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Reproducibility of Optically Stimulated Luminescence Dosimeters
in Mixed Radiation Fields

by

Connor Harper

A thesis
submitted in partial fulfillment
of the requirements for the degree of
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To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Connor Harper find it satisfactory and recommend that it be accepted.

Dr. Tony Forest,
Major Advisor

Dr. Dan Dale,
Committee Member

Dr. Mikle Ellis,
Graduate Faculty Representative

To My Father

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I would like to thank Dr. Forest for his mentorship and guidance throughout my graduate education. I would like to thank Dr. McNulty for providing the experimental beam time used to gather the data within this thesis. The last person I would like to thank is my friend and colleague, Jeff Burggraf, for help throughout my education at Idaho State University.

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Reproducibility of Optically Stimulated Luminescence Dosimeters in Mixed Radiation Fields

Thesis Abstract—Idaho State University (2018)

NanoDot^{tm} Optically Stimulated Luminescence dosimeters (OSLs) are used at the Idaho Accelerator Center (IAC) to measure radiation dose. An expected dose for an experimental setup is established by simulating the experimental apparatus and the OSLs. After calibrating the OSLs using a known radiation source, they were used to measure the dose from an accelerator based radiation source. The OSLs ability to reproduce the dose from the accelerator's radiation was measured. Irradiating the OSLs in a bremsstrahlung photon field indicates that the OSLs are reproducible to 4.87% over a large range of dose.

Key Words: OSLs, IAC

Chapter 1

Introduction

Optically Stimulated Luminescence Dosimeters (OSLs) are used at the Idaho Accelerator Center (IAC) in Pocatello, Idaho to measure radiation dose. Dose measurements began with the Dot^{tm} OSLs, but issues with reproducibility led to the use of the newer nanoDot^{tm} OSLs. These OSLs were calibrated using calculated exposures from a ^{137}Cs source because there were questions about just how reproducible and responsive the OSLs are to ionizing radiation. Once the exposure is quantified in terms of dose, the relationship between actual dose and the OSL's measurement can be established by fitting a line to the measured data points. The purpose of this thesis is to determine how reproducible dose measurements are when using optically stimulated luminescence dosimeters in a mixed radiation field of photons and electrons.

Chapter 2

Theory

2.1 Optically Stimulated Luminescence

Optically stimulated luminescence describes the emission of light from the recombination of electrons (holes) with free holes (electrons) in the conduction (valence) band. Incident ionizing radiation creates electron-hole pairs. As the hole or electron moves across the band gap, they can become trapped in imperfections in the crystal lattice. Photons, from a green light emitting diode are used to free trapped electrons (holes) by moving them to the conduction (valence) band such that they recombine with trapped holes (electrons)[4]. The recombining process results in the emission of blue light that escapes the crystal and is counted by a photomultiplier tube.

2.2 Optically Stimulated Luminescence Dosimeters

NanoDot^{tm} OSLs are a carbon-doped aluminum oxide crystals, small enough to be irradiated in a multitude of experimental settings and is reusable when annealed. The average crystal diameter measured using a sample of the detectors is 0.501 $\pm$ 0.007 cm with a thickness of 0.03 $\pm$ 0.001 cm. These dimensions yield an average volume of 5.89 x 10^{-3} $\pm$ 1.9 x 10^{-4} cm^3. This crystal is contained within a (1.01 $\pm$ 0.001 cm) x (1 $\pm$ 0.002 cm) x (0.196 $\pm$ 0.002 cm) ABS plastic square to prevent it from annealing in daylight, as seen in Figure 2.1.

Use of the OSLs can involve irradiating a single OSL or an array of OSLs varying in size, shape, and number of detectors. The spatial location of each OSL is logged by associating the unique serial number from each detector with its coordinates in the array's plane perpendicular to the incident beam. Having the position of each OSL logged during experiments yields a measurement of the incident radiation field intensity as a function of position.

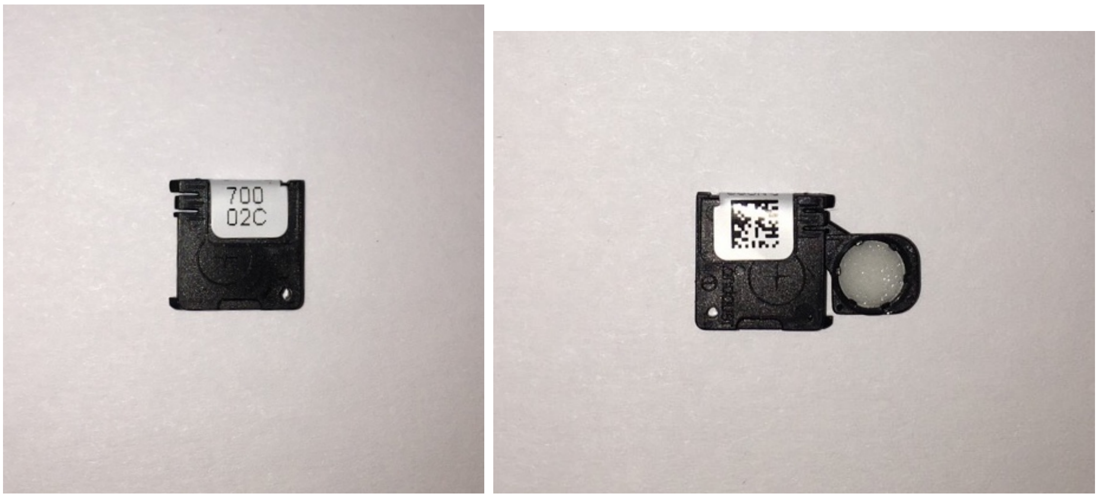

Figure 2.1: (Left) Front of a nanoDot$^{\text{tm}}$ OSL with serial number. (Right) Back of a nanoDot$^{\text{tm}}$ OSL with exposed crystal.

Ionizing radiation deposits energy into the crystalline structure of the OSL through the mechanisms described in section 2.1. One source of this radiation is the 25B Linac at the Idaho Accelerator Center (IAC). Electrons are fired from this accelerator and hit an aluminum converter to produce a bremsstrahlung photon beam. Following the converter is a sweeping magnet to redirect any charged particles away from the OSL array. Photons then ionize the crystal structure through pair production, Compton scattering, and the photoelectric effect, with the photoelectric effect being the lead contributor. If the bending magnet is removed, then irradiating with an electron beam becomes a mixed field due to the production of photons from the electrons traveling through and interacting with the air. The incident electrons deposit energy through ionization of the lattice structure.

The OSLs are then annealed in order to be reused. A visible spectrum light source is used to anneal the OSLs following each use to clear the dose from a previous irradiation. To clear the OSLs, the crystal is exposed, as in Figure 2.1, and then placed on the face of the light source. The photons produced by the light source interact with the trapped electrons and holes enabling them to recombine and emit a photon[4].

The annealing process releases the energy stored in the crystal therefore reducing the measured dose from any previous irradiation to background levels. The background OSL photomultiplier tube (PMT) counts are measured once the clearing is complete to make sure the clearing was successful as well as measure the background counts. Once irradiated, the PMT counts are measured again, giving the total PMT counts. The direct change in PMT counts is now readily available once the background measurement is subtracted from the post-irradiation PMT counts. This quantity is referred to as background subtracted PMT counts. The internal structure of the OSL reader can be found in Appendix A.

2.3 Energy Deposition Simulations

To begin the process of simulating a pulse of electrons from the 25B Linac at the IAC, the number of electrons per pulse must be found. Using a 50 mA peak current and a pulse width of $500 \frac{ns}{pulse}$, the number of electrons per pulse is found to be $1.6 * 10^{11} \frac{e^-}{pulse}$. In order to save computation time, the number of electrons simulated is scaled down by five orders of magnitude to $1.6 * 10^{6} \frac{e^-}{pulse}$. The beam is incident upon a titanium beam pipe window and begins to diverge as it enters 50 cm of air, before hitting the OSL crystal. The incident electron beam loses energy traversing the air and other materials between the accelerator exit window and the crystal.

The energy lost by the electrons due to its interaction with materials, aluminum and air, is accounted for. The total energy deposition is then scaled up by five orders of magnitude to account for only simulating a fraction of a single pulse of the linac. Finding the simulated dose per pulse is accomplished by dividing the deposited energy by the mass of the OSL crystal. This gave the dose in units of Gray; which were then converted directly to Rad (1 Gy = 100 Rad) to be used in comparison to measured results.

