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Fast Luminosity Measurement and Beam Parameter Determination

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Abstract

The creation of beamstrahlung at the interaction region will be a new phenomenon at the International Linear Collider. The energy depositions from beamstrahlung and incoherent pairs can be analyzed by suitable detectors to obtain information about the beam parameters. The analysis of the energy deposition on a calorimeter near the beam pipe allows to reconstruct the parameters of the particle bunches and to measure the luminosity bunch by bunch. The necessary systems have been optimized and designs for different beam crossing angles of the ILC have been developed. First results from a full Geant4 simulation are shown. GamCal, a new system for measuring the energy of beamstrahlung photons, is able to provide additional, beneficial information about the collision.

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1 Introduction

At the *International Linear Collider* electron and positron bunches will be brought into collision with a center of mass energy of up to 500 GeV in the first step and up to 1 TeV after an upgrade. The physics goals require a high luminosity of about $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is achieved by a small beam cross section and high intensities of the colliding beams. Ideally the luminosity $\mathcal{L}$ can be calculated by

$$\mathcal{L} = H_D \frac{N^2 n_b f_r}{4\pi\sigma_x\sigma_y}, \tag{1}$$

where N is the number of particles per bunch, n_b is the number of bunches per train and f_r is the repetition frequency of the bunch trains. The variables σ_x and σ_y are the beam sizes in horizontal and vertical direction. They are in the nanometer range and a Gaussian particle distribution within the bunch is assumed. H_D is the luminosity enhancement factor due to the pinch effect with $H_D > 1$ for colliding beams of opposing charge. The downside of the pinch effect is the creation of beamstrahlung due to the deflection of the particles. The beam parameters of the ILC are carefully chosen to keep the amount of created beamstrahlung low. For the nominal beam parameter set defined in Ref. [1] the energy loss due to beamstrahlung is about 2 %. The interaction of the beamstrahlung photons leads also to the creation of electron–positron pairs by coherent and incoherent pair production. The deflection of these pairs by the bunch scatters a considerable fraction of them into the ILC detectors. The detector systems have to be able to cope with the pairs as background. However one can use beamstrahlung and pairs originating from beamstrahlung as a benefit: The luminosity as given in Equ. 1 assumes perfect conditions of the collision. Deviations from the ideal collision have to be kept small and a careful alignment of the nanometer scale beams has to be guarantied. The conventional procedure is using beam position monitors (BPMs) and fast kickers to apply a position and angle correction to compensate offsets and residual vibration induced jitters on the final focus system. The BPMs are not delivering the complete information about the beam properties during the collision itself. However the beamstrahlung offers the unique possibility to obtain a fast measure of beam parameters like beam sizes, emittances, beam intensities and the instantaneous luminosity. An electromagnetic calorimeter, BeamCal, in the very forward region of the ILC detectors is hit by the beamstrahlung pairs and can be used for that purpose. GamCal is a system designed to measure the energy of the beamstrahlung photons, which provides additional independent information.

2 Geometry of the Very Forward Region

The first design of the very forward region was based on the detector concept for the TESLA accelerator [2]. For TESLA a head-on collision of the approaching beams was planned with the use of fast kickers to extract the beam after the collision. To simplify the extraction scheme of the beam for the ILC a crossing angle between the beams is the baseline design. The major distinction is into small crossing angles like 2 mrad and large crossing angles of 14 mrad and more. A crossing angle of 14 mrad is the choice for the baseline configuration of the ILC [3]. The Large Detector Concept (LDC) is one of the detector concepts for the ILC [4] and the very forward region is designed, as an example, for this concept, albeit it is also suitable for all other concepts. A sketch of the very forward region for the case of a 14 mrad beam crossing angle is shown in Fig. 1.

