# Contents

# Chapter 1

# Calorimeter R&D

## 1.1 Scintillator Strips

### 1.1.1 Introduction

The CALICE scintillator strip-based ECAL (ScECAL) uses a scintillator strip structure to deliver the granularity and resolution required of an ILC detector. Each strip is individually read out by a Multi Pixel Photon Counter (MPPC, a silicon photon detector produced by Hamamatsu Photonics KK̇ [1]). Although plastic scintillators have been widely used in calorimeters, this is the first time that a highly granular calorimeter has been made using scintillator strips. Such an ECAL has a smaller cost than alternative technologies using silicon sensors (e.g. [2]). The MPPC has promising properties for the ScECAL: a small size (active area of $1\times1\,\mathrm{mm}^2$ in a package of $4.2\times3.2\times1.3\,\mathrm{mm}^3$), excellent photon counting ability, low cost and low operation voltage (80 V), with disadvantages of temperature-dependent gain, saturation at high light levels, and a relatively high dark noise rate. The use of tungsten absorber material minimises the Moliere radius of the calorimeter, an important aspect for the effective separation of particle showers required by PFA reconstruction. The chosen strip geometry allows a reduction in the number of readout channels, while maintaining an effective granularity given by the strip width, by the use of appropriate reconstruction algorithms. One such algorithm, know as the Strip Splitting Algorithm [3], has been developed and demonstrated to perform well in jets expected at ILC.

### 1.1.2 Recent Milestones

- introducing a new scintillation light readout scheme, with different scintillator strip shape by having better homogeneity
- photo-sensor of increased number of pixels in 1mmx1mm, this leads larger dynamic range for the calorimeter
- more experience on the FE read out board and ASICs

They are not published yet, instead some proceedings

### 1.1.3 Engineering Challenges

- wrapping the scintillator strip and align them on the FE read out layer automatically
- mass test facility for the read out layer

### 1.1.4 Future Plans

- optimizing scintillator layer: shape of scintillator strip, how to read out scintillation light, the location of photo-sensor, size and shape of photo-sensor and mass production scheme
- developing photo-sensor with Hamamatsu photonics company, to have lager dynamic range and mass test scheme
- establish a detector fabrication plan

### 1.1.5 Applications Outside of Linear Colliders

- photo-sensor named MPPC from Hamamatsu photonics INC is employed for the T2K experiment, CMS upgrade (HC-CAL), BELLII detector (end-cap muon)
- PET and SPECT development

## 1.2 Silicon-Tungsten ECAL in ILD

### 1.2.1 Introduction

The silicon-tungsten electromagnetic calorimeter for ILD aims to develop a highly granular detector optimized for particle flow performance. The calorimeter uses a sandwich architecture with $5 \times 5\,\mathrm{mm}^2$ silicon pads as active elements embedded in an alveola structure made of tungsten. The group is active in the development of simulation software and algorithms for calorimeter reconstruction, as well as engineering for the design, and fabrication of the readout chips.

### 1.2.2 Recent Milestones

The work is now focusing on the construction of a technological prototype. This is a new milestone after the successful operation of the "Physics Prototype" in the years 2004–2011, including large scale beam tests at DESY, CERN at FNAL and data analysis [4]. An analysis of data recorded in 2007 [5] gives confidence that embedding the front end electronics into the calorimeter layers does not compromise the detector performance.

For the technological prototype, the SKIROC ASIC will be embedded into the calorimeter layers and mounted on 9 layer PCBs that will be as thin as 1.5 mm. Silicon wafers, the PCB and the 16 mounted circuits constitute the Active Signal Units or ASUs. Up to ten of these ASUs will be assembled to form a calorimeter layer. The technology of the interconnections was applied with success to first units of the technological prototype.

A series of beam tests with simplified ASUs have been carried out in the years 2012 and 2013 at DESY. The analysis of these data validated the concept of the front end electronics but will also allow for correcting a small number of shortcomings of the SKIROCs ASIC. These will be corrected in the version SKIROC2b that is supposed to be produced at the end of 2014. A paper on the analysis of the 2012 data has been submitted to JINST in March 2014. Particularly in summer 2013 (i.e. Post-DBD phase), update? the SKIROC ASIC has been operated in power pulsed mode. For this bias currents of the ASIC are shut down and raised with a given frequency (5 Hz for ILC, 10 Hz in our beam tests). The good agreement between the MIP spectra obtained in power pulsed and conventional mode (see e.g. [6]) give confidence that this technology can indeed be applied for a calorimeter at a linear collider and more precisely at the ILC. More studies are needed as the technological prototype grows in size.

Other recent accomplishments include:

- R&D on scalable technology for all the involved large detector aspects (integration of embedded readout chips, on thin supporting electronics boards, in self-supporting tungsten–carbon mechanical elements ensuring the cooling and protection; all made of exchangeable elements with a quality control procedure; the associated DAQ). is this completed?
- Realization of a large self-supporting W–Carbon fiber structure with integrated stress monitoring (using Fiber Bragg Grating) date?
- Beam tests of base sensor units of the technological prototype
- Submission of a paper on the analysis of 2012 beam test data to JINST [7],[8].
- Reconstruction tools adapted to the high granularity calorimeters (photon reconstruction [GARLIC], Advanced clustering [ARBOR], event displays [DRUID]) Recent? Reference Reference Reference
- Operation of SKIROC [9] in pulsed power mode (with 5 Hz as foreseen by ILC baseline and with 10 Hz as envisioned in high luminosity operation).
- SiECAL test beam experiments were carried out in Jul. 2012, Feb. and Jul. 2013 to test the SiECAL technological prototype. The front-end electronics of the prototype was integrated into an active layer to realize a highly granular calorimeter. In the 2012 test beam, we operated six layers under a continuous current mode. The achieved signal to noise ratio was greater than 10 with SKIROC2 ASICs. In the 2013 test beams, we successfully operated and took data with the prototype under a power pulsing mode. At the same time, we found several issues related to the power pulsing operation. Digital lines on the front-end electronics disrupts analog signals. We had to wait 600 μs for the electronics to stably take the data. We measured pedestal signals in a magnetic field, and confirmed that active channels were working in stable up to 2 T.

As for the R&D of silicon sensors, we measured several new samples with different guard ring types. It is known that a Si sensor makes small fake signals along with its sensor edge when a large amount of current is generated by an electromagnetic shower in a calorimeter. If the fake signal is reasonably small, we can use the Si sensor for the ILD. To test the fake signal, we introduced an infrared laser system in Kyushu University to measure the Si sensor response with a similar condition of beam test in a laboratory scale. We are setting up a multi-pixel readout system without SKIROC2 ASIC. We can then measure the intrinsic Si sensor properties with the IR laser system. Studies on the SiECAL optimization have been performed with full ILD detector simulation. We performed simulation studies with different setting of PCB thickness, dead volume related the sensor edge, and fraction of dead channels. We found:

- The PCB thickness does not change the performance of the jet energy resolution.
- The dead volume proportionally degrades the performance, but the current Si sensor design is acceptable.
- The fraction of dead channels does not much degrade the jet energy resolution up to the fraction of 5%.

