# Fast Beam Diagnostics with Energy Measurements in Forward Calorimeters at the ILC Detectors

Summer Student Project Work
DESY 2006

Ernst von Oelsen
BTU Cottbus
e-Mail: oelseern@tu-cottbus.de

September 13, 2006

## Abstract

In the future linear $e^+e^-$ colliders like the ILC will provide new possibilities for experiments at the TeV scale giving us new insights into the mechanism of mass generation or the nature of dark matter. Due to the complexity of the accelerator one has to use computer simulations of bunch collisions in order to optimize beam and collider parameters. Key parameters of an $e^+e^-$ collider are the center-of-mass energy, $\sqrt{s}$, and the luminosity, $\mathcal{L}$. The Luminosity is defined as the proportional factor between the event rate, $R_{ev}$, and the cross section, $\sigma_{cs}$, of a certain process:

$$R_{ev} = \mathcal{L} \times \sigma_{cs}. \tag{1}$$

The center-of-mass energy determines e.g. the mass range for the search of new particles. As larger the luminosity the higher is the number of events of a detectable process. Thus a high luminosity allows to study processes with small cross sections. The luminosity determines the sensitivity of the collider. In order to offer a high luminosity it is important to study processes allowing to monitor and optimize the luminosity continously. A new phenomenon at high energy $e^+e^-$ colliders with small bunch sizes is beamstrahlung and pair production by beamstrahlung photons. The measurement of the energy of these beamstrahlung photons and pairs offers a possibility for real-time beamdiagnostics that allows luminosity optimization as shown in this work.

## 1 Introduction

In a simple model one can write for the luminosity [7]:

$$\mathcal{L} \propto \frac{N^2 n_B f_{rep}}{4\pi\sigma_x\sigma_y}, \tag{2}$$

where $N$ is the number of particles of each bunch, $n_B$ is the number of bunches per train and $f_{rep}$ is the frequency of bunch trains. The product $\sigma_x\sigma_y$ is the cross section of the beams, and the factor $4\pi$ comes from the assumption that the particles - and in the same way the beam charges - obey a GAUSSian distribution.

Here I present a study how to use the beamstrahlung photons and pairs, both measured by special detectors, for the optimization of the luminosity.

### 1.1 Experimental Setup

At the Interaction Point (IP) of the ILC positron and electron bunches are brought to collision. The ILC detector is positioned around the IP as shown in Fig. 1 (the IP is on the left margin at $z = 0$). The FCal group is performing design studies for the forward region of the ILC detector. There will be three main detector types:

- The LumiCal detector will improve the detector's hermeticity by identification of electrons and photons down to polar angles of a few mrad. LumiCal will measure the Bhabha event rate for the measurement of the luminosity. The theroetical cross section for Bhabha scattering at small polar angles can be calculated precisely in QED. Counting the rate of Bhabha events, the luminosity can be determined using Equ. 1. It is planned to measure the luminosity with a precision of $10^{-4}$. The size of the cross section for Bhabha scattering is sufficient to obtain this accuracy over a longer running period, e.g. one year. But it is too small for real-time diagnostics on a bunch by bunch basis.

- The PhotoCal and GamCal will be installed a few hundred meters behind the IP. They are designed to measure beamstrahlung photons.

- The BeamCal will detect energy deposittion down to a few mrad. It is designed not only to detect the total energy but also the spatial distribution of $e^+e^-$ pairs stemming from beamstrahlung. The latter allows access to the geometrical parameters of the beam. As the energy measurement is a real-time measurement the BeamCal provides an easy way for real-time beam and luminosity diagnostics and optimization. In addition, BeamCal will also detect single high energy electrons, on top of the beamstrahlung pairs. This is important for background suppression in particle searches.

The nominal ILC bunch and collider parameters can be seen in Tab. 1.

| | |
|---|---|
| # of particles per bunch [$10^{10}$] | 2 |
| particle energy [GeV] | 250 |
| bunch length [$\mu m$] | 300 |
| bunch height [$nm$] | 5.7 |
| bunch width [$nm$] | 655 |
| Normalized emittances [$mm\,mrad$] | 10.0/0.04 |
| magnetic field strength [$T$] | 4 |
| # of bunches per train | 2820 |
| repetition frequency $f_{rep}$ [$Hz$] | 5 |

Table 1: Nominal ILC parameters.

As declared in [1] we use a right-handed coordinate system centered at the IP with the positive $z$-axis pointing in the flight direction of the $e^-$-bunch and the $y$-axis pointing upwards. Fig. 2 shows a drawing of such a coordinate system.

