Recent Results of Radiation Hardness Studies on CVD Diamond Detectors

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Abstract

The inherent properties of diamond are well suited for use in tracking detectors, especially in the high rate and high radiation environments of future colliders such as the LHC. To survive in this environment, detectors must be radiation hard. In order to demonstrate the radiation hardness of CVD diamond, we exposed samples to large fluences of 300 MeV pions, 500 MeV and 24 GeV/c protons, and 1 MeV neutrons. The signal response to minimum ionizing particles is measured before and after irradiation. Results show that CVD diamond is an extremely radiation hard material and well suited for use in regions of highest radiation at the LHC.

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[22] Presented Pixel 98 Talk

1 Overview of CVD Diamond Detectors

Tracking detectors in future high energy experiments will be exposed to increasingly higher levels of radiation. The potential damage to both the sensors and electronics caused by expected levels of radiation is in many cases exceeding current detector technology. A search for new sensor material which might be inherently radiation hard has yielded two candidates: gallium arsenide and chemical vapor deposited (CVD) diamond. We report here results from recent pion, neutron and proton irradiation studies on CVD diamond detectors.

Chemical vapor deposited (CVD) diamond is a polycrystalline, high band gap material. It tends to grow in a columnar structure where the grain size increases from the substrate (nucleation) side to the growth side. The charge collection efficiency is related to the grain size: it is close to zero near the substrate side and grows linearly to the growth-side surface[2]. To improve the average bulk charge collection efficiency, material from the substrate side can be polished away.

Table 1 lists some properties of CVD diamond in comparison to silicon. The most distinctive feature of diamond is its large band gap, 5.5 eV. This large band gap along with the associated large cohesive energy are responsible for much of the radiation hardness of diamond. The large band gap also makes diamond an excellent electrical insulator. As a result, a large electric field can be applied without producing significant leakage current. Thus, there is no need for a reverse biased *pn*-junction and the diamond detector functions much like a "solid-state" ionization chamber.

Although diamond appears ideal in many characteristics, it does have one limitation: its large band gap, which determines many of its outstanding properties, also makes the signal size about half that of silicon for an equivalent thickness in radiation lengths. On average, 3600 electron-hole pairs are created per 100 μm of diamond traversed by a minimum ionizing particle. The quality of current CVD diamond material does not allow the above limit of signal size to be achieved due, most likely, to imperfections in the the crystal lattices that cause the produced charge to become trapped before it is fully collected. Compensating for this loss of signal is diamond's lower dielectric constant and negligible leakage current: both of which tend to reduce frontend noise.

Prototype detectors using CVD diamond have been constructed. An electromagnetic calorimeter prototype using CVD diamond as the active sensor material has been built and tested in 1993[7]. Microstrip tracking detectors have also been constructed and tested by RD42[8]. Testing of a prototype pixel detector by RD42 is detailed elsewhere in these proceedings.

