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Characterisation of a synthetic single crystal diamond detector

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Abstract

When treating cancer by radiation therapy it is always the goal to irradiate the tumour as much as possible and to spare the healthy tissue around it. For this a new type of radiation therapy called Volumetric Modulated ARC Therapy (VMAT) has been developed. During VMAT treatment the radiation machine rotates around the patient delivering focused beams of radiation to the tumour. Because the radiation can come from multiple angles the radiation dose to healthy tissue is reduced while the radiation dose to the tumour is increased. Because VMAT uses focused radiation bundles it is required to have detectors that can measure dose in a point. The diamond detector is a promising detector for this type of detection.

Before the detector can be used for measurements it has to be characterized. This includes characterisation for the dependence of the orientation of the detector, the temperature dependence of the detector, the energy dependence of the detector, the long-term stability of the detector and the pre-irradiation of the detector. For all characterisations except the characterisation for energy dependence the detector was radiated using a Cobalt-60 source.

The characterisation for the orientation of the detector was done by irradiating the detector under various angles. This characterisation is split into the axial angles and radial angles. The dependence of the angles has been investigated with the detector in air as well as the detector submerged in 5 cm of water. The characterisation for the temperature dependence of the detector has been determined by placing the detector in a phantom of water. The detector was radiated while in water of 10 °C, 20 °C and 30 °C. The energy dependence of the detector was determined by radiation the detector with an X-ray tube. The amount of charge measured per Gray of radiation was calculated for mean photon energies of 51 keV, 69 keV, 86 keV, 105 keV and 1,25 MeV. The long-term stability of the detector was investigated by performing the exact same measurement multiple times over the course of the internship and then comparing the results. The pre-irradiation dose required to stabilize the signal from the detector has been determined by not radiating the detector for multiple days and then doing a measurement without pre-irradiation. By calculating how long it takes to stabilize the signal from the detector the amount of Gray needed to pre-irradiate it can be calculated.

Measurements showed that the detector has a large dependence on orientation. Axial angle orientation showed a maximum of 1,4% deviation in measured dose in air and a maximum of 1% deviation in measured dose in water. The dependence on axial angle showed a maximum of 31,4% deviation in measured dose in air and 4,3% in water. Results show that the amount of dose measured deviates a maximum of 3% when the temperature of the water is 10 °C above or below the standard temperature of 20 °C.

It was determined that over the range of 51 keV to 1250 keV photon energy the response of the detector deviates 14%. Lastly the amount of pre-irradiation needed until the detector signal is stable was calculated. The average amount of dose needed to pre-irradiate the detector is 25 gray and with the Cobalt-60 source this equals 45 minutes of pre-irradiation.

The conclusion of the characterisation of the detector is that it can only be used for measurements if the medium around the detector provides enough build-up. When this is not the case the deviation of the response of the detector is too large.

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# Introduction

When treating cancer by radiation therapy it is always the goal to irradiate the tumour as much as possible and to spare the healthy tissue around it. For this a new type of radiation therapy called Volumetric Modulated ARC Therapy (VMAT) has been developed. During VMAT treatment the radiation machine rotates around the patient delivering focused beams of radiation to the tumour. Because the radiation can come from multiple angles, the radiation dose to healthy tissue is reduced while the radiation dose to the tumour is increased. Because VMAT uses focused radiation bundles it is required to have detectors that can measure dose in a point. The diamond detector is a promising detector for this type of detection.

The diamond detector is a type of detector that recently is getting more attention due to the fact that a new technology has been discovered. This technology makes it possible to create synthetic diamonds with minimum imperfections. Before diamond detectors were not popular because natural diamonds have considerable variations in dimensions and impurities, which considerably affects dosimetric properties such as linearity with dose rate.

Important properties of a detector are temperature dependence, photon energy dependence, dependence on orientation, pre-irradiation and long-term stability.

In the labs of VSL there is a special climate system that ensures the temperature is always 20 °C. VMAT radiation therapy is performed in hospitals. Because hospitals don’t have a special climate system the environment temperature will vary. For this reason it is important to characterise the detector for temperature dependence.

During the VMAT treatment the radiation machine will rotate around the detector, to accurately determine dose distribution it is required to characterise the detector for directional dependence. When the radiation machine rotates the detector will frequently be outside the bundle of radiation. Outside the bundle the detector only detects scattered radiation which has a lower energy. If the detector has a large photon energy dependence it will be hard to accurately measure the actual amount of dose. For this reason the energy dependence is another important property of the detector.

Long-term stability is important to determine the re-calibration interval. The long-term stability is investigated in this report.

Diamond detectors using synthetic diamonds will still contain some impurities. These impurities in the diamond can absorb a certain amount of radiation. To accurately measure the amount of dose during a treatment it is important the diamond detector has been pre-irradiated. The amount of pre-irradiation needed is another property of the detector that needs to be characterised.

The goal of this research is to characterise the diamond detector for all these properties.

# Diamond detector

In this chapter the construction of the diamond detector will be described, the theory behind the functioning of the detector and various material properties of diamond that are important for radiation detectors.

## Construction of the diamond detector

The diamond detector is constructed as a Schottky diode. A Schottky diode is a semiconductor with instead of a n-doped part it uses a metal which is called the Schottky contact. In this case that metal is aluminium. The construction of the detector starts at the bottom (see fig 1). The bottom part of the detector consists of a high pressure high temperature (HPHT) single crystal diamond. On this HPHT substrate a conductive boron-doped layer is placed. This layer is created using a technique called chemical vapour disposition (CVD). Using this technique it is possible to create layers of diamond with minimum imperfections and impurities. On top of the CVD boron-doped layer a nominally intrinsic diamond film is deposited. Lastly an aluminium contact is thermally evaporated on the diamond surface. An overview of the layers is displayed in fig 1.

To protect these layers of diamond and metal it is placed in a small tube of epoxy and PMMA. The total structure can be seen in fig 2.