GEANT4 is used to simulate the interaction of ionizing radiation with the OSLs to mimic the experimental setup and to discern a baseline expected dose per pulse for the 25B Linac at the IAC. It is important to understand the divergence of the incident electron beam, because larger divergence leads to lower electron flux through the OSL crystal. Glass slides were irradiated before the experimental run at 50 cm and 100 cm from the end of the beam pipe separately to find the beam divergence as a function of distance. The standard deviation in the beam spot was found by using a scan of each glass slide and then using ROOT's TASImage function to create histograms which were then converted from pixels to centimeters in the X and Y dimensions, as seen in Figure 2.2. Using these two images, the divergence is calculated by assuming a linear increase between the standard deviations of the images. It is then possible to extrapolate back to the end of the beam pipe and infer the spot size as the beam enters the air once the standard deviation ratio in beam intensity is found. The ratio of the 50 cm to 100 cm standard deviation is 0.572. The characteristics of the beam divergence are included in the GEANT4 macro in appendix B.

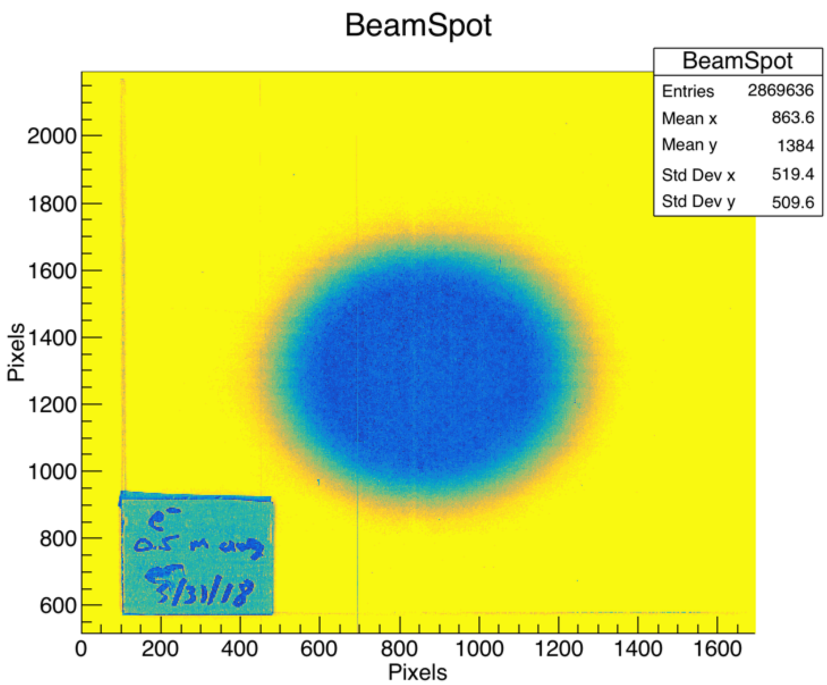

Figure 2.2: Processed image of irradiated glass slide at 50 cm before beam retune. X axis: 266 $\frac{Pixels}{cm}$ Y axis: 270.83 $\frac{Pixels}{cm}$

Due to a systematic failure of a gate valve in the accelerator, the beam had to be retuned after the initial images were created, and a third glass plate was then irradiated at 50 cm from the end of the beam pipe for the retuned beam. The beam used to irradiate the OSLs had a standard deviation of 1.585 cm, inferred from the hot spot of the glass plate irradiated at 50 cm. Assuming similar divergence characteristics, the spread was scaled using the same scaling factor of 0.572. Using this information to extrapolate back to the end of the beam pipe, the beam had a calculated sigma of 0.908 cm. Another important quantity is the angular sigma. With both of the sigmas and the distance of 50 cm between them, the opening angle of the divergent beam is calculated through the inverse tangent and similar triangles. This value was calculated at 0.776 degrees. The simulation was performed using the sigma of 0.908 cm, angle of 0.776 degrees, and assuming a gaussian beam distribution in both position and angle. The beam divergence assumed is shown in Figure 2.3.

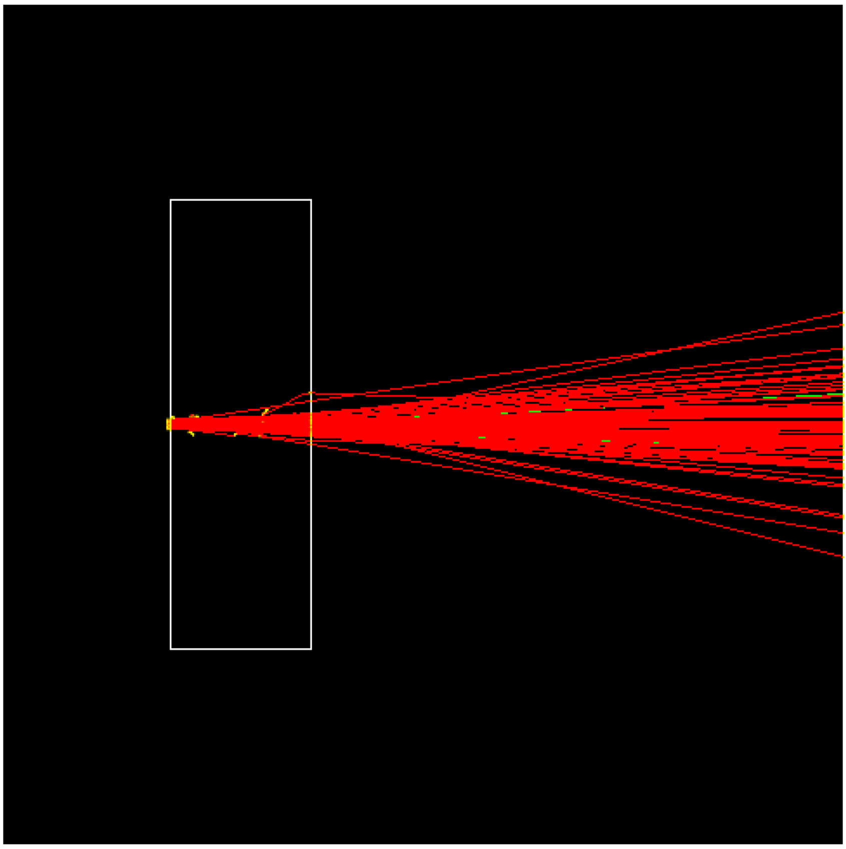

Figure 2.3: 8 MeV electron beam propagating through 50 cm of air to show beam divergence.

The total deposited energy found in the GEANT4 simulation was 2,696.2 MeV.

As the number of particles simulated was scaled down by five orders of magnitude, the deposited energy was scaled up by the same factor. The simulated dose is found by dividing the scaled deposited energy by the mass of the OSL crystal.

$$\text{Deposited energy per pulse} = (2696.2) \text{ x } 10^5\text{MeV} = 4.320 \text{ x } 10^{-5}\text{J}$$

$$\frac{4.320 \text{ x } 10^{-5} \frac{\text{J}}{\text{pulse}}}{2.35 \text{ x } 10^{-5} \text{ Kg}} = 1.84 \; \frac{\text{Gy}}{\text{pulse}} = 184 \; \frac{\text{Rad}}{\text{pulse}}$$

Chapter 3

Experimental Apparatus

NanoDot^{tm} OSL performance was determined by first calibrating the detectors with a known radiation source of photons, then they were exposed to a bremsstrahlung photon field, and thirdly, a mixed electron and photon field created by the 25B linear accelerator. A radioactive source of ^{137}Cs with a known activity of 9.3 Ci was used to irradiate the OSLs for calibration. A description of this source is given below in section 3.1. After a reproducible calibration is found, the OSLs are exposed to a radiation field of only bremsstrahlung photons using electrons accelerated by the linac described in section 3.2. The accelerator exit port converter is removed, along with the bending magnet to irradiate the OSLs in a mixed field of electrons and photons. A description of both experimental setups is given below in sections 3.3.1 and 3.3.2.

3.1 ^{137}Cesium Source

A ^{137}Cs source with an activity of 9.3 Ci was used to calibrate the OSLs by measuring the relationship between the PMT counts measured using the OSL reader described in Appendix A, and the OSLs exposure to the Cs source. The ^{137}Cs source uses a system of interlocks to safely expose the OSLs to the source's radiation. The source is enclosed by a lead container, often called a "pig", as shown in Figure 3.1. There is an acrylic face plate bolted to the front of the pig at a set distance of 11.2 cm to absorb beta particles emitted by the source. Inside the pig is an air controlled shutter to shield the source while not in use. The OSLs are positioned 30 cm from the faceplate of the source. Once the interlock requirements have been satisfied, the air supply is turned on allowing the shutter to be opened.

Figure 3.1: Containment unit for the Cs-137 source.

The exposure rate from the source is determined based on the distance (D) from the source, the activity (A) of the source, and a gamma ray constant (Γ). The exposure rate for any given distance is calculated in units of Roentgen per hour using the equation

$$\dot{R} = \frac{\Gamma A}{D^2} \text{ [1]}$$

A gamma ray constant of $\Gamma = 0.33\frac{(m^2)(R)}{(Ci)(hr)}$ and activity $A = 9.3\ Ci$ provided by the Idaho State University Technical Safety Office is used in these calculations. The source activity quantifies the radiation emitted through a solid angle of 4π. The distance from the faceplate to the surface of the source needs to be taken into account because of the inverse squared distance dependence of the exposure rate. The total distance D is , D =

(distance to faceplate + 0.112m).

