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Calorimetry at a future e^+e^- collider

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The requirements on calorimetry for future e^+e^- linear colliders are formulated. Approaches and recent R&D results for electromagnetic and hadron calorimeters for the TESLA detector are given.

1. INTRODUCTION

The physics program for an electron–positron linear collider (LC) with the collision CMS energy between $90-800$ GeV is dominated by final states containing many jets. Among them, the production of heavy bosons $W's, Z's$ and probably Higgses followed by hadron and lepton decays are the most important. The resolution of calorimeters in the energy range of the future LC is mediocre. More promising method called here "analytic energy flow" (AEF) [1] relies on precision measurements of charged tracks in the tracker and photons in the fine grained electromagnetic calorimeter (ECAL). These particles represent about 90% of an event energy. The remaining 10% of energy with large fluctuations, of course, must be separated from charged track deposits in the fine grain hadron calorimeter. The behaviour of the detector with respect to jets is then the following. The strong magnetic field sweeps the charged particles away from the neutrals and the separation between photons and neutral hadrons is done in a calorimeter with a large interaction to radiation length ratio. The presence of a charged lepton is a signature of the presence of a neutrino.

To profit from the AEF new effective software algorithms are as important as new detectors. A complete set of generation and reconstruction programs exists in Europe [2] and in the United States [3]. Practically all approaches use the following steps:

- charged track–cluster association using the charged track extrapolation
- unassociated clusters in calorimeters are identified with neutral particles - photons or neutral hadrons

The AEF performance of program packages will be tested with the same events with W^+W^-, $Z\bar{Z}$, $W^+W^-\nu\bar{\nu}$, $Z\bar{Z}\nu\bar{\nu}$, $t\bar{t}$ final states. The goal is to reach the energy resolution for jets $\sigma/E \sim 30\%/\sqrt{E}$. The particle identification and reconstruction put requirements on calorimeters:

`cell size of the ECAL` is comparable to the Molière radius to resolve π^0 from 2γ's

`longitudinal segmentation of ECAL` is fine to allow high quality 3D shower reconstruction and to evaluate hypotheses for different types of particles - 10 segments are recommended

`cell size of the HCAL` is comparable to 1 X_0 to follow the core of the hadron shower made by electromagnetic component of the hadron cascade

Based on the above considerations and also on the previous detailed studies [4] an R&D program for calorimeters was formulated [5] and accepted by DESY PRC in autumn 2001. The main task of the R&D program is to choose the technology

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and to optimize the calorimeter design. A prototype of the calorimeter (1 m^3) will be built and tested in beams in 2003-4. The results of the tests will help to tune and optimize the simulation and reconstruction software. This work will be done within CALICE Collaboration [6].

2. THE ECAL DESIGN

The requirement of ECAL is to identify photons down to energies of several hundreds MeV without collecting fake ones. To identify electrons, accurately measure photons and electrons in jets. To optimize the separation between photons, electrons and hadrons, the calorimeter should be far from the interaction point, dense and highly granular with large ratio of interaction λ_I (cm) over radiation X_0 (cm) lengths. The

material	λ_I	X_0	ρ_M (cm)	λ_I/X_0
Fe	16.8	1.76	1.69	9.5
Cu	15.1	1.43	1.52	10.6
W	9.6	0.35	0.93	27.4
Pb	17.1	0.56	1.00	30.5

comparison for iron, copper, tungsten and lead is given in the table. The need of containing high energy electromagnetic showers leads to the length of $\sim$ 24 X_0. The tungsten radiator provides a very compact detecting medium. To reach the transversal size close to Molière radius ρ_M the obvious solution is to use silicon diodes as sensing detectors. This solution is proposed in [4] and called a Si-W calorimeter. To keep a good energy resolution it should finely sample the showers in non projective geometry without cracks. By using 30 thin layers of sampling (0.4 X_0) followed by 10 coarser ones (1.2 X_0), the calorimeter is only 19 cm thick and has an energy resolution close to $10\%/\sqrt{E}$. The sensing pad size of 1 cm^2 is made on 4" Si wafers 0.5 mm thick of high resistivity of 5 kΩ.cm. Because of large pad area and higher noise they are AC coupled to the front-end electronics mounted above pads. The mechanical structure is not sufficient for dissipation of heat and an active cooling is mandatory. This can be