*Fig 1: An overview of how the layers of diamond and aluminium are constructed to create a Schottky diode.[9]*

*Fig 2: schematic overview of the geometry of the diamond detector.[9]*

## Theory behind the diamond detector

The process of detecting radiation with the diamond detector starts by the photon radiation from the source producing secondary electrons in the medium around the different parts of the detector. The secondary electrons may have a considerable kinetic energy, and dependent on this energy will travel a certain distance while losing its energy in small amounts. The secondary electrons produce ionizations when they lose energy in the medium they travel through. Ionizations made in the sensitive part of the detector produce the measurement signal. These ionizations and the measurement signal are a measure for the dose absorbed in the sensitive part of the detector and can be related to the dose to the medium in absence of the detector. The measurement signal is produced by the free electrons and in the sensitive volume. Due to the potential difference in the sensitive layer the free electrons drift towards the ohmic contact and produce the signal. The potential difference in the sensitive layer is caused by the way the detector is constructed making the intrinsic diamond film the depletion region of the Schottky diode. Because of the build-in potential the detector requires no external voltage to operate.

## Material properties of diamond

The reason why diamond is an excellent material for radiation is due to a few of its properties. These include radiation hardness, tissue equivalency and band gap. What these properties have to do with radiation detector will be described in this paragraph.

### Radiation hardness

Radiation hardness is the ability of the material to keep its properties after radiation. For a radiation detector this is an important aspect. If the material used has a small radiation hardness, in time the material will change its properties and this might affect the effectiveness of the detector. [4]

### Tissue equivalency

Tissue equivalency is mostly important in clinical dosimetry. In clinical dosimetry it is needed to know exactly how much dose a patient will absorb. To measure this accurately it is best if the atom number of the detector material is equivalent to tissue. The way a photon interacts with material depends on the energy of the photon and the atomic number of the material. Tissue is not composed of one type of element but research has shown that the way photons interact with tissue can be approximated as an element with an effective atomic number of 6,5.
Diamond has an atomic number of 6 and thus can be seen as nearly tissue-equivalent. [4]

### Band gap

The band gap of a material determines how much energy is needed for the excitation of an electron into the conduction band. The larger the band gap the more energy an electron needs. This has its advantages and its disadvantages. When the electron requires a higher amount of energy, the chance that an electron will randomly receive enough energy is smaller. This energy can come from heat or crystal vibrations. The current that is caused by these random free electrons is called the dark current. This dark current adds to the signal of the detector and thus reduces the accuracy. The smaller the dark current the more accurate the signal. The disadvantage of a large band gap is that secondary electrons with the same energy will free fewer electrons thus the current will be smaller. To counter this the irradiation time per measurement needs to be longer to collect enough charge to correctly determine the amount of dose.

# Equipment and measurement setup

## Description of measurement setup

In the following sub-paragraphs the equipment and measurement setup used for the experiments is explained. This includes the principle of the x-ray tube, the Gammatron Unit, the electrometer and the positional equipment.

### X-ray tube

This paragraph will describe the general theory behind an x-ray tube. It will also describe the x-ray tube used during experiments in this report.

**Principles of the x-ray tube**

An x-ray tube is an instrument that produces x-rays of various energies and intensities depending on certain settings. Inside the x-ray tube is a vacuum and on one side is the cathode and on the opposite side the anode. The cathode consists of a filament of a material that has a very high melting temperature, such as tungsten. This is a necessity because the filament is heated up to very high temperatures so that electrons are “boiled” out of the material. The cathode is heated using an electrical current. The amount of current determines the temperature of the cathode. The higher the temperature the more electrons will be “boiled out”. Over the cathode and anode a voltage potential is set that has a maximum value of 320 kV. The electrons emitted by the cathode are free in vacuum and are attracted to the anode due to the voltage potential. The electrons will accelerate towards to the anode and crash into it. This quick deceleration produces x-rays by brehmstralung processes. Only 1% of the energy of the electrons will be converted into radiation and the rest will become heat. This causes the anode to reach very high temperatures. This is one of the reasons the anode is made out of tungsten. [1]

The x-rays coming from the tube are different in energy and produce a spectrum. The spectrum of the beam depends on a number of things such as the voltage and the material of the anode. The material of the anode determines the energy of the characteristic x-rays coming from the x-ray tube. To use just one type of energy of the spectrum filters can be used. These filters are lead, copper or aluminium plates and the thicker the plates the higher energy the radiation has to have to get through the filter.

**X-ray tube used during the experiments**

The x-ray tube used for the experiments is the Philips MCN 321. The maximum voltage that can be applied over the x-ray tube is 320 kV. The anode material is tungsten en the x-rays go through an inherent filter (exit window of the beam) of 4 mm thick molybdenum.

### Gammatron Unit

The Gammatron Unit is the device that holds the Cobalt-60 source owned by VSL. This source was placed at VSL in February 2012 and at that time the source had an activity of 177 TBq. It was brought to the Netherlands from Russia and is the strongest source that VSL has in its possession.

The Cobalt-60 source is at all times stored inside the Gammatron Unit. When a radiation beam is needed part of the inner shielding rotates inside the fixed outer shielding to position the source for an opening in the shielding. The unit has two collimators to set the width of the beam and to shape the penumbra. As for all radiation units the Gammatron Unit can only be operated after activation of the safety system.

Cobalt-60 emits two gamma photons with an energy of 1173,2 keV and 1332,5 keV which can be approximated to an average of 1252,85 keV.

The size of the beam can be adjusted with the collimator. During the experiments for this investigation the size of the beam was always set on 100x100 mm at a distance of 1 meter. Using positional equipment the detector is placed in the middle of the beam. The used positional equipment will be shown and discussed in paragraph 3.1.5.

### Electrometer

The electrometer is the device that collects the electrical charge coming from the diamond detector. It collects the charge using a capacitor. The electrometer used for the measurements is a Keithley 6517A. This electrometer has four ranges for the charge mode, 2nC, 20nC, 200nC and 2µC. For the experiments done with the diamond detector the 2nC range was chosen. The reason for this is, is that the amount of charge coming from the detector during the measurements is quite small. It was tested during the first measurement that after two minutes of irradiation the 2nC capacitor was filled for about 1,4nC. To have an accurate measurement it is recommended the capacitor is filled up to about 70%. This way the accuracy of the charge accumulated is higher and there is no risk of the capacitor to become overflowed. A capacitor overflows when the amount of charge is larger than the maximum the capacitor can handle, in this case 2nC. If more charge is coming from the detector it will be simply not be collected and the reading will be inaccurate.

