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Radiation damage in the diamond based beam condition monitors of the CMS experiment at the Large Hadron Collider (LHC) at CERN

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ABSTRACT

The Beam Condition Monitor (BCM) of the CMS detector at the LHC is a protection device similar to the LHC Beam Loss Monitor system. While the electronics used is the same, poly-crystalline Chemical Vapor Deposition (pCVD) diamonds are used instead of ionization chambers as the BCM sensor material. The main purpose of the system is the protection of the silicon Pixel and Strip tracking detectors by inducing a beam dump, if the beam losses are too high in the CMS detector. By comparing the detector current with the instantaneous luminosity, the BCM detector efficiency can be monitored. The number of radiation-induced defects in the diamond, reduces the charge collection distance, and hence lowers the signal. The number of these induced defects can be simulated using the FLUKA Monte Carlo simulation. The cross-section for creating defects increases with decreasing energies of the impinging particles. This explains, why diamond sensors mounted close to heavy calorimeters experience more radiation damage, because of the high number of low energy neutrons in these regions. The signal decrease was stronger than expected from the number of simulated defects. Here polarization from trapped charge carriers in the defects is a likely candidate for explaining the difference, as suggested by Transient Current Technique (TCT) measurements. A single-crystalline (sCVD) diamond sensor shows a faster relative signal decrease than a pCVD sensor mounted at the same location. This is expected, since the relative increase in the number of defects is larger in sCVD than in pCVD sensors.

1. Introduction

The CMS beam condition monitor (BCM) [1–3] uses poly-crystalline Chemical Vapor Deposition (pCVD) diamond detectors on various positions inside CMS. At $Z = \pm 1.8$ m away from the interaction point (IP) BCM1L is placed. On each end there are four diamonds arranged around the beam pipe at a radius of 4.5 cm. At $Z = \pm 14.4$ m away from the IP the BCM2 detectors are placed with two rings of detectors per end. The inner ring with $R = 5$ cm has four diamond sensors, the outer ring with $R = 28$ cm with eight diamonds.

The pCVD diamonds are chosen as detectors for this system since they are very small. The diamonds were metallized at Rutgers University with W/Ti metallization. Diamond is considered to be more radiation hard than silicon. The main difference in radiation hardness comes from larger inelastic cross-section for silicon to produce nuclear fragments, which are predominantly responsible for displaced atoms (see Table 1 in [4]). Due to the high band gap the dark current is low, independent of temperature and does not increase with irradiation. With increasing radiation damage, the diamond looses signal strength due to an increased trap density, but in order to experience a significant signal loss hadronic irradiations with fluences $O(10^{15}\,\text{cm}^{-2})$ are necessary. However, a faster signal decrease is possible at high enough beam intensity by the decrease of the electric field in the sensor by the trapped ionization charges, which create an electric field opposite to the field from the bias voltage. This “polarization” reduces the signal much more than the expected signal decrease. From Monte Carlo simulations with FLUKA [6,7] one expects a signal decrease to 50% of the initial value after an integrated luminosity of 800 fb^{-1} [1]. In practice we see a signal decrease to 50% after a few fb^{-1}.

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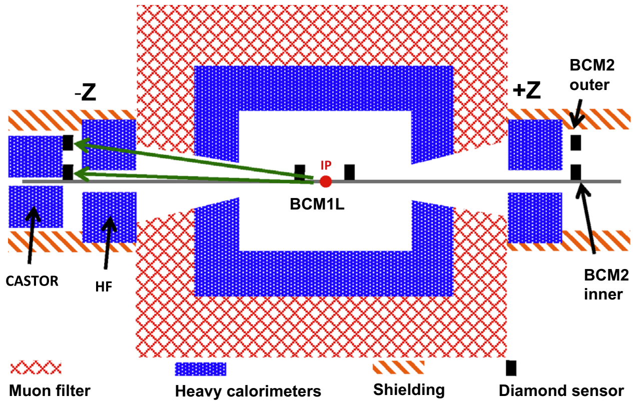

Fig. 1. Sketch of CMS showing the locations of the BCM detectors.

