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Design and Performance of the Cooling System for the Electromagnetic Calorimeter of CMS

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Abstract

For the physics program of the CMS experiment at the LHC to be carried out successfully, excellent electromagnetic calorimetry is required. Given the thermal properties of CMS ECAL, keeping the constant term of the energy resolution below 0.5% needs its temperature to be stabilized at 18 °C within 0.05 °C. A prototype module of ECAL with the final cooling system has been tested at CERN to check its integration with the read-out electronics and verify that it complies with the severe thermal requirements. The thermal performance of the cooling system is reported here.

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1 CMS overview

The CMS experiment is one of the two multi-purpose detectors that will take data at the Large Hadron Collider (LHC) at CERN starting from 2007. The physics goals of the experiments operating at the LHC are diverse, ranging from understanding the origin of mass (searches of the Higgs boson) and physics beyond the Standard Model to precision measurements on known particles exploiting the huge production rates. The detectors need to have excellent performance in identifying leptons, reconstructing masses of heavy decaying particles and particle discrimination. To achieve this and to detect neutrinos through missing energy, the calorimeters need to be as hermetic and accurate as possible [1].

CMS is composed of different subdetectors, each optimized for different complementary measurements.

Placed closest to the interaction point, is a tracking system (pixel layers and silicon strips) which will perform charge and momentum measurements using the $4T$ magnetic field. Outside the tracker, but still within the magnetic coil there are the two calorimetric subdetectors.

The first, a homogeneous electromagnetic calorimeter (ECAL [2]), based on scintillating PbWO_4 crystals which measures the energy of high energy electrons and photons.

Secondly, a sampling hadronic calorimeter consisting of layers (17 in the barrel, 19 in the endcaps) of brass absorbing material interleaved with plastic scintillator.

The outermost subdetector is dedicated to the muon detection. The barrel muon system relies on drift tubes in the central region, and on cathode strip chambers in the endcaps. Resistive plate chambers are used throughout the central and forward region as additional, fast, muon triggering detectors.

2 ECAL structure

The CMS electromagnetic calorimeter is composed of 75848 PbWO_4 scintillating crystals. Their shape and size slightly changes along η and a typical crystal volume is $24.7 \times 24.7 \times 230 \text{ mm}^3$. The crystals' length corresponds to $26 X_0$.

Both halves of the ECAL barrel consist of 18 supermodules (wedges in ϕ), divided in four modules. To avoid cracks aligned with particle trajectories, the axes of the crystals are tilted by 3° with respect to the direction from the interaction point both in η and in ϕ . The crystals are grouped in subunits of 5×2 held together by a glass fiber alveolar structure. Two photodetectors are glued on the back of each crystal embedded in a plastic capsule. For the barrel, avalanche photodiodes (APD's) produced by Hamamatsu are employed. Such devices have an 80% quantum efficiency and have been chosen since they are able to operate in the $4T$ magnetic field with a gain equal to 50 and are able to withstand the severe irradiation of ten years LHC running. One capsule out of 10 is equipped with a $130 \text{ k}\Omega$ resistor employed as a thermometer (thermistor). The value of its resistance is used to measure the temperature with a resolution of less than 0.02°C .

Just outside the APD's, there is a thick aluminum plate (the grid) which holds the weight of the crystals and in which the connectors for the read-out electronics are embedded.

The two endcaps consist of identically shaped crystals, shorter (220 mm, $25 X_0$) but slightly larger than the barrel crystals. The endcaps are divided into mechanical units of 5×5 crystals held together by an alveola. The crystals are off-pointing by angles between 2 and 5° .

The electronics and the cooling system are placed just outside the grid. The electronic read-out chain follows a modular structure whose basic elements are groups of 5×5 crystals which corresponds, in the barrel, to a trigger tower. Each APD is connected to a preamplifier which is followed by an ADC, and five of such channels sit on the same Very Front End board (VFE). Groups of five VFE's are plugged into the same motherboard which hosts also the Low Voltage Regulator board (LVR) supplying them.

To absorb the thermal power dissipated by the electronics and maintain the ECAL temperature stable at the level of 0.05° , a cooling system has been designed which ensures a good integration with the electronics and a feasible mounting procedure. Moreover this allows easy mounting and replacing of electronics components with no need to remove any of its parts. It employs water flow to thermalize the detector.

In the ECAL barrel, each supermodule is independently supplied with water at 18°C . A module of type 2, M0', was used for the tests described below and can be seen in figures 1 and 2. The water runs through a bent pipe (thermal screen) placed in front of the crystals which thermally decouples them from the tracker, and through the four modules. The modules and the screen are in parallel. In each of the modules the water goes along a set of pipes, connected in parallel, which are embedded in the grid and run along η . The aim of this part of the circuit is to make the grid as protective as possible. On top of the grid and below the motherboards a 10 mm thick layer of insulating foam (Armaflex®) is placed to minimize the heat flowing toward the crystals by convection. The water

is then collected by return pipes (visible on top of the Armaflex[®] in figure 1) and distributed through a comb to a set of aluminum cooling bars, all in parallel (see fig. 2).