Besides the choice of the electrometer range two other settings had to be investigated. These are the MeterConnect option and the Guard option. The reason these two settings were investigated is that these settings have an influence when measuring with ionisation chambers. The MeterConnect option connects the intern voltage supply of the electrometer to the detector. As explained in chapter 2 it works without a voltage applied to it. In theory it would make no change for the measurement if the option MeterConnect would be turned on or off. The guard option grounds the internal voltage supply of the electrometer. Because the internal voltage supply is not used when measuring with the diamond detector to turn the guard on or off would theoretically have no effect on the measurement. To be sure these settings had no effect on the measurements the MeterConnect and the Guard option were always set to on. In fig 3. A simplified schematic of the electrical circuit of the Keithley 6517A is displayed.



*Fig 3: A simplified schematic of the electrical circuit of the Keithley 6517A.*

### Positional equipment

Being able to accurately (re)position the detector is very important, because of its contribution to the uncertainty of measurements. The position of the detector can be split in two parts, the position regarding the distance from detector to the source and the position of the detector in the bundle. Of these two the position of the detector regarding the distance from detector to the source is the more important one. The reason for this is that the amount of radiation reduces with the inversed square law, meaning that if the detector is 1 mm higher or lower than the reference point this will result in a change of dose of 0,2%. The bundle coming from the Cobalt-60 source is fairly uniform so if the detector is not placed in the exact middle it won’t change the amount of dose.

The detector is placed in the middle of the beam using a number of alignment lasers. The lasers cross at exactly the middle of the beam of the Cobalt-60 and are at a distance of 1000 mm of the source. This is the reference distance used when measuring radiation with the Cobalt-60 source.

Because the distance from the detector to the source is very important when measuring radiation the lab also contains a catheto-interferometer.

This optical system itself has a laser based interferometer system that is accurate up to a nanometre. But because the laser is placed by seeing if it is the exact spot by eye, the accuracy is less. The uncertainty of the system after taking this human error into account was determined by VSL and is 1,44·10-3 mm. Therefore the detector is adjusted by hand till it is positioned within ±0,5 mm from the reference point. The remaining difference in distance to the reference point will be corrected using the formula described in paragraph 3.2.2.

When the detector is submerged in water the catheto-interferometer is also used to determine the thickness of the layer of water above the detector. This also requires high accuracy because the thickness of the layer of water determines a large amount of the build-up. The reference depth of the detector under the water is 50 mm. The placement of the detector regarding the layer of water above the detector is adjusted until it is within ±0,5 mm of the reference depth.

## Corrections

In this chapter all the corrections that were used when measuring relative dose will be described. This includes the correction for the decay of the Cobalt-60 source, the correction for the source detector distance, correction for the air column between the detector and the source and the correction for the leak measurement.

### Correction for the decay of Cobalt-60

The source used for various measurements during this research is the Cobalt-60 source at VSL. As with every radioactive material it decays and thus the dose rate at a certain point in the radiation field becomes less over time. To be able to compare the results of measurements, a correction has to be made for this decay. VSL uses the first of January of each year as a reference date. The correction for the decay of the Cobalt-60 source to this reference date can then be calculated with formula 1.

 $k\_{decay}=e^{λt}$ (1)

In which:

*kdecay* The correction factor for the decay of the Co-60 source []
*λ* The decay constant of Co-60 [s-1]
*t* The amount of time passed since the reference date [s]

### Correction for the source detector distance (SDD)

As explained in paragraph 2.1.5 the detector is aligned within ±0,5 mm from the reference distance and depth. After this the remaining distance will be measured using the catheto-interferometer. Using this measured distance a correction factor, ksdd, is calculated. As known the amount of radiation reduces according to the inverse square law, with 1/*r*2 in which *r* is the distance in meters between the detector and the radiation source. The reference distance used for all measurements is 1 meter. The correction factor is calculated with formula 2.

 $k\_{sdd}=\frac{r^{2}}{r\_{0}^{2}}$ (2)

In which:

*r* The distance from the detector to the source [m]
*r0* The reference distance, this case 1 meter [m]
*ksdd* The correction factor []

### Correction for the air between detector and source

During the measurement there will be a column of air between the detector and the source. The reference dose rate and kerma rate determined with the primary standards is known in the absence of the air column. Therefore a correction is applied to correct for the air attenuation. The amount of radiation absorbed by the air depends on the density of the air, the length of the air column and the air absorption coefficient. The density of the air depends on air pressure and temperature of the air. Both pressure and temperature are measured during every measurement. Because the air absorption coefficient used is referenced at standard temperature and pressure the measured pressure is divided by the standard pressure and the standard temperature is divided by the measured temperature. The total calculation for the correction factor is done by using formula 3.

 $k\_{a}=e^{μ\_{0}\left(SDD-d\right)∙\frac{p}{p\_{0}}∙\frac{T\_{0}}{T\_{}}}$ (3)

In which:

SDD The source detector distance [m]
*d* The used water depth during the measurement [m]
*p* The average pressure during the entire measurement [Pa]
*p0* Standard pressure: 101,325 kPa [kPa]
*T0* The temperature in which *µ0* is valid. In this case 273,15 °K [K]
*T*The average temperature measured at the detector [K]
*µ0* The air absorption coefficient for the used nuclide at 273,15°K [m-1]

### Correction for leakage current

Leakage current is the current that is measured in the absence of the radiation field. For leakage current two forms are distinguished, the leakage current of an empty capacitor and the leakage current of a charged capacitor.

The first type of leakage current is caused by environmental effects and is usually smaller than the second type of leakage current. The second type of leakage current is caused by environmental effects and also because of defects in the capacitor that cause it to slowly release charge.

To correct for both types of leakage current a leak measurement of an empty capacitor is performed at the start of every measurement and at the end of the measurement a leak measurement of a full capacitor is performed. The average of these two will be calculated and subtracted from the currents measured during radiation.