As will be discussed, this signal decrease by polarization can be prevented by an alternating bias high voltage.

2. Radiation environment of detectors

The radiation environment of the different BCM detectors is influenced by their location of installation. Fig. 1 shows a sketch visualizing the location and the resulting radiation environment.

The neutron flux, which is the main source for damage, is related to the heavy calorimeter material. High energetic hadrons hitting calorimeters produce low energetic albedo neutrons.[1] The closer the BCM detectors are to heavy material the higher is the neutron content. BCM1L is quite far away from heavy material, hence the neutron content is quite low. BCM2 located inside the forward shielding is placed in an increased albedo neutron field. The BCM2 detectors on the $-Z$ end have been exceptionally highly exposed to many neutrons since the CASTOR detector, a heavy quartz tungsten calorimeter, was installed directly behind BCM2 $-Z$ during the 2011 running period. The albedo neutron field is quite similar comparing the inner and the outer detectors at BCM2.

In total there are five groups of BCM detectors with the same radiation environment: BCM2 inner $+Z$, BCM2 inner $-Z$, BCM2 outer $+Z$, BCM2 outer $-Z$ and BCM1L. The behavior after irradiation of the detectors in one group is the same. For simplification all data presented here is calculated by averaging within the groups.

3. Normalization of data to instantaneous luminosity

The particles hitting the diamond detectors are almost entirely collision products. The signal from beam background is negligibly small. The signal measured is therefore to the first order proportional to the instantaneous luminosity. The collision rates at LHC and hence the signal in the BCM detectors is not constant, but vary over the duration of a fill.[2] To compare the detector efficiency over all fills the normalization is done in the following way:

The data is analyzed on a fill by fill basis. For every selected fill the data from the BCM detectors is plotted with respect to the official CMS offline luminosity. A linear fit is applied to the data and the expected detector signal at nominal luminosity ($10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$) is extrapolated. For the definition of 100% signal strength the signal of the unirradiated detectors is used.

This method of normalization has certain errors:

- The error on the linear fit can be propagated to an error value on the extrapolated value. This error is comparably small.
- The linear fit has a certain offset value which is not consistent with the linearity of the system. The noise values observed during inter-fill periods are negligibly small. This offset is a measure of the non linearity of the system. An error value to the extrapolated signal is calculated by constraining the linear fit to a zero offset and extrapolating to the same instantaneous luminosity. This number is used as a worst case systematical error. This is the dominant error of about 10–20%.

The total error on the normalized values for each analyzed fill is obtained from adding both error values in quadrature. This error is shown on the data points on Fig. 2 and 3. They are also used as a weight to the fit (Data points with high errors have lower weight in the fit.).

3.1. Comparison of 2011 and 2012 data

With the 2012 run the radiation environment changed slightly. The collision energy of the LHC increased from 7 TeV to 8 TeV giving a slightly (about 10%) increased radiation field at all BCM detectors, for both signal and radiation damage. The CASTOR detector, which was the main source of damaging neutrons for BCM2 $-Z$, was removed. This resulted in a decrease of albedo neutrons in that location. The amount of radiation damage decreased significantly. Due to the small interaction cross-section of neutrons with the diamond detector the signal rates decreased slightly only due to this.

In order to compare the signal efficiencies of 2012 with 2011 the data has to be corrected. This is done by performing a FLUKA Monte Carlo simulation of the CMS detector for the 2011 and the 2012 case. The expected detector signal is calculated by scoring the total energy deposition in the diamonds. The ratio of the results for both simulation runs give the correction factors, which are about 10%, but different for each location. The statistical error on the simulation gives an additional error on the data points for 2012.

4. Observed decrease in signal strength

For every analyzed fill the integrated luminosity over all previous fills is calculated from the CMS offline lumionsity. The normalized signal strength for each fill is calculated as described in Section 3 and plotted as function of the integrated luminosity. The result with data from 2011 can be found in Fig. 2. For all positions a decrease in signal strength is visible. It is most pronounced in BCM2 on the $-Z$ end, the least decrease was observed in BCM1L. Also plotted is a fit to the data using the parametric formula, which is motivated by the assumption that the number of traps increases with integrated luminosity and the signal is inversely proportional to the number of traps:

$$S(L) = \frac{S_0}{1 + S_0 \cdot k' \cdot L} + c$$

where S is the signal, S_0 the unirradiated signal, L the integrated luminosity, k' a damage constant and c an offset. This hyperbolic decrease provides a good fit.

