

# Contents

|    |       |  |    |
|----|-------|--|----|
| 2  | 1     | Experimental results   | 2  |
| 3  |       | <i>Diamond irradiation study</i>                                 |    |
| 4  | 1.1   | Measurement setup . . . . .                                      | 3  |
| 5  | 1.1.1 | Preamplifiers . . . . .  | 3  |
| 6  | 1.1.2 | Diamond samples . . . . .  | 5  |
| 7  | 1.1.3 | Readout devices . . . . .  | 6  |
| 8  | 1.1.4 | Setup for the efficiency study using $\beta$ particles . . . . . | 6  |
| 9  | 1.1.5 | Room temperature $\alpha$ -TCT setup . . . . .                   | 7  |
| 10 | 1.1.6 | Cryogenic $\alpha$ -TCT setup . . . . .                          | 7  |
| 11 | 1.2   | Charged particle pulses and spectra . . . . .                    | 9  |
| 12 | 1.2.1 | Noise limitations . . . . .                                      | 9  |
| 13 | 1.3   | Radiation limitations . . . . .                                  | 11 |
| 14 | 1.3.1 | Quantifying radiation damage in diamonds . . . . .               | 12 |
| 15 | 1.3.2 | Long-term measurement stability . . . . .                        | 15 |
| 16 | 1.4   | Temperature limitations . . . . .                                | 21 |
| 17 | 1.4.1 | Temperature-variant $\alpha$ -TCT before irradiation . . . . .   | 23 |
| 18 | 1.4.2 | Temperature-variant $\alpha$ -TCT after irradiation . . . . .    | 25 |
| 19 | 1.5   | Conclusion . . . . .   | 32 |

<sup>20</sup> **Chapter 1**

<sup>21</sup> **Experimental results**

<sup>22</sup> *Diamond irradiation study*

<sup>23</sup> This chapter contains the measurement results of data taken with diamond sensors.  
<sup>24</sup> First the measurement setup is described (section 1.1). Then the measured particle  
<sup>25</sup> spectra are shown in 1.2. This is followed by a study of effects of irradiation damage  
<sup>26</sup> on the electrical signal of the diamond detector and its lifetime. The last section  
<sup>27</sup> shows the results of the measurements of irradiated diamond samples at cryogenic  
<sup>28</sup> temperatures. The aim of these studies is to find the operational limitations of dia-  
<sup>29</sup> mond detectors for spectroscopy and tracking applications. The studies compare the  
<sup>30</sup> experimentally acquired data with the theory from the previous chapter and define  
<sup>31</sup> limitations of the diamond detectors in terms of noise, radiation and temperature.

<sup>32</sup> Diamond sensors are mainly used for two types of measurements: particle counting  
<sup>33</sup> and spectroscopy. The first type of measurements depends on the sensor's efficiency –  
<sup>34</sup> the ability to detect all or at least a known percentage of radiation quanta (particles  
<sup>35</sup> or photons) that hit it. The energy of the radiation is not so important; what bears  
<sup>36</sup> the information is the rate and the spatial distribution. Here the radiation does  
<sup>37</sup> not necessarily stop in the bulk, but rather continues its way. In spectroscopy, on  
<sup>38</sup> the other hand, the idea is that a particle stops within the sensor, depositing all  
<sup>39</sup> its energy, which is then measured via the freed charge carriers. The aim of the  
<sup>40</sup> experiments described in this chapter is to:

- <sup>41</sup> 1. Quantify the efficiency of the sCVD diamond in counting mode,
- <sup>42</sup> 2. Quantify the degradation of efficiency with respect to the received radiation  
<sup>43</sup> dose,
- <sup>44</sup> 3. Quantify the macroscopic effects on charge carrier behaviour with respect to  
<sup>45</sup> the received radiation dose and
- <sup>46</sup> 4. Define limitations for its use in spectroscopy.

<sup>47</sup> The results discussed here show that there are several limitations for using diamond as  
<sup>48</sup> a measurement device. All of them need to be taken into account for the measurement

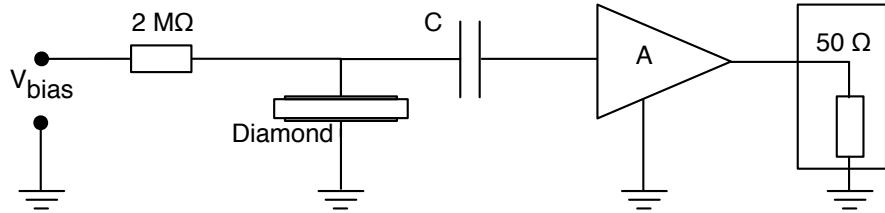


Figure 1.1: Diagram of a diamond detector readout chain.

device to perform reliably and stably. The first step is to build a setup that is insensitive to external electromagnetic interferences and minimises electrical noise in the system. The setup needs to be calibrated before use. Then, the measurement conditions have to be defined, such as the temperature, the type of radiation and its flux. This allows us to estimate the lifetime of the detector and predict the longterm change of the signal. This change can then be accounted for when interpreting the output data.

## 1.1 Measurement setup

To get reliable measurement results, great care has to go towards designing a measurement setup that minimises the noise in the measurements. Shielding has to be applied wherever possible. For instance, aluminium foil can be wrapped around the exposed parts of the system to shield them from external radio-frequency (RF) interferences. In addition, the sensors have to be covered to prevent the light from shining directly onto them. The incident photons can deposit enough energy to increase the leakage current of the detector.

The measurements using diamond that are explained in these chapters were carried out using several measurement setups, but they are all similar in terms of the electrical signal chain. The measurement chain consists of three main parts: a diamond sensor, a signal preamplifier and a readout device, as seen in diagram 1.1. The signals propagating along the analogue chain (before being digitised by the readout device) are fast – in the GHz bandwidth range – and with low amplitudes – of the order of tens of  $\mu\text{V}$ . This gives rise to importance of RF shielding. Also, the connection between the carrier and the preamplifier has to be as short as possible to avoid capacitive signal losses in the transmission line. Finally, the system needs to be grounded properly.

### 1.1.1 Preamplifiers

Two preamplifiers are used for the measurements, one sensitive to charge and the other to current. *CIVIDEC Cx* (figure 1.2a) is a charge sensing amplifier. Its high SNR (equivalent noise charge of  $300 + 30 \text{ pF}^{-1} \text{ e}^-$  and a reported gain of  $\sim 12 \text{ mV/fC}$ ) makes it a good choice for spectroscopic measurements with diamond

## 1.1. MEASUREMENT SETUP

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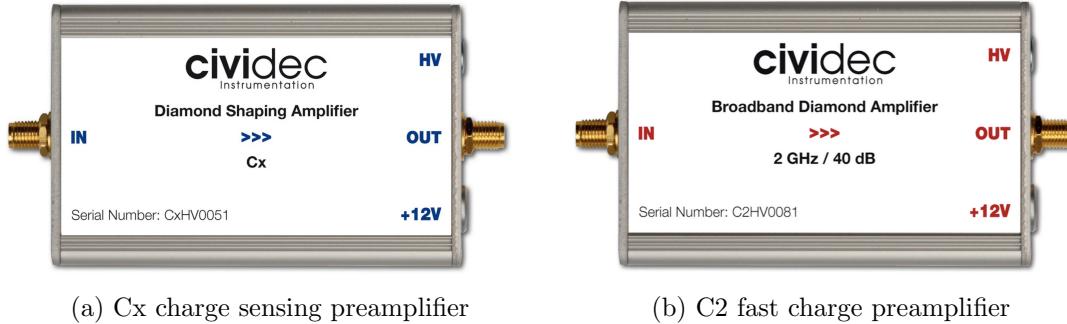


Figure 1.2: Amplifiers used for the charge and current measurements

78 sensors. *CIVIDEC C2* (figure 1.2b) is a fast current preamplifier with a 2 GHz band-  
 79 width limit. It is used for TCT measurements because of its fast response and a good  
 80 SNR. Both are embedded in an RF-tight aluminium box to reduce the noise pickup.  
 81 Both have an AC coupled input and an output with a  $50 \Omega$  termination.

### 82 Calibration

83 The amplifiers have to be calibrated before use to determine their gain. Both are  
 84 calibrated using a square signal generator with a known amplitude step of  $U_{\text{in}} =$   
 85  $(252 \pm 5)$  mV. A 2 GHz oscilloscope with a 10 GS/s sampling is used to carry out  
 86 these measurements.

87 In the case of the Cx charge sensitive amplifier, the signal is routed through a  
 88 capacitor with a calibration capacitance  $C_{\text{cal}} = (0.717 \pm 0.014)$  pF and then to the  
 89 input of the amplifier. The pulse area behind the capacitor is  $a_{\text{cal}} = (5.0 \pm 0.5)$  pVs,  
 90 with the signal amplitude on the output amounting to  $U_{\text{Cx}} = (1.95 \pm 0.05)$  V. The  
 91 input voltage step combined with the calibration capacitance yields a calibration  
 92 charge  $Q_{\text{cal}} = C_{\text{cal}} \cdot U_{\text{in}} = (181 \pm 5)$  fC. The gain of the Cx amplifier is therefore  
 93  $A_{\text{Cx}}^Q = \frac{U_{\text{Cx}}}{Q_{\text{cal}}} = (9.3 \pm 0.4)$  mV/fC or  $A_{\text{Cx}}^a = \frac{U_{\text{Cx}}}{a_{\text{cal}}} = (390 \pm 40)$  mV/pVs. The area-based  
 94 amplification factor has a higher uncertainty ( $\sim 10\%$ ) than the amplitude-based  
 95 factor ( $\sim 4\%$ ) due to the measurement limitations of the oscilloscope. Nevertheless,  
 96 it can be used as an estimate for the integrated charge of a current pulse.

97 To calibrate the C2 current amplifier, only the amplitude gain has to be measured.  
 98 The input signal amplitude has to be such that it keeps the output amplitude within  
 99 the amplifier's linear range, that is  $\pm 1$  V. The signal from the generator is therefore  
 100 routed through a 36 dB attenuator to decrease its amplitude to  $U_{\text{inAtt}} = (3.95 \pm$   
 101  $0.05)$  mV. Two amplifiers with different gains have been measured, because both  
 102 are used for the measurements at different times. The output of the first amplifier  
 103 amounts to  $U_{\text{C2-1}} = (860 \pm 5)$  mV. This yields the amplification gain equal to  $A_{\text{C2-1}} =$   
 104  $\frac{U_{\text{inAtt}}}{U_{\text{C2-1}}} = (217 \pm 3)$ . The second amplifier has the output equal to  $U_{\text{C2-2}} = (632 \pm 5)$  mV  
 105 with the gain equal to  $A_{\text{C2-2}} = (152 \pm 3)$ .

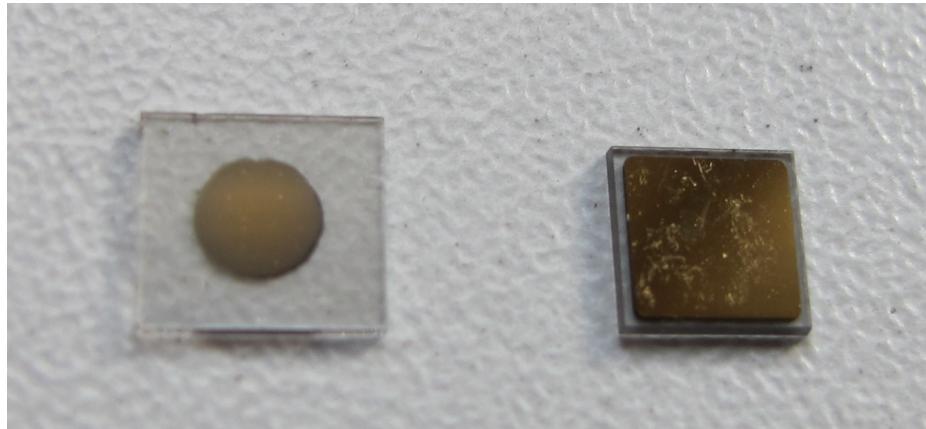


Figure 1.3: Two scCVD diamond samples: A IIa 1scdhq (left) and an E6 S37 (right)

### <sup>106</sup> 1.1.2 Diamond samples

<sup>107</sup> Detector-grade diamonds are very difficult to produce, mostly because it is very diffi-  
<sup>108</sup> cult to ensure a high enough purity of the lattice. The sensor samples used for these  
<sup>109</sup> studies were bought at Element Six (E6) [2]. They all have the same standard dimen-  
<sup>110</sup> sions. sCVD diamonds with dimensions  $4.7 \times 4.7 \text{ mm}^2$  are already sufficiently large  
<sup>111</sup> for most of the beam monitoring applications and still affordable. One of the samples  
<sup>112</sup> with dimensions of  $5.6 \times 5.3 \text{ mm}^2$  produced by IIa Singapore [3] was also sent to CERN  
<sup>113</sup> to be characterised. The target thickness for all the samples is  $500 \mu\text{m}$ . Diamonds  
<sup>114</sup> this thick yield a high enough signal-to-noise ratio for MIPs to be measured by the  
<sup>115</sup> electronics. Table 1.1 shows all the samples used for this study. Two of them were  
<sup>116</sup> later irradiated with 300 MeV pions and then compared to the pre-irradiated state.  
<sup>117</sup> Irradiation doses for damaging the material need to be high – above  $10^{12}$  particles  
<sup>118</sup> per  $\text{cm}^2$  to be able to observe change in the sensor’s behaviour.