2 Characterization of Diamond Detectors

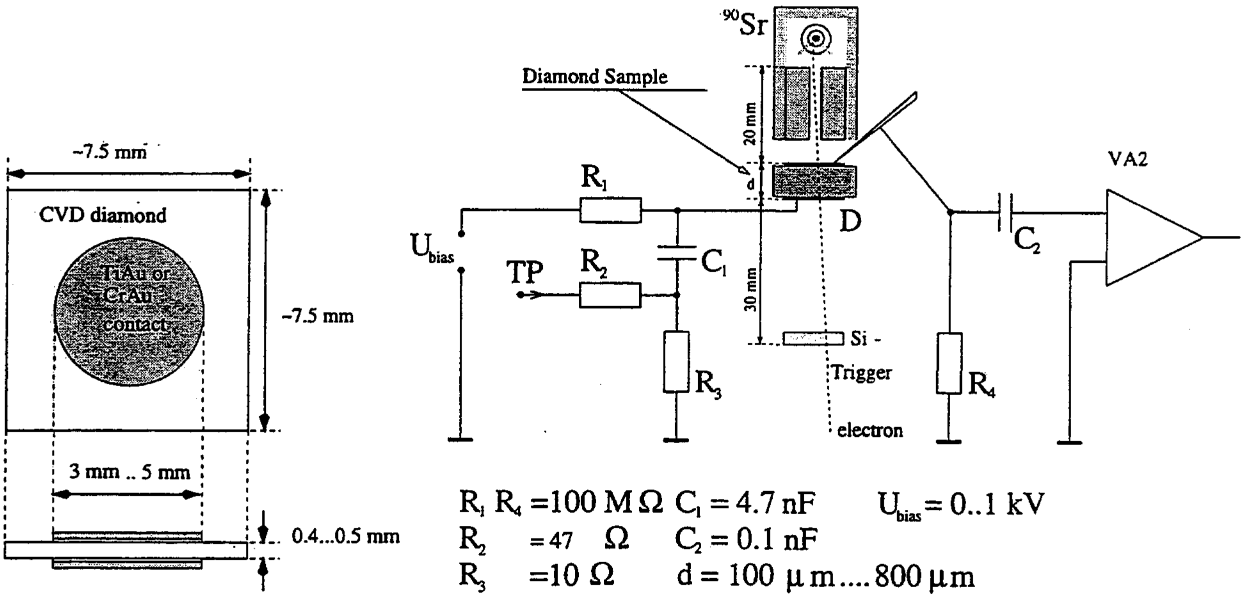
A simple and reliable method to characterize the charge collection efficiency of diamond detectors before and after each irradiation is needed to determine whether or not significant damage has occurred. Figure 1 shows such a system. As shown, a ^{90}Sr beta source

Property	Diamond	Silicon
Band Gap [eV]	5.5	1.12
Breakdown field [V/cm]	10^7	3×10^5
Resistivity [Ω-cm]	$> 10^{11}$	2.3×10^5
Intrinsic Carrier Density [cm^{-3}]	$< 10^3$	1.5×10^{10}
Electron Mobility [$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$]	1800	1350
Hole Mobility [$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$]	1200	480
Saturation Velocity [μm/ns]	220	82
Thermal Conductivity [W m^{-1} K^{-1}]	1000-2000	150
Dielectric Constant	5.6	11.9
Cohesive Energy [eV/atom]	7.37	4.63
Neutron Transmutation Cross Section [mb]	3.2	80
Energy to create e-h pair [eV]	13	3.6
Mass Density [gm/cm^3]	3.5	2.33
Ave Number of e-h Pairs Created/100 μm [e]	3600	7300

Table 1: Comparison of Properties of Diamond and Silicon[1]

is normally incident onto one diamond surface and a silicon diode trigger is placed on the opposite surface. With proper collimation most triggers result, on average, in a beta electron depositing approximately minimum ionizing energy through the bulk of the diamond. With electrodes placed on both surfaces and with a voltage (typically 1V/μm) applied, the electron-hole pairs produced move in opposite directions in response to the applied electric field. A signal can thus be measured using a charge-integrating amplifier.

