Proton Irradiation of CVD Diamond Detectors for High Luminosity Experiments at the LHC

The RD42 Collaboration

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Abstract

CVD diamond shows promising properties for use as a position sensitive detector for experiments in the highest radiation areas at the Large Hadron Collider. In order to study the radiation hardness of diamond we exposed CVD diamond detector samples to 24 GeV/c and 500 MeV protons up to a fluence of 5×10^{15} p/cm^2. We measured the charge collection distance, the average distance electron hole pairs move apart in an external electric field, and leakage currents before, during, and after irradiation. The charge collection distance remains unchanged up to 1×10^{15} p/cm^2 and decreases by $\approx$40 % at 5×10^{15} p/cm^2. Leakage currents of diamond samples were below 1 pA before and after irradiation. The particle induced currents during irradiation correlate well with the proton flux. In contrast to diamond, a silicon diode, which was irradiated for comparison, shows the known large increase in leakage current. We conclude that CVD diamond detectors are radiation hard to 24 GeV/c and 500 MeV protons up to at least 1×10^{15} p/cm^2 without signal loss.

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1 Introduction

Solid state tracking devices have become one of the mainstays of general purpose high energy physics detectors. Detectors in future high energy and nuclear collider experiments will be exposed to high radiation levels. At a distance of 10 cm from the beam axis at the Large Hadron Collider (LHC) at the European Laboratory of Particle Physics (CERN) detectors are expected to receive a 1 MeV neutron equivalent fluence of 1×10^{15} per cm^2 during 10 years of operation [1]. There are very few materials which can withstand this level of radiation. CVD diamond is a radiation resistant detector material which may be able to operate close to the interaction region at future experiments [2, 3]. Radiation resistance of CVD diamond has been demonstrated for photons up to 10 MRad [4] and electrons up to 100 MRad [5] and is currently being studied for pions and neutrons [6]. Here we describe a proton irradiation of CVD diamonds and show results on charge collection and beam induced currents.

The first proton irradiation of CVD diamond samples was carried out at TRIUMF, Canada in 1995. The protons had a kinetic energy of 500 MeV and diamond samples (LANL-1,2,3,4) were irradiated up to $\approx 10^{14}$ p/cm^2. The proton beam at TRIUMF was continuous with a maximum flux of 8×10^8 $p/\mathrm{cm}^2/\mathrm{s}$. In June 1997 additional CVD diamond samples (CD12-P1,P2,P3, CD17) were irradiated at the Proton Synchrotron (PS) at CERN in Switzerland up to a total fluence of 5×10^{15} p/cm^2. The protons had a momentum of 24.2 GeV/c. At CERN, there were either 2 or 3 spill extractions during 14 s accelerator cycle. The average number of protons per spill was 2.9×10^{10} $p/\mathrm{cm}^2/\mathrm{spill}$. The cross section for 500 MeV protons with protons or neutrons in carbon is only a few percent below the value for 24 GeV/c protons [7]. The damage constant for both proton momenta therefore is expected to be the same and one can directly compare the TRIUMF irradiation with the CERN irradiation.

1.1 Irradiation Setup

A schematic view of the CERN irradiation setup is shown in Fig. 1. Samples were mounted

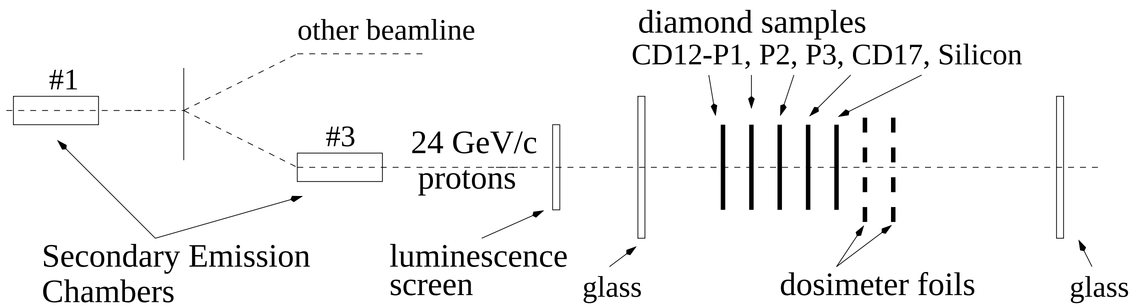

Figure 1: Schematic view of the proton irradiation setup at CERN. Samples were located about 3 m behind the end of the beam pipe exit. Due to the relatively high proton momentum flux attenuation along the sample stack is negligible.

in slide holders along the beamline. The flux was measured by two secondary emission chambers (SEC). The beam position could be verified using two glass plates in front and behind the samples which darkened at the beam spot. In order to monitor the presence and actual beam position a luminescence screen was used which was mounted a few centimeters in front of the irradiation stage. The luminescence light from the proton beam could be observed with a camera as soon as protons were present. For silicon detectors the operation temperature matters since the leakage current increases with increasing temperature. The temperature during diamond irradiation at CERN was stable between 23°C and 27°C and between 6°C and 10°C at TRIUMF.

1.2 Samples and Dosimetry

The samples were provided by DeBeers [8] and Norton [9]. All samples were cut from 4" diamond wafers with a thickness between 500 μm and 700 μm. The sample quality from both manufacturers is similar with regard to electrical and optical material properties. Fig. 2 shows a photo of an irradiated diamond and an irradiated silicon diode. The diamond samples were metallized on both sides with ohmic Cr/Au contacts. Samples irradiated at CERN had a central dot with a guard ring.

The absolute proton fluence was measured using an aluminum foil activation method. The amount of ^{24}Na generated in the Al-foil under proton irradiation is proportional to the fluence. ^{24}Na decays with a half life time of 15 hours and emits photons of 1.368 MeV. The intensity of this γ-line was measured in a spectrometer and gives the proton fluences. Fig. 3 shows the fluence on samples for the CERN irradiation period up to 5×10^{15} p/cm^2. After 70 hours the number of particle extractions was increased from two to three spills per 14 s cycle. Diamond strip detector CD17 received a fluence of 3×10^{15} p/cm^2. Sample CD12-P1 received the highest fluence of 5×10^{15} p/cm^2.

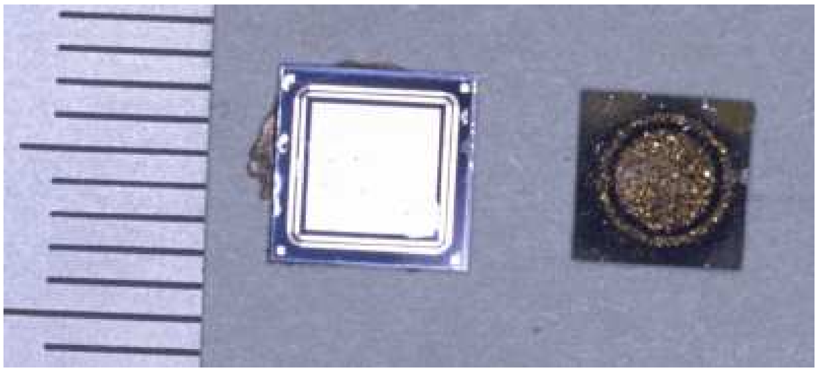

Figure 2: Photo of an irradiated CERN diamond sample (right) and the irradiated Silicon diode (left). The diamond samples were metallized with ohmic contacts on both sides. The substrate side had a single round contact, the growth side a round contact and a guard ring. The scale is in mm.

