R&D for Very Forward Calorimeters at the ILC Detector

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Special calorimeters are needed to instrument the very forward region of an ILC detector. These devices will improve the hermeticity being important for new particle searches. A luminometer is foreseen to measure the rate of low angle Bhabha scattering with a precision better than 10^{-3}. A calorimeter adjacent to the beam-pipe will be hit by a large amount of beamstrahlung remnants. The amount and shape of these depositions will allow a fast luminosity estimate and the determination of beam parameters. However, the sensors must be extremely radiation hard. Finely segmented and very compact calorimeters will match the requirements. Due to the high occupancy fast FE electronics is needed. A possible design of the calorimeters is presented and an overview on the R&D status is given [1].

1 The Challenges

Two calorimeters are foreseen in the very forward region of the ILC detector near the interaction point - LumiCal for the precise measurement of the luminosity and BeamCal for the fast estimate of the luminosity [2]. Both will improve the hermeticity of the detector. A third calorimeter, GamCal, about 100 m downstream of the detector, will assist beam-tuning. Also for beam-tuning a pair monitor is foreseen, positioned just in front of BeamCal.

LumiCal will measure the luminosity using as gauge process Bhabha scattering, $e^+e^- \rightarrow e^+e^-(\gamma)$. To match the physics benchmarks, an accuracy of better than 10^{-3} is needed. For the GigaZ option even an accuracy of 10^{-4} is aimed [4]. Hence, LumiCal is a precision device with challenging requirements on the mechanics and position control. All detectors in the very forward region have to tackle relatively high occupancies, requiring special FE electronics and data transfer equipment.

BeamCal is positioned just outside the beam-pipe. A large amount of low energy electron-positron pairs originating from beamstrahlung will deposit their energy in BeamCal. These depositions, useful for a bunch-by-bunch luminosity estimate and the determination of beam parameters [3], will lead, however, to a radiation dose of several MGy per year in the sensors at lower polar angles. Hence extremely radiation hard sensors are needed to instrument BeamCal. A pair monitor, consisting of a layer of pixel sensors positioned just in front of BeamCal, will measure the distribution of beamstrahlung pairs and give additional information for beam parameter determination.

A small Moliere radius is of invaluable importance for both calorimeters. It ensures an excellent electron veto capability for BeamCal even at small polar angles, being essential to suppress background in new particle searches where the signatures are large missing energy and momentum. In LumiCal the precise reconstruction of electron and positron showers of Bhabha events is facilitated and background processes will be rejected efficiently.

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GamCal will be positioned about 100 m downstream and is foreseen to measure the amount and energy distribution of beamstrahlung photons. These are complementary informations to assist beam-tuning and determine beam parameters at the interaction point.

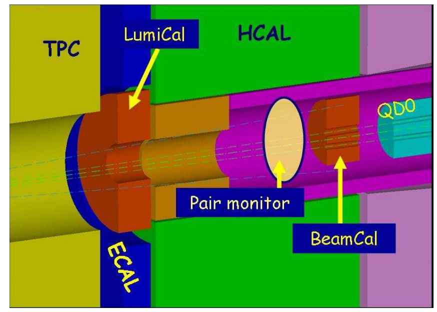

Figure 1: The very forward region of the ILD detector. LumiCal, BeamCal, Pair Monitor, and QD0 are carried by the support tube. TPC denotes the central track chamber, ECAL the elecromagnetic and HCAL the hadron calorimeter.

2 The Design of the Very Forward Region

A sketch of the very forward region of the ILD detector, as an example, is shown in Figure 1. LumiCal and BeamCal are cylindrical electromagnetic calorimeters, centered around the outgoing beam. LumiCal is positioned inside and aligned with the forward electromagnetic calorimeter. BeamCal is placed just in front of the final focus quadrupole.

2.1 LumiCal

Monte Carlo studies have shown that a compact silicon-tungsten sandwich calorimeter is a proper technology for LumiCal [5]. In the current design [6], LumiCal covers the polar angular range between 32 and 74 mrad. The 30 layers of tungsten absorber disks are interspersed with silicon sensor planes. The FE and ADC ASICS are positioned at the outer radius in the space between the disks. The small Moliere radius and finely radially segmented silicon pad sensors ensure an efficient selection of Bhabha events and a precise shower position measurement. The luminosity, $\mathcal{L}$, is obtained from $\mathcal{L} = \mathcal{N}/\sigma$, where $\mathcal{N}$ is the number of Bhabha events counted in a certain polar angle range and σ is the Bhabha scattering cross section in the same angular range calculated from theory. The most critical quantity to control when counting Bhabha events is the inner acceptance radius of the calorimeter, defined as the lower cut in the polar angle, as illustrated in Figure 2. Since the angular distribution is very steep, a small bias in the lower polar angle measurement will shift the measured value of the luminosity. From Monte Carlo studies of the given design a tolerance of a few μm is estimated for the inner acceptance radius [7]. Since there is bremsstrahlung radiation in Bhabha scattering, also cuts on the shower energy will be