Fig. 3 includes the 2011 data and the 2012 data analyzed so far. The decrease in signal continued in 2012 for BCM1L and BCM2 on $+Z$ as shown by the hyperbolic fit. The BCM2 $-Z$ did not experience a decrease in signal over 2012. The fit to the 2011 data is extrapolated and does not agree with the data in 2012 any more.

[1] Neutrons produced in heavy material by impinging particles and scattered back are referred to as albedo neutrons.

[2] One fill is called the time period over filling the LHC with protons and colliding the beams until they are dumped.

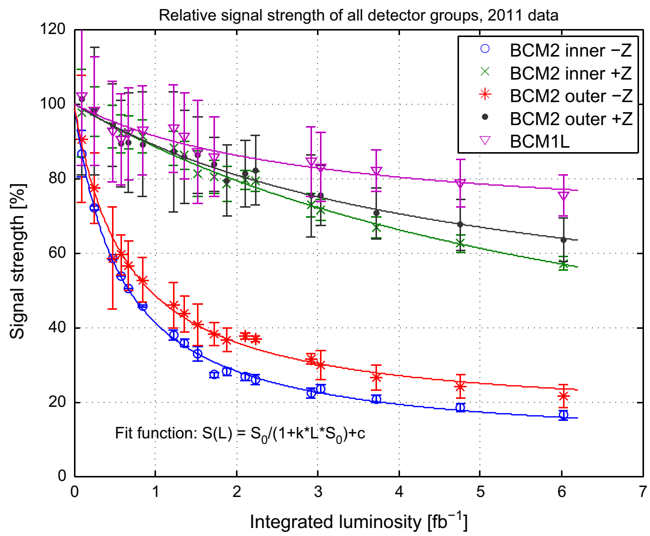

Fig. 2. Signal strength of BCM detectors relative to the signal of the unirradiated detectors as function of integrated luminosity for the 2011 running period.

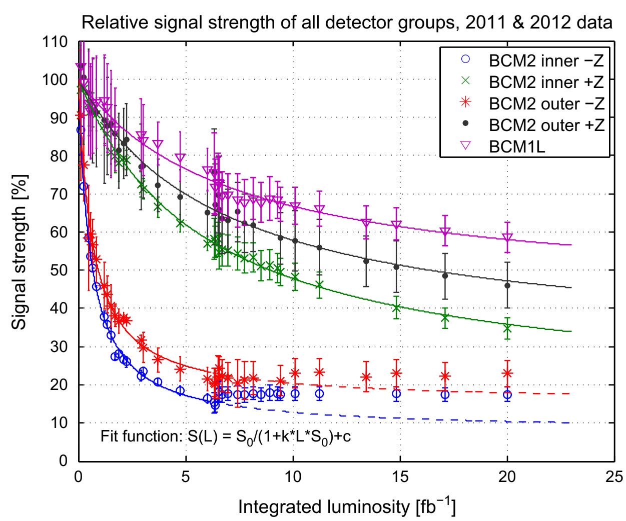

Fig. 3. Relative signal strength of BCM detectors as function of integrated luminosity for the 2011 and 2012 running period up to a total of 20 fb^{-1}. The hyperbolic fit to the data of BCM1L and BCM2 +*Z* tracks the decrease of the efficiencies of these detectors. The slope of the BCM2 detectors on the −*Z* end changed significantly. This is shown by extrapolating the 2011 fit to the full axis. A decrease is not measurable any more for BCM2 −*Z*.

This is expected since the CASTOR detector was removed, and with it a significant source of damage. Although the radiation field in 2012 is now very comparable between BCM on +*Z* and −*Z* the decrease is different. BCM2 on −*Z* is already heavily damaged in 2011 and is now on the rather flat part of the hyperbolic curve while BCM2 +*Z* is still on the steeper slope.