For almost all measurements prior to the measurement a leak measurement on the empty capacitor was performed. After this five readings were done which was followed by two more leak measurements, one with a full capacitor and one with an empty capacitor. After this five more readings followed and the measurement ended with another leak measurement of a full capacitor. Using the measurement program made by VSL it is possible to adjust the amount of leak measurements per reading.

# Characterisation procedure

In this chapter all the characterisation procedures will be described. These are the characterisation of the orientation of the detector, characterisation of the energy dependence of the detector, characterisation of the temperature dependence of the detector, the characterisation of the long-term stability and the characterisation of the pre-irradiation of the detector.

## Characterisation of the orientation of the detector

For the application of the diamond detector it is important to determine the directional dependence. This directional dependence is separated in two parts. The detector will be rotated radially and axially. The experiments were performed using the methods described in the following section.

### Axial rotation

To be able to rotate the detector and radiate it, a small tube has been made. A picture of this tube with the detector inside it can be seen in fig 4**.** The detector was placed horizontally below the source at a distance of 1000 mm. If the SDD was larger or smaller than the 1000 mm it was corrected by using the correction for SDD explained in paragraph 2.2.3. To remember which side of the detector was the top side, a small white mark has been made on the detector which can also be seen in the picture in fig 4. The first measurement for the axial rotation was with the white mark pointing towards the source. This was used as the 0 degrees point. The detector was then radiated 10 times for 120 seconds. After the 0 degrees measurement the detector was turned 45 degrees and again radiated 10 times for 120 seconds. This process was repeated until the detector had made a full circle. The same process has been repeated in water to see if the results are the same. The reason for this is that the measurements for which the detector will be used, it will be placed in an anthropomorphic phantom. This will cause a certain amount of build-up and the layer of water simulates this.



*Fig. 4: picture of the small tube with the diamond detector inside it.*

*Fig 4: picture of the tube designed to hold the diamond detector.*

### Radial rotation

The dependence of the detector response on radial rotation of the detector was measured in a positioning and rotation device made in collaboration the Mechatronics Lab of VSL. The design is displayed in fig. 5.



*Fig. 5: design of the device for positioning and rotation the detector.*

As can be seen in fig. 5 the detector was placed in a tube which is attached to a rail. The lines pointing towards the rail present angles of 15 degrees. Using this device the radial angle could be changed easily without changing the distance between the source and the detector. The first measurement was done with the detector positioned vertically. This is used as the 0 degrees point. The detector was then radiated 10 times for 120 seconds. After this the detector was moved 15 degrees and again radiated 10 times for 120 seconds. This process was repeated until the detector had been radiated at every angle from -90 degrees to 90 degrees. The detector was then turned 90 degrees axially and again measured at every angle from -90 degrees to 90 degrees. This same process has been repeated with the detector submerged in water.

## Characterisation of the energy dependence of the detector

During the VMAT treatment the radiation machine rotates around the detector, when this happens the detector will often be placed outside the radiation bundle. At these moments the detector will only detect scattered radiation, which has much lower photon energy. If the response of the detector has a large energy dependence the actual amount of dose will differ from the measured amount of dose. Therefore the energy dependence of the detector needs to be characterised.

The energy dependence of the detector was measured by irradiating it with the x-ray tube and with the Cobalt-60 beam. With the x-ray tube the mean photon energy can easily be adjusted by changing the voltage of the x-ray tube. The maximum photon energy will be set on 100 keV, 135 keV, 180 keV and 250 keV. Because this range of energies is still quite small the energy dependence will also be measured using the Cobalt-60 which radiates photons with an average energy of 1,25 MeV.

The photons coming from the source, being either the x-ray tube or the Co-60, will encounter three different mediums. These mediums are air, PMMA, and diamond. The response of the detector depends on how many of the photons interact with the mediums and if the photons interact how much of the energy is absorbed by the electrons. The energy absorbed depends on the mass energy coefficient of the medium. For the measuring of the energy dependence of the detector the mean energy of the photons ranges from 51 keV to 1252 keV. Because the signal of the detector is compared against the signal of the monitor and the monitor has a mass energy coefficient of air, the ratio of the mass energy coefficient of the detector material and the mass energy coefficient of air will show if there is an energy dependence. The ratio of the mass energy coefficients for various energies is displayed in table 1.

*Table 1: The ratio of the masse energy coefficient of the detector materials and the mass energy coefficient for air for energies ranging from 51 keV to 1,25 MeV.*

|  |  |  |
| --- | --- | --- |
| *E* (keV) | ratio PMMA /air *μe/ρ* (cm2/g) | ratio diamond/air *μe/ρ* (cm2/g) |
| 51 | 0,732 | 0,600 |
| 69 | 0,873 | 0,700 |
| 86 | 0,966 | 0,950 |
| 126 | 1,083 | 1,050 |
| 1250 | 1,067 | 1,120 |

.

As seen in table 1 the ratio changes so it is expected that the detector has an energy dependence.

## Characterisation of the temperature dependence of the detector

The characterization for the temperature dependence of the detector was done in the 30x30x30 cm3 phantom filled with water. All the labs in VSL have a special climate system that regulates the temperature and is always set on 20 °C. For this reason the temperature of the air around the detector cannot be varied but by placing the detector in water the temperature dependence of the detector can still be determined.

The temperature of the water inside the phantom was varied from 10 °C to 30 °C. The temperature was measured using a thermistor and placed in an insert in the phantom. 10 °C is chosen as a minimum temperature because in the technical manual it states that the detector should not be used in water with a temperature lower than 10 °C. The water of 10 °C is obtained by cooling it to 4 °C and then slowly letting it warm up in the phantom. VSL has special machines to cool the water to exactly 4 °C because this is the temperature of water that is needed for the water calorimeter. When the water was a little above 10 °C the detector was placed in the water phantom and was pre-irradiated. After this a normal measurement was started. Since the water temperature is slowly increasing and the temperature is not measured exactly at the point of detector, the measured temperature might differ. According to the manual the temperature dependence of the detector is (0,05 ±0,03) %/°K. During a single measurement series the variation in temperature was less than 0,25 °K. Using the specified temperature dependence of the manufacturer it is expected that this uncertainty on the real temperature of the detector has negligible effect on the results.