The collision of $e^+$ and $e^-$ bunches is simulated using the program GuineaPig [4]. It reads parameter values from an input file. This input file contains parameters, e.g. particle energy, bunch dimension, bunch charges and crossing

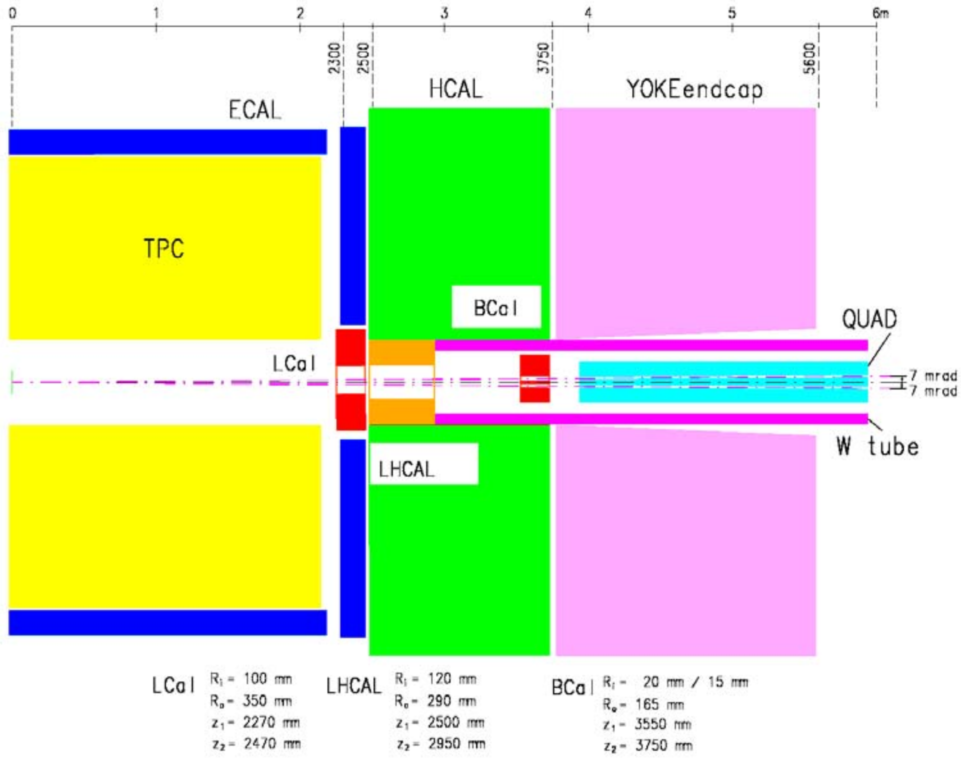


Figure 1: Scheme of the Very Forward Region of the ILC. LCal and BCal (in the text declared as LumiCal and BeamCal are cylindrical calorimeters adjacent to the beampipe. TPC is the tracking detector, HCAL and ECAL are the hadronic and electromagnetic calorimeters.

angles. The nominal ILC parameters for crossing angles are `angle_x = 0.0` and `angle_y = 0.0` for head-on collisions. Fig. 3 shows the meaning of the two angles: the half crossing angle in $x$-direction is represented by `angle_x` while the half crossing angle in $y$-direction is represented by `angle_y`. The beams are focussed before they collide. The nominal focus point is the IP in the $z = 0$ plane, but GuineaPig allows also to shift the horizontal and vertical waists in $z$ direction. The parameters used in GuineaPig for this item are `waist_x` and `waist_y` which can be changed seperately. One has to consider that both beams are internally described in different coordinates (see 5.4 for details).

### 1.2 Theoretical Background

If the two bunches approach each other they feel the attractive Coulomb force that focusses the bunches. This is known as the pinch effect. Due to it the trajectories of $e^-$ are bent towards the

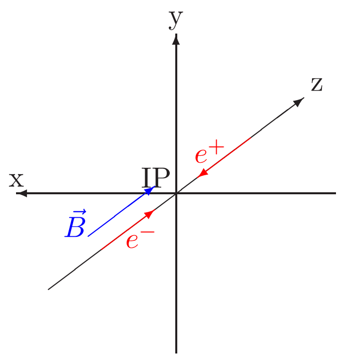


Figure 2: The coordinate system used for the description of beam collisions at the ILC.

center of the $e^+$ bunch and vice versa. During this acceleration they irradiate photons called beamstrahlung. The photons are emitted very collinearly to the beam pipe.

Since the photons pass through the remaining bunch particles incoherent pair production can happen. The dominant pair production process is the Bethe-Heitler process:

$$\gamma e \rightarrow e e^+ e^-$$

A beamstrahlung photon converts into a Bethe-Heitler pair after interacting with a bunch particle [2]. The cross section for this process is about $38\,mb$, which is nearly twice the cross section for the Landau-Lifshitz process ($ee \rightarrow eee^+e^-$). A third pair production process is the Breit-Wheeler process ($\gamma\gamma \rightarrow e^+e^-$), but its cross section is negligible. The pairs are deflected to larger angles by the charge of the oncoming beam and hit the BeamCal. They may be backscattered and induce background in the tracking detector. So the goal is to get a high luminosity and at the same time keep the amount of pairs small. This is done by using flat beams ($\sigma_x >> \sigma_y$).

