FCAL: Development of highly compact and precise luminometers

1 Motivation for Forward Calorimetry at Linear Collider Detectors

Forward calorimters at linear collider detectors are indispensable to measure precisely a key quantity needed to convert count rates in cross sections, the luminosity. The gauge process is low angle Bhabha scattering, which can be calculated with high precision in Quantum Electrodynamics. Since Bhabha scattering has a very steep dependence on the polar angle, an excellent angular resolution is required for its measurement, making the mechanical precision of the device and the granularity to be a challenge. Very forward calorimeters are also foreseen for beam tuning in a fast feedback system to maximise the luminosity during data taking. Last but not least, forward calorimeters increase the angular coverage of the detector, improving such the missing energy measurement, important e.g. for SUSY models resulting in low momentum particles in their decay chain.

2 FCAL concept

Two special electromagnetic calorimeters are foreseen in the very forward regions of a linear collider detector, denoted hereafter as LumiCal and BeamCal. In front of BeamCal a layer of pixel detector, deboted as Pair Monitor, will support beam tuning. These calorimeters will deliver both a fast and a

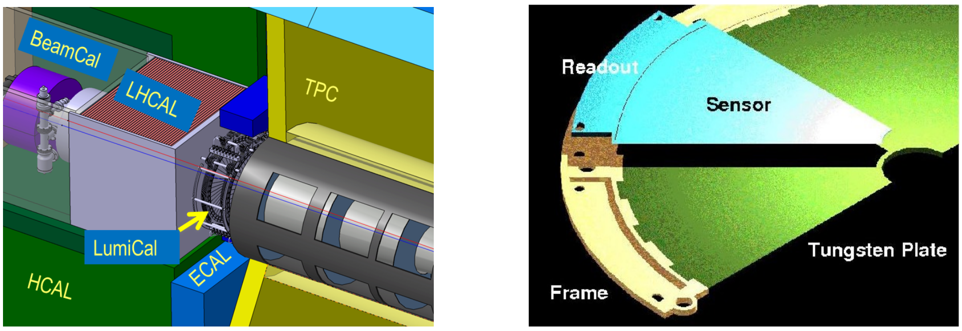

Figure 1: Left: The very forward region of the ILD detector. LumiCal, BeamCal and LHCAL are carried by the support tube for the final focusing quadrupole QD0 and the beam-pipe. TPC denotes the central track chamber, ECAL the electromagnetic and HCAL the hadron calorimeter. Right: A half layer of an absorber disk with a sensor sector and front-end electronics.

precise measurement of the luminosity and extend the detector coverage to low polar angles. In addition, a LHCal extends the hadron calorimeter coverage to very small polar angles. Detailed Monte Carlo studies have been performed to optimize the design of the calorimeters, estimate the background from physics processes and understand the impact of beam-beam interactions on the luminosity measurement [1]. A sketch of the design is shown in Figure 1 (left).

To ensure a high efficiency for single high energy electron detection on top of the large and widely spread background from beamstrahlung, calorimeters with a small Molière radius are needed. Such compact calorimeters also ensure the necessary precision in the angular reconstruction of Bhabha scattering events.

Due to the high occupancy originating from beamstrahlung and two-photon processes, both calorimeters need a dedicated fast readout. In addition, the lower polar angle range of BeamCal is exposed to a large flux of low energy electrons, resulting in depositions up to one MGy per year. Hence, radiation hard sensors are necessary.

Since in both calorimeters a robust electron and photon shower measurement is essential, a small Molière radius will be preferable. Compact cylindrical sandwich calorimeters using tungsten absorber disks of one radiation length thickness, interspersed with finely segmented silicon (LumiCal) or GaAs (BeamCal) sensor planes, as sketched in Figure 1 (right), are found to match the requirements from physics [1]. LHCal will be designed with a small hadronic interaction length, to fit into the limited space available.