 To measure the temperature dependence of the detector above 20 °C, hot water from the tap was used. Because the detector cannot withstand temperatures higher than 35 °C it cannot be placed in the phantom until the water was cooled down to 35 °C. The detector was then pre-irradiated and after that measurements were performed while the water slowly cooled down to 20 °C.

## Long-term stability of the detector

The long-term stability of a detector is an important aspect for a detector. Long-term stability is the stability over the period of at least a year or more. The long term stability of the diamond detector is expected to be good. This is because diamond has a large radiation hardness, as explained before in the chapter about the diamond detector, radiation hardness is how much dose can be delivered to a material before its response starts to change.

The stability of the diamond detector will be tested by repeating the same measurement every 3-4 weeks over the period of the internship, which is four months. The long-term stability measurement is performed with the detector placed horizontally with a 0 degrees axial angle. Over the course of the measurements the Cobalt-60 source will decay and the amount of Gray/hour will become less. This will be taken into account and the results will be corrected for decay as well as the other corrections mentioned earlier in the rapport. According to the technical manual of the detector the longer-term stability of the detector is ≤ ±0,5% per year.

The result of the long-term stability measured can be used to calculate when the detector needs to be re-characterised.

## Characterisation for pre-irradiation of the detector

In general detectors used for precise and accurate dosimetry need to be pre-irradiated before the actual measurement. This is done to stabilize the detector signal. The amount of dose needed for a detector to stabilize the signal differs per detector. For each detector type the theoretical reason for pre-irradiation may differ. In the case of the diamond detectors the pre-irradiation is needed to fill traps in the diamond[4]. These so-called traps and impurities are certain energy states that aren’t allowed but can still capture electrons because of defects in the crystal. These electrons that are trapped are not added to the signal of the detector. According to this theory the detector should measure less radiation when it hasn’t been pre-irradiated.

To measure the amount of radiation the detector needs to stabilize after a certain amount of time of being inactive, several measurements were performed. The detector was placed at an SDD of 1000 mm and radiated for 60-90 minutes in intervals of 120 seconds. From the results graph can be seen when the amount of radiation becomes stable. To determine when the detector was stable enough the following procedure was used. For example when the pre-irradiation measurement was 90 minutes this results in 45 readings of irradiation, because one reading is 120 seconds. The moving average of 10 readings was taken. Of this moving average the relative standard deviation was taken in comparison with the moving average of the last 10 readings. It was decided that when this relative standard deviation of the average was 0,1% or lower the reading was stable.

Using this method the amount of time it takes to pre-irradiate the detector can be calculated. But taking in considering the decay of the source and pre-irradiating the detector with different sources than the Co-60 from VSL, the amount of Gray needed to pre-irradiate the detector had to be calculated. This was done calculating the activity of the source when the measurement was performed and then multiplying this with the radiation time.

# Determination of uncertainties

In this chapter the uncertainty of all the measurements will be determined. The calculation of the uncertainty is split in two parts. First the external uncertainty (Type B) of all the equipment will be determined. After this the statistical uncertainty (Type A) will be calculated for each measurement. The type A uncertainty and type B uncertainty combined are the total uncertainty to complete the uncertainty budget for that characterisation.

## External uncertainties

 External uncertainties are the uncertainties that are caused by the instrument itself. For example, when measuring the pressure with the barometer, there is an uncertainty caused by the resolution of the barometer. This uncertainty is the same for each measurement with that barometer. All of the instruments used for the measurements are calibrated by VSL and have all their external uncertainties calculated and documented. In table 2 all the external uncertainties of the various instruments, physical constants and measured quantities are displayed.

Table 2: The external uncertainties of the used instruments or physical constants.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| symbol | description | estimate *xi* | standard uncertainty *u*(xi) | probability distribution  | sensitivity coefficient *Ci* | Uncertainty contribution *U*i % |
| Measurement distance |
| *r* | distance | 0,01 mm | 0,01 | normal | 2 | 0,02 |
| Pressure |
| *p* | calibration | 0,002 kPa | 0,002 | normal | 0,0098 | 0,002 |
| *p* | reading  | 0,001 kPa | 0,007 | rectangular | 0,0098 | 0,001 |
| *p* | drift | 0,0115 kPa | 0,007 | rectangular | 0,0098 | 0,006 |
| Temperature |
| *T* | calibration | 0,0065 °C | 0,007 | normal | 0,0034 | 0,002 |
| *T* | reading | 0 °C | 0 | rectangular | 0,0034 | 0 |
| *T* | drift | 0,01 °C | 0,029 | rectangular | 0,0034 | 0,01 |
| Decay |
| *t* | time | 15,6 ms | 0,013 | rectangular | 1 | 0,005 |
| *λ* | decay constant | 0,09% | 0,005 | rectangular | 1 | 0,05 |
| Electrometer |
| *Q* | calibration  | 0,05% | 0,05 | normal | 1 | 0,05 |
| *Q* | reading  | 0,00% | 0 | rectangular | 1 | 0 |
| *Q* | drift | 0,10% | 0,058 | rectangular | 1 | 0,058 |

## Total uncertainty for the axial rotation dependence measurements

For each of the measurements of the axial angle the relative standard deviation of the readings was calculated. The highest relative standard deviation for a reading in air was 0,139 %. This will be used as the type A uncertainty of the axial dependence in air. The total uncertainty of type B for the axial angle measurement is 0,0945%. Together they add up for a total uncertainty of 0,168%. For the deviation of the reference angle, all measurements werenormalized to the measurement of the reference angle. This results in a total uncertainty of 0,238%. The type B uncertainty for the measurement in water is slightly higher because of the uncertainty of the thickness of the layer of water. Due to human error it is estimated that the uncertainty of the axial angle of the detector is 1 degree.

Table 3: Uncertainty budget of the measurement of the axial angle dependence of the detector in air.

