Measurements of Polarization in LEP

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Abstract: This report summarizes the work of the Polarimeter Working Group. The aim was to study
the feasibility of measuring the degree of polarization to a precision where its contribution to
the uncertainty on the Left–Right asymmetry, $\Lambda_{LR}$, is small compared to the required
uncertainty for this parameter. Including the systematic effects considered in this report, we
conclude that the electron longitudinal polarization can be measured with a precision of
$\approx 0.3\%$ in less than 20 minutes of LEP operation.

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1. Introduction

The polarimeter working group has studied the feasibility of measuring the degree of polarization in LEP to a precision required for an accurate measurement of the left–right asymmetry ($\Delta A_{LR} = 0.0025$). The chosen method is the Compton scattering of laser light by the LEP beams, which, in the case of transverse (vertical) polarization, gives rise to an up–down asymmetry. For longitudinally polarized beams, the energy spectrum of the recoil photons changes drastically when the circular polarization state of the laser light is reversed, forming the basis of our proposal for a longitudinal polarimeter.

Chapter 2 describes the proposed scheme for measuring $A_{LR}$ and establishes the precision with which the polarization has to be measured. The principles behind the measurement are outlined in chapter 3, followed by a chapter on the laser system. Transverse and longitudinal polarimetry are dealt with in chapters 5 and 6. Finally our conclusions are given in chapter 7.

2. The Required Precision of the Polarization Measurements

We assume that the LEP physics program with polarized electrons will use the so called "Blondel Scheme" [1], where the 4 electron and positron bunches have the following longitudinal polarization states:

| electron bunches | 1← | 2 | 3 | 4← |
| positron bunches | 1 | 2→ | 3 | 4→ |
| cross sections | $\sigma_1$ | $\sigma_2$ | $\sigma_3$ | $\sigma_4$ |
| event numbers | $N_1$ | $N_2$ | $N_3$ | $N_4$ |

Electron bunches 2 and 3 and positron bunches 1 and 3 are unpolarized and the other bunches are either left or right-handed longitudinally polarized as indicated by the arrows.

The four measured cross sections can be expressed via the polarization of the electron bunches ($P^-_e$) and the positron bunches ($P^+_e$), namely
\[ \sigma_1 = \sigma_u (1 - P^- c \Lambda_{LR}) \]
\[ \sigma_2 = \sigma_u (1 + P^+ c \Lambda_{LR}) \]
\[ \sigma_3 = \sigma_u \]
\[ \sigma_4 = \sigma_u [1 - P^+ c P^- + (P^+ c - P^- c) \Lambda_{LR}] \]

This procedure yields a measurement of the Left–Right asymmetry \( \Lambda_{LR} \) at the \( Z^0 \) peak and an absolute calibration of the polarimeters. The importance of a very precise measurement of \( \Lambda_{LR} \) for the physics programme at LEP has been underlined elsewhere [2]. To achieve an accuracy of \( \Delta \Lambda_{LR} = 0.0025 \) with about 10\(^9\) \( Z^0 \) events, the polarization measurements should reach the following precision [2,3]:

a) \( \delta P_e \approx (1 - 2) \times 10^{-7} \) in several minutes to average cross-sections taken with different polarization levels;

b) \( \delta (\Delta P_e) \approx 3 \times 10^{-3} \) where \( \Delta P_e \) is the difference in polarization between two polarized like sign bunches;

c) \( \delta P_e \approx 5 \times 10^{-3} \) for the "unpolarized" bunches.

3. The Principles of Compton Polarimetry

3.1 Kinematics

Although the theoretical treatment of Compton scattering refers to the electron centre of mass system, from the experimental point of view the laboratory system is the relevant one. We summarise below some required transformation formulae. We define \( k_0 \) and \( k \) as the momenta of the incoming and outgoing photons in the laboratory system, \( \delta \) as the laboratory incident angle of the laser photon with respect to the electron beam direction and \( \theta_{lab} \) as the scattered photon polar angle. The quantity \( \gamma \) will as usual be defined as \( \gamma = E_e / m_e c^2 \). In the electron CM system, \( q_0 \) and \( q \) are the incoming and outgoing photon energies and \( \theta \) and \( \phi \) the scattering angles. All energies and momenta are in units of electron rest mass. With these definitions (see also Fig. 1) we have the following relations:
\[
\frac{1}{q} - \frac{1}{q_0} = 1 - \cos \theta \\
\gamma \tan \theta_{\text{LAB}} = \sin \theta / (1 - \cos \theta) \\
q_0 / \gamma k_0 \approx 1 + \cos \theta_{\text{lab}} \approx 2 \\
k \approx \gamma q (\cos \theta - 1)
\]

To apply these formulae to LEP we will use throughout this paper the value of \( F_c \approx M_{Z^0}/2 \) (46 to 47 GeV). If not otherwise stated, we will discuss polarimetry with a circularly polarized pulsed laser, Nd:YAG (frequency doubled) with \( \lambda = 532 \) nm, equivalent to a photon energy of 2.33 eV.

The backward laboratory angle of the photon as a function of the scattered angle in the electron CMS is given in Fig. 2. The same figure also shows the corresponding backward scattered photon energy. This one to one correspondence between the angle \( \theta \) and the photon energy is further illustrated in Fig. 3.

Note that:

a) The very small backward angle range of the recoiling photons which typically is of the order of 10 to 20 \( \mu \) rads.

b) Even though no direct measurement of the scattering angle is possible, it can be measured indirectly through the scattered photon energy \( E_\gamma \) which is spread between 0 and about 29.5 GeV. For a fixed LEP energy the \( E_\gamma \) limit will increase as the laser energy increases.

c) The energy of the recoil electron in the Compton scattering is also well defined and may be measured instead (as proposed by SLC) or even in coincidence with the final state photon.

\[3.2 \text{ Cross Sections}\]

The total Compton scattering cross section for unpolarized particles is given in the electron center of mass system by the Klein – Nishina formula:
where $q_0$ is the incoming photon energy (in the electron centre of mass system) and $r_e$ is the classical electron radius. The dependence of this cross section on the laser energy is shown in Fig. 4, from which a cross section value of about 300 mb results for a laser of $\lambda = 530$ nm and an electron beam having an energy of $E_e = 47$ GeV.

The differential Compton scattering cross section is given by [4]:

$$d\sigma / d\Omega = 0.5 \left( r_e q / q_0 \right)^2 \left( \Phi_0 + \Phi_1 + \Phi_2 \right)$$

with

$$\Phi_0 = (1 + \cos^2 \theta) + (q_0 - q)(1 - \cos \theta)$$

$$\Phi_1 = \xi_1 \sin^2 \theta$$

$$\Phi_2 = -\xi_3 (1 - \cos \theta) \left( \hat{\mathbf{z}} \cdot (\hat{\mathbf{q}}_0 \cos \theta + \hat{\mathbf{q}}) \right)$$

where $q$, $\theta$ and $\phi$ are the scattered photon momentum and angles in the electron CM system, with

$$\xi = (\xi_1, \xi_2, \xi_3) = \text{Electron Polarization Vector (unit normalization)}$$

and

$$\xi = (\xi_1, \xi_2, \xi_3) = \text{Photon Polarization Vector}$$

where the $x$, $y$, and $z$ axes are respectively oriented horizontal, longitudinal and vertical.

Here we will consider a fully circular polarised laser beam i.e. $\xi = (0, 0, \mp 1)$.

**Case I. Transverse polarized electron beam**, i.e. $\xi = (0, 0, \pm P)$. In this case one has for the $\Phi$: the following expressions:

$$\Phi_0 = (1 + \cos^2 \theta) + (q_0 - q)(1 - \cos \theta)$$

$$\Phi_1 = 0$$

$$\Phi_2 = \mp P (1 - \cos \theta) q \cos \phi \sin \theta$$

which implies a $\phi$ dependence, the magnitude of which is proportional to the electron polarization $P$.

From this it follows that for a given angle $\theta$ the maximum up-down asymmetry $A(\theta)$ is:

$$A(\theta) = \left\{ \frac{d\sigma}{d\Omega} (\phi = 0^\circ) - \frac{d\sigma}{d\Omega} (\phi = 180^\circ) \right\} / \left\{ \frac{d\sigma}{d\Omega} (\phi = 0^\circ) + \frac{d\sigma}{d\Omega} (\phi = 180^\circ) \right\}$$

which for transverse polarized electrons case reduces to:

$$A(\theta) = \Phi_2 (\phi = 0^\circ) / \Phi_0$$

This asymmetry property has been used in the past and will also be utilized in LEP to measure the degree of transverse polarization of the electron and positron bunches.
Case II. Longitudinal polarized electron beam, i.e. $\zeta = (0, \mp P, 0)$. In this case one obtains for the $\Phi_i$

$$\Phi_0 = (1 + \cos^2 \theta) + (q_0 - q)(1 - \cos \theta)$$

$$\Phi_1 = 0$$

$$\Phi_2 = \mp P (1 - \cos \theta) (q_0 + q) \cos \theta$$

which means that no $\phi$ asymmetry is present and $\Lambda(0) = 0$. However, a difference in the scattering cross section exists between lefthand and righthand circularly polarized photon beams, which can be expressed either as a function of $\theta$ or as a function of $P_y$ ($= k$) as shown in Figs. 5 and 6. The maximum difference between the two cross sections occurs at the CMS backward direction corresponding to the highest energy value, $P_y$, of the scattered photons. One can therefore define for the longitudinal polarization case, an asymmetry quantity $\Lambda_{lo}$ which is equal to

$$\Lambda_{lo} \theta = \frac{(d\sigma/d\Omega \ (P_y = -1) - d\sigma/d\Omega \ (P_y = +1))}{(d\sigma/d\Omega \ (P_y = -1) + d\sigma/d\Omega \ (P_y = +1))}$$

which is shown in Fig. 7 as a function of $\cos \theta$ where $P_y = +1$ and $P_y = -1$ corresponding respectively to a righthand and lefthand circularly polarized photon beams.