With the calculated exposure rate ($\dot{R}$) found in units of Roentgen per hr using these known values, it is possible to find the total exposure (R_{tot}) the OSLs are subjected to by integrating the exposure rate over the time the OSL was exposed to the source.

$$R_{tot} = \int_{t_0}^{t_f} \dot{R}\ dt$$

It is necessary when working with exposure to be able to convert from Roentgen to Rad (1.14554 Roentgen = 1 Rad) as exposure is calculated in Roentgen and dose is measured in Rad or Gy. The relationship between background subtracted PMT counts and dose is found by converting each calculated exposure from Roentgen to Rad and plotting it with the corresponding PMT counts measurement and fitting a line to the data.

3.2 25B Linac

The RF frequency of the IAC's S-Band 25B Linac is 2856 MHz with an energy range of 4 - 25 MeV. With peak currents being easily able to reach 100mA, and pulse widths from 50 ns to 4 μs, this accelerator is able to operate at the simulated parameters of 8 MeV, 500 ns pulse width, and 50 mA peak current. The 0° port of the accelerator is pictured in Figure 3.2.

Figure 3.2: 0° port leading to end of beam pipe.

3.3 Experimental Procedure

3.3.1 Photon Field

In order to expose the OSLs to a bremsstrahlung photon field, a one inch thick aluminum brick and 60 mT sweeper magnet were inserted at 50 cm from the end of the beam pipe, as shown in Figure 3.3. The aluminum brick was used as the converter, followed by the sweeper magnet to redirect any charged particles away from the resulting photon beam. An array of 17 OSLs was placed at a distance of one meter from the end of the beam pipe and then irradiated. An image of this array is located in Figure 3.4. This setup was irradiated twice with different arrays of OSLs to gather dose per pulse information for the photon beam. Each array was exposed to approximately 52000 pulses at a rep rate of 250Hz. The run plan can be found in Appendix C. Figure 3.5 shows a digital construction of the average OSL dose measurement of the two arrays.

To discern dose per pulse and reproducibility information from the measurements of the photon beam, the OSLs are subjected to the same beam characteristics throughout the custom run-plan. These characteristics consist of a beam energy of 8 MeV, pulse width of 500 ns, and a peak current of 50 mA.

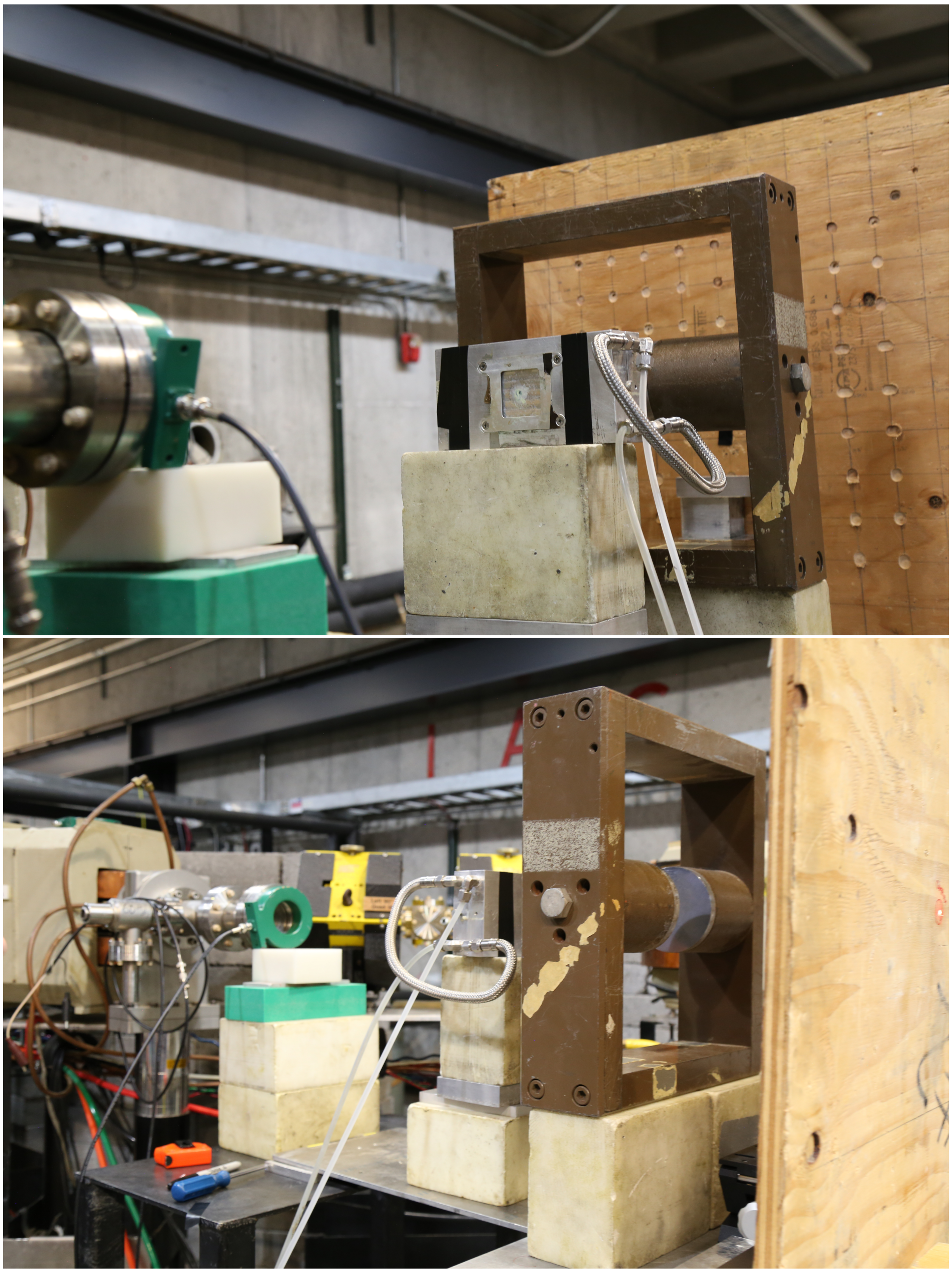

Figure 3.3: (Top) Looking in the direction of beam travel to see the front face of the aluminum brick. (Bottom) 10.16 cm diameter and 7.62 cm gap sweeping magnet used to change the direction of travel of all charged particles.

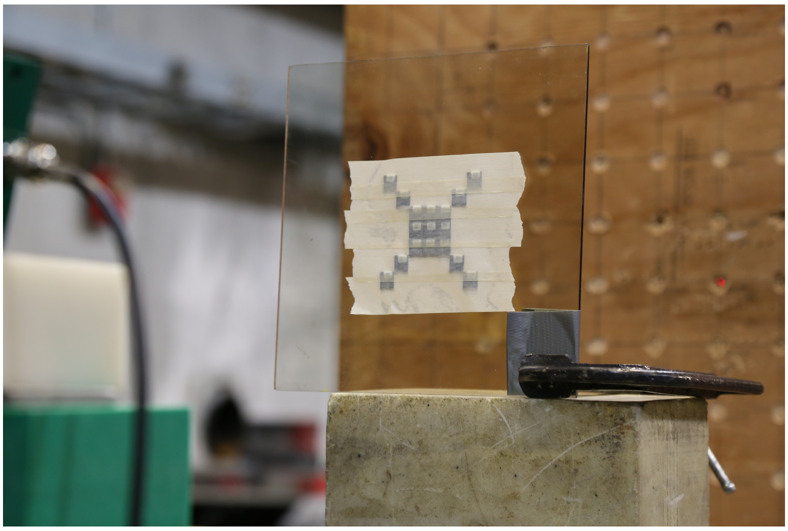

Figure 3.4: Array of 17 OSLs mounted for irradiation.

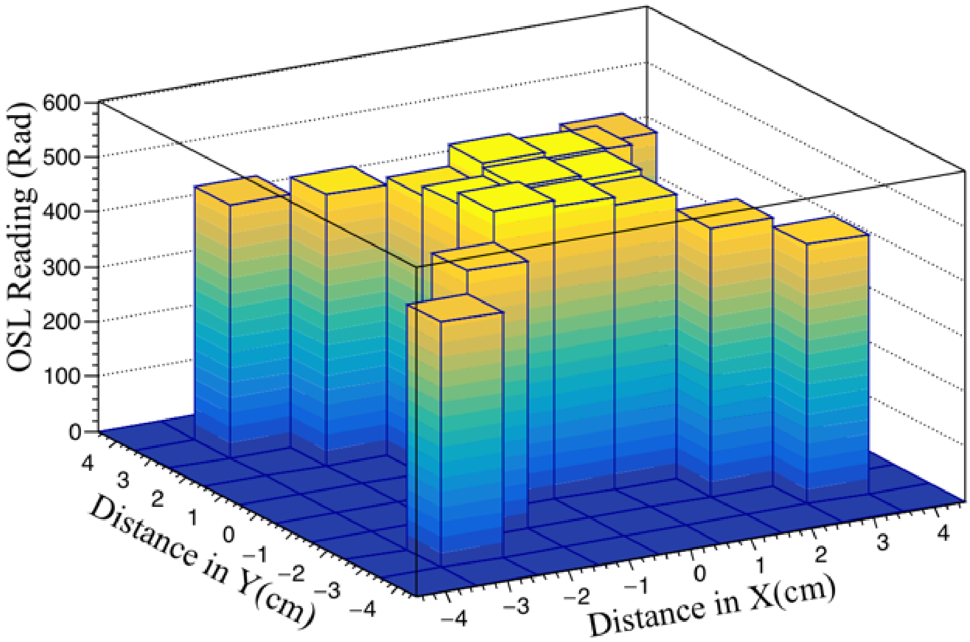

Figure 3.5: Average dose of the two arrays irradiated by the photon beam. Each square corresponds to the physical size and location of each OSL irradiated.

