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Measurement of the bulk leakage current of silicon sensors of the CMS Preshower after an integrated luminosity of 6.17 fb^{-1} , at $\sqrt{s} = 7 \text{ TeV}$

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ABSTRACT: The CMS Preshower is part of the CMS Electromagnetic Calorimeter (ECAL) system. It is a sampling calorimeter that was installed to improve π^0 rejection in the forward direction. It is composed of two layers of lead, each followed by a layer of silicon sensors. The Preshower is installed at each end of CMS, at about $\pm 310 \text{ cm}$ from the CMS interaction point. 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.

This paper presents the measurements of the bulk current increase from the 2010 and 2011 LHC runs, corresponding to an integrated luminosity of 6.17 fb^{-1} , including luminosity taken outside stable beam conditions, at a centre-of-mass energy of 7 TeV .

A computer program based on the Hamburg model was developed for calculating the effects of simultaneous irradiation and annealing on the bulk leakage currents. The calculated currents, as a function of time, were found to be in good agreement with the bulk leakage currents measured in 2011. The program will be used to estimate the long-term evolution of the bulk leakage currents. The absolute level of the bulk leakage current, and its radial dependence, is in good agreement with the predictions obtained with the Hamburg model folded with the FLUKA simulation of the CMS radiation field.

KEYWORDS: Models and simulations; Si microstrip and pad detectors; Radiation damage to detector materials (solid state); Calorimeters

On behalf of the CMS collaboration.

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1 Introduction

When the LHC experiments were designed in the 1990s a particular emphasis was placed on evaluating and understanding radiation effects on silicon sensors. The goal of the R&D was to develop sensors that would work and deliver useful data for the whole lifetime of the LHC, which, at that time, was 10 years. It was expected that in those 10 years the LHC would deliver an integrated luminosity of about 500 fb^{-1} [1, 2].

Radiation fields were simulated for each CMS sub-detector containing silicon sensors in order to estimate the dose and the non-ionizing energy loss (NIEL) as a function of position. For the Preshower [3], the FLUKA simulations gave a maximum fluence of 0.4×10^{14} charged hadrons/cm² and 1.6×10^{14} n/cm² neutrons for an integrated luminosity of 500 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$ at the innermost radius, $R=45 \text{ cm}$ at $Z = 305 \text{ cm}$, corresponding to a pseudorapidity $|\eta| = 2.6$.

Sensors were irradiated to the expected fluences (and above) and their characteristics re-evaluated. It was found that the leakage current increases linearly with the radiation and that the effective doping concentration changes with the creation of the acceptor centres and the removal of donors [4–8]. It was also found that these changes vary with time after the radiation damage occurs and that the time constants are a function of the temperature. A model was developed, using the Hamburg description [9] to parameterize the evolution of the current and the effective doping concentration with time and temperature. One aspect, however, could not be studied with realistic conditions: irradiation of sensors on a real timescale with simultaneous annealing. Irradiations to large doses/fluences (e.g. 10 years LHC equivalent) were typically carried out over several hours followed by a long term annealing.

This work presents measurements of leakage current increases, induced by LHC radiation, of the CMS Preshower silicon sensors at the end of 2011 and the beginning of 2012 and compares them to expectations, taking into account the radiation received and the annealing during and after the irradiation. Although calculations show that the full depletion voltage of sensors should have changed by up to 20 V, such a measurement is not straightforward *in situ*. Depletion voltage measurements are on-going and will be the subject of a separate note.

Section 2 describes the CMS Preshower, including the powering of the sensors and its cooling system, the latter being very important for stable operation of the detector. The results of the simulation of the radiation field are presented in section 3. Section 4 describes the calculations of the annealing effects based on the Hamburg model. In section 5 we present the measurements of the current and compare them with the model prediction. The last section contains a summary and conclusions.

2 Description of the CMS preshower

The CMS Preshower (ES) is a sampling calorimeter comprising two layers, each layer consisting of a lead absorber followed by silicon sensors that was installed to improve the π^0 rejection in the forward direction. It measures the position and the energy deposited in the lead from electromagnetic showers. It is placed between the Tracker and the Endcap electromagnetic calorimeter (EE), which is made of lead tungstate (PbWO_4) scintillating crystals.