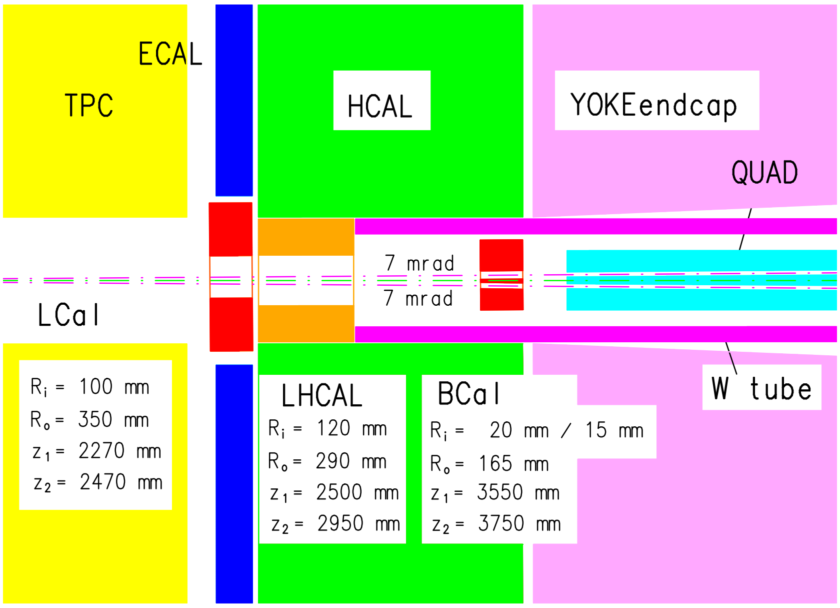

Figure 1: Very Forward Region of the Large Detector Concept for a 14 mrad beam crossing angle. TPC is the time projection chamber for track reconstruction, ECAL is the electromagnetic calorimeter in the end cap, HCAL is the hadronic calorimeter, YOKEendcap is the instrumented return yoke for the solenoid field, QUAD is the final quadrupole of the beam delivery system, which is enclosed by the tungsten beam pipe. LCal is the luminosity calorimeter, LHCAL is the low angle hadron calorimeter and BCal is the beam calorimeter.

The difference between the crossing angles is clearly visible when comparing the distribution of pairs from beamstrahlung as shown in Fig. 2. Using 2 mrad crossing angle as shown in Fig. 2(a) the distribution of pairs is concentrated around the beam pipe. Using large crossing angles the distribution of pairs is much more spread out. This is shown in Fig. 2(b) for a crossing angle of 20 mrad. The reason is mainly the magnetic field configuration of a DID[1]. The magnetic field is optimized for large crossing angles by adding a horizontal b-field component as described in [6]. In [5] the design of the very forward region of the ILC for a 20 mrad crossing angle case is discussed in more detail.

The implications for the very forward region are:

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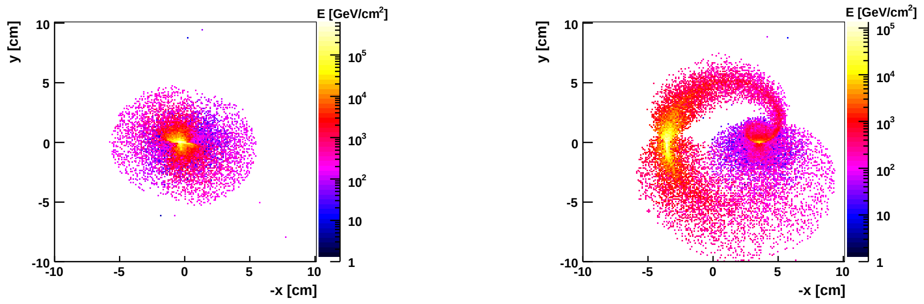
[1] Detector Integrated Dipole

- For small crossing angles: the minimal inner aperture of the BeamCal is about 20 mm, allowing to let pass the incoming and the outgoing beams through the same opening.

- For large crossing angles changes are necessary: to reduce systematic uncertainties in the luminosity measurement the LumiCal and the BeamCal must be centered on the outgoing beam axis and tilted correspondingly to face the interaction point (IP). The inner angular acceptance limit of LumiCal has to be enlarged from 26 to 44 mrad to prevent pairs from beamstrahlung hitting LumiCal. This would lead to a significant increase in the background in the inner detector [7]. The outer radius of BeamCal has to be enlarged to 165 mm to keep the angular coverage. The main geometric parameters are summarized in Tab. 1.

scheme	R_{in} [mm]	R_{out} [mm]	blind area
head-on	15	100	no
2 mrad	20	100	no
14 mrad	15/20	165	40°
20 mrad	15/20	165	30°

Table 1: Geometries of the BeamCal for different crossing angles. For a crossing angle larger than 14 mrad the two given inner radii specify the opening for the incoming/outgoing beam. A blind area of the given angular range is planned for the outgoing beams. Nevertheless the outer radius in this angular range will be instrumented.



(a) 2 mrad beam crossing angle and solenoid magnetic field of 4 T

(b) 20 mrad beam crossing angle and DID magnetic field of 4 T

Figure 2: Energy flux from beamstrahlung pairs produced in one bunch crossing after tracking through the magnetic field to the nominal BeamCal z-position.

The BeamCal is planned as a sandwich calorimeter which will be divided longitudinally into 30 layers of 1 X_0 each. To achieve the necessary compactness and a small Molière radius R_M, tungsten is chosen as the absorber material with a thickness per layer of 3.5 mm $\approx$ 1 X_0. The amount of absorbed energy in the sensors from beamstrahlung pairs is in the range of some MGy per year of operation (see also Sec. 4.2.2) and thus using a radiation hard sensor material is mandatory. Polycrystalline CVD[2] diamonds have been shown to withstand doses of electromagnetic radiation of several tens of MGy [8]. This material is available on wafer scale and its possible use for the BeamCal is under investigation. A thickness of 300 μm is assumed for the sensor. An interconnect layer of 200 μm thickness is assumed to be sufficient to route the sensors' signals to the outer radius of the calorimeter where the readout electronics will be situated.

3 Optimized BeamCal Segmentation

The granularity of the BeamCal has to be high to efficiently detect high energetic electrons or photons on top of the background from beamstrahlung pairs. On the other hand a fine granularity increases the total channel number, which is not only a cost driver but also determines the power dissipation and the produced data rates. It is therefore necessary to estimate the impact of a change in the pad size on the electron reconstruction. In Fig. 3 the inefficiency to reconstruct a 200 GeV electron is shown versus the pad size for two different regions of the calorimeter: for the region of high background in red (high inefficiency) and for the region of low background in blue (low inefficiency).

