Memorandum from the CALICE Collaboration to the DESY-PRC

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Progress Report on Calorimeter R&D for the Future Linear Collider

The CALICE Collaboration

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1 Introduction

1.1 The CALICE project

The goal of the CALICE collaboration is to design a calorimeter, both electromagnetic (ECAL) and hadronic (HCAL), optimized for jet reconstruction in e^+e^- collisions at centre of mass energies between 90 and 1000 GeV, hereafter called the FLC (for Future Linear Collider). Work on the ECAL is centred on a silicon-tungsten sampling calorimeter, while several different technologies for the HCAL, including both analog and digital readout, are being actively considered. The aim is to find the optimal configuration of calorimetry from these potential choices.

We propose to establish the list of the relevant parameters for this optimisation, to estimate through simulation the expected performance for each proposed detector design, and to cross check the validity of the detector simulation of these variables with real measurements. This program could be classified into three categories:

1. The first and most obvious category is testing the technical feasibility of the proposed detector (e.g. the high level of integration for the ECAL with a total thickness for $24X_0$ of about 20 cm, the reliability of photodetectors in a 4 Tesla field for scintillator readout, etc.).

2. The second category consists of checking the performance of the proposed detector for jet reconstruction, through the development of dedicated "Energy Flow" Algorithms (EFAs). The performance is tested by taking examples of important channels from the physics program expected at the FLC with the detector simulated with GEANT3 or GEANT4 [1]. Our experience within the collaboration already indicates it will not be possible to use a single algorithm for the various different designs of the calorimeter, without a strong bias in the respective performance. A dedicated EFA may have to be used and tuned for each ECAL and HCAL combination.

3. Last but not least, the performance is directly related to variables (e.g. for hadronic showers, the lateral deposition, the pattern of the shower, etc.) for which the validity of the detector simulation can be questioned [2]. We therefore propose to validate (or modify) the simulation, and therefore the expected performance, by checking the relevant variables using a prototype in test beam. This tuning of the simulation program must be done with detector technologies close to the ones proposed. For example, from ALEPH data, the basic principle of the digital HCAL seems correct, but the fundamental pieces, like the energy resolution, cannot be checked for two reasons, namely the coil is in between the ECAL and the HCAL in the ALEPH apparatus and the digital readout is only along the drift-tube and hence is only one dimensional in each layer. As a consequence, we consider the construction of these prototypes and the measurement of the relevant variables in a test beam as an essential part of the proposed program of R&D. Figure 1 shows a schematic view of the ECAL and HCAL prototype foreseen for the beam test.

1.2 The CALICE collaboration

As of the end of October 2002, the CALICE collaboration consists of 138 physicists from 24 institutes and 8 countries. This is the only collaboration of that size with such an ambitious program in this domain of FLC R&D.

All the four main regions involved in HEP contribute to the effort, with 2 Asian, 3 US, 13 European and 6 Russian institutes being members. This common world effort is of primary importance in showing the possibilities of inter-regional collaboration and will help greatly in forming the detector collaboration once the FLC is approved, independent of the site decision.

1.3 The CALICE schedule

The agenda of the R&D program is driven by the fact that the information for the calorimeter technology decision may have to be available for the end of 2006. This is because, in the case of an accelerator decision prior to 2005, a calorimeter Technical Design Report (TDR) has to be delivered to the FLC community and to the funding agencies at this date. Under this constraint, we envisage the following schedule:

- Mid 2003 - completed design of prototype, start of construction
- Early 2004 - end of prototype construction
- Mid 2004 - first data taking in test beam
- Mid 2005 - complete the test beam program
- Mid 2006 - complete analysis of the test beam data and start writing the calorimeter TDR

2 Status of the silicon-tungsten ECAL studies

The ECAL prototype will consist of 30 layers of silicon wafers sandwiched between tungsten plates. Each layer contains 9 silicon wafers in a 3×3 array and each wafer contains 36 diode pads, giving a total of 9720 channels.

2.1 Mechanical structure

2.1.1 Status of the prototype mechanics

As of the end of September 2002, the first 40 plates of the tungsten needed for the study of the first stack of the prototype have been delivered by ITEP and IHEP to the LLR at Ecole Polytechnique. The metrology of the plates (planarity, thickness homogeneity, density, etc.) has been performed at ITEP and IHEP and they appear within tolerance. Their mechanical quality is under test at the LLR.

In addition, the first study of the carbon fibre/tungsten structure shows very good behavior between the two components. A first small module test has been built and is shown in figure 2.

The expected schedule is the following:

- End 2002 - the structure of the first stack is completed
- End 2002 - the tungsten-carbon fibre elements for the detector slab are completed
- Mid 2003 - the second stack is completed
- End 2003 - the third stack is completed

2.1.2 R&D on the full detector mechanics

Two aspects of the R&D have made important progress in the recent months. First of all, the possibility to put the very front-end electronics readout inside the detector has been investigated. In order to study this possibility, power dissipation and a possible cooling system have been studied with dedicated simulation software (SPICE and SAMCEF). A prototype with a PCB, heat source and temperature measurement is under construction at the LLR, in order to validate the SPICE simulation, but also to give the value at the edge of the PCB (border and cooling tube) for the more sophisticated program SAMCEF. One of the important pieces to understand is the heat transfer perpendicular to the PCB, through the carbon fibre and the tungsten sheet. A first possible design of the cooling system has been studied at the LLR and with industry.

The second aspect concerns the design of the detector slab, and the industrial implications. Several laboratories have close contact with industry and studies have been performed in order to establish a level of cost per unit surface area. The conclusion is positive, with a cost/cm^2 which gives an estimate of a total cost for the calorimeter significantly smaller than for a "typical" LHC detector calorimeter.