| <sup>119</sup> | Name   | Type | Producer | Dimensions [ $\text{mm}^2$ ] | Thickness [ $\mu\text{m}$ ] | Electrode | Irradiated                                |
|----------------|--------|------|----------|------------------------------|-----------------------------|-----------|---|
|                | S37    | sCVD | E6       | $4.7 \times 4.7$             | 548                         | Cr/Au     | no  |
|                | S50    | sCVD | E6       | $4.7 \times 4.7$             | 537                         | Cr/Au     | no  |
| <sup>120</sup> | S52    | sCVD | E6       | $4.7 \times 4.7$             | 515                         | Cr/Au     | $1 \times 10^{14} \pi \text{ cm}^{-2}$    |
|                | S79    | sCVD | E6       | $4.7 \times 4.7$             | 529                         | Cr/Au     | $3.63 \times 10^{14} \pi \text{ cm}^{-2}$ |
|                | ELSC   | sCVD | E6       | $4.7 \times 4.7$             | 491                         | Cr/Au     | no  |
|                | 1scdhq | sCVD | IIa      | $5.6 \times 5.3$             | 460                         | Cr/Au     | no  |

<sup>121</sup> Table 1.1: Diamond sensor samples used

<sup>122</sup> The diamond samples have quoted impurity densities of  $\leq 2 \times 10^{14} \text{ cm}^{-3}$  and nitro-  
<sup>123</sup> gen incorporation of  $\leq 1 \text{ ppb}$ . The electrodes were added by various companies and  
<sup>124</sup> institutes. For instance, S52 was metallised by a company DDL (now defunct) while  
<sup>125</sup> the Physics Department of the University of Firenze, Italy metallised the S79. There  
<sup>126</sup> are also several techniques for producing the electrodes. The DDL contacts consist  
<sup>127</sup> of three layers: DLC (diamond-like carbon)/Pt/Au with 4/10/200 nm thicknesses,  
<sup>128</sup> respectively. The metallisation for S79, on the other hand is made up of Cr/Au with

## **1.1. MEASUREMENT SETUP**

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129 a total thickness of  $\sim$ 400 nm. The area coverage also differs from sample to sample.  
130 Diamonds must not be metallised until the very edge as the proximity of contacts  
131 with a high potential can lead to sparking. However, the areas not covered by the  
132 metallisation are less efficient because the fringe fields at the edges are not as strong  
133 as in the middle. This effectively reduces the sensitive area of the sensors. In the  
134 diamonds used here the effective area was anywhere from  $9\text{ mm}^2$  to  $18\text{ mm}^2$ . Leakage  
135 current through the bulk was below 1 ns, but increased for the irradiated samples.  
136 The capacitance was of the order of  $(2.0 \pm 0.3)\text{ pF}$ .

### **1.1.3 Readout devices**

137 Electrical signals in diamond detectors are in the GHz frequency range. To preserve  
138 this information, the readout device has to have a high bandwidth limit. For in-  
139 stance, a 250 MHz limit is enough for the spectroscopic measurements with the Cx  
140 charge amplifier, but might be insufficient for the current measurements with the C2  
141 amplifier. Two devices are used take data shown in this chapter. The first choice is a  
142 2 GHz LeCroy WaveRunner 204MXi-A. This specific model has a high enough limit  
143 for the fast current preamplifier signals. It offers a versatile solution for analogue sig-  
144 nal readout – it is fast to set up and reliable. It is very convenient for use in lab tests  
145 and for experiments where small amounts of data are taken and where speed is not  
146 crucial. However, its slow acquisition speed turns out to be a bottleneck in the test  
147 beam experiment. Its initial 100 Hz readout rate decreases to a mere 20 Hz within  
148 20 minutes, because every single trigger is saved as a separate file and the Windows  
149 operating system is not capable of handling 10000+ files in a single directory eas-  
150 ily. This is why it has been exchanged with a DRS4 [1], an analogue readout device  
151 developed by PSI, Switzerland. This compact device is capable of recording up to  
152 four waveforms at a time at a steady rate of up to 500 Hz. Its 700 MHz bandwidth  
153 limitation is sufficient for the signal from the charge amplifier.

### **1.1.4 Setup for the efficiency study using $\beta$ particles**

155 The efficiency study of the diamond sensors has been carried out at CERN in the  
156 North Hall test beam facility. There a straight high-energy particle beam of  $\pi_{120}\text{ GeV}$   
157 is provided to the users to calibrate their detectors. The beam had a transverse spread  
158 of  $\sigma = 10\text{ mm}$  in both axes. The particle rate is of the order of  $10^4\text{ }\pi\text{ cm}^{-2}\text{ s}^{-1}$ . A  
159 diamond sensor embedded in a PCB carrier has been placed in the beam spot per-  
160 pendicular to the beam and connected via an SMA connector directly to a charge  
161 amplifier (described below). The amplified signal is read out using a LeCroy oscil-  
162 loscope and a DRS4 analogue readout system (both described below). A computer  
163 is used as a controller and data storage for the readout device. A beam telescope is  
164 used as a reference detector. It is a device that helps to cross-check the measurements  
165 of the devices under test (DUTs) and to carry out spatially resolved studies on the  
166 DUTs. It consists of several pixellated sensor planes placed in series, which can track  
167 a particle's trajectory with a precision of a few  $\mu\text{m}$ . The sensor planes are positioned  
168

in front of the DUT and behind it. Then the beam telescope acts as a trigger system – it triggers the readout of both the telescope data and DUT data when both the planes in front and behind the DUT recorded a hit by the incident particle. A particle detected by all the planes within the DUT window and the DUT itself counts towards its efficiency whereas a hit missed by the DUT means that the DUT is not 100 % efficient. To discard the hits that miss the DUT completely, a region of interest (ROI) can be chosen in the beam telescope planes. The equation for calculating the sensor efficiency is therefore

$$\epsilon = \frac{N_{\text{DUT}} \wedge N_{\text{telescope}}}{N_{\text{telescope}}} \quad (1.1)$$

for an ROI smaller than the sensitive region of the diamond.

### 1.1.5 Room temperature $\alpha$ -TCT setup

This TCT study is a follow-up of an extensive diamond TCT study at cryogenic temperatures [13]. The room-temperature TCT measurements have been carried out in the lab. The setup consists of a diamond sensor embedded in a PCB carrier, a current amplifier and an oscilloscope. To measure  $\alpha$  particles, their energy loss during their trajectory has to be minimised. Therefore the diamond is placed inside a vacuum chamber. The chamber is a steel tube with a diameter of 5 cm. On one side it is connected to a vacuum pump via a steel pipe. A feedthrough with an SMA connector is placed on the other side. A C2 current amplifier is connected directly onto the feedthrough. The amplified output is connected to the oscilloscope via an SMA cable. An  $^{241}\text{Am}$  source with a diameter of 2 cm and a height of 0.5 cm is fixed onto the sensor carrier (figure 1.4a, figure 1.4b). Then the carrier is inserted in the chamber and fixed in place using an air-tight clamp. The pump can then be switched on. It is capable of providing the inside pressure as low as  $10^{-4}$  mbar after approximately one hour of operation, but measurements can take place even after five minutes of evacuation, at around  $10^{-3}$  mbar. The most important thing to bear in mind is to switch the bias voltage of the sensor OFF during the process of evacuation, because the gas becomes more conductive at the pressure of the order of  $10^{-1}$  mbar, which is at the bottom of Paschen's curve [9]. A failure to switch off the bias voltage may cause a spark between the signal and ground line, destroying the amplifier.

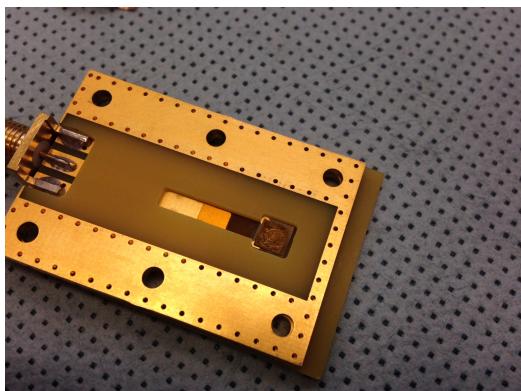
### 1.1.6 Cryogenic $\alpha$ -TCT setup

The experiment at cryogenic temperatures has been carried out in the cryolab at CERN. The room-temperature TCT setup has to be modified to allow for measurements at temperatures as low as 2 K. It consists of three parts:

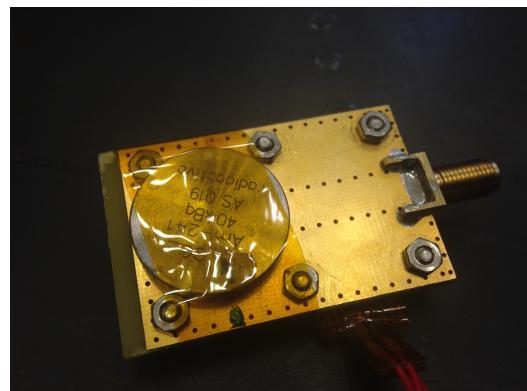
- 202 1. a cryostat – a thermally insulated cylinder capable of containing liquid helium,
- 203 2. an inlet – an air-tight mechanical tube with valves and feedthroughs at the top  
204 that is lowered in the liquid helium and

## 1.1. MEASUREMENT SETUP

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(a) PCB carrier with an embedded diamond sample



(b) Radioactive source over the carrier

Figure 1.4: Positioning of the  $\alpha$ -source on top of the sensor carrier

- 205     3. the diamond sample embedded in a PCB carrier with a fitted temperature  
206     sensor, a heater and cables leading to the feedthroughs.

207     The setup is described in detail in [13].

208     When the diamond sample is placed in the PCB carrier and the  $^{241}\text{Am}$  source is in  
209     place, the inlet is sealed and lowered in the empty cryostat. Then the inside volume  
210     of the inlet is evacuated to down to  $10^{-5}$  mbar while the liquid helium is flowing into  
211     the cryostat. To improve the thermal contact between the diamond and the coolant,  
212     a small amount of helium gas is added inside the evacuated inlet, setting the vacuum  
213     to around  $10^{-3}$  mbar. This value changes with time, because the gas condenses on  
214     the walls of the inlet, reducing the number of floating particles. For this reason the  
215     helium gas has to be added on an irregular basis. Every addition causes a significant  
216     undershoot of the sample temperature, which had to be corrected for using a heater  
217     placed on the back of the PCB carrier. Also, the added gas deteriorates the vacuum  
218     inside the inlet. It is very important to monitor the pressure so as not to let it rise  
219     above  $10^{-2}$  mbar. The gas at this pressure is significantly more conductive and could  
220     cause a short circuit between the two diamond plates or in the SMA connectors,  
221     destroying the amplifier. Furthermore, at approximately 60 K the helium gas has to  
222     be evacuated from the inlet to avoid a potential explosion due to the expansion of  
223     the gas with temperature.

224     When the sample is cooled to the minimum temperature achievable by means  
225     of liquid helium without over-pressurising it (4.2 K), the measurements start. A  
226     temperature sensor placed on the back of the PCB carrier is used to measure the  
227     temperature of the sample. After every temperature data point, the current through  
228     the heater placed in the PCB next to the diamond sample is increased, warming up  
229     the sample. The initial temperature time constant of the order of tenths of seconds at  
230     low temperatures increases with temperature. Even more so when helium is evacuated  
231     from the inlet at 60 K, removing the thermal bridge between the wall of the inlet and  
232     the diamond sample. At the room temperature (RT), the time constant increases to

233 the order of minutes.

## 234 1.2 Charged particle pulses and spectra

235 In previous chapter the ionisation profiles for different types of radiation were dis-  
236 cussed. It is known that  $\beta$  and  $\gamma$  radiation induces a triangular electric pulse whereas  
237  $\alpha$  radiation induces a rectangular one. However, their amplitude, width and rise/fall  
238 time depend heavily on the type of interaction with the diamond, the purity of the  
239 diamond and the bandwidth of the amplifier and the oscilloscope. This section shows  
240 the signal pulses of  $\alpha$ ,  $\beta$  and  $\gamma$  radiation with their respective energy distributions for  
241 the case of a diamond detector. Then follows a discussion of effects of noise on these  
242 measurements.

243 A CIVIDEC C2 current amplifier together with the LeCroy oscilloscope (both  
244 with a bandwidth limit of 2 GHz) has been used to record the pulse shapes whereas  
245 the Cx charge amplifier is used for charge measurement. A 2 GHz bandwidth limit  
246 defines the minimum rising time equal to  $t_r \simeq \frac{0.34}{BW} = \frac{0.34}{2 \times 10^9} = 170$  ps, therefore  
247 the system is capable of measuring pulses with a minimum FWHM  $\simeq 170$  ps. This  
248 already makes it impossible to measure the initial peak in the  $\alpha$  response due to the  
249 two flavours of charge carriers travelling. If a charge carrier travelling through the  
250 bulk takes  $t_{t1} \sim 6$  ns to get to the electrode on the other side ( $d_1 \sim 500$   $\mu m$ ), the  
251 carrier with the opposite charge and a shorter path to the closer electrode – max.  
252  $d_2 \sim 10$   $\mu m$  – only takes  $t_{t2} \sim \frac{d_2}{d_1} t_{t1} = 120$  ps. A drift time this short induces a  
253 current pulse that is too narrow for the C2 amplifier or the oscilloscope to be able to  
254 observe.

255 Figure 1.5 shows a set of pulses and an averaged pulse for  $\alpha$ ,  $\beta$  and  $\gamma$  radiation  
256 using an  $^{241}Am$ ,  $^{90}Sr$  and  $^{60}Co$  source, respectively. The particles are measured with  
257 the non-irradiated sCVD diamond S37.  $\alpha$  particles always produce the same signal  
258 pulse, but with a high noise RMS. The averaging suppresses the noise while still  
259 retaining most the information. It does, however, smear the rising and falling edge,  
260 increasing the rise time. The  $t_r$  is now of the order of 0.5 ns. Both  $\beta$  and  $\gamma$  pulses  
261 look similar - triangular and with a wide range of amplitudes. Here the pulse count  
262 is low, so the pulses with a high amplitude are not recorded. A trigger set very high  
263 would be needed to “catch” them with the oscilloscope.