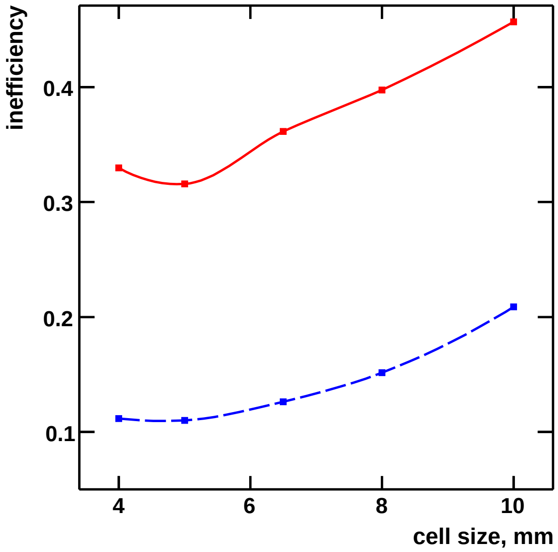


Figure 3: Inefficiency to reconstruct a 200 GeV electron in the BeamCal in two regions of different background [9].

The electron reconstruction efficiency of the BeamCal is optimal for a segmentation corresponding to 0.5 R_M. This segmentation would lead to channel numbers of $\approx$ 3000

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[2] Chemical Vapor Deposited

channels per layer. For the purpose of beam diagnostics a coarse segmentation of 0.8 R_M is assumed, which leads to a channel number of about 1500 channels. This results still in a reasonable electron reconstruction efficiency. Details about this analysis can be found in [9].

4 Fast Luminosity Monitoring and Beam Parameter Reconstruction

The energy deposition from electron–positron pairs originating from beamstrahlung is a background to the electron reconstruction but it can, however, be used to determine properties of the colliding beams and to tune the collision. This task can be divided in:

- to provide a real–time signal of the instantaneous luminosity with a low latency. The specifications are that the signal should be available within a few bunch crossings after the specific collision, which is a time scale of about $1\,\mu$s. The signal should furthermore be roughly proportional to the luminosity. An either analog or digital signal can be fed into the beam steering system FONT [10, 11]. It has been shown in Ref. [12] that the inclusion of such a signal into the feedback system is able to increase the overall luminosity by 10 to 15 %.

- The fast beam parameter reconstruction. The spatial distribution of the energy deposition from beamstrahlung pairs contains a lot of information about the parameters of the colliding bunches, which are: beam sizes $\sigma_{x,y,z}$, emittances $\varepsilon_{x,y}$, offsets $d_{x,y}$, waist shifts $W_{x,y}$, angles $\alpha_{h,v}$, rotation ϕ_l and beam intensities respectively the number of particles per bunch N_b. A set of observables is defined from the spatial energy deposition in the BeamCal. As the dependences of the observables on variations of the beam parameters are too complicated to be solved analytically a fast beam parameter reconstruction algorithm is needed [13].

4.1 Fast Luminosity Measurement

Possible signals which can be provided to the beam feedback system are:

- the number of pairs originating from beamstrahlung which hit the acceptance region of BeamCal. The number of pairs is proportional to the electronics signal of a preshower sensor layer, which is placed before the first absorber layer of the BeamCal.

- the energy of the pairs originating from beamstrahlung. For the precise measurement of the energy all the sensor layer signals have to be readout and summed up. A reduced readout of some layers in the range of the shower maximum (around layer 6) could be an alternative.

- The energy of the beamstrahlung photons. For the measurement of the beamstrahlung photon energy another detector subsystem, the GamCal, will be developed. The GamCal will be able to measure at least a part of the beamstrahlung photon spectrum.

Each of these possible measurements can provide valuable information about the collision and can serve as input for the luminosity optimization as described in Section 4. Combinations of the measurements are proved to be even more powerful. However, the feedback system FONT has to be supplied with an appropriate processed input signal within the allowed latency of about $1\,\mu$s including signal delays by cabling.

In Fig. 4 a first scheme for the technical implementation is shown. The preamplifier and shaper part has to be fast enough for a bunch–to–bunch operation. Different gains serve as a calibration mode using signals of minimum ionizing particles, mips, and as the standard operation mode where signal sizes up to 10^4 mips are expected. A circuit for external charge injection allows the cross calibration of the two modes. If a dynamic dual gain operation is needed the shaper part could be implemented as a dual stage with different gains. A first analog buffer can be implemented so that the following digitization can be done during the next bunch crossing.

Digitization and the read out link are the critical aspects for the BeamCal electronics. In [14] it was shown that for the highly efficient electron veto capability a digital resolution of 10 bit is needed. The digitization of about 10^5 channels per bunch crossing will be a challenge. If the full data is read out in real time gigabit-links are necessary, which are constrained by the available space and power and might be harmed by electromagnetic interference by the beam.

