Reply to LHCC Questions in Regards the CMS HCAL TDR

Summary collected by Dan Green
[CMS HCAL Project Manager]
from the HCAL community

August 22, 1997

1. Energy Resolution:

In general, the design aim was to achieve a stochastic coefficient of 100% and a constant term of 5%. The combined system achieves this goal (Fig. 1.25 of the HCAL TDR), while the stand alone resolution is somewhat better (Fig. 1.25 also). We have verified that this energy resolution does not degrade the physics processes. One could build a better calorimeter but it would not improve the physics performance of CMS. For example, the process H → WW → J+J+l+ν was studied. Very simple estimates of the rms error of the dijet mass, dM, due to jet energy resolution lead to:

$$dM/M = (dE/E)/\sqrt{2} \qquad (1)$$

Since the fixed cone jet finding algorithm has errors due to clustering, pileup, and out of cone radiation which are at the level of dM/M from 6% to 10% [1], [2], depending on dijet boost, we impose the condition that dE not degrade this resolution. The baseline defined in the TDR fulfills this condition, since the jet EM energy is well measured and since the jet energy error is less than the error on any of its components [2].

A baseline process that has been studied is H → bb for a Higgs mass of 100 GeV. Two cases were studied, with HCAL stochastic coefficient 85% and 120% and constant term 6% and 10% respectively. These values span the baseline CMS HCAL performance as specified in the HCAL TDR. No effect due to resolution was seen, as shown in Fig. 1.

The missing energy resolution is also not adversely effected by the measured HCAL performance, as shown in Fig. 1.14 of the HCAL TDR.

2. Angular Resolution:

The angular resolution was chosen so as not to degrade the dijet mass resolution in the extreme (worst) case of boosted W from a heavy Higgs (Pt ~ 0.5 TeV for the W, mass ~ 1 TeV for the Higgs). The results are shown in Fig. 2, which indicate that for towers with transverse segmentation better than $\Delta\eta = \Delta\varphi < 0.1$ there is no degradation. One could do better, but there is no Physics which requires better angular resolution.

A simple calculation, for symmetric decays, is that the boosted W has a mass error dM due to angular width of the tower = $\Delta\eta$.

$$dM/M \sim \Delta\eta(M_H/M_W)/4\sqrt{6} \qquad (2)$$

Using Eq.2 makes the behavior seen in Fig.2 plausible. Only the large mass Higgs gives a noticeable contribution to dM, and that only for $\Delta\eta > 0.1$. For smaller tower sizes the mass resolution is dominated by "intrinsic" detector independent effects.

A summary of detector dependent effects is given in Fig. 3. The two plots show the mass resolution for low Pt Z and for low Pt Z' of 1 TeV mass. The labels a - g refer to: a = cone R =0.7, b = a + the underlying event, c = b + different HCAL resolutions up to 70% stochastic + 4% constant, g = d + e/h = 1.3 (effective e/h). Clearly, the 25 overlapping events of LHC operation at full luminosity will further soften the detector dependent effects. In any case, we see no serious degradation of performance due to detector dependent effects.

An additional study [3] of boosted W, showed that, for the baseline tower size the cm decay angular distribution W → JJ can be used as a significant cut in the search for heavy H. The results for W + J backgrounds are shown in Fig.4 for parton level and 3 possible tower sizes. Clearly, the TDR baseline tower size is sufficiently small. In this study all hits in a cone R = 0.7 were taken to be the W, while the 2 jets were found within this large cone.

3. Intercalibration of the CMS Calorimetry:

There are ECAL, H1, H2, and HO longitudinal compartments. The individual HCAL towers are first calibrated using the radioactive source. It was shown in SDC [1] , that the source tracks a muon calibration good to 2%. Therefore, the radioactive source allows an HCAL tower to tower and compartment to compartment calibration good to better than 2% on the mean energy. Note that this is less than the constant term, so that calibration will not degrade the calorimeter energy error even as the calorimeter itself will not limit the physics performance of CMS.

The ECAL will be calibrated in a test beam. After installation, Z → ee decays will be used to maintain the resolution. Note that ECAL is not a sampling device, and thus shows no magnetic field effects.The HCAL will be calibrated using a few towers in a test beam, and transferring that calibration to other towers and compartments using the radioactive source. The HCAL H1, H2 and HO compartments thus have an initial calibration set by the radioactive source with a beam calibration carried over from a few modules placed in a test beam and exposed to a variety of energies of beams of electrons and pions.

In addition muons in the beam provide a cross check of the source measurement. We also will construct a cosmic ray test stand which will be housed in the HCAL assembly area, building 168. A prototype for this device was already built for SDC and will be used at Fermilab to establish the cross calibration of the source and cosmic ray muons. This device will be used to establish the tower response of the assembled wedges in comparison to the source which was used to track each and every tile during the manufacturing QC phase.

The procedure outlined on pg. 429 of the HCAL TDR will be used to transfer the calibration from test beams to jets and from HB/HE to HF. Note that in the test beam H2 we were able to intercalibrate each layer of the HCAL with only 1-1.5 p.e./mip (see Fig. 1.21 of the HCAL TDR).

