Hutson, C., & Reichmann, M. (2019). New test beam results of 3D and pad detectors constructed with poly-crystalline CVD diamond. *Nuclear Inst. and Methods in Physics Research, A*.
<https://doi.org/10.1016/j.nima.2019.162675>

Peer reviewed version

License (if available):
CC BY-NC-ND

Link to published version (if available):
[10.1016/j.nima.2019.162675](https://doi.org/10.1016/j.nima.2019.162675)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the accepted author manuscript (AAM). The final published version (version of record) is available online via Elsevier at [10.1016/j.nima.2019.162675](https://doi.org/10.1016/j.nima.2019.162675). Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

A study of the radiation tolerance of CVD diamond to 70 MeV protons, fast neutrons and 200 MeV pions

The RD42 Collaboration: L. Bäni ^{24,*} , A. Alexopoulos ³, M. Artuso ²⁰, F. Bachmair ²⁴ , M. Bartosik ³, H. Beck ²³, V. Bellini ², V. Belyaev ¹², B. Bentele ¹⁹, A. Bes ²⁷, J.-M. Brom ⁷, G. Chiodini ²⁶, D. Chren ¹⁸, V. Cindro ⁹, G. Claus ⁷, J. Collot ²⁷, J. Cumalat ¹⁹, S. Curtoni ²⁷, A. Dabrowski ³, R. D'Alessandro ⁴, D. Dauvergne ²⁷, W. de Boer ¹⁰, C. Dorfer ²⁴ , M. Dünser ³ , G. Eigen ³⁰, V. Eremin ⁶, J. Forneris ¹⁵, L. Gallin-Martel ²⁷, M.-L. Gallin-Martel ²⁷, K. K. Gan ¹³, M. Gastal ³, A. Ghimouz ²⁷, M. Goffe ⁷, J. Goldstein ¹⁷, A. Golubev ⁸, A. Gorišek ⁹ , E. Grigoriev ⁸, J. Grosse-Knetter ²³, A. Grummer ²¹, B. Hiti ⁹, D. Hits ²⁴ , M. Hoeferkamp ²¹, J. Hosselet ⁷, F. Hügging ¹, C. Hutton ¹⁷, J. Janssen ¹ , H. Kagan ¹³ , K. Kanxheri ²⁸, R. Kass ¹³, M. Kis ⁵, G. Kramberger ⁹ , S. Kuleshov ⁸, A. Lacoste ²⁷ , S. Lagomarsino ⁴, A. Lo Giudice ¹⁵, I. López Paz ²², E. Lukosi ²⁵, C. Maazouzi ⁷, I. Mandić ⁹, S. Marcatili ²⁷, A. Marino ¹⁹, C. Mathieu ⁷, M. Menichelli ²⁸, M. Mikuž ⁹ , A. Morozzi ²⁸, F. Moscatelli ²⁸, J. Moss ²⁹, R. Mountain ²⁰, A. Oh ²² , P. Olivero ¹⁵, D. Passeri ²⁸, H. Pernegger ³ , R. Perrino ²⁶ , F. Picollo ¹⁵, M. Pomorski ¹¹, R. Potenza ², A. Quadt ²³, F. Rarbi ²⁷, A. Re ¹⁵, M. Reichmann ²⁴ , S. Roe ³, O. Rossetto ²⁷, D. A. Sanz Becerra ²⁴ , C. J. Schmidt ⁵, S. Schnetzer ¹⁴, S. Sciortino ⁴, A. Scorzoni ²⁸, S. Seidel ²¹ , L. Servoli ²⁸, D. S. Smith ¹³, B. Sopko ¹⁸, V. Sopko ¹⁸, S. Spagnolo ²⁶, S. Spanier ²⁵, K. Stenson ¹⁹, R. Stone ¹⁴, B. Stugu ³⁰, C. Sutura ², M. Traeger ⁵, W. Trischuk ¹⁶, M. Truccato ¹⁵, C. Tuvè ², J. Velthuis ¹⁷, S. Wagner ¹⁹, R. Wallny ²⁴ , J. C. Wang ²⁰, N. Wermes ¹, J. Wickramasinghe ²¹, M. Yamouni ²⁷, J. Zalieckas ³⁰, M. Zavrtanik ⁹, K. Hara ³² , Y. Ikegami ³¹, O. Jinnouchi ³³ , T. Kohriki ³¹, S. Mitsui ³² , R. Nagai ³³ , S. Terada ³¹, Y. Unno ³¹

¹ Universität Bonn, Bonn, Germany

² INFN/University of Catania, Catania, Italy

³ CERN, Geneva, Switzerland

⁴ INFN/University of Florence, Florence, Italy

⁵ GSI, Darmstadt, Germany

⁶ Ioffe Institute, St. Petersburg, Russia

⁷ IPHC, Strasbourg, France

⁸ ITEP, Moscow, Russia

⁹ Jožef Stefan Institute, Ljubljana, Slovenia

¹⁰ Universität Karlsruhe, Karlsruhe, Germany

¹¹ CEA-LIST Technologies Avancées, Saclay, France

¹² MEPhI Institute, Moscow, Russia

¹³ The Ohio State University, Columbus, OH, USA

¹⁴ Rutgers University, Piscataway, NJ, USA

¹⁵ University of Torino, Torino, Italy

¹⁶ University of Toronto, Toronto, ON, Canada

¹⁷ University of Bristol, Bristol, UK

¹⁸ Czech Technical University, Prague, Czech Republic

¹⁹ University of Colorado, Boulder, CO, USA

²⁰ Syracuse University, Syracuse, NY, USA

²¹ University of New Mexico, Albuquerque, NM, USA

²² University of Manchester, Manchester, UK

²³ Universität Göttingen, Göttingen, Germany

²⁴ ETH Zürich, Zürich, Switzerland

²⁵ University of Tennessee, Knoxville, TN, USA

²⁶ INFN-Lecce, Lecce, Italy

²⁷ LPSC-Grenoble, Grenoble, France

- 28 INFN-Perugia, Perugia, Italy
 29 California State University, Sacramento, CA, USA
 30 University of Bergen, Bergen, Norway
 31 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
 32 University of Tsukuba, Tsukuba, Japan
 33 Tokyo Institute of Technology, Tokyo, Japan
 * Correspondance: lukas.baeni@cern.ch

