GENERATION AND APPLICATION OF LASER COMPTON SCATTERED γ-RAYS AT THE COMPACT ERL

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Abstract

We proposed a nondestructive assay (NDA) method for U-235, Pu-239, and minor actinides in spent nuclear fuel assembly in a water pool, where nuclear fuel materials are detected using nuclear resonance fluorescence (NRF) with laser Compton scattering (LCS) gamma-rays generated by collision of high energy electrons and laser photons. For developing the LCS-NRF NDA method, we recently launched a research program supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. In the program, we plan to demonstrate generation of LCS gamma-rays at the Compact ERL, a test facility of energy-recovery linac for future light sources. In the present paper, we describe the experimental plan and the current R&D status.

コンパクト ERL におけるレーザーコンプトンγ線の発生と核種非破壊測定実証試験の計画

1. INTRODUCTION

We proposed applications of mono-energetic gamma-ray beams to nondestructive measurements of nuclear materials for the nuclear safeguards and security purposes [1,2]. The gamma-ray is generated via laser Compton scattering (LCS), which is collision of high-energy electrons and laser photons as shown in Fig. 1. The LCS gamma-ray is distinct from other conventional gamma-ray sources in its energy tunability, narrow energy width and small divergence. The energy of LCS gamma-ray is a function of electron energy E_e, laser photon energy E_L, collision geometry and given by

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

As seen in Eq.(1), the gamma-ray energy has correlation with the scattering angle. Thus, we can obtain a mono-energetic gamma-ray by putting a small collimator to restrict the scattering angle.

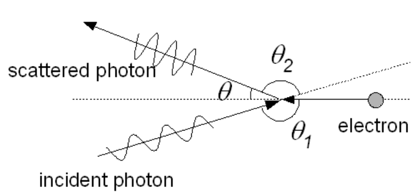

Figure 1: Principle of gamma-ray generation via laser Compton scattering

Utilizing this LCS gamma-ray beam in combination with nuclear resonant fluorescence (NRF), we can make nondestructive measurement of arbitrary nuclides. The principle of LCS-NRF is as follows. When a nucleus is irradiated with gamma-ray and the energy of the gamma-ray is identical with transition energy from the ground state of the nucleus, the incident gamma-ray is effectively absorbed in the nucleus and subsequently the nucleus de-excite by gamma-ray emission. The energies of the states excited by NRF are inherent in the atomic number and mass of the nucleus of interest. Thus, nondestructive measurements of stable and unstable nuclides are possible by LCS-NRF method as shown in Fig. 2 [1].

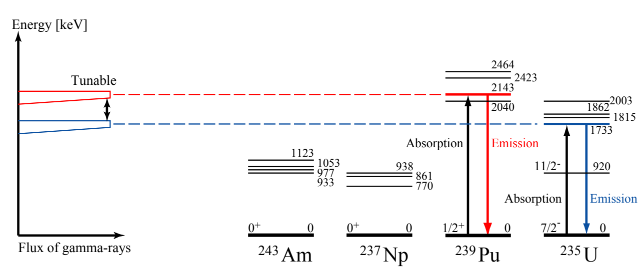

Figure 2: Schematic view of nondestructive measurement of nuclide using nuclear resonance fluorescence with mono-energetic gamma-rays.

We have proposed nondestructive measurements of Pu in a spent nuclear fuel assembly by using the LCS-NRF method. The advantage of our proposal is that the amount of Pu contained in spent nuclear fuel can be measured with keeping the fuel in a water pool. From a preliminary estimation, statistical uncertainty in the measurement is less than 2% for a measurement time of 3000-4000 s with a gamma-ray source having a photon flux of 1×10^{13} ph/s [2].

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2. Design of a Gamma-ray source for Pu-NDA

For the generation of high-flux gamma-rays via laser Compton scattering, we need to increase collision density of laser and electron beams. Therefore, a small emittance and high-current electron beam and a high-power laser are necessary. Since average flux is essential rather than peak flux in the application of gamma-ray to the non-destructive measurement of nuclide, the electron beam current and the laser power should be evaluated in a sense of average values.