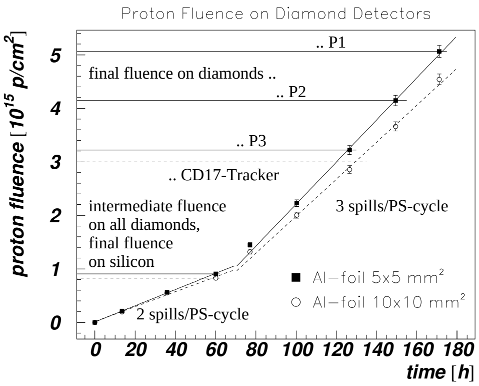

Figure 3: Proton fluence on diamond samples CD12-P1,P2,P3 and CD17 as a function of time up to 5×10^{15} p/cm^2. The proton fluence was measured every 20 hours using Al-foils. Two curves are shown which were measured using foils of different size. They differ slightly since the proton beam has its highest intensity in the center. The slope of the fluence increases above 70 hours since the extraction changed from 2 to 3 spills per cycle. The graph shows the final fluences reached on each sample.

2 Charge Collection Properties

The charge, Q_{col}, which can be collected at the electrodes after one charged particle traverses the diamond characterizes the performance of the detector. A minimum ionizing particle, *mip*, deposits 245 keV in a diamond of a thickness $D = 500$ μm. The energy which is necessary to excite one electron-hole pair in diamond is 13.6 eV. One obtains the number $\left\langle Q_{\mathrm{gen}}^{(mip)} \right\rangle / D = 36$ e/μm of generated electrons or holes for a *mip*. Electron hole pairs separate in the applied electric field and travel towards the electrodes where they induce a charge Q_{col}. The mean measured charge $\langle Q_{\mathrm{col}} \rangle$ is related to the charge collection distance d of the diamond bulk. Using the approximation from [10] one finds

$$d \approx \frac{\langle Q_{\mathrm{col}} \rangle}{\left\langle Q_{\mathrm{gen}}^{(mip)} \right\rangle / D} = \frac{\langle Q_{\mathrm{col}} \rangle}{36\ e/\mu\mathrm{m}}, \tag{1}$$

which relates the charge collection distance to the induced charge at the electrodes. The induced charge can be measured with a charge sensitive amplifier. A setup for measuring charge collection distance is described in [6, 10]. The energy loss of protons in diamond at 500 MeV and 24 GeV/c is slightly greater than that of a *mip*. Appropriately scaling for the energy loss of protons with such energy and momentum one finds 42 eh-pairs/μm and 38 eh-pairs/μm generated respectively. Fig. 4 shows a characteristic signal distribution measured on sample CD12-P1 before irradiation, after 0.9×10^{15} p/cm^2 and after 5×10^{15} p/cm^2. The sample was measured in its electron pumped state before irradiation and in the proton pumped state after irradiation. Pumping occurs at a relatively low dose *e.g.* from ^{90}Sr during a measurement of charge collection distance [6, 10] and during proton beam exposure. The charge distributions are fit by a convolution of Landau's energy loss distribution function for thin detectors and a Gaussian associated with the noise. The measured noise in the characterization setup is about 350 e independent of the irradiation dose. The most probable charge signal, corresponding to the peak of the fit curve, and the mean signal increase slightly after a dose of 0.9×10^{15} p/cm^2 compared to before irradiation. This is probably due to additional pumping by the proton beam. Other samples show no change in pulseheight distribution at this fluence compared to before proton irradiation. After the highest fluence of 5×10^{15} p/cm^2 the most probable charge signal is decreased by 20% compared to before irradiation, while the mean value decreases by about 40% due to fewer events with high charge signals in the Landau tail.

Fig. 5 shows the pumped charge collection distance as a function of the applied electric field at different proton fluences on CD12-P2. In a range from 0 to ± 0.8 V/μm charge collection distance increases. Above $\approx \pm 0.8$ V/μm the velocity of charge carriers saturates and charge collection remains nearly constant. The voltage is applied in a loop starting at 0 V, increasing

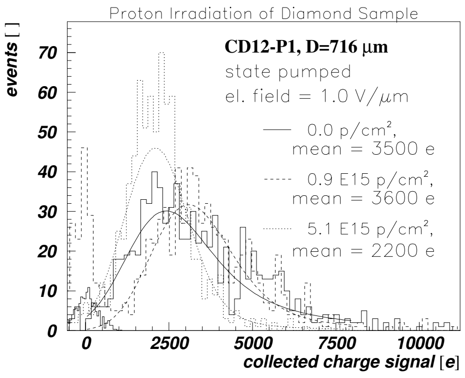

Figure 4: Measured charge signal distribution (histogram and fit) at 1 V/μm before proton irradiation, after 0.9×10^{15} p/cm^2 and after 5×10^{15} p/cm^2.

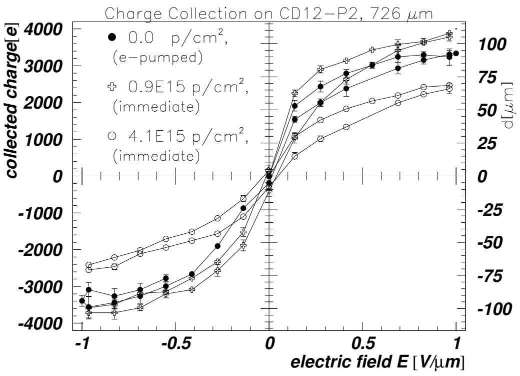

Figure 5: Charge Collection distance as a function of the applied electric field at different proton fluences on sample CD12-P2.

slowly to +1 V/μm, then decreasing to -1 V/μm and back to 0 V. The measured curve shows a hysteresis because of the resistivity and capacitance of the diamond. Before proton irradiation charge collection distance of sample CD12-P2 is (92 ± 4) μm at 1 V/μm. After irradiation with

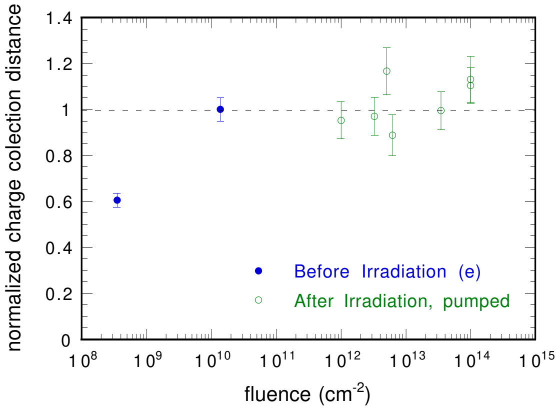

Figure 6: Charge collection distance on LANL-diamond samples as a function of the proton fluence normalized to the electron pumped charge collection distance before proton irradiation. These data were taken on LANL-samples irradiated with 500 MeV protons at TRIUMF.