4. The Laser System

The choice of the multi-photon technique [5], to be discussed in chapter 5 and section 6.3.2, implies the use of high peak power, low repetition rate lasers.

4.1 Choosing the Laser

For a given machine energy $E_c$, the analysing power of a polarimeter depends on the laser wavelength. For longitudinal polarimetry shorter wavelength lasers have better analysing power, as shown in Fig. 8 where $A_{lo} (\cos \theta = -1)$ is plotted against $\lambda_{laser}$. Furthermore, a shorter wavelength laser will also increase the maximum energy available to the recoil photon, which may be advantageous in avoiding some background sources. At the same time, due to energy conservation, the recoil electrons will have lower energy which could facilitate their extraction from the collider ring for analysis.

For transverse polarimetry for $\approx 50$ GeV beams, lasers operating in the visible region are optimal. A Nd-laser operating on the fundamental frequency ($\lambda_{laser} = 1060$ nm) or an Excimer laser (XeCl,
308 nm) would produce a slightly reduced transverse asymmetry while a CO₂ laser (10600 nm) would give a much smaller one.

Excimer lasers with 20 MW peak power at \( \lambda_{\text{laser}} = 308 \) nm up to 250 Hz repetition rate are at present commercially available. The higher repetition rate would certainly constitute an advantage provided the associated average power can be transmitted through the optical system. Drawbacks are cost, a more complex structure including toxic gas manipulation (XeCl, KrCl or KrF) and the need of quartz lenses due to the shorter wavelength.

Nd:YAG lasers with 50 \( \div \) 100 MW peak power at 532 and 1060 nm are available; their repetition rate is in the range of 10 \( \div \) 50 Hz due to the solid state structure.

Both devices can produce pulses durations in the range of 5 to 8 ns. More reasonable costs and wider experience at DESY and SLAC with Nd:YAG lasers have substantial advantages and this type of laser has indeed been chosen.

### 4.2 The Laser pulse duration \( \tau_\gamma \)

The luminosity from two Gaussian distributions intersecting at an angle \( 2\delta_\gamma \) depends on the longitudinal rms sizes of the interacting bunches. In our case the dependence of the luminosity on the laser pulse duration has been investigated for the interaction with an electron bunch of the appropriate rms dimensions. The results are illustrated in Fig. 9, where the luminosity for crossing angles \( 2\delta_\theta = 2, 4 \) and 6 mrad is shown as a function of the laser pulse duration. It can be seen that a \( \approx 20\% \) reduction in the relative luminosity occurs for an rms pulse duration of 3 ns when colliding at an angle of 2 mrad and it reaches \( \approx 38\% \) for \( \tau_\gamma = 5 \) ns.

The laser pulse duration should be chosen to be \( \leq 3 \) ns rms (7 ns FWHM) to keep the reduction in the luminosity within reasonable limits.

### 4.3 Present Laser performance

In order to gain experience prior to installation of the IEiP transverse polarimeter, a Nd:YAG laser with the following characteristics has been purchased. The 7 mm diameter by 115 mm long rod is placed in a cavity defined by a convex mirror associated to a converging lens on one side and a flat
semitransparent mirror on the other side. The fundamental wave length is 1064 nm, in the infrared. A frequency doubler gives a final 532 nm wave length in the green, that is 2.33 eV or 3.7 \(10^{-19}\) Joules per photon. The laser is pulsed at 30 Hz, providing 250 mJ at 1064 nm and 90 mJ at 532 nm, i.e. 7.5 Watts and 2.7 Watts respectively. The pumping light is provided by two flash lamps dissipating 30 Joules per pulse from the discharge of a 30 \(\mu F\) capacitor bank. The full width half height duration of the pumping light signal is .25 msec, leading to a .28 msec fluorescence time delayed by .2 msec relative to the flash signal. When the fluorescence reaches a maximum, a 3.6 kV voltage is applied to a Pockels Cell inserted in the optical cavity. Its starts a laser signal of 7 nsec at FWHM. The jitter is less than .5 nsec and the amplitude variation is small as shown in Fig. 10.

At the laser output the light density has an oval form. The vertical extension (z axis) is 7 mm, the horizontal one is 4 mm. The emittance is however 5 to 8 times greater than expected from pure diffraction. The structure of the beam light is not Gaussian and the optics will have to be a compromise between the smallest spot and the best homogeneity at the interaction point. The laser parameters are collected in Table 1.

Before installation an amplifier will boost the existing laser output to 190 mJ at 532 nm. Furthermore new products are already available and it is possible that a new higher performance Nd:YAG laser be provided.

**Table 1: Present Laser performance.**

<table>
<thead>
<tr>
<th>Laser type: Nd:YAG Quantel – longitudinal monomode</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavelength</td>
</tr>
<tr>
<td>photon energy</td>
</tr>
<tr>
<td>repetition rate</td>
</tr>
<tr>
<td>peak power</td>
</tr>
<tr>
<td>pulse length (FWHM)</td>
</tr>
<tr>
<td>pulse energy</td>
</tr>
<tr>
<td>peak intensity</td>
</tr>
<tr>
<td>CW power</td>
</tr>
<tr>
<td>time jitter (rms)</td>
</tr>
<tr>
<td>output emittance</td>
</tr>
</tbody>
</table>

5. The LEP Transverse Polarimeter

A condensed version of the detailed account on the measurement of the electron transverse polarization in LEP, given in reference 5a, is presented where we concentrate on relative bunch to bunch effects.
5.1 Introduction

The transverse laser polarimeter has become a part of the standard equipment in e± storage rings above 1 GeV. The laser polarimeter is based on spin dependent Compton scattering of circularly polarized photons from a high energy electron/positron beam, already discussed in chapter 3. The Compton rate is given by

\[ n_\gamma = L_{e\gamma} \sigma_{e}\langle P_e \cdot P_\gamma \rangle \]

where

\[ L_{e\gamma} = \frac{N_e N_\gamma}{\Sigma} \]

is the luminosity of the electron beam–laser interaction, \( f \) the laser repetition rate, \( N_e \) the number of electrons bunch, per bunch, \( N_\gamma \) the laser pulse intensity and \( \Sigma \) the interaction area.

From these formulae one can calculate a value of \( n_\gamma \) of 7 \( 10^4 \) for the ideal intersection situation using the nominal values of the LEP I electron bunches and the laser specifications as given in Table 1. In practice, however, it is expected that several factors will reduce significantly the backward Compton scattered photon flux. Among them are the laser light losses along the optical path, the laser pulse duration and incomplete overlap of the laser spot with the electron bunches. We therefore assumed conservatively throughout this work that at each laser beam–electron bunch collision, the effective number of Compton photons useful for polarization measurements is about 1000 photons.

In Table 2 we present some parameters which are relevant for the LEP polarization physics programme.

**Table 2: Some relevant LEP parameters** [6]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>47 GeV / beam</td>
</tr>
<tr>
<td>No. of bunches</td>
<td>4 e⁻ ; 4 e⁺</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>4.16 ( 10^{11} )</td>
</tr>
<tr>
<td>Circulating current</td>
<td>3/4 mA/bunch</td>
</tr>
</tbody>
</table>

The backscattered high energy \( \gamma \)–rays travel towards a detector which records their vertical angular distribution. If the electron beam is transversally (vertical) polarized, an up–down asymmetry in the
\( \gamma \) rate is present and two different vertical distributions are obtained depending on the left-right polarization \( P_\gamma \) of the photons.

The electron polarization level can be deduced, by comparing the backscattered \( \gamma \) rates for the two helicity configurations of the laser beam through the up-down asymmetry

\[
\Lambda(z) = \frac{n_\gamma R(z) - n_\gamma L(z)}{n_\gamma R(z) + n_\gamma L(z)}
\]

where \( n_\gamma R(z) \) and \( n_\gamma L(z) \) are the counts of the backscattered \( \gamma \)'s at a vertical position \( z \), for the two helicities ( R, L ) of the laser beam.

The multi-photon technique of illumination is used, requiring a high peak power laser to produce about \( 10^3 \) photons per interaction.

### 5.2 Monitoring the Laser Polarization

The circularly polarized light is generated by inserting a \( \lambda/4 \) wave plate on the original linearly polarized laser beam. Left- and right-hand polarization light states are obtained by rotating by \( \pm 90^\circ \) the \( \lambda/4 \) plate or by an electro-optical device (Pockels cell). The photon helicity has to be changed rather often during data taking to average out false asymmetries coming from drifts in the closed orbit slope at the interaction region.