### 1.2.3 Plans of the near future

The different units of the SiW Ecal for the ILD detector need to be assembled into detector layers of up to two meter in length comprising up to 10 detection units dubbed ASUs. For this we propose to develop an assembly line, incorporating the reception and the test of the material, the alignment of the ASUs and the interconnection, with a continuous monitoring for quality control purposes. The deliverable is a still manual assembly bench capable for a small production of layers. Based on the manual assembly bench we will propose an automatized system for mass assembly together with industrial partners. A survey to search for partners is part of the proposal. A goal is to design the system such that it can be easily duplicated at other sides. In the ideal case the assembly bench is versatile enough to reply to needs for other detector systems than ILD (e.g. CMS). Other Detector R&D plans include:

- Test beam experiments with long SiECAL slabs using new front-end electronics with SKIROC2 ASICs,
- Completion of the SKIROC3 ASIC, which has all the features needed at the ILC.
- Combined test beam experiments with ScECAL and AHCAL,
- Development a DAQ system (set up of hardwares, development of software and firmware) for the combined tests.
- Further R&D of silicon sensors, using the IR laser system, to determine the final design.
- Irradiation test with several types of Si sensors.

- Looking for Japanese companies which can produce SiECAL front-end electronics in prospect of mass production.

- Further optimization of SiECAL and Hybrid ECAL with full ILD detector simulation.

### 1.2.4 Engineering Challenges

The following challenges will have to be addressed when proposing this technology for an ILC detector:

- Silicon wafer cost reduction when used for calorimetry; direct contact with producers established (Hamamatsu, On-Semi, ...).

- A chip with the good dynamic, noise, power dissipation (using power pulsing), etc.

- Integration in a compact device, ensuring all the requests (precision: electronic and mechanic, heat production, reliability)

- Industrialization of solutions; scalability of tests for a 100M channel detector.

### 1.2.5 Applications Outside of Linear Colliders

- CEPC, TLEP and CMS upgrade have possible applications for this technology

- The compact Silicon-W design has been used in the PAMELA satellite (very similar to physics prototype) [10]

## 1.3 Silicon Tungsten SiD ECAL

This note describes the theory of the mechanical aspects of the E-Cal system for SiD. The E-Cal barrel consists of stacks of tungsten heavy metal plates which are arranged in modules surrounding the beamline. Full cylindrical coverage of the baseline design is attained with twelve modules (see Figure 1.1) occupying a radial envelope from 1265 mm to 1409 mm. The total barrel length is 3.53 m. Each module uses 20 inner plates which are 2.5 mm thick followed by ten 5 mm thick plates. Gaps between adjacent plates are 1.25 mm and house the silicon detectors with their associated cables (see Figure 1.2). These hexagonal silicon detectors are electrically connected to each other with thin, flexible circuits which are read out on both ends of a module (see Figure 1.3). Panels of detectors increase in width as they get closer to the beamline. To minimize silicon waste and to maximize coverage, fractions of hexagons complete the panel edges (see figure 4). By cutting the silicon in strategic locations, only a few different silicon shapes may be needed to achieve the 31 different panel widths. The tungsten plates are connected together on their longitudinal edges as well as in the field of detectors. Space for fasteners in the field is achieved by chamfering the corners of the hexagonal detectors. The field fasteners hold the plates together, provide a uniform 1.25 mm standoff height, and assist with inter-plate shear. The fasteners

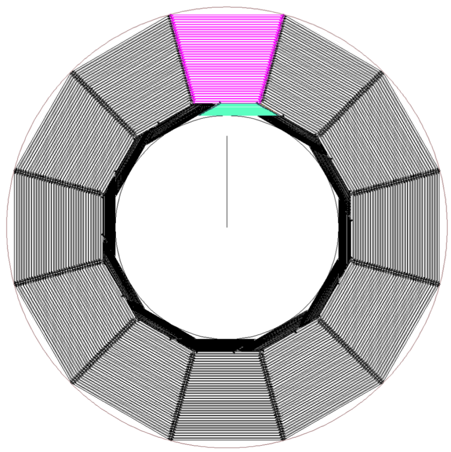

Figure 1.1:

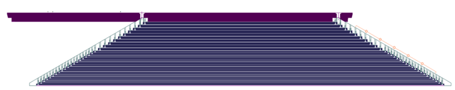

Figure 1.2:

near the edges of the plates close the module profile and lend torsional rigidity to the structure. An FEA simulation of the proposed configuration should be done to properly size the fasteners (see Figure 1.5).The modules, which weigh about 5 tons each, are mounted to stainless plates which are used as the first layer of the next detector system (H-Cal). This first H-Cal plate is unique in that its two longitudinal edges form a guide system to locate the E-Cal to the H-Cal system. The H-Cal modules are first bolted together to form the H-Cal barrel. Interleaving structural side battens maintain spacing for the H-Cal plates and extend inward to the E-Cal support plates. The inner ends of these battens act in concert as the female portion of the E-Cal guide system. The E-Cal modules are slid into place in the inner H-Cal bore. Extension plates complete the inner H-Cal first layer, since the E-Cal barrel is shorter. H-Cal detector panels are installed after this structure is complete (see Figure 1.7). Only simple detector layouts have been done for the E-Cal endcaps so far. These layouts show that using full and partial hexagons could yield fairly good coverage with only a few shapes. (see Figure 1.8).

## 1.4 DECAL

The studies of a digital ECAL (DECAL) continue in the UK, in spite of very significant funding difficulties. In December 2008, the STFC Executive recommended sufficient funding to allow the SPiDER Collaboration to construct a full physics prototype DECAL, as outlined in [11]. By December 2009, the funding for SPiDER had still not been

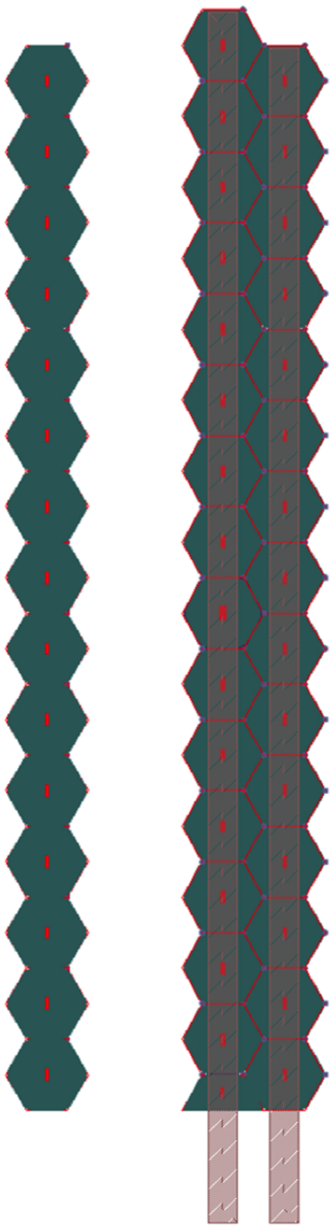

Figure 1.3:

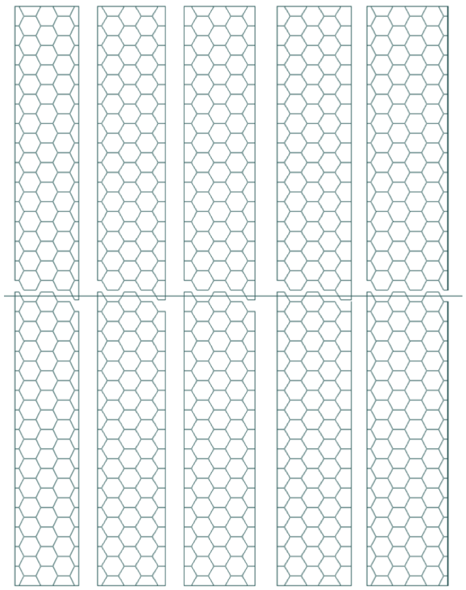

Figure 1.4:

