The Optical and Electronic Readout of the HCAL Tile calorimeter

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1. Introduction

The TESLA HCAL is a sandwich sampling calorimeter with stainless steel or brass absorber and scintillator tile detector plates. Together with the inner ECAL and the tracking system the energy and angles of all particles and jets can be measured with high resolution. The complete TESLA detector is described in ref. 1. more details on the HCAL can also be found in ref. 2. The complete technical design of the HCAL is described in ref. 3.

In the following the readout line with the individual components and their required performance is described in some detail.

2. Performance requirements for the calorimeter

The essential task for the HCAL is the optimal lateral and longitudinal separation of individual hadronic clusters, the energy measurement of these clusters for optimal energy flow measurements (ref. 1,2) – together with the track and momentum measurement with the TPC – and the MIP track finding in such a multi–cluster environment. This requires small calorimeter cell sizes.

The sensitivity for rare SUSY events with large missing transverse momentum can be significantly improved with a good time measurement which is essential to suppress cosmic background events. A time resolution of 2–3 ns for each individual calorimeter cell will be possible with such a HCAL.

In addition the identification and tracking of event correlated muons will be possible for selection and understanding of such SUSY events. Cosmic and beam halo muons have to be used for online energy calibration of all individual cells.

3. Scintillator tile sizes and calorimeter cells

Each HCAL barrel module is an assembly of 38 sandwich layers, the HCAL endcaps have 45 sandwich layers in the inner region – where the endcap ECAL is mounted in front – and 8 additional sandwich layers in the endcap outer region at larger distance from the beam (ref.3). Each sandwich layer represents a depth of 0.15λ or 1.14 X_0. Tiles of subsequent sandwich layers are grouped together to calorimeter cells, which form cell layers, from 3 tiles/cell in front to 7 tiles/cell in back. The barrel HCAL has a longitudinal segmentation of 9 cell layers and the endcaps have 10 (12 outside) cell layers (Table 1).

	barrel	endcap < 2m	endcap > 2m
sandwich layers	38	45	8 + 45
cell layers	9	10	2 + 10

Table 1, The HCAL segmentation in sandwich layers and cell layers

The lateral tile and cell sizes and the grouping of subsequent tiles to cells are listed in Table 2. The tiles increase in the actual proposed HCAL version with calorimeter radius. They have approximately quadratic lateral dimensions. Within cells the subsequent tiles are rather similar in size growing smoothly with calorimeter depth.

barrel		**lateral**	**endcap**		**lateral**
cell layer	**sandwiches**	**tile sizes**	**cell layer**	**sandwiches**	**tile sizes**
			outer ring 1	4	13 x 13
			outer ring 2	4	13 x 13
1	3	5 x 5	1	3	9 x 9
2	3	5 x 5	2	3	9 x 9
3	3	6 x 6	3	3	9 x 9
4	4	7 x 7	4	4	11 x 11
5	4	8 x 8	5	4	11 x 11
6	4	9 x 9	6	4	11 x 11
7	5	10 x 10	7	5	12 x 12
8	5	12 x 12	8	5	12 x 12
9	7	16 x 16	9	7	21 x 21
			10	7	21 x 21
all	**38**	**cm^2**	**all**	**45**	**cm^2**

Table 2, The cell sandwich structure and rough tile sizes for barrel and endcap modules.

4. The scintillator tiles

The scintillator tiles are 5 mm thick with lateral sizes increasing from 5 x 5 cm^2 in front to 25 x 25 cm^2 in the last layers. A MIP deposes 1 MeV of energy in each scintillator tile. The tiles will be assembled as tile plates before insertion in the stainless steel absorber gaps of the calorimeter stacks. Reflector sheets or reflective paintings on the tiles avoid escape of scintillation light and cross talk to neighbours.

5. The readout fibres (ROF's)

The amount of scintillation light produced, proportional to the energy deposed in the scintillator, has to be measured efficiently. Since photodetectors can not be inserted in the tight gaps of the calorimeter stack, the produced light has to be transferred to appropriate places outside the calorimeter volume.
An efficient way to transport the light to the photodetectors is via long double–clad transparent fibres. Fibres of ≈1mm diameter are stable enough and are flexible within a bending radius larger than 2 cm. Clear transparent fibres with a light attenuation length of ≈12m (at light wavelength of 600 nm) are available.

6. The wavelength shifter fibres (WLS)

The scintillation light has to be transferred into WLS fibres. Such fibres absorb blue light (≈400–500 nm) within a few absorption depths (≈300 µm for BCF91A from BICRON) and transfer it to green light (≈600 nm), photon by photon with an efficiency of 70–80%. The refraction index ratio of fibre core and inner clad layer defines the fraction of light directly accepted by total reflection. It is ≈6–8%, if the light emitted in both fibre directions is used and the downstream end of the fibre is coated with a mirror reflector layer. Such a coating with e.g. vaporised pure aluminium can be applied in a vacuum furnace. To get ≥ 80% of reflectivity, the fibre end has to be mechanically polished before.