### 264 1.2.1 Noise limitations

265 Noise is a major limiting factor in particle detection. It defines the minimum measur-  
266 able particle energy and the minimum measurement resolution. It is hence important  
267 to minimise the electric noise in the detector signal. The major noise contribution  
268 comes from poor shielding from external electromagnetic sources. These often cause  
269 ringing, whereby the signal oscillates with a frequency defined by the external source.  
270 The ringing makes high-frequency measurements impossible. Another source of noise  
271 is the sensor itself. In the case of silicon, natural light increases the number of ther-

## 1.2. CHARGED PARTICLE PULSES AND SPECTRA

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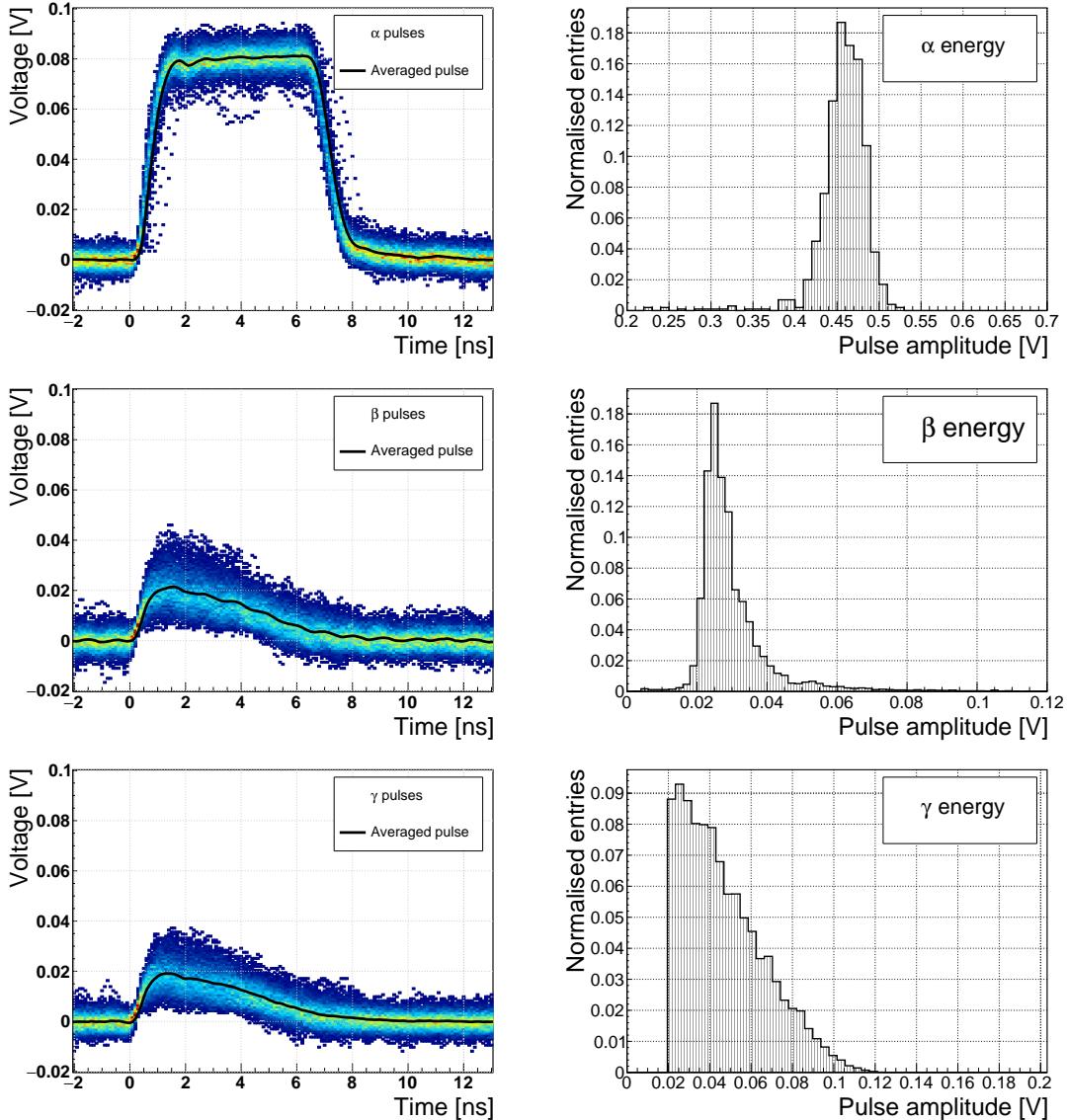


Figure 1.5: Superimposed and averaged pulses (a, b and c, current amplifier) and distributions of deposited energy (d, e, f, charge amplifier) for three types of radiation. Note the scale on the X axis of the distributions.

272 mally excited free charge carriers, increasing the leakage current. This is not the  
 273 case for diamond, which is with its high energy band gap insensitive to visible light.  
 274 Nevertheless, any noise produced by the sensors is amplified by the signal amplifiers,  
 275 which add an additional noise of the analogue electrical circuit to the amplified  
 276 signal. Finally, the digitisers add the quantisation noise to the digitised signal. If  
 277 the measurement range is significantly higher than the actual measured signal, the  
 278 quantisation noise can be a significant contributor to the decrease of the overall mea-  
 279 surement resolution.

280 **1.3 Radiation limitations**

281 Exposure to ionising radiation degrades sensors. It deforms the lattice by displacing  
282 the atoms. Various types of lattice defects can be created in diamond, similar to those  
283 in silicon: vacancies, interstitials etc. [14] These deformations introduce new discrete  
284 energy levels between the valence and conduction band. Charge carriers drifting in  
285 their vicinity can get trapped, their energy falling to the energy level of the trap.  
286 Their emission back to the conduction band depends on how deep the trap is (how  
287 far away from the conduction band it is). The carriers caught in the shallow traps of  
288 the order of 100 meV below the conduction band are excited back up already by means  
289 of the thermal excitation. This phenomenon has a short time constant, dependant  
290 on the environmental temperature. Those stopped by deep traps near the middle  
291 of the band gap need more energy and thus more time to be emitted to either the  
292 conduction or valence band. Some charge carriers remain trapped for long periods.  
293 If they build up in a certain region of the diamond, their charge starts affecting the  
294 surrounding electric field – space-charge forms. It can either help or counteract the  
295 field, depending on the polarity of the carrier.

296 The energy band jumping goes the other way, too. The carriers in the valence  
297 band may use the intermediate energy levels as “stepping stones” to jump to the  
298 conduction band and start drifting in the externally applied electric field. This is  
299 called the leakage current.

300 The electrons and holes stopped in these traps cause a decrease of the induced  
301 current on the electrodes. This yields a lower integrated charge in an irradiated sensor  
302 than that in a non-irradiated one. Charge collection efficiency is therefore correlated  
303 with the level of irradiation.

304 This section contains a study of the effects of pion ( $\pi_{300 \text{ MeV}}$ ) irradiation on the  
305 charge collection efficiency of sCVD diamond detectors. To carry out this study,  
306 two diamond samples have been irradiated to doses of  $1 \times 10^{14} \pi \text{ cm}^{-2}$  (S79) and to  
307  $3.63 \times 10^{14} \pi \text{ cm}^{-2}$  (S52). Then a test beam campaign has to be carried out to observe  
308 the charge collection efficiency at different bias voltage settings. The efficiency values  
309 acquired are used to determine the effective drop in efficiency with respect to received  
310 radiation dose. This is to test if the collected charge  $Q$  is inversely proportional to  
311 the received dose  $\Phi$ . A procedure defined by a collaboration researching diamond  
312 behaviour RD42 has been applied to the measured values to extract the damage factor.  
313 The next subsection contains measurements and results of a long-term stability study  
314 using  $\alpha$  and  $\beta$  particles. In particular, the charge collection efficiency as a function  
315 of time is measured during the measurements with  $\beta$  and  $\alpha$  radiation. To investigate  
316 this effect on the scale of charge carriers, the change of TCT pulses with time is  
317 observed. Finally, a procedure that improves the pulse shape and with it the charge  
318 collection is proposed.

### **1.3. RADIATION LIMITATIONS**

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#### **319 1.3.1 Quantifying radiation damage in diamonds**

**320** Radiation damage varies with the type of radiation (particles or photons) and its  
**321** energy. There are several models existing [12, 11] that try to explain the impact  
**322** of irradiation and to provide *hardness factors* to compare the radiation damage be-  
**323** tween different particles. The standard way is to convert the damage into *neutron*  
**324** *equivalent* [6]. Some models have been extensively verified with simulations and with  
**325** experiments. In these experiments charge collection in sensors is measured before  
**326** and after irradiation. This procedure is repeated several times, with a measurement  
**327** point taken after every irradiation. When a set of measurements of charge collection  
**328** is plotted against the radiation dose received by a specific particle at a specific energy,  
**329** a damage factor  $k_\lambda$  can be extracted. Damage factors have to be measured across a  
**330** range of energies and types of radiation to properly quantify the damage in the sen-  
**331** sors. They are then compared against the simulations to verify that the experimental  
**332** observations are in line with the theory.

**333** Diamond is an expensive material and the technology is relatively new as com-  
**334** pared to silicon. Therefore not many institutes are carrying out diamond irradiation  
**335** studies. To join the efforts, the RD42 collaboration [5] was formed. It gathers the  
**336** experimental data from diamond irradiation studies. Unlike with silicon, the exper-  
**337**imental results so far show no significant correlation with the NIEL (non-ionising  
**338** energy loss) model [12], which correlates detector efficiency with the number of lat-  
**339**tice displacements. Therefore an alternative model was proposed [11], correlating the  
**340**diamond efficiency with the number of displacements per atom (DPA) in the bulk.  
**341**The idea is that if the recoil energy of an incident particle is higher than the lattice  
**342** binding energy (42 eV for diamond), the atom is displaced from its original position.  
**343**The newly formed vacancy acts as a trap for drifting charge carriers. The more dis-  
**344**placements that form in the bulk, the higher is the probability that a drifting carrier  
**345** will get trapped, effectively reducing the induced signal. However, different types of  
**346** particles interact differently with the bulk. In addition the mechanisms of interac-  
**347**tion at low energies are different to those at high energies. To assess the damage  
**348** for individual particles at a range of energies, simulations need to be run first. The  
**349** simulation shown in [11] shows the DPA model for a range of energies of proton, pion  
**350** and neutron irradiation in diamond. Figure 1.6 contains the simulation results as  
**351** well as the superimposed empirical results of several irradiation studies. According  
**352** to the figure, a 300 MeV pion beam damages the diamond bulk twice as much as a  
**353** 24 GeV proton beam. The data points obtained by RD42 are also added to the figure.  
**354** They have been normalised to damage by 24 GeV protons. Finally, the data point  
**355** measured in the scope of this thesis has been added for comparison. The derivation  
**356** is done below.

#### **357 Irradiation with a $\pi_{300 \text{ MeV}}$ beam**

**358** The samples were irradiated at the Paul Scherrer Institute (PSI) [4] by means of a  
**359** beam of pions with an energy of 300 MeV (kinetic energy 191.31 MeV) and with a

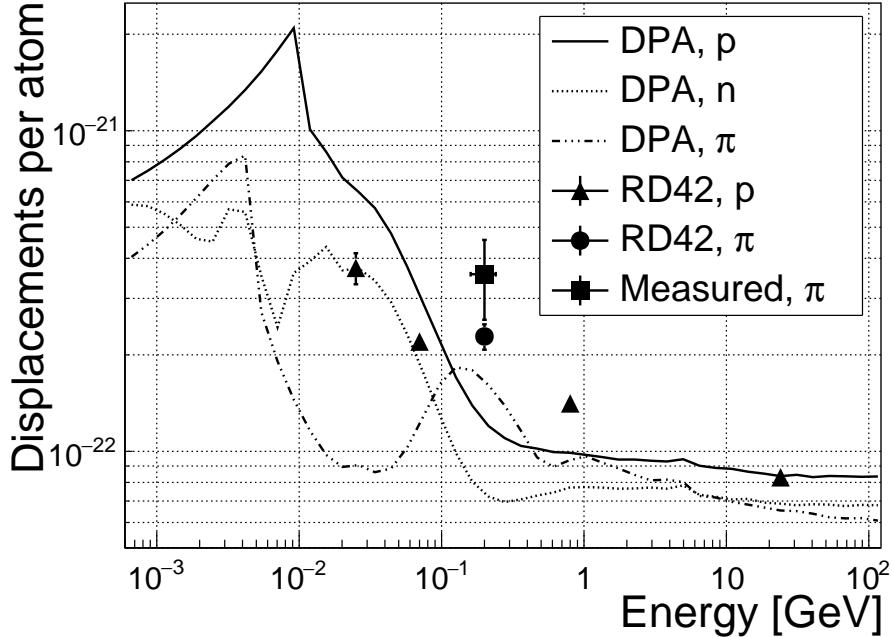


Figure 1.6: Diamond radiation damage - a model based on displacements per atom [11]. Added are data points for protons and pions by RD42 [17] and one data point for pions measured in the scope of this thesis.

360 flux of up to  $1.5 \times 10^{14} \pi \text{ cm}^{-2}$  per day. The system has a 10 % uncertainty on the  
361 beam energy. In addition, their quoted uncertainty on the measurement has an error  
362 of  $\pm 20\%$ . Looking at the pion damage curve in figure 1.6,  $\pi_{300 \text{ MeV}}$  point sits on a  
363 steep section of the DPA curve. This means that a deviation in beam energy can  
364 have a significant effect on the damage.

