Compton Cherenkov Detector Development for ILC Polarimetry

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In order to fully exploit the physics potential of the ILC, it will be necessary to measure (and control) beam parameters to a permille level precision. In case of the beam polarisation, this can only be achieved with dedicated high energy Compton polarimeters and by improving the detector linearity, as well as the calibration of the analyzing power. This note summarises results of an early testbeam period with the Cherenkov detector of the SLD polarimeter, linearity measurements of readout electronics and photodetectors and compares simulation results of the SLD Cherenkov detector with those of a new ‘U-shaped’ prototype.

1 Polarisation and precision

The measurement and control of beam parameters to a permille level precision will play an important role in the ILC’s ambitious physics programme \cite{2,3}. This means, not only the luminosity and the beam energy need to be measured precisely, but also the polarisation of the electron and positron beams have to determined with unprecedented accuracy. While this has already been achieved at previous colliders for beam energy measurements, the precision of polarisation measurements has to be improved by at least a factor of two compared to the up to now most precise polarisation measurement of the SLD polarimeter \cite{5}. It is planned to achieve $dP/P = 0.25\%$ or better.

The polarisation measurement at the ILC will combine the measurements of two dedicated Compton polarimeters, located upstream and downstream of the $e^+e^-$ interaction point, and data from the $e^+e^-$ annihilations themselves. While $e^+e^-$ annihilation data will finally (after several months) provide an absolute scale, the polarimeters allow for fast measurements and, in case of the upstream polarimeter, probably even resolve intra-train variations, give feedback to the machine, reduce systematic uncertainties and add redundancy to the entire system \cite{4}.

Circularly polarised laser light hits the $e^+(e^-)$-beam under a small angle and typically in the order of 1000 electrons are scattered per bunch. 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 (known) laser helicity is directly proportional to the beam polarisation. Since the electrons’ scattering angle in the laboratory frame is less than 10 $\mu$rad, a magnetic chicane is used to transform the energy spectrum into a spacial distribution and lead the electrons to the polarimeter’s Cherenkov detector. It consists of staggered ‘U-shaped’ aluminum tubes lining the tapered exit window of the beam pipe. The tubes are filled with the Cherenkov gas C$_4$F$_{10}$ and are read out by photodetectors. Electrons traversing the basis of these ‘U-shaped’ tubes generate Cherenkov radiation which is reflected upwards to the photodetectors \cite{6}.

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Developing a Cherenkov detector suitable for achieving the aforementioned precision of $dP/P = 0.25\%$ demands improvements in various areas of the experimental setup. Of utmost importance, however, is the linearity of the detector response, or the ability to control and correct for a non-linear response. The following areas of work are briefly discussed: testbeam data analysis, linearity measurements of readout electronics and photodetectors (PDs), simulation and design of a new prototype detector.

2 Testbeam results

In November and December 2007, the SLD Cherenkov detector (Fig. 1(a)) was set up in the DESY-II testbeam for two short periods of time. From different orientations of the detector, either using the Cherenkov drift section (indicated in red) or not (beam incident on the area indicated in blue), the reflectivity of the aluminum channels was measured to be about 90%. As can be seen from Fig. 1(b), the cross talk between adjacent channels is asymmetric with more Cherenkov photons detected in channels left of the one on which the beam is centered.

![Figure 1: (a) The open SLD Cherenkov detector; different colours indicate different sections. (b) Asymmetric cross talk in channels 4 and 6, while the beam is centered on channel 5.](image)

Further tests included a setup where some of the original photodetectors were exchanged for newer types, especially three multianode photomultipliers and also a new silicon-based photomultiplier. However, results from these measurements are not discussed here.

3 Linearity measurements of electronics and photodetectors

A component test stand is used to study different types of photodetectors. They are set up in a light-tight box and read out via a high resolution double range 12-bit VME charge-to-digital converter (QDC), with either 200 fC or 25 fC per LSB (least significant bit). A blue LED ($\lambda = 472$ nm) connected to a function generator is used to generate the light detected by the PD. Before testing the linearity of the PDs themselves, the differential and integral non-linearity (DNL, INL) of the QDC has also been measured.