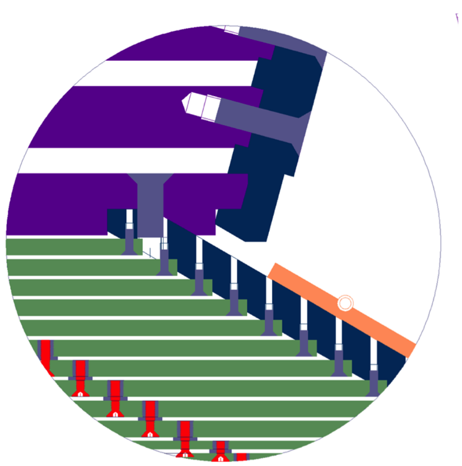

Figure 1.5:

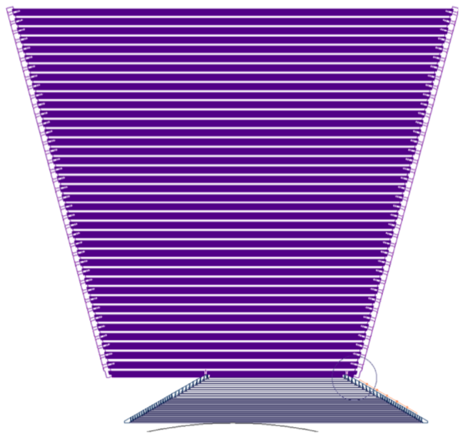

Figure 1.6:

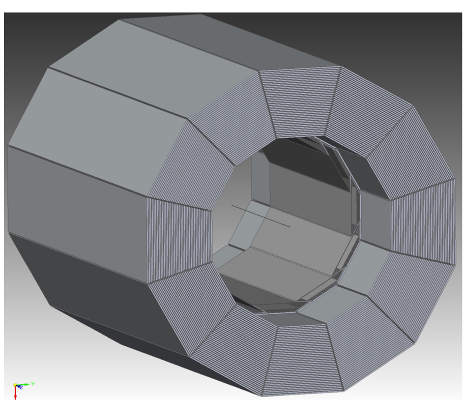

Figure 1.7:

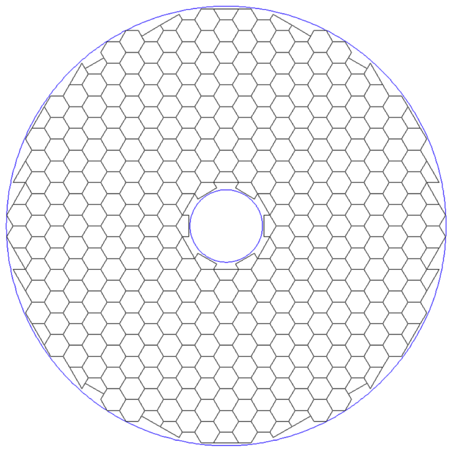

Figure 1.8:

issued and STFC informed the Collaboration that they would not do so.

The UK groups in SPiDER have demonstrated that the INMAPS technology developed specifically for the DECAL application is viable in terms of basic pixel efficiency. INMAPS is implemented as a 0.18 μm CMOS process in which a deep P-well implant stops signal charge from being absorbed in N-well circuits, and therefore allows the use of both NMOS and PMOS within the pixel, as well as (optionally) high resistivity silicon in the thin epitaxial layer to reduce the charge collection time.

### 1.4.1 Test Beams in 2010

Following a successful test beam run at CERN in September 2009 using 120 GeV pions, two further data taking runs have been carried out. The first of these was at DESY in March 2010, for which the primary goal was to quantify the peak electromagnetic shower density observed downstream of specific absorber materials. A secondary goal was to make further pixel efficiency measurements. Data were recorded with the 1-5 GeV electron beam, using a configuration in which four TPAC 1.2 sensors were aligned precisely along the beam direction using the same custom-built mechanical frame as at CERN. Absorber material (W, Fe, Cu) was placed downstream of these, followed immediately by a further pair of TPAC sensors, to study the shower density.

To complement the DESY run, similar, additional data was recorded at CERN in September 2010, using the EUDET telescope alone as it has finer pitch than the TPAC sensor, with positrons between 10 and 100 GeV. The same slabs as those at DESY were used together with new slabs due to the higher energies available at CERN. Initial results of shower multiplicities are presented in [12].

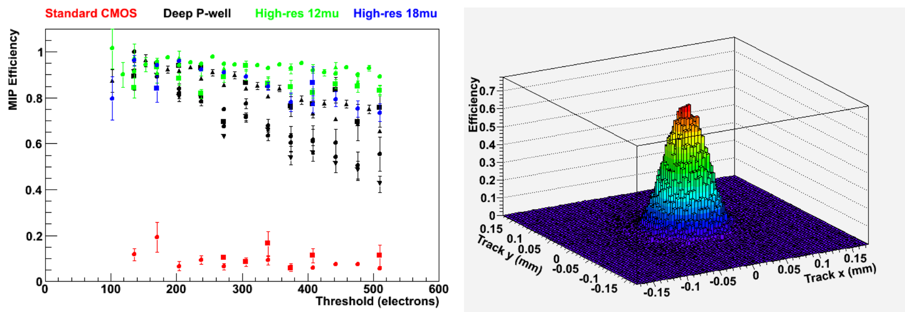


Figure 1.9: (left) Distribution of the probability of a pixel registering a hit in response to a MIP, as a function of distance to the projected track, and (right) MIP efficiency as a function of the sensor digital threshold, for all four sensor variants studied.

### 1.4.2 Pixel efficiency results

The studies of pixel efficiency from CERN 2009 testbeam and DESY were performed using a set of six TPAC 1.2 sensors aligned along the beam direction, in which the outer four sensors served as a beam telescope, while the two innermost sensors were considered as the devices under test. The trajectory of the beam particle was projected onto the plane of both of these sensors, and each pixel of the test sensors was examined for the presence of hits as a function of the distance from the projected track. The MIP hit efficiency was determined by fitting the distribution of hit probability to a flat top function, convoluted with a Gaussian of the appropriate resolution to allow for finite tracking performance. This efficiency, folded for all pixels together, is illustrated in Figure 1.9

The MIP efficiency was determined per pixel for both the DESY and CERN data, and for each of the four pixel variants tested. The variants (and corresponding marker color in Figure 1.9) are:

1. (red) in 12 µm standard (non-INMAPS) CMOS;
2. (black) 12 µm deep P-well CMOS;
3. (green) deep P-well within a 12 µm high resistivity epitaxial layer;
4. (blue) deep P-well within an 18 µm high resistivity epitaxial layer.

The results [13] are summarized in Figure 1.9, for a range of the sensor digital thresholds representative of the signal levels expected in DECAL pixels due to charge spreading. (A typical MIP signal in a 12 µm epitaxial layer of silicon is 1200 electrons and a single pixel absorbs at most 50% of this due to charge spreading.)

