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Undulator Background In The Final Focus Test Beam Experiment With Polarized Positrons*

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Abstract

In the proposed E-166 experiment at SLAC, 50 GeV electrons pass through a helical undulator, and produce circularly polarized photons, which interact with a tungsten target and generate longitudinally polarized positrons. The background is an important issue for an experiment under consideration. To address this issue, simulations were performed with the code GEANT3 to model the production of secondary particles from high-energy electrons hitting an undulator. The energy density of photons generated at the target has been analyzed. Results of the simulations are presented and discussed.

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In the proposed E-166 experiment at SLAC, 50 GeV electrons pass through a helical undulator, and produce circularly polarized photons, which interact with a tungsten target and generate longitudinally polarized positrons. The background is an important issue for an experiment under consideration. To address this issue, simulations were performed with the code GEANT3 to model the production of secondary particles from high-energy electrons hitting an undulator. The energy density of photons generated at the target has been analyzed. Results of the simulations are presented and discussed.

1 Introduction

E-166 is the proposed experiment for the verification of polarized positron production for the Linear Collider (Alexander et al., 2004). According to the original suggestion (Balakin and Michailichenko, 1979), high-energy electrons pass through a helical undulator and produce circularly polarized photons, which after interaction with tungsten target, generate longitudinally polarized positrons. The generation of polarized positrons using a helical undulator constitutes part of international activity on positron production for a future Linear Collider (Ivanyushenkov et al., 2005, Strahovenko et al., 2005).

In the E-166 experiment (see Fig. 1), the 50 GeV electron beam propagates inside 1 m long undulator followed by a drift space of 35 m. Polarized photons generated in the undulator are analyzed by the Silicon-Tungsten (Si-W) calorimeter which is placed along the axis. Polarized positrons are analyzed by a Cesium-Iodine (Cs-I) calorimeter after reconversion of positrons to photons at the second target shifted by 45 cm from the axis. In this paper we discuss the effect of background particles generated by primary high-energy electrons impinging on the undulator.

2 Simulation set-up

E-166 experiment operates with a 50 GeV electron beam with $1x10^{10}$ electrons per bunch. After passing through 1 m long undulator with parameter K = 0.17 and undulator period of $\lambda_u = 0.25$ cm, each bunch of electrons generates $4x10^9$ photons. The total energy of the photons at the Si-W detector is estimated to be 500 TeV with possible maximum noise of 25 TeV. The total energy of the photons at the Cs-I detector is estimated to be 2-5 GeV with possible maximum noise of 100 MeV. The purpose of this paper is to evaluate the background generated by the primary electron beam in the undulator and to determine tolerable particle losses in the undulator.

Fig. 2 illustrates the simulation set-up of the Final Focus Test Beam (FFTB) line of SLAC linac. The beamline includes an undulator (1), quadrupole magnet (2), bending magnets (3) and lead shields (4), (5). In simulations the undulator was replaced by a thin iron tube with length of 1 m and internal diameter of 0.88 mm. To prevent background in front of the undulator a tungsten collimator with the length of 30 radiation lengths (RL) (10.5 cm) is used. Simulations were performed for two cases: illumination of the internal part of the undulator and illumination of collimator by halo electrons (see Fig. 3).

In FFTB line, the r.m.s. electron beam size is $\sigma = 4x10^{-5}$ m, which is approximately 10 times smaller than internal radius of the undulator, R = 0.44 mm. The undulator can be hit by halo electrons surrounding the beam core. To define divergence of halo electrons, let us take into account the normalized r.m.s. beam emittance in the FFTB line is $\gamma\varepsilon = 3x10^{-5}\,\pi$ m.rad, therefore, the r.m.s. beam divergence for beam energy of $\gamma = 10^5$ is

$$\left(\frac{dx}{dz}\right)_{rms} = \frac{\varepsilon}{\sigma} = 7.5\cdot 10^{-6}. \qquad (1)$$

