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R&D program for the TESLA Tile Hadron Calorimeter

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1 Introduction

The TESLA linear collider facility produces $e^+ e^-$ interactions with collision energies from 500 to 800 GeV. The proposed High Energy Physics Research Program alongside the proposed TESLA particle detector for the measurement of particles and jets are described in detail in [1].

The HCAL, a hadronic sampling-sandwich calorimeter with a scintillator tile readout is also described in [1, 2]. Technical details on the mechanical calorimeter stack design, construction and installation are given in [3], the optical and electronic readout (RO) chain envisaged is proposed in [4]. The discussion for detailed optimization and performance studies of this RO chain with all components is the topic of this paper.

The performance of the HCAL is tightly connected to the maximum light yield of the optical system. Minimum ionizing particles (MIPs) available as cosmic ray muons, have to be used for relative and absolute calibration of all 205 000 HCAL calorimeter cells. Thus the yield of photons per crossing MIP has to be maximized to get a sufficiently large distance between the signal, pedestal and noise level (of order $> 3\sigma$), and a good time measurement (in the region of a few ns).

2 The scintillator tiles

Blue standard plastic scintillators with high photon yield (10 000 photons/MeV) and fast decay times (< 3 ns) have to be used. The solutions are discussed in [5]. The attenuation length for the blue light has to be > 2.5 m since in the large scintillator tiles (up to $25 \times 25\ cm^2$) a long light path with several reflections is often needed before the connected WLS fibre is hit. The tile has to be wrapped with appropriate reflector material of reflectivity >80%. Diffuse and mirror reflecting wrappings or coatings have to be compared.

3 The WLS fibre

Such fibres are available from Bicron and Kuraray. Green shifting fibres are commonly used - red shifting fibres are also possible [6]- with diameters between 0.6 and 1.2 mm,They are typically double clad with 2 layers of 20 μm of decreasing optical refraction index. The fraction of converted light which is really kept within the transport acceptance of the WLS fibre grows with the difference in refraction index of the fibre core and second cladding.

The optimal diameter of the WLS fibre and thus the width of the grooves is connected to the absorption depth for the entering blue scintillator light in the WLS fibre. Bicron quotes a mean free path of about $300\mu m$. The blue to green light conversion efficiency depends on the optimal spectral adaptation of the emitted scintillator light to the WLS converter ingredient used.

4 The Tile/WLS coupling

The measured light yield depends on the quality of the optical coupling between the scintillator and the WLS fibre. This coupling has to be studied carefully. WLS fibres can be put as circles, double circles or spirals directly on the surface of the scintillator tiles or can be inserted with several windings in a circular groove inside the tile. Mechanically matted groove surfaces give about 20% better light transfer [6]. The typical achieved photon transfer in the fibres is about $16 - 25\%$, depending on tile size, as measured by one of the authors [7] in a R&D project for the HERA-B ECAL. Systematic studies have been started at DESY to find an optimal method. Scintillator tile to WLS fibre transfer is studied and discussed in detail in [8].

The useful length of the inserted WLS fibre is determined by the attenuation length of the produced WLS light within the fibre. The attenuation length for BCF91A is larger than 3.5 m. Half of the light emitted in the WLS fibre goes in the wrong direction and has to be reflected at the open end of the fibre, with the highest possible efficiency. The detail studies of tile/WLS coupling are described in [9].

5 The clear readout (ROF) fibre

At the WLS-ROF connection the best light transition (20-35% transition loss reported in [6]) has to be found. Thin tubes to house the fibres, so as to connect and enforce the connection are probably needed for mechanical stability.

Fibres with very long attenuation length of > 10m are needed to reach the photodetectors outside the calorimeter volume. Double cladding will help to improve transmission and protect against mechanical damage in the strong fibre bending ($\sim 2cm$) along the fibre path. The attenuation length decreases with decreasing radius and the number of bendings along the way of the fibres. This has to be studied and optimized. The fibres also have to be sufficient light tight to avoid random photonic noise. Most of such noise and also the Cerenkov light maximum produced by the particle showers inside the long ROF in the calorimeter volume can be suppressed by using green light mixers at the far end in front of the photodetectors.