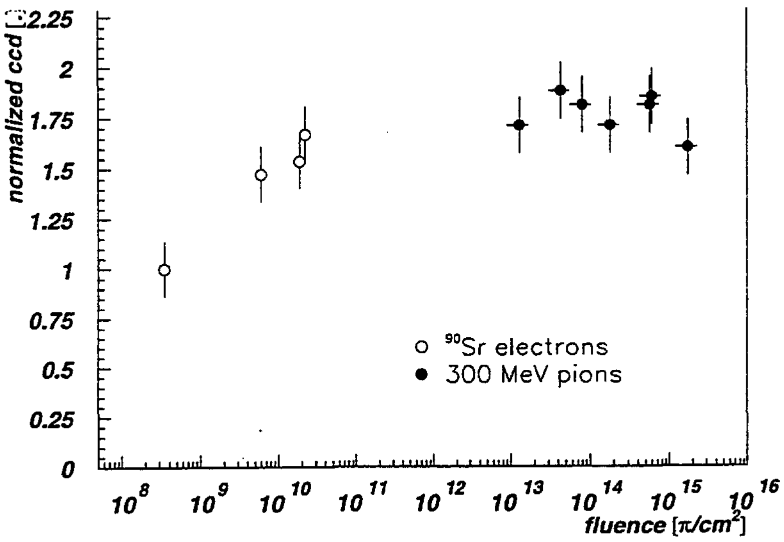
Figure: 1 ^{90}Sr Measurement System



3 Pion Irradiation Study

In 1994 and 1995, diamond detectors were irradiated with 300 MeV pions at PSI, in Villingen, Switzerland. A total fluence of 1.8 x $10^{15}\pi/\mathrm{cm}^2$ was obtained over this period. The diamonds were kept at room temperature before, during and after irradiation. Figure 2 shows the results of the irradiation by comparing charge collection before and after irradiation using the ^{90}Sr characterization setup described above.

Figure 2: Pion Irradiation of CVD Diamond



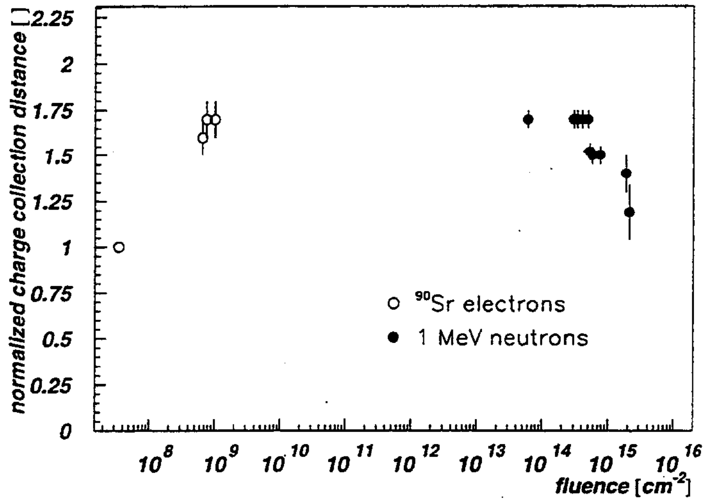
The diamond detectors studied have varying charge collection efficiencies, but are all shown normalized to 1, measured at the lowest fluence using ^{90}Sr. The four lowest fluence points are all taken using ^{90}Sr, prior to pion irradiation, and illustrate the "pumping" or increase in charge collection efficiency of diamond detectors with modest levels of ionizing irradiation. This pumping effect can be explained by the eventual filling or neutrallization of traps in the bulk diamond by the ionization from irradiation. Once a trap is filled it can no longer trap or impede the progress of the charge carriers as they move to the electrodes, thus increasing the effective collected charge. These traps stay neutrallized for extremely long periods of time (months) if the diamond are kept light-tight.

The points labled "300 MeV Pions" are mesurements performed using ^{90}Sr but "pumped" by the pion irradation to the given fluence. There is no significant degradation of the charge collection up to 1.8 x $10^{15}\pi/cm^2$.

4 Neutron Irradiation Study

Neutron irradiation studies have been carried out at the ISIS neutron spallation source at RAL, Chilton, UK. The source had two energy maxima: one below 10KeV and one of interest at 1 MeV. The study completed in 1996 achieved a fluence of 1.9 x $10^{15} n/\text{cm}^2$. All samples were biased at 100V to sample the beam induced current during irradiation and maintained at room temperature before, during and after irradiation.

