The Compact Muon Solenoid Experiment

Conference Report

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Experience with constructing and operating the world's largest silicon-based electromagnetic calorimeter - the CMS Preshower

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Abstract

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Experience with Constructing and Operating the World's Largest Silicon-Based Electromagnetic Calorimeter - the CMS Preshower

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Abstract—The Preshower detector, part of the CMS Endcap Electromagnetic Calorimeter, is designed to have good spatial resolution to distinguish between photons and neutral pions. The Preshower is a sampling detector with two layers of lead absorber, each followed by 1.9 mm pitch silicon strip sensors. Each of the 4288 DC-coupled sensors has an active area of 61×61 mm², making a total surface area of around 16 m². The Preshower was installed and commissioned in CMS in 2009 and has been used in data taking ever since. The design, construction, commissioning and operational experience will be described, including the observation and mitigation of radiation-induced bulk and surface effects. The calibration strategy will also be discussed.

I. THE CMS PRESHOWER DETECTOR

THE Preshower (ES) is installed at each end of CMS, at about ± 310 cm from the CMS interaction point, and placed in front of the electromagnetic calorimeter endcap (EE) [1]. The ES covers $1.653 < |\eta| < 2.6$. The outer and inner radii are 125 cm and 45 cm, respectively. The location and coverage of the ES detector is illustrated in Fig. 1. The ES has two layers: lead radiators (2X0 and 1X0, respectively) initiate electromagnetic showers from incoming electrons/photons whilst silicon strip sensors placed after each radiator measure the energy deposited and the transverse shower profiles.

There are 4288 sensors with custom-made chips and hybrids. The silicon sensors are made on 4" float zone, n-type material, with total volume of $63 \times 63 \times 0.32$ mm³. They have 32 p⁺ implanted strips, 1.8 mm wide and at a pitch of 1.9 mm. The active area is 61×61 mm². The sensors are arranged in X-Y grid.

The ES front-end electronics can operate in two modes: High Gain (HG) is used for precise calibration purposes; Low Gain (LG) has a higher dynamic range more suitable for physics data taking.

II. OPERATIONAL EXPERIENCE IN CMS

After the installation finished in 2009, the analysis of the noise performance in HG and LG modes was performed. The average intrinsic noise is around 5.6 (2.5) ADC counts for HG (LG) meeting specifications. The total percentage of fully functional strips is around 97% (up to Oct. 2012).

The ES occupancy is calculated as the percentage of strips with a reconstructed energy greater than 4 sigma of the noise. Fig. 2 and Fig.3 show the occupancy as functions of pseudo-

rapidity ($|\eta|$, averaged over all ϕ) and azimuthal angle (ϕ , averaged over all $|\eta|$) at 7 TeV collisions. The ϕ variations are due to the X-Y geometry of the ES and are well-simulated in Monte Carlo. The occupancy is eventually expected to be a few percent at high $|\eta|$ with 14 TeV collisions and 10^{34} cm⁻²s⁻¹ luminosity.

Fig. 1. Longitudinal view of a CMS quadrant showing the ES location and coverage.

Fig. 2. ES occupancy as a function of pseudo-rapidity ($|\eta|$, averaged over all ϕ).

Fig. 3. ES occupancy as a function of azimuthal angle (ϕ , averaged over all $|\eta|$).

The ES is a sampling calorimeter and essentially counts the number of charged particles passing through the silicon. The design-goal precision of calibration is set to 5%. This corresponds to a contribution of about 0.25% to the overall EE+ES energy resolution. In-situ ES calibration is performed by using charged particles with momentum greater than 1 GeV pointing to the ES from minimum bias collision data. Fig. 4 shows the energy distribution for a silicon sensor and the distribution is fitted by a Landau function convoluted with a Gaussian function. The MIP value is defined to be equal to the fitted peak position. The distribution of the measured MIP values for all sensors is shown in Fig. 5.

Fig. 4. Energy distribution for a silicon sensor, requiring tracks with momentum greater than 1 GeV pointing to the ES.

Fig. 5. The distribution of measured MIP values for all ES sensors.

After in-situ calibration and measurement of the noise, an estimation of the signal to noise for single ionizing particles can be made. The design specification of the ES was to have signal-to-noise ratio for single charged particles of about 8 for HG mode. The observed ratio, shown in Fig. 6, is between 9 and 11.

The precision of in-situ calibration is estimated to be about 2.2%, which is better than the design goal [2].

Fig. 6. ES signal-to-noise ratio for single charged particles for HG mode.

The expected precision of the ES position measurement is about 550 μm . The precision of the ES position measurement has been performed by using high energy tracks (transverse momentum is greater than 20 GeV). The calculated ES precision (σ_{ES}) is given by:

$$\sigma_{\text{ES}} = \sqrt{\sigma_{\text{total}}^2 - \sigma_{\text{track}}^2}$$

where σ_{total} is the fitted Gaussian width from residual plots in Fig. 7 and σ_{track} is the average trajectory prediction error from the Tracker to ES. For the four ES planes the average tracker error is 500 μm and the total width is 800 μm , leading to a measured ES precision of about 600 μm , in good agreement with prediction [3].

Fig. 7. Residual plots showing the position accuracy of charged tracks with $p_T > 20$ GeV incident on the ES.