From the results shown in the figure, it is observed that the standard, non-INMAPS sensors have markedly low efficiencies, which is attributed to signal charge being absorbed by in-pixel PMOS transistors. In contrast, the use of the deep P-well reduces the absorption of signal charge by N-wells in the circuitry, improving very substantially the pixel efficiency by a factor of $\approx 5$. The addition of the high resistivity epitaxial layer further improves the pixel efficiency to $\approx 100\%$.

### 1.4.3 Future plans

It is no longer an option to plan for a physics prototype DECAL and the short-term future of the DECAL project is extremely uncertain at present. A program of radiation hardness has been conducted on 2011 and the results are summarized in [12, 14]. This is in part to understand how the TPAC sensor would satisfy the requirements of ALICE ITS and SuperB . The studies which have been carried out so far are in the process of being finalized, and a series of papers, e.g. [15], are in preparation to document what has been achieved. The technology development has been taken over by the Arachnid collaboration who are testing the CHERWELL chip (designed and manufactured by the SPiDeR collaboration but never used due to money constraints) to evaluate the performance for ALICE and SuperB.

## 1.5 Resistive Plate Chambers

### 1.5.1 Description of the DHCAL

The Digital Hadron Calorimeter or DHCAL uses Resistive Plate Chambers (RPCs) as active elements. The chambers are read out with $1 \times 1\,\mathrm{cm}^2$ pads and 1-bit (digital) resolution. A small-scale prototype was assembled and tested in the Fermilab test beam in 2007 to validate the concept. Based on the success of the small-scale test [1-6], a large prototype with up to 54 layers and close to 500,000 readout channels was built in 2008 – 2011. Each layer measured approximately $96 \times 96\,\mathrm{cm}^2$ and was equipped with three chambers, stacked vertically on top of each other. For tests with particle beams the DHCAL layers were inserted into a main stack of 38 or 39 layers, followed by a tail catcher with up to 15 layers. For the tests performed at Fermilab the main stack contained steel absorber plates. At CERN the absorber plates were made of a Tungsten based alloy. In both cases the tail catcher featured steel absorber plates. In the various test beam campaigns combined, spanning the years 2010 – 2012, the DHCAL recorded around 14 Million muon events and 36 Million secondary beam events, where the latter contained a mixture of electrons, muons, pions, and protons.

### 1.5.2 Current R&D activities

The analysis and publication of the test beam results are currently the highest priority of the DHCAL group. Major challenges, such as the calibration (or equalization) of the response of the RPCs and the detailed simulation of the response of RPCs, are very close to having been overcome [7-11]. Parallel to the analysis of test beam data, the group is pursuing the following R&D activities:

### Development of 1–glass RPCs

The DHCAL prototype featured a standard chamber design based on RPCs with two resistive plates. It is possible to eliminate one of the glass plates in future applications. The advantages are: close to unit pad multiplicity with significant simplification of the calibration and monitoring procedure, reduced thickness of the active element, higher rate capability, and insensitivity of the response to the surface resistivity of the resistive layer (used to apply the High Voltage). To date several 1-glass RPCs have been assembled. The chambers tested very well with cosmic rays. Tests in particle beams are planned for future test beam campaigns.

### Development of high-rate RPCs

Due to the high bulk resistivity of glass (and Bakelite), RPCs are notoriously rate limited [16]. The DHCAL group is addressing this shortcoming with the developments of semi-conductive glass (in cooperation with COE college) and low-resistivity Bakelite (in co-operation with USTC). First chambers with samples of low-resistivity glass plates have been assembled and have been tested in the Fermilab test beam.

### Development of a High-Voltage distribution system

With up to 50 layers in a single calorimeter module, a cost-effective way to distribute the High-voltage to individual layers is required. A system capable to regulate the voltage within a few 100 V, to monitor both the current and the voltage, and to switch off individual channels, is being developed. A first prototype controlling a single channel has been assembled and tested successfully with an RPC. The development is currently on hold due to lack of funding.

### Development of a gas recycling system

The operation of RPCs requires a gas mixture, which is both costly and environmentally harmful. To limit the effect of releasing gas into the environment, the DHCAL group is developing a gas recycling system. The system is based on a new approach, appropriately labeled "Zero Pressure Containment". A prototype of the gas collection subsystem is currently being assembled; however, progress is again slow due to lack of funding.

### Development of the next generation front-end readout system

The next generation front-end readout system will contain several upgrades compared to the current system: higher channel count, token ring passing, low power operation, power pulsing, and improved internal charge injection systems. To proceed, the project is awaiting funding from both US and Chinese agencies.

## 1.5.3 Engineering challenges

Several engineering challenges remain to be addressed before an RPC-based DHCAL can be proposed as an option for a colliding beam detector. Following is an (incomplete) list of the major issues:

- Industrialization of the construction of RPCs.
- Design of the readout boards, covering the entire area of the layer (with varying width). The design is expected to feature only a minimum number of different boards.
- Design of the gas distribution system, which ensures equal pressure in all layers of a given module, independent of its orientation.
- Development of a cooling strategy for the front-end boards, which will include power pulsing, as well as active cooling.
- Development of a module assembly procedure.

### 1.5.4 Plans for the coming years

The activities of the coming years depend strongly on the progress with the Japanese intentions to host the ILC. Assuming the ILC project goes ahead, the DHCAL group will a) Complete the analysis and publication of the test beam data, b) Complete the R&D projects listed above, and c) Start the development of the design of calorimeter modules. In case, the ILC is not going forward, the group plans on completing the data analysis and to continue the tests of high-rate RPCs. Other R&D projects, such as the development of distribution systems, will be put on hold.

### 1.5.5 Applications beyond the ILC

The DHCAL technology was specifically developed for the hadron calorimeter of the ILC, with its low particle rate and radiation dose. To export the technology to other environments, the rate capability of the chambers and the radiation hardness of the readout need to be improved. The former is being addressed with low-resistivity plates (glass and Bakelite), while the latter will require a new front-end readout system based on an ASIC using a smaller feature size. Possible applications are the tail catcher of the forward calorimeters of CMS and the outer wheels of the ATLAS muon system. Both options are being pursued actively.

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## 1.6 GEM

### 1.6.1 Introduction

The group pursues the development of Gas Electron Multiplier technology for instrumenting a digital hadronic calorimeter (DHCAL) at the ILC.

### 1.6.2 Recent Milestones

### 1.6.3 Engineering Challenges

### 1.6.4 Future Plans

### 1.6.5 Applications Outside of Linear Colliders

## 1.7 Analog HCAL

### 1.7.1 Introduction

With the advent of silicon photo-multipliers (SiPMs), the scintillator tile technology became a candidate for highly granular particle flow calorimetry. With analog read-out, energy and spatial resolution can be optimized independently. The particle flow performance is well understood; all published studies using PandoraPFA are based on this technology.

The CALICE AHCAL was the first large LC hadron calorimeter prototype to be exposed to test beams. Analysis is nearly complete and mostly published; the results validate the technology and the simulations.

The development of engineering solutions for a realistic detector is on its way. The integration of read-out electronics and calibration system into the detector layers has been demonstrated. The next step, an integrated stack, is being prepared. In parallel, as improved photo-sensors become available from industry, the design of the basic read-out cell – the tile with SiPM – is optimized with regard to mass production procedures.