The photon circular polarization level might be affected by strains in the window separating the machine vacuum from the atmosphere due to birefringence of the material. This effect cannot be numerically quantified and has to be studied in the laboratory prior to the installation of the apparatus. Cure of possible effects could impose larger window diameters. Optical elements in the light path can also induce some depolarization in the photon beam.

The effective circular polarization \( P_\gamma \) of the laser beam at the Laser Interaction Region (LIR(\gamma)), chosen for the transverse polarimeter, has to be properly measured if the absolute polarization of the electron beams is aimed at. A possibility, illustrated in Fig. 11, envisages a "remote polarimetry" on the light deflected after the interaction into the UIJ4 junction where some instrumentation can be installed.

It is estimated that the laser polarization can be known in absolute terms to about 1%, and that long
term drifts can occur. It is clear however that the laser polarization will be identical for the different bunches at a given time to a much better accuracy.

5.3 Background Considerations

The background will consist of two components: beam–gas bremsstrahlung and synchrotron radiation. In the following the background conditions in the straight section 1.SS1 are investigated.

5.3.1 Beam–Gas bremsstrahlung.

The total cross section \( \sigma_{gb} \) [mb] for the beam–gas bremsstrahlung can be found in Ref. 7 and is given by

\[
\sigma_{gb}(\epsilon_s) = 57.3 [6.37\epsilon_s - 6.37 \ln(\epsilon_s) - 2.34\epsilon_s^2 - 4.03]
\]

where \( \epsilon_s = k/E \) is the ratio between the photon and the electron energies. Photons below \( \epsilon_s = 0.2 \) will not reach the detector. Computing the rate of gas bremsstrahlung photons with the following parameters

- residual gas \( <Z> = 5 \)
- average pressure = 5.10^{-9} \text{ Torr}
- path length = 500 m

leads to an upper limit of 2 photons per interaction at 1 mA / bunch.

5.3.2 Synchrotron radiation.

A formula giving the number \( N_{sr} \) of photons/s/mA/m emitted above a certain energy \( u(\text{keV}) \) as a function of the energy \( E \) and the bending radius \( \rho \) is given in [8]:

\[
N_{sr} = 4.6 \cdot 10^{16} \exp(-0.45 u_E/E^2) \sqrt{(1/E^3/\rho^3)}
\]

The layout, described later in section 5.4, has been chosen in order to eliminate all background from the main dipoles. The remaining backgrounds to which the detector is sensitive \( E_p > 0.5 \text{ MeV} \), are quantified in Table 3, where are trajectories of 10 m (10% dipole), 2 m (both miniwigglers), 6.5 m (16 c.o. correctors) and 24 m (24 quadrupoles) are considered as contributing \( N_d \) photons to the s.r. background.
Table 3: Flux of synchrotron radiation photons with energy > 0.5 Mev.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\rho$ (km)</th>
<th>$\epsilon_c$ (keV)</th>
<th>$N_d$ ($10^{17}$/mA/s)</th>
<th>$P_d$ (GeV/crossing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% dipole</td>
<td>30.96</td>
<td>12</td>
<td>$5.6 \times 10^{-17}$</td>
<td>$2 \times 10^{-12}$</td>
</tr>
<tr>
<td>quadrupoles</td>
<td>$\approx 10$</td>
<td>$\leq 40$</td>
<td>$\leq 1.5 \times 10^{-3}$</td>
<td>$\approx 50$</td>
</tr>
<tr>
<td>corr. dipoles:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td>2</td>
<td>184</td>
<td>220</td>
<td>$7.5 \times 10^6$</td>
</tr>
<tr>
<td>50%</td>
<td>4</td>
<td>92</td>
<td>5.2</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>30%</td>
<td>6.7</td>
<td>55</td>
<td>.07</td>
<td>$2 \times 10^3$</td>
</tr>
<tr>
<td>mini-wigglers</td>
<td>0.877</td>
<td>420</td>
<td>$10^3$</td>
<td>$3.6 \times 10^7$</td>
</tr>
</tbody>
</table>

It can be seen that the dominating effects come from the mini-wigglers and the correcting dipoles for which the deposited power $P_d = u I N_d$ for $I = 3$ mA/beam is

$$3.4 \times 10^{11} \text{ GeV/s} \rightarrow 7.5 \times 10^6 \text{ GeV/crossing} \quad \text{(corr: dipoles at 100%)}$$

$$P_d =$$

$$1.6 \times 10^{12} \text{ GeV/s} \rightarrow 3.6 \times 10^7 \text{ GeV/crossing} \quad \text{(miniwigglers)}$$

These figures have to be compared with the energy deposited by the backscattered $\gamma$-beam. If $\approx 10^3$ $\gamma$'s per interaction are produced with an average energy of about 25 GeV with the multiphoton technique, the deposited energy is $\approx 2.5 \times 10^4$ GeV/crossing.

Two conclusions can be drawn from Table 3:

(i) The operation of the polarimeters is incompatible with the miniwigglers.

(ii) The 16 correcting dipoles in LSS1 should not be powered (if all used at the same time) to more than $\approx 30\%$ of their maximum. Orbit correction procedures will have to take this recommendation into account.
5.4 Layout

According to the previous considerations a layout for the polarimeter has been adopted which prevents the synchrotron radiation from the main dipoles from falling into the detector.\textsuperscript{1}

As shown in Fig. 11 the photon beam produced by a laser installed in the Optical Laboratory in the building US15 in front of IP1 is directed towards the LEP tunnel through a $\approx 16$ m long channel drilled in the rock. The light is then deflected towards the LIR\textsubscript{T} located between the quadrupoles QL4 and QL5 at both sides of IP1, $\approx 66$ m downstream.

A more detailed layout of the polarimeter in LSS1 is shown in Fig. 12. The Compton–backscattered y’s will travel together with the LEP beams along the LSS1 straight section and will be separated from the electrons (positrons) in the 10% dipole B4WL when entering the arcs. As shown in Fig. 13 the $\gamma$–rays will leave the LEP vacuum chamber at the end of the first dipole B4/1 and after passing between the two external coils of the quadrupole QL13 will reach the $\gamma$–detector through a $\approx 40$ m long evacuated path.

The detector will be installed between the dipole B4/3 and the tunnel wall at about 275 m from the LIR\textsubscript{T} ($\approx 341$ m downstream IP1).

The following modifications are required to provide the necessary channel for the extraction of the photons.

1) The dipole B4/2 must be reversed.

2) The two external coils of the quadrupole QL13 need to be modified to provide a 20 mm vertical aperture to the $\gamma$–beam.

3) The vacuum chamber in dipole B2R of B4/1 has to be enlarged.

4) The orbit correcting dipole MCHA next to QL13 has to be reversed.

\textsuperscript{1} The synchrotron radiation emitted in the first normal bending magnet B4/1 does not hit the detector because of the 0.754 mrad deflection in the B4WL 10% dipole.
5.5 The Laser Beam and the Interaction Region (LIR)^

5.5.1 The illumination point.

For a given value of the degree of polarization of the circulating beams the asymmetry depends on the optical parameters at the LIR and on its distance from the detector. For the foresen LEP optics an illumination point 1 meter outside the D− quadrupole Q14 has been chosen. The LEP beam characteristics in the Vertical (V) and Horizontal (H) directions are given in Table 4. Vertical beam profiles for both laser helicities are shown in Fig. 14.

Table 4: Twiss parameters for the electron beam at the LIR

(E_e = 55 GeV, ε_h = 55.6 nm, ε_v = 2.2 nm)

<table>
<thead>
<tr>
<th></th>
<th>LIR</th>
<th>Last mirror M6</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>mm</td>
<td>μrad</td>
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</table>

5.5.2 The special vacuum insertion.

Experience at PETRA has shown that total internal reflection prisms inside the vacuum chamber were seriously damaged. Metallic mirrors will be used in LIR for the final steering of the laser onto the electron beam.

The laser beam from the optical lab. will reach a special vacuum insertion and enter the vacuum chamber through a quartz window to be deflected by the retractable metallic mirror M6 (Fig. 15). This will be introduced at the end of the LEP acceleration cycle and after the beam adjustments at the flat top so that the beam−to−mirror clearance can be reduced to about 10 mm (i.e. ≈ 26 σ_eV). a second mirror M6′ will recuperate the laser light after the interaction.
5.5.3 Collision angle and laser spot size.

The collision angle should be chosen to maximize the luminosity of the interaction for a given laser pulse length. The necessity of having a small crossing angle to produce a long interaction region has to be balanced with the importance of reducing the sensitivity to the vertical orbit misalignment. Interactions at very small angles are moreover limited by the position of the last mirror relative to the electron beam, which is in turn defined by the mirror dimensions and hence by the laser spot size at the interaction, for a given emittance of the laser beam.

The influence of the laser spot size on the luminosity has been studied. The relative luminosity is shown in Fig. 16 as a function of the laser spot size at the interaction for collision angles $2\delta_0 = 0, 2, 4$ and $6$ mrad. Requiring a $10$ mm clearance between the beam and the wedge of the mirror $M_e$ and taking into account the laser beam emittance, a $2$ mrad collision angle can be obtained with a nominal laser spot size

$$\sigma_y^* = 0.6 \text{ mm}$$

A smaller laser size at LIR_I would require to increase the interaction angle to accommodate the larger mirror dimensions within the $10$ mm clearance, with no net advantage in the luminosity.