3.3.2 Mixed Field

Exposing OSLs to a mixed electron and photon beam is accomplished by placing an OSL at the 25B Linac zero degree exit port. There are photons present in the beam as electrons interact with the air between the end of the beam pipe and the OSLs. These photons are unable to be removed from the field without attenuating the electron beam. Using tape to secure an OSL to a glass plate at 50 cm from end of beam pipe, and a laser centered on the end of the beam pipe, the OSL can be exposed to electrons on the beam axis. This setup is used to gather dose per pulse information. Then, by varying the number of pulses which impinge upon the OSLs, a pulse versus dose relationship can be established.

Once single OSLs had been irradiated on-axis, a 4 x 4 array of 16 OSLs were inserted and exposed to the electron beam. As the 4 x 4 array did not allow for a symmetric orientation while having an OSL centered on-axis, the future arrays were modified to consist of 17 OSLs. Images of the two different array geometries can be seen in Figures 3.4 and 3.6. This modification created more data points for the on-axis dose per pulse measurements. The OSLs were measured before and after irradiation to see how much dose was deposited. The discrete profiling of the incident beam on the array of 17 OSLs is depicted in Figure 3.7.

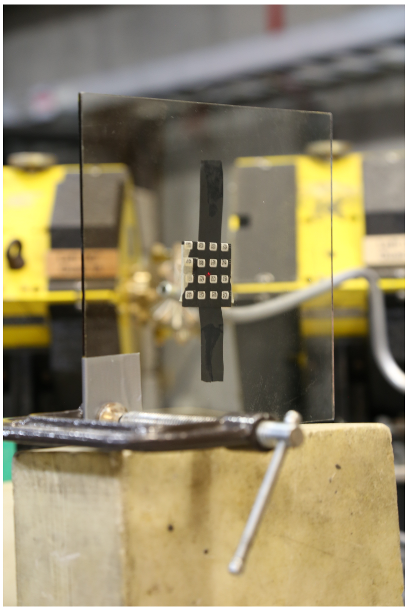

Figure 3.6: Array of 17 OSLs mounted for irradiation.

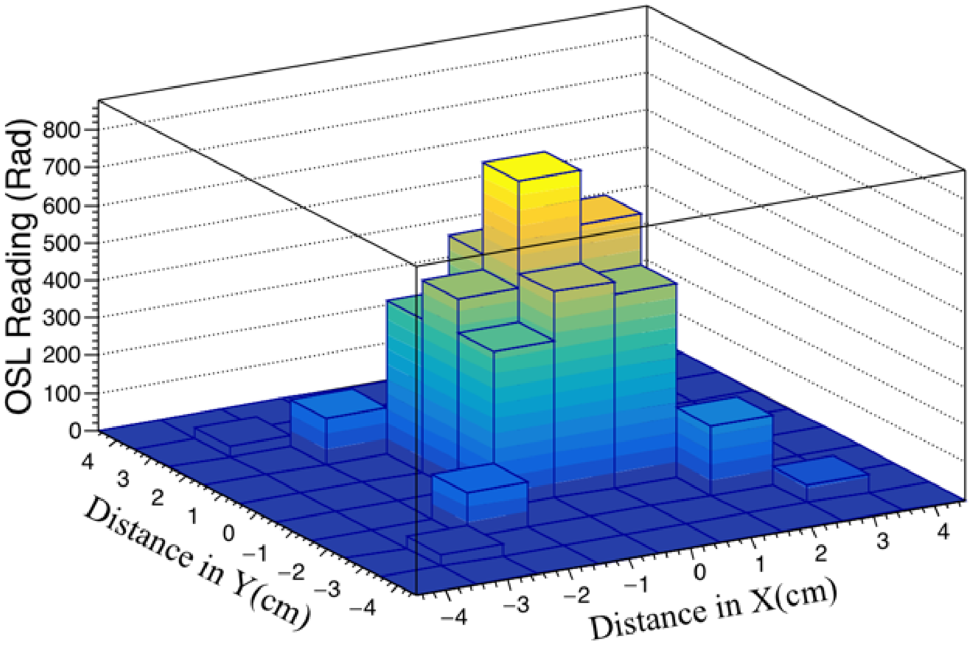

Figure 3.7: Calculated dose from the OSLs irradiated in the electron beam. Each square corresponds to the physical size and location of each OSL irradiated.

Chapter 4

Data Analysis

The relationship between PMT counts and calculated exposure was completed and then followed by the irradiation of the OSLs in the bremsstrahlung photon beam and mixed photon and electron field. The analysis of the PMT counts and exposure relationship is described in section 4.1. along with the equation of the fit with the calculated uncertainties. This is used to calculate all of the dose measurements for the irradiation with the 25B linac. After the dose measurement analysis in section 4.2, the uncertainties were calculated and propagated from the high dose calibration.

4.1 nanoDot^{tm} OSL Calibration

The response of the nanoDot^{tm} OSLs to electrons and photons can be quantified in terms of dose using a calibration. Initial attempts to calibrate the OSLs were to follow the manufacturers guidelines, through which two different calibrations are created; a low dose, and a high dose, seen in Figures 4.1 and 4.2 respectively. The low dose calibration is used by the OSL reader when the measured dose is less than 10 Rad, and the high dose is used for any values exceeding 10 Rad. These calibrations are created by reading in pre-dosed OSLs provided by Landauer so the OSL reader software can create a linear fit between PMT counts and dose. Using these calibrations assumes that the pre-dosed OSLs have not been subjected to any other exposure during the shipping and storing before use. It was this assumption that led to the creation of a custom calibration using a Cs-137 source. Using a source of known activity allows for calculated exposure rates to be related to background subtracted PMT counts with a quantifiable uncertainty in the dose on the OSL.

It is possible to eliminate the effect of unknown factors that could have altered the listed dose on the pre-dosed OSLs by subjecting a set of OSLs to a range of known total exposures. By using a calculated exposure and a well-known source to irradiate the OSLs, a linear relationship between the known exposure and background subtracted PMT counts can be established. A set of fifteen previously unexposed OSLs was chosen at random and exposed to the 9.3 Ci Cesium-137 source described in section 3.1 to begin calibrating the OSLs.

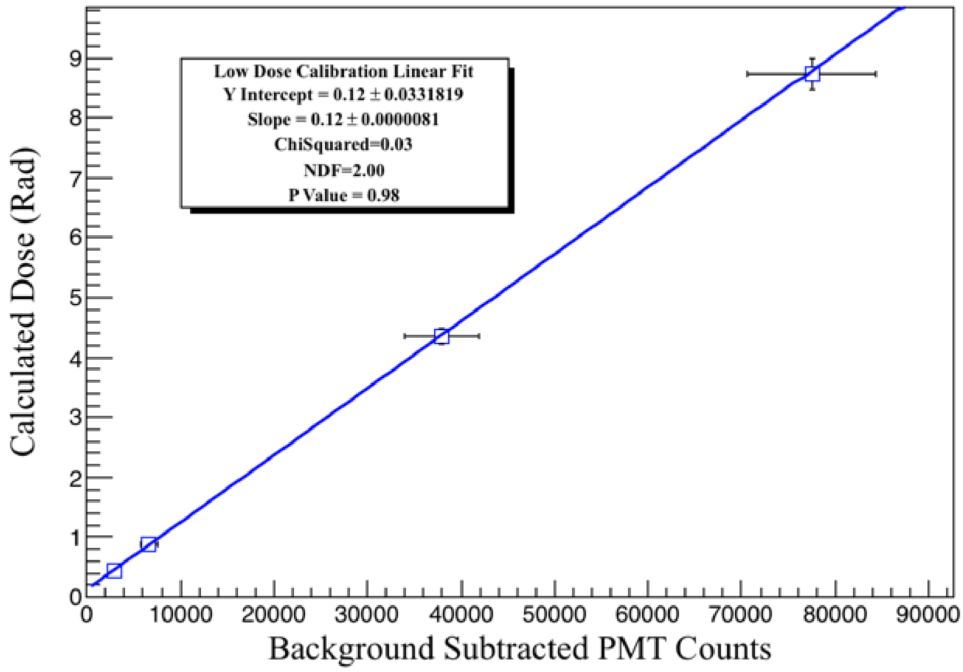

Figure 4.1: Low dose calibration.

