FCAL R&D ON FORWARD CALORIMETERS*

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The FCAL Collaboration performs MC studies and develops detectors for the forward region of a future linear e^+e^- collider. The forward region sets challenging requirements on several detector parameters, such as detector compactness, radiation hardness or readout ASICs parameters. We present R&D activities focused on the development of prototype detectors able to cope with these requirements.

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1. Introduction

The objective of the FCAL Collaboration is to design and optimise the very forward region of a future Linear Collider (ILC, CLIC) detector. This comprises the development of a luminosity calorimeter, called LumiCal, for precise luminosity measurement, and the development of a beam monitor detector, called BeamCal, for a fast luminosity estimation and beam parameters control. Both calorimeters should also ensure the detector hermeticity in the forward region. The very forward region of a linear collider detector with the BeamCal and LumiCal detectors is shown in figure 1.

The LumiCal gives a precise measurement of luminosity using the Bhabha scattering $e^+e^- \to e^+e^-(\gamma)$ gauge process. For a given rate of Bhabha events, N_{B}, determined in a certain θ-range, the luminosity is obtained as

$$L = \frac{N_{\mathrm{B}}}{\sigma_{\mathrm{B}}}\,, \tag{1}$$

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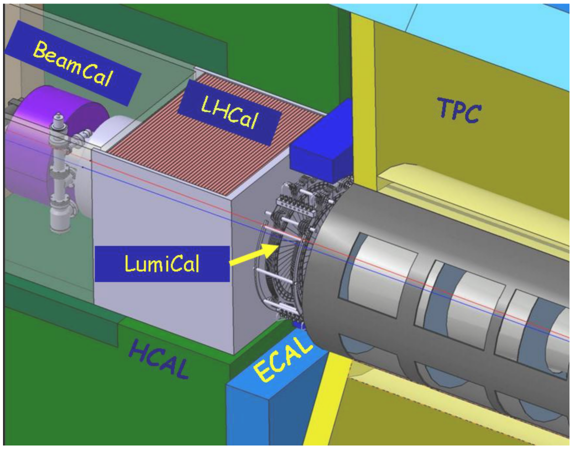


Fig. 1. The very forward region of the ILD detector, containing the BeamCal and LumiCal calorimeters.

where $\sigma_{\rm B}$ is the integral of the differential cross section [1]

$$\frac{d\sigma_{\rm B}}{d\theta} = \frac{2\pi\alpha_{\rm em}^2}{s}\frac{\sin\theta}{\sin^4(\theta/2)} \approx \frac{32\pi\alpha_{\rm em}^2}{s}\frac{1}{\theta^3}\,, \tag{2}$$

over the considered θ-range. Because of the steep θ dependence of the cross section, the most critical quantity to control when counting Bhabha events is the inner acceptance radius defined as the lower cut in the polar angle. Hence, a very precise θ measurement is needed. Furthermore, the θ range must be chosen such that the number of Bhabha events measured provides the required relative statistical uncertainty of 10^{-3} at ILC (at CLIC 10^{-2}). By choosing the lower bound of the polar angle between 40 and 60 mrad, the latter requirement can be reached.

The BeamCal is positioned at the edge of the detector adjacent to the beam pipe. At the energies of ILC or CLIC linear colliders, there is a new phenomenon to tackle — the beamstrahlung, which leads to radiation of photons, and this, in turn, to the production of huge amounts of low energy e^+e^- pairs. A large fraction of these pairs will deposit their energy in the BeamCal. These deposits are useful for a bunch-by-bunch luminosity estimate and determination of beam parameters [2], however, they lead to a radiation dose of about one MGy per year in the sensors at low polar angles. Hence, radiation-hard sensors are needed for the instrumentation of the BeamCal.

The MC simulation and optimization studies performed within FCAL led to the concept and specifications of both forward calorimeters:

— Sandwich type sampling calorimeters: Si–W for LumiCal, GaAs–W for BeamCal;

— Both comprise: 30 layers at ILC, or 40 layers at CLIC. One W absorber layer coresponds to one radiation length;

— Very compact calorimeters (small Moliere radius) are needed;

— Low polar angle acceptance: LumiCal 42–67 mrad at ILC and 38–110 mrad at CLIC, BeamCal 5–45 mrad at ILC and 15–38 mrad at CLIC.