2.2 Silicon wafer production

The masks for the wafers have been designed at MSU and IPAS-Prague. A first batch of 25 wafers at MSU and 5 wafers at IPAS-Prague have been produced. Out of these 30 wafers, 29 wafers are of good quality, that is with a leakage current smaller than 30 nA at the over-depleted voltage (about 250 Volt for 530 μm of depletion thickness) [3], which fully complies with the QA (quality assurance) requirements.

This rate of production is a very significant success, particularly if it can be maintained for the rest of the production of about 250 wafers. It is planned to perform moat of this production in 2003 in order to finish the prototype construction in the first months of 2004.

The design of the test mount for the silicon wafers on the detector slab is under progress at the LLR, where manpower and expertise is available. It is planned to have the whole fabrication chain ready for the end of spring 2003.

2.3 Electronic readout

In order to read out the 9720 channels of the physics prototype, a very front-end (VFE) ASIC has been produced at LAL, directly derived from a previous chip developed for Opera HPDs. It includes 18 channels (matching the silicon pad granularity) of charge preamplifiers, 180 ns shaping amplifiers and track-and-holds and fully multiplexed output.

The charge preamplifier integrates the incoming signal on a 1.5 pF feedback capacitance, providing a gain of 4 mV/MIP (1 MIP = 40 ke$^-$). Its large input PMOS exhibits a noise density of 1.5 nV/$\sqrt{\text{Hz}}$ at $I_d = 0.5$ mA, equivalent to an ENC of 1500e$^-$ for a 70pF input capacitance. The following shaping amplifier is a CR-RC architecture with a peaking time of 180 ns and unity gain. The track-and-hold stores the signal on a 2 pF capacitor with a $\sim$40 mV pedestal dispersion over the 18 channels and can be read out at 5 MHz. The total dynamic range covered by the VFE is around 12 bits, up to 600 MIP with a linearity around 1%. This VFE chip was sent to foundry (AMS 0.8μm BiCMOS) in June 2002 and received back at LAL in September.

The PCB which houses 3 wafers and 6 VFE chips has also been designed and is now in production. It also includes a calibration system and is connected to the digitising part of the readout via a flat twisted-pair cable. The full production of PCB and VFE chips is planned for 2003.

The digitising and data acquisition part of the readout is under development in the UK. This will be a custom-built system based on VME, with wide use of FPGAs to allow flexibility. All 9720 channels will be digitised using 16-bit ADCs and read out for every event. The system is aiming for a 1 kHz peak rate, giving a 100 Hz sustained rate when allowing for the beam line duty factor. The timescale for this system is to build prototypes of the main digitising and readout boards by early 2003, with production towards the end of 2003 and testing complete in mid 2004.

In parallel to these developments dedicated to the test beam, the R&D for the final detector electronics is going on in Clermont and LAL, with the submission of test structures such as multiple gain shaping amplifiers, low power ADCs and large dynamic range and low power preamplifiers in burst mode.

3 Status of the tile HCAL studies

The goal of the tile HCAL R&D activity is the development of a ~1 m^3 prototype as described in the proposal to the PRC (October 2001 and addendum in May 2002). The preparation of such a prototype requires detailed software simulation and reconstruction studies to find the feasible limits in cluster separation and localisation and to allow for sufficient shower containment within the limited detector volume. A large granularity also improves the energy measurement when software compensation on an individual cell level is applied. Detailed hardware R&D studies have to prove the feasibility of such a hardware concept and to demonstrate that the proposed granularity allows the desired performance in the (so far unachieved) local energy and cluster resolution and track-cluster assignment.

3.1 Recent progress

3.1.1 Tile-fibre system

Intensive R&D studies have been carried out at all collaborating institutions for the selection and optimisation of the components of the tile-fibre system (TFS) and have lead to a significantly improved light yield. With a scintillator based on Poly-Vinyl-Toluol (BC-408, Bicron) and a standard photomultiplier of ~11% photocatode efficiency, a yield of ~25 photoelectrons/MIP/tile is measured for the best geometrical TFS configuration. A new reflector foil with 99% reflectivity (3M, Super-Radiant), proper polishing of the fibre end and careful cleaning of the tile surfaces contributed significantly to the enhanced light yield and equalises the light yield from different TFSs. Figure 3 shows some of the promising results in light yield achieved through optimisation of the tile-fibre coupling for the best available scintillator (BC-408) and an interesting Russian scintillator with cheap Poly-Styrol as the base material. The studies are described in detail in a long R&D report which is in preparation [4]. New and cheaper plastic scintillators based on Poly-Styrol were developed in Russia with ~70% of the optimal TFS light yield mentioned above.

3.1.2 Photodetectors

The wavelength-shifted light from 3 or more tiles (representing a calorimeter cell) is collected at the front of appropriate photodetectors which should be able to operate in a 4 Telsa field. Signals of > 600 photons were found for cells with the optimised TFS. The small photodetector signals from MIPs are used for energy calibration and have to be well separated from the photodetector noise spectrum. The measured light yield allows the use of APDs (Hamamatsu single detectors or pixel arrays, e.g. Hamamatsu S8550 with 32 pixels) with a good signal/noise separation ($> 6\sigma$) for MIPs. Newly developed small semiconductor photodetectors (Si-PMs, MEPHI) also show also a very promising performance. Both detector types are well suited as candidates for the prototype.

Photomultipliers as used for the bulk of the present studies have to operate in magnetic fields smaller than 40mT and so would have to be placed outside the flux return yoke with a long optical fibre readout in the final FLC detector. They are only considered as a fall-back option for the prototype. All photodetector candidates considered were operated in test beams (all at DESY, some at CERN and Protvino) and showed very satisfying gains and MIP/noise separation. To collect information on operation and performance of the various photodetectors, the prototype should be equipped with larger samples of the different candidate photodetector types. A detailed plan for the layout of the different types can be made only after additional photodetector studies as outlined below.

