Memorandum to the DESY-PRC

from the CALICE Collaboration

The CALICE Collaboration

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1. Introduction

The CALICE collaboration is studying the design of calorimetry for a future linear collider (LC) with centre-of-mass energies up to a TeV. The collaboration has defined an R&D program, specified in the previous submission PRC-DESY 02-01, which involves two parallel efforts that complement each other. These efforts are to build prototypes of possible LC calorimeters and to look at future technical options. The prototype electromagnetic calorimeter (ECAL) is a tungsten-silicon sampling device. The hadronic calorimeter (HCAL) is a sampling calorimeter with steel as radiator, with two possible options for the active detector being considered. One is based on scintillator tiles read through photodetectors and with standard analogue or semi-digital electronic readout, called AHCAL for analogue HCAL. The second uses gas detectors with small pad sizes and digital electronic readout, called DHCAL for Digital HCAL. This document gives the current status of the prototypes as well as on the future technical studies.

2. The electromagnetic calorimeter (ECAL)

2.1 The prototype

The ECAL prototype will be constructed from 30 layers of tungsten wrapped in carbon fiber. The active detectors will be silicon diode wafers with a pad size of $1\times1cm^2$. The very front end (VFE) electronics will provide preamplification and will be located outside of the active area, but on the same PCB as the silicon wafers. This PCB will then be connected via cables to VME readout electronics which provide digitization and readout.

A schematic view of the prototype is shown on fig. 1, with a different color used for each of the three stacks of ten layers, where each stack has a different tungsten thickness. This choice ensures a good resolution at low energy, due to the thin tungsten ($0.4X_0$ per layer) in the first stack, and a good containment of the electromagnetic showers, due to tungsten thicknesses two and three times larger in the second and third stacks, respectively. The overall thickness is about 20 cm or $24X_0$.

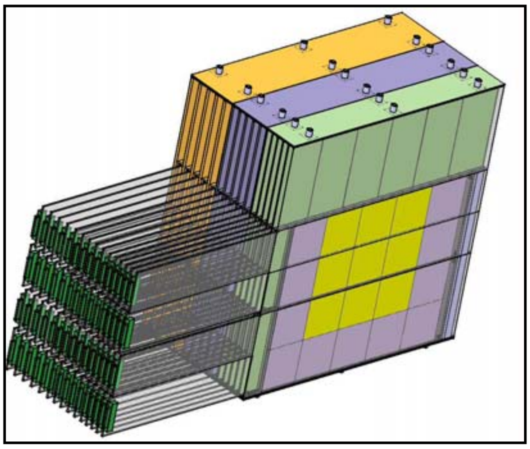


Figure 1: Schematic view of the prototype.

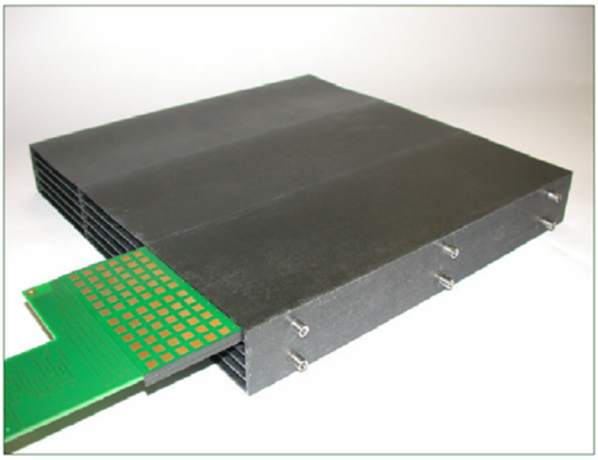
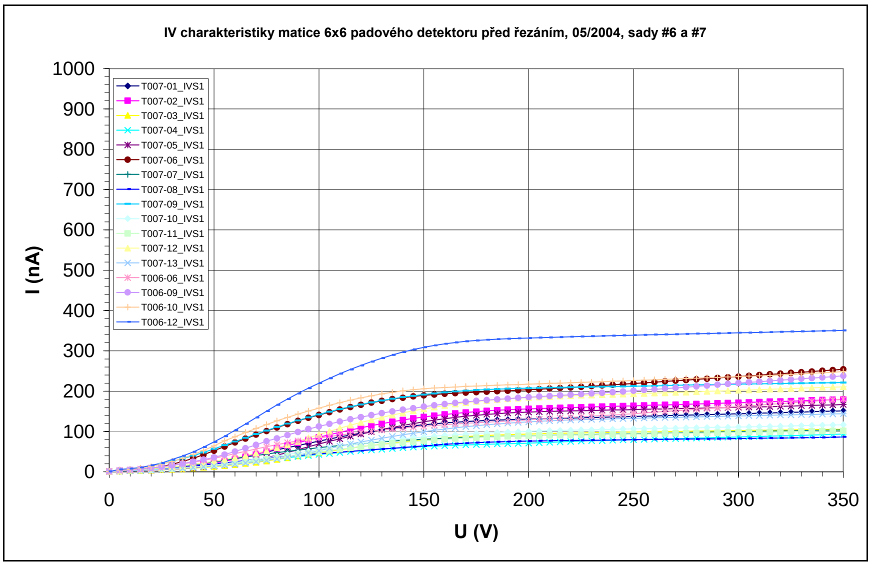


Figure 2: Photograph of the structure of stack 1.

The structure is constructed by wrapping half of the tungsten sheets in carbon fiber, leaving free spaces (called “alveoli”) between each tungsten sheet. Detector slabs are inserted into the alveoli, where each detector slab consists of two active layers and one tungsten sheet. The LLR group has already produced the first stack structure as shown in fig. 2. Each active layer is made of a PCB (14 layers, thickness 2.1mm) and up to six high resistivity silicon wafers (thickness 500 µm). The PCB has been designed at LAL-Orsay and will be produced in Korea under the control of KNU.

2.2 The active device

The wafers are cut to a size of 62×62 mm^2 which contains an array of 6×6 pads, each 10×10 mm^2, with a space reserved for the guard ring of about 1mm. It should be noted that there is only one set of guard rings per wafer. The wafers will be operated in overdepleted mode at a potential of around 250V. The first batch of production wafers, made in Russia by the MSU group and , is of very high quality, with a typical leakage current less than a few nA/pad for all the pads, although for a few per cent of the wafers, 1 or 2 pads of the 36 have currents up to 20 nA/pad. Recent deliveries of high quality silicon sensors have been produced in Prague, managed by the Institute of Physics of the Czech Academy of Science, and present the same very nice behavior, as illustrated in figure below



I-V curve per matrix for the recent Prague deliveries

The Russian production is about finished and the Czech is under progress.

The connection to the PCB is made by conductive glue on each pad, with AC coupled readout. For future designs, amorphous silicon deposited directly on the pad to make the resistance and capacitance is being considered and is one of the objectives of the R&D program within the CALICE-ECAL groups. For the prototype, the AC coupling is realized using discrete components on the PCB.

2.3 The very front end electronics

The silicon wafer diodes are read by a VFE chip developed by the LAL-Orsay group. It consists of a preamplifier with two gains, a shaper and a multiplexer. This chip handles 18 channels and has low noise and a large dynamic range. A schematic view of the VFE is shown in fig. 3.

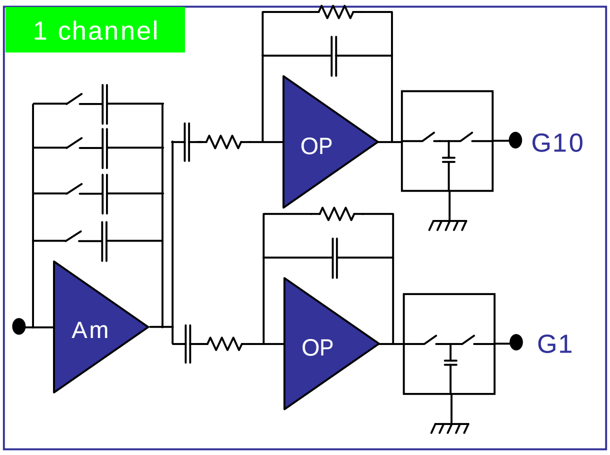


Figure 3: Schematic view of the VFE chip.

Tests of the chip presents a linearity of 0.2%, a signal uniformity better than 2% and crosstalk of less than 0.2%, all over the 600 MIPs dynamic range. Some results on the signal uniformity and the noise are shown in fig. 4. Three versions of the VFE chip has been designed, fabricated, measured and tested, with improvements on linearity and noise with each new version. The values above come from measurements performed on version 2. The latest version, FLC_PHY3, will be used for the prototype.

All the required 540 VFE chips for the prototype have already been produced and will be tested by the end of May 2004.

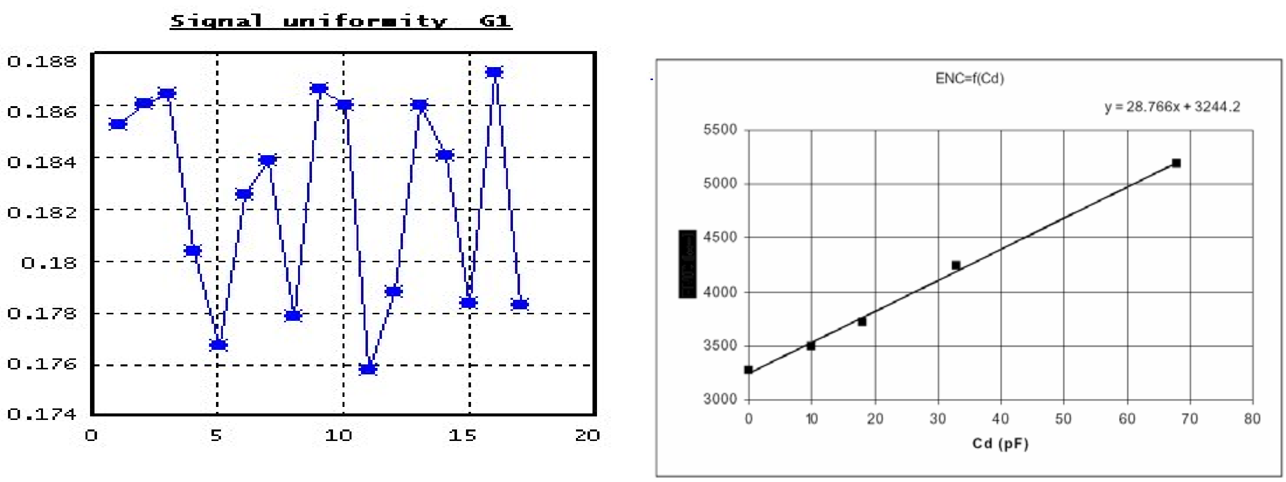


Figure 4: Left: signal uniformity for all 18 channels, showing it is well within 2%. Right: noise as a function of the input capacitance.

The fully populated PCB with the silicon wafers and the VFE chips is shown in fig. 5.

