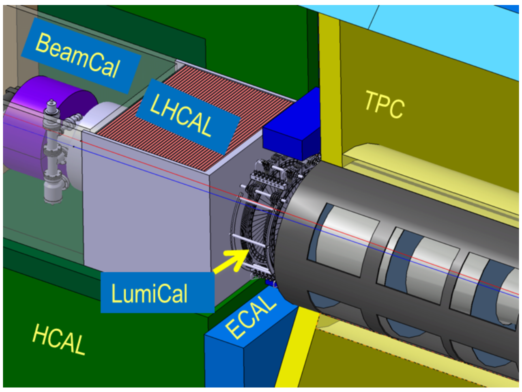
FCAL R&D
Development of highly compact and precise luminometers

Contents

1 Forward Calorimetry at Linear Colliders

1.1 Mission and Challenges

Two special calorimeters are foreseen in the very forward regions of a linear collider detector, denoted hereafter as LumiCal and BeamCal. These calorimeters will deliver both a fast and a precise measurement of the luminosity and extend the detector coverage to low polar angles, important e.g. for new particle searches with missing energy signature. Detailed Monte Carlo studies have been performed in all member institutes to optimise the design of the calorimeters, estimate the background from physics processes and understand the impact of beam-beam interactions on the luminosity measurement. More details can be found in Ref. [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 very compact calorimeters are needed. In addition, compact calorimeters facilitate the reconstruction of Bhabha scattering events. Due to the



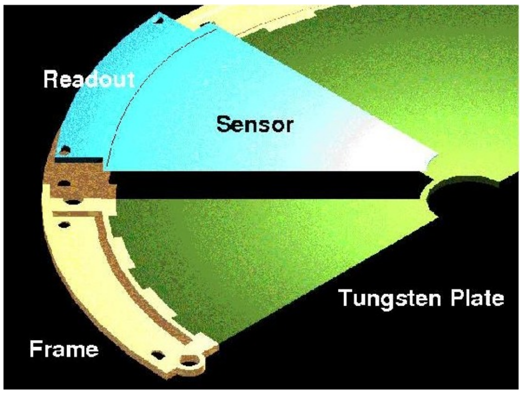


Figure 1: Left: The very forward region of the ILD detector. LumiCal, BeamCal and LHCAL are carried by the support tube for the final focusing quadrupole QD0 and the beam-pipe. TPC denotes the central track chamber, ECAL the electromagnetic and HCAL the hadron calorimeter. Right: A half layer of an absorber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

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 needed.

1.2 Mechanical Concept

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] .

2 Towards a Technical Design

2.1 Sensors and ASICs

Large area GaAs sensors, as shown in Figure 2, were developed and produced in JINR (Dubna) 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 semi-insulating GaAs material with a

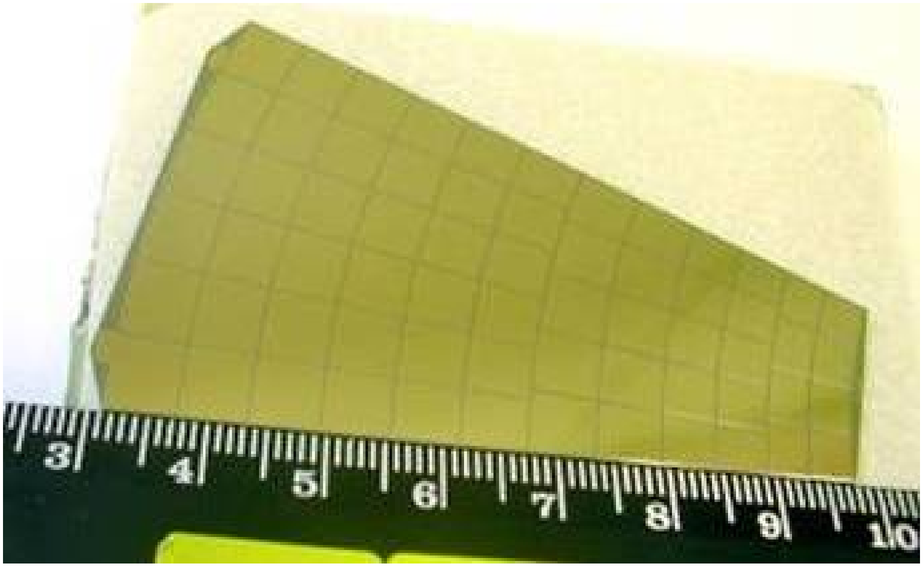


Figure 2: A GaAs pad sensor developed for BeamCal.

resistivity of about 10^7 Ωm. 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 and manufactured by Hamamatsu Photonics. Their shape 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 [2].