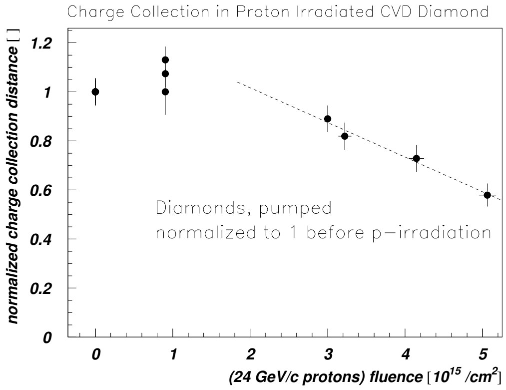

Figure 7: Charge collection distance on CERN-diamond samples as a function of the proton fluence. Samples were depumped under fluorescent light after proton irradiation and then pumped under ^{90}Sr. Only fully pumped charge collection values are shown. The charge collection distance is normalized to its electron pumped value before proton irradiation.

0.9×10^{15} p/cm^2 the charge collection distance is increased by about 10% compared to before proton irradiation. Other samples show less increase in charge collection distance at this fluence. CD12-P2 was irradiated up to 4×10^{15} p/cm^2. After this fluence its charge collection was decreased by about 27% to (68 ± 3) μm.

Fig. 6 shows the charge collection distance as a function of proton fluence for the samples irradiated at TRIUMF. The pumped value of the charge collection distance before proton irradiation is scaled to be one. The unpumped value before irradiation is also plotted at 2×10^8 electrons/cm^2 and used for the relative normalization. The higher fluences up to 1×10^{14} p/cm^2 are proton fluences. The "After Irradiation" points in Fig. 6 were all measured immediately after dismounting from the irradiation area and as a result were in their pumped states. This explains the factor 1.5 and 2 increase over the "Before Irradiation" point at 2×10^8 electrons/cm^2. These samples show no decrease in charge collection up to 1×10^{14} p/cm^2.

Fig. 7 shows the relative charge collection distance as a function of proton fluence for the diamond samples irradiated at CERN. After irradiation with 0.9×10^{15} p/cm^2 the pumped values are slightly increased compared to before proton irradiation. The next measurement at 3×10^{15} p/cm^2 shows a decrease by 10% compared to before proton irradiation. Measurements on the other samples at higher fluence show a decreasing charge collection distance. A linear fit to the values above 3×10^{15} p/cm^2 intersects the ordinate value one at a fluence of $\approx 2 \times 10^{15}$ p/cm^2. Charge collection distance normalized to the pumped value before proton irradiation appears to decrease linearly above $\approx 2 \times 10^{15}$ p/cm^2 and reaches 60 % at 5×10^{15} p/cm^2. As noted earlier the decrease of the most probable value is 20% at a fluence of 5×10^{15} p/cm^2. No decrease in charge collection distance below 1×10^{15} p/cm^2 is observed and we therefore conclude that CVD diamond is radiation hard up to at least 1×10^{15} protons/cm^2.

3 Particle Induced Currents during Proton Irradiation

A number, ΔN_p, of protons interact in diamond and generate electron-hole pairs. The sum of electron-hole pairs generated by one proton has a charge $\Delta Q_{\text{gen}}^{(p)}$. Using the charge collection distance d [Eq.1] and assuming that the beam uniformly irradiates the contact area A one obtains the particle induced current I_{pic} in diamond

$$I_{\mathrm{pic}} \approx d \cdot \frac{A}{D} f_p \frac{\Delta Q_{\mathrm{gen}}^{(p)}}{\Delta N_p}, \tag{2}$$

with the proton flux f_p and sample thickness D. This equation relates the charge collection distance to the particle induced current. All diamond samples were biased during irradiation and the induced current depends via $d(U)$ on the bias voltage U. In particular, U=100 V was applied to samples in the CERN irradiation. The detectors were irradiated under bias voltage which allowed us to measure the proton induced current when a proton spill swept over the samples and also to measure the leakage current during spill breaks when no protons were present.

Fig. 8 shows the proton flux, as measured by the secondary emission chamber, and current measured on CD17 during the the first 55 hours of the proton irradiation at CERN. Protons were only present during a spill of 300 ms. In this time the ON-spill current on CD17 and the proton flux could be measured. The OFF-spill current was measured in breaks between spills. The difference between the ON- and OFF-spill current is the particle induced current. This current correlates with the proton flux. The OFF-spill current shown on the same scale as the ON-spill current is negligibly small. It remains constant during irradiation for all samples. The graph also shows that the induced current in diamond does not change with time and proton fluence which reached 1×10^{15} p/cm^2 [see Fig. 3] after 70 hours. At some points the induced current is low although protons were present (e.g. from 30 h to 35 h). This happened because beam steering magnets changed temporarily and shifted the beam spot by several millimeters to essentially miss the detectors. Fig. 9 shows the same

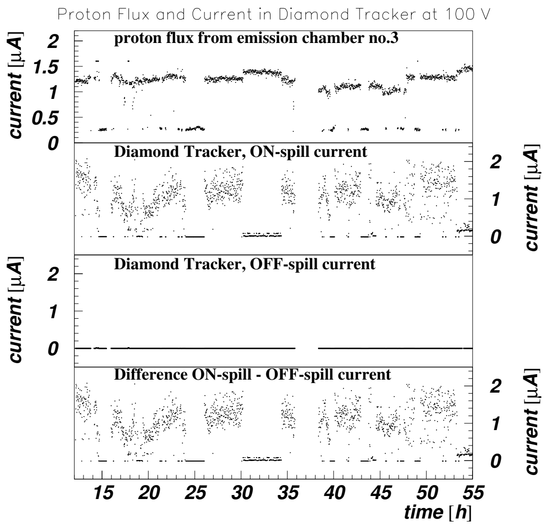

Figure 8: Proton flux as measured by the SEC and current on a 2.9 mm^2 contact pad on the diamond strip detector CD17 during proton irradiation. The thickness of the diamond detector is 490 μm. The current was measured ON- and OFF-spill.

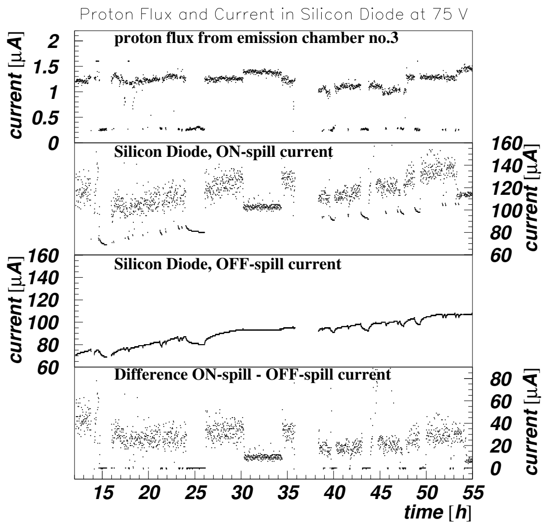

Figure 9: Proton flux and current in a silicon diode during proton irradiation for comparison with the current in a diamond detector.

measurement on the p-on-n silicon diode behind the diamonds. The induced current, the difference between ON- and OFF-spill current, correlates with the proton flux and recognizes the beam shift mentioned above, as well. The dark current in silicon increases from its original value of 60 μA to 110 μA and is also visible as an offset to the ON-spill current. During the extended periods when the beam was off the silicon diode anneals and the dark current decreases exponentially but increases immediately and non-linearly when the beam comes back. It should be noted that the radiation damage induced OFF-spill current for the silicon diode is comparable to the difference between the ON-spill and OFF-spill currents pointing out the difficulty of using silicon detectors in high fluence regions.

