PRC R&D 01/02

A calorimeter for the e^+e^- TESLA detector
Proposal for R&D

Abstract

A proposal for R&D to design the optimal electromagnetic and hadronic calorimeters for the e^+e^- TESLA detector is presented. The design choices will be tested with respect to the technological possibilities, evaluated from the industrial point of view, validated by a test with beam.

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Institutes list

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DESY - Hamburg (**DESY**)

Institute of High Energy Physics - Protvino (**IHEP**)

Institute of Physics, Academy of Sciences of the Czech Republic - Prague (**IPASP**)

Institute of Theoretical and Experimental Physics - Moscow (**ITEP**)

Laboratoire de l'Accélérateur Linéaire - Orsay (**LAL**)

Laboratoire de Physique Corpusculaire - Clermont (**LPC**)

Lebedev Physics Institute - Moscow (**LPI**)

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Tashkent University (**TU**)

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Contents

1 Introduction

In the TESLA TDR [1] different options for the proposed calorimeter are described. A large part of the physics programme will require the reconstruction of final states containing a large multiplicity of jets. Examples of such events are $e^+e^- \rightarrow$ZH with Z decaying in jets and Higgs into $b\bar{b}$ jets, $e^+e^- \rightarrow$ ZHH with six jets, $e^+e^- \rightarrow t\bar{t}$ with up to six jets, and the separation between $\nu\bar{\nu}W^+W^-$ and $\nu\bar{\nu}ZZ$ with four jets final states. The reconstruction of the four momenta of the partons through the study of jets will be a key requirement The experience at LEP and SLD has shown that the best way to reconstruct the partonic level, consists in using an energy flow (EFLOW) technique combining the tracking and calorimetric informations. Therefore, besides the energy measurement, the role of the calorimeters is the identification of neutral particles (photons, K0, neutron) and the rejection of the debris of the interaction of the charged hadron(s), the charged hadrons being measured by the tracking devices.

The goal of this R&D program therefore is an optimisation of the device which goes far beyond intrinsic, single particle performances, but to do an overall optimization of the system for the reconstruction of the energy flow in the event.

The purpose of this proposal is to describe the work needed to find a suitable calorimeter concept. A common program for both the electromagnetic and the hadronic calorimeter is presented.

The base line version of the electromagnetic calorimeter (ECAL) is a challenging silicon tungsten sandwich (W-Si) [1] mounted in front of the hadron calorimeter (HCAL) inside the coil. Two solutions for the hadron calorimeter are considered in this proposal, one makes use of scintillating tiles interleaved with a stainless steel radiator (the baseline in the TDR), the second replaces the tile plates by gas chambers read in a digital mode by small cells.

The performance of the calorimeter is driven by the requirements of the physics program at TESLA. To fully understand the power of a particular calorimeter design the intrinsic performance of the calorimeter is not a sufficient measure. Instead the combined calorimeter and tracking system has to be studied and understood. Apart from studies of the hardware this also requires extensive software development and sophisticated tools. Therefore in this proposal the work needed in this area is described as well.

Technological R&D will be needed in several areas to demonstrate the feasibility of the different parts of the proposed calorimeter, and to identify the optimal technological

[1] An alternative electromagnetic calorimeter based on the Shashlik technology is presented in a separate proposal.

choices, before a prototype module can be constructed. In the end a prototype will be needed to fully understand and check the performance, of both hardware and software.

2 The tungsten-silicon ECAL

2.1 Introduction

A first design of the W-Si ECAL is described in the TDR. It consists of 30 layers of tungsten-silicon sandwich (0.4 X0 each) followed by 10 layers of 1.2 X0 each. The mechanical structure is built by wrapping the tungsten sheets with carbon fiber impregnated with epoxy. Empty spaces, called hereafter alveoli, are left between two consecutives tungsten sheets, where the active layers (silicon-tungsten-silicon) called hereafter detector slabs, can be inserted. Figure 1 shows a schematic view of the detector slab. More details can be found in reference [1].

The technical solutions proposed for this design have to be tested and evaluated. Moreover, the feasibility and the cost/performance optimisation have to be further studied to reach a definite conclusion at the end of the foreseen R & D.

