Simulation of a Silicon and a Fiber Detector for Precise Energy Measurement at the ILC

DESY Zeuthen Summer School
Project Report

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Abstract

To measure the beam energy at the ILC with the precision of $\Delta E_b/E_b = 10^{-4}$ or better, a method based on inverse Compton backscattering is currently investigated. The basic idea of this method is the following: beam electrons (positrons) are interacting with a laser by inverse Compton backscattering and the final state particles as well as non-interacting beam particles pass through a spectrometer magnet. By measuring the positions of the unscattered electrons, the scattered electrons and the backscattered photons behind the magnet with a resolution in μm-range, one can calculate the beam energy with the required resolution. In this study simulated data of produced particles have been taken to simulate first the interaction with two different kinds of detecors by using GEANT4 and later on the response of each detector. Within the interaction-simulation the main focus was directed on the deposited energy inside the detector to know whether a cooling device will be necessary. The main focus of the simulation was of course the resolution of the position. The simulations were made for a silicon and a fiber detector to find out which of the detectors will give a better resolution of the position and whether the resolution is generally good enough.

1 Introduction

A basic requirement for precision experiments in high energy physics is the accurate measurement of the beam energy. This becomes especially important for precise threshold scans and particle resonance reconstruction. The future International Linear Collider (ILC) with beam energies around 250 GeV intends to measure particle masses with a precision in the range of 50 MeV. For this aim the incident e+/e- beam energy E_b has to be known with a relative uncertainty of 10^{-4} .

One method of measuring the beam energy is by Compton backscattering. In section 2 I will briefly explain the idea of the method and the experimental setup. However, the main focus of this study consists of simulations of two different detectors with respect to position measurement and its accuracy, which is the most important part of the Compton backscattering method. Therefore in section 3 two detectors and its operating principles are described. In section 4 the deposited energy of the particles inside the detectors is evaluated and in section 5 the readout of the detectors is simulated and analysed.

2 Principle of Measuring the Beam Energy by Compton Backscattering

2.1 The Inverse Compton Scattering

Compton scattering describes an elastic scattering between an electron at rest and a photon. Within this process an energy-momentum of the photon is transfered to the electron, so that the total enery of the photon decreases and that of the electron increases. If the photon scatters off from a moving electron, this process is called inverse Compton scattering, which will be the situation in our case: A photon with energy ω_L scatters off from a high energy electron of the beam with energy E_b:

$$E_b + \omega_L \rightarrow E_{sct} + \omega_{sct}$$

In this case the final state photon energy increases and the one of the electron decreases. In particular, for maximum energy transfer, a minimum total energy of the electrons occurs. This so-called electron edge energy E_{edge} is related to the beam enery E_b as

$$E_{Edge} = \frac{1}{\frac{1}{E_b} + \frac{2\omega_L(1+\cos\alpha)}{m^2}}, \tag{1}$$

whereas ω_L is the photon energy, α the angle between the electron beam and the incident photons and m the electron rest mass. By knowing ω_L, α and m, it is possible by measuring the edge energy to calculate the beam energy E_b.

2.2 Experimental Set-Up

To measure E_{Edge} a magnetic spectrometer will to be used. The sketch in Fig.1 shows this concept.

As explained in [2], a laser with energy ω_L will be shot on the electron beam with energy E_b under the crossing angle α, which is close to zero. After that, scattered electrons, unscattered beam electrons and the backscattered photons will pass a magnetic field.

The backscattered photons are not affected by the magnetic field. Therefore, the position of the photons x_γ will represent the position of the original electron beam, and will be set in our simulation to x_0=x_γ=0. In order to measure the photons, they will be sent through a converter to create electron-positron pairs. These pairs can be detected by a high spatial resolution electromagnetic detector, placed at the distance L behind the magnet. The scattered and unscattered electrons will be separated by the bending magnet according to their energy. For low bending angles θ, the following equation relates the electron energy E to the position x in the detector plane:

