Response of scCVD Diamond Under Sub-Bandgap Irradiations Measured by the CAPTAN Readout System

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Response of scCVD Diamond Under Sub-Bandgap Irradiations
Measured by the CAPTAN readout system.

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Abstract

The radiation hardness of diamonds makes them a strong candidate to replace the inner most part of the CMS tracking detector. Polycrystalline diamond has been shown to regain some its CCD under sub-bandgap irradiations due to the depolarization of the diamond sensor. Monocrystalline diamonds that have suffered proton radiation damage exhibit a similar CCD reduction due to polarization. This study shows that monocrystalline diamond sensors can benefit from sub-bandgap irradiations in a similar manner observed in the depolarization effect seen in polycrystalline diamond sensors.
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Introduction

The Large Hadron Collider (LHC) at CERN is the world’s largest, highest energy synchrotron accelerator. It spans a circumference of 27 kilometers (~17 miles) along the border of France and Switzerland near Geneva (figure 1).[1] Increasing the luminosity (flux) of the LHC would allow for more interactions to be recorded in a smaller amount of time. This makes getting good statistics easier since it takes less time to observe the same number of events. In order to compensate for the increase in radiation due to the increased in luminosity, the detector technology must also be considered.

![Figure 1: An aerial view of the LHC.][1]

The Compact Muon Solenoid (CMS) is one of six detectors on the LHC. This apparatus consists of 5 regions designed to study proton beam collisions that measures a particle’s charge and momentum.[1,11] The tracker (figure 2) is the innermost region and the innermost layer of the tracker operates closest to the interaction point in a very radiation harsh environment.[1,11] The current tracker consists of 13 layers of silicon pixel and silicon strip detectors in the central region and 14 layers in the forward region.[1,11] As high energy particles traverse the tracker they can cause radiation damage to the silicon crystal structure. Damage to the crystal lattice reduces the efficiency and increases the “dark current” (noise) of the detector. If the efficiency becomes too low or the noise too high, the

![Figure 2: CMS Silicon Tracker][1]
detector must be replaced. Replacing the tracking detector in the CMS is costly and time consuming. In order to study higher energy proton collisions in a cost effective manner, a more radiation hard material must be used in the innermost layers of the CMS tracker. Chemical vapor deposition (CVD) synthetic diamonds have the same crystal structure, and operate similarly to silicon crystal semiconductors. However, diamonds have a much smaller nucleon inelastic cross section. This is the main factor contributing to the one order of magnitude increase in radiation hardness for diamond compared to silicon.[18]

Even though diamond has similar electronic properties when compared to silicon, much detail about how diamonds react to radiation still has yet to be explored. If a diamond based tracker is to replace the current silicon based tracker in the CMS detector, diamond sensors must be able to operate in a similar manner to the current silicon sensors. Furthermore, diamond films cannot be directly swapped in place of the current silicon sensors.[4] The larger bandgap of a diamond lattice means that fewer electron-hole pairs will be liberated by a particle of a given energy when compared to silicon. Fewer liberated electron-hole pairs per particle reduces the magnitude of the signal. The difference in signal strength between silicon and diamond sensors means that the current silicon tracking electronics was not designed to be sensitive enough to accurately measure signals from a diamond film. While it is true that a direct substitution of diamond for silicon is not suitable for the tracker upgrade, the current silicon electronics can be used to test how diamonds react to electronics that would be similar to what could be used in a final diamond-semiconductor tracker.

The current readout system used in the CMS Test Beam is known as the CAPTAN system (Compact and Programmable Data Acquisition Node). It is a highly adaptable, high resolution tracker that was developed at the Fermi National Accelerator Laboratory in Illinois to read out
sensors bump-bonded to CMS pixel electronics. Before the next generation diamond tracking detector can be installed into the CMS detector, CVD diamonds must be characterized with the current CAPTAN tracking system to make sure that the test bench measurements coincide with the CAPTAN measurements. This paper will focus on how irradiated and non-irradiated monocrystalline diamonds respond to sub-bandgap, red light irradiation in the context of reducing the effects of polarization under different radiation exposure rates.