Figure 1: The grid of the module M0' (type 2) covered with Armaflex[®]. The grid inlet and outlet (collecting the return pipes) can be seen. On top left a mounted motherboard.

These devices host the VFE cards and the LVR cards and have been designed to absorb the heat dissipated by both. A thermally conductive paste (gap filler 2000, by BergquistTM) is used to make a good contact between the electronic components and the housing (a metal plate hosting each of the boards), while a conductive pad (ultrasoft gap pad, produced by BergquistTM) is employed to couple the housing and the cooling bars. Both the gap pad and the gap filler have been irradiated with a dose equivalent to 10 years of LHC environment [3] and have shown no change or loss of performances.

Figure 2: Cooling bars of M0'. Part of the VFE's and of the LVR's (with colored supply cables) are in place.

3 ECAL thermal properties

There are two physical reasons why the stabilization and the monitoring of the temperature are crucial for the energy resolution of ECAL: firstly, the number of photons emitted by scintillation (light yield, LY) is temperature dependent; secondly, the amplification factor of the APD (M) is also sensitive to the temperature. Both such variations are negative when the temperature increases.

The two effects have been studied at testbeams which were performed at CERN on the module M0' during the summer 2002 [4] and on the supermodule SM1 in 2003 [5]. The behavior of crystals with electrons was studied while the temperature of the setup was changing from 18 to 19°C (thermal step). The relative variation of the response R to the energy deposition when the temperature varies has been measured to be:

$$\beta = (-4.09 \pm 0.6)\%^{\circ}\text{C}^{-1}, \quad (1)$$

where 0.6% corresponds to the spread of β among the channels. A detailed study of the temperature effect on the

APD multiplication factor (M) was also carried out on the same thermal step. That was done by injecting laser light in each crystal. Since the transparency of PbWO_4 is not affected by thermal changes, the effect observed for the laser light is due to a variation in the APD gain only [4]. The relative variation of the response R to the laser light when the temperature varies has been measured to be:

$$\alpha = (-2.43 \pm 0.06)\%^\circ\text{C}^{-1} \quad (2)$$

Comparing the results available for the thermal coefficients shows that the spread on β is mostly due to the variation of the crystal response rather than to the changes in the APD gain.

4 Energy resolution

For ECAL, which has as benchmark the golden channel for the Higgs search $H \rightarrow \gamma\gamma$, the energy resolution can be described by the formula $\sigma_E/E = a/\sqrt{E} \oplus b/E \oplus c$, where a accounts for the stochastic fluctuations (photostatistics and containment), b is due to the noise in the electronics and c is the constant term comprising uncertainties from the calibration and the temperature stability which is the subject of the present work.

The thermal contribution to the energy resolution of CMS ECAL is:

$$\frac{\delta E_{meas}}{E_{meas}} = \beta \Delta T \quad (3)$$

where ΔT is the temperature uncertainty. Such a contribution affects the constant term c in the parametrization of the energy resolution. The performance target for the cooling system has been to keep the contribution to the energy resolution resulting from thermal fluctuations to a negligible level as compared to the other contributions to the constant term, which means that the temperature stability to be achieved is within 0.05°C .

Another possible approach is correcting for thermal effects event by event [4]. In this case one can only use $\langle\beta\rangle$, which is the average of β among the channels. The uncertainty on E_{meas} left after the correction can be estimated by

$$\left(\frac{\sigma_{E_{meas}}}{E_{meas}}\right)_{corr} = \Delta T \sigma_\beta \oplus \langle\beta\rangle \delta T_{meas}, \quad (4)$$

where δT_{meas} is the uncertainty in determining the temperature of each crystal. Contributions to δT_{meas} are due: firstly to the fact that not all the crystals have their own thermistor; secondly, that even for those that are equipped with a thermistor, the thermal coupling in between the resistor and the crystal (plastic of the capsule, glue used to fix the APD to the crystal) is not known accurately a priori and may differ from one channel to another.

5 Thermal tests at CERN

Starting in the summer 2003 thermal tests have been carried out at CERN on the module M0' which is a module of type 2 consisting of 400 crystals. All of them were equipped with fake VFE and LVR electronics cards, i.e. the components of the read-out circuits were replaced with resistors dissipating heat mimicking the foreseen power dissipation at CMS (see table 5). Such fake electronics were supplied by 8 power units dissipating 72.7 W per trigger tower, 1160 W for the whole M0', which corresponds to about 3 W per channel.

Table 1: Power dissipated by the fake electronics.

