Instrumentation of the very forward Region of a Linear Collider Detector

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***Abstract*— The very forward region of a linear collider detector is a particularly challenging area for instrumentation. For the TESLA project a luminometer (LAT) at small polar angles is forseen to perform a high precision (O(10^{-4})) luminosity measurement, requiring the control of the systematics on the corresponding level. Monte Carlo simulations to optimize the shape and the structure of the calorimeter are presented. A second calorimeter (LCAL) is positioned just adjacent to the beampipe. Into this device a large amount of beamstrahlung remnants, several ten TeV per bunch crossing, is scattered, resulting in an radiation dose of about 10 MGy per year. The distribution of the beamstrahlung has to be measured in order to assist in the tuning of the beams at the final focus. Furthermore, single hard electrons have to be measured, or at least vetoed. The latter is important, since events with high energetic electrons near the beampipe are a serious background in many search channels with missing energy and momentum. Monte Carlo simulations for a heavy crystal calorimeter and a diamond/tungsten sandwich structures are presented and compared. First results on sensor tests are given.**

***Index Terms*— Linear Collider, Luminosity Measurement, Beam Diagnostics, Radiation Hard Calorimeters.**

I. Introduction

The detector for TESLA is described in the Technical Design Report (TDR) [1]. In Figure 1 the current layout of the very forward region is shown with some details. Two calorimeters are proposed: the LCAL adjacent to the beampipe covering a polar angle range between 4 and 28 mrad and the LAT covering polar angles between 26 and 82 mrad.

II. Experimental Situation

The area of the LCAL is strongly affected by electrons or positrons originating from beamstrahlung photon conversions.

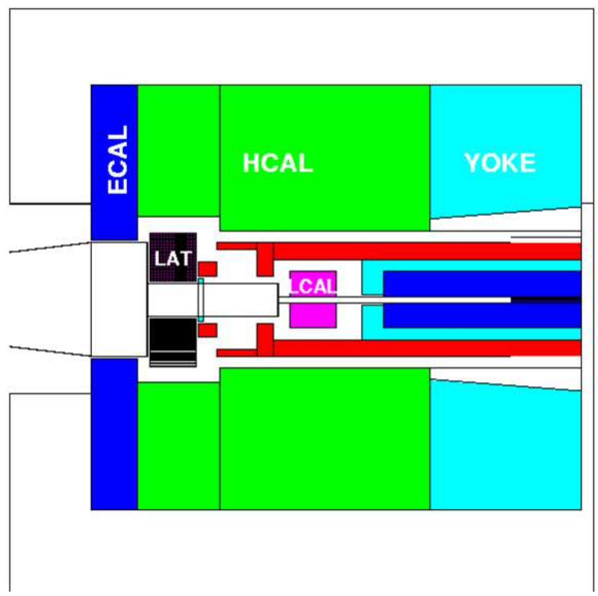

Fig. 1. The two forward calorimeters LCAL and LAT. The conical beampipe on the left points to the interaction region. Vertical and horizontal scales are different.

The deposited energy per bunch crossing in LCAL at $\sqrt{s}$ = 500 GeV is shown in Figure 2 as function of the distance from the beampipe and in the plane perpendicular to the beam direction. This distribution depends strongly on the beam parameters and has to be measured in order to support the beam tuning to maximal luminosity during accelerator operation. In addition, hard electrons from two-photon processes have to be