Version v14 submitted to *Sensors*

Abstract: We have measured the radiation tolerance of commercially available diamonds grown by the Chemical Vapor Deposition process by measuring the charge created by a 120 GeV hadron beam in a 50 μm pitch strip detector fabricated on each diamond sample before and after irradiation. We irradiated one group of samples with 70 MeV protons, a second group of samples with fast reactor neutrons (defined as energy greater than 0.1 MeV) and a third group of samples with 200 MeV pions, in steps, to $(8.8 \pm 0.9) \times 10^{15}$ protons/ cm^2 , $(1.43 \pm 0.14) \times 10^{16}$ neutrons/ cm^2 and $(6.5 \pm 0.5) \times 10^{14}$ pions/ cm^2 respectively. By observing the charge induced due to the separation of electron-hole pairs created by the passage of the hadron beam through each sample, on an event-by-event basis, as a function of irradiation fluence, we conclude all data sets can be described by a first order damage equation and independently calculate the damage constant for 70 MeV protons, fast reactor neutrons and 200 MeV pions. We find the damage constant for diamond irradiated with 70 MeV protons to be 1.61 ± 0.07 (stat) ± 0.15 (syst) $\times 10^{-18}$ $\text{cm}^2/(p \mu\text{m})$, the damage constant for diamond irradiated with fast reactor neutrons to be 2.65 ± 0.13 (stat) ± 0.16 (syst) $\times 10^{-18}$ $\text{cm}^2/(n \mu\text{m})$ and the damage constant for diamond irradiated with 200 MeV pions to be 2.0 ± 0.2 (stat) ± 0.5 (syst) $\times 10^{-18}$ $\text{cm}^2/(\pi \mu\text{m})$. The damage constants from this measurement were analyzed together with our previously published 24 GeV proton irradiation and 800 MeV proton irradiation damage constant data to derive the first comprehensive set of relative damage constants for Chemical Vapor Deposition diamond. We find 70 MeV protons are 2.60 ± 0.27 times more damaging than 24 GeV protons, fast reactor neutrons are 4.27 ± 0.34 times more damaging than 24 GeV protons and 200 MeV pions are 3.2 ± 0.8 more damaging than 24 GeV protons. We also observe the measured data can be described by a universal damage curve for all proton, neutron and pion irradiations we have performed of Chemical Vapor Deposition diamond. Finally, we confirm the $FWHM/MP$ ratio of the signal spectrum, a measure of the spatial uniformity of the collected charge, decreases with fluence for polycrystalline Chemical Vapor Deposition diamond and this effect can also be described by a universal curve.

Keywords: Chemical Vapor Deposition; single-crystalline diamond; polycrystalline diamond; charge collection distance; mean drift path; schubweg; radiation tolerance; radiation damage constant

1. Introduction

Diamond-based radiation monitors are now routinely used in high-energy physics experiments (e.g., at the Large Hadron Collider (LHC) [1]). Their role has become critical in protecting more sensitive devices against extreme beam conditions and in contributing to a precision measurement of the luminosity the accelerator delivers. As a result, quantifying the radiation resistance, or damage constant, of diamond is critical to its use in future upgraded high energy facilities [2,3].

In a previously published paper [4] we describe the methodology we used to measure the damage constants of polycrystalline CVD (pCVD) diamond and single-crystalline CVD (scCVD) diamond irradiated with 800 MeV and 24 GeV protons. The work described herein uses the same methodology to measure the damage constants of Chemical Vapor Deposition (CVD) diamond irradiated with 70 MeV protons, fast reactor neutrons with energies greater than 0.1 MeV and 200 MeV pions. In

addition, in this manuscript, we derive universal curves for the damage as a function of fluence and the full width at half maximum divided by its most probable value ($FWHM/MP$) of the signal spectrum as a function of fluence which may then be used to predict the effects of radiation on any planned diamond detectors.

2. Sample Preparation

Two types of CVD diamond were used in this work. The first is single-crystalline which, as the name implies, is ideally one single diamond crystal devoid of grains and grain boundaries. High purity single-crystalline material has been shown to collect the full charge deposited in the material but the material area is currently limited to $\sim 7\text{ mm} \times 7\text{ mm}$. The second is poly-crystalline which, as the name implies, is made up of a collection of randomly oriented individual crystal grains and thus grain boundaries. In poly-crystalline material the collected charge is less than the deposited charge due to the grain boundaries and their associated dislocations and traps. A high quality, $500\text{ }\mu\text{m}$ thick, pCVD diamond collects approximately half of the deposited charge but can be grown in very large areas up to 15 cm diameter wafers. In order to quantify the radiation tolerance of scCVD diamond and pCVD diamond, we used a series of commercially available diamonds for this study [5].

In preparing the diamond devices for testing, a $50\text{ }\mu\text{m}$ pitch strip detector was fabricated on each sample. The same strip width and strip detector pitch was used for both pCVD and scCVD diamond. The bias side was fabricated using photolithographic techniques with a single pad. The readout side was fabricated with photolithographic techniques with $25\text{ }\mu\text{m}$ wide strips with a $25\text{ }\mu\text{m}$ gap between strips producing a device with $50\text{ }\mu\text{m}$ pitch. The strip pattern was enclosed with a guard ring at the same potential as the strips to minimize any edge or surface currents from being picked up by the individual electronic channels. After metalization of both sides with $500\text{ }\text{\AA}$ Cr and $2000\text{ }\text{\AA}$ Au, each device was annealed at $400\text{ }^{\circ}\text{C}$ for 4 minutes in an N_2 atmosphere. The bias electrode side of the device was attached with silver paint [6] to a ceramic hybrid containing a bias pad and RC bias filter circuit to power the device. The ceramic hybrid was mounted adjacent to a G-10 printed circuit board which housed the IDE AS VA2.2 readout chip [7] so each readout strip could be directly wire bonded from the diamond strip detector to a VA2.2 readout channel.