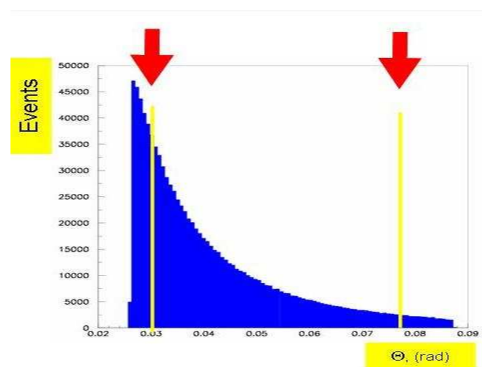

Figure 2: The polar angle distribution of Bhabha events in the LumiCal. The arrows indicate the acceptance region in the polar angle θ.

applied. The criteria to select good Bhabha events hence define requirements on the energy resolution and, more challenging, on the control of the energy scale of the calorimeter. The latter quantity must be known to about a few per mill [8]. Monte Carlo simulations are also used to optimise the radial and azimuthal segmentation of silicon pad sensors for LumiCal [5] to match the requirements on the shower position measurement performance.

A first batch of prototype sensors [9] is ordered from Hamamatsu Corp. These sensors will be available in spring 2009. At the first stage they will be studied in the laboratories. In a later stage, they will be instrumented with Front-End (FE) electronics for investigations in the test-beam and to prepare a calorimeter prototype for systematic performance studies. FE and ADC ASICS are designed with a shaping and conversion time less than 300 ns, being potentially able to readout the calorimeter after each bunch crossing. The range of sensor pad capacitance and the expected signal range in electromagnetic showers originating from Bhabha events are taken from Monte-Carlo simulations [10]. A prototype of the FE ASIC, manufactured in 0.35 μm AMS technology, is shown in Figure 3. The FE ASIC can be operated in low and high amplification mode. The high amplification mode allows to measure the depositions of minimum ionising particles. This option allows to use muons from the beam halo or from annihilations for the calibration and sensor alignment studies. The low amplification mode will be used for the measurement of electromagnetic showers. Tests of these ASICS prototype are ongoing in the laboratory [11]. Results on linearity, noise and cross talk measured in the laboratory are matching the requirements for the performance derived from Monte-Carlo simulations. For 2010 multi-channel prototypes of the ASICS are planned, allowing to instrument prototypes of sensor planes to investigate the performance of the full system in the test-beam. For the position monitoring a dedicated laser system is under development. A small scale prototype was designed and built [12] and the measured performance matches the requirements.

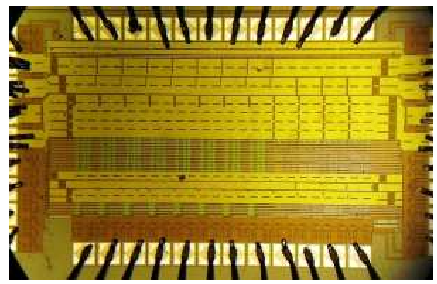

Figure 3: Prototypes of the FE ASIC prepared for systematic tests in the laboratory.

2.2 BeamCal

BeamCal is designed as a sensor-tungsten sandwich calorimeter covering the polar angle range between 5 and 40 mrad. The tungsten absorber disks will be of one radiation length thickness and interspersed with thin sensor layers equipped with FE electronics positioned at the outer radius. In front of BeamCal an about 5 cm thick graphite block is placed to absorb low energy back-scattered particles. BeamCal will be hit after each bunch-crossing by a large amount of beamstrahlung pairs, as shown in Figure 4. The amount, up to several TeV per bunch crossing, and shape of these deposition allow a bunch-by-bunch luminosity estimate and the determination of beam parameters [3]. However, depositions of single high energy electrons must be detected on top of the wider spread beamstrahlung. Superimposed on the pair depositions in Figure 4 is the local deposition of one high energy electron, seen as the dark or red spot at the bottom. Using an appropriate subtraction of the pair deposits and a shower finding algorithm which takes into account the longitudinal shower profile, the deposition of the high energy electron can be detected with high efficiency and modest energy resolution, sufficient to suppress the background from two-photon processes in a search e.g. for super-symmetric tau-leptons [13].