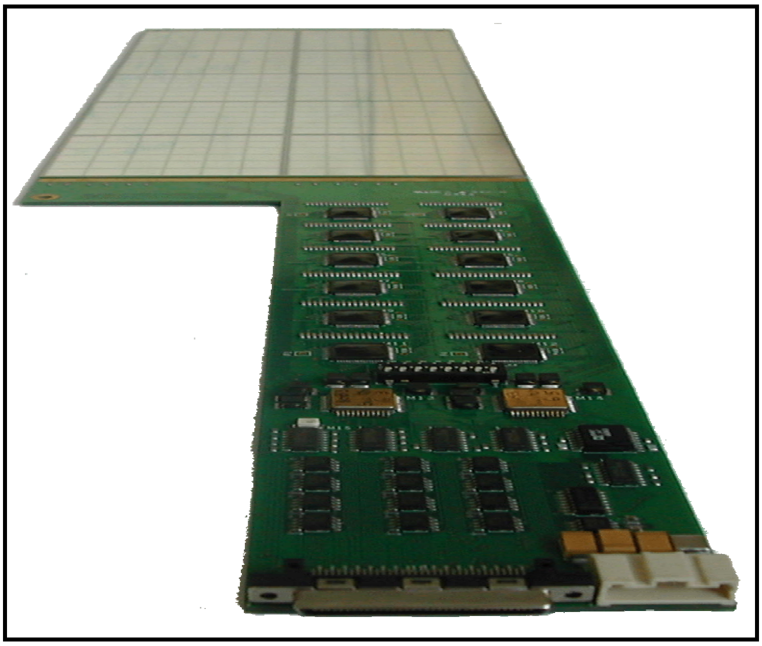


Figure 5: The first full size PCB with silicon wafers and the front-end electronics installed.

2.4 Assembly and testing

One of the important advantages of a silicon device is the stability of the response with time and temperature. In order to check this, the detector will be calibrated with cosmic muons using a test bench developed at the LLR, before going to a beam test in DESY at the end of 2004. A dedicated DAQ system (SSD for Single Slab DAQ) has been developed to read out the two PCBs of a single detector slab. It is based on a National Instrument PCI board with 32 differential input channels multiplexed differential channels, a sampling rate of 1.25 Mb/s per channel, a dynamic range of 12 bits and a 32 bit PCI interface.

The SSD, together with a cosmic test bench, will be used to validate the assembly, mounting and performance of each PCB. In addition, the wafer thickness is known only to a tolerance of ±3%, as specified by the wafer producers. A calibration of the MIP signal will be made for every pad and the results will be used to intercalibrate the different channels. Such a variation of thickness could be one of the major components of the constant term of the final calorimeter and correcting for this effect could dramatically improve the energy resolution.The SSD has been used to produce the first measurements of the MIP level from the full chain of the detector, namely:

Silicon diodes – Conductive glue – $\mathbf{PCB}_{\mathbf{(Version\ KNU\text{-}1)}}$ – $\mathbf{VFE}_{\mathbf{(version\ FLC\text{-}PHY2)}}$ – $\mathbf{DAQ}_{\mathbf{(SSD\ version)}}$

Because of a small delay in the commissioning of the cosmic test bench, for the first test, a radioactive ^{90}Sr β decay source was used. It has been used to measure the noise on the overall chain from the silicon detector to the DAQ and to validate the assembly of the prototype PCBs. Figure 6 shows the signal and noise measured in this way, which was found to give a MIP signal/noise ratio of 5/1. Further improvement on this ratio is expected with the last version of the VFE chip (FLC-PHY3).

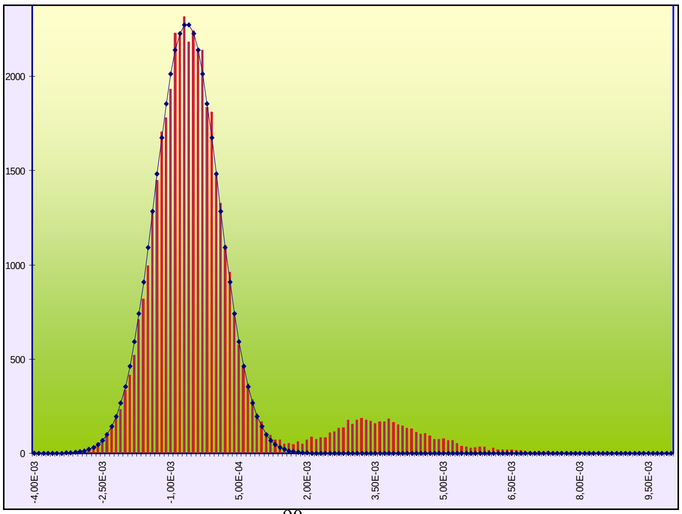


Figure 6: Pedestal and ^{90}Sr β signal in a prototype PCB.

The cosmic test bench is made of scintillators, PMTs, a trigger, a command generator and data acquisition. The detection system is made of four planes of scintillators (two in each direction) read by PMTs. The trigger is defined by a time coincidence between PMTs from all four planes. The generated

trigger is output as a NIM level, ready to be used by any DAQ system. The command generator card is built using a Xilinx CPLD, with the master clock from the DAQ board, but with a possible connection to an internal clock. The signal transmission is in LVDS, through a TTL translator. Slow control and calibration for each detector slab is sent through a USB port. The calibration can be performed in two modes, one where readout and validation go through the USB port and one with external validation. The injected value can be done from the ADC output on the DAQ board, or from a totally external node, with the TTL translator. A schematic view of the cosmic test bench is shown in fig. 7.

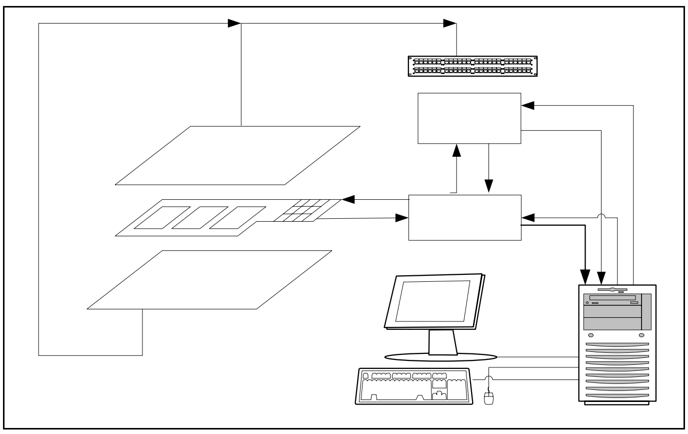


Figure 7: Schematic view of the cosmic test bench, with the DAQ for the assembly test and calibration of the detector slab.

2.5 The DAQ for the prototype

The readout of the full prototype, where there are about 10,000 channels, will be done with custom designed VME readout boards. These have been developed by the UK groups and are based on the CMS tracker readout front-end board (FED). The timing, multiplexing and calibration control for the VFE board are sent as LVDS signals by the readout board. The multiplexed analogue differential VFE channel outputs are digitised on the board using a 16-bit, 500 kHz ADC, which allows complete readout of the VFE PCB within 100 μs. The resulting ADC data are buffered in an 8 MByte memory, allowing up to 1600 events to be stored before VME access is needed. This should allow an event rate above 1 kHz during a spill and the goal is to achieve an average of more than 100Hz over a run. Two prototype readout boards were produced in November, of which one is shown in fig. 8. The full system of six boards is scheduled for fabrication in summer 2004.

The two prototype boards have been used in the cosmic test bench to read out the prototype PCBs. Figure 9 shows the cosmic signal measured using these boards and this confirms the signal/noise value of 5/1.

Figure 8: Prototype DAQ readout board.

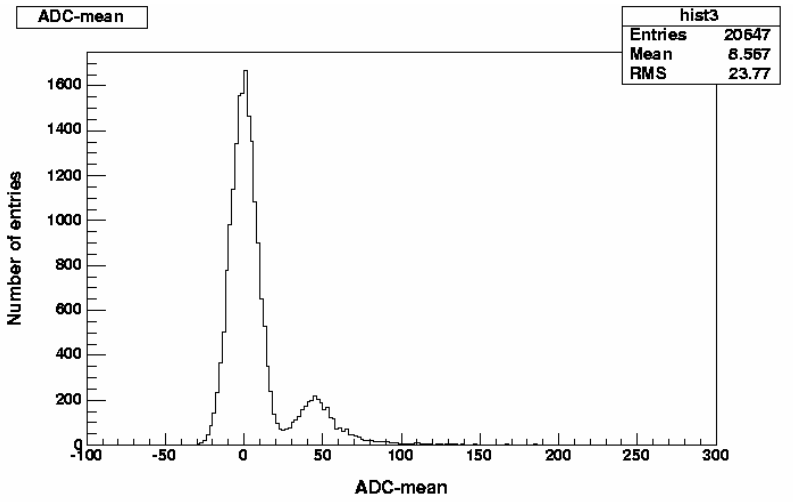


Figure 9: Pedestal and cosmic MIP signal on a prototype PCB with the DAQ for the prototype.

2.6 Support structure

A standalone support table which can move the prototype along both axes (horizontal and vertical) is being designed and will be produced by LAL-Orsay before the first beam test at DESY at the end of 2004. Figure 10 shows a schematic view of this proposed support structure.

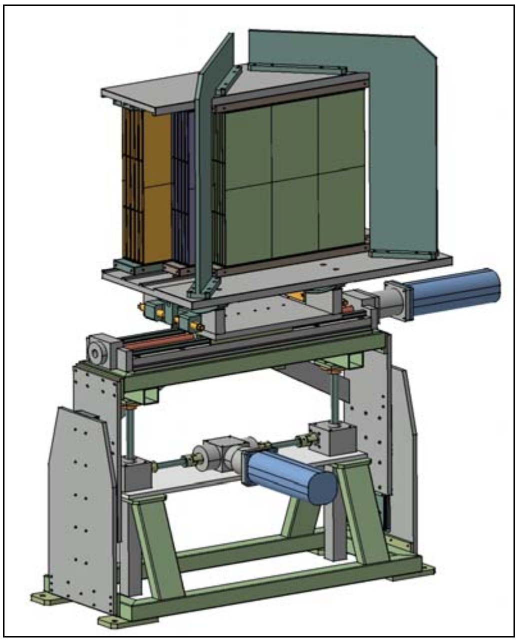


Figure 10: Schematic view of the support structure design.

2.7 Overview of the ECAL production

The table below shows the status of the various parts of the ECAL production.

Items	Status	Comments
Tungsten plates	Funded and produced	Good production, no problem so far
Structure with carbon fiber	Funded, first structure produced, second and third in production	
Wafer sample 1	Produced by MSU, funded by IN2P3	Small problem of size not within tolerance; will delay mounting
Wafer sample 2	First test batch produced at Prague in April 2004	First batch of 15 wafers received
PCB for testing	Version KNU-1	Fill the requirement
PCB for prototype	Version KNU-2 in test	Would be the prototype version
VFE chip	Designed, produced	
Calibration DAQ	Tested and running	Ready for assembly validation and calibration
Full prototype DAQ	Under test at the LLR cosmic test bench	Board prototypes produced , firmware in development. Production this summer
Support table	Funded, designed at LAL-Orsay In construction	

2.8 The silicon-tungsten electromagnetic technological R&D

The R&D on the technology for the full scale detector is progressing in several different directions.