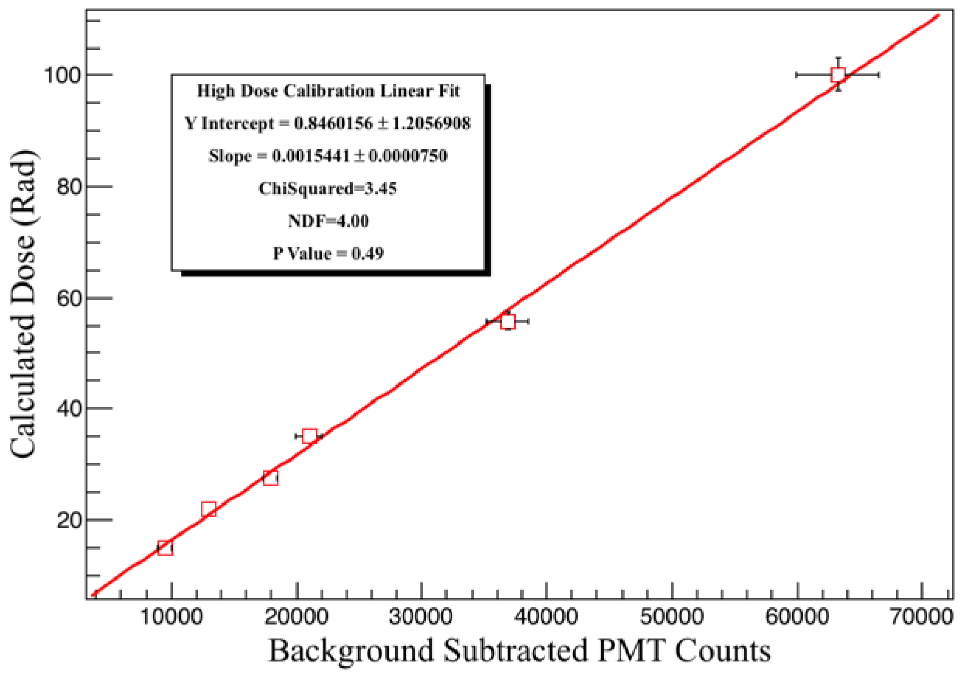

Figure 4.2: High dose calibration.

The 15 OSLs were exposed to the Cs-137 source for the same amount of time for each calculated exposure and then each was measured by the OSL reader. The PMT counts were recorded and a standard deviation was determined using:

$$\sigma = \sqrt{\frac{\Sigma(x_i - \bar{x})^2}{n - 1}}$$

Where x_i is each PMT measurement, $\bar{x}$ is the average of the PMT counts and n is the number of OSLs subjected to the same exposure. The standard deviation was used as the uncertainty in the PMT counts for the calibration. The original source certificate was unable to be located. All certificates for other known sources on hand stated a systematic uncertainty of 3%. This value was then used as the uncertainty in all calibration exposure calculations using the Cs source.

With the standard deviations in the PMT counts calculated, the relative error for each calculated exposure can be calculated. It was found that the relative error of the PMT counts varied between 3% and 5.3%. The relative percent error is found by

$$Rel.Err. = \frac{\sigma_{PMT}}{PMT\ Average} * 100\%$$

4.2 Experimental Data

4.2.1 Photon Field

The expected dose from a bremsstrahlung photon field 100 cm from the end of the beam pipe was expected to be less than that of a mixed electron and photon field. Electrons are more effective at depositing energy in the crystal than photons. From the two arrays of 17 OSLs, the central OSL PMT counts were measured after around 50 pulses to give a benchmark dose per pulse for the photon field. It was concluded that 52,000 pulses could be used to irradiate the arrays without concern of saturation. The PMT counts for each OSL array were measured and the high dose calibration was used to calculate the total dose following the completion of the mixed field irradiation study. The uncertainty in each dose calculation was propagated through from the high dose calibration in section 4.1. The raw data is fed into a custom data analysis script, found in Appendix C, once the compilation of each measurement was complete. The average dose per pulse for the mixed field irradiation was found to be 10.38 $\pm$ 0.70 mRad. The uncertainty in these measurements is dominated by the uncertainty in the high dose calibration. No uncertainty was estimated for the accelerator dose per pulse used to produce the bremsstrahlung photon field.

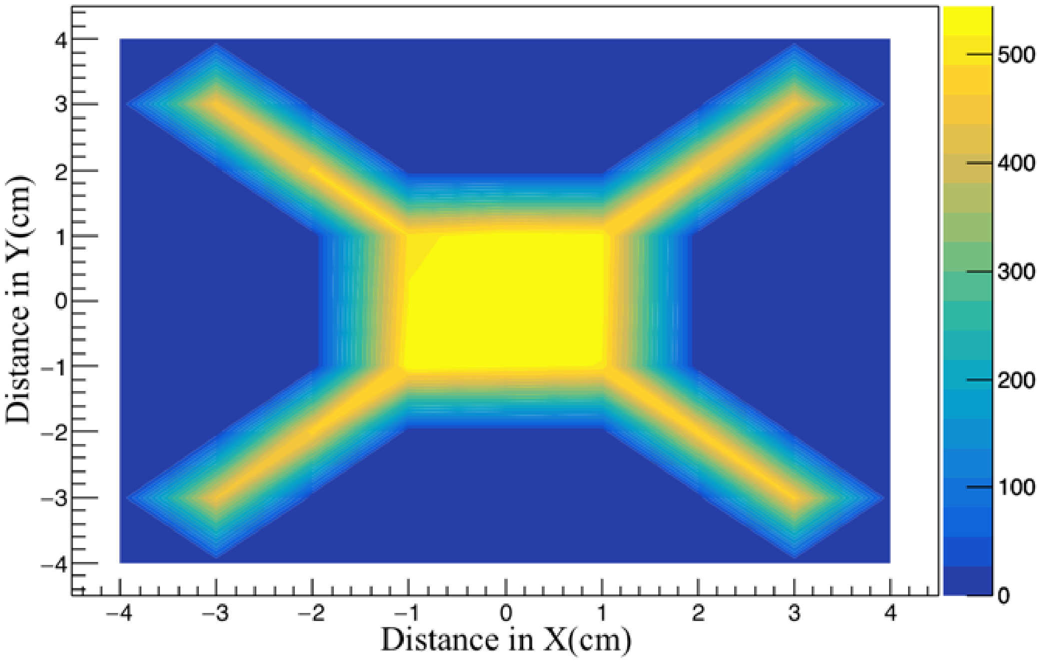

Figure 4.3: Contour plot of the average photon dose measurements in Rad.

A projection of Figure 4.3 along the X = Y and X = -Y axis is shown in Figure 4.4 and 4.5 respectively. The binning was chosen to be the same physical size as the OSL. Fitting a gaussian to each projection gives a rough interpretation of the shape of the beam impinging onto the OSLs. The doses used in the filling of the histograms is the average from the corresponding diagonal in each array.

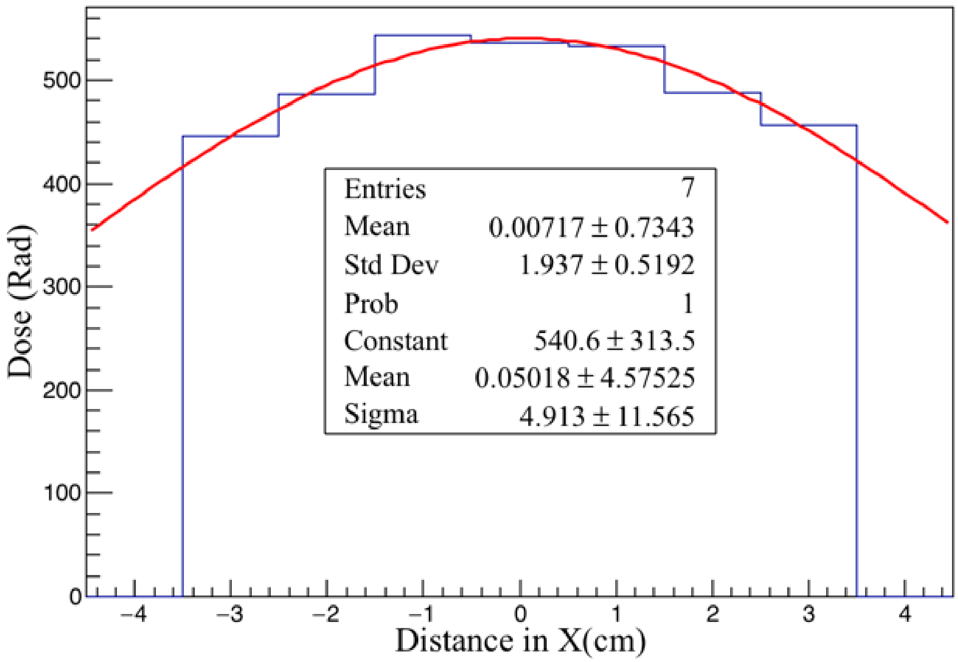

Figure 4.4: X = Y diagonal averages of the two photon arrays.

