

## DESIGN OF A MULTI-TURN ERL FOR HYBRID K-EDGE DENSITOMETER

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### Abstract

Hybrid K-edge densitometer (HKED) is used for concentration measurement of U, Pu and minor actinides in liquid solution samples. We propose a multi-turn small-size energy-recovery linac (ERL) to produce laser-Compton scattered X-rays for the HKED. The X-rays with good monochromaticity and energy tunability allow measurement of nuclear materials faster than the existing HKED systems based on X-ray tubes. The ERL energy is 85 MeV to produce 130-keV X-rays. In the present design, we adopt a racetrack configuration, in which electrons are accelerated six times by L-band superconducting linac and decelerated six times for the energy recovery. Design and expected performance of the ERL-HKED are presented.

### INTRODUCTION

Nuclear fuel reprocessing is a key to the utilization of nuclear power as a safe, sustainable and economical source of primary energy. A nuclear fuel reprocessing facility uses solution-based chemical procedures to separate the fissile materials, U and Pu, from the fission products (FP) and other radioactive wastes. The separated U and Pu are shipped and reused for new nuclear fuel. In order to establish a nuclear fuel cycle with more economical and less vulnerability to nuclear terrorism, utilization of MOX fuel with artificial contamination of FP and minor actinide (MA's) is proposed for the future nuclear fuel reprocessing facilities. Such facilities for recycle of unpurified Pu and MAs need advanced technologies for their material accountancy and safeguards. Considering their characteristic features and prospected requirements from future implementation of international safeguards, rapid measurement and non-destructive analysis (NDA) technologies for Pu and MAs are necessary.

Here we propose to use high-intensity energy-tunable mono-energetic X and  $\gamma$ -ray sources generated by laser Compton scattering (LCS) for rapid measurement and NDA for Pu and MAs. We introduce two advanced NDA systems using LCS X and  $\gamma$ -ray source. One 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  $\gamma$ -rays produced by collisions of laser and 350 MeV electrons. The other is the advanced hybrid K-edge (A-HKED) densitometry system for measurement of concentrations of U, Pu and MAs in solution by using X-ray of 100-

130 keV generated from 85 MeV electrons.

In this paper, we present the concept of the advanced NDA systems and the design of 85-MeV ERL for A-HKED.

### LCS $\gamma$ -RAY SOURCE FOR Pu-NDA

A resonant excitation of definite nuclear states of a nucleus occurs when the nucleus absorbs an electromagnetic radiation equal to the excitation energy. This excitation state instantaneously decays mainly to a lower state with re-emission of the radiation equivalent to the absorbed radiation. This process is nuclear resonance fluorescence (NRF). The NRF spectrum is a unique fingerprint of nuclide, and we can identify and assay radioisotopes from the NRF spectrum [1].

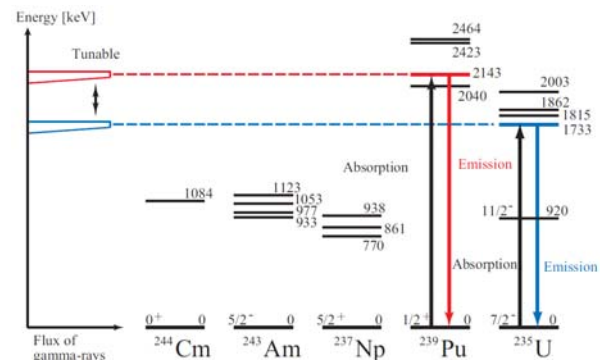


Figure 1: Detection of a specific isotope by energy-tunable monochromatic  $\gamma$ -ray and nuclear resonance fluorescence

We proposed non-destructive assay of plutonium (Pu-NDA) in spent nuclear fuel by using a combination of a mono-energetic LCS  $\gamma$ -ray and NRF. Figure 1 shows the principle of the Pu-NDA. Detection of Pu-239 is possible by irradiation of spent nuclear fuel with a  $\gamma$ -ray beam tuned at the resonance energy of Pu-239, 2143 keV.

The proposed NDA system has several advantages over the existing systems: (1) nondestructive measurement of isotopes of Pu and other nuclear material in samples is possible, (2) a monochromatic  $\gamma$ -ray tuned at a fluorescence energy is essential to improve signal-to-noise ratio in the energy-resolved  $\gamma$ -ray measurement by separating the fluorescence  $\gamma$ -ray from back-ground noise, most of which is generated through Compton scattering of  $\gamma$ -rays in the samples, (3) measuring many kind of isotopes is practically possible by scanning the  $\gamma$ -ray energy, (4) measurement of isotopes hidden by thick shield is possible.