It seems to be a difficult task to mark and guide all the individual fibres in such a way that the subsequent tiles building the individual calorimeter cells can be found and assembled in front of the photodetectors. An appropriate ordering, marking and bookkeeping of the ROF's has to be developed.

6 The sampling gap

The long ROF's have to be fixed at the end of the tile plates before insertion in the calorimeter stacks. The tolerances are tight, if 1mm thick ROF's are used, 0.5 mm free space is available in the sandwich gap.

It was shown that the response to a particle shower in a strong magnetic field varies slightly with the air gap thickness between preceding absorber and the following tile plate, results were presented in [10]. Naturally for barrel HCAL top and bottom modules, differences are produced by the up/down asymmetry of the gaps due to gravity. To get equal response everywhere, such gaps have to be avoided or kept constant for all calorimeter modules around the barrel cylinder by pressing the tile plates against the preceding iron absorber plate. Appropriate clamps and tools have to be developed.

7 The choice of the photodetectors

In the presence of the strong 4 T magnetic field only photodetectors with response and gain insensitive to the strength and orientation of the magnetic field can be used. It was shown in [11] that, e.g. Avalanche Photo Diodes (APD's) fulfill such a requirement. The large number of photodetectors (205 000 in total) needed also introduces a serious cost/photodetector limit as a selection criterion.

The relatively low signals of MIP's used for online calibration [4] require a large gain. Typically PM's have a gain of $\approx 10^4$ to 10^6 at 2 KV supply voltage, much larger than the gain of ≈ 100 for APD's at about 100 - 150 V. Thus APD's need special designed low noise charge sensitive pre-amplifiers adapted to the capacity of the detector. The gain of photomultipliers (PM's) is very sensitive to strength and orientation

Photodetector type	Performance in 4T	gain	HV typical	noise/MIP	size	cost
vacuum PM, convent.	no	1×10^6	2 KV	very small	large	high
vacuum photo diode	yes, orientation	4	200V	small	medium	medium
vacuum PM, mesh type	no	4×10^5	1KV	very small	medium	high
HPD	yes, orientation	1000	10-20KV	small	medium	high
APD	ok	100	150V	few sigma	small	low
MRD	ok	1×10^4	100V	few sigma	small	low

Table 1: Comparison of available photodetectors

to the magnetic field. So far only mesh tube photomultipliers can work in magnetic fields when orientated parallel to a field of less than 2 Tesla. Vacuum Photo Diodes, Triodes or Tetrodes are used for some forward calorimeters in HEP, but they have a very small gain and need special low noise pre-amplifiers. Probably they are not able to be used for MIP detection. Hybrid Photo Diodes (HPD's) have a large gain when orientated parallel to the field, but they need quite a large supply voltage of 4-8 KV, they have relatively large dimensions and frames and are expensive.

Only Avalanche Photo Detectors (APD's) and Metal Resistor Diodes (MRD's) (the former are also silicon photodiodes with avalanche amplification), are insensitive to the strength and orientation of the magnetic field.

At present APD's are the first choice for use in the TESLA/HCAL. A lot of relevant information can be found in [12]. Since only detectors with small photo cathodes of <10 mm^2 are needed, it should be possible to keep the detector capacity (<20 pF) and the dark current(<2 nA) small. A reasonable criterion for sufficient separation of MIP's from noise would be a signal to noise distance of $> 3\sigma$, when the most probable MIP peak is taken.

The gain of the APD's is varying with temperature by about -2%/degree, but these temperature fluctuations can be kept small when the APD's are housed in cooled (about -10 degree) temperature stabilized electronic boxes. Such cooled APD's show significantly less noise and show larger gain. Further gain stability improvement can be achieved by monitoring the photodetector response continuously with LED's as described in [13].

