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Recent progress with very forward calorimeters for linear colliders

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On behalf of the FCAL collaboration

Recent developments for very compact calorimeters designed for precise luminosity measurement (LumiCal) and beam monitoring (BeamCal) in the very-forward region of future linear colliders are presented. Silicon pad sensors for LumiCal have been equipped with modern read-out electronics and tested in the laboratory. Ultra-compact assemblies of these sensors, with only 1 mm spacing between tungsten absorber plates, have been developed. This stack has been exposed to few-GeV electron and muon test beams at CERN and DESY. First results on shower development in such a compact stack are presented and compared to Geant4 simulations.

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1. Introduction

Future e^+e^- colliders offer a rich experimental program that addresses many open questions in elementary particle physics. For the moment, two such colliders, distinguished by their acceleration concepts, are being studied, the International Linear Collider (ILC) [1], based on superconducting cavities, and the Compact Linear Collider (CLIC) [2, 3] with the two-beam accelerating concept. Two types of detectors are under design for the ILC, the International Large Detector (ILD) and the Silicon Detector (SiD) [4]. Similar concepts were developed for CLIC, though a recent study is focused on a single detector model optimized for 3 TeV centre-of-mass beam energy. Forward regions of the ILC and CLIC detectors are equipped with compact calorimeters designed for the accurate luminosity measurements and for extending the capabilities of the experiments for physics studies in the high rapidity region (see e.g. [5]). The layout of one arm of the forward region of the ILD experiment is presented in Fig. 1. LumiCal is an electromagnetic sampling calorimeter with 30 layers of 3.5 mm ($1X_0$) thick tungsten absorbers and silicon sensors placed in one millimeter gaps between absorber plates. It is designed for a precision measurement of integrated luminosity using Bhabha scattering as a gauge process [6]. BeamCal is positioned to cover the smallest forward angles and has a similar design as LumiCal, but the sensors must withstand much higher radiation doses. For the current baseline design GaAs sensors are considered. BeamCal provides a bunch-by-bunch luminosity estimate and the determination of beam parameters using the energy deposition of incoherent pairs. It aims also on high energy electron tagging at low polar angles [7]. LHCAL is a calorimeter which covers the angular gap between LumiCal and ECAL and provides additional forward coverage inside the HCAL endcap.

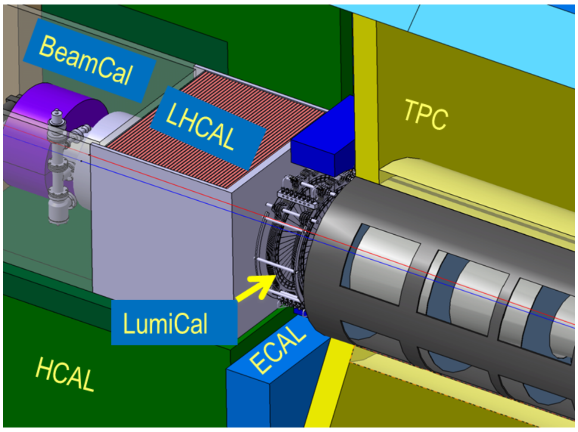


Figure 1: The very forward region of the ILD detector. LumiCal, BeamCal and LHCAL are carried by the support tube for the final focusing quadrupole QD0 and the beam-pipe.

The present review will mostly focus on the LumiCal prototype development and study, where most progress has been recently achieved. These results and the experience gained are going to be applicable to other FCAL subsystems.

2. Forward Calorimeter Prototypes

The first LumiCal detector module prototype was successfully built and tested in a multilayer configuration at CERN with a 5 GeV e^-/μ^- beam [8]. The sensor module had a thickness of about 4 mm and had 32 out of 256 pads connected to the readout electronics. For the module assembly, the LumiCal silicon sensor was glued to a 2.5 mm thick PCB with conductive glue to provide the bias voltage to the sensor's n-type bulk. Kapton fan-out with copper traces was glued on the other side of the sensor which has 256 sensitive pads implemented as aluminum covered p-implants. Ultrasonic wire bonding was used to connect sensor pads to the fan-out traces and the other side of the fan-out to the conductive traces on the PCB which finally led to the board with front-end electronics. A detailed description of the test-beam setup and some essential results were previously presented in [8]. The recent analysis of the test-beam data was devoted to the study of the transverse structure of the electromagnetic shower and the Molière radius measurement.

