High-Energy Photons from Compton Scattering of Light on 6.0-GeV Electrons*

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Compton scattering of optical photons on 6.0-GeV electrons has been observed at the Cambridge Electron Accelerator. A giant-pulsed ruby-laser burst of 0.2 J, impinging upon a 2-mA circulating electron current, was observed to yield about 8 scattered photons per pulse. These photons acquire, through a twofold Doppler shift, energies of hundred of MeV, and are expected to retain to a high degree the polarization of the laser beam. The observed yield is compatible with predictions based upon the theory of Compton scattering.

THE scattering of optical photons from a laser on extreme-relativistic electrons has been predicted[1–3] to yield a high-energy output photon beam which preserves to a high degree the polarization of the incident light beam. Photons of energy up to 0.85 GeV are expected from the interaction of 6943-Å quanta from a ruby laser and 6-GeV electrons available from existing accelerators. It is also predicted by the Klein–Nishina formula that the spectrum of the outgoing photon number is roughly constant; it varies only by a factor of about 2 in the energy range 0–0.85 GeV, which may be compared with the $1/E$ dependence of normal bremsstrahlung. The theory also predicts that a plane-polarized light beam (as available from a laser) will yield plane-polarized output photons. The degree of polarization depends upon the outgoing photon energy and has a maximum of better than 99% for the 0.85-GeV end of the output spectrum. Our observations confirm the existence of this effect for multi-GeV electrons.[4] The output yield is consistent with an approximate calculation based upon the interaction geometry. These results confirm the possibility of using polarized photon beams produced by Compton scattering for the study of high-energy phenomena in bubble and spark chambers.

This experiment used the internal 6-GeV electron beam of the Cambridge Electron Accelerator (CEA). The active element of the Q-switched laser was a pink X-cut ruby crystal, 1 cm in diameter and 7 cm long. One end was provided with a multilayer dielectric coating, about 60–70% reflecting at 6943 Å; the other end was uncoated. The ruby was mounted in a commercial laser cavity, a cylindrical reflector, together with and parallel to a single flash lamp.[5] The optical pumping energy was normally between 750 and 850 J. Total measured output energies were typically about 0.2 J appearing in two or three giant pulses, each about 30 nsec wide and 200–300 nsec apart. Electrical pulses derived from the rotating Q-switch prism and from the synchrotron peaking-strip were put, after suitable delays, into coincidence to trigger the pumping flash lamp; this resulted in laser output pulses occurring only during the desired time when the circulating electron beam was at full energy.

The injection system for bringing the laser and electron beams into head-on collision, together with the rest of the apparatus, is shown schematically in Fig. 1. The laser beam is directed toward a lens of 2.5-in. clear aperture and 96-in. focal length. This lens, which is made of radiation resistant glass, forms the entrance window to the accelerator vacuum. The laser beam then impinges on a thin mirror and is reflected upstream along a line tangent to the circulating electron beam at one of the synchrotron's straight sections. The resulting interaction region is about 3 ft long. The lens and the flat mirror combine to focus an image of the laser aperture at the point where the laser and electron beams intersect. Energetic photons produced by Compton scattering then pass back along the tangent line, through the mirror, through a 0.002-in. stainless-steel vacuum window, and out into the experimental area. The optically flat mirror is made of 0.2-in. quartz, coated with a dielectric multilayer to reflect a maximum of 6943-Å light at a $7\frac{1}{2}°$ angle of incidence. During runs, the synchrotron radiation progressively destroyed the reflective coating in a horizontal band about 0.25 in. wide. To protect the mirror from accelerator-synchrotron-radiation damage between experimental runs, a remotely controlled 0.25-in. thick stainless-steel curtain was interposed between the mirror and the electron beam.

Two factors govern the choice of this injection optics.

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[1] Richard H. Milburn, Phys. Rev. Letters **10**, 75 (1963).
[2] F. R. Arutyunian and V. A. Tumanian, Phys. Letters **4**, 176 (1963).
[3] F. R. Arutyunian, I. I. Goldman, and V. A. Tumanian, Zh. Eksperim. Teor. Fiz. **45**, 312 (1963) [English transl.: Soviet Phys.—JETP **18**, 218 (1964)].
[4] There is recent experimental evidence that this mechanism, when applied to 600-MeV electrons, leads to observable photons with energies up to 7 MeV. See O. F. Kulikov, Y. Y. Telnov, E. I. Filippov, and M. N. Yakimenko, Phys. Letters **13**, 344 (1964).
[5] TRG Inc. Model 104 ruby laser, with EG&G type FX-42 lamps.

