



Performance of a thin epitaxial diode as a relative dosimeter in standard radioprotection beams

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ABSTRACT

The performance of a radiation-hard epitaxial (EPI) diode as a relative dosimeter is investigated for standard radioprotection beams (N-60, N-80, N-100, and N-150 qualities). The diode operates in short-circuit current mode, in which the net output current is linearly proportional to the dose rate. The corresponding collected charge, calculated as the integral of the current signal, is proportional to the dose.

The EPI diode features a thin n-type epitaxial layer (50 μm) grown on a 300 μm -thick n-type Czochralski Si substrate. The p⁺-n junction, with a 25 mm² active area, is formed by a highly doped p-type silicon layer ($\leq 1 \mu\text{m}$) on the front side of the diode. This structure, which maintains a constant active volume with a thin entrance window and negligible dark current, may enhance its suitability for dosimetry applications in continuous low-energy spectra and low dose rates typical of standard radioprotection beam qualities. Irradiations are performed using the Pantak-Seifert 160HS Isovolt X-ray generator, with radiation beams previously standardized using a Radcal 10X5-180 ionization chamber. Data collected with N-60, N-80, N-100, and N-150 beam qualities confirm a linear relationship between current and dose rate, as well as between charge and dose. The lowest current measured, 1 pA, and the corresponding limit of detection in terms of dose rate, 8.5 $\mu\text{Gy}/\text{min}$ (for N-60 beam quality), are slightly lower than those disclosed by a few commercially available Si diode-based dosimeters. However, the associated current and charge sensitivities show a significant energy dependence for photons above 100 kV. Regardless of beam energy, most dosimetric parameters align with international protocol recommendations, including repeatability, long-term stability, angular response, dose-rate dependence, and signal-to-noise ratio. The results indicate that these radiation-hard epitaxial diodes can be used for the first time to monitor radiation protection beams in real time.

1. Introduction

Semiconductor devices like diodes, transistors, and diamond detectors have a broad application as relative dosimeters in radiation protection, medical imaging, and radiation therapy (Rosenfeld, 2002, 2016; Kumar et al., 2014; Oliveira et al., 2016; Damulira et al., 2019; Jursinic, 2019, 2023; Rosenfeld et al., 2020; Yamaguchi et al., 2021; Pettinato et al., 2023). Among them, diodes have been considered the best option for online dosimetry due to their simple structure, straightforward operating principle, and the large availability of devices with suitable technical characteristics for dosimetry. Usually, the diode operates in short-circuit current mode and remains unbiased to

minimize the dark current contribution to the radiation-induced current signal. The dosimetric parameter is the net output current linearly dependent on the dose rate within certain limits. The corresponding collected charge (obtained offline by integrating the current signal) is proportional to the dose.

For decades, our group has investigated the response of diode-based dosimetry systems in applications covering high levels of dose and dose rates, for example, in gamma and electron radiation processing, down to those involved in mammography, diagnostic radiology, and computed tomography beams. Several diode types, with distinct structures and production techniques, have been applied, including a few radiation-hard devices developed in the R&D framework of high-energy

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experiments. The resistance to radiation damage is enhanced by designing devices with different structures (device engineering) or tailoring the impurity density in the silicon bulk grown through distinct techniques (defect engineering). A combined approach of these two strategies outcomes the epitaxial diode under investigation in this work. It has a thin n-type epitaxial (EPI) layer (50 μm thick) grown on a 300 μm Cz Si substrate. The p⁺-n junction is formed by a highly doped p-type silicon layer ($\cong 1 \mu\text{m}$) on the front side of the diode. Although this type of diode is designed to withstand severe irradiation (tens of MGy) from high-energy charged particles, neutrons, and gamma rays, its outstanding electrical and structural characteristics open new possibilities for dosimetry of low-energy photon beams (below 150 kV tube voltage), which are typical in medical imaging. In this field, the major dosimetry concerns are response stability and dose measurement accuracy rather than the radiation damage effects. Epitaxial diodes, along with advancements in their production technology, possess three key features that enhance low-energy photon dosimetry: i) thin entrance windows that minimize beam attenuation; ii) sensitive volumes that remain nearly constant with small thicknesses (on the order of tens of microns); and iii) very low dark currents, enabling the detection of current signals induced by low dose rates. A few good results have been achieved with EPI diodes as dosimeters for mammography, diagnostic radiology, and computed tomography beams (Bruzzi et al., 2007; Santos et al., 2011; Aldosari et al., 2013; Gonçalves et al., 2014, 2024). They all motivate further investigation into the dosimetric response of this type of diode to continuous low-energy spectra and small dose rates typical of standard N-60, N-80, N-100, and N-150 radiation protection beam qualities according to ISO 4037 (2019). For this type of application, some authors have successfully investigated the use of low-cost commercial diodes (Oliveira et al., 2016; Kržanović et al., 2021; Falcão Neto, 2023), and high-cost commercial dosimeters developed for low-dose beams are also available on the market, among which the RTI-Piranha (2025), RaySafe i3, 2025, the Mirion-Instadose (2025) and Polimaster, 2025 are good examples. In all these cases, the measured dosimetric quantity is the charge deposited in the silicon diode. In this context, this work aims to evaluate the real time dosimetry response of an EPI diode, in which the dosimetric quantity measured is the photocurrent produced in the sensitive volume of the EPI diode by the incident radiation, following internationally accepted guidelines regarding dose rate and dose-response linearities, current and charge sensitivities, dose rate effects, energy dependence, repeatability and long-term stability parameters, limit of dose rate detection, and directional response.