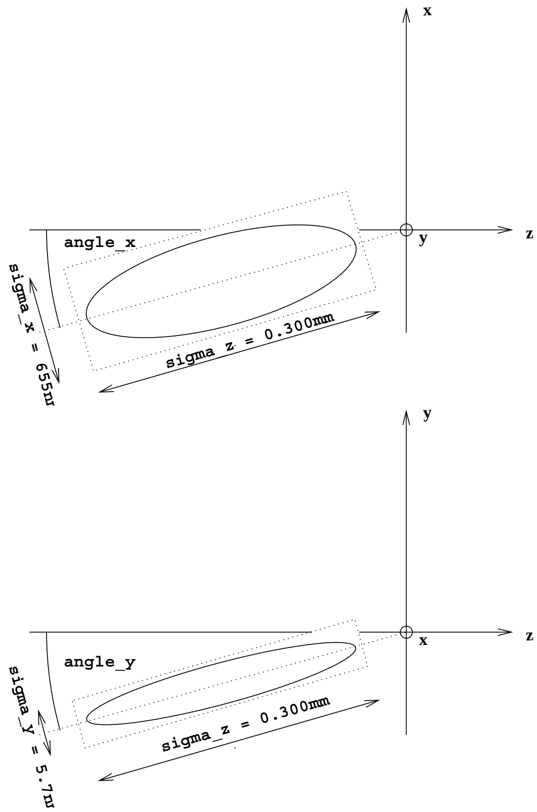


Figure 3: The half shifting angles $\alpha_x/2$ and $\alpha_y/2$ defined as the angle between the bunch direction of flight and the $z$-axis in the $(xz)$ and $(yz)$ plane, respectively.

If the two bunches do not collide in a head-on collision the bending of the trajectories of bunch particles becomes stronger as the whole bunch is twisted. In fact this happens as long as the distance between the bunches' center does not get too big. Due to the stronger bending the photon radiation increases. Simulations have been made studying the influence of vertical and horizontal offsets (see Ref. [6]). These simulations have shown that there is a strong dependence of the luminosity on the offsets. Not only the luminosity depends on the offsets but also the energy of the pairs and the beamstrahlung photons. As described in [6] the luminosity is almost proportional to the ratio $\frac{E_{pair}}{E_{photon}}$. Both energies can be measured fast, so this quantity provides a possibility for real-time luminosity measurement and optimization.

In these simulations the flight directions of both bunches were still parallel to the $z$-axis. Here I study the dependence of the luminosity on the beam crossing angles $\alpha_x$ and $\alpha_y$. Again, I look for quantities, measured with BeamCal or GamCal, proportional to the luminosity.

The pairs are produced by interactions between photons and $e^+e^-$ particles. The total number of pair particles is porportional to the number of photons. The propability for pair production should also be proportional to the length of the bunch rest which the photons have to fly through [6]. As one can see in Fig. 4, the effective path length a beamstrahlung photon has to go through the oncoming $e^+/e^-$ beam decreases if the crossing angle is increased. There is a critical angle from which on the length of the overlap zone does not depend any more on the bunch length $\sigma_z$. For any crossing angle $\theta_c > \alpha_{critical}$ the path length $l_p$ obeyes the relation

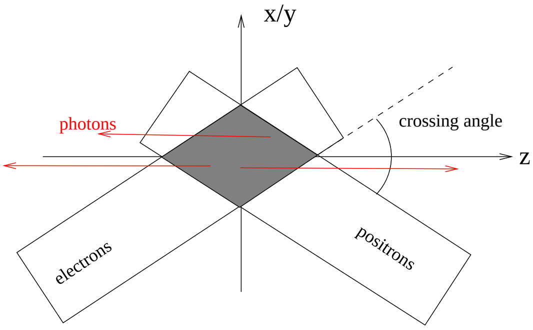


Figure 4: Illustration of the angle dependence of the effective overlap zone.

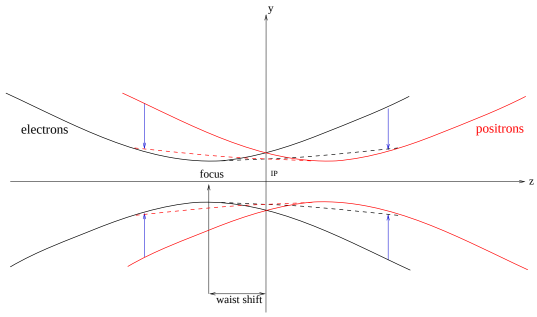


Figure 5: Bent $e^+e^-$ trajectories (dashed lines) due to focussing Coulomb force (blue arrows).

$$l_p \leq \frac{\sigma_{x/y}}{sin(\alpha_{x/y}/2)} \quad (3)$$

Thus one would expect that the number of pairs decreases by increasing the crossing angle as there is less propability for interaction between pairs and photons. In fact this case was observed, even when the number of photons increased in the case of vertical crossing angles.

Besides the vertical/horizontal offsets and crossing angles there is an additional parameter which the luminosity depends on. As the beams are focussed before colliding one can study the dependence on the position of the focal point. Nominally the beams are focussed to the IP in the $z = 0$ plane. As already shown in [3] one can increase the luminosity if the beams' vertical waists are shifted a few $\mu m$ in front of the $z = 0$ plane. The bunches are then not only squeezed by the focus system of the ILC but also by the attractive Coulomb force. The trajectories of the beam particles then have a larger longitudinal component with respect to the $z$-axis as shown in Fig. 5. (One could say that the pinch effect works as a bunch compressor). Thus the particles can pass through a denser oncoming bunch and there is more interaction.

# 2 Simulation Results

## 2.1 Results of $\alpha_x$ - shifting

The simulations of a horizontal crossing angle $\alpha_x$ were done in a range from zero to 50.0 mrad. Within this margin the luminosity decreased by a factor of about 20 as shown in Fig. 6. The simulations have shown that the luminosity dependence of the crossing angles is symmetric for positive and negative angles and centered at 0.0 rad, so only the positive angles are plotted.