Now, the halo electrons occupy a phase space area, which is 10 times larger than the ellipse of the beam core. Thus, based on these estimates, the divergence of the halo electrons is expected to be

$$\left(\frac{dx}{dz}\right)_{halo} = 10\cdot\left(\frac{dx}{dz}\right)_{rms} = 7.5\cdot10^{-5}. \qquad (2)$$

The code GEANT3 (GEANT, 1994) was used in all simulations presented herein. Figs. 3 and 4 illustrate illumination of the undulator by a single 50 GeV electron beam and the resulting background. The secondary particles generated contain mostly photons. Figs. 5 and 6 illustrate the energy density of photons, dE/dS, at the distance of 35 m from the undulator as a function of radial displacement:

$$\frac{dE}{dS}(r) = \frac{\sum_{i=1}^{N} E_i}{2\pi\, r\, dr}, \qquad (3)$$

where E_i is the energy of an individual photon. All values are normalized with respect to that of a single primary electron. The results presented are for two nominal energy values of the primary electrons: 28 GeV and 50 GeV. The distributions of photons reaches peak values at the axis and are rapidly reduced with radius. Thus, each distribution is presented by two plots with different scales. Photons within a radial displacement of $r < 0.15$ cm are a cause for concern as they can affect the Si-W detector, and will give rise to background noise. The average energy of these photons are 0.2 GeV per primary 50 GeV electron and 0.12 GeV per primary 28 GeV electron. This means that 4% of the energy of each electron hitting the internal part of undulator is transmitted into the Si-W detector. The background to Si-W detector should not exceed 25 TeV, and the total losses in undulator are limited to 125 electrons per bunch, which is equivalent to a relative electron beam loss of 10^{-8}.

To prevent background generation, a 30 RL tungsten collimator in front of the undulator is used (see Fig. 3b). The internal diameter of the collimator is 0.73 mm and this was selected to be smaller than that of the undulator to ensure that no halo electrons with a divergence of 10^{-4} will hit the internal part of the undulator. The results of the simulations are presented in Fig. 6. The level of background is reduced by three orders of magnitude compared to that from electrons hitting internal part of the undulator. Due to good shielding (and, therefore, poor statistics of secondary particles), only photons at a large distance from the axis were detected. No photons were detected near axis within r< 0.15 cm.

3. Coulomb elastic scattering on residual gas in undulator

As a consequence of the small diameter of the undulator, the vacuum in the undulator is approximately 1 mTorr and this might account for the elastic scattering of primary electrons on the residual gas, and for the additional electron losses in the undulator. In order to estimate the fraction of scattered electrons in the undulator, consider the cross-section of elastic Coulomb scattering given by the Rutherford formula:

$$d\sigma(\theta) = \left(\frac{Z\, r_e}{\gamma\beta^2}\right)^2 \frac{d\Omega}{4\,(\sin\frac{\theta}{2})^4}\,, \tag{4}$$

where r_e is the classical radius of the electron, Z is the charge of residual gas atoms, $d\Omega = 2\pi \sin\theta\, d\theta$ is the cone angle. The number of particles per volume, n, is given by the perfect gas equation:

$$n = \frac{N_A\, P}{R\, T}\,, \tag{5}$$

where $N_A = 6 \times 10^{23}$ mol^{-1} is the Avogadro's number, $R = 8.31$ J mol^{-1} K^{-1}is the ideal gas constant, P is the gas pressure, and T is the absolute temperature. After passing through the gas of length L, the fraction of particles scattered within an anglular interval of $[\theta, \theta+\Delta\theta]$ is

$$\frac{dN_\theta}{N} = n\, L\, d\sigma(\theta)\,. \tag{6}$$

The probability of scattering of particles within the angular interval $[\theta_{min}, \theta_{max}]$ is obtained via integration of Eq. (6)

$$P_\theta = \int_{\theta_{min}}^{\theta_{max}} \frac{dN(\theta)}{N} = 4\pi n L \left(\frac{Z\, r_e}{\gamma\beta^2}\right)^2 \left(\frac{1}{\theta_{min}^2} - \frac{1}{\theta_{max}^2}\right). \tag{7}$$

