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# Radiation Dose in the CDF 2000 Engineering Run: What the Silicon Saw

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**Abstract**

We present dosimetry measurements for the barrel-4 silicon for the CDF 2000 engineering run. Using thermal luminescent dosimeters (TLDs) we measured both the effective photon and thermal neutron doses at multiple locations surrounding the SVX-II silicon detectors. We find the maximum photon/minimum ionizing dose at a radius of 2.99 cm of 1.8 kRad corresponding to the radial location of SVX layer 0. Analysis of the data yields a radial dependence of the effective $\gamma$ dose of $r^{-\alpha}$ where $\alpha = 1.253 \pm 0.070$.

## 1 Introduction

It has long been known that the run II silicon vertex detector in CDF would have to be replaced due to radiation damage [1]. In order to plan a replacement for SVX-II, one would like to know when the sensors and readout chips will no longer provide useful data. A key element to estimating the lifetime of the SVX-II detector is an accurate estimate of the radiation dose which the sensors and readout electronics will see during run 2. We present here a measurement of the integrated radiation dose seen by the barrel-4 silicon during the CDF 2000 engineering run using thermal luminescent dosimeters. This measurement represents the first time CDF has measured the radiation field inside the tracking volume.

Thermal luminescent dosimeters (TLDs) work on the principle that when ionizing radiation passes throught the TLD material, the energy loss stimulates a transition to a metastable state. The number of molecules in the metastable state is related to the absorbed dose of ionizing radiation. Phonons from subsequent heating further excite the material to an allowed optical transition. Counting photons during heating of the TLD material then gives a measure of the total absorbed dose. Sensitivity to neutrons is obtained by using a material which absorbs neutrons and emits ionizing radiation. Heating the TLD material for prolonged periods of time, annealing, resets the TLD material. All TLD materials are annealed prior to exposure.

# 2 Method

We used two types of TLDs for this measurement. Sensitivity to ionizing radiation is achieved using 4.2 mm diameter, by 0.9 mm thick round $^7$LiF chips (TLD-700). Sensitivity to a combined photon and neutron dose is achieved using $3.4 \times 3.4 \times 0.9$ mm$^3$ square $^6$LiF chips (TLD-600). Because the TLD chips were unlabelled and had their own calibration constants, they were placed in specified locations in labelled holders to facilitate their later identification. The TLD holders are made of 0.48mm thick FR-4 material measuring 1.27 cm $\times$ 4.44 cm. Two 1.11 cm diameter holes are machined at one end of the holder to contain the TLD chips. The TLD chips are then held in place using 3mil thick kapton tape. Each TLD holder contained three TLD-700 chips and many holders contained two TLD-600 chips. The configuration of the chips and holders is shown in figure 1.

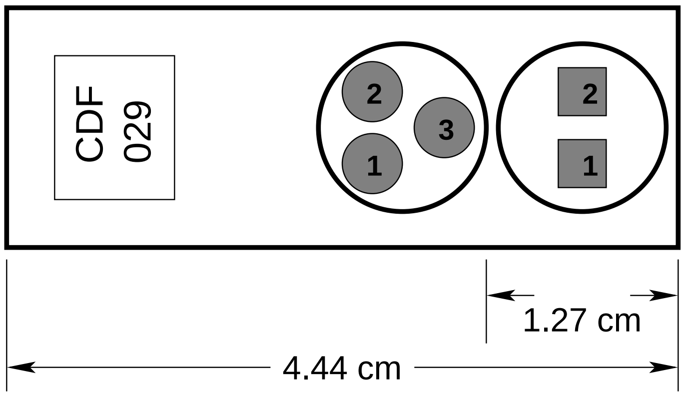


Figure 1: Diagram of Thermal Luminescent Dosimeter (TLD) holder showing the placement of the TLD-700 (circles) and TLD-600 (squares) in the holder.

