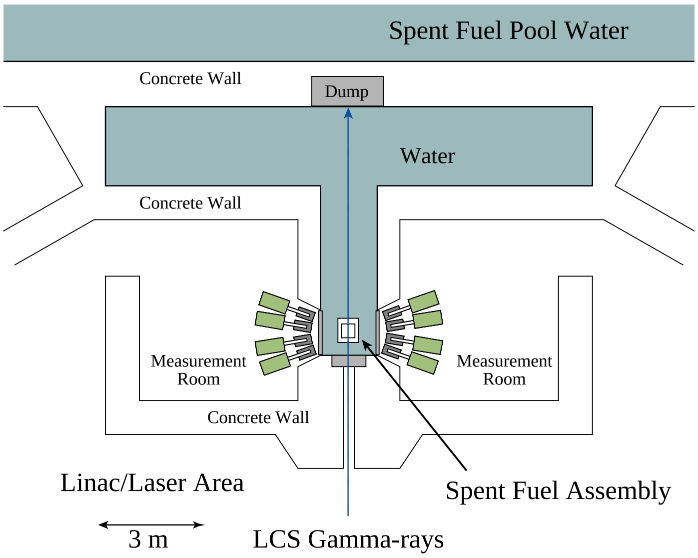


Figure 8(b). Measurement layout of LCSγ・NRF Pu-NDA system for a spent fuel in pool water.

Results of simulation calculations of NRF measurement of $^{239}$Pu in spent fuel assemblies in pool water with GEANT4 (JAEA) code are shown in Fig. 9(a), Fig. 9(b) and Fig. 9(c).

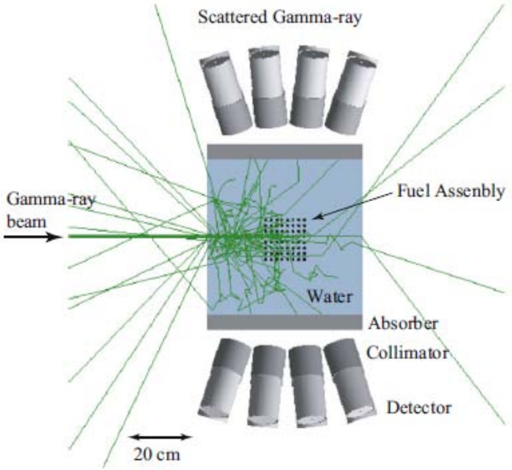


Figure 9(a). Result of simulation calculation of behaviours of incident γ-rays for a BWR 8×8 type spent fuel assembly

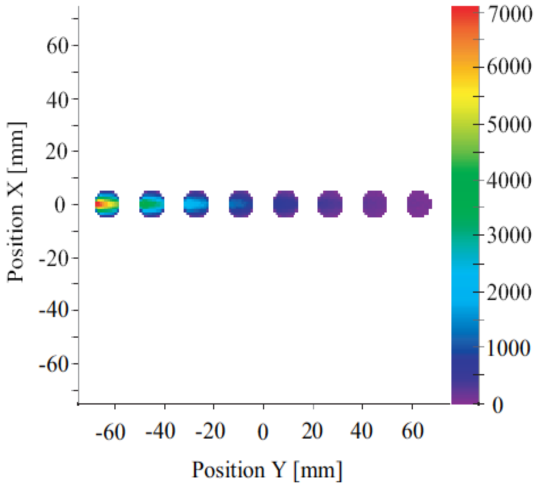


Figure 9(b). Distribution of NRF events in the fuel assembly consisting of 8×8 fuel rods.

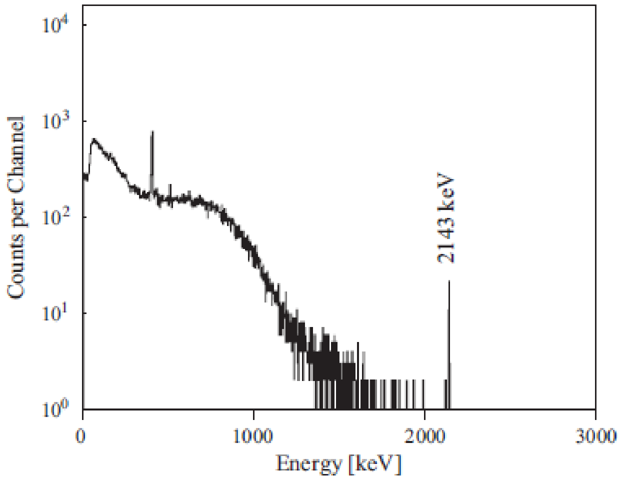


Figure (9(c). Calculated energy spectrum of the NRF γ-rays. (The 2.143 MeV γ-ray is clearly observed with a low signal-to-noise ratio.)