Therefore, we have confidence that an absolute calibration of each tile good to 2% will be initially available and will be tied to test beam and cosmic ray muon data.

4. Monitoring of the Calibration.

The H1 compartment can be calibrated with unity weight by appealing to “continuity” in hadronic showers, as shown in Fig.5. As stated in the TDR, we will overweight the H1 contribution to the calorimeter sum in order to correct for the large e/h ratio of ECAL, as discussed later.

The relative weight of the H1 compartment has a fairly shallow minimum, as seen in Fig.6a. Hence, the source is again sufficient to set the initial calibration.

The function of the H1 compartment is not to establish the hadronic shower development per se, but rather to sample how much of the jet has deposited its energy in ECAL and thence raise the response to correct for the large e/h response of the crystal ECAL. We have studied the optimal depth of H1 and chosen to have a single sample as close to the back of ECAL as possible. The study using H2 test beam data for an H1 compartment of 1 and 3 layers on HCAL (3 cm/layer) is shown in Fig.6a and Fig.6b. The linearity is restored in both cases. In the case of a single layer, the H1 response must be increased by a factor 4.5 with respect to a muon calibration of that layer, indicating that H1 is used to increase the low ECAL pion response.

The energy resolution using a constant weight for H1 is shown in Fig.6b. Clearly, the single layer of H1 is superior to the 3 layer case. The minimum resolution for 300 GeV pions goes from 10%, muon weighted, to 8.5%, optimally weighted. Note that the minimum is 9.3% in the 3 layer case. Note also that the best weight is near to that which restores linearity, as might be expected. Clearly, using more HCAL depth segments washes out the information from ECAL contained in H1, and, as the memory of ECAL is lost, the ability to correct for the large ECAL e/h ratio is lost.

The HO layer will have an initial calibration set by the sources. In situ, “continuity” between the calorimetry inside the magnet and that outside will be sufficient to maintain the calibration. The relationship is shown in Fig.7 for 300 GeV pions. Clearly, the required degree of accuracy is not very stringent.

Clearly, the initial calibration can be continuously monitored in situ by appeal to hadron shower “continuity”. In addition, as the radioactive source deposits a fixed absolutely normalized amount of energy into the tiles, a cross check exists for all tiles during the annual long shut down and access. We will also have muons which give absolute calibration of each compartment in situ during data taking. The CDF endplug calorimeter, using similar techniques, achieved a 2-3% absolute calibration.

5. The HPD R&D Plan.

The optics of the HPD are well understood, having been tested in a 5T magnetic field at U. of Minnesota and derived from first principles [4]. We plan to make the transit time as short as is possible, < 0.2 nsec, by asking DEP to provide devices with the minimum practical distance between photocathode and PIN diode. This choice will make CMS as magnetic field insensitive as possible.

The HPD which is the CMS baseline is a DEP "T type" pixel device. The illumination of the PIN diode is by "backside" (n+) bombardment. The p and n+ layers are thin and highly doped, while the n layer is the main charge collection element. The electrons move to the n+ side, while the holes move to the p junction. In DC (high rate) coupled operation the charge is taken off the p side. Since the 10 kV incident electrons stop quickly in the Si, the illumination is "point" and occurs in a low field region. Thus the e contribute little to the signal, and the holes move slowly at the beginning as the fields are low near the n+ layer [5].

For a standard 300μm thickness, the drift time for the holes, is 53 nsec just at depletion. This is too slow, and we have an agreement from DEP to halve the thickness in the next set of pixel devices for CMS. We will also use the n+ layer to operate in an overdepleted mode. The expected baseline rise time will then be < 10 nsec. See Fig. 8.9 of the HCAL TDR and reduce the values by > 2x.. The design aim is to have the HPD not degrade the intrinsic tile/WLS effective deflourescence time, $\tau \sim 12$ nsec [6].

At present, we are exploring doing exposures using the Californium facility at Oak Ridge National Lab. The spectrum can be moderated to a reasonable approximation of the predicted neutron and gamma spectrum in the calorimeter. Exposures would be with bias on , and 10 years of LHC operation would be compressed into two weeks. We plan to irradiate the entire chain of HPD, QIE, ADC, and optical driver.

Initial neutron irradiation of the HPD indicte that there will be n increased dark current. However, the fluctuations in the current are not increased which implies that performance is not degraded.

6. HPD Alignment in the B Field:

The trajectory of the photoelectrons in the HPD follows the B field in a tight helix. The passive layer between pixels is ~ 200 μm, while the gap between cathode and PIN diode is ~ 1.5 mm. Therefore, we need to align the B and E fields to ~ 5 degrees to avoid image cross talk.