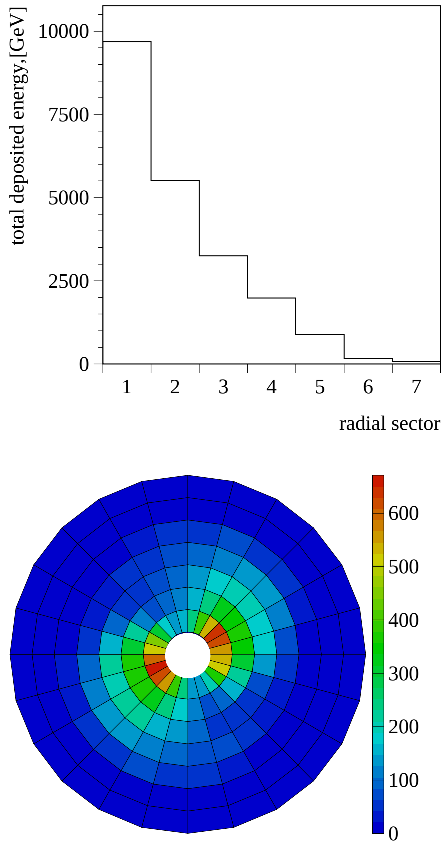

Fig. 2. The energy deposition in the LCAL induced by beamstrahlung remnants as function of the distance from the beam pipe (top) and in the plane perpendicular to the beam (bottom). The centre-of-mass energy is 500 GeV and standard machine parameter settings are used [1]. A radial sector corresponds to about 1 cm. The units on the right scale are GeV.

measured or at least vetoed to an as small as possible angle to the beam. The latter is important, since events with high energetic electrons near the beampipe (two-photon processes) are a serious background in many search channels with missing energy and momentum. Last but not least the calorimeter has to shield the central part of the detector against backscattered particles from downstream beam and beamstrahlung interactions. The depositions of beamstrahlung remnants integrate to a total dose of about 10 MGy/year, requiring radiation hard sensors.

III. Potential Technologies for LCAL

A high granularity is necessary in order to identify the depositions from individual high-energetic electrons and photons on top of the background from beamstrahlung remnants. The transversal granularity should not be larger than a Molière radius otherwise a large amount of beamstrahlung is integrated into the signal of a hard electron or photon and also position measurement becomes less precise.

A. *Silicon-Tungsten or Diamond-Tungsten Sandwich Calorimeter*

Silicon-Tungsten calorimeters were successfully used in LEP experiments [2]. The Molière radius is small, typically of the order of a centimeter, leading to very narrow showers for high energetic electrons. A possible structure of the calorimeter is sketched in Figure 3. It consists of two half-barrels placed just outside the beampipe. Between the tungsten disks diamond or

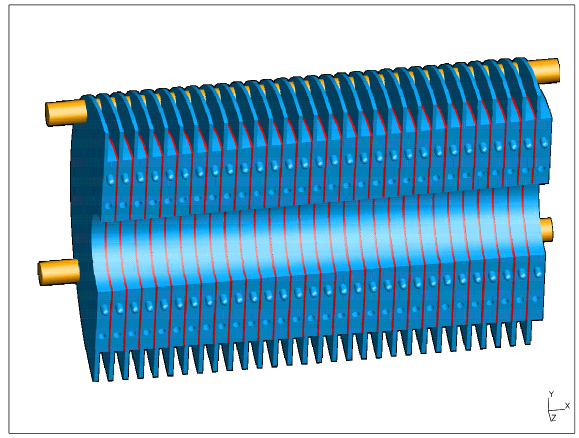

Fig. 3. The structure of a half barrel of the sandwich calorimeter. Between the tungsten disks diamond sensors are interspersed.

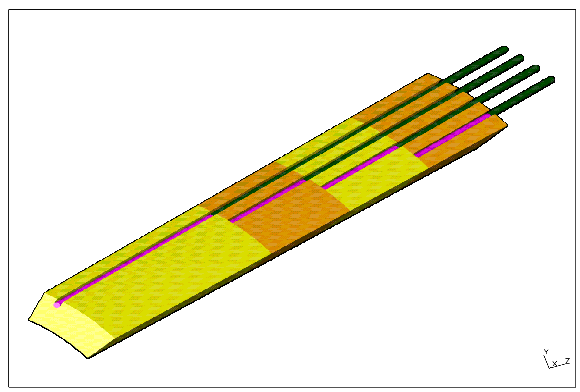

Fig. 4. Scintillator pieces forming a segment of the crystal calorimeter. Each piece is connected to an optical fiber, which crosses, optically isolated, the crystals to the rear end of the calorimeter.

silicon sensors are interspersed. The thickness of the absorber is chosen to be one radiation length and that of the the sensor to be 500 μm.

