Energy-Recovery Linac for a High-Flux Quasi-Monochromatic Gamma-Ray Source

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A high-flux quasi-monochromatic gamma-ray source utilizing an energy-recovery linac (ERL) is proposed. Since the energy-recovery linac is able to generate a high-power electron beam with small emittance, it is an ideal driver for a laser Compton gamma-ray source. Preliminary estimation has suggested that gamma-ray flux of an ERL-based facility is 10^9-10^{10} photons/sec/keV, which exceeds existing laser Compton facilities by several orders of magnitude. Such a high-flux gamma-ray source is applicable to nondestructive assay of radionuclides for nuclear waste management as well as scientific research of nuclear physics and nuclear astrophysics. In this paper, we present the design of an ERL-based gamma-ray source, technological issues to realize such source, and expected performance.

I. INTRODUCTION

High-brightness and high-flux photon generation is one of the most attractive applications of electron accelerators. X-ray light sources based on electron storage rings are now utilized in wide area of scientific and industrial applications. Recently, it was reported that an X-ray light source contributed to efficient shutdown of a nuclear weapon plant, where an estimated cost of $37 billion for complete clean-up of the plant was successfully reduced to $3 billion.[1] This enormous saving of the clean-up cost was thanks to a novel finding of migration behavior of actinides in the environment, which an X-ray light source revealed. There are many developmental efforts in the world towards next-generation X-ray light sources and high-power FELs, which will extend the research frontier of the photon science. In the present paper, we discuss a possible generation of high-flux quasi-monochromatic gamma-rays utilizing advanced accelerator technologies. The combination of an energy-recovery linac and a high-power mode-locked laser realizes significant enhancement of a gamma-ray flux from laser Compton scattering, in which a gamma-ray flux of 10^9-10^{10} ph/sec/keV can be obtained. The gamma-ray source can be applied to nondestructive assay of radioactive nuclides in nuclear wastes.

II. NUCLEAR RESONANCE FLUORESCENCE BY LASER SCATTERED γ-RAYS

Nondestructive assay of radionuclides is a key technology for efficient and secure management of radioactive wastes discharged from the nuclear fuel cycle and research and medical applications of radioisotopes. Nondestructive assay of high-energy gamma-ray emitters such as Co-60 and Cs-137 is possible by measuring spontaneously emitted gamma-rays at the outside of the object. This method, however, can not be applied to measurements of alpha- and beta-ray emitters, which often dominate the degree of hazard of the waste. In order to assay alpha- and beta-ray emitters, we have proposed a novel method based on nuclear resonance fluorescence triggered by high-flux quasi-monochromatic gamma-rays.[2]

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).[3] Since the gamma-ray spectrum of NRF is a unique fingerprint of nuclide, we can identify and assay radioactive nuclides using NRF spectra.

Generation of gamma-rays via collisional interaction of laser photons with relativistic electrons is laser Compton scattering (LCS). Since the energy of LCS gamma-ray has correlation with scattering angle with respect to the electron beam, a quasi-monochromatic gamma-ray can be obtained by putting appropriate collimator at the downstream of the gamma-ray path. Tuning the energy of LCS gamma-ray at the NRF energy, we can greatly improve signal-to-noise ratio in the NRF measurements by separating the fluorescence gamma-ray from back-ground noise, most of which is generated through Compton scattering of gamma-rays in the object and has an energy lower than the incident gamma-ray. The principle of the NRF method with a LCS gamma-ray is shown in Fig.1.

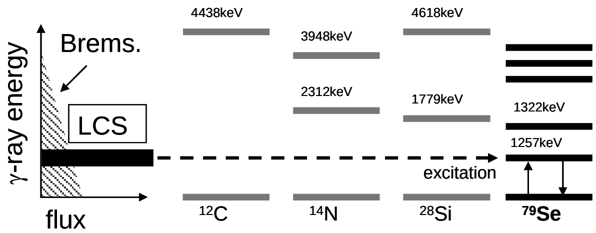

Fig. 1. Nuclear resonance fluorescence of Se-79 by irradiation of 1257-keV gamma-ray. Spectra of LCS gama-ray and Bremsstrahlung gamma-ray are plotted for reference.