An energy-recovery linac (ERL) is the best apparatus to accelerate electron beams of small emittance and high-average current [3]. The ERL is a novel type of accelerator to generate a high-quality electron beam with a high-average current. An electron beam from an injector is accelerated by time-varying radio-frequency (RF) field stored in a superconducting linear accelerator and subsequently is transported to a recirculation loop. After the recirculation, the electron beam is injected again to the superconducting accelerator with the deceleration RF phase. The recirculated electrons are decelerated and feed back the energy to the superconducting RF cavity. This recycled RF energy is again used to accelerate subsequent electrons. The ERL is thus composed of an injector, a superconducting linac, an energy recovery loop. Fig. 3 shows a schematic view of the LCS gamma-ray source designed on the basis of the ERL.

In a LCS gamma-ray source, cross section of the Compton scattering is not so large that most of electrons and photons do not contribute to the gamma-ray generation. Recycling the electrons and photons are, therefore, important to realize high-flux and high-intensity gamma-ray sources. The ERL technology enables us to recycle an electron beam as described above. Recycling of laser photons, on the other hand, is achieved by laser super cavity. A laser super cavity is a high-finess Fabry-Perot optical cavity to store a high-power laser. Laser photons stored in a cavity interact with electrons many times to generate gamma-rays. For a nondestructive measurement of Pu in spent nuclear fuel, we design a gamma-ray source to produce a gamma-ray at a flux of $1x10^{13}$ ph/s. The gamma-ray source consists of a 350-MeV, 10-mA ERL and a laser super cavity [4].

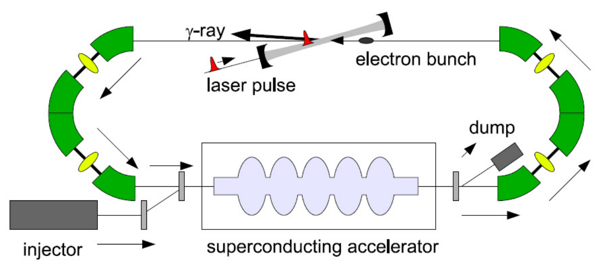

Figure 3: A schematic view of Compton γ-ray source utilizing an energy-recovery linac (ERL).

3. R&D status for the LCS-gamma ray Source

In order to obtain a high-flux and high-intensity gamma-rays from laser Compton scattering, there are key technologies: small-emittance and high-average current electron beams in an ERL, storage of high-power laser pulses in a laser super cavity, collision of electrons and laser photons at a small spot size, stabilization of beams, and so on. We present R&D status for these key technologies.

A flux of gamma-ray is inversely proportional to the dimension of electron and leaser beams at the collision spot. The laser spot size (w) is a function of laser wavelength (λ) and Rayleigh length (Z_R) and given as $\pi w^2 = \lambda Z_R$ for an ideal case of single transverse mode. An electron beam can be focused at a spot size of $\sigma^2 = \varepsilon\beta$, where ε is emittance and β is betatron function at the collision point. In order to achieve a tight focusing at the collision point, small emittance is an essential property for the electron beam. The electron beam emittance also affects the energy bandwidth of LCS gamma-ray. The energy of LCS gamma-ray is correlated with scattering angle as shown in Eq. (1). The gamma-ray energy, however, deviates from the theoretical value, when the electron beam has non-uniform momentum in transverse direction due to a finite emittance. According to a detail analysis, the effects of emittance on the gamma-ray energy spread becomes significant for $\varepsilon_n > \lambda/4\pi$, where ε_n is normalized emittance and λ is laser wavelength. As a typical parameter with 1μm lasers, normalized emittance of 0.1 mm-mrad is a targeting value to be developed.

We are developing a photocathode DC electron gun to generate small-emittance electron beams at high-average current at JAEA [5]. The design parameters of the gun are average current of 10-100 mA, normalized emittance of 0.1-1 mm-mrad and the maximum repetition rate of 1300 MHz. In order to achieve these parameters, the gun is designed to operate at 500-kV, which is the highest value ever achieved in similar type of guns. We have developed a novel design of ceramic insulator and successfully demonstrated a high-voltage operation at 500-kV [6].