7. The optimisation of the scintillator to WLS fibre transfer

There are several possibilities to transfer the blue light in to the WLS fibres as discussed in ref. 5. As a guide about 10–35% of the scintillation photons produced will enter the WLS fibres and will be converted. To get a maximum of the scintillation light into the WLS fibre care has to be taken to cover a large area of the scintillator tile with optimally positioned fibre loops. A detailed R&D program to optimise such a system is on the way (ref.5).

8. The routing of the readout fibres

Efficient optical connections are needed between the WLS fibres and the ROF's and also for the connection to the photodetectors. Direct gluing with an optical cement will yield a stable connection and rather good light transfer, losses of < 25% are possible. Since light of several subsequent tiles has to be collected for cells as given in table 2, the light from several ROF's has to added in front of the photodetectors where light mixers have to be used.

The routing of the fibres for instance of a barrel HCAL module is discussed in the following. Such a module is an assembly of about 32000 tiles with the same number of ROF's. These fibres leave the module at the downstream end of the tile plates with a maximal density of 10 fibres/cm. The fibres have to be ordered and collected to cells at this place where the density is still relatively low, with all sandwiches together the fibre density reaches a maximum of about 320 fibres/cm. At the readout end of the inserted tile plates the fibres are arranged in the order needed for cell assembly and additionally marked by various different colours. They will be grouped together in groups of 3 to 7 fibres and inserted in long light tight and flexible pipes which carry the cell number. The total length of the ROF's can be kept below 6m.

For each barrel module 4096 such numbered flexible pipes have to be guided along the 170 mm deep gap between barrel and endcaps to the photodetectors in the readout boxes. A disk of 70 mm is completely free for the routing, the remaining 100 mm have to be shared with the TPC support bars and readout cables of the trackers and the ECAL. Certainly the detailed routing of all these pipes with bending radii above 3 cm is a difficult task

For easy access and replacement of components the readout boxes will be placed behind the endcap calorimeter. It is foreseen to fix them along the inner cryostat wall in order to keep the area of the endcaps free for their installation and access. At present one such box is assigned to each module. With small size photodetectors as e.g. conventional APD's of 0.5 x 0.5 cm^2 arranged in tight arrays and integrated readout circuits the boxes have a minimum size of 1100 cm^2 with a depth which seems not critical. The boxes have to be cooled down to about −10°C and have to be stabilised in temperature within about +/− 0.5°C. A depth of 20–30 cm should be sufficient. The input connector for the ROF's of individual cells will be probably 'cut cone shaped light mixer's with 7 small holes to pick up the individual fibres.

For each half barrel 16 of such boxes have to arranged with azimuthal separation along the inner circumference of the cryostat. The boxes for the endcap quadrants can be directly fixed to their individual modules in order to keep the calorimeter in operation during movements of the endcaps.

9. The photodetectors

The photodetectors are placed inside the 4 T magnetic field and thus have to be insensitive to field strength and field orientation. Many types of silicon avalanche photodiodes (APD's) are available, e.g. from HAMAMATSU, Japan. Their performance has been studied in detail by the CMS collaboration (ref. 6,7.) for the use in crystal calorimetry and by the SCROD collaboration (ref. 8) for detection of cosmic muons. Such photodiodes have a quantum efficiency for green light of 73%. The photocathode sizes needed are in the range of 3 x 3 to 5 x 5 mm^2 according to capacities of 20–70 pF. The gain depends on the bias voltage applied, a gain factor of 2000 can be reached with bias voltage below 200V. The noise produced grows with their capacity and is dominated by the leakage current passing the multiplication region. At a gain of 800 the leakage current is about 30 nA (ref. 9) at 23°C and decreases significantly with temperature. To get sufficient signal distance with respect to MIP's a maximum of the primary photons has to be collected along the optical chain.

	operation	corr. factor	electrons	photons	sigma	deduced from:
photoelectrons from a 5 mm thick tile of 40 x 40 mm2			**6**			**A. Karar et al**
photons from 6% photocathode efficiency	**x 1/0.06**			**92**		**Hamamatsu**
for 3 tiles (smallest cell)				**275**		**HCAL detector**
light yield improvement by gluing fibre in grooves >> better opt. contact	**x**	**1**		**275**		**A. Karar et al**
optical connector transition losses	**x**	**0,725**		**199**		**A. Karar et al**
total maximal fibre length in m	**in m**	**5,25**				**HCAL detector**
light attenuation length for 540 nm	**in m**	**12,4**				**Bicron**
light attenuation factor		**0,65**		**131**		**calculated**
connection to photodetector		**0,9**		**118**		**estimated**
conversion in APD e– signal/MIP		**0,73**	**86**		**9,3**	**A. Karar et al**
U=60 V, –6°C, ~ gain 6		**6**	**515**		**55,6**	**C. Cheshkov et al**
U=100 V, –6°C, ~ gain 18		**18**	**1544**		**166,7**	**C. Cheshkov et al**

Table 3, Estimate of the final electron signal yield

An estimate of the final signal yield is given in Table 3. All the light losses are taken from different experiments (ref. 5.) and from the HAMAMATSU data book. As a result from such a theoretical estimate with low gain about 500 electrons can be collected from an APD with a noise of 60 electrons.