Also, as shown in Fig. 10, this system has possibilities of direct measurement of Pu in vitrified waste and hulls as well although precise simulations of NRF reaction using appropriate codes are necessary.

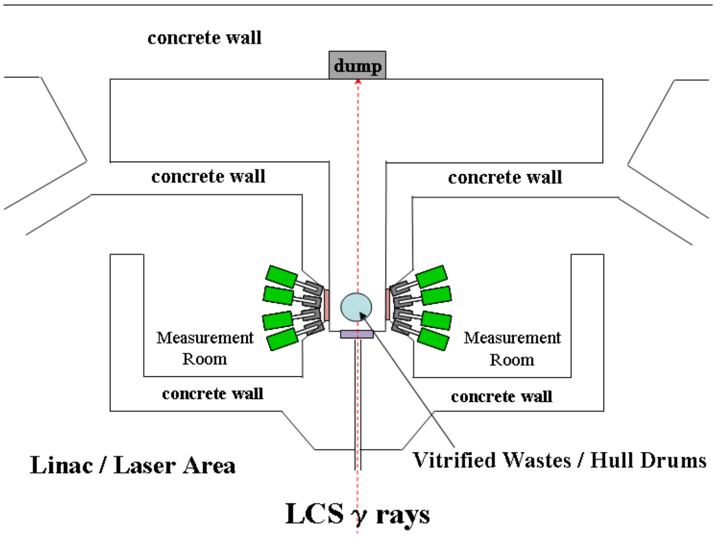


Figure 10. A LCSγ・NRF Pu-NDA system of vitrified waste / hull drums.

In addition, a LCSγ・NRF Pu-NDA system could be applied to non-destructive isotopic composition analysis of a specific actinide element in small samples, if the data of NRF reaction cross sections for each resonance state in individual isotope is experimentally fixed [5]. Fig. 11 shows an image of state candidates of Pu isotopes for NRF. There are scissors mode states in each Pu isotope nucleus in the energy range ～ 2 MeV excitation (All of actinide isotopes have the same scissors mode states.) . We are able to use these scissors mode states of actinide isotopes for NRF measurement with identifying each isotope utilizing deep penetrability of high energy (MeV class) γ-rays of a specific excitation energy of the isotope. However, experimental researches for these scissors mode states in actinide isotopes have been done in slow speed so far. We are able to promote these experimental researches rapidly by using a prototype LCSγ・NRF Pu-NDA system.

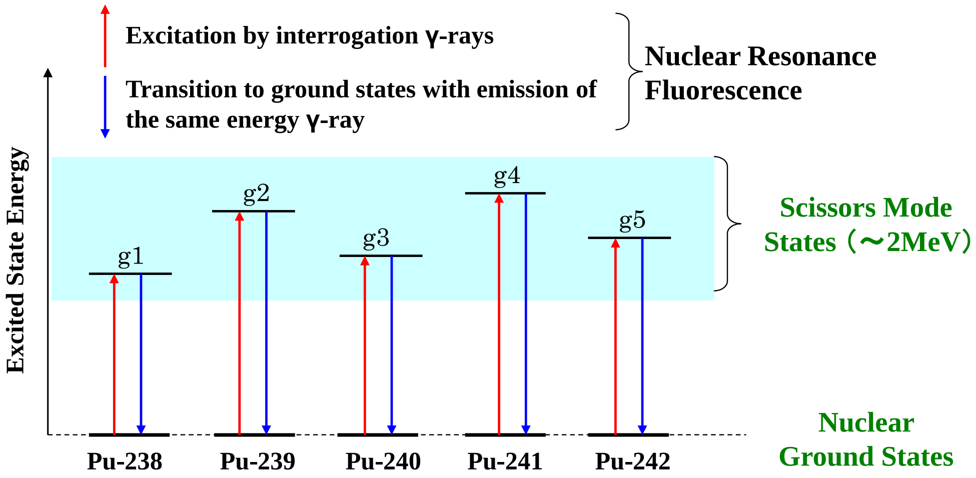
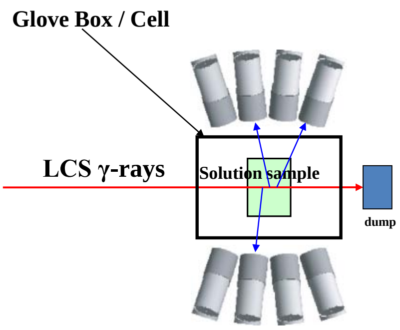