- Two chips will be produced in 2004. The goal is the design and test of a new VFE chip type post-prototype. It is in progress at LAL-Orsay and LPC with production of an ASIC called FLC-TECH1, which will include ADC(s) and will work in pulsed mode. One of the goals is to validate the simulation of the chip which predicts power dissipation in pulsed mode of about 100 μW/channel.

- Thermal simulation at MSU, at LLR and at KNU has begun to see the impact of the geometry, material used, etc. The goal is to validate designs regarding the power dissipation.

- The development of a cooling prototype at LLR and KNU is under way. A test bench for temperature and heat transfer measurements in a structure made tungsten-carbon fiber is under development. It will measure the constraints at the limit of the structure, which will then be used in a simulation program. It can also be used to test different ways of cooling, from passive to active liquid flow.

- A review of possibilities for on-detector readout electronics for final project, where available space is very small. It includes a study of “improved” zero suppression at the digital level for an ECAL module.

The funding for this part of the project is not established.

2.9 Conclusions

The ECAL prototype is under construction and the production of the various components is more or less on schedule or has a small delay. The complete ECAL device will be tested on the cosmic test bench of the LLR- Ecole Polytechnique before the end of October 2004. Assuming there are no significant problems, a test with low energy electron beam at DESY is proposed before the end of 2004.

In 2005, the aim is to go to FNAL or IHEP to use more energetic test beams including, most importantly, hadron beams together with the two HCAL options.

3. The digital hadron calorimeter (DHCAL)

3.1 Introduction

The purpose of this project is to develop a Digital Hadron Calorimeter (DHCAL) for the Linear Collider detector. A calorimeter optimized for the application of Particle Flow Algorithms (PFAs) features a very fine segmentation, of the order of 1 cm^2 laterally and layer-by-layer longitudinally, for both the electromagnetic and the hadronic parts of the calorimeter. With this fine segmentation, the energy resolution for neutral hadrons (the component of hadronic jets to be measured with the HCAL) obtained with digital or analogue readout is comparable.

3.2 Overview of the project

The group explores two different choices for the active medium of a DHCAL: Gas Electron Multipliers (GEMs) and Resistive Plate Chambers (RPCs). GEMs are being studied by a group at University of Texas at Arlington and RPCs are being investigated by a group in Russia (IHEP Protvino and Dubna) and, independently, by a group in the U.S. (Argonne, Boston, Chicago, Fermilab). In comparison, GEMs offer the advantage of lower operating voltages (hundreds of Volts compared to several thousand Volts for RPCs) and RPCs offer easier assembly techniques, mechanical robustness and larger electronic signals (several pC compared to several fC). A choice between the two technologies will be based on a comparison of their performance as active medium of a prototype calorimeter section in test beams.

3.2 Recent progress

In the following we shall briefly summarize recent progress of the different subprojects:

a) Gas Electron Multipliers

The group assembled a prototype 2-layer GEM and measured some of its characteristics with cosmic rays and radioactive sources. The gain of the chamber was determined to be of the order of $3.5x10^3$, which is consistent with measurements done on similar chambers by the CERN GDD group. The signals from the chamber are being read out using the QPA02 chip developed by Fermilab for Silicon Strip Detectors. Tests with an area of nine 1 cm^2 readout pads are foreseen for the near future. Significant effort was spent developing a mechanical assembly process for two-layer GEMs. The assembly technique was developed with Kapton foils, but will soon be tried with real GEM foils. Finally, the group investigated alternative sources of GEM foil production. First interactions with the 3M corporation, also located in Texas, have been encouraging.

For efforts concerning the development of the electronic readout system, see below under c3).

b) Resistive Plate Chambers at IHEP-Protvino (Russia)

The group carried out an extensive study of the performance of mono-gap glass RPC prototypes with 1 x 1 cm^2 anode readout pads. The RPC prototypes were operated in saturated avalanche and in streamer mode. In both modes the chambers showed excellent detection efficiency (>95%) and low pad multiplicity (<1.4) for single tracks. Comparing the two operation modes, the group concludes that the saturated avalanche mode is to be preferred, mostly due to its higher rate capability and safer operation mode. Overall, the chambers meet the requirements on the performance of the active medium of a digital hadron calorimeter for the Linear Collider, as determined by simulation studies.

As a result of our studies, the group recommends the use of RPCs with the following features:

- Single-gap chambers (for simplicity reasons)
- Thin glass sheets as resistive plates (commercially available)
- Gas gaps of 1.2 – 1.6 mm thickness
- Resistive anode plates as thin as possible
- Anode pads with a size of about 1 cm^2
- Operation in saturated avalanche mode
- Use of the following gas mixture: TFE/IB/SF_6, with 5% Isobutene and a few % SF_6
- Signal discrimination at about 2 mV (for 50 Ω loads)

Further details have been documented in the publication "RPC as a Detector for High Granularity Digital Hadron Calorimetry", DESY-04-057 (March 2004).

A 1 m^2 RPC prototype plane was constructed for use in the 1 m^3 DHCAL prototype section. The chamber rests on a 2 mm steel sheet which provides the necessary rigidity of the structure. The uniformity of the response was measured with cosmic rays using 2 x 16 orthogonal x and y readout strips, each with an area of 96 x 6 cm^2. A MIP detection efficiency of 95% was measured with a uniformity of ±2%. The chamber performed satisfactorily for the use in the 1 m^3 prototype section and can, if needed, be produced in the required quantity.

RPC prototypes with 64 pads of 1 x 1 cm^2 were assembled to be tested in a 5 T magnetic field at DESY. The chambers are readout with the 8 channel Minsk chips together with ALTERA FPGAs. Two such prototypes were successfully tested with cosmic rays.

The group plans the following activities in the next few months:

- Construction of a mini DHCAL prototype with 10 planes of 64 channels each
- Tests of a mini DHCAL prototype in an electron beam
- Development of 64 channel PCB readout boards containing the new Minsk front-end chip
- Production of 40 planes of 1 m^2 RPCs for the prototype section. Each plane will contain 96 x 96 readout pads
- Installation of the front-end electronics on RPCs as it becomes available

c) Resistive Plate Chambers (US)

The group assembled a total of five Resistive Plate Chambers each with an area of 20 x 20 cm^2. Three of these chambers feature double gas gaps and two chambers were built with a single gas gap. The chambers were thoroughly tested with cosmic rays. The analog measurements were performed using the RABBIT system developed for CDF and the digital measurements used a VME based digital readout system developed and built by this group. In the following we briefly summarize the many tests performed with the chambers:

- The MIP detection efficiency of the chambers, the charge of the signals and the streamer fraction were measured as function of applied high voltage with a single readout pad of 10 x 10 cm^2 and analog readout.
- The MIP detection efficiency and the noise rate were measured as a function of applied high voltage with a single readout pad of 10 x 10 cm^2 and digital readout (amplifier and discriminator).
- The above measurements were repeated with a number of different gas mixtures.
- The geometrical acceptance of the chambers was measured using a cosmic ray test stand with tracking capability.
- Measurements were performed with multiple pads: 25 pads of 1 cm^2 each. The MIP detection efficiency and the pad multiplicity were measured as a function of applied high voltage with both analog and digital readout.
- The mechanical properties of the chambers under gas pressure and as a function of applied high voltage were determined.

From these tests we conclude that RPCs are an excellent candidate for the active medium of a digital calorimeter: the MIP detection efficiency is high (> 95%), the noise rate is extremely small (< 0.5 Hz/cm^2), the pad multiplicity is of the order of 1.3 to 1.4 (with digital readout).

The group also developed a conceptual design for the readout of a larger prototype calorimeter section. The design is centered on a front-end ASIC with 64 input channels. The specifications of the functions of the ASIC have been documented and discussions concerning the design and prototyping of the ASIC have initiated with the chip design group at Fermilab. An effort is being made to build a chip which can be used by both the GEM, see section c.1), and the RPC approach. For the latter the chip can accommodate signals from chambers operating in both avalanche and streamer mode.

The group plans to complete all R&D concerning the chamber design and the electronic readout system in calendar year 2004. Assuming adequate funding, the group will proceed with the construction of a 1 m^3 prototype section consisting of 120 chambers of 33 x 100 cm^2 and the corresponding electronic readout system in calendar year 2005. Tests in particle beams are foreseen for 2006.

In the next few months we plan to:
- Complete the measurements of the pad multiplicity with digital readout.
- Construct and test a set of larger chambers similar in size to the one's to be used in the prototype section.
- Document the specification of the entire electronic readout system for the prototype section.
- Initiate the prototyping of the different parts of the electronic readout system.

In summary, the group has now almost completed Phase I of the project, the feasibility studies, and is initiating the prototyping of the electronic components of the readout system for the prototype section (Phase II). Funding permitting, the construction of the prototype section and its electronic readout system (Phase III) will start in calendar year 2005. Phase IV, testing in particle beams, is expected to commence in calendar year 2006.

3.3 Summary

In summary, the group plans to build a 1 m^3 prototype section of a Digital Hadron Calorimeter with 40 planes of active medium. RPCs have been proven to perform adequately for the use in such a calorimeter. Specific recommendations concerning the details of the chamber design have been made. In addition, the use of GEMs as active medium is being investigated. Two design efforts for the electronic readout system of the 1 m^3 prototype section are underway: one based on a chip being developed by a group in Minsk and one based on a chip being developed in collaboration with Fermilab. Contingent on the availability of adequate funding, construction of the RPCs and the corresponding readout system for the prototype section will start in calendar year 2005. Tests in particle beams will initiate in calendar year 2006.

4. The analogue hadronic calorimeter (AHCAL)

4.1 Introduction

The scintillator based option of a sampling hadron calorimeter relies on a proven technology for the active medium. However, the particle flow concept with its emphasis on spatial separation of particle showers requires longitudinal and transverse segmentations much smaller than in existing hadron calorimeters. Novel photo-detection devices for the light readout, operating in high magnetic fields, open up new possibilities for the construction of fine-grained scintillator based detectors on a large scale.

The CALICE collaboration is pursuing the development and construction of a cubic metre sized test beam prototype hadron calorimeter to be tested together with the ECAL and tail catcher. The goals of the program are

- To establish the new readout technologies on intermediate scale in an accelerator environment and to address operational issues such as calibration schemes and long-term stability;
- To collect hadronic shower data in unprecedented granularity as a basis to validate and improve the simulations of the shower development in a scintillator sampling structure;
- To further develop the reconstruction and pattern recognition algorithms within the particle flow approach;
- To optimize the use of spatial and amplitude information offered by the scintillator as active medium, i.e. granularity and analogue energy resolution;
- And to explore the semi-digital concept in which only minimum amplitude information is used in the form of a small number of thresholds with relatively simple electronics.

The overall goal is to demonstrate that the high performance demands imposed by the LC physics programme can be met with the chosen approach, and to lay the ground for conceptual detector design choices to be made by the time a linear collider is supposed to be ready for approval (in 2008).

