U
77

Institut de Physique Nucléaire de Lyon

Université Claude Bernard

IN2P3 - CNRS

SCAN-9904004

CERN LIBRARIES, GENEVA

LYCEN 98106
December 1998

Overview of the CMS electromagnetic calorimeter

J.P. Ermenwein

Presented to the International Conference on Advanced Technology and
Particle Physics (Villa Olmo) 5-9 October 1998, Como, Italy

Submitted to Nuclear Physics B - Proceedings supplements

Overview of the CMS electromagnetic calorimeter

J.P. Ernenwein^a

On behalf of the CMS collaboration

^aInstitut de Physique Nucléaire de Lyon, IN2P3-CNRS et Université Claude Bernard, Villeurbanne, France

This article presents an overview of the electromagnetic calorimeter of the CMS (Compact Muon Solenoid) experiment. This detector will be installed in the LHC (Large Hadron Collider) in 2005. This paper describes the characteristics of this homogeneous calorimeter made with PbWO_4 scintillating crystals read out with avalanche photodiodes (barrel) and vacuum phototriodes (endcaps). This calorimeter will play an important role in Higgs physics.

1. Physics at CMS

CMS [1] is a general purpose detector, which will be installed in the LHC collider at CERN. The LHC will accelerate protons at an energy of 7 TeV, yielding a center-of-mass energy of 14 TeV. The expected integrated luminosity is 30 fb^{-1} during 3 years, and about three times more for a second period of about 7 years. The first run is foreseen for 2005.

Heavy ions will also be accelerated in the LHC, and four experiments will take place within the collider : ATLAS and CMS for general purpose physics, ALICE for heavy ions physics, and LHCb for b physics.

The crossing rate will be fixed at 40 MHz for proton-proton collisions, resulting in high luminosity, but also in hostile environment with radiation rates ranging from 0.15-0.3 Grays per hour in the low rapidity region to 15 Gy/h in the forward regions.

CMS will be used for Higgs searches, in the context of both Standard Model and non-minimal models. It will also be used for other new particle searches (for example supersymmetric particles), b physics and heavy ion physics.

The detector consists of central trackers, electromagnetic and hadronic calorimeters, surrounded by a magnetic superconducting solenoid producing a field of 4 Tesla, and muon detectors.

The CMS electromagnetic calorimeter is well adapted for Higgs searches at low luminosity, in

a mass region between 100 and 150 GeV/c^2 . The particle is mainly produced via gluon-gluon fusion, and in this range of mass a clean signature of the Higgs will be its decay into two photons. The theoretical width of the Higgs is still relatively small ($< 20 \text{ MeV}$), so that measurement will be dominated by the experimental resolution.

However, the $H \rightarrow \gamma\gamma$ branching ratio is low, and consequently the total cross section, and the signal must be separated from the irreducible background. To be able to observe a significant signal at low luminosity requires excellent resolution, which has motivated the choice of an homogeneous rather than sampling calorimeter.

2. The choice of the electromagnetic calorimeter

The CMS electromagnetic calorimeter comprises a barrel ($|\eta| < 1.479$) and two endcaps. The active medium is made of lead tungstate (PbWO_4) scintillating crystals. The light produced by an incident particle is read by avalanche photodiodes (APD) in the barrel and vacuum phototriodes (VPT) in the endcaps. The photodetectors are followed by a preamplifier and a floating point sampling ADC. Then, the digitized samples are serialized and brought out of the detector via an optical link. All the electronic components are radiation hard.

The resolution of a calorimeter can be

parametrized by the following formula :

$$\frac{\sqrt{E}}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \quad (1)$$

where :

- a is a stochastic coefficient having contributions from shower containment, photostatistics, and photodetector characteristics,
- b is a constant term, depending on containment and calibration,
- c is an electronic noise coefficient, depending on photodetector and electronic readout characteristics.

Given the CMS electromagnetic calorimeter design goals, a, b and c should not exceed respectively 3 %, 0.55 % and 200 MeV for the barrel, and 6 %, 0.55 % and 900 MeV for the endcaps.

If these specifications are met, it will be possible to discover the Higgs in CMS during the low luminosity period, in the 100-150 GeV region, using the 2-photon decay channel.

3. The lead tungstate crystals

For more details please see the report of the dedicated presentation given in this conference [2].

The advantages of PbWO_4 crystals are many :

- The high density of this material (8.2 g/cm^3), permits a compact calorimeter. The radiation length (X_0) and the Molière radius are 0.89 cm and 2.19 cm, respectively. The length of a crystal is 23 cm ($26 X_0$) for the barrel and 22 cm for the endcaps, and the area of the front face is of the same order as the Molière radius.
- the scintillating process is fast, 85 % of the light is emitted in 20 ns. The wavelength of the light is approximately 450 nm.
- the lead tungstate is intrinsically radiation hard. When irradiated at a rate of 0.15 Gy/h, the induced loss in light production saturates at less than 5 %.