Figure 11. Nuclear state candidates of Pu isotopes for NRF (Image).

Fig. 12 shows an idea of non-destructive isotopic composition assay of Pu in solution samples. In this assay, 5 measurements with energies of g1, g2, g3, g4 and g5 for $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, and $^{242}$Pu, respectively, are done.



| Measurements with<br>the same intensity of γ-rays and<br>the same time duration |
|---|
| Measurement 1 with energy g1 （Pu-238） |
| Measurement 2 with energy g2 （Pu-239） |
| Measurement 3 with energy g3 （Pu-240） |
| Measurement 4 with energy g4 （Pu-241） |
| Measurement 5 with energy g5 （Pu-242） |

The isotopic composition of Pu could be analyzed based on counting data of each measurement combined with cross section data of each Pu isotope.

Figure 12. Non-destructive assay of isotopic composition of Pu in solution samples.

## 3. A trial application of SBD concept for advanced safeguards systems using LCS X/ γ -ray source

### *3.1 First step to SBD concept ( A Proposal of deployment of advanced safeguards systems)*

In section 2, we showed the proposals of the advanced (next generation) safeguards systems. The advanced system AT1 (A-HKED system), which has the capability of speedy measurement, could be applied to analyses of U, Pu and MA concentrations in solution samples. The AT2 (LCSγ・NRF Pu-NDA system) technology, which is on the same strategy with the AT1 development (just by changing electron energies), could be applied not only to “NDA for Pu in spent fuel assemblies” but also to “NDA for Pu in the next generation of the fresh MOX assemblies (with FPs and MAs), and in vitrified waste and hulls (including end-pieces)”. In addition, the AT2 technology could be applied to non-destructive assay of isotopic compositions of element in samples.

As an example of application of SBD concept, here we show a possible arrangement of these advanced systems into a joint–use on-site laboratory (OSL) of a hypothetical facility, for which we take a model facility with combination of reprocessing and MOX fuel fabrication. Fig. 13 shows a design of buildings including joint-use OSL with advanced safeguards systems using LCS X/γ-ray sources.