2. Materials and methods

2.1. Diode and dosimetry probe

The EPI diode under investigation features a 50 μm thick n-type epitaxial silicon layer with a resistivity of 50 Ωcm . The EPI layer is based on a highly Sb-doped n-type Czochralski (Cz) silicon wafer, 300 μm thick, and a resistivity of 0.02 Ωcm . The pad diodes are manufactured by CiS in Germany using a p⁺-n-n⁺ structure with a 25 mm² active area and a 1.25 mm³ sensitive volume. The p⁺ electrode is formed through boron implantation to a depth of 0.6 μm . The Cz substrate serves as the backside n⁺⁺ ohmic contact, with an area of 1 cm². For processing details and diode characteristics, refer to Lindström et al. (2006), Hönniger et al. (2007); a cross-sectional diagram of the EPI diode is presented elsewhere (Gonçalves et al., 2024). For clarity, Fig. 1a and b provide a schematic diagram of the experimental setup and a picture of the EPI diode with the light-tight PMMA probe that features a thin (8.3 mg/cm²) black paperboard entrance window.

To operate the diode in short-circuit mode, without an externally applied voltage, the planar pad (p⁺) signal electrode is connected via low-noise Lemo® coaxial cable to the input of a Keithley® 6517B electrometer. The backplane (n⁺⁺) is grounded in this setup, while the guard ring structure is left floating.

2.2. Irradiation setup

Irradiations are conducted using a Pantak-Seifert 160HS Isovolt X-ray generator, with radiation beams previously standardized with a Radcal 10X5-180 ionization chamber, traceable to the Physikalisch-Technische Bundesanstalt (PTB), within a standard deviation of 3.5%. The probe is positioned at the center of a circular irradiation field with a 42 cm diameter, achieving 99% homogeneity at a distance of 250 cm from the X-ray tube (focal spot). Additionally, a circular plane-parallel transmission ionization chamber (PTW® model TN34014-0040) is placed at the exit of the X-ray beam to monitor irradiation, along with the radioprotection beams, for reference. The presence of this ionization chamber does not affect the X-ray spectrum. According to the manufacturer of the ionization chamber (PTW, 2025), the energy response within the studied X-ray energy range is less than $\pm 4\%$. The air kerma rates and main characteristics of the beam qualities investigated in this study are provided in Table 1. The dosimetric parameters are evaluated for radioprotection beam qualities established in accordance with ISO 4037 (2019).

2.3. Dose rate response and limit of detection (LoD)

The dose-rate response is investigated for N-60/80/100/150 beam

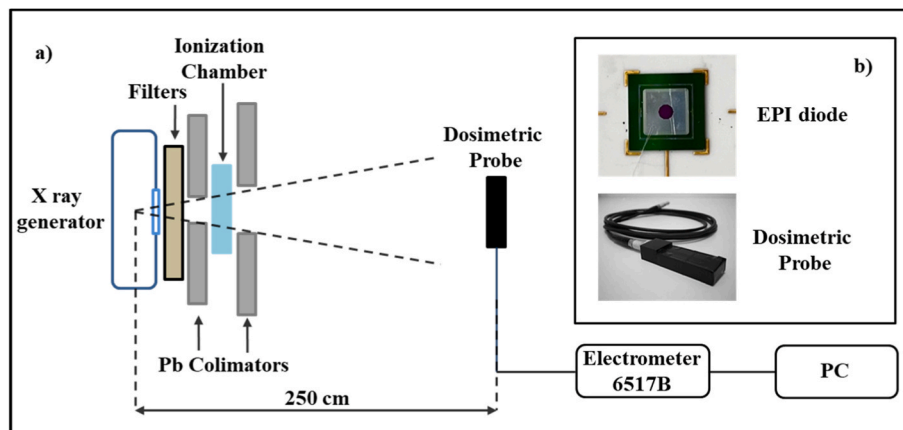


Fig. 1. a) Schematic diagram of the experimental setup; b) pictures of the EPI diode and dosimetric probe.

