Misalignment sensitivity of laser and electron beams in the $\gamma\gamma$ collider at TESLA

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1 Introduction

The work I engaged in during my time as a summer student in the TESLA group at DESY Zeuthen was oriented towards investigating the misalignment sensitivity of the laser and the electron beams in the $\gamma\gamma$ collider at TESLA. This was in practice carried out by varying different electron beam and laser beam parameters and studying the resulting Compton conversion coefficient and total photon energy.

2 The linear collider at TESLA

The TESLA (Tera Electron Volt Energy Superconducting Linear Accelerator) collider will be designed for studying electron-positron interactions as well as photon-photon and photon-electron interactions. The high energy photons needed for the photon-photon and photon-electron interactions can be produced efficiently via Compton backscattering of laser light off the high energy electrons. In the following text, only the $\gamma\gamma$ collider, i.e. the study of photon-photon interactions, at TESLA is considered.

The setup of the $\gamma\gamma$ collider consists of two, almost counterpropagating, electron beams and two, almost counterpropagating, laser beams. See figure 1. The two electron beams, typically of energy E_0 = 250 GeV, travel towards the interaction point (IP), and collide with the focused laser beam at the conversion point (CP), located a distance b (typically on the order of a few millimeters) from the IP. Here, the photons scatter and then follow the direction of the electrons to the IP, where they then collide with an opposite but otherwise similar beam of high energy photons or electrons. When a short laser pulse of a duration of the order of ps with a flash energy on the order of a couple of Joules is used, it is possible to 'convert' almost all the electrons to high energy photons.

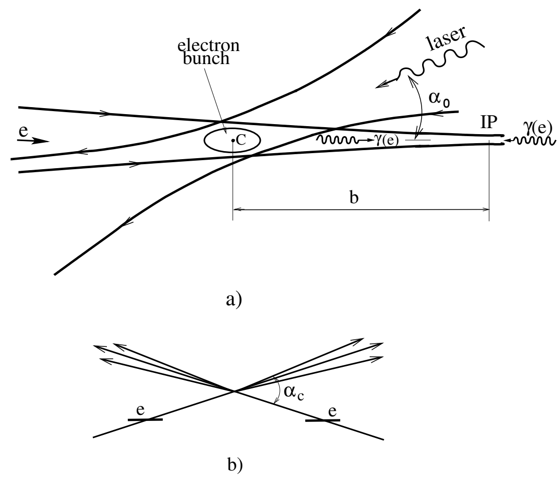

Figure 1: Scheme of $\gamma\gamma$, γe collider

Further investigation on the misalignment sensitivity of the laser beams and the electron beams is desired, in order to possibly improve the setup. The future aim is then to derive an error signal for a control loop that continuously checks and corrects the alignment of the beams.

Possibly there is a difference in the behaviour between the total photon energy ($E_{\gamma,tot}$) and the square of the Compton conversion coefficient k^2 (k = N_γ/N_e, where N_γ = no. of resulting photons and N_e = no. of incoming electrons) due to beam strahlung (electron-electron interaction). k^2 is calculated indirectly by subtracting the quotient between the number of electrons that have not undergone a conversion due to Compton scattering and the total number of initial electrons from one. For this reason, the resulting $E_{\gamma,tot}$ and the k^2 have been studied separately, though $E_{\gamma,tot}$ has been investigated to a greater extent, i.e. as a function of a larger variety of parameters.

3 The CAIN software

CAIN (a successor of ABEL) is a FORTRAN Monte-Carlo code, developed to do simulations on interactions between high energy electrons, positrons and photons. In the following work, the CAIN version 2.35 [1] has been used. In this version, the physical objects which appear are particle beams (which may consist of high energy electrons, positrons and photons), laser beams, external fields and magnetic beamlines.

4 The summer student project

4.1 Default values for the investigated parameters

The parameters in the following tables are the ones that have been investigated in this project. The values given here, which can also be found in the TESLA Technical Design Report (TDR), are the ones suggested as the default values for the collider. They are listed here as a reference, to in some way justify the range of values that were chosen for the simulations.