The off-detector part has to be able to store the data of a full bunch train, which is of the order of a few 100 Mbyte or up to 1-2 Gbyte for a 150 ns operation and a high segmentation. At least part of the data, will be used to serve for the fast luminosity feedback. As this has to be in real time the data will be fed directly from the detector to a dedicated processor. DSP's or FPGA's will be able to process the data and feed a digital information to the feedback system FONT. The total time budget is of the order of a few bunch crossing (about $1\,\mu$s) including wiring. The development of the electronics and the production of prototypes will be a focus of the FCAL collaboration in the next years. More details on the estimation of the data rates can be found [15].

4.2 Beam Parameter Determination

Our efforts have concentrated on the investigation of the implications by the recent changes in the geometry and the feasibility of the reconstruction algorithm presented in [13]. Firstly we investigate on the level of a simplified simulation and in 2006 we developed a standalone simulation of the forward region based on the GEANT4 libraries. The possibility of using more sophisticated fitting routines for the offline reconstruction of beam parameters has been investigated in [16].

For either version we use the Monte-Carlo software Guineapig [17] for the simulation of the beam–beam interaction and the creation of beamstrahlung photons and pairs.

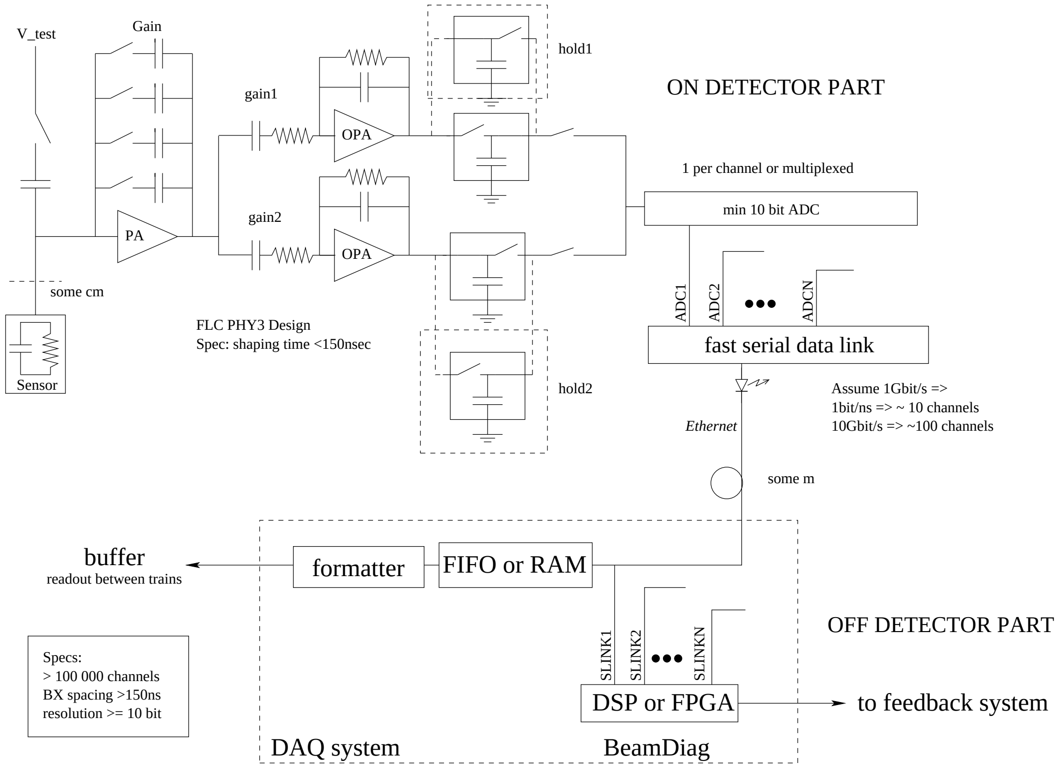


Figure 4: Schematic overview of the readout concept for BeamCal.

4.2.1 Simplified Simulation

The simplified simulation uses a Fortran based code to track the particles created at the interaction point to the z-position of the BeamCal front face. A constant magnetic field is assumed without any inhomogeneities or misalignments. The acceptance area of the BeamCal is used with a realistic segmentation. For each segment of the BeamCal the sum of the energies of the particles hitting the segment is used for further observable determination. Crossing angles have been implemented by simulating a head-on collision and Lorentz-boosting the created particles accordingly. This scheme is generally agreed to produce results comparable to a collision with crossing angles using a crab cavity like system to compensate for the luminosity loss. For large crossing angles the possibility of using the *Detector integrated Dipole* magnetic field configuration is approximated by rotating the magnetic field vector according to half of the crossing angle toward the incoming beam (DID) respectively the outgoing beam (Anti-DID).

The results for a single parameter analysis using the simplified simulation for the different accelerator designs are summarized in Tab. 2. The resolution is the spread (σ) of the results of 30 events at nominal beam parameters by using the beam parameter reconstruction method based on the Moore-Penrose inverted Taylor matrix of 1^{st} order as described in [13].

