Gamma-Ray Production in a Storage Ring Free-Electron Laser

V. N. Litvinenko, B. Burnham, M. Emamian, N. Hower, J. M. J. Madey, P. Morcombe, P. G. O'Shea, S. H. Park, R. Sachtschale, K. D. Straub, G. Swift, P. Wang, and Y. Wu
Free Electron Laser Laboratory, Department of Physics, Duke University, Durham, North Carolina 27708

R. S. Canon, C. R. Howell, N. R. Roberson, E. C. Schreiber, M. Spraker, W. Tornow, and H. R. Weller
Department of Physics, Duke University, and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708

I. V. Pinayev, N. G. Gavrilov, M. G. Fedotov, G. N. Kulipanov, G. Y. Kurkin, S. F. Mikhailov, V. M. Popik, A. N. Skrinsky, and N. A. Vinokurov
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

B. E. Norum
University of Virginia, Charlottesville, Virginia 22901

A. Lumpkin and B. Yang
APS, Argonne National Laboratory, Argonne, Illinois 60439
(Received 24 February 1997)

A nearly monochromatic beam of 100% linearly polarized γ rays has been produced via Compton backscattering inside a free electron laser optical cavity. The beam of 12.2 MeV γ rays was obtained by backscattering 379.4 nm free-electron laser photons from 500 MeV electrons circulating in a storage ring. A detailed description of the γ-ray beam and the outlook for future improvements are presented. [S0031-9007(97)03322-X]

PACS numbers: 41.60.Cr

One of the applications of Compton backscattering has been the generation of high energy γ rays. The head-on collision of relativistic electrons and photons creates a pencil-like beam of γ rays whose exact energy, E_γ, depends on the angle (θ) between the direction of the incident electrons having energy E_e, and the generated γ rays. For the case of $\gamma = E_e/m_e c^2 \gg 1$, we have

$$E_\gamma \cong \frac{4\gamma^2 E_{\rm ph}}{1 + (\gamma\theta)^2 + 4\gamma \frac{E_{\rm ph}}{m_e c^2}}, \qquad (1)$$

where $E_{\rm ph}$ is the energy of the initial photons. Clearly, E_γ peaks at $\theta = 0$. The strong dependence of the γ-ray energy on its outgoing angle makes the use of a collimator as a means to produce nearly monoenergetic γ rays an attractive possibility, although the ultimate energy resolution $\Delta E_\gamma / E_\gamma \cong (\gamma\theta)^2$ is, in the most interesting cases, limited by the angular divergence and energy of the electron beam. This divergence is defined by the emittances and the β functions (where $2\pi\beta$ is the local wavelength of the transverse oscillation) of the electron beam at the point where the photons and electrons collide.

Currently operating γ-ray production facilities use conventional laser photons backscattered from ultrarelativistic electrons in storage rings and linacs [1,2]. At present, the appearance of third generation storage rings with extremely low emittances and high power free-electron lasers (FELs) is giving rise to a new generation of monoenergetic γ-ray facilities. In storage ring FELs, the same electrons which are used to generate light also collide with it to produce γ rays. Besides being able to realize nearly monoenergetic beams by means of simple collimation (due to the low emittances), an FEL having high intracavity power is expected to result in an enhancement of flux by a factor of more than 10^3 compared to that produced using conventional laser beams [3–5]. This method of γ-ray production, proposed as early as 1983 [6], has some additional advantages which include (i) the alignment of the electron and the optical beams required for operation of the FEL guarantees the alignment for γ-ray production, (ii) simultaneous measurement of the energy of the recoiling electrons (tagging) is not required so that the useful γ-ray flux is neither limited by the tagger count rate nor the frequency at which γ rays are produced, (iii) picosecond electron bunches and optical pulses are naturally synchronized, and (iv) continuous tuning of the FEL provides for a smooth variation of the γ-ray energy.

This technique has already been used to generate x rays using low energy linac-driven FELs [7,8]. We recently learned of γ-ray production at other facilities based on Compton backscattering and FELs [9–11].