Beam parameters:

Parameter	Numerical value (TDR)
Offset	0 mm
$Loff_x$	0 mm
α_c	34 mrad
b	2.1 mm
β_x	1.5 mm
β_y	0.3 mm

Laser parameters:

Parameter	Numerical value (TDR)
τ(rms)	1.5 ps
τ(FWHM)	3.5 ps

Offset, which is used only in part 1 of the project, is the offset in the x-direction of the right-going electron beam with respect to the laser beam. This is not mentioned in the TDR, and is therefore assumed to have default value equal to zero.

$Loff_x$, which in the present study is introduced for the first time and is used in part 2 of the project, is the offset in the x-direction of the left-going laser beam with respect to the axis of the electron beam. Its default value is assumed to be zero.

The crab angle, α_c, is the angle at which the electron bunches are tilted with respect to the direction of propagation of the electron beam. b is, as stated before, the distance between the interacion point and the conversion point.

β_x and β_y are the dimensions of the electron beam , horizontal and vertical, respectively. Two different values for the laser pulse duration, τ, have been studied in greater detail — namely $\tau = 2$ ps and $\tau = 3$ ps. Both numbers represent the FWHM value of the laser pulse duration.

4.2 Default values for other important parameters

Default values for a number of other important parameters are:

Parameter	Numerical value
$\sqrt{s}$	500 GeV
Z_R	1.1 mm
a(rms)	13.6 μm
A	5.6 J
λ	1.06 μm
σ_z(rms)	0.3 mm

$\sqrt{s}$ is the centre of mass energy. Z_R is the Rayleigh length, which is connected with the laser beam focal spot size a(rms) in the following way

$$Z_R = \frac{2\pi a^2}{\lambda} \quad .$$

A is the laser flash energy, λ is the laser wave length and σ_z(rms) is the electron bunch length.

4.3 Part 1: Influence of lateral offset on the Compton conversion coefficient

During this initial part of the project, only a partial setup, with one electron beam (right-going) and one laser beam (left-going) was used. The Compton conversion coefficient was studied for $\tau = 1$ ps, 2 ps, 3 ps and 4 ps (FWHM). For each of these four laser pulse durations, the lateral offset between electron beam and laser beam was varied from -0.04 mm to +0.04 mm, which corresponds to an interval of 5.8 a, in steps of 0.005. The objective was to see whether or not an asymmetry between positive and negative offset was present. The resulting k^2 was plotted as a function of the offset and a Gaussian fit was made. The behaviour was very similar for all four values of τ, and therefore only the graphs of $\tau = 2$ ps and $\tau = 3$ ps are included in the report. For comparison, graphs of the total photon energy as a function of the lateral offset are also included, for the same values of τ. Results are shown in figures 2 and 3.

4.4 Part 2: Influence of various parameters on the total number of photons produced

In total seven different simulations have been carried out. Five of them were done using $\tau = 2$ ps

and two using $\tau = 3$ ps. Both these values of τ, as well as the following, are FWHM.
One simulation studied the dependence of the total photon energy on the offset in the x-direction of the left laser beam — in a similar way as in Part 1. Here, $\tau = 2$ ps was used. The laser offset $Loff_x$ was varied from -0.028 mm to + 0.028 mm in steps of 0.004 mm. Also the Compton conversion coefficients as a function of $Loff_x$ has been plotted. See figure 4. In figure 4 (right), the total photon energy as well as the separate photon energies for the left-going and right-going laser beams have been plotted. In figure 5 the electron energies (total, left-going, right-going) and positron energies (total, left-going, right-going have been plotted as a function of $Loff_x$.
In all the following simulations, Offset and $Loff_x$ have been set to zero. Two simulations, one for $\tau = 2$ ps and one for $\tau = 3$ ps, investigated the influence of the crab angle on the total photon energy. The crab angle was varied from 0 (implying that the electron bunches travel in the same direction as the electron beam) to 68 mrad, in steps of 2 mrad. See figure 6 (left). As the crab angle is increased, the total photon energy decreases, due to a reduced spatial overlap between electron and the corresponding counterpropagating laser bunch.
Two simulations, again one for $\tau = 2$ ps and one for $\tau = 3$ ps, were done to see how the distance b influenced the total photon energy. b was changed from 0.5 mm to 3.7 mm in steps of 0.2 mm. See figure 6 (right). A possible explaination for the shape of these graphs is that, as b increases, the probability for coherent pair-production becomes larger (the probability rate is constant, and thus the probability increases as the distance, and consequently also the time, increases). The increase in coherent pair-production causes the $E_{\gamma,tot}$ to drop. [6], page 45
The last two simulations, both with $\tau = 2$ ps, studied the influence the beta parameters β_x and β_y of the left-going beam had on the total photon energy — whether the dependence was proportional or not. In the first of these two simulations, β_x was varied from 0.5 mm to 2.0 mm in steps of 0.1 mm and in the second β_y was varied from 0.1 mm to 1.5 mm, also in steps of 0.1 mm. During these two simulations the β_x and β_y of the right-going beam were kept fixed at 1.5 mm and 0.3 mm, respectively. See figure 7. A larger radius of the electron beam is related to a smaller total photon energy. This is because the luminosity of the electron bunch is redused.