At TRIUMF the proton beam was a continous beam and its intensity could be controlled between 0 $p/\mathrm{cm}^2/\mathrm{s}$ and 8×10^8 $p/\mathrm{cm}^2/\mathrm{s}$. The flux was measured with an ionization chamber, whose current was proportional to the flux. Fig. 10 shows the induced current in diamond sample LANL-3 as a function of the ionization chamber current. The induced current in diamond is found to be proportional to the proton flux as expected by Eq. 2. The induced current also indicates that the charge collection distance does not change up to 8×10^8 $p/\mathrm{cm}^2/\mathrm{s}$ (equivalent to 5 nA proton beam current) and shows the particle rate capability of diamond detectors. The ratio of the proton induced current in diamond and proton flux measured by the ionization chamber was measured as a function of proton fluence [Fig. 11]. This ratio is constant up to 10^{14} p/cm^2 and agrees with the unchanged charge collection distance up to this fluence.

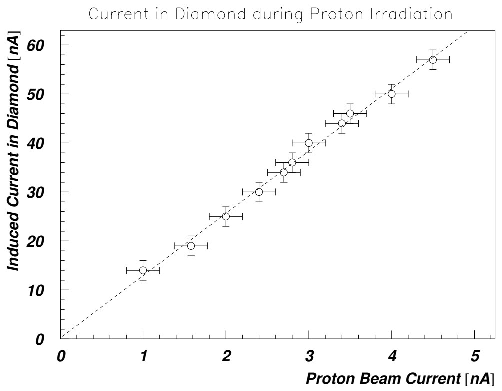

Figure 10: Beam induced current in diamond LANL-3 as a function of the proton beam current. The proton flux at a proton beam current of 5 nA is 8×10^8 $p/\mathrm{cm}^2/\mathrm{s}$. The line is a fit to the data.

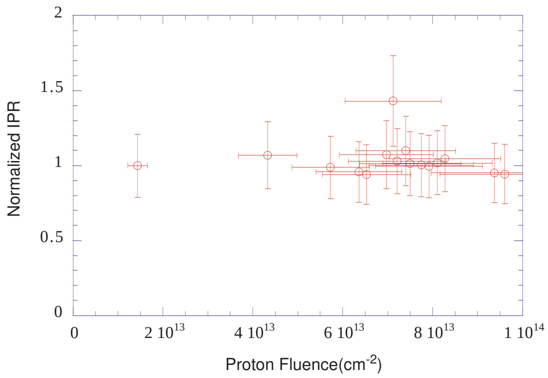

Figure 11: Ratio (IPR) of the proton induced current in diamond LANL-3 and proton flux measured by the ionization chamber as a function of the proton fluence on the diamond sample.

Eq. 2 can be transformed to predict the charge collection distance at a given proton flux and an induced current. Using the characteristic flux at CERN of 2.9×10^{10} $p/\mathrm{cm}^2/\mathrm{spill}$ and an induced current of (1.5 ± 0.3) μA [Fig. 8] in CD17 (which corresponds to 0.5 μC in the 0.3 s spill period) one finds a collected charge of (3320 ± 650) e which implies a charge collection distance of $\approx (87 \pm 17)$ μm for CD17 at 100 V in agreement with the ^{90}Sr measurement of (72 ± 4) μm at 100 V. A similar calculation for the silicon diode with a particle induced current of (40 ± 7) μA [Fig. 9] implies a charge of (16150 ± 3000) e which is less than one would expect for an unirradiated, fully depleted silicon diode of 300 μm thickness (≈ 27200 e). This is indicative of damage in the silicon diode above a fluence of 1.5×10^{14} p/cm^2.

4 Summary and Conclusion

CVD diamond detector samples were irradiated with 500 MeV protons up to 1×10^{14} p/cm^2 at TRIUMF and 24 GeV/c protons up to a fluence of 5×10^{15} p/cm^2 at CERN. At TRIUMF no decrease in charge collection distance is observed below 1×10^{14} p/cm^2 and at CERN no decrease below 1×10^{15} p/cm^2.

At a fluence of 3×10^{15} p/cm^2 charge collection distance decreases by 10%. Beyond a fluence of 2×10^{15} p/cm^2, the charge collection distance appears to decrease linearly with a slope of -14 %/(10^{15} p/cm^2) to 60% at 5×10^{15} p/cm^2. It is important to notice that the most probable charge signal of the detectors decreases by only 20% at the highest fluence compared to before irradiation. This indicates that for a fixed threshold cut below the most probable value there would be no loss of efficiency compared to before irradiation. The dark current on diamond samples before and after irradiation is unchanged, being of the order of a few pico Ampere. The current during irradiation shows a prompt response to protons and is proportional to the flux. In contrast to the fluence dependence observed in the leakage current in silicon detectors, the OFF-spill current for the diamond detectors is independent of proton fluence. The ON-spill current is of the order of micro Ampere and its response to protons does not change.

The results indicate that the present state CVD diamond detectors are radiation hard up to proton fluences of at least 1×10^{15} p/cm^2 and instantaneous rates of at least 1×10^9 $p/\mathrm{cm}^2/\mathrm{s}$. This is very strong evidence that diamond based detectors will be able to withstand the harsh environment of high luminosity experiments at the LHC very near to the interaction region.