A ramp ($f = 10$ Hz) is used as input signal while the QDC is triggered by a short random gate of 50 ns duration. The probability for each transition to occur at a certain QDC code bin is measured and compared to an ideal distribution. If the QDC was ideal, a uniform
distribution of code bins would be expected. The ratio between the measured and the ideal distribution is the code bin width, from which the DNL can be calculated as the deviation of the ideal code bin width of 1 LSB. The INL for a certain QDC code bin is then given by the sum of DNLs up to this bin. Both distributions are rather flat and a fit to the mid range of codes, from 200 to 800 QDC bins, gives an INL from 1 to 2 LSBs, corresponding to 0.1-0.2% of the full scale range.

The most extensive linearity studies have been performed on 2x2 multianode photomultipliers (MAPM, Hamamatsu R5900U-M4). The spectrum of QDC counts is fitted by a modified Poisson function to determine the number of incident photoelectrons. The ‘true’ number of photoelectrons expected for a certain amount of light cannot be determined since the relation between light yield and LED bias voltage is not calibrated. However, the method used to measure the PD’s INL is independent of the absolute scale of the LED and only depends on the length of a rectangular pulse lighting the LED. Varying this pulse length ensures a linear variation of the amount of light on the photocathode of the PD. The pulse length is varied between 30 ns and 150 ns in steps of 5 ns. Figure 2 shows the results of several measurement series. As can be seen in Fig. 2(b), the correction is highly successful for the 3rd and 4th measurement series with a resulting INL of less than 0.1%, but fails for the 2nd measurement (Fig. 2(c)), where the INL is only about 0.25%. However, these results show that the PD non-linearity can be measured and thus controlled to a precision of 0.1%. A second method relying on optical filters will be used to cross check these results.

Figure 2: PD linearity measurements obtained using the pulse-length method: (a) reference measurement, (b) 2nd and (c) 3rd measurement series, corrected using the 1st measurement. (d) The four measurement series ordered in time.

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Another two methods were developed to measure the DNL; one measures the difference between the PD’s response to the initial (variable) pulse $P_i$ and its response to the pulse $P_i + p$ with $p$ being a very small fix pulse. For the second method, a 4-hole mask is applied to the PD so that the ratio of the sum of single pulses through each hole and one pulse through all four holes simultaneously gives the DNL.

4 Prototype simulation and design

A smaller prototype has been simulated and constructed to study the entire Cherenkov detector design. This simplified version of the envisioned detector consists of only two U-shaped aluminum channels with a cross section of 8.5 mm$^2$ embedded in a box flooded with the Cherenkov gas C$_4$F$_{10}$. The gas is non-flammable and was chosen mainly because of its high Cherenkov threshold of about 10 MeV. The electron beam will pass through the basis of the U-shaped channels, entering and exiting through thin aluminum windows, and produce Cherenkov photons which are then reflected towards a photodetector mounted on the hind U-leg. The front U-leg is solely for calibration purposes with two LEDs mounted there, one per channel.

For the design of the prototype detector and also for the interpretation of future testbeam data, an optical simulation based on GEANT4 has been created. However, the PD response, i.e. mainly the PD’s quantum efficiency is simulated separately using simple ROOT macros. Figure 3 shows a comparison between the simulated illumination of a single channel of the SLD detector and the new U-shaped prototype. The strong asymmetry visible for the SLD-type channel in Fig. 3(a) is avoided with the new design (Fig. 3(b)), where only a slight inhomogeneity in the light intensity is seen. The reduction of cross talk and the avoidance of geometry-based asymmetries was the main reason to choose the peculiar U-shaped geometry for the prototype detector.

An illumination scan with $4 \times 4$ points per channel and 10,000 electrons per shot leads to Fig. 4 where (a) depicts the light yield on the PD anode for electrons entering the Cherenkov section at a fixed $y$ position, but variable $x$ position. (Due to the geometry, a certain $z$ position on the PD anode corresponds to a certain beam position $y$ in the channels at the U-basis.) Figure 4(b,c) show the corresponding calculated asymmetries in the light intensity for scans in the $x$- and $z$-directions, respectively.
Figure 4: (a) Illumination scan of a testbox channel with 10,000 $e^-$ per shot. (b,c) Asymmetries calculated from the light intensity on the photocathode for different scans: $A_{x+x-}$ for fixed $z$ position and $A_{z+z-}$ for fixed $x$ position.

The photodetector mounting on the hind U-leg is realized exchangeably to enable the testing of several different PDs (and different read-out modes) within one setup.

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