**Chemical Vapor Deposition Diamonds**

Chemical vapor deposition (CVD, figure 3) diamonds are synthetic diamond crystals that offer a high degree of control over the properties of the diamond film produced.

![Figure 3: CVD diamond films.](image)

The level of purity, size and low cost make CVD diamonds a revolutionary material that will lead to new classes of experiments and applications [3,8]. Since CVD-diamond-growth technology is still in its infancy, many of the specific procedures for growing diamonds are not yet made publicly available. The general method for growing CVD diamonds is by injecting a gas mixture (which always contains carbon) into a low pressure chamber (plasma reactor, figure 4), then feeding energy into the chamber that generates a plasma that breaks down the gasses and deposits a crystalline carbon structure (diamond) onto the substrate.[3,5,8] The substrate used and gasses present dictate the final crystal quality of the diamond.[3,10] Even though growing CVD diamonds is highly controlled process, improving the diamonds’ quality and size remains a topic of research. [9]
There are two types of diamonds being considered: polycrystalline CVD (pCVD) diamonds and single crystalline CVD (scCVD or monocrystalline) diamonds. PCVD diamonds are usually grown on silicon substrates and are defined by their numerous crystal orientations. Between the different crystal orientations exist grain boundaries, which contain impurities and affect the diamond’s ability to output charge (signal). ScCVD diamonds are grown on high pressure high temperature diamonds (which don’t have to be electronic grade) and contain only one crystal grain orientation. Since scCVD diamonds have no grain boundaries, a good, pure scCVD sample will output what is theoretically expected for a minimum ionizing particle traversing the diamond bulk (36 electrons per 1μm of semiconductor from a minimum ionizing particle traversing the diamond bulk or full charge collection).

**Growing CVD Diamonds**

In the field of growing CVD diamond there are two competing factions: the private and public (scientific) sectors. Element Six is the world’s dominant diamond producing company (for all types of applications). They have pioneered many CVD diamond advancements, and in 2001 produced the first scCVD crystal that output full charge collection. Since Element Six is
a private organization their intellectual property is not public. Moreover, the scientific community has also made efforts to grow CVD diamonds.[8] In general, they trail Element Six’s ability to consistently produce high quality diamond sensors. However, the scientific community has made great advances in recent years, and can develop specialized CVD technologies that Element Six might not otherwise deem profitable.[2,8]

There are three factors that determine the type of crystal grown. The substrate, gasses present, temperature, and chamber pressure.[8] The substrate provides a surface for the diamond to grow on.[8] Many different types of materials can be used as a substrate; however, silicon and diamond are the predominate substrates chosen for electronics grade CVD films. [3,8] The gasses present also play an important role in CVD growths. The standard gas mixture is a methane-hydrogen mixture (generally 5% methane and 95% H₂).[8] The carbon deposited onto the substrate comes from the methane, and the hydrogen facilitates the plasma’s presence.[8] Dopants (such as nitrogen and boron) can be added to the gas mixture to facilitate the diamonds growth;[3] however, they usually have a negative effect on the electronic properties of the diamond film.[3,9] The pressure at which the diamond film is grown does not largely impact the diamond growth (crystal structure or purity), but plays an important role in the stability of the plasma present during the growth process.[8]

Producing consistent high purity large area CVD diamond films continues to be the largest obstacle if diamonds are to replace silicon in the CMS tracker.[9] Since CVD films are such a contemporary material and their use in electronics is only a small fraction of their potential uses, the future for researching CVD diamond films is optimistic.[8] If CVD diamond films are to replace the silicon wafers in the CMS tracker a better understanding of the growth process must be established.
**Band Gap Model for Semiconductors (Diamond)**

The transport of electrons is most easily understood by investigating the energy band structure of diamond material. Figure 5 depicts the band structure of a diamond and is characterized by a noticeable “gap” between the top of the valence band and the bottom of the conduction band. “Bands” are the states of electron energies that are allowed in the diamond material. The energies within the band gap are not allowed in a theoretical electronically perfect diamond.

