PRODUCTION OF QUASI-MONOCHROMATIC PHOTON BEAMS FROM COMPTON BACKSCATTERED LASER LIGHT AT ELECTRON STORAGE RING

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ABSTRACT

Generation of quasi-monochromatic photon beams of energy variable between 1.7-6.5 MeV has been observed by inducing the Compton backscattering of Nd-YAG laser light on electrons of energy 305-606 MeV at the injection straight section in an electron storage ring of Electrotechnical Laboratory. The experimental method and some of the spectra obtained are presented.

INTRODUCTION

Since the prediction of Milburn,[1] and Arutyunian and Tumanian[2] on the production of high-energy quasi-monochromatic photon beams by exploiting the backward Compton scattering of laser light from a high-energy electron beam, some experiments have been made at synchrotrons[3,4] and a linac.[5] The method is characterized by excellent signal-to-noise ratio and rather low intensity compared with other two methods, the annihilation in flight and the so-called channeling radiation. Storage rings are most suitable for this purpose because of the high effective beam current. The first experiment at a storage ring was achieved at Frascati.[6] The present experiment is the second using a storage ring and the first in the rather low energy region.

THEORETICAL BACKGROUND

The kinematics associated with the scattering is quite simple. The process is schematically shown in Fig. 1 with angles greatly exaggerated in the case of laboratory frame. Note that $K_1 \simeq 2\gamma k_1$ where $\gamma = E/\mu$ with μ being the electron rest mass. The final photon energy k_2 in the lab. frame is written

$$k_2 = k_1(1-\beta\cos\theta_1)/[1-\beta\cos\theta_2 + k_1(1-\cos\chi)/E] \qquad (1)$$

where $\chi = \theta_2 - \theta_1$ and $\beta = v/c$ with v and c the velocities of of the electron and light. Eq. (1) is greatly simplified by a small-angle approximation valid when $\gamma \gg 1$, in the case of head-on collision ($\theta_1 = \pi$), as[7]

$$\rho \equiv k_2/k_{2max} \simeq [1+a(\gamma\theta_2)^2]^{-1} \qquad (2)$$

$$k_{2max} \simeq 4\gamma^2 k_1 a \qquad (3)$$

$$a \simeq [1+4\gamma k_1/\mu]^{-1} \qquad (4)$$

where a is regarded as a measure of the extent to which electron recoil spoils the double Doppler enhancement, $4\gamma^2$, of the incident quantum energy. Eq. (1) or (7) shows that the energy of the final photon is uniquely determined by the angle θ_2, so that a collimation in the backward cone of angles will narrow the photon spectrum

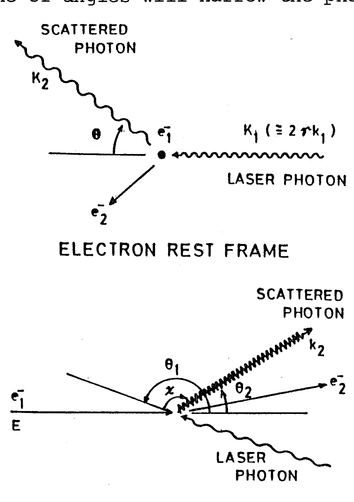

Fig. 1 Schematics of laser + electron scattering.

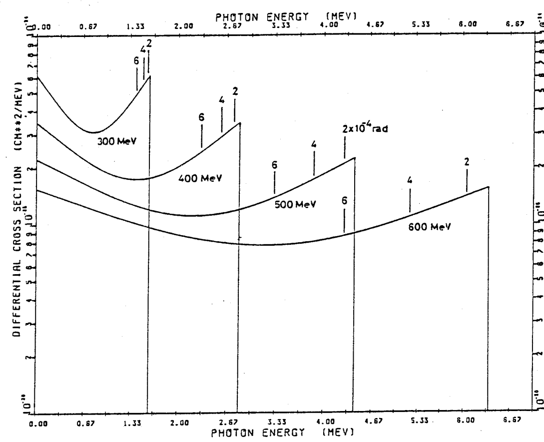

Fig. 2 Theoretical photon spectra.

confined to a region between k_{2max} and some low-energy cut-off k_{2min}.