4.1. Single crystal diamond

At the same location as BCM2 inner on +*Z* a prototype single-crystalline CVD diamond (sCVD) was installed during 2011. This diamond has a different metallization than the pCVD.[3] This diamond was replaced with a new sCVD diamond in the 2012 run. In Fig. 4 the measured detector current for both sCVD and the regular pCVD diamond installed at the same location is plotted, including the hyperbolic fit. The signal is normalized to the size of a detector with $1 \times 1\ \mathrm{cm}^2$ and 400 μm thickness. The initial signal of the sCVD detectors is significantly higher than the signal of the pCVD detector. One can see that the sCVD looses the signal faster than the pCVD. This is expected since the relative increase in traps is higher in a sCVD compared with a pCVD, which in an unirradiated state that already has many traps and acts like a pre-damaged sCVD diamond. Therefore the pCVD decreases along the rather flat part of the hyperbolic curve.

As earlier mentioned there is also a difference in the metallization between the pCVD diamond and the sCVD diamonds. The influence of the metallization on the signal loss, comparing two detectors with the same bulk material but different metallization, has not yet been quantified.

5. Polarization

Charge carriers generated by ionizing radiation are separated by the electric field and drift along the field lines. With a certain probability the charge carriers get trapped and form a fixed local charge. The electron density is higher close to the positive electrode and hence more electrons are trapped there. Likewise the hole density is higher close to the negative electrode and more holes are trapped there. This leads to a buildup of an internal electric field, which counteracts the applied HV field. As introduced already in Section 1, we refer to this process as “polarization”. Polarization leads to a deformation of the electric field. Certain regions may become field free and do not act as detector volume any more.

This effect increases with radiation damage since with a higher number of defects, more charge can be trapped. When the charge is released the polarization field decreases again. The strength of the polarization field corresponds to the net equilibrium reached between the trapping and detrapping of charge. This leads to a dependency of the polarization on the number of charge carriers and hence the rate of ionizing particles.

One way of avoiding the buildup of polarization is to alternate the HV polarity. Before the polarization can build up the HV is flipped. The charge carriers are now in the opposite position removing the polarization again. This leads to the same charge carrier density, and hence no polarization, if the frequency for polarity change is sufficiently high.

6. Measurements of removed diamond sensors

After the 2011 run three diamonds were removed from the system. One diamond from the BCM2 outer position on +*Z*, one from BCM2 outer on −*Z* and the prototype sCVD. The FLUKA simulated hadron fluences are pCVD from BCM2 +*Z*: O(10^{13} cm^{-2}), pCVD from BCM2 −*Z*: O(10^{14} cm^{-2}), and sCVD: O(2×10^{13} cm^{-2}).

6.1. Charge collection distance (CCD) measurements

The measurements of CCD of the removed diamonds are shown in Fig. 5. Data from a measurement before installation was available for both pCVD diamonds. The low damaged pCVD from BCM2 +*Z* (Fig. 5(a)) does not show any difference before and after irradiation. The highly damaged pCVD from BCM2 −*Z* (Fig. 5(b)) does show a decreased CCD after irradiation especially at lower field strength. With higher HV the internal field becomes less dominant compared to the applied HV field and the CCD reaches almost the values of the unirradiated state.

In Fig. 6 the measured CCD as function of HV is plotted for an alternating HV polarity to avoid the buildup of polarization.

[3] Metallization was performed at GSI, Germany.

The applied alternating HV had a square wave function with a frequency of 0.1 Hz and an edge slope of 50 V/μs. Already at low applied field (~0.5 V/μm) the CCD reaches its maximum value when the alternating HV is used. With a constant HV it is necessary to apply rather high fields (> 1 V/μm) to reach maximum CCD. This shows that the reduced CCD at low fields using constant HV is due to polarization.

Comparing the measurements from the highly damaged pCVD one can see from Fig. 5(b) that before irradiation there was no polarization visible (full CCD at low fields), but after irradiation the diamond suffers from polarization. With alternating HV the measurement (Fig. 6(b)) compares well to the data from before irradiation.