Table 4: Uncertainty budget of the measurement of the axial angle dependence of the detector in water.

|  |
| --- |
| uncertainty of charge measurement in air |
| type A | 0,14% |
| type B | 0,09% |
| combined uncertainty | 0,17% |
| uncertainty of deviation from reference angle |
| total uncertainty reference angle | 0,17% |
| total uncertainty angle | 0,17% |
| combined uncertainty | 0,24% |

|  |
| --- |
| uncertainty of charge measurement in water |
| type A | 0,14% |
| type B | 0,01% |
| combined uncertainty | 0,17% |
| uncertainty of deviation from reference angle |
| total uncertainty reference angle | 0,17% |
| total uncertainty angle | 0,17% |
| combined uncertainty | 0,24% |

## Total uncertainty for the radial angle measurements

The uncertainty of the measurement for the radial angle dependence was calculated the same way as the uncertainty of the measurement of the axial angle dependence. The results are displayed in table 3 and table 4. Due to human error it is estimated that the uncertainty of the radial angle is 1 degree.

Table 5: Uncertainty budget of the measurement of the radial angle dependence of the detector in air.

Table 6: Uncertainty budget of the measurement of the axial angle dependence of the detector in water.

|  |
| --- |
| uncertainty of charge measurement in air |
| type A | 0,19% |
| type B | 0,09% |
| combined uncertainty | 0,21% |
| uncertainty of deviation from reference angle |
| total uncertainty reference angle | 0,21% |
| total uncertainty angle | 0,21% |
| combined uncertainty | 0,30% |

|  |
| --- |
| uncertainty of charge measurement in water |
| type A | 0,14% |
| type B | 0,01% |
| combined uncertainty | 0,17% |
| uncertainty of deviation from reference angle |
| total uncertainty reference angle | 0,17% |
| total uncertainty angle | 0,17% |
| combined uncertainty | 0,24% |

## Total uncertainty of the energy dependence measurements

According to calibrations done by VSL the total type B uncertainty of the ratio of the detector and monitor of the x-ray tube is 1%. By calculating the relative standard deviation of the readings of the energy dependence measurement the Type A uncertainty was calculated. The total uncertainty is displayed in table 7. The uncertainty of the mean energy of the photons is estimated to be 1 keV.

Table 7: total uncertainty of the measurements of the energy dependence of the detector.

|  |
| --- |
| uncertainty of response |
| type A | 0,21% |
| type B | 1,00% |
| combined uncertainty | 1,02% |

## Total uncertainty of the temperature dependence measurements

For the characterisation of the temperature dependence the response of the detector has been measured as a function of temperature. The uncertainty of the response variation with temperature of the detector is the uncertainty of the charge collected by the electrometer. The uncertainty in the dose rate is caused by the fact that the dose rate was measured with the absolute standard of VSL and this measurement had an uncertainty of 0,002% The uncertainties for the measurements of the temperature dependence of the detector are displayed in table 8.

Table 8: Uncertainty budget of the measurements of the temperature dependence of the detector

|  |
| --- |
| uncertainty of measured charge |
| type A | 0,13% |
| type B | 0,01% |
| combined | 0,16% |
| measured dose |
| uncertainty dose rate | 0,00% |
| uncertainty decay | 0,05% |
| combined uncertainty | 0,05% |
| uncertainty of response |
| uncertainty measured charge | 0,16% |
| uncertainty of calculated dose | 0,05% |
| combined uncertainty | 0,17% |

## Total uncertainty of the long-term stability measurements

The uncertainty of the response of the detector for the long-term stability is calculated in the same way as the response of the detector for the temperature dependence. The results are displayed in table 9.

Table 9: Uncertainty budget of the measurements of the long-term stability of the detector.

|  |
| --- |
| uncertainty of measured charge |
| type A | 0,09% |
| type B | 0,01% |
| combined | 0,13% |
| uncertainty of measured dose |
| uncertainty dose rate | 0,00% |
| uncertainty decay | 0,05% |
| combined | 0,05% |
| uncertainty of response of stability measurement |
| uncertainty measured charge | 0,13% |
| uncertainty of calculated dose | 0,05% |
| combined uncertainty | 0,14% |

## Total uncertainty of the pre-irradiation dose measurements

The uncertainty of the pre-irradiation dose is calculated in the same way as the dose of the temperature dependence measurement. The results are displayed in table 10.

Table 10: Uncertainty budget of the measurements of the pre-irradiation of the detector.

|  |
| --- |
| uncertainty of measured dose |
| uncertainty dose rate | 0,00% |
| uncertainty decay | 0,05% |
| combined uncertainty | 0,05% |

# Results

In this chapter all the results of the characterisations will be discussed.

## Results for the direction dependence of the detector

### Radial dependence

The results of the measurement of the radial direction dependence are shown in fig. 7. The data is normalised to the measured current at an angle of zero degrees. It is clear that the detector has a large dependence on the radial angle. When the detector is turned 90 degrees from the starting position the response of the detector increases by a factor of 1,31 with an uncertainty of 0,24%.

*Fig. 7: Graph of the results of the dependence of the radial angle of the detector. On the x-axis the radial angle and on the y-axis the ratio of the response of the detector at the reference angle and the measured angle.*

In fig. 8 the results of measurement of the dependence of the radial angle in water are shown. As can be seen the results are a lot different from the measured in air. The deviation from the 0 degrees response has greatly gone down, from a maximum ratio of 1,31 to a maximum ratio of 1,045 with an uncertainty of 0,24%. Besides this the graph also shows that response of the detector is asymmetric. Although both sides show that when the detector is turned 15 degrees towards the either side the response lowers but after that the results deviate. Towards the -90 degrees angle the response of the detector climbs steadily while towards the 90 degrees angle the response seems to climb more exponential.

The results do prove that the large deviation from the 0 degrees response for the radial angle measurement in air is due to the build-up in the detector. It is therefore recommended to not use the detector in air.

*Fig. 8: Graph of the results of the dependence of the radial angle of the detector when submerged in water. On the x-axis the radial angle and on the y-axis the ratio of the response of the detector at the reference angle and the measured angle.*

It is expected that the reason for this, is that the build-up inside the detector is larger when the detector is tilted horizontally. Because this measurement was in air there is not much build-up before the radiation reaches the detector. In the technical manual of the detector it is not shown that the detector has such a large dependence on radial angle. This is possibly because the detector is meant to be used in water or anthropomorphic phantoms.