The scintillator HCAL effort is driven by an international group of institutes, involving contributions from the Czech Republic (Prague), Germany (DESY and Hamburg University), Russia (ITEP, JINR, LPI, MEPhI), and the US (Northern Illinois), and receiving strong support from France (LAL) and the UK groups in CALICE.

At the previous PRC review, we reported on optimization studies of the basic detector element consisting of a scintillator tile coupled via a wavelength shifting fibre to a photodetector. Good separation of a minimum ionizing particle (MIP) signals– typically 25 photo-electrons (p.e) - from pedestal was achieved for 5x5x0.5cm^3 tiles read out with conventional multi-anode photo-multipliers (MAPMs), avalanche photo-diodes (APDs) and novel Geiger mode Silicon diodes (SiPMs).

In the meantime, a small pre-prototype calorimeter, the “minical”, has been constructed and instrumented with up to 108 channels. It has been operated successfully with all three kinds of photo-detectors in the DESY electron test beam. Based on this operational experience and extensive simulation studies, the design for the cubic-metre prototype has been optimized. We report here on simulation studies, on detailed studies of photodetector properties, on the results from the minical test beam program and present the design of the prototype which is presently entering the construction phase.

4.2 Prototype optimization

Shower separation studies

The prototype granularity has been optimized with respect to the capability to separate nearby hadronic showers. In the particle flow approach, for the HCAL it is particularly important to properly measure the energy of individual neutral hadrons in a dense environment. The algorithm developed at DESY and ITEP reconstructs the tree structure of hadronic showers on a topological basis and is thus able to separate the energy depositions of partially overlapping showers. It has been adapted to each of the granularities under study: square tile of 1cm, 3cm and 5cm size, and the case where two 3cm tiles in subsequent layers are jointly read out (“3x3x2”).

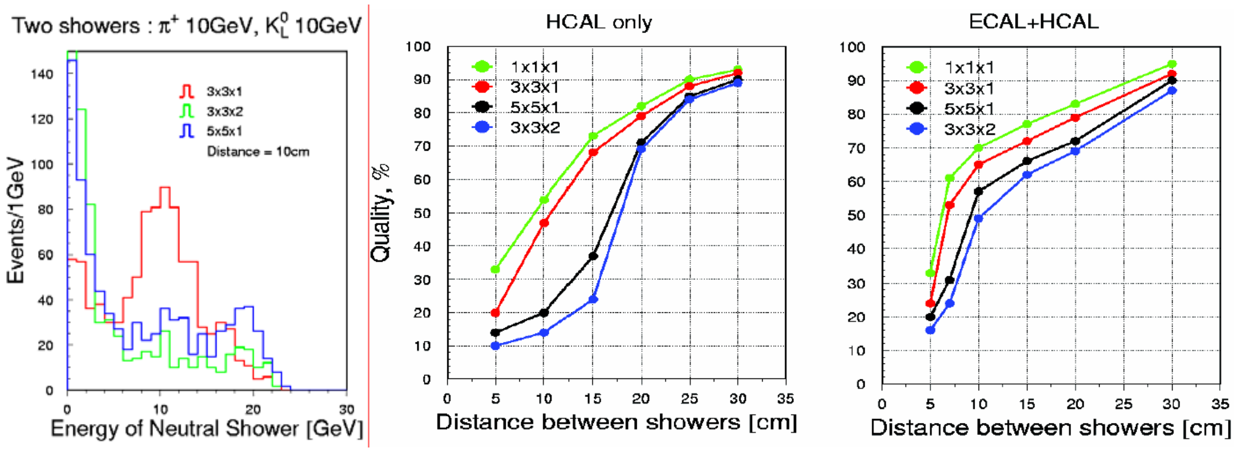


Figure 11: Energy of reconstructed neutral kaons (left), fraction of neutral kaons with reconstructed energy matching the true one within ±3 standard deviations (single particle resolution), as a function of distance to next charged hadron; right: with the ECAL prototype simulated in front of the HCAL.

Two particle events with a charged pion and a neutral kaon have been simulated and reconstructed. The energy reconstruction quality of the neutral kaon is studied as a function of the tow-particle separation. It is found that 3cm tiles clearly allow better separation performance, and that maximum longitudinal readout segmentation is mandatory. Readout of two layers of 3cm tiles with one photodetector degrades the performance more than enlarging the tile size to 5cm, although the number of channels per square metre active detector would be larger. This conclusion can be drawn also from a study of the fraction of cells with energy depositions originating from two different nearby particles and is thus independent of the specific reconstruction algorithm in use.

For cost reasons, only a core of the prototype with 30cm x 30 cm transverse dimension can be instrumented with the optimal granularity. It has been verified that larger tile sizes outside this region have only negligible impact on the performance. The depth of the core of 30 layers is necessary mostly for good reconstruction quality in the (semi-)digital approach (see below).

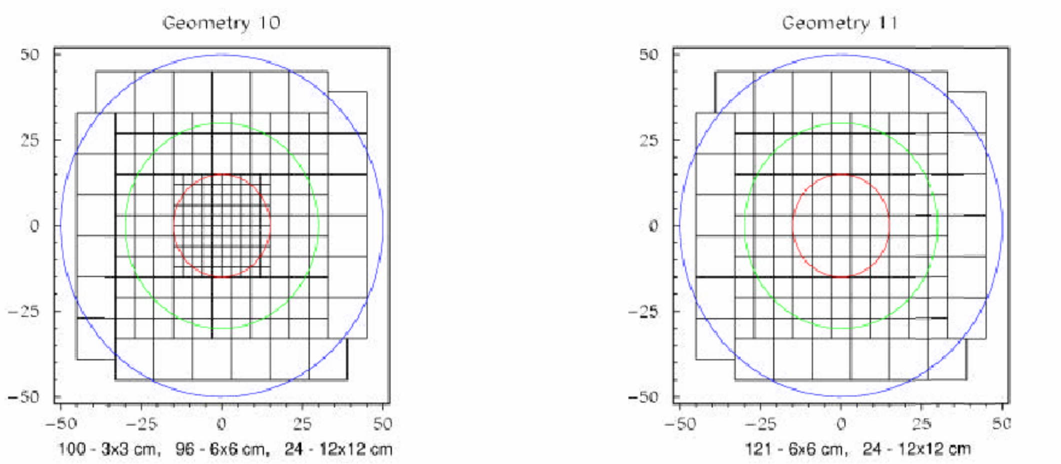


Figure 12: Tile geometry of prototype layer 1-30 (left) and 31-38 (right) **.**

Semi-digital considerations

Scintillator cells as small as 3cm are considered as a candidate for digital calorimeter readout. The energy resolution is expected to be better than in the analogue case at low energies, due to the suppression of Landau fluctuations of the deposited energy. (This could of course be reversed with a more elaborate use of the measured amplitude in the analogue case.) The degradation of the resolution at higher energies is due to an increasing probability of multiple hits per cell in dense showers. It can be overcome either by reducing the cell size further, or by adding minimum amplitude information in the form of thresholds. Scintillator as active medium allows to trade between granularity and dynamic range. The semi-digital approach developed at NIU consists of a moderate choice of granularity combined with a 2 bit readout. This concept can be tested with the planned prototype.

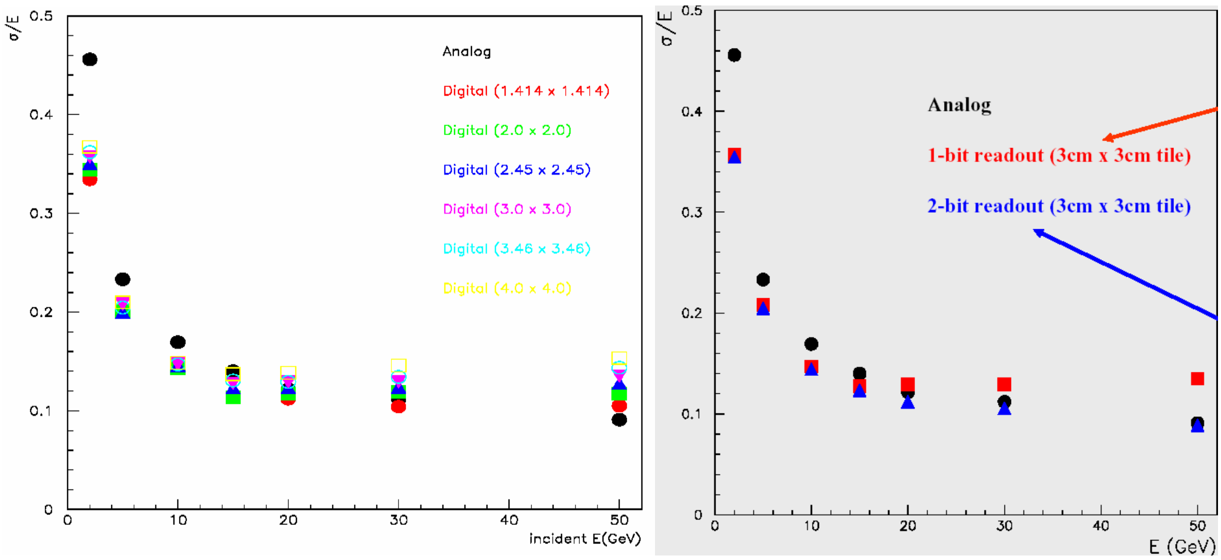


Figure 13: Hadron energy resolution as a function of energy for different cell sizes and numbers of thresholds.

Tail catcher studies

Models of hadronic shower simulation differ particularly in the tails. The HCAL in the TESLA TDR design is located inside the solenoid and only about 4 interaction lengths deep, and so is the planned test beam prototype. It is therefore planned to complement the test beam set-up with a tail catcher and muon system which should serve a twofold purpose: it should provide a reasonable measurement of the longitudinal shower tails, and it should be a prototype system for the study of muon tracking and identification within the particle flow reconstruction.

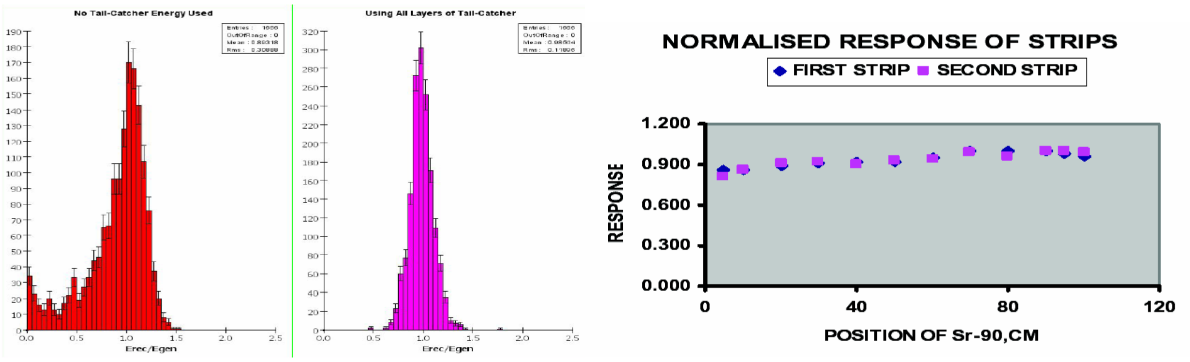


Figure 14: Fraction of reconstructed energy for a 50 GeV pion in the cubic metre prototype without and with a tail catcher system; uniformity scan along 1m long 5 cm wide extruded scintillator strips**.**

The system envisaged by the NIU group is based on 5cm wide extruded scintillator strips and will use the same photo-detectors and readout electronics as the HCAL prototype. This strip width is well matched to the transverse position uncertainty introduced by multiple scattering, which is found to rise smoothly from 1 to 2 cm for a MIP as it passes from the first to the last layer through the tail catcher.