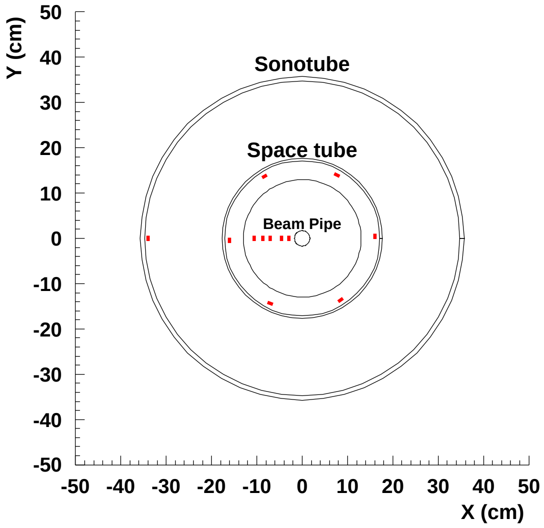


Figure 2: X-Y view of the inner tracking region. Dots indicate the location of TLD holders.

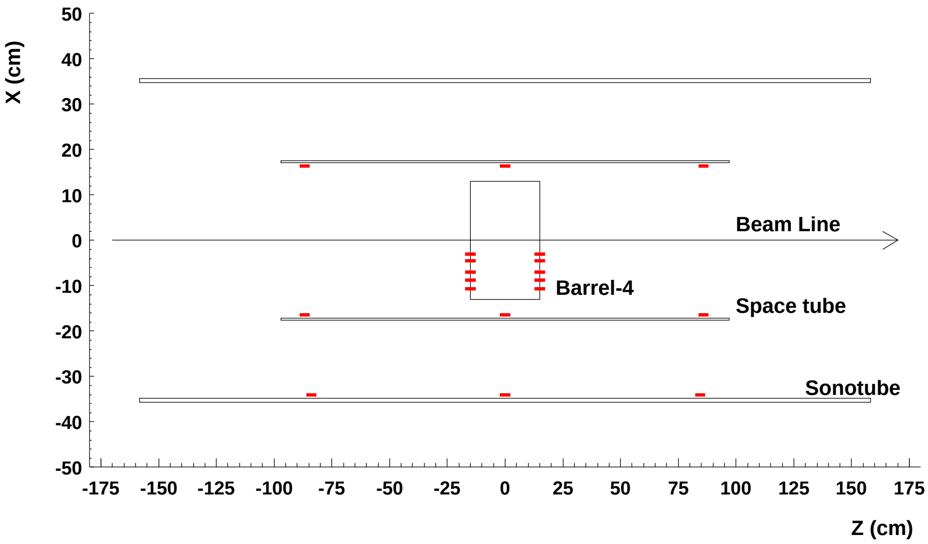


Figure 3: X-Z view of the inner tracking region. Dots indicate the location of TLD holders.

The CDF coordinate system uses the proton beam to define the $z$ direction and the $y$ direction as up (away from earth's center). Using these conventions, TLD holders were placed in several locations to obtain information about the radial, azimuthal and $z$ dependence of the radiation dose. To obtain information about the radial dependence of the radiation dose, TLD holders were placed at both ends of the support structure for the 5 layers of barrel-4, in the middle ($z = 0$) of the barrel-4 space tube and sonotube. Each of these holders contained 3 TLD-700s and 2 TLD-600s and were in the $\phi = 180°$ position. Another set of holders, containing only photon sensitive TLD-700 chips were placed at both ends of the barrel-4 space tube and 5 additional positions in $\phi$. Finally 2 additional TLD holders were place near the ends of the cardboard sonotube in the $\phi = 180°$ position. Figures 2 and 3 show the locations of the TLD holders as they were installed. A few dosimeters were not installed to act as a control sample for subtracting radiation due to background sources. More detailed summary of the locations of the dosimeters follows in a subsequent section.

The dosimeters were installed prior to SVX being inserted into the CDF central outer tracker. The beam related portion of their dose was taken over the period (add dates here). During this period the Tevatron delivered a total of $7.07 \times 10^{17}$ protons, $0.38 \times 10^{17}$ antiprotons and an integrated luminosity of $58 \pm 17 \mathrm{nb}^{-1}$ [5].