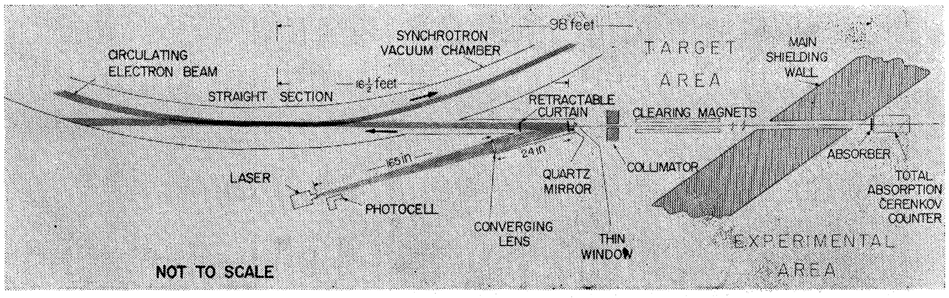

FIG. 1. Injection system and experimental geometry.

First, the normal laser beam results, at high powers, from the excitation of many cavity modes and diverges with a typical angle of 10 mrad. A focusing element is therefore needed to concentrate this light beam in the interaction region. Second, the synchrotron structure requires that optical elements be placed a minimum of about 15 ft from the interaction region, and also imposes restrictions upon the vertical entrance aperture. The laser beam injection was aligned optically by means of an externally illuminated vertical wire placed in the desired interaction region inside the accelerator straight section and sighted from the laser position. Final alignment was established by observing the illumination of the wire by the laser light. The wire used actually served at the synchrotron target for the production of normal bremsstrahlung beams. Prior experience with this target, together with staining from the circulating electron beam, enabled the interaction point to be established vertically within a few hundredths of an inch. From visual observations involving horizontal scanning of the focused laser beam across this target wire, it was estimated that the bulk of the light energy lay within an irregular figure of about 0.2- to 0.25-in. maximum diameter. This target wire was, of course, withdrawn during observations of the Compton scattering.

The interaction region was located in a straight section of the synchrotron and about 1.15 in. inward from the normal equilibrium orbit. The orbit was locally perturbed by a "beam bumping" technique in such a way as to steer the circulating beam into position at the desired time when the laser was fired. It was possible to sweep the electron beam horizontally across the interaction region. The cross section of the electron beam depends upon energy. At 6 GeV we estimate it to measure about 0.25 in. horizontally and 0.12 in. vertically. These dimensions are inferred from scanning the electron beam across a target wire, and from the height of synchrotron-radiation stains on the vacuum chamber, the target wire, and the mirror surface.

After leaving the accelerator, the output beam of scattered photons is roughly collimated and passed through an array of permanent clearing magnets totalling 16 kG-ft. It then passes through a 16 ft long, 4-in. diameter hole in the main shielding wall into a total absorption Čerenkov counter[6] consisting of a square array of four 8-×8-×70-cm bars of lead glass. Each glass is viewed by a photomultiplier, and the four outputs are added into one common signal. This counter was calibrated at CEA in an analyzed secondary positron beam of very low intensity and the high voltages were chosen to obtain linearity up to 6 GeV and to provide uniformity. This counter easily subtended the expected high-energy photon beam from the Compton scattering, but no actual tests of the collimation efficiency were made beyond a careful geometrical alignment. A $\frac{1}{4}$-in. iron plate was placed in front of the Čerenkov counter to absorb the soft photon radiation from circulating electrons.

To monitor the laser firing, a photomultiplier was mounted near the laser and arranged in such a way as to view stray optical reflections. Provided with a deep red filter, this photomultiplier gave a strong-fast signal from the laser output light. The approximate total intensity of the circulating electron beam was given by a signal from pickup electrodes. The primary component of the signal was the 1.3-Mc/sec electron orbital frequency, while the detailed pulse shape and height reflected the gross bunching of the electrons around their orbit, and their intensity.