3.1.3 Preamplifiers, shapers and electronics

For the APDs, charge sensitive preamplifiers are needed with a gain of ~5mV/fC. Three options with promising performance have been identified:

- A ITEP/Minsk preamplifier. A prototype is available and this was tested with MIP signals. It is expected that ~30 components will soon be used in the minical tests at DESY.
- The ECAL preamplifier/shaper option, adapted from the OPERA preamplifer. This is not optimised for the tile HCAL with respect to photodetector capacity and gain. Work is foreseen in Prague to modify and optimise, the ECAL preamplifier, with some help from the LAL-Orsay electronic group, towards the specific needs of the HCAL.
- A low-noise RF type preamplifier optimised to the APD 32 pixel array. This has been designed in Prague and tested in the beam test at DESY. A gain of 20 mV/40000 e^- (corresponding to a MIP signal) was measured. The preamplifier has a large bandwidth (500MHz) and the noise density on input is $4\text{nV}/\sqrt{\text{Hz}}$.

All preamplifier versions will be optimised for performance and tested for acceptable gain and MIP/noise separation. Appropriate signal shapers will be used to feed track-and-hold buffers. A decision for the design of a multi-channel preamplifier board (16 or 32 channels) prototype is needed in spring 2003.

The digitisation and readout electronics to be used depends on which of the preamplifiers is used. For example, using a modified version of the LAL-Orsay ECAL chip would probably allow the UK ECAL electronics to also be used for the tile HCAL; the other preamplifier options above may not be compatible and so would require further electronics development.

3.1.4 Optimal prototype structure and cell granularity

Simulation studies with PYTHIA generated events have started to optimise the tile/cell structure to get smallest reconstructed cluster size and track/cluster-centre residuals. With the actual cell granularity (PRC proposal 2001) a close track/cluster assignment can be achieved within ~2.5 cm depending on the showers. Further investigations aim mainly to optimise the granularity structure in this aspect.

3.2 Future work towards the prototype

Future work is planned as follows:

- The development of new, cheap Russian scintillators will continue in the coming 6 months (Protvino) with optically cleaner Poly-Styrol and also a new optimised wavelength-shifter (Protvino). This will be followed by repeated TFS optimisation studies with such scintillators at ITEP, LPI and Prague.
- As proposed in the last PRC meeting, the minical array with up to 150 tiles in 64 cells will be operated in cosmic and beam tests at DESY for studies on precision gain-monitoring with LEDs, cell calibration with cosmic MIPs and further ageing studies.
- A test device with a LED-UV-light source for the high precision measurement of ageing effects in tight fibre loops is in operation at DESY and aims for ~0.5% sensitivity to light yield losses.
- Photodetectors (APDs and Si-PMs) have to be optimised in pixel size and performance. So far, the Si-PMs have only $1 \times 1\text{mm}^2$ pixel sizes. A larger size of $\sim 2 \times 2\text{mm}^2$ will

be available for tests in spring 2003, but the cost will significantly increase and probably approach the APD price. The possible use of APD pixel arrays is being investigated in Prague aiming for a reduction in both the readout space required and the cost. In addition to the existing 32 channel array, some single APD channels have been ordered for studies of gain, detector capacity and excess noise behaviour. It is foreseen that at least two different photodetector options will be used in the prototype. The preamplifiers to be developed have to be adapted to the capacity and gain of the different photodetectors.

The schedule is as follows; for 2003, optimisation of the individual calorimeter components will proceed up to May. This will be followed by design and construction of the prototype stack up to the end of August, with prototype assembly during September-December For 2004, monitoring, calibration and DAQ studies will occur up to the end of April, with first test beam in June.

4 Status of the digital HCAL studies

The application of EFAs to the reconstruction of the energy of hadronic jets requires a calorimeter with very high segmentation. Monte Carlo simulations indicate that readout pad sizes as small as 1 cm^2 may be necessary to provide the best possible separation of the different components in a hadronic jet. With this fine segmentation the HCAL has of the order of 50 million channels, which for financial reasons cannot be equipped with analog readout. Therefore, a number of institutes are investigating the merits of an HCAL where only the yes-no hit information is read out. In Monte Carlo studies, the energy resolution provided by such a digital hadron calorimeter (DHCAL) turns out to be comparable to the resolution obtained by the same calorimeter with a complete analog readout.

Several different readout devices are being investigated as possible choices for the active medium of the DHCAL, namely resistive plate chambers, gas electron multipliers and scintillator tiles. In the following we summarize briefly the various ongoing R&D efforts for each option.

The groups involved plan to construct a 1 m^3 prototype to be tested in beam starting in the second half of 2004. These tests will provide the basis for validating the various Monte Carlo simulation programs and for the decision-taking process concerning the technology to be used in the HCAL. It is hoped that a common mechanical structure can be used for all the HCAL options, including the tile HCAL.

4.1 Resistive plate chambers

RPCs as an active medium for the DHCAL are being investigated by several groups (Dubna, Moscow, Protvino, LLR, Seoul, Argonne, Boston, Chicago, and Illinois). RPCs offer several advantages: their design is highly flexible, the readout can be segmented into pads of small size, they have been used and are in use in a large number of high energy physics experiments, they perform reliably and they are cheap to build. Concerns are the possible cross-talk between pads, the slow re-charging speed if used in a high-rate environment at small angles, and possible long-term ageing effects. Only chambers using glass as resistive plates are being considered, due to the superior reliability of glass compared to bakelite, the other commonly used material in RPCs.