The Klein-Nishina formula, summed over final spin and polarization states and averaged over initial states, and after the Lorentz transformations, is expressed, for the head-on collision, as follows:

$$d\sigma_t/d\Omega = 2[r_0 k_2/(\mu x_1)]^2$$
$$\times[4(1/x_1+1/x_2)^2 - 4(1/x_1+1/x_2) - (x_1/x_2 + x_2/x_1)] \qquad (5)$$

$$x_1 = -(2\gamma k_1/\mu)(1-\beta\cos\theta_1) \qquad (6)$$

$$x_2 = (2\gamma k_2/\mu)(1-\beta\cos\theta_2) \qquad (7)$$

where r_0 is the classical electron radius. Note that cross section is strongly forward-peaked. Though there is a very interesting feature that most of the polarization of incident light is retained, it will not be discussed here. The energy spectra of final photons calculated from Eqs. (5) and (1) are shown in Fig. 2 for a few electron kinetic energies T=E-μ. The figure upon each vertical bar indicates the scattering angle θ_2 in units of 0.1 mrad. Obviously, the collimation is critical in this kind of experiment especially for higher electron energies.

The ideal photon yield per pulse is given by

$$Y = 2N_e N_p \sigma d/(A c\tau) \qquad (8)$$

where N_e and N_p are the total number of electrons and light quanta per pulse, σ is the cross section integrated over θ_2 from zero to the collimation half-angle θ_c, d is the average interaction length, and A and τ are the larger of the cross-sectional areas and pulse lengths of electron and photon beams. Eq. (8) is ideal in that it assumes no divergence of incident electron and photon beams. Table 1 shows the yields according to

Table 1

Ideal photon yields

T (MeV)	k_{2max} (MeV)	θ_c (mrad)	Δk_2 (MeV)	$\Delta k_2/k_{2min}$ (10^{2})	σ (barn)	Y (γ/s/mA/W)
		0.1	0.0055	0.34	0.0034	11
		0.2	0.022	1.4	0.013	44
300	1.61	0.3	0.048	3.1	0.029	96
		0.4	0.084	5.5	0.049	164
		0.5	0.13	8.6	0.073	242
		0.1	0.086	1.4	0.013	44
600	6.38	0.2	0.33	5.5	0.049	162
		0.3	0.70	12	0.097	324
		0.4	1.1	22	0.15	497
		0.1	0.27	2.4	0.023	76
800	11.3	0.2	1.0	9.7	0.080	265
		0.3	2.0	22	0.15	493

Eq. (8) with d=1.5 m, A=10 mm^2 (laser beam), and τ=1 sec (continuous in the present case), for various T and θ_c. The above conditions are close to the present experimental ones. $\Delta k_2=k_{2max}-k_{2min}$, and Y is the photon number per 1 sec with 1-mA electrons circulating in the ring and the laser beam power 1 W.

EXPERIMENT

The present experiment has been made at the injection straight section of a storage ring of Electrotechnical Laboratory[8] injected by a linac.[9] The experimental arrangement is shown in Fig. 3. A Nd-YAG laser beam (λ=1.0641 μm and the power 0.7-1.2 W) enters the window of a vacuum chamber inside the bending magnet denoted by DSR-1 after being reflected by a mirror and passig through a lens (f=2.0 m), and then interact with the stored electron beam at the straight section between the DSR-1 and the DSR-8. The photons survived goes out of the window of a vacuum chamber inside the DSR-8. The size of the laser beam is about 4 mmϕ just before the focusing lens and about the same height and 8 mm wide at the exit window because of curved shape of the entrance window. The spectrum of the laser light has been accurately measured by a calibrated monochromator and a silicon photodiode after a slit to be peaked at 1.06413 μm with FWHM 2.1×10^{-5} μm. The laser power is monitored occasionally after the exit window.

The lead collimator consists of two blocks with the face 100×100 mm^2 and the length 150 mm with holes of 0.9 -3.9 mmϕ in the center. The block closer to the Ge detector is the actual collimator and the other in front is an auxiliary one for the shielding against the bremsstrahlung background. The collimator is manually movable perpendicular to the beam line to be adjustable to the line, since the electron orbit slightly changes with energy. The distance between the centers of the interaction region and the actual collimator is 8.0 m. The photon spectra are measured by a 33.9-cm^3 pure Ge detector and the pulse signal is sent, after amplification, to a pulse height analyzer (PHA) in a measurement room located about 150 m apart. A single-channel analyzer with a scaler is connected to the amplifier output in order to make the search for the beam centerline easy.