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 micrograph of the prototype, glued and bonded on the PCB, is shown Figure 3. 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

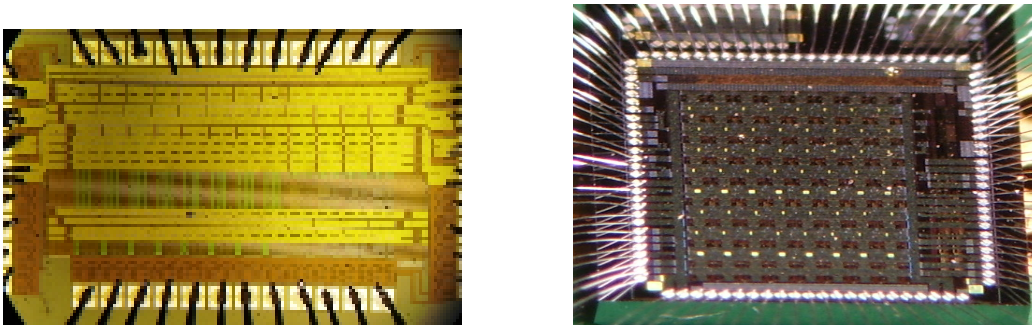


Figure 3: Left: Micrograph of front–end ASIC. Right: Micrograph of ADC ASIC.

comprises eight 10-bit power and frequency (up to 24 MS/s) scalable pipeline ADCs and the necessary auxiliary components. A micrograph of the prototype is shown in Figure 3.

A dedicated ASIC development is ongoing for BeamCal [7] in the Pontificia Universidad Catolica de Chile with a special option for a fast readout of an reduced amount of information from each bunch-crossing to be used for a fast feedback system for beam-tuning.

A prototype of a pixel sensor readout for the pair monitor, positioned in front of BeamCal was designed in SoI technology, build and tested by Tohoku University [8].

2.2 Test-beam Results

Several test-beam campaigns were done to investigate the performance of single fully instrumented sensor planes, both for LumiCal and BeamCal. Prototypes of sensor planes assembled with FE and ADC ASICs, as shown in Figure 4, were built using LumiCal and BeamCal sensors [9]. The detector plane prototypes were installed in an electron beam and

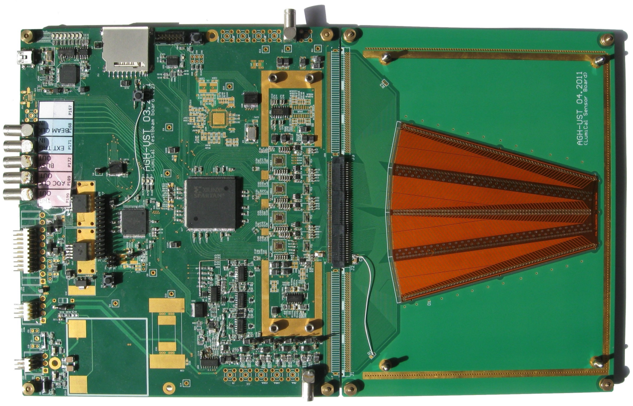
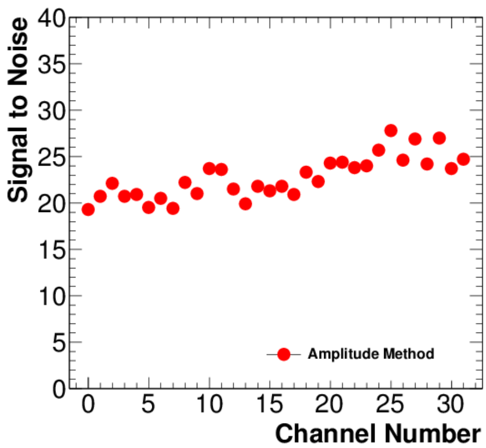


Figure 4: Photograph of LumiCal readout module with sensor connected.

the trajectories of beam particles were measured by four planes of a silicon strip telescope. The front-end electronics outputs were sampled synchronously with the beam clock, a mode later used at the ILC. Data were taken for different pads and also for regions covering pad



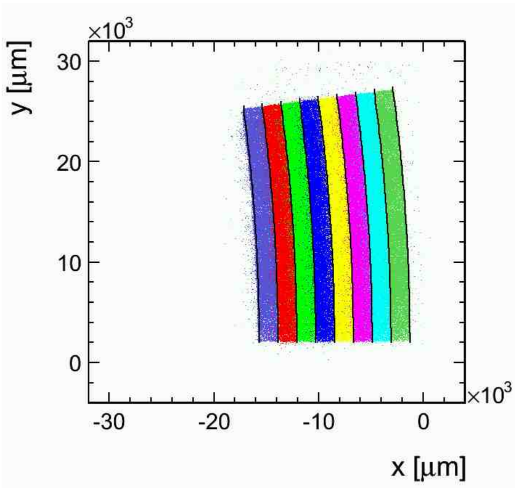


Figure 5: Left: The signal-to-noise ratio of all readout channels. Right: Distribution of the predicted impact points on pads with a color coded signal.

boundaries. Signal-to-noise ratios of better than 20 are measured for beam particles both for LumiCal and BeamCal sensors, as illustrated in Figure 5 (left). The impact point on the sensor is reconstructed from the telescope information. Using a colour code for the signals on the pads the structure of the sensor becomes nicely visible, as also seen in Figure 5 (right). The sensor response was found to be uniform over the pad area and to drop by about 10 % in the area between pads.