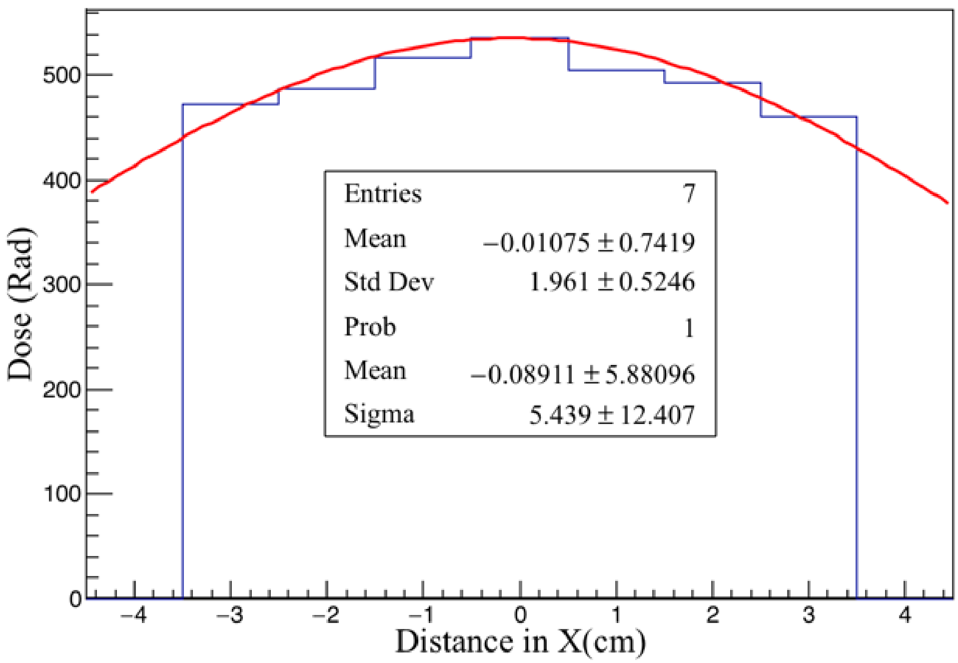

Figure 4.5: X = -Y diagonal averages of the two photon arrays.

4.2.2 Electron Beam

The mixed electron and photon field irradiation study began with the dosing of single OSLs followed by irradiating an array of 17 OSLs. The single OSLs were positioned on axis for the incident beam at a distance of 50 cm from the end of the beam pipe. Each OSL received a small number of pulses, varying from two to six. The relationship between total dose and number of pulses is shown in Figure 4.6. Details of the run plan used to gather this data is located in Appendix D.

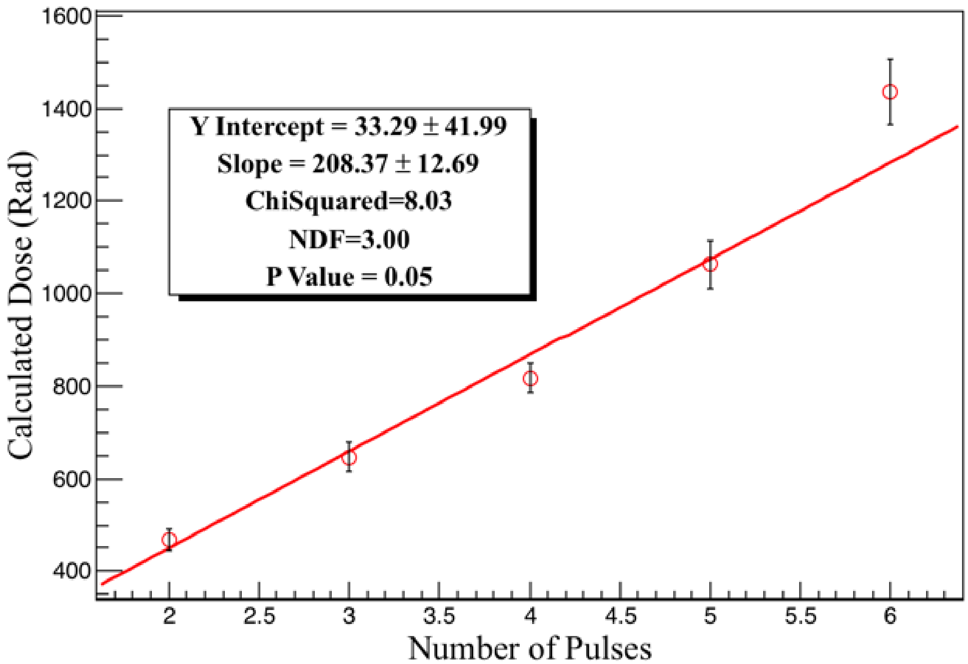

Figure 4.6: Linear fit of number of pulses versus calculated dose for all electron beam on axis OSLs with the relative uncertainty in each dose measurement.

Starting with single OSLs positioned on-axis for the electron beam at a distance of 50 cm, each was irradiated with two to six pulses. Using the OSL reader, PMT counts for each OSL are measured. The dose can then be calculated using PMT counts and the high dose calibration. A single array of 17 OSLs was irradiated with the electron beam following the completion of the single OSLs. This array provides off-axis dose information and it covers a large enough area to provide an interpretation of the general shape of the electron beam. Projections of the diagonal axes from Figure 4.7 are used to look at the shape of the beam along the X = Y diagonal in Figure 4.8 and the X = -Y diagonal in Figure 4.9. The difference in the sigmas between the photon field and mixed field diagonals is due to the beam diverging from the interactions of the converter. Photons are emitted with a larger opening angle as the electron beam interacts with the converter and 100 cm of air, while the mixed field beam only traverses 50 cm of air.

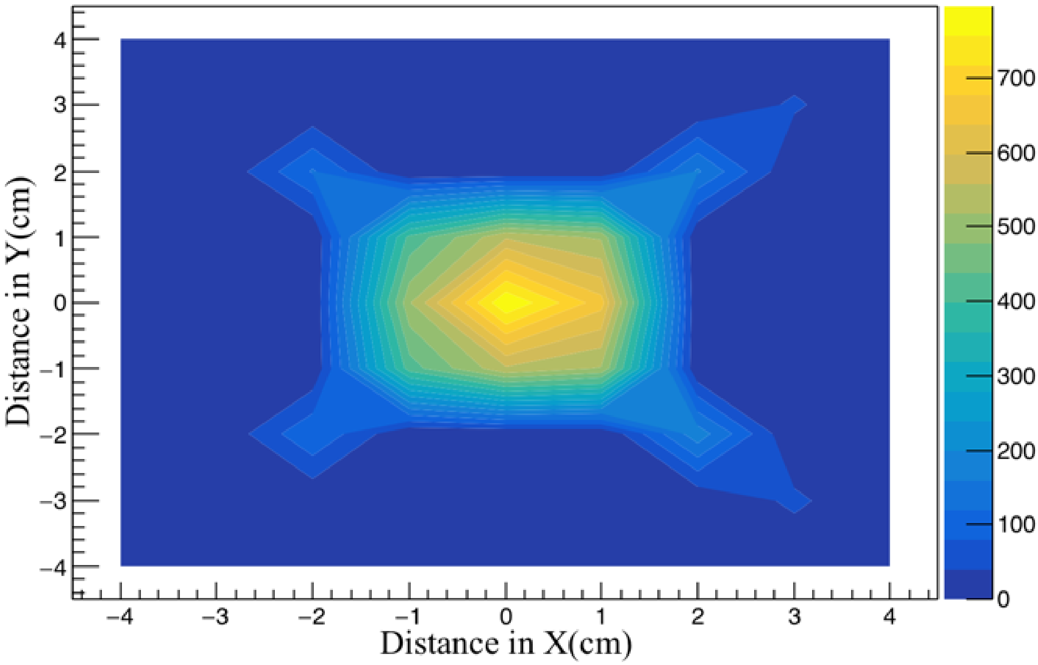

Figure 4.7: Dose intensity of the OSL array irradiated with the mixed field.