In laser Compton scattering, the energy of scattered gamma-ray E_γ is a function of laser photon energy $E_L=h\nu$, electron energy $E_e=mc\gamma^2$, and scattering geometry shown in Fig.2:

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

where $\beta= (1-1/\gamma^2)^{1/2}$ is the electron velocity in units of light speed. A combination of laser wavelength of 1μm and electron energy of 350 MeV gives 2 MeV gamma-rays.

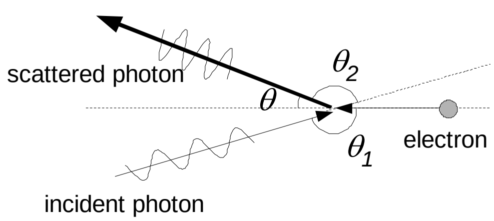

Fig. 2. Principle of laser Compton scattering. A high-energy photon is generated by scattering of an incident photons with a high-energy electron.

A flux of gamma-ray for an ideal head-on geometry is estimated by

$$F_{total} = \frac{fN_e N_L \sigma_C}{A}, \qquad (2)$$

where f is the collision frequency, N_e is the number of electrons in an bunch, N_L is the number of photon in a laser pulse, σ_c is the cross-section of Compton scattering, A is the effective sectional area of beams at the collision point and given by $A=\pi w^2/2$ for a Gaussian beam. In order to obtain a high-flux gamma-ray, it is necessary to increase the density of both electrons and photons at the collision point.

A mode-locked laser based on ytterbium-doped fibers recently demonstrated high-average power operation, 131 W at 73 MHz, and the power can be further increased by adding the pump power.[4] The photon density at the collision point can be further improved by using a laser supercavity. The laser supercavity is a Fabry-Pérot optical cavity comprising two mirrors of high reflectivity. When optical pulses from a mode-locked laser are injected to a laser supercavity, the pulses can be stacked inside the cavity by making the round-trip time of the pulse inside the cavity exactly equal to the laser pulse interval. The ratio of the intracavity and the injection laser power, G, is a function of mirror properties: transmittance T and reflectivity R,

$$G = \frac{T}{(1-R)^2}, \qquad (3)$$

where we assume the cavity consists of two identical mirrors. Since a mirror having a reflectivity of 99.9% or better is commercially available for visible and near infrared lasers, the amplification factor of 1000 or more is reasonably attainable. In the research of compact X-ray sources at KEK, a laser supercavity with amplification factor of 1000 has been demonstrated.[5] We consider that the combination of a mode-locked fiber laser and a supercavity is suitable for the high-flux gamma-ray source. Figure 3 shows a schematic representative of a LCS apparatus equipped with a supercavity.

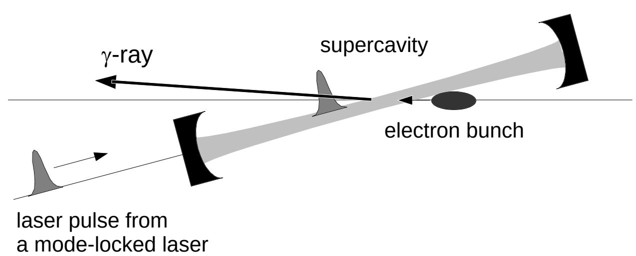

Fig. 3. Generation of a gamma-ray by laser Compton scattering inside a laser supercavity. The cavity length is 1.15 m and the crossing angle is 3.5 degree in the present proposal.