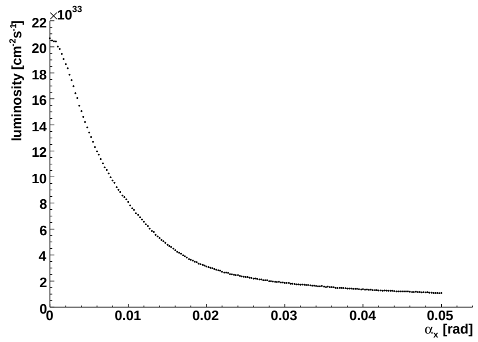


Figure 6: The luminosity as a function of the horizontal crossing angle $\alpha_x$.

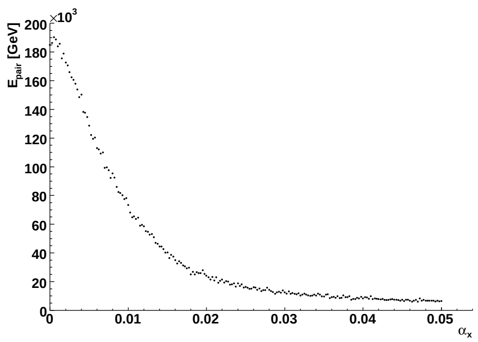


Figure 7: The total pair energy, $E_{pair}$, as a function of $\alpha_x$.

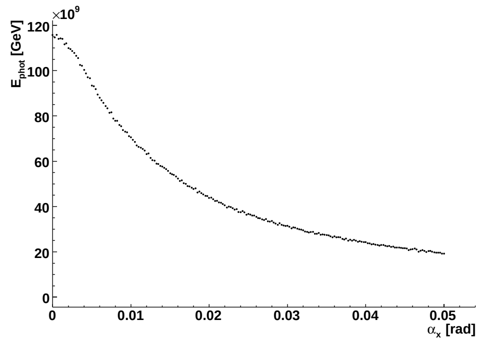


Figure 8: The total photon energy,$E_{photon}$, as a function of $\alpha_x$.

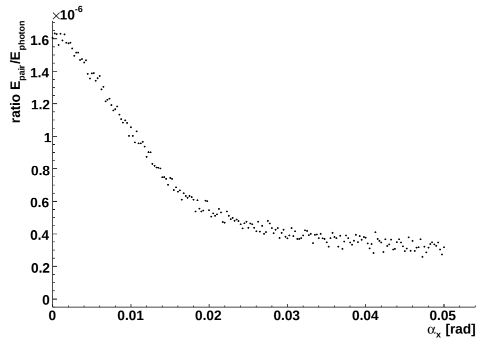


Figure 9: The ratio $E_{pair}/E_{photon}$ as a function of $\alpha_x$.

The pair energy, as shown in Fig. 7, shows a dependence similar to the one of the luminosity. The photon energy as a function of the crossing angle $\alpha_x$ does not have such a sharp maximum as the luminosity does (Fig. 8). The luminosity decreases to about 5% of its nominal value while the photon energy decreases to about 17% of its nominal value in the range from zero to 50 mrad (Fig. 6 and 8). In the same way the ratio $\frac{E_{pair}}{E_{photon}}$ has a larger width than the luminosity does. The best correspondence seems to be the one between the luminosity and the pair energy as illustrated in the common plot in Fig. 10.

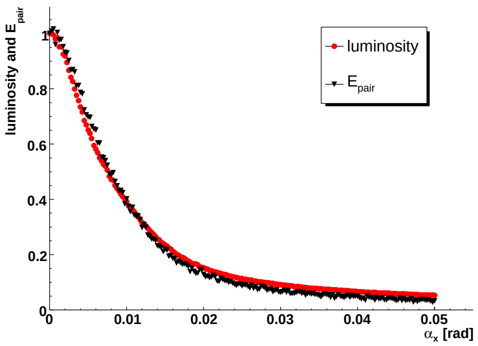


Figure 10: A normalized plot of the luminosity and $E_{pair}$ as functions of $\alpha_x$.

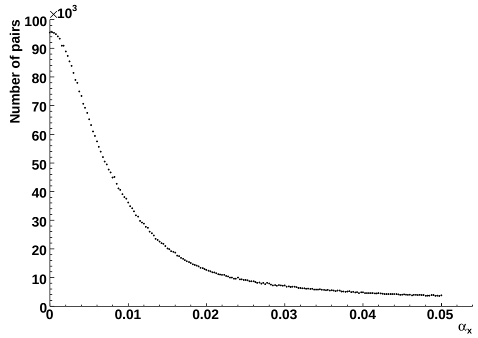


Figure 11: The number of pair particles, $N_{pair}$, as a function of $\alpha_x$.