At the earlier stage of the present experiment, there were no good collimators, and a collimator of 100 ×100×100 mm^3 block with a tapered aperture of 2.8-5.9 mm ϕ, and that with an aperture of 14.8 mmϕ, which happened to be at hands, were used. At the time, the distance between the centers of the interaction region and the collimator was 6.9 m, and the focusing lens in front of the entrance window was not used. The laser beam size in this case was measured to be 8.0 mmϕ (FWHM) just after the exit window by the use of a silicon photodiode. This arrangement will be called in this report the old arrangement, in contrast to the new one of Fig. 3.

RESULTS AND DISCUSSION

Some of the photon spectra obtained are shown in Figs. 4-6. Each of the figures titled (a) shows the total spectrum (LCS+BG), the background spectrum due to bremsstrahlung radiation and natural background (BG(B+N)), and the contribution of the natural background (BG (N)). The BG(B+N) spectrum was measured just after each total spectrum had been obtained, and the natural BG was measured at some later time with no beam in the ring. The amount of natural BG is, of course, proportional to the counting time, while the bremsstrahlung BG is roughly proportional to the beam loss since the electron beam current always decays. Then the BG subtraction was done as follows. First, the natural-BG spectrum measured later was normalized to that during the BG(B+N) measurement by the sums of peak areas of ^{40}K and ^{208}Tl by assuming the same spectral shape. The contribution of the natural BG to the total spectrum was then determined, scaling with counting time, since the detector setting was the same for the scattering experiment and the BG(B+N) measurement. After subtraction of the natural-BG component from both the total and the BG(B+N) spectra, the remaining BG spectrum was normalized to that in the total spectrum by the count sums of the highest-energy parts where only the bremsstrahlung radiation contributed, and the bremsstrahlung component of the BG was subtracted from the total (-natural BG) spectrum. The final spectrum is shown in (b) in each figure, which is due solely to the scattered photons. The procedure is important when the laser-beam power is low, as in the present case. The beam currents at the beginning and at the end of the counting are written in each figure. The aperture size of the auxiliary collimator is written between the parentheses. The arrow shows the photon energy k_{2min} corresponding to the collimation half angle.

Fig. 4 shows the result of a measurement in the old arrangement with electron energy 338 MeV. The background problem is moderate at such low energy. Fig. 4 (b), after the BG subtraction, demonstrates clearly the full-energy peak. The peak-to-Compton ratio is not very good because of the small detector size. Ideally, the spectrum should show a sharp cut-off at k_{2min}, but it is not seen clearly in the figure. Even if the multi-Compton events in the detector are taken into account, the peak seems to be too dull. One of the reasons is a divergence θ_e of the electron beam in the ring. Although the divergence has been measured[10] to be less than 0.1 mrad, θ_c in this case is only 0.3 mrad. The

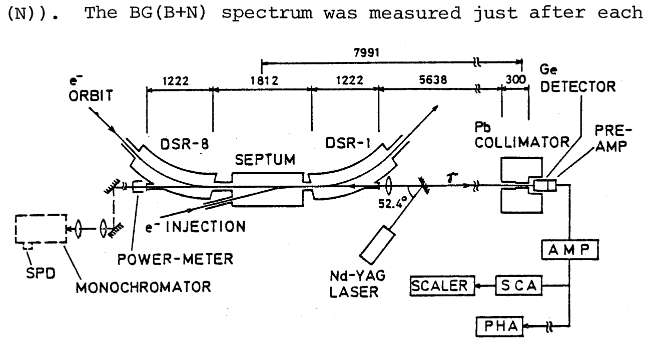

Fig.3 Experimental arrangement.