Valence band electron energies that are bound to individual lattice atoms and do not contribute to electrical current. While electron energies in the conduction band are not bound to atoms and are free to traverse the diamond bulk. Since the Fermi Level (the energy of the highest energy electrons in the diamond) exists very close to the top of the valence band there is a minimum amount of energy needed to excite an electron from the valence band to the conduction band. Thus if a particle is traversing the diamond lattice and deposits at least the energy associated with the band gap an electron in the valence band can be excited to the conduction band. If a voltage is applied to the diamond the electron and hole (charge deficiency in the valence band) will be influenced to drift towards the positive and negative electrodes respectively (for the hole-vacancy, electrons in the valence band are the “mobile” charge carriers but it is convenient to model the hole as moving). The electron-hole pair signal can be measured and thus information regarding the particle that traversed the diamond semi-conductor can be inferred.

![Figure 5: Band gap for a diamond semiconductor.](image)
An electrically impaired CVD diamond will have defects in the lattice that hinders an electron-hole pair’s ability to traverse the diamond. [3,9,11] Electron or holes can be trapped or allowed to recombine with their opposite charge at these defect sites.[11] If an electron or hole is trapped or recombined with its opposite charge that portion of the signal will be lost. High energy particles (such as the particles that the detector is measuring) can knock lattice atoms from their native positions inducing defects in the lattice. This is one process by which a sensor becomes radiation damaged.[9] Electronically well behaved diamonds that have suffered radiation damage will have their electrical properties reduced due to radiation induced lattice defects.

**Methods for Studying Charge Collection**

**Charge Collection Distance**

Charge collection distance (CCD) is how a diamond’s efficiency is quantified. The CCD of a diamond refers to how far an electron-hole pair can traverse the diamond’s crystal lattice before it is lost.[9] A theoretically ideal diamond will output 100% of the electron-hole pairs created.[9] This would correspond to a CCD that is limited by the thickness of the diamond. If an ideal diamond was 1mm thick it would have a CCD of 1mm (if a diamond is thicker than its mean free path, its CCD will correspond to the mean free path). Since a particle’s ability to liberate electron-hole pairs in a

![Figure 6: Landau distribution of the electron output from a pCVD detector in a pumped (right distribution) and depumped (left distribution) state.][9]
sample is driven by statistics, recording a reliable (low error) CCD requires data acquisition over a large sum of hits.[4] The electrons liberated from each particle passing through a sample is characterized by a Landau distribution which is then used to calculate the sample’s CCD (figure 6).

**CCD Characterization Method**

The methods for studying charge collection are nearly ubiquitous from lab to lab. The general experimental setup is outlined in figure 7. A high voltage (which can be positive or negative) is applied to one side of a diamond film and the other side is set to ground. The electrodes which are placed on the substrate and growth sides of the diamond apply an uniform electric field to the diamond bulk. When an ionizing particle traverses the diamond it excites electrons from the diamond’s valance band to its conduction band. The electron-hole pair signal is swept away by the voltage, amplified by a charge-sensitive pre-amp and then finally fed into a pulse shaper that differentiates the signal. The derivative pulse is then sent into an analog to digital converter that

![Diagram](image-url)
outputs a digital signal into a data recording device (usually a computer). This all culminates to an output pulse like the one depicted in figure 7. Slight variations in the schematic exist from experiment to experiment; however, these variations do not produce different results in CCD measurements.