3 Prototype Construction and Beam Tests

3.1 Currently used Sensors and ASICs

Large area GaAs sensors, as shown in Figure 2 (left), were developed and produced in collaboration with partners in industry. The Liquid Encapsulated Czochralski technology is used. The sensors were doped by a shallow donor (Sn or Te), and then compensated with Chromium. This results in a

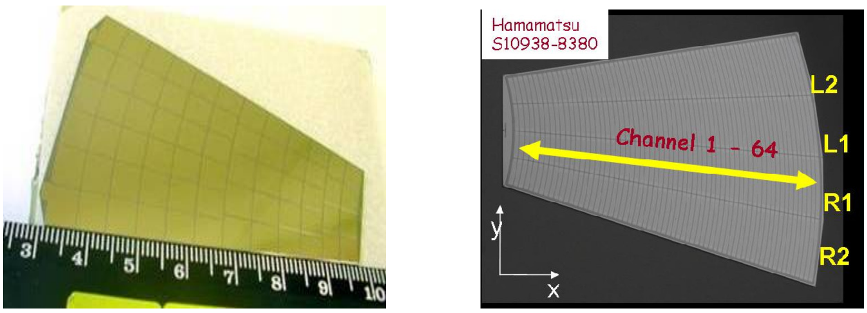

Figure 2: Left: A GaAs pad sensor developed for BeamCal, Right: A silicon pad sensor manufactured by Hamamatsu Photonics.

semi-insulating GaAs material with a resistivity of about $10^7 \Omega m$. The sensors are 0.5 mm thick with pads of a few mm^2 area. The operation voltage is about 100 V with leakage current per pad less than 500 nA.

Prototypes of LumiCal sensors have been designed at the Institute of Nuclear Physics PAN in Cracow [2] and manufactured by Hamamatsu Photonics. Their shape, as shown in Figure 2 (right), is a ring segment of 30°. The thickness of the n-type silicon bulk is 0.320 mm. The pitch of the concentric p^+ pads is 1.8 mm and the gap between two pads is 0.1 mm. The bias voltage for full depletion ranges between 39 and 45 V, and the leakage currents per pad are below 5 nA.

Dedicated ASICs were designed choosing an architecture [3, 4] comprising a charge sensitive amplifier and a shaper. ASICs, containing 8 front–end channels, were designed and fabricated in 0.35 μm CMOS technology. A variable gain in both the charge amplifier and the shaper is implemented by a mode switch. The peaking time of the shaper output signal is 60 ns. More results of the measurements of the performance were published elsewhere [5]. A dedicated low-power, small-area, multichannel ADC is designed and produced [6]. It comprises eight 10-bit power and frequency (up to 24 MS/s) scalable pipeline ADCs and the necessary auxiliary components. The readout system containing 32 channels (four pairs of 8-channel front–end and ADC ASICs) was developed and used successfully in several test-beams, confirming that the chosen readout architecture fulfills the LumiCal requirements.

3.2 Development of FLAME Readout ASICs

The main limitation of the existing readout is the number of channels, allowing to build only small (32 readout channels) prototype of detector modules. For this reason a new development of LumiCal readout ASICs called FLAME (FcaL Asic for Multiplane rEadout) has been started. The block diagram of FLAME is shown in Figure 3. The FLAME uses the same architecture as the previous readout, with analog front–end and 10-bit ADC in each channel. The main differences and improvements are listed below.

- FLAME is developed in smaller size TSMC 130 nm CMOS technology. This choice allows to obtain large reduction of power consumption and much better radiation hardness.

- FLAME is a System on Chip (SoC) solution comprising all functionality (analog front–end, ADC, data serialization and transmission) in one ASIC. It will simplify the architecture of the overall readout system and minimise the number of its components.

- FLAME ASICs comprise 32-channels. Designing a readout board with 8 ASICs one can build a detector module reading the whole LumiCal sensor tile, containing 256 channels.

- FLAME is built of two identical 16-channel blocks. The data from each block is sent out by a very fast (5.2 Gbps) serializer and serial data transmission block. The output data is coded and formatted so that it may be directly received by fast FPGA links.

The development of FLAME is in advanced stage. Two prototypes of critical blocks, i.e. 8-channel front-end plus ADC ASIC and serializer and data transmission ASIC, were designed fabricated and tested. Presently the design of complete FLAME is ongoing.