### 1.7.2 Recent Milestones

Past and present R&D: test beam data analysis The following results using data taken the first AHCAL "physics" prototype in 2006 – 2011 at CERN and Fermilab have been published in peer-reviewed journals:

1. Detector construction, noise and aging studies [29]
2. Electromagnetic linearity and resolution [30]
3. Hadronic linearity and resolution, software compensation [31]
4. Test of particle flow algorithms (AHCAL with SiW ECAL) [32]
5. Studies using a scintillator SiPM based tail catcher [33]
6. Geant 4 validation with pion showers [34]
7. Geant 4 validation with tungsten absorber (low energy) [35]
8. Imaging capabilities, track segments [36]

We consider all of them as critical for validating a given HCAL technology. Papers [34], [35] and [36] appeared in the last year since the ILC TDR was handed over.

*Preliminary* results have been made public in the form of *CALICE Analysis Notes* after thorough internal reviewing on the following topics:

1. Combined performance SiW ECAL + AHCAL + Tail Catcher [37]
2. Leakage estimation using shower topology [38]
3. Time structure of showers in Fe and W [39]
4. Geant 4 validation with protons [40]
5. Parameterization of pion and proton shower shapes [41]
6. Geant 4 validation with tungsten absorber (high energy) [42]

Notes [40], [41] and [42] appeared in the last year since the release of the ILC TDR. The studies are actively being followed up towards final publication; only the leakage study is presently uncovered due to lack of manpower.

Studies of the combined performance of the AHCAL in conjunction with the scintillator tungsten ECAL with MPPC readout are on-going. Results are expected in the coming year and will make the analysis of the first generation test beam data complete.

Data taking with a first, partially instrumented stack of the second generation has started at DESY and will continue in fall 2014 with electrons and hadrons at CERN. A framework for analysis software exists, but there is still a lot to do. In particular, calibration and correction procedures for timing measurements need to be developed.

The CALICE test beam results are nowadays the primary source of validation for hadron shower simulation, according to Geant 4 representatives, and extremely valuable for other HEP experiments, e.g. at the LHC, as well.

We finally note that test beam analysis plays an important role in training our students. Roughly speaking, each paper or note corresponds to one or several PhD theses. It is a distributed effort; the results have been obtained at DESY, CERN, MPI Munich, Hamburg, Heidelberg, Mainz and Wuppertal universities, ITEP Moscow and Northern Illinois University.

### 1.7.3 Past and present R&D: technology

#### Optimization of the scintillator SiPM read-out cell

As a consequence of the wide success of SiPM applications in other fields, e.g. in medical imaging, the development of improved sensors is dynamically pursued in industry, and several groups (ITEP, MEPhI, Shinshu, Hamburg) are in close contact with leading producers. Progress has been made in terms of dark rate, noise above MIP threshold and dynamic range. In addition, the samples are much more homogeneous than at the time of the first prototype, which results in a simplification of commissioning and calibration procedures.

In the time since the TDR, tile SiPM cells without wave-length shifting fiber have been developed, following a design by MPI Munich. One is based on machined, individually wrapped scintillator plates (Hamburg), the other one on injection-molded tiles (ITEP). Both are using sensors from KETEK, those on the molded tile have a very large dynamic range. 300 devices have been produced and tested at ITEP, and more than thousand devices have been produced and tested with semi-automatic procedures at Hamburg and Heidelberg. Part of them has been integrated into the test beam set-up early this year. This version is a good candidate for a baseline design for a full detector, but more data taking and analysis is needed.

Industrialization of the SiPM and tile design and production procedures is a long-standing item, but tests with industrial facilities such as automatic pick-and-place machines have begun only recently (Mainz). This needs to be continued in the coming years, fed back into the cell optimization, and awaits a feasibility demonstration at larger scale.

An alternative design, with photo-sensors integrated in the read-out electronics board, has been proposed some time ago (Northern Illinois), but the detailed development of the corresponding sensor and scintillator configuration has only recently been taken up again (NIU, Mainz, ITEP). It has the potential to result in further simplifications (which should be read as cost and time savings), but poses higher performance requirements to the SiPM and raises new issues in the quality assurance and integration chain. The goal is to develop such an alternative solution in the next 2–3 years.

### Electronics and active layer integration

The design of the active layers (DESY) with integrated read-out ASICs (LAL/OMEGA) and calibration system (Wuppertal) has been basically validated in beam tests of a single HCAL layer consisting of four base units (HBUs) at CERN in 2012 and reported in the TDR. An HBU reads $12 \times 12$ tiles with 4 ASICs. The present ASIC belongs to the 2nd generation ROC family used also in ECAL and SDHCAL. An HCAL layer carries interfaces for DAQ, calibration and power supply, which already have a compact design fulfilling space constraints at an ILC detector.

The main difference between the integrated electronics and that of the physics prototype is the self-triggered operation and on-detector zero-suppression, which implies much higher demands on controlling the noise behavior and ensuring a stable detector response. It is thus mandatory to re-establish the calorimeter performance with a full-scale beam test. However, this is out of reach with present funding levels.

Further R&D in the next years has to be done both on the ASIC and on the PCB. For the ASIC, development of a 3rd generation ROC chip will start after fixing open issues with the 2nd generation (OMEGA). The 3rd will have a more robust slow control architecture and channel-wise buffer management which improves rate capabilities. In parallel, an alternative design of the analog part (Heidelberg), which can handle a larger range of sensor gain needs to be complemented with a digital part.

The PCB with integrated photo-sensors, as counterpart of the corresponding tile design (see 1.7.3), needs to be developed, taking automatic production and quality assurance into account. The PCB is also one of the main cost drivers of a particle flow HCAL. Dedicated R&D, in close cooperation with industrial manufacturers, is necessary to bring the cost down. First contacts have been made (DESY, Heidelberg, SKKU Korea).

### System integration

While the integration of layers is well advanced, that of entire stacks or module has only begun. Since the TDR release, efforts concentrated on developing a multi-layer DAQ capable of reading larger systems (DESY, Mainz). An intermediate version has been used in an electron beam test of an 8 layer stack at DESY in early 2014.

Work has been intensified to further develop the DAQ towards a scalable system, with the goal to have it ready for beam tests at CERN starting in fall 2014. It involves integration of a dedicated module data concentrator, which collects signals from all layers for sending them to the off-detector data receiver.

Further work will be required to integrate the HCAL DAQ into a higher level system for the purpose of combined beam tests, for example with a tracking device for uniformity studies, or with an ECAL for inter-calibration and combined performance. The same is true for slow control data.

A power supply system with optimized channel density per module is being developed at Dubna.

It has been demonstrated that temperature-induced variations of the SiPM gain can be compensated by adjusting the bias voltage (Prague, Bergen). The approach has the potential to stabilize the detector response and trigger efficiency and thus simplify operations significantly. Automatic procedures based on this principle need to be developed and implemented for a test at system level.

On the mechanical side, a cooling system needs to be developed. The ASICs integrated in the detector layers are power-pulsed and do not need active cooling, but the interfaces, in particular the power regulators, do. A simple solution for beam tests is on the way (DESY), but a leak-less under-pressure based system for a large detector still needs to be prototyped.