365 Two diamond samples, S52 and S79, were put in the  $\pi_{300 \text{ MeV}}$  beam in the 2014  
366 PSI irradiation campaign; S52 to  $(1 \pm 0.21) \times 10^{14} \pi \text{ cm}^{-2}$  and S79 to  $(3.63 \pm 0.77) \times$   
367  $10^{14} \pi \text{ cm}^{-2}$ . During the process, the golden electrodes got slightly activated, but the  
368 activation decayed in two weeks.

### 369 Charge collection efficiency and charge collection distance

370 Three diamonds – non-irradiated S37 and irradiated S52 and S79 – were tested in  
371 a  $\pi_{120 \text{ GeV}}$  test beam in the SPS North Experimental Area at CERN [8] before and  
372 after irradiation. The goal was to estimate the charge collection efficiency (CCE) and  
373 charge collection distance (CCD) as a function of irradiation dose. The samples were  
374 primed (pumped) prior to data taking using a  $^{90}\text{Sr}$  radioactive source. The data were  
375 then taken at a range of bias voltages ranging from 30 V to 900 V, yielding between  
376 0.06 V/ $\mu\text{m}$  and 1.8 V/ $\mu\text{m}$  electrical field in the bulk. Every data point contained  
377 approximately  $5 \times 10^4$  measured particles. The charge deposited by the particles  
378 was measured using a CIVIDEC Cx charge preamplifier. As expected, the integrated

### 1.3. RADIATION LIMITATIONS

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<sup>379</sup> amplitude spectrum followed a landau distribution. Its most probable value (MPV)  
<sup>380</sup> was used to calculate the most probable collected charge  $Q_i$ :

$$Q_i [e^-] = \frac{Q_i [fC]}{1.6 \times 10^{-4}} = \frac{MPV [mV]}{A [mV/fC]} \cdot 6.241 \times 10^4 \quad (1.2)$$

<sup>381</sup> where  $A = 9.2 \text{ mV/fC}$  is the preamplifier gain factor. The CCD was then calculated  
<sup>382</sup> using the average number of electron-hole pairs produced per micrometer in diamond  
<sup>383</sup>  $\delta_d = 36 \text{ e-h } \mu\text{m}^{-1}$  (from table ??):

$$CCD = \frac{Q_i}{\delta d} \quad (1.3)$$

<sup>384</sup> The resulting CCD for the three measured samples at bias voltages ranging from  
<sup>385</sup>  $0.2\text{--}1.6 \text{ V } \mu\text{m}^{-1}$  is shown in figure 1.7a. S37 exhibits a full collection distance already  
<sup>386</sup> at  $0.4 \text{ V } \mu\text{m}^{-1}$  whereas the irradiated samples have a more gentle increase of CCD  
<sup>387</sup> with increasing bias voltage. It is evident that at  $1 \text{ V } \mu\text{m}^{-1}$  the maximum CCD has  
<sup>388</sup> not been reached in the case of S79 and S52. Nevertheless, to compare the measured  
<sup>389</sup> data point with those provided by RD42, the CCD at  $1 \mu\text{m}$  has to be taken.

#### 390 Irradiation damage factor

<sup>391</sup> The irradiation damage factor  $k$  is a way to quantify irradiation damage of a specific  
<sup>392</sup> particle at a specific energy. Via this factor different types of irradiation can be  
<sup>393</sup> compared. It is obtained experimentally by measuring the CCD of a number of  
<sup>394</sup> samples at various irradiation steps and fitting the equation 1.5 to the data.  $\lambda$  is the  
<sup>395</sup> measured CCD,  $\lambda_0$  is the CCD of a non-irradiated sample and  $\Phi$  the radiation dose.  
<sup>396</sup> As a reference, the damage factor for 24 GeV protons is set to  $1 \times 10^{-18} \mu\text{m}^{-1} \text{ cm}^{-2}$ .

$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k_\lambda \cdot \Phi \quad (1.4)$$

$$\lambda = \frac{\lambda_0}{k_\lambda \lambda_0 \Phi + 1} \quad (1.5)$$

<sup>397</sup> The data points with the maximum CCD obtained in the test beam measurements  
<sup>398</sup> are plotted against radiation dose received (see figure 1.7b). Equation 1.5 is fitted  
<sup>399</sup> to the data points and a damage factor  $k_\lambda = (4.4 \pm 1.2) \times 10^{-18} \mu\text{m}^{-1} \text{ cm}^{-2}$  was  
<sup>400</sup> obtained. This value is for a factor of two higher than the damage factor obtained by  
<sup>401</sup> RD42. This could be due to an insufficient priming time ahead of the measurement.  
<sup>402</sup> In addition, the diamond samples have not been polished and re-metallised after  
<sup>403</sup> irradiation, as is the case for the RD42. Also, with only two samples measured, the  
<sup>404</sup> statistical uncertainty is high. Nevertheless, it can be concluded that the 300 MeV  
<sup>405</sup> pions damage the diamond bulk more than the 24 GeV protons.

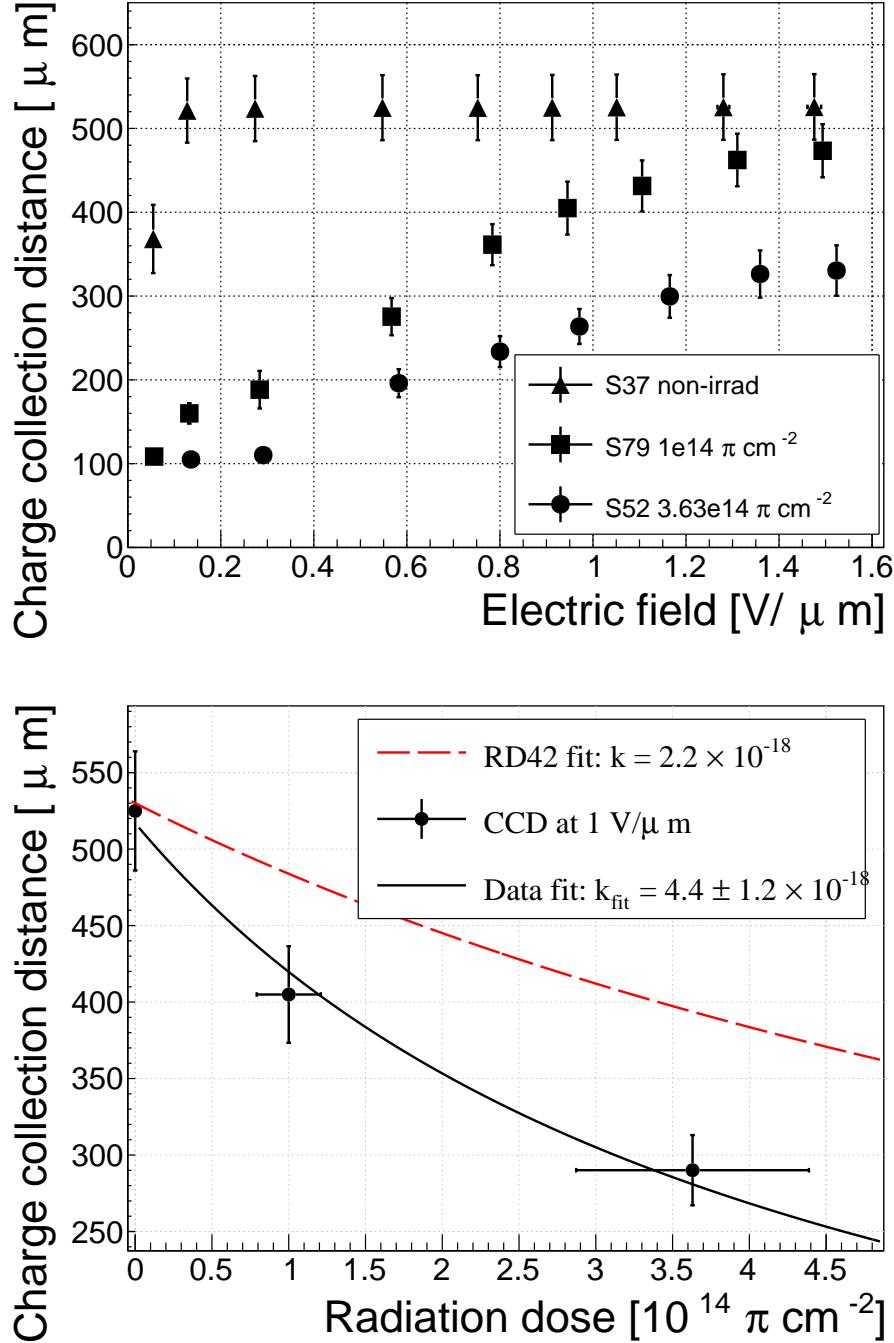


Figure 1.7: First figure shows the CCD for S37, S79 and S52 at a range of bias voltage settings. The charge collection distance at  $1 \text{ V}/\mu\text{m}$  bias voltage for the three diamond samples is then compared to the RD42 data for pion irradiation in the second figure. The data points are about 15–25 % lower than expected from the RD42 data [17].

<sup>407</sup> **1.3.2 Long-term measurement stability**

<sup>408</sup> An important requirement for particle detectors is a stable performance over long  
<sup>409</sup> periods of time. For instance, the charge collection for a defined radiation type and

### **1.3. RADIATION LIMITATIONS**

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410 quantity must not change over time or has to change in a predicted way. Diamonds  
411 are stable as long as their environment and their operating point does not change  
412 significantly. The stability of diamond detectors depends on many factors (material  
413 purity, polishing process, electrode material, irradiation damage etc.). The aim is  
414 to study the behaviour of diamond under controlled conditions, with the goal to  
415 understand its limitations. One of these limitations is for sure the received radiation  
416 dose as it can affect the long-term stability of the sensor during operation.

417 The three diamond samples (S37, S79 and S52) have been exposed to two different  
418 types of ionising radiation for a longer period to see if their behaviour changes over  
419 time. Two parameters have been observed in particular:

- 420     1. Charge collection of  $\beta$  particles and  
421     2. Charge collection and ionisation profile of  $\alpha$  particles.

422 The results in this and in the next section will show that, in both cases, priming plays  
423 an important role in improving the diamond measurement stability.

#### **$\beta$ long-term stability**

425 The diamond samples have undergone a long-term stability test using  $\beta$  radiation.  
426 This has been done using a  $^{90}\text{Sr}$  source emitting  $\sim 2$  MeV electrons at a rate of  
427 approximately  $10^4 \text{ e}^- \text{ cm}^{-2}$ . To simulate the initial conditions in HEP experiments,  
428 the sensors must not be primed before starting the measurements. The measurement  
429 setup consists of a diamond sample (S37, S52 or S79) with the Cx spectroscopic  
430 amplifier, a silicon diode with a C6 amplifier for a trigger and a  $^{90}\text{Sr}$  source on  
431 top. A particle emitted by the source traverses the sensor bulk and hits the silicon  
432 diode, triggering the analogue signal readout. The source is left on the top for the  
433 course of the experiment. The measurements, however, are taken at discrete times.  
434 For every data point, approximately  $10^4$  triggers are recorded. The offline analysis  
435 of the recorded signal pulse amplitudes yields a landau distribution for every data  
436 point. The most probable value (MPV) of the distribution is proportional to the  
437 collected charge by the diamond sensor. The resulting graph of charge collection over  
438 time (see figure 1.8) shows that the charge collection efficiency improves when the  
439 diamond sensor is primed with a  $\beta$  source. This is especially evident in the case of  
440 the two irradiated samples. S79 achieves close to a full efficiency whereas S52 reaches  
441 about 50 %. Both increases are significant. At a received dose of approximately  
442  $4 \times 10^6$  particles the signal stabilises. As expected, the signal of the non-irradiated  
443 S37 does not change with time – this pure sCVD diamond sample has the maximum  
444 collection distance from the start of the measurement.

445 It should be noted that the  $\sim 2.28$  MeV electrons emitted by this source are not  
446 MIPs; their charge deposition is higher than that of an electron MIP, according to  
447 the Bethe-Bloch distribution [7]. Nevertheless, for the purpose of these measurements  
448 this energy was adequate since only the relative change in charge collection was of  
449 our interest.

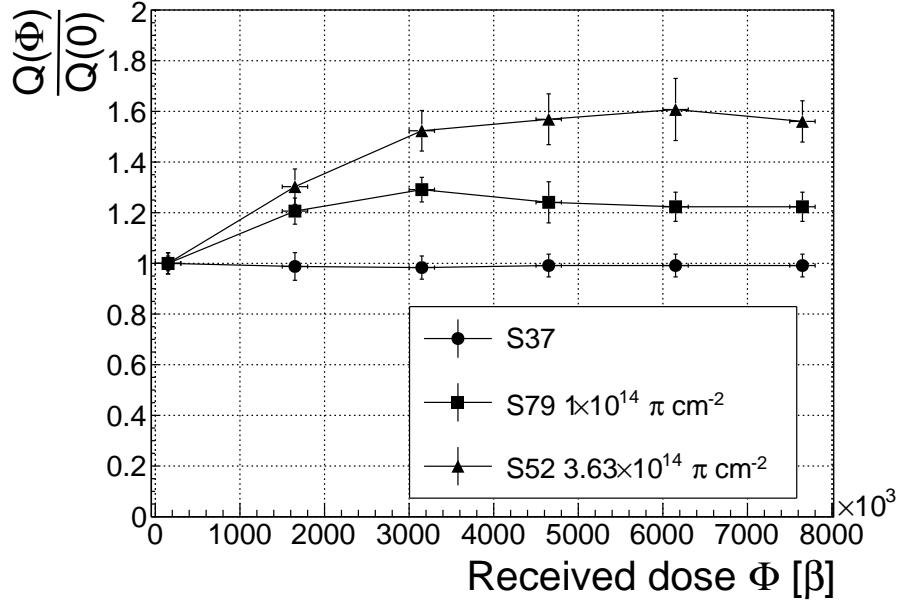


Figure 1.8: Relative increase of charge collection over time due to priming with the  ${}^{90}\text{Sr}$  radioactive source. The bias voltage for this measurement is  $1 \text{ V}/\mu\text{m}$ .