However, the light yield measured at the back face of a crystal is only 60 to 100 photons per MeV of incident energy.

This low light yield demands a readout via photodetectors with gain. The presence of the magnetic field leads to a preference for avalanche pho-

todiodes for the barrel, and vacuum phototriodes for the endcaps, where the radiation rate is too high for APD's.

The temperature sensitivity of lead tungstate light yield, but also of APD gain (about -2 %/°C for each), requires a temperature stability of 0.1°C at 16-18°C, the chosen run temperature.

Figure 1. VPT and APD design

4. The photodetectors

For more details please see the report of the dedicated presentation given in this conference [3].

Functional drawings of both VPT and APD are shown in figure 1. Table 1 lists the main characteristics of the two photodetectors.

4.1. The APD's

The low light yield of lead tungstate crystals demands photodetectors having internal gain, but the use of photomultipliers is not possible because of the strength of the magnetic field. Avalanche photodiodes are good candidates, despite their small sensitive area. Specific developments have been made by two suppliers : EG&G and Hamamatsu.

Hamamatsu was recently chosen as the supplier for the final production. The resulting APD's are well-suited for particle physics use. The chosen operating gain will be approximately 50, and two APD's will be used per crystal, to increase the

Table 1
Parameters of VPT's and APD's

	VPT	APD
Area	177 mm ²	25 mm ²
Capacitance	a few pF	100-200 pF
Quantum efficiency at $\lambda=450$ nm	15%	80%
Operating gain	6-7 in 4 Tesla	50
Voltage [†]	$V_{anode} = 1000V$ $V_{dynode} = 800V$	300-600 V
Voltage sensitivity [†]	< 0.1%/V	4-9%/V
Temperature sensitivity [†]	< 1%/°C	2.3%/°C
Dark current [†]	1-10 nA	2-10 nA
Excess noise factor $F^{\dagger}$	1.5-2	2-2.5

[†] : at operating gain

sensitive area (50 mm²). Their high quantum efficiency at the operating wavelength of 450 nm enables them to provide approximately 4 primary photoelectrons per MeV.

However, some difficulties are introduced by the APD's : an extremely high level of voltage and temperature control is required, and the potentially significant capacitance results in increased electronic noise.

The statistical fluctuation in the number of avalanche electrons is responsible for the excess noise factor F , as for photomultipliers, and this factor has a contribution to the stochastic term in energy resolution : $a = a_c \oplus \sqrt{F/N_{ppe}}$, where a_c is containment and scintillating efficiency contributions and N_{ppe} the number of primary photoelectrons. This factor contributes also to the electronic noise.

Over the running period of approximately 10 years, the dark current will increase due to irradiation, to the effect that its contribution to electronic noise will surpass that from capacitance. The result will be a factor two on the noise.

4.2. The VPT's

The irradiation dose at large rapidity angles is too high for APD's. The chosen photodetector is a vacuum phototriode (VPT), which is more radiation hard. Suppliers foreseen at the present time are Hamamatsu, RIE St. Petersburg, and Electron Tubes Ltd.

A vacuum phototriode is a photomultiplier

with only one stage of amplification (see figure 1). The advantages of VPT's are low capacitance and very low voltage and temperature sensitivity (see table 1). If radiation hard glass is used for the faceplate, susceptibility to radiation damage is small.

Drawbacks include low quantum efficiency and effect of the magnetic field on the gain. The axial magnetic field causes a drop in gain by a factor 2, yielding a gain of approximately 7, but the sensitive area is approximately 3.5 times larger than that of the 2 APD's.

5. Readout of photodetectors

For more details please see the report of the dedicated presentation given in this conference [4].

The readout of the photodetectors has to be done by radiation hard or at least radiation tolerant electronics, with low consumption in order to avoid temperature increase in the detector. A schematic view of the readout chain is displayed in figure 2.

A transimpedance preamplifier will convert the photo-current provided by the photodetector to voltage. It must be linear over the entire dynamic range : ≤ 0.3 % up to 200 GeV and ≤ 2 % up to 2 TeV. The baseline radiation hard solution is BiCMOS DMILL, with a bipolar solution also under study (HARRIS UHF-1). The preamplifier supplies four gain outputs : $\times 1$, $\times 4$, $\times 8$ and $\times 32$,

Figure 2. CMS electromagnetic calorimeter readout principle

and has a power consumption of approximately 150 mW. At the present time only non radiation hard versions have been tested in particles beam. The tested circuits are in BiCMOS AMS technology which is easy to translate into BiCMOS DMILL.

The gain selection is then done by a Floating Point Unit placed between the preamplifier and the 12 bits ADC. The highest non-saturated gain output is selected, while a code representing this gain is put into two additional bits. This circuit will be built in the same technology as the preamplifier. Its power consumption is around 250 mW.