The CMS field is shown in Fig.8 as taken from the Magnet TDR. The HPD are located at a radius ~ 2 m and at z ~ 4.3 and 5.5 m respectively for HB and HE as given in Fig. 1.2 of the HCAL TDR. The field there is quite axial, as we will confirm in a field map planned to be done prior to installation of HB and HE into the magnet. Therefore, we will align the HPD axially, with small adjustments for optimal alignment.

The alignment scale is several degrees with respect to the local field direction. We anticipate that no problems with the alignment will be encountered.

7. Timing Capabilities of HCAL:

HB and HE:

The timing characteristics of the tile-fiber structures were described in Section 9.2.1 of the CMS HCAL TDR. The shape of the light pulse in one layer is an initial step followed by an exponential decay corresponding to the fluorescence characteristics of the combined scintillator - waveshifter system. Measurements on the materials selected for HB and HE give the time constant as ~ 12 nsec using a single exponential approximation. The test results are shown in Fig.9 where the fit to a single exponential yields 8.2 nsec for an SDC tile/WLS [6]. The signal is 90% contained in ~ 1 LHC crossing. This waveform is only realized a high light levels. For low energy showers, Poisson fluctuations can considerably distort the shape.

The final waveform arises from convoluting the light emission shape with the impulse response of the HPD and summing over the various layers, each with a slightly different arrival time. Our present estimate is that, on average, 68% of the signal occurs in the event crossing itself, 29% occurs in the subsequent 25 nsec interval, and 3% occurs in the interval following that.

The readout of a tower is done as a waveform digitizer; the amount of charge in each 25 nsec interval is digitized and stored in a pipeline memory. For each accepted event, five consecutive samples are readout: two before the crossing of interest to obtain the baseline level and two after the crossing of interest to obtain the true energy. A fit is done to the five samples to extract the energy deposited in the tower corrected for baseline shifts and time of arrival. In the case of pile-up, such as another hit in that tower in either of the two crossings following the one of interest, a cruder extraction algorithm is used producing an energy value with a larger uncertainty.

Resolution on the arrival time of a signal is affected by pileup and depends strongly on the size of the signal. For high light levels, 100 photoelectrons or more, and in the absence of pileup, the resolution is easily at the 1 nsec level as it depends only on the relative heights of the signals in the three bins. For low light levels, the resolution degrades as Poisson statistics on the emission of photons becomes significant. For example, 10 photoelectrons becomes 6.8, 2.9, and 0.3 in the three bins on average. The fluctuation of just one photoelectron from the first bin into the second bin would pull the fitted time later by about 3 nsec. Nevertheless, at the 10 pe level, HCAL will provide muon timing to a single LHC bunch from HOB and HOE.

Similar scintillator calorimeters, e.g. CDF, with comparable light yields, e.g. 20 p.e./mip, have achieved 2-3 nsec timing resolution. Our intent is to measure this carefully with our first preproduction prototype in the H2 test beam in 1998, where we will have HPD close to the final product.

Timing Capabilities HF

The light pulse produced is due to Cerenkov radiation from relativistic shower particles and, as such, is very fast. A very fast photomultiplier tube has been selected for the readout that can easily produce pulses shorter than 10 nsec (Figure 8.16, HCAL TDR). Therefore all of the light produced by a given event is collected in that crossing interval; there is no pileup previous or subsequent crossings. Because of this, HF has no timing capability other than to know, unambiguously, which crossing generated the signal. We are currently exploring the issue whether better timing information from HF is useful as it is clearly achievable.

8. HF Quartz Fiber Procurement:

9. HF Magnetic Shielding:

The magnetic field at the PMT location for HF is ~ 200 G. This level of stray field does not require heroic measures. We plan to use a soft iron box to house the PMT and to surround each PMT with a coaxial soft iron cylinder and inside that a “mu-metal” magnetic shield. This technique has been standardized for some time. A schematic of the HF PMT box is shown in Fig.10, showing the PMT and magnetic shielding locations.

10. HF Location:

The HF location was chosen so as to reduce the radiation burden on the CMS tracker, on the forward muon system and on HF itself. If HF were nearer the interaction point, the rates in the tracker would increase. In addition, the location of HF allows the forward muon system to be very well shielded from the CMS calorimetry.

Finally, the radiation burden on HF is reduced a factor ~ 4 simply by moving it a factor 2 further away from the source than the HE location. In addition, this factor also helps in jet pattern recognition, as the jets have a factor 2 larger spatial extent in HF. Note that, even with this factor, and with the quartz fiber technique reducing the effective detected lateral extent of hadrons, the effective size of a hadron shower is ~ the size of a jet at $|\eta| \sim 5$. The decision of CMS was to locate HF so as not to compromise the tagging jet pattern recognition capabilities of HF.

The use of tagging jets may well turn out to be crucial if WW scattering at high mass is the manifestation of electroweak symmetry breaking via strong VV interactions.

11. HE/HF Interface:

The response to jets is given in Fig. 1.56 of the HCAL TDR. The $|\eta| = 3$ boundary has been studied, and the CMS calorimetry is quite homogeneous across the HB/HE boundary and the HE/HF boundary. Note that tile/WLS calorimetry allows us to have the active sampling layers extend essentially all the way to the calorimeter boundary. We have exploited this feature of the CMS technology choice in order to pull the HF back and thus achieve better jet measurements and reduced dose in HF.