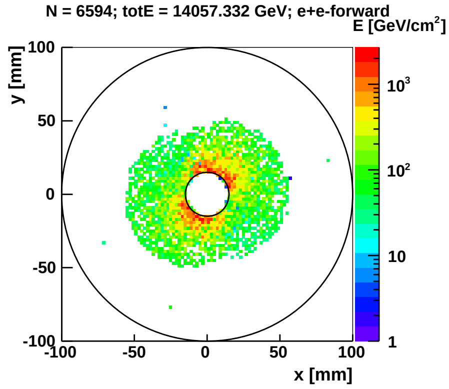


Figure 12: The energy deposition in the BeamCal for head-on collision.

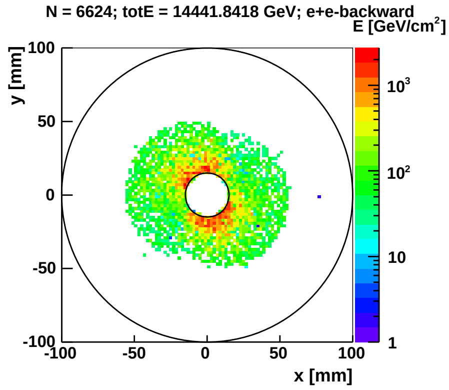


Figure 13: The energy deposition on the opposite side for head-on collision.

The second set of simulations show the energy distribution as a function of $\alpha_x$ on the front face of BeamCal. Fig. 12 shows a typical energy deposition for a head-on collision (Note: This is the picture as seen from the detector looking in negative $z$-direction). The plots do not include the resolution of the detectors. What can be seen is that the energy distribution is symmetric (for fixed energy) to a mirror line that is just tilted due to the magnetic field along the $z$ axis. Note that the total energy counted by the detector is not exactly equal to the whole pair energy calculated by GuineaPig as the detector can only measure particles that arrive between the inner and outer radii of the calorimeter. The energy distribution is symmetric to the IP. For comparison Fig. 13 shows the energy deposition on the opposite side.

When the crossing angle is increased one can clearly see that the number of pairs decreases (see Fig. 11). Also less energy is deposited in the BeamCal (see text line above Fig. 12 to 14). Furthermore the area of highest energy deposition moves from the center to the bottom. If one considers the ratio of the number of detected particles and measured energy one can see that the energy per particle decreases with increasing crossing angle: it starts with 2.13 GeV per particle for head-on collision, and decreases down to 1.86 GeV, 1.53 GeV and 1.28 GeV per particle for crossing angles of 10 mrad, 15 mrad and 25 mrad.

## 2.2 Results of $\alpha_y$ - shifting

The simulations cover a vertical crossing angle $\alpha_y$ in a range from zero to 1.2 mrad. One can see clearly in Fig. 15 that the luminostiy decreases when the crossing angle $\alpha_y$ is increased. As the luminosity remains almost constant for $\alpha_y > 0.4 \times 10^{-3}$ rad the plots show the luminosity in the range from zero to 0.2 mrad only.

There is a sharp maximum at $\alpha_y = 0.0$ rad, much sharper than for $\alpha_x$. The pair energy decreases monotonously as shown in Fig. 16. It decreases to 14% of its nominal value. The photon energy now increases (Fig. 17). The ratio $\frac{E_{pair}}{E_{photon}}$ decreases to 9% (Fig. 18). Now the best correspondence exists between the luminosity and the energy ratio. The common normalized plot of the luminosity and energy ratio is illustrated in Fig. 19.

Besides the fact that the luminosity decreases much faster by increasing the vertical crossing angle $\alpha_y$ one can see that the number of photons that are emitted increases for small angles, reaches a maximum and then decreases (Fig. 20). This can be unterstood if one remembers the different magnitudes of the bunch dimensions: as

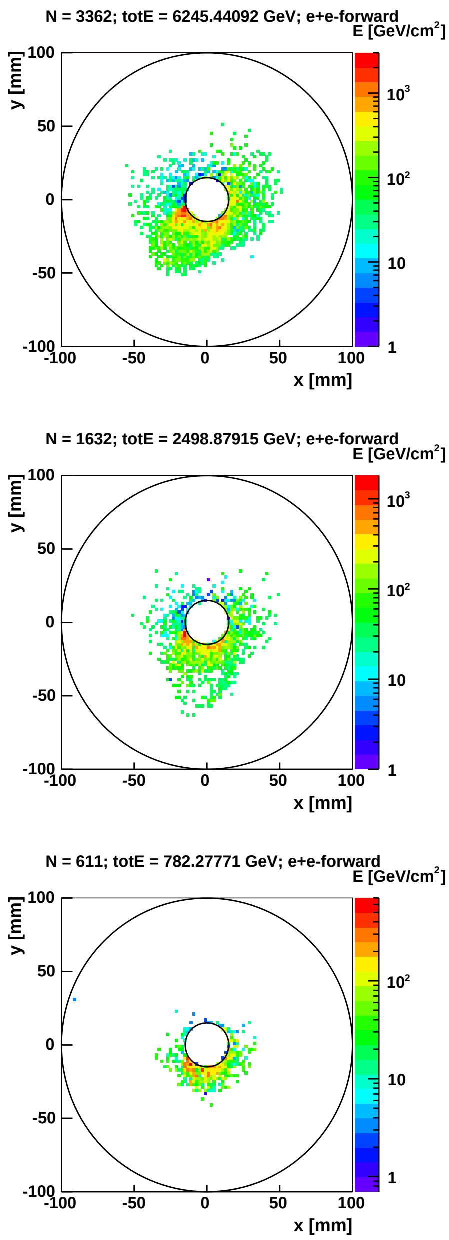


Figure 14: Energy deposition on the front face of the BeamCal for $\alpha_x = 10$ mrad (top), 15 mrad(center), 25 mrad(bottom).