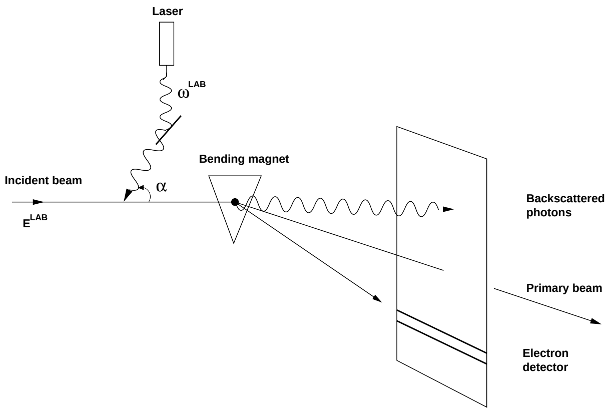

Figure 1: Sketch of the experimental setup, as taken from [1].

$$x = ec \cdot (L + \frac{l}{2}) \cdot \frac{B \cdot l}{E}, \tag{2}$$

where e is the electron charge, c the speed of light, B the magnetic field and l the length of the magnet in beam(=z)-direction. Due to the fact that the energy of the scattered electrons is lower than the energy of the unscattered electrons, the bending angle and therefore the position x_{Edge} in the detector plane will be larger.

By knowing the parameters of eq. (2) and (1) and measuring the positions x_γ and x_{Edge}, one can calculate E_b via these two equation .

The beam energy precision mainly depends on the accuracy of B$\cdot$ l, L and $x_{Edge} - x_\gamma$. If $\Delta(B \cdot l)/(B \cdot l) = 10^{-5}$ and $\Delta L = 10\mu m$, which is expected to be achievable, $\Delta(x_{Edge} - x_\gamma)$ has to be measured with micrometer precision in order to ensure a beam energy accuracy of $\Delta E_b/E_b = 10^{-4}$ [1].

A very important aspect of this approach is its non-destructive character. Since the energy measurement will be done before the interaction between the two incident beams, the number of interacting particles out of $2 \cdot 10^{10}$ electrons per bunch has to be small. But in order to get a good statistical significant signal, the interaction rate may not be too small. A good compromise is to allow for about 10^6 electrons to interact with the laser light.

3 Detectors

In order to measure the positions of the particles with mircometer precision two different typs of detectors are considered. The parameters of the detectors are assumed as described below.

3.1 Silicon Strip Detector

The silicon strip detector (Fig.2) consists basically of a 300 μm x 1 cm x 1 cm n-type silicon, with a density of 2.33 $g \cdot cm^{-3}$, with p+ diode strips of aluminium contacts in an interval of 25 μm, which leads to 400 strips for the detector. On the opposite side an n+ diode with an aluminium plate is implanted. For 300 μm thickness an operating voltage of 160 V will be used to get free depletion. When a minimum ionizing particle enters the detector, it creates about 100 electron-hole pairs per μm, whereas the exact number is proportional to the deposited energy of the particle inside the detector, which is around 39 keV/100μm for a minimum ionizing particle. The electrons drift to the aluminium strips and will be readout as the signal. To get the best position resolution, every strip should be read out, so that a resolution better than 2 μm is achievable.

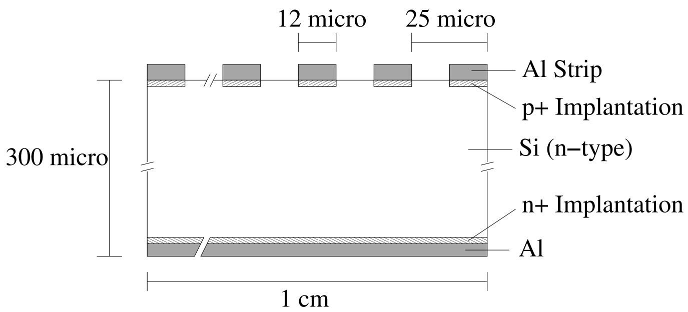

Figure 2: Sketch of a Silicon Strip Detector

3.2 Quartz Fiber detector

The fiber detector (Fig.3) consists of 100 single fibers, with 20 fibers arranged to one layer. Each layer is displaced by 0.1 mm in x with regard to the previous layer. A single fiber is assumed to be a rectangular fiber of a 0.5 mm x 0.5 mm x 1 cm of quartz, with a density of 2.32 $g \cdot cm^{-3}$, and a total reflecting cladding of 10 μm thickness. Staggering is of advantage because spatial resolution is improved.