We have performed full GEANT simulations of the CMS boundary at HE/HF for tagging jets. Roughly half of these jets appear in HE, the other half in HF. There is a slight loss on energy from jets which strike HE and intiate the showering of individual hadrons there. In the magnetic field, some jet energy is swept away from striking HF. As shown in the TDR, this effect is not dramatic. It does not significntly degrade the tag jet pattern recognition nor the tag jet Etɟ measurement. We have also looked at missing Et in dijet events generated by mismeasures of jets in the HE/HF region. The spectrum shown in Section 1 of the TDR indicates that real backgrounds from ν dominate at even moderte values of missing Et.

Finally, we are evaluating whether lining the $|\eta| = 3$ cone of steel in the forward muon system with active scintillators is cost effective in reducing the losses at the HE/HF interface even further. If they appear to be they can easily be added.

12. HB Depth inside the Solenoid:

The decision on the depth inside the coil can only be taken when the size of the CMS tracker and ECAL are finalized. In particular, the space requirements of the ECAL electronics are not yet perfectly well known. As the TDRs for both ECAL and Tracking will be completed by the end of 1997, the decision is imminent. A quantitative comparison of the performance of the calorimetry is provided in Fig. 1.22 and Fig. 1.23 of the HCAL TDR. The difference in the tails in the two cases is not overwhelming; one simply must wait longer to make the discovery of SUSY.

13. HB Sampling Gap:

Our FEA implies that the maximum deformation in a slot is a 0.4mm decrease of the gap. The gap is nominally 9.5mm +- 0.2mm, or 9.3mm minimum. The scintillator package is 7.63mm nominal, +- 0.62mm for a maximum thickness of 8.25mm. The deformed absolute minimum gap is 9.3mm - 0.4mm = 8.9mm. So even if all tolerances go in the worst direction for this gap, there will still be 0.65mm of clearance. As noted elsewhere, we have designed a series of elastic clips which will always define the scintillator package to be pressed against the rear of the absorber slot. The scale for deformations with respect to performance is 4% shift per mm of distance to the rear of the slot. The nominal gap is 0.9 mm, and the worst case of 0.4 mm less, implies a worst case shift of 1.6% in the calorimeter energy scale. This is less than the “constant term” of 5% which is our design goal.

14. B Field Effect in HB:

The basic effect is not unexpected [7]. We measured the "brightening" of the scintillator per se, and showed that it saturated at a value ~ (6-7) % for fields above ~ 2 T. This effect is well tracked by the muon component of the H2 test beam and by our radioactive source calibration method. We show a figure from the N.I.M. paper in Fig.11. The data shown contains tiles alone and tiles illuminated by e beams. At B = 3T the e beam illuminated data show more effect than the source illuminated tile data.

The data from DESY using a 6 GeV e beam, and the CMS Shashlik data both clearly indicate an effect above and beyond the brightening, being some 10% at 3T. Thus, our results confirm these earlier measurements and separate the effects of increased path length in a sampling calorimeter and the effect of scintillator brightening. The effect is well reproduced in Monte Carlo models, being an electromagnetic phenomena.

The existence of the magnetic field effect on the barrel energy response requires the use of in situ calibration [8]. We plan to calibrate barrel wedges in a test beam and to transfer the a-priori calibration to all wedges using the radioactive source. A typical in situ signal that can be used is the dijet mass from top decays with a W peak (Fig. 1.15 of the HCAL TDR).

The B field influence on the shower development of hadronic showers requires that we be careful to control the systematics of the sampling gap. As shown in the TDR, the field causes a ~ 4% energy shift, with a sensitivity of 4%/mm depending on the location of the scintillator "megatile" package in the absorber gap. We plan to insert clips to force the package to the rear of the gap. As the clearance is only ~ 1 mm total, the systematic error is < 4%/√12, , or 1.15% which, when folded in quadrature with the 5% constant term is a small effect on the HCAL resolution at all energies.

Clearly, we plan to check this operation at full field using in situ physics processes. We have studied several [8], which allow us to rather rapidly make the few % corrections which are needed to correct in the HCAL barrel for the field effect

15. Scintillator Thickness Tolerance;

The scintillator is manufactured by a casting technique on glass molds. This technique has a natural variation of about +- 10% from the sides of the casting to the middle. Specifying this variation allows the vendor to have a good yield. If we specify tighter variation, we will end up paying for the scintillator that falls outside the cuts. Based on CDF experience (where the same thickness variation was specified), we expect a+-5% variation to increase the total cost of the scintillator by a factor of about 1.5 times.

Note that, the achieved tile to tile variation is 6.5% (see Fig. 6.34 of the HCAL TDR). For that error in manufacture, the induced constant term in the energy resolution is < 2% (see Fig. 6.6 HCAL TDR). This error is well within our stated requirements.