After suitable inversion, gating, and delaying, the signals from the laser light, Čerenkov counter, and instantaneous electron-beam-intensity were displayed in this order on a common trace in an oscilloscope triggered by the initial laser output pulse. In this way the relative phases of the various signals were locked together throughout the run. Typical oscilloscope traces are shown in Fig. 2. Positive pulses are from the light output of the laser (at the beginning of trace) and from successive passes of the circulating bunch of electrons (at the end of trace). Negative pulses are from the Čerenkov counter. Timing measurements were made from the leading edges of the three laser pulses.

Save for occasional background pulses located randomly along the trace, most of the Čerenkov pulses are closely correlated in time with the laser output, as illustrated by the pulse-delay distribution of Fig. 3. The three peaks are identified as associated with energetic Compton-scattered photons from the first, the second, and the third laser pulses, respectively. The sharp definition of the last two peaks reflects the rather uniform spacing of the successive laser pulses. These peaks become even sharper if the delay of each pulse is

[6] We are grateful to Dr. P. D. Luckey for the loan of this counter assembly.

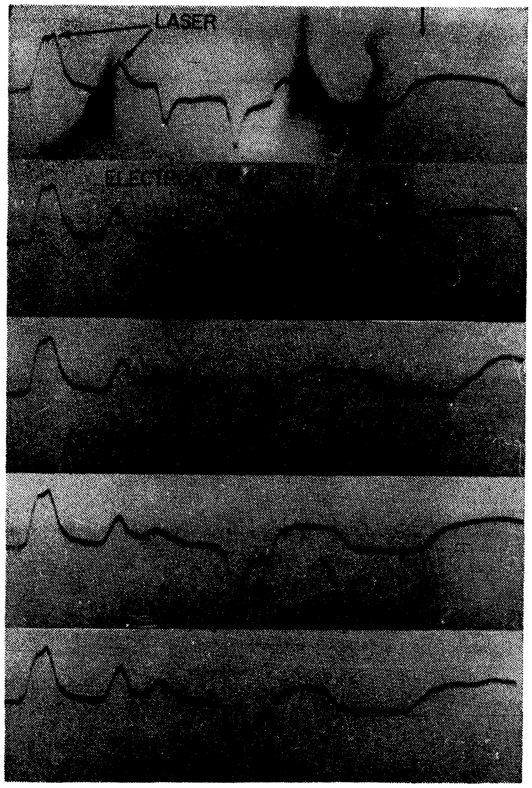

FIG. 2. Typical oscilloscope traces. From left to right: (1) laser output pulses (positive), (2) Čerenkov pulses (negative), (3) total electron-beam-intensity signals (positive). Arrow shows onset of first laser pulse.

taken with respect to its parent laser pulse. The full width at half-height of these peaks, and therefore of the laser output pulses, is about 30 nsec. The Čerenkov-counter signals are evidently correlated directly with the laser output.

Evidence that the same Čerenkov pulses are also correlated with the presence of the orbiting electrons is shown in Fig. 4. A set of pictures was taken in which there *existed* a Čerenkov pulse in the proper time correlation with the first laser pulse. For these pictures the

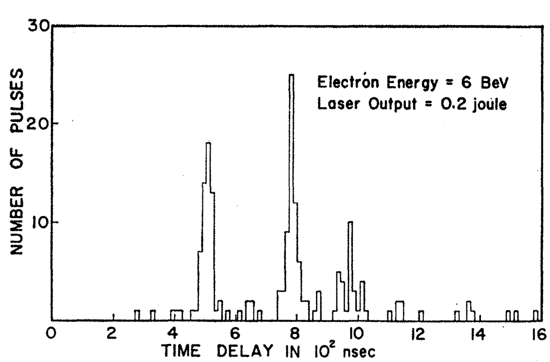

FIG. 3. Delay distribution of Čerenkov pulses referred to first laser pulse.