5.6 The Recoil $\gamma$-beam — Apertures and Diaphragms

For LEP I ($E_e = 45 \pm 60$ GeV), the backscattered $\gamma$-beam energy lies in the range 15 to 40 GeV. The transmission of the Compton backscattered $\gamma$'s to the detector is limited by the available apertures on the line of flight (Fig.15). The diaphragms are essentially located in the modified vacuum chamber inside the B4/I dipole (Horizontal diaphragm $D_H = 50$ mm) and between the external coils of the quadrupole QL.14 (Vertical diaphragm $D_V = 20$ mm).

The $\gamma$-beam dimensions at the diaphragms and at the detector location are collected in Table 5 for $E_e = 45$ GeV.
Table 5: $\gamma$ - beam dimensions at diaphragms and detector for $E_\gamma = 45$ GeV

<table>
<thead>
<tr>
<th>position</th>
<th>dist. from LIR$_T$ (m)</th>
<th>$\sigma_\gamma$II (mm)</th>
<th>$\sigma_\gamma$V (mm)</th>
<th>diaphragm (mm)</th>
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<tr>
<td>mid B4/l</td>
<td>220.6</td>
<td>9.5</td>
<td>2.3</td>
<td>50 (H)</td>
</tr>
<tr>
<td>out QL13</td>
<td>235.6</td>
<td>10.2</td>
<td>2.5</td>
<td>20 (V)</td>
</tr>
<tr>
<td>detector</td>
<td>$\approx$275</td>
<td>11.8</td>
<td>2.9</td>
<td></td>
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</tbody>
</table>

Note that at 45 GeV:

(i) the horizontal aperture in B4/l is $5.3 \sigma_\gamma$II

(ii) the vertical aperture in QL13 is $8.0 \sigma_\gamma$V

(iii) the minimum required sensitive area of the detector is

$$S_{det} \geq 63 \text{ mm} \times 24 \text{ mm} \ (H \times V)$$

5.7 Considerations on the $\gamma$ - detector

A very compact calorimeter will monitor the rate of the backscattered $\gamma$'s. The sandwich-like structure, derived from the solution adopted for the Bhabha relative luminosity monitors [9], will be composed of two vertical Silicon double half-planes separated by 10 r.l. Tungsten converters and followed by a 20 r.l. Tungsten shielding (Fig. 17). Two Silicon strip planes$^2$ will allow one to check the profiles of the incoming $\gamma$ - beam in both planes during the calibration phase.

A Silicon/Tungsten calorimeter [9] with only two sensitive planes has a resolution of $\approx 125%/\sqrt{E}$. At an average $\gamma$ energy of about 25 GeV this resolution amounts to $\approx 25\%$ and will contribute by only 6\% to the statistical fluctuations when a bunch of $\gamma$'s are recorded.

The detector has an horizontal plane of symmetry and allows for simultaneous recording of the backscattered $\gamma$'s above and below the center of gravity of the distribution. The total energies $E_\gamma$Ru

---

$^2$ 32 mm / 16 channels covering $\pm 6 \sigma$ of the $\gamma$'s distributions at the detector.
+ $E_{\gamma} L_d$ and $E_{\gamma} R_d$ recorded in the upper (u) and the lower (d) halves of the calorimeter for both photon helicities can be combined to give the asymmetry

$$\Lambda = \frac{E_{\gamma} R_u - E_{\gamma} R_d + E_{\gamma} L_d - E_{\gamma} L_u}{E_{\gamma} R_u + E_{\gamma} R_d + E_{\gamma} L_d + E_{\gamma} L_u}$$

This asymmetry is insensitive to systematic errors originating from drifts in the closed orbit at LIR $\Gamma$. An analogous algorithm can be set up to monitor a possible offset at the detector, and this information will be used as a feedback to control its vertical position for a proper compensation. The simultaneous acquisition would also make the measurements insensitive to fluctuations in the nominal electron beam rms dimensions at LIR $\Gamma$.

The evaluation of the analyzing power of the polarimeter for the nominal beam gives

$$\Pi_{\Gamma} (P_{\gamma} = 1) = \frac{\partial \Lambda}{\partial P_c} \approx 11.33\%$$

One can also determine the beam polarization by a measurement of the centroid displacement, $\Lambda \langle V \rangle$, of the recoiling beam in the Silicon strip detector. For $P_c = 1$ the distribution width is 3 mm rms and the displacement is 0.812 mm when the laser polarization is reversed (see Fig. 14).

### 5.8 Rates, Accuracies and Measuring Time

The adoption of the multi-photon technique, as in the case of the longitudinal polarimetry (see sec. 6.3), provides a backscattered $\gamma$-rate

$$r_{\gamma} \approx (1 + 3) \cdot 10^4 \text{ Hz}$$

The relative statistical accuracy $\delta \Lambda / \Lambda$ for the asymmetry is a function of $\Lambda$:

$$\frac{\delta \Lambda}{\Lambda} \approx \frac{1}{\Lambda \sqrt{2 \langle n_{\gamma L,R} \rangle}}$$

where $\langle n_{\gamma L,R} \rangle$ is average number of counts at each photon helicity required for a given accuracy.

Introducing the analyzing power the measuring time in terms of the polarization level $P_c$ and the accuracy on $\Lambda$ is
\[ T_{\text{meas}} = \frac{< n_{yL,R} >}{r_y} \approx 10^{-4} \text{ [s]} \]

The measuring time \( T_{\text{meas}} \) is shown in Fig. 18 as a function of \( P_e \) for different accuracies \( \delta A/A \).

For the centroid measurement method a precision of \( \delta P_e = 1\% \) is reached for \( \approx 10^6 \) photons corresponding to about 1 to 2 minutes data collection time.

5.9 Systematic Effects.

In this section we address the question of how accurately the transverse polarimeter can measure the absolute and the relative bunch to bunch polarization. Systematic errors coming from offsets in the electron beam position or divergence are large. However they can easily be eliminated by by centering the \( \gamma \) detector on the average of the recoil beam. Other systematic errors which arise from the effects of uncertainties in the electron beam size and divergence, due to the finite measuring resolution and knowledge of the \( \beta \) functions, have been investigated. This has been done, using the layout shown in Fig. 12 and the polarimeter detector of Fig. 17 with a slit of 2 mm, by generating about \( 3 \times 10^5 \) Compton scattering events with a simulation program. It was found that the asymmetry method is sensitive to systematic effects of the beam vertical spot size. This uncertainty in the polarization measurement can be eliminated by a normalization of the measured asymmetry to the vertical rms dimensions of the recoil photon beam or by using the centroid method.

Finally we note that if an accurate spatial detector were to be added to the front of the \( \gamma \) detector, it might be possible to use it to measure more accurately the beam divergence — however there are no plans at present to implement such an improvement.

6. Longitudinal Polarimetry

6.1 Introduction

As discussed in chapter 3, the longitudinal polarimeter proposed for IEP is based on Compton scattering of a circularly polarized laser beam on the IEP \( e^\pm \) beams, where the degree of the electron
(positron ) polarization is derived from the different energy spectra of the recoil photons when the laser beam polarization is reversed.

Fig. 19 illustrates the detection end of the system. Scattered photons exit from the LEP straight section through special vacuum tubes and windows (not shown in Fig. 19) where they are converted into $e^+ e^-$ pairs in a thin lead or crystal converter. A sweeping magnet then provides a vertical momentum dependent separation and calorimeters 1–4 detect the converted $e^\pm$ in appropriate energy ranges. This scheme will also separate the wanted $e^+ e^-$ pairs from the backgrounds. Arguments will be presented for the choice of the multi-photon mode of operation.

Many of the considerations of the chapters on the laser system (chapter 4) and transverse polarimeter (chapter 5) are also relevant for the longitudinal polarimeter. In particular we assume for the time being that the same type of laser will be used, although we are aware of new products in this field which have better performance than the device described in chapter 4. As for monitoring the laser beam and apertures, their problems and solutions are similar to those outlined for the transverse polarimetry (sections 5.2 and 5.6) and thus will be adopted also here.

### 6.2 Detector Design

The detector for the longitudinal polarimeter might well resemble that used successfully by the UA7 collaboration [10], namely a 20 radiation length Silicon/Tungsten calorimeter.

The longitudinal development of the shower is measured at 11 sampling points. A 4" diameter Silicon wafer is placed every two radiation lengths. Four of these wafers are segmented into 5 mm wide strips, for the horizontal and vertical coordinates, and placed at 6 and 10 radiation lengths. The strip width is 11 mm for the front vertical plane and for the 45° oriented U plane placed at 8 radiation lengths.

The shower signal was amplified by a linear preamplifier and shaping amplifiers and transmitted to a Lecroy 2281 ADC system. The calibration of the preamplifier and ADC system was made by injecting a test pulse in front of the preamplifier.

The energy deposit in the Silicon had been calibrated using 976 keV electrons from decay of isotope Bi²⁰⁷. The thickness uniformity of each Silicon wafer was better than 25 μm by construction. The absolute thickness varies from 8 to 1.2 mm.
The longitudinal development of the showers generated by electrons at different energies is shown in Fig. 20. Superimposed is a fit to the data using current formulas, such as the one given by the Particle Data Group [11].