We made proof-of-principle experiments at a LCS  $\gamma$ -

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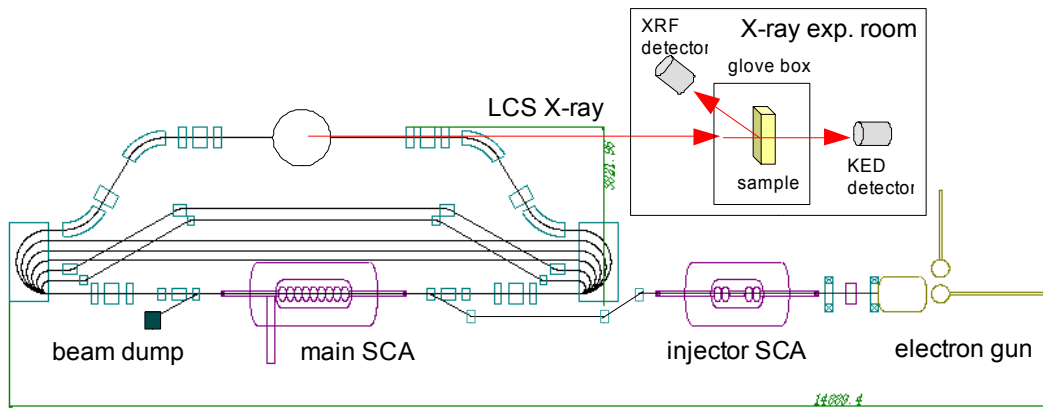


Figure 2: Schematic view of the 85-MeV ERL for 100-130 keV LCS X-rays, which is applicable to the advanced hybrid K-edge densitometer.

ray facility of National Institute of Advanced Industrial Science and Technology (AIST). In the experiments, we measured Pb-208, C-12, N-14 hidden in iron plates [2][3].

For the Pu-NDA system, we have designed a 350-MeV ERL to produce a high-flux LCS  $\gamma$ -ray in energy range of 1-2 MeV. A combination of a 350-MeV 10-mA ERL and a laser super cavity enable to generate a high-flux  $\gamma$ -ray,  $10^{13}$  ph/s. Details of the  $\gamma$ -ray source and the Pu-NDA system are described elsewhere [4][5].

### DESIGN OF A 85-MeV ERL FOR LCS X-RAYS

In order to construct the Pu-NDA system discussed in the previous section, we need to mature the technologies for a high-flux LCS sources, which are generation of a small-emittance and high-current electron beam, a high-average power laser system, a high-finesse optical cavity, stable collision of laser and electron beams, and so on. For this purpose, we need to construct a prototype machine, which is a LCS X-ray source based on an 85-MeV ERL. Using X-rays of 100-130 keV from the 85-MeV ERL, we propose an advanced hybrid K-edge (A-HKED) densitometry system for measurement of concentrations of U, Pu and MAs in solution.

Figure 2 shows a schematic view of the 85-MeV ERL as a current design. The ERL is an ideal device for a high-flux X and  $\gamma$ -ray sources based on the laser Compton scattering, because the electrons only lose a small fraction of their energy and recycling of the energy of spent electron beam is the key to increasing the LCS flux. For the industrial application of LCS X and  $\gamma$ -ray sources to nuclear fuel reprocessing plants, the electron accelerator should be compact. Thus, we designed a multi-turn ERL, in which an electron beam recalculates six times for the acceleration and another six times for the deceleration. The shape of ERL is almost same as a racetrack microtron. The operation parameters are listed in Table 1.

The injector consists of a 500-kV DC gun, 1.3-GHz buncher and a superconducting booster, which is similar to injectors for ERL X-ray light sources under development. The DC gun is equipped with a semiconductor photocathode, GaAs with Cs deposited on the surface, i.e. a negative electron affinity (NEA) cathode. The electron beam at the merger has energy of 7 MeV and a normalized emittance smaller than 1 mmrad for a bunch charge of 10 pC.

The accelerator voltage of the main linac is chosen to be 13 MV so that the electron beam energy becomes 85 MeV after six-pass recirculation. This accelerator voltage is achieved by single 9-cell cavity operated at 1.3 GHz, which is TESLA-like cavity or ERL cavity developed by KEK-JAEA-ISSP [6].