B. *Crystal Calorimeter with Fiber Readout*

A homogeneous crystal calorimeter promises better energy and time resolution as compared to a sandwich calorimeter. The Molière Radius has to be kept as low as possible. Therefore the material should be as dense as possible. We are currently thinking of $PbWO_4$ as scintillator. Longitudinal segmentation is obtained by cutting the crystals into pieces and attaching a fiber to every piece of crystal. Each scintillator piece of a calorimeter segment, as sketched in Figure 4, is readout by an optical fiber. The fibers are routed to the back of the calorimeter into an area of low activity. The light from the fibers is read there with multichannel photo-tubes or avalanche photodiodes.

C. *A heavy Gas Ionisation Chamber*

The structure of this calorimeter is similar to the Diamond-Tungsten sandwich calorimeter. Instead of the diamond sensors a heavy gas, e.g. C_3F_8, is used to measure the deposited energy. The electrons from the ionisation are collected by copper pads on a PCB, which is positioned in the center of the gap between two tungsten absorber disks.

D. *Results from Simulation of LCal*

Simulations are done both for a crystal and a diamond tungsten calorimeter. The background stemming from beamstrahlung is generated using the Monte Carlo program Guinea Pig [3]. Single electrons are simulated with energies between 50 and 250 GeV using the GEANT [4] based detector simulation package BRAHMS [5]. In the following the simulations for the sandwich calorimeter are reported. An algorithm is applied to detect local deposition from high energetic electrons on top of the background from beamstrahlung remnants. The efficiency to detect electrons is shown for several electron energies in Figure 5 for regions with low and high background. An electron

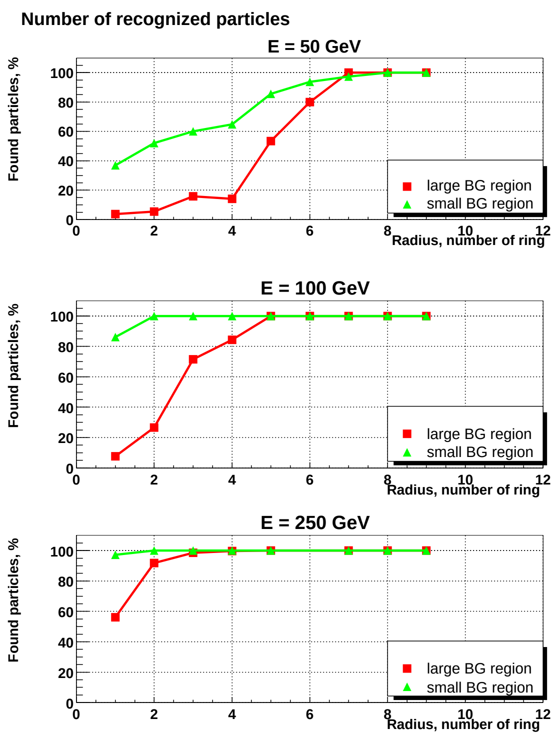

Fig. 5. The efficiency to identify an electron of energy 50, 100 and 250 GeV as function of the radius in the large background region (squares) and the low background region (triangles).

of 250 GeV is detected even in regions with high background with almost 100% efficiency. Only near the innermost radius the efficiency drops due to shower leakage. Electrons of 50 GeV are identified with high efficiency only at larger radii. The rate of fake electron vetoes in e^+e^- annihilation events was estimated. A first source is of physical nature. The spectrum of electrons from beamstrahlung has a tail to large energies. A second source is due to fluctuations in the background. Large local upward fluctuations may lead to an electron-like signature, which is accepted by the algorithm as an electron. In about 3% of the events an electron is faked for energies above 50 GeV. For new particle searches this would be an acceptable level. Similar investigations are done with a heavy crystal calorimeter The performance is in general slightly worse than for the diamond tungsten calorimeter.