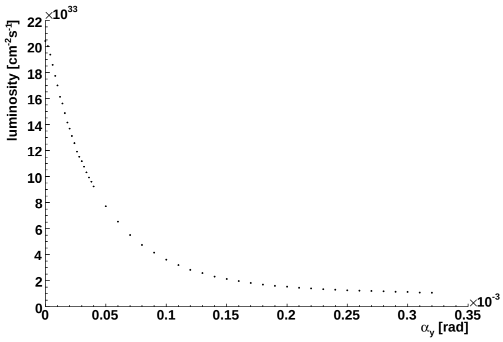


Figure 15: The luminosity as a function of the vertical crossing angle $\alpha_y$.

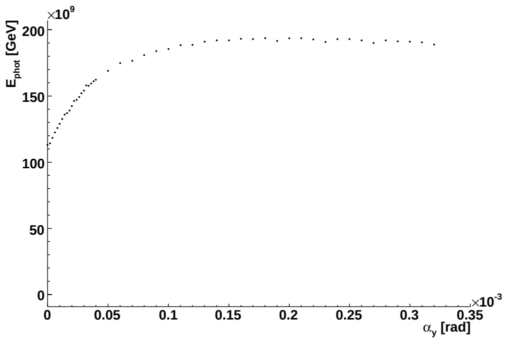


Figure 17: The photon energy, $E_{photon}$, as a function of $\alpha_y$.

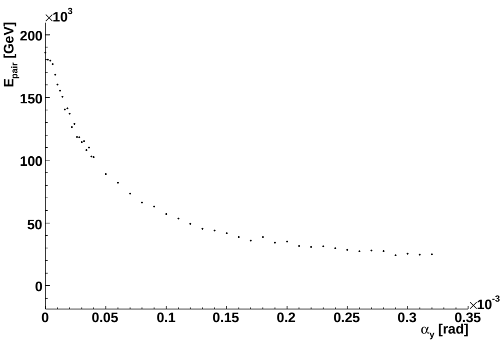


Figure 16: The total pair energy, $E_{pair}$, as a function of $\alpha_x$.

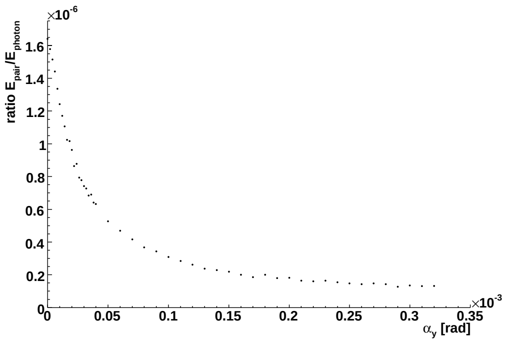


Figure 18: The ratio $E_{pair}/E_{photon}$ as a function of $\alpha_y$.

the bunch height $\sigma_y$ is much smaller than the width, there is much less interaction between beamstrahlung photons and the oncoming bunch for vertical crossing angles. The same behaviour was already observed for vertical offsets [6].

As the $\alpha_y$ dependence of the pair energy is much stronger than the one for $\alpha_x$ there is much less significance in the BeamCal signal (Fig. 21). The only evident change is the amount of deposited energy, but there is almost no change in the spatial didstribution. Also the symmetry between the detection in forward and backward direction remains. While the average energy per particle decreased for increasing $\alpha_x$ it increases for increasing $\alpha_y$ ($2.08\,\text{GeV}, 2.25\,\text{GeV}$ and $2.29\,\text{GeV}$ for vertical crossing angles of $0\,\text{mrad}$, $0.1\,\text{mrad}$ and $0.2\,\text{mrad}$).

## 2.3 Results of waist shifting

The simulation of an horizontal and vertical waist shift was done in a range of $\pm 500\,\mu\text{m}$. There was no significant depencence of the luminosity on the waist shift in $x$ direction.

One can clearly see a dependence of the lumi-

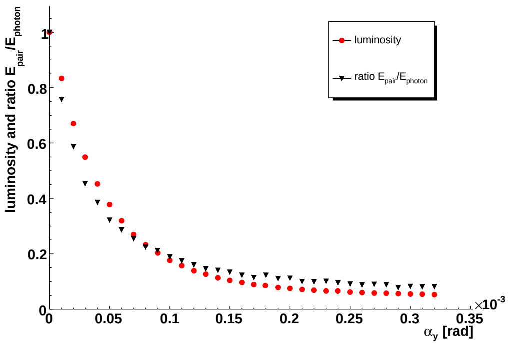


Figure 19: A normalized plot of the luminosity and $E_{pair}/E_{photon}$ as functions of $\alpha_y$.