Table 1: Parameters of the 85-MeV ERL and the LCS X-ray source

Electron Beam	
repetition	100 MHz
energy	85 MeV
bunch charge	10 pC
normalized emittance	2 mm-mrad
rms beam size at the collision	70 $\mu$ m
rms pulse length	3 ps
rms energy spread	1E-3
Laser beam	
wavelength	1064 nm
repetition	100 MHz
pulse energy at the amplifier	1 $\mu$ J
rms beam size at the collision	70 $\mu$ m
rms pulse length	1 ps
enhancement of supercavity	1000
collision angle	8 deg
X-ray	
energy	100-130 keV
flux	$\sim 1 \times 10^8$ ph/s/keV

A 72-MeV superconducting racetrack microtron MUSL-2 was built at Illinois University in 1975. The beam current of MUSL-2 was limited below 1  $\mu\text{A}$  due to the beam break up (BBU) [7]. In recirculation linacs, superconducting microtron and ERL, BBU is mainly caused by higher-order modes (HOM) on superconducting cavities. The HOM-BBU becomes more crucial as the number of recirculation becomes large. Superconducting cavities with strong HOM damping is, therefore, a critical component for recirculation linacs.

In the ERL projects for high-power FELs and future X-ray sources, superconducting cavities to accelerate high-average current have been developed. An L-band 9-cell cavity developed by KEK-JAEA-ISSP achieves a BBU threshold current over 600 mA at a 5-GeV ERL [8]. Utilizing such superconducting cavities, we can accelerate an electron beam of high-average current even in a multi-ERLs.

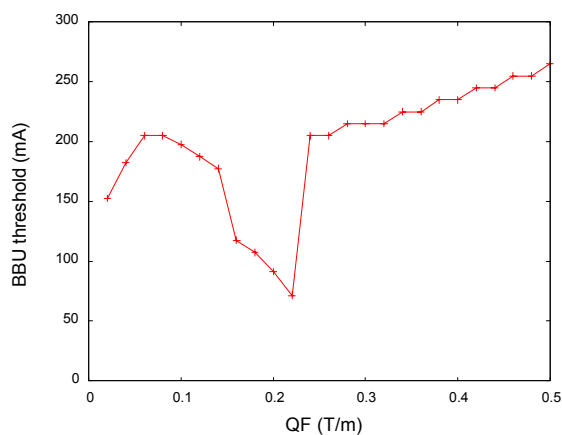


Figure 3: Threshold current of beam-breakup as a function of strength of quadrupole magnets at the both ends of the main linac. The simulation assumed a simple six-loop ERL without bypass orbits.

We made a preliminary estimation of the BBU threshold current in the 85-MeV ERL with the KEK-JAEA-ISSP ERL cavity. In the estimation, we assume a simple six-loop ERL without bypass orbits in the first and second loops and we use a simulation code bi [9]. Figure 3 shows a BBU threshold current as a function of field strength of quadrupole magnets at the both ends of the main linac. As we can see in Fig. 3, the BBU threshold is high enough,  $> 100$  mA, to operate the ERL with a 1-10 mA beam.

A cryomodule of superconducting linac has a large transverse dimension, which may interfere with electron beam orbits in the low energy section of the multi-loop ERL. In the microtron at Illinois, they adopted chicane-like bypass orbits for the first and second recirculations. In our ERL, we utilize similar bypass orbits as shown in Fig. 2. The bypass orbits are located at a position where the electron beam has nonzero horizontal dispersion. Thus, the bypass orbits should be designed to be transparent to the dispersion function. Moreover, the racetrack ERL

requires moderate beam focusing during the recirculation, i.e. no strong quadrupole focusing. Possible design of the bypass orbits to fulfill these conditions is a particular type of orbit that has a drift-like transport matrix:

$$R^+ = \begin{pmatrix} 1 & a & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & b \\ 0 & 0 & 0 & 1 \end{pmatrix} \text{ or } R^- = \begin{pmatrix} 1 & a & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & -b \\ 0 & 0 & 0 & -1 \end{pmatrix},$$

where  $a$  and  $b$  are positive values. A bypass orbit with a  $R^-$  matrix can be realized by four-dipole chicane with quadrupole magnets at the middle of the chicane.