5 Evaluation and Conclusions

5.1 Part 1: Influence of lateral offset on the Compton conversion coefficient

As can easily be seen from the four plots, all four curves are nicely bell-shaped and fit the Gaussian very well. The curves are all almost completely symmetrical with respect to the zero offset value. It is therefore not possible to determine from one of these curves whether an offset resulting in a particular k^2 is positive or negative.
It is however possible to determine this by using a method called dithering. This is a periodic scanning of the lateral offset and the resulting photon luminosity. These scans result in a sinusoidal pattern if lateral offset and $L_{photons}$ are measured as functions of time. Then there will be a phase shift between the measured luminosity and the actual position of the laser focus. This phase shift will have a different sign for each of the two possible directions of movement of the scanned laser focus.

5.2 Part 2: Influence of various parameters on the total number of photons produced

In picture 4 (left), it can be seen that the Compton conversion coefficient behaives in a manner similar to the total photon energy (figure 4 (right)) — although the pattern in the left figure is more irregular than in the right.
When looking at figures 4 (right) and 5 (left), one can see that an increase in the total photon energy is accompanied by a decrease in the total electron energy. This is due to conservation of energy. After decomposition of the total energy into left-going and right-going components, it can be seen that energy conservation is also fulfilled for the two left-going and right-going components, independent of each other.
When looking at figure 5 (right), it is apparent that the total positron energy is two orders below the energy of photons and electrons. This means that the positrons play a negligible role in the scattering process and therefore need not to be considered further.
If figure 5 (left) is studied in detail, it is apparent that $E_{\gamma,left}$, i.e. the energy of the left-going photons, is almosts constant for the entire interval. This is no surprise, since this parameter depends on, and arises from, the right-going laser beam, which is not changed in any way during the simulation. In the same way, as the lateral offset of the left-going laser beam is varied, $E_{\gamma,right}$ changes accordingly.
Previous simulations show that if both laser beams

are turned off and only the two electron beams are interacting, then a value of about $2.11{\cdot}10^{21}$ eV for the total photon energy is achieved at zero offset. This energy is due to beamstrahlung. This value is roughly the same as the value for $E_{\gamma,right}$ at zero offset. The reason for this is that both electron beams have some value for the total energy that has to remain constant throughout all interactions. Details of this value and its origin are not yet fully known. Further investigations are necessary.

If, on the other hand, only the left-going laser beam is switched off, a value of $3.03{\cdot}10^{21}$ eV for the total photon energy is reached for zero offset. The values of total electron energy, left-going electron energy and right-going electron energy are about $6.95{\cdot}10^{21}$ eV, $2.80{\cdot}10^{21}$ eV and $4.15{\cdot}10^{21}$ eV, respectively, in this case. This can be explained by the fact that when the left-going laser beam is turned off, the right-going electron beam will not experience any interactions which in turn will reduce its beam energy. Further insights into the reasons for this behaviour requires more detailed simulations.

6 Acknowledgements

I would like to thank my supervisor Guido Klemz for all his help and instructions during my stay here. I would also like to thank Klaus Mönig for all the times he helped me with the CAIN software and FORTRAN programming.