The results given in table 2 show the feasibility of the algorithm also for the updated geometry and the different designs. The reconstruction of two and more parameters

beam			2 mrad	20 mrad		14 mrad	
parameter	unit	nominal		DID	Anti-DID	DID	Anti-DID
σ_x	nm	655	2.0	3.0	2.3	3.4	2.3
$\Delta\sigma_x$	nm	0	6.5	8.4	5.2	8.6	5.0
σ_y	nm	5.7	0.4	0.5	0.4	0.5	0.2
$\Delta\sigma_y$	nm	0	0.4	0.3	0.5	0.5	0.5
σ_z	μm	300	4.6	4.8	4.1	5.1	4.1
$\Delta\sigma_z$	μm	0	4.9	8.5	5.4	8.2	5.5
ε_x	mm mrad	10	7.6	9.1	—	—	—
$\Delta\varepsilon_x$	mm mrad	0	5.1	—	—	—	1.7
ε_y	μm mrad	40	1.3	1.0	1.2	1.2	1.2
$\Delta\varepsilon_y$	μm mrad	0	11.2	3.7	8.4	7.4	15.8
d_x	nm	0	14.2	8.3	12.1	9.2	10.7
d_y	nm	0	0.7	1.2	0.6	0.8	0.7
W_x	μm	0	—	—	—	—	—
W_y	μm	0	24	17	26	19	25
α_h	mrad	0	0.12	0.05	0.16	0.04	0.16
$\Delta\alpha_h$	mrad	0	0.12	0.03	0.18	0.03	0.11
α_v	mrad	0	0.02	0.02	0.02	0.02	0.02
$\Delta\alpha_v$	mrad	0	0.02	0.02	0.01	0.02	0.01
ϕ_l	mrad	0	11.0	—	3.8	11.8	—
$\Delta\phi_l$	mrad	0	1.2	4.4	1.1	3.0	1.9
N	10^{10}	2.0	0.01	0.01	0.01	0.01	0.01
ΔN	10^{10}	0	0.01	0.03	0.01	0.03	0.01

Table 2: Precision of the beam parameter reconstruction for small and large crossing angles (with DID and Anti-DID like magnetic field). Each beam parameter is given as average and difference of the two beams.

simultaneously is possible with a moderate loss of precision. The 1^{st} order Taylor expansion is used to describe the correlation between beam parameters and observables. The entries of the Taylor matrix normalized to sigmas are shown in Fig. 5. One notes that the definition of observables has still potential for improvements, e.g. for the definition of the observables T1 and T2 [18]. One can also note the small number of significant observables for the reconstruction of the emittances.

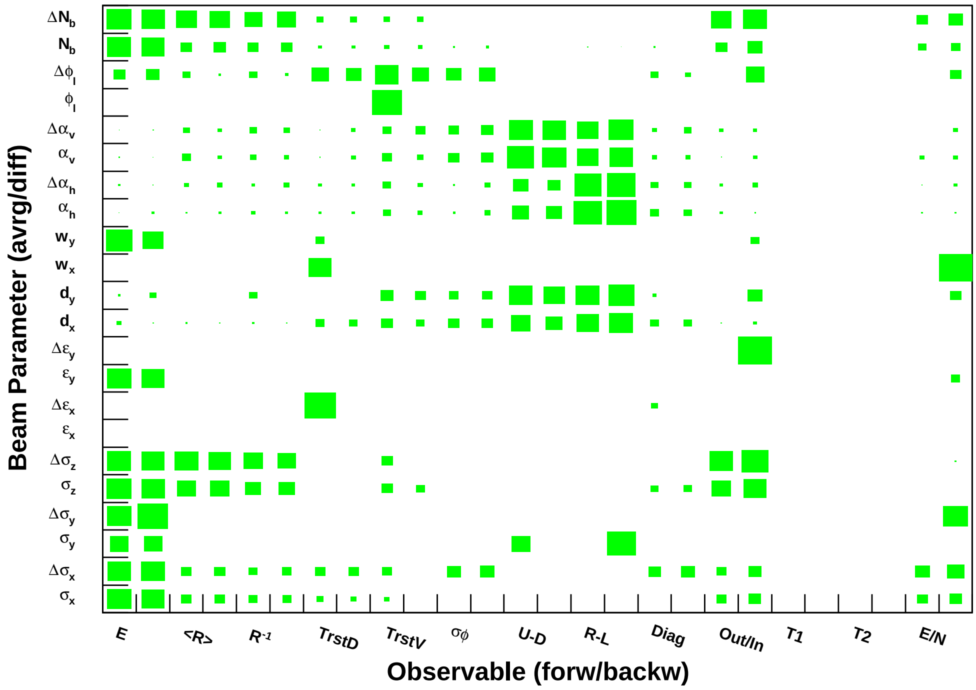


Figure 5: Significance of observables when reconstructing beam parameters. Entries are normalized to sigmas and represent the entry in the Taylor matrix. The definition of the observables can be found in [13]