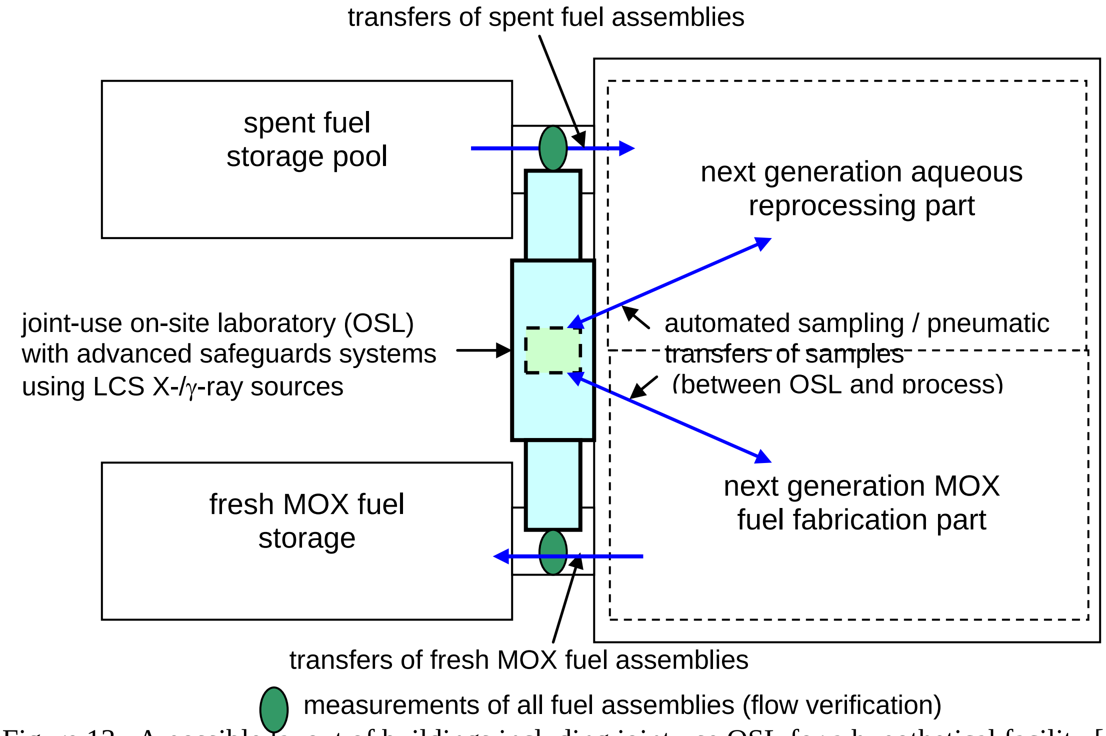
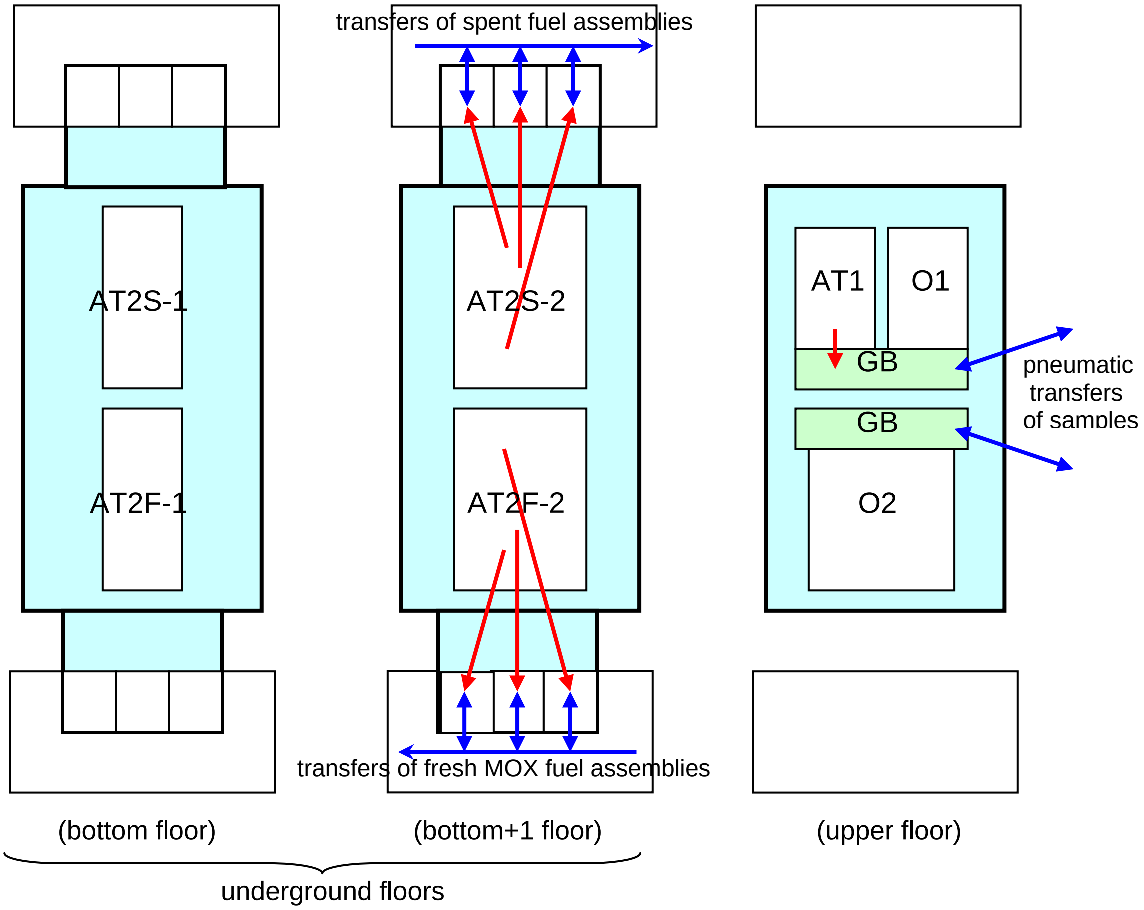


Figure 13. A possible layout of buildings including joint-use OSL for a hypothetical facility [5].