2.3 Radiation Damage Studies

Two studies of the radiation tolerance of potential BeamCal sensors have been carried out. The radiation tolerance of prototype GaAs sensors has been explored by exposing the sensors to direct irradiation from a high-intensity electron beam of about 10 MeV [10], which is an energy expected from beamstrahlung remnants at the ILC. It was found that the sensors can be operated up to approximately 1 MGy of this type of radiation without a significant increase in the leakage current [11]; however, significant loss in the response to ionising particles was observed. In addition, several different silicon-diode sensor technologies were exposed to varying levels of radiation induced by the SLAC End Station A Test Beam (ESTB). For this study, the ESTB test beam, with energies varying between 3 and 11 GeV, was directed into a tungsten beam stop. The beam stop was split at approximately shower-max and the sensor inserted, leading to an exposure incorporating the full spectrum of particle species that will irradiate the BeamCal sensors. Both n-type bulk oxygenated float-zone and magnetic Czochralski detectors were explored, with exposures varying from 0.2 to 2.2 MGy as allowed by the limited exposure rate and beam availability. It was found that, after allowing for a short period of controlled annealing, all sensor types withstood the maximum dose that they received with little loss in response to ionizing particles [12], but with some increase in leakage current. Further annealing studies, geared towards achieving a minimal post-irradiation leakage current, continue. Further irradiation studies in the ESTB are planned for the spring running periods of 2014 and 2015. The sensor assessment (charge-collection efficiency) apparatus at the Santa Cruz Institute for Particle Physics is being adapted for the evaluation of pad sensors, which will allow for radiation damage studies of the prototype GaAs sensors in this realistic electromagnetic shower environment. Studies to push the silicon diode sensors to higher levels of irradiation are also planned.

2.4 Technological Prototype

Currently the goal of FCAL is to prepare a calorimeter prototype 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 testbeam results the calorimeter may be redesigned. For the prototype calorimeter a mechanical structure, a sufficent amount of front-end and ADC ASICs, FPGAs for data concentration and a data acqusition system are needed.

2.4.1 Mechanical Stack

A flexible mechanical structure, as shown in Figure 6, has been built as part of the AIDA I project at CERN, to ompose a calorimeter prototype instrumented both with LumiCal and BeamCal sensors. Tungsten absorber plates, glued on a permaglass frame, are precisely positioned on a precise rod assembly, and interspersed with fully assembled sensor planes. The flatness of the absorber plates is better that 50 μm to allow high compact packing of sensor and absorber planes.

2.4.2 Alignment and Position Monitoring

I laboratory set-up for position monitoring has been contructed by IFJPAN Cracow using semi-transparent silicon sensors. Test measurments demonstrated that position monitoring with μm precison is possible.

2.4.3 Front-End and ADC ASICs

To match the requirements of extremely low power consumption and taking into account possible radiation fields in the very forward region, a new development of the front-end and ADC ASICs in deep submicron 130 nm CMOS technology has been pursued within AIDA by UST Cracow. These ASICs will be sufficiently fast to be used both in LumiCal and BeamCal. The overall readout architecture, so far successfully produced in 350 nm CMOS technology and used in the test-beam measurements as described above, has not been changed and comprises separated front-end and ADC ASICs for each readout channel. For both FE and ADC ASICs prototypes, as shown in Figure 7, are produced and under test. The result so far are very promising.