3. Sample Description

To determine the radiation tolerance of CVD diamond against protons, neutrons and pions seven samples with different properties were measured before and after irradiation. Two samples were irradiated with 70 MeV protons in steps up to a fluence of $8.8 \times 10^{15}\text{ p/cm}^2$, two samples were exposed to fast reactor neutrons up to a fluence of $14.3 \times 10^{15}\text{ n/cm}^2$ and three samples were irradiated with 200 MeV pions up to a fluence of $0.65 \times 10^{15}\text{ }\pi/\text{cm}^2$. After each irradiation a $50\text{ }\mu\text{m}$ pitch strip detector was fabricated on each sample and each device was characterized in a 120 GeV hadron beam. The properties of the 70 MeV proton irradiated samples are listed in Table 1, Table 2 shows the properties of the fast neutron irradiated samples and Table 3 presents the properties of the pion irradiated samples. The initial unirradiated signal response of each sample was determined before any irradiations by fabricating a single pad detector on each diamond sample and measured by using a calibrated setup [8] with a ^{90}Sr β -source.

4. Sample Irradiations

Proton irradiations

Samples 1 and 2 were irradiated in the beam course 32 at the CYRIC facility of the Tohoku University [9]. This facility provided a 70 MeV proton beam to the beam course in the intensity of 100 nA to 1300 nA , with a beam spot size of 7 mm of full width at half maximum (FWHM). The beam was scanned over the samples to get a uniform irradiation over the sample area. The particle fluence for each group of samples irradiated was measured by evaluating the activation of an aluminum foil

Table 1. Properties of diamonds irradiated with 70 MeV protons and the fluence they received. The initial unirradiated *ccd* values are given separately for positive and negative bias polarity.

Diamond Type	Thickness (μm)	Area (mm^2)	Initial <i>ccd</i> (μm)	Fluence (10^{15} p/cm^2)
Sample 1 pCVD	518	10×10	227/238	0 8.8 ± 0.9
Sample 2 pCVD	506	10×10	216/216	0 0.96 ± 0.10 1.81 ± 0.18

Table 2. Properties of diamonds irradiated with neutrons and the fluence they received. The initial unirradiated *ccd* values are given separately for positive and negative bias polarity.

Diamond Type	Thickness (μm)	Area (mm^2)	Initial <i>ccd</i> (μm)	Fluence (10^{15} n/cm^2)
Sample 3 pCVD	512	5×5	214/204	0 14.3 ± 1.4
Sample 4 pCVD	510	10×10	295/292	0 5.5 ± 0.5

Table 3. Properties of diamonds irradiated with pions and the fluence they received. The initial unirradiated *ccd* values for the scCVD diamond sample are given separately for positive and negative bias polarity. For samples 6 and 7, only one bias polarity was measured for the unirradiated samples. For these samples the initial *ccd* values are listed for comparison but were not used in the analysis.

Diamond Type	Thickness (μm)	Area (mm^2)	Initial <i>ccd</i> (μm)	Fluence ($10^{15} \pi/\text{cm}^2$)
Sample 5 scCVD	497	5×5	497/497	0 0.65 ± 0.14
Sample 6 pCVD	520	5×5	222	0 0.32 ± 0.07
Sample 7 pCVD	508	5×5	228	0 0.61 ± 0.14

for that group of samples irradiated. This method typically measures the dose for each irradiation step to roughly 10 %.

Neutron irradiations

Samples 3 and 4 were irradiated in channel F19 of core 189 at the TRIGA nuclear reactor of the Jožef Stefan Institute (JSI) [10] with neutrons. At this facility, the neutron energy spectrum goes from 10^{-8} MeV to 7 MeV [10,11]. The neutron lethargy spectrum ($\log(E_0/E)$) of the F19 channel in core 189 is shown in Fig. 1. Fast neutrons are defined as having an energy greater than 0.1 MeV. The fast neutron spectrum peaks between 1 MeV and 2 MeV. Fast neutron fluxes up to $4 \times 10^{12} \text{ n}/(\text{cm}^2 \text{ s})$ are available and were measured as a function of reactor power using gold foil activation [12]. To measure the fast neutron accumulated dose, the power of the reactor is set and the exposure time is recorded. This system typically measures the accumulated dose for each irradiation step to $\sim 10\%$.

Pion irradiations

Samples 5, 6 and 7 were irradiated at PSI [13] with 200 MeV positive pions. Irradiations were performed by personnel from the CERN IRRAD facility [14]. The fluences were determined at CERN by measuring the activation in an aluminum foil mounted directly to each sample [15]. In addition to

Figure 1. Lethargy neutron spectrum of channel F19 in core 189 of the TRIGA reactor, at full reactor power (250 kW) [11].

the statistical error, the CERN IRRAD website quotes an uncertainty of 20 % for these measurements, due to the uncertainty on the hardness factor, which was added in quadrature to the statistical error.

5. Test Beam Analysis

The analysis of data in this work uses same analysis procedure and methods described in Ref. [4]. A brief description is given below and a detailed description can be found in Refs. [16,17].

Data from an 8-plane silicon strip telescope [18], based on 50 μm pitch strip detectors with one or two floating intermediate strips, were used to reconstruct the predicted particle position in the diamond detector to roughly 1.3 μm . A transparent reconstruction algorithm was used to reconstruct the signal charge (and actual position) of the particle in the diamond [4]. In this algorithm the charge on the highest five contiguous strips within a 500 μm window of the predicted particle position are summed to calculate the signal charge and actual position of the particle in the diamond detector. In Fig. 2 we present the evolution of the measured signal charge spectrum after the 70 MeV proton irradiations. In Fig. 3 the evolution of the measured signal charge spectrum after neutron irradiations is shown. In all cases the signal charge spectra get narrower with fluence and the average value decreases with fluence. In Fig. 4 the measured signal charge spectrum of an scCVD diamond sensor before and after pion irradiation is shown. The average value of the spectrum decreases with fluence. The same overall effects were observed previously in the 24 GeV and 800 MeV proton irradiations [4,19].