To sum up, diamond is a good choice for  $\beta$  radiation detection. Even if damaged by radiation, it reaches a stable charge collection at a received dose of  $\sim 4 \times 10^6$  MIP particles. The efficiency decreases with a high irradiation dose (effects visible above  $10^{12} \text{ MIP cm}^{-2}$ ). However, the decrease can be accounted for if the damage factor and the rate and energy of the particles are known.  $\gamma$  radiation has a similar impact on the diamond as the  $\beta$  because the ionisation mechanism is the same. The incident photons, if they interact with the diamond, prime the bulk, causing the increase in charge collection efficiency. The difference, however, is that the interaction probability (cross section) is lower for gammas [18, 10].

#### 459 $\alpha$ long-term stability

This part discusses the stability of irradiated diamond sensors during  $\alpha$  measurements. An  ${}^{241}\text{Am}$  source is used, emitting  $\alpha$  particles with a mean energy of 5.5 MeV. It is safe to assume that they will behave differently than when subject to  $\beta$  radiation. This is due to the point-like charge carrier creation when an  $\alpha$  particle penetrates the bulk and stops at a depth of  $\sim 14 \mu\text{m}$  (for a 5.5 MeV particle). The deposited energy produces  $\frac{5.5 \text{ MeV}}{13.6 \text{ eV}} = 4 \times 10^5$  e-h pairs. Compared to a MIP, which produces an MPV of  $500 \mu\text{m} \times 36 \text{ e-h } \mu\text{m}^{-1} = 18 \times 10^3$  e-h pairs in a  $500 \mu\text{m}$ , the collected charge is for a factor of 22 higher. In addition, the energy is deposited in a small volume –  $14 \mu\text{m}$  in depth and  $\sim 20 \text{ nm}$  radially [13]. This dense distribution of charge carriers affects their behaviour at the start of the drift. Furthermore, carriers of only one polarity drift through the sensor while those of the opposite polarity almost instantly

### 1.3. RADIATION LIMITATIONS

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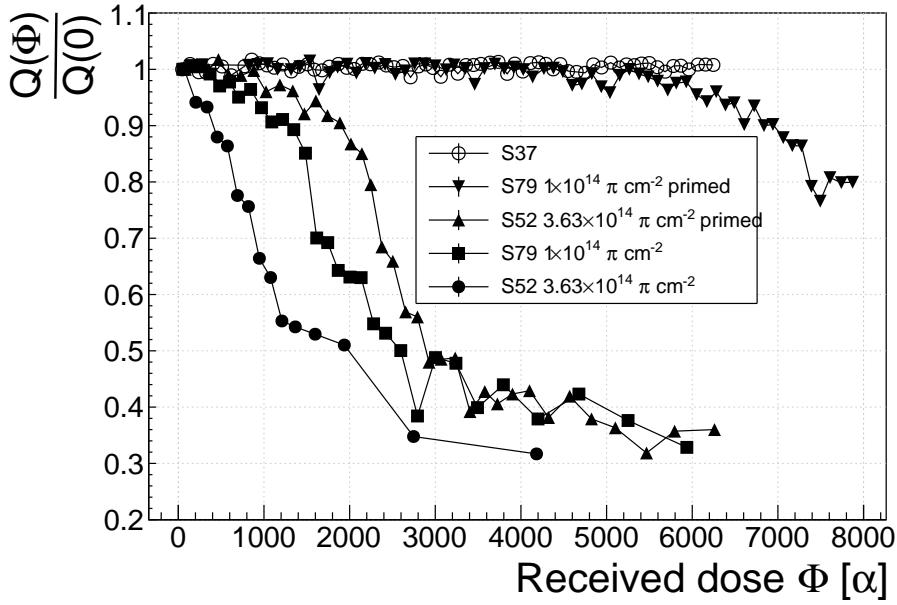


Figure 1.9: Relative decrease of collected charge with time for non-irradiated and irradiated diamond samples.

471 recombine with the adjacent electrode. Taking into account that the diamond bulk  
 472 has been damaged by irradiation, these two phenomena might have an effect on the  
 473 operation of the detector on a macro scale.

474 The first test has been carried out using the Cx spectroscopic amplifier, with  
 475 the bias voltage of the samples set to +500 V. Figure 1.9 shows the results of 6500  
 476 recorded hits at a rate of  $\sim 7$  particles per second. The collected charge  $Q(\Phi)$  for  
 477 the non-irradiated sample is stable as compared to the initial collected charge  $Q(0)$   
 478 (plotted as a relative value  $\frac{Q(\Phi)}{Q(0)}$ ). It is expected that the irradiated samples will have  
 479 a lower charge collection efficiency than the non-irradiated sample. However, their  
 480 initial efficiency suddenly drops after a certain period of time. The initial efficiency  
 481 after priming with  $\beta$  particles is higher than that without priming, but eventually it  
 482 deteriorates again. In addition, the spread of measured energies increases significantly.  
 483 Finally, the particle counting rate decreases with the decreased efficiency.

484 To investigate this sudden drop in efficiency, the current pulse shapes using a  
 485 C2 current amplifier have to be observed (see figure 1.10). The shape of the pulse  
 486 holds more information about the charge carrier properties in the sensor than solely  
 487 the value of the integrated charge. This time only the primed S79 sample has been  
 488 tested. Both hole and electron collection are observed to determine whether they  
 489 behave differently or not. The sample has been measured long enough for the pulse  
 490 shapes to start changing. The data in figures 1.10 show that the initially stable pulses  
 491 start deteriorating – suddenly several different shapes start appearing, some still very  
 492 similar to those from the beginning while the others with almost zero amplitude.

493 Some charges get stopped in the charge traps in the bulk for a long time, building

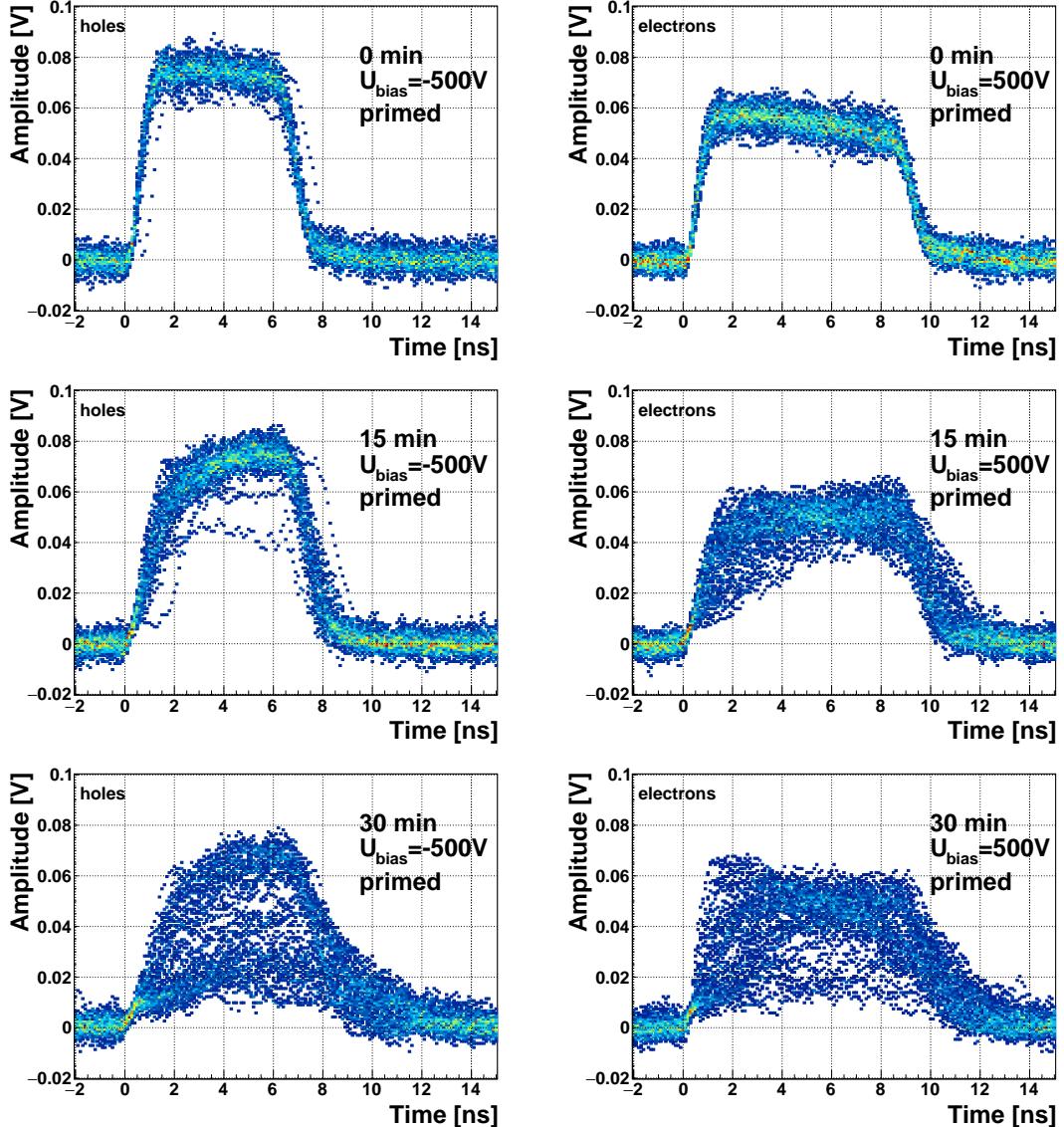


Figure 1.10: The signal of the irradiated and primed S79 deteriorates with time for both polarities. Every plot contains 60 superimposed pulses.

494 up regions of space charge. The built up space charge affects the electric field, making  
495 it non-uniform. The non-uniform field in turn affects the drifting carriers, slowing  
496 them down or speeding them up, depending on the field gradient. Since the movement  
497 of the carriers is inducing the electric current, the field gradient can be observed in  
498 the signal.

499 The second test with the C2 current amplifier has been carried out as follows: At  
500 the beginning of the test when the diamond is still operating stably, 60 pulses are  
501 recorded. An average pulse is calculated. This is a reference pulse for the subsequent  
502 measurement points. Then an RMS of the single pulses with respect to the reference  
503 pulse is calculated and the values are summed together ( $\sigma_{ref}$ ).

### 1.3. RADIATION LIMITATIONS

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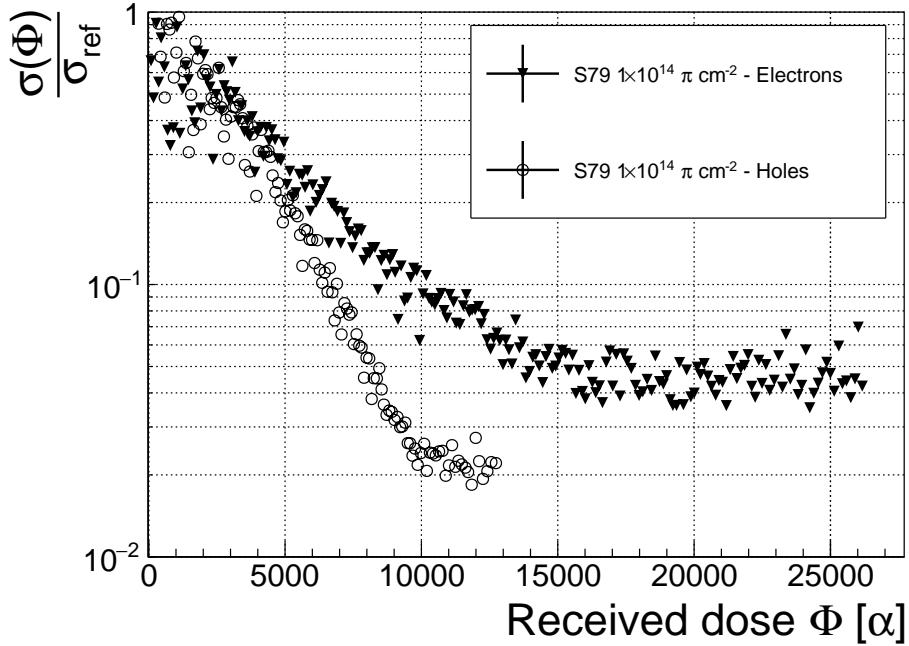


Figure 1.11: Deterioration of the pulse shapes with time

504 All the subsequent data points also consist of a set of 60 pulses. At every data point  
 505 the summation of the RMS values of the individual pulses with respect to the initial  
 506 averaged pulse is calculated ( $\sigma$ ). The ratio between the initial  $\sigma_{\text{ref}}$  and discrete values  
 507  $\sigma$  gives a measure of change of the pulse shape with respect to the reference pulse at  
 508 the start of the measurement. Figure 1.11 shows the ratio  $\frac{\sigma_{\text{ref}}}{\sigma(\alpha \text{ dose})}$ . From the data  
 509 obtained it can be concluded that initial pulse shape quickly starts deteriorating. In  
 510 fact, the deterioration of the shape follows an approximate exponential decay function,  
 511 which can be fitted to the data. The resulting decay constants for electrons and holes  
 512 are  $\tau_e = (4400 \pm 150) \alpha^{-1}$  and  $\tau_h = (3300 \pm 140) \alpha^{-1}$ . The electrons retain the initial  
 513 shape for longer. The deteriorated shapes also seem to be for a factor of 2 better  
 514 than those of the holes.