The photo cathodes of the light detectors used have to be green (or red) sensitive, fitting to the maximum light emission of the WLS. Also due to the assembly of several ROF's on the same photocathode the photon conversion efficiency and the multiplication has to be uniform across the cathode surface.

The performance and state of art of all kind of photodetectors and pre-amplifier/shapers is discussed in detail at a special conference [14] .

The selection of small and cheap stable avalanche photodiodes with low dark current, capacity and excess noise requires special efforts in cooperation with a commercial large scale producer.

Since APD's gain is relatively small, other solution are studied in some research projects:

– silicon avalanche photodiodes on the base of metal-resistor semiconductor structures, MRS's, [15] and

– limited Geiger-mode microcell silicon photodiodes [16],

both are based on silicon photodiodes with a pixel structure for electron amplification and a high resistive layer as anode. This resistive layer of ρ about 10^5 to 10^7 Ohm cm delivers the bias multiplication voltage to the individual pixels and avoids overall discharge of the common bias voltage. Pixel diameters are 1.8×1.8 micrometers with 5 micrometer pitch [15] and 10×10 micrometers[16]. The amplification in the strong field near the pixels relay on Geiger discharge, a gain of 10^5 to 10^6 can be reached, with 10^4 pixels/cm^2.

Both studies show so far 3 major disadvantages:

—low single photon detection efficiency (a few % only), but the photo transparent layers can be improved. It is hoped to increase the efficiency up to 'geometrical efficiency' that is about 20-30%,

– a relatively high level of dark current is observed, the rate so far is 10^4 at -40 degree and

– due to the limited number of pixels ($10^4/mm^2$) the linearity range is limited. In our case we would need 10 mm^2 detector area with 10^5 pixels which should cover a dynamic range of 3000, equivalent to 68 photons (MIP) to 2.6×10^5. Due to the large noise the photon detection efficiency has to be high for small numbers of photons. With a conversion efficiency of 10 saturation of the large signals will be observed, but such nonlinearities can be calibrated.

The advantages are the large gain and the insensitivity to the magnetic field. So far such detectors are research objects only and not available in large quantities.

8 The pre-amplifier/shaper requirements

The required pre-amplifiers, possessing a large gain and low noise have to be designed according to the capacity and charge produced by the selected photodetector. The CMS collaboration at the LHC/CERN will use commercial operation amplifiers with a 16 bit dynamic range, 2 amplifiers per channel, integrated in a monolithic ASIC. The pulse shapers (shaping time of 40-100 ns) have to fit the shape requirements for the following digitalization and can be integrated in the ASIC's.

9 The Analogue to Digital Conversion

The large dynamic range of the cell signals (from 20 MeV for MIP's to 70 GeV for electromagnetic showers per HCAL cell) requires

– 16 bit linear ADC's or,

– 2 linear > 8 bit ADC's/channel connected to pre-amplifiers of different gain or,

– appropriate non-linear 10-12 bit ADC's.

Since no hardware trigger signals will be used in the experiment, a continuous signal registration with fast clocked FADC's is preferred to gated ADC's. It will be cheaper to use 2 FADC's/channel with smaller dynamical range and double-gain pre-amplifier/shapers in front, instead of one 15 bit FADC. With 100-200 MHz commercial FADC's fed by pulse shapers with an appropriate small shaping time of 20-50 ns a time resolution of 2 ns should be achievable for each calorimeter cell, even with small MIP signals.

Another possibility is to digitize the integrated signal and read it by usual gated ADC's, using discriminators to make a gate and deliver a time signal information of about 400 MHz in connection with tick marks of the detector or an astronomical clock.

To conceptualize and design such a large ADC readout system is a major task.