4.2.2 BeCaS - Geant4 Simulation of the BeamCal

The standalone simulation BeCaS is based on the GEANT4 library package [19] and features a detailed material description as described in Sec. 2 of the BeamCal, a LumiCal mock-up, a graphite shield to reduce backscattering and a mock-up for the final quadrupole of the beam delivery system. A first sensor layer is positioned in front of the graphite shield. The signal of the sensors in this layer is proportional to the number of pairs hitting BeamCal, as no showering occurred so far. Different segmentations, beam crossing angles and magnetic field configurations are implemented in BeCaS as well. One of the major advantages compared to the idealistic simulation is the realistic development of the electromagnetic shower in the detector, while the simulation is fast enough to compute several hundred input files for the beam diagnostics algorithm. The energy deposition in each sensor cell is recorded by the simulation. As an example one can use this information to estimate the ionizing dose expected for the sensors. This is shown in Fig. 6 for the case of a 20 mrad crossing angle and DID magnetic field configuration assuming a 100 % operation time per year. The maximal dose is 3.3 MGy/a and it is accumulated by the sensors close to the beam pipe.

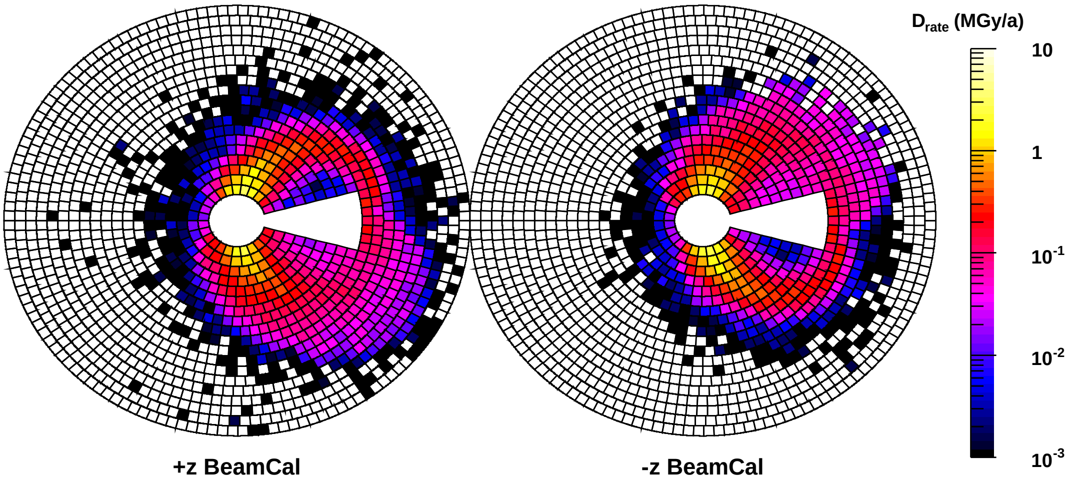


Figure 6: Expected ionizing dose per year of BeamCal. This case is for a 20 mrad beam crossing angle and DID magnetic field configuration. The running time of the accelerator is assumed to 100 %.

Another standalone program is used to calculate the observables and to write out the data for further computation with the beam parameter reconstruction software. At the moment only a reduced set of observables is used (8 out of 13). The simulation data includes now also the longitudinal information about the shower profile, which can be used for the definition of additional observables to improve the beam diagnostics. On the other hand it is also interesting to know which minimal set of information is sufficient to reconstruct the beam parameters.

As an example of our current investigation Fig. 7 shows the resolution for the reconstruction of the bunch length σ_z in μm when only the energy depositions of one or two sensor layers are considered. When using the full detector information one is able to reconstruct the bunch length with 7.8 μm. Using the reduced information of only one or two layers a similar resolution can be achieved. Layers around the shower maximum (layer 5-10) show the best resolution.

This result is an important aspect for the further development of the readout architecture as the amount of information which has to provided for the beam diagnostics can be significantly reduced.

So far the realistic simulation has been performed using realistic magnetic field configurations for the 2 and 20 mrad crossing angle case. In the next steps the study will be