### Direction dependence and leakage

Another thing that was noticed while measuring the dependence of the radial angle was the large relative standard deviation of the readings of each measurement. This was especially when the radial angle was small. In fig.9 the separate readings of the measurements at 0 degrees radial angle is shown.

*Fig. 9: Graph of the reading of the measurement with the detector at a radial angle of 0 °. On the x-axis the time passed since radiation and on the y-axis the amount of current measured.*

As can be seen in the graph of fig. 9 there are two readings that significantly deviate from the rest of the readings. These are the first reading and the sixth reading. Both of these are the readings directly after the leakage readings. This deviation decreases gradually as the radial angle increases. Fig. 10 shows the graph of the readings of the measurements at a 90 degrees radial angle. It can be seen that the first and sixth reading don’t deviate anymore as in the 0 degrees measurement.

*Fig. 10: Graph of the reading of the measurement with the detector at a radial angle of 90 °. On the x-axis the time passed since radiation and on the y-axis the amount of current measured.*

To visualize this effect more clearly, the relative standard deviation of each of the measurements has been calculated with and without the first measurement after the leak measurement. Then the relative standard deviation of the readings including the reading after the leak measurement and relative standard deviation excluding the reading after the leak measurement were subtracted of each other and the result was the graph in fig 11.

*Fig. 11: Graph of the difference in relative standard deviation between the measurement including the reading after the leak reading and excluding the reading after the leak reading.*

The graph in fig. 11 clearly shows that the difference in relative standard deviation gradually goes down as the radial angle increases. There is no reference at all in the technical manual that an effect like this can occur. The same effect occurs for the measurements in water but here the difference in standard deviation is slightly smaller. The results are seen in fig 12.

Fig. 12: Graph showing the difference in relative standard deviation between the measurements of the radial angle with and without the reading after the leak measurement. On the x-axis the angle of the radial angle and on y-axis the relative standard deviation subtracted.

It is interesting to see that in both graphs the difference in relative standard deviation is not at its largest at the 0 degrees point while the form of the does suggest that.

### Axial dependence

The results for the measurement of the dependence of the axial angle of the detector are shown in fig. 13.

*Fig. 13: Graph of the results of the dependence of the axial angle of the detector. On the x-axis the axial angle and on the y-axis the ratio of the response of the detector.*

The 0 degrees point is seen as the base point and the rest of the graph shows how the response of the detector deviates from the 0 degrees point. It was noticed that the deviation was a lot smaller for the axial angle comparing to the radial angle. The maximum deviation of the response occurred at an angle of 135 degrees and was a 1,4% deviation. For metrology standards this is still quite high. It was suspected that this deviation was caused by the difference in build-up under certain angles. For this reason the same measurements have been performed in a water phantom. The results are displayed in fig. 14.

*Fig. 14: Graph of the results of the dependence of the axial angle of the detector when submerged in water. On the x-axis the axial angle and on the y-axis the ratio of the response of the detector.*

The results of the axial angle measurement in water are similar to the ones in air. The maximum deviation from the 0 degrees response is 0,5% smaller. From this can be concluded that at certain angles there is less build-up in the detector which causes the response to be smaller. The reason for the difference in build-up can is that the thickness of the PMMA around the diamond part of the detector is not exactly the same.

## Results of the energy dependence of the detector

With the detector the amount of radiation has been measured when placing it the detector in the bundle with mean photon energy of 51 keV, 69 keV, 86 keV and 126 keV radiation. The signal coming from the detector in current has been converted to charge and with the dose rate of the source the amount of Gray per nC has been calculated. The results are shown in Fig 15.

*Fig. 15: Graph of the results of the energy dependence of the detector. On the x-axis the energy of the radiation particles and on the y-axis the calculated amount of Gray per Coulomb.*

It was expected that the amount of Gray radiation needed to produce 1 nC of charge would increase as the energy of the particles went down. The theory behind this was discussed in paragraph 4.2. For the 51 keV, 69 keV and the 126 keV measurement the amount of Gy/nC does indeed goes down as the energy of the particles increase. The 86 keV measurement breaks this pattern by needing nearly 7% less Gy per nC than when the energy of the particles is 126 keV. Although there are no signs that the 86 keV measurement was inaccurate, because it falls out it is recommended that it is measured again.

For the Co-60 source the amount of Gy/nC was also calculated. The particles coming from the Co-60 source have an average energy of 1,15 MeV. Much higher than the particles coming from the X-ray tube. The result was 0,96 Gy/nC, showing that the detector, detects less radiation when the energy of the particles is higher. One possible explanation for this can be that the measurement of the Co-60 source was done with a different type of electrometer and capacitor. Although it is unlikely that that would cause such a large difference. The maximum deviation from the average response of the detector is 14%.

## Results of the temperature dependence of the detector

The temperature dependence of the detector was measured by placing the detector in a phantom of water and varying the temperature of this water. The results of the measurements are shown in Fig. 16.

*Fig. 16: Graph of the results of the temperature dependence of the detector. On the x-axis the temperature of the water the detector was placed in and on the y-axis the calculated response of the detector in nC/Gy.*

According to the theory explained in paragraph 4.3 there should be little to no dependence of temperature. The results of the measurement show that there is indeed temperature dependence. As the temperature of the water goes down to 11°C the response of the detector went down by 2,6% and at 30 °C the response of the detector went down by 2,2 %. What caused this temperature dependence is not clear. One reason could be that the water that was used for 30 °C water was not demi-water.

## Results of the long-term stability of the detector

The stability was measured four times since the beginning of the internship. The results are displayed in table 11. As can be seen the amount of Gray needed to generate 1 nC charge varies slightly. The stability measurement performed on the 4th of March differs most from the rest. It is possible that because the detector hadn’t been used much up to that time it didn’t fully stabilize yet. The third column shows the deviation in percentages from the average of the four stability measurements. According to the technical manual the long-term stability of the detector should be less than ±0,5% per year. The stability measurements during this internship were over a period of time of almost three months. To investigate the long-term stability more thoroughly it is recommended a stability measurement is performed every month.