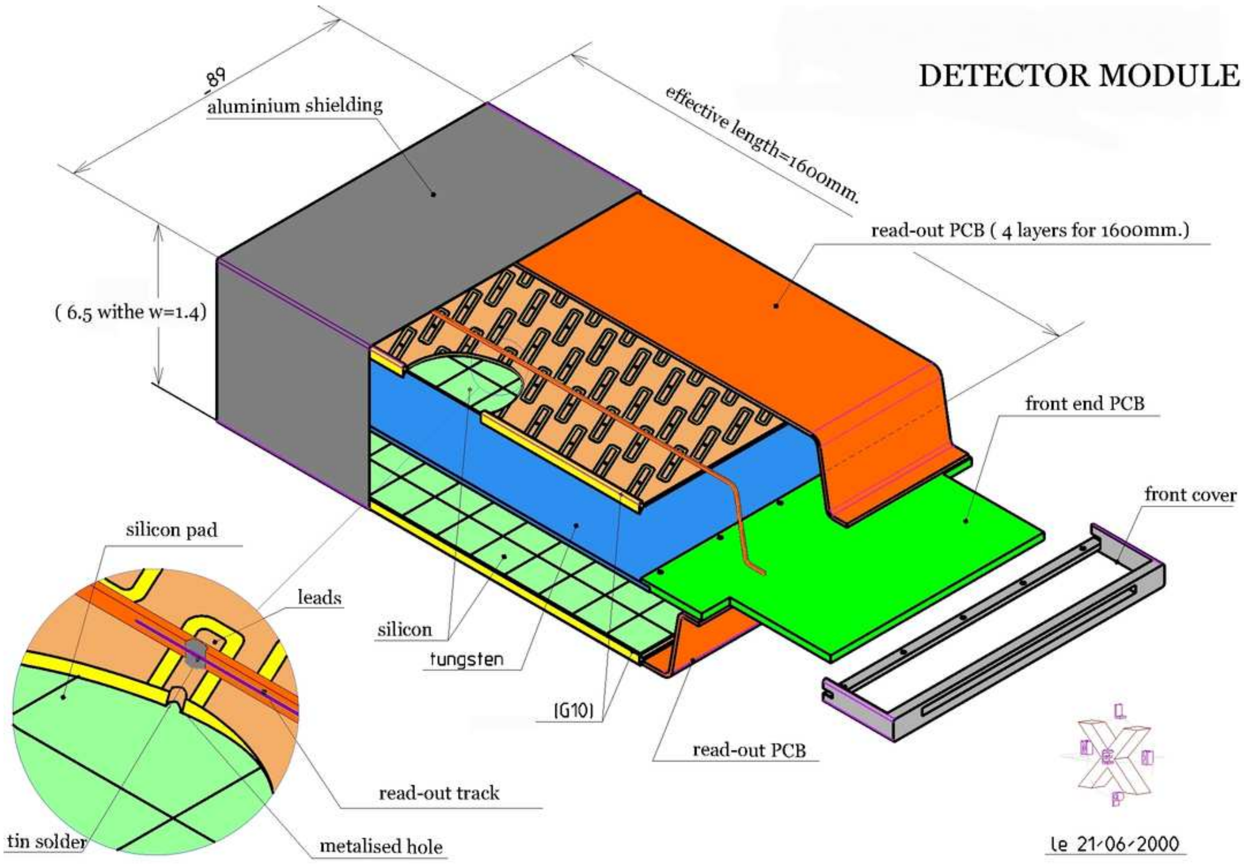

Figure 1: A schematic view of the detector slab, with the read-out lines.

The technological R&D and the relevant questions concerning the detector element (detector slab) are first described, from the Si matrix to the micro-mechanics of the different elements and the extraction of the diode signals.

The electronics R&D is then presented, especially for the front-end part, which is the most challenging part. A prototype is needed to interact with the other R&D for what concerns the particle behaviour in such a calorimeter, which governs the level of quality to be reached by the other elements. i.e. the precision on the tungsten density, the level of noise and precision of the pre-amplifier in the very front-end. The test beam with the ECAL in front of a HCAL device could be seen as the ultimate test as quoted in the introduction.

There is also another fundamental question for which prototyping is needed, the proposed detector presents a high level of integration, the full thickness of the ECAL is about 20 cm, while the front-end electronics has to deal with a density around 160 channels/cm^3. Prototyping is therefore mandatory to get proper answers about the feasibility/defaults/problems to reach this level of integration. For all these R&D including the physics prototype itself, the software will interact continuously to improve/change the design of the detector. So, last but not least, the software R&D is then described.

2.2 The detector elements

2.2.1 The silicon detector matrix

Silicon diodes of ~1x1 cm^2 area will be created on silicon wafers of 4 or 6 inches diameters, depending on the available technology. They will be cut in the form of squared matrices of size optimised to fit the global design which uses alveoli. The characteristics required for the diodes are reported in Table 1.

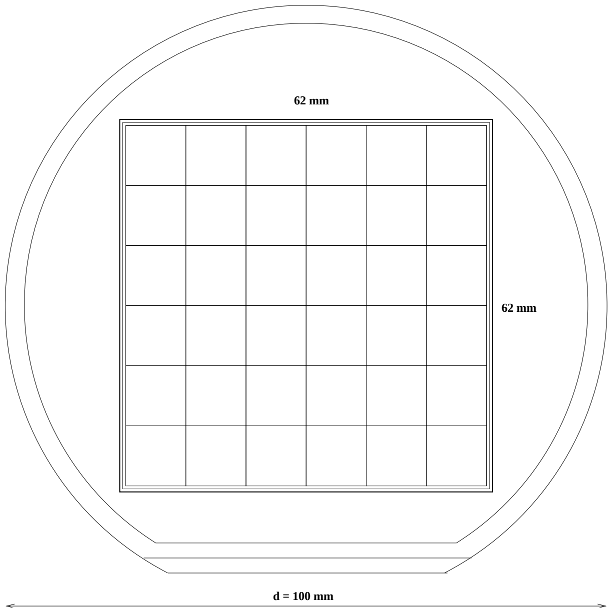

Figure 2: A schematic view of a silicon matrix with the guard ring.