For a 'real beam simulation', which includes seismic movements, the behavior of the beam-feedback system and a luminosity optimization at the beginning of the bunch-train crossing [1], the same investigations as reported above are performed. The results obtained are very similar to the ones with ideal beam. The total energy deposited in the LCAL is larger for the real beam. However, the rms of the energy depositions of subsequent bunch crossings is similar to the ideal case. This is nicely seen in Figure 6.

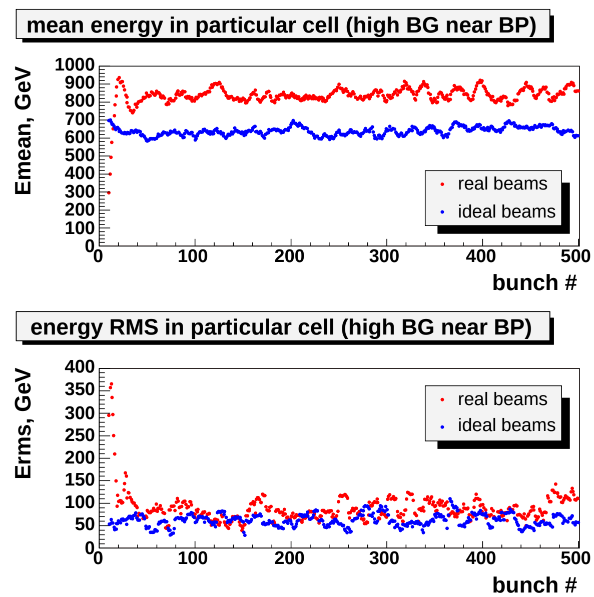

Fig. 6. The average energy and the rms of the energy integrated over ten bunch crossings for real and ideal beam simulations. The quantities are shown for a typical calorimeter cell near the beampipe as function of the bunch number for the first 500 bunch crossings.

E. *Results from Simulation of LAT*

The LAT will be a device for highly precise luminosity measurement. At LEP experiments [2] Silicon-Tungsten

[1] We would like to thank G. White for providing us with with the Monte Carlo output of his bunch train simulations

TABLE I

THE MAXIMAL ALLOWED UNCERTAINTIES FOR SEVERAL GEOMETRICAL QUANTITIES OF THE LAT

Quantity	maximum allowed value
Beam offsets	200 μm
Inner calorimeter radius	1 μm
Distance between calorimeters	60 μm

calorimeters were used very successfully for the measurement of the luminosity. Hence we consider for the simulations a Silicon-Tungsten sandwich calorimeter with a similar structure as the LAT shown in Figure 3. The gauge process is Bhabha scattering, $e^+e^- \rightarrow e^+e^-(\gamma)$. In the first study the requirements on the mechanical tolerances of the calorimeter are estimated using the Monte Carlo generator BHLUMI [6]. To match the 10^{-4} accuracy in the measurement of the rate of Bhabha events the results given in Table I are obtained. To reach this goals a laser alignment system is under investigation.

Monte Carlo studies using single electrons of 250 GeV energy have been done to optimize the segmentation of the Silicon-Tungsten calorimeter. The calorimeter is subdivided radially in cylinders, azimuthally in sectors and longitudinally in rings. Each ring consists of tungsten and a sensor plane. The thickness of the tungsten disk is one radiation length. In Figure 7 the resolution in the polar angle θ is shown for different longitudinal and transverse segmentation. A θ resolution of about 70 μrad seems feasible. A systematic offset