515 Finally, an effort has been made to find a way for the pulse shapes to return to  
 516 their initial state. Five methods are listed:

- 517 1. Removing the source and leaving the bias voltage switched on,
- 518 2. Removing the source and switching the bias voltage off,
- 519 3. Priming with  $\gamma$  at a rate of  $400 \text{ s}^{-1} \text{cm}^{-1}$  without applied bias voltage,
- 520 4. Priming with  $\beta$  at a rate of  $1000 \text{ s}^{-1} \text{cm}^{-1}$  with applied bias voltage and
- 521 5. Priming with  $\beta$  at a rate of  $1000 \text{ s}^{-1} \text{cm}^{-1}$  without applied bias voltage.

522 The diamond sample S79 is first primed using a  $^{90}\text{Sr}$  source for about one hour.  
 523 Then the bias voltage is switched on and an  $^{241}\text{Am}$  source is put on top. The pulses

produced by the incident  $\alpha$  particles have a proper rectangular pulse at the beginning, but then start changing – first gradually and later increasingly more in an erratic way, as described in the text above. After approximately 30 minutes, one of the methods is tested. When a “healing” procedure is started, a set of 60 pulses is taken at irregular points of time to observe the change in the pulse shape and to assess the quality of the “healing” procedure. Then the bias voltage is switched off and the sample is primed again to reset its state before starting with the next run.

The results depicted in figure 1.12 show that the methods (3) and (5) improve the shape, method (2) helps slowly, (1) does not show any change with time and (4) at first improves, but then significantly degrades the shape. The effect observed in method (4) has already been described in [15]. The “healing” process therefore depends on the rate of radiation, the bias voltage and the time of exposure. The ionising radiation creates free charges, which quickly recombine close to the place of generation. It is likely that they also release the charges trapped during the measurement, reducing the overall effect of the space charge. The traps get filled with both flavours of carriers, thus they are neutralised. The pulse shape gradually returns to its initial state.

|     | Procedure | Source           | Bias voltage | Effectiveness |
|-----|-----------|------------------|--------------|---------------|
| 540 | 1         | /                | ON           | no            |
|     | 2         | /                | /            | slow          |
|     | 3         | $^{60}\text{Co}$ | /            | YES           |
|     | 4         | $^{90}\text{Sr}$ | ON           | no            |
|     | 5         | $^{90}\text{Sr}$ | /            | YES           |

541 Table 1.2: Effectiveness of healing procedures

542 In summary, the shape of the pulses caused by  $\alpha$  radiation changes with time  
543 for irradiated samples. The shape of the pulses gets distorted and becomes erratic.  
544 Charge collection decreases and its spread increases. This happens even faster for  
545 non-primed diamonds. To “heal” the diamond – to bring the pulse shapes back to  
546 their initial shape – the sample must be primed using a  $\beta$  or a  $\gamma$  source for several  
547 minutes at the bias voltage set to 0 V. Switching to the inverse polarity for a few  
548 seconds helps a bit, but in a long run distorts the signal, which cannot get back to  
549 its initial shape.

## 550 1.4 Temperature limitations

551 A test has been carried out to evaluate the effect of temperature changes on the  
552 output signal of the diamond sensors. A cryostat filled with liquid helium is used to  
553 cool down the sensor during the measurement process. The current signal response  
554 to  $\alpha$ -particles is measured at 18 temperature points between 4 K and 295 K. At every  
555 temperature point, a set of 300 pulses is read out at various bias voltages. Resulting  
556 data show that the charge collection is stable down to 150 K, where it starts decreasing  
557 and stabilises again at about one third of the initial value at 75 K. This behaviour  
558 was first measured and discussed by H. Jansen [13].

## 1.4. TEMPERATURE LIMITATIONS

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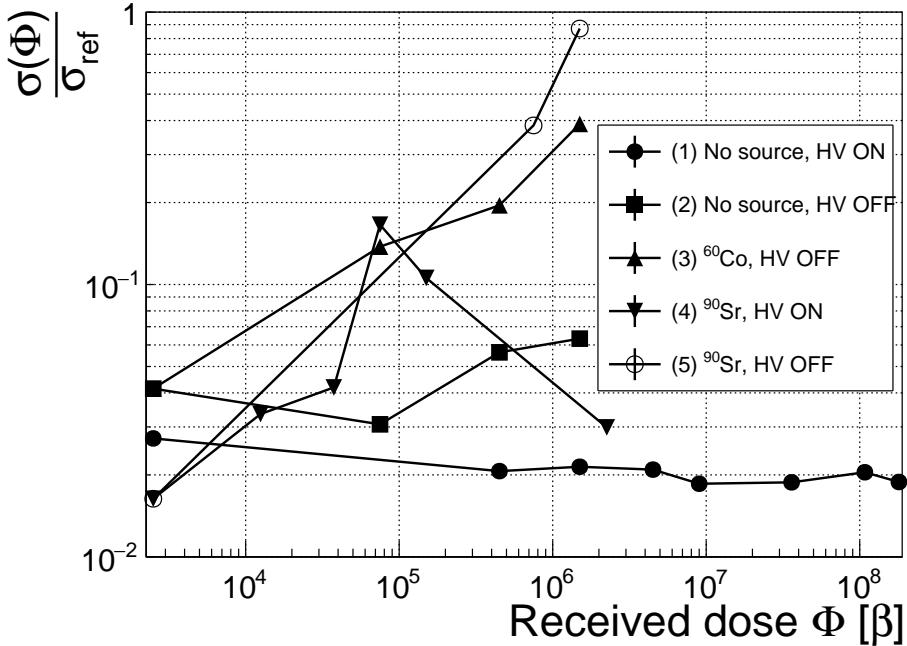


Figure 1.12: Five procedures for the “healing” process for an irradiated diamond that was exposed to  $\alpha$  radiation at bias voltage switched on for at least 30 minutes at a rate of  $10^4 \text{ s}^{-1}$ .

559     The band gap energy in diamond is equal to  $E_g = 5.5 \text{ eV}$  while the average energy  
 560     to produce an electron-hole pair is  $E_{e-h} = 13.25 \text{ eV}$ . This means there is excessive  
 561     energy deposited in the diamond bulk. The incident  $\alpha$ -particle stops within  $\sim 10\text{--}15 \mu\text{m}$  of the bulk,  
 562     transferring all its energy to the lattice during deceleration. A  
 563     part of this energy directly ionises the carbon atoms, creating free electron-hole pairs.  
 564     The positively charged hole and the negatively charged electron in the hole attract  
 565     each other via the Coulomb force and may undergo a bonding process during which  
 566     a phonon is emitted.

567     The remaining energy, however, is converted into lattice vibrations (phonons [19,  
 568     13]). This means that the lattice within the ionisation volume (approximately  $\sim 15 \mu\text{m} \times \sim 2 \text{ nm}$   
 569     in size) is briefly heated up. The hot plasma then cools down to the temperature of  
 570     the surrounding material by heat dissipation, (i.e. phonon transport). The free elec-  
 571     tron binds the free hole into a bound state (not recombination) – the exciton [16].  
 572     The exciton binding energy is 80 meV. At higher temperatures, the lattice provides  
 573     enough energy to excite the electron from the exciton state back to the conduction  
 574     band. At lower temperatures, however, the exciton lifetime increases, which means  
 575     that it will take a longer time for the electrons to get re-excited to the conduction  
 576     band. The re-excitation lifetime at room temperature is  $\sim 30 \text{ ps}$ , increasing to  $\sim 150 \mu\text{s}$   
 577     at 50 K [13]. This means that some of the bound electrons will not even start drifting  
 578     within the period of  $\sim 10 \text{ ns}$ , which is the expected carrier drift time. When they  
 579     are finally freed, the current they induce is already hidden in the electronics noise.

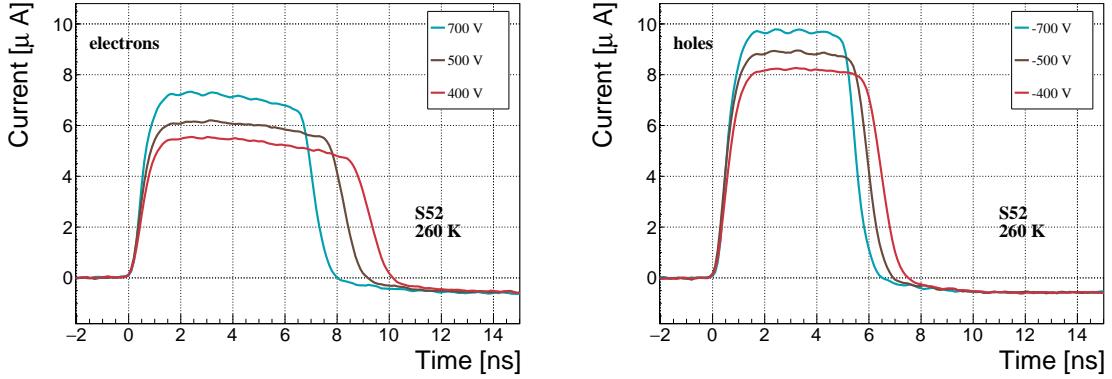


Figure 1.13: Varied bias voltage at a fixed temperature

580 The effective area of the observed current pulse is therefore smaller than that of a  
581 pulse induced by all the carriers drifting at the same time. This in effect reduces the  
582 measured collected charge. The longer the time constant, the lower the measured  
583 collected charge, as shown in figure 1.17 below.

#### 584 1.4.1 Temperature-variant $\alpha$ -TCT before irradiation

585 Three sCVD diamond samples have been tested at a range of temperatures using  
586 the  $\alpha$ -TCT technique. At each temperature point, the bias voltage is set to several  
587 positive and negative values. A set of 300 pulses is recorded at every data point  
588 and averaged offline. The resulting averaged pulses of sample S37 at the 260 K  
589 temperature point and a bias voltage of  $\pm 400$  V,  $\pm 500$  V and  $\pm 700$  V are shown in  
590 figure 1.13. The pulses induced by holes as charge carriers are shorter than those  
591 induced by electrons, which means that holes travel faster in diamond. The area of  
592 the pulse, however, is the same for both polarities, which corresponds to the fact that  
593 the same amount of charges is drifting in both cases.

594 Figure 1.14 shows pulses at a bias voltage set to  $\pm 500$  V across the range of  
595 temperatures between 4 K and 295 K – room temperature (RT). Several conclusions  
596 can be drawn by observing their shape. First, the pulse shapes change with decreasing  
597 temperature. The pulse time gets shorter, hinting at the faster carrier drift velocity  
598  $v_{\text{drift}}$ . Second, between 150 K and 75 K there is a significant change in shape - the  
599 time constant of the rising edge increases significantly and the pulse area decreases.  
600 From 75 K down to 4 K there is no significant observable change. Last, the top of  
601 the pulse at the S52 is not flat, which means that a portion of the drifting charge is  
602 lost along its way. This is due to charge trapping, likely by means of crystal defects  
603 or impurities.

#### 1.4. TEMPERATURE LIMITATIONS

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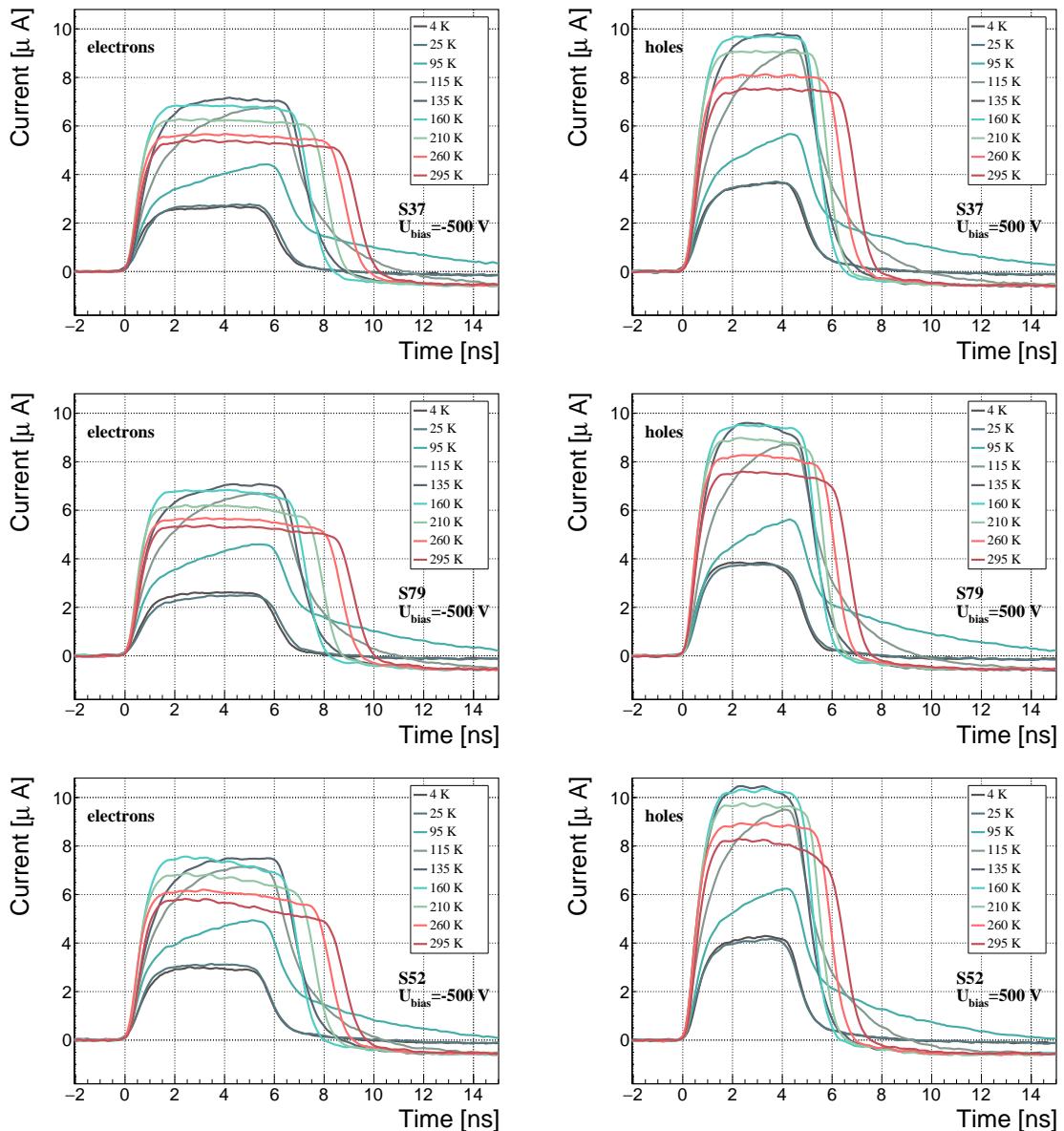


Figure 1.14: Several data points between 4 K and 295 K at a bias voltage of  $\pm 500$  V

604 **1.4.2 Temperature-variant  $\alpha$ -TCT after irradiation**

605 The irradiated S79 and S52 have been re-tested in the cryostat after irradiation.  
606 The aim was to see how their pulse shapes change with decreasing temperature,  
607 in particular the decaying top of the pulses (see figure 1.15). The decay time gives  
608 information on trapping of charge carriers while travelling through the diamond bulk.  
609 A variation of the decay time constant as a function of temperature might help to  
610 reveal the type and depth of the charge traps. To observe these effects or lack thereof,  
611 a number of requirements has to be met. First, the diamond samples are intentionally  
612 not primed prior to the experiment because priming would improve the pulse shapes  
613 and possibly change the decay time constant of the signal. Second, keeping in mind  
614 that the pulse shape of irradiated diamonds changes with time, the duration of the  
615 measurement of an individual data point has to be short – of the order of 30 seconds.  
616 Last, the sequence of the bias voltage settings is important, the reason for which is  
617 explained below.