Fig. 21a represents the energy resolution of the calorimeter as a function of the incident beam energy. The data points agree well with the Monte Carlo prediction $25\% / \sqrt{E} + 1.1\%$. The constant term comes from the limited number of Tungsten plates. After correction for the losses (1% at 10 GeV, 3.2% at 100 GeV) due to the limited number of radiation lengths, the linearity of the calorimeter was better than 1%.

The position resolution is shown in Fig. 21b as a function of the energy and can be expressed by $3.8(\text{mm}) / \sqrt{E(\text{GeV})}$. Lower points are for the horizontal direction (5 mm strip width) and upper points correspond to the U plane (11 mm strip width).

Fig. 22 (from reference 12) shows a typical example of the lateral distribution of the shower at incident electron energy of 4.5 GeV. The response does not change much when the incident beam is close to the edge of the detector [13].

This detector looks perfectly suited to our needs for the measurement of longitudinal polarization.

6.3 Counting Rates

Two modes of operation are in principle possible:

6.3.1 The Single Photon Mode

In this mode one analyses single Compton scattering events. This requires the average number of recoil photons entering the polarimeter detector per laser shot to be less than one, $N_y \approx 0.1$ being reasonable. The photon detector of the polarimeter can then be adjusted to have a low photon energy threshold, $F_c$. We define $F_L$ and $F_R$ as the average recoil photon energy (above the cutoff) respectively for left and right circular polarized photons which can be expressed in the following way:

\[
F_L = F_0 (1 + \Pi_L P_e) \\
F_R = F_0 (1 - \Pi_L P_e)
\]

where $F_0$ is the average energy for $P_e = 0$ and $\Pi_L$ is the analyzing power which depends on $F_c$.

From these one can then calculate $P_e$ through the relation

23
\[ P_e = \frac{1}{\Pi_L} \frac{(E_L - E_R)}{(E_L + E_R)} \]

The obvious advantages of this single photon detection mode are:

a) The measurement is independent of the photon-electron luminosity \( \mathcal{L}_{\gamma e} \) which is hard to control and monitor; and

b) One is able to cope with the background of low energy photons.

However this method has two severe drawbacks.

a) The first is its high sensitivity even to a very low background of high energy photons with \( E > E_c \), e.g. those from radiative Bhabha scattering,

\[ e^+ e^- \rightarrow e^+ e^- \gamma \]

or from beam-gas bremsstrahlung in the straight section.

b) The second concerns the sampling time. The relative error in measuring the polarization is approximately given by

\[ \delta P_e = \left( \frac{1}{\Pi_L} \right) \left( N_s \bar{N}_\gamma F \right)^{-0.5} \]

where \( N_s \) is the number of laser pulses and \( F \) is the fraction of Compton photons with \( E_\gamma > E_c \).

For \( \Pi_L = 0.15 \) and \( F = 0.3 \) the precision of \( \delta P_e = 0.003 \) will be reached when \( N_s \approx 1.5 \times 10^7 \) which is a long time if one uses a 10 Hz laser. The sampling time may be somewhat reduced with the choice of a higher frequency laser.

The two drawbacks mentioned above make the single photon mode a rather unpractical proposition.

6.3.2 The Multi-photon Mode

We next consider the multi-photon mode where a high power laser is used and a high \( \mathcal{L}_{\gamma e} \) results. The polarization is given by the same expression as for the case of the single photon mode. The total energy of the beam of recoiling photons is measured, many such recoil photons being recorded for each laser shot. This total energy is sensitive to the beam polarization, but the technique has at first sight a reduced analysing power \( \Pi_L \) and is sensitive to the relative fluctuations of \( \mathcal{L}_{\gamma e} \), which may be large, between the different electron and positron bunches. In this mode the relative polarization error is given by

\[ \delta P_e = \left( \frac{1}{\Pi_L} \right) \delta (\Delta \mathcal{L}_{\gamma e}) \left( N_s \right)^{-0.5} \]
If we take for example $\delta (\Delta \mathcal{L}_{\text{cy}}) = 0.05$ (just a guess until we have some operational experience) and $\Pi_L = 0.15$ one needs to have $N_s = 1.2 \times 10^4$ shots to obtain $\delta P_e \approx 0.003$. This gives an acceptable sampling time of about 20 min for a 10 Hz laser.

A variation on the straightforward multi-photon mode overcomes the problems mentioned above and increases significantly the analyzing power. To measure the polarization free of uncertainty in $\mathcal{L}_{\text{cy}}$ one has to be able to retrieve the spectral information of the individual Compton photons. This can be achieved by converting the photons into electron pairs the momenta of which are then magnetically analysed. A schematic outline of such a system is shown in Fig. 19. The Compton photons hit a thin convertor of about 0.1 radiation length. The thickness of the convertor is determined by two factors. The first is the need to minimize the radiation corrections and the second to have a sufficient yield of photons conversion to electron pairs in order to keep the sampling time within an acceptable limit. The electron pairs are then passing through a sweeping magnet of $\approx 0.2$ Tm and are detected by four calorimeters situated symmetrically to have equal efficiency detection for electrons and positrons. A sandwich of Tungsten and Silicon detectors having some 20 radiation lengths should be an adequate solution for the proposed calorimeters. A considerable reduction of synchrotron radiation background in the calorimeter can be achieved by deflecting the electrons and positrons away from the LEP ring plane. Finally additional information could be obtained from the unconverted photons which are captured by an additional counter placed in the Compton straight flight line (not shown in the the figure). This counter may also be utilized as supporting luminosity counter since it will be sensitive to the radiative Bhabha scattering, $e^+ e^- \rightarrow e^+ e^- \gamma$, (see also ref. 14).

The beam polarization $P_e$ in this setup is given by:

\[ P_e = \left( \frac{1}{\Pi_L} \right) \frac{Q_L - Q_R}{Q_L + Q_R} \]

with

\[ Q_L = \left( \frac{E_{23}}{E_{14}} \right)_L \quad \text{and} \quad Q_R = \left( \frac{E_{23}}{E_{14}} \right)_R \]

where $E_{ij}$ is the energy deposited in the calorimeters $i$ and $j$. For a setup where calorimeters 2 and 3 detect electrons between 20 and 29.5 GeV and the calorimeters 1 and 4 between 5 and 10 GeV, the analysing power $\Pi_L$ is equal $\approx 52\%$. With this system about 3% of the recoil photons will be recorded in the electron calorimeters and at least $\sim 10^3$ Compton photons/laser shot are expected for the type of laser under consideration. About 34000 laser pulses will be needed to achieve an accuracy of $\delta P \approx 0.003$.
6.4 Analyzing Power and Systematic Errors

Two independent programmes have been developed and used to evaluate the analyzing power \( \Pi_L \) of the proposed longitudinal polarimeter and its systematic errors. They arrive at the same conclusions, which are described below.

6.4.1 Analyzing Power and Resolution.

Referring to Fig. 19, the Compton photon distributions were generated using the equations of chapter 3 and the beam parameters of section 6.6. The electron energy spectrum of the converted photons is shown in Fig. 23. Using a 0.15 Tm sweeping magnet following a 10% radiation length converter the energy limits of the low energy calorimeters (1 & 4) and the high energy calorimeters (2 & 3) were varied in order to optimize the resolution.

Results for the analyzing power [15] are shown in Table 6, where the horizontal variable is the upper energy limit of calorimeters 1 & 4, and the vertical variable is the lower energy limit of calorimeters 2 & 3. Table 7 shows the precision of the polarization measurement obtained with 17,000 laser shots for each laser helicity, corresponding to about 20 mins with a 10 Hz rep. rate. Note that the optimum resolution does not correspond to maximum analyzing power — the optimum of the latter occurs at points where the counting rate would be very low.

Fixing the upper limit of calorimeters 2 & 3 at or above the maximum energy of the recoil photons \( \approx 29.5 \text{ GeV} \), Fig. 24 shows how the resolution varies with the lower energy limit. The different curves correspond to various upper limits of the calorimeters 1 & 4 fixing their lower limit to 5 GeV. As a result of these studies we have chosen the following ranges:

\[
\begin{align*}
\text{Calorimeters 1 & 4} & \quad 5 < E < 10 \text{ GeV} \\
\text{Calorimeters 2 & 3} & \quad 20 < E < 29.5 \text{ GeV}
\end{align*}
\]

which yield for 17,000 double laser shots the following analyzing power and resolution values for the nominal beam:

\[ \Pi_L = 0.522 \quad \text{and} \quad dP_e/P_e = 0.314 \% \]

Some redundancy could be built into the system if a set of position measuring devices (MWPC's or Silicon strips) were positioned in front of the calorimeters which will provide independent momentum values of the converted electrons. Furthermore they would not be subject to "edge" effects and so might turn out to be essential in analyzing the calorimeter data to the required high precision.
### Table 6: Analyzing powers $\Pi_L \ (%)$ for different energy ranges.

<table>
<thead>
<tr>
<th>$E_{23}$ range [GeV]</th>
<th>28 − 29.5</th>
<th>27 − 29.5</th>
<th>26 − 29.5</th>
<th>25 − 29.5</th>
<th>24 − 29.5</th>
<th>23 − 29.5</th>
<th>22 − 29.5</th>
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### Table 7: The error $\delta P_e \ (%)$ for different energy ranges.