The average distance an electron-hole pair drifts apart under the influence of an applied electric field or “charge collection distance” (ccd) was calculated from the measured signal charge spectrum by

$$ccd = \overline{q^{\text{signal}}} \times \frac{1 \mu\text{m}}{36 e} \quad (1)$$

where $\overline{q^{\text{signal}}}$ is the average of the measured signal charge spectrum in units of e and $36 e$ is the average number of electron-hole pairs created per micron for a minimum ionizing particle (MIP). We measured this quantity by evaluating the signal response of an unirradiated scCVD diamond sample to a ^{90}Sr β -source. After correcting the electronic gain, offset and deposited charge, we determined the constant necessary to collect full charge. This measurement was performed for positive and negative bias polarity independently. The unirradiated scCVD diamond used was 497 μm thick. In a measurement cycle, we took data at multiple voltages up to ± 500 V. In the source setup used, the electrons from ^{90}Sr

Figure 2. The signal charge spectrum evolution for samples irradiated with 70 MeV protons biased at $E = +2 \text{ V}/\mu\text{m}$. The pulse height spectrum before irradiation was measured using a setup with a ^{90}Sr β -source and a single pad metallization on the diamond. The integral of each spectrum has been normalized to unity.

Figure 3. The signal charge spectrum evolution for samples irradiated with fast neutrons biased at $E = -2 \text{ V}/\mu\text{m}$. The pulse height spectrum before irradiation was measured using a setup with a ^{90}Sr β -source and a single pad metallization on the diamond. The integral of each spectrum has been normalized to unity.

are 8 % above minimum ionizing [8]. Our result, after all corrections, is $(36.0 \pm 0.8) \text{ e}/\mu\text{m}$ for positive bias voltage and $(35.9 \pm 0.8) \text{ e}/\mu\text{m}$ for negative bias voltage. These results are consistent with previous work [8,20,21]. The ccd can be expressed by [22]

$$\frac{ccd}{t} = \sum_{k=e,h} \frac{\lambda_k}{t} \left[1 - \frac{\lambda_k}{t} \left(1 - e^{-\frac{t}{\lambda_k}} \right) \right] \quad (2)$$

where t is the thickness of the diamond and λ_k is the average distance an electron or hole drifts in an infinitely thick sample of a given material. Using (2), the schubweg or average total distance the

Figure 4. The signal charge spectrum evolution for the scCVD diamond sample irradiated with 200 MeV pions biased at $E = +2 \text{ V}/\mu\text{m}$. The pulse height spectrum before irradiation was measured using a setup with a ^{90}Sr β -source and a single pad metallization on the diamond. The integral of each spectrum has been normalized to unity.

Figure 5. The $1/\lambda$ for pCVD diamond in the 70 MeV proton irradiation. The two values shown at each fluence are the values for positive (solid markers) and negative (open markers) bias at $E = \pm 2 \text{ V}/\mu\text{m}$. The data was fit with a first order damage curve independently for each sample.

electron-hole pair moves apart, defined as the sum $\lambda = \lambda_e + \lambda_h$, was calculated for each beam test measurement from the measured ccd , assuming the ratio $\lambda_h/\lambda_e = 1.3^{+0.8}_{-0.6}$ [4]. The effect of not knowing this ratio exactly was quantified in Ref. [4] and determined to not change the results of this analysis within the quoted errors.

6. Measurement of Damage Constants

After each irradiation step, the diamond devices were characterized in a 120 GeV hadron test beam at CERN. In a measurement cycle, the device under test was measured with both positive and negative bias voltage to obtain the sum of mean drift paths, λ , for an electric bias field of $\pm 2 \text{ V}/\mu\text{m}$.

Figure 6. The $1/\lambda$ for pCVD diamond in the fast neutron irradiation. The two values shown at each fluence are the values for positive (solid markers) and negative (open markers) bias at $E = \pm 2 \text{ V}/\mu\text{m}$. The data was fit with a first order damage curve independently for each sample.

Figure 7. The $1/\lambda$ for scCVD and pCVD diamond in the pion irradiation. The two values shown at each fluence are the values for positive (solid markers) and negative (open markers) bias at $E = \pm 2 \text{ V}/\mu\text{m}$. The data was fit with a simple damage curve independently for each diamond type. The uncertainty for unirradiated scCVD diamond comes from not knowing the upper initial mean drift distance exactly.

A first order damage model was used to describe the irradiation damage effects. The model relates the inverse sum of mean drift paths, $1/\lambda$, linearly with the irradiation fluence by [23]:

$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k\phi \quad (3)$$

where k is the damage constant and λ_0 accounts for charge traps in the unirradiated state. The inverse sum of mean drift paths as a function of irradiation fluence is shown in Fig. 5 for 70 MeV proton irradiations, in Fig. 6 for fast neutron irradiations and in Fig. 7 for 200 MeV pion irradiations. For each sample, the damage model was fitted to the data points to derive the slope. The damage

constant k_i of particle species i was derived from the slopes of the individual samples. For the pion irradiated samples, the damage model was fitted separately to the data of scCVD and pCVD diamond samples irradiated with pions and the observed damage constants were combined. The final results of the damage constants for 70 MeV proton irradiations, fast neutron irradiations and 200 MeV pion irradiations are:

$$\begin{aligned} k_{\text{pCVD}}^{\text{proton}} &= 1.61 \pm 0.07 (\text{stat}) \pm 0.15 (\text{syst}) \times 10^{-18} \frac{\text{cm}^2}{p \mu\text{m}} \\ k_{\text{pCVD}}^{\text{neutron}} &= 2.65 \pm 0.13 (\text{stat}) \pm 0.16 (\text{syst}) \times 10^{-18} \frac{\text{cm}^2}{n \mu\text{m}} \\ k^{\text{pion}} &= 2.0 \pm 0.2 (\text{stat}) \pm 0.5 (\text{syst}) \times 10^{-18} \frac{\text{cm}^2}{\pi \mu\text{m}}. \end{aligned}$$

The general form of the statistical and systematic errors are given in Ref. [4]. Specifically, in this work, the statistical errors are dominated by the error in the fits while the systematic errors are dominated by the signal calibration, the pulse height dependence on track position and the pulse height dependence on bias polarity.

In Table 4 the relative damage constants are compared to the 24 GeV proton and 800 MeV proton results from Ref. [4]. 70 MeV protons are found to be more than twice as damaging as 24 GeV protons, fast reactor neutrons were observed to be more than four times more damaging than 24 GeV protons and 200 MeV pions are more than three times as damaging as 24 GeV protons. These results are roughly consistent with displacement per atom (DPA) [24].