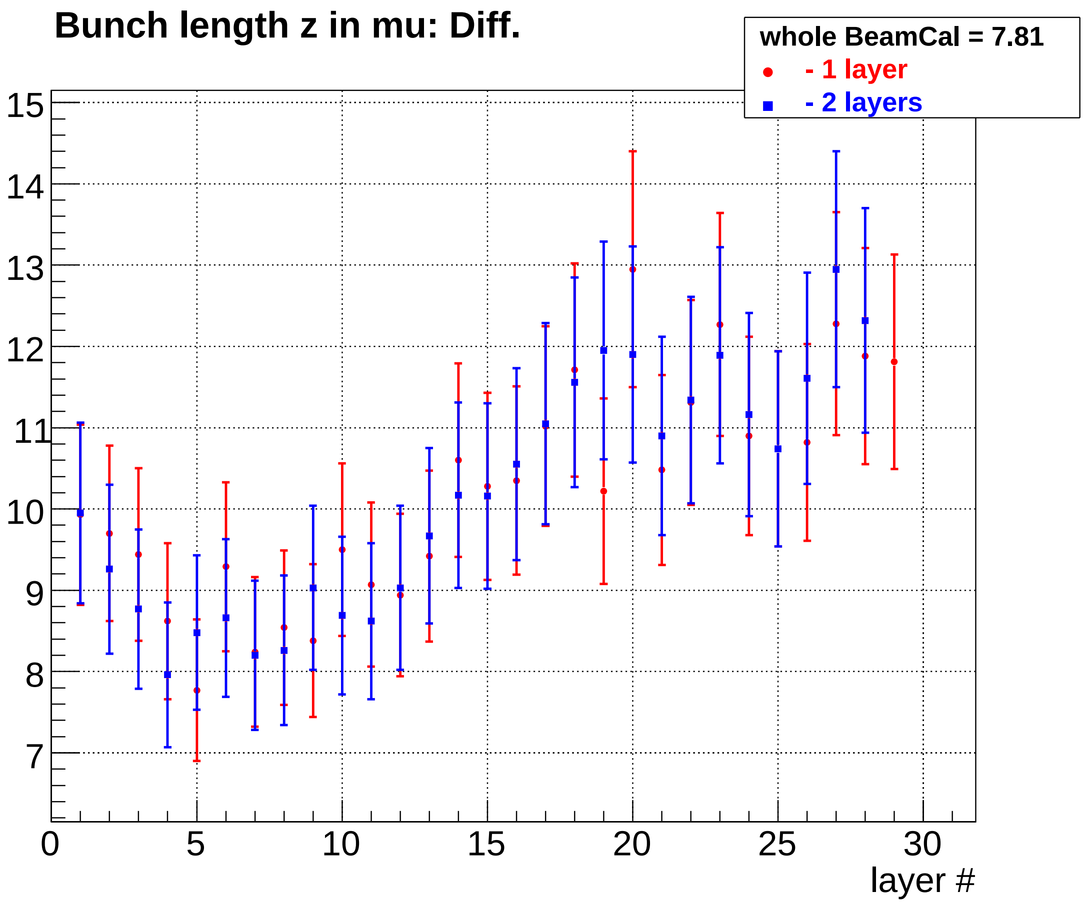


Figure 7: Precision of the reconstruction of the bunch length σ_z for using only the energy information of one or two layers of BeamCal as a function of the layer number.

extended and done for the current baseline of 14 mrad. The effect of digitization will be studied also.

4.3 Analysis of Beamstrahlung Photons

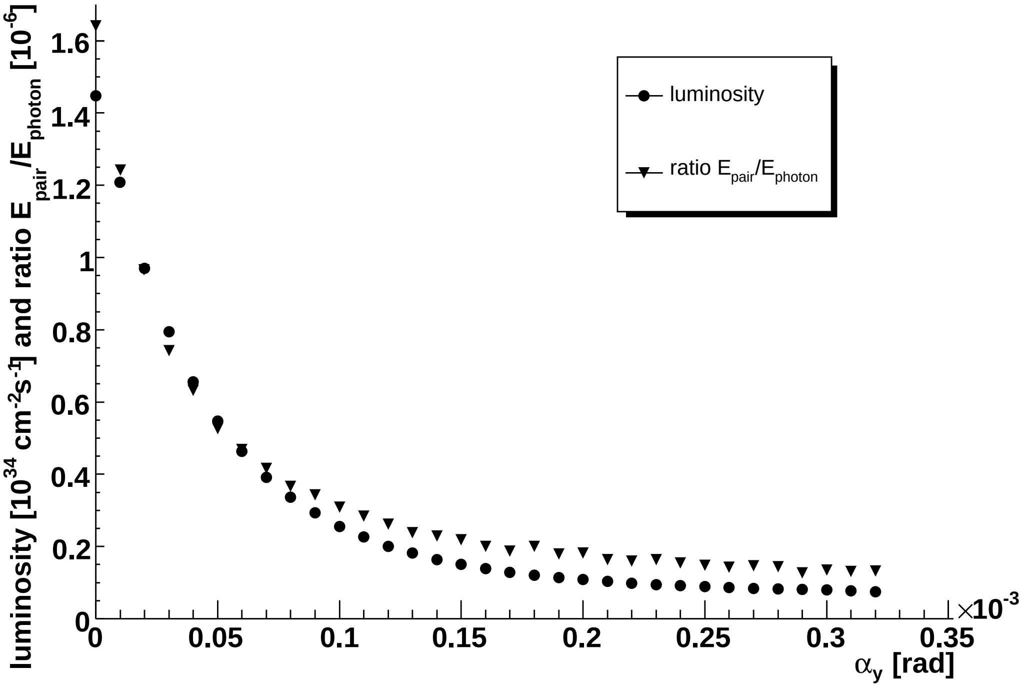
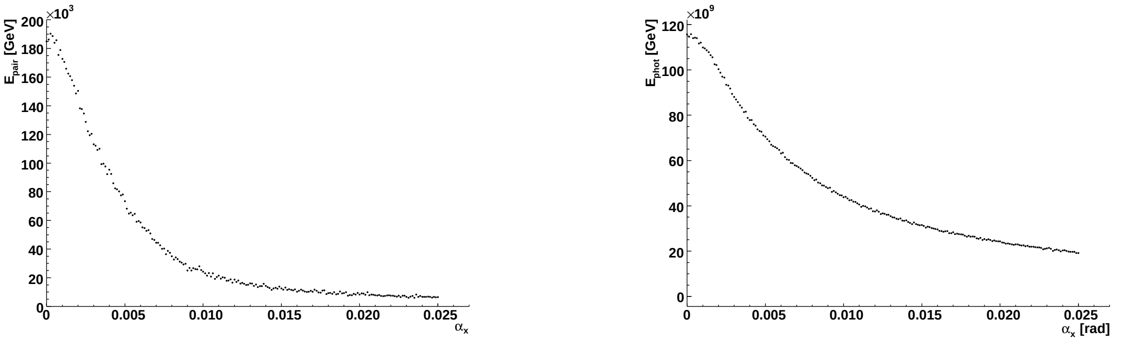