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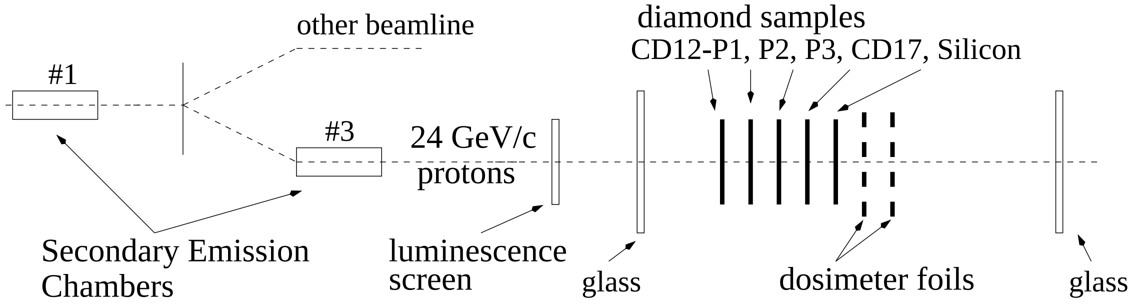
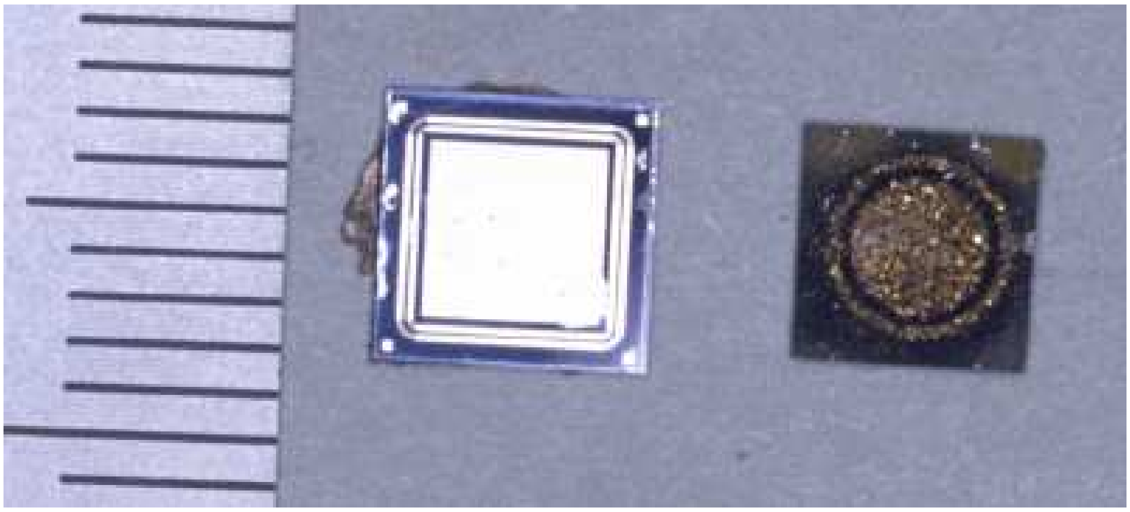
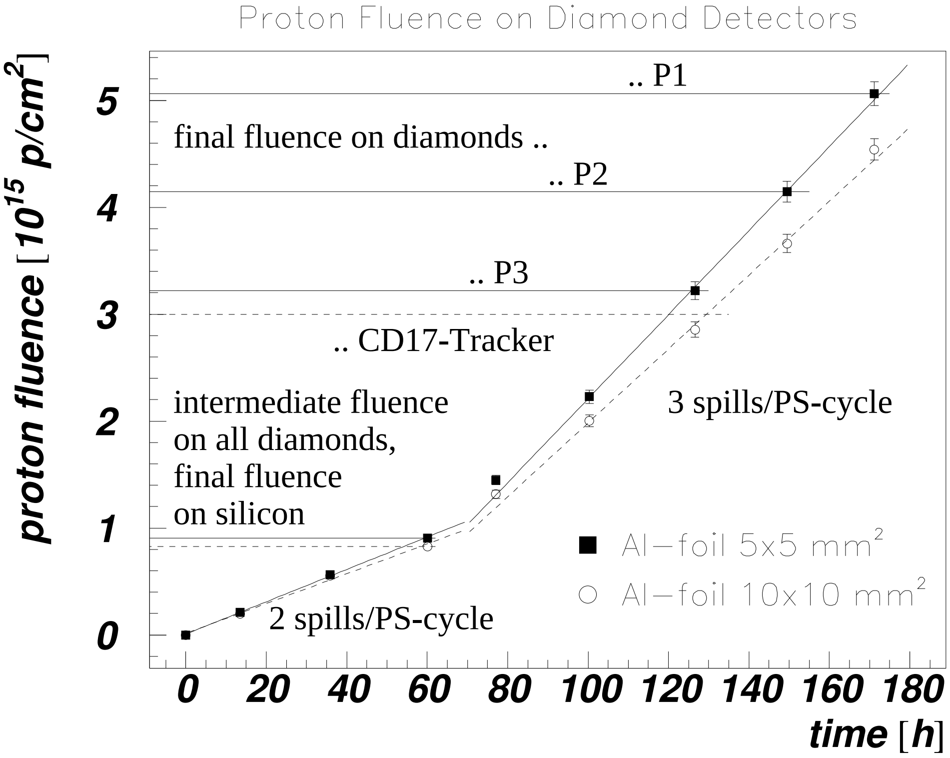
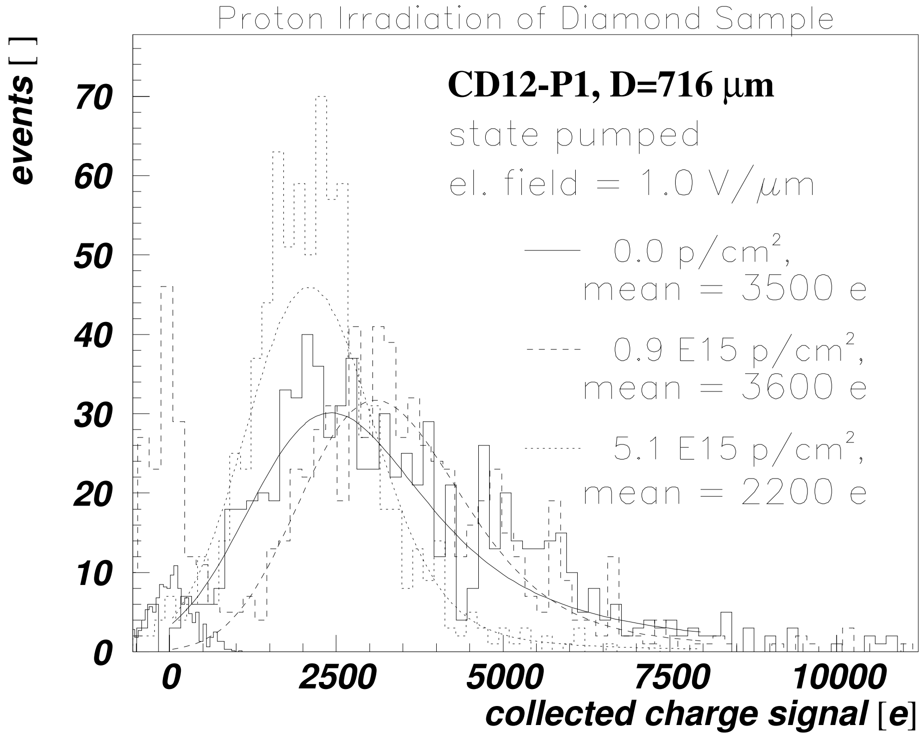


other beamline
#1
#3
24 GeV/c
protons
diamond samples
CD12-P1, P2, P3, CD17, Silicon
Secondary Emission
Chambers
luminescence
screen
glass
dosimeter foils
glass