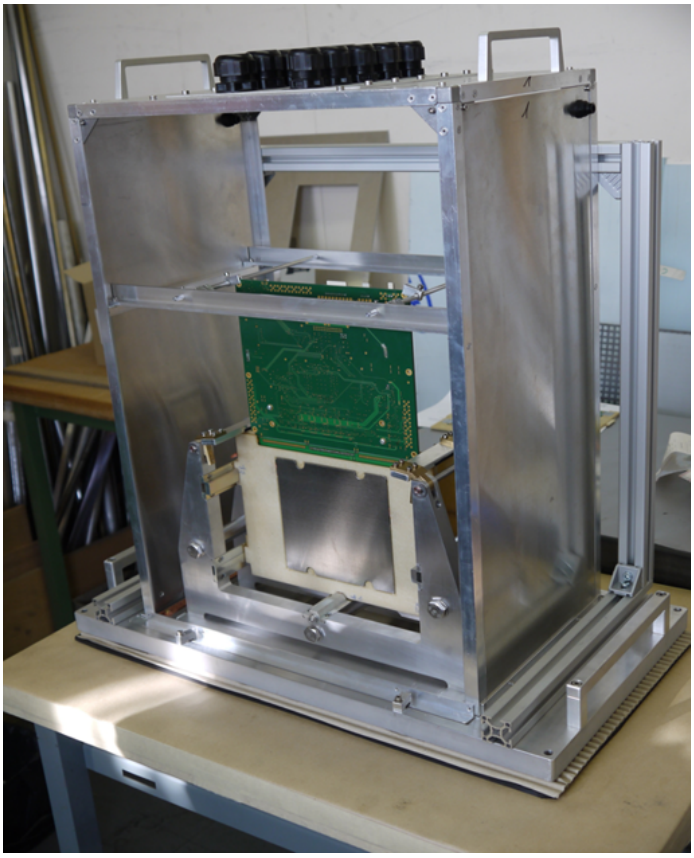


Figure 6: Photograph of the flexible mechanical structure. Tungsten absorber plates, glued on perma-glass frames, are put into slots of the rod assembly.

2.4.4 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 which may deliver data in the so called AIDA protocol. The design of this device is currently under discussion. The higher level DAQ will depend on the functionality of the data concentrator. For the readout of test-beam data we have software, mainly developed by University of Tel Aviv, which can be easily adopted. For a final device FCAL will follow the developemnts of a common DAQ for all subdetetors.

3 Engineering Challenges

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

- a slim assembled sensor plane. The space between absorber planes must be kept as small as possible. The fan-out to move the signals from the sensor pads to the outside

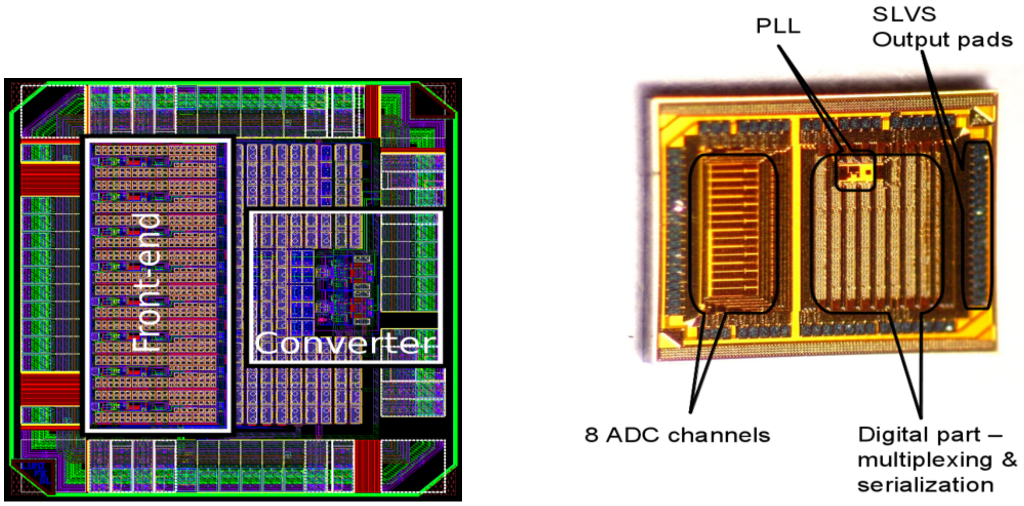


Figure 7: Left: 8 channel FE ASIC in 130 nm technology. Right: ADC ASIC in 130 nm technology.

radius must be very thin and hence a new connectivity technology must be applied.

- multichannel front-end and ADC ASICs for the prototype. A compromise must be found between integration, miniaturisation and costs.
- operation using power pulsing.
- a dedicated solution for data concentration, data reduction and transmission.
- precise alignment and position monitoring.

4 Perspectives of this R&D for Applications beyond the ILC

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 and LHC. A design for beam-loss monitors for XFEL is prepared. In addition, front-end ASICs are under development for the upgrade of the LHCb tracker.

5 Member Institutes of FCAL

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DESY, Zeuthen, Germany;

IFIN-HH, Bukharest, Romania;
IFJPAN, Cracow, Poland;
ISS Bukharest, Romania;
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Tel Aviv University, Tel Aviv, Israel;
Tohoku University Sendai, Japan;
University of Colorado Boulder, USA;
University of California Santa Cruz, USA;
VINCA Institute of Nuclear Science & University of Belgrade, Belgrade, Serbia

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