Generation of small-emittance electron beams from a photo cathode is also under investigation. The gun is equipped with a semiconductor photo cathode, GaAs, which has a surface of negative electron affinity (NEA). The NEA surface is suited for small emittance beams, because photo-produced electrons in a cathode are thermalized before emitting from the surface. In order to confirm the small-emittance capability of NEA-GaAs cathodes, we measured initial emittance of the cathode as a function of a spot size of laser illumination at the cathode surface. As a result, the emittance is almost linearly proportional to the laser spot size, which is explained by a fact that the emittance is dominated by thermal motion of electrons, thermal emittance. The experimental data indicates that effective temperature of electrons emitted from the cathode for a drive laser of 633 nm is 54 meV, which is small enough to obtain a normalized emittance of 0.1 mm-mrad [7].

Superconducting accelerator for high-average current electron beams is another key component in an ERL. For acceleration of high-average current beams, we need to care large power of higher-order modes (HOMs), which are excited by bunched electron beam passing through superconducting cavities. It is known that HOMs induce instabilities of electron beams in an ERL. We have optimized cavity shape and beam pipe diameter for efficient extraction of HOMs from the cavity. The extracted HOMs are absorbed by ferrite damper attached to the inner surface of beam pipes. From a numerical simulation, beam current threshold for the beam instability is high enough, 600 mA for a 5 GeV ERL, and the cavity fulfills the requirements of LCS gamma-ray sources [8].

A laser super cavity for the laser Compton scattering is also under development. Laser super cavity is a Fabry-Perot cavity consisting of high-reflectivity mirrors. A train of laser pulses generated from a mode-locked laser is injected to a laser super cavity and stacked inside the cavity. An intrinsic parameter of laser super cavity is enhancement factor, which is the ratio of injected laser power and stored laser power. The enhancement factor depends on reflectivity of mirrors and cavity geometry. Stability of mirror position is also important for a laser super cavity. In order to achieve enhancement factor over 1000, mirror position must be stabilized with an accuracy of sub-angstrom. An enhancement factor of 750 has already been demonstrated at a 2-mirror cavity developed by KEK-LUCX group [9]. For the further enhancement of laser power in a super cavity, improvement of feedback system and reduction of phase noise both in a mode-locked laser and a super cavity are necessary. For this purpose, a new laser super cavity with a 4-mirror configuration and a high-power mode-locked laser are under development at KEK under Quantum Beam Technology Program [10,11].

For studying feasibility of nondestructive measurement utilizing LCS gamma-ray, we are developing a Geant4-based NRF code [12] and provide the code to a USDOE-JAEA collaboration program on NRF simulation codes, where two NRF codes, NRFGeant4 and MCNP-X are compared and checked with each other. Improvement of physics models of nuclear resonance fluorescence and competitive processes such as nuclear Thomson scattering and Delbrück scattering is also an item of the collaboration. Benchmark experiments using U-238 targets were carried out at HIGS facility, Duke University.

4. Demo-experiment at the Compact ERL

For developing the LCS-NRF NDA method, the Integrated Support Center for Nuclear Nonproliferation and Nuclear Security (ISCN) of Japan Atomic Energy Agency (JAEA) recently launched a research program supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. In the program, we plan to demonstrate generation of LCS gamma-rays at the Compact ERL, a test facility of energy-recovery linac for future light sources [4]. The Compact ERL (cERL) is now under construction and will be completed in FY2012 to provide a 35-MeV electron beam at the initial operation [13,14]. We also have a future plan to reinforce the electron beam energy by additional accelerator structures and the second recirculation loop. For the generation of LCS gamma-ray, we install a laser super cavity at the recirculation loop of the Compact ERL.