The average distribution of the deposited energy in transverse plane is symmetric with respect to the longitudinal shower axis and does not depend on the azimuthal angle. Its radial dependence is characterized by a narrow core, and a broadening tail. Several approaches were used to approximate this distribution: weighted sum of two exponential functions [9, 10] or of two Gaussians [11]. Another function was used by Grindhammer and Peters [12]. Similar function is used for the tail description in the present study while the core is approximated by the Gaussian:

$$F(r) = (A_C)e^{-(\frac{r}{R_C})^2} + (A_T)\frac{2rR_T^2}{(r^2+R_T^2)^2} \; . \tag{2.1}$$

Here R_C (R_T) is the median of the core (tail) component and A_C, A_T are their weights. On average, only 10% of the deposited energy lies outside a cylinder with the Molière radius $R_{\mathscr{M}}$. This property can be used in order to estimate the size of the electromagnetic shower in the lateral direction. Assuming the function (2.1) is normalized to unity, the value of $R_{\mathscr{M}}$ can be found from the following equation:

$$0.9 = \int_0^{2\pi} d\varphi \int_0^{R_{\mathscr{M}}} F(r) r dr \; , \tag{2.2}$$

The function $F(r)$ can be reconstructed using the test-beam data or the MC simulation. Fig. 2 shows $F(r)$ integrated along one transverse direction in comparison with the data and MC simulation. One can see that the function (2.1) provides a good approximation of the data and simulation which are also in good agreement between each other.

The Molière radius for the LumiCal prototype used in the test-beam can be also estimated using the following formula [11]:

$$\frac{1}{R_{\mathscr{M}}} = \frac{1}{E_s}\sum\frac{w_j E_{cj}}{X_{0j}} = \sum\frac{w_j}{R_{\mathscr{M}j}} \; , \tag{2.3}$$

where j runs over elements composing the material in the calorimeter layers, w_j is a mass fraction of the element and $R_{\mathscr{M}j}$ its Molière radius.

During the test-beam, only four LumiCal modules were available and in order to study the development of the electromagnetic shower three configurations of absorbers and sensitive layers were used. This allowed to sample the shower after $1X_0$ and then from $3X_0$ to $9X_0$ with a step of $1X_0$. For one of the configurations, where four detector modules are placed after 3, 5, 7 and 9 tungsten absorbers (it roughly corresponds to shower sampling at $3X_0$, $5X_0$, $7X_0$ and $9X_0$), equation (2.2) gives a preliminary result of $R_{\mathscr{M}} = 1.6 \pm 0.2$ cm. The study is in progress to combine all configurations and compare it with MC simulation. The formula (2.3) gives $R_{\mathscr{M}} = 1.7$ cm, which is in good agreement with the measurement. A comparison of the components contributing

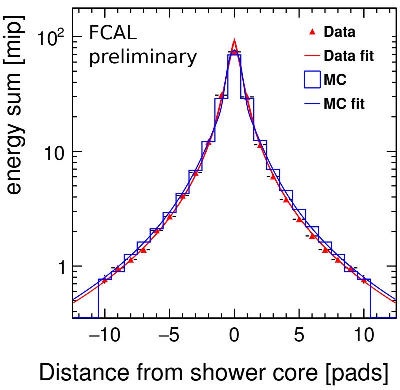


Figure 2: Shower average lateral profile of test-beam data and MC simulation for one of the setup configurations. The line describes the fit of F(r) to the data (red) and MC (blue). One pad corresponds to 1.8 mm.

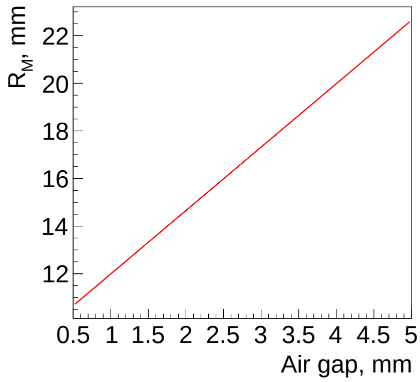


Figure 3: The Molière radius of a stack of $1X_0$ tungsten absorber plates as a function of the air gap between them.