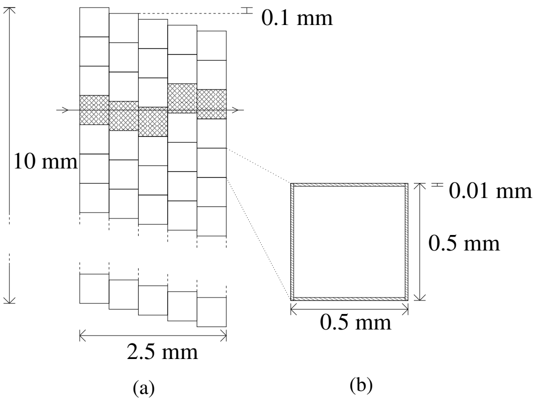

Figure 3: Sketch of (a) the quartz fiber detector and (b) a singel quartz fiber

If a high energetic charged particle travels through the fiber with a velocity higher than the phase velocity of the quartz, Cerenkov light will be emitted. With a chance of about 98 % the emitted light will stay in the fiber, because of the cladding. Therefore, there is a chance of cross talk with a propability of $\sim$ 2 %. The optical photons are travelling through the whole fiber and some light guide to a PMT, where the photons will be transform into a signal. The probability that a high energetic charged particle, which travels through a fiber and produces a signal, is about 80 % .

Because of the displacement of the layers, the position measurement accuracy of a single particle is about 0.1 $\pm$0.029 mm. Since in our simulation we don't deal with single particles but with about 10^5 particles per bunch crossing, we expect a much higher precision on the position measurement by fitting the signal distribution.

4 Energy Deposition Simulation

Before we started of the position measurement simulation, we estimated the deposited energy within the detectors for two reasons: a) we tried to figure out, whether a cooling system will be necessary and b) to calculate the radiation dose for each detector. All of the simulations for the deposited energy were performed with GEANT4.

4.1 Deposited Energy within the photon detector

To measure the position of the photon beam, it was sent through a converter (tungsten of 15 radiation lenghts) in order to create electron-positron pairs. In this way, also new (high energetic) photons are created, and there will be some surviving backscattered photons, which have not been converted. Therefore we have to deal with three different kinds of particles after the converter: e^+/e^- pairs, new photons and non-converted Compton backscattered photons.

Furthermore, as a kind of background, photons of synchrotron radiation (SR), created by the electrons inside the magnetic spectrometer,are also expected. Then enter also the converter and create electron-positron pairs and photons. Thus, three additional kinds of particle generate signals and deposite energies in the detector.

The interactions of the backscattered photons within the converter had already been simulated, so that we take these data and start our simulation right in front of the detector.

As said before, one ILC electron bunch is planned to consist of $2 \cdot 10^{10}$ electrons, from which 10^6 electron are assumed to interact. Due to the enormous number of particles per bunch crossing only a fraction of them was used for simulation studies. The rates of particles entering the detector are given in Tab.1. These rates are based on $2 \cdot 10^7$ beam particles for charged particles creation by SR, $2 \cdot 10^6$ beam particles for the produced by SR gammas and 10^3 Compton events per bunch crossing.

Table 1: Number of particles per bunch crossing entering the detector

particle	amount of particles entering the detector
produced charged particles by backscattered photons	148224
produced gammas by backscattered photons	2504597
surviving gammas of backscattered photons	3
produced charged particles by SR	1766
produced gammas by SR	3303
surviving gammas of SR	6576

For the silicon strip detector we implemented a singel box of silicon as a sensitive detector inside GEANT4 with the dimensions 300 μm x 1 cm x 1 cm positioned between x_1=-0.5 cm and x_2=0.5 cm in a distance of L=50 m behind the magnet.

For the fiber detector we implemented some 100 single fibers with the configuration as explained in section 3. The only difference with respect to the configuration in section 3 was, that the whole fiber consists of quartz without cladding.

In Tab.2 the deposited energy of all particle types are shown, but now scaled to $2 \cdot 10^{10}$ beam electrons per bunch, respectively, 10^6 Compton events.