618 Unfortunately it is not possible to avoid temporal pulse changes. For instance,  
619 one measurement point takes approximately one minute. After the measurement, the  
620 bias voltage polarity is swapped for a few seconds to bring the diamond back into its  
621 initial state. But a few seconds with respect to a minute is not enough. Therefore,  
622 when the bias voltage is set to the next value, there is still some residual effect of  
623 the previous measurement. Similar to the effects of polarisation, this effect is also  
624 decreasing the pulse height. This can be observed in figure 1.15, which shows the  
625 resulting pulses of S52 for bias voltages of  $\pm 200$  V,  $\pm 300$  V,  $\pm 400$  V and  $\pm 500$  V  
626 at 230 K and 260 K. In this case the measurements sequence is: 230K (200 V,  
627 300 V, 400 V, 500 V, -500 V, -400 V, -300 V), 260 K (-200 V, -300 V, -400 V, -  
628 500 V, 500 V, 400 V, 300 V). The changes in pulse shapes for holes at 230 K and  
629 260 K cannot be attributed to the temperature change. Instead, the explanation  
630 could lie in diamond “polarisation”. This means that, when exposed to an electric  
631 field with  $\alpha$  measurements ongoing, the diamond builds up an internal electric field  
632 of inverse polarity, which effectively reduces the overall electric field. This internal  
633 field does not dissipate when the external bias voltage is switched off. It can be  
634 said that the diamond becomes “polarised”. When switching the polarity of the  
635 external bias voltage, the internal and external electric field point in the same direction  
636 at the beginning, increasing the overall electric field and with it the pulse height.  
637 In figure 1.15, this happens when switching from 500 V (figure 1.15a) to -500 V  
638 (figure ??) at 230 K. The built up polarisation contributes to the pulse having a  
639 sharp rising edge and a high amplitude. This effect decays during the next two  
640 voltage points. There would be a handful of ways to avoid this polarisation effect in  
641 the data:

- 642 1. After every data point invert the bias voltage and leave it to return to a neutral  
643 state for the same amount of time,
- 644 2. Make a hysteresis of data points, going from minimum negative to maximum  
645 positive bias several times,

## 1.4. TEMPERATURE LIMITATIONS

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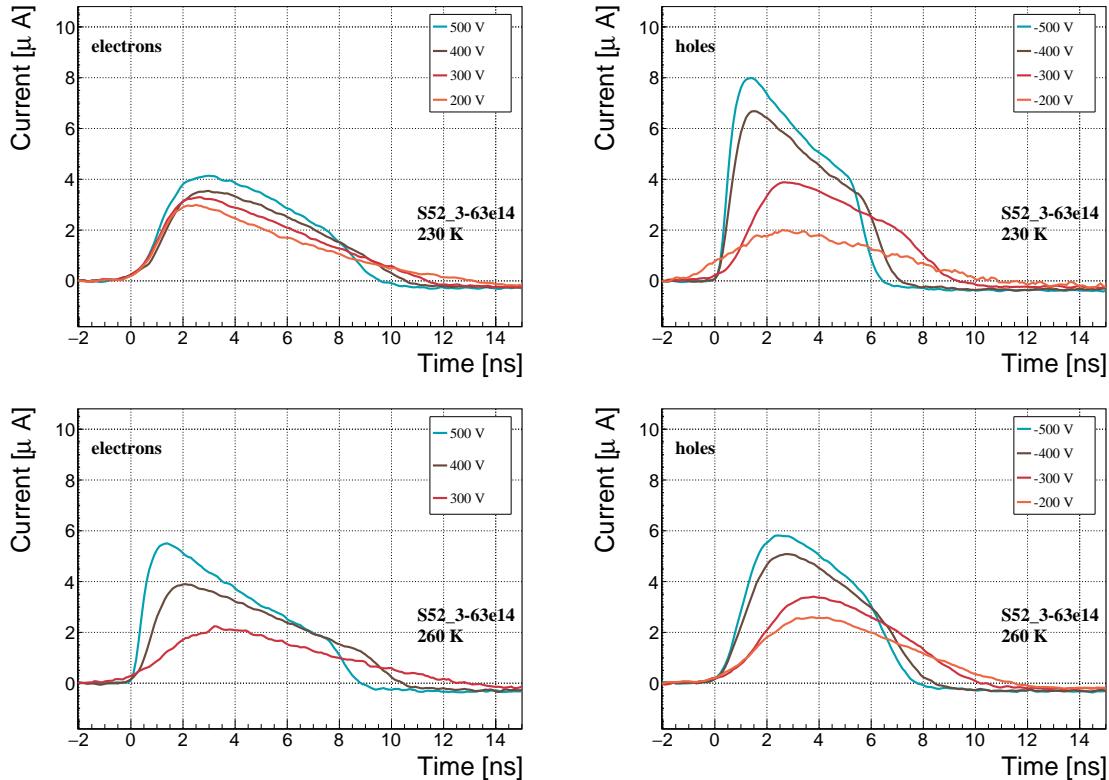


Figure 1.15: Varied bias voltage at a fixed temperature for an irradiated sample

646        3. Reduce the measurement time at every bias voltage setting.

647        Unfortunately, options (1) and (2) are very time consuming and would increase the  
 648        overall experiment time to over one day. The third option would worsen the resulting  
 649        averaged pulses. In the end an alternative option was chosen: alternating the start-  
 650        ing bias voltage and the sequence at every temperature point. With this option, a  
 651        meaningful systematic error in analysing the pulse shapes can be attained.

652        Figure 1.16 shows the irradiated S52 and S79 as well as the non-irradiated S37  
 653        for comparison, all at a bias voltage of ±500 V and at several temperature points  
 654        between 4 K and RT. It is evident that the radiation damage affected the shape of  
 655        the pulses across all temperatures.

### 656        Collected charge as a function of temperature

657        The area below the current pulse is proportional to the charge collected by the dia-  
 658        mond detector. The collected charge is observed as a function of temperature. First,  
 659        the amplitude values of the averaged pulses at a bias voltage of ±500 V and across the  
 660        temperature range between 4 K and 295 K have to be integrated. Then a calibration  
 661        factor is used to derive the charge for all data points. This factor is obtained using  
 662        a Cx charge-sensitive amplifier. The resulting values for electrons and holes are plot-  
 663        ted in figures 1.17a and 1.17b, respectively. Thesis [13] gives a model that explains

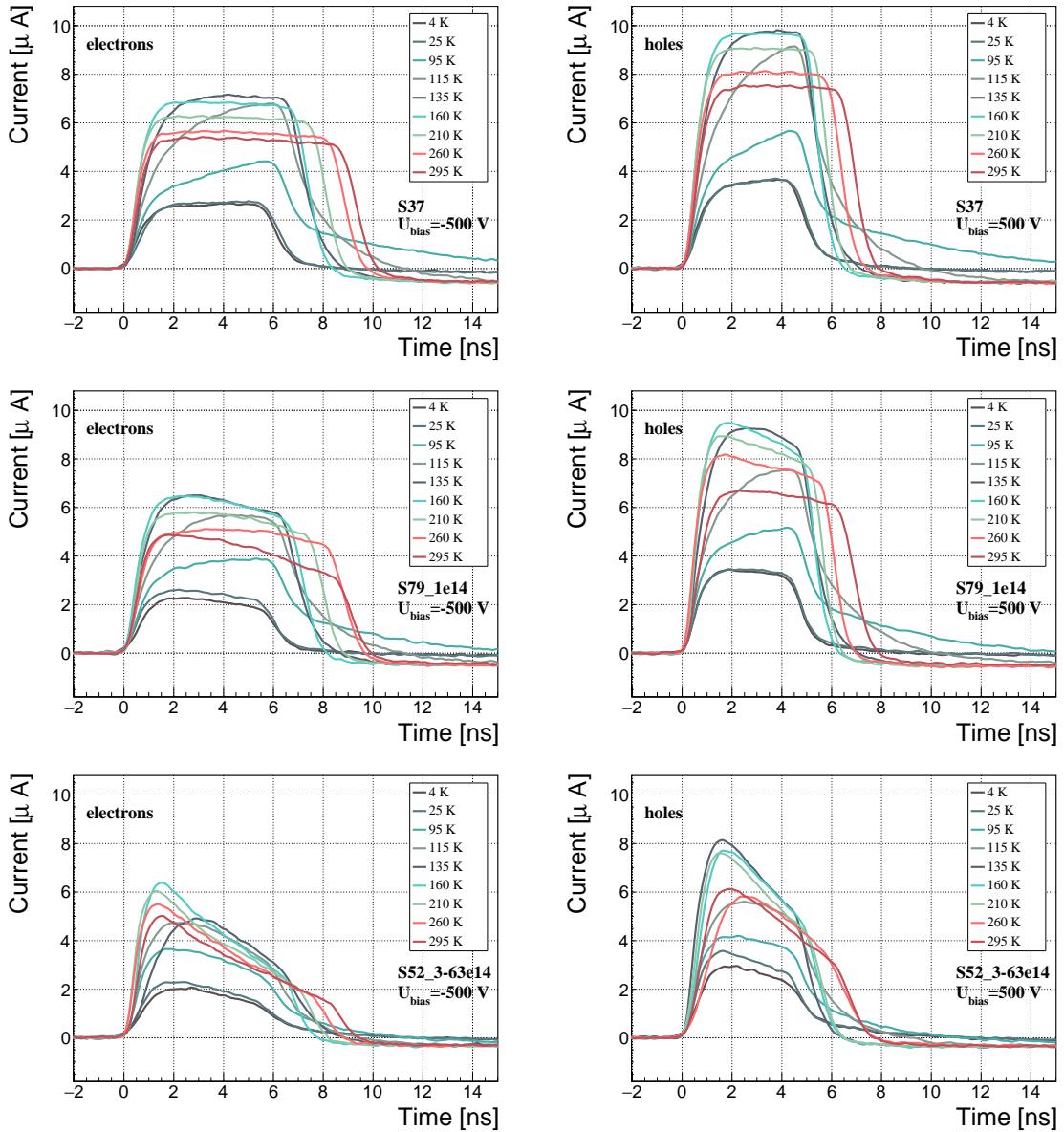


Figure 1.16: After irradiation: several data points between 4 K and 295 K at a bias voltage of  $\pm 500$  V

the drop in charge below 150 K. The new contribution are the data points for the irradiated samples. The values for them are lower than the those of non-irradiated samples, which is expected.

The values for all samples are fairly stable in the range between 4 K and 75 K and between 150 K and 295 K. However, in the values for the irradiated S52 some excursions can be observed. This is due to the sequence of the measurement steps, which introduced a hysteresis effect and is explained in the preceding text.

The collected charge drops significantly from 150 K down to 75 K. In the non-irradiated samples the values in the lower temperature range are approximately 0.30

## 1.4. TEMPERATURE LIMITATIONS

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of the values at the high range. For the irradiated ones this difference is lower – a factor of 0.35 for S79 and 0.5 for S52. An interesting detail is that the ratio between the values for non-irradiated samples and their irradiated counterparts at the lower range is different than at the higher range. Looking at the values for the electron collection in figure 1.17a: for S52 the lower ratio is equal to 1.28 and the higher equal to 1.7. For S79 these ratios are 1.00 and 1.09, which means that the difference in charge collection between 4 K and 75 K before and after irradiation is negligible.

### Charge trapping

The carriers drifting through the bulk get stopped by the charge traps with a certain probability. This trapping happens uniformly throughout the diamond, decreasing the number of carriers in the charge cloud. Therefore the absolute number of trapped carriers decreases. At the same time the absolute number of trapped carriers per unit of length decreases. The resulting function for the number of drifting carriers per unit of length is a decaying exponential function:

$$I(t) = I(0) \cdot e^{-\frac{t-t_0}{\tau}} + I_0, \quad (1.6)$$

where  $I(0)$  is the initial induced current,  $I_0$  is the end current,  $t$  is time,  $t_0$  is temporal displacement of the pulse and  $\tau$  is the decay time constant. This value tells how long it takes before the amplitude of the pulse decreases to 63 % of its initial height.