10 Mechanical R&D

The design and construction of the barrel and endcap calorimeter modules is described in [3]. The modules weigh 15.3 to (barrel) and 42 to (endcaps). The gaps in the sandwiches for insertion of the scintillator tile plates are 6.5 mm deep with 0.5 mm free space to cope with the tolerances. Since the "Finite Element Calculations" quoted in [3] are simulation results only, with building parts of ideal shapes, surfaces and physical behaviour, it is absolutely necessary to build a test module soon, to study the achievable gap width tolerances, the behaviour of such a module in 4 T field, and the variations of the gaps during the module rotation operations required for installation module.

The most critical modules are the barrel stack modules that will, sitting on each other, assemble a complete cylinder of 245 to. It is not necessary to build a barrel stack of full length, the mechanical behaviour can probably be studied effectively with a 1 m stack length.

Such a stack skeleton can also be used, when filled with an appropriate tile structure and connected to a readout and data collection system for detailed tests with cosmic muons beam tests with electrons, protons and pions [13]. Physical performance tests with real incident particles are needed soon.

A detailed R&D program for such a module is being discussed. Finally a proposal will be submitted to the Physics Research Comitte at DESY in May 2001.

11 The software preparation

For the pulsed LED or laser light injection [13], readout and analysis a special calibration software is needed that determines the on-line calibration of all calorimeter channels.

A pattern recognition software needs measurement of actual mean pedestal values, pile up rejection and application of measured calibration factors.

The model of calibration data-base has to be developed.

12 Preparation of R&D

For the optimization of the response, energy resolution and calibration of the scintillator tile sandwich calorimeter a thorough collection of all available documented information is needed and detailed studies of all the individual components have be be carried out before their optimal couplings can be investigated and definitely fixed for a prototype calorimeter.

13 Interested groups

This work will be shared by different groups from

1. Institute of Theoretical and Experimental Physics, ITEP, Moscow, Russia
2. Lebedev Physics Institute, Moscow, Russia
3. Moscow Engineering and Physics Institute, MEPHI, Russia
4. Moscow State University, Moscow, Russia
5. University of Prag and Academy of Science, Prag, Czech
6. University of Tashkent, Uzbekistan
7. DESY, Germany.

Some work has already started at DESY:

– on light yield studies by V. Korbel (DESY) and V. Saveliev (MEPHI) together with 2 diploma students,

– on design and construction studies for the HCAL absorber structure by V. Korbel, P. Hassler, C. Martens (DESY), S. Shuvalov (ITEP),

– on simulation and optimization of the HCAL cell structure by V. Morgunov (DESY and ITEP).

14 Updated detailed task list of the proposed R&D studies:

- Basic absorber material studies:
  - Absorber, iron (or brass),
  - thickness tolerances ($\pm$ 0.1 mm ?),
  - flatness ($\pm$ 0.1 mm ?),
  - magnetic permeability (E316L, μ=1.02, $<$ 1.01 at 4 T),
  - magnetic field distortion, induced magnetic, forces (dH/dt), define upper limits,
  - elasticity for wall sheets.
- Scintillator tile studies
  - light yield,
  - decay time,
  - attenuation length,
  - plastic scintillator material production,
  - treatment, moulding or cutting,
  - surface treatment, matted, polishing, no polishing,

  - radiation hardness, aging stability.

- Reflector for scintillator
  - foils, paper or paint,
  - mirror or diffuse reflection.
- Wavelength shifter (WLS) fibres
  - compare all available products (Bicron, Kuraray,..?),
  - available/wanted fibre diameter,
  - light containment : single or double cladding,
  - conversion efficiency for blue to green light,
  - conversion depth,
  - attenuation length vs. bending radius,
  - minimum bending radius for cladding protection,
  - open fibre end reflector aluminum vaporization in vacuum),
  - aging and radiation hardness (specially for endcap).
- Clear readout fibres (ROF's)
  - compare all available products,
  - light containment (cladding layers),
  - attenuation length (also vs. bending radius),
  - optimal diameter,
  - minimum bending radius,
  - light tightness (vs. electronic noise),
  - fibre protection,
  - aging and radiation hardness (specially for endcap).
- Light mixer (ROF's to photodetector window)
  - optimal material,
  - shape,
  - optimal color (for attenuation of background photons).
- Light coupling between components
  - optical glues (see e.g. ATLAS, CMS,...),
  - connectors.
- Optimization of light yield
  - scintillator to WLS coupling
    * on scintillator surface,
    * in grooves,
    * -optimal tile border shapes.
  - reflector at free end of WLS fibre,
  - homogeneity across tile area ,
  - how to achieve equal response of all tiles in a cell?,