At the ILC it is planned to have 15000 bunch crossing per second, so that with this frenquency there is a total power as also shown in Tab.2.

The difference of the deposited energies of a factor eight between both detectors is due to the fact that the fiber detector thickness is about eight times larger than that of the silicon detector and both materials have almost the same density.

With this power, there will be no cooling system necessary.

In order to calculate the radiation dose, we assume that the deposited energy is only located in the range of highest occupancy of [-0.5mm,0.5mm] in x- and y-directions. The results are shown in Tab.3. With this radiation dose, there will be problems with the lifetime of the detectors. A silicon detector might withstand a dose of only 10 kGy, while a quartz fiber about 300 MGy. Hence, a silicon detector will only survive for a very short time and should not be used under this circumstances.

Table 2: Deposted energies within the detectors

particle	silicon detector	fiber detector
charged particles produced by backscattered photons	23.933 TeV	165.989 TeV
gammas produced by backscattered photons	1283.67 GeV	29.564 TeV
surviving gammas of backscattered photons	0 GeV	0 GeV
charged particles produced by SR	318.37 GeV	1970.8 GeV
gammas produced by SR	15.73 GeV	417.9 GeV
surviving gammas of SR	12.46 GeV	817.6 GeV
total deposited energy	25.563 TeV	198.756 TeV
total power P_{dep}	0.0614 W	0.4776 W

Table 3: Deposited energy and absorbed dose in x- and y-range of [-0.5mm,0.5mm]

	silicon detector	fiber detector
deposited Energy E_{dep}	3859.92 GeV	22493.76 GeV
absorbed dose	0.8956 Gy	0.6207 Gy
absorbed dose per year	13.434 GGy	9.3105 GGy

4.2 Deposited Energy within the edge electron detector

To simulate the deposited energy close to x_{Edge} we use the simulated data of 10^6 Compton electrons, so we had the right number of scattered electrons per bunch. For this simulation we implemented the silicon, respectively, the fiber detector inside the GEANT4 program between x_1=140mm and x_2=150mm and at a distance of L=25 m behind the magnet.

Table 4: Deposted energies within detectors

	silicon detector	fiber detector
deposited energy	2513.69 MeV	22065.09 MeV
power P_{dep}	6.04 pW	53.02 pW

In order to calculate the absorbed dose close to x_{Edge}, we took the deposited energy within the whole y-range and of x between [140mm,145.8mm]. The upper limit is $x_{Edge}\approx$145.8mm since the whole energy is deposited before the edge.

Table 5: Absorbed doses inside the detectors

	silicon detector	fiber detector
absorbed dose	$9.932\cdot10^{-6}$ Gy	$10.507\cdot10^{-6}$ Gy
absorbed dose per year	1.4898 MGy	1.57605 MGy

The results are shown in Tab.5. Regarding the amount of absorbed dose, a fiber detector turns out to be usable for sure.

5 Position Measurements

5.1 Measurement of x_γ

To simulate the measurement at x_γ we rely on the same data as used in the simulation of the energy deposition. Than means the simulations were done for less particles according to Tab.1 and afterwards scaled to the right number.

Although we had six different kinds of data samples, we selected only those relevant for the detector used.

5.1.1 x_γ - Measurement by the Silicon Detector

As explained in the description of the silicon detector, the amount of created electron-hole pairs is proportional to the total deposited energy, which results from all interactions within the detector. Only charged particles and gammas from the backscattered photons and charged particles from SR were included in our simulation.

To evaluate the response of the detector, we were confronted with a problem based on the operation of GEANT4. When GEANT4 simulates interactions of a single particle going through matter, it divides the total pass length into several steps. The only information provided by GEANT4 is, whether an interaction took place within this length or not, the starting and ending points of the length, the energy at these points and of course the deposited energy within this length. It is not possible to get the right position of an interaction nor the number of interactions over this length. Since a certain amount of energy (3.6 eV) is needed to create an electron-hole pair, we took the deposited energy inside a certain length and used that as an representative for the number of produced electron-hole pairs. As the position of the production the end point of the step length was used.