3.3 Data Concentrator and DAQ

In order to operate a large amount of sensor planes the readout has to be orchestrated. For this purpose a FPGA based data concentrator is foreseen. The prototype of a DAQ module based on an AC701 evaluation board which contains Artix 7 FPGA has been built [7]. The module will read data sent by FLAME (ASIC), process them and send to an external data store using ethernet transmission. The current prototype architecture with the generated blocks inside the FPGA is shown in Figure 4.

3.4 High Quality Tungsten Absorber Plates

A batch of 25 absorber plates has been fabricated by partners in the industry. The absorber composition is W 92.5%, Ni 5.25%, and Cu 2.25%. The material density is 18.0 g/cm^3. The thickness of the plates has been assessed using a Zeiss 3D coordinate measurement system with a precision 2.5 μm. Front and back side measurements were done. The deviation from planarity is for most of the plates within 50 μm as shown in Figure 5.

3.5 Mechanical Stack

A flexible mechanical structure, as shown in Figure 6, has been built as part of the AIDA project, to compose a technological calorimeter prototype instrumented both with LumiCal and BeamCal sensors. Tungsten absorber plates, glued on a permaglass frame, are precisely positioned on a rod assembly, and interspersed with fully assembled sensor planes. The flatness of the absorber plates is better than 50 μm to allow for highly compact packing of sensor and absorber planes. This stack will be completed with absorber plates of the necessary quality up to a total thickness of 30 radiation length.

4 Test-beam Results

Test-beams were used to continue radiation hardness studies and study partly instrumented calorimeter prototypes. Recent milestones were the measurements in the test-beam of a four sensor-layer prototype [8] and of

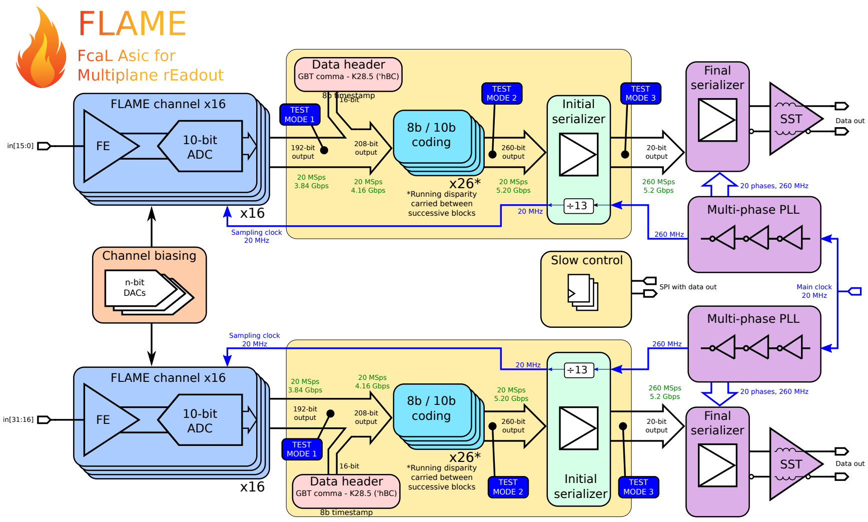

Figure 3: A block diagram of FLAME readout ASIC.

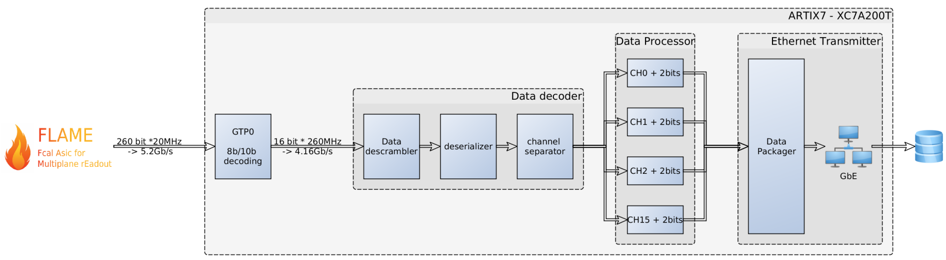

Figure 4: Block diagram of the prototype FPGA module.

