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(A)

BEAM PROFILE MEASUREMENT BY BACKSCATTERING OF LASER PHOTONS IN PETRA

by

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1. Introduction

In electron or positron storage rings the beam profile is usually measured by synchrotron radiation. This method works well for carrying out relative measurement of the beam profile and for detecting beam oscillations, but the calibration of the whole optical system is difficult when carrying out absolute measurements of the beam profile.

In this paper a new method is described in which the beam profile of an electron beam is detected by backscattering laser photons by the electron beam. With the help of a movable remote-controlled mirror the laser beam is deflected and focussed into the electron beam. When the focus of the laser beam is smaller than the electron beam the number of backscattered photons depends on the electron density in the interaction region between laser beam and electron beam. The beam profile can be measured by moving the remote-controlled mirror. The backscattered high energy photons are detected outside the vacuum chamber by a total absorbing shower counter.

2. Kinematics and cross-sections of the Compton effect

The differential cross-section of the Compton effect is generally described in the rest-frame of the electron.

In the rest frame two vectors $\vec{K}_1$ and $\vec{K}_o$ are defined (fig. 1). $\vec{K}_o$ has the same direction as the incoming photon in the rest frame. The length of the vector is identical with the energy of the incoming photon in units of the electron rest mass. $\vec{K}_1$ is defined in similar manner for the scattered photon. $\vec{K}_o$ can be calculated by well known methods (e.g. (1)) where the lorentz-invariant products of two four vectors in the laboratory and the rest frame are compared.

In the laboratory system the laser photon with an energy of E_{phot} hits the electron beam at an angle ϕ (fig. 2). For $\gamma = E_{el}/m_o >> 1$ (E_{el} = electron energy in the laboratory system, m_o = rest mass of the electron) and for $\phi < \pi$ the following relation is valid:

$$|\vec{K}_o| = \frac{\gamma}{m_o} E_{phot} (1 + \cos\phi) \qquad (1)$$

In the rest frame the angle ϕ is transformed into the angle ϕ^*:

$$\sin\phi^* = \frac{1}{\gamma} \frac{\sin\phi}{1 + \cos\phi} \qquad (2)$$

In the rest frame for Compton scattering (2) the following formula yields

$$\frac{1}{|\vec{K}_1|} - \frac{1}{|\vec{K}_o|} = 1 - \cos\Theta \qquad (3)$$

wherein Θ is the scattering angle defined in fig. 1.

The cross-section of the compton effect depends both on the polarization of the laser beam and the electron beam. Assuming a linearly polarized laser beam (a laser cavity with Brewster angles) the cross-section is independent of whether the particle beam is polarized or not. The cross-section is

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_o^2 \left(|\vec{K}_1|^2/|\vec{K}_o|^2\right) \left((1 + \cos^2\Theta) + (|\vec{K}_o| - |\vec{K}_1|)(1 - \cos\Theta) + z_1^0 \sin^2\Theta\right) \qquad (4)$$

r_o .. classical electron radius

z_1^0 .. describes the linear polarization of the laser beam in the following manner

If two unity vectors

$$\vec{A}_1^0 = \frac{\vec{K}_o \times \vec{K}_1}{|\vec{K}_o \times \vec{K}_1|} \; ; \quad \vec{A}_2^0 = \frac{\vec{K}_o \times \vec{A}_1^0}{|\vec{K}_o|} \qquad (5)$$

are defined, the incoming linearly polarized laser beam can be described by the following formula:

$$a_1 \vec{A}_1^o \exp(i \vec{K} \vec{x}) + a_2 \vec{A}_2^o \exp(i \vec{K} \vec{x}) \qquad (6)$$

where $\vec{K}$ is the wave vector. a_1 and a_2 define the degree of polarization relative to the two unity vectors. According to the above definitions the factor z_1^o is

$$z_1^o = a_1^2 - a_2^2 \qquad (7)$$

This definition of polarization is different from the well known definition of polarization in real physical space.