For gamma-ray generation in a supercavity, we need to install the supercavity at an oblique angle with respect to the electron beam. Equation (1) shows that the gamma-ray energy is a function of the crossing angle of laser and electron beams. Degradation of gamma-ray energy is, however, not serious for a small crossing angle of a few degrees

III. ENERGY RECOVERY LINAC

An energy-recovery linac (ERL) is a novel type of accelerator which produces an electron beam of high-quality and high average-current. In an energy-recovery linac, an electron beam is accelerated by superconducting

RF linac and the beam after use is decelerated in the same linac. Thus the electron energy is converted back into RF energy and recycled to accelerate succeeding electrons. The energy recovery technology has a great impact on accelerator-based photon sources. In an ERL, it is possible to accelerate an electron beam of high-average current with rf generators of small capacity. Adding to this excellent conversion efficiency from the electric power to the electron beam power, the ERL has an advantage essential to generation of high-brightness electron beams. Since an electron bunch in an ERL goes to a beam dump after deceleration and another fresh electron bunch is accelerated every turn, the ERL is free from degradation of electron beam emittance caused by multiple recirculation of electrons. Beam brightness of an ERL can be increased by adopting a high-brightness injector such as a photocathode electron gun. An ERL is, thus, quite different from a storage ring, in which emittance and temporal duration of electron bunches are restricted by equivalent state of electron beam dynamics, bunch thermalization, after a number of turns in the storage ring.

The energy-recovery linac has been developed for high-power free-electron lasers[6,7,8] and now plays an important role for future X-ray light sources.[9] We propose that the energy-recovery linac can work for a high-flux gamma-ray source as well. An energy-recovery linac equipped with a high-brightness injector such as a photo cathode gun produces an electron beam of normalized emittance as small as a few mm-mrad, and high-average current, 10-100 mA. This excellent property of the ERL contributes directly to a significant enhancement of the gamma-ray flux from laser Compton scattering. One may worry that some of electrons lose their energy or alter their momenta via Compton scattering with laser photons and these perturbations on the electron beam results in failure of energy recovery. However, the Compton scattering cross-section is so small that the loss of electron energy is not an issue in a well-designed energy-recovery linac, which accepts energy spread of the electrons as large as several percent in the return arc.[10,11]

A research project towards a future ERL X-ray light source has launched in Japan by collaboration team of JAEA, KEK, ISSP and other laboratories.[12] The ERL light source will be a 5-GeV, 100-mA scale. We plan to build a test ERL, 60-200 MeV, to demonstrate technologies relevant to the future ERL light source. Two major components, an electron gun and a superconducting cavity, are under development in the collaboration team.

An electron gun is required to generate a small emittance electron beam with a high-repetition rate. In Japan Atomic Energy Agency, we are developing a photocathode DC gun of 250 kV-50 mA for this purpose.[13] We have also demonstrated a high-performance AlGaAs photocathode, which has higher quantum, efficiency and longer life time than conventional GaAs cathodes.[14] As for the superconducting linac, design of cavity shape is completed and a prototype is under fabrication. The cavity is optimized for strong HOM damping to support high-average current operation over 100 mA.[15]

These R&D activities are basically for the future ERL X-ray light source in Japan, but the components under developments are absolutely common to the ERL gamma-ray source. Design of a gamma-ray source utilizing these ERL components is introduced in the next section.

IV. DESIGN OF AN ERL γ-RAY SOURCE

IV.A. Basic parameters

For radioactive nuclides of interest, NRF energy is around 0.5-4MeV. This range of gamma-ray energy can be covered by a combination of a 350-MeV ERL and a 1μm laser and its second harmonic. Figure 4 shows gamma-ray energy as a function of electron energy and laser wavelength.

The collision frequency of laser Compton scattering is restricted by length of the supercavity. In order to avoid interference of cavity mirrors and the electron beam, we chose the collision frequency at 130 MHz, the 10th subharmonic of the fundamental frequency of the superconducting cavity. With this choice of frequency, the supercavity is 1.153 m long, and mirrors of 6 cm in diameter can be installed at a crossing angle of 3.5 degree.

