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Fast and precise luminosity measurement at the international linear collider

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Abstract. The detectors of the ILC will feature a calorimeter system in the very forward region. The system comprises mainly two electromagnetic calorimeters: LumiCal, which is dedicated to the measurement of the absolute luminosity with highest precision and BeamCal, which uses the energy deposition from beamstrahlung pairs for a fast luminosity measure and the determination of beam parameters. The FCAL system is designed as a universal system fitting all detector concepts. It was implemented and simulated as a subsystem of the *large detector concept* [1]. The studies are carried out within the FCAL collaboration.

Keywords. International linear collider; forward calorimetry; beamstrahlung; forward region; LumiCal; BeamCal; luminosity; beam diagnostics.

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1. Introduction

To reach the necessary high luminosity at the international linear collider, smallest beam sizes and a very high bunch charge are needed. The high electromagnetic fields inside and near the bunches lead to a deflection of the particles when the bunches cross. This so-called pinch effect enhances the effective luminosity but also causes an energy loss by the radiation of photons – the beamstrahlung. Using flat beams ($\sigma_x/\sigma_y > 100$) is a measure to minimize the amount of beamstrahlung. A fraction of the photons generates electron–positron pairs. The pairs are deflected by the bunch charge and are captured in the magnetic field of the ILC detectors. The very forward region is hit by these pairs and has to be designed accordingly to minimize the amount of backscattered particles. Other requirements on the functionality of the forward region are:

- The extension of the sensitive volume of the ILC detector to lowest angles. The electron veto capability in the range of several mrad is especially interesting in certain SUSY scenarios [2].

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- The precise determination of the total luminosity by measuring the number of produced Bhabha events in a certain angular interval. The LumiCal has been designed for this purpose.
- The fast investigation of the collision quality for intrabunch feedback and the determination of beam parameters. BeamCal will be hit by a large amount of pairs from beamstrahlung. The amount and spatial distribution of the energy deposition from them will be used for this purpose.

LumiCal and BeamCal are compact electromagnetic sandwich calorimeters using tungsten as an absorber and silicon as a sensor. For the inner part of the BeamCal a sufficiently radiation hard material like polycrystalline CVD diamonds is foreseen. In the current design each calorimeter is segmented longitudinally into 30 layers consisting of the sensor, the absorber and an interconnection structure.

2. Layout of the forward region for LDC

The layout of the forward region [3] of the large detector concept (LDC) is shown in figure 1 for a small crossing angle of 2 mrad for the two colliding beams. The LumiCal is located at $z = 2270$ mm completely outside the HCAL end cap. This scheme offers a simplified opening procedure to reach the inner detector. The LumiCal covers a polar angle range between 26 and 155 mrad. The BeamCal covers smallest polar angles between 5.6 and 28 mrad.

The layout for the case of a larger crossing angle of 20 mrad between the two beams is similar. However, LumiCal and BeamCal must be centered along the outgoing beam creating a tilt of 10 mrad with respect to the detector axis. The studies justifying this change are shown later. The inner radius of LumiCal is increased to 100 mm to avoid pairs hitting the inner edge of LumiCal and the outer radius of BeamCal is increased to keep the angular overlap. A small not instrumented area in the BeamCal r–ϕ plane is needed at the position where the incoming beam enters the detector. In table 1 the major parameters of the two layouts are summarized.

3. The luminosity calorimeter – LumiCal

The precise determination of the luminosity at the ILC is necessary for the calculation of cross-sections. The desired precision on the luminosity $\Delta\mathcal{L}/\mathcal{L} \approx 10^{-4}$, is a challenging task. Bhabha events counted in the acceptance region of LumiCal offer the necessary statistics and a well-known theoretical description.

A source of background are two-photon events. Four-lepton processes, $e^-e^+ \rightarrow e^-e^+l^-l^+$ ($l = e, \mu, \tau$), have been studied. In these events the beam electrons are typically scattered under small polar angles carrying most of the energy. The remaining leptons are spread over the whole polar angle range and can also hit the LumiCal acceptance region. Figure 2 shows the energy and angular distributions of the electrons from the four-fermion processes scattered into LumiCal and BeamCal.

Results from different generators and simulation packages [4] show that the rate of four-lepton events found in the LumiCal acceptance region is approximately a