III. BULK LEAKAGE CURRENT OF SILICON SENSORS

The sensors are exposed to a wide spectrum of ionizing and non-ionizing radiation, causing an increase of the bulk leakage current and a change of the effective doping concentration, resulting in a change of the full depletion voltage. The bulk leakage current decreases with temperature. We want to maintain operation, without changing the applied bias voltage and without tripping the HV supplies, by reducing the temperature. The simulation helps predict the behavior of leakage current with time and temperature. It also helps us estimate when to reduce the temperature.

FLUKA package [4, 5] was used to simulate particle rates across the whole CMS detector. The particle fluence was derived from the Monte Carlo simulation using events generated by DPMJET3 [6]. The radiation damage to silicon sensor from each particle is scaled to the damage from 1 MeV neutron based on known bulk damage behavior properties, as functions of particle type and energy. Only non-ionizing energy loss (NIEL) bulk damage is calculated. The average fluence, as a function of radius, is shown in Fig. 8 for an integrated luminosity of 1 fb^{-1} . The calculated fluence has a maximum at $R = 45$ cm ($|\eta| = 2.6$) corresponding to a value of $4.53 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$.

Hamburg model [7] was used to calculate the increase of the leakage current due to radiation and the simultaneous annealing. The increase of the current due to non-ionizing radiation for a fluence (Φ) is calculated as:

$$\Delta I = \alpha \times \Phi \times V$$

where V is the volume of the silicon sensor and α is the radiation induced damage rate, which is a function of time and temperature. The temperature was 10.9°C in 2011. Fig. 9 shows the results of the calculations as well as the integrated luminosity for 2011.

Fig. 8. Calculated 1 MeV equivalent neutron fluence as a function of the radial distance from the beam line, for an integrated luminosity of 1 fb⁻¹. The curve represents an average for the 4 ES planes.

Fig. 9. Calculated volume current and integrated luminosity as a function of time calculated for 1 cm³ of silicon at a distance of 45 cm ($|\eta| = 2.6$) from the beam line. The temperature was about 10.9°C in 2011.

A. Leakage current measurement – Radial dependence

The leakage current measurements have been carried out to assess the bulk damage of the sensors, in particular as a function of their distance from the beam. The measurement was performed at the end of 2011. The total luminosity for 2010 and 2011 is 6.17 fb⁻¹, includes the luminosity taken outside stable beam conditions. The measured leakage current was converted to 0°C for an easier comparison of results from LHC experiments. Fig. 10 shows the current per unit volume of silicon at 0°C, as a function of distance from the beam line, and curve showing the expected values from FLUKA and the Hamburg model.

In order to get a better comparison of measured and calculated currents, a group of sensors from a single producer were selected, which were believed to be largely free of excess surface currents. The distribution of the ratio of the measured to calculated current is shown in Fig. 11 together with a

Gaussian fit, which gives an average value of 0.97 and an rms of 0.03.

Fig. 10. Volume leakage current measured as a function of the distance from the beam, after an integrated luminosity of 6.17 fb⁻¹. The solid line indicates the expected values based on FLUKA simulations and calculations of the Hamburg model for 0°C. Points far from the blue line are due to sensors with excess surface currents.

Fig. 11. Ratio of measured to calculated sensor current. The 5 events with a ratio above 1.3 are believed to come from sensors suffering from excess surface currents. The plot includes sensors from one specific producer only.

B. Leakage current measurement – Time dependence

Due to budget limitations only 192 high voltage channels were purchased in the first stage. Each channel powers 6–35 sensors. The sensors were sorted into ladders according to their full depletion voltages. The difference of full depletion voltages would not exceed 25 V on a ladder. The operating voltage of a channel is the highest full depletion voltage of the group of sensors.

Continuous monitoring of leakage current is only performed at the level of the power supply channels. The calculated current can be only compared to the measured current from the group of sensors.

Eight high voltage channels were selected which supply sensors with almost no anomalous surface currents. Fig. 12 shows the measured and calculated currents as a function of time during 2011 and the first days of LHC operation in 2012 for two of the selected channels: channel 1 supplying 28 silicon sensors and channel 2 supplying 7. Sensors supplied from channel 1 are further away from the beam line and receive much less radiation than sensors supplied from

channel 2, which explains the current of channel 1 is not 4 times higher than the current of channel 2.

The distribution of the ratio of the measured to calculated current is shown in Fig. 13 together with a Gaussian fit, which gives an average value of 0.97 and an rms of 0.03.

Fig. 12. Current measured on 2 high voltage channels supplying 28 and 7 sensors for channels 1 and 2, respectively, as a function of time. The open symbols represent the calculated current as a function of time based on the Hamburg model.

Fig. 13. Ratio of measured to calculated current for the 8 high voltage channels for multiple measurements performed in 2011. The Gaussian fit gives a mean of 0.97 and an rms of 0.03.

IV. CONCLUSIONS

The CMS Preshower detector was installed and has been fully operational taking LHC collision data. In-situ calibration with charged particles has been carried out and achieves the required accuracy. The precision of the Preshower position measurement is about 600 μm , which agrees with expectation.

The bulk leakage currents of silicon sensors were measured after an integrated luminosity of 6.17 fb^{-1} at 7 TeV. These measurements show that calculated currents, based on FLUKA simulation and Hamburg model, agree with the measured currents to the 3% level. The program can be used to predict the long-term evolution of bulk leakage currents from the Preshower. These measurements also indicate that the ES sensors can be used to measure accurately the fluence at the CMS endcaps.

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