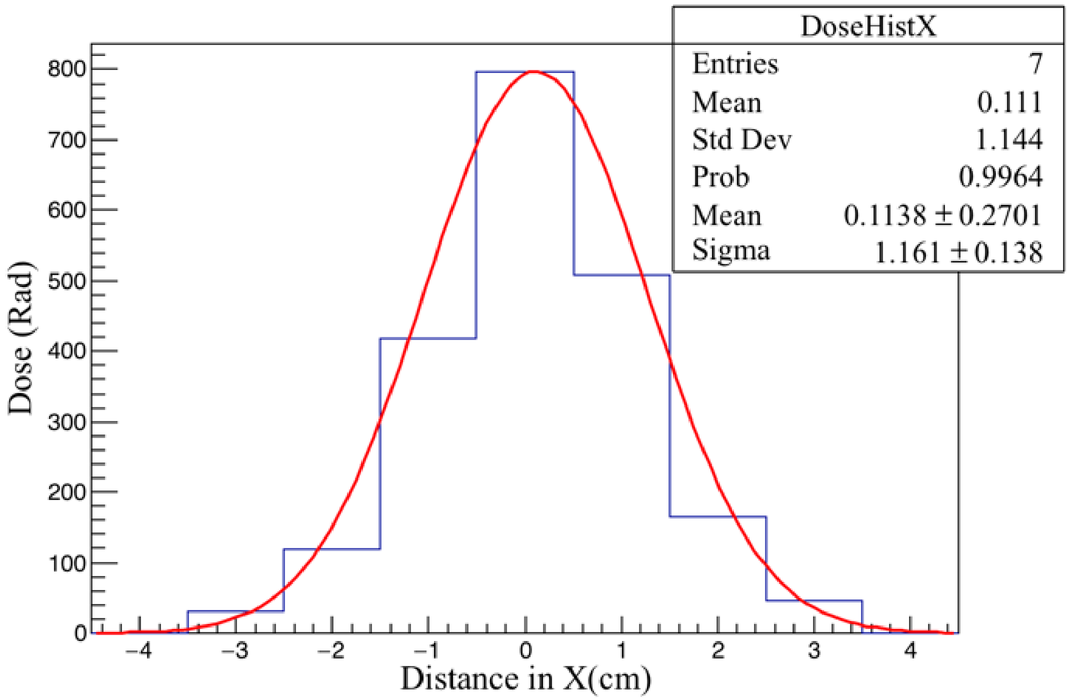

Figure 4.8: X = Y diagonal projection from Figure 4.7. Shows a discrete shaping of the beam with a gaussian fit.

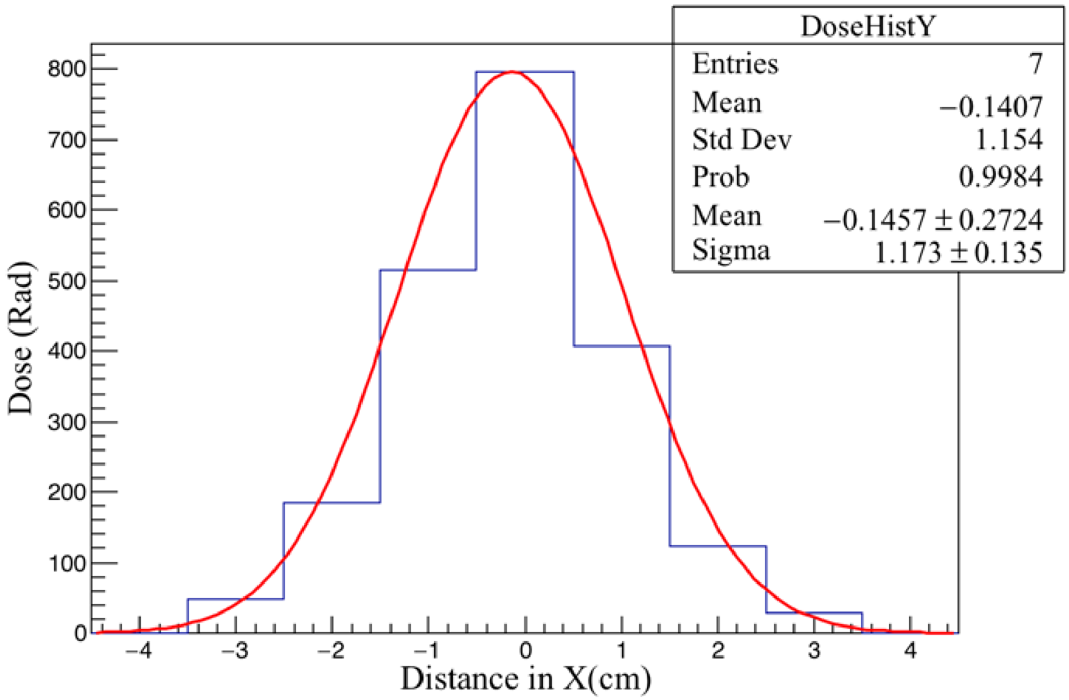

Figure 4.9: X = -Y diagonal projection from Figure 4.7. Shows a discrete shaping of the beam with a gaussian fit.

After irradiation, the OSLs were analyzed using the OSL reader. The measured PMT counts were used to calculate the average dose per pulse through the high dose calibration. The mean dose per pulse for the electron beam study is 215.14 ± 7.13 Rad. The relative uncertainty for the mean dose per pulse is ± 6.98%, which is greater than that of the calibration uncertainty. The increase in uncertainty is due to factors from the instability of the electron beam. The dose for each PMT measurement was calculated via the high dose calibration fit in the form of:

$$Dose = [(slope)(PMT\ Counts) + Y_{int}] \pm \sigma_i$$

4.2.3 Experimental Uncertainty

Any measured dose in this experiment has an uncertainty that is propagated through from the high dose calibration. All of the doses were calculated directly from the measured PMT counts and then input into the following:

$$Dose = [(slope)(PMT\ counts) + Y_{int}] \pm \sqrt{(\sigma_{slope}(PMT\ counts))^2 + (\sigma_{Y_{int}})^2}$$

Following these calculations, the average dose per pulse can be calculated using

$$\frac{Dose}{Pulse} = \frac{\Sigma Dose_i \pm \sqrt{\Sigma\ \sigma_i^2}}{Total\ Pulses}$$

Where σ_i is the uncertainty in the dose and $dose_i$ is the dose calculation with no sigma.

With the standard deviation calculated for each individual measurement, the relative percent error is found with the same formula as in section 3.4, except with PMT counts replaced with dose.

$$Rel.\ Err. = \frac{\sigma_{dose_i}}{Dose_i} x100\%$$

The calculations for the relative errors yield 4.87% for each measurement. This relative error shows that the dose is known to within $\pm 4.87\%$. This result is also consistent with the manufacturer's specifications on reproducibility[2].

Chapter 5

Conclusion

The relative uncertainty intrinsic to an Optically Stimulated Luminescence dosimeter was observed to be 4.87% over a large dose range using a known source and a bremsstrahlung photon field, this is consistent with the manufacturers 5% value. The OSLs were irradiated to an average of 540 Rad using a bremsstrahlung photon field produced by the 25B linac at the Idaho Accelerator Center. The OSLs were calibrated using a known source and it is the uncertainty from this calibration that dominates the uncertainty in the measurements made. The activity of the ^{137}Cs source is effectively constant over the time scale of the calibration exposures. This allowed for exposing the OSLs to a dose equivalent to that listed on the supplied calibration OSLs.

The OSLs were also subject to a mixed field of electrons and photons. The mixed field dosage ranged from 460 - 1440 Rad. The mixed field irradiation study found the reproducibility of the OSLs to be 6.98%. This increase in uncertainty from 4.87% to 6.98% is partially attributed to instability in the accelerator as the OSL's systematic uncertainty is included in the 6.98% value. The uniformity of the bremsstrahlung photon field at 100 cm is greater than that of the mixed field at 50 cm, which also contributes to the increase in uncertainty. Even though the radiation fields given to the OSLs may not have been as stable as the known source, the calibration uncertainty continues to be the dominant uncertainty. The mixed field dose is measured relative to the same dose as given by photons because the calibration was completed using a photon source. This work has observed that the OSLs are reproducible to 4.87% in a bremsstrahlung photon field and 6.98% in a mixed electron and photon field.

Appendix A

OSL Reader

The MicroStar i reader uses a long pass filter and LED to shine green light on the exposed crystal. The incident photons cause the crystal to luminesce as described in section 2.1. The emitted photons then pass through a blue light filter and are counted by the PMT. A diagram of the internal components can be found in Figure A.1.