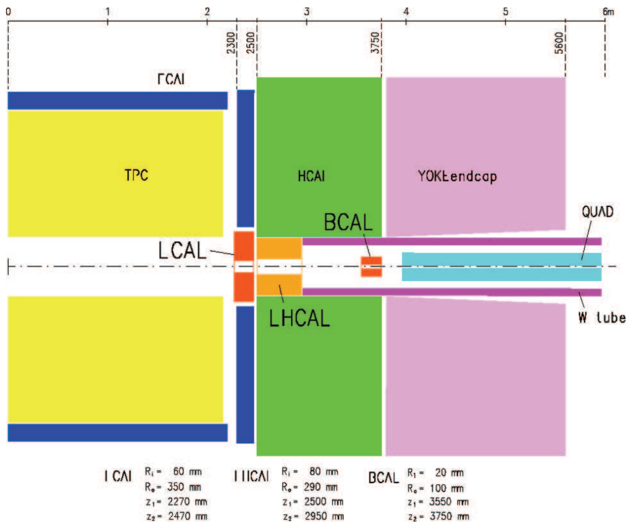

Figure 1. Layout of the forward region of the LDC for a crossing angle case of 2 mrad. LCal denotes LumiCal and BCal denotes BeamCal. Other visible parts of the LDC are the hadronic end cap (HCAL), the electromagnetic calorimeter (ECAL), the time projection chamber (TPC), which is the main tracker of LDC, a low angle hadronic calorimeter (LHCAL) and the instrumented iron end cap yoke (YOKEendcap). Also shown is the tungsten beam tube supporting the final focus quadrupole (QUAD).

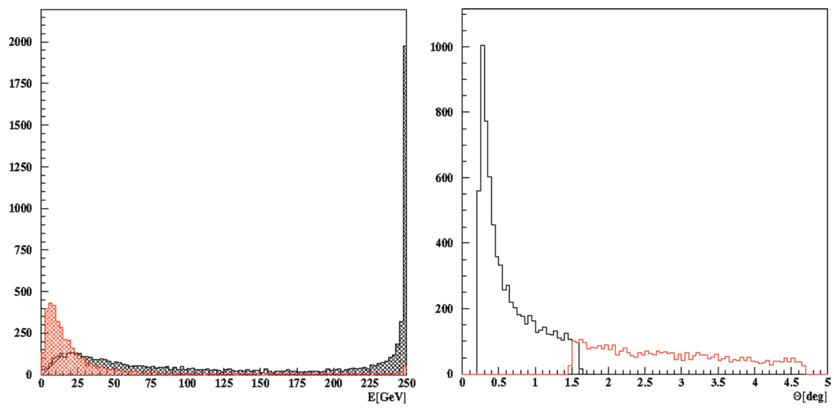

Figure 2. Four-fermion processes: energy (left) and polar angle distribution (right) of electrons. Hits in the acceptance region of BeamCal are shown in black and of LumiCal in red.

factor of 10 lower than the Bhabha occupancy. It is therefore necessary to reject the background events efficiently. By defining the following cuts: an acolinearity cut $|\Delta\theta| < 8$ mrad, an acoplanarity cut $|\Delta\phi| < 5°$ and a relative energy cut $(E_\mathrm{L} + E_\mathrm{R})/2E_\mathrm{beam} > 0.75$, a rejection rate of 10^4 can be achieved, while preserving 98% of the signal. A harder definition of the cuts can improve the signal-to-background

Table 1. Geometrical parameters of the very forward region in the LDC design. The two values of R_i for BeamCal in the 20 mrad case correspond to the radii of the holes for the beam pipe for the incoming/outgoing beam.

		LumiCal		BeamCal	
Parameter	Unit	2 mrad	20 mrad	2 mrad	20 mrad
z-position	mm	2270	2270	3550	3550
Length	mm	200	200	200	200
Tilt	mrad	1	10	1	10
R_i	mm	60	100	20	15/20
R_o	mm	365	365	100	165
ϕ_i	mrad	26	44	5.6	5.6
ϕ_o	mrad	155	155	28	46

ratio even further, but this leads to a higher loss of the signal events of up to 20%. The studies are ongoing including all two-photon final states and a full detector simulation.

The required luminosity precision poses a major challenge on the mechanical precision of LumiCal. As an example our studies show that to reach a precision of $\Delta\mathcal{L}/\mathcal{L} = 10^{-4}$ the inner radius of the calorimeter has to be known with a precision of about 4 μm. A large crossing angle between the beams and its impact on the LumiCal performance has been studied recently. A sample of Bhabha events is generated with BHLUMI [5]. Energy and scattering angle cuts are applied first for the nominal settings. Then shifts of several geometry parameters are performed and the analysis is repeated. The effect on the luminosity is estimated as $\frac{\Delta\mathcal{L}}{\mathcal{L}} = \frac{\Delta N}{N} = \frac{N_\text{shift} - N_\text{nom}}{N_\text{nom}}$, where N_nom is the number of accepted events at the nominal position and N_shift is the number of accepted events after the parameter shift. In figure 3 is shown $\Delta\mathcal{L}/\mathcal{L}$ for a radial beam offset of 1 mm as a function of the azimuthal angle ϕ of the offset. Also shown is $\Delta\mathcal{L}/\mathcal{L}$ as a function of the azimuthal angle of a polar tilt of 100 mrad.

To minimize the ϕ-dependent systematic shifts the calorimeter is centered along the outgoing beam.

4. The beam calorimeter – BeamCal

BeamCal will be hit by about 10^4 pairs from beamstrahlung depositing about 10 TeV energy per bunch crossing. The energy deposition leads to a very high dose in the BeamCal ($\mathcal{O}(10^7)$ Gy per year) and makes the use of radiation-hard material mandatory.