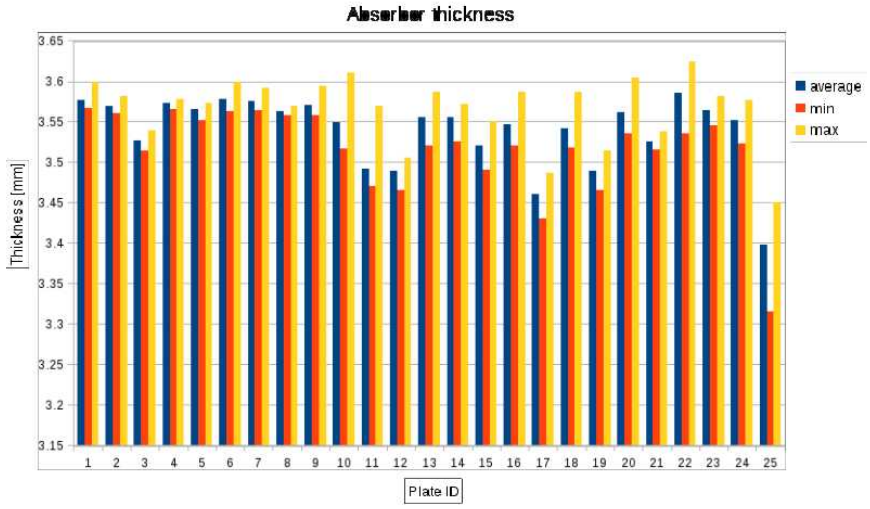

Figure 5: Thickness of the tungsten absorber planes. Average thickness and minimum and maximum deviation from planarity is shown.

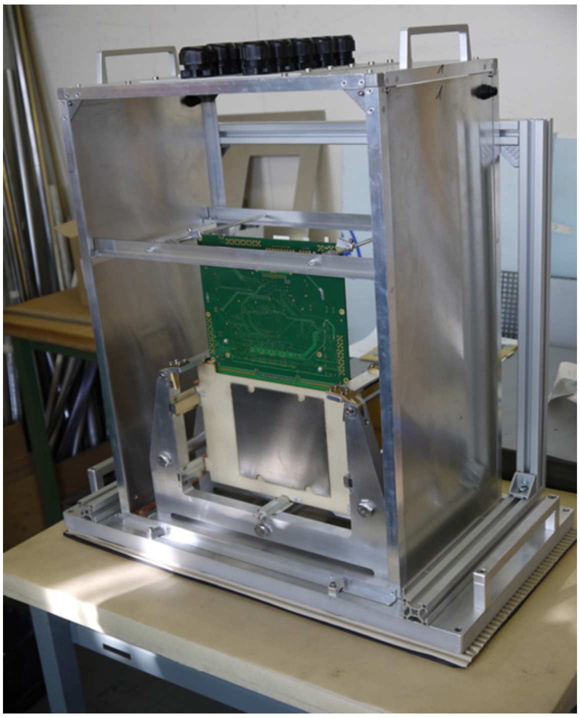

Figure 6: Photograph of the flexible mechanical structure. Tungsten absorber plates, glued on permaglass frames, are put into slots of the rod assembly.

a six sensor-layer prototype. The results on the performance, being for the latter prototype still preliminary.

4.1 Radiation Damage Studies

Two studies of the radiation tolerance of potential BeamCal sensors have been carried out. In the first study, the radiation tolerance of prototype GaAs sensors has been explored by exposing the sensors to direct radiation from a high-intensity electron beam of about 10 MeV [9], which is typical of the energy expected from beamstrahlung remnants at ILC. It was found that the sensors can be operated at room temperature up to approximately 1 MGy without a significant increase in the leakage current [10]; however, significant loss in the response to ionizing particles was observed. This loss can be partially compensated, however, by increasing the bias voltage. In addition, a new round of GaAs:Fe prototype production includes a small dopant concentration of iron, which is expected to mitigate radiation damage effects. Characterization of these new prototypes is expected soon.