Table 1

Characteristics of radioprotection beam qualities from Pantak-Seifert 160HS Isovolt generator.

Quality	Tube voltage (kV)	Tube current (mA)	Additional Filter (mm)	Mean Energy (keV)	Air Kerma Rate ($\mu\text{Gy}/\text{min}$)
N-60	60	20	0.6 Cu + 4.0 Al	48	324.44
N-80	80	20	2.0 Cu + 4.0 Al	65	172.40
N-100	100	20	5.0 Cu + 4.1 Al	83	80.95
N-150	150	20	2.5 Sn + 4.0 Al	118	686.12

qualities by recording current readings as a function of dose rate within 16.22 $\mu\text{Gy}/\text{min}$ and 729.99 $\mu\text{Gy}/\text{min}$. Variations in the dose-rate are accomplished by varying the X-ray tube current from 1 mA to 45 mA (encompassing the operational limits of the X-ray generator for N-beam qualities), as presented in Table 2.

For each dose rate, the electrometer (operating in current mode) continuously acquires data over five consecutive irradiation cycles, consisting of switching the beam on (shutter on) for 60 s, then switching it off (shutter off) for 60 s. The background (BG) currents, acquired when the shutter is closed, are important for estimating the signal-to-noise ratio (SNR), the minimum detectable current, and the Limit of Detection (LoD) of the dosimeter in terms of dose rate.

SNR can be calculated (Pettinato et al., 2023) as the ratio of the average X-ray photocurrent ($\bar{i}_{ph}$), measured at each dose-rate value, and the standard deviation of the background current ($\sigma_{BG \text{ current}}$), according to equation (1):

$$SNR = \frac{\bar{i}_{ph}}{\sigma_{BG \text{ current}}} \quad (1)$$

The Limit of Detection (LoD), or the lowest detectable dose rate, corresponds to an SNR of 3 (Pettinato et al., 2023). Consequently, the minimum detectable current signal from the diode, with statistical reliability, is defined as 3 times the standard deviation of the background current. In our case, the LoD in dose rate stems from the dose rate response for the N-beams quality gathered under the same experimental conditions.

2.4. Repeatability

The repeatability of the current signals is quantified for all beam qualities at the conditions described in Table 1 (radiation beams standardized with a Radcal 10X5-180 ionization chamber). Five consecutive current signals, each lasting 60 s, followed by a pause of 60 s, are taken for beam qualities. The repeatability parameter is evaluated using the coefficient of variation (CV), defined as the standard deviation expressed as a percentage of the mean value for each set of current readings (IEC 60846-1, 2009), as in equation (2):

$$CV (\%) = \frac{\sigma_{i_{ph}}}{\bar{i}_{ph}} \cdot 100\% \quad (2)$$

Table 2

– Dose rate range for N-beam qualities by varying the X-ray tube current from 1 mA to 45 mA.

Quality	Tube voltage (kV)	Tube current (mA)	Dose rate range ($\mu\text{Gy}/\text{min}$)
N-60	60	1 – 45	16.22 – 729.99
N-80	80	5 – 35	43.10 – 301.70
N-100	100	10 – 30	40.48 – 121.43
N-150	150	1 – 20	34.31 – 686.12

2.5. Long-term stability

The long-term stability (or reproducibility) of the EPI diode response is assessed over one semester by monthly irradiation of the diode with N-60/80/100/150 beam qualities under the same reference conditions, including positioning, exposure time (five consecutive current signals, each lasting 60 s, followed by a 60-s pause), and dose rate, as shown in Table 1. In each irradiation step, the output current value is the average of five consecutive readings.

2.6. Angular response

The directional response of the N-60 and N-150 beam qualities is investigated by manually rotating the dosimetric probe coupled to a commercial goniometer (Optron®, model GN1 200) with a resolution of 1°. The rotation is performed from -90° to $+90^\circ$ to ensure compliance with the ISO 29661 (2012) and IEC 60846-1 (2014) standards. At each angle, five consecutive current signals are recorded for 60 s at a constant dose rate: 324.44 $\mu\text{Gy}/\text{min}$ (N-60) and 686.12 $\mu\text{Gy}/\text{min}$ (N-150). The averaged current data are normalized to unity at an incidence angle of 0° , where the beam strikes the front surface of the diode perpendicularly.