### Infrastructure for production, quality assurance and characterization

The AHCAL is probably the sub-detector with the largest number of individual components. While the number of electronics boards, layers and interfaces is similar to other ECAL or HCAL options, the large quantity of tiles and SiPMs deserves special attention. This affects production and quality assurance, but also characterization, i.e. test bench measurements of parameters to be used later for calibration purposes.

While it would be premature to discuss building up full production infra-structure, conceptual solutions need to be developed and exercised using demonstrators, which could be seen as prototypes of future installations. The demonstration requires reasonably large samples of detector elements, in the order of 10000, as they would be needed for a next generation full prototype.

A semi-automatic test stand for SiPMs and tiles has been developed at Heidelberg and used for the elements of the early 2014 beam test. It needs to be adapted for future designs, e.g. with SiPMs integrated in the PCB.

Automatic assembly of HBUs (Mainz), i.e. of placing and soldering tiles and SiPMs on the PCB, needs to be demonstrated in practice, too. First encouraging tests with individual samples have been reported, but obviously only larger scale tests can validate the concept.

**Absorber structure**

The absorber structure bears more challenges than conventional hadronic calorimeters. Due to the much finer longitudinal segmentation and the imperative to minimize the total radius inside the coil, there are many active gaps with tight tolerances. A design has been developed and prototyped, which achieves the required tolerances with a cost-effective roller-leveling process without machining off excess material (DESY). Two test structures have been built; one covers the full transverse cross section of a barrel module, the other the full lateral extension. The cassettes (DESY, MPI Munich) housing the active elements have the final design and are used in beam tests.

These structures need to be investigated with respect to their robustness against earthquakes (DESY). Simulations of the whole ILD structure have been initiated, and measurements on the test structures exposed to accelerating forces should be done.

As enough active elements become available for instrumenting several active layers at full size, the thermal simulations should be verified with measurements, too.

### 1.7.4 Summary

The AHCAL effort has produced a number of significant results in the time since the ILC TDR:

- Publication of 3 journal papers and 3 preliminary results in the form of internally reviewed notes, on Geant 4 validation with pions and protons in steel and tungsten, including new observables like track segments
- Development, production and beam test of a new, simplified tile SiPM system without wave-length shifting fibers and improved sensor performance
- Test with electron beams of a small stack with second generation electronics and DAQ in a realistic absorber structure

The AHCAL is ready to make the next step towards a realistic full-scale prototype and a technical design report. In order to achieve this, coordinated R&D is required in the following areas:

Software and analysis:

- Completion of physics prototype test beam analysis
- 2nd generation prototype reconstruction and simulation software
- Development of timing reconstruction
- Analysis of 2nd generation test beam data

Tile SiPM system:

- Development of scintillator SiPM system with SiPM on the PCB
- Development of associated assembly, quality assurance and characterization procedures
- Development of associated PCB

Electronics:

- 3rd generation ASIC of ROC family
- ASIC for larger range of SiPM gains
- PCB cost optimization

System integration:

- Scalable DAQ
- Module level data collector
- Integration of DAQ and slow control into higher level system
- Implementation of temperature compensation scheme
- Power supply system
- Cooling system

Mass production concepts:

- Semi-automatic test stands
- Automatic placement and soldering of tiles and SiPMs

Absorber structure:

- Earthquake stability calculations and tests
- Thermal tests with full-scale instrumented and powered structures

There are ample opportunities for new groups to join into any of these fields, depending on the special competences they wish to contribute.

Particular engineering challenges are

- Assess and ensure earthquake stability of the absorber structure whilst maintaining a minimum of dead material
- Developing an active layer element consisting of tiles, SiPMs and readout electronics that can be automatically assembled, including production and quality assurance procedures

### 1.7.5 Engineering Challenges

### 1.7.6 Future Plans

## 1.8 SDHCAL

Engineering Challenges missing

### 1.8.1 Introduction

The Micromegas R&D is primarily intended for Particle Flow calorimetry at future linear colliders. It focuses on hadron calorimetry with large-area Micromegas segmented in very small readout cells of $1 \times 1\,\mathrm{cm}^2$. This granularity provides unprecedented imaging capability which can be exploited to improve the measurement of jet energy. Past and current R&D efforts are described with emphasis on achievements since the publication of the ILC Detailed Baseline Design.

### 1.8.2 Hadron calorimeter design

The design of calorimeters at a future linear collider is optimised for the reconstruction of jets with a Particle Flow method. The SiD HCAL will be segmented in cells of $1 \times 1\,\mathrm{cm}^2$. With a total instrumented area of $3000\,\mathrm{m}^2$, the number of readout channels will reach $30 \times 10^6$. This unprecedented granularity can be achieved with gas detectors, thin PCBs and embedded front-end ASICs.

In addition, calorimeters will be placed inside the solenoid magnet to insure good matching of electron and charged hadron tracks with their energy deposits in the ECAL and HCAL. To limit cost, a very compact mechanical design is mandatory: e.g. the SiD HCAL would feature 40 layers within $\sim$ 110 cm. This design relies on very thin active layers to achieve fine sampling ($\sim 0.1\,\lambda_{\mathrm{int}}$ / layer) and good hadron energy resolution ($\sim 50\%/\sqrt{E}$). The targeted active layer thickness and length in the barrel HCAL modules are 8 mm and 3 m respectively. To minimise dead zones, readout boards will be placed at the two ends of the barrel modules. Along the beam direction, ASIC will be daisy chained and PCBs connected together with flat connectors and cables.

Active cooling of the active layers is extremely challenging with this design. Instead, it is considered to limit heat dissipation and gradients inside the calorimeters by power-pulsing the front-end circuitry. Power-pulsing is possible because of the particular time structure of the ILC beam. This structure also drives the design of the ASICs which will be self-triggered. During collisions, signals will be processed and stored in memory with a timestamp synchronous to the ILC clock. Between bunch trains, memories are first read out, then the ASIC are turned off. With an ILC duty-cycle of 0.5%, the power consumption can be reduced down to $10\,\mu\mathrm{W}$ / channel.

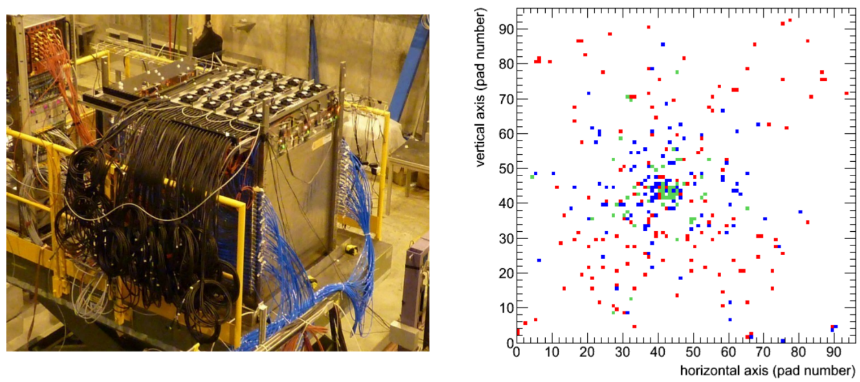


Figure 1.10: SDHCAL prototype in a beam line at the SPS at CERN (left). Event display of a 150 GeV pion shower measured in a Micromegas prototype after $2\,\lambda_{\text{int}}$ of steel (right), the color indicates the threshold passed: red for 1, blue for 2 and green for 3.