For $\theta_{max} >> \theta_{min}$, the second term in Eq. (7) can be neglected. Finally, for the electron beam propagating in gas

$$P_\theta = \frac{4\pi n L}{\theta_{min}^2} \left(\frac{Z\, r_e}{\gamma\beta^2}\right)^2. \tag{8}$$

The value of θ_{min} can be estimated as a ratio of: radius of the aperture of the undulator, R, to the length of the undulator, L:

$$\theta_{min} = \frac{R}{L} = 0.44 \text{ x } 10^{-3}. \tag{9}$$

Taking the E-166 parameters $Z = 7, \gamma = 10^5$, $n = 3.2\text{x}10^{-19}$ m^{-3} (corresponding to a pressure of 1 mTorr), the probability of a near-axis electron being scattered at an angle sufficient to hit the undulator tube is

$$P_\theta = 0.79 \text{ x } 10^{-10}. \tag{10}$$

Applying this to the FFTB in which there are 1 x 10^{10} electrons, results in approximately 1 electron per bunch hitting the undulator tube due to the elastic Coulomb scattering.

Conclusions

Simulations were performed with the code GEANT3 to estimate background generation from 50 GeV and 28 GeV electrons hitting the internal part of undulator in the E166 experiment concerned with polarized positron generation. It was determined that 4% of the power of each electron hitting the undulator is transformed in the photon detector. The tolerable beam losses in the undulator are limited to 10^{-8}. Utilization of a 30 RL tungsten collimator in front of the undulator results in background suppression by 3 orders of magnitude. Particle losses in the undulator due to elastic scattering on residual gas at vacuum pressure of 1 mTorr are of the order of 10^{-10} and are not of primary concern.

Acknowledgements

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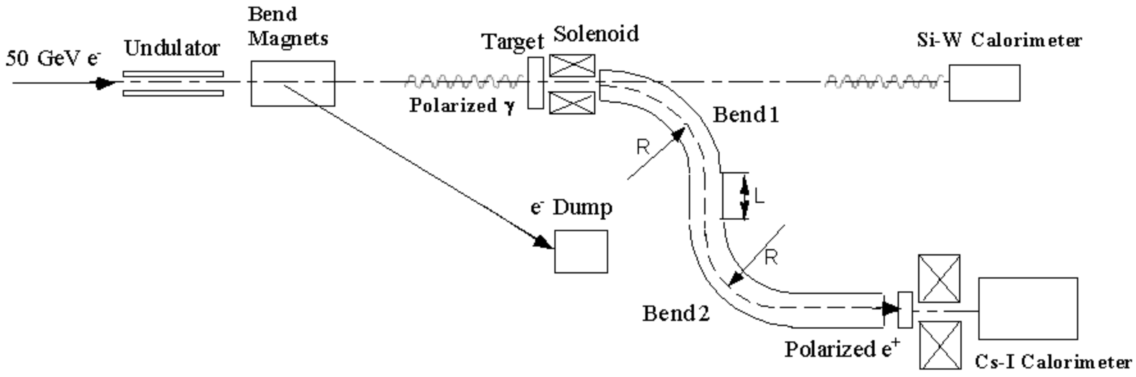

Fig. 1. Layout of experiment.