16. Energy Dependence of the B Field Effect:

As stated above, the effect is not new, nor is it poorly understood.
Since the effect is due to the EM part of the hadronic shower, and since that fraction - Fo - increases with hadronic energy, there is an intrinsic energy dependence to the magnetic field effect. We have taken an extensive data set in the H2 test beam for pions and electrons and for no field and 3 T field strength and for 20, 30, 50, 100, 150 and 300 GeV beam energies.

The B field effect is a change in the HCAL response to the EM component of a hadronic shower. The e/γ energy is deposited in ECAL. The HCAL response to pions is:

$$E(B=0) = e*Fo + h*(1-Fo) \quad (3)$$
$$E(B=4T) = e*Fo*(1+\delta) + h*(1-Fo)$$

The HCAL response to electrons is:

$$Ee(B=o) = e \quad (4)$$
$$Ee(B=3T) = e*(1+\delta)$$

We use the electron beam to determine the increased response to the EM part, δ. It s understood in Eq.3 and Eq.4 that muons are used to normalize the energy responses in order that the scintillator brightening effect be removed. The data shown in the HCAL TDR indicate that, in the orientation of the scintillator package with the least sensitivity - scintillator toward the rear of the gap - , the factor δ is ~ 10%.

If e/h = 1, and if Fo = 1/2, then the effect on pion response is a 5% increase. We expect Fo to --> 1/3 at low energies and to --> 1 at asymptotic energies. For e/h = 1, the full variation in response is from a 3% increase at low energies to a 10% increase at very high energies. Note that this variation is small, correctable, and less than the residual nonlinearity shown in the TDR due to the e/h ratio being different from 1.

17. HE Optical Package:

18. Magnet Trips:

19. FEA of HB and HE:

Shear forces in HB

The bolts do not take shear force. (For them to do so, the bolt shaft would have to be tight against the clearance hole in the unthreaded plate. In this case the bolt could not be inserted.) Rather, all shear is taken on the shear keys or shear pins. The details of how the shear key is engaged during assembly is described in Section 2.8.6 of the HCAL TDR .

FEA loading assumptions for HB and HE

The HB will be installed permanently inside the cryostat in the collision hall. This will be done in a very controlled, slow manner, taking of order a week. In contrast, the HE, installed on the endcap iron structure, will be moved (along with the endcap structure) during each access to the interior of CMS. Therefore the HE must be designed to accommodate these routine operations, while the HB does not.

HB FEA model allowing larger deformations

Initially we studied 2 variations of the wedge FEA model. In one model the bolted plate had a moment, and there was no penetration of the plates. The second model was one where the bolt was modelled as a point spot weld, with no moment, and the plates could inter-penetrate. The second model was found to have larger deformations AND larger internal forces. For this reason, the second model was chosen as a worst case estimator.

20: Radiation Damage to Scintillator:

As shown in the TDR, the best estimate for HB and HE of the radiation field indicates that the dose in HE is ~ 3 Mrad at $|\eta| = 3$. The dose due to minbias falls off with increasing angle as $1/\theta^3$ or $\exp(3|\eta|)$. Thus the region where there is a large dose is very localized in a few towers of HE. We relate the dose to the damage roughly as an exponential with a characteristic dose as a parametrization of the induced color centers reducing the transmitted light output.

$$\text{Light Yield} = \exp(-D/Do) \qquad (5)$$

In the TDR we presented data on our baseline tile/WLS assembly. For comparison we show here the SDC data [6] in Fig.12. This semilog plot illustrates the validity of Eq.3. Note that at a dose of 3 Mrad, the tile/WLS has lost 60% of its light output. We have chosen SCSN81 scintillator and BCF91A WLS because they combine machineability with reasonable radiation hardness. This baseline is justified in detail in the SDC TDR [1].

Note that for $|\eta| < 2$, the dose is < 0.4 Mrad. In that region, the damage is < 20%. As shown in the TDR the induced constant term with 2 HCAL compartments is ~ 4% for a 50% light loss and the functional dependence is roughly linear. Thus, for the $|\eta| < 2$ region, we have a 1.6% induced constant term folded in quadrature with the undamaged 5% HCAL constant term. Therefore, the baseline is to maintain only 2 hadronic compartments in the wide angle region.

For the $2 < |\eta| < 3$ region the dose is < 3 Mrad, indicating a damage < 60% light loss. As shown in the TDR, the 2 compartment light loss would induce a ~ 7 % constant term. To alleviate the loss of energy resolution, we adopt a third longitudinal compartment of depth ~ 2 λ directly behind H1. The 3 compartment HCAL has a ~ 1% induced constant term for 60% loss of light.

In addition, the radiation field has some error, and therefore it is prudent to have some additional handles on the radiation damage. To that end we added yet another compartment in the small angle region of HE and also extended the angular range where there is 3 compartment coverage. These give us added protection. Finally, during long annual shutdowns, one can use the radioactive source to map out the damage profile and then use photographic “masking” at the HPD “cookie” to make the HE longitudinal profile uniform again. The technique loses light, but as the physics resides largely in Et, that the loss of physics capability is small.