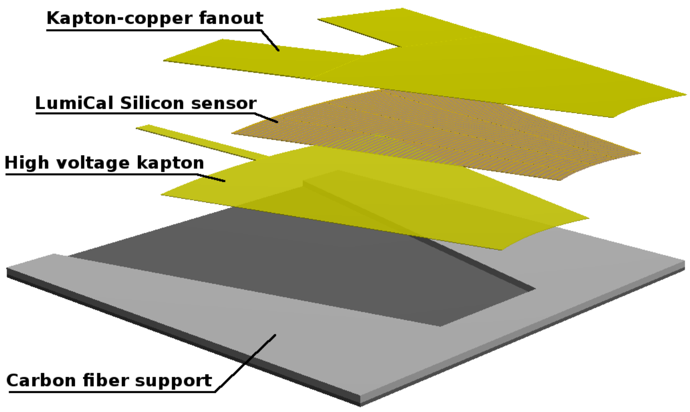
to the Moliere radius in formula (2.3) shows that the most significant contribution to increasing the Molière radius is the air gap between absorbers and LumiCal detector modules. It can be seen (Fig. 3) that the Molière radius is reduced by a factor of two reaching 1.2 cm as the distance between tungsten absorbers shrinks from 4.5 mm to 1 mm. For the test-beam setup, the gap of 4.5 mm is needed to position LumiCal modules with a thickness of about 3 mm in the calorimeter stack. The conceptual design of LumiCal foresees the distance between ablorbers of 1 mm and it was shown in MC simulation [6] that the precision of luminosity measurement with this geometry matches the requirements of the experiments.

3. Thin LumiCal Module Design

There could be many approaches for designing detector modules for a calorimeter of submillimeter thickness. This work is aimed to use the same LumiCal sensor, which was studied in labs and in test-beams. The sensor was briefly described in section 2, more information can be found in [8, 13]. It is essentially an array of diodes produced on one side of high resistivity n-type silicon wafer surrounded by three guard rings. This sensor structure mostly determines the main functional elements of the module which needs to supply bias voltage to the n-side of the sensor and connect sensitive elements to the front-end electronics. It was interesting to connect all 256 pads of the sensor to readout electronics and study their performance as they have different geometry and also can be affected by the nonuniformity of the dopant concentration in the silicon substrate. In addition, the module should be mechanically solid enough to allow easy handling during lab and beam tests.

The next generation of the readout chip and front-end electronic board for the LumiCal module are in a development process while the existing prototypes though successful, have only 32 channels and a rather big size. A temporary solution would be a front-end electronics which was developed for other experiment, and can be relatively easily adapted for the LumiCal sensor. After a short study the APV-25 chip hybrid board developed for the silicon strip detector of the CMS experiment was chosen. It has 128 channels and two boards can read the whole LumiCal sensor.

The new design of the module uses kapton-copper foils for the high voltage supply and the fan-out, connecting the sensor with the front-end board (Fig. 4). The high voltage supply foil is 70 μm thick and is applied to the back side (n-type bulk) of the sensor. The fan-out foil is 120 μm thick. The high voltage part was glued to the sensor with a conductive glue, after that the fan-out was glued to the front side of the sensor using epoxy and then ultrasonic wire bonding was used to connect conductive traces on the fan-out to the sensor pads. Special fixtures were designed and produced to ensure the necessary thickness and uniformity of the three glue layers between different components of the LumiCal detector module, whose area is about 10×8 cm^2.



Layer	Thickness
Fan-out	120
Adhesive	10
Si sensor	320
Adhesive	15
HV kapton	70
Adhesive	15
Support	100
Total:	650 μm

Figure 4: Thin LumiCal module assembly. The table shows the thickness of each layer in μm and the total anticipated thickness of the module.

Another problem which has to be solved is a reliability of the connections between sensor pads and fan-out traces. The ultrasonic wire bonding performs well under electrical tests, but the height of wire loops has to be reduced as much as possible in order to fit the 1 mm gap between the absorber plates. The parameters of the bonding machine were studied and tuned to make the loop as low as possible and technically acceptable. Eight modules were assembled and prepared for test-beam in 2016. The sampling based measurements which were done using a confocal laser scanning microscope shows the loop height is about 50 μm.