Fig. 14 shows an interior layout of joint-use OSL to accommodate the following systems,

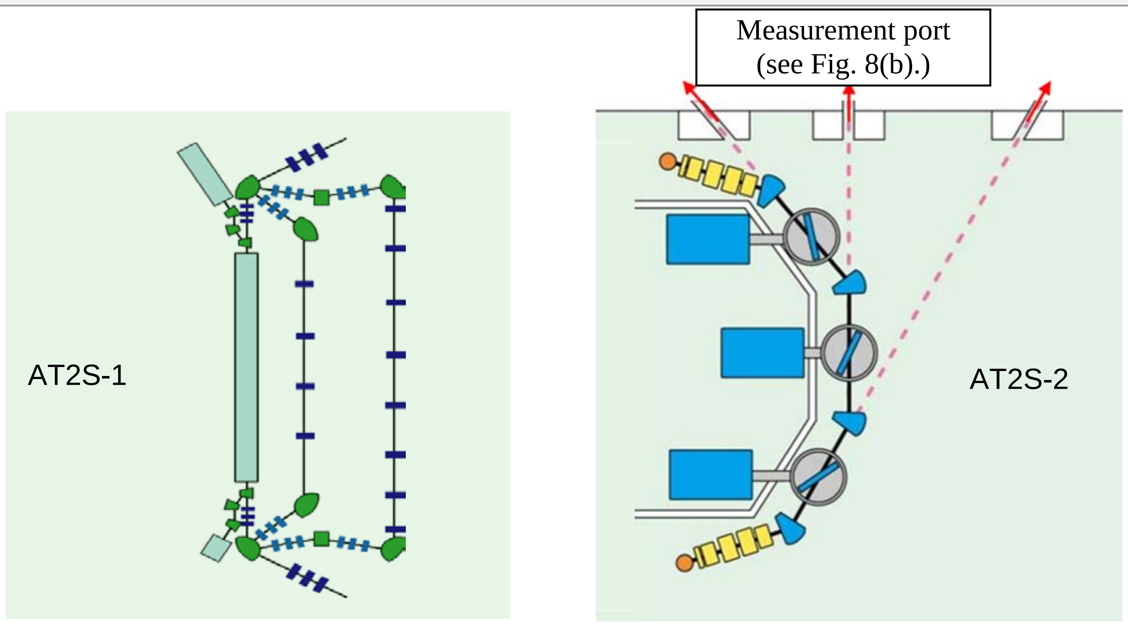
AT1 : A-HKED system
AT2 : LCS γ･NRF Pu-NDA system.

In the OSL, pneumatic transfer systems automatically bring small assay samples (for material accountancy and for safeguards verification from process equipment) to designated glove boxes. It sends the finished samples back to the process area. Because the maximum length of the LCS γ･NRF Pu-NDA system of AT2 is about 15 meters (see Fig. 8(a)) and consists of heavy magnets, it is desirable to place, at least, 2 loops of electron accelerators on the bottom floor of OSL and to place γ-ray source and assay part on the floor right above the bottom as shown in Fig. 14 and Fig.15. Since the LCS γ･NRF Pu-NDA system could be applied to measure fresh MOX fuel assemblies with FPs and MAs (including $^{244}$Cm) (like as spent fuel assemblies), we need to install another LCS γ･NRF Pu-NDA system (AT2F) for fresh fuel.



AT1 : Advanced HKED (A-HKED) system
AT2S-1 : 1st & 2nd loop of LCS γ NRF Pu-NDA system for spent fuel assemblies
AT2S-2 : 3rd loop and assay part of LCS γ NRF Pu-NDA system for spent fuel assemblies
AT2F-1 : 1-st & 2-nd loop of LCS γ NRF Pu-NDA system for fresh fuel assemblies
AT2S-2 : 3rd loop and assay part of LCS γ NRF Pu-NDA system for fresh fuel assemblies
← : X-rays and γ-rays
→ : Transfers of nuclear materials
O1 : Other advanced analytical systems for solution samples
O2 : Other advanced analytical systems for MOX samples
(LIBS(Laser Induced Breakdown Spectroscopy)+AIRS(Ablation Initiated Resonance Spectroscopy) system)
GB : Glove box for analytical treatment for small samples

Figure 14. A possible layout in joint-use OSL [5].