The schematic drawing of the LumiCal calorimeter is shown in figure 2.

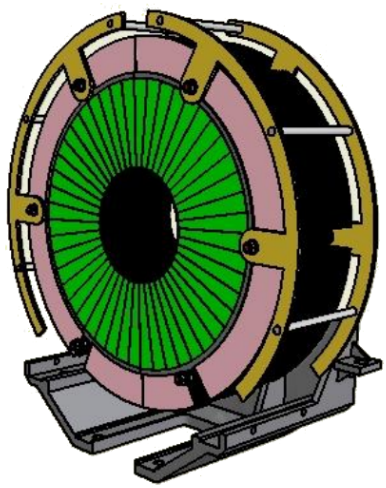


Fig. 2. A schematic drawing of LumiCal detector.

The main challenges of these detectors are: compactness (Moliere radius $\sim$ 1 cm); rad-hard sensors for BeamCal ($\sim$ 1 MGy/year radiation dose); dedicated readout ASICs (Application Specific Integrated Circuit) for both calorimeters (fast readout, high occupancy, low power). The FCAL Collaboration performs R&D program to develop detector technologies for the required specifications. Prototype BeamCal and LumiCal detector modules, comprising sensors, ASICs, absorber, and precise mechanics have been developed, and are discussed in this paper.

2. FCAL R&D for forward detector prototype

In the past, the FCAL Collaboration performed several beam-tests to verify the operation of LumiCal/BeamCal detector prototypes. These beam-tests were done with a single plane of LumiCal or BeamCal detector and their results were reported elsewhere [3]. Recently, a multilayer prototype of a forward detector was built and a first beam-test with four LumiCal sensor planes was performed at the end of 2014. The beam-test data are currently being analysed. Here, we report on the construction of this multilayer calorimeter prototype.

To build a prototype of the BeamCal or the LumiCal calorimeter the main required components are:

— Detector modules containing sensors for BeamCal/LumiCal, readout ASICs, and back-end electronics;

— Precise absorber layers;

— A precise mechanical frame;

— A data acquisition system (DAQ).

Prototypes of these components were developed within the FCAL Collaboration and will be discussed in the following. Regarding the DAQ, in the performed FCAL beam-tests, a global DAQ software EUDAQ [4] was used to collect the data from the detectors, and a trigger logic unit (TLU) [5] was used to generate and distribute the trigger to sub-detectors.

2.1. Detector modules

A fully assembled detector module is shown in figure 3 [6]. In order to increase the system flexibility and to allow operation with different sensors, the module consists of separate sensor-board and readout electronics board. As seen in figure 3, the LumiCal sensor is covered by a kapton fan-out delivering the signals from the sensor to the front-end electronics. The signals