Now a program, based on ROOT, checked, whether the particle position was on a strip of the detector or in between. If the position was on a strip, the total energy was deposited to that strip. If the position was in between two strips, the energy was splitted according to the proportionality of the distances. For example, if the position was right in the middle, each strip got half of the energy. By this simulation the signal represents the total deposited energy at a certain position, which is in turn proportional to the created numbers of electron-hole pairs.

We could transform the energy into a charge by taking the average energy needed for an electron-hole pair, but this would not change our results.

With this simulation the detector response distribution become wider compared to the original distribution, as expected. This effect is shown in Fig.4 , where only the data of the charged particles of the backscattered photons are compared before and after the detector.

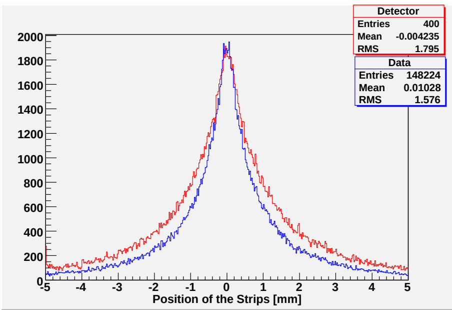

Figure 4: Position distribution of incoming charged particles (blue) and the response of the detector (red).

While matching the energy to each strip, the program also created an error for each bin. The content of each bin is the sum of all deposited energies at this strip, which is $N \cdot \bar{E}$, whereas N is the number of all entries and $\bar{E}$ the mean value of the deposited energies. So, calculating the mean energy and its error, the error for each bin is then

$$\frac{\sigma_{bin}}{N \cdot \bar{E}} = \sqrt{(\frac{\sigma_N}{N})^2 + (\frac{\sigma_{\bar{E}}}{\bar{E}})^2}, \tag{3}$$

whereas $\frac{\sigma_{\bar{E}}}{\bar{E}}$ is the relativly error of the deposited energy and $(\frac{\sigma_N}{N})$ is the relativly error of the number of entries for each bin. We assumed that the last error to be Poisson distributed so that

$$\frac{\sigma_{bin}}{N \cdot \bar{E}} = \sqrt{(\frac{1}{\sqrt{N}})^2 + (\frac{\sigma_{\bar{E}}}{\bar{E}})^2} \tag{4}$$

With this error, the position, respectively, the response distributions were fitted. For the distribution of the particles from Compton backscattered photons a single Gaussian plus a constant was used:

$$g(x) = A \cdot e^{-\frac{(x-x_0)^2}{2\sigma_g^2}} + B \tag{5}$$

For the e^+/e^- particles from SR we used a more complicated function as proposed in [2]

$$f(x) = \frac{\sigma_f}{\sqrt{2\pi}}(c-a)e^{-\frac{(x-x_0)^2}{2\sigma_f^2}} + \frac{1}{2}((a-c)(x-x_0) + (b-d))erfc(\frac{x-x_0}{\sqrt{2}\sigma_f}) + c(x-x_0) + d \tag{6}$$

The distributions and the fit results can be seen in Fig.5. For the particles from backscattered photons we fitted in the range of [-0.5,0.5], while for the particles from SR the whole range of the detector was used.