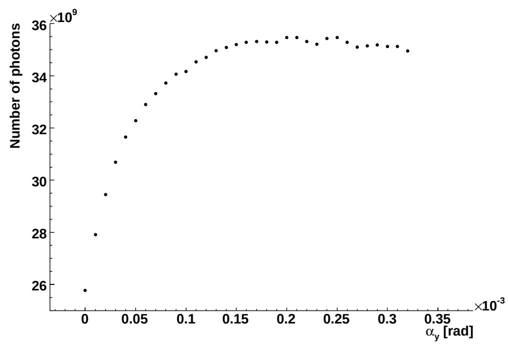


Figure 20: The photon number, $N_{photon}$, as a function of $\alpha_y$.

nosity on a waist shift in $y$ direction as shown in Fig. 22. The luminosity can be increased by 10% of its nominal value if the vertical waist is shifted to $z \simeq 250\,\mu$m in front of the IP. Like before in the crossing angle variation the luminosity's curve has the same characteristic as the one of the energy ratio (Fig. 23). This simulation has already been done for the TESLA accelerator. We just wanted to see whether there is a similar possibility for tuning the luminosity also in case of the ILC parameters.

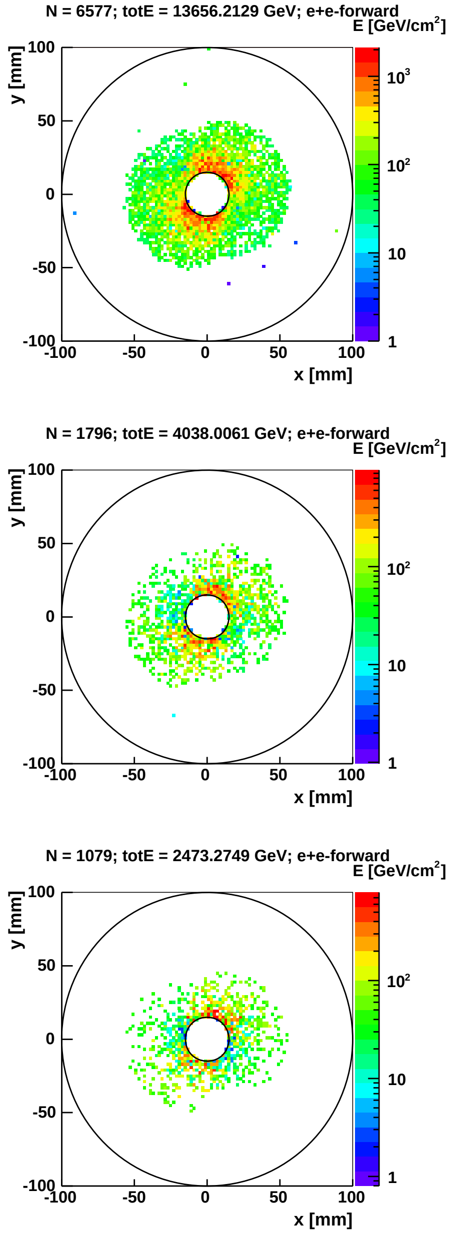


Figure 21: Energy deposition on the front face of the BeamCal for $\alpha_y = 0\,$mrad (top), $0.1\,$mrad(center), $0.2\,$mrad(bottom)

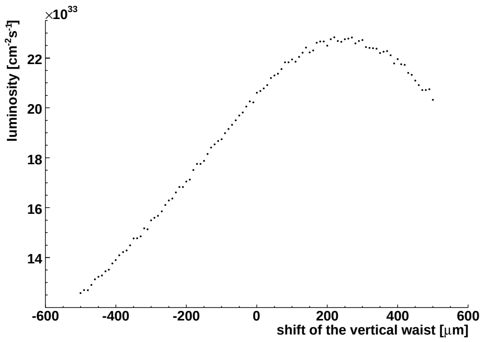


Figure 22: The luminosity as a function of the shift of the vertical waist.

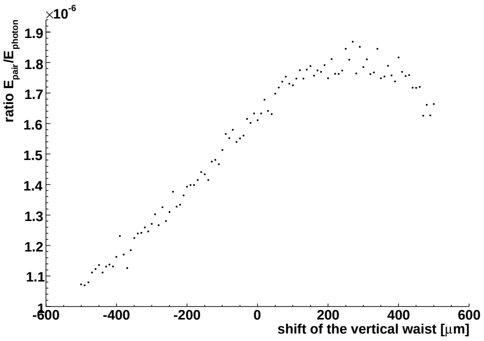


Figure 23: The ratio $E_{pair}/E_{photon}$ as a function of the shift of the vertical waist.

# 3 Conclusion and Outlook

The results show that one can find an appropriate quantity measured in the BeamCal for both $\alpha_x$ and $\alpha_y$. In the case of horizontal crossing angles one finds a proportionality between the luminosity and the pair energy. For vertical crossing angles the luminosity is nearly proportional to the ratio $\frac{E_{pair}}{E_{photon}}$.

The energy measurement in the BeamCal provides information about the beam properties only for horizontal crossing angles. The amount of deposited energy decreases much faster for vertical crossing angles. These small angles do not lead to a characteristic space-resolved energy deposition. On the other hand one can see a characteristic shift of the energy deposition for increasing horizontal crossing angles. The shape of the energy deposition is different from the one for horizontal/vertical offsets as calculated in [6] which allows to distinguish between both cases.