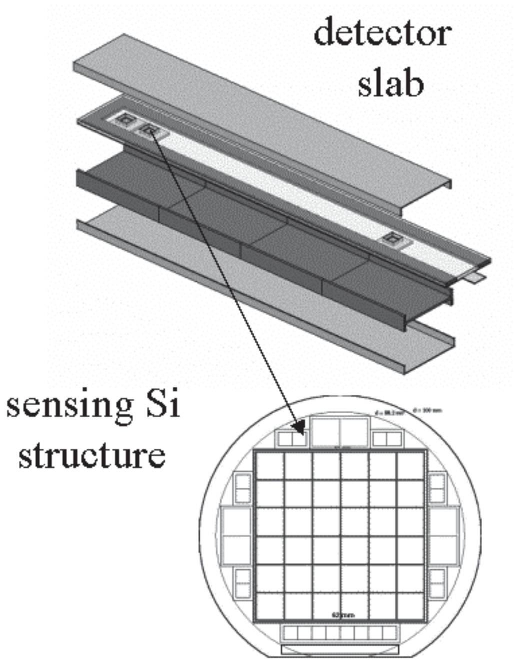

Figure 1. The smallest construction unit of ECAL is a detector slab 150 cm long which contains sensing Si diodes in arrays of 6 x 6 pads, each pad of 1 cm^2 area. It is supported by an H profile made of tungsten–carbon–epoxy molding and covered from top and bottom. Slabs are interleaved with W absorber plates and arranged into larger alveoli structure (not shown).

done by tiny pipes laying on sides of silicon diodes and running parallel the long sides of a detector slab (see Fig. 1). The front-end chip for the prototype is directly derived from a chip done for the Opera experiment.

The ongoing studies with prototyping concern the Si sensor design, cooling, the pick-up noise control, the front-end electronics, the building of the detector slabs and of mechanical structure.

3. THE HCAL DESIGN

As mentioned in the Introduction the main task of the hadron calorimeter HCAL is to identify properly clusters of neutral hadrons - mainly

n, K_L^0 and to measure their energy. The best compact hadron calorimeter [7] would use tungsten as radiator but mainly the price considerations incline to the solution with the stainless steel or copper (less favourable due to eddy currents caused by magnet quenching). The current design counts on stainless steel plates 2 cm thick with 6.5 mm gap for the sensing structure. The new role of the hadron calorimeter which acts as a coarse tracking device leads to small pads. As mentioned in the Introduction their size is governed by the radiation length of the calorimeter material which is of several cm's. There are two approaches to the HCAL performance. In the traditional one, the energy is given by the sum of analog signals from sensing cells. The second approach relies on the number of particle passages through the the sensitive cells of the calorimeter. Such discrete counting requires a high granular calorimeter. Number of binary counts is proportional to the deposited energy. This solution is called the digiHCAL contrary to the first solution which uses scintillator tiles of sizes 5x5 cm^2 and larger and is called here the tileHCAL. In both cases the calorimeter is 4.4 λ deep in the barrel and 12.8 λ in the end-cap.

3.1. The tileHCAL

The status of design of calorimeter can be found in [8]. Plastic scintillator plates 5 mm thick serve as active layers. The scintillation light produced in the tiles enters the attached wavelength shifter (WLS) fibres where it is reemitted as green light at around 500 nm wavelength. About 5% of emitted light is captured in the double clad WLS fibre and guided to sensitive photo-detectors outside the calorimeter volume. Different types of photo-detectors are studied for optimal photo-cathode efficiency, gain and large signal to noise ratio. Possible choices are:

- avalanche photo-diode arrays
- silicon photomultiplier arrays (pixel or metal resistor photo-diodes)
- multi-anode photomultiplier arrays