Two approaches were tested for constructing the sensor mechanical support structure. One is made using 3D printing and another produced from a carbon fiber composite. Two mechanical prototypes of the detector modules were assembled using these two supporting structures and fake sensors. Both approaches allow producing detector module with less then 1 mm thickness, 0.8 mm for 3D and 0.9 mm for the carbon fiber composite. The mechanical stability of the prototype made with carbon fiber composite is significantly better and that method is chosen for the detector production. For the LumiCal module prototype the carbon fiber support is thinned down to 100 μm in the sensor gluing area, while the surrounding part remains 600 μm.

The assembled modules were successfully installed in the 1 mm gap between the tungsten absorbers during the 2015 and 2016 test-beam campaigns. The calorimeter prototypes with four and six sensitive layers were tested and the data analysis is in progress.

4. Summary

The recent development of the LumiCal detector demonstrated the feasibility of constructing a compact calorimeter consistent with the conceptual design, which is optimized for a high precision luminosity measurement in e^+e^- collider experiments. The experience and the techniques developed for the LumiCal module construction can be deployed for other FCAL subsystems. Many ongoing studies in the FCAL collaboration could not be covered in this short review. This includes extensive work on the development of readout chips with exceptional characteristics, search for radiation hard sensor technologies for BeamCal, simulation study of the design optimization and performance of all FCAL subsystems. This information can be found in the publications, conference talks, master and PhD thesis presented on the FCAL web page [14].

References

[1] *The International Linear Collider. Technical Design Report, Volume 2: Physics*. 2013. arXiv:1306.6352 [hep-ph].

[2] P. Lebrun, L. Linssen, A. Lucaci-Timoce, D. Schulte, F. Simon, S. Stapnes, N. Toge, H. Weerts, J. Wells, *The CLIC Programme: Towards a Staged e+e- Linear Collider Exploring the Terascale : CLIC Conceptual Design Report.* arXiv:1209.2543 [physics.ins-det]

[3] The CLIC, CLICdp collaborations, *Updated baseline for a staged Compact Linear Collider.* CERN Yellow Report CERN-2016-004; arXiv:1608.07537 [physics.acc-ph]

[4] *The International Linear Collider. Technical Design Report, Volume 4*: Detectors, 2013. arXiv:1306.6329 [physics.ins-det].

[5] B. Krupa, B. Pawlik, T. Wojtoń and L. Zawiejski, FCAL collaboration, *Photon structure functions at the ILC energy range.* The European Physical Society Conference on High Energy Physics 22−29 July 2015; Vienna, Austria.

[6] H. Abramowicz et al., *Forward instrumentation for ILC detectors.* JINST 5 (2010) P12002.

[7] A. Sailer, A. Sapronov on behalf of the CLICdp collaboration, *High Energy Electron Reconstruction in the BeamCal.* CLICdp Note, CLICdp-Note-2016-005.

[8] O. Borysov, V. Ghenescu, A. Levy, I. Levy, S. Lukic, J. Moron, A.T. Neagu, T. Preda, O. Rosenblat (On behalf of the FCAL collaboration), *Results from the October 2014 CERN test beam of LumiCal.* Proceedings of the LCWS2015, Whistler BC Canada, November 2-6, 2015.

[9] G. A. Akopdjanov, A. V. Inyakin, V. A. Kachanov, R. N. Krasnokutsky, A. A. Lednev, Yu. V. Mikhailov, Yu. D. Prokoshkin, E. A. Razuvaev and R. S. Shuvalov, *Determination of Photon Coordinates in A Hodoscope Cherenkov Spectrometer.* Nucl. Instr. and Meth. 140 (1977). p.441.

[10] G. Ferri et al., *The Structure of Lateral Electromagnetic Shower Development in Si/W And Si/U Calorimeters.* Nucl. Instr. and Meth. A273 (1988) p.123.

[11] K.A. Olive et al., *(Particle Data Group)*, Chin. Phys. C, 38, 090001 (2014) and 2015 update.

[12] G. Grindhammer and S. Peters, *The Parameterized Simulation of Electromagnetic Showers in Homogeneous and Sampling Calorimeters.* 2000, hep-ex/0001020.

[13] H. Abramowicz et al., *Performance of fully instrumented detector planes of the forward calorimeter of a Linear Collider detector.* JINST 10 (2015) P05009.

[14] FCAL Collaboration, http://fcal.desy.de.