The electrical properties of the silicon pads and the signal routing are discussed in Ref. [2]. The schematic layout of the sensor module 6x6 diodes matrix on 4 inch silicon

Active area	$\sim$1x1 cm^2
Thickness	$\sim$ 500 μm
Capacitance	$<$ 25 pF
Leakage current	$\sim$ 25 nA/cm^2 at 20°C
Depletion voltage	$\leq$ 250 V

Table 1: Si diodes requirements

wafer is shown on Fig. 2. The proposed R&D project will investigate the following items:

- the uniformity of the charge collection over all the active sensor area. Particular attention will be paid to the study of the edge effects to optimise the charge collection efficiency on the rim of the sensor module;

- different biasing and readout coupling schemes and their production technologies will be tested. One of the proposed techniques for AC coupling is the use of amorphous silicon technology, it is under investigation at the LPNHE-X and PICM at the Ecole Polytechnique;

- together with the study of the sensor parameters, the implication sensors defects (i.e dead pads, dead wafer,...) on the overall detector performance will be studied using simulation software tools.

The proposed time schedule and a cost estimate are presented in Tables 2 and 4.

2.2.2 The radiator plates

The tungsten radiator plates of thickness from 1.4 mm to 4.2 mm, will be used as the support of the Si wafers. The tests of the assembly of Si matrices with tungsten sheets will be made with respect to the induced mechanical constraints and stress. An alternative possibility for the radiator could be a tungsten alloy. This solution will be investigated, with a special care for the density homogeneity.

2.2.3 The assembly issues

A realistic detector module will be built to investigate the assembly process, mechanical properties of the components, tooling and different assembly techniques. At this level, a crucial criterion for all the prototype studies will be to find solutions which could be transfered to the industry for all the assembly process of a full scale detector. Such an approach is mandatory to successfully cope with the assembly of a detector consisting in hundred of thousands of silicon wafers as it is proposed for the global project.

2.2.4 How to get the signal out

The Si matrices are placed on both sides of W plates. The width of the plate depends on the silicon wafer radius available from the producer. The maximal length of the plate is 160 cm. Each side of the plate is fully covered with Si diodes. The read-out electronics is installed at the end of each plate.

To extract the diode signal, on the top of the wafers, a G10 board connects the pads through metallised holes to flat cables, which carry the signals to the end of the detection slab. Within the space of 1 cm about 140-160 signals have to be taken out. A possible solution would be to use thin printed circuit boards. A very high density solution where 50 μm thin wires are embedded with a pitch of 300 μm into a plastic sheet is under study. The back sides of all the Si matrices are glued to the W plate or to a very thin conductive layer that covers the plate to provide the return line for the current. The proposed agenda for the R&D and a cost estimate are presented in Tables 2 and 4 respectively.

2.3 The electronics

2.3.1 The front-end electronics

The readout of the W-SI calorimeter is based on high density front-end chips located inside the calorimeter. Each chip would service 128 channels, featuring amplification, shaping, local storage and output multiplexing. This density, similar to chips used in trackers, has to be reached for calorimeters where the dynamic range is larger by orders of magnitude. In particular, the smooth coexistence of low noise preamplifiers and elaborate digital electronics needs to be studied. Also, the handling of large dynamic range analog signals within the constraints of deep sub-micron processes may require the development of new analog architectures.