This multi-slope technique enables a good resolution, despite the very large dynamic range and the low number of ADC channels. The ADC is a commercial sampling model which operates at 40 MHz, the LHC crossing rate. This circuit, supplied by Analog Devices (AD9042), is radiation tolerant thanks to its fully complementary bipolar technology (XFCB) and its design, but its power consumption of 600 mW is the largest of all the readout chain components.

Downstream from the ADC, a low-power and intrinsically radiation hard serializer will perform at the constant frequency of 40 MHz the parallel-

to-serial operation (resulting in 800 Mbit/s) on the signal samples bits and FPU bits.

The technology is CHFET complementary GaAs (Honeywell), and the target power consumption should be approximately 100 mW.

A VCSEL and an optical fiber of 80 m constitute the last link in this light-to-light system. The fiber transmits the digitized signal to the counting room where it is deserialized and treated by the trigger and data acquisition systems. In this way more flexibility can be accorded to the upper-level readout, and non radiation hard components can be used for trigger electronic.

6. The electromagnetic calorimeter structure

For more details please see the report of the dedicated presentation given in this conference [5].

6.1. Barrel

The barrel of the electromagnetic calorimeter will consist of $360(\phi) \times 2 \times 85(\theta)$ crystals. The smallest ensemble of crystals is called a sub-module, composed of $2(\phi) \times 5(\theta)$ crystals put in a reflective alveola (glass fiber with aluminium

Figure 3. Structure of a sub-module.

coating). This structure is shown in figure 3.

The two APD's, assembled in a capsule, are glued onto the crystal. One capsule per submodule includes a temperature sensor. An aluminium tablet ensure the mechanical stability of the ten crystals. 40 or 50 submodules are assembled together into a module by a 3 cm-thick aluminium grid. The signals from the APD's and temperature sensor are transmitted to electronic cards through the tablet and grid by shielded Kapton cables (length of 9 to 20 cm). A double cooling system enables the evacuation of the heat produced by the electronics. A schematic view of a module is given in figure 4.

Three modules of 400 crystals and one module of 500 (small η) are joined together along η into a supermodule. A half-barrel consists of 18 identical supermodules.

Figure 4. Structure of a module.

6.2. Endcaps

Each endcap consists of 7810 crystals grouped into supercrystals. A supercrystal is a set of 5×5 crystals fixed on a support plate. Positional spacers ensure a pointing geometry.

The inner and outer peripheral supercrystals are truncated to reproduce a disk shape.

In order to provide a better $\gamma - \pi^0$ separation in the forward region, a preshower is placed in front of crystals. It consists of Al-Pb absorbers (approximately 3 radiation lengths) and silicon detectors [1].

7. Monitoring and calibration

To have the required resolution on the measured energy, it is very important to perform a precise calibration of the calorimeter.

Before the installation of the calorimeter on the LHC site, each module will be placed in electron test beam for a precalibration of each crystal, at 2 energy points.

During the run of the CMS experiment, a light monitoring system will track the behaviour of each channel. It is well established that radiation only affects light transmission in the crystal, and not the scintillating process itself, so that there is a relationship between the response to incident particles (the physics) and the response to an injected light on the crystal front face.

A laser system will send two wavelengths (red and green) to the front face of each crystal and

to reference PN photodiodes. This system will provide a way to monitor with precision the calibration constants.

The following physics processes will be used to calibrate the calorimeter during the running periods :

- $W \rightarrow e\nu$ will enable to calibrate using the electrons momenta measured in the tracker,
- $Z \rightarrow e^+e^-$ will be used for an independent calibration.

Combining these methods, it will take approximately 35 days at low luminosity to have a calibration at the level of 0.3 %.

8. Conclusions

At present, construction of a prototype of the first module of the CMS electromagnetic calorimeter is under way.

The production of crystals has started, and their radiation hardness has reached the required level.

The APD parameters are near the requested values, and the latest improvements undertaken by the supplier should yield better devices in the course of 1999.

The front-end electronics will be fully tested in 1999, with radiation hard versions.

Acknowledgments

I would like to acknowledge all CMS ECAL collaborators, and S. Gascon-Shotkin for her comments.

REFERENCES

1. The CMS Electromagnetic Calorimeter project, Technical Design Report, CMS collaboration, CERN/LHCC 97-33, CMS TDR 4, 15 december 1997.
2. E. Auffray-Hillemans, First results of the pre-production crystals from Russia, CMS Collaboration, this proceedings.
3. V. Puill, Recent results on APDs for CMS electromagnetic calorimeter, CMS Collaboration, this proceedings.
4. F. Martin, CMS electromagnetic calorimeter readout, CMS Collaboration, this proceedings.
5. M. Lebeau, Architecture and mechanical design of the CMS electromagnetic calorimeter at CERN-LHC, CMS Collaboration, this proceedings.