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<td>.331</td>
<td>.325</td>
<td>.323</td>
<td>.325</td>
<td>.321</td>
<td>.320</td>
<td>.321</td>
<td>.320</td>
<td>.317</td>
</tr>
<tr>
<td></td>
<td>.861</td>
<td>.570</td>
<td>.450</td>
<td>.387</td>
<td>.352</td>
<td>.331</td>
<td>.325</td>
<td>.323</td>
<td>.325</td>
<td>.321</td>
<td>.320</td>
<td>.321</td>
<td>.320</td>
<td>.317</td>
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<td></td>
<td>.871</td>
<td>.577</td>
<td>.454</td>
<td>.391</td>
<td>.355</td>
<td>.333</td>
<td>.325</td>
<td>.323</td>
<td>.325</td>
<td>.321</td>
<td>.320</td>
<td>.321</td>
<td>.320</td>
<td>.317</td>
</tr>
<tr>
<td></td>
<td>.884</td>
<td>.585</td>
<td>.460</td>
<td>.396</td>
<td>.359</td>
<td>.337</td>
<td>.329</td>
<td>.327</td>
<td>.329</td>
<td>.325</td>
<td>.324</td>
<td>.325</td>
<td>.324</td>
<td>.321</td>
</tr>
<tr>
<td></td>
<td>.899</td>
<td>.595</td>
<td>.468</td>
<td>.402</td>
<td>.364</td>
<td>.341</td>
<td>.333</td>
<td>.331</td>
<td>.333</td>
<td>.329</td>
<td>.328</td>
<td>.329</td>
<td>.328</td>
<td>.325</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_{14}$ range [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 − 6</td>
</tr>
</tbody>
</table>

27
6.4.2 Systematic Errors.

As for the transverse polarimeter, we have investigated the effect of off-centring the beam at the converter, both in position and angle, and of adjusting the LEP beam properties (spot size, divergence and beam energy) by amounts typical of the relative precision with which they are known. Offsets in position or divergence could be eliminated experimentally by exploiting the possibility to switch off the laser circular polarization or by measuring the recoil beam centroid with an on-axis calorimeter. We found that the systematic errors introduced in the knowledge of the analyzing power due to the above uncertainties in the LEP beam properties, are small compared to the required precision. In Table 8 we present the dependence of the analysing power on the bunch to bunch relative beam properties. We conclude that the bunch to bunch systematic is of the order of 1%. The systematic for absolute measurement of the longitudinal polarization is estimated to be larger by an order of magnitude.

Table 8: Variations in analyzing power ($\Pi_{L}$).

<table>
<thead>
<tr>
<th>Relative bunch to bunch change</th>
<th>Change relative to nominal beam (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal beam + $\delta V = 50 \mu m$</td>
<td>+0.026</td>
</tr>
<tr>
<td>nominal beam + $\delta \sigma V = 50 \mu m$</td>
<td>+0.051</td>
</tr>
<tr>
<td>nominal beam + $\Delta V = 1.0 \mu rad$</td>
<td>+0.004</td>
</tr>
<tr>
<td>nominal beam + $\delta \sigma V = 0.5 \mu rad$</td>
<td>−0.002</td>
</tr>
<tr>
<td>nominal beam with $\Delta E_{e} / E_{e} = \pm 0.02%$</td>
<td>$\mp 0.01$</td>
</tr>
</tbody>
</table>

6.5 Background Estimates

The background estimates are very different for the two types of spin rotator under study. Arc rotators have no magnets in the experimental straight sections and are designed so that the weak (10%) bends at the extremities of the straight sections are preserved. Their background situation is therefore analogous to that described in section 5.3 for the transverse polarimeter. Straight section rotators, however, change the layout significantly in the straight sections surrounding the experiment by introducing a strong bend near ($\approx 30 - 50$ m) to the experiments. The two cases are dealt with separately.
6.5.1 Background Estimates in the Case of Arc Rotators.

The main sources of background in the longitudinal polarimetry are due to Synchrotron radiation, beam–gas bremsstrahlung, radiative Bhabha Scattering and 2–photon annihilation processes, where the last two are proportional to luminosity. These backgrounds are identical to those encountered in the LEP transverse polarimetry and apart from the last, are described in some detail in section 5.3. The introduction of arc rotators in the accelerator ring should not affect the background level. In any case due to the fact that the electron calorimeters (1, 2, 3 and 4; Fig. 19) may have a lower energy cutoff, $E_c$ and are situated outside the LEP ring plane, these background sources are by far less harmful than they are for transverse polarimetry.

I) Synchrotron Radiation

The sources of synchrotron radiation that may affect LEP longitudinal polarimetry are the weak (10%) dipole magnets, the orbit correctors and the straight section quadrupoles. Note that the straight sections where the LEP experiments have their detectors do not contain miniwiggler. It is assumed that the orbit correctors are all running at 30% of their maximum strength and that the beam is off axis in the quadrupoles as in section 5.3.2. The effects of these accelerator ring elements can be estimated with the formula given in section 5.3.2 and are quantified in Tables 3 and 10.

II) Electron Beam–Gas Bremsstrahlung

As in the case of the transverse polarimeter (see section 5.3.1), the estimate of this background is based on formulae given in Ref. 7. The background from beam–gas Bremsstrahlung depends on the gas residues in the LEP straight section of about 600 m seen by the converter and on the number of electrons in a bunch. One can safely assume that the residual gas in the ring behaves like an ideal gas and that it consists mainly of Carbon and Oxygen. Hence, for bunches with $4.16 \times 10^{11}$ electrons and a 600 m length, the probability $Pr$ for an electron with an energy $E_c$ to radiate a photon with an energy $k$ is:

$$Pr (E_c, k) \, dk \approx 0.09 \, \tau \, dk/k$$

where $\tau$ is the pressure in the ring in units of $10^{-10}$ Torr. If the detector system has a lower energy cutoff of 5 GeV, the beam–gas background will be less than 1 photon/shot (Table 10) for the estimated average pressure of $\tau = 4.7$ in the LEP straight sections equipped with r.f. cavities. In the
straight sections without r.f. cavities the pressure is expected to be $\approx 2 \times 10^{-10}$ Torr and the background scales down accordingly.

III) Radiative Bhabha Scattering

The cross section for radiative Bhabha scattering, $e^+ e^- \rightarrow e^+ e^- \gamma$ has been studied in reference 16 for the case of unpolarized electron beams. Here we will use that study to estimate the expected background from that radiative process. Since some of the colliding bunches are longitudinally polarized, the background estimate given below will be somewhat over estimated. The basic formula for this process is:

$$d\sigma / dy = \{(2\pi r^2 e_c) / (1 - y)\} \{2(1 + y^2) - (4/3) y\} \{\ln (y^2 4y/(1-y) - 0.5)\}$$

where $\gamma = E_e / m_e$ and $E_e - E'_e = k$ is the energy of the radiated photon and $y$ is defined to be $y = E'_e / E_e$.

Using this expression it is estimated that for a luminosity of $\rho_{cc} = 10^{31}$ cm$^{-2}$ s$^{-1}$, a total of about 500 GeV is deposited per bunch crossing. As mentioned before, this background essentially rules out the single photon polarimetry. With the multi-photon detection system proposed here about 10% of these photons will be converted and due to the energy cut only 10% of these will be recorded.

IV) $e^+ e^- \rightarrow \gamma \gamma$ Annihilation into 2 Photons

The cross section for this process produces a pair of photons having the same energy as the beam electrons. The differential cross section, which has maxima in the forward and backward directions, is given by:

$$d\sigma / d(\cos \theta) = \pi \alpha^2 / (2E_e^2) \{ \Lambda^2 + B^2 \cos^2 \theta \} / \{ \Lambda^2 - B^2 \cos^2 \theta \}$$

where $\Lambda = 0.5 s - m_e^2$ and $B = 0.5 s (1 - 4 m_e^2 / s)^{0.5}$ and $s = (2 E_e)^2$.

Without radiative corrections the calculated background is negligible. The effect of radiative corrections on this cross section has been studied by F. Berends and R. Kleiss [17] – the cross section increases by about 23%.

V) Summary of Background Estimates in the case of Arc Rotators.
Table 9: Signal and background estimates with arc rotators.

<table>
<thead>
<tr>
<th>Source</th>
<th>At Converter</th>
<th>At Calorimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E &gt; .1</td>
<td>E &gt; 5</td>
</tr>
<tr>
<td></td>
<td>1000 $\gamma$</td>
<td>850 $\gamma$</td>
</tr>
<tr>
<td>Compton signal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sync. Radiation</td>
<td>(&gt; 6 \times \text{signal})</td>
<td>&lt; 0.06 (\times \text{signal})</td>
</tr>
<tr>
<td>Beam – Gas</td>
<td>3$\gamma$</td>
<td>1$\gamma$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow e^+ e^- \gamma$</td>
<td>78$\gamma$</td>
<td>23$\gamma$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \gamma \gamma$</td>
<td>&lt; 1$\gamma$</td>
<td></td>
</tr>
</tbody>
</table>

In Table 9 we present rough estimates for the background effects at the photon converter and at the calorimeters which are compared with the expected Compton signal for \(\mathcal{L}_{ee} = 10^{31} \, \text{cm}^{-2} \, \text{s}^{-1}\) and \(4.16 \times 10^{11}\) particles/bunch. The energies (E) in the Table are in GeV.