RPCs with different geometrical designs based on a single gas gap have been studied. The design with anode readout pads outside the gas gap and cathode strips for operational control (see figure 4 for a schematic drawing) shows a superior performance compared with other designs. The chambers have been tested for single particle efficiencies and noise rates and have performed satisfactorily, giving single particle detection efficiencies of the order of 98%. Detailed studies of the cross-talk between adjacent pads, the rate capability and ageing effects are foreseen for the near future. The total thickness including the front-end electronics mounted on the chamber is 6.5 mm. Further tests with chambers featuring multiple gas gaps are also in preparation.

Two approaches for the pad readout are being considered. The first utilizes square shaped printed circuit boards with a central readout chip. Here, the signal from 64 pads is routed to one chip via transmission lines located on a separate layer of the printed circuit board. The second approach uses long strips, of the order of 1 m, together with a clocked readout to provide the position coordinate along the strips. Prototypes of the first option have been tested successfully.

Construction and tests of a RPC plane together with the readout electronics are underway and aim for completion in spring 2003. This plane will be equipped with high voltage and gas distribution systems and low voltage connectors, satisfying the boundary conditions imposed by the mechanical design of the HCAL for the TESLA detector.

4.2 Gas electron multipliers

A group at University of Texas at Arlington is investigating the use of Gas Electron Multipliers (GEMs) as a possible active medium. GEMs offer similar advantages to RPCs, but are operated at much lower voltages, a few hundred volts per stage, compared to 5-10 kV between the two conductive layers of RPCs. The group has obtained several GEM foils from CERN and is studying their characteristics, such as the signal shapes and the dependences on the potential differences across the drift, transfer and induction gaps. The group plans soon to initiate the design and construction of their own GEMs for trials with cosmic rays and in a test beam.

4.3 Scintillator tiles

A group at Northern Illinois University is investigating the use of scintillator in a highly segmented DHCAL. The group initiated a vigorous R&D program to optimize the choice of scintillator material, wrapping, wavelength-shifting fibres, fibre routing and readout devices, similarly to the effort by the tile HCAL groups. In tests involving of the order of 100 hexagonally shaped cells, yields of 25-30 photoelectrons/MIP have been obtained with VLPCs as readout devices.

The group is in the process of setting up a cosmic ray and radioactive source test stand. The optimization tests involving all components from the scintillator material to the readout device are expected to be completed within the next twelve months. Assembly of a ten layer test module, to be tested with cosmic rays, is planned for 2003. In the long term, the group is planning to address the issue of structural support and fibre routing, including tooling for automated mechanical assembly, leading to the construction of a 1m^3 test module.

4.4 Readout electronics

Work in France and Korea has resulted in a scheme for reading out the DHCAL using a simple charge-to-voltage "conditioner" circuit feeding directly into an FPGA, which then does zero-suppression, channel labelling, etc. This should in principle be adaptable for use with any of the DHCAL options. The downstream electronics is still to be defined but again, use of the UK readout electronics, effectively as a digital-VME interface, is not excluded.

5 Status of the software studies

The design and the optimization of the calorimeters is intimately related to the performance of the jet or di-jet EFA; physics studies, such as the trilinear gauge coupling of the higgs boson, indicate a typical resolution of $30\%/\sqrt{E_{jet}}$ that should be considered as a minimal goal. The respective performance of the different detector designs have then to be evaluated with the analysis of relevant benchmark physics processes through the corresponding best EFAs. The setup of a coherent comparison is a difficult task and requires iteration. Efforts are ongoing in this field in both simulation verification and EFA studies.

5.1 Simulation verification and detector response studies

The calorimeters have been simulated in detail both in GEANT3 and GEANT4. Extensive comparisons between both programs have been (and still are being) made to ensure that the results of the simulations are in satisfactory agreement, for the purpose of the comparison between the detector projects. Having defined the absorber and active media properties, the simulation is used to compare the transverse and longitudinal segmentation of the detector. The GEANT4-based simulation is able to simulate several other detector pieces (TPC, VXD, SIT, FTD, etc.) in several different models. In this way, the GEANT4-based simulation should become, like the GEANT3-based one, a complete simulation tool for the study of a detector for the FLC. One of the key issues of the test of the prototype in electron and hadron beams is to validate explicitly the GEANT4 simulation.

Mokka, the GEANT4-based simulation, has been used to study a sampling silicon-tungsten ECAL, with sensitive cell sizes of the order of the Molière radius (typically $\sim$1 cm^2), together with a DHCAL with a 1cm^2 cell. A significant difference in the detector response has been demonstrated when using RPCs or scintillator as the sensitive material for the DHCAL. Again, these simulation results need be validated against real data from the prototype to evaluate the reliability of GEANT4 when simulating the full detector.

5.1.1 Software studies in the UK

The UK groups are assessing the dependence of detector simulation results on the choice of the underlying Monte Carlo packages by comparing the physics content of Mokka/GEANT4, Brahms/GEANT3 and Fluka. These investigations will identify specific aspects of the physics modelling which are uncertain and hence may affect jet or particle energy measurements. Such studies will be used to guide the choice of test beam conditions (combinations of incident angle, energy and particle species) which will be most powerful in resolving discrepancies between models. Having critically tested the Monte Carlo model, it can be used with confidence for FLC detector optimisation.

In studies so far, single particles (e.g. e^-, μ^- and π^-) have been generated at normal incidence to the ECAL barrel at energies in the range 2-15 GeV, and quantities such as the longitudinal and transverse shower profiles have been examined. To avoid differences arising from the definition of detector geometry itself, Mokka was used to write out GEANT3 Fortran code which has subsequently been implemented in the Brahms program. For similar reasons, an interface between the GEANT4 geometry classes and Fluka (FLUGG) is being used.

Initial comparisons between GEANT3 and GEANT4 simulations have been performed using the TESLA TDR description of the detector geometry. Later studies will also consider the testbeam prototype geometry. The impact of various simulation models on EFAs will also be addressed, as well as "benchmark" physics processes such as $\nu\bar{\nu}\mathrm{W}^+\mathrm{W}^-$ and $\nu\bar{\nu}\mathrm{Z}^0\mathrm{Z}^0$.