Component	Power (W)	Number per Trigger Tower
ADC	0.96	25
Preamplifier	0.96	25
LVR digital	7.8	1
LVR analog	13	1

A total number of 110 sensors were read-out, comprising the 40 thermistors, 8 voltage supplies, the flux and temperature of the cooling water. All the remaining were temperature probes (PT100 or AD590) distributed around

the module on the grid, the cooling bars and on the electronics boards. The cooling water was chilled and thermalized at the level of 0.01°C by a cooling unit produced by Lauda and the flow set to 0.30 ls^{-1} to reproduce the operating conditions of CMS. An extra cooling unit, not foreseen in CMS, was employed to supply an auxiliary water circuit running around the basket which contains the alveolae in order to have the best possible insulation from the changes of the temperature in the laboratory. The module was mounted on a metal cradle which can rotate around the ϕ direction. This was necessary to perform tests simulating all the orientations of ECAL in CMS. Indeed, since convection plays an important role in the heat propagation, both the vertical structure of the endcaps and the whole 2π coverage of the barrel needed to be inspected.

As an overestimate of any possible thermal variation that might affect CMS ECAL, tests have been performed measuring the temperature difference of M0' when the whole electronics was on (T_{on}) with respect to when it was off (T_{off}). All the measurements have been repeated in three different ϕ positions: with the electronics on top of the module (12 o'clock in CMS), at a side (3, 9 o'clock) and below (6 o'clock). The results for $T_{on} - T_{off}$ are shown respectively in fig. 3, 4 and 5, each reporting the temperature excursions $T_{on} - T_{off}$ for each of the thermistors available. Such excursions are obtained subtracting from the mean of the temperature measurements performed when the power is on (typically lasting a few hours and therefore consisting of about 10^3 values) the mean of the temperature measurements performed when the power is off (lasting similarly). This procedure ensures the statistical uncertainty on the single thermal excursion $T_{on} - T_{off}$ to be negligible and leaves only the systematic uncertainty due to the calibration procedure of the sensors which is estimated to be less than 0.01°C .

Figure 3: $T_{on} - T_{off}$ for the 33 thermistors available when M0' crystals are on top (12 o'clock). Mean is 0.022°C , RMS 0.007°C

Figure 4: $T_{on} - T_{off}$ for the 32 thermistors available when M0' crystals are at a side (3 o'clock). Mean is 0.044°C , RMS 0.021°C

For the average increase in the temperature an upper limit can be put:

$$\langle \Delta T \rangle_{\text{CMS}} \ll \langle \Delta T \rangle_{\text{on-off}_{6 \text{ o'clock}}} = 0.056^\circ\text{C} \quad (5)$$

Figure 5: $T_{on} - T_{off}$ for the 33 thermistors available when M0' crystals are below (6 o'clock). Mean is 0.056 °C, RMS 0.016 °C.

Due to the convective heat flow, the average temperature increase $\langle T_{on} - T_{off} \rangle$ is minimum when the crystals are below the electronics and maximum when they are above. For the same reason, the spread is maximum for vertical regions of ECAL (3, 9 o'clock). Values in $T_{on} - T_{off}$ for the measurement performed at 3 o'clock are shown in figure 6. Two patterns are observed. The temperature excursions decrease from left to right since the water, running in the grid in the opposite direction, warms up along its way. They also decrease from the bottom to the top of the plot since in the 3 o'clock positions the crystals placed above in the module receive a bigger heat flow.

Figure 6: $T_{on} - T_{off}$ when M0' crystals are at 3 o'clock position. Values are shown for each of the 16 trigger towers. Color convention at the side. In the plot η runs horizontally, ϕ vertically. The water flows from the right to the left and crystals labelled with 10 are on the bottom in the module. White bins correspond to trigger towers where values for $T_{on} - T_{off}$ were not available.

6 Conclusions

Given that $\langle \Delta T \rangle_{\text{CMS}} \ll 0.056^\circ \text{C}$ (eq. 5) and that $\frac{\delta E_{\text{meas}}}{E_{\text{meas}}} = \beta \Delta T$, in case no correction for the thermal effects were applied, the contributions to the energy resolution of the temperature variations, are limited by:

$$\left(\frac{\sigma E_{\text{meas}}}{E_{\text{meas}}} \right)_{\text{thermal}}^{\text{no corr}} \ll 0.23\% \quad (6)$$

A realistic value for $\langle \Delta T \rangle_{\text{CMS}}$, rather than the upper limit of eq. 5, is the subject of current work and will allow an estimate, and not just an upper limit, for the contribution of the temperature instabilities to the energy resolution.

This result shows that the cooling system fully complies with the requirements for the thermal stability of CMS ECAL. Therefore, taking into account that it also provides good integration with the electronics and allows for

a feasible mounting procedure, we can conclude that the test performed at CERN in 2003-2004 has successfully validated the cooling system of CMS ECAL.

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