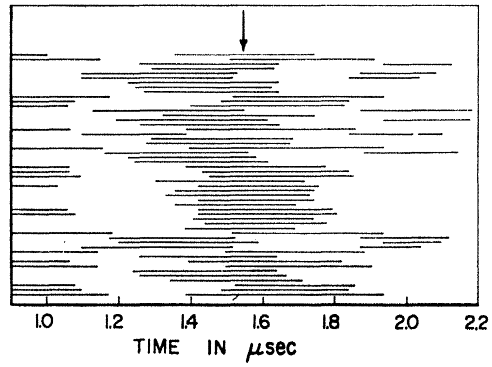

FIG. 4. Time distribution for beam-intensity signals, when a Čerenkov pulse occurs *within* time interval associated with first laser pulse. Horizontal bars represent time interval during which beam-intensity signal is larger than half-maximum. Arrow locates *maximum* of signal density.

time interval during which the beam-intensity pulse was larger than half its maximum was measured. This interval, for each event, is plotted as a line in Fig. 4, on a time scale relative to the first laser pulse. It is evident that virtually all the intensity pulses overlap a common time delay. The arrow locates the maximum of this signal density. A similar plot of events for which there was *no* Čerenkov pulse during the time interval associated with the first laser pulse is shown in Fig. 5. Very few intensity pulses overlap the common time delay found in Fig. 4. The arrow locates the minimum of the beam-intensity signal density. It is seen that both distributions complement each other in the sense that the maximum of one coincides with the minimum of the other. The value of this delay makes it possible to obtain an estimate of the instantaneous electron current associated with a particular Čerenkov pulse. There being no apparent time correlation between the laser output and the orbital electron bunching, we conclude that the bulk of the observed Čerenkov output occurs only when both orbiting electrons and laser photons are present

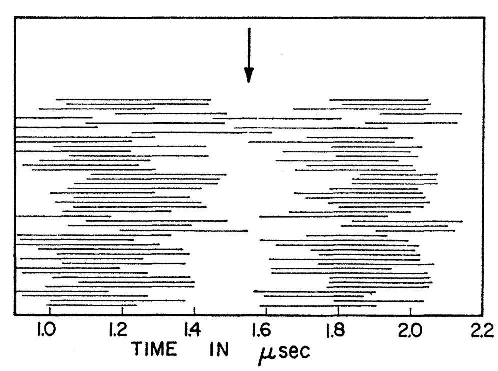

FIG. 5. Time distribution of beam-intensity signals when a Čerenkov pulse occurs *outside* time interval associated with first laser pulse. Horizontal bars represent time interval during which beam-intensity signal is larger than half-maximum. Arrow locates *minimum* of signal density.

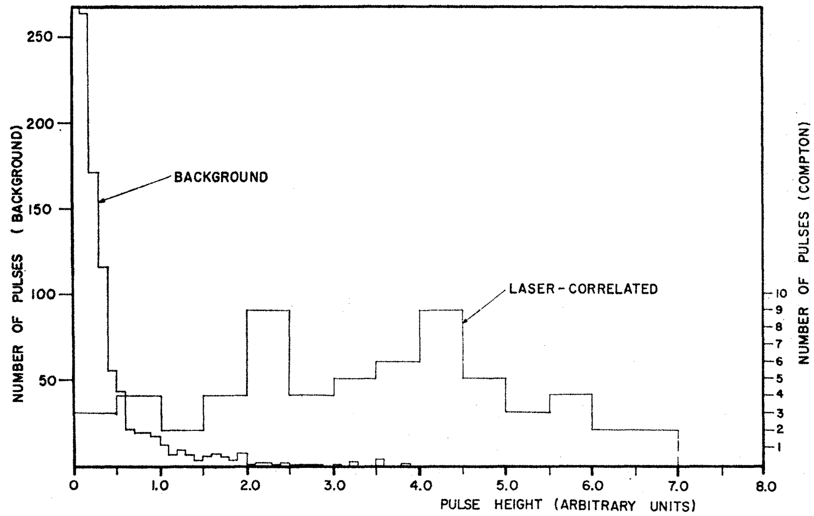

FIG. 6. Čerenkov-counter pulse-height distributions. Laser-correlated pulses are associated with second laser pulse. (2.3 units=3 GeV).

simultaneously in the interaction region, and hence that it results from the predicted Compton-scattering process. Also observed was a background of Čerenkov pulses, usually small, which was independent of laser operation and phased only with the electron beam. This background increased with the residual gas pressure in the vacuum chamber, and was quantitatively consistent with bremsstrahlung from the gas and related secondary processes.