Complementary studies are also in progress on using wide angle Bhabha scattering into the ECAL endcap region to measure the differential luminosity spectrum.

5.2 Status of the reconstruction and EFA software

Several attempts are presently being made to build up a complete reconstruction code based on the actual design of the detectors and some algorithms already exist.

REPLIC (REconstruction Package for the LInear Collider) is a FORTRAN package for reconstruction of simulated FLC events. It was created at the LLR (Ecole Polytechnique).

The main parts of REPLIC are a track finder, photon finder, neutral hadron finder and lepton identification. The most advanced part of REPLIC now is a photon finder usable in multi-jets environments. It has been shown to fulfill the basic requirement on the jet energy resolution of $30\%/\sqrt{E_{jet}}$. In addition, a photon reconstruction algorithm, EMILE, dedicated to the low energy photons, shows encouraging results.

The present status of the photon reconstruction is quite advanced; photon reconstruction and identification codes exist, efficient down to very low energy photons. The situation is more tricky as far as the neutral hadron reconstruction in the whole calorimeter system is concerned. Preliminary EFA studies show that neutral hadron reconstruction, i.e. the ability to separate showers from charged and neutral hadrons, is the main issue for excellent EFA performance. Here the situation is less advanced, particularly with regard to neutral hadron reconstruction in a multi-jet environment with a DHCAL.

5.2.1 Software studies in the US

In January 2002, members of Northern Illinois University, University of Texas at Arlington and Argonne National Laboratory began collaborating on EFAs, simulations, and software development efforts. The efforts have concentrated on the design and optimization of the HCAL when coupled with a dense, fine-grained ECAL of the type proposed by both the ECFA/DESY and North American detector study groups.

Towards the optimization of the HCAL design, this team has started investigating both analog (cell energy measurements) and digital (hit counting) readout methods as functions of the cell size. Our preliminary findings indicate that for small enough cell sizes, the digital method yields a more precise measurement of the hadron energy, suggesting that hit density fluctuations are smaller than energy fluctuations in a hadronic shower. Several independent approaches to the implementation of an EFA are taking shape. These will help us determine the optimal cell sizes and geometry for best charged/neutral hadron shower separation in jets within the context of some specific overall detector parameters.

The UTA group is in the process of setting up various Monte Carlo simulations tools for detailed studies of digital hadron calorimetry. The Pandora-Pythia generator package has been used to provide ASCII HEPEvt output format for input to GEANT4 tools, including Mokka, which has been successfully implemented as our detector simulation tool.

5.2.2 Software studies at DESY

At DESY, simulation studies with single particles have started, using a simple model of the prototype and a reconstruction based on H1 software. The goal is to optimize prototype and reconstruction parameters, and to study shower size and leakage, the dynamic range of cell signals, linearity requirements and achievable resolution with software compensation.

With the cell granularity as presented as a first approach in the 2001 PRC proposal, good track/cluster association can be achieved along 9 cell layers in depth within $\sim$1.5 cm. The mean transverse cluster radius is $\sim 6.5 \pm 1.6$ cm and in the longitudinal direction a cluster size of 8-25 cm is found, with mean of $\sim$15.5 cm. Further investigations aim now to optimize the cluster reconstruction in order to get agreement between the charged track momentum and the reconstructed cluster sum.

The identification and energy measurement for neutral particle showers will be studied by varying the distance of the cluster pattern of two independently generated particles. The software is ready and first results have been used for cross-checks. Conclusions on optimal stack structure, cell sizes and the active volume of the prototype can be expected in the coming months.

To investigate the EFA quality dependence on the tile HCAL cell sizes, several barrel geometries that differ in tile sizes have been implemented in Brahms. This includes a full GEANT3-

based simulation and reconstruction of the detector according to the TDR description.

5.3 Future perspective

The efforts on the software part of the R&D for the CALICE collaboration are driven by the following steps:

- build up a reconstruction code based on the present complete design of the different cal-rimetric systems,
- check with test beam data the GEANT4 simulation and the performance for single parti-cles,
- simultaneously, improve the EFAs by exploring the most promising algorithms,
- optimize the geometry design.

Some of these items are in a good shape in so far as it is now possible to set up a comparison scheme between the different detector options. It has been agreed to compare the performance for several physics benchmark processes based on the di-jet masses. Excellent candidates are the pair production of W bosons at a centre-of-mass energy of 800 GeV, where one W decays leptonically; the boost experienced by the W bosons makes the decay products very close together in the detector. The setup of the comparison scheme is in progress; it has to follow the items defined above, which will require care and hence significant time and effort.

6 The beam test program

One of the most important goals of the CALICE collaboration over the next three years is to use the "physics prototype" calorimeters in a wide-ranging test beam program. The physics prototype will consist of an ECAL of 30 layers, each having an 18×18 array of 1×1 cm^2 diodes, and an HCAL stack of 38 layers. This stack would accomodate any of the HCAL options, which vary from 1500 channels for the tile HCAL to 350000 channels for the DHCAL. The program includes testing all HCAL options so that a careful comparison can be made.

6.1 Schedule

The schedule for the beam test is driven to some extent by the "time-early" constraints of the TESLA schedule. It is possible that a FLC site decision and approval could emerge by 2004/5. This would rapidly lead to a global FLC detector collaboration being formed and would probably require a narrowing of technology choices for some systems such as the calorimetry. The CALICE effort is driven by the need to have data in time to contribute to those technology choices and so the aim is to start the beam test program in summer 2004, with the full program likely to take around one year. In summer 2004, it is likely that the ECAL and at least one of the HCAL options will be ready, while the other options will be included in the tests as they become available. Even if the FLC decision is not made on this (probably optimistic) timescale, it does not mean the data would not be needed and it would still put CALICE significantly ahead.