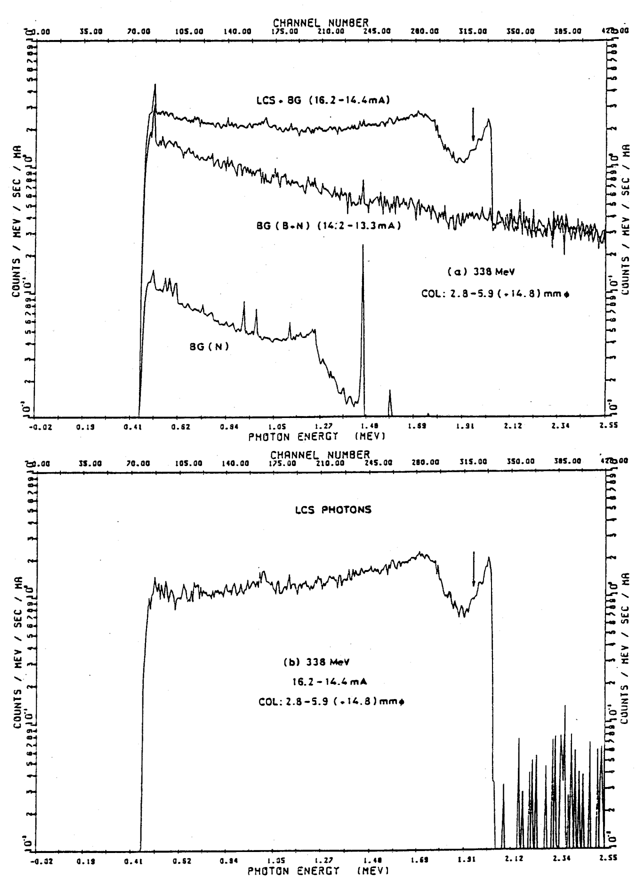

Fig. 4 Photon spectra with T=338 MeV (old arrangement).

photon energy resolution is not determined only by θ_c as in the ideal case described before but actually by

$$\Delta\theta = (\theta_e^2+\theta_c^2)^{1/2} \tag{9}$$

Secondly, the laser beam sees not only the straight electron beam but the small parts of the curved orbit at the exit of DSR-8 and at the entrance of DSR-1 also. Finally, a small misalignment of the collimator from the beam axis might have enlarged the peak width. A simulation or a Monte Carlo calculation is necessary to resolve these effects, though it has not been tried yet in the present work.

The photon spectra in the new arrangement with almost the same electron energy as in Fig. 4 are shown in Fig. 5 for comparison. The effect of the narrower collimator is drastic. The width of the full-energy peak is almost half of that in Fig. 4. The cut-off, however, is not seen again. The problem of the beam divergence etc. discussed above is even more serious in this case of better collimation. The absolute yield is smaller than that in Fig. 5. This is natural because of the above effects, and furthermore, the small collimation aperture is comparable with the horizontal beam width of the stored electrons. Note that the problem of the bremsstrahlung BG is less serious in the new arrangement, while the effect of the natural BG is relatively prominent partly because of the low current of the electron beam. The sharp dips seen in Fig. 6(b) is due to a failure to adjust strictly the amplifier gain and the PHA zero point in the measurement of natural BG.

The photon spectra obtained with electron energy 501 MeV are shown in Fig. 6. The full-energy peak is seen clearly even at such high energy and with the poor counting efficiency of the detector. The problem of the bremsstrahlung BG becomes serious as the energy increases.

Similar spectra with electron energies higher than 600 MeV have also been obtained, though they are not shown in the present report because of the lack of space.