- study gaps between tiles,
  * reflector sheet,
  * reflector painting,
  * no separator at all,
  * cross talk to neighbored tiles,
- WLS to ROF coupling,
- ROF to LM coupling,
- LM to photodetector coupling.

- Tooling studies for production series of the optical RO
  - tile production,
  - WLS spiral shaping,
  - WLS open end mirroring,
  - WLS fixing or insertion in tile,
  - WLS-ROF connections,
  - ROF guiding/fixing to tile board,
  - ROF protection on tile plate,
  - ROF-LM connection.
- Studies required for tile plate insertion
  - engineering design,
  - sandwich gap tolerances,
  - sandwich gap spacers,
  - tile structure, individual tiles or machined tile plates,
  - support sheets for tile planes,
  - table tests of assembled tile plates ,
  - insertion of tile plates,
  - fixation of tile boards in gaps,
  - optimal ROF marking, ordering and bundling,
  - support structure for ROF's,
  - light tightness.
- Electronic
  - Photodetectors, Properties
  - APD's,
  - MRD's,
  - HPD's,
  - Photomultipliers,
  - capacity, noise, gain, MIP to noise distance,
  - magnetic field behaviour,
  - Pre-amplifier,
  - capacitive noise,
  - gain,

  - pulse shaping,
  - digitization scheme/method,
  - Analogue to Digital Conversion,
  - no trigger, no gate,
  - 100-200 MHz FADC's,
  - 15-16 bit, or 2 x 8 bit enough,
  - investigation of LHC solutions,
  - Readout Electronic and Data Acquisition
  - which equipment for final detector,
  - which equipment for beam test and prototyping.

- The calibration methods
  - Calibration with muons,
  - Calibration with radiation sources,
  - LED monitoring,
  - at tile level,
  - at input of light mixers.

- Test module
  - design of stack structure,
  - construction of stack structure,
  - manipulation of plates and modules,
  - assembly,
  - electronics for soon, preliminary use,
  - individual channel tests with cosmic muons.

- Software
  - calorimeter shower simulation and reconstruction
    * for longitudinal containment,
    * to improve energy resolution,
    * lateral and longitudinal cell sizes for angular resolution,
    * and individual cluster separation.
  - algorithms for μ-calibration
  - with pedestal measurement and noise subtraction,
  - for calorimeter cell online readout,
  - algorithms for FADC charge and time measurements,
  - individual event reconstruction,
  - algorithms
    * for energy weighting,
    * for shower cluster analysis.

- Investigation of detailed costs for test module
  - calorimeter skeleton,
  - the optical system,
  - photodetectors,
  - Analogue to Digital Conversion and RO.

References

[1] The ECFA/DESY study group for TESLA, *Technical Design Report for a Detector at TESLA*, to be published in 2001 and http://www.desy.de/~lcnotes/tdr/.

[2] V. Korbel, *The HCAL Detector at TESLA, contribution to the Linear Collider Workshop*, LCWS2000, FNAL, to be published and http://conferences.fnal.gov/lcws2000/web/Korbel_D5/.

[3] P. Hassler, V. Korbel, S. Kock, J. Kuhlmann, C. Martens, N. Meyners, V. Morgunov, S. Shuvalov, M. Siemens , K. Sinram, *The Hadronic Tile Calorimeter for the TESLA Detector, Design, Construction and Installation*, LC-Det-2001-049, 2001 and http://www.desy.de/~lcnotes/.