The energy of the scattered photon E^{lab}_{phot} in the laboratory system is

$$E^{lab}_{phot} = |\vec{K}_1| \, m_o \cdot (\gamma + \sqrt{\gamma^2 - 1} \cos\Theta) \qquad (8)$$

wherein the above-mentioned transformation techniques are used. The photon has its maximum energy at $\Theta = 180^o$:

$$E^{lab}_{phot,Max} \approx 2\gamma \, |\vec{K}| \qquad (9)$$

(For PETRA at 8.5 GeV and laser light of 5000 Å: $E^{lab}_{phot,Max} = 2.1$ GeV).

This means from the laboratory point of view that the backscattered photons gain the maximum possible energy. The angle Θ is transformed into Θ_{lab} by the following formula:

$$\cos\Theta_{lab} = \frac{\gamma}{\sqrt{\gamma^2-1}} - \frac{1}{\gamma\sqrt{\gamma^2-1} + (\gamma^2-1)\cos\Theta} \qquad (10)$$

3. Experimental set-up

The set-up is part of a polarization detection system at PETRA using a laser source and a γ-detector. The experimental set-up is sketched in fig. 3. The laser beam emerging from the laser is focussed by a lens, deflected by a movable, remote-controlled mirror and enters the vacuum chamber via a window. The beam is deflected towards the electron beam, penetrates the electron beam and leaves the vacuum chamber by another window. The position of the beam can be monitored with the help of a screen and a tv-camera. All the optical elements except the laser are inside the PETRA tunnel.

The experiments were performed with an Ar-ion-laser with a total output cw-power of 17 W (all visible lines). The laser beam is scanned through the electron beam by tilting the movable mirror as demonstrated in fig. 4. In order to achieve a high local resolution, the laser beam is focussed by the above mentioned lens. The local resolution Δx of the system is limited by the divergence ϕ of the laser beam and the focal length of the lens f :

$$\Delta x \approx 2f \cdot \phi \qquad (11)$$

The backscattered photons travel through the $e^- \cdot e^+$ interaction region together with the electrons (fig. 5). The photons leave the electron beam in the first weak bending magnet and leave the vacuum-chamber in the 84 % bending magnet. The photon beam now has to pass through the adjacent quadrupole. The coils of the quadrupole are separated by 20 millimeters. This gap is also effective in separating charged particles from the photons. A movable remote controlled collimator is installed in front of the quadrupole.

The detector is a wolfram shower counter with high energy resolution (fwhm $\sim 0.22/\sqrt{E_{GeV}}$). A veto counter is in front of the shower counter.

The rate of the backscattered photons in the case of PETRA is given by

$$f = 1.41 \cdot \frac{P_L \cdot J}{\sigma_x} \qquad (12)$$

P_L ... laser power in Watt

J ... beam current in mA

σ_x ... horizontal standard deviation of the electron beam in cm

4. Experimental results

First measurements are demonstrated in fig. 6. The horizontal beam profile is measured in the interaction quadrupoles in PETRA at 8.5 GeV. The beam profile for two different beam optics is compared. In both cases the electron beam current is 1 mA (this means that 2 bunches of electrons circle around the machine and each bunch is filled with 1 mA). The background level in relation to the number of backscattered photons was different for both optics for the following reasons: firstly, the transversal beam density in the so-called M100 optics is higher and secondly, the dimensions of the beam are greater and the background level increases with increasing beam dimensions.

In the case of the M100 optics the effect of the backscattered photons was 9 % above the background level. The effective laser power at the interaction point between laser beam and electrons is less than the 17 W at the laser output due to the reflectivity of the mirrors (the movable mirror outside the vacuum and the vacuum mirror). The measured reflectivity of one mirror is about 60 %. Taking into consideration all reflectivity losses at the optical surfaces only about 30 % of the output power (about 4.7 W) interacts with the electron beam.

5. Summary

These experiments demonstrate that the beam profile of a relativistic electron beam can be effectively measured by backscattering of laser photon. It is shown that the beam profile can be detected even with relatively weak laser beams of several watts. With the help of Q-switched solid-state or dye lasers operating in the MW-region beam profiles could be detected with satisfactory accuracy within very short time.

Literature

(1) e.g. Hagedorn, R., Relativistic Kinematics, Benjamin, W.A., Inc., New York, Amsterdam, 1964

(2) Lipps, F.W., Tolhoek, H.A., Polarization Phenomena of Electrons and Photons, II, Physica XX, (1954) 395

Figure captions

Fig. 1: Definition of the parameters of Compton scattering in the rest frame of the electron.