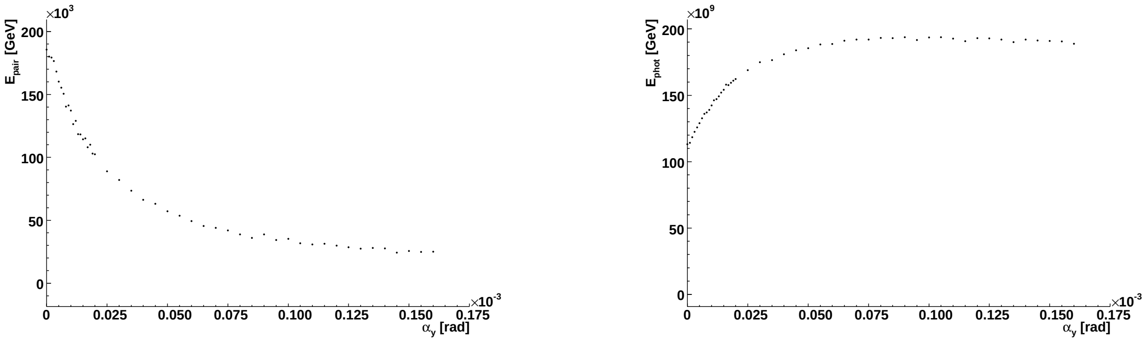
Figure 8: A normalized plot of the luminosity and E_{pair}/E_{photon} as functions of the vertical pivot angle α_y.

The analysis of beamstrahlung photons offers the possibility of achieving an independent source of information about the collision. The necessary system, GamCal, is under investigation by the FCAL Collaboration. The placement of a thin target in the extraction beam line seems the most promising option. The generation of electron-positron pairs in the target is dominated by the beamstrahlung photons. A deflection magnet is used to extract the part of the generated particles with a charge opposite to the one of the accompanying beam. The deflected particles' spectrum will be measured in a dedicated electromagnetic calorimeter. GamCal is supposed to be built in the beam line about 100 to 150 m downstream from the interaction point. Further studies are ongoing.
As shown in [20] a quantity like the ratio of the total energy of the pairs from beamstrahlung over the energy of the beamstrahlung photons $\frac{E_{pair}}{E_{photon}}$ is almost proportional to the luminosity. The dependence of the quantity $\frac{E_{pair}}{E_{photon}}$ is shown in Fig. 8 as a function of the vertical pivot angle α_x. This angle is defined as the rotation in vertical direction



(a) The total pair energy, E_{pair}, as a function of α_x.

(b) The total photon energy,E_{photon}, as a function of α_x.



(c) The total pair energy, E_{pair}, as a function of α_y.

(d) The total photon energy, E_{photon}, as a function of α_y.

Figure 9: Total pair and photon energy as function of the horizontal and vertical pivot angle α_x and α_y.

of the particle bunch with respect to it's optimal orientation for maximal luminosity. The quantity is therefore very interesting for the optimization of the collision.

The luminosity is very sensitive to the control of both pivot angles. An interesting aspect of the use of the energy from beamstrahlung photon as additional source of information, is the potential to distinguish between variations of beam parameters from their nominal values e.g. of the two pivot angles. In Fig. 9 the dependence of the total energy of photons and pairs on the deviation of the pivot angles from their nominal value is shown. The increase of the total photon energy for a non-optimal vertical pivot angle in Fig. 9(d) gives a clear signature compared to changes of the horizontal pivot angle shown in Fig. 9(b). In contrast to this behaviour the pair energy decreases for both cases as shown in Fig. 9(a) and Fig. 9(c).

5 Conclusion

Two calorimeters in the very forward region, BeamCal and GamCal deliver information about the collision parameters. They can provide a fast luminosity feedback signal which can be used to optimize the collision and to increase the overall luminosity. A detailed analysis of the energy deposition of pairs originating from beamstrahlung and from beamstrahlung photons offers the possibility to reconstruct parameters of the colliding beams. This can be used for further optimization. The performance of the beam parameter reconstruction has been investigated for small and large beam crossing angles with the corresponding geometry of the forward region and using different magnetic field configurations. Apart from the simplified simulation a dedicated Geant4 simulation has been developed. First results show comparable results and they indicate the feasibility of using only a reduced set of information of BeamCal without major degradation. The studies continue with a focus on the requirements of the hardware development which is pursued by the FCAL Collaboration.

Acknowledgement

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