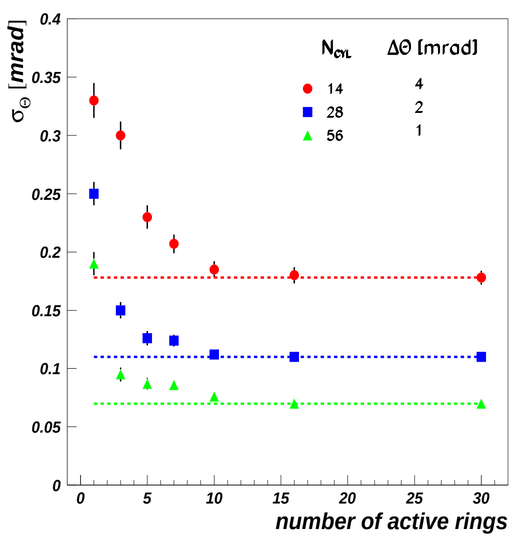

Fig. 7. The dependence of the resolution obtained in the polar angle θ for different numbers of cylinders as function of the number of rings in the calorimeter.

has been observed in the reconstruction of θ, in particular when the shower maximum is in the transition region between two rings. This needs further investigations.

TABLE II

THE ACCURACIES REACHED FOR SEVERAL BEAM PARAMETERS FROM THE ANALYSIS OF THE ENERGY DEPOSITIONS IN THE LCAL

Quantity	nominal value	precision
bunch width in x	553 nm	1.2 nm
bunch width in y	5.0 nm	0.1 nm
bunch length in z	300μm	4.3μm
beam offset in x	0	7 nm
y	0	0.2 nm

IV. BEAM DIAGNOSTICS

The spatial and spectral distributions of the beamstrahlung remnants depend on the beam parameters. Appropriately defined moments of these distributions can be used to monitor and tune beam parameters. As an example the dependence of the deposited energy, weighted with the radius and integrated, on the beam spot size in the horizontal plane is shown in Figure 8. Analyzing a set of moments and asymmetries of the deposited

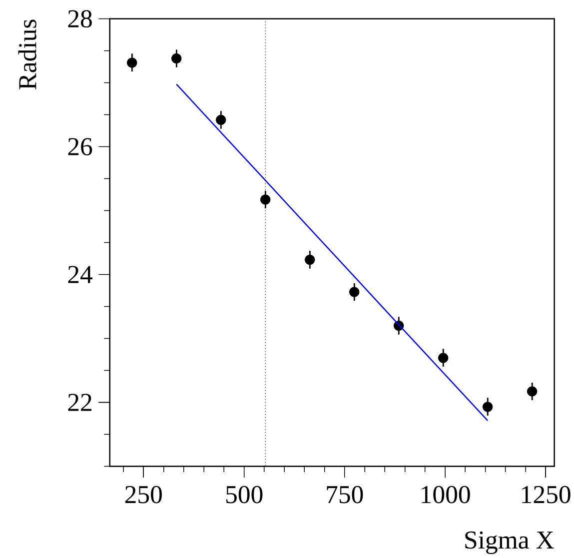

Fig. 8. The dependence of the integral over the radial distributed energy of the beamstrahlung depositions on the horizontal beam size σ_x

radiation results in the precisions for the determination of beam parameters as listed in Table II: Also for emittances and waist shifts a good sensitivity is obtained. These results for each of the parameters are obtained keeping all other parameters at their nominal values. The precisions show the big potential in these measurements for the determination of beam parameters.

V. SENSOR TESTS

A. Diamond sensors

A sample of CVD diamond sensors 12x12 mm^2 in size and 300 μm thick was obtained from a Fraunhofer Institute in Germany. The surfaces of the sensors are metallised with 10 nm Ti and 400 nm Au. An example of an assembled sensor is