If all else fails, or if there is a catastrophic beam loss or accident, the HE scintillator sectors are thought to be constructed with a replaceable inner small angle segment. These could be replaced during a long access shutdown, but this is not thought to ever be needed during normal operation of CMS.

21. Pileup Noise in Higgs Searches:

There was an initial study of Z → JJ for low and high Pt Z bosons [9]. The pileup clearly adversely effects the Z mass resolution, see Fig.13. In addition, we have studied pileup noise for H → ZZ → llνν and for H → WW → lνJJ. [10]. For the ZZ case, the missing Et cuts depended sensitively on the pileup, necessitating a tower Et cut before the global Et was computed. For the WW case, the usefulness of the cuts is reduced by pileup. This being the case, CMS HCAL is designed to be fast. The tile/WLS time constants were measured to be < 12 nsec [6]. These are well matched to the LHC bunch crossing time of 25 nsec. The HPD will be required to not degrade the intrinsic speed of the tile/WLS active sampling.

Yes, pileup makes things worse, but the resolution degradation is an unavoidable physics effect. We have chosen the fastest available calorimeter technology to minimize the effect. H → bb is likely to be a low-luminosity physics topic, both in the associated production mode and in the cascade decays of SUSY particles. In both cases cross sections are high, and there is a premium on the best b-tagging being available, so it would be done at 10^{33} with negligible pileup.

22. Dijet Mass Distribution and Pileup:

This process has been studied. [9,10]. The fractional mass resolution of a Z -> JJ is shown in Fig.13 with and without pileup as a function of cone size. For 1 bunch pileup at full luminosity the degradation of resolution is already noticable. Therefore, there is a premium on keeping the sensitive time of HCAL as short as 1 bunch spacing, 25 nsec.

23. Muon Signal and Timing:

A single exponential fit to the time response of the scintillator-waveshifter combination gives 11.3 nsec (HCAL TDR, page 405) or 8.2 nsec as measured in SDC tile\WLS [6]. Our simulations of the time structure include the impulse response of the HPD and a rectangular distribution for the loop length effect. The result is, on average, 68% of the signal occurs in the event crossing itself, 29% occurs in the subsequent 25 nsec interval, and 3% occurs in the interval following that. At 10 photoelectrons average, the three samples yield 6.8, 2.9, and 0.3 photoelectron signals. There are significant Poisson fluctuations on these average values.

The efficiency of a simple sliding, three-sample sum algorithm is very high in the absence of pileup from adjacent crossings. Simulation of the efficiency as a function of luminosity is work in progress. At the present level of understanding, the occupancy in the tailcatcher compartments (HOB and HOE) is well below 1%, closer to 0.1% because of the depth in the absorber. Therefore, the spread in arrival time of the muon signal is not critical for the muon detection efficiency.

24.Sensitivity of the Fibers to Showers:

The fibers in question are clear, so that the signals induced by showers would be due to Cerenkov emission. This effect is thought to be small. A similar device, the CDF endplug calorimeter, had the fiber readout scanned by the test beam, with no discernable effect. We plan to scan the crack region in the H2 test bean to look for both “hot” and “cold” spots in the calorimetry in our 1998 test beam runs.

25. Electronics Packaging:

For the roughly 9000 channels in the barrel (HB) and end cap (HE) readout boxes, the packaging is determined by the locations, small pockets carved out of the absorber as indicated in Figure 9.1 of the HCAL TDR. The smallest possible footprint is necessary to minimize the effect of lost material on calorimeter performance. In addition, the digitized results from three channels are multiplexed onto one fiber readout link. Thus, the natural grouping of channels is by threes, 3, 6, 9,… channels per group. A three-channel printed circuit card unit was the optimum in terms of space utilization in HB as all of the readout cards are accommodated in the space between the two columns of fibers from the calorimeter layers. Using 6 or 9 channel cards makes the box longer in the z-dimension. The three-channel card also works well for HE making for a compact design there as well. There are a total of 60 readout boxes in HB and HE.

The tail catcher compartments in the barrel (HOB) comprise about 2200 channels, but require 60 separate readout stations to keep the readout fibers to a practical length. On average, there are only 36 channels per readout station. This makes a crate solution completely impractical, and the choice made was to use the same technology in HOB as developed for HB and HE. Everything is the same except the width of the box is smaller as appropriate to the smaller number of HPDs. A side benefit is the high reliability that comes from meeting the HB and HE requirements.

The forward calorimeters are compact objects with open access to the sides. A crate-based system was chosen and there are four 9U VME64 crates planned per end to house the cards. Because the noise floor and ADC granularity requirements are quite challenging, it was decided not to solve the problem twice, once for the readout box three-channel cards and once for a 9U by 400 mm card. Instead, the three-channel cards will be converted to mezzanine cards on a 9U carrier board for a total of 33 channels per VME card.