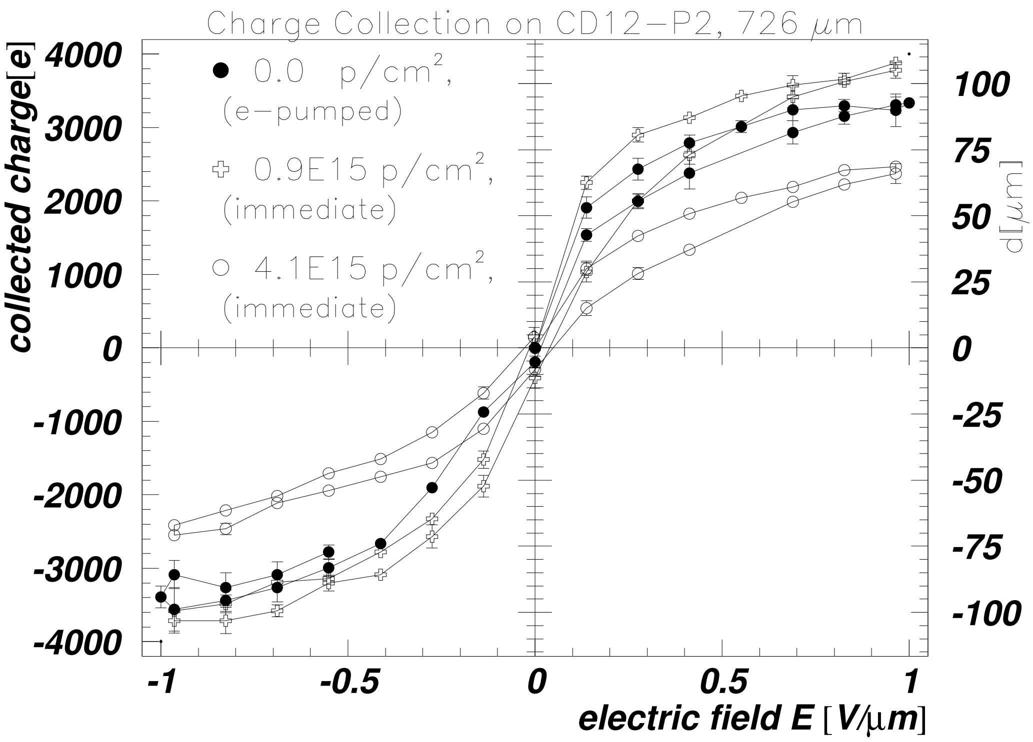




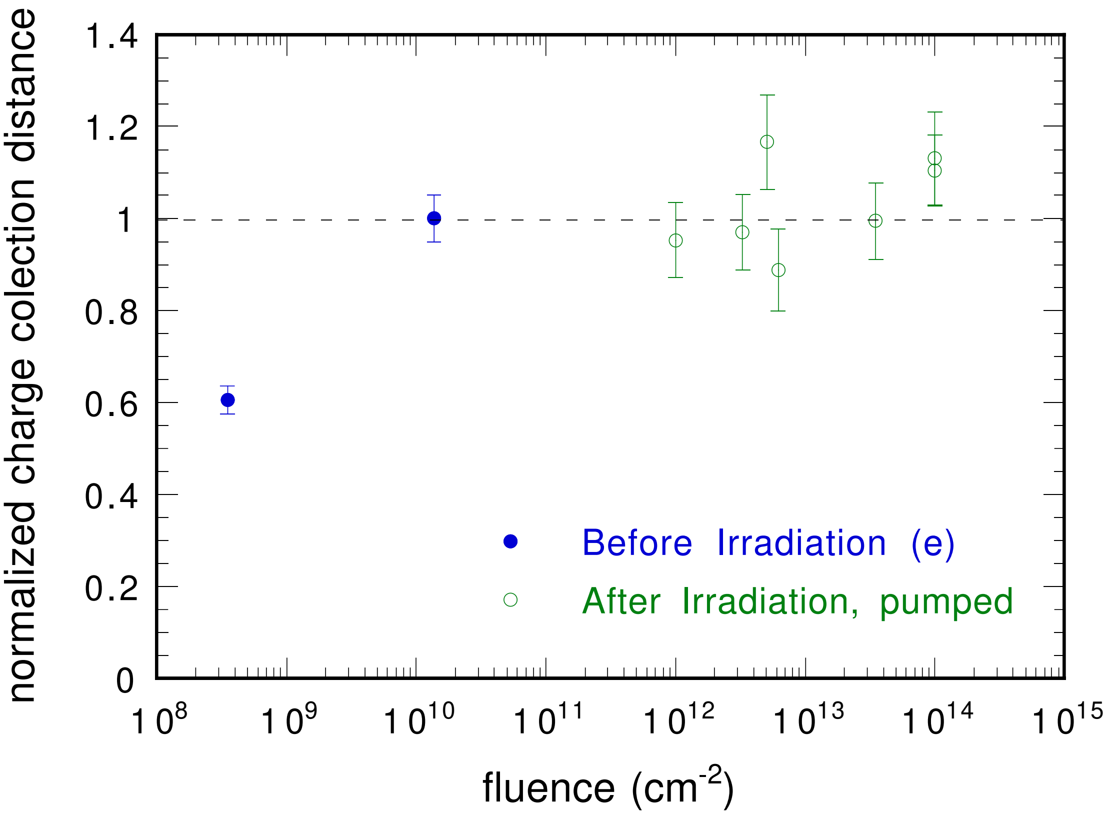
Proton Fluence on Diamond Detectors
proton fluence [10^{15} p/cm^2]
time [h]
.. P1
final fluence on diamonds ..
.. P2
.. P3
.. CD17-Tracker
intermediate fluence
on all diamonds,
final fluence
on silicon
3 spills/PS-cycle
2 spills/PS-cycle
Al−foil 5x5 mm^2
Al−foil 10x10 mm^2
0
1
2
3
4
5
0
20
40
60
80
100
120
140
160
180



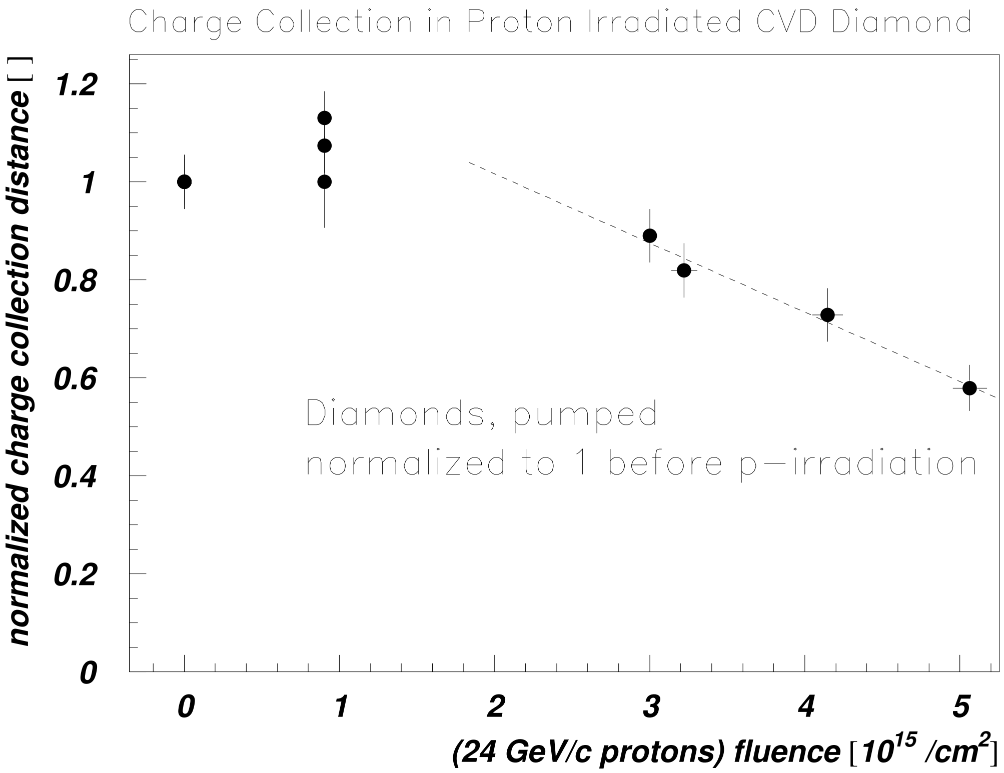
Proton Irradiation of Diamond Sample
CD12-P1, D=716 μm
state pumped
el. field = 1.0 V/μm
0.0 p/cm², mean = 3500 e
0.9 E15 p/cm², mean = 3600 e
5.1 E15 p/cm², mean = 2200 e
events [ ]
collected charge signal [e]
0
2500
5000
7500
10000
10
20
30
40
50
60
70



