Cherenkov detector prototype for ILC polarimetry

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Abstract. Precise knowledge of all beam parameters is crucial to fully exploit the physics potential of the International Linear Collider (ILC). A sufficiently accurate measurement of the beam polarisation can only be achieved using dedicated high energy Compton polarimeters combined with well-designed Cherenkov detectors. The requirements have been evaluated and a suitable Cherenkov detector prototype has been designed, simulated and constructed accordingly. This prototype allows nearly all aspects of the final detector to be studied and has been operated successfully in a testbeam of which first results are presented as well.

1. High energy polarimetry at the ILC
The physics programme of the ILC will rely heavily on the accuracy with which the relevant beam parameters can be controlled [1, 2]. Two dedicated, high-energy Compton polarimeters measure the beam polarisation up- and downstream of the $e^+e^-$ interaction point. Each should reach a systematic accuracy of at least $\delta P/P = 0.25\%$, improving previous measurements by a factor of two. Detailed descriptions of the polarimeters can be found in [3].

Compton polarimetry ensures a non-destructive measurement of the longitudinal beam polarisation. Circularly polarised laser light is shot under a small angle onto the individual bunches causing typically $\mathcal{O}(10^3)$ electrons per bunch to undergo Compton scattering. The energy spectrum of the scattered particles depends on the product of laser and beam polarisations, so that the measured rate asymmetry w.r.t. the laser helicity is directly proportional to the beam polarisation. The differential Compton cross section exhibits a large polarisation asymmetry near the Compton edge energy, which hardly depends on the chosen beam energy [3]. A magnetic chicane transforms the energy spectrum into a spatial distribution measured by Cherenkov detectors. Since Cherenkov radiation is independent of the electron energy ($\beta \approx 1$), the number of Cherenkov photons is directly proportional to the number of Compton electrons, which allows this type of detector to measure the energy spectrum of many electrons arriving simultaneously in one channel [4].

2. Prototyp design and optical simulation
The design of the ILC polarimeter Cherenkov detectors is driven by a set of requirements, also used as a basis for the design, simulation and construction of a compact two-channel prototype. They are: (i) a high and homogeneous light yield per Compton electron, also for short wavelengths due to the $1/\lambda^2$ dependence of Cherenkov radiation ($\rightarrow$ geometry/surfaces), (ii) gas- and light-tightness ($\rightarrow$ response stability/linearity), (iii) thin inter-channel walls, (iv) robustness w.r.t. backgrounds and (v) calibration system ($\rightarrow$ in-situ, beam-indep. response monitoring).
Contrary to the ILC design of staggered U-shaped channels lining the tapered exit window of the beam pipe as depicted in figure 1(a), the prototype detector consists of only two parallel, non-staggered channels, but still allows to study all relevant aspects of the full detector as well as the entire experimental setup [4]. Figure 1(b) shows one such gas-filled aluminium channel, where Compton-scattered electrons traversing the U-base emit Cherenkov photons reflected upward to the photodetector.

![Figure 1.](image)

The detailed optical simulation of the prototype, based on Geant4 [5] serves to determine key figures such as the photon yield per electron, the average number of reflections and possible asymmetry effects due to the utilized materials or chosen geometry, especially the square channel cross section. A length of 15 cm is chosen as a reasonable balance between the production of Cherenkov light and alignment & reflection constraints.

Figure 2 shows the internal structure with a single electron (red) passing from left to right through the U-base of one detector channel. It emits Cherenkov light (green), which is reflected upward at the end of the U-base towards the photodetector. Cherenkov light produced outside the channel structure in the ambient gas cannot reach the photodetectors. The square channel cross section of $8.5 \times 8.5 \text{ mm}^2$ matches the anode layout of two multi-anode photomultipliers (MAPMs), such that one quadrant covers one detector channel. These MAPMs [6] were chosen based on earlier stand-alone studies of different photodetector types [7, 8].