Figure 3: Neutron Irradiation of CVD Diamond

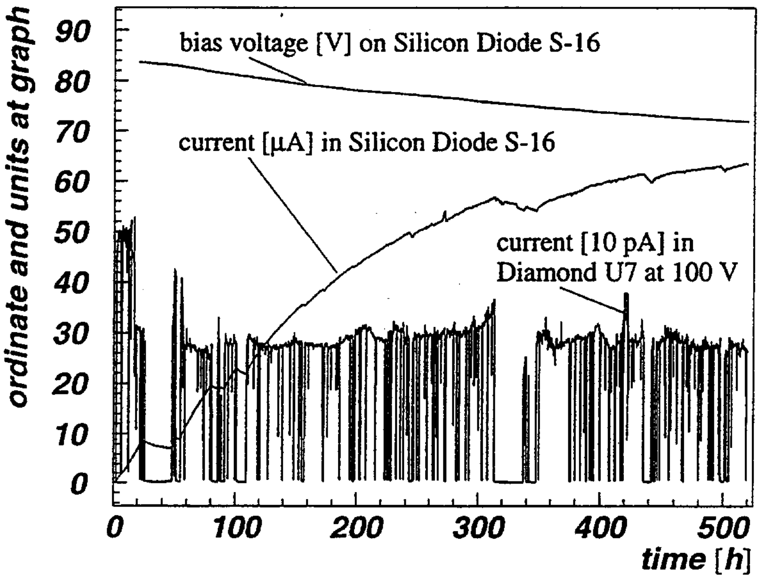


As shown in Figure 3 above, starting a little less than 10^{14} and up to 5 x $10^{15} n/\text{cm}^2$, the relative charge collection "pump-up" value agrees well with that for ^{90}Sr low fluence measurements. This pump-up is most likely due to a photon component in the beam. At 1.9 x 10^{15} n/cm^2 there is a 15% decrease in charge collection.

Figure 4 below shows the beam induced currents measured thougout the irradiation period. The current for diamond detector labeled U7 shows good correlation to the beam current structure (not shown), with clear periods of beam off at 20-50 hours and at 315-340 hours as well as many brief segments of beam instability.

For comparision, a silicon diode of comparable area was also irradiated and its current measured. As can be seen in Figure 4, the silicon diode current is two orders of magnitude higher than for the diamond detector and shows an increase in current throughout the irradiaton period. During the extended periods when the beam was off, the current decreases slightly (evidence of annealing) but does not return to the pre-irradiated value.

Figure 4: Neutron Beam Induced Current



5 Proton Irradiation Studies

5.1 Triumf irradiation

A proton irradiaton study at Triumf was performed in 1994 and 1995. A fluence of 8 x $10^{13} p/cm^2$ was achieved using protons of 500 MeV kenetic energy with a flux of 8 x $10^8 p/cm^2/s$.

Figure 5 shows the charge collection efficiency of diamond detectors, again normalized to 1 at the lowest, unpumped ^{90}Sr fluence. A typical pump-up factor of 1.5 to 1.7 is evident for the measurments made after the high fluence irradiations with protons. Hence there is no apparent decrease in the charge collection efficiency up to the maximum fluence.