The decaying exponential function has been fitted to the decaying top of the averaged pulses at bias voltages of  $\pm 400$  V and  $\pm 500$  V across all temperatures excluding the transitional range between 75 K and 150 K. The resulting decay time constants  $\tau$  for an individual temperature point are not equal, which stems from the fact that the pulses change with time due to “polarisation”. This counts as a systematic error. Therefore the fitted  $\tau$  for  $\pm 400$  V and  $\pm 500$  V are averaged into one value representing the measurement at that temperature point. Figure 1.18a shows the fitted  $\tau$  for the five samples between 4 K and 295 K. In principle, the time constants should be infinite for a perfect and non-irradiated sample. Here a slightly tilted top of the pulse due to space charge is already successfully fitted with an exponential function, resulting in a  $\tau$  of the order of  $(200 \pm 20)$  ns $^{-1}$ . Consequently the fitting method is not adequate for non-irradiated samples. For the irradiated samples, the fit becomes increasingly more meaningful. As seen in figure 1.18a, the fitted values of the irradiated samples are fairly stable across all temperatures. There is a slight increase in the decay time constant of the S52 from  $(6.0 \pm 0.5)$  ns $^{-1}$  above 150 K to  $(8.5 \pm 0.9)$  ns $^{-1}$  below 75 K. On the other hand, this step is not observable in the S79 data. With only one sample exhibiting this behaviour, the effect is not significant enough. Judging by the data acquired, the samples would need to be irradiated to doses above  $1 \times 10^{14} \pi \text{ cm}^{-2}$  to quantify this effect in detail. So far this effect will not be regarded as significant for the scope of this thesis. Building on this assumption, the conclusion is that the signal decay time constant for irradiated sCVD diamond is constant across the temperature range between 4 K and 195 K, excluding the transitional range between 75 K and 150 K.

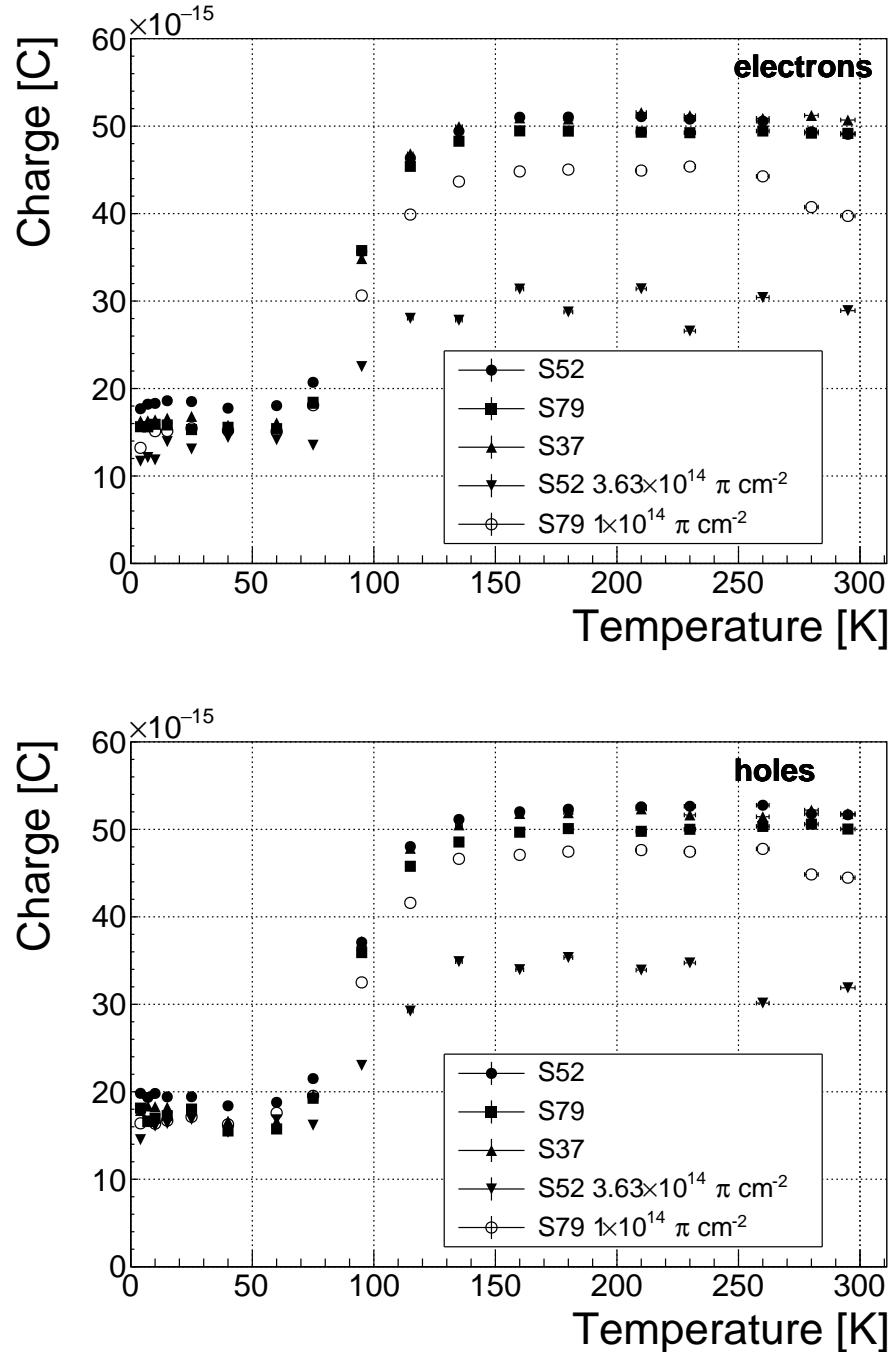


Figure 1.17: Collected charge as a function of temperature

713 Taking into account the conclusions above, all the values can be averaged into one  
 714 decay constant. Figure 1.18b shows these values for all samples as a function of the  
 715 received  $\pi_{300 \text{ MeV}}$  radiation dose. To estimate the carrier lifetime with respect to the  
 716 radiation dose received, a similar model is used than that in section 1.5. This model  
 717 states that the inverse of the carrier lifetime is linearly decreasing with increasing

## 1.4. TEMPERATURE LIMITATIONS

718 radiation dose:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \kappa_\tau \cdot \Phi \quad (1.7)$$

719

$$\tau = \frac{\tau_0}{\kappa_\tau \tau_0 \Phi + 1} \quad (1.8)$$

720 where  $\tau_0$  is the lifetime for a non-irradiated sample (real lifetime, therefore of the order  
721 of  $400 \text{ ns}^{-1}$ ),  $\tau$  is the lifetime of an irradiated sample,  $\Phi$  is the received radiation dose  
722 and  $\kappa_\tau$  the lifetime degradation factor. For these data the fitted factor is equal to  
723  $\kappa_\tau = (3.6 \pm 0.8) \times 10^{-16} \text{ s cm}^2 \pi_{300 \text{ MeV}}^{-1}$ . Using this factor, the steepness of the decay  
724 in the pulse shape with respect to radiation dose can be estimated. This can help  
725 when designing a system where current pulse shape is an important factor.

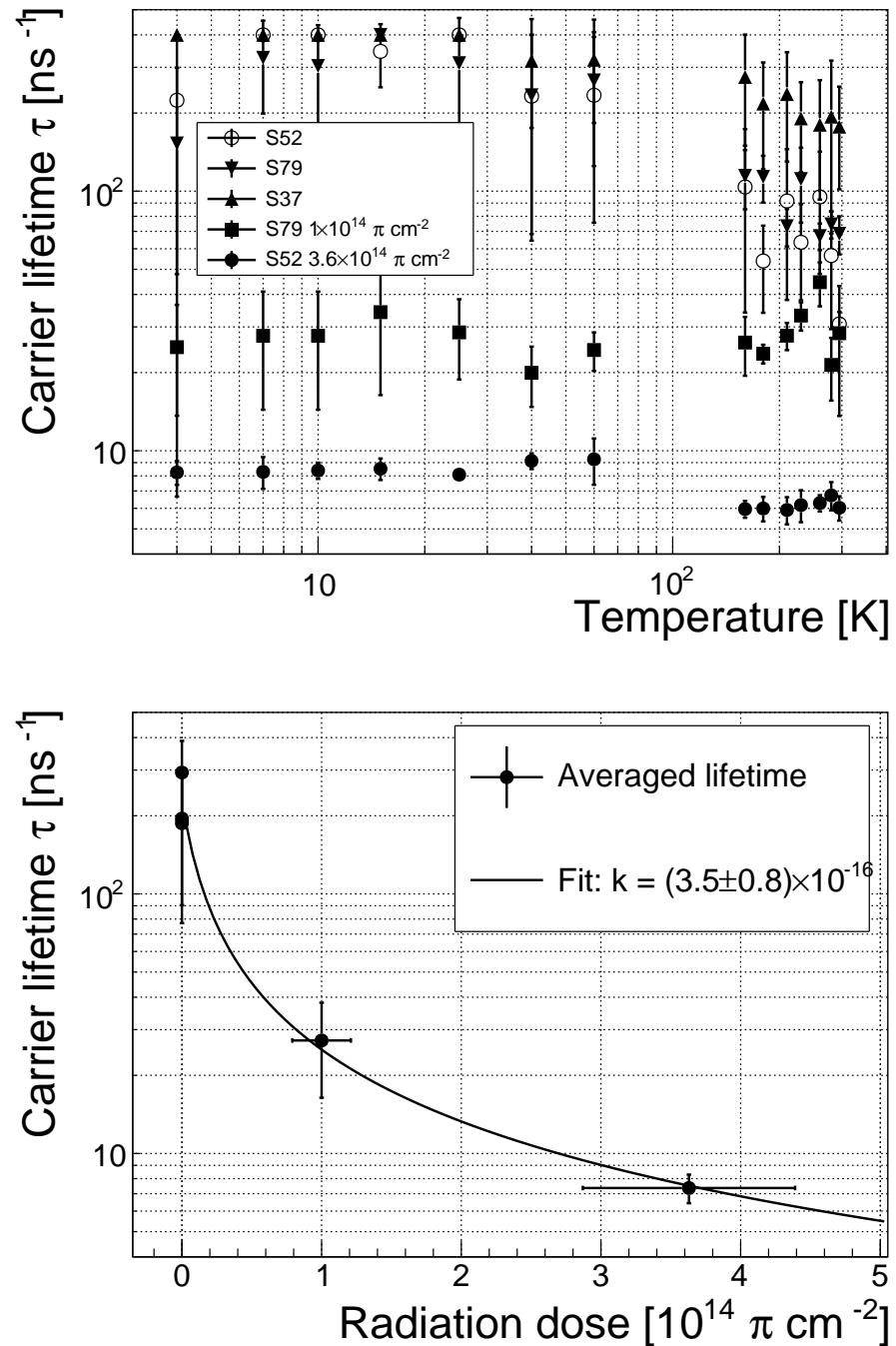


Figure 1.18: Charge carrier lifetime decreases with irradiation, but is stable across the range of temperatures between 4 K – 75 K and 150 K – 295 K. The first figure shows the carrier lifetime as a function of temperature whereas the second figure depicts the carrier lifetime averaged over all temperatures and plotted against the  $\pi$  irradiation dose

726 **1.5 Conclusion**

727 This chapter gives an overview of the capabilities and limitations of diamond as  
728 a particle detector. Three effects on diamond were studied – noise, radiation and  
729 temperature, the focus being on the latter two.

730 Two sCVD diamond detectors were irradiated with 300 MeV pions. They were  
731 tested alongside a non-irradiated sample to observe the changes in the ability to detect  
732  $\alpha$ ,  $\beta$  and  $\gamma$  radiation. Their charge collection efficiency was measured in a test beam  
733 facility using . The results were compared to the results from the RD42 collaboration  
734 and a DPA model. A radiation damage factor  $k_\lambda = (3.0 \pm 1.0) \times 10^{-18} \mu\text{m}^{-1} \text{cm}^{-2}$  was  
735 obtained for  $\pi_{300 \text{ MeV}}$  particles. The data point was not in agreement with the data  
736 provided by RD42 nor with the model. However, the irradiation process and the low  
737 number of tested samples hold a relatively high statistical uncertainty. In addition,  
738 there was no diamond surface treatment done in between the measurements, as is the  
739 case in the study conducted by RD42. The results obtained in the course of these  
740 measurements will also be fed into the existing pool of data in the RD42 collaboration.

741 The next step was to test the long-term capabilities for  $\alpha$  detection. The shape  
742 of the ionisation profile was investigated to determine the behaviour of the charge  
743 carriers in the irradiated diamond. An exponential decay was observed in the pulses  
744 of irradiated samples, proving that there are charge traps in the bulk that were created  
745 during irradiation. Then a long-term stability test was carried out. The results show  
746 that the irradiated diamond detectors do not provide a stable and reliable long-term  
747 measurement of  $\alpha$  particles. This might be due to a space-charge build-up in the  
748 bulk, which changes the electric field, affecting the charge carriers. A procedure to  
749 improve the pulse shape using  $\beta$  and  $\gamma$  radiation was proposed.

750 Finally, the diamond sensors were cooled down to temperatures between 4 K and  
751 295 K. Their response to  $\alpha$  particles was observed. The results of the non-irradiated  
752 and irradiated samples were compared. The effect of reduction for the number of  
753 drifting charges due to exciton recombination was observed in both sets of data.  
754 The second set had a superimposed effect of charge trapping during the drift, which  
755 was represented by an exponential decay in the signal. The decay time constant  
756 did not change with temperature. Therefore all temperature points for individual  
757 samples were averaged and the decay time constants were plotted against the received  
758 radiation dose. A damage factor equal to  $\kappa_\tau = (3.5 \pm 0.8) \times 10^{-16} \text{ s cm}^2 \pi_{300 \text{ MeV}}^{-1}$  for  
759 non-primed diamonds was defined.

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