![Figure 2.](image)

Two types of aluminium are implemented according to the reflectivities of different quality aluminium. Three of the four walls of each channel are made of diamond-milled aluminium with...
a reflectivity $R_{\text{alam}} \approx 80\%$, while the inter-channel wall consists of a 300 $\mu$m thin foil of rolled aluminium with only $R_{\text{roll}} \approx 36\%$. Perfluorobutane ($C_4F_{10}$) with its 10 MeV-threshold is chosen as Cherenkov gas making the detector robust against background from low energetic charged particles. Since a precise knowledge of the absolute photon yield is not crucial for the rate asymmetry measurement, the refractive index ($n = 1.0014$) is assumed independent of the wavelength, as well as of the temperature and pressure inside the detector box ($T = 20 ^\circ \text{C}$ and $p = 1 \text{ atm}$, respectively). Two scenarios with the same beam parameters (Gaussian profile, $\sigma_x = \sigma_y = 1.5 \text{ mm}$) but different reflectivities for the inter-channel wall are simulated to study its influence on the expected light yield. While the distribution is symmetric about the $x$ and $z$-axes when all four channel walls are simulated with the same reflectivity, a clear asymmetry emerges about the $x$-axis when the inter-channel wall is simulated with reduced reflectivity (figure 3). The white dot indicates the beam $y$-position which translates directly to the $z$-position in the readout plane.

This asymmetry, as well as the X-pattern (observed also for equal reflectivities of all walls) are due to a combination of the square channel cross section and the Cherenkov angle of perfluorobutane for relativistic electrons ($\Theta = 3^\circ$). From a grid scan with 4 positions of $10^4 \, e^-$, asymmetries are calculated as: $A_{k=x,z} = (I_{k}^+ - I_{k}^-)/(I_{k}^+ + I_{k}^-)$ where $I_{k}^+$ corresponds to the intensity in the right (upper) half of a channel and $I_{k}^-$ to the intensity in the left (lower) half, respectively. However, these asymmetries are not displayed here, but are included in figure 6(a,b) on page 5 for comparison with the respective asymmetries determined from testbeam data.

3. Beam tests at the ELSA accelerator

Beam tests with the prototype detector were performed in an external beam line at the ELektronen-Stretcher-Anlage (ELSA) in Bonn, Germany. The beam is extracted for 4.0 s of every $5.1 \text{ s}$ cycle (filling, acceleration, extraction), can be focussed to about $1 - 2 \text{ mm}$ spot size, and the extracted current can be adjusted from about $10 \text{ pA}$ to $200 \text{ pA}$ by partial filling [9]. Using the beam clock signal as gate for the QDC (charge sensitive ADC) adjusted to last for the filled part, this leads to respectively 35 to 700 electrons traversing the detector per ELSA turn, compared to about 250 electrons expected in an ILC polarimeter Cherenkov detector.

The detector is filled with $C_4F_{10}$ at 140 mbar and sits on its turnable base plate mounted on a movable stage. Moving the stage horizontally ($x$) and vertically ($y$) scans the incident beam position on the entrance window, so that the detector alignment w.r.t. the beam line can be obtained from beam data. The adjustment procedure requires one $y$-scan for each channel and a series of $x$-scans across both channels for different tilt angles $\alpha_y$. Typically, for a tilted detector the maximal Cherenkov signal at a given beam position is smaller than for a perfectly

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Light yield at the photocathode for a reduced reflectivity of the inter-channel wall.}
\end{figure}
aligned detector. Determining the beam $x$ position of the highest signal for each tilt angle leads to $\alpha_y = (1.33 \pm 0.03)^\circ$ for the best alignment, which is approximated by $\alpha_y = 1.35^\circ$ due to the step size of the rotational mechanism.