4.3 Tile HCAL components

Scintillator tile fibre optimization

The light yield of the tile fibre systems had been optimized and is adequate for the HCAL application. Documentation on detailed studies had been submitted to the previous PRC review. For 3, 6, and 12 cm tiles, produced from polystyrene by the Russian company Vladimir and read out with Kuraray Y11(300) wavelength shifter fibres, 21, 28, and 17 p.e per MIP, respectively, have been registered with SiPMs at ITEP. These yields provide a signal to noise ratio which allows a precise calibration of individual cells using MIPs. Due to saturation effects in the photo-detectors, higher light yields for MIPs are not favourable. The fibre groove had circular ("sigma") shape except in the 3cm case where a quarter circle was used. The sigma shape gives better uniformity and somewhat more light than the quarter circle It would be the preferred choice also for the smallest tile size, if long-term studies (NIU) are confirmed which indicate that no ageing effects occur even for the small required bending radii. However, it should be noted that for small tiles uniformity is less critical than for large ones.

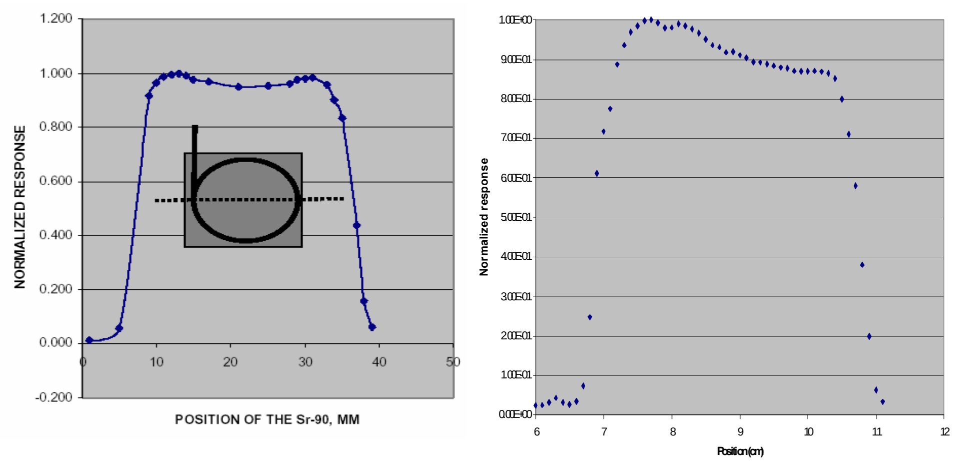


Figure 15: Uniformity scans for tiles with circular (left) and quarter circle grooves (right). The scan in the second case is along the diagonal perpendicular to the fibre.

Photodetector studies

SiPMs: The Silicon photomultiplier is a multi-pixel avalanche photo-diode operated in Geiger mode. It has been developed in a cooperation of DESY, MEPhI and the Russian company PULSAR. Photo-electrons initiate a discharge limited to a single pixel which provides a gain of typically 10^6, comparable to that of vacuum PM tubes. The output signal is the analog sum of the binary single pixel signals and thus proportional to the light intensity. The dynamic range is determined by the total number of pixels being 1024 (on an area of about $1mm^2$) for the type under consideration for the HCAL.

Due to the small size, the relatively low operation voltage of about 50V and the high amplitude signal which can be transmitted to remote electronics, the device is ideally suited to be mounted directly on scintillator tiles, which allows to avoid the mechanical complications of optical fibre routing for readout. The high channel density demanded by the particle flow requirements can thus much more easily be realized.

The photon detection efficiency depends on the bias voltage, which also affects the gain and the noise level. Typically a working point is chosen with a gain of about 10^6, yielding an efficiency of 10-15% (including geometrical losses due to the pixel-to-pixel separation). The total noise rate is typically 2 MHz, dominated by single pixel signals and decreasing steeply with threshold. For the chosen working point, light yields around 25 p.e per MIP are obtained in 5cm tiles with a circular wavelength shifting fibre for light collection. With a threshold setting corresponding to 95% efficiency for MIP detection, the noise level is comparable to the cosmic ray induced rate. The sensitivity of the signal to temperature changes is about 4%/K and requires monitoring.

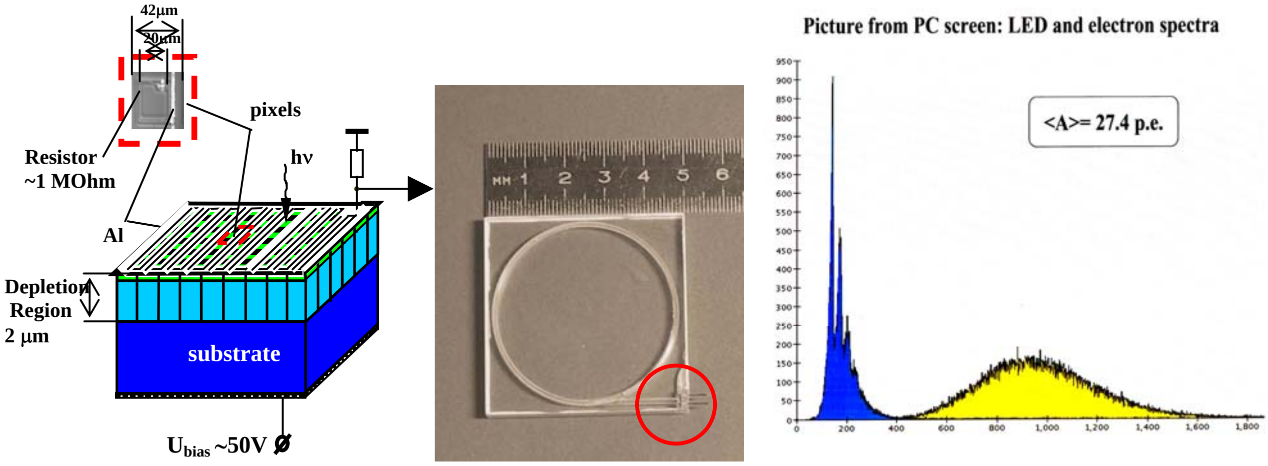


Figure 16: Sketch of a SiPM, SiPM mounted on a tile, pulse height spectrum from a tile irradiated by LED light and a beta source.

Since the recovery time of a fired pixel is of the same order as the decay time of the wave length shifter (about 20-30ns), a single pixel can be fired more than once during a scintillator induced light pulse, and the effective total number of pixels, which determines the saturation behaviour, is found to be larger than 1024 and pulse shape dependent. In order to correct the measured signals for the non-linear response of the photo-detector, a universal response function can be used, if the system is calibrated in units of pixels/MIP.

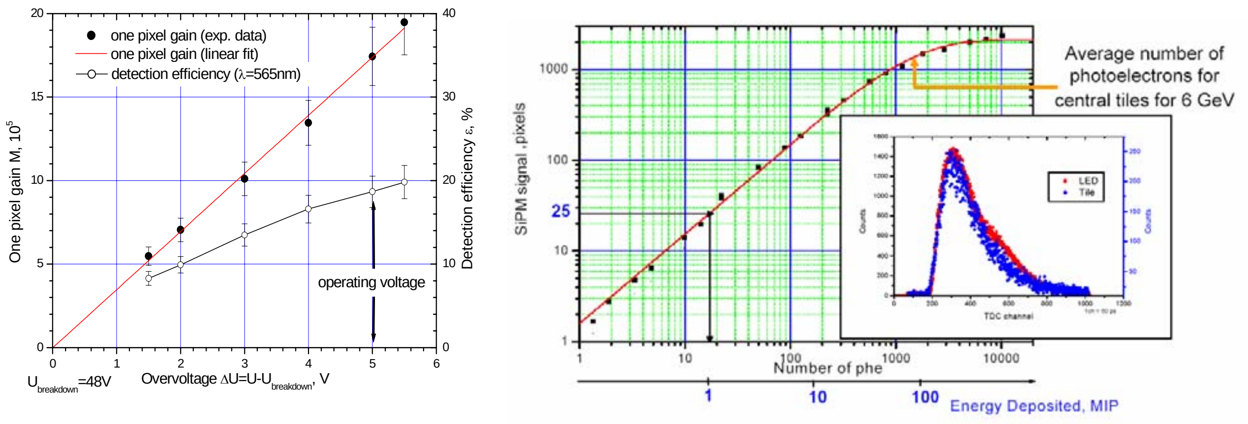


Figure 17: SiPM gain and efficiency vs bias voltage, response function for scintillation light signals.

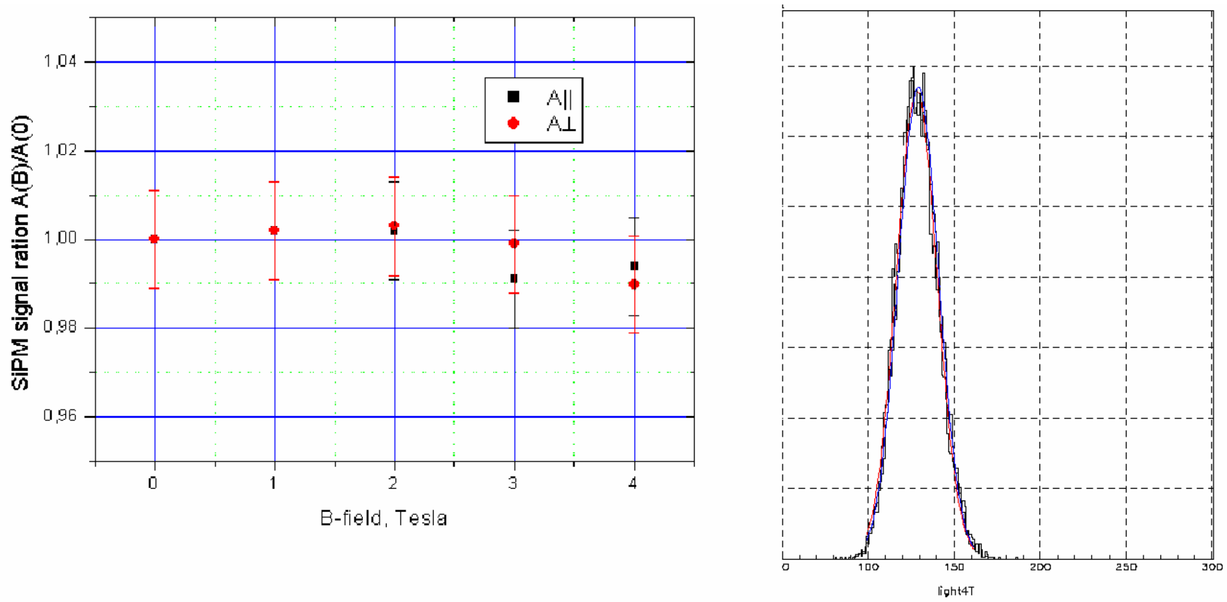


Figure 18: SiPM response to LED light (corresponding to about 150 pixels) vs magnetic field (left), pulse height spectrum for B=0 and B=4T (right).