(bottom floor) (bottom+1 floor)

Figure 15. Vertical structure of LCSγ･NRF Pu-NDA system [5].

### *3.2 Interaction steps between researchers of advanced safeguards systems and facility designers*

For realizing SBD of FNFC facilities, the following interaction steps are necessary,

Step-1; researchers show images of advanced safeguards systems to facility designers based on their research.

Step-2; facility designers take important design information on safeguards systems into process systems of demonstration (or test) facility.

Step-3; demonstration and improvement of both systems based on the conceptual design.

Step-4; construction of a FNFC facility with the advanced safeguards systems

In subsection 3.1, we showed a concrete idea of deployment of the advanced safeguards systems using LCS X/γ -ray source for Step-1. The systems which we are proposing do not intrude into process systems much. The AT1 (A-HKED) system is installed at besides terminal GBs of pneumatic transfer systems widely used in nuclear fuel facilities and the AT2 (LCS γ･NRF Pu-NDA) systems are installed neighbouring rooms to predesigned measuring ports.

Hereafter we need to proceed to develop the proposed systems for demonstration. In JAEA, we are conducting an R&D program on energy-recovery linac (ERL), which includes developments of a small-emittance electron gun and a high-current superconducting linac. For the X-ray source based on an 85-MeV ERL shown in Fig. 4, we utilize a photocathode DC electron gun [6] and an L-band superconducting cavity [7], both of which have been developed in collaboration with KEK for a future X-ray light synchrotron source. The laser super-cavity for the LCS source is also under development at KEK for an LCS X-ray source [8]. In order to reduce the footprint of ERL, we consider to employ a multi-loop ERL, in which an electron beam is accelerated many times to increase its energy up to 85 MeV like a racetrack microtron. After the LCS X-ray generation, the beam is decelerated in a reverse way. Table 4 shows parameters of the LCS X-ray source for the HKED.

Table 4. Parameters of the LCS X-ray source for the HKED.

| Electron beam | | Laser beam | |
|---|---|---|---|
| Energy (variable) | 75-90 MeV | Wavelength | 1064 nm |
| Bunch charge, repetition | 10 pC , 100 MHz | Pulse energy, repetition | 100 mJ, 100 MHz |
| Normalized emittance | 5 mm-mrad | Enhancement of supercavity | 1000 |
| Rms size at the collision points | 100 μm | Rms size at the collision points | 100 μm |
| Bunch duration (rms) | 5 ps | Bunch duration (rms) | 5 ps |
| X-ray photon | | | |
| Energy (variable) | 100-150 keV | Spectral intensity | 4x10$^8$ ph/s/keV |

For the NRF NDA system, we need to carry out a study of Monte Carlo simulation codes for the NRF application. Now, two simulation codes, MCNP-X and GEANT4, are available for tracking γ-rays in materials including the NRF process. However, comparison of two simulation codes and verification with experimental results have not been made yet. Our study intends to make benchmarking of these simulation codes with an experiment by irradiating a uranium target with mono-energetic γ-rays.

## 4. Summary

Corresponding with the needs of advanced safeguards technologies for FNFC facilities, we presented two types of next generation non-destructive assay (NDA) systems of nuclear material using LCS X/γ-ray sources in an energy range of from 100 keV to 3 MeV. One is the advanced Hybrid K-edge densitometry system using a ～150 keV LCS X-ray source for measuring concentrations of actinides in solutions. Another is the NRF Pu-NDA system using a 1～3 MeV LCS γ-ray source for measuring Pu (and other actinides) amounts in spent fuel assemblies and high active wastes and for assaying isotopic compositions of actinide elements. These two types of advanced NDA systems (using LCS X- and γ-ray sources) are able to cover the most areas of assay (i.e. concentrations in solutions, isotopic compositions of small samples, absolute amounts in item and bulk materials) for safeguards and material accountancy. The advanced safeguards technology based on LCSX/γ-ray sources is essential for construction of safeguards and material accountancy systems in the FNFC facilities.

We also showed a concrete idea for deploying these advanced NDA systems in a hypothetical FNFC facility with less intrusive to process equipment as the first trial for application of SBD concept to FNFC facilities.

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