The ES is installed on the two endcaps of CMS at about 310 cm from the interaction point. These detectors are referred to as ES+ and ES-. A schematic cross section of the ES is shown in figure 1. Each of the two planes comprises a lead absorber, a cooling screen, and a layer of silicon sensors and readout electronics. The front plane (F), is nearest to the interaction point, followed by the rear plane (R). The two planes at each end of CMS are referred to as ES+F and ES+R, and ES-F and ES-R respectively. The absorbers comprise two half-disks with inner and outer radii of about 45 cm and 121 cm, respectively.

The “windows” are made of a honeycomb-like structure filled with paraffin to slow down and absorb neutrons generated in the calorimeters in order to reduce the neutron fluence through the ES and Tracker. In order to run at temperatures below 0°C the walls of the ES are lined with 0.9 cm thick insulating foam. Heating films are glued to the inner walls of the windows to regulate the outer wall temperature to $18 \pm 0.1^\circ\text{C}$ due to the temperature sensitivity of the EE.

The silicon sensors are made on 4” float zone, n-type material, with total volume of $63 \times 63 \times 0.32 \text{ mm}^3$. They have 32 p^+ implanted strips, 1.81 mm wide and at a pitch of 1.9 mm. The guard rings define the active surface area, which is $61.0 \times 61.0 \text{ mm}^2$. The sensors are glued to ceramic support plates mounted on aluminium tiles, which are in direct contact with the absorber. Each sensor is read out through a hybrid printed circuit equipped with the “PACE” front-end readout chip [10]. The hybrids are in direct mechanical and thermal contact with the ceramic support. The assembly of sensor with ceramic support and front-end hybrid, all mounted on an aluminium tile, is known as a micromodule.

The cooling screens, comprising 6 mm thick aluminium half-disks with the same radial dimensions as the absorber, contain C_6F_{14} coolant, which circulates in concentric channels.

Figure 1. Schematic cross section of the Preshower showing the layout of the windows, cooling screens, absorbers, silicon sensors and digital readout electronics.

Groups of between 6 and 10 micromodules are assembled into larger structures, called ladders. All surfaces make good thermal contact with each other. A printed circuit board, called a “system motherboard” (SMB), containing ADCs, the data concentrator (K-chip) and voltage regulators, as well as other integrated circuits providing the clock and control signals, is mounted on top of the ladders. The SMBs also include plug-in mezzanines for optical transmission/reception of data/control signals. Figure 2 shows the layout of part of a ladder on the absorber. The heat generated by the silicon sensor and the hybrid is evacuated through the aluminium tile to the absorber walls. The power dissipated by the digital electronics is also evacuated to the absorber through the aluminium heat sinks and the pillars of the tiles. A picture of a ladder is shown in figure 3, where one can see two front sensors and the SMB. The active components of the motherboard are mounted on the underside of the printed circuit board, where they are in thermal contact with heat sinks.

The power for the electronics and the bias voltage for the silicon sensors are distributed through the SMBs. In order to limit the number of cables between the detector and the service cavern, two neighbouring sensors (a “pair”) are biased from the same high voltage line. However, on some ladders on the inner and outer periphery there is a single sensor (a “singlet”) connected to the high voltage line.

The ES comprises 1072 sensors per plane, corresponding to 4288 sensors in total. Due to budget limitations only 192 high voltage channels were purchased in the first stage. Therefore each channel powers between 6 and 35 sensors. The sensors were sorted into ladders according to their full depletion voltage, which was measured as part of the acceptance tests. Care was taken so that the difference of full depletion voltages would not exceed 25 V on a ladder. The assignment of ladders to the high voltage channels followed the same principle. The operating voltage of a channel is the highest full depletion voltage for the group of sensors, as measured during the sensor acceptance tests. The current measurements were made at these voltages.

Figure 2. Schematic layout of the silicon sensors and readout electronics on the absorber. The horizontal scale has been enlarged to show the thinner structures more clearly.

Figure 3. An example Preshower ladder, comprising 8 micromodules and 8 hybrids, covered by a system motherboard (SMB). Two of the sensors are visible beyond the SMB, on the left hand side.