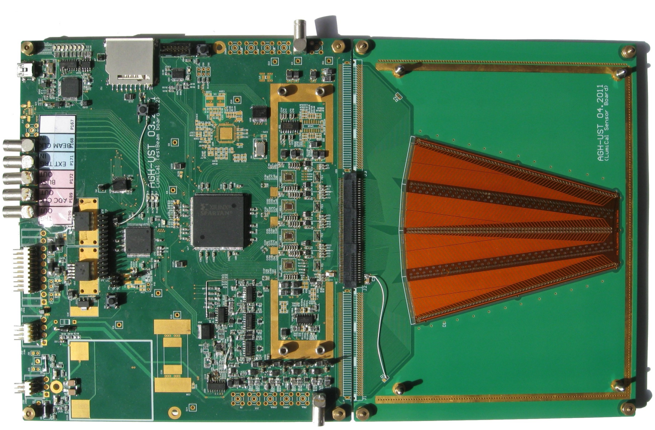


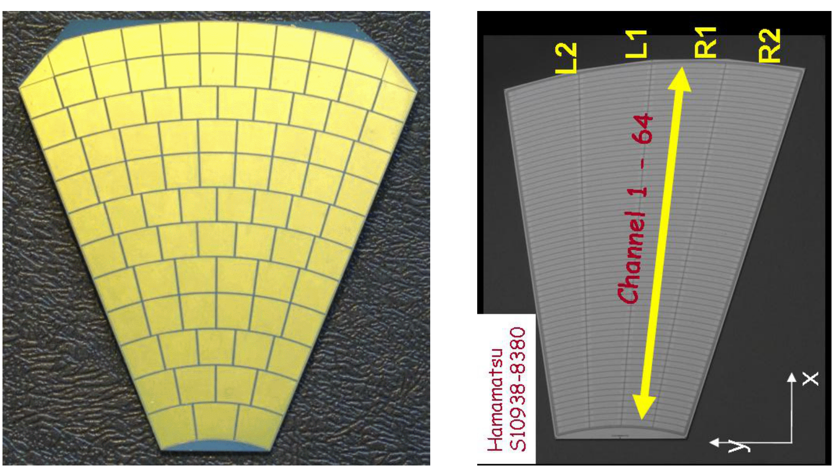
Fig. 3. Photograph of a LumiCal readout module with sensor connected.

are then amplified, shaped and continuously digitised on the readout electronics board. Four pairs of front-end and ADC ASICs, 8 channels each, giving 32 channels in total, are placed on the readout board. The digitised signals from the ADC ASICs are processed by the FPGA-based back-end electronics.

2.1.1. Sensors

The BeamCal detector will be exposed to a large flux of low energy electrons, resulting in depositions of up to one MGy for a total integrated luminosity of 500 fb^{-1} at 500 GeV. Hence, radiation-hard sensors are needed. The BeamCal prototype sensors were produced by the Tomsk State University. A gallium arsenide prototype 45° sector of 500 μm thickness is seen in figure 4 (a). The metallisation layer is subdivided into 12-ring segments with innermost radius of 20 mm and outermost radius of 84 mm. Each ring segment is divided into pads of approximately 5×5 mm^2 size.

Prototypes of LumiCal silicon sensors (see figure 4 (b)) were manufactured by Hamamatsu Photonics [7]. Their shape is a ring segment of 30° and it contains four sectors of 7.5° each. The inner radius is 80 mm and the outer radius 195 mm. The thickness of the n-type silicon bulk is 320 μm. The pitch of the concentric p+ pads is 1.8 mm and the gap between two pads is 100 μm.



(a) (b)

Fig. 4. (a) A prototype of a GaAs sensor sector for BeamCal. (b) The layout of a sensor tile for LumiCal. L1, L2, R1, R2 mark four sectors of a single tile.

2.1.2. Readout ASICs

Each channel of the front-end ASIC comprises a charge sensitive amplifier, a pole-zero cancellation circuit (PZC), and a first order CR–RC shaper [8]. It was designed to work in two modes: the physics mode and the calibration mode. In the physics mode (low gain), the detector should be sensitive to electromagnetic showers resulting in high energy deposition and the front-end electronics should process signals up to almost 10 pC per channel. In the calibration mode (high gain), it should detect signals from relativistic muons, the so-called Minimum Ionizing Particles (MIPs), to be used for calibration and alignment. To match the ILC timing, the shaper peaking time T_{peak} was set to about 60 ns. The prototype ASIC containing 8 front-end channels was designed and fabricated in 0.35 μm four-metal two-poly CMOS technology. The area occupied by a single channel is 630 μm $\times$ 100 μm. The photograph of the prototype glued and bonded on the PCB is shown in figure 5.

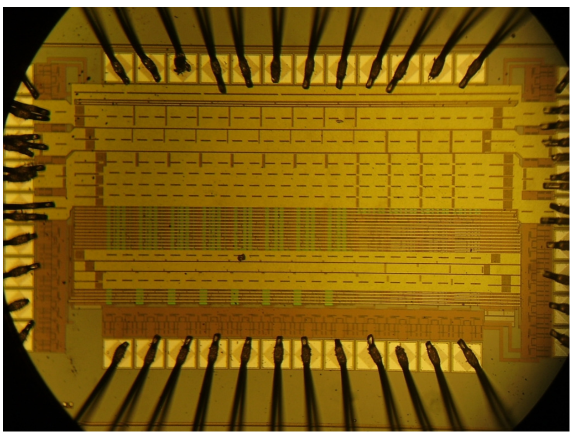


Fig. 5. A micrograph of a front-end ASIC.