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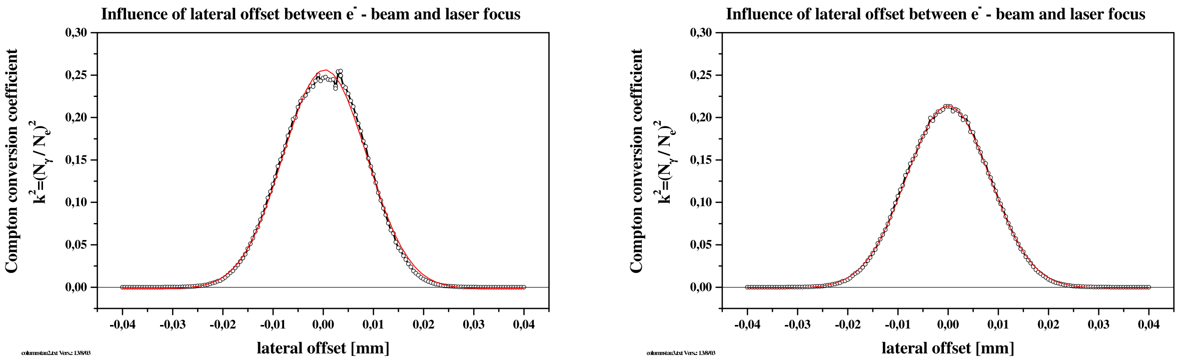

Figure 2: (Left: Laser pulse duration = 2 ps Right: Laser pulse duration = 3 ps)

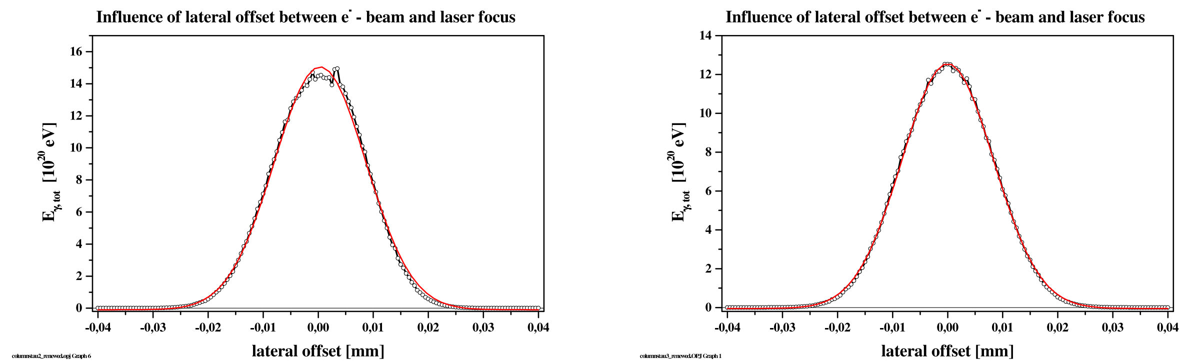

Figure 3: (Left: Laser pulse duration = 2 ps Right: Laser pulse duration = 3 ps)

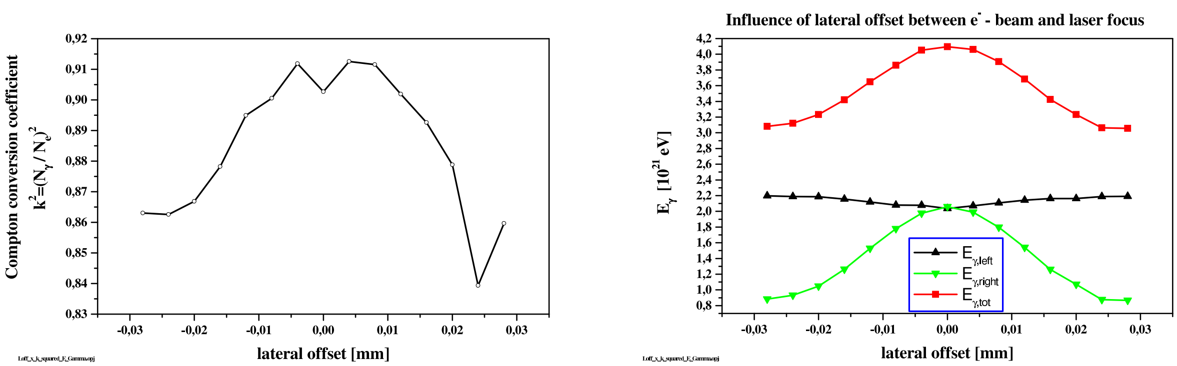

Figure 4: Left: Compton conversion coefficient as a function of the offset of the laser beam. Right: Photon energy as a function of the offset of the laser beam.