Finally one should note that the remaining background which enters the calorimeters can be experimentally monitored by observing the counting rate with laser on and off and partially understood by having circulating beams in the accelerator without producing luminosity.

6.5.2 Backgrounds in the Case of Straight Section Rotators

The sources of background are the same as for arc rotators, namely synchrotron radiation, electron beam – gas bremsstrahlung, radiative Bhabha scattering and annihilation into 2 photons. Clearly the last two will be the same as for the arc rotators, since they depend only on luminosity.

A description of a straight section rotator and polarimeter is given in section 6.7 and shown in Fig. 25 (where electron detection is also considered). At the converter the synchrotron radiation background will be much higher than reported in the last subsection due to the proximity of “bend 2” of the spin rotator. However it should not be troublesome since it cannot produce electron – positron pairs which would be detected in the calorimeters 1-4. The beam – gas bremsstrahlung background will be smaller than that reported in Table 9, due both to the shorter length of straight section “seen” by the detectors and the better vacuum near the experiments.
6.6 Layout, Installation and Cost (Arc Rotator)

Many of the arguments which determined the layout, laser interaction region (to be denoted by LIRL when referring to the longitudinal polarimeter), crossing angle and apertures (sections 5.4, 5.5 and 5.6) of the transverse polarimeter are also valid for the longitudinal polarimeter and will therefore not be dealt with in detail here. The requirements of having a good overlap of the round laser beam with the LEP electron/positron beam, of achieving a high luminosity and of being able to extract most of the recoil photons for analysis leave us with a clear choice for the laser interaction region, which is chosen to be at the exit of the quadrupole QS10 (see Fig. 12). The Twiss parameters and electron beam sizes, together with the recoil photon beam parameters are collected in Table 10.

Note that the electron beam sizes are comparable with those of the transverse polarimeter. The photon beam dimensions include the spread of the scattering process (10.9 μrad).

The case for having an optical laboratory for monitoring purposes has already been made. Since the longitudinal polarimeter will be installed in one of the experimental straight sections, it is assumed that the laser will be housed near to the middle of the straight section (near an experiment) in an accessible place. The need for "remote polarimetry" will be reviewed in the light of experience with the LEP transverse polarimeter.

The extraction channel of the scattered γ rays, similar to that shown in Fig. 13 for the transverse polarimeter, requires the following to the standard LEP layout.

Table 10: Twiss parameters and beam sizes at the LIRL and converter.

(E = 55 GeV, \( \eta_h = 55.6 \text{ nm} \), \( \epsilon_v = 2.2 \text{ nm} \))

<table>
<thead>
<tr>
<th></th>
<th>( e^\pm ) at LIRL</th>
<th>( \gamma ) at Converter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( H )</td>
<td>( V )</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>-0.469</td>
<td>2.782</td>
</tr>
<tr>
<td>( \beta )</td>
<td>11.745</td>
<td>84.115</td>
</tr>
<tr>
<td>( \sigma_e )</td>
<td>0.808</td>
<td>0.430</td>
</tr>
<tr>
<td>( \sigma'_e )</td>
<td>76.00</td>
<td>15.12</td>
</tr>
</tbody>
</table>
1) The horizontal component of B4/2 must be reversed. Probably the straight section side of B4/2 will be the first vertical bend of the arc rotator.

2) The dipoles B4/3 have to be reversed.

3) The two external coils of the quadrupole QL13 need to be modified to provide a 20 mm vertical aperture to the γ-beam.

4) The vacuum chamber in dipole B2R of B4/1 has to be enlarged.

5) The orbit correcting dipole MCHA next to QL13 has to be reversed.

Note that the above modifications are identical to those for the transverse polarimeter, except for the turning of bending magnets B4/3 and the vertical bend of of the rotator.

The costs of the above modifications are given in Table 11, for the case of a polarimeter on one side only of the interaction point i.e. for either e+ or e−, not both.

A major cost is the laser itself, the optical transport elements, the monitoring devices, the sweeping magnet and of course the detector. Finally it should be noted that this first cost estimate should be considered as a lower limit and that costs of the magnet power supply, cabling etc. are not included.

**Table 11: Cost estimates of the LEP changes and polarimeter components**

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost (in KSF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum chambers in B4/1, QS13 and B4/2.</td>
<td>30 KSF</td>
</tr>
<tr>
<td>Coils of QS13.</td>
<td>20 KSF</td>
</tr>
<tr>
<td>Reversed B4/2,3 magnets. Coil connections.</td>
<td>10 KSF</td>
</tr>
<tr>
<td>Laser.</td>
<td>100 KSF</td>
</tr>
<tr>
<td>Optical path elements</td>
<td>20 KSF</td>
</tr>
<tr>
<td>Laser monitoring devices</td>
<td>20 KSF</td>
</tr>
<tr>
<td>Sweeping Magnet</td>
<td>20 KSF</td>
</tr>
<tr>
<td>γ calorimeters.</td>
<td>60 KSF</td>
</tr>
<tr>
<td><strong>TOTAL (1 side only)</strong></td>
<td><strong>280 KSF</strong></td>
</tr>
</tbody>
</table>

6.7 *Longitudinal Polarimetry by Electron Detection*

In the previous chapters we have discussed polarization measurements utilizing only the backward scattered Compton photon. An additional information on the beam polarization can clearly also be
extracted from the outgoing Compton electron energy which may be measured alone or in conjunction with its associated Compton photon.

For a given Compton scattering event, the relation between the energy of the final state electron and photon is simply given by \( E_e = E_{\text{beam}} - E_\gamma \) so that the differential cross section \( d\sigma/dE_e \) is readily inferred from the expression for \( d\sigma/dE_\gamma \) (see also Fig. 6). For \( E_{\text{beam}} = 47 \text{ GeV} \) the Compton electron energy spectrum ranges from about 17 GeV to 47 GeV. This means that Compton electrons well below the beam energy, say less than 35 GeV, will be deflected out of the LEP.

To achieve a successful setup for a polarimeter which uses both the Comptons photon and electrons, the following obvious requirements are needed:

1) compatibility with the LEP and rotators design
2) acceptable low background of photons and off–momentum electrons
3) sufficient space for the detection equipment

Here we outline a scheme for such a longitudinal polarimeter keeping in mind the fact that both the final state electrons and photons do emerge in a very narrow cone around the accelerator beam line. This is illustrated in Fig. 25 where a preliminary setup of the equipment is shown. The Laser beam illumination point and the rotator are placed in the space of about 25 m between the quadrupoles QT1 and QT2 of the LEP straight section. The rotator, schematically drawn in the insert of the figure, is of the Richter–Schwitters type (more details can be found in the machine physics section of this Yellow Report). The vertical bend can be realized by 3 C–shaped magnets placed on their “back” so that the Compton electrons can be extracted out of the LEP ring and be detected and momentum analysed by a pair calorimeters (5 and 6 in Fig. 25) which define two momentum ranges.

The Compton photon analyzing method is similar to that described previously in Chapter 6. The Compton photon hits a thin converter and the emerging electron–pair are further momentum analyzed by a flat magnet so that it will not interfere with the circulating LEP beams which pass right above it. The magnetic field, of about 1.5 Tm, sweeps horizontally the electron pairs into a set of four calorimeters (1, 2, 3 and 4 in Fig. 25). As in previous chapters we will also here consider the operation of this polarimeter setup in the multi–photon mode. With this arrangement and a similar Laser electron bunches illumination system as discussed in the previous chapters, the estimated off–momentum electron and photon backgrounds can be controlled and do not seem to pose any serious problem.

The analyzing power of this polarimeter system can be defined as
\[ \Pi_{e^{\gamma}L} = \frac{\{T_L + Q_L - T_R - Q_R\}}{\{T_L + Q_L + T_R + Q_R\}} \]

with 
\[ T_L = \left( \frac{E_s}{E_a} \right)_L \quad \text{and} \quad T_R = \left( \frac{E_s}{E_a} \right)_R \]

measured by the electron calorimeters 5 and 6 and \( Q_L \) and \( Q_R \) are energy sum ratios obtained from

the photon detection system as defined in chapter 6.3.2.

In Table 12 we give the values of the combined analyzing power \( \Pi_{e^{\gamma}L} \) for several operating

energy range values of the electron counters 5 and 6 taking a pointlike Laser beam Compton scattering. The analysing power values were obtained for the optimal setup of the Compton photon detection

system alone (with an analyzing power of \( \approx 52\% \)), namely:

\[ 5 < E_{14} < 10 \text{ GeV} \quad \text{and} \quad 20 < E_{23} < 29.5 \text{ GeV}. \]

These table values are higher than that for a Compton photon polarimeter and do as expected depend

on the energy gap between the counters 5 and 6. A rough estimate indicates that for a given statistics

of Compton scattering collisions the addition of information on the scattered electron improves the

polarization precision measurement by about a factor 2.