**ScCVD Diamonds Charge Collection**

The first scCVD crystal (which was made by Element Six) was tested by the RD42 collaboration in 2002.[4] The sensor demonstrated full charge collection, which is consistent with what is expected for a pure, high quality diamond.[4,9] The most probable charge output vs. thickness using a Sr$^{90}$ source is graphed up to .77 mm in thickness (figure 8).[4] The graph displays a linear charge vs. thickness trend which indicates that the CCD of the scCVD sample tested was dependent on the thickness of a sensor. This means that the scCVD sensor tested was of high purity and did not have large defects or grain boundaries for the electron-hole pairs to get trapped in.[4]

As long as a scCVD sample is high quality it will demonstrate full charge collection.[4,9] This is consistent with the theoretical expectations of a diamond’s solid state response.[4,5,9] ScCVD diamonds have been made as big as 1cm$^2$ and as thick as .77 mm, but the reproducibility of growing such large high quality scCVD samples has been problematic.[4,9]
scCVD diamonds are to replace the silicon detectors in the CMS tracker, consistent high quality, large area scCVD films must be grown in a cost effective manner.

**PCVD Diamonds Charge Collection**

**Priming**

“Priming” or “pumping” is the act of pre-irradiating a sample before testing.[4,6] The domain boundaries, impurities, and other lattice defects between different crystal orientations in pCVD crystals act as electron-hole traps, and reduce the overall CCD of the sample.[7,6] Pumping or irradiating the diamond before collecting data, has been shown to fill some of the deep traps which makes it easier for an electron-hole pair to traverse the diamond, thus improving the sample’s CCD.[6] There are two types of defects that form in pCVD crystals: intragranular and grain boundary defects.[6] Intragranular defects form uniformly throughout the sample, and grain boundary defects form along the grain boundaries due to individual grain orientations competing for space during the growth process.[6] Even though the exact theoretical mechanisms behind the priming effect are unclear,[6] the improvement of the CCD for a pumped sample has been very well documented.[3,4,6] The exact efficiency increase is dependent on individual crystal sample, but priming a diamond prior to data collection generally increases the CCD anywhere from 6% to over 50%. [4,6] The increase in CCD will last about 40 minutes in “normal” lab conditions, and gradually decrease until it is unnoticeable after about 12 hours.[6] Furthermore, priming’s efficiency increase is dependent on the side of the crystal that is irradiated. If the growth side is irradiated the efficiency will increase by about 13%, and if the substrate side is irradiated the CCD will increase by about 6%. [6] This effect is most likely attributed to the growth process of individual crystal orientations.[4,6] When a pCVD crystal is grown each grain orientation grows up in a conical shape.[3,6,9] The smaller “weaker” crystal
orientations get overtaken by the larger ones and the result is a higher quality (more uniform) top growth side when compared to the substrate side.[6,9]

**Polarization**

Polarization is a well-documented effect observed in both pCVD diamond films. This effect is due to the buildup of charge at different defect sites that create a polarization electric field in the diamond that opposes the influence of the applied bias electric field which reduces the CCD of the sample. [15]  

Polarization has been observed to be so great that the remnant polarization field left in the diamond (that slowly discharges) after the bias voltage has been turned off is strong enough to “self-bias” (with opposite polarity from the original bias voltage) the diamond and allow for the measurement of particle signals. Some unrated scCVD diamonds show a small polarization, but it is often very weak and quickly vanishes.

**CCD’s Spatial Dependence**

The grain boundaries that define pCVD diamonds act as traps for the electron-hole pairs are is responsible for the lower CCD’s of pCVD sensors.[4,6,8,9]  

As represented in figure 9 there is a noticeable spatial dependence of the CCD for pCVD diamonds.[7] The local response areas on the CCD map are comparable in size to the individual grain orientations of the sample.[7,8] The CCD is also dependent on the Z (vertical) direction as well. The Z dependence of charge collection is not heavily dependent on
the individual grain orientations in the diamond, but instead depends on the distance from the substrate.[7] The charge collection (and therefore crystal quality) of the sample increases as the diamond grows up away from the substrate.[7,9] However, the increase of the quality as a function of thickness is a well-known attribute of CVD diamonds.[7,9] The CCD for pCVD diamond perpendicular to the growth direction has been documented to be 40% to 70% lower than the CCD measured parallel to the growth direction.[7] In order to draw conclusions about the mechanisms that drive discrepancies between parallel and antiparallel CCD measurements, further studies must be conducted.[8] Moreover, it is clear that the CCD of pCVD sensors are greatly reduced by the inconsistencies in the crystal lattice that characterize them.