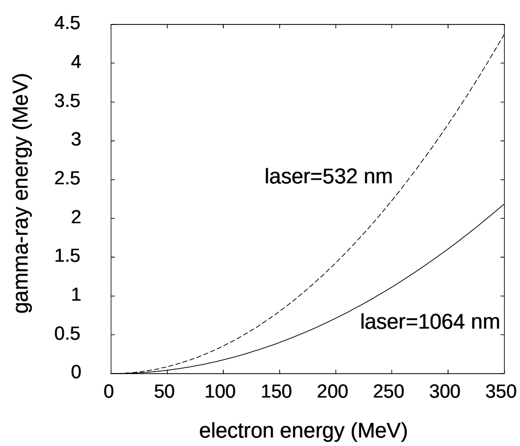

Fig. 4. gamma-ray energy as a function of electron energy and laser wavelength.

IV.B. Injector

The injector for the ERL gamma-ray source consists of a 500-kV DC gun, a 1.3-GHz buncher, and a superconducting booster as shown in Fig. 5, which is similar to that of an ERL X-ray source. The DC gun is equipped with a semiconductor photocathode, GaAs or AlGaAs, with Cs deposited on the surface. The surface with Cs deposition shows negative electron affinity, which is essential to extraction of electrons with thermal energy as small as room temperature.[16]

The design parameters of the injector are listed in Table 1. Electron bunches with 100 pC charge are produced at repetition of 130 MHz and accelerated up to 7 MeV by superconducting booster (2-cell, 2-cavity), which corresponds to a beam power of 90 kW (7 MeV, 13 mA). The injector performance has been confirmed by numerical simulations with PARMELA.[17] Simulation results show that transverse normalized emittance and the energy spread after the injector are 1.0 mm-mrad and 0.3%, respectively.

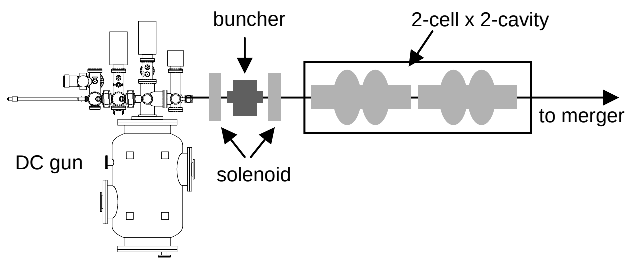

Fig. 5. Configuration of the ERL injector. The injector consists of a 500-kV DC gun, a normal conducting buncher and a superconducting booster (2-cell, 2-cavity).

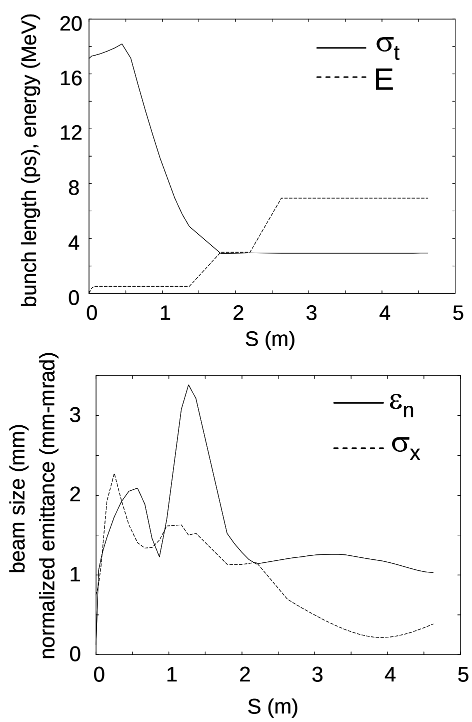

Fig. 6. Performance of the injector simulated by PARMELA. The upper plot shows electron energy E and bunch length σ_t, the lower plot shows normalized emittance ε_n and beam size σ_x along the beam path.

The accelerator gradient is 10 MV/m at the 1st cavity and 15 MV/m at the 2nd cavity. The smaller gradient at the 1st cavity is chosen to prevent emittance growth at the fringe field of the 1st cell entrance, where the electrons have small energy, 500keV, and time varying fringe field may cause emittance growth.

Two solenoid magnets before and after the buncher are for the emittance compensation. The focusing strength of two solenoid magnets to minimize the transverse emittance at the exit of the injector is determined by multi-variable optimization routine developed before.[18]

Since the injector does not receive benefit of energy-recovery, we need to install RF sources enough to produce the electron beam, 90 kW in our case, which can be provided by two 30-kW IOT's for each cavity.