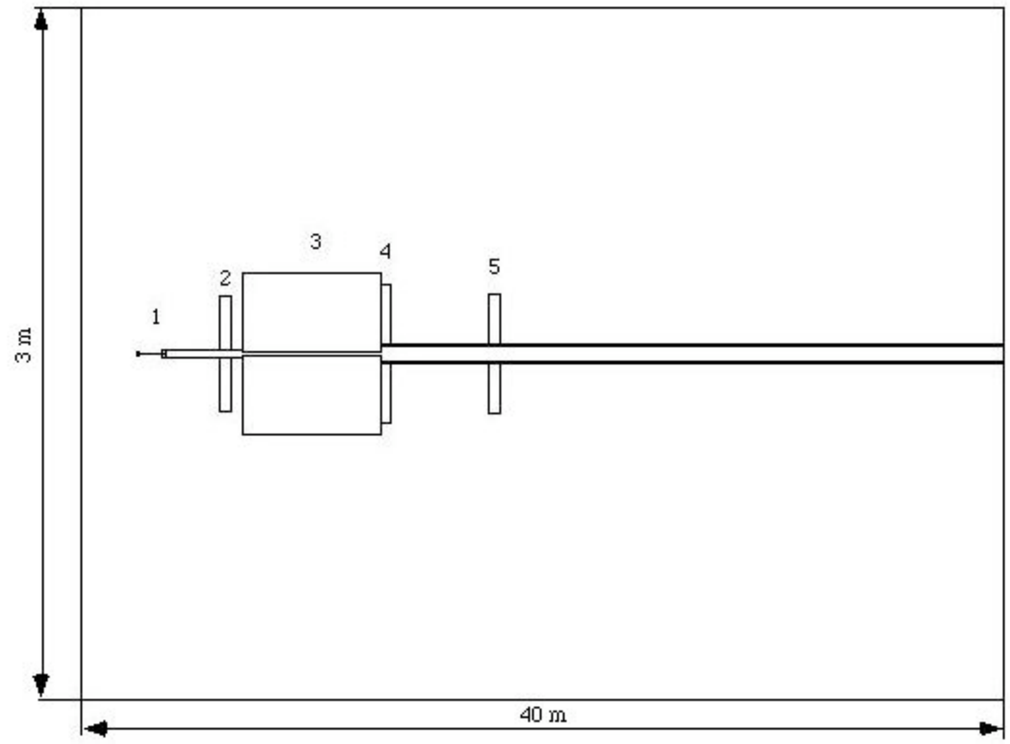

Fig. 2. Simulation set-up: 1 –undulator, 2- quadrupole, 3-bending magnets, 4, 5- lead shield.