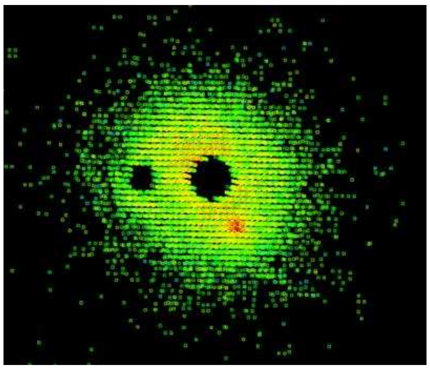

Figure 4: The distribution of depositions of beamstrahlung pairs after one bunch crossing on BeamCal. Superimposed is the deposition of a single high energy electron (dark or red spot in the bottom part). The black holes correspond to the beam-pipes.

The challenge of BeamCal are radiation hard sensors, surviving up to 10 MGy of dose per year. So far we have studied polycrystalline CVD diamond sensors of 1 cm^2 size, and larger sectors of GaAs pad sensors as shown in Figure 5. Polycrystalline CVD diamond sensors are irradiated up to 7 MGy and are still operational [14]. GaAs sensors are found to tolerate nearly 2 MGy [15]. Since large area CVD diamond sensors are extremely expensive, they may be used only at the innermost part of BeamCal. At larger radii GaAs sensors seem to be a promising option. These studies will be continued in future for a better understanding of the damage mechanisms and possible improvements of the sensor materials. The FE ASIC development for BeamCal, including a fast analog summation for the fast beam feedback system and an on-chip digital memory for readout in between two bunch trains [16] is progressing, and we may expect first prototypes in 2009.

3 The Pair Monitor

The pair monitor consists of one layer of silicon pixel sensors just in front of BeamCal to measure the distribution of the number of beamstrahlung pairs. Monte Carlo simulations have shown that the pair monitor will give essential additional information for beam tuning. In addition, averaging over several bunch crossings, e.g. the beam sizes at the interaction point might be reconstructed with per cent precision [17]. A special ASIC is developed for the pair monitor and prototypes are under study. In a later stage, the pixel sensor and the ASIC are foreseen to be embedded in the same wafer. The latter development will be done in SoI technology [18].

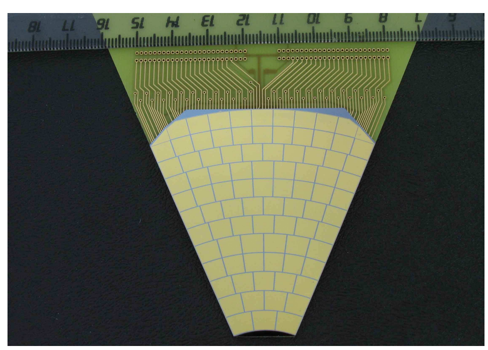

Figure 5: A prototype of a GaAs sensor sector for BeamCal with pads of about 0.3 cm^2 area.

4 GamCal

GamCal is supposed to exploit the photons from beamstrahlung for fast beam diagnostics. Near the nominal luminosity the energy of beamstrahlung photons supplements the data from BeamCal and Pair Monitor improving the precision of beam parameter measurements and reducing substantially the correlations between several parameters [3]. At low luminosity the amount of depositions on BeamCal might not be sufficient to assist beamtuning, however GamCal will still give robust information.

To measure the beamstrahlung spectrum a small fraction of photons will be converted by a thin diamond foil or a gas-jet target about 100 m downstream of the interaction point. The created electrons or positrons will be measured by an electromagnetic calorimeter. For the time being we have a rough design of GamCal. More detailed Monte Carlo studies are necessary to fully understand the potential of GamCal for beam tuning and beam parameter determination.

5 Priority R&D Topics for FCAL

The current research work covers several fields of high priority to demonstrate that the designed devices match the requirements from physics. These are:

- Development of radiation hard sensors for BeamCal. The feasibility of BeamCal depends essentially on the availability large area radiation hard sensors.
- Development of high quality sensors for LumiCal, integration of the FE electronics in a miniaturised version and tuning of the full system to the required performance.
- Prototyping of a laser position monitoring system for LumiCal. In particular the control of the inner acceptance radius with μm accuracy is a challenge and must be demonstrated.
- Development and prototyping of FE ASICS for BeamCal and the pair monitor. There are challenging requirements on the readout speed, the dynamic range, the buffering depth and the power dissipation. In addition, a scheme for data transfer to the back-end system has to be worked out.
- Design of GamCal and estimate of its potential for a fast feedback beam-tuning system.

6 Acknowledgments

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