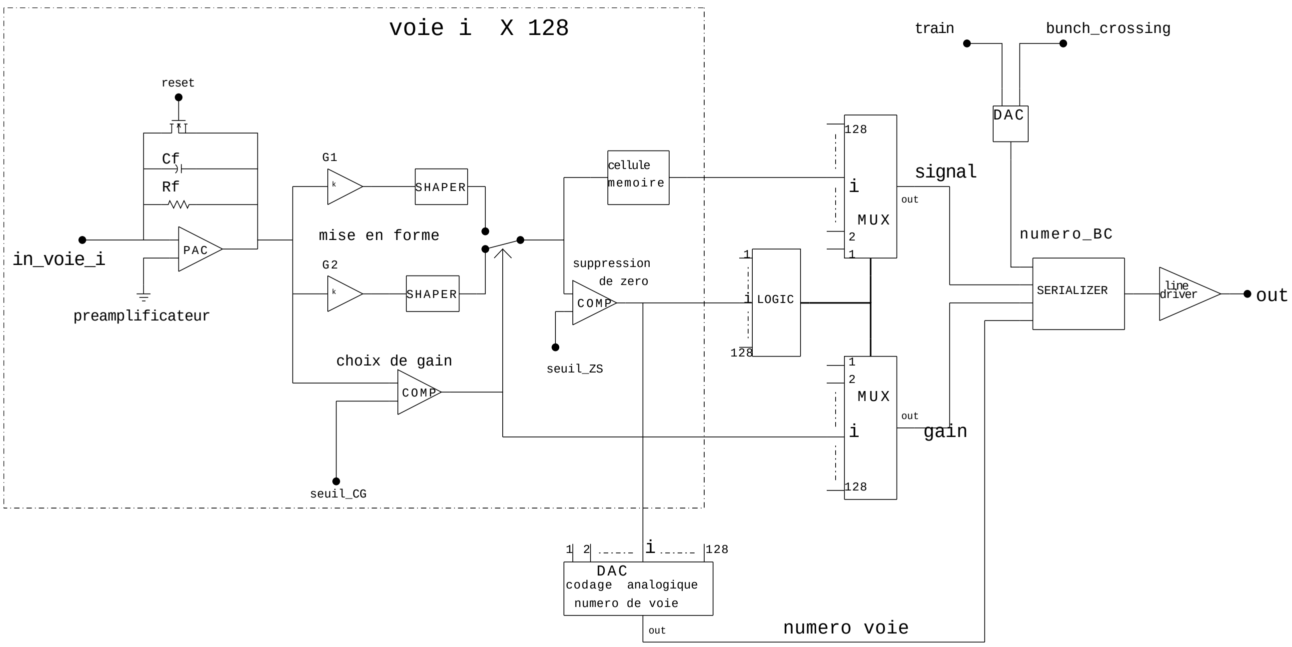

Figure 3: Synoptic diagram of the front-end architecture.

A preliminary synoptic diagram is displayed on Fig. 3. Face to the high dynamics, mono-gain or multi-gain options have to be addressed. According to requested precision, quite simple ADC may be envisaged with the multi-gain option. Then the opportunity to include such ADCs on the chip itself will be investigated. About the storage question, the best stage where the digitalization is performed, has to be researched and corollary the depth of the pipeline. To decrease the noise level, the manner to manage the current level in the preamplifier has to be examined.

The compromise between the integration ability and the power consumption is a real challenge. Then, BiCMOS and SiGe technologies, will be tested. The BiCMOS technology presents the advantage of a well establish behaviour in the 0.8 μm thick and most of the developments may be based on simulation followed by layout elaboration. The compatibility between the two technologies in 0.8 μm thick allows an easiest approach of the SiGe technology in a first step. Then their complete performances can be respectively compared. Further developments with a thiner technology (0.35 μm) can afterwards be tackled. These studies could start with reasonable engineering manpower and the submission of one or two chips with test structures per year. The cost estimate is presented in Table 4.

2.3.2 The digital conversion and DAQ

This part of the electronics for the prototype is under study. It is investigated to use existing cards with ADC's and a DAQ system coming from tests for LHC experiments. These cards could process 16 channels with 10 bits ADC's. That solution would be simpler and cheaper than to develop a dedicated solution.

2.4 The physics prototype

Besides specific R&D mentionned above, the behaviour of the calorimeter as a whole has to be tested. Then, a prototype is needed in order to study the following items :

- test of the response for electron(photon): i.e importance of the inactive zone, dead wafer(s), dead pad(s) on the reconstruction of the e.m. shower (ECAL)
- test of all technological aspects (Si detectors production, Tungsten processing and tolerance) (ECAL/HCAL)
- test to hadron/muon response with the HCAL, tile or digital. (ECAL/HCAL)

The following design has been adopted for the physics prototype : 30 layers of silicon sensors made from 4 inch wafers which corresponds to 6x6 cm^2 silicon matrix. The pad size is about 1x1cm^2. For the time being, two mechanical versions are under consideration, first with 6 cm width alveoli and one silicon matrix per alvelous, second a 12 cm width alveolus with two silicon matrices per alveolus. GEANT simulation of the two solutions, including very detailled description of the dead zone, material thickness and geometry, will allow to choose the solution with the best behaviour for single electromagnetic particle.

The number of Si matrices strongly depends on the funding. Anyway this number has to be greater than two wafers per layer, which represents the minimal value needed to test the response in the inter-space between wafers. A better ratio consists in 4 wafers per layer, which allows also to test the response at the aveoli boundary. With this configuration the overlapping between alveoli is realised and the transverse covering

	2001	2002	2003	≥2004
Software studies - Eflow vs design	x	x	x	x
Software studies - input for hardware	x	x	x	x
Metrology of tungsten plates		x	x	x
Micro-mechanics detec. slab			x	x
Electrical readout, flat cable		x	x	x
connectors/bonding on PCB	x	x	x	x
Si diode gluing/bonding	x	x		
Si area/cost optimisation		x	x	x
Front-end chip (∼20 channels)	x	x		
Front-end chip (∼50 channels)		x	x	
Front-end chip (∼100 channels)			x	x
Front-end digital part	x	x	x	x
First test overall readout				x
production 1/2 module version 0				x

Table 2: Proposed agenda for the R&D on the W-Si ECAL for a TESLA detector

is ∼1.5 interaction length, which allows the study of the hadron shower behaviour in the detector.

The first test of the ECAL physics prototype could be done with a minimum of two wafers per layers, but to fulfill the test program, it is needed to have 4 wafers per layer. A proposed agenda and a cost estimate are presented on Tables 3 and 4 respectively.