Fig. 2: Compton scattering in the laboratory system. The laser beam hits the electron at an angle of ϕ.

Fig. 3: Experimental set-up with the laser, the movable mirror for scanning the laser beam, the vacuum mirrors and the screen for monitoring the laser beam position.

Fig. 4: The laser beam is scanned through the electron beam by tilting the mirror outside the vacuum.

Fig. 5: Position of the laser and the detector.

Fig. 6: Horizontal beam profile in the interaction quadrupoles for two different particle beam optics. Solid line: M25 optics, dashed line M100 optics. Beam energy 8.5 GeV.

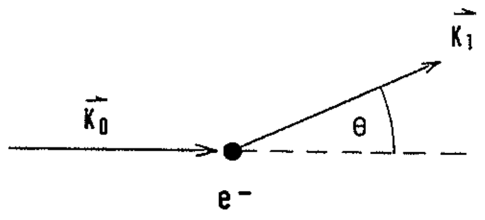


fig. 1

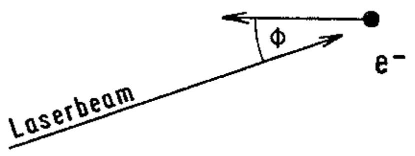


fig. 2

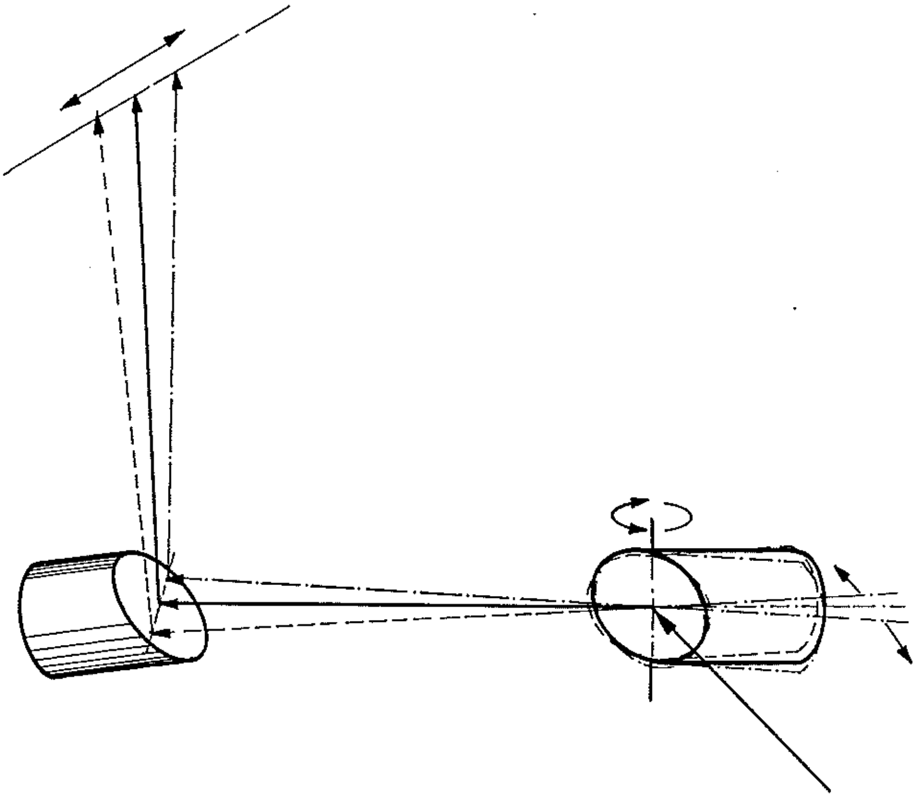


Fig. 4

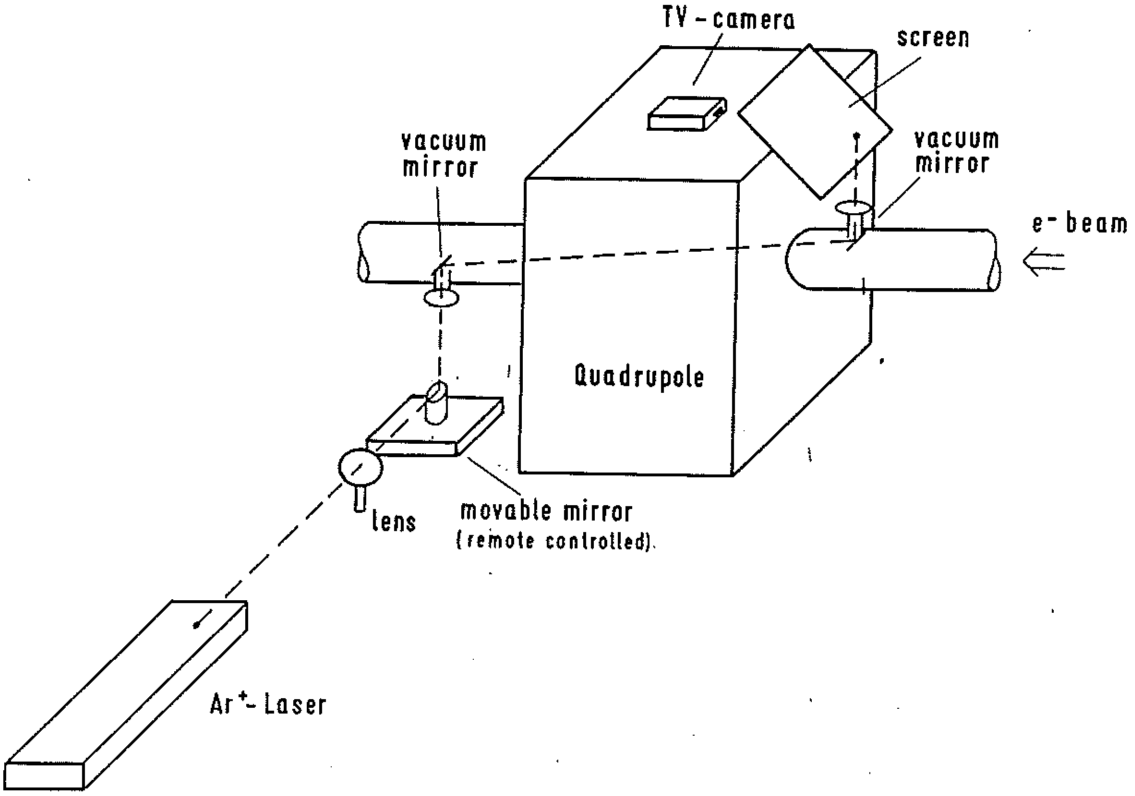
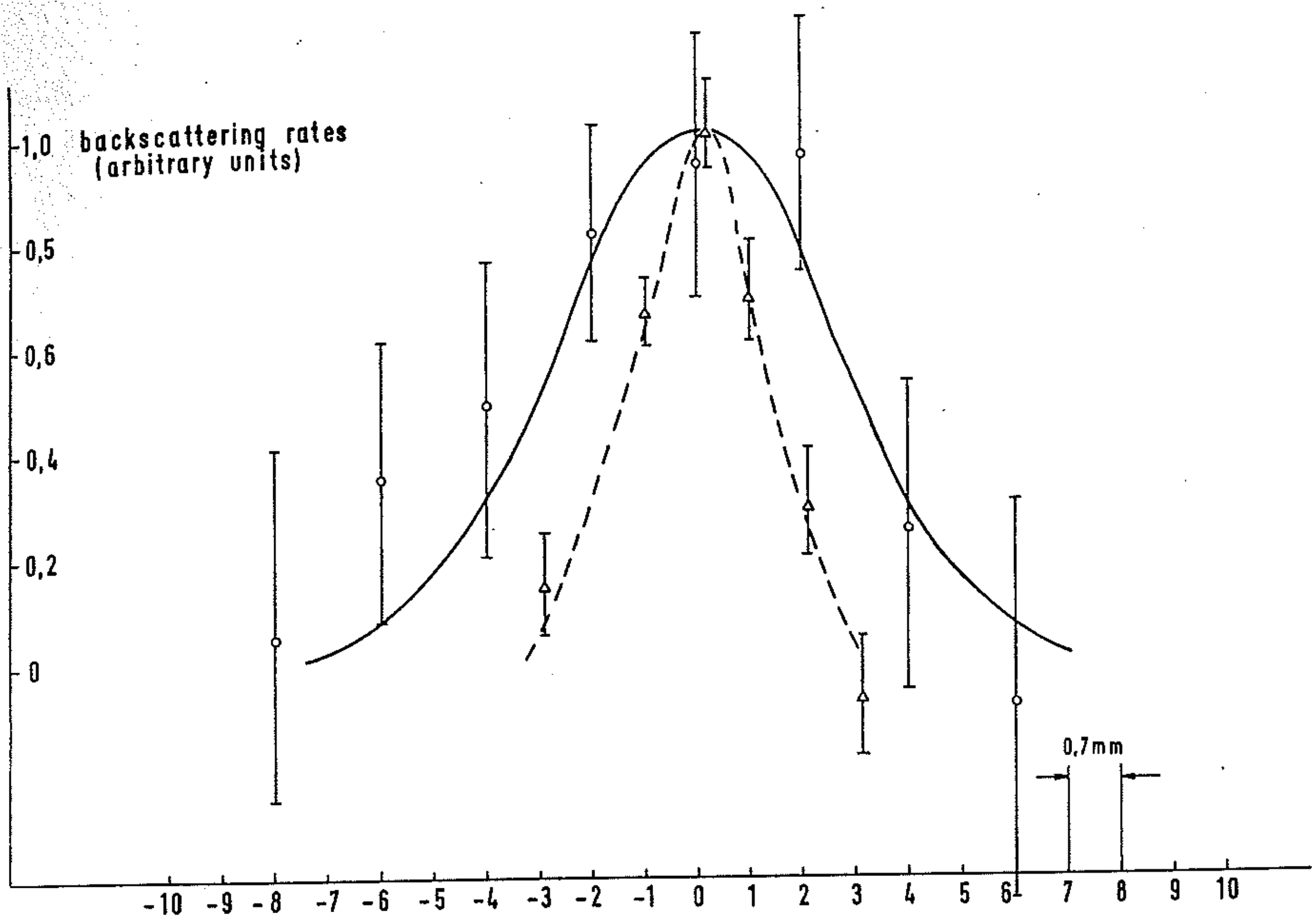