TABLE I. Injector Parameters

Gun voltage	500 kV
Electron energy at the merger	7 MeV
Cathode diameter	3 mm
Bunch charge	100 pC
Bunch repetition	130 MHz
Initial normalized emittance	0.2 mm-mad
Normalize emittance at the merger	1.0 mm-mrad
Initial bunch length	20 ps (rms)
Bunch length at the merger	3 ps (rms)
Energy spread at the merger	0.3 %
Acc. Field (buncher)	1.2 MV/m
Acc. Field (1st SC cavity)	10 MV/m
Acc. Field (2nd SC cavity)	15 MV/m

IV.B. Main Linac and Return Loop

A 350-MeV ERL loop has been designed as shown in Fig. 7. The electron beam from the injector merges with the recalculating beam by 3-dipole merger. Longitudinal space charge force of an electron bunch along the merger modifies electron energy and results in dispersive motion after the merger, that is transverse emittance growth. This type of emittance growth can be suppressed by envelope matching technique.[19]

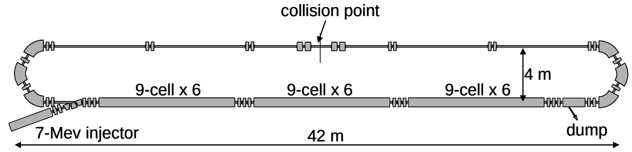

Fig. 7. Layout of the 350-MeV ERL.

The main linac utilizes 9-cell superconducting cavities under development for the 5-GeV ERL light source in Japan. The cavities are driven at 1.3 GHz same as International Linear Collider's frequency. The cavity shape is optimized for high-average current operation and shows excellent tolerance against beam breakup (BBU). The BBU threshold is calculated as 600 mA for the 5-GeV ERL and 1.1 A for the 350-MeV ERL. The main linac consisting of 18 superconducting cavities, which are divided into 3 modules and focusing quadrupole triplets are installed between the modules. The quadrupole magnets provide transverse focusing for both accelerating and decelerating beams. The final energy of 350 MeV is achieved by accelerating gradient of 20 MV/m.

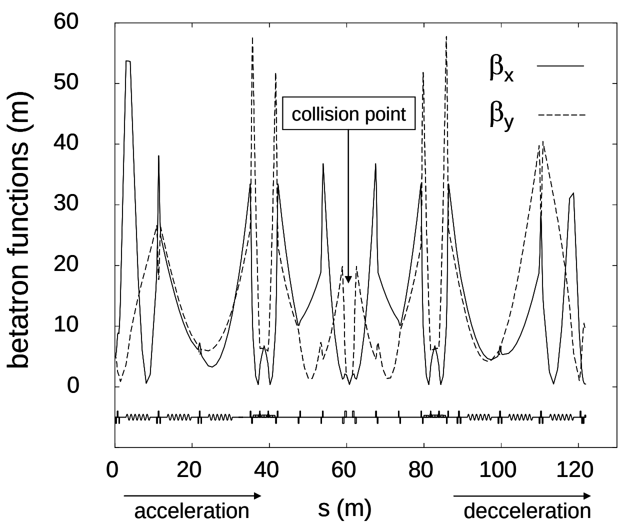

Fig.8. Betatron functions along the ERL loop from the merger to the dump.

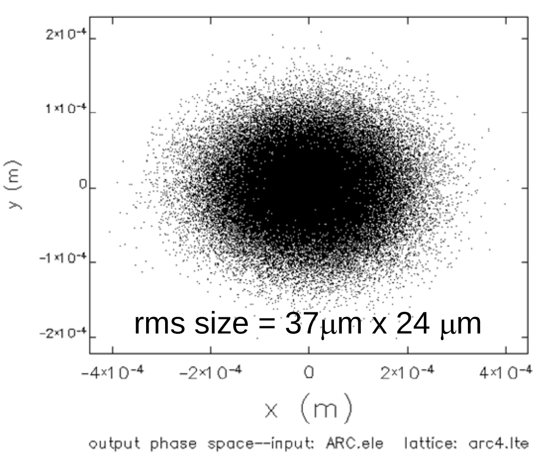

Fig. 9. Transverse profile of the electron beam at the collision point.