In the second study [11], several different solid-state sensor technologies were exposed to varying levels of radiation induced by electrons from the SLAC End Station A Test Beam (ESTB). For this study, the ESTB test beam, with energies varying between 3 and 15 GeV, was directed into a tungsten beam stop. The beam stop was split at the depth of the shower maximum and the sensor inserted, leading to an exposure incorporating the full spectrum of particle species that will irradiate the BeamCal sensors. Silicon diode and bulk GaAs, Sapphire and SiC sensors were exposed to doses of up to 6 MGy of ionizing radiation, along with the attendant dose of non-ionizing hadronic radiation associated with the electromagnetic shower. For GaAs, observed charge collection loss was similar to that of the first study, although a room-temperature leakage current of order 10 μA/cm^2 was observed for 1 MGy-scale doses for a sensor bias of 600 V. No significant leakage current was observed for SiC and Sapphire sensors irradiated to 0.8 MGy and 3 MGy, respectively. For these doses, the charge-collection loss in SiC was approximately 50% and for Sapphire, which has low charge collection even before irradiation, approximately 75%. Observed charge collection loss was somewhat better for silicon diode sensors: a p-type, float-zone sensor irradiated to 6 MGy experienced less than 40% charge-collection loss. However, the silicon diode sensors developed a significant leakage current. After beneficial annealing, leakage currents of several hundred μA/cm^2 per MGy of exposure were observed for room-temperature operation at full depletion voltage. Lowering the operating temperature to -30° C reduced the leakage current by over two orders of magnitude. A study [12] based on a simulation of the BeamCal radiation field making use of the FLUKA Monte Carlo[13], and damage coefficients determined from the ESTB results, estimated the accumulated power draw for a BeamCal instrumented with silicon diode sensors operated at -30° C would be less than 10 W per year of operation.

4.1.1 Performance of a Prototype Calorimeter

Prototypes of detector planes assembled with FE and ADC ASIC, as shown in Figure 7, were built using LumiCal and BeamCal sensors [14], and successfully operated in test-beam [15]. In the next step four detector planes

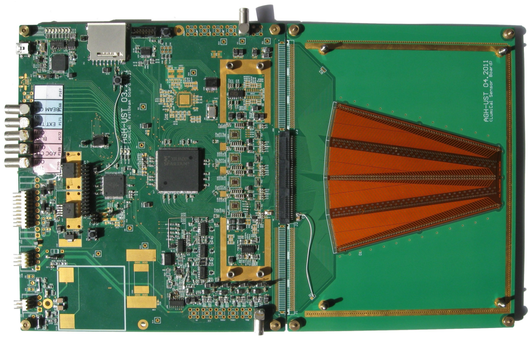

Figure 7: Photograph of a fully instrumented detector plane for FCAL.

using silicon sensors were used to study the performance of a prototype calorimeter in an electron and a muon beam. Different numbers of uniform absorber plates were positioned in front and in between the detector planes in each run, allowing to study the longitudinal and lateral shower development. This first prototype, due to the large thickness of the instrumented readout boards, was not as compact as finally needed, but allowed the demonstration that the multilayer operation and readout is successful. In addition, very good agreement between data and Monte Carlo simulation was obtained in the lateral and longitudinal shower development and the precision of the shower position reconstruction. The Molière radius was measured to be 24.0±1.7 mm

In following test-beam campaigns eight thin detector planes, as shown in Figure 8, interspersed by tungsten absorbers of 1 radiation length thickness were used. The sensors were read out using the APV25 chip [16, 17] hybrid board. It has 128 channels and two boards read a whole LumiCal sensor. Capacitive charge dividers were used to enlarge the dynamic range of the APV25 chip. The powering circuits and the fan-out part which connects silicon sensor pads with the front-end board inputs were made from flexible Kapton-copper foils with thickness of 70 μm for the high voltage one, applied to the back n-side of the sensor and about 120 μm for the fan-out. Ultrasonic wire bonding was used to connect conductive traces on the fan-out to the sensor pads. A support structure made of carbon fiber composite with a thickness of 100 μm in the sensor-gluing area provides mechanical stability. The ultrasonic wire bonding proved to provide good electrical performance,