The ES cooling is very efficient. The temperature difference between the front and rear planes is about 0.5°C in the present operational configuration with the coolant temperature at 9°C at the inlet to the ES (section 4.1). This is despite the fact that the ladders on the front plane also face the cooling screens for the rear plane. In contrast, the ladders on the rear plane face the insulating foam through which heat can leak from the external surroundings. A higher temperature might have been expected for the rear plane, which has proved not to be so.

3 FLUKA simulation of the radiation field

The FLUKA [11, 12] package was used to simulate particle rates across the whole CMS detector [13]. The particle fluence was derived from the Monte Carlo simulation using events generated by DPMJET3 [14]. In early simulation runs the geometry was implemented from pre-production drawings. The geometry has now been upgraded to match, as far as possible, the actual detector. The simulation assumes an azimuthal symmetry for the detector in order to improve the statistics.

A total of one thousand proton-proton collisions were simulated in five separate runs using a centre-of-mass energy of 7 TeV. The particle flux is scored in a grid with 2.5 cm bin size in Z (distance along the beam axis) and in R (distance from the beam axis). The statistical error of the simulation is calculated for each scoring bin by comparing the different runs and is between 2% and 8%. At regions of lower flux the statistics are worse than at high flux rates, hence the statistical error is larger at areas of lower flux. The particle flux incident on the Preshower includes many different particle types and energies. The radiation damage to silicon from each particle is scaled to the damage from 1 MeV neutrons (n_{eq}) based on known bulk damage properties, as a function of particle type and energy. Only NIEL-type bulk damage is calculated.

The number of equivalent 1 MeV neutrons/cm² per p-p collision, from FLUKA, is scaled to the integrated luminosity using the inelastic p-p collision cross-section of 73.5 mb [15]. For the subsequent calculations of the annealing effects an average fluence for the 4 planes of the ES was taken. The average fluence, as a function of radius, is shown in figure 4 for an integrated luminosity of 1 fb^{-1} . The calculated fluence has a maximum at $R = 45.0\text{ cm}$ corresponding to a value of $4.53 \times 10^{11} n_{eq}/\text{cm}^2$. At larger radii the fluence decreases exponentially. The particle fluence decreases slightly for lower radii, because of the presence of a polyethylene moderator in this region. The fluence calculated for sensors at 45.0 cm from the beam line was used as an input to the calculation of the radiation induced bulk current and simultaneous annealing, as described in section 4.

4 Calculation of leakage current versus time, including annealing effects

The Hamburg model was used to calculate the increase of the leakage current due to radiation and the simultaneous annealing [9]. The annealing rate is a strong function of the temperature. The temperature of the silicon sensors is estimated in section 4.1. The bulk current calculations are described in section 4.2.

4.1 Temperature estimate

The sensor temperature is derived from the temperatures of the hybrid and the cooling screens. Space limitations, due to the compact assembly, prohibited the placement of temperature probes

Figure 4. Calculated 1 MeV neutron equivalent 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 four Preshower planes.

directly on the sensors. Each front-end hybrid contains a detector control unit (DCU), which monitors the voltages to the PACE chip and measures the approximate hybrid temperature. There are 1072 of these temperature probes on each plane. Although they are not direct silicon temperature measurements, they provide information about the uniformity of the temperature and the stability of the cooling. Figure 5 shows the distribution of the temperatures measured on the hybrids for the four planes on December 8, 2011, just before the detector was switched off after the 2011 LHC run finished.

The distributions are approximately Gaussian with values of $12.1 \pm 0.4^\circ\text{C}$, $12.5 \pm 0.5^\circ\text{C}$, $12.3 \pm 0.5^\circ\text{C}$, $12.9 \pm 0.5^\circ\text{C}$ for ES-F, ES-R, ES+F and ES+R, respectively.

The average hybrid temperature was $12.45 \pm 0.15^\circ\text{C}$. This excludes periods involving LHC technical stops when the temperatures could change due to technical interventions in CMS. An average for the front and rear planes (see figure 5) was taken since the differences are small and at the limits of the temperature measurement precision.