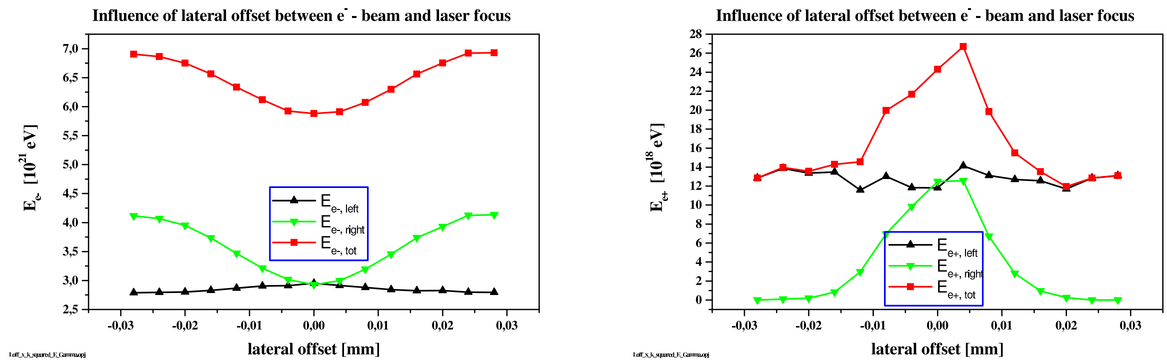

Figure 5: Left : Electron energy as a function of the offset of the laser beam. Right: Positron energy as a function of the offset of the laser beam.

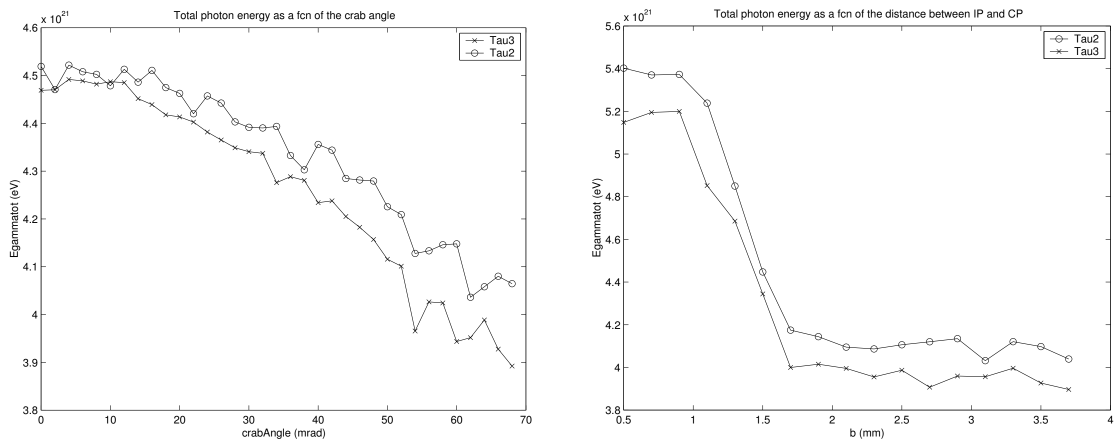

Figure 6: Left: $E_{\gamma,tot}$ vs. crab angle. Right: $E_{\gamma,tot}$ vs. b.

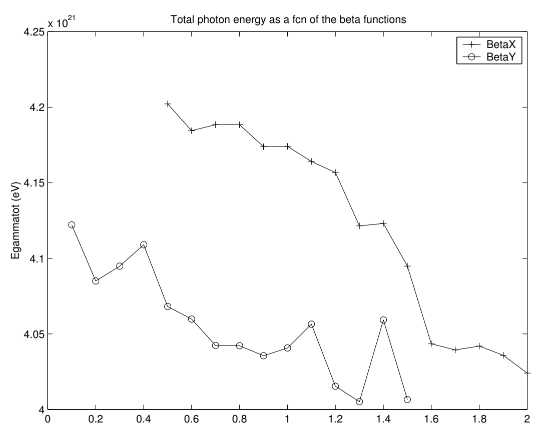

Figure 7: Combination of the graphs of β_x and β_y.