**PCVD Diamond’s Response to Sub-bandgap Irradiation**

Sub-bandgap irradiation has been observed to “depolarize” poor quality, unirradiated, pCVD diamonds [16]. It is thought that polarization is due to buildup of charge (either holes or electrons) at defect sites. Since defect sites are evenly distributed in the diamond bulk and a bias voltage is applied to the diamond, holes are more likely to be trapped near the negative electrode and electrons are more likely to be trapped near the positive electrode.[16] This buildup of charge is responsible for “polarization” in diamonds and reduces the CCD of a sample by opposing the applied bias electric field. If sub-bandgap irradiations have enough energy to excite electrons from the valence band to the defect level fewer electron-hole pairs will be lost to

![Figure 10: Depolarization of defected CVD diamond due to subbandgap irradiation.](image)
defects (figure 10).[16] It is known that non-radiation damaged scCDV crystals are not sensitive to sub-bandgap, (visible) light. However, the interaction of sub-bandgap radiation with radiation damaged scCVD diamond films has not yet been fully explored. If CCD degradation in radiation damaged scCVD diamond films can be partially regained by sub-bandgap irradiations similar to what has been observed in pCVD diamonds, the lifetime of a scCVD detector could be extended reducing the cost to operate that detector.

The CAPTAN System

The pixel detectors in the CMS tracker can be read out by the CAPTAN system. Since diamond and silicon semiconducting mediums are so similar a diamond sensor film can be directly substituted in for a silicon sensor using the current silicon based electronics. This substitution however, is not optimal. Diamond has a much smaller leakage current when compared to silicon (the current associated with the finite resistance of the semiconducting medium under bias voltage), and puts out fewer electrons per ionizing particle when compared to silicon sensors.

Figure 11: The CAPTAIN core board and pixel detector card.
(diamonds have lower noise and put out smaller pulses). If a new diamond tracker is to be used in the CMS detector, more sensitive diamond based electronics will have to be developed; however, the current silicon based electronics are suitable to study how diamond sensors respond to a pixelated readout system that is similar to what would be used in a final version of a diamond based CMS tracker. The CAPTAN system consists of two main components: the main core board and pixel detector cards (figure 11). The main core board acts as analog to digital (ADC) converter that allows the CAPTAN to interface with a computer. A user can configure the CAPTAN, record runs, and calibrate test cards from the computer’s interface. The CAPTAN system uses pixelated detectors in order to increase its spatial resolution. Pixel detectors operate in a similar manner to the CCD characterization setup, but differ in one major way. Pixel detectors interface with the diamond bulk via a Read Out Chip (ROC, 4160 pixels for each read out chip that measure .15mm x .1mm figure 12) that have individual pixel electrodes and signal processing electronics (the amplifier and pulse shaper as described in the CCD characterization setup) on the signal side of the diamond film. Each pixel is “bump bonded” (electrically interfaced to a pixel electrode by a small indium “bump”) to an individual channel on the read out chip (ROC). Since each channel can output a signal, a pixel detector can create a 2D map of hits (figure 13) in addition to providing the raw number of liberated electron-hole pairs in the semiconductor bulk. The CAPTAN system also allows for multiple cards, multiple planes of detectors, and multiple CAPTAN’s to be tested at once. This allows a user to create high resolution, 3D tracks of a particle’s trajectory and energy.
Setting Up the CAPTAN

The CAPTAN system uses a set of proprietary software that was developed in conjunction with the CAPTAN hardware at Fermi Lab. The software consists of: a Global Master (GM), CAPTAN Controller (CC) and Graphical User Interface (GUI). The GM and CC allow a computer to interface with the CAPTAN system and their exact functions are unimportant; however, the GUI is used to program, record data and calibrate the CAPTAN system.