### 1.8.3 Recent Milestones

#### The SDHCAL

The SDHCAL is a prototype of imaging hadron calorimeter equipped with 50 layers of gaseous detectors of $1 \times 1\,\text{m}^2$ interleaved by steel absorbers (Figure 1.10 (left)). Each detectors is segmented in pads of $1 \times 1\,\text{cm}^2$ and the processed pad signal is coded over 2-bits (Figure 1.10 (right). The number of readout channels per layer imposes to integrated the front-end electronics directly on the gaseous detector printed-circuit-boards (PCB). Several CALICE groups are involved in this project.

#### The $1 \times 1\,\text{m}^2$ Micromegas prototype

**Mechanics** The Micromegas layers for the SDHCAL are made out of 6 high-voltage units installed together inside a gaseous chamber (Figure 1.11 (right)). Each unit is an 8 layer PCB with a Bulk Micromegas mesh, readout pads and front-end ASICs; it is dubbed Active Sensor Unit (or ASU). A drift gap of 3 mm is defined by spacers and a frame. Spacers are inserted in between ASUs, resulting in an inactive area of 2%.

**Electronics** Electronics connections to the DAQ as well as services (power cables, gas pipes) are provided on one side of the prototype. ASU-to-ASU connections are therefore mandatory and are made with dedicated connectors and flexible cables (Figure 1.11 (left)). They are used to distribute clocks and supply power to the ASICs, high voltage to the meshes, to configure the ASICs and read out data. Prior to assembly, 4 ASUs were chained and functional electronic tests were successfully performed. These key features make the design of the $1 \times 1\,\text{m}^2$ Micromegas prototype fully scalable to the required size of a HCAL module at a future LC (at most 2 m in the SiD detector concept).

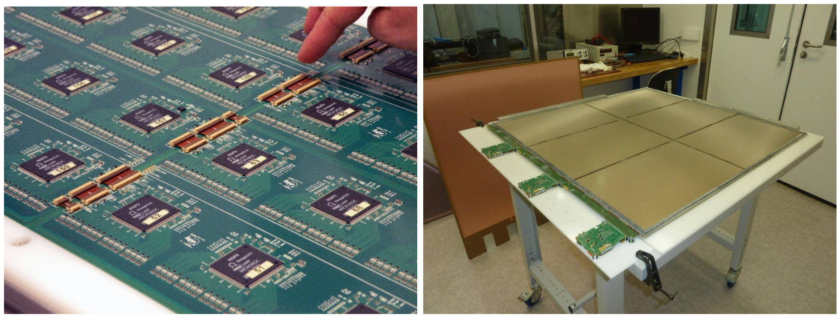

Figure 1.11: Photographs of interconnections between 2 Active Sensor Units (left) and a $1 \times 1\,\mathrm{m}^2$ Micromegas prototype during assembly showing 6 of these units and a drift cover (right).

**Noise and detection efficiency** A few prototypes were constructed [43] and extensively tested in beam at CERN [44]. Noise conditions were excellent both during standalone tests and inside the CALICE SDHCAL. ASIC thresholds can be lowered down to about 20% of a minimum ionising particle (MIP) signal at a typical running gas gain of 1500. Efficiency in excess of 95% are easily reached while keeping a pad multiplicity below 1.1 for MIPs. The actual charge threshold is as low as 1−2 fC; it is achieved on ASIC test-boards as well as once mounted on ASUs. The contribution of the PCB internal capacitances to the overall detector noise is therefore negligible.

**Standalone performance** Thanks to a precise control of the gas gaps and electronics settings, ASIC-to-ASIC variations of efficiency are below the percent in all tested prototypes. Although the statistics is low, the construction process seems reproducible. Stability with rate in high-energy hadron showers is excellent. Except occasional sparks, no effect of beam rate was observed on the pion response up to roughly 30 kHz beam rate; which was the highest rate during the tests. The measured spark probability lies in the range of $10^{-6} \ldots 10^{-5}$ per showering pion at a running gas gain of 1500.

### Resistive prototypes

While the Bulk Micromegas mesh is made of steel wires and is very resistant to sparking, sensitive front-end ASICs can suffer irreversible damage. Protections in the form of current-limiting diodes networks soldered on PCB were proved so far efficient. To simplify the PCB design and possibly reduce the overall detector cost, it is however desirable to get rid of diodes. It is well known that sparks can be suppressed by means of resistive coatings on the anode pad plane. This solution is used with great success in tracking detectors. Because it modifies the signal development, it needs some adaptation to calorimetry so as to preserve linearity and keep a narrow pad response function for Particle Flow reconstruction.

First resistive designs using resistive strips and pads were implemented on small

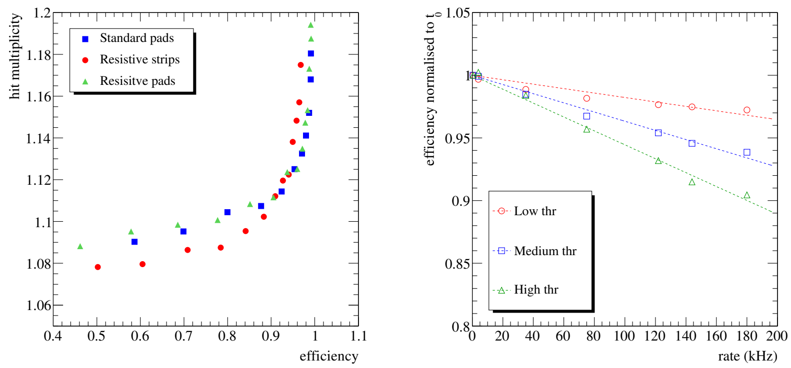


Figure 1.12: Pad multiplicity versus efficiency to 3 GeV electrons for 2 resistive and 1 non-resistive (or standard) Micromegas prototypes (left). Efficiency dependence on rate in a resistive prototype for 3 values of threshold (right). The electron beam spot is $\sim 2 \times 2\,\text{cm}^2$.

size prototypes. In a mixture of $Ar/CO_2$, full suppression of sparking was demonstrated up to gas gain in excess of $10^4$. At comparable gas gains, resistive and non-resistive prototypes show similar response to traversing charged particles, reaching high efficiency and low pad multiplicity. Compared to non-resistive ones, the evacuation of charge is slowed down in resistive prototypes which are thus subject to rate-dependent drops of gas gain. Expected efficiency losses have been observed at (3 GeV electrons) rates in excess of $10\,\text{kHz/cm}^2$. This limit is compatible with the resistivity of the coated material. At lower rates, it could be shown that the linearity of a Micromegas calorimeter to electrons is not affected by the resistive coatings, up to 5 GeV, which was the maximum energy available during the testbeam campaign.

### 1.8.4 Engineering Challenges

### 1.8.5 Detector R&D plans for the coming years

Plans for the coming years include maintaining a commitment to linear collider detector R&D and possibly seek new applications. Despite a decline of resources, an R&D program to optimise resistive Micromegas for calorimetry is established. Linearity, rate capability and spark protection in dense electromagnetic showers will be checked up to high-energy and for detector designs with a large variety of resistivity and geometry. These measurements will be necessary to validate the resistive Micromegas technology for calorimetry at a future LC. Also, the on-going R&D for high-luminosity LHC (HL-LHC) detector upgrades are an appealing perspective. In particular, the possibility to equip the backing part of the CMS forward calorimeter is being investigated. Such high-rate application will put strong stability constraints on resistive Micromegas, making the optimisation work mentioned above even more relevant.