To apply an analog-to-digital conversion in each front-end channel, a dedicated low power, small area, multichannel 10-bit ADC was designed [9]. For an ILC detector, a sampling rate of about 3 MS/s is sufficient, while for the beam-test purpose a much faster ADC, allowing few samples per pulse, is beneficial. To meet both requirements, a general purpose variable-sampling-rate ADC with scalable power consumption was developed. A micrograph of the multichannel ADC prototype, glued and bonded on a PCB, is shown in figure 6. It comprises eight 10-bit ADCs with variable power and sampling frequency (up to 24 MS/s), a configurable digital serializer circuit, fast Low Voltage Differential Signaling (LVDS) I/O block, a set of digital-to-analog converters for automatic internal current and voltage control, a precise bandgap voltage reference, and a temperature sensor. The prototype ASIC was fabricated in 0.35 μm, four-metal two-poly CMOS technology. The active size of the ASIC is 3.17 mm $\times$ 2.59 mm.

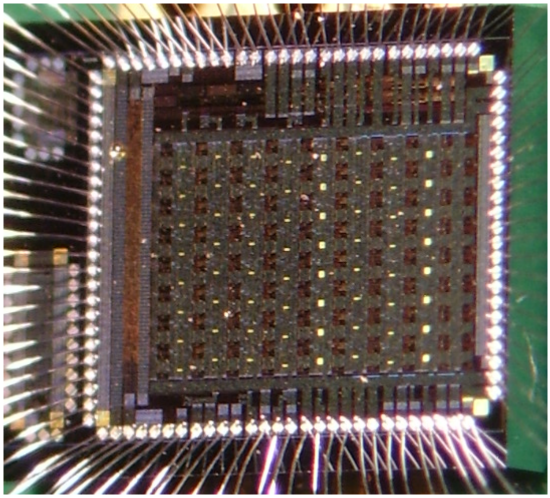


Fig. 6. A micrograph of an ADC ASIC.

2.1.3. Back-end electronics

To analyse the beam-test data and to perform pile-up studies, a sufficiently high ADC sampling-rate and very high internal-data throughput between the ADC and the FPGA-based back-end electronics was assured. The signals from 32 channels are sampled with a 20 MS/s rate, and digitised with a 10-bit resolution, resulting in a raw data-stream of about 6.4 Gb/s. To fulfil the high throughput requirements, the back-end electronics was implemented on a low-cost, high-density Spartan XC3500E FPGA [10] and an ATxmega128A1 microcontroller [11]. The digitised data stream is continuously recorded in a buffer inside the FPGA. When a trigger is received, the acquisition is interrupted and the microcontroller firmware builds an event packet and transmits it from the readout electronics board to a host PC.

2.2. Absorber layers

Absorber plates are needed in the FCAL calorimeter to generate particle showers. Both BeamCal and LumiCal contain absorber layers, each corresponding to around one radiation length, interspersed with sensor layers. To obtain the most compact showers, a very dense material is needed, and tungsten, often used for such applications, was chosen. Tungsten absorber plates of 3.5 mm thickness, corresponding roughly to one radiation length each, were produced. Tungsten plates were bought from Plansee — Cime Bocuze in France, while metrology measurements were done at CERN. A photograph of a tungsten plate glued to a permaglass frame is shown in figure 7. For a very compact calorimeter, the distance between two tungsten plates has to be as small as possible. For FCAL, at most 1 mm gap between absorber layers is specified. This translates into a required distance of 1 mm ± 50 microns over the entire surface of the tungsten plates, which, in turn, implies excellent tungsten plate flatness. The most stringent tolerance required on one W plate face is the 10 microns flatness. The second face has to be located with respect to the first within a tolerance of 40 microns. The ± 50 microns accuracy was achieved for nearly all configurations (for various distances between tungsten plates), with the five PLANSEE tungsten plates.