Before a test can be run the CAPTAN and detectors must be prepared for testing. The CAPTAN is simple to setup and involves establishing a connection from the CAPTAN to the computer and setting the clock on CAPTAN’s field-programmable gate array (the processing unit on the CAPTAN). Most of the detector electronics setup is trivial; however, the register values Vana and Vthres must be considered for each card. Vana controls the amount of voltage that is applied to the amplifier in the post processing circuitry, and Vthres sets the threshold for a pixel to be considered “hit” and read out. These two register values work together to set the effective threshold for the ROC and must be adjusted so that the threshold is just above the noise window so that the number of extraneous noise hits is minimized. Setting the mask for the ROC is the final step in preparing the detector card for data acquisition. For each ROC that is being tested a mask can be written to the card. This mask allows a user to turn certain pixels “off” from data collection. If a particular pixel or area of the card is noisy those pixels can be “turned off” in order to operate at a lower threshold. Not all semiconductor films cover the entire ROC and

Figure 13: 2D hit map on a typical sensor. The color scale (from red to green) represents the relative number of events each pixel has recorded.
masking out the areas that are not in use is also a convenient way to reduce the number of false hits recorded during a data collection.

**Charge Calibration and Clustering**

The data collected during a test run does not directly correspond to the mean charge and number of hits that were recorded during a test run. A charge calibration in which the CAPTAN injects a known amount of charge into each pixel and records the signal must be conducted first. The charge calibration creates a calibration curve for each pixel by a stepped process of increasing the amount of known charge injected into each pixel and recording the output. The calibration curve for each pixel can be merged with the data file that the CAPTAN records during a test run to create a histogram of the number of this and mean charge collected during the test (figure 14). These histograms can be cut in order to cut out noise hits.

A particle’s signal is not usually collected in a single pixel but rather distributed over a “hit cluster.” When the data file and calibration file are merged the merging code must be able to “cluster” pixels that were hit by the same particle into one event. The clustering done at CU is defined by the time stamp associated with hit pixels, any number of adjacent pixels hit at the same time are considered a cluster so that even if charge is dissipated over a large area it is still counted as a single event.
The Experiment
The two 500 nm thick diamond films used for this experiment were E6-DDL-M1 (M1) and PLT-32a (PLT). M1 is a scCVD diamond film that was irradiated at Los Alamos with proton irradiation ($3.2 \times 10^{14} \text{proton} \times \text{cm}^{-2}$ and has suffered radiation damage). PLT is a scCVD crystal that has not undergone any intense proton radiation and is not radiation damaged. These films were chosen because prior to M1’s exposure to high energy proton radiation, both detectors were electronically very similar. Both of these films have been bump bonded to ROC’s that can be used in conjunction with the CAPTAN system at CU. A $S\text{r}^{90}$ beta source was used for this experiment. Three different radiation rates were tested for the M1 sensor. The rate of radiation was controlled by varying the distance the source was away from the detector. Consistency in height and position of the source was controlled by a Plexiglas box with a source mount at the top and test card slots that were machined so that test cards could be easily and accurately slid into position (figure 15). This study was mostly concerned with the rate dependence of the detector and not the actual rate itself, thus the somewhat arbitrary variance of detector height to alter the radiation rate is more than adequate. Moreover, since the clock that sets the sample rate for the CAPTAN system is slower than the rate of the $S\text{r}^{90}$ source the measured effective rate will represent only a
fraction of the actual rate of the Sr\textsuperscript{90} source. Since this experiment is only concerned with the detectors dependence on different rates this discrepancy will not detract from the observed effects of rate dependence of the detectors.