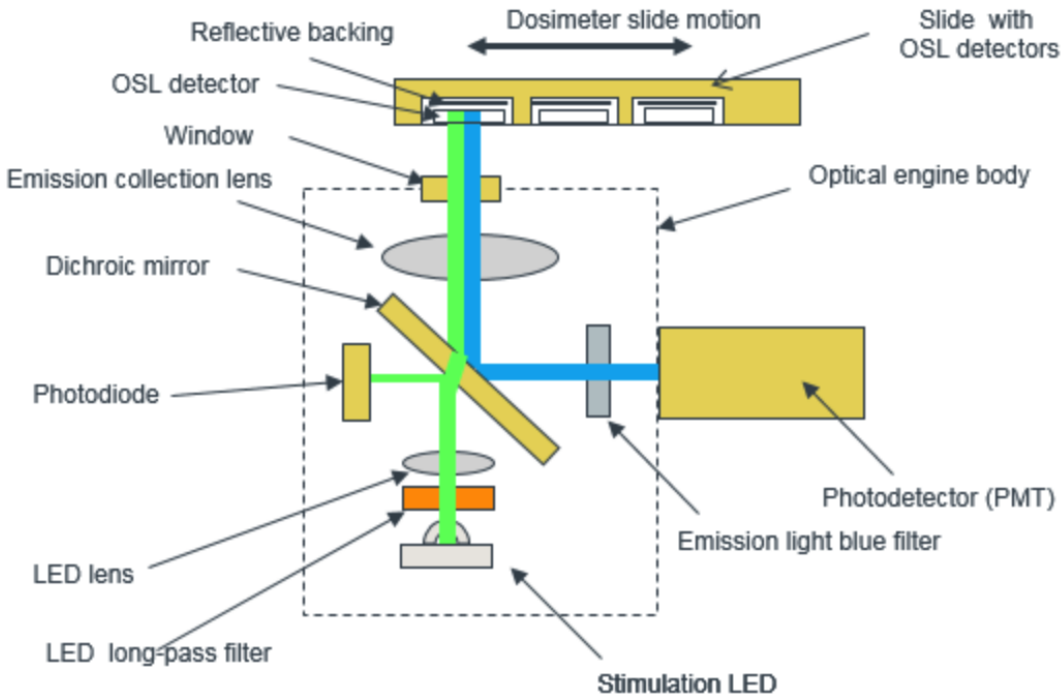

Figure A.1: Diagram of internals of OSL reader [3].

The OSL reader pictured in Figure A.2, has software capable of calibrating the reader, through which low dose and high dose calibrations are created. These different calibrations give separate calibration factors. To create the calibrations for the software, Landauer supplies pre-dosed OSLs providing five measurements to encompass the device's dynamic range. Due to uncertainty in exposure between dosing and usage, a custom calibration is used to reduce error in succeeding measurements. The OSL reader calculates the dose based on the observed number of PMT counts (N_{PMT}), OSL sensitivity (Q_{OSL}), and calibration factor (C_f). The equation used for this calculation is:

Figure A.2: Front of OSL reader.

The OSL reader has software capable of calibrating the reader, through which low dose and high dose calibrations are created. These different calibrations give separate calibration factors. To create the calibrations for the software, Landauer supplies pre-dosed OSLs providing five measurements to encompass the device's dynamic range. Due to uncertainty in exposure between dosing and usage, a custom calibration is used to reduce error in succeeding measurements.

$$Dose(mRad) = \frac{N_{\text{PMT}}}{(\text{C}_{\text{f}})(Q_{\text{OSL}})}$$

Appendix B

GEANT4 Macro

```
/gps/particle e-
    /gps/pos/type Beam
    /gps/pos/rot1 1 0 0
    /gps/pos/rot2 0 1 0
    /gps/pos/shape Circle
    /gps/pos/centre 0 0 -91 cm
    /gps/pos/sigma r 0.908 cm
    /gps/ang/rot1 0 1 0
    /gps/ang/rot2 1 0 0
    /gps/ang/type beam1d
    /gps/ang/sigma r 0.776. deg
    /gps/energy 8 MeV
    /run/beamOn 1560550
```

Appendix C

Data Analysis Script

```
//This function takes the raw data from dose measurements and

//creates 3 histograms


void Dosedist()

{

//Initiate variables

Int_t NbinsX,NbinsY,HistBinsX,HistBinsY;

Float_t MaxX,MaxY,MinX,MinY;

//Set number of bins for histograms

HistBinsX=9;

HistBinsY=9;

//Set maximum and minimum X and Y values in cm

MaxX=4.5;

MaxY=4.5;

MinX=-4.5;

MinY=-4.5;

//Create the individual histograms

TH2F *DoseHist=new TH2F("DoseHist","DoseHist",NbinsX,MinX,MaxX,NbinsY,

MinY,MaxY);

TH1F *DoseHistX=new TH1F("DoseHistX","DoseHistX",HistBinsX,MinX,MaxX);

TH1F *DoseHistY=new TH1F("DoseHistY","DoseHistY",HistBinsY,MinY,MaxY);

//Begin data stream

    ifstream in;

    Float_t x,y,z;

//Set number of data points (must be bigger than or equal to number of lines
```

```
in data file)
    const static int num_points=17;
//Initiate arrays of length num_points
    Float_t x_data[num_points], y_data[num_points], z_data[num_points];
  Int_t i;
  i=0;

//Open file called "filename.tsv"
in.open("filename.tsv");
//Feed in data from filename.tsv
while(in.good()){
    in >> x >> y >> z;
//Set arrays equal to a simple variable
      x_data[i]=x;
      y_data[i]=y;
      z_data[i]=z;
//Fill histograms
DoseHist->Fill(x,y,z);

//Fill lower left to upper right diagonal
if(y==x)
DoseHistX->Fill(x,z);
//Fill upper left to lower right diagonal
if(x==-y)
DoseHistY->Fill(y,z);
  i++;
  }
in.close();
```

```
//Set draw type for each histogram
    DoseHistX->SetOption("hist");
    DoseHistY->SetOption("hist");
    DoseHist->SetOption("colz");


//Create new canvas for DoseHistX and set options
TCanvas * c1 = new TCanvas();
     DoseHistX->SetTitle("X = Y Diagonal");
     DoseHistX->GetXaxis()->SetTitle("Distance in X(cm)");
     DoseHistX->GetYaxis()->SetTitle("Dose (mRad)");
     DoseHistX->GetXaxis()->SetTitleOffset(.95);
     DoseHistX->GetYaxis()->SetTitleOffset(.95);
     DoseHistX->GetXaxis()->CenterTitle();
     DoseHistX->GetYaxis()->CenterTitle();
     DoseHistX->Fit("gaus");
     DoseHistX->Draw("hist sames");
//Create new canvas for DoseHistY and set options
TCanvas * c2 = new TCanvas();
     DoseHistY->SetTitle("X = -Y Diagonal");
     DoseHistY->GetXaxis()->SetTitle("Distance in X(cm)");
     DoseHistY->GetYaxis()->SetTitle("Dose (mRad)");
     DoseHistY->GetXaxis()->SetTitleOffset(.95);
     DoseHistY->GetYaxis()->SetTitleOffset(.95);
     DoseHistY->GetXaxis()->CenterTitle();
     DoseHistY->GetYaxis()->CenterTitle();
```

```
    DoseHistY->Fit("gaus");
    DoseHistY->Draw("hist sames");
    gStyle->SetOptFit(1011);
//Create new canvas for DoseHist and set options
TCanvas * c3 = new TCanvas();
    DoseHist->SetTitle("Beam Intensity");
    DoseHist->GetXaxis()->SetTitle("Distance in X(cm)");
    DoseHist->GetXaxis()->SetTitleOffset(1.0);
    DoseHist->GetYaxis()->SetTitle("Distance in Y(cm)");
    DoseHist->GetYaxis()->SetTitleOffset(1.0);
    DoseHist->GetZaxis()->SetTitle("OSL Reading (mRad)");
    DoseHist->GetZaxis()->SetTitleOffset(1.25);
    DoseHist->GetXaxis()->CenterTitle();
    DoseHist->GetYaxis()->CenterTitle();
    DoseHist->SetStats(0);
    DoseHist->Draw("colz");

}
```

Appendix D

Run Plan

Shot Number	Number of Pulses	Number of OSLs	Dose (Rad) (0,0)	Dose/pulse (Rad) (0,0)	Al Brick with W Converter
1	6	1	768.10344	128.017	Out
2	6	1	795.26442	132.54407	Out
3	6	16	Off Center	Off Center	Out
4	6	17	592.89645	98.816075	Out
5	6	1	1435.75504	239.292	Out
6	2	1	468.28238	234.14119	Out
7	4	1	842.87814	210.719535	Out
8	5	1	1062.99342	212.598684	Out
9	6	1	646.63748	215.5458267	Out
10	4	17	796.48564	199.12141	Out
11	51948	17	531.9275	.01023961461	In
12	52106	17	541.85896	.01039916631	In
13	4	1	771.12338	192.780845	Out
14	4	1	841.583	210.39575	Out
15	4	1	832.54936	208.13734	Out

Bibliography

[1] K. E. Holbert. Health physics. Technical report, Arizona State University, 03 2011.

[2] Landauer. nanoDot^{tm} Dosimeter, 2017.

[3] Landauer Europe, 9, rue Paul Dautier CS 60731, 78457 Velizy Villacoublay Cedex, France. OSL TECHNOLOGY PRINCIPLE, 2018.

[4] K. J. Thomsen. Optically Stimulated Luminescence Techniques in Retrospective Dosimetry using Single Grains of Quartz extracted from Unheated Materials. PhD thesis, University of Copenhagen, Denmark, 2004.