The temperature of the cooling screens is estimated from the average of the temperatures of the coolant at the inlet and the outlet. The coolant flow is around 0.9 l/sec, replacing the coolant inside the ES about every 6 seconds. On December 8, 2011, the temperatures at the inlets and outlets were measured to be 8.7°C and 9.2°C for ES- and 8.7°C and 9.1°C for ES+, giving an average of 8.9°C for the cooling screens. The silicon sensors are therefore assumed to be between 8.9°C and 12.45°C since they are placed between the cooling screens and the hybrids.

The operational temperature of the silicon was estimated by comparing the leakage currents taken when the cooling was off, with the detector in thermal equilibrium with its ambient surroundings, with those taken during operation. The temperature of the thermal equilibrium was measured

Figure 5. Distribution of the temperature measured on each of the four planes of the Preshower.

using additional temperature sensors placed at a number of different locations throughout the ES detector volume. Based on these measurements the silicon sensor temperature was determined to be 2°C above the cooling screen temperature during operation. For this analysis the coolant temperature measurements are retrieved from the database once per day and the average value is calculated. The coolant temperature plus the sensor temperature offset of 2°C on day k , is used for the annealing temperature, T_k , in the following calculations.

The silicon sensor temperature averaged over the whole of 2011 was 12.9°C, somewhat higher than the values mentioned above. This is because the average includes periods of technical interventions when the cooling system was switched off and thus the silicon was around room temperature.

4.2 Calculations

The increase of the current due to non-ionizing radiation of a fluence Φ is calculated as:

$$\Delta I = \alpha \Phi V \quad (4.1)$$

where V is the volume of the silicon sensor. The damage function, α , in equation (4.1) is the radiation induced damage rate, which is a function of time, t , and annealing temperature, T_k , ex-

pressed by:

$$\alpha(t, T_k) = \alpha_I \exp\left(-\frac{t}{\tau_I}\right) + \alpha_0 - \beta \ln\left(\frac{t}{t_0}\right) \quad (4.2)$$

where $\alpha_I = 1.23 \times 10^{-17}$ A/cm and $t_0 = 1$ min are constants. The parameter β represents the annealing and was measured for a range of temperatures between 21°C and 106°C with an average of $\beta = (3.07 \pm 0.18) \times 10^{-18}$ A/cm [9]. We found in our calculations that using this value, the annealing was overestimated for the average ES temperature of 12.9°C and over the timescale of a year. We have, therefore, used the lower limit of the measurement, $\beta = 2.9 \times 10^{-18}$ A/cm.

$\tau_I(T_k)$ is a function of the annealing temperature and can be calculated from:

$$\frac{1}{\tau_I} = k_{0I} \exp\left(-\frac{E_I}{k_B T_k}\right) \quad (4.3)$$

with $k_{0I} = 1.2 \times 10^{13} \text{ s}^{-1}$, $E_I = 1.11 \text{ eV}$ and k_B is Boltzmann's constant $= 8.62 \times 10^{-5} \text{ eV/K}$.

α_0 is also a function of the temperature and can be described as:

$$\alpha_0 = c_1 + c_2 \times \frac{1}{T_k} \quad (4.4)$$

with constants $c_1 = -8.9 \times 10^{-17} \text{ A/cm}$ and $c_2 = 4.6 \times 10^{-14} \text{ AK/cm}$.

Although the LHC produces damaging radiation over continuous periods of typical duration measured in hours, the daily fluence is taken to be delivered instantaneously at a fixed time every day to make the calculations simpler. The increase in current given by equation (4.1) is calculated using a sum of daily fluences and an average daily silicon temperature. After substituting with equations (4.2), (4.3) and (4.4) it can be expressed as:

$$\Delta I = V \sum_{j=1}^{i-1} \varphi_j \times \left[\alpha_I \times \exp\left(\sum_{k=j}^{i-1} \eta_k\right) + c_1 + c_2 \times \frac{\sum_{k=j}^{i-1} \frac{1}{T_k}}{i-j} - \beta \times \ln((i-j) \times 1440) \right] \quad (4.5)$$

where the index i represents the number of days since the first irradiation and also when the measurement was taken. In addition, i must be greater than 1. The index k runs between the day of irradiation, j , with respect to the first irradiation, and the day of measurement, i . The formula refers to the current calculation with the sensor at 20°C. Equation 6 is used to derive the current I at sensor temperature T .