A red LED (most probable wavelength of 650nm) was used to quench the diamond during tests and was located 1cm away from the diamond (figure 16). The intensity of the LED was 2.4 mW/cm\textsuperscript{2} at a distance 1cm from the side of the LED. In another study the actual effect of the red light irradiation was shown to be somewhat independent of intensity.

This is due to an apparent large plateau of CCD increase associated with an intensity of red light greater than 1mW/cm\textsuperscript{2}.[18]

The M1 and PLT sensors were pumped using the same Sr\textsuperscript{90} beta source used for testing in the dark at 0V for at least 1 hour before testing. Before data could be taken the voltage was smoothly ramped up until the diamond was at 1V/um (500V for each sensor, each ramp up took approximately 1 minute). Once the voltage was fully ramped up data collection was started. Each test run consists of 7 data points that were taken in the dark or in the dark with the red LED on (no external light sources). A data point consists of a 10 minute run where the number of clusters and mean charge are recorded. Between each 10 minute data collecting period the system was left for 5 minutes to “rest” under the same conditions that data was collected (under radiation, in the dark, with the red LED on or off).
For each series of 7 data points there were four 10 minute runs taken in the dark (red LED off) and three runs that were taken with under red light radiation. The red LED was turned on right after the 4th data collection run had finished so that the sensor was exposed to 5 minutes of red light radiation exposure before the start of the 5th test was started.

The CAPTAN system was used to collect the data for each run and the threshold was set for each card so that it was just above the noise window. A mask (figure 17) was used for both sensors which masked out an area smaller than the effective sensor area so that only a region of “good” sensor was under test.

Figure 17: The ROC area, sensor area, masked area, and cut are.

Once the test runs were collected they were post-processed using a charge calibration that was taken using the same register settings as the test runs were taken at, and the files were clustered and merged with the charge calibration file using a proprietary clustering code that was developed at CU. The same charge calibration file was used to merge all test runs for individual cards. Centers of hit clusters were restricted to be at least one pixel in from the mask that was written to the ROC during data collection in order to reduce the amount of charge that was dissipated outside of the final data collection area (the cut area of figure 17). Finally a lower and upper limit were placed on the calculated histograms. The upper limit and the lower limits (5000 e− < hit cluster < 100,000 e−) were imposed to cut out any uncertainty in the calibration curve uncertainty near the upper and lower limits of the charge calibration.
Results

Using the Plexiglas box described above the radiation damaged M1 sensor was tested at 3 different effective rates (8 Hz, 1 Hz and 2 Hz for M1 which correspond to the 3 different heights tested in the Plexiglas box). The results are summarized in figure 18. It is clear that the radiation damaged M1 sample does become depumped after the bias voltage has been applied and then recovers a significant portion of charge when the sensor is quenched with sub-bandgap radiation from the red LED (the red light is turned on at the 55 minute mark for each test and is denoted by a red line). There is also an apparent rate dependence for polarization as evidenced by the larger CCD reduction for the top and middle slots when compared to the lowest (lowest rate) slot.

The difference in average charge and rate between the top slot and the lower slots is due to low energy beta particles emitted from the $^{90}\text{Sr}$ source. When the sensor is placed in the middle and lower slots the low energy $^{90}\text{Sr}$ beta decay emissions ($E < 0.546 \text{ MeV}$) are dissipated in atmosphere and the only the $^{90}\text{Y}$ beta emissions ($E \leq 2.28 \text{ MeV}$) deposit energy in the detector.