2.5 The collaborating institutions

The institutes which express interest in the various aspects of this R&D proposal are listed in Table 5.

2.6 The agenda and costing

Table 2 summarises the R&D foreseen for the W-Si ECAL for a TESLA detector, while Table 3 reports the proposed agenda for the realisation of a prototype. A first cost estimate is given in Table 4.

3 months period →	2001 2/4	2001 3/4	2001 4/4	2002 1/4	2002 2/4	2002 3/4	2002 4/4	2003 1/4	2003 2/4
Tungsten/alloy selection	x								
Structure construction		x	x	x					
R&D Si. matrices	x	x	x						
R&D AC coupling	x	x	x						
First run Si. prod.		x	x						
Final run Si. prod.				x	x				
Si matrices packaging					x	x	x		
R&D readout line/PCB		x	x	x					
Detect. slab construction					x	x	x		
Readout elec. design	x	x	x	x					
Front-end/PCB production					x	x	x	x	
Overall readout prod.						x	x	x	
Overall readout test						x	x	x	
DAQ design			x	x	x				
DAQ production/test						x	x	x	x
Test with cosmics								x	x
Installation in beam hall									x

Table 3: Proposed agenda for the W-Si ECAL physics prototype

	2001	2002	2003
Mechanics	25K€	15K€	15K€
Electronics	35K€	35K€	35K€
Silicon Packaging	20K€	20K€	25K€
Prototype mechanics	40K€	20K€	-
Prototype silicon	45K€	45K€	-
Prototype read-out	30K€	70 K€	-
TOTAL	195K€	205K€	75 K€

Table 4: W-Si ECAL cost estimate for each part of the R&D.

	Institutes
Mechanics	IHEP, IPASP,ITEP, MEPhI, MSU, LPNHE-X
Electronics	IPASP, LAL, LPC , MSU
Silicon matrix	CUP, IPASP, LPNHE-X, MSU
Software	DESY, IHEP, LAL, LPC, LPNHE-X
Prototype	CUP, IHEP, IPASP, ITEP, MEPhI, LAL, LPC, LPNHE-X, MSU

Table 5: List of the Laboratories interested in the R & D for the W-Si calorimeter

3 The tile HCAL calorimeter

3.1 Motivation for the tile HCAL R&D

The main motivation for the HCAL R&D program is to perform the necessary measurements to understand and optimize the performances of the detector and complete its design. The most important innovation addressed by this program is the energy flow measurement [1] capabilities of such a fine grained calorimeter. In this respect, the calorimeter should be able to provide sufficient information about the spatial distribution of energy to complement the tracking system in finding the optimal estimate of the energy and direction of partons. This study thus goes much beyond the intrinsic resolution of a single detector element, and requires an understanding of the structure of the detector as a whole. In this section, we present the important questions that need to be addressed to be able to confront actual measurements with our simulations in order to optimize the design of the HCAL, both from a hardware and a reconstruction software point of view. A detailed description of the laboratory research studies to be carried out is available in [3], where a summary of references to results from earlier R&D is also presented. In [4] the problems with calorimeter cell monitoring and calibration are explained and possible solutions are discussed.

Several scintillator–tile calorimeters are either in construction or under development [5]. The structure of recent calorimeters are shown in Table 6. There energy resolutions, along with the predicted energy resolution of the TESLA calorimeter, are shown in Figure 4.

	Depth $[\Lambda]$	sampling		segmentation [cm]		$\frac{\sigma}{E} = \frac{A}{\sqrt{E}} + B + \frac{C}{E}$				
		abs[cm]	scint[mm]	trans.	long.	A%		B%		C%
LHCB	7.3	Fe, var.	4	13×13 26×26	2	79.1	$\oplus$	7.8	+	0
CMS	6.2	Brass, 4	4	14×14 21×21	2	77.0	$\oplus$	5.5	+	0
H1 forw	8.2	$PbSb_4$, 1.4	3	20×20	4	60.0	$\oplus$	3.0	+	0
ATLAS	8.9	Fe, var.	3	20×20	4	41.9	+	1.8	$\oplus$	1.8
NOE	3.7+	Fe, 5	2 + 3	5×5	28	43.0	+	1.5	+	0
JLC	6.4	Pb, 0.8	2 + 2	20×20	4	46.7	$\oplus$	0.9	+	0
FLC	5.4	Fe, 2	4	5×5 20×20	8	40.0	$\oplus$	5.0	+	0
NLC	?	Pb, 0.8	2	$? \times ?$	?	40.0	$\oplus$	2.0	+	0

Table 6: Characteristics of modern tile hadron calorimeters – test beam results and predictions. All calorimeters include different type of ECAL in front of HCAL. The energy resolution is shown for the complete detectors.