The γ-ray beams which will be available using this method of production will have properties which open up many new possibilities for basic research and applications. For example, we are developing a nuclear physics research program, designed to exploit the flux, energy resolution, and polarization of the presently available γ-ray beams [5]. We are also investigating a number of other applications of the γ-ray beam, including precision

γ-ray transmission radiography, cancer therapy, and positron beam production.

The present scheme is illustrated in Fig. 1. The 1.1 GeV race-track shaped Duke electron storage ring has demonstrated the ability to store an average current of 155 mA at an injection energy of 230–280 MeV. The demonstrated ramping capabilities of this ring provide for an operational beam energy from 230 MeV up to 1.1 GeV. Low emittances (at 500 MeV $\epsilon_x = 4.5$ nm rad and $\epsilon_y < 0.4$ nm rad and horizontal and vertical β functions of 4 m at the collision point) are determined by the lattice of the ring, which has a very large dynamic energy aperture of 5%–6% [12]. At present, the energy acceptance is limited by the rf system and is 17.5 MeV (3.5%) at an electron energy of 500 MeV. This makes it possible to preserve all electrons in the γ-ray production process for all measurements presented below. This "no-loss mode" produces an electron beam having a lifetime of 2–3 h, determined by intrabeam scattering and finite vacuum.

The OK-4 FEL is an optical klystron (OK) invented by Vinokurov and Skrinsky [13]. It consists of two wigglers separated by a buncher (B in Fig. 1) and provides for a factor of 5–10 enhancement in the gain compared to conventional FELs. The present 53.73 m long (one-half the ring circumference) narrow band uv optical cavity is comprised of two multilayer spherical mirrors, each with a 27.27 m radius of curvature. The reflectivity band of these mirrors limits the lasing to a smoothly tunable range of 345–413 nm (3.6–3.0 eV). The spectrum consisted of a very narrow line with a FWHM $\delta\lambda/\lambda = (1\text{–}3) \times 10^{-4}$. The present setup provides a Rayleigh range of 3.3 m at the center of the OK-4, where electrons and photons collide. The collision point was designed to be inside of a field-free region 20 cm long, since the presence of magnetic fields at the collision point would curve the trajectory of the electron beam and thereby degrade the quality of the γ-ray beam [9]. A detailed description of the OK-4 FEL and the Duke storage ring is published elsewhere [12,14].

The measurements reported below were obtained with a photon wavelength of 379.4 nm and an electron energy of 500 MeV ($\gamma = 978.5$). Two electron bunches, each of which corresponded to a current of 1.2 mA spatially separated by one-half the circumference of the ring, participated in both lasing and γ-ray production. The power in the lasing cavity was 0.54 W with a photon flux of 1.03×10^{18} sec^{-1}. This mode of running differs from our future plans [3–5] in which one bunch will be used for lasing and the second bunch will act only as the target for backscattering. The main disadvantage of the present scheme arises from the fact that the participation of the target bunch in the lasing process leads to additional energy diffusion which increases its energy spread, typically 0.4%–0.5% FWHM in the present case, compared to a natural FWHM of 0.06%.

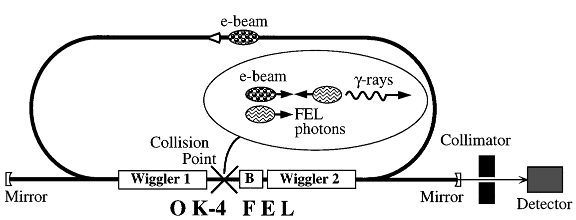

FIG. 1. Schematic of the OK-4/Duke storage ring FEL and γ-ray source. Two electron bunches spatially separated by one-half the circumference of the ring participate both in lasing and γ-ray production via Compton scattering of intracavity photons. A collimator installed downstream selects a narrow cone of quasimonoenergetic γ rays.