## ADVANCED HYBRID K-EDGE DENSITOMATOR

Figure 4 shows the performance of LCS X-ray at the 85-MeV ERL, in the bandwidth and the number of X-ray photons with an on-axis collimator are calculated by Monte Carlo code CAIN [10]. The X-ray bandwidth (rms) and the number of photons are 430 eV (0.36%) and 1.4, respectively, for a collimator aperture of 0.4 mrad. This photon number corresponds to X-ray flux of  $1.4 \times 10^8/\text{s}$  at 100 MHz repetition.

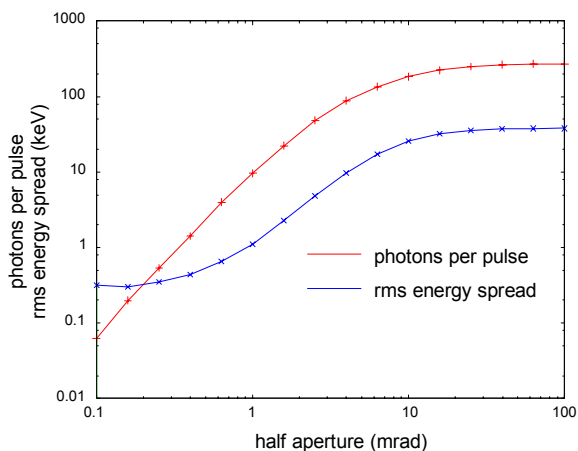


Figure 4: Performance of the LCS X-ray source calculated by Monte Carlo simulation. Photons per pulse and rms energy spread of X-ray are plotted for a collimator aperture.

The hybrid K-edge/K-XRF densitometer (HKED) [11] is a non-destructive assay method for the determination of nuclear material concentration in solution samples. The HKED is utilized for international safeguards and material accountancy in nuclear fuel reprocessing facilities. In the HKED, an X-ray generator (X-ray tube at 150 kV, 10 mA) produces broadband bremsstrahlung X-ray photons. The X-rays, after collimation and filtering, passes a solution sample containing nuclear material. The concentration of the most-abundant element is determined by K-edge densitometer and concentrations of other elements are derived from XRF signals [12].

The Advanced HKED (A-HKED) proposed in the present paper is based on mono-energetic X-rays from LCS instead of an X-ray tube. With this high-flux mono-energetic X-ray beam, we can measure nuclear materials in solutions faster than those available in the conventional HKED systems. The principle of fast measurement is as follows. The energies of K-absorption edge for U, Np and Pu are separated with intervals of 2.6%. Thus, we can distinguish the absorption effect of each element by using an X-ray beam with 1% energy spread. In the A-HKED, only two measurements slightly below and above the K-absorption edge are required for the determination of element concentration, while acquisition of wide-range energy spectrum is necessary in the conventional HKED. The measurement in the A-HKED, a simple photon counting, can be done by scintillator detector which is working at counting rate higher than a Germanium detector used in the conventional HKED. We consider the measurement time of the A-HKED is about 10 times faster than the conventional HKED [12]. Systematic measurement errors in the conventional HKED may occur due to instability of X-ray tube voltage and heating of a sample by thermal flux from the X-ray tube. The A-HKED is free from such errors, if it is operated with an  $I_0$  monitor, a common apparatus to monitor the incident X-ray flux in synchrotron radiation experiments.

The rapid and accurate measurement of nuclear material by A-HKED meets requirements in future nuclear fuel reprocessing facilities, where integrated safeguards approach including random interim inspections is plan to be adopted.

## SUMMARY AND OUTLOOK

We have proposed two NDA systems for nuclear materials: one for the measurement of nuclear material inventory in spent nuclear fuels and the other for the measurement of nuclear material concentration in solution samples. Both systems are based on a laser Compton

scattering photon source. The energy-recovery linac to produce a small-emittance high-average current electron beam is an ideal device to realize such photon sources.

Development of accelerator components for the ERL, photo cathode DC guns and superconducting cavities, is carried out by JAEA in collaboration with KEK, ISSP, Nagoya University and Hiroshima University. Recently, we have achieved stable high-voltage operation of 500-kV DC gun, which utilizes segmented ceramic insulator covered with guard rings [13]. As for the superconducting cavities, acceleration gradient of 25 MV/m was obtained for an L-band 9-cell cavity optimized for a high-average current beam [14].

We are also conducting a design study of a multi-loop ERL for the NDA systems. As seen in this paper, multi-loop racetrack-type ERL can be a compact photon source to produce 100-130 keV X-rays for the A-HKED.

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