Of biggest importance for the establishment of the SiPM as a working device for a big detector with many channels was the successful operation of a pre-prototype calorimeter with 108 channels in the DESY test beam (see below). In addition, in order to test the long-term stability of the SiPMs, various parameters characterizing the functionality have been carefully monitored over an integrated time span of several years, and in tests where the diodes were heated op to a temperature of 90 degrees. The insensitivity of signal response and noise behaviour to magnetic fields was verified in tests using the 5 Tesla R&D magnet at DESY.

APDs: Avalanche photodiodes are considered as alternative photodetector. They have lower gain (of the order of 100) than SiPMs, but the advantages are higher quantum efficiency and wider dynamic range. The relative sensitivity to voltage and temperature instabilities is moderate but increases with gain. The development of sensitive low noise preamplifiers is therefore a central issue, and stability and monitoring play an important role.

Most studies (at Prague and DESY) have been made with a set of 40 APDs of type Hamamatsu S8664-55 with 3x3mm^2 active area, in addition one 32 channel matrix APD was investigated. Within the set, the gain was measured to be uniform within 50%, which allows operation with common HV supply, but the voltage must be stabilized to 10^{-4} in order to ensure a gain stability within 1%. Mostly for cost reasons, one APD is used to read out 3 tiles via optical fibres. In this mode the APD response must not depend on the fibre position on the surface. The surface homogeneity was a concern for other APD types. It was therefore checked in dedicated scans of 12 APDs to be better than 6%.

Different lines of preamplifier development have been followed. Single channel voltage and a charge sensitive preamplifiers have been built, and in addition a modified version of the integrated 18 channel ECAL chip has been developed for APD readout. They all deliver sufficient signal to noise ratio.

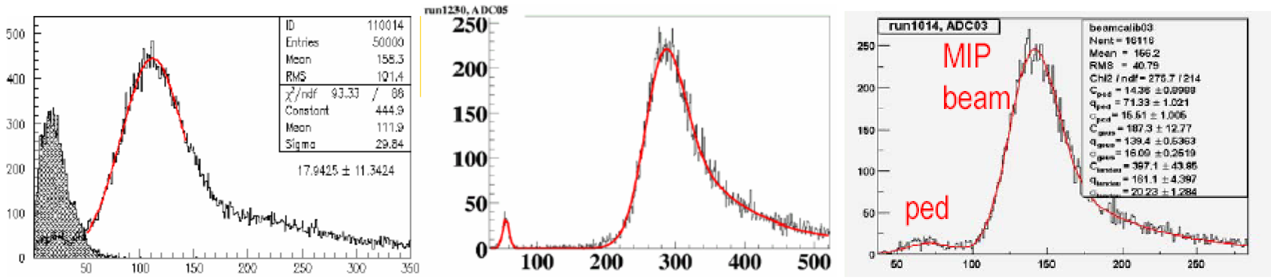


Figure 19: Pulse height spectra for APDs read out with a voltage sensitive preamp, a charge sensitive integrated preamp, and an integrated 18 channel preamp chip.

4.4 The Minical program

The minical is a a flexible calorimeter set-up which is operated with comic rays and in the DESY electron test beam at energies from 1 to 6 GeV. The goal of the program was to acquire operational experience with a system with of the order of 100 channels, and to use well understood electromagnetic showers for the development of a detailed detector understanding in terms of simulations. This program is considered as an important step for the design of the physics prototype and for the later extraction of physics information on the shower development from hadronic test beam data. Construction and operation was a collaborative effort of the DESY, Hamburg, ITEP, LPI, MEPhI, and Prague groups

The minical is built as 27 layer sandwich structure with 2 cm steel absorber plates and 1 cm gaps to accommodate the active detector modules. These modules were aluminium cassettes equipped with 3 x 3 scintillator tile arrays in 11 layers, which provides 97% containment at 6 GeV. The scintillator tile size was 5x5x0.5cm^3. Readout proceeds either via 108 directly coupled SiPMs or via optical fibres with 36 APDs or 3 16-channel MAPMs. (MAPMs cannot be operated in strong magnetic fields, but are used here as reference device and to validate the simulations.) The cassettes can be transversely moved out of the absorber structure and can be directly exposed to the electron beam for calibration.

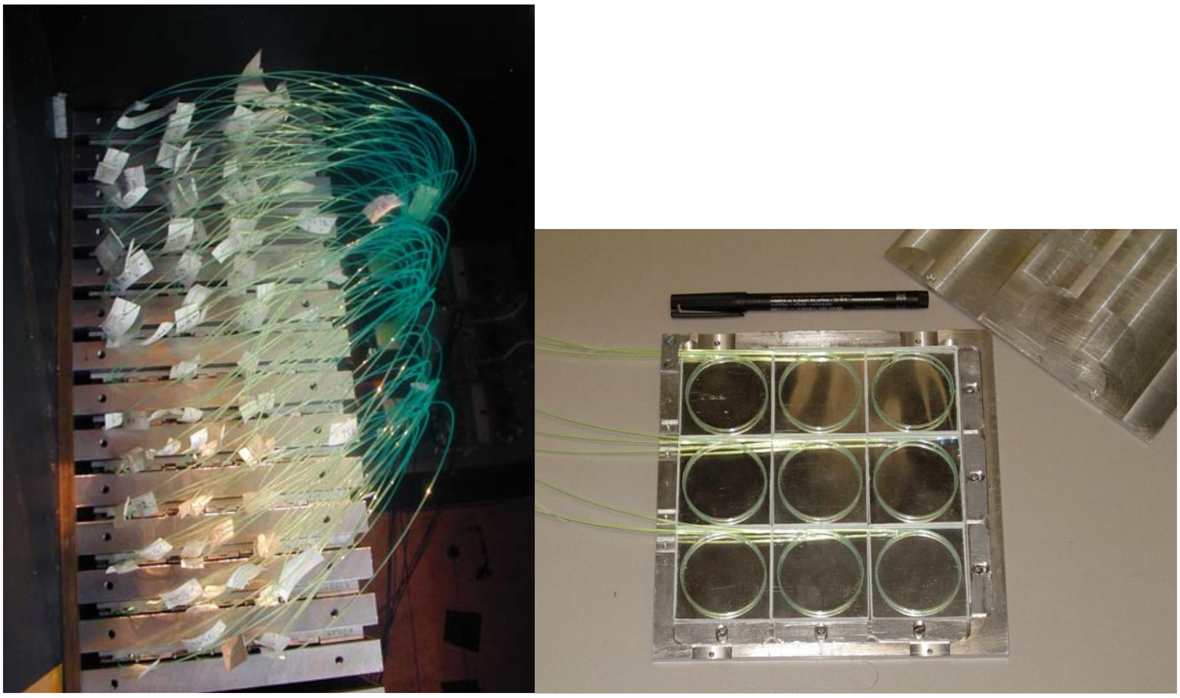


Figure 20: Minical structure and one active layer cassette.

The beam has an energy spread of about 3% and energy dependent intensity. Using a scintillator trigger coincidence with 3x3mm^2 active area, the maximum event rate was 200 Hz at 3 GeV.

For the readout charge integrating 10bit ADCs and a CAMAC system have been used. The data were locally acquired on a Linux PC and converted into ROOT n-tuples for analysis; conversion into the internationally agreed LCIO data format is also possible. Slow control information (bias voltages, temperatures) is recorded simultaneously.

The minical structure has been implemented in a GEANT4 simulation framework. The simulation of the idealized detector response is complemented by a step which models the signal formation and accounts for the finite photo-electron statistics and for the non-linear photo-detector response (in the SiPM case).

For calibration, the spectrum generated by the passage of the electron beam through the cassettes - without steel absorber - is used. The most probable value of this distribution is named “MIP” and constitutes the common energy scale for data and simulation; the calibration makes no reference to the beam energy. For this procedure a good reproduction of the single particle pulse height spectra is essential.

To determine SiPM non-linearity corrections, LED runs with additional preamplifiers were taken to measure the number of fired pixels corresponding to the MIP signals. This factor had a roughly Gaussian distribution for the 108 channels, with a mean of 25 and width of 5. Using a common correction function for all cells provides already good linearity in the total energy response; with individual channel corrections also a reasonable description of the spectra for cells in the core and the tail of the shower can be obtained.

For the correction of the APD data, information from temperature sensors and from an LED system with PIN diode monitoring is being used. This allows to stabilize the single APD response to LED signals to better than 2%.

The full analysis of the APD data is still in progress, the current status indicates a performance similar to that obtained with the other photodetectors. We compare below linearity and resolution obtained from MAPMs and SiPMs with simulations for the SiPM case. The simulated MAPM resolution is only marginally better than in the SiPM case, because the photo-electron statistics is very similar and the effect of the non-linearity on the resolution is small. The response is linear within 2% except at 1GeV, where the beam energy uncertainty is being re-investigated. The response in units of "MIPs" is very well predicted by the simulation. The parameterized resolution is predicted within the errors, if beam energy spread and tile-to-tile miscalibrations within a systematic uncertainty of 5% are included. The constant term is found at the 2% level which, according to simulations, is almost entirely due to leakage. There appears to be some underestimation of the resolution at lowest energies, which is subject of further analysis.