Table 11: the results of the long-term stability measurements.

|  |  |  |
| --- | --- | --- |
| date | Gy/nC±  | deviation (%) |
| 4-3-2014 | 0,999 | -1,0% |
| 9-4-2014 | 0,987 | 0,3% |
| 30-4-2014 | 0,986 | 0,4% |
| 28-5-2014 | 0,987 | 0,3% |

## Results of the pre-irradiation of the detector

For the results of the pre-irradiation one graph of the measurements is displayed in fig. 17 to show what the result looks like.

*Fig. 17: The result of a pre-irradiation measurement, each dot is a reading. On the x-as is the amount of time passed since the start of the measurement and on the u-axis is the current measured.*

From fig. 17 can be seen that the amount of current measured drops very quickly in the beginning and then gradually keeps getting smaller. From the spike in the beginning it can be noted that pre-irradiation is very important, if a normal measurement would be done the first few measurements would give a much higher reading than it should.

To find out if the amount of pre-irradiation needed has connection to the amount of the time the detector had not been radiated the duration of inactivity has been varied. The results are shown in table 12. It is clear that when the detector has been inactive for a period of 4 days or longer the amount of pre-irradiation needed is about 25 Gray.

*Table 12: results of the pre-irradiation measurements and the calculated amount of Gray needed to pre-irradiate the detector.*

|  |  |  |  |
| --- | --- | --- | --- |
| date pre-irradiation | date of last measurement | days in between | amount of gray needed±0,05%  |
| 21-3-2014 9:33 | 19-3-2014 16:44 | 1,7 | 14,1 |
| 25-3-2014 9:53 | 21-3-2014 11:17 | 3,9 | 25,4 |
| 15-4-2014 9:23 | 10-4-2014 16:32 | 4,7 | 23,8 |
| 22-4-2014 7:53 | 15-4-2014 11:17 | 6,9 | 26,5 |
| 28-5-2014 11:44 | 20-5-2014 17:33 | 7,8 | 27,6 |
| 9-4-2014 11:33 | 28-3-2014 15:19 | 11,8 | 23,9 |
| 19-3-2014 11:58 | 4-3-2014 17:56 | 14,8 | 24,9 |

From table 4 it appears that as long as the detector has been inactive for more than two days the amount of Gray required to pre-irradiate the detector is around 25 Gray. To be sure of a good measurement it is recommended that the detector is pre-irradiated for 30 Gray.

# Conclusions

Characterisation of radial angle dependence showed that the maximum response variation of the detector when measuring in air was 1,31 with an uncertainty of 0,24%. In water the maximum response variation of the detector was 1,04 with an uncertainty of 0,24%. This deviation is mostly caused by the difference in build-up inside the detector when the detector is irradiated from different directions. The technical manual states a maximum variation in response of 5%

The axial angle showed a maximum response variation of 1,014 with an uncertainty of 0,24% when measuring in air. In water the response of the detector showed a maximum variation in response of 1,01 with an uncertainty of 0,24%. In the technical manual there is no specification of the response variation for the axial angle of the detector.

Characterisation of the energy dependence of the detected showed that over the range of 51 keV to 1,25 MeV the response of the detector deviated a maximum of 14%. According to the technical manual the maximum deviation should be only ±8%. A possible explanation for the larger deviation in response is that the for the 1,25 MeV measurement a different measurement setup was used.

For the characterisation of the temperature dependence of the detector, the response of the detector was measured with the detector submerged in water of 10 °C, 20 °C and 30°C. 20 °C was taken as the reference point. The response at 10 °C has a variation of 1,026 with an uncertainty of 0,17 % while the response at 30 °C has a variation of 1,022 with an uncertainty of 0,17 %. These variations of temperature are quite extreme and in practice the temperature of the environment will most likely not vary more than one to two °C. Therefore it can be concluded that temperature dependence is small enough for it to be used in VMAT treatments.

The long-term stability measurements showed a maximum deviation of average response of the detector of 1%. This maximum deviation occurred at the first stability measurement and it can be that this one deviates more than the others because the detector wasn’t fully stabilized yet since it was just new. It is recommended to perform a stability measurement each month so the long-term stability can be determined more accurately.

The pre-irradiation dose of the detector was successfully determined. When the detector has not been used for two or more days it is recommended to pre-irradiate the detector with 30 Gray to have a stable signal. This is a lot more than the technical manual states, which is 5 Gray. It is unknown when the manufacturer considers the response of the detector to be stable and therefore these two values cannot be compared accurately.

The final conclusion is that the detector can be used for the VMAT treatments but only if the detector is surrounded by a medium that causes sufficient amount of build-up.

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# Appendix

Original internship assignment

### Karakterisatie diamant detector

In de radiotherapie worden patiënten bestraald met steeds geavanceerdere bestralingsapparatuur. Deze apparatuur biedt meer geavanceerde mogelijkheden om de stralingsdosis zoveel mogelijk in de tumor af te geven en zo weinig mogelijk daarbuiten. Verificatie van de afgegeven dosis in de patiënt is in de meeste gevallen niet mogelijk en dient daarom plaats te vinden in antropomorfe fantomen. VSL werkt aan het meten van absolute dosis verdelingen in een antropomorf fantoom met behulp van radiochromic film. Een manier om de gemeten dosis verdeling absoluut te maken is met behulp van een gekalibreerde detector die de dosis in een punt absoluut kan meten. Recentelijk is hiervoor een nieuw type diamant detector aan geschaft. Het doel van deze stage opdracht is deze detector te karakteriseren zodat alle dosimetrische aspecten die een rol spelen bij het bepalen van absolute dosis in een antropomorf fantoom bekend zijn. Als tweede stap kunnen deze karakterisatie metingen gebruikt worden om een correctiefactor te bepalen of een onzekerheid in te schatten.

* Stabiliteit
* Energie afhankelijkheid
* Temperatuursafhankelijkheid
* Richtingsafhankelijkheid
* Dosis tempo afhankelijkheid
* Lekstroom van de detector

Verder dienen er tools ontwikkeld te worden om de detector te kunnen kalibreren tegen de primaire standaard en om de detector in het antropomorf fantoom te gebruiken.