6.2 Requirements

The requirements for the beam test are clear. The program must duplicate the wide range of conditions which will occur in the FLC detector so as to be able to tune the simulation. This range should allow the simulation to interpolate, not extrapolate, and so should bracket all the expected conditions. Specifically, the main issue is simulation of hadronic interactions so that pion beams are essential. However, it will be necessary also to check the EM interactions so electron beams will be needed, while additionally some muon beam time might be useful too. Considering the energy range needed: the lowest momentum charged track which would reach the calorimeters would be around 1.5 GeV/c. Hence, the lowest momentum beam required is around 1 GeV/c. The upper momentum needed is given by the structure of hadronic jets. At FLC energies, the most common momentum is around 5 GeV/c but the spectrum continues up to around 50 GeV/c at a non-negligible level. Hence, a highest energy of at least 50 GeV is required. Clearly, several other energies to fill in this large range will also be needed. Furthermore, in the final detector, due to the magnetic field, low momentum particles enter the calorimeter at an angle; the beam test should study both normal incidence and other angles, particularly for low momentum particles. In addition, there will be some material in front of the calorimeter so than "preshower" material slabs of varying thicknesses would be useful. These will also generate fake jets and so give some data for studies of separation of showers.

There are several places which could fulfill many of these requirements and the tests may be done at several locations. It would clearly be more straightforward to do all tests in one place, which would mean either CERN, FNAL or Protvino. In all cases, the availability of beams in 2004 is not clear, although it is known that CERN has no beam in 2005. The most likely options are therefore FNAL or Protvino and we will monitor developments closely. We also envisage earlier, smaller scale debugging runs, for example with just the ECAL, and the electron beam lines at DESY would be ideal for this.

There are likely to be of order 10^2 different combinations of particle type, energy, angle and preshower with each of the HCAL options. For each, of order 10^6 events will be needed to accurately measure distribution tails and so tune the simulation carefully. The resulting data are likely to have a size of order 1 TByte in total. This data set will be an extremely valuable resource for any groups interested in FLC calorimeter design.

6.3 Necessity

There is a strong need to perform beam tests for several reasons. Studies of the various simulation programs available have shown discrepancies between them as well as with data [5]. This is particularly true for the hadronic interaction response. Because of the small cell sizes of the proposed calorimeters, CALICE will be able to show the inner structure of hadronic showers in detail, effectively for the first time. The main arguments for this fine-grained calorimetry depend on the EFA performance. Careful tuning of the simulation is needed to ensure that the results obtained for a proposed calorimeter are not invalidated by the discrepancies in the simulation description.

It is also clear that the interactions in calorimeters made of different materials, such as gas and scintillator, show quite large differences [6]. To illustrate this point, figure 5 shows the width of $K0_L$ induced showers [1] at various hadron energies, for both gas and scintillator HCAL options, where in both cases only the digital hit information is used. The showers are slimmer in the case of gas detector. This can be traced mostly to the density ratio between the two active media. Even though the sensitivity to MIP is similar, the probability for neutral, photon or neutron, to interact in the gas is much lower. Therefore, the gas calorimeter is less sensitive to the gamma halo in the electromagnetic showers and to the neutron halo in the hadronic part. In the case of scintillator, a threshold of 0.5 MIP has been applied, when in the case of gas, no threshold was applied.

Following the simulation we made with GEANT4 the separation between hadronic showers

[1] The width is defined in the transverse plane as the mean value of the two possible maximum widths (X-Y) using only digital information.

would be better in the gas as the showers are narrower. However, it must be noted that this simulation results may depend strongly on the proper modeling of the low energy tails of the shower.

Therefore, it is essential to check this result by a direct comparison between scintillator and gas detector in the same beam conditions, validating , or invalidating, the detector simulation for this very specific and delicate case.

There is also the issue of operational experience for at least some of the technology choices, e.g. GEMs, where few large scale tests have been done. It is hoped that the work of CALICE will narrow the number of options which need to be considered for major development in the period following the three years of this project. This is hopefully the timescale by which the FLC will become better defined and a detector collaboration is being formed. To proceed with a new technology without any significant operational experience in realistic conditions would be difficult to justify.

The CALICE collaboration is unique in several ways. It is larger than any other FLC calorimeter R&D group by an order of magnitude. It therefore has the resources to be able to undertake such an ambitious and wide-ranging beam test program. It is also the only group to be studying both ECAL and HCAL systems in an integrated way. This will allow a full investigation of the calorimeter performance as a whole. As such, we view it as being of primary importance that CALICE proceed with the beam test program.

7 Conclusions

The CALICE collaboration has continued to expand with several new groups having joined in the past year. Consequently it is now by far the largest FLC calorimetry R&D group in the world. The new groups have also allowed an expansion in the scope of the project and several different digital HCAL options are now able to be considered.

There has been good technical progress in many areas. All aspects of the ECAL work are producing results within requirements. The studies of the tile HCAL fibres, tiles and wrapping technology have resulted in large gains in light yield. The digital HCAL options have reached various stages of development but all could be ready for testing with beams by 2005.

The simulation and software effort has also made much progress. Much of the detailed software infrastructure is now in place so that serious comparisons of GEANT3, GEANT4 and Fluka are under way. Studies of the final detector performance with realistic EFAs are well advanced, with quite sophisticated pattern recognition techniques already being used.

Plans for the beam tests themselves are firming up. Most of the equipment needed has been proposed for funding, although there are still some uncovered items. Various bids for funding will be considered in the next few months and the financial situation will be clearer by mid 2003. The simulation effort will start refining the requirements for the beam tests, to examine which measurements are most sensitive to the simulation differences. The beam test program is considered to be a vital part of the CALICE program and significant effort is going into these preparations; we invite the PRC to recognise its importance.