Furthermore there is the possibility to increase the luminosity by about 10% by shifting the focusses of the beams. The interesting fact was found that there is also a similarity between the luminosity and the energy ratio. Contrary to the behaviour for offsets and crossing angles this result has not been derived from an analytical model.

Up to now the calculations have been done with only one parameter different from the nominal parameters. One next step could consist of calculations where e.g. both crossing angles are shifted. Efforts are going on in finding analysis methods to extract information out of the spatial energy deposition in the BeamCal [5]. Furthermore one has to study the influence of the missing energy that can not be detected in the BeamCal due to the extension of the beam pipe.

# 4 Acknowledgement

I would like to thank DESY, especially DESY Zeuthen for offering the summer student program. Special thanks go to Dr. Wolfgang Lohmann for being my supervisor, and to Dr. Christian Grah and Martin Ohlerich for constructive and helpfull critics and discussions. Furthermore I'd like to thank Daniel Schulte for answers on problems with GuineaPig.

# References

[1] Christian Grah. Coordinate system for the 20 mrad crossing angle case of the ILC. *Internal DESY note*, 2005.

[2] Ekaterina Kuznetsova. *Design Studies and Sensor Tests for the Beam Calorimeter of the ILC Detector*. PhD thesis, Humboldt-Universitaet Berlin, 2005.

[3] O. Napoly and D. Schulte. Beam beam effects at the TESLA linear collider. *DESY TESLA-01-15*, 2001.

[4] Daniel Schulte. *Study of Electromagnetic and Hadronic Background in the Interaction Region of the* TESLA *Collider*. PhD thesis, Universitaet Hamburg, 1996.

[5] Achim Stahl. Diagnostics of colliding bunches from pair production and beamstrahlung at the IP. *LC-DET-2005-03*, 2005.

[6] Wolfgang Lohmann William M. Morse and Martin Ohlerich. Monitoring the ILC bunch parameters with beam-strahlung measurements. *LC note, in preparation*, 2006.

[7] Kaoru Yokoja. Beam-beam phenomena in linear colliders. 1995.


# 5 Appendix

## 5.1 Numerical Specialties

GUINEA PIG uses two coordinate systems for the two bunches: a right-handed one for beam 1 ($e^+$) and a left-handed one for beam 2 ($e^-$). The bunch length is measured in $z$-direction, the bunch width along the $x$ axis and the height along the $y$ axis. Note that this system is different from the one used to describe the whole collision process! In his own system each bunch is flying in negative $z$ direction.

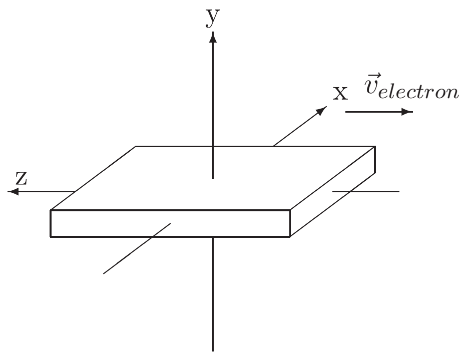


Figure 24: left-handed coordinates for the $e^-$ bunch

For calculations the beams are cut longitudinally into `n_z` slices, while each slice is cut into `n_x` $\times$ `n_y` cells. The calculations are done in a volume $V =$ `cut_x` $\times$ `cut_y` $\times$ `cut_z`. If one does not consider that the ratio of `n_y` to `cut_y` (depending on $\sigma_y$) is close to but greater than 1 (`cut_y` measured in *nm*), the results become physically senseless. As reference data we took the values calculated for the nominal ILC parameters, especially the luminosity should nearly keep its nominal value of $1.4 \times 10^{34}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$ (per bunch crossing) independent of the numerical parameters.

## 5.2 $\alpha_y$ - shifting

For simulating a vertical crossing angle $\alpha_y$ one only has to set `angle_y` $= 0.5 \times \theta_c^{vertical}$ as the parameter `angle_y` is applied to both beams.

For symmetry reasons I varied the value of $\alpha_y$ in a fixed range from zero to 1.2 mrad. Within this range the value of the luminosity decreased by a factor of 10 which should be easy enough to measure. Previous calculations proved that the results are symmetrically distributed around $\theta_c = 0.0$ .
As the beam dimension in y-direction is 5.7 nm , one has to set the `cut_y` parameter to more than 300 nm . In order to keep the ratio `n_y` to `cut_y` close to 1 I set `n_y = 512` and `cut_y = 500.0`. This results in a ratio of about 5 slices per bunch height.

### 5.3 $\alpha_x$ - shifting

In order to cover an angle range that is sufficiently big (we desided to cover the range from zero to 0.2 mrad) I set `cut_x = 20000.0` and `n_x = 512`. This leads to a ratio of about 150 slices per bunch width. For smaller angles one wastes a lot of CPU time if the `cut_x` parameter is not fitted dynamically but it ensures that there are no changing numerical effects that might appear if one fits the size of the grid during the simulation.

### 5.4 waist shifting

The values for `waist_y` are measured in different directions in each coordinate system. If one does not set `waist_y.1` and `waist_y.2` explicitely to the same value, GuineaPig just shifts the IP out of the coordinates' origin, but both beams are focussed in the same plane $z =$`waist_y`.