Detectors differ in basic parameters which are given in the following table where ϵ gives a photoconversion efficiency for green light. The photodetectors should be linear in the signal range from a mip to maximal shower cell energy (0.03-15 GeV). This requires a dynamic range of 500. For

detector	ϵ (%)	gain	bias volt.(V)
APD	70-85	100-400	300
Si-PM	12-18	10^6	30-50
PM	11-15	10^4-10^7	500-2000

further questions of signal processing, calibration and monitoring see e.g. [9]. Actual R&D studies started in autumn 2001 and have come already to concrete results which will be used and further tested in the first prototype – minical – a tile calorimeter of size 21x21x75 cm^3 which will be exposed to cosmics and to 2 GeV electron beam at DESY. The best yield for 5x5 cm^2 tiles is obtained with the Bicron BC-408 scintillator viewed by a Y11(200) double clad WLS-fibre from Kuraray. From Russian scintillators the best is a polystyrole based scintillator from Protvino SC-306 with a LY $\sim$ 70% of BC-408. The effort is put to further improve this scintillator. The optimal fibre wrap is Tyvek but an improvement of several tens % was observed using special superreflector foils from 3M (see Fig. 2). At present fibres are read by Hamamatsu multi-anode PMs with 4x4 channels. ADC spectra show sufficient LY up to 17 photoelectrons for a tile (see Fig. 2). The study of tile–fibre coupling showed that this result can be improved with two fibre loops in the groove in the tile. The LY is $1.5 - 1.7$ higher than in the simplest configuration with a fibre on the tile side. Complete results from the investigations will be soon published.

The final detector will be placed in 4 T magnetic field and photo-detectors insensitive to magnetic field must be used. The first results with 32 element Hamamatsu Si APD array S8550 are promising. A low noise charge preamplifier developed in CALICE collaboration is used. In parallel new developments with Si-PMs are done in Moscow Institutes.

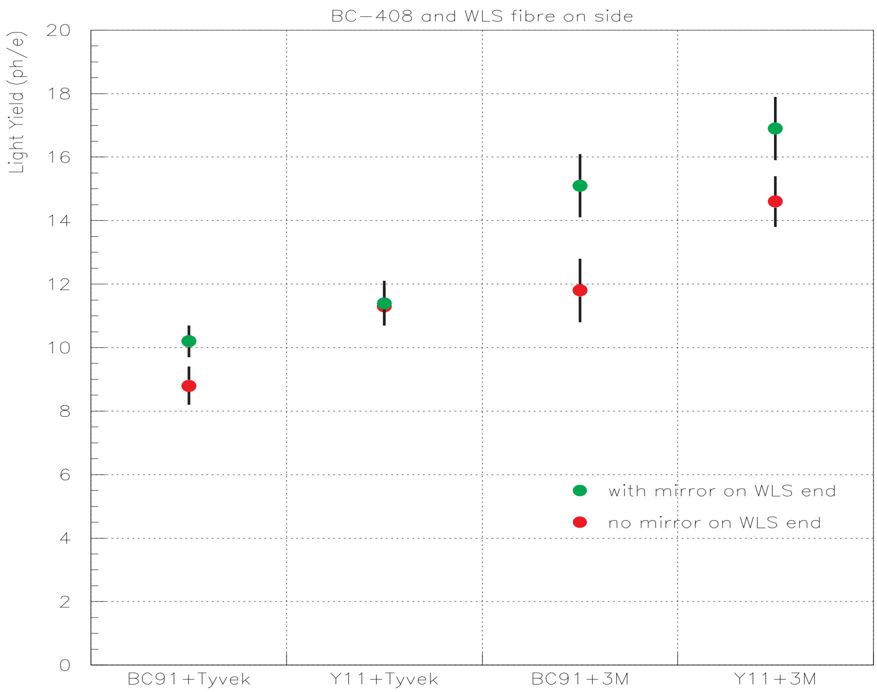

Figure 2. Light yield in photo-electrons from Bicron BC-408 tiles 5x5 cm^2 in side contact with a WLS 1 mm fibre with mirror (light circles) and without mirror (dark circles) on the fibre end. Double clad fibres from Kuraray Y11(200) and Bicron BC 91A are compared for two different tile reflectors: two layers of Tyvek paper and a super-reflector foil from 3M. The highest light yield is achieved with Y11(200) fibre and 3M foil. The effect of fibre mirror is modest. The light from fibre was read by a PM.