**Table 12:** Combined Electron–Photon Analysing Power (\( \Pi_{e^{\gamma}L} \))

<table>
<thead>
<tr>
<th>E5 Range (GeV)</th>
<th>E6 Range (GeV)</th>
<th>Gap (GeV)</th>
<th>( \Pi_{e^{\gamma}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 – 26</td>
<td>27 – 35</td>
<td>1.0</td>
<td>558</td>
</tr>
<tr>
<td>15 – 24</td>
<td>28 – 35</td>
<td>4.0</td>
<td>595</td>
</tr>
<tr>
<td>15 – 23</td>
<td>29 – 35</td>
<td>6.0</td>
<td>615</td>
</tr>
<tr>
<td>15 – 22</td>
<td>30 – 35</td>
<td>8.0</td>
<td>633</td>
</tr>
</tbody>
</table>

6.8 New Ideas on Longitudinal Polarimetry using Crystals

Several novel and interesting ideas concerning the use of single crystals for the polarization measure-

ment of electron bunches have been proposed. Since these are given with some details in two separate papers [18,19] following this one, we will here briefly summarize their main ideas.

The use of crystals can be applied in several ways, either as an improvement on the Compton

scattering analysis scheme outlined here, or as an independent polarization measurement tool.
One considerable improvement may be obtained by replacing the "amorphous" metal converter of the longitudinal polarization detector (see chapter 6) by a crystal. With an optimum choice of crystal and orientation angles, the ratio of the photon absorption coefficient to the inverse radiation length is then at least 2.2 times better than for a conventional converter. This will allow a higher electron-pair conversion rate without increasing the subsequent unwanted radiation effects.

The possibility of measuring the polarization of electron bunches using the radiative Bhabha scattering

\[ e^+ e^- \rightarrow e^+ e^- \gamma \]

with a crystal detector is described in ref 19. In this scattering process, the single bremsstrahlung photons are circularly polarized whenever the electrons (positrons) are longitudinally polarized. The circular polarization of the photons can be measured in two different ways, either by a thin crystal converter or even better, by a thick crystal used as a photon absorber. An estimate of the statistical error on a polarization measurement using a copper crystal gives an error of \( \approx 0.38\% \) for a luminosity of \( 10^{31} \text{ cm}^{-2} \text{ sec}^{-1} \), a polarization level of 50% and a 5 hour run. A further analysis is required to evaluate the systematic errors.

7. Conclusions

7.1 Transverse Polarimeter

A detailed study of the LEP transverse polarimeter showing attractive performance has been presented. A layout optimised on the basis of background estimates has been defined and the laser-electron beam interaction region designed to achieve the best conditions for the Compton interaction. The laser has been chosen to optimize the performances of the polarimeters in the 40 to 100 GeV per beam LEP energy range.

The proposed structure for the \( \gamma \)-detector makes use of compact Silicon calorimeters similar to those adopted for the relative luminosity monitors and provides a measurement of the asymmetry which is insensitive to systematic errors from closed orbit drifts within the acceptance of the \( \gamma \) transport channel.
A study of systematic effects indicates that the error in the absolute transverse polarization measurement will be about 2%, mainly due to the laser degree of polarization uncertainty, when the centroid method is used. This precision is more than adequate for the LEP energy calibration and transverse polarization studies. The systematic effects coming from the beam parameters and which affect the relative transverse polarization measurements are much smaller and in the order of a few %.

7.2 Longitudinal Polarimeter

The detailed design of the overall system depends on the design of the spin rotators. Nevertheless, we have shown that even a longitudinal polarimeter based on Compton photons alone, can be built with the following properties:

1) separation of the Compton photons from the electron beams.
2) insensitivity to fluctuations in $S_{ey}$.
3) very low level of background.
4) adequate sampling rate.
5) insensitivity to bunch differences.
6) systematic effects are very small.

We have shown that the bunch to bunch relative level of longitudinal polarization of electrons and positrons beams in LEP, can be measured in less than 20 minutes, to the precision of 0.3% needed for conclusive Left – Right asymmetry measurements in $e^+ e^-$ reactions.

The error on the absolute longitudinal polarization measurement however, will be comparable to the one to be achieved with the transverse polarimeter.

For the case of a straight section rotator, an improvement of the analysing power and resolution can be obtained by adding an electron detection system.

Acknowledgements

Our thanks are due to P. Hobson for his detailed technical remarks on the laser system and to R. Rossmanith for his many helpful comments concerning the transverse polarimetry.
References


   b) J. Badier et al. (The ALEPH Polarization Working Group), ALEPH 87 – 17 NOTE 87 – 5.


Fig. 1  Diagram for Compton scattering in the laboratory frame of reference and in the electron centre of mass system.

Fig. 2  The Compton scattering angle, $\theta_{\text{LAB}}$, in the laboratory system as a function of the electron center of mass scattering angle $\theta$. The corresponding recoil photon laboratory energies are also indicated.
Fig. 3 The relation in Compton scattering between the recoil photon laboratory energy and the \( \cos \theta \) in the electron center of mass system.

\[
\begin{align*}
\lambda_{\text{LASER}} &= 530 \text{ nm} \\
E_e \text{ (LAB) } &= 47 \text{ GeV} \\
E_T \text{ (LAB) } &= 47 \text{ GeV}
\end{align*}
\]

Fig. 4 The total Compton scattering cross section as a function of photon energy in the electron center of mass system. The cross section value for a beam energy of 47 GeV and a laser wavelength 530 nm is also shown.

\[
\begin{align*}
E_e \text{ (LAB)} &= 47 \text{ GeV} \\
\lambda_{\text{LASER}} &= 530 \text{ nm}
\end{align*}
\]

Fig. 5 The Compton differential cross section as a function of \( \cos \theta \) is shown for longitudinally polarized electrons with \( P_e = +1 \) scattered by left-handed \( (P_\gamma = -1) \) and right-handed \( (P_\gamma = +1) \) laser beams.

\[
\begin{align*}
\lambda_{\text{LASER}} &= 530 \text{ nm} \\
E_e \text{ (LAB) } &= 47 \text{ GeV} \\
|P_e| &= 1
\end{align*}
\]

Fig. 6 The Compton differential cross section as a function of the recoil photon energy in the laboratory system for longitudinally polarized electrons with \( P_e = +1 \) scattered by left-handed \( (P_\gamma = -1) \) and right-handed \( (P_\gamma = +1) \) laser beams. The corresponding \( \cos \theta \) values are also indicated.

\[
\begin{align*}
\lambda &= 0.53 \mu\text{m} \\
|P_\gamma| &= 1 \\
E_e &= 47 \text{ GeV}
\end{align*}
\]

40
Fig. 7 The asymmetry $A_{10} (\cos \theta) = [d\sigma/d\Omega(P_\gamma = -1) - d\sigma/d\Omega(P_\gamma = +1)] / [d\sigma/d\Omega(P_\gamma = -1) + d\sigma/d\Omega(P_\gamma = +1)]$ as a function of $\cos(\theta)$.

Fig. 8 The laser analysing power, defined as $A_{10} (\cos \theta = -1)$, for longitudinal polarimetry is given as a function of the laser wavelength.

Fig. 9 Effect of the laser pulse duration on luminosity.
Fig. 10 The measured Laser output pulse (Oscilloscope trace).

Fig. 11 The laser beam optical path and the 'remote light polarimetry' in the UJ14 junction for the LEP transverse polarimeter.
Fig. 12  A sketch of the LEP half straight section containing the transverse polarimeter, shown from the e⁺e⁻ interaction region to the arc. Also given is a schematic drawing of the laser optical path from the laser laboratory to the colliding point with the LEP positron beam (taken from reference 5). The exit place of the recoil photons and the location of a Compton photon detector are also shown.

Fig. 13  Detail of arc layout showing e⁺ and γ beam paths for the transverse polarimeter.
Fig. 14 Vertical beam profiles at the transverse polarimeter $\gamma$ detector

Fig. 15 Detailed layout of the special vacuum insertion at the transverse polarimeter LIR$_T$. 
Fig. 16 Effect of transverse rms round laser beam dimensions on the luminosity for different values of the crossing angle $\delta$.

Fig. 17 Schematic of the $\gamma$-detector layout of the transverse polarimeter.
Fig. 18  Measuring time versus the $e^*$ polarization level $P_e$ for the transverse polarimeter.

Fig. 19  A schematic view of a proposed Compton photon detector for longitudinal polarimetry of electrons.
Fig. 20  Longitudinal electron shower development.

Fig. 21  Energy resolution (a) and position resolution (b) of the UA7 calorimeter.
Fig. 22  Lateral electron shower distribution at 4.5 GeV incident electron energy in the UA7 calorimeter.

Fig. 23  Normalized positron energy spectrum of converted photons in the longitudinal polarimeter. The two curves are for opposite laser circular polarizations.
Fig. 24 The resolution on the measurement of longitudinal polarization versus the lower energy limit of calorimeters 2 & 3 keeping their upper energy limit at 29.5 GeV. The different curves are for the upper energy limit of calorimeters 1 & 4 keeping their lower limit at 5 GeV. Upper energies of 9, 10, 11, and 12 GeV of calorimeters 1 & 4 correspond to solid, dashed, dashed-triple dotted and dashed-dotted lines respectively.

Fig. 25 A scheme for longitudinal polarimetry in a straight section (Richter–Schwitters) rotator, where both recoil photons and electrons are detected. The upper left insert shows a side view of the rotator—the other insert shows a top view of the photon detection system. The main figure is a side view relative to the incident electron beam direction.