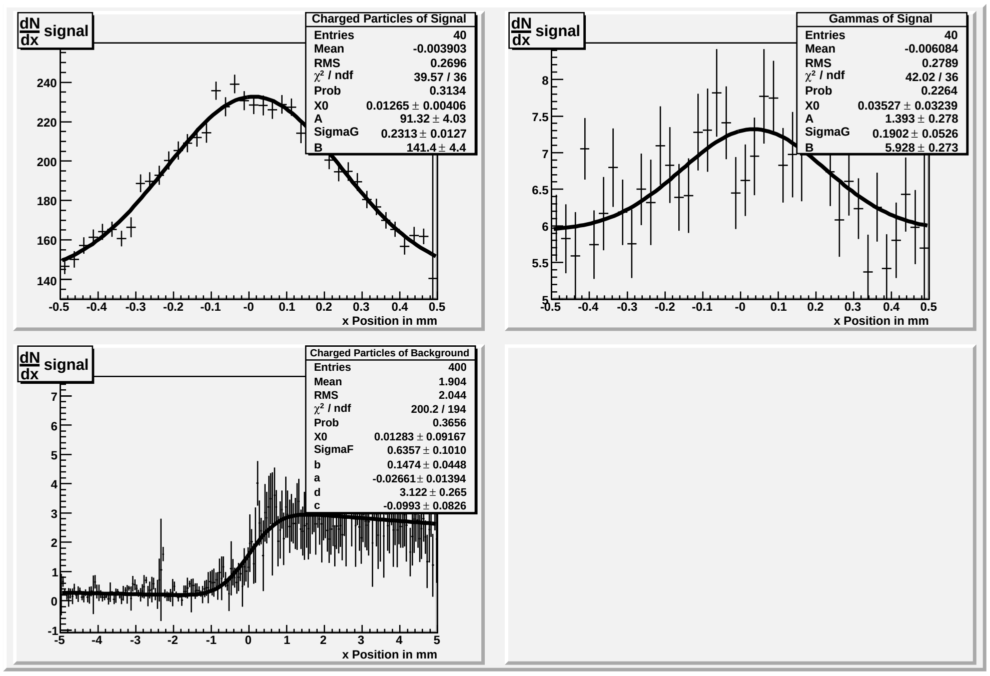

Figure 5: Charged particle response distribution from backscattered photons (top-left), from gammas of backscattered photons (top-right) and from SR (bottom-left)

Now, the fitted results were normalized to the correct number of particles expected, with the assumption that the mean position value is at $x_0 = 0$, because we assumed the difference to x_0 to be statitical fluctuation.

In Fig.6 are shown the three final distributions. The bottom-right histogram is the sum of the other three histograms. For the fitting procedure of this histogram we used the sum of eq.(5) and (6), with the two slops equal zero, as indicated by the third distribution, resulting to much better fit.

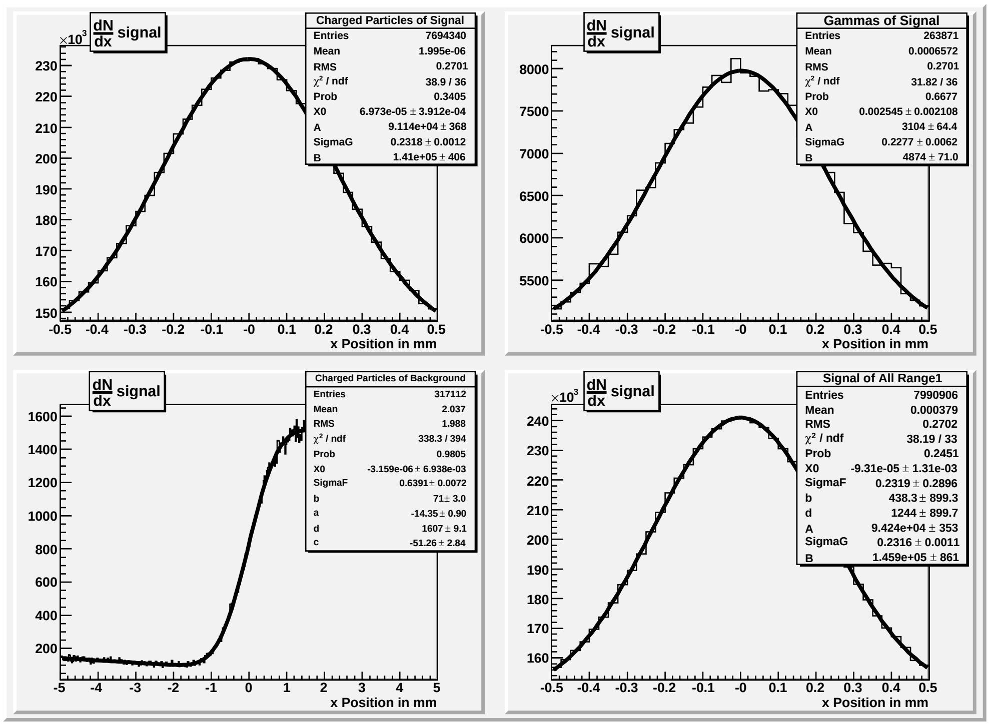

Figure 6: Detector response distribution of charged particles from backscattered photons (top-left) of gammas from backscattered photons (top-right) of charged particles from SR (bottom-left) and the sum of these distributions (bottom-right) together with the fit results

From the sum histogram one can see that the error of X_0 is σ=1.31 μm and $\Delta x = x_0 - x_{exp} = x_0$ is in the range of one σ, so this shows the accuracy we were looking for.