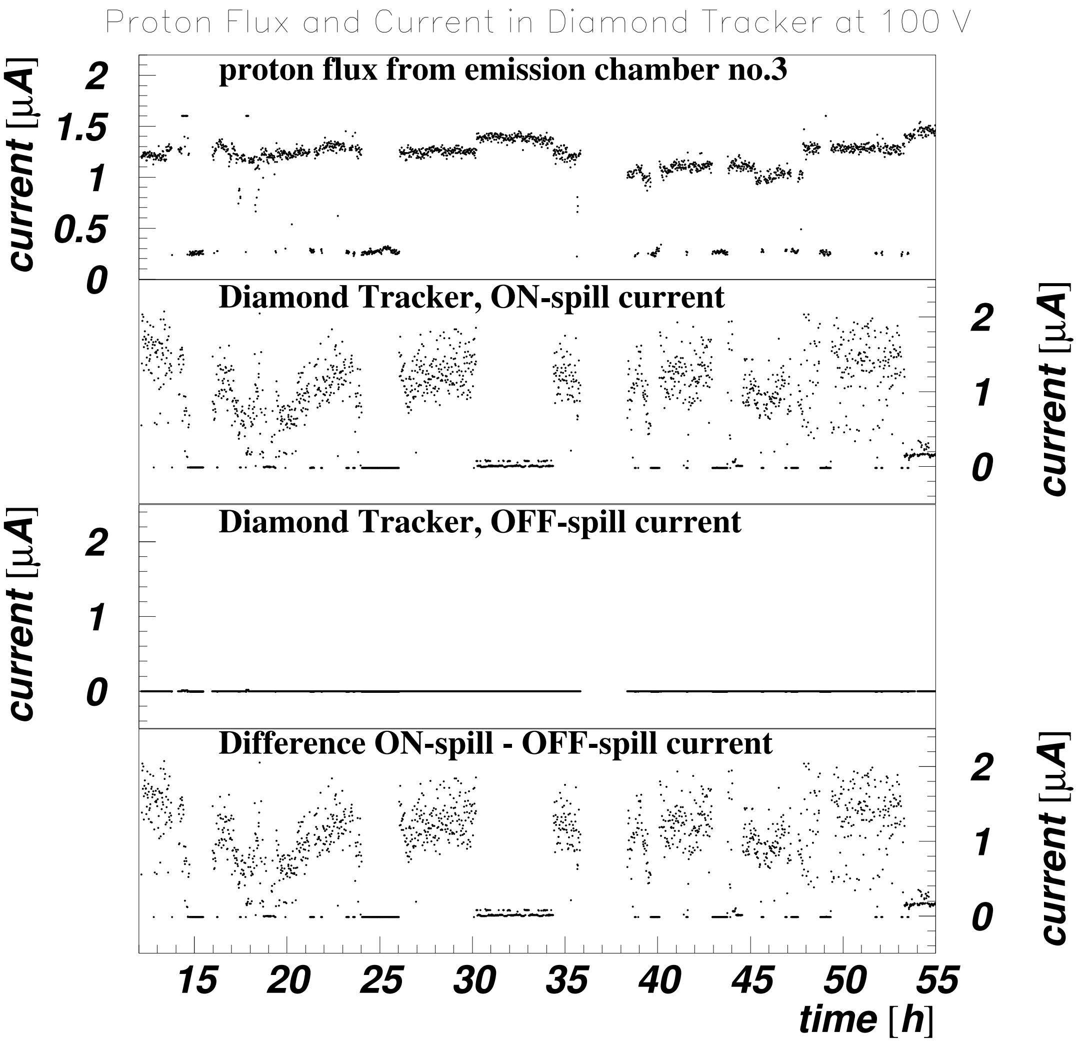
Charge Collection on CD12−P2, 726 μm
collected charge[e]
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
0.0 p/cm², (e−pumped)
0.9E15 p/cm², (immediate)
4.1E15 p/cm², (immediate)
100
75
50
25
0
-25
-50
-75
-100
d[μm]
-1
-0.5
0
0.5
1
electric field E [V/μm]



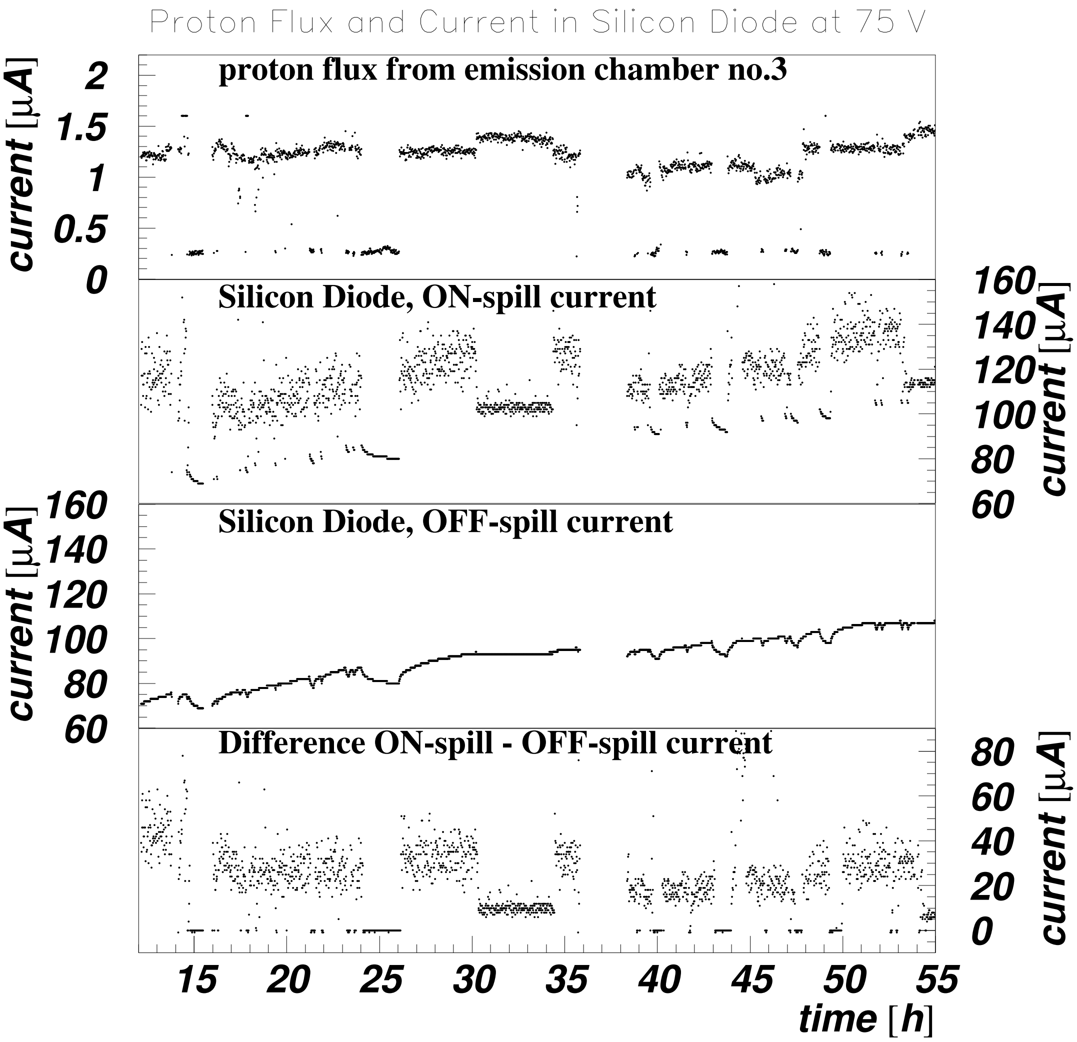
normalized charge colection distance
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
fluence (cm^{-2})
Before Irradiation (e)
After Irradiation, pumped