Gamma rays were first detected using a 10 in. $\times$ 10 in. NaI (Tl) detector centered on the γ-ray beam axis approximately 30 m from the collision point. This detector has been previously used in numerous capture reaction studies, and its properties are well known [15]. It was necessary to attenuate the γ-ray flux by the use of 10 cm of Pb in order to reduce the count rate in this detector to a manageable level. The energy-calibrated NaI detector indicated that the observed γ rays had an energy of 12.2 MeV. The flux, corrected for the detector efficiency and the attenuation of the lead, was observed to be 2.0×10^5 γ's per sec, compared with the calculated value of 2.6×10^5 γ's per sec, which is based on the photon and electron fluxes given above.

The second phase of our measurements attempted to monochromatize the γ rays by installing a 3 mm diameter Pb collimator approximately 30 m downstream of the collision point and in alignment with the axis of the electron beam (see Fig. 1). The 10 cm thick collimator attenuated the off-axis γ rays by a factor of 290. The resulting γ-ray flux was detected using a "142%" high-purity germanium (HPGe) detector, whose axis was aligned along the electron beam direction. We have used the FEL laser beam for visual prealignment of the collimator. Minor fine tuning of the collimator alignment was accomplished by maximizing the count rate in the HPGe detector, indicating that it was on axis. This detector has an energy resolution of about 5 keV for 12 MeV γ rays and therefore the linewidths observed should be a direct measure of the beam energy spread. The energy scale of the detector system was calibrated using radioactive sources, including the 4.4 MeV γ-ray line from an AmBe source. The observed flux was about 100 times less than the uncollimated flux measured above, as expected. The resulting spectrum is displayed in Fig. 2. It should be noted that this spectrum represents the convolution of the detector response function with the γ-ray energy distribution. The full-energy peak and the first escape peak are clearly visible along with Compton scattered events. In order to obtain a measure of the energy spread in the beam, the full-energy peak was fit to a Gaussian whose centroid was constrained to be

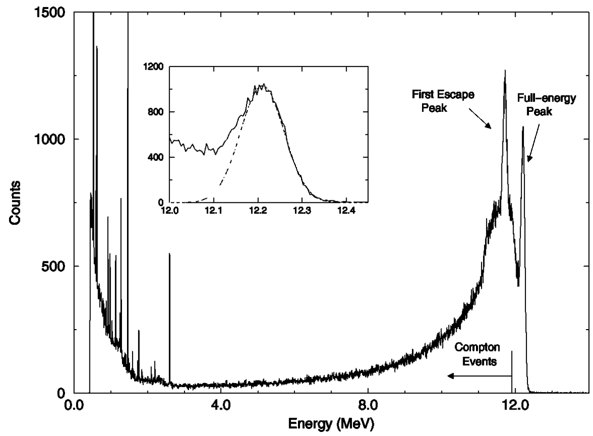

FIG. 2. Full γ-ray spectrum as measured by a HPGe detector. The full-energy and first escape peaks associated with the 12.2 MeV γ-ray beam are clearly visible. The inset shows a Gaussian fit to the full-energy peak. The fit has a FWHM of 120 keV.

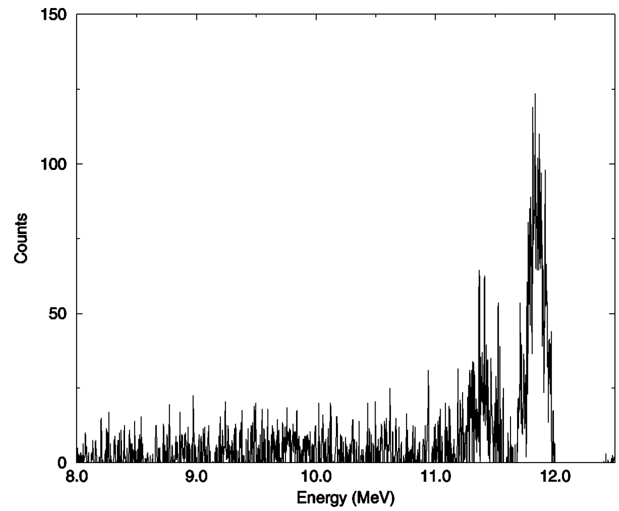

FIG. 3. First escape peak spectrum after background subtraction.

located at 12.2 MeV. The resulting Gaussian fit, shown in Fig. 2, indicated a FWHM of 120 keV, corresponding to a 1% energy spread in the γ-ray beam. The Gaussian was fit to the high energy edge of the peak to minimize the contribution from the Compton edge and other lower energy events. Fitting a Gaussian to the entire peak gives an energy spread of 1.25%.