Some of the detector dimensions, such as the channel width or the distance between channel centers, can be extracted from beam data. A comparison of these derived values with the given prototype specifications can be used to disentangle different effects connected either to the detector itself, to its alignment w.r.t. the beam line, or exclusively to the beam. Figure 4(a) shows $x$-scan data recorded with the $2 \times 2$ MAPM (R7600U-03-M4) and an ellipsoidally elongated beam spot. Two Gaussian fits indicate the respective channel centres to be at $x_{\text{right}} = (7.4 \pm 0.1) \text{ mm}$ and $x_{\text{left}} = (16.4 \pm 0.1) \text{ mm}$, leading to a distance of $\Delta x = (9.0 \pm 0.2) \text{ mm}$. This agrees well with the nominal distance of $\Delta x_{\text{nom}} = (8.5 \pm 0.3) \text{ mm}$ given by the channel width plus the thickness of the inter-channel wall. Figure 4(b) shows $x$-scan for the R7400U-06 single-anode photomultiplier (SAPM), where a broad plateau is observed. The width of the signal region is determined from two sigmoidal fits to the edges of the plateau at 50% of its height. The width is $w = (9.4 \pm 0.3) \text{ mm}$ with the error dominated by the table position accuracy. This value is larger than the nominal width ($w_{\text{nom}} = 8.5 \text{ mm}$) hinting towards residual misalignment and a non-Gaussian beam profile. The dominant reason for the MAPM data not exhibiting an equally clear plateau is the different beam spots delivered by ELSA, aside from possible cross-talk in case of the MAPM and incomplete channel coverage of the SAPM.

The anode of the $8 \times 8$ MAPM (R7600-00-M64) is finely segmented with 16 anode pads covering one detector channel, thus offering spatial resolution within a single channel. Two QDC channels were broken leaving only six channels to realise the readout configuration illustrated in figure 5(a). The numbers indicate the QDC channel utilised to read out the sum signal of either four or eight MAPM anode pads. Figure 5(b) shows the result of an $x$-scan across both detector channels. As expected, the signals in QDC channels 2 and 3 are about twice as large as in the other channels due to the different grouping of anode pads. The asymmetric response reflects the beam position. For each QDC channel, the largest signal is observed when the beam enters on the opposite side of the detector channel confirming the prediction from simulation of one glancing angle reflection for most of the photons (see section 2). The same $x$-scan data is displayed again in figure 5(c), scaled and mirrored to correct for the different pad locations w.r.t.
the beam position and the different number of pads grouped into one readout channel. Possible reasons for the remaining shape and amplitude differences comprise gain variations between the pads and residual detector misalignment.

From the beam position measurements with the 8×8 MAPM using QDC 4 to 7 on one detector channel, two different x- and z-asymmetries are determined according to the description at the end of section 2. They are displayed in Figure 6, together with those determined from simulated data. The displayed errors correspond to 10% relative gain differences between the anode pads. Uncertainties in common between different pads cancel from the asymmetries.

Qualitatively the measured asymmetries agree well with the simulation. $A_x$ exhibits an offset in x and a more shallow slope as expected due to the lower reflectivity of the inter-channel wall, demonstrating the optical quality of the channel surfaces and a sufficiently detailed description in the simulation. Quantitatively, $A_{upper}^x$ exhibits a different slope, while $A_{right}^z$ is shifted suggesting residual misalignment and gain variations. These asymmetries can be exploited to determine the beam position even within a single detector channel, if a segmented photodetector is employed.
4. Conclusions
Compton polarimeters will be employed to measure the ILC beam polarisation to a precision of \( \delta P/P = 0.25\% \) using Cherenkov detectors to register the scattered Compton electrons.

A compact two-channel prototype has been designed, simulated and constructed. It allows nearly all aspects of the final detector to be studied. The prototype has been operated successfully in a testbeam using four different PDs and the corresponding results are in good agreement with a detailed simulation. A newly developed method to extract intra-channel position information has been applied to the testbeam data in studying the detector response as a function of the beam position. This will lead to a determination of each channel’s acceptance which is important to control systematic effects on the final polarisation measurements.

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