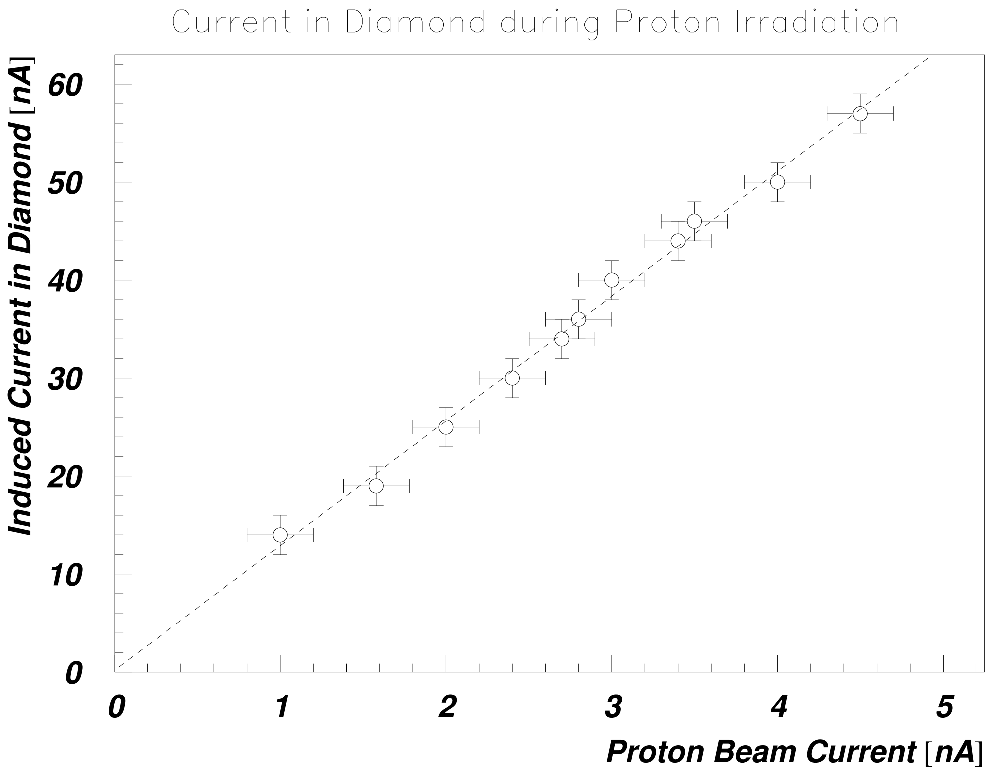
Charge Collection in Proton Irradiated CVD Diamond
normalized charge collection distance [ ]
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
(24 GeV/c protons) fluence [10^{15} /cm^2]
Diamonds, pumped
normalized to 1 before p−irradiation

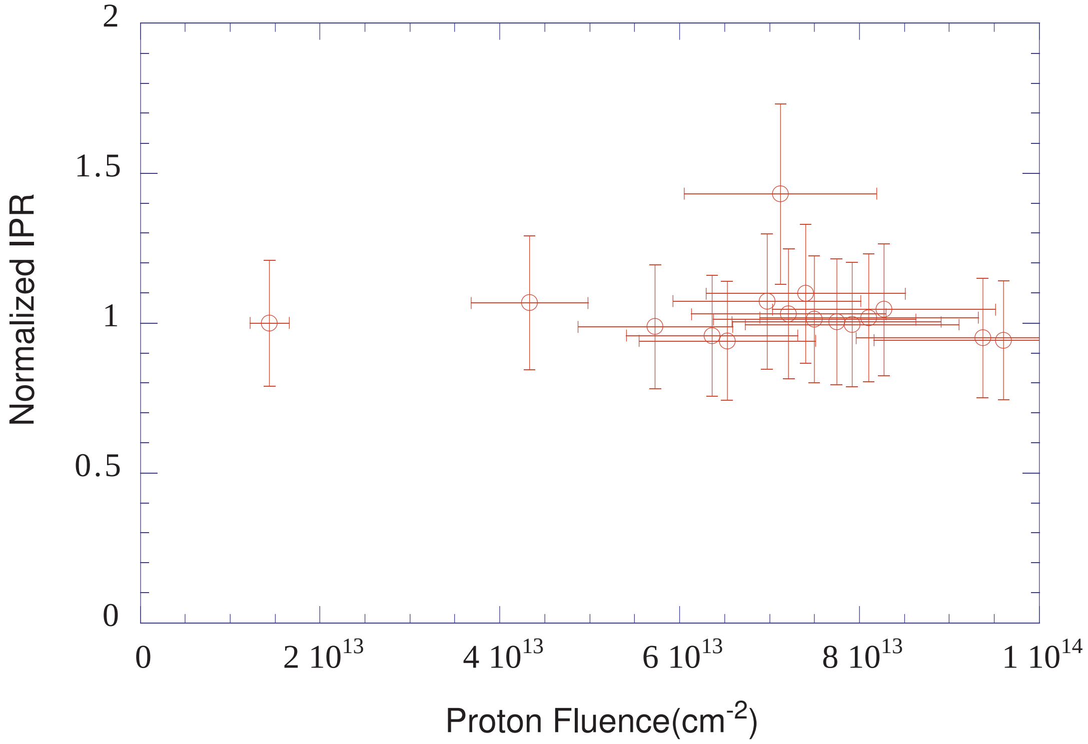


Proton Flux and Current in Diamond Tracker at 100 V
proton flux from emission chamber no.3
Diamond Tracker, ON-spill current
Diamond Tracker, OFF-spill current
Difference ON-spill - OFF-spill current
current [μA]
2
1.5
1
0.5
0
15 20 25 30 35 40 45 50 55
time [h]



Proton Flux and Current in Silicon Diode at 75 V
proton flux from emission chamber no.3
Silicon Diode, ON-spill current
Silicon Diode, OFF-spill current
Difference ON-spill - OFF-spill current
current [μA]
time [h]


Current in Diamond during Proton Irradiation
Induced Current in Diamond [nA]
Proton Beam Current [nA]
0
10
20
30
40
50
60
0
1
2
3
4
5



Normalized IPR
2
1.5
1
0.5
0
0
$2\ 10^{13}$
$4\ 10^{13}$
$6\ 10^{13}$
$8\ 10^{13}$
$1\ 10^{14}$
Proton Fluence(cm^{-2})