The energy spread of the γ-ray beam is determined by the energy and momentum spread in the electron beam and the FEL photons, as well as by geometrical considerations. A detailed analysis of these factors is given in [3]. A calculation of the γ-ray energy spread was performed using measured values of these parameters. The results indicated that we should observe an energy spread of approximately 1.2%, in good agreement with our measured value. It is worth noting that the main contribution to the γ-ray energy resolution came from the energy spread induced by lasing. This observation makes it apparent that we should prevent lasing of the target bunch for future improvement of the γ-ray energy resolution.

An additional measurement was made in an attempt to obtain a somewhat clearer observation of the γ-ray energy distribution, unencumbered by the detector response function. In order to achieve this, we inserted the HPGe detector into a NaI annulus which had a 10 cm inside diameter and a 23 cm outside diameter. If only events in the HPGe detector which are coincident with 511 keV events in the NaI detector are observed, one should see only those γ rays associated with the first escape peak events in the full spectrum. Unfortunately, the NaI shield allowed a background to leak into this spectrum due to its poor energy resolution. However, this could be subtracted by setting gates above and below the region of the 511 keV line in the NaI to obtain a background spectrum. The resulting background subtracted γ-ray spectrum is shown in Fig. 3. This spectrum, which shows only the first escape peak and its associated Compton scattered events, provides convincing confirmation of the fact that the γ-ray beam is a nearly monochromatic beam with a FWHM energy spread of about 1.2%.

Our final measurement of the beam properties consisted of a measurement of the linear polarization of the γ-ray beam, expected to be close to 100%. This measurement was performed using the $^2\mathrm{H}(\vec{\gamma}, np)$ reaction. Previous measurements [16] indicated that the asymmetry of the neutrons produced at a reaction angle of 90° should be 0.95 ± 0.02. Our measurements utilized a 4 cm $\times$ 6 cm scintillating C_6D_{12} liquid target positioned with its symmetry axis perpendicular to the beam axis. The signal produced by protons in the scintillator was used to "tag" the desired neutron events in two identical 13 cm diameter calibrated neutron detectors positioned 23 cm from the center of the scintillating target. These two BC501 detectors were mounted so that one was in the horizontal plane and the other was in the vertical plane directly above the scintillating deuterium target. Pulse-shape discrimination techniques were used to distinguish between the detection of neutrons and γ rays in the neutron detectors. The result of our asymmetry measurement was 0.82 ± 0.05. Correcting this value for the finite geometry of our experimental setup gave an asymmetry of 0.88 ± 0.05. A correction for the effects of neutron multiple scattering in the C_6D_{12} target leads to a final corrected asymmetry of 0.93 ± 0.06, which is consistent with a 100% linear polarization for the γ-ray beam.

The results of these preliminary tests confirmed a number of important statements that we have published in the past. First, the self-consistent theory of the storage ring FELs developed and used for the prediction of the OK-4/Duke FEL γ-ray source performance [17] (i.e., the flux, energy resolution, and polarization observed in the present work) has been substantiated. Therefore, we can rely on the predictions given in [3–5]. Second, we have proven that a simple collimator can be used to generate nearly monochromatic γ rays having a FWHM energy resolution on the order of 1%. Finally, by creating γ rays from 10 to 16 MeV by varying both the wavelength of the OK-4 laser [18] and the storage ring energy, we have demonstrated the tunable nature of the γ rays produced using this technique.