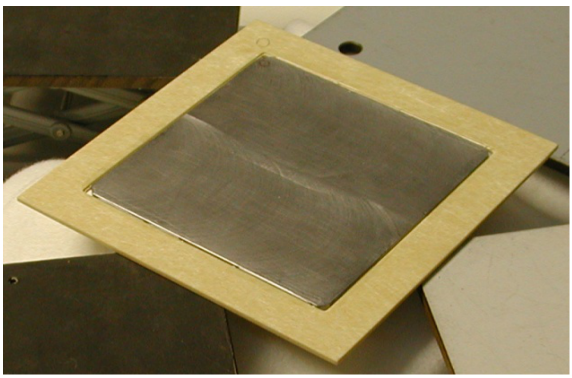
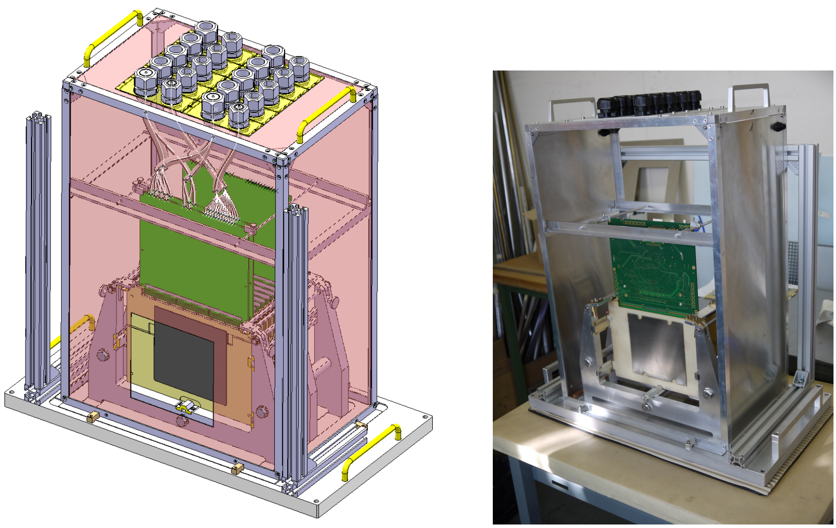


Fig. 7. Photograph of a tungsten plate.

2.3. Precise mechanical frame

For shower development studies in beam-tests, a precise mechanical frame, holding sensor and absorber planes, is needed. The prototype of such a mechanical frame was designed, built, and tested (see figures 8 (a), (b)). The prototype may hold up to 30 tungsten plates (140 mm $\times$ 140 mm $\times$ 3.5 mm) parallel to each other, with a gap between plates equal to 2 mm or 1 mm. The sensors are inserted in these gaps. The gap between plates has to be precise: 2 mm or 1 mm $\pm$ μm all over the tungsten plate surface. Insertion and removal of tungsten plates in the infrastructure has to be fast and easy. A dedicated structure has to support all sensor and electronic card services.

A mechanical chassis was built which is able to support 30 tungsten alloy plates mounted in very accurate aluminium combs in order to get a distance in between each plate equal to the reference distance ±50 microns. Two sets of aluminium combs have been machined, one with 1 mm gaps and one with 2 mm gaps. They are easily mountable on the chassis. Since the current detector modules are not yet compact enough, they are inserted in the slot of a tungsten plate. A photograph of the mechanical frame with an absorber plate and detector module inserted is shown in figure 8 (b).