A reduction of the maximum CCD (at high fields) was not observed after irradiation, as expected from the high radiation hardness observed in test beams [5].

The reduction in detector signal strength observed in CMS, as shown in Section 4, is higher than the decrease of CCD. Hence the reduction of CCD is not the main reason for the observed signal decrease. The reduced signal was probably attributed to a buildup in polarization. As explained in Section 5, the buildup of polarization can be stronger in an high rate environment. Therefore the signal in an intense radiation field, like in CMS, could be even more reduced than in the CCD measure environment.

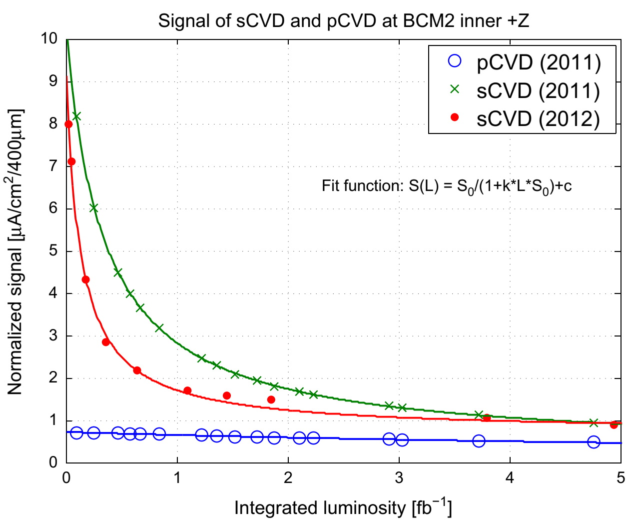

Fig. 4. The measured detector current, normalized to detector size, of the two prototype single crystal diamond and a poly crystal diamond at the same location as function of integrated luminosity. The sCVD detectors show significantly more initial signal than the pCVD, but the sCVD signal decreases faster.

6.2. *Transient current technique (TCT)*

The electric field inside a sensor can be determined by the Transient-Current-Technique (TCT): after introducing electron–hole pairs on one side of the detector, e.g. by a radioactive α source, one observes the current generated by the drift of the charge carriers due to the internal electric field of the sensor. This current as function of time is proportional to the electric field as function of distance. For an undamaged detector the electric field is constant and one obtains a square TCT signal with a length proportional to the maximum drift time. By creating the charge carriers either at the cathode or anode the drift from electrons or holes can be observed.

The used measurement setup consists of a Picosecond 5531 bias tee, a MITEQ AM-1309 amplifier, a Tektronix TDS 5104B oscilloscope and a Keithley 2410 as HV source. As α source a 3.56 kBq^{241}Am source was used.