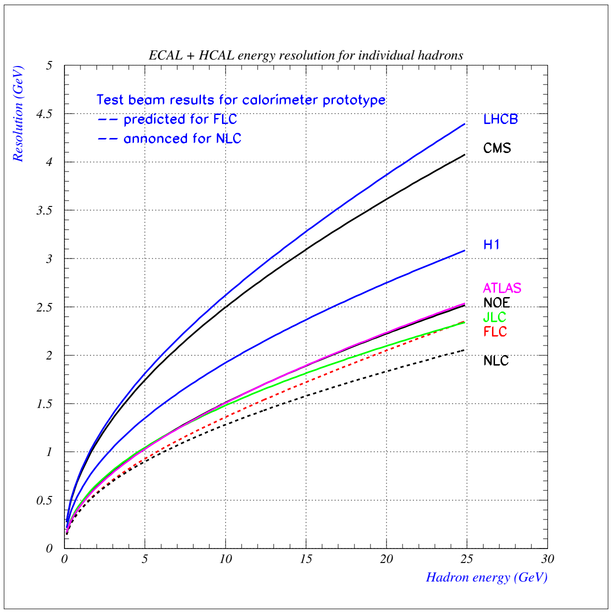

Figure 4: Low energy part of energy resolution

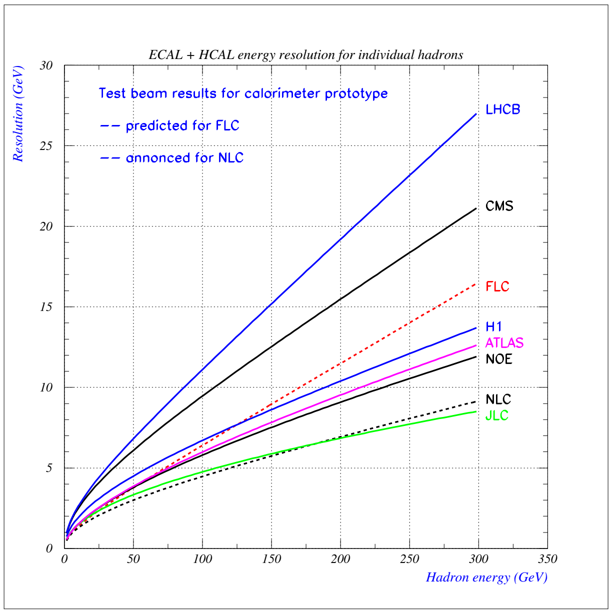

Figure 5: High energy part of energy resolution

3.2 Current tile HCAL design

The HCAL is a stainless steel/scintillator tile sampling calorimeter with high granularity to allow excellent longitudinal and lateral cluster reconstruction.[2] Cells of several layers of scintillator elements (called tiles) are presently foreseen. The calorimeter should have seven such cells in depth. A total of about 800000 tiles of 5 mm thickness with sizes ranging between 5×5 and $16 \times 16 cm^2$ will be assembled in roughly 160000 calorimeters cells.

The scintillation light produced in the tiles will be read out by green wavelength shifter fibers. The converted light will be guided towards photodetectors installed outside of the calorimeter volume. Clear fibers will be used as light guides. The light of all fibers of a cell will be

mixed in front of the photodetectors, which will have to be able to operate in a magnetic field of 4 Tesla.

The HCAL design includes a barrel calorimeter assembled from 2 half barrels and 2 endcaps. Together, they surround the interaction region nearly hermetically, with holes of 5^o around the beam line. A detailed description is given in the Technical Design Report [1]. The design and construction of the different calorimeter modules and the assembly of a hermetic calorimeter is described in [6].

The readout of the light signal followed by the conversion to digital information is discussed in [7]. A gain between 200 and 400 can be expected if APD are used. Additional charge sensitive preamplifiers with 12 bit linearity range will be inserted in front of the analog-to-digital converters. The dynamical range should cover energies from MIPs (with an energy deposition of about 100 MeV) to the maximal energy deposition of 70 GeV per cell.

3.3 The R&D program

The different items of the proposed R&D program are detailed in [5]. The R&D program is divided in the four following parts:

3.3.1 Prototype studies

A reduced size prototype of a HCAL barrel section would be built and partly equipped with the minimal required number of cells. Most of the efforts would be directed towards understanding the energy flow capabilities of the detector. These measurements would include studies of cluster separation, simulation of jets by overlaying patterns of various particles measured individually, jet energy resolution for different angles of incidence, and identification of muons in hadronic clusters.

These tests would be completed by energy resolution measurements on a wide range of energies, e/pion separation measurements and shower leakage studies. Measurements of these last properties were already performed in the past using similar calorimeters [5].

3.3.2 Software development and simulation studies

Several aspects of the reconstruction software of the HCAL needs to be addressed. The energy flow reconstruction procedure still has to be optimized, as well as the procedure

[2]Such a hadronic calorimeter is the first choice of the ECFA-DESY group working on calorimeter studies for TESLA.

for energy weighting (software compensation). A prototype of the HCAL would provide important inputs to complete this work. The combination of these measurements and the results of the software development are essential for the optimization of the cell size and structure of the HCAL.

3.3.3 Detector components

Efforts also have to be invested in developing the detector components. The performance of large calorimeters with a small tile size of 5×5 cm^2 has not been studied before in detail. In particular, the optimization work currently underway has to be pursued and extended to the choice of photodetectors, preamplifiers and ADCs with the appropriate dynamical range and performances.