The loop consists of two triple-bend achromatic arcs, whose bending radius is 1.2 m and a quadrupole magnet is installed between two bending magnets. In general design of ERL loops, flexible momentum compaction is often desired for bunch compression. In the gamma-ray source, however, such flexibility is not necessary and we fix each arc as non-isochronous setting of R_{56}=1.4 m. This simple design realizes small footprint of the return arc.

The collision point for the laser Compton scattering requires small betatron function for both x and y planes to increase the electron density there. We have designed beam optics having $\beta x=\beta y=0.4$ m at the collision point as shown in Fig. 8. Assuming normalized emittance of 2.5 mm-mrad (x) and 1.0 mm-mrad (y), we have the RMS beam size 37 μm (x) and 24 μm (y) at the collision point, which are comparable to the laser spot size with Rayleigh length of 1.1 cm.

V. EXPECTED PERFORMANCE OF THE γ-RAY SOURCE

We employ a mode-locked laser with a gain medium of ytterbium-doped fiber, whose wavelength is 1064 nm. The laser is operated at 130 MHz and provides 2 ps pulses with 1.8 μJ energy, which corresponds to an average power of 234 W. The spot size at the collision point is chosen at 30 μm (rms of laser power density profile) equivalent to Rayleigh length of 1.1 cm. The supercavity is assumed to have an enhancement factor of 3000. All the parameters of the ERL gamma-ray source are listed in Table 2.

A gamma-ray flux for the ERL parameters listed in Table 2 and geometry of head-on collision can be estimated by Eq. (2), and found to be 2.8×10^{13} ph/sec, which gives spectral density of 1.5×10^{10} ph/sec/keV with an assumption of a flat spectrum. The more precise number of the flux and the spectral density can be calculated by Monte Carlo simulation code, CAIN.[20] Figure 10 is a result of CAIN simulation including all the inhomogeneous effects such as oblique collision, emittance and energy spread of the electron bunch, spatial distribution of laser and electron pulses, and so on. The result shows that the total flux is 1.0×10^{13} ph/sec and the spectral density around 2.1 MeV is 6.8×10^{9} ph/sec/keV. The flux and the spectral density obtained by Monte Carlo simulation are somewhat smaller than the analytical estimation because of inhomogeneous effects.

TABLE 2. Parameters of the ERL gamma-ray source

Electron beam	
Repetition	130 MHz
Energy	350 MeV
Bunch charge	100 pC
Normalized RMS emittance (x/y)	2.5 / 1.0 mm-mrad
RMS beam size at the collision (x/y)	37 / 24 μm

Pulse length (RMS)	3 ps
Energy spread (RMS)	3 E-4
Laser	
Wavelength	1064 nm
Repetition	130 MHz
Pulse energy	1.8μJ
RMS beam size at the collision	30 μm
Pulse length (RMS)	2 ps
Enhancement of supercavity	3000
Collision angle	3.5 degree
gamma-ray	
Energy (1064 nm laser)	2.2 MeV
Energy (532 nm laser)	4.4 MeV
Total flux	1 x 10^{13} ph/sec
Peak spectral density	6.8 x 10^{10} ph/sec/keV

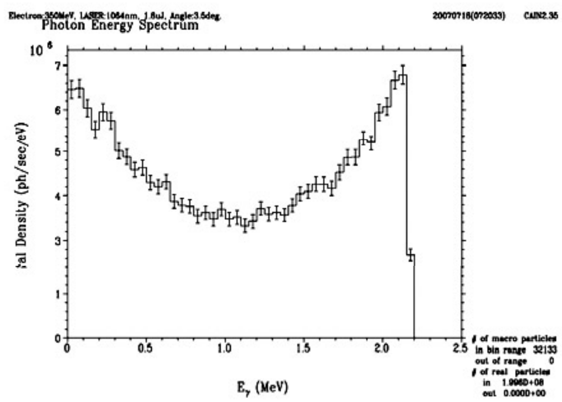

Fig. 10. Gamma-ray spectrum calculated by CAIN with parameters listed in Table 2.