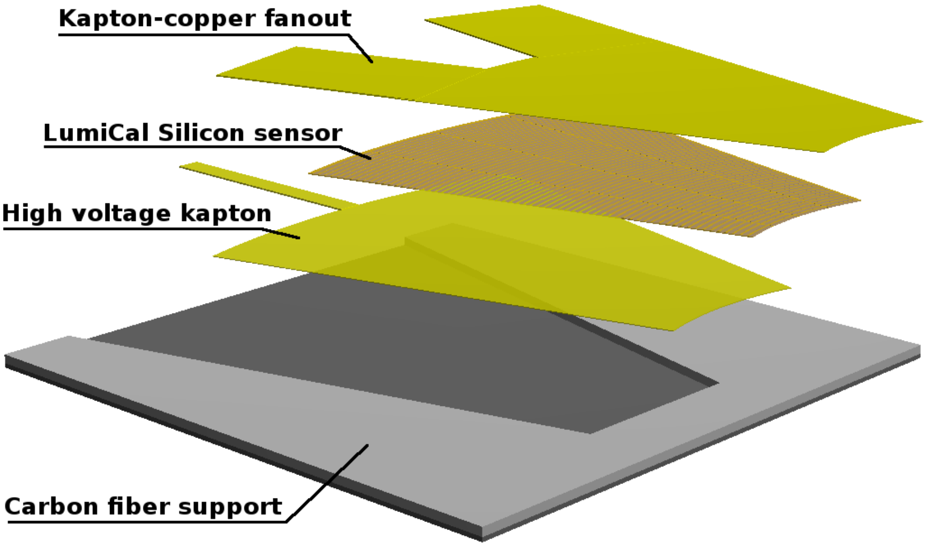

Figure 8: Thin LumiCal module assembly. The thickness of adhesive layers (not shown) between components is within 10 - 15 μm. The total thickness is 650 μm.

but for a module thinner than 1 mm, the wire loops, which are typically 100$-$200 μm high, cause a serious problem when the module needs to be installed in a 1 mm gap between absorber plates. The bonding machine was tuned to make the loop as low as possible and technically acceptable. The sampling based measurements, which were done using a con-focal laser scanning microscope, show that the loop height is in the range from 50 μm to 100 μm. The total thickness of the sensor plane was 650 μm.

The calorimeter prototype was studied in a 1 to 5 GeV electron beam at DESY. The shower position was reconstructed with a resolution of (440$\pm$20)μm. The average transverse shower profile is shown in Figure 9 for data and Monte Carlo simulation. Very good agreement is found. The effective Molière radius is determined to be 8.1$\pm$0.3 mm in data and 8.4$\pm$0.1 mm in Monte Carlo simulations.

5 Engineering Challenges

Engineering challenges within the current and future research of FCAL are the following:

- A slim assembled sensor plane. First prototypes of a ultra-thin sensor planes have been successfully manufactured and used in test-beam measurements. These technologies need to be completed and transferred into mass production.