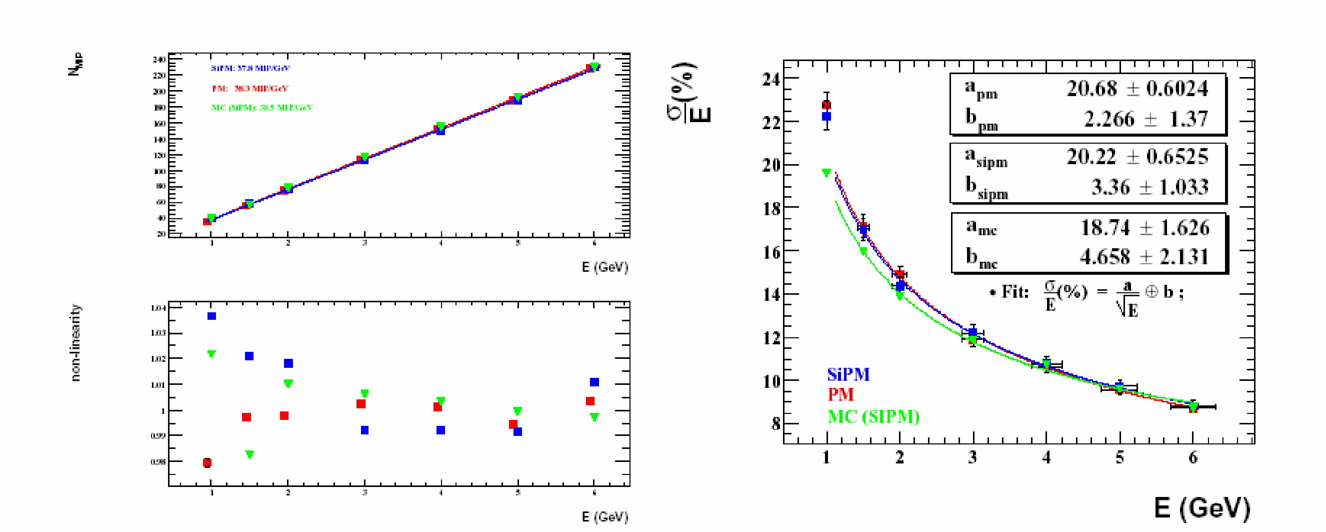


Figure 21: Linearity and resolution for minical data with SiPMs and MAPMs, compared with simulations

4.5 Preparations for the physics prototype

The excellent operational experience with the minical and the established calibration and correction procedures provide sufficient confidence to proceed towards the physics prototype (PPT). The granularities demanded by particle flow considerations and in particular in the semi-digital approach can be realized at reasonable cost today only with SiPMs, which have therefore been chosen as baseline design for the PPT. However, partial instrumentation using alternative technologies is also foreseen. The design of the active detector modules relies as much as possible on extrapolations of techniques already verified in the minical cassettes, and on the experience acquired during their production at ITEP. Yet, the scaling in channel count by two orders of magnitude demands new approaches in several areas, for example for photo-detector selection, HV supply and read-out electronics. The production of components has been initiated while new solutions are still being developed.

The scintillator tiles for the prototype will be produced by injection moulding. A mould has been produced for all tile sizes needed. The tiles will be equipped with WLS fibres and SiPMs at ITEP. The groove will be machined with a computer controlled milling device which can produce also the fitting for the SiPM with sufficient mechanical accuracy. The tiles will not be individually wrapped, only the surfaces perpendicular to the beam will be covered by large single sheets of 3M reflector foil. To optically decouple neighbouring tiles, the edges will be mated by chemical treatment. Measurements at ITEP have proven that this suppresses optical cross talk to the percent level.

The first mass-produced batch of 5000 SiPMs has just been delivered from the manufacturer and is on the test bench. Quality control and characterization proceed in several steps. Only very coarse tests to exclude basic malfunctions are performed by the producer, all further steps are done at the contributing institutes. The first stage of quality control is performed at MEPhI with entire wafers on a probe station and ensures that the individual detectors operate in Geiger mode and reach sensitivity to visible light at acceptable dark currents. For the second and third stage semi-automatic test set-ups are under development at ITEP. On one of them SiPM parameters like gain, inter-pixel cross talk, noise and temperature sensitivity will be recorded as a function of bias voltage. The other will characterize the light yield of the full tile fibre system in terms of registered photo-electrons per MIP and finally determine the optimal working point for each device. The data base holding the results of these procedures will be a very important ingredient for commissioning, operation and data analysis.

The mechanical design of the calorimeter, developed by DESY and ITEP, follows a modular concept with active detector cassettes independent from the absorber stack structure. The cassette design is based on signal transportation via 1mm thin coax cables as in the minical. A prototype with dummy tiles has been built at DESY and was used to verify mechanical tolerances and cable routing procedures. Meanwhile orders for 40 cassettes (including 2 spares) have been placed. The mechanical parts will be produced at DESY and shipped to ITEP for assembly. After initial tests, the cassettes will be returned to DESY and equipped with the FEE cards for further tests and commissioning.

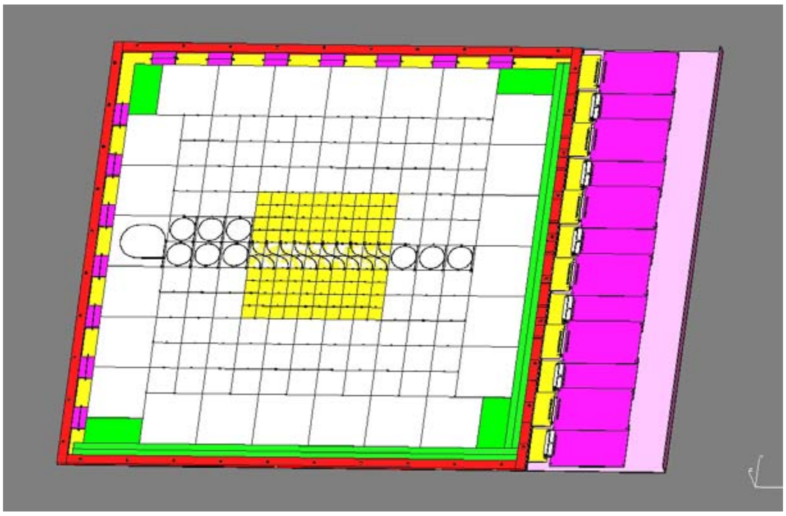


Figure 22: HCAL prototype cassette with front end electronics cards.

The absorber stack design (DESY) is aimed at providing maximum flexibility for test beam experiments with varying beam conditions and detector configurations. Horizontal and vertical scans can cover the entire front face. Angular scans with 38 layers can cover a range up to 35 degrees with respect to normal incidence. Larger angles, which occur abundantly in linear collider events, are possible if the number of layers is reduced, for example up to 45 degrees with 36 layers. In all cases the beam axis remains centrally with respect to the high granularity core. The gap widths are adjustable, in order to accommodate different types of active detectors, even within the same gap. The sampling structure can be varied by the same means. The design foresees also an option to turn the detector into horizontal position, to allow for cosmic data taking during longer interruptions of beam operation.

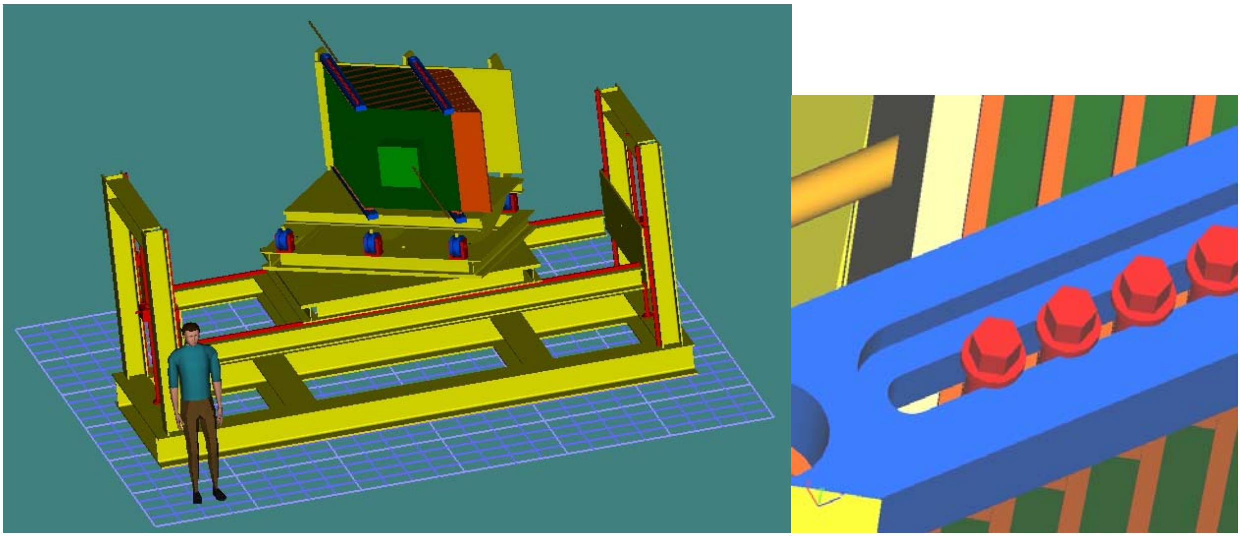


Figure 23: HCAL absorber stack on movable table, detail.

The LED monitoring system is still being optimized (DESY and Prague). A solution which provides light for SiPM gain adjustment via observation of single pixel peaks like in the minical is at hand. Current studies are aiming at maximizing the light intensity such that the saturation behaviour can be measured in situ. Using UV light stimulates the scintillator and allows to monitor the entire signal generation chain. PIN diode monitoring would provide a valuable handle on light yield stability independent of MIP data.

For the front end electronics (FEE), different paths have been followed. Given the fact that the number of channels is now similar to that of the ECAL prototype, a similar degree of integration appears reasonable. For reasons of cost and schedule, a solution based on the ECAL FEE is considered as baseline option. For the data acquisition, this will then allow basically just extending or duplicating the ECAL system, and it will facilitate the integration of ECAL and HCAL in a common test beam experiment. An alternative, FADC-like concept with early digitization of the fast signals and subsequent FPGA analysis of the pulse has also been proposed and successfully tested by the JINR group; this approach will also be followed for the future. The group also studies time-over-threshold methods for semi-digital readout.

The ECAL readout concept relies on slow shaping of the detector signal, which both optimizes the energy resolution of the Si sensors and acts as delay to match the latency of about 150 ns for trigger generation and distribution. Long shaping of SiPM signals bears a risk of pile-up of dark noise signals (with rates of 2 MHz for 1 p.e). While this would have negligible effects at MIP amplitudes, it could pose a problem for the separation of single pixel peaks for calibration and gain adjustment. It could been shown in measurements done at MEPhI that the single pixel structure of the SiPM pulse height spectrum can be resolved with pulses of 300ns width and 110ns peaking time.The test was done using the preamplifier stage of the first version of the ECAL chip together with an external shaper. A first design of an 18 channel chip has now been proposed by the LAL group, it is adapted to SiPM input and compatible with the ECAL DAQ. The shaping characteristics are being optimized. An option for fast shaping of calibration signals – to be used with calibration triggers only - is also included. In addition a circuitry for bias adjustment to be integrated in the chip has been designed.