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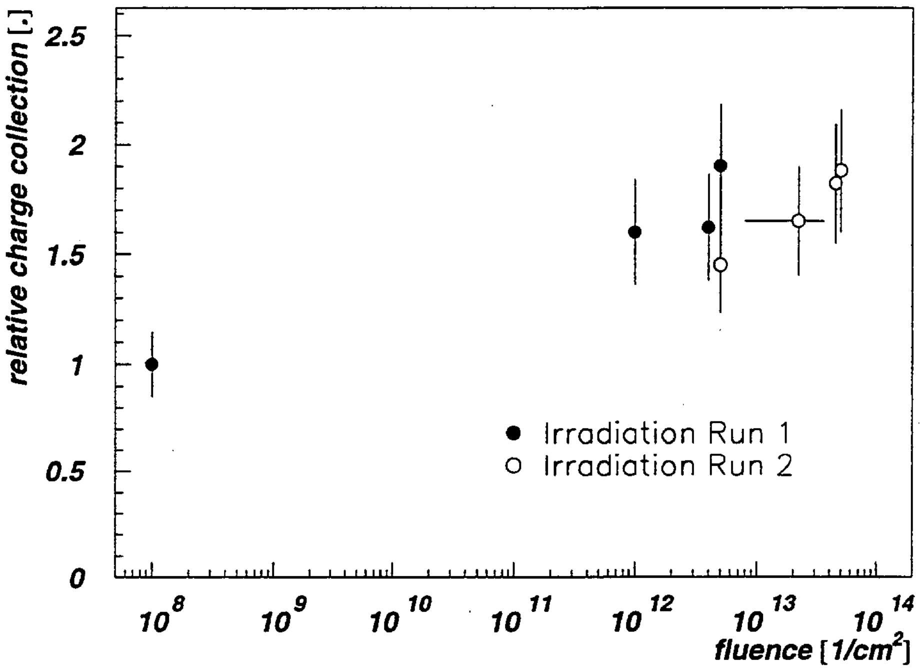
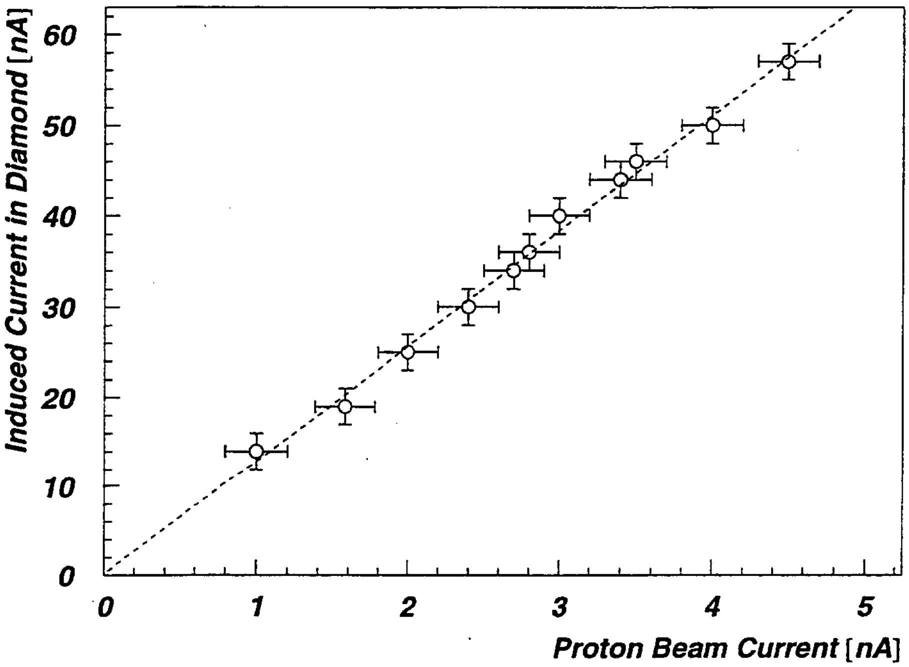
Figure 5: Triumf Proton Irradiation of CVD Diamond



The Triumf proton beam was continuous and the flux could be controlled between zero and 8 x $10^8 p/cm^2/s$. The flux was measured with an ionization chamber whose current was propostional to the flux. Figure 6 shows the beam induced current in one of the diamond detectors as a function of current in the ionization chamber. The linear response of the diamond current to the proton flux suggests that the charge collection efficiency of diamond is unchanged up to 8 x $10^8 p/cm^2/s$, which is equivalent to a 5 nA proton beam current and demonstrates the high rate capability of CVD diamond detectors.