$$I(T) = I_0 \times \left(\frac{T}{T_0}\right)^2 \times e^{\frac{E_{ef}}{2 \times k_B} \times \left(\frac{1}{T_0} - \frac{1}{T}\right)} \quad (4.6)$$

where $T_0 = 292.05 \text{ K}$, and I_0 is the current measured at T_0 . For the effective band gap, E_{ef} , a value of 1.21 eV has been used, as recommended by the RD50 collaboration [16].

The parameter $\eta_k = -\frac{86400s}{\tau_{I,k}}$, where $\tau_{I,k}$ is calculated from equation (4.3) for the temperature, T_k , and 86400 is the number of seconds in one day. Similarly the constant 1440 in equation (4.5) is the number of minutes in one day.

The calculation is carried out for each day, j , for a silicon volume of 1 cm^3 placed at a radial distance of $R = 45.0 \text{ cm}$ from the beam line, the location that, according to the FLUKA simulation, receives the highest fluence. The luminosity delivered by the LHC is retrieved from the CMS database each day, j , and then converted into the fluence, φ_j , using the conversion factor of $4.53 \times 10^{11} \text{ n}_{eq}/\text{cm}^2/\text{fb}^{-1}$ (see section 3).

Figure 6. Volume current and integrated luminosity as a function of time calculated for 1 cm^3 of silicon at a distance of 45.0 cm from the beam line for temperatures retrieved from the database.

The expected current was calculated for each day from March 29, 2010, when LHC delivered the first collisions. Figure 6 shows the results of the calculations as well as the integrated luminosity for 2011. The current increase and the luminosity were very low in 2010 and, although taken into account in the calculations, they are not presented in the figure. The current is calculated using the temperature retrieved from the database.

5 Current measurements

5.1 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 radial distance from the beam. A hardware intervention was required to access the currents on pairs or single sensors, since the current delivered by the standard HV distribution serves many sensors at different positions. The radial distance of a single sensor from the beam line was taken to be its centre, while for a pair of sensors the centre was taken from the corresponding rectangle. The measurements were performed on December 14, 2011, six days after the detector was powered down for the year-end technical stop. It allowed enough time to stabilize the temperature of the whole ES detector to that of the ambient environment, which takes about 24 hours. The average temperature of the 4 silicon planes was 18.9°C . The currents were measured at the operating bias voltage. Sensors operated at 25 V above their full depletion voltage (V_{fd}) had currents that were only a few percent higher than when biased at their V_{fd} . For each sensor pair or singlet, the current measured prior to irradiation was subtracted. The measured current was converted to 0°C , as recommended by the RD50 collaboration [16] for an

Figure 7. 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 . The measurements were carried out at 18.9°C , but the data are converted to the equivalent currents at 0°C . Points far from the line are due to sensors with excess surface currents.

easier comparison of results from all LHC experiments. The conversion was carried out using equation (4.6).

The total integrated luminosity for 2010 and 2011 was 6.17 fb^{-1} . It includes the luminosity taken outside stable beam conditions, which is not included in the luminosity calculated for physics, since the associated radiation also damages the silicon. This contribution corresponds to about 0.31 fb^{-1} .

Figure 7 shows the current per unit volume of silicon at 0°C , as a function of distance from the beam line, after an integrated luminosity of 6.17 fb^{-1} . The solid line represents the results of the FLUKA simulation and Hamburg model calculations described above. The sensor volume used for the normalization is the product of the active surface and the thickness, which is 1.19 cm^3 . Most of the data are grouped in a band that is highly correlated with the curve for the calculated currents. There are about 100 sensors with a current higher than expected. These sensors had large currents that were provoked by radiation from pp collisions but at a fluence or dose that was well below either that expected for bulk damage or known effects from surface damage. The properties of these anomalous currents were studied and it was concluded that the effect was surface related, most likely a charging-up of the oxide layer near the oxide-silicon interface. Neither the temperature nor voltage dependence of these currents behaved like bulk damage; it was thus felt that these sensors should not be included in the bulk damage study reported here.