Table 4. Relative damage constants for 24 GeV protons, 800 MeV protons, 70 MeV protons, 200 MeV pions and fast reactor neutrons. The radiation damage constants of 24 GeV protons and 800 MeV protons are from Ref. [4]. The relative radiation damage constant of 25 MeV protons is derived from Ref. [25].

Particle species	κ
24 GeV protons	1.0
800 MeV protons	1.67 ± 0.09
70 MeV protons	2.60 ± 0.27
25 MeV protons	4.4 ± 1.2
Fast neutrons	4.27 ± 0.34
200 MeV pions	3.2 ± 0.8

7. Universal Damage Curve

As shown in Ref. [4], scCVD and pCVD diamond follow the same damage model. However, the damage curve of species i for each diamond sample j starts at a different values of $1/\lambda_{0,j}$, due to the initial collection distance of the sample. The initial $\lambda_{0,j}$ of sample j was derived by fitting a slope equal to the damage constant k_i to the data points. Table 5 lists the parameter $\lambda_{0,j}$ of the tested samples. In Fig. 8, the $1/\lambda$ as a function of fluence for 70 MeV proton, fast neutron and 200 MeV pion irradiations is compared to the result of 24 GeV proton and 800 MeV proton irradiations [4] with the data points shifted by $1/\lambda_{0,j}$. The difference in slope of the dashed lines in this figure reflects the difference in damage constants. Fig. 9 shows the data from Fig. 8 in the dotted box to illustrate the relation of the low fluence data and the damage curves.

Since scCVD and pCVD diamond follow the same damage model in (3) and different irradiations have different shift, it should be possible to generate a universal damage curve. To accomplish this the fluences were scaled by

$$\phi_{24\text{ GeV } p \text{ eq}} = \kappa_i \times \phi_i \quad (4)$$

Figure 8. The $1/\lambda$ for scCVD (solid markers) and pCVD (open markers) diamond. As reference the 800 MeV proton and 24 GeV proton data from Ref. [4] are plotted. Each pCVD point is shifted by $1/\lambda_{0,i}$. The dotted box indicates the zoom area shown in Fig. 9.

Figure 9. The $1/\lambda$ for scCVD (solid markers) and pCVD (open markers) diamond up to a fluence of $7 \times 10^{15}/\text{cm}^2$ (zoom of dotted box in Fig. 8). As reference the 800 MeV proton and 24 GeV proton data from Ref. [4] are plotted. Each pCVD point is shifted by $1/\lambda_{0,i}$.

Table 5. Parameter $\lambda_{0,j}$ and fluence offset $\phi_{0,j}$ of diamond sample j for 70 MeV protons, fast reactor neutrons and 200 MeV pions. The derived $\lambda_{0,j}$ is not universal since it is sample dependent.

Diamond j	$\lambda_{0,j}$ (μm)	$\phi_{0,j}$ ($10^{15}/\text{cm}^2$)
Sample 1	339 ± 21	4.7 ± 0.6
Sample 2	322 ± 15	5.0 ± 0.6
Sample 3	291 ± 21	5.5 ± 0.7
Sample 4	531 ± 27	3.0 ± 0.4
Sample 5	$11\,000 \pm 20\,000$	0.15 ± 0.29
Sample 6+7	420 ± 60	3.8 ± 0.7

Figure 10. The $1/\lambda$ for scCVD (solid markers) and pCVD (open markers) diamond. Each pCVD point is shifted by $1/\lambda_{0,i}$. The fluence of each point was scaled by the relative damage constant, κ_i , to the 24 GeV proton equivalent fluence. The damage model (dashed line) is fitted to the data points.

Figure 11. The λ for scCVD (solid markers) and pCVD (open markers) diamond. The fluence of each point was scaled by the relative damage constant to the 24 GeV proton equivalent fluence. Each point is shifted by $\phi_{0,j}$ which represents the starting value of sample j in 24 GeV proton equivalent fluence space. The dashed line is the fit of the damage model in (3) to the data points. The gray band indicates the variation of the fit parameters by one standard deviation.

where κ_i is the relative radiation damage constant defined as $\kappa_i = k_i/k_{24\text{GeV}p}$. The measured $1/\lambda$ as a function of 24 GeV proton equivalent fluence is shown in Fig. 10 and illustrates the universality of the first order radiation damage model described above.

Instead of the offset $1/\lambda_{0,j}$, the separation of the damage curve of species i for individual diamond samples may be interpreted as a fluence offset, $\phi_{0,j}$. Thus the initial signal response of pCVD diamond

corresponds to irradiated scCVD diamond. The fluence offset in units of 24 GeV proton equivalent fluence of each diamond sample was calculated using:

$$\phi_{0,j} = \frac{\kappa_i}{\lambda_{0,j}k_i} = \frac{1}{\lambda_{0,j}k_{24\text{GeV}p}} \quad (5)$$

where k_i is the damage constant for particle species i and $\lambda_{0,j}$ the initial sum of mean drift paths of sample j derived from the fit to the data points of sample j with fixed k_i . The fluence offset $\phi_{0,j}$ is listed in Table 5. To facilitate predictions of the signal response as a function of particle fluence, the measured λ of the five data sets were plotted as a function of 24 GeV proton equivalent fluence. To obtain a universal curve the fluence of species i was scaled as in (4) and each diamond data point was shifted by the fluence offset $\phi_{0,j}$. The measured λ as a function of 24 GeV proton equivalent fluence of the data is presented in Fig. 11.

8. Measurement of the FWHM/MP Ratio

The initial non-uniformities in unirradiated pCVD material are mainly due to the interior crystal structure where single grains have different charge collection properties causing a spatial variation of the Landau-like distributions in the material [19]. This effect was clearly demonstrated in Ref. [4] where we showed the quantity R ,

$$R = \frac{FWHM}{MP}, \quad (6)$$

is also a measure of the uniformity of the material. The smaller the quantity R the narrower the normalized signal charge distribution is across the material. Here we use the full width at half maximum, $FWHM$, normalized by the most probable value, MP , of the signal response [4] to analyze its irradiation dependence.¹ In order to compare with previous beam test results for R we used a +120 GeV/c hadron beam, which are near minimum ionizing, as we did previously [4].