On a longer term and if resources are sufficient, a Micromegas calorimeter prototype should be constructed so its performance can be compared to concurrent detector technologies. Some performance have already been studied with Monte Carlo simulation, the minimal prototype dimensions are known as well as its cost. This final step of the project naturally comes after optimisation of the resistive coating and would complete the R&D on Micromegas calorimetry.

### 1.8.6 Applications Outside of Linear Colliders

## 1.9 DualReadout

### 1.9.1 Introduction

The scientific goal of RD52 (previously the DREAM collaboration) is to understand the fundamental limitations to hadronic energy resolution and, in general, the limitations to achieving high-quality calorimetric performance in Gaussian energy resolution, mean response linearity, and ease and precision of calibration.

### 1.9.2 Recent Milestones

The essential features of our fiber dual-readout calorimeters are (a) near-perfect optical conduits (fibers) for read-out, (b) fine spatial sampling on the mm-scale, (c) dual measurement of scintillation light in scintillating fibers (all charged particles) and simultaneous Cerenkov light in clear fibers (only electromagnetic particles), (d) absolute fiber-absorber volume uniformity, and (e) low-noise readout with PMTs below 100 MeV per ton of calorimeter. This design achieves a Gaussian response, a linearity near 1% from 20-300 GeV, and excellent energy resolution. The calibration is by a direct electron beam into each calorimeter tower.

About 30 dual-readout papers are published in Nucl. Intrs. Meths., Rev. Sci. Instr., and JINST, including dual-readout in several crystals, a planar geometry, as well as fibers in several geometries. We have built and tested Pb-based and Cu-based dual-readout modules and are designing a W-based test module. Typical readout of the Pb-modules is shown in Figure 1.14 for 20, 60, and 100 GeV pion beams in the H8 beam of the North Area at CERN. Simple dual-readout yields a Gaussian and linear response, currently limited by lateral leakage fluctuations in the Pb-based modules of about 1 tonne. The record holder for linear, Gaussian energy resolution is still the SPACAL module of 20 years ago, built by Wigmans at CERN to demonstrate the newly understood concept of "compensation". SPACAL was a Pb-scintillating fiber module of mass 20 tonnes that collected scintillation light for 100-200 ns to achieve compensation from the np $\rightarrow$ np recoils in the scintillating fibers. We show in Fig. 2 the hadronic energy resolutions for single pions for SPACAL, DREAM, and the new RD52 modules, plotted vs. $1/\sqrt{E}$, so that the slope is the stochastic term and the intercept is the constant term. A calorimeter with the ILC goal for hadronic energy resolution of $\sigma/E = 30\%/\sqrt{E}$ is shown as the thin red line. We have not yet achieved this goal, but we know we are limited merely by lateral leakage fluctuations which can be suppressed by a larger module. As shown in Fig. 2 we are closing in. There are

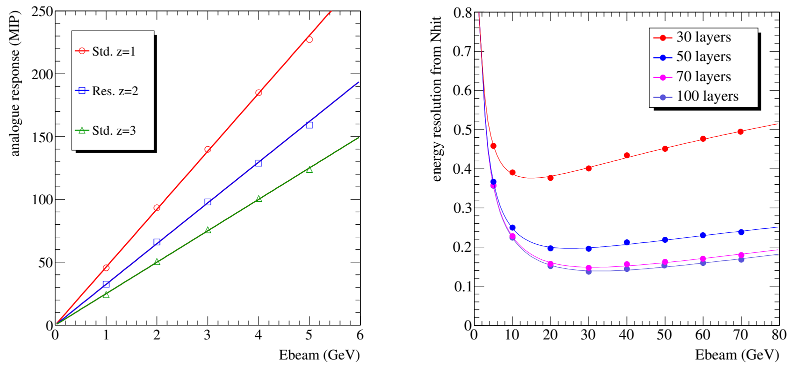


Figure 1.13: Electron response of a virtual Micromegas SDHCAL deduced from measurements of longitudinal shower profiles in non-resistive (z=1 and z=3) and resistive (z=2) Micromegas prototypes placed behind increasing thicknesses of passive material (left). Geant4 calculation of the energy resolution to pions of a Micromegas DHCAL of 30 to 100 layers based on simple hit counting (right).

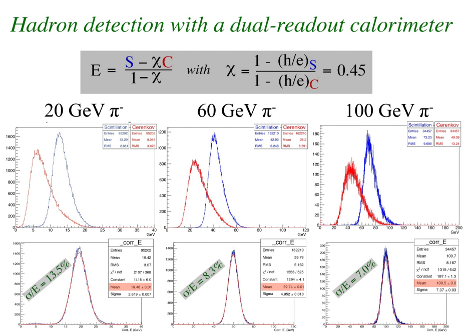


Figure 1.14: Raw scintillation and Cerenkov data for 20, 60, and 100 GeV pion beam, and the dual readout response below

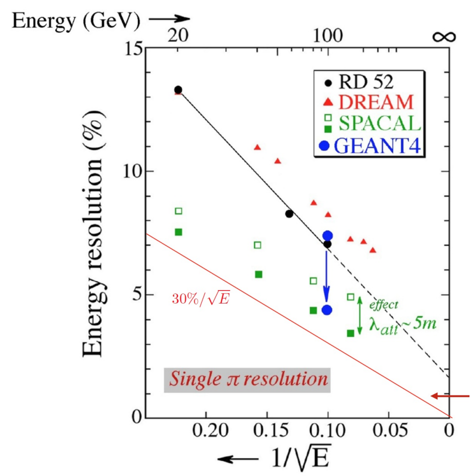


Figure 1.15: Hadronic energy resolution for SPACAL, DREAM, and RD52 modules

several improvements over the results in Figure 1.15 for (a) Cerenkov photoelectron yield, (b) photocathode efficiency, (c) fiber quality, (d) optical uniformity and, finally, (e) absorber mass. All of these are planned for testing one year from now at CERN. We expect, based on our data, simulations, and our understanding, that we are likely to achieve a resolution of about $30\%/\sqrt{E}$ with a small constant term. This would result in 3% energy resolution at 100 GeV and about 2% energy resolution at the highest SPS beam energies available at CERN.

### 1.9.3 Engineering Challenges

Manufacturing of the high-precision absorber, whether Pb or Cu or W. Assembly of a large calorimeter involves a lot of fibers which can and must be automated. Control of the optics to 1% is a challenge. It should be emphasized that we do not have engineers working on RD52, but rather find simple solutions which achieve the physics goals without expending large funds. On a construction project, engineering design would improve all our results.

### 1.9.4 Future Plans

Solving the problems of projective geometry; implementation of SiPM readout; manufacture of a tungsten W-absorber with full dual-readout capability; test of a gaseous dual-readout calorimeter.

### 1.9.5 Applications Outside of Linear Colliders

High precision calorimetry is vital to many experiments, both collider and fixed target; dual-readout is considered for a space station experiment; and, a high-precision dual-readout calorimeter is being considered for an electron-ion col- lider.

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Complete papers, figures, proposals, status reports, and photos are accessible at our website: http://highenergy.phys.ttu.edu/dream/.

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