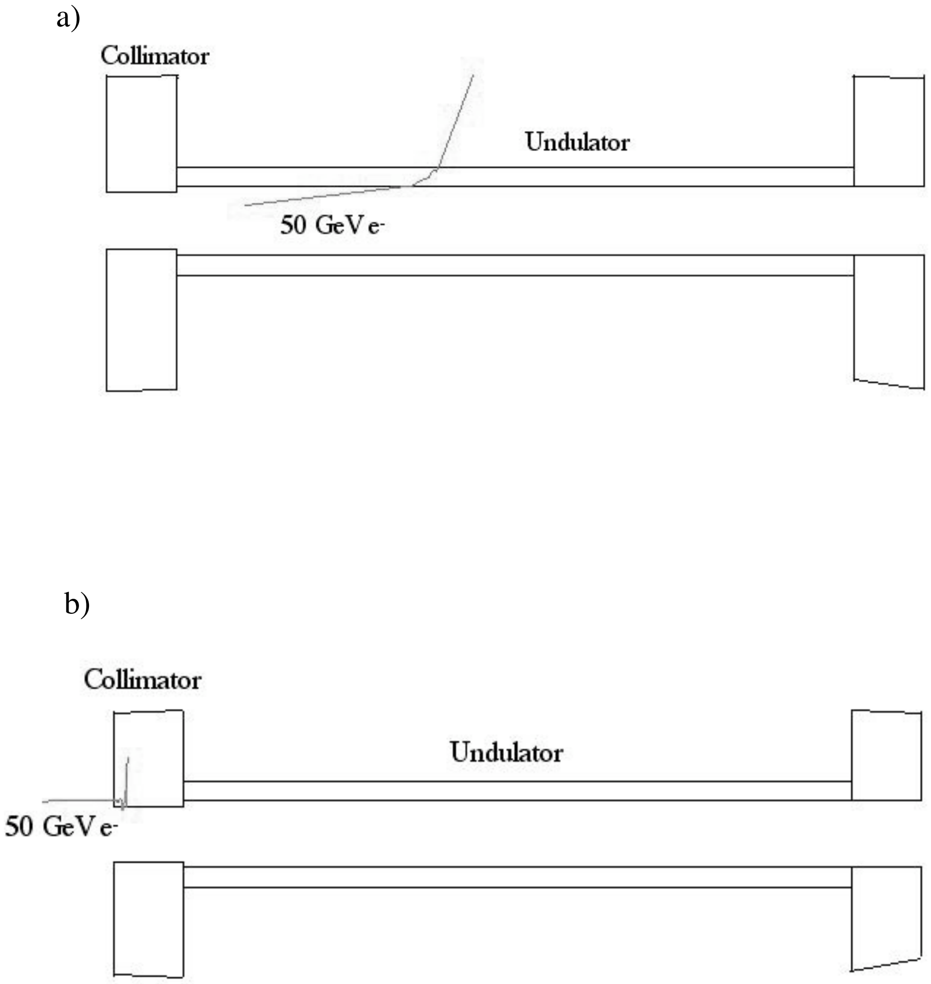

Fig. 3. High energy electron hitting (a) internal part of undulator, (b) collimator.