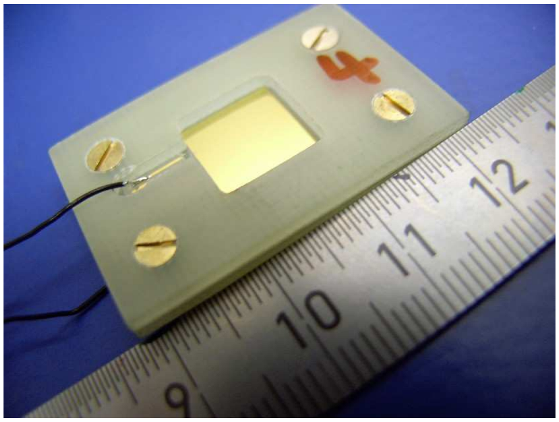

Fig. 9. A diamond sensor assembled for test measurements.

shown in Figure 9. The dependence of the current on the applied high voltage is shown in Figure 10. The data showing an almost

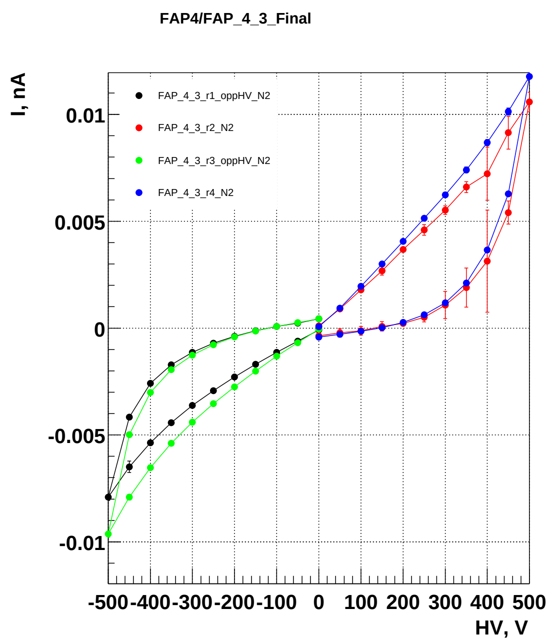

Fig. 10. The dependence of the current on the voltage on the two metal-areas of the diamond. The two curves are measurements of the same sensor.

linear dependence are obtained by ramping up the voltage. Ramping down the voltage leads to a sharp drop of the current, which may be due to polarization effects in the material. The resistance is in the order of 100 TΩ in the voltage range studied. The charge collection efficiency is measured using minimum-ionizing electrons from a ^{90}Sr source and resulted to values of 20% at 300 V.

B. Scintillation Counters

The light-output for plastic scintillator segments similar to the one shown in Figure 4 is measured first by contacting it directly to the cathode of an photomultiplier and then by using a readout fiber. The reduction of the signal due to the fiber readout is about 75%. Hence, the longitudinal segmentation using fiber readout is promising in such a calorimeter.

C. Heavy Gas Ionization Chamber

A heavy gas ionization chamber as shown in Figure 11 [7] was operated in a 20 GeV electron beam at the IHEP Protvino.

Fig. 11. A picture of the heavy gas ionization chamber used for testbeam studies at the PS of the IHEP Protvino.

The chamber was filled with C_3F_8 and the current collected by readout-pads of a size of 4x4 cm^2 was measured as function of the applied voltage. Keeping the beam intensity constant a very stable ionization current was obtained, showing that this technique is promising.

VI. Conclusion

Two compact calorimeters are forseen in the very forward region of a linear collider detector for highly precise measurements of the luminosity and, at very low angles, both for beam optimization and extended detector coverage. The measurement of the luminosity requires excellent spatial precision of the detector and precise and homogeneous sensors to avoid systematic biases. The calorimeter nearest to the beampipe has to tackle with a high radiation dose. Hence radiation hard sensors must be used. Several technologies are under study. The result from Monte Carlo simulations show that even for a realistic beam simulation high energetic electrons could be identified in this region with high efficiency. The distribution of the radiation in this calorimeter shows a high sensitivity to several beam parameters and can be used for luminosity optimization. Laboratory tests with CVD diamond sensors, with scintillators and using a heavy gas ionization chamber are ongoing. The first results obtained so far are promising.

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