In the near future, we are planning to demonstrate the full scale operation of the OK-4/Duke γ-ray source in the no-loss mode: generation of 2–55 MeV, 100% linearly polarized γ rays having a flux of 10^9–10^{11} per sec. In addition, we should be capable of operating in the "loss" mode (γ rays of 55–160 MeV) producing 100% linearly polarized γ rays with a flux of $1-5 \times 10^8$ per sec. To reach this goal, it will be necessary to extend the operational range of the FEL into the deep uv region (~10 eV, i.e., 120 nm) at the nominal beam energy of 1 GeV.

Further increases of the high energy γ-ray flux will require a reliable, full energy injector capable of delivering 6.5 nC per sec of electron beam to refill the electrons lost in the γ-ray production. A well defined program of modifications of the Duke storage ring, its rf system, the collision point, and the OK-4 wiggler and its optics are expected to provide monoenergetic (ultimately 0.1% energy resolution), 100% polarized (with variable polarization, i.e., linear—horizontal or vertical; circular with switchable helicity; or elliptical) 1–225 MeV γ-ray beams.

The authors acknowledge the contributions to this project of V. V. Anashin, P. Cable, G. Detweiler, S. Edwards, J. Faircloth, H. Goehring, S. Goetz, E. I. Gorniker, J. Gustavsson, L. G. Isaeva, M. Johnson, R. Jones, L. Kennard, C. Kornegay, J. L. Lancaster, H. Mercado, J. Meyer, O. Oakley, A. D. Oreshkov, V. M. Petrov, J. Patterson, T. V. Shaftan, I. K. Sedlyarov, E. Szarmes, E. M. Trakhtenberg, V. G. Vesherevitch, P. D. Vobly, J. Widgren, E. A. Wulf, and E. I. Zinin. This work was supported in part by the U.S. Department of Energy, Office of High-Energy and Nuclear Physics, Grant No. DF-FG05-91ER40619, by the Office of Naval Research Grant No. N00014-94-1-0818, and by AFOSR Contract No. F49620-93-1-0590.

[1] A. M. Sandorfi, in *Polarized Photon Facilities—Window to New Physics,* (Brookhaven National Laboratory, Upton, NY, 1995).

[2] G. Ya. Kezerashvili *et al.,* in *Proceedings of the Conference on High Energy Spin Physics, Bloomington, IN, 1994,* edited by K. J. Heller and S. L. Smith, AIP Conf. Proc. No. 343 (AIP, New York, 1995), p. 260.

[3] V. N. Litvinenko and J. M. J. Madey, SPIE **2521**, 55 (1995).

[4] V. N. Litvinenko and J. M. J. Madey, Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 580 (1996).

[5] T. S. Carman *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **378**, 1 (1996).

[6] A. M. Sandorfi *et al.,* IEEE Trans. Nucl. Sci. **30**, 3083 (1983).

[7] F. Glotin *et al.,* Phys. Rev. Lett. **77**, 3130 (1996).

[8] F. Carroll (private communication).

[9] M. Hosaka *et al.,* in Proceedings of the Eighteenth International FEL Conference, Rome, 1996 (to be published). Note: the energy resolution observed here was affected by the fact that the collision did not occur in a field-free region.

[10] M. E. Couprie *et al.* (private communication).

[11] H. Ohgaki *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 602 (1996).

[12] Y. Wu *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 74 (1996).

[13] N. A. Vinokurov and A. N. Skrinsky, Report No. INP 77-59, 1977.

[14] V. N. Litvinenko *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **375**, 46 (1996).

[15] H. R. Weller and N. R. Roberson, IEEE Trans. Nucl. Sci. **28**, 2 (1981).

[16] W. Del Bianco *et al.,* Phys. Rev. Lett. **47**, 1118 (1981). Note: a slight extrapolation was used to obtain the value at 12.2 MeV.

[17] V. N. Litvinenko *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **358**, 369 (1996).

[18] V. N. Litvinenko *et al.,* SPIE (to be published).