Avalanche photodiodes are small in size with volume < $1cm^3$, need operation voltages of ≈200 V and will be much cheaper than conventional vacuum photomultipliers.

An alternative could be the use of Hybrid Photo Diodes (HPD's) when they are capable to operate in magnetic fields of 4T. But they need operation voltages of order of 10 KV and are quite large in size and rather expensive.

Conventional vacuum photomultipliers operate in small magnetic fields of a few Gauss only. If all other solutions fail, such photomultipliers have to be installed outside the field volume far away from the coil with very long (≈10m) ROF's and also still some additional magnetic shielding.

It should also be mentioned that at present silicon pixel APD's are in development (ref.10,11) with a pixel density of 10^5 pixels on 10 mm^2. Such MRS APD's have an interesting large gain of 10^4–10^5 , but suffer so far from low photo conversion efficiency (10–20%) and large single pixel noise. Nevertheless they would, due to the limited pixel density, show a reproducible perfect dynamic suppression of large signals which could well be used to reduce the required dynamic range of the ADC's as discussed in the following. It could be interesting to follow the further improvement of such photodetectors.

10. Preamplifier and shaping

The signal current of the APD's has to be amplified in special designed preamplifiers which have a large current gain to ease the final signal analysis, suppress the capacitive noise induced by the APD's as much as possible and shape the signal as needed to get optimal time resolution.

For APD's from Hamamatsu with 10 mm^2 sensitive area, 10 pF of capacity and typically 10 nA dark current at again of 6 at 60 V (gain 18 at 100 V) a noise excess factor of 1.7 (2.0) is measured. Table 4 shows for the MIP signals for 2 gains (see Table 3) and 2 shaping times the amplitude/sigma for MIPs.

APD–gain	shaping time (ns)	sigma	amplitude/sigma
6	100 ns	148	3,5
6	250 ns	214	2,4
18	100 ns	253	6,1
18	250 ns	300	5,2

Table 4, Estimate of the observed MIP signal width with all noise sources included.

Smaller shaping times would improve the signal/noise ratio when all signal can be collected within the shaping gap, but due to the significant large detector capacity of 10 pF, an increasing fraction of the signal will be lost. APD's with optimal small area, low capacity and low dark current are needed, being one of the major efforts for the coming R&D studies.

For APD's with 1pF capacity at 100 V and a dark current of < 1nA a signal to noise ratio of about 7 can be reached (ref. 12).

The SCROD collaboration (ref. 8.) measured with a special designed low–noise amplifier (amplifier noise of 2800 electrons at 70 pF APD detector capacitance) a noise of 8–10 electrons for a signal of 600 electrons/MIP. The APD and amplifier temperature was 17°C, the shaping time of the amplifier was 30 ns with an integration time of 50 ns only.

11. Analogue Digital Conversion

The signals – current to voltage transformed in the shapers – are analysed in Analogue to Digital Converters (ADC's). The required linearity range as described in ref. 4 can be covered by 12 bits. This range has to be extended by additional 3–4 bits needed for calorimeter calibration with muons.

Since the experiment will not relay on hardware triggering, trigger signals for ADC gates will not be available. This favours the use of permanently running flash ADC's (FADC's) with subsequent continuous readout into digital pipelines. The shaped signals from the shaper allow the reconstruction of the interaction time. With a shaping time of 50 ns and the use of 100–200 MHz clocked FADC's the interaction time can be measured with a precision of a few ns.

An other possible solution would be the use of standard cheap ADC's with signal gates produced by additional discriminators with optimally adjustable thresholds. Besides the gating the discriminator signals can than be also used for accurate time measurement or time flagging of the individual channels.

For both solutions the dynamic range, integration time and costs of the ADC's can be reduced when appropriate preamplifiers of multiple gain are used.

The development of an optimal ADC system for the HCAL is a major task for the next R&D step.

12. Readout and assembly of the events

The digitised information of all 205 000 channels is fed to digital pipelines and read out in the time gap between the bunch trains. This gap has also to be used to

- subtract pedestals,
- actualise the calibration factors,
- compress the information,
- reject background events and
- store the surviving information.

For permanent online calibration the data acquisition with cosmic muons has to go on continuously.

13. Conclusion

Based on the various presented hardware options for the optical readout of the scintillator tile signals and many fruitful discussions with experts I am convinced that an excellent solution for the HCAL on the base of APD's and FADC's can be developed soon.

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