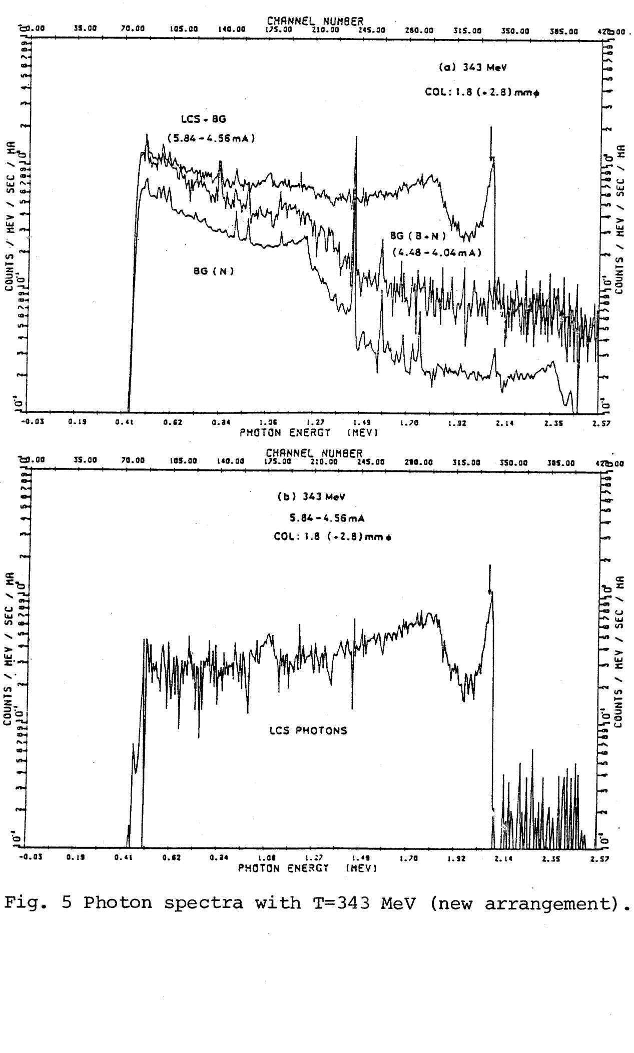

Fig. 5 Photon spectra with T=343 MeV (new arrangement).

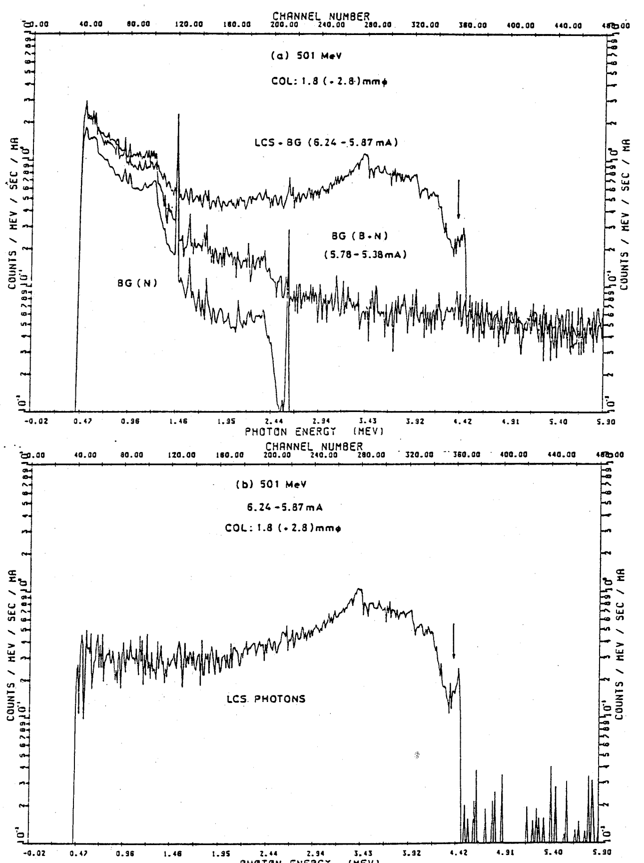

Fig. 6 Photon spectra with T=501 MeV (new arrangememt).

CONCLUSIONAL REMARKS

The generation of quasi-monochromatic photon beams with energy variable between 1.7-6.5 MeV has been successfully confirmed in the present series of experiments. Though the absolute photon yields have not been measured accurately yet, they are considered to be about 1/4 to 1/8, depending on the collimation, of those shown in Table 1 by assuming the absolute full-energy-peak efficiency to be of the order of 1×10^{-2} at 1 MeV and 1×10^{-3} at 6.5 MeV. The problem is so important in the practical use of the photon beam that they will be measured precisely by the use of a large NaI scintillation detector. A 100-W Nd-YAG laser will be introduced also in the near future, so that the BG contribution will become negligible. Finally, this phenomenon is useful for quantitative beam studies in storage rings, as has been pointed out by Sauer et al.[11] Especially, the present experiment is efficiently applied to the determination of the electron energy because the maximum photon energy is precisely determined from the electron energy through Eq. (1). The data have already been delivered to some users of the ETL storage ring.

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