3.2. digiHCAL

For this option it is proposed to use gaseous detectors. Two candidates are considered [10]: thin resistive plate chambers (RPC) with glass sheets as resistive plates and short drift tube (SDT) chambers with 2–3 mm tube length. Both options have to work in the streamer/Geiger mode providing large output signals to simplify digital front-end electronics. Cosmic and beam tests were performed with small 80x80 mm^2 RPC prototypes in streamer mode. Commercially available glass sheets of 1 mm thickness were used for resistive plates with $\rho \sim 10^{13}$ Ω.cm. Gas gap was 1.2 mm. The gas mixture selected for the streamer operation was TFE:N_2:IB = 80:10:10. All prototypes had 16 pads of 1 cm^2 area with 1 mm gap between pads. The exposition in the 5 GeV positive beam showed 98% efficiency for 7.5 kV HV and 50–200 mV thresholds. At 200 mV threshold the hit multiplicity reached 1.3 level.

The same beam set up was used also for the SDT chamber prototype. The gas mixture selected for RPC showed low efficiency for SDT. It was found that the best properties had the mixture rich of isobutane Ar:TFE:IB = 10:10:80. At HV of 7.5 kV the hit multiplicity was reasonably low 1.05 and efficiency at 96%.

It seems that both the RPC and SDT chamber options are promising for the digital calorimeter. The RPC option has a low rate capability (< 10 Hz/cm^2) and relative large cell to cell signal overlap ($\sim 30\%$). The SDT chamber option has efficiency slightly lower. Non flammable gas

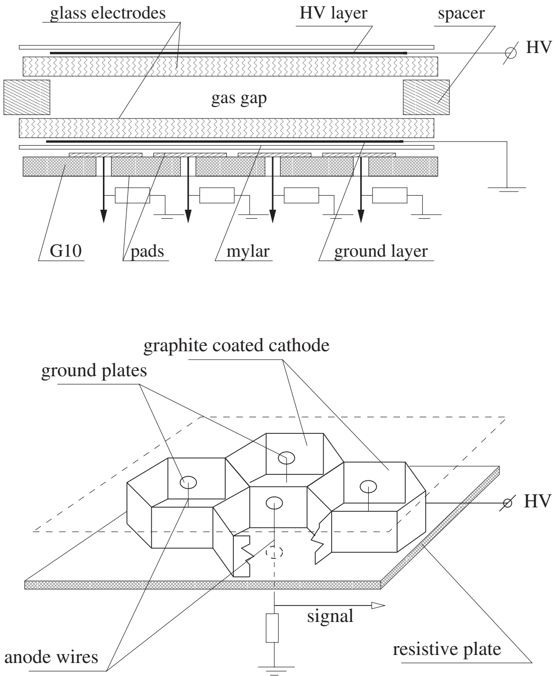

Figure 3. Scheme of RPC prototype (upper part) and a sketch of SDT chamber (lower part) for digiHCAL.

mixture is an open topic. Easy technology for the mass production (60 million channels for the final calorimeter) has to be found.

4. CONCLUSIONS.

To finalize the design of a calorimeter for a linear collider a considerable effort is needed both on the technical and software sides. The electromagnetic calorimeter as a sandwich of tungsten and silicon appears to be adequate from the point of view of physics, it remains to be fully proved technologically. For the hadron part a choice has to be made between two possibilities. For the decision full simulation and reconstruction as well as building of prototypes is foreseen. Due to the limited future access to high energy test beams a world wide effort is needed.

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