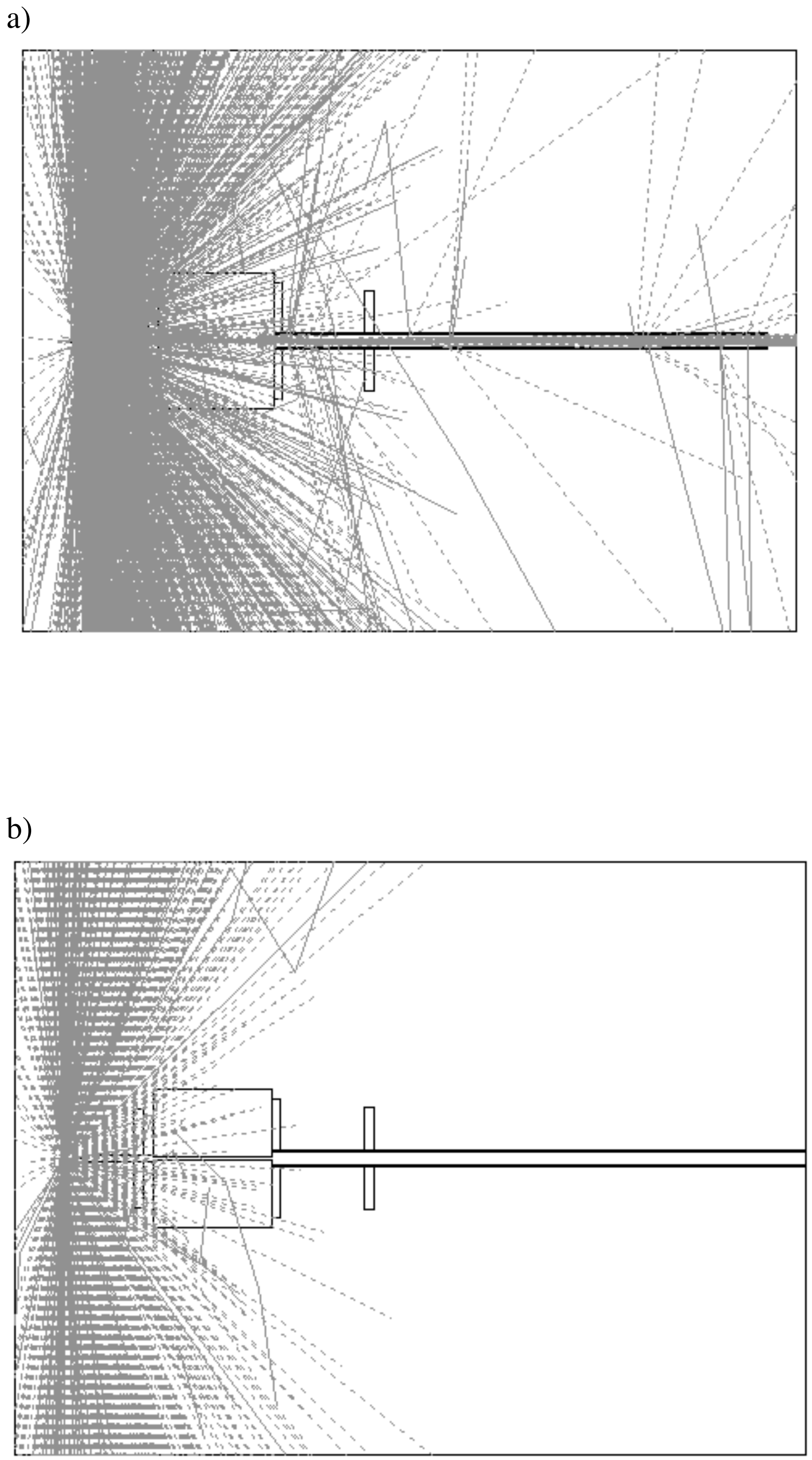

Fig. 4. (a) Background from electrons hitting internal part of the undulator, (b) background from electrons hitting the collimator.