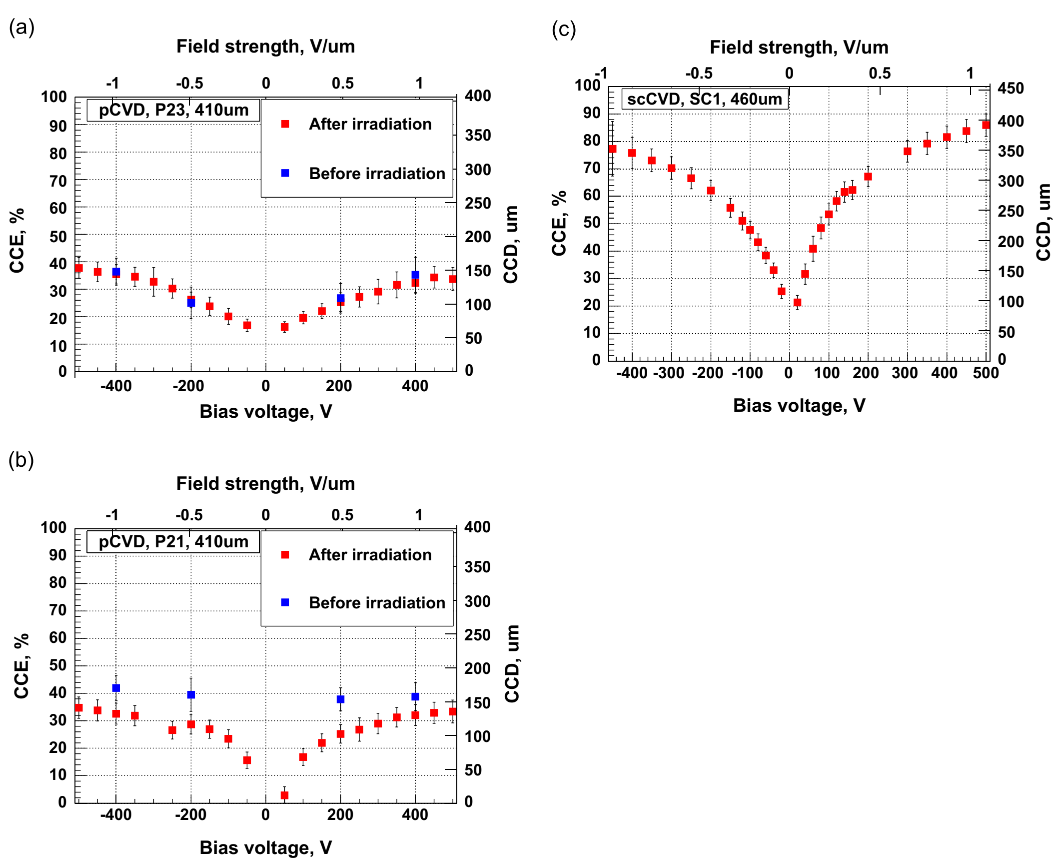

Fig. 5. CCD measurements of removed diamonds using constant HV. (a) pCVD from BCM2 outer +*Z*, (b) pCVD from BCM2 outer −*Z*, and (c) sCVD from BCM2 inner +*Z*.