The results of the 70 MeV proton irradiations are shown in Fig. 12. The results of the neutron irradiations are presented in Fig. 13. The value R decreases for both irradiation species as a function of fluence, confirming the observation with pCVD diamond in Ref. [4]. The value R as a function of 200 MeV pion fluence is shown in Fig. 14 and is compatible with the findings in Ref. [4].

To compare the results of the different particle species, the fluence of each data point was scaled to 24 GeV proton equivalent fluence using (4). In Fig. 15 the value R of the five data sets (24 GeV protons, 800 MeV protons, 70 MeV protons, 200 MeV pions and fast neutrons) is shown as a function of 24 GeV proton equivalent fluence. The pCVD data points all fall on a single curve which decreases with fluence. The scCVD data all fall on a different curve which is compatible with being flat with fluence. This is illustrated in Fig. 16 where scCVD diamond data are shown in blue and pCVD diamond data are shown in red. The two curves taken together indicate the pCVD samples are becoming more uniform with irradiation and approaching the uniformity of single-crystal diamond.

9. Comparison with Silicon

Once the damage constants are determined, the damage constants for diamond may be compared with the damage constants for silicon. The collected charge in silicon devices depends on the electric field and trapping times. The trapping time τ_i at a temperature T and time after irradiation, t , is inversely proportional to the fluence [26,27]:

$$\frac{1}{\tau_i} = \beta_i(T, t) \times \phi. \quad (7)$$

¹ We normalized to MP , since the inherent distribution is Landau-like and for Landau distributions the measured mean depends on the number of events attained.

Figure 12. The $FWHM/MP$ as a function of fluence in the 70 MeV proton irradiation measured in a +120 GeV/ c hadron beam at CERN. The two values shown at each fluence are the values for positive (solid markers) and negative bias (open markers) at $E = 2 \text{ V}/\mu\text{m}$.

Figure 13. The $FWHM/MP$ as a function of fluence in the fast neutron irradiation measured in a +120 GeV/ c hadron beam at CERN. The two values shown at each fluence are the values for positive (solid markers) and negative bias (open markers) at $E = 2 \text{ V}/\mu\text{m}$.

Figure 14. The $FWHM/MP$ as a function of fluence in the pion irradiation measured in a +120 GeV/ c hadron beam at CERN. The two values shown at each fluence are the values for positive (solid markers) and negative bias (open markers) at $E = 2 \text{ V}/\mu\text{m}$.

Figure 15. The $FWHM/MP$ for scCVD (solid markers) and pCVD (open markers) diamond. The fluence of each point was scaled by the relative damage constant to the 24 GeV proton equivalent fluence.

From the measurements of trapping times which require a fully depleted detector, the mean drift path of the charge carriers, λ , may be calculated using the relation

$$\lambda = v_e \tau_e + v_h \tau_h \quad (8)$$

where v_i are the drift velocities of electrons and holes, respectively. Using (7) and (8), $1/\lambda$ as a function of fluence for silicon may be described by

$$\frac{1}{\lambda} = \frac{1}{\frac{v_e}{\beta_e} + \frac{v_h}{\beta_h}} \times \phi = k\phi \quad (9)$$

Figure 16. The $FWHM/MP$ of scCVD and pCVD diamond samples irradiated with 24 GeV protons, 800 MeV protons, 70 MeV protons and fast reactor neutron for positive (solid markers) and negative bias (open markers) at $E = 2 \text{ V}/\mu\text{m}$. The fluence of each point was scaled by the relative damage constant to the 24 GeV proton equivalent fluence. The dashed line represents a constant fit to the scCVD diamond data points (blue) extrapolated to $40 \times 10^{15} \text{ p}/\text{cm}^2$ for illustrative purposes.

where k is a damage constant.

In Fig. 17 the damage constants measured at an electric field of $2 \text{ V}/\mu\text{m}$ and at $T = 20^\circ\text{C}$ for diamond and silicon were used to generate the inverse sum of mean drift paths versus fluence plot up to a fluence of $10^{15} \text{ particles}/\text{cm}^2$. The dashed lines are the diamond results from this work and Ref. [4] for the irradiations of 24 GeV protons (blue), 800 MeV protons (red), 70 MeV protons (green), 200 MeV pions (purple) and fast neutrons (orange). The solid lines are the silicon data from RD50 [28] for proton (blue and red), pion (purple) and neutron (orange) irradiations. The sum of mean drift paths is obtained from charge collection measurements at room temperature, assuming a uniform electric field of $2 \text{ V}/\mu\text{m}$. Drift velocities at $2 \text{ V}/\mu\text{m}$ were derived from Ref. [29] and trapping times were taken from Ref. [27] after 80 min of annealing at 60°C .

The results from Fig. 17 show that for proton irradiations diamond is much less radiation sensitive than silicon (greater than a factor of two) for all proton energies while for neutron irradiations silicon is comparable in radiation tolerance to diamond.

10. Summary

A study of CVD diamond material before and after a series of irradiations with 70 MeV protons, fast reactor neutrons and 200 MeV pions is presented. The decrease in signal response is in agreement with a first order damage model. The measured data have been compared to previous measurements of CVD diamond samples irradiated with 800 MeV protons and 24 GeV protons [4]. Furthermore, the five data sets have been combined in a universal damage curve for diamond material which allows predictions to be made for potential applications.

The decrease in $FWHM/MP$ of the signal response of the collected charge as a function of particle fluence has been confirmed for pCVD diamond material irradiated with 70 MeV protons and fast reactor neutrons. Moreover, the measurements of this paper have been combined with previous measurements [4] into a universal curve.

Finally, the radiation damage constants of diamond have been compared to the radiation damage constants of silicon. For proton irradiations, diamond has been found to be more radiation tolerant than silicon, while a comparable radiation tolerance against neutrons has been observed.

Figure 17. The $1/\lambda$ for CVD diamond and silicon for proton, pion and neutron irradiations at an electric field of $2 \text{ V}/\mu\text{m}$. The charge collection was measured at room temperature. The dashed lines are diamond results from this work and Ref. [4] for irradiations at 24 GeV protons (blue), 800 MeV protons (red), 70 MeV protons (green) and fast neutrons (orange) and the solid lines are the silicon damage data from RD50 [28] for proton (blue and red), pion (purple) and neutron (orange) irradiations. The curves for irradiations with 25 MeV protons were taken from Ref. [25].