TV - camera
screen
vacuum mirror
vacuum mirror
e- beam
Quadrupole
lens
movable mirror
(remote controlled).
Ar+- Laser

fig. 3

fig. 6


backscattering rates
(arbitrary units)
1,0
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0,4
0,2
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0,7mm
-10
-9
-8
-7
-6
-5
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-2
-1
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1
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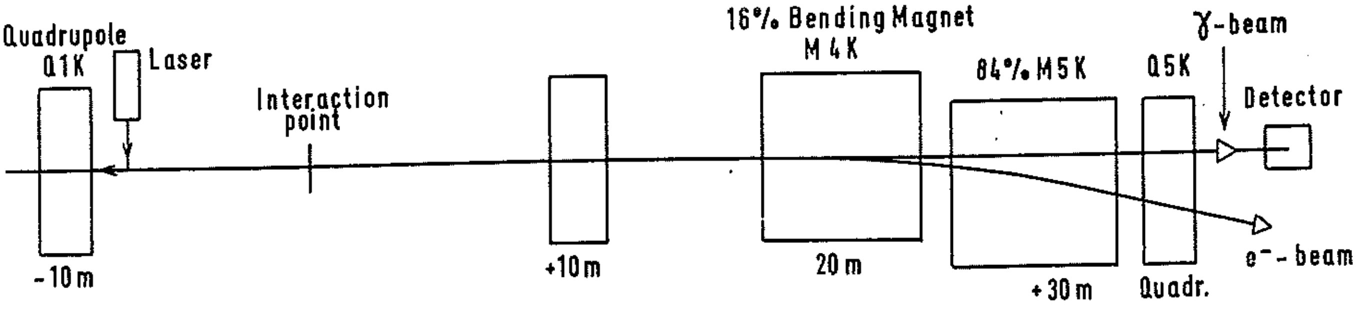
Quadrupole
Q1K
Laser
Interaction
point
16% Bending Magnet
M4K
84% M5K
Q5K
γ-beam
Detector
e⁻-beam
-10m
+10m
20m
+30m
Quadr.

fig. 5