(a) (b)

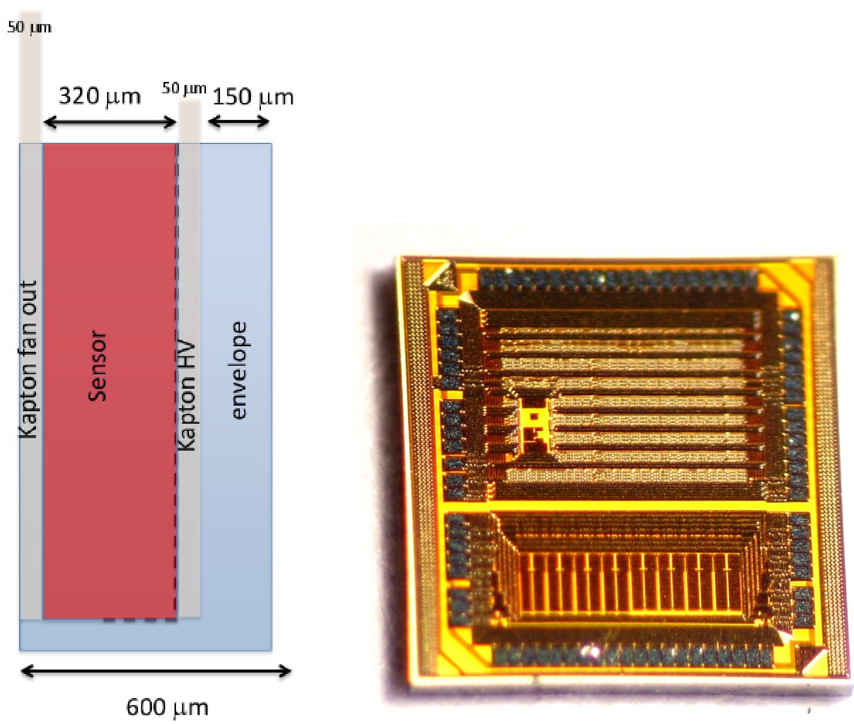
Fig. 8. (a) Schematic diagram of the precise mechanical frame. (b) Photograph of the frame prototype with absorber plate and detector module inserted.

3. Recent R&D activities

Although the first multilayer forward detector prototype was built and used in beam-tests, this prototype does not fulfil all the requirements of the final detector system. In particular, it is not compact enough and does not allow to obtain a small enough Molière radius of particle shower in the detector. This is due to the fact that the detector module (both the sensor part and the readout part) is not thin enough. For the final system, the thickness of the sensor part should be less than 1 mm and the readout part less than 4.5 mm thick. In the present system, the thick PCB boards and several large external components on the readout board make both the sensor and readout parts significantly thicker. Therefore, the main FCAL R&D activities are now directed towards the development of a new more compact detector module.

The development of a new sensor module based on a thin carbon fiber envelope has started recently. The schematic diagram shown in figure 9 (a) should allow to achieve the sensor module with a thickness of about 600 μm. First prototypes of carbon fiber envelope and kapton fan-out have been already produced giving very promising results.

Regarding the readout, the main activities are directed into the design of a new readout ASICs comprising all needed functionalities such that almost all external components would be eliminated. At the same time, new ASICs are designed in modern submicron CMOS processes, in order to reduce significantly the dissipated power and improve radiation hardness. New low power front-end electronics has been developed both for the BeamCal detector [12] and for the LumiCal detector [13]. Other readout blocks like ADC, PLL have been developed too. As an example, a photograph of a prototype 8-channel ADC designed in CMOS 130 nm is shown in figure 9 (b). The tests are still ongoing, but a good functionality of this ADC has been already verified while the quantitative measurements are in progress.



(a) (b)

Fig. 9. (a) Schematic diagram of a prototype sensor module. (b) Photograph of prototype ADC ASIC fabricated in CMOS 130 nm process.

Besides the described R&D focused directly on the more compact detector prototype, also general purpose R&D like the ones regarding new radiation-hard sensor materials (sapphire, rad-hard silicon) or precise laser based alignment system for LumiCal (using semi-transparent sensors), are conducted.

4. Summary

The FCAL Collaboration conducts R&D activities and develops new detector technologies for the forward region in future linear collider. In the last years, significant progress was made and key component prototypes, such as radiation-hard sensors, dedicated readout ASICs, precise absorber plates, and a precise mechanical frame were developed and produced. At the end of 2014, for the first time, a multilayer prototype of a LumiCal detector was built and used in beam-tests. The collected data are currently being analysed. In parallel, other R&D activities are continuing, in particular the ones focused on thinner detector modules and new readout ASICs, with the goal of improving the compactness of the calorimeter.

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