5.1.2 x_γ - Measurement by the Fiber Detector

For this simulation the same detector was implemented into GEANT4 as for the deposited energy measurement. When a charged particle enters a fiber, Cerenkov light is created and the program assigns a hit to this fiber. So, a hit distribution is generated for all fibers as well as for each layer.

Normally, the position error for a particle is $\sigma = \frac{500\mu m}{\sqrt{12}} = 144\mu m$. However due to the staggering of 5 layers as assumed the error is now $\sigma = \frac{100\mu m}{\sqrt{12}} = 29\mu m$ provided the particle creates light in each layer.

We matched every fiber to its position and put the number of hits in a histogram with the bin size of $100\mu m$ instead of $500\mu m$, but at that point we recognized a problem: the strength of the signal decreases with increasing layer number as shown in Fig.7.

The sum of these distributions results to the final histogram in Fig.8, and due to its strange behaviour no fitting procedure was possible.

The reason for the light decrease was due to the loss of the particle's kinetic energy when passing through the detector. At the beginning of each layer the number of charged particles, fast enough to create Cerenkov light , decreases on the way through the detector.

In order to reduce the position error and to get a better resolution, we proposed a fiber detector with a fiber size of 100μm x 100μm arranged in three layers and staggered by 33μm. With this

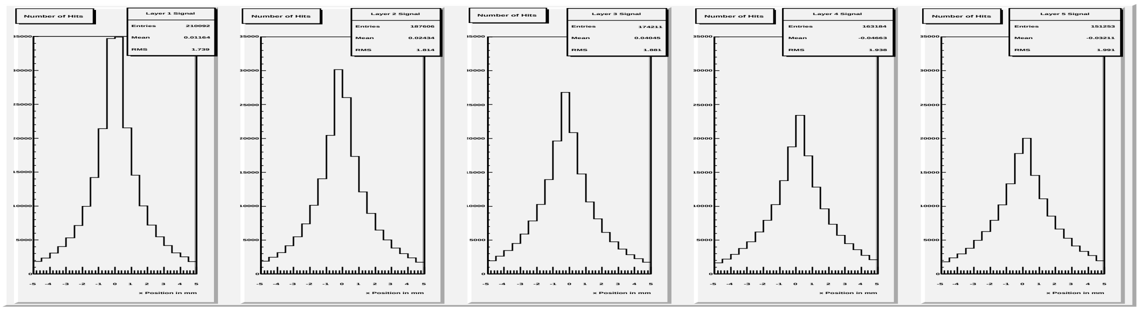

Figure 7: Hit distribution for layer 1 to 5.

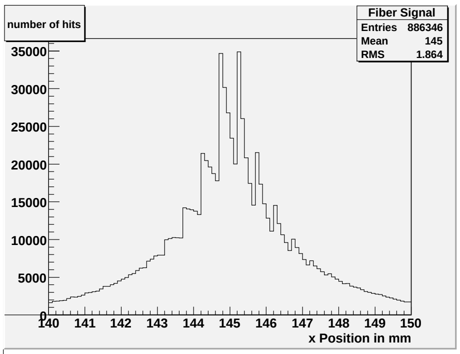

Figure 8: hit distribution of all layer combined in one histogram

detector we hope that the energy loss of the particles is so small that a combination of all three layers would make sense. But after a small preinvestigation of just the charged particles from the backscrattered photons, we figured out that the problem still exists. Also for this new detector, the energy loss of the particles was too high to be combined in one histogram for fitting.