2.7. Dose response

The dose response, given by the charge produced in the sensitive volume of the diode as a function of absorbed dose, is evaluated for all beam qualities covering doses up to 6.8 mGy (N-150). The corresponding collected charge, calculated as the integral of the current signal, is proportional to the dose. The main dosimetric features, including linearity and the corresponding charge sensitivity, as determined from the slope of the linear plot, are also investigated. The energy dependence is assessed by variations in the charge sensitivity values obtained across all beam qualities. For comparison, similar measurements are carried out with the electrometer in charge mode. This approach allows comparison of charge repeatability results obtained directly from the electrometer with current repeatability. As previously described for dose rate, the minimum detectable dose is also obtained through the 3σ method for all beam qualities.

The dose-rate effect on the dose response is evaluated using the N-60 by irradiating the diode at a constant dose (686 μGy) under dose rates of 162.22 $\mu\text{Gy}/\text{min}$ and 729.99 $\mu\text{Gy}/\text{min}$. Variations in the charges relative to the average value across the whole set are used as a parameter to assess whether the dose response is dose-rate independent within the range investigated.

2.8. Uncertainties

The combined uncertainty for each performance characteristic is determined by adding all components (types A and B) of the standard uncertainties in quadrature (JCGM 100, 2008). The sources of combined uncertainties include the standardized ionization chamber (3.5%), the electrometer precision (1.0%), the source-detector distance (0.05%), the goniometer (0.05%), the chronometer (0.004%), and the thermometer (0.01%). These combined uncertainties are expanded using a coverage factor of $k = 2$, corresponding to a confidence level of 95%. In all figures, the experimental values are displayed with their respective error bars, which may sometimes be too small to be visible next to the symbols representing the data points. Additionally, the uncertainties in current and charge sensitivities stem from the data fitting performed in the Origin software.

3. Results and discussion

3.1. Dose rate response

Fig. 2 shows the linear dose rate response for N-60/80/100/150 beam qualities, covering the air kerma rate range from 16.22 $\mu\text{Gy}/\text{min}$ to 729.99 $\mu\text{Gy}/\text{min}$. Variations in air kerma rates are achieved by changing the X-ray tube current from 1 mA to 45 mA, as described in Table 2. The current sensitivities, assessed through the slope of the linear plots, are shown in Table 3. The coefficients of determination (COD), R^2 , are better than 0.99992.

The minimum detectable current and the corresponding LoD for dose rate are also presented in Table 3.

3.2. Repeatability

The output current signals delivered by the EPI diode, consecutively irradiated with all beam qualities, are presented in Fig. 3. The current profiles are acquired at the same dose rate, 80.95 $\mu\text{Gy}/\text{min}$, to better assess the energy response. They show relatively stable current signals, with more fluctuations at the N-100 quality.

In order to access the repeatability parameter, through the coefficient of variation, five consecutive current signals, each lasting 60 s, followed by a pause of 60 s, are taken for all beam qualities at a constant tube current of 20 mA (as described in Table 1). The first set of current readings is plotted in Fig. 4. The CV for current signals (CV_i) and the corresponding signal-to-noise ratios for current (SNR_i) are presented in Table 4.

All these parameters comply with the international protocols for radioprotection dosimetry (ISO 29661, 2012, and IEC 60846-1, 2014).

3.3. Long-term stability

The current readings normalized to the average current over five months, gathered for all N-beam qualities, are depicted in Fig. 5. The high long-term stability of the current response, better than 2%, complies with the requirement of the ISO 29661 (2012), and IEC 60846-1 (2014) standards.

3.4. Angular dependence

The angular dependence of the diode response for the N-60 and N-150 beam quality is shown in Fig. 6. Each point is the average of five current readings normalized to unity at an incidence angle of 0° (normal

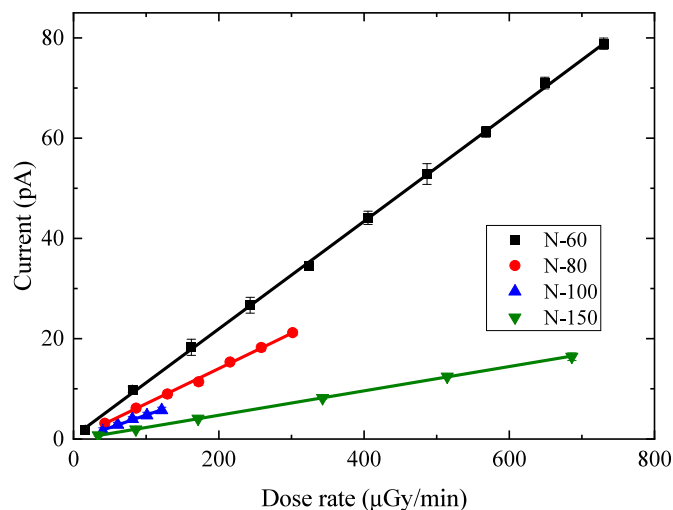


Fig. 2. Dose rate response of the EPI diodes irradiated with N-60/80/100/150 beam qualities. The slope of the linear plot gives the current sensitivity (S_i).