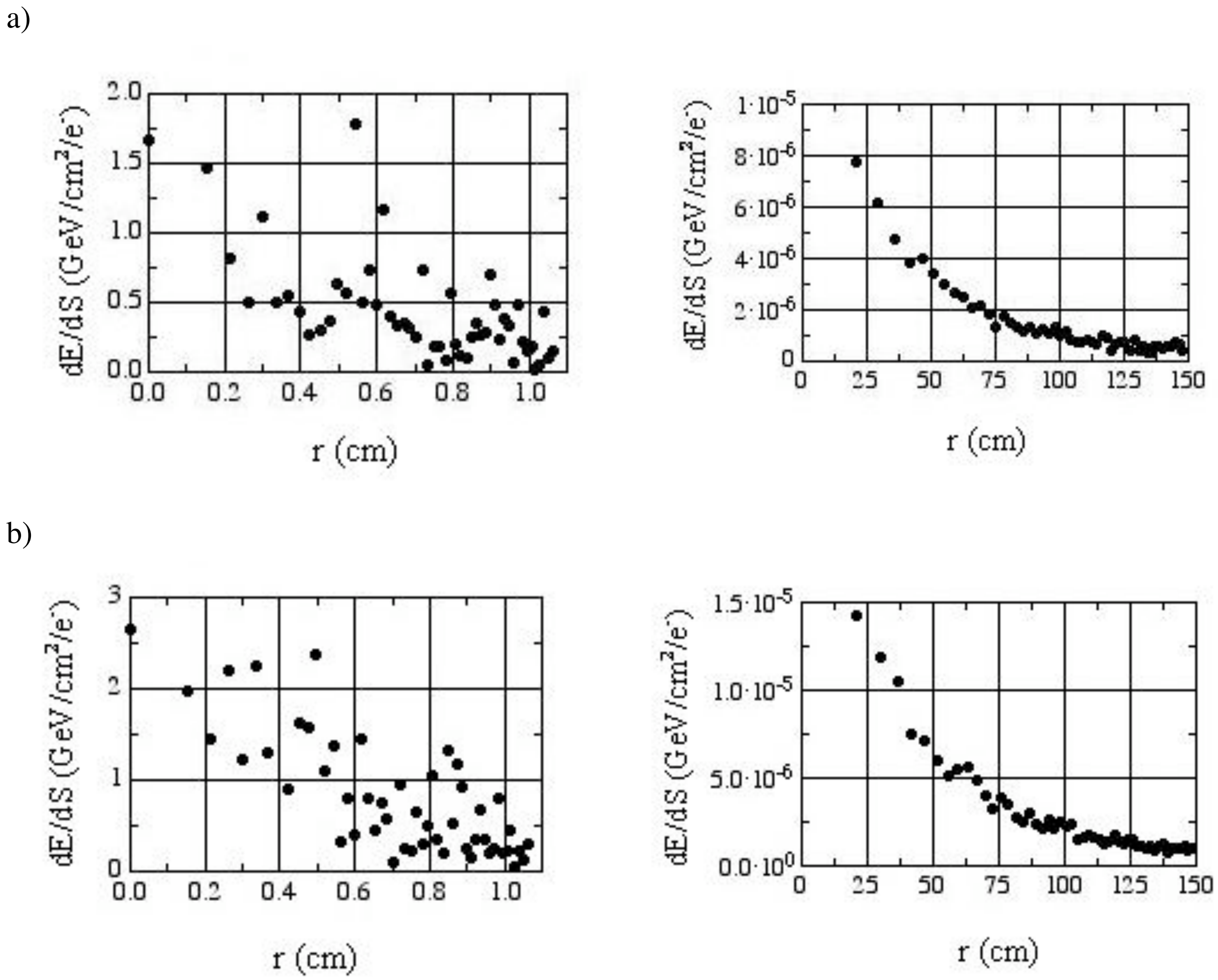

Fig. 5. Photon energy density at the exit of the system from electrons hitting undulator tube: a) 28 GeV electrons, b) 50 GeV electrons.

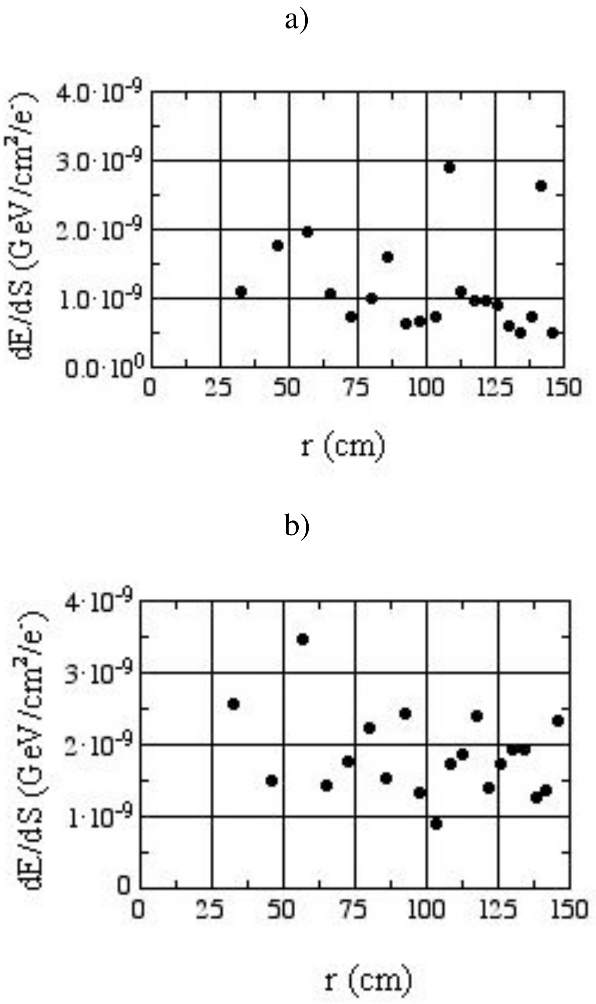

Fig. 6. Photon energy density from electrons hitting collimator: (a) 28 GeV electrons, (b) 50 GeV electrons.