Author Contributions: Software, F. Bachmair, L. Bäni, G. Claus, M. Goffe, M. Reichmann, D. A. Sanz Becerra, R. Wallny; Formal Analysis, F. Bachmair, L. Bäni, D. Hits, H. Kagan, G. Kramberger, M. Mikuž, A. Oh, W. Trischuk; Investigation, A. Alexopoulos, M. Artuso, F. Bachmair, L. Bäni, M. Bartosik, H. Beck, V. Bellini, B. Bentele, A. Bes, J.-M. Brom, G. Chiodini, V. Cindro, G. Claus, J. Collot, J. Cumalat, S. Curtoni, A. Dabrowski, R. D'Alessandro, D. Dauvergne, W. de Boer, C. Dorfer, M. Dünser, G. Eigen, V. Eremin, J. Forneris, L. Gallin-Martel, M.-L. Gallin-Martel, K. K. Gan, M. Gastal, A. Ghimouz, M. Goffe, J. Goldstein, A. Golubev, A. Gorišek, E. Grigoriev, J. Grosse-Knetter, A. Grummer, B. Hiti, D. Hits, M. Hoferkamp, J. Hosselet, F. Hügging, C. Hutton, J. Janssen, H. Kagan, K. Kanxheri, R. Kass, M. Kis, G. Kramberger, S. Kuleshov, A. Lacoste, S. Lagomarsino, A. Lo Giudice, I. López Paz, E. Lukosi, C. Maazouzi, I. Mandić, S. Marcatili, A. Marino, C. Mathieu, M. Menichelli, M. Mikuž, A. Morozzi, F. Moscatelli, J. Moss, R. Mountain, A. Oh, P. Olivero, D. Passeri, H. Pernegger, R. Perrino, F. Picollo, R. Potenza, A. Quadt, F. Rarbi, A. Re, S. Roe, O. Rossetto, D. A. Sanz Becerra, C. J. Schmidt, S. Schnetzer, S. Sciortino, A. Scorzoni, S. Seidel, L. Servoli, D. S. Smith, S. Spagnolo, S. Spanier, K. Stenson, R. Stone, B. Stugu, C. Sutura, M. Traeger, W. Trischuk, M. Truccato, C. Tuvè, J. Velthuis, S. Wagner, R. Wallny, J. C. Wang, N. Wermes, J. Wickramasinghe, M. Yamouni, J. Zalieckas, M. Zavrtanik, K. Hara, Y. Ikegami, O. Jinnouchi, T. Kohriki, S. Mitsui, R. Nagai, S. Terada, Y. Unno; Data Curation, F. Bachmair, L. Bäni, M. Goffe, A. Gorišek, D. Hits, J. Janssen, H. Kagan, G. Kramberger, A. Oh, M. Reichmann, D. A. Sanz Becerra, S. Seidel, R. Wallny, K. Hara, Y. Ikegami, O. Jinnouchi, T. Kohriki, S. Mitsui, R. Nagai, S. Terada, Y. Unno; Writing, F. Bachmair, L. Bäni, D. Hits, H. Kagan, G. Kramberger, A. Oh, W. Trischuk; Supervision, M. Artuso, W. de Boer, J.-M. Brom, G. Chiodini, G. Eigen, V. Eremin, M.-L. Gallin-Martel, J. Goldstein, A. Golubev, F. Hügging, H. Kagan, M. Kis, M. Mikuž, J. Moss, A. Oh, P. Olivero, H. Pernegger, R. Potenza, A. Quadt, S. Schnetzer, S. Sciortino, S. Seidel, L. Servoli, S. Spanier, W. Trischuk, C. Tuvè, S. Wagner, R. Wallny, N. Wermes; Project Administration, H. Kagan, W. Trischuk; Funding Acquisition, J.-M. Brom, J. Goldstein, H. Kagan, M. Mikuž, J. Moss, A. Oh, H. Pernegger, A. Quadt, S. Seidel, S. Schnetzer, W. Trischuk, R. Wallny, N. Wermes, K. Hara, S. Terada, Y. Unno

Funding: The research leading to these results received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 654168. This work was also partially supported by the Swiss National Science Foundation grant #20FL20_154216, ETH grant 51 15-1, Swiss Government Excellence Scholarship ESKAS No. 2015.0808, UK Science and Technology Facilities Council grant ST/M003965/1 and the U.S. Department of Energy through grant DE-SC0011726.