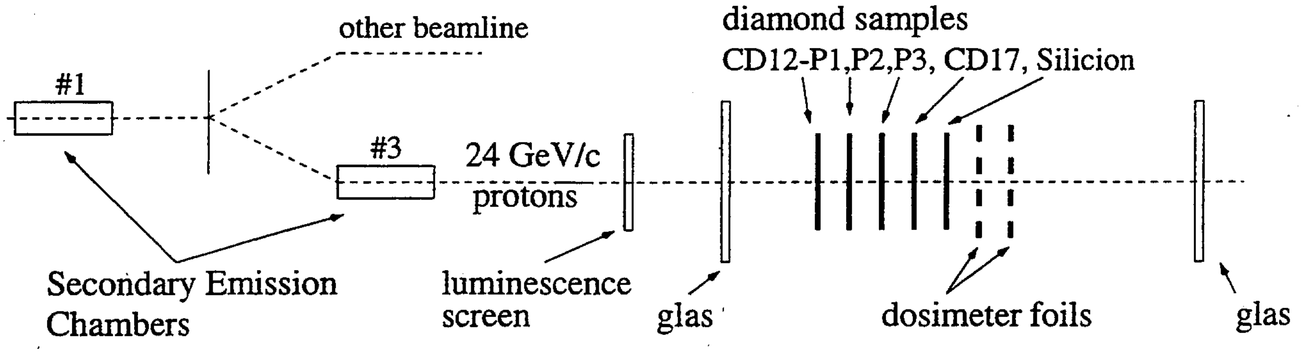
Figure 6: Triumf Beam Induced Current



5.2 CERN PS irradiation

In June of 1997, there was a 2 week irradiation at the PS at CERN in beamline T7. The beamline setup is shown below in Figure 7. A fluence of 5 x $10^{15} p/cm^2$ was achieved with an average flux of 2.9 x $10^{10} p/cm^2$/spill. A spill lasted 0.3 seconds, with two or three spill extractions in a 14 second accelerator cycle. The proton momemtum was 24.2 GeV/c.

Figure 7: CERN PS Beamline Setup



The proton flux was measured by two secondary emmission chambers. Proton fluence was determined by an aluminum foil activation method. The amount of ^{24}Na generated in the aluminum foil is proportional to the total fluence and can be determined by gamma spectroscopy. Figure 8 relates the integrated flux given by the two secondary emmission chambers to the Al foil dosimetry mesurements.

Figure 8: CERN PS Proton Fluence

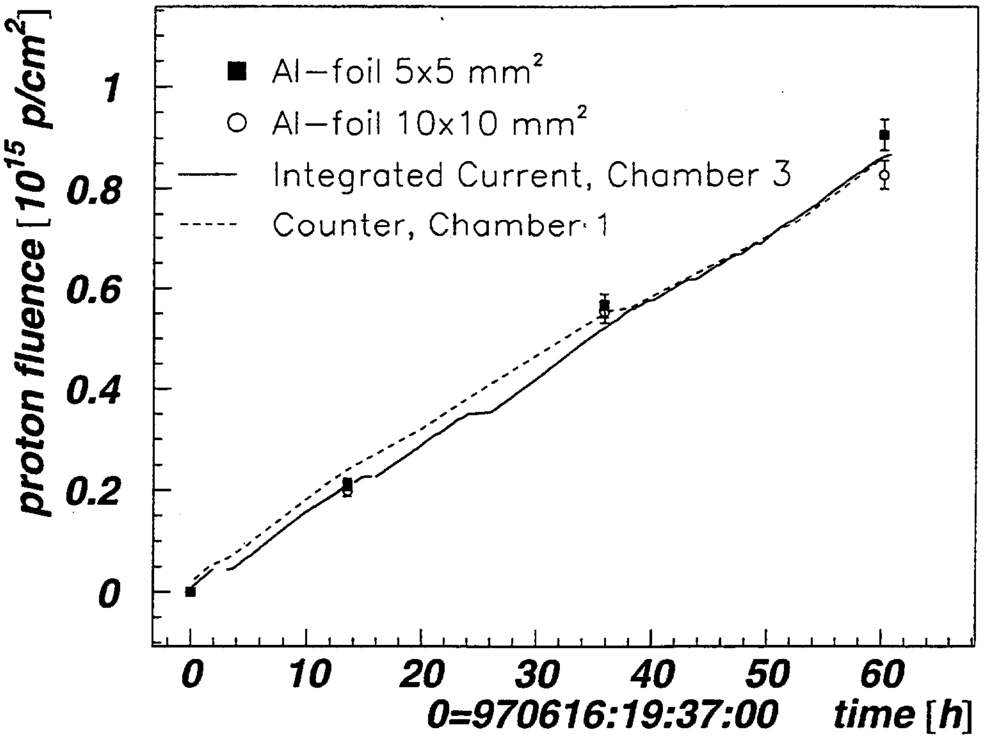


Figure 9 shows the fluence received by each sample. Note that after 70 hours the number of spill extractions per accelerator cycle increased from 2 to 3.

Figure 10 shows the pumped charge distribution before irradiation, after 0.9 x $10^{15}p/cm^2$ and after 5 x $10^{15}p/cm^2$ for the sample that reached the highest proton fluence. The mean and most probable charge are slightly higher after the dose of 0.9 x $10^{15}p/cm^2$ compared to before proton irradiation. This is likely due to incomplete pumping during the ^{90}Sr measurment. The charge measurement after the highest fluence show a 20% decrease in most probable and a 40% decrease in mean due to fewer events with high charge in the Landau tail.