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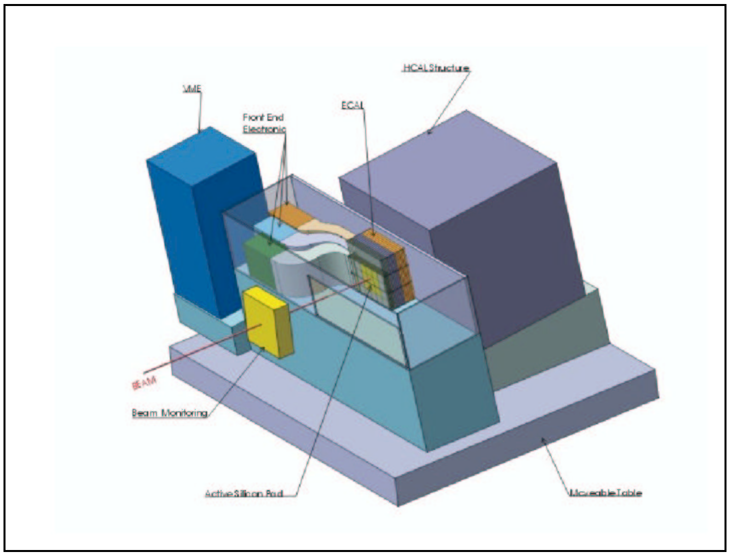

Figure 1: A schematic view of the ECAL and HCAL prototype for the beam test.

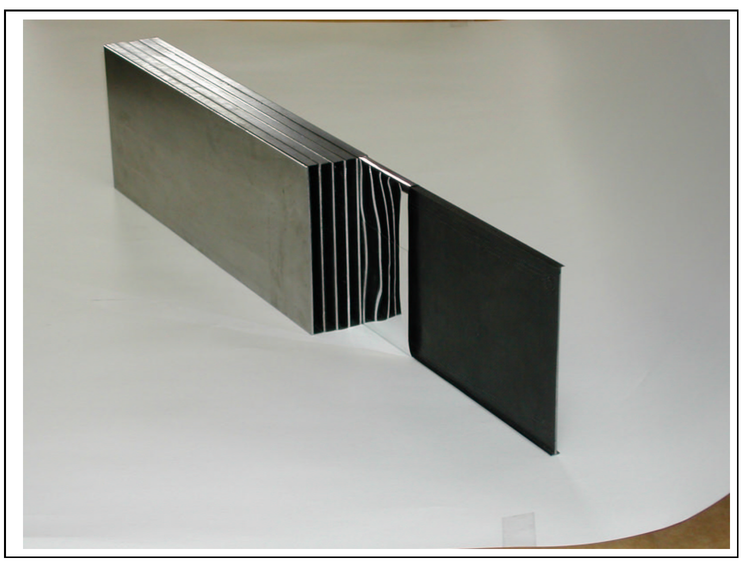

Figure 2: Photograph of the small prototype of the ECAL first stack.

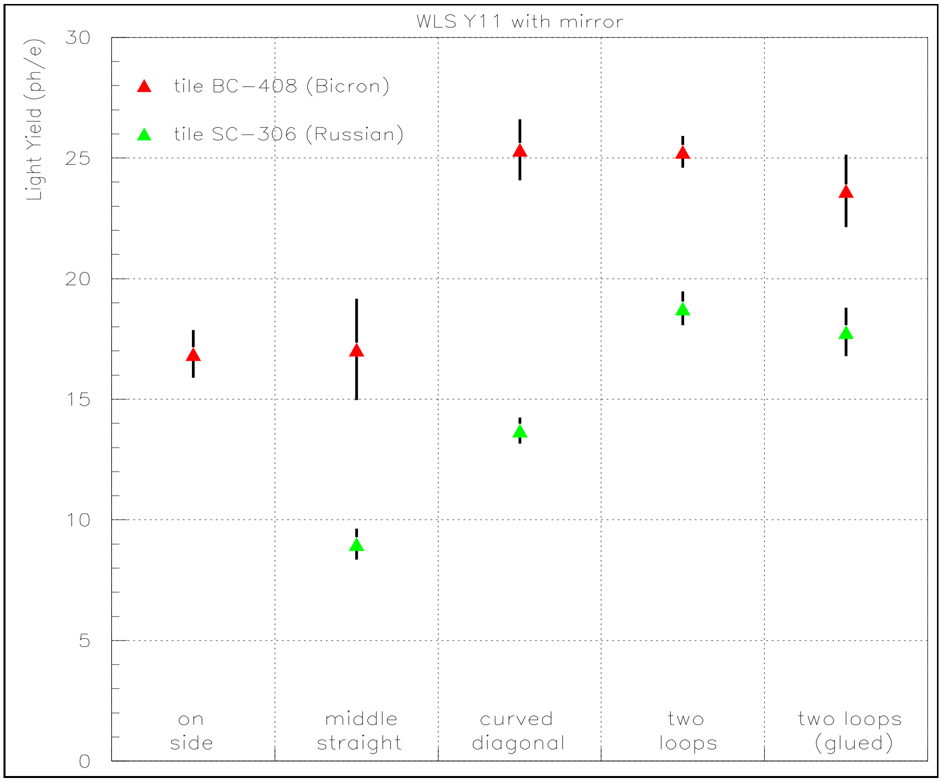

Figure 3: The light yield measurements for the tile HCAL (see text).