[4] V. Korbel, *The Optical and Electronic Readout of the HCAL Tile calorimeter*, LC-DET-2001-52, 2001 and http://www.desy.de/~lcnotes/.

[5] S.V. Belikov et al, *Characteristics of Molded Polystyrene Scintillator for Electromagnetic Calorimeter of the PHENIX Apparatus*, Instruments and Experimental Techniques, Vol.39, No.4, 1996, p.498.

[6] C. Cheshkov et al. *Application of avalanche photodiodes as a readout for scintillator tile-fiber systems*, NIM A440, 38, 2000.

[7] S. Shuvalov, DESY and ITEP, private communication.

[8] H.S. Budd, et al., *Fiber R&D for the CMS HCAL*, http://de.arXiv.org/abs/hep-ex/0102031.

[9] E.N. Gushin, *Development of Preshower detector for LHCB Experiment*, Proceedings of the VIII. International Conference on Calorimetry in High Energy Physics, Lisbon, 542, 1999,

S.V. Belikov, S. White, Yu.E. Gutnikov, A.G. Denisov, A.I. D'yachkov, V.V. Zharkov, E.P. Kistenev, V.I. Kochetkov, A.V. Makeev, V.A. Mayatskii, E.A. Mel'nikov, and A.P. Usachev *Search for optimal reflectors for the scintillator-WLS system*, Instruments and Experimental Techniques, 40, 1997, 33,

A. A. Durum et al, *Study of the Light-reflection covers for scintillator Counters with WLS Fiber Readout*, to be published,

K. Hara, Y. Miyamoto, I. Nakano, J. Suzuki, K. Takikawa, K. Yasuoka (Tsukuba U.), *Optics of large scintillating tiles with wavelength shifting fiber readout: application to a hadron calorimeter*, NIM, A365:370-377, 1995,

A.P. Ivashkin, Yu.G. Kudenko, O.V. Mineev (Moscow, INR), J. Imatato (KEK, Tsukuba), *Scintillation ring godoscope with WLS fiber readout* NIM A394, 321,1997,

S. Aota et al. *Mass production of tile/fiber units for the CDF plug upgrade EM calorimeter*, NIM A420, 48, 1999.

[10] S. Kunori, *B-Field Effects on Scintillator and Calorimetry*, Proceedings of the VII. International Conference on Calorimetry in High Energy Physics, Tucson, (1997), 224.

[11] J. Marler et al., *Studies of avalanche photodiode performance in a high magnetic field*, Nucl. Instr. & Meth. A 449 (2000), 311.

[12] A. Karar, Y. Musienko and J. Ch. Vanel, *Characterisation of Avalanche Photodiodes for Calorimetry Applications*, NIM A428, (1999), 413,

K. Dieters et al, *Properties of the most recent Avalanche Photodiodes for the CMS Electromagnetic Calorimeter*, NIM A442, (2000), 193,

Y. Musienko et al, *Studies of Neutron Irradiation of Avalanche Photodiodes using 252Cf*, NIM A447, (2000), 437.

[13] V. Korbel, V. Morgunov, *Calibration and Monitoring of the HCAL Tile Calorimeter*, LC-DET-2001-51, 2001 and http://www.desy.de/~lcnotes/.

[14] Proceedings of the 2nd International Conference on New Developments in Photodetection, Beaune, France, 1999, Nucl. Instr. & Meth. A 442 (2000), 171.

[15] V. Saveliev, V. Golovin, *Silicon Avalanche Photodiodes on the Base of Metal-Resistor-Semiconductor (MRS) Structures*, NIM A442, (2000), 223.

[16] G. Bondarenko et al, *Limited Geiger-mode microcell silicon photodiode: new results*, NIM A442, (2000), 187.