Table 3

Current sensitivities (S_i), minimum detectable current (as 3 times the standard deviation of the dark current) and the Limit of Detection (LoD) in dose rate for the N-beams. The uncertainties related to current sensitivities are those from the plot fitting.

Quality	Tube voltage (kV)	S_i ($\text{pA} \cdot \text{min} \cdot \mu\text{Gy}^{-1}$)	Minimum detectable current (pA)	LoD - dose rate ($\mu\text{Gy}/\text{min}$)
N-60	60	0.1074 ± 0.0008	0.93	8.5
N-80	80	0.0700 ± 0.0012	0.65	9.3
N-100	100	0.050 ± 0.003	0.55	11.5
N-150	150	0.02431 ± 0.00011	0.61	25.5

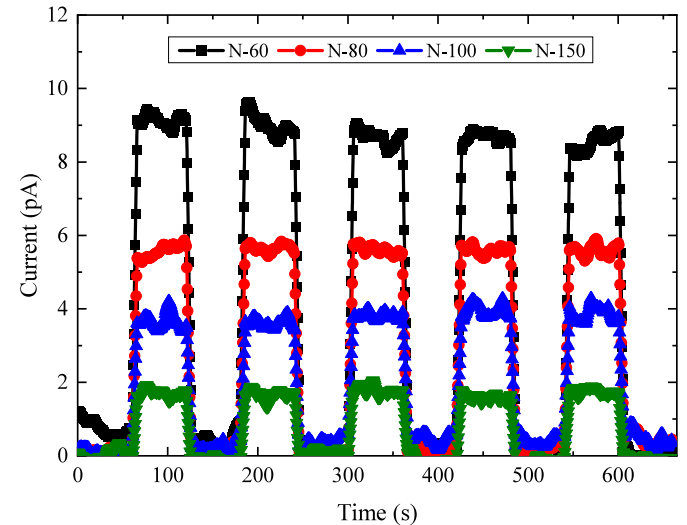


Fig. 3. Current signals from the EPI diode consecutively irradiated with all radioprotection beams, under the same dose rate, 80.95 $\mu\text{Gy}/\text{min}$.

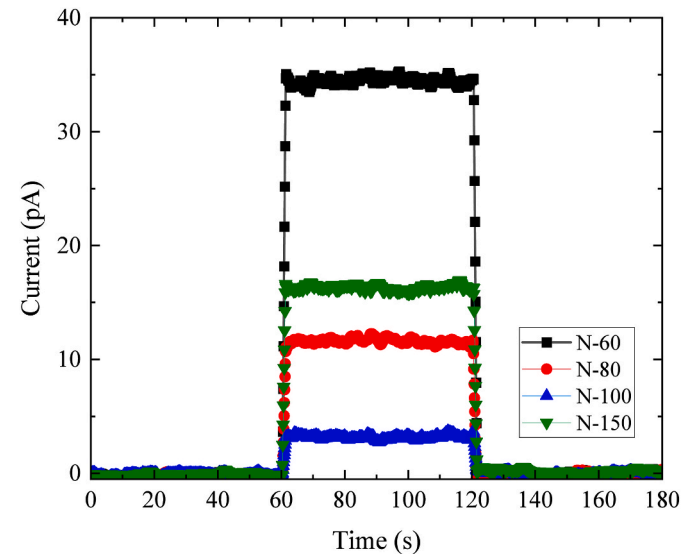


Fig. 4. Current signal profiles taken for all beam qualities at the conditions described in Table 1. The overall instrumental uncertainties are 4% for the N-60 beam quality.

incidence to the diode surface). Regardless of the rotation direction and beam quality, good agreement is found for angles within $\pm 30^\circ$ followed by a gradual decay of intensity with increasing rotation angle up to 90° . A 10% reduction in the signal amplitude occurs at a rotation angle close

Table 4

– Repeatability parameters and signal-to-noise ratios for current signals recorded with the standard radioprotection beam qualities.