Because of this problem, we thought about of another way of analysing the data. We just considered a detector of one layer with 100μm x 100μm fibers and fitted the spectrum. The resolution was surprisingly good, $x_0 = 1.18\mu m \pm 5.26\mu m$ as shown in the Fig.9

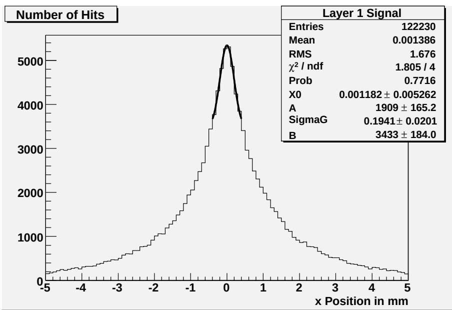

Figure 9: fitting distribution of the first layer

To get even better results, one can take the data of each layer, fit the individual distributions and calculate the mean. For this procedure, the layers must not necessarily be staggered, but using a detector of some smaller fibers is very helpful.

In my opinion, the possibility to get good results by simulating a fiber detector with smaller fibers and using the method of single layer analysis is pretty good.

5.2 Measurement of x_{Edge}

As already pointed out in the section 4, there is no need to scale the data, because we worked with the correct number of particles that is going to be used at the ILC.

5.2.1 x_{Edge} - Measurement by the Silicon Detector

For the silicon detector we used basically the same method as for x_γ. The deposited energy determines the produced electron-hole pairs, which have to machted to the most adjacent strip position, including charge division. After accounting for the error by eq.(4), the fitting procedure given by eq.(6) was applied.

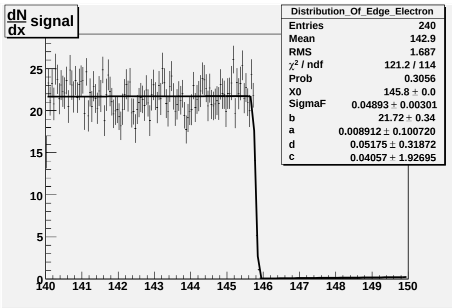

Figure 10: Distribution of the edge electrons together with the fit results

The results are shown in Fig.10, and the edge position was fitted as x_{Edge}=145.793±0.0032mm, in very good agreement with our expectations.

5.2.2 x_{Edge} - Measurement by the Fiber Detector

For the fiber detector we also matched the number of hits to the fiber's positions and combined the data of all five layers in one histogram. Because in this case the electrons have high energies, no problems due to loss of energy occured. The number of Cerenkov electrons was constant for all layers.

After combining of all layer informations, the distribution was fitted using also eq.(6).

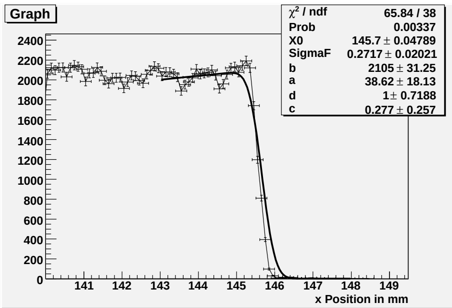

Figure 11: Distribution of the edge electrons

The results for the edge position is x_{Edge}=145.660±0.048mm , with a non-acceptable error, which is determined by the large fiber size of 500μm.

It is expected that a single-layer fiber detector with fibers of 100μm x 100μm results to a much better accuracy of x_{Edge}.

6 Conclusions

Using two kinds of detectors (silicon and fiber) for position measurements of the backscattered photons and edge electrons we first figured out, that the absorbed dose from particles created in the converter by the backscattered photons is much to high for both detector types. Therefore, another way to measure x_γ have to be found.

For the edge electrons, the silicon detector provides good position resolution but the absorbed dose was also too high for this detector. Therefore, another detector, a quartz fiber detector, was taken into consideration.

Assuming a staggered 5-layer detector with fibers of 500μm x 500μm as an example, the results were not very convincing. We found that the dimensions of the single fibers were too big, so that we had problems to get the accuracy we need.

In my opinion, it would be a good suggestion to focus on a fiber detector of only one layer with smaller fibers to obtain a precision as anticipated.

Acknowledgements

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References

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[2] J. Lange, Compton backscattering as a mean of measuring the beam energy at the international linear collider, September 2006.