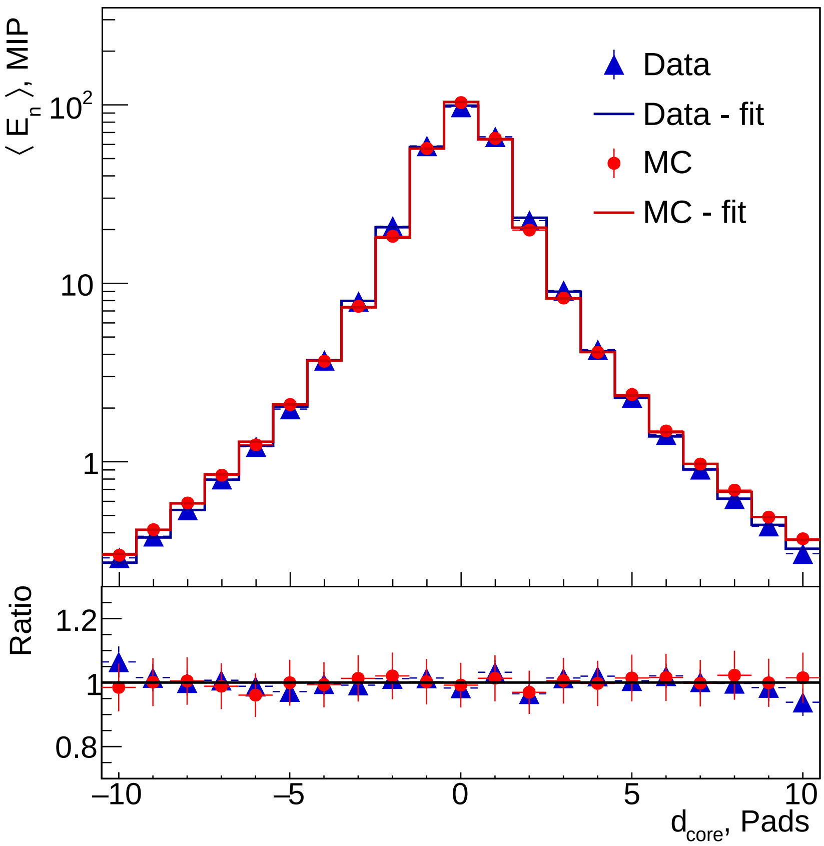

Figure 9: The average transverse shower profile, $\langle E_n^{det} \rangle$, as a function of the distance from the core, d_{core}, in units of pads, for data (blue triangles) and MC simulation (red circles). The histograms are the results of fits to data and MC using a parametrisation of the shower shape. The lower part of the figure shows the ratio of the distributions to the fitted function, for the data (blue) and the MC (red).

- Multichannel front-end and ADC ASICs for the technological calorimeter prototype. A compromise must be found between integration, miniaturization and costs.
- Operation using power pulsing to avoid active cooling.
- A dedicated solution for data concentration, data reduction and transmission, allowing read out of the full calorimeters after each bunch crossing.

- Precise alignment and position monitoring. The inner radius of LumiCal has to be controlled with a precision of about 10 μm, and the distance between the calorimeters on both sides of the IP with a precision of 100 μm.
- Montage and demontage of the calorimeters must be done when the beam-pipe is installed. The calorimeters must be segmented at least in two half cylinders, and corresponding auxiliary mechanics has to be developed.

6 Future Plans

6.1 Novel Sensor Materials

The performance of single crystal Sapphire sensors to detect minimum ionising particles has been studied for the first time [18]. Sapphire sensors are a promising alternative for GaAs to instrument the region near the beam-pipe where a high radiation field is expected.

With Hamamatsu Photonics the design of edge-less silicon sensors is under preparation. Using edge-less sensors in LumiCal would avoid performance losses in gaps between sensor segments.

6.2 Technological Calorimeter Prototype

Currently the goal of FCAL is to prepare a full depth calorimeter prototype instrumented with more than 20 detector planes for test-beam measurements. These measurements are essential firstly to develop and test engineering solutions to build a very compact calorimeter and secondly to verify the results of Monte Carlo studies. Depending on the test beam results the calorimeter may be redesigned. For the prototype calorimeter a mechanical structure, a sufficient amount of front-end and ADC ASICs, FPGAs for data concentration and a data acquisition system are needed. In addition, two-planes of a pixel tracker in front of LumiCal will be prepared to improve the polar angle resolution.

6.3 Alignment and Position Monitoring

A laboratory set-up for position monitoring has been constructed by IFJ-PAN Cracow using semi-transparent silicon sensors [19]. Test measurements demonstrated that position monitoring with μm precision is possible. A design how to integrate the system in a larger detector has still to be developed.

6.4 Front-End and ADC ASICs

The FLAME development, pursued within AIDA by UST Cracow, will be completed, and an amount of sensors will be fabricated to be used in the larger calorimeter prototype.

A dedicated ASIC development is ongoing for BeamCal [20] with a special option for a fast readout of a reduced amount of information from a few bunch-crossings to be used for a fast feedback system for beam-tuning [21]. A small prototype of a pixel sensor readout for the pair monitor, positioned in front of BeamCal was designed in SoI technology [22]. This development is foreseen to be continued.

6.5 Data Acquisition

Ongoing further work will focus on the ethernet transmission.The higher level DAQ will depend on the functionality of the data concentrator. For the readout of test-beam data software is developed, mainly by the University of Tel Aviv, which can be easily adopted. For the final device FCAL will follow the developments of a common DAQ for all detectors.

7 Applications Outside of Linear Colliders

The expertise acquired within FCAL for radiation hard sensors and fast front-end electronics was used to build, commission and operate fast beam-conditions monitors at the CMS experiment at LHC. Radiation hard sensors developed within FCAL are used as beam-loss monitors with excellent time resolution at FLASH, XFEL and LHC. In addition, front-end ASICs are under development for the upgrade of the LHCb tracker.

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