Quality	Tube voltage (kV)	CV _i (%)	SNR _i
N-60	60	1.0	35
N-80	80	2.7	26
N-100	100	8.5	10
N-150	150	2.5	30

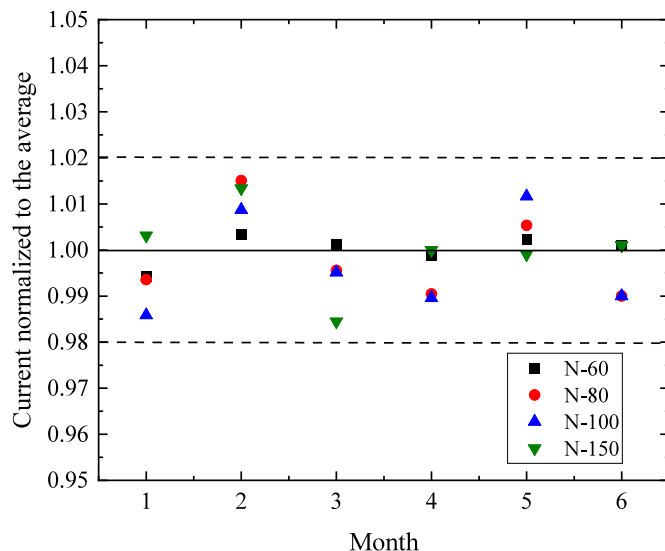


Fig. 5. – Long-term stability for N-beam qualities. Each data point is the mean of five monthly measurements, normalized to the average over five months. The dashed lines represent the maximum current variation (2%) recommended by the ISO 29661 (2012), and IEC 60846-1 (2014) standards.

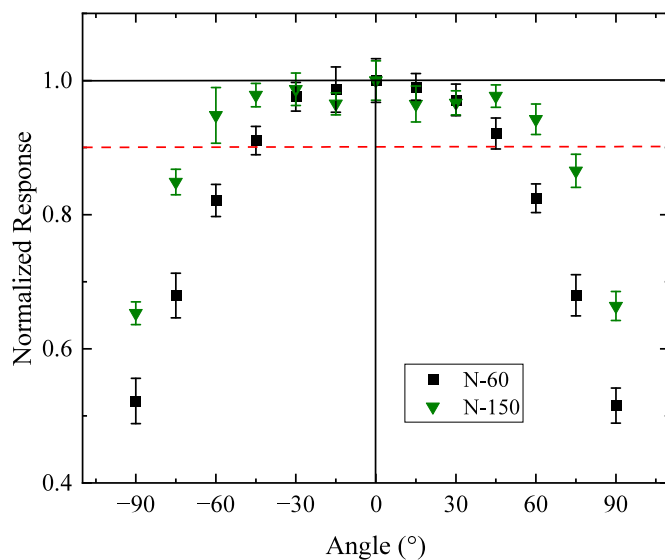


Fig. 6. Angular response of the EPI diode for N-60 and N-150 beam qualities. The dashed lines show the maximum variation $\leq 10\%$ required by the ISO 29661 (2012) and IEC 60846-1 (2014).

to 45° relative to the normal to the diode surface for N-60 beam quality. This effect is linked to the beam's energy loss as it traverses a greater distance before reaching the diode's sensitive volume, resulting in greater attenuation in the probe's entrance windows (8.3 mg/cm²) and the diode (0.14 mg/cm²). For this reason, the directional response

depends on the beam energy and is affected by the diode's structural characteristics and its assembly on the probe. It is corroborated by the angular response of the N-150, where the 10% energy loss occurs only at roughly 70° . However, even at the lowest beam energy (N-60), the response variation of less than 10% over an angular range of $\pm 45^\circ$ still meets the ISO 29661 (2012) and IEC 60846-1 (2014) requirements.

3.5. Dose response and charge sensitivity

Figs. 7 and 8 show the dose responses of the EPI diode for the radioprotection beam qualities presented in Table 1. On the ordinate axis, the charges are obtained by offline integrating the current signals measured online (Fig. 7) or by directly reading the electrometer operating in charge mode (Fig. 8). Regardless of the charge assessment method, all data sets are fitted by linear functions with coefficients of determination (COD), R², better than 0.997. These results assure that the charge is linearly dependent on the absorbed dose, although an evident energy dependence is observed among the N-beam qualities. This dependence translates into the charge sensitivity variations presented in Table 5. Falcão Neto (2023) found similar behavior in the energy dependence of the BPW-34 diode used in the dosimetry of N-40-120 beams. To compare the performance of the EPI diode in both current and charge mode for the N-beams studied, Table 6 shows the values of the average charge and the corresponding coefficients of variation (CV_Q) and signal-to-noise ratio (SNR_Q) measured with the electrometer as an integrator (charge mode) and the beams under reference conditions (Table 1).