Figure 8. Ratio of measured-to-calculated sensor current for sensors from a single producer. The 5 events with a ratio above 1.3 are believed to come from sensors suffering from excess surface currents. The mean value and the sigma refer to the Gaussian fit.

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 figure 8 together with a Gaussian fit, which gives an average value of 0.97 and an rms of 0.03. The good agreement, over nearly one order of magnitude, suggests that the FLUKA calculations describe correctly the radiation field at the Preshower.

5.2 Time dependence

The behaviour of the measured current as a function of time has been compared to the calculations. Continuous monitoring of leakage current is only performed at the level of the power supply channels, which, as mentioned in section 2, power between 6 and 35 sensors. The calculated result cannot be compared to the current from a single sensor, but only to the group of sensors. As a consequence, we assume a simple scaling factor for each sensor in the group supplied from the same high voltage channel.

To make the comparison between calculated and measured leakage current, eight high voltage channels were selected which supplied sensors with almost no anomalous surface currents. Figure 9 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. The calculated current was scaled to the current measured for each channel on October 29, 2011, at the end of the proton run.

Sensors supplied from channel 1 are at an average radial distance from the beam axis of 79 cm

Figure 9. 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. The calculated current was scaled to the current measured for each channel on October 29, 2011, at the end of the proton run.

and thus receive much less radiation than sensors supplied from channel 2, which are at an average radial distance of 52 cm. This explains why the ratio of the currents is not a factor of 4, which might be expected from the ratio of the number of sensors supplied by each channel. For a period of about three months, between December 6, 2011, and March 8, 2012, the detector was powered down and the cooling was turned off. The sensors reached the ambient temperature after about 24 hours, and then varied between 19°C and 21°C. For this period there were no current measurements and only temperature measurements taken from the coolant monitoring system. The currents of six other HV channels give similar agreement.

Figure 10 shows the distribution of the ratio of the measured-to-calculated current for all the measurements performed in 2011 for the 8 high voltage channels considered. The Gaussian fit, also plotted, gives a mean of 0.97 and an rms of 0.03. The good agreement indicates that the Hamburg model predicts the evolution of the leakage current with time and temperature to the level of a few percent, and that the values of the parameters used in the model are reasonable.

6 Summary and conclusions

The bulk leakage currents of silicon sensors of the CMS Preshower were measured after an integrated luminosity of 6.17 fb^{-1} at a centre-of-mass energy of 7 TeV. The dependence of the leakage current from the bulk damage on the radial distance of the sensor from the beam line is in good agreement with that expected using a FLUKA simulation of the radiation field. The simulation

Figure 10. 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 a sigma of 0.03.

gives a value for the fluence of $4.53 \times 10^{11} \text{ n}_{eq}/\text{cm}^2$ for 1 fb^{-1} for the maximum fluence. This occurs at a radial distance from the beam of 45 cm corresponding to $|\eta|=2.6$.

Assuming that the LHC will restart in 2015 at 14 TeV centre-of-mass energy¹ and will eventually deliver a total of 500 fb^{-1} , the total fluence predicted at a distance of 45 cm from the beam axis is around $3 \times 10^{14} \text{ n}_{eq}/\text{cm}^2$.

A program based on the Hamburg model to account for the simultaneous effects of irradiation and annealing was used to calculate the Preshower leakage current as a function of time. The ratio of measured-to-calculated current for sensors without additional surface component is 0.97 with an rms of 0.03.

The calculated current accurately tracks the measured current as a function of time, showing that the model and simulation can be used to predict the future evolution of Preshower currents with accumulated radiation. Conversely, the Preshower sensors can be considered as providing very accurate estimates of non-ionizing radiation in the endcaps of CMS.

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¹Previous studies have shown that the fluence scales with the square root of the energy, so 14 TeV collisions are expected to result in about 1.41 times higher fluence than 7 TeV collisions. A full FLUKA simulation at 14 TeV will provide a more accurate estimation of the fluence but is beyond the scope of this paper.

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