The energy deposited in BeamCal can be used to obtain a very fast information on the quality of the collision. Compared to the signals from beam position monitors the BeamCal signal has the advantage of being dependent on the collision quality. It has been shown [6] that the achievable luminosity can be increased by including a fast luminosity signal in the feedback system. The simulation included as a fast

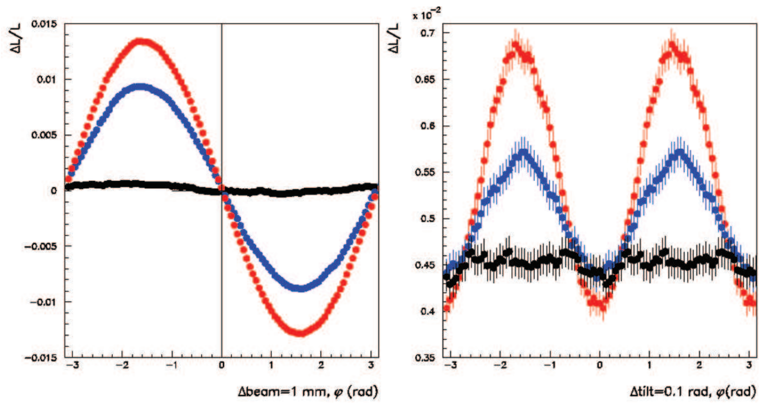

Figure 3. Relative shift in the luminosity as a function of the azimuthal angle of a beam offset of 1 mm (left) and of the azimuthal angle of a polar tilt angle of 0.1 rad (right). The cases are: LumiCal centered along the outgoing beam (black) and centered on the detector axis for a 14 mrad (blue) or 20 mrad (red) crossing angle [4].

signal the number of pairs deflected in the BeamCal acceptance region. This signal was fed into the feedback system FONT [7] and used to optimize the collision. An improvement of up to 12% was found for 500 GeV and standard beam parameter settings.

The energy deposition in the BeamCal can also be used to determine beam parameters [8]. A set of suitable observables like total energy, radial moment, asymmetries etc. is calculated from the spatial energy deposition at the BeamCal front face as shown in figure 4 for a 20 mrad and detector integrated dipole (DID), magnetic field configuration [9]. The dependence between the observables and the beam parameters is simplified using the first term of the Taylor expansion, resulting in a linear relation. Our analysis uses the Moore–Penrose matrix inversion method. The simulation is done for the different crossing angles and magnetic field configurations currently under discussion. Results for the precision of the beam parameter reconstruction are given in table 2.

The achieved precision is very high and only a minor degradation is found when changing from the 2 mrad to the 20 mrad layout. The reconstruction of multiple parameters is also feasible but results in a loss of accuracy. No showering in the detector has been used so far. To achieve a more realistic detector simulation a Geant4 simulation of the forward region is currently under development, which also uses a precisely parametrized magnetic field.

5. Summary and conclusion

The FCAL collaboration investigates the potential and the requirements of a calorimeter system in the very forward region of the ILC detectors. A measurement of the absolute luminosity with a precision of $\Delta\mathcal{L}/\mathcal{L} = 10^{-4}$ seems feasible. Four-fermion processes have been investigated as a physics background and a set of cuts

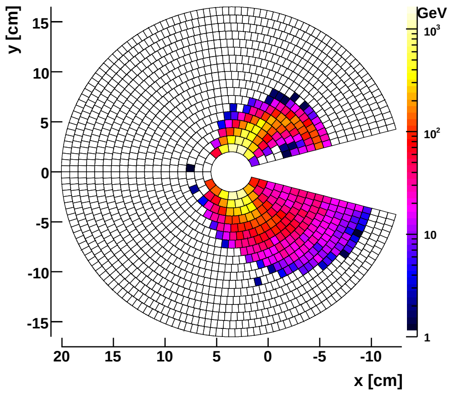

Figure 4. Energy flux from beamstrahlung pairs at the BeamCal z-position for a 20 mrad and DID field configuration (LDC coordinate system). An angular range of 40° is not instrumented in the region of the incoming beam.

Table 2. Precision of the reconstruction of selected beam parameters for 2 and 20 mrad crossing angle. The reconstruction of a single parameter and of two parameters simultaneously is given.

		Single parameter		Double parameter
Beam parameter	Nominal	2 mrad	20 mrad (DID)	20 mrad (DID)
σ_x	655 nm	3.1	2.9	2.8
$\Delta\sigma_x$	0 nm	5.2	7.4	7.6
σ_y	5.7 nm	0.3	0.2	0.2
$\Delta\sigma_y$	0 nm	0.3	0.4	0.4
σ_z	300 μm	4.8	8.5	11.1
$\Delta\sigma_z$	0 μm	3.7	6.3	7.4

has been shown to effectively reduce the background rate. To avoid a high systematic sensitivity to beam displacement and calorimeter tilts the LumiCal must be placed around the outgoing beam. Beamstrahlung pairs can be analyzed using the BeamCal, which allows a precise determination of beam parameters. In addition, the signal from these pairs can be used to tune the collision as part of the feedback system.

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