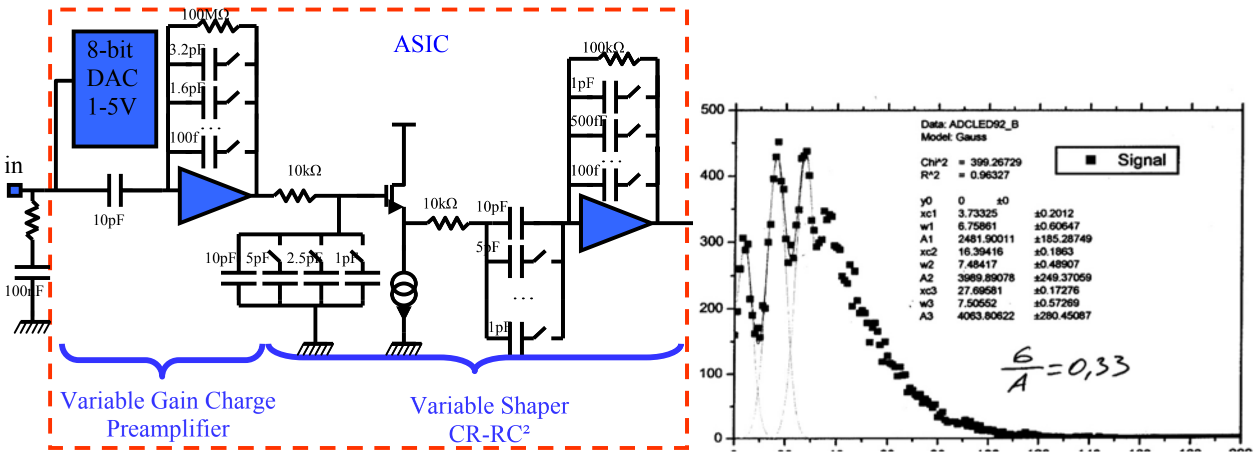


Figure 24: First proposal of schematics for integrated SiPM FE; measured SiPM response with slow shaping.

4.6 Test beam requirements

The main goal of the test beam is to study the details of the hadronic shower development to the extent that is required for topological reconstruction of their structure. Large data samples will be needed for this purpose. In order to obtain a quantitative estimate of the precision necessary to test the simulation models, test beam data simulated at Cambridge with the Geant 3 and the Geant 4 programs have been compared. Differences are clearly visible in samples of 10,000 events, and they depend on energy, particle type (pion or proton) and active detector material. Taking variations of impact point and incidence angle into account, one arrives at data sets of the order of 10^8 events, which require a few weeks of beam time with a DAQ system capable of taking events at 1 kHz. To allow for feedback from analysis, several such periods will be needed.

In order to match the typical particle energies in linear collider events, the energy range of the test beam should extend at least up to 50 GeV, but availability of small energies close to 1 GeV is equally important. Different types (pions, protons, and muons) are needed, with high purity (from particle identification devices, e.g. Cerenkov counters) or at least with exactly known composition. A tracking system must provide the impact point with at least 1mm precision. More demands, including such on infrastructure have been formulated in a document prepared by the worldwide LC test beam group.

4.7 Organizatorial issues

Schedules

The interleaved sequence of detector component production, quality control and assembly requires detailed time planning. We give here only some milestones to characterize the expected time line

May 2004	first batch of SiPMs available for quality assessment
June 2004	prototype FEE chip design
August 2004	assembly of first cassette
October 2004	test of FEE prototype with first cassette at DESY
Spring 2005	commissioning of complete set of cassettes and electronics, integration with ECAL; ready for hadron test beam

Responsibilities

The tile HCAL R&D effort has a relatively high degree of task sharing. The table below indicates for the different areas the institutes with main responsibility. In most cases, other institutes, not listed, also contribute

Mechanics	DESY, ITEP
Scintillator tile fibre system	ITEP
SiPM production and tests	MEPhI, ITEP
Cassette assembly	ITEP
LED system	DESY, Prague
FEE	LAL, MEPhI, JINR
DAQ	UK groups
APD option	Prague, DESY
Slow control	DESY, LPI
Software and simulation	DESY, NIU
Tail catcher	NIU, DESY
Coordination	DESY, ITEP

4.8 Further R&D activities

We list here areas where continuous R&D in parallel to the PPT will be necessary:

- development for a detector unit with single cell readout with APDs, to be tested in the PPT,
- further optimization and industrialization of Geiger mode pixel photodetectors,
- evaluation of the potential of other new photodetector developments as they arise,
- industrialization of scintillator production,
- further integration of readout electronics (integrate digitization step into front end),
- full detector mechanical and conceptual design.

It is clear that also the scintillator based HCAL effort will continue to have a strong software branch. An important goal is to perform a careful optimization of gain and dynamic range with respect to the performance in LC physics events, incorporating feedback from test beam analysis. .

4.9 Summary

The AHCAL group has progressed well towards the realisation of a test beam program with a cubic metre scintillator steel prototype. This is backed by the minical program, which established the novel photo-detectors as successfully operating in a detector system, and advanced simulation studies. The scintillator HCAL effort has been further internationalized, and its scope has been extended towards studies on a tail catcher/muon system. The scintillator systems are expected to become ready in time to join the ECAL beam test.

5 Reconstruction software

The most novel feature of the Linear Collider calorimeter design concept proposed by members of the Calice collaboration is the very high transverse and longitudinal granularity of the detector. This was motivated by the "particle flow" approach to jet energy reconstruction. The high spatial resolution in the calorimetry is required in order to separate energy depositions from the main components of jets - charged particles, photons and neutral hadrons. The high granularity has also led to the idea that only digital readout may be required in the hadronic calorimeter, just counting hit cells rather than summing their energies.

The design of the calorimeters can be optimised using Monte Carlo simulations, but especially in the case of hadronic showers it is essential to validate the simulation tools using real test beam data,for all the main detector technologies. This is a key part of the Calice program. As part of our preparations for the test beams, we have been carrying out detailed comparisons between different Monte Carlo packages, especially their hadronic interaction codes. Significant differences are found, for example in hadron energy response and transverse shower width, which may be expected to affect the performance of jet reconstruction. We are therefore also writing and studying reconstruction algorithms in order better to understand their behaviour.

Two Fortran codes to perform jet energy reconstruction using particle flow ideas have already been written by members of Calice:
Replic: This code (based largely on work at LLR) was used for the original Tesla TDR work, and established the viability of the technique for achieving a jet energy resolution close to the desired $30\%/\sqrt{E(\mathrm{GeV})}$
Snark: This code (based on work at DESY and ITEP) is available as part of the widely used Brahms simulation package.
Both of these codes are somewhat tied to specific detector geometries and code frameworks. Several activities are currently taking place in Calice to develop new reconstruction techniques which exploit the novel features provided by calorimeters of high spatial resolution and segmentation. At this stage it seems

important to pursue different techniques in parallel, and Calice provides a framework within which new ideas are exchanged and discussed. Most of the current work was presented at the recent LCWS 2004 workshop in Paris.

The currently active areas in Calice include the following:

- At DESY and ITEP, a new clustering algorithm is being developed for a scintillating tile hadronic calorimeter. The algorithm aims to identify substructures within hadronic showers, such as track-like groups of hits, probable electromagnetic showers, and isolated hits which are likely to be associated with neutrons. In this way, the response of the calorimeter to different components of the shower can be equalised (“software compensation”) and an impressive improvement in energy resolution may be achieved. The impact on two-particle resolution is also being studied.

- A number of studies are being pursued by the UK members of Calice. Systematic studies of Monte Carlo models available in Geant3 and Geant4 have been performed and comparisons with Fluka are also being made. Work has also started on implementing realistic electronics effects into the simulation, and understanding the effect these have on shower reconstruction. Two new partcile flow algorithms are also under development: the first uses an algorithm which tracks showers from layer to layer of the calorimeter, while the second is based on a complementary minimal spanning tree technique. In both cases, the intention is to produce a performing algorithm which will allow different detector geometries and technologies to be compared meaningfully.

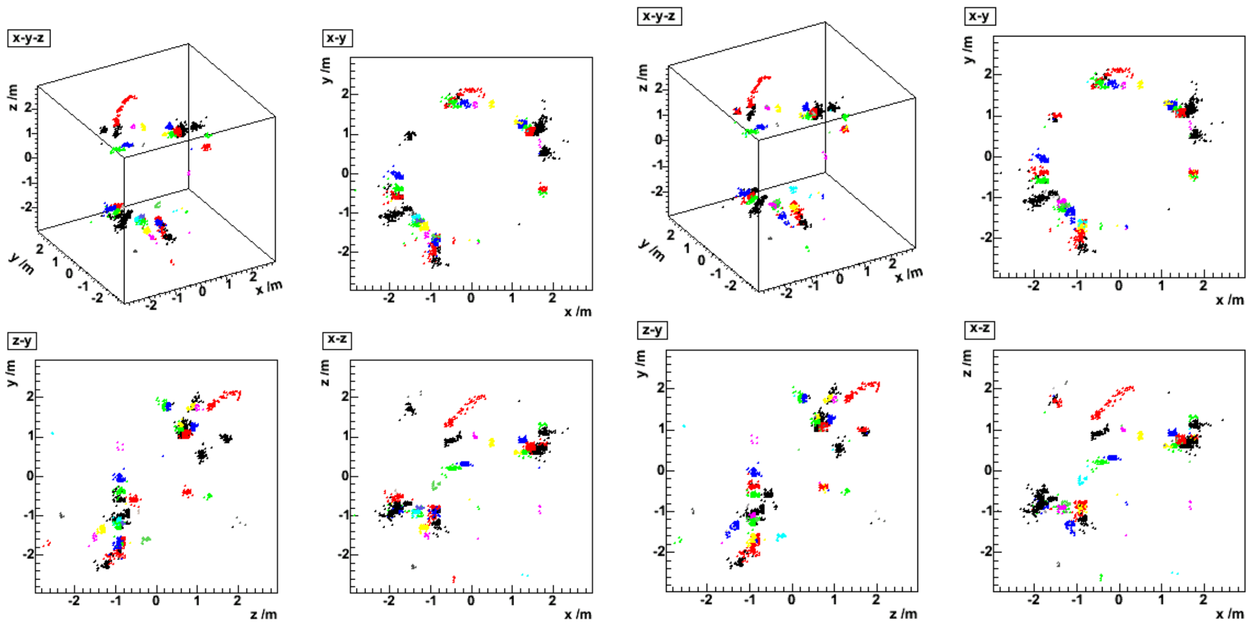


Figure 25: Simulated calorimeter hits. The colour coding represents the assignment to primary particles, according to Monte Carlo truth (left) or reconstruction right**.**

- At DESY, a small HCAL prototype (“Minical”) using scintillating tiles has been tested in an electron beam, and extensive comparisons between reconstructed events and Monte Carlo have been reported. In general, very good understanding of the detector performance has been achieved.

- Work is under way at NIU to study a “semi-digital' hadronic calorimeter, based on small scintillator tiles read out with three thresholds (2 bits). This looks a promising approach in terms of improving hadronic energy response. Both energy-weighted and density-weighted cluster reconstruction techniques are being investigated.

- Particle flow studies are also being pursued at Argonne, mainly in the context of an RPC-based hadron calorimeter, although he algorithm development is largely independent of the active detector medium. A particular feature of this work is the use of track reconstruction as an input to cluster-finding in the calorimetry - many other algorithms leave the track-calorimeter association to be treated after clustering.

- Calice collaborators at UTA are studying a GEM-based digital hadron calorimeter, and have recently presented results on energy measurement and two-particle separation.

6 Conclusion

The collaboration has made significant progress towards a prototype for a combined ECAL+HCAL test beam series. The group is prepared for a timely start of the test beam program, to use the next years as a window of opportunity for laying the ground for basic detector design choices.
Taking into account the information given above, the collaboration proposes to proceed further, asking for test beam in DESY for the beginning of December 2004, and to ask for period of hadron beams test in the years 2005-2006.