The estimate for VME crates on page 503 of the HCAL TDR refers to the digital electronics located in the underground equipment room adjacent to the detector cavern, not to the front end electronics discussed above. This estimate is in conflict with the one made on page 483 in the Trigger and Data Acquisition Electronics chapter, and it is an undetected failure to update all instances of the VME crate count estimate in the TDR. Please consider the number on page 503 as an outdated (and uncorrrected) estimate.

26. HF Noise Floor Requirements:

The HF noise floor discussion on page 408 of the HCAL TDR does indeed neglect the contribution from the photomultiplier tube gain dispersion. It assumes that the width of the single photoelectron signal is entirely due to the electronics noise, basically that the tube behaves like an HPD. This is clearly not correct, and the true situation is the exact opposite. The width of the single photoelectron signal is determined by gain dispersion not electronics noise, and the resulting noise floor requirement is comparable to that for the HPDs in HB and HE.

27. Minimum HPD Gain Requirement:

The working number of 2000 for HPD gain was chosen as a conservative value to deliberately confront, in the TDR, issues of noise, source current readout, and ADC granularity. In addition, the high voltage required for this gain is less than 10 kV. All devices fabricated so far easily operate at gain 2500 and higher. The vendor has advised that operation at gain 3000, about 12 kV, would pose no problems based on their long experience with the night vision parent device. Our strategy was not to execute the TDR based on gain 3000 and discuss separately the consequences of only achieving gain 2000, but to design for gain 2000 and use operation at gain 3000 as our contingency against falling short on the noise floor figure.

28. Ground and Cooling:

A single point ground architecture is planned with that point located at the readout box to minimize EMI problems. The cooling system uses flexible 3/8 inch diameter “power supply” reinforced hoses, a separate supply and return pair for each readout box. This choice was made because of cost; it avoids the expensive pipe fitting that comes with using rigid metal lines. However, it also avoids any ground loop problems from the cooling system as the hoses are fabricated from synthetic rubber.

The electronics is packaged as board doublets laminated to both sides of a copper plate. This lamination is done using thermally conductive but electrically insulating material. Therefore, all of the electronics is electrically isolated from the cooling system. We may provide the capability of making a single point ground connection between the two systems just in case we want them connected. As designed, the cooling system can be grounded without grounding the electronics.

29. Impact of the Source on Front End Electronics:

The source calibration system uses extreme over-sampling and has no effect on the design of the frontend electronics. In order to implement this calibration technique, it is required that the trigger and DAQ system be able to take a few 10,000s of events as the source moves across the detector and be able to average the data from these events to a reasonable precision. Since the calibration will occur off-line (not during data taking), the main impact is on the trigger system which has to provide a source of triggers to the frontends so they will pass the data along. The processing of the data can be done anywhere in the computing farm system, which should have more than enough capacity for the task.

Radioactive source data is taken using the normal 40 MHz data recording scheme. The pipeline is simply filled with samples of the source the sum of which constitute a D.C. measurement. A histogram is accumulated for each data point which is then fit to a Poisson distribution convoluted with the Gaussian noise shape. The calibration consists of determining the mean number of photoelectrons per 25 nsec interval. Further discussion can be found on pages 425 and 443 of the HCAL TDR. Normal trigger services are used, but in-crate processors are needed to accumulate and fit the histograms. These processors are planned to be the normal Detector Control System in-crate processors as this resource is idle during such calibration. Extra electronics are not required but additional functionality is needed in the Front End Drivers to provide a data path from the trigger and DAQ electronics to the controls processor.

30. The Advantages of a CW Base for HF:

31. The HV Fanout and HB/HE Risk:

One high voltage supply serves all HPDs in a given readout box. This supply is located in the underground service room adjacent to the detector cavern where it is accessible at all times. To protect against coupled failures taking out a large number of channels, separate high voltage leads are brought in for each individual HPD in a box. Should high voltage problems arise, the HPD in question can be removed from the “bulk” supply and put on a separate individual supply or left off in the worst case.

32: Cooling and Heat Load, Leak Risks:

We originally designed the cooling system to handle 500 watts, the current best estimate is less than 300 watts. Even at 500 watts we had at least a 50% margin in terms of cooling headroom. Unless the power consumption in the crate goes up by more than a factor of 2, we have no problem, and even a factor of 3 could easily be handled by increasing the flow rate and/or the ΔT of the water.

The power dissipation engineering estimate is on the high side for several reasons. The QIE power consumption is based on 2 micron technology while an 0.8 micron BiCMOS process is envisioned. The ADC is a catalog item, but the most likely outcome is that the ADC is brought on-board the digital control ASIC eliminating the high power of driver/receiver circuits. The optical links power budget was taken at the level of today's commercial technology, not at the anticipated level of such technology in 4 year's time.

Cooling hoses were sized based on these power consumption estimates and only moderate operating pressures. The rating of the hose is such that the flow can be increased by a factor of 4 by going to full design pressure. This feature is not a design outcome, rather it is due to sticking to commercial catalog hoses and avoiding a custom product. The next size smaller hose would be operating at about 70% of capacity if the heat load turned out to be as high as the escalated estimate in the TDR.