Acknowledgments: The RD42 Collaboration gratefully acknowledges the staff at CERN for test beam time, their help in setting up the beam conditions and for their assistance in making our tests a success. We would also like to thank Profs. T. Shinozuka, T. Wakui, and the staff of the CYRIC Irradiation Facility at Tohoku University in Sendai, Japan for their help in the 70 MeV proton irradiations (experiments 8705 and 9214) and the staff of the TRIGA Nuclear Reactor at the Jožef Stefan Institute in Ljubljana, Slovenia for their help in making the neutron irradiations possible.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. CERN The European Organization for Nuclear Research, CH-1211, Genève 23, Switzerland. For additional information see: <https://home.cern/>.
2. G. Apollinari *et al.*, "High-Luminosity Large Hadron Collider (HL-LHC): Preliminary Design Report, Chapter 1: High-Luminosity Large Hadron Collider HL-LHC," CERN Yellow Reports: Monographs, CERN-2015-005, CERN Geneva, 2015; DOI: [10.5170/CERN-2015-005.1](https://doi.org/10.5170/CERN-2015-005.1).
3. G. Apollinari *et al.*, "High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V.0.1," CERN Yellow Reports: Monographs, Volume 4/2017 CERN-2017-007-M, CERN Geneva 2017; DOI: [10.23731/CYRM-2017-004](https://doi.org/10.23731/CYRM-2017-004).
4. L. Băni, *et al.* [RD42 Collaboration], "A study of the radiation tolerance of poly-crystalline and single-crystalline CVD diamond to 800 MeV and 24 GeV protons," J. Phys. D: Appl. Phys. **52**, 465103 (2019); DOI: [10.1088/1361-6463/ab37c6](https://doi.org/10.1088/1361-6463/ab37c6).
5. The samples used in this study were electronic grade CVD diamond purchased from Element Six Technologies, Global Innovation Centre, Fermi Ave., Harwell, OX11 0QR, United Kingdom. and II-VI Incorporated, 375 Saxonburg Blvd., Saxonburg, PA 16056-9499, USA. URL <http://www.iiviiinfrared.com>.
6. Dotite silver paint D-550. Fujikura Kasei Co., LTD. 6-15, Shibakoen 2-chome, Minato-ku, Tokyo 105-0011 Japan; TEL. 81-3-3436-1100 <https://www.fkkasei.co.jp/english/product/electric/dotite/05.html>
7. Integrated Detector and Electronics (IDE) AS designed the VA circuits. <http://www.ideas.no>.
8. S. Zhao, "Characterization of the electrical properties of polycrystalline diamond films," Ph.D. Thesis, The Ohio State University, (1994); URL: http://rave.ohiolink.edu/etdc/view?acc_num=osu1394810346.
9. Cyclotron and Radioisotope Center (CYRIC), Tohoku University, Sendai, Miyagi, Japan. For additional information see: <http://www.cyric.tohoku.ac.jp>.
10. L. Snoj, G. Žerovnik and A. Trkov, "Computational analysis of irradiation facilities at the JSI TRIGA reactor," Appl. Radiat. Isot. **70**, 483 (2012); DOI: [10.1016/j.apradiso.2011.11.042](https://doi.org/10.1016/j.apradiso.2011.11.042).
11. K. Ambrožič, G. Žerovnik and L. Snoj, "Computational analysis of the dose rates at JSI TRIGA reactor irradiation facilities," Appl. Radiat. Isot. **130**, 140 (2017); DOI: [10.1016/j.apradiso.2017.09.022](https://doi.org/10.1016/j.apradiso.2017.09.022).
12. E. S. Krištof, "Characterization of neutron flux in the exposure channel F19 of the TRIGA Mark II reactor in Ljubljana," Nuclear Energy in Central Europe '98. 43 (1998).
13. Paul Scherrer Institute (PSI), 5232 Villigen, Switzerland. <https://www.psi.ch>.
14. CERN IRRAD proton facility, <https://ps-irrad.web.cern.ch/ps-irrad/external.php>.
15. M. Glaser, F. Ravotti and M. Moll, "Dosimetry assessments in the irradiation facilities at the CERN-PS accelerator," IEEE Trans. Nucl. Sci. **53**, 2016–2022 (2006); DOI: [10.1109/TNS.2006.880569](https://doi.org/10.1109/TNS.2006.880569).
16. F. Bachmair, "CVD Diamond Sensors in Detectors for High Energy Physics," Ph.D. Thesis, ETH Zürich, (2016); DOI: [10.3929/ethz-a-010748643](https://doi.org/10.3929/ethz-a-010748643).
17. L. Băni, "Top Quarks and Diamonds," Ph.D. Thesis, ETH Zürich, (2017); DOI: [10.3929/ethz-b-000222412](https://doi.org/10.3929/ethz-b-000222412).
18. C. Colledani *et al.*, "A Submicron Precision Silicon Telescope for Beam Test Purposes," Nucl. Instr. and Meth. A **372**, 379 (1996); DOI: [10.1016/0168-9002\(95\)01414-4](https://doi.org/10.1016/0168-9002(95)01414-4).
19. D. Meier, "CVD Diamond Sensors for Particle Detection and Tracking," Ph.D. Thesis, Universität Heidelberg, (1999).
20. L. S. Pan *et al.*, "Particle- and photoinduced conductivity in type-IIa diamonds," J. Appl. Phys. **74**, 1086 (1993); DOI: [10.1063/1.354957](https://doi.org/10.1063/1.354957).
21. M. Muškinja *et al.*, "Investigation of charge multiplication in single crystalline CVD diamond," Nucl. Instr. and Meth. A **841**, 162 (2017); DOI: [10.1016/j.nima.2016.10.018](https://doi.org/10.1016/j.nima.2016.10.018).
22. K. Hecht, "Zum Mechanismus des lichtelektrischen Primärstromes in isolierenden Kristallen," Z. Phys. **77**, 235 (1932); DOI: [10.1007/BF01338917](https://doi.org/10.1007/BF01338917).
23. F. Hartjes *et al.* [RD42 Collaboration], "Parameterisation of Radiation Effects on CVD Diamond for Proton Irradiation," Nucl. Phys. B (Proc. Suppl.) **78**, 675 (1999); DOI: [10.1016/S0920-5632\(99\)00623-4](https://doi.org/10.1016/S0920-5632(99)00623-4).
24. M. Guthoff, W. de Boer and S. Müller, "Simulation of beam induced lattice defects of diamond detectors using FLUKA," Nucl. Instr. and Meth. A **735**, 223 (2014); DOI: [10.1016/j.nima.2013.08.083](https://doi.org/10.1016/j.nima.2013.08.083).

25. J.-W. Tsung *et al.*, “Signal and noise of diamond pixel detectors at high radiation fluences,” JINST 7 (2012) P09009; DOI: [10.1088/1748-0221/7/09/P09009](https://doi.org/10.1088/1748-0221/7/09/P09009).
26. G. Kramberger, V. Cindro, I. Mandić, M. Mikuž and M. Zavrtanik, “Determination of effective trapping times for electrons and holes in irradiated silicon,” Nucl. Instr. and Meth. A 476, 645 (2002); DOI: [10.1016/S0168-9002\(01\)01653-9](https://doi.org/10.1016/S0168-9002(01)01653-9).
27. V. Cindro *et al.*, “Radiation damage in p-type silicon irradiated with neutrons and protons,” Nucl. Instr. and Meth. A 599, 60 (2009); DOI: [10.1016/j.nima.2008.11.007](https://doi.org/10.1016/j.nima.2008.11.007).
28. RD50 Collaboration, <http://rd50.web.cern.ch/rd50/>.
29. C. Jacoboni, C. Canali, G. Ottaviani and A. Alberigi Quaranta, “A review of some charge transport properties of silicon,” Solid-State Electronics 20, 77 (1977); DOI: [10.1016/0038-1101\(77\)90054-5](https://doi.org/10.1016/0038-1101(77)90054-5).

© 2020 by the authors. Submitted to *Sensors* for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).