Generation of quasi-monochromatic gamma-rays is possible in LCS by putting a collimator at downstream of the collision point. In our gamma-ray source, the energy spread of gamma-rays obtained by a collimator of 1 mm in diameter at 10 m from the collision point is found to be ΔE/E=10% (full width) from Eq.(1). The gamma-ray spectrum may be diluted by inhomogeneous effects, which is not included in Eq.(1). We have checked gamma-ray spectral broadening by electron beam emittance and non-zero crossing angle of the collision. Figure 11 shows results from CAIN simulations with a collimator of 0.1 mrad, where three gamma-ray spectra are shown: (1) for the design parameters in Table 2, (2) for zero-angle collision, (3) for twice larger electron beam emittance than the design parameters. These results emphasize the importance of small emittance for the generation of a quasi-monochromatic gamma-ray. In our design, we have carefully checked possible emittance growth and its compensation by simulations with PARMELA[17] and ELEGANT.[21] The simulations show that normalized emittance of 1 mm-mrad is obtained at the merger and 2.5/1 mm-mrad (x/y) at the collision point. The growth of emittance in x-plane is due to coherent synchrotron radiation in the arc.

In the nondestructive assay of nuclear waste using nuclear resonance fluorescence, measurement time required is a function of the NRF cross-section, a gamma-ray flux within the resonant width, and efficiency of detectors. We are investigating performance of the assay system using a modified version of GEANT4[22] including an NRF routine. In the simulations, it has been confirmed that the sharp cutoff of the higher-energy edge in the gamma-ray spectrum, as seen in Fig. 11, is essential to keep good signal-to-noise ratio in the NRF measurements. This is because that most of back-ground noise comes from Compton scattering of incident gamma-rays by electrons inside an object to assay and the noise has lower energy than the incident gamma-ray photons. Detail description of the NRF measurements is presented in an accompanying paper.[23]

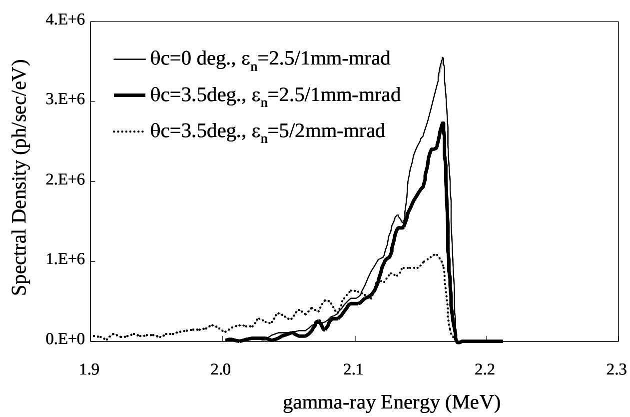

Fig. 11. Gamma-ray spectra with a collimator of 0.1 mrad. Three spectra are plotted for different beam emittance, ε_n, and collision angle, θ_c. These results show that small emittance is necessary to obtain a narrow spectrum.

VI. CONCLUSIONS

We have proposed a high-flux quasi-monochromatic gamma-ray source utilizing an energy-recovery linac and a mode-locked fiber laser. The energy-recovery linac generates a high-brightness electron beam with high-average current, and the fiber laser is scalable to high-average power operation. These excellent properties lead to significant enhancement of a gamma-ray flux from laser Compton scattering. We have designed a 2-4 MeV gamma-ray source based on a 350-MeV ERL and an ytterbium-doped fiber laser. The gamma-ray flux is expected to reach 10^9-10^{10} ph/sec/keV, which exceeds the performance of existing facilities by several orders of magnitude. We consider such a high-flux gamma-ray source with a help of nuclear resonance fluorescence is applicable to nondestructive assay of radionuclides for the management of radioactive wastes.

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