Regardless of the dose rate, the coefficients of variation for current signals (Table 4) are higher than those for charge measurements. This difference is expected because instantaneous variations in background currents directly affect online signal acquisition. However, this effect is mitigated in charge measurements taken with an electrometer. Similarly, identical behavior is observed for the signal-to-noise ratio (SNR) values, also presented in Table 4. Physically, these sensitivity discrepancies might be due to slight variations in the diode response with the energy and dose rate of the beams. However, as shown in Fig. 9, the response dependence on dose rate is ruled out by the charges generated at a constant absorbed dose (686 μ Gy) across different dose rates for the N-60 beam quality.

Analysis of the dose-response curves (Figs. 6 and 7) shows that higher beam energy is associated with lower charge sensitivity,

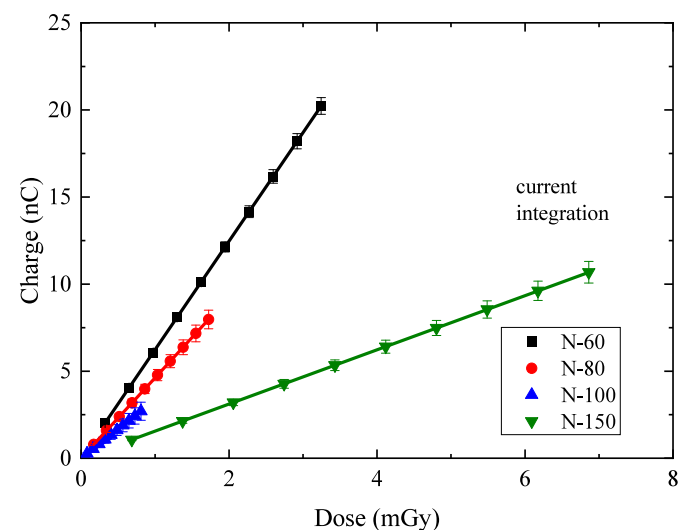


Fig. 7. Dose response of the EPI diode for radioprotection beam qualities. The charge values are obtained by offline integrating the current signals. The different slopes of the linear plots indicate discrepancies in charge sensitivity across all beam qualities. The maximum instrumental uncertainty is 4%.

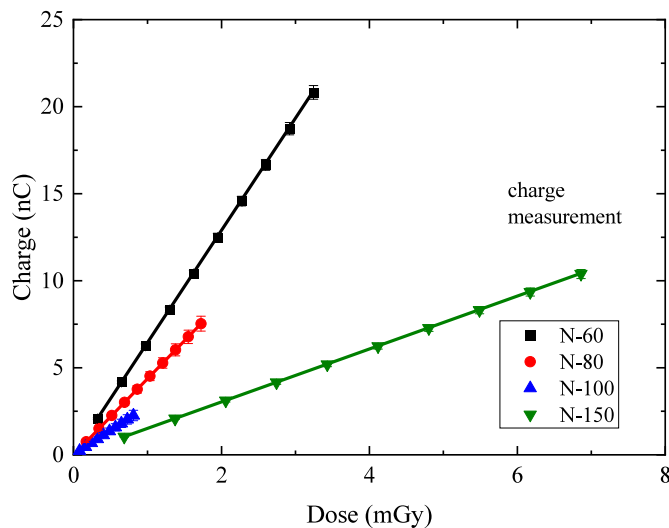


Fig. 8. Dose response of the EPI diode for radioprotection beam qualities. The charges are acquired by the electrometer operating in charge mode. The different slopes of the linear plots indicate discrepancies in charge sensitivity across all beam qualities. The maximum instrumental uncertainty is 4%.

Table 5

– Charge Sensitivities (S_Q) of the radioprotection beams from both charge assessment methods (integrating the current signals and using the electrometer in charge mode). The errors stem from the linear data fitting.

Quality	S_Q - offline integration of the current signal ($\mu\text{C}\cdot\text{Gy}^{-1}$)	S_Q - charge mode ($\mu\text{C}\cdot\text{Gy}^{-1}$)
N-60	6.24 ± 0.15	6.44 ± 0.16
N-80	4.6 ± 0.3	4.37 ± 0.25
N-100	3.3 ± 0.7	2.78 ± 0.19
N-150	1.56 ± 0.09	1.52 ± 0.04

Table 6

– Values of mean charge, CV_Q , and SNR_Q for the EPI diode obtained in charge mode for the N-60/80/100/150 beam qualities at reference conditions (Table 1).