3.3.4 Mechanical tests

Individual calorimeter modules are large and heavy. Thin side walls are foreseen to support the stack plates, with no additional spacers inside the stack. The construction of a barrel module prototype would help test the mechanical stability of such a detector and optimize the mechanical design and the assembly procedure.

3.4 Present studies and time plans

R&D activities have started at DESY, ITEP, LPI and MEPHI some time ago. Groups in Prague and Uzbekistan are already in the collaboration, and discussions with other interested institutes are ongoing. Studies of the Scintillator-WLS-ROF-complex are well underway, and a test device has been set up to obtain the first results on the tile light yield from MIPs. These tests were performed with $10 \times 10 cm^2$ tiles with one loop of 1 mm WLS fiber. A light yield equivalent to ≥ 50 photons/MIP for the full calorimeter cell with 3 tiles was obtain.

The R&D planning is presented in Table 7. The sharing of contributions between the collaborating institutes is shown in Table 9.

3.5 Material costs

A cost estimate for the barrel module prototype versions with 600 and 1000 active channels is given in Table 8. A total of 20 kDM (8 kDM + 12 kDM) would be needed to start the proposed R&D program this year. This sum would cover the cost of items such as:
– scintillator plates of different light yield and attenuation length,
– single and double clad WLS fibers,
– double clad ROFs,
– plastic material for light mixers,
– reflector foils and paint,
– optical glues,
– photodetectors,
– preamplifiers.

year:... period:..	2001 2/4	2001 3/4	2001 4/4	2002 1/4	2002 2/4	2002 3/4	2002 4/4	2003 1/4	2003 2/4
order material for R+D	x	x							
scintillator-WLS studies	x	x	x						
ROF-light mixer studies	x	x	x						
material procurement for protot.			x	x	x				
DAQ development	x	x	x	x					
tile plates design	x	x							
tile plates assembly				x	x	x			
fiber routing design	x	x	x						
prototype stack design	x	x							
prototype stack product.		x	x						
prototype stack tests				x	x				
photodiode selection	x	x	x	x					
photodiode delivery, tests					x	x			
preamplifier selection	x	x	x	x					
preamplifier delivery, tests				x	x	x			
ADC selection	x	x	x	x					
ADC delivery, tests				x	x	x			
cooled electronic box				x	x				
gain monitoring (LED)	x	x			x	x			
electr. linearity monit.	x	x			x	x			
tile plates test+calibration				x	x	x			
equipment of prototype					x	x			
prototype test with muons						x	x		
beam tests at DESY,ITEP,CERN						x	x	x	x

Table 7: Time schedule for prototype production

	for 600 channel	for 1000 channels
Basic material for R+D	10.000	10.000
Steel for barrel prototype,7to	11.000	11.000
Tools for plates and stack assembly	21.000	21.000
Scintillator,0.5kEuro/m^2,15/23m^2	7.500	11.500
WLS fibers, 5 wdgs,2.2/3.5 km	3.300	5.250
Clear ROF, 5m/tile, 11/18 km	13.750	22.500
APD"s, $3 \times 3mm^2$, Hamamatsu, 25Euro	15.000	25.000
Preamplifiers, 10Euro/piece	6.000	10.000
FADC's 60-100MHz, or ADC's, 40Euro/ch.	24.000	40.000
Power supplies	5.000	5.000
Transport of stack to DESY	7.500	7.500
Sum for prototype of 600/1000 channels	124.050	168.750

Table 8: Material cost estimation in Euro

Task	Institute
HCAL stack studies and construction	ITEP, DESY,IPASP,CUP
Scintillator-WLS-ROF	DESY, ITEP, LPI, CUP, TU
Tile plate assembly	ITEP, DESY, IPASP
ROF routing	ITEP
Photodetectors	MEPhI, DESY, ITEP
Preamplifiers	ITEP, MEPhI
ADC's	DESY, LPI
Cooled electronics boxes	CUP, ITEP
LED monitoring	IPASP, ITEP
Cell size and structure studies	DESY, ITEP
Reconstruction software	DESY, ITEP
Calibration studies	DESY, ITEP
Data acquisition	use existing equipment, coordinated by DESY

Table 9: Contribution

4 The digital calorimeter for HCAL

4.1 Introduction

The studies performed for the TESLA-TDR have shown that a digital calorimeter could be very efficient for the reconstruction of neutral hadron and/or muon identification in jet. Moreover, using the purely digital signal, the number of cells touched, is linear in energy and that the resolution is slighly better than the analogic one. It has been shown [1] that using more information from the shower behaviour (i.e. volume, lateral extension,) the resolution can be further improved. The structure is, like for the tile calorimeter, made of stainless steel plates. The detecting medium has to be sensitive to m.i.p signals and in order to optimise the number of interaction length inside the coil, the detecting device must have a thickness of 6 mm maximum.