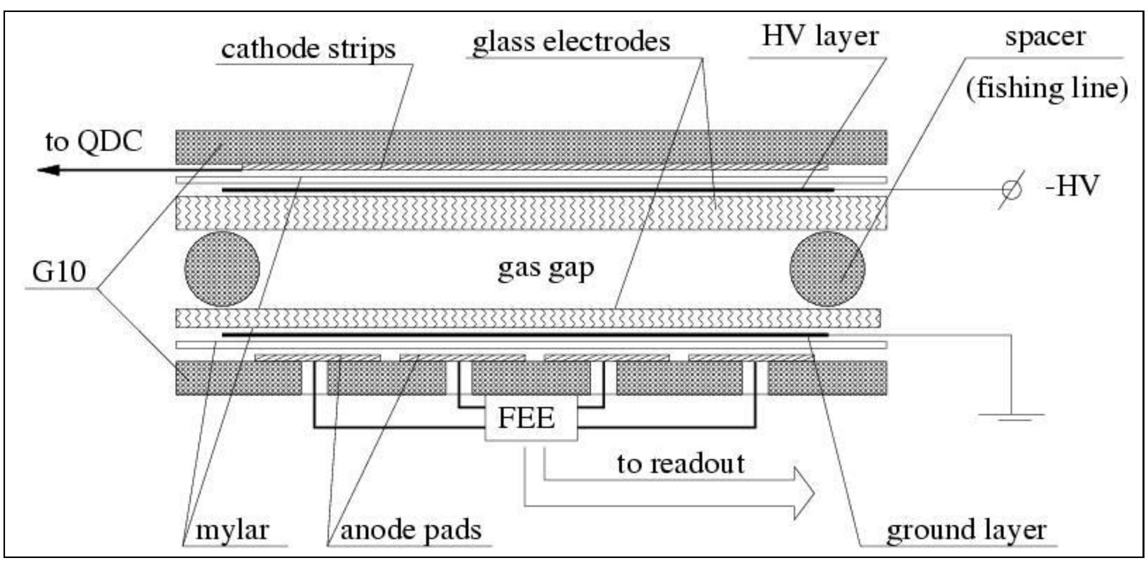

Figure 4: Geometrical design of an RPC with pads outside the gas gap.

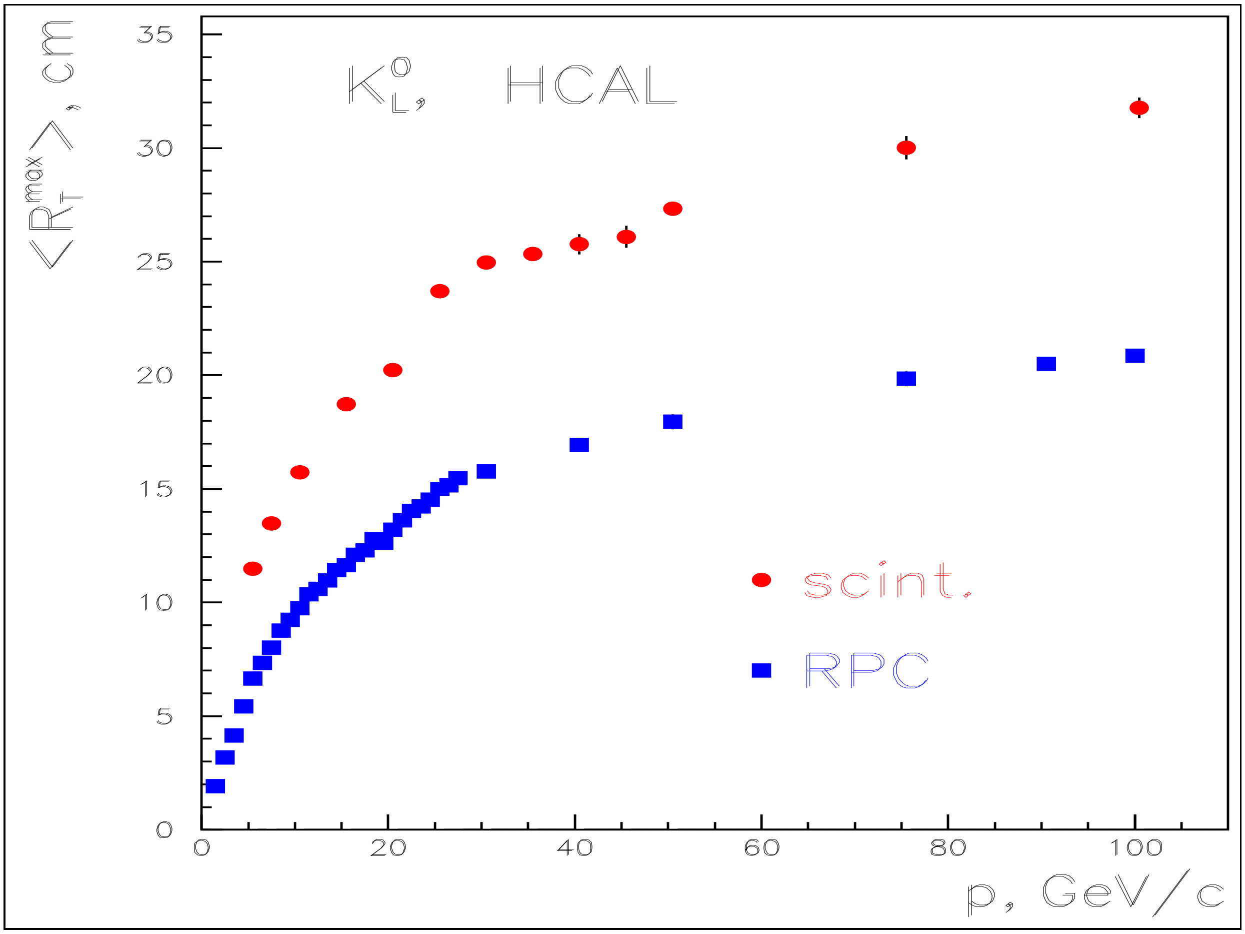

Figure 5: The width of hadronic showers for the gas and scintillator DHCAL options as a function of the hadron energy.