Figure 9: CERN PS Proton Fluence on CVD Diamond

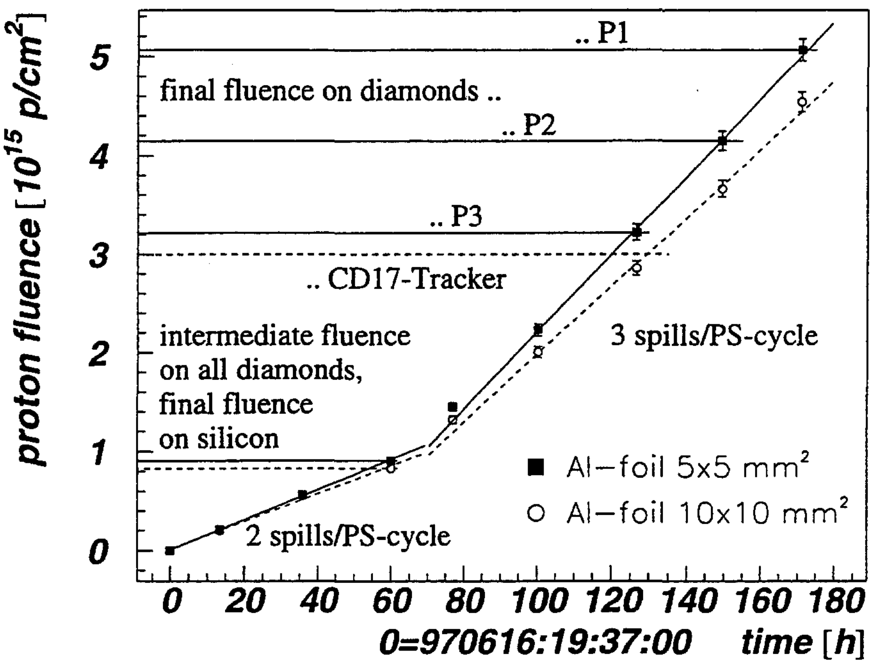


Figure 10: Diamond Collected Charge Histogram, Before and After p Irradiation

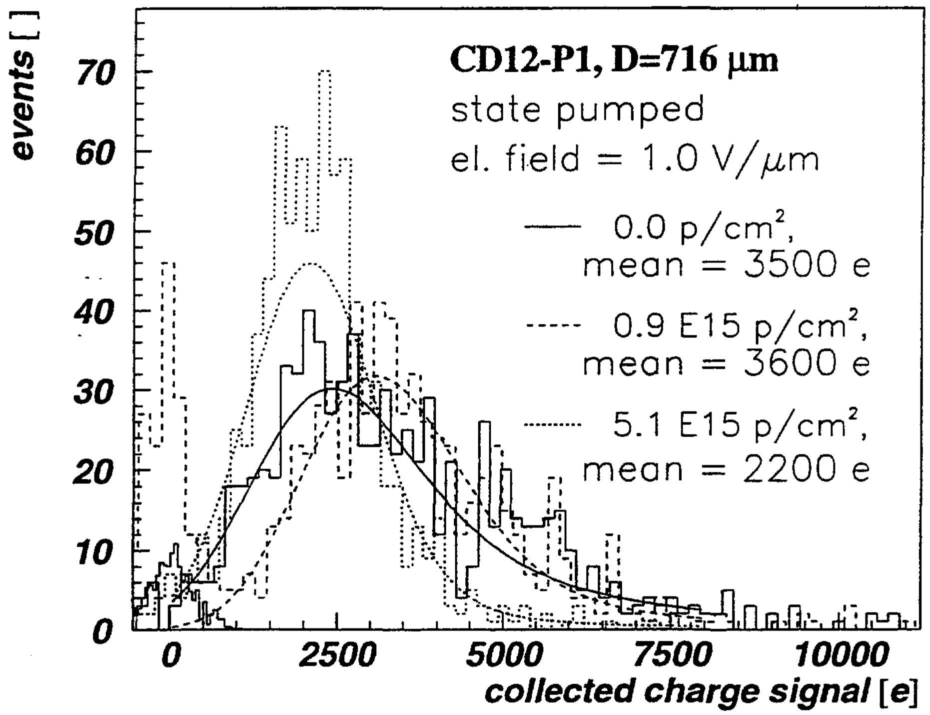
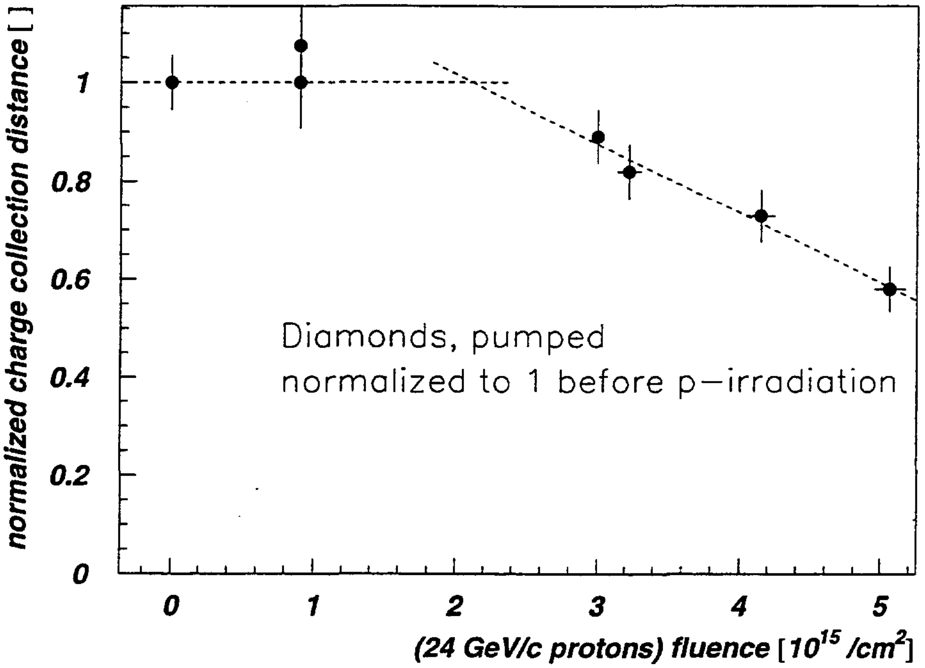


Figure 11 shows relative charge collection (normalized to the unirradiated pumped value) as a function of fluence for all samples. Up to 0.9 x $10^{15} p/cm^2$ there is no decrease in pumped charge collection. The data from 3 to 5 x $10^{15} p/cm^2$ suggests a linear decrease in charge collection reaching a net 40% decrease at 5 x $10^{15} p/cm^2$.

Figure 11: Charge Collection of Proton Irradiated Diamonds



6 Summary and Future Work

CVD diamond detectors have been shown to handle high beam flux without any degradation of charge collection. Furthermore, the dark current of the diamond detectors is unchanged when measured before and after irradiations, and is typically a few pA.

The results of the above irradiations are summarized in Table 2. For comparison, the expected dose at a radial distance of 7.5 cm from the beam line for one year of LHC running at design luminosity is also given. These results indicate that diamond detectors will survive the radiation exposures expected for LHC pixel detectors for at least ten years of LHC running.

There are new data from recent irradiations (1997) using pions and neutrons which are currently under analysis. The data are taken with higher quality CVD diamond and extend the reach in fluence. It is clearly important to continue these studies with the highest grade diamond material available.

	1 LHC Year [10] $r = 7.5$ cm	Dose Required to Damage Diamond
Neutrons	5×10^{13} cm^{-2}	2×10^{15} cm^{-2}
Charged Hadrons	2×10^{14} cm^{-2}	$> 2 \times 10^{15}$ cm^{-2} π
		$> 2 \times 10^{15}$ cm^{-2} p

Table 2: Summary of diamond irradiations.

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