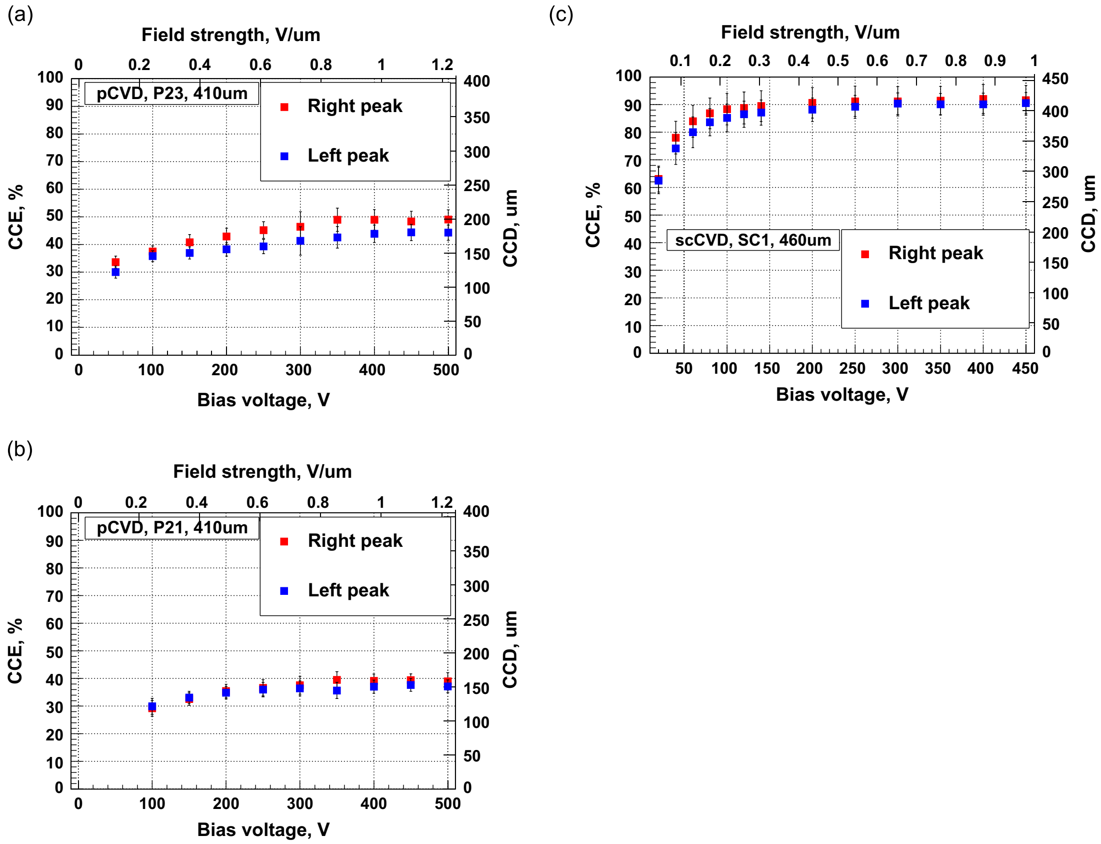

Fig. 6. CCD measurements of removed diamonds using alternating HV polarity. Right peak and left peak refers to the signal with one or the other polarity. (a) pCVD from BCM2 outer $+Z$, (b) pCVD from BCM2 outer $-Z$, and (c) sCVD from BCM2 inner $+Z$.

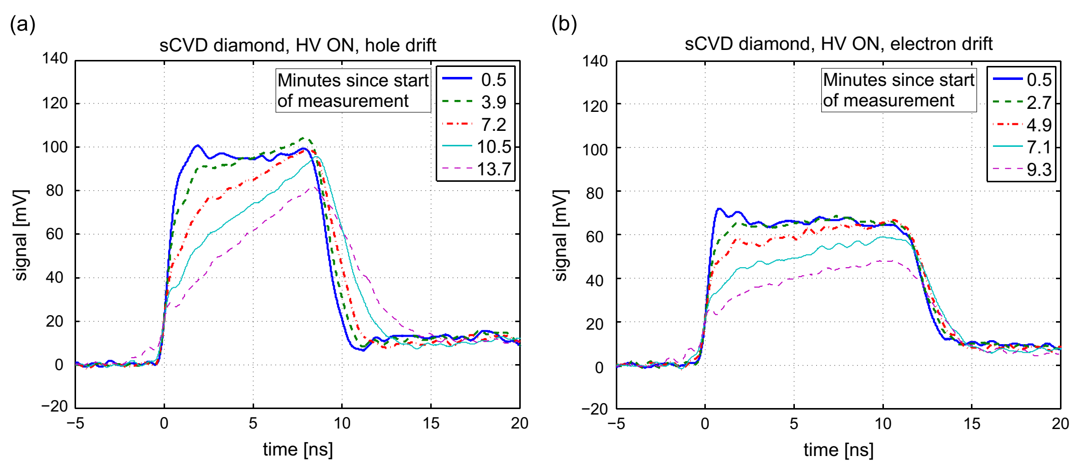

Fig. 7. TCT measurements of the removed sCVD diamond measuring hole drift (a) or electron drift (b). The legend gives the minutes since the measurement started. At first a clear square pulse is observed. With time the signal height decreases showing the buildup of a polarization field.

Since α-particles are stopped in any material an external trigger cannot be used. The oscilloscope is set to trigger on the pulses directly at a 30 mV level. About one single trace per second is stored and later an average over several curves is formed. For the averaging the curves are realigned using a software discrimination at a level of 20 mV.

Fig. 7 shows the TCT scans with the removed sCVD diamond for electron and for hole drift. At the start of the measurement a clear square pulse is visible for both charge carriers showing that there is a constant electric field without internal fields from trapped charges. With time the signal height decreases showing the reduction of the electric field and hence the buildup of a polarization field.

7. Summary

A significant reduction in signal output over 2011 and 2012 was observed in the BCM system at CMS. The measured charge collection distance of removed detectors does not show a reduction after irradiation strong enough to explain the decrease in signal. Measurements using the transient current technique show that the diamond detectors are susceptible to polarization effects, which can explain the unexpected large decrease in signal during operation even after hadron fluences of the order of $10^{14}\,\mathrm{cm}^{-2}$. A method of avoiding the buildup of polarization for future detectors is to alternate the polarity of the HV field.

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