4.2 The detecting device

Different technical solutions are being investigated. The detecting medium can be made of resistive plate chambers, wire chambers operated in limited Geiger mode or even thin wire chambers like in the ALEPH electromagnetic calorimeter. The signal is collected on small pads (typically 1x1 cm^2). For the first two solutions the signal is big enough to switch shift registers, in the second an amplification is needed. The bits are read serially and, as the occupancy is small, zero suppression is applied early. For a better separation between showers the use of heavier radiator is considered. The proposed R&D will have to determine the best option, taking into account the fraction of dead area, the dead time, the signal/noise ratio at the m.i.p. level and eventually the cost for the final detector, where a very large area of chambers is needed.

4.3 The prototype

To test the ideas and principles of the digital HCAL, 40 chambers with 2D readout have to be produced. To test the reconstruction of the hadronic shower in such a device, the size of the chambers is determined to be about 10 interaction lengths, in order to efficiently cover the lateral extension of hadronic shower. With stainless steel as radiator, it corresponds to a size of the chambers of about 1x1 m^2. The pad size has been already studied in the ECFA/DESY workshop using GEANT simulation and it has been shown that a pad size of 1x1 cm^2 optimises both the reconstruction and resolution.

4.4 Cost estimate and proposed agenda

A first cost estimate based on the ALEPH calorimeter chambers working in streamer mode, gives a total of about 75 keuro for the total of 40 chambers of 1x1 m^2. In addition, a total of 2650 man-hours is needed. Further detailled estimation will be done in a near future for the different types of chambers. The construction needs about 12 months. The agenda could therefore be the following:

- 6/12 months studies of the different types of chambers
- 6/12 months construction

which allows to have the digital HCAL ready for the 2003 test beam.

5 The software

5.1 The simulation

The calorimeters have been simulated both in a GEANT3 [8] and in a GEANT4 based context[9]. Both simulations include full shower simulation, cluster finding and reconstruction. Extensive comparisons between both systems have been made to ensure that the results of the simulations agree. The simulation of the prototype is ready for the W-Si ECAL within the framework of GEANT4, but the HCAL part remains to be done.

5.2 The energy flow (EFLOW)

The real tests of the design of the calorimeters are the ENERGY FLOW performances. The high granularity calorimeters proposed with the W-Si ECAL fulfill the request to perform the particle reconstruction. A preliminary ENERGY FLOW jet resolution better than $35\%/\sqrt{E_{\mathrm{jet}}}$ has been performed [10], which indicate the potential improvement achievable with respect to previous detector implemented on e^+e^- machines. Nevertheless, the physics studies indicates that the exploration of the multi-jets needs an ENERGY FLOW jet resolution in the range of $30\%/\sqrt{E_{\mathrm{jet}}}$. How this resolution depends on the ECAL/HCAL geometry/design is one of the main issue of the software R&D.

The goal of the ECAL R&D is to provide the performances of the W-Si ECAL and its impact on physics processes through the ENERGY FLOW. Optimization of the W-Si ECAL geometry is also a major issue. Software will be used to give the essential inputs to the hardware part and will allow to evaluate the consequences of the results from the prototype studies on the detector performances. The following steps would drive the effort on the software part of the R&D :

i) built up a reconstruction code based on the actual design including the study of the delicate zones, *ii)* improve the ENERGY FLOW resolution as well as isolated particles and *iii)* optimize the geometry design.

The various aspects of the software related to the W-Si ECAL R&D are listed in a turn below.

5.3 The detector response studies

Input for the hardware study : an estimation of the detector occupancy (esp. in Endcaps) is needed. This includes Bhabha, two-photons and beamstrahlung processes. The question about the machine background has to be settled. The study of these points will be performed with `MOKKA`. A dedicated simulation of the prototype is needed to perform the studies and to cross-check the `GEANT.4` simulation parameters with real data.

Optimization of the geometry : the actual design consists in 40 layers with double tungsten thickness in the 10 last ones. The ENERGY FLOW resolution has to be tested with respect of different parameters set for the number of layers, layer thickness, pad size, tungsten density. Such tests have to be done with respect of the adequation with the HCAL geometry; it is essential to bear in mind this point for the ENERGY FLOW concept. The fraction of inactive zone (between the wafer of pads) could have an important impact of the ENERGY FLOW resolution. The study (and impact) of the crack geometry has to be done and evaluated with the prototype.

6 Beam test definition

The proposed beam test of the calorimeter is designed to check the energy resolution, the lepton identification and more important, the reconstruction of hadronic and electromagnetic shower in the calorimeter. The proposed calorimeter has been optimized for jet reconstruction, where the average energy of the charged hadrons/leptons, photon(s) neutron(s) and neutral hadron(s) is relatively small. Therefore, the beam energy must range from low energy (about 2 GeV/c namely the minimal transverse momentum for a track to reach the calorimeter in the TDR design of the overall detector) to relatively medium energy ($\sim$50-100 GeV/c). The use of DESY beam (low energy), Protvino beam and/or the H4 beam at CERN is considered.

7 Summary

The design of the calorimeter for a TESLA detector will be studied. When fulfilled, the proposed R&D program on the tungsten-silicon ECAL and on the tile or digital HCAL will give a clear picture on this design/feasibility/performances and cost.

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