<table>
<thead>
<tr>
<th>Slot</th>
<th>Max Percent Reduction of Rate</th>
<th>Max Percent Reduction of the Average Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>40% +/- 2%</td>
<td>17% +/- 1%</td>
</tr>
<tr>
<td>Middle</td>
<td>11% +/- 6%</td>
<td>29% +/- 2%</td>
</tr>
<tr>
<td>Bottom</td>
<td>0% +/- 10%</td>
<td>1% +/- 6%</td>
</tr>
</tbody>
</table>

Table 1: Percent reduction of the rate and average charge before red light irradiation for M1.

There also appears to be a discrepancy in the magnitude of the reduction of the rate and average charge recorded between the top slot, middle and lower slots (summarized in table 1). In the top slot the number of entries is reduced by 40% by the fourth data point whereas the middle and lower slots were reduced by 11% and 0% respectively. This effect is can be attributed to the
Figure 18: The rate and average charge for the M1 sensor in the top, middle and bottom slot, and the rate and average charge for the PLT sensors in the top slot. The red line on each graph denotes when the red light was turned on.
dispersion of the lower energy Sr$^{90}$ beta emissions into the atmosphere. For the top slot the lower energy Sr$^{90}$ beta emissions contribute low energy clusters (that are just above threshold) to the number of events recorded. A small reduction in the carrier mobility will reduce the charge measured for the low energy Sr$^{90}$ beta particles bringing some pixels below threshold (and therefore not counted any more). The number of events recorded from the higher energy Y$^{90}$ beta emissions; however, will not be affected greatly since their clustering energy is so far beyond threshold.

The mean charge was reduced by 17% in the top slot by the fourth data point and 29% and 1% in the middle and lower slots. For the measured mean of the top slot there are two energy clusters contributing to the mean charge (from the lower energy Sr$^{90}$ and the higher energy Y$^{90}$ beta emissions). The CCD reduction due to polarization will “cut out” the lower energy hits leaving the higher energy hits still contributing to the average charge measured. This means that a reduction in carrier mobility will not reduce the measured mean charge as much since the lower energy clusters will not be “pulling the mean down” as much any more. Furthermore, the mean for the middle slot will be significantly reduced since there are mostly Y$^{90}$ beta particles contributing to the mean charge. Any reduction of the carrier mobility in the diamond bulk will directly reduce the mean charge of an event. The bottom slot appears to have a constant rate and a mean charge trend that is consistent with the higher rate slots (although the effect is small). The minimal reduction of both hits and mean can be contributed to the rate dependence of polarization in the diamond bulk. The rate for the bottom slot is too low for a significant polarization to build up in the diamond and thus only a very small reduction in the mean charge (1%) was observed and effectively zero change was observed in the number of events.
The unirradiated PLT sensor was only tested at the top slot (at an effective rate of 22 Hz) and its results are summarized in figure 18. This sensor’s CCD does not appear to be degraded by polarization build-up or enhanced by sub-bandgap red light radiation. This is consistent with previous studies with unirradiated scCVD crystals. Both the mean charge and the number of events for the PLT sensor appear greater than that measured by the M1 sensor. This is most likely due to the fact that the ROC’s used for this experiment were not designed for diamond films and thus there is some ambiguity in the thresholds set for each sensor. M1 was also radiation damaged and does not exhibit full charge collection post irradiation. Regardless of the discrepancy in hits and mean for the PLT sensor, the sensor’s carrier mobility does not appear to be affected by beta emissions or sub-bandgap red light irradiation.

**Conclusion**

After testing both proton irradiated and unirradiated monocrystalline detectors with the CAPTAN system, our data shows that a radiation damaged scCVD crystal that have an observed CCD reduction due to polarization can be reclaimed by sub-bandgap red light illumination. The exact mechanisms that drive this effect are unclear; however, irradiating damaged scCVD crystals with red light during operation does appear to be a practical solution for regaining at least some of the CCD lost to radiation damage. The nonirradiated PLT sensor’s CCD was not sensitive to the rate of radiation exposure or sub-bandgap red light irradiation which is consistent with expectations for high quality scCVD diamonds.
References

[1] CERN. *LHC the Guide*. CERN.