Figure 4 shows a floor layout of the cERL in a 2-loop configuration. In the 2-loop configuration, an electron beam is accelerated twice in the same superconducting cavities and decelerated twice, where 245 MeV electron beam is available. As the first stage of the cERL construction, we plan to operate the cERL at a lower energy with a smaller number of superconducting cavities in a single-loop configuration and later reinforce the superconducting cavity to upgrade the electron beam energy to the full specification.

Construction of the cERL is in progress as scheduled regardless of the earthquake disaster. We have refurbished the construction site, which is an old experimental hall originally used for a 12-GeV proton synchrotron. A cryogenic plant and high-power RF sources have already been installed and commissioning is underway. After completion of the construction and the beam commissioning of the cERL, a demo-experiment for nondestructive measurement is planed in FY2013. In the demo-experiment, we irradiate a mock-up of spent nuclear fuel assembly with LCS gamma-rays as shown in Fig. 5. Since the gamma-ray energy at the Compact ERL is relatively low and cannot cover the NRF energy of Pu, we will use an alternative material that has resonance within available gamma-ray energies. Possible alternative materials and resonance energies are Dy-161 for 25 keV, Tb-159 for 58 keV, Ta-181 for 136 keV and Lu-175 for

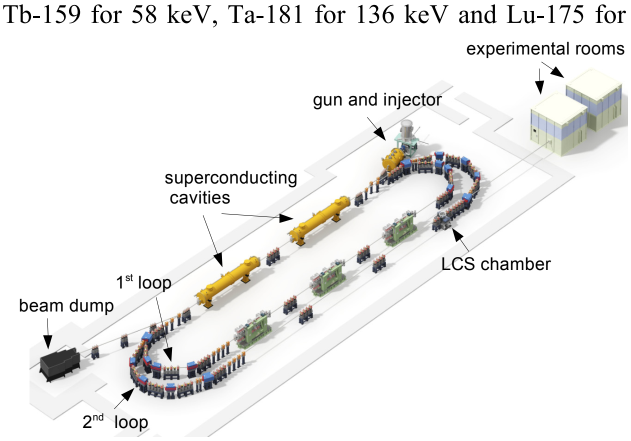

Figure 4: A schematic view of the Compact ERL after upgrade to a 2-loop configuration.

251 keV, and so on.

5. Summary

Mono-energetic gamma-ray beams of high-flux and high-intensity from laser Compton scattering is becoming available owing to advanced technologies of electron accelerator and laser. We have proposed a non-destructive measurement technique based on nuclear resonance fluorescence triggered by LCS gamma-ray beams. This technique can be applied to non-destructive measurements of Pu in spent nuclear fuels for nuclear safeguards and nuclear security purposes. In order to develop technologies relevant to LCS gamma-ray generation and improve the accuracy and reliability of the non-destructive measurement, we have launched a R&D program. In the program, we plan to generate a LCS gamma-ray at the Compact ERL and utilize the gamma-ray for a demo-experiment of non-destructive measurement. We are also developing a Monte Carlo simulation code for NRF measurements in cooperation with US-DOE.

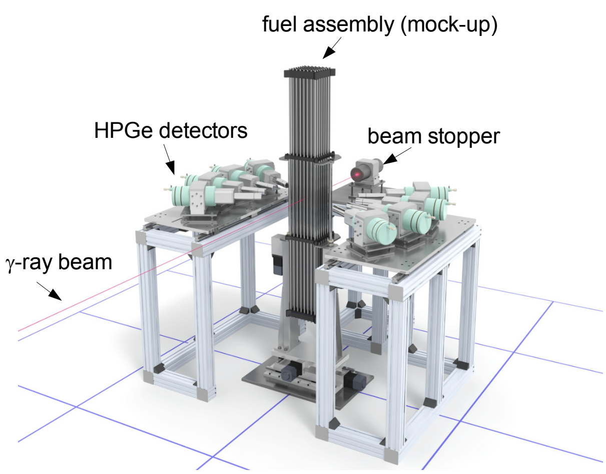

Figure 5: A schematic view of a demo-experiment for nondestructive measurement of nuclide by mono-energetic gamma-ray beam at the Compact ERL.

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