Coolant leaks anywhere in the detector could have major consequences; there are electronic systems and high voltages more or less everywhere. Cooling systems more than an order of magnitude larger than those for HCAL provide for the ECAL and the Tracker. The CMS integration group does not favor the "leakless" cooling system for two reasons, cost and past experience. Costs are high because gravity limits the vertical extent of the system to less than 10 meters, probably about 8 meters in practice, so that many systems at many different elevations are needed. Their past experience in L3 has been mostly bad.

The connections to the decoder boxes are NOT quick connects but are permanent connections of a type which have historically been proven to be of high reliability. Further, the pressures needed for the cooling loops are less than 5% of the working rated pressures of the lines and are less than 1% of the rated burst pressures of the lines. We believe that with adequate quality control during assembly and by pressure testing the system first using a gas, the system will provide reliable leak-free operation.

The preferred mitigations are in the area of prevention. High quality installations which adhere to a piping code permit a quantitative failure mode analysis as the failure rate per operating year is known. It is possible to design for an acceptable failure rate over 10 years. Operating at reduced pressures as is the case for HCAL also reduces the failure probability by reducing stress and erosion at bends or elbows, but a hard quantitative evaluation of the improvement factor is not available. Finally, there is the human factor, and discussions have begun about protecting the cooling lines from induced external damage.

References:

[1] SDC Technical Design Report, April 1, 1992, SDC-92-201

[2] Physics Requirements for LHC/SSC Calorimetry, D. Green, p 47, Calorimetry in High Energy Physics, Oct., 1991, World Scientific.

[3] Search for Heavy Higgs in the Channel H $\rightarrow$ WW -> lνJJ, I. Gaines et al., Fermilab FN-634, Nov., 1995

[4] Electron Optics in Hybrid Photodetectors in Magnetic Fields, Fermilab TM-1992, Dec. 1996, D. Green

[5] Charge Collection in a Hybrid Photodetector, D. Green. - 1997

[6] G. Zhang et al., Measurements of Decay Time and Absolute Light Yield for calorimeter Tile/Fiber Samples, SDC Note, June 23, 1993.

[7] M. Bertoldi et al.,Scintillators in magnetic fields up to 20T, Nucl. Inst. And Meth. A 386 301, (1997)

[8] In Situ Calibration of the CMS HCAL Detector, J. Freeman and W. Wu, Fermilab TM-1984, Dec. 1996.
Study of Calorimeter Calibration with τ's in CMS, D. Denegri, R. Kinnunen, A. Nikitenko, CMS 1997/039, May, 1997.

[9] A. Beretvas et al., Dijet mass resolution at high luminosities in the CMS calorimeter, Fermilab FN-626, Oct. 1994

[10] I. Gaines et al. Search for heavy Higgs in the channle H -> ZZ ->llνν, Fermilab FN-632, CMS TN/95-084.
I. Gaines et al., Search for heavy Higgs in the channel H -> WW ->lνJJ, Fermilab FN-634, Nov. 1995.

Figure Captions:

Figure 1: Dijet mass resolution for H → bb for a 100 GeV mass Higgs. The plots are for HCAL energy resolutions which span the baseline TDR design. The effect of calorimeter resolution is minimal.

Figure 2: Dijet mass resolution as a function of HCAL transverse segmentation. The circled Monte Carlo is for W → JJ with W at rest, while the points are for boosted W with Pt = 0.5 TeV.

Figure 3: Dijet mass resolution for Z and Z' (1 TeV) for low Pt and for high Pt. The conditions a-g are defined in the body of the text.

Figure. 4: Dijet cm angular distributions for different HCAL tower transverse segmentation.

Figure 5: Scatter plot showing the correlation of the H1 compartment energy with the remainder of the CMS calorimeter energy.

Figure 6a: Fractional energy resolution for 300 GeV pion beam for 1 and 3 layer H1 compartment as a function of the constant weit=ght applied tothe H1 readout.

Figure 6b: Mean energy for a 300 GeV pion beam for 1 and 3 layer H1 compartment as a function of the constant weight applied to the H1 readout.

Figure. 7: Scatter plot of energy inside the solenoid vs the energy outside the solenoid in the HO layers for single 300 GeV pions.

Figure 8: Field map for the CMS Magnet as a function of (r,z).

Figure 9. Data on tile/WLS timing read out by a PMT.

Figure 10: Schematic of the HF PMT box, where the magnetic shielding is indicated.

Figure. 11: Data on scintillator response to magnetic fields at fields up to 10T. There are source illuminated and e beam illuminated data for comparison.

Figure. 12: The fractional light loss for several test modules in SDC as a function of dose in Mrad. The exponential behavior is evident.

Figure 13: The fractional mass resolution for Z $\rightarrow$ JJ as a function of jet cone size for low Pt Z bosons. The effects of pileup are shown, with and without a tower Et cut.