Were the typical larger laser-correlated Čerenkov pulses due to single photons, their measured pulse heights would correspond to 6- to 8-GeV quanta. They were, in fact, comparable to the largest background bremsstrahlung pulses (see Fig. 6). Identifying the laser-correlated Čerenkov pulses with the Compton-scattering process, the spectrum of which predicts a mean output photon energy of about 425 MeV, one infers that they must be composite with 15–20 photons present on the average. Some of the Čerenkov pulses indeed showed evidence of such structure (see Fig. 2). By this argument, we then infer that an average of about 8 scattered photons were entering the Čerenkov counter during each laser firing. The heights of these composite Čerenkov pulses were proportional, within statistics, to the product of the electron beam and laser light intensities at the instant of passage of the laser pulse (see Fig. 7).

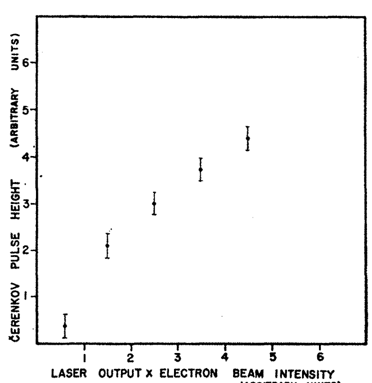

FIG. 7. Variation of laser-correlated Čerenkov signals with the product of laser output and electron-beam intensity.

The measured laser output was about 0.2 J, or 7×10^{17} photons, per pulse, and the circulating electron current was about 2 mA, or 10^{10} electrons per cycle. The total Compton cross section at 6 GeV being 575 mb and the laser pulses being much shorter than the synchrotron period, the predicted average yield per laser pulse is thus 40 scattered photons, or about five times the observed number. The measured 20% efficiency is not considered unreasonable in view of our present inability during accelerator operation to optimize the interaction geometry or to measure the injected light energy.

Our results are compatible in order of magnitude with the theory. They indicate that a useful output beam of Compton-scattered photons can be readily obtained with a practical efficiency of at least 10% and form an experimental basis for extrapolation to more intense or more energetic systems.

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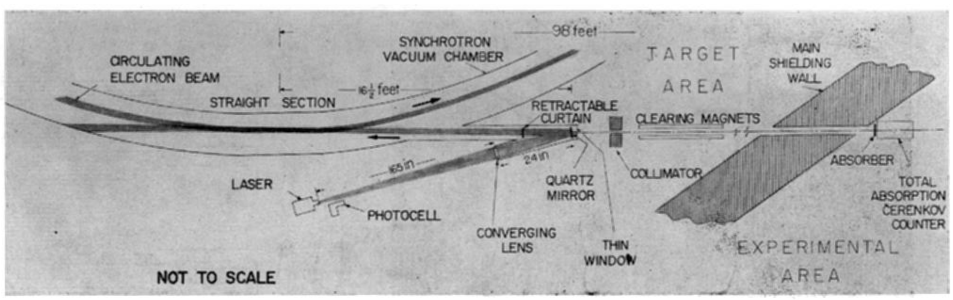

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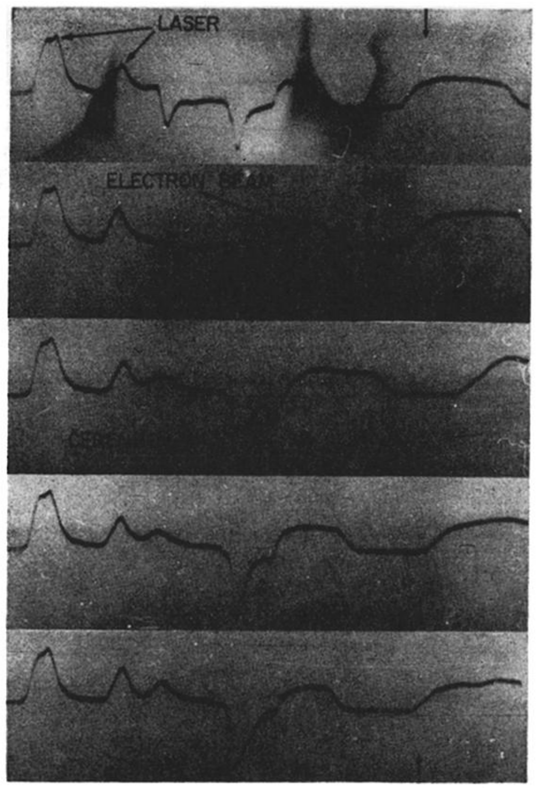

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