Quality	Mean charge (nC)	CV_Q (%)	SNR_Q
N-60	2.082 ± 0.008	0.5	229
N-80	0.734 ± 0.015	2	185
N-100	0.176 ± 0.011	5	21
N-150	1.039 ± 0.016	1.5	108

regardless of the charge acquisition method. It is endorsed by the agreement among the overall sensitivity data shown in Table 5. The energy dependence is more pronounced for photons exceeding 100 kV tube voltage, supporting our previous findings with the same EPI diode for diagnostic radiology and computed tomography beams (Gonçalves et al., 2024). Such differences in charge sensitivity might stem from the partial energy deposited by different photon beam qualities within the diode's sensitive volume. Simplified calculations based on the EPI layer thickness (50 μm), average beam energy, and the corresponding absorption coefficient corroborate this hypothesis. However, the energy dependence, a well-known drawback of Si diodes, does not prevent their use as dosimeters as long as they are calibrated against a reference standard ionization chamber. The calibration procedure, recommended even for energy-independent dosimeters, enables the introduction of correction factors that enhance the accuracy and reliability of dose measurements. On the other hand, the use of appropriate filters could significantly reduce the energy dependence of the EPI diode, as is the case with commercially available dosimeters. This study is underway.

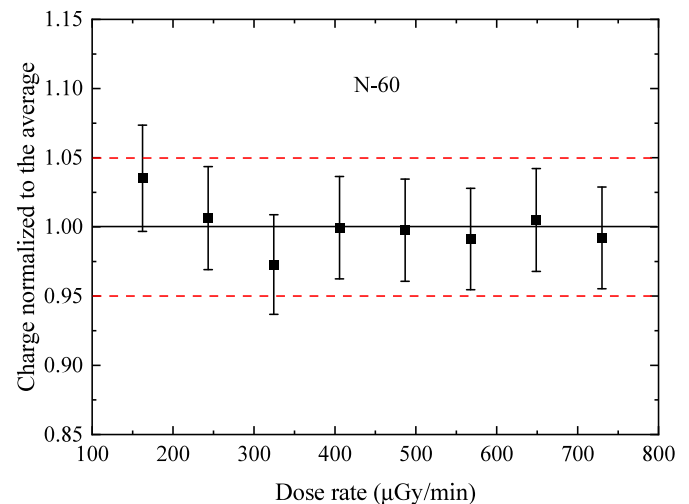


Fig. 9. Dose-response dependence on the dose rate for the N-60 beam quality. The dose rate range (162–730) $\mu\text{Gy}/\text{min}$ is achieved by varying the beam current from 10 to 45 mA. For each dose rate, the diode is irradiated at 686 μGy . The dashed lines represent the limits of the dose rate dependence recommended by the IEC 60846-1 (2014) norm.

4. Conclusions

The performance of a radiation-hard epitaxial (EPI) diode as a relative dosimeter is investigated for standard radioprotection beams. The data collected with N60, N80, N100, and N150 beam qualities confirm a linear relationship between current and dose rate, as well as between charge and dose, despite significant sensitivity variation for photons exceeding 100 kV tube voltage. Such differences in charge sensitivity stem from the partial energy deposited by different photon beam qualities in the thin epitaxial active layer (50 μm). Energy dependence is a known drawback of any diode-based dosimeter and is usually addressed by proper calibration against a reference ionization chamber for each beam quality. This well-established procedure is essential for ensuring the accuracy of dose measurements for all relative dosimeters, regardless of whether they depend on radiation energy.

The special structure of the EPI diode, responsible for a constant sensitive volume with almost negligible dark current, proves to be useful in measuring very low dose rates (12.66 $\mu\text{Gy}/\text{min}$) with repeatability parameter less than 5%, long-term stability better than 2%, and a reasonable SNR (≥ 10 in the worst case).

Additionally, the narrow entrance window, the small active layer of the EPI diode, and improvements in its production technology enhance the dosimetric response to continuous low-energy spectra and small dose rates typical of standard radioprotection beams. This remains true for most dosimetric parameters assessed in this study, which adhere to international protocol guidelines for radioprotection dosimetry. Furthermore, the overall results indicate that these radiation-hard epitaxial diodes can be used for the first time to monitor radiation protection beams in real time.

CRediT authorship contribution statement

Josemary A.C. Gonçalves: Data curation, Formal analysis, Investigation, Methodology, Resources, Writing – review & editing. **Patrícia L. Antonio:** Data curation, Investigation. **Leonardo C. dos Santos:** Investigation. **Linda V.E. Caldas:** Funding acquisition, Writing – review & editing. **Helen J. Khoury:** Funding acquisition, Writing – review & editing. **Viviane K. Asfora:** Data curation, Investigation. **Maria P.A. Potiens:** Investigation. **Carmen C. Bueno:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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