# 3 TLD Calibration and Dosimetry

The TLD photon response was measured by exposing each TLD chip to a known dose from a well calibrated source and measuring the light yield as the chip is heated. The "photon" response was calibrated at Fermilab's Radiation Physics Calibration Facility using a 1 Rad exposure to a $^{137}$Cs source [2]. The light yield measurements from each chip were made by the Fermilab radiation safety group using a Harshaw model 4000 TLD reader [3]. The TLD reader records the total charge in nC integrated from a PMT viewing the TLD chip while it is heated. Figure 4 summarizes the 1 Rad photon reponse of all TLD chips. The response of individual TLD chips was found to be reproducible to within 1%.

In order to understand the response of the TLD chips as a function of absorbed dose, we exposed 10 chips to doses ranging 1–3000 Rad. The TLD response when unexposed is negligible. Figure 5 a) shows a typical response for a single chip compared with a linear response assumption. Even on a log scale it is evident that the TLD material is non-linear at the highest doses available to us. In order to quantify this effect, we calculate the expected response, $R_{line}$, assuming a linear model:

$$R_{line}(D) = D \cdot R_{measured}(1) \tag{1}$$

where $D$ is the delivered dose and $R_{measured}(1)$ is the measured 1 Rad response. The TLD response when unexposed is negligible. One can then form the ratio:

$$K(D) = \frac{R_{line}(D)}{R_{measured}(D)}. \tag{2}$$

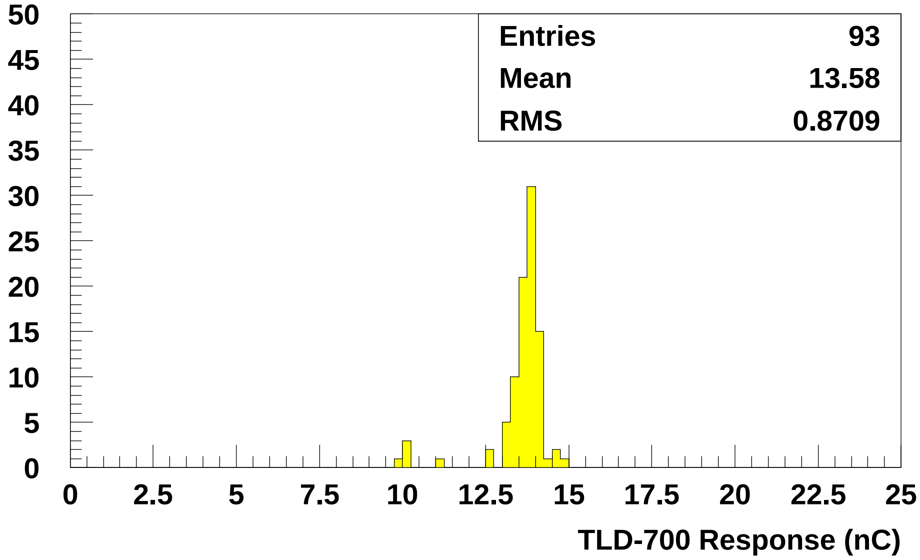


Figure 4: Gamma response for TLD-700 chips to a 1 Rad $^{137}$Cs exposure.

Figure 5 b) shows the average ratio, $K(D)$, for the 10 dosimeters as a function of the delivered dose $D$. The uncertainties arise from the RMS of the $K(D)$ distribution for the 10 TLD chips. As evident from the figure, the TLD response is linear for doses below 100 Rad. Here we calculate the dose seen by the dosimeter as:

$$D_{lin} = \frac{R_{measured}(D)}{R_{measured}(1)}. \tag{3}$$

For doses above 100 Rad it is convenient to modify the results of equation 3 by a multiplicative correction factor, $K(D_{lin})$, where we've substituted the actual dose with the predicted dose using the result from equation 3.

$$D_{actual} = K(D_{lin}) \cdot D_{lin}. \tag{4}$$

Table 1 summarizes the TLD linearity correction as a function of $D_{lin}$. The same data are summarized in Figure 6

The dose from each TLD chip was calculated using equation 4 and calibration constants obtained from 1 Rad $^{137}$Cs exposures. We calculate a holder dose and its estimated uncertainty using the mean and RMS of the three separate TLD-700 measurements in a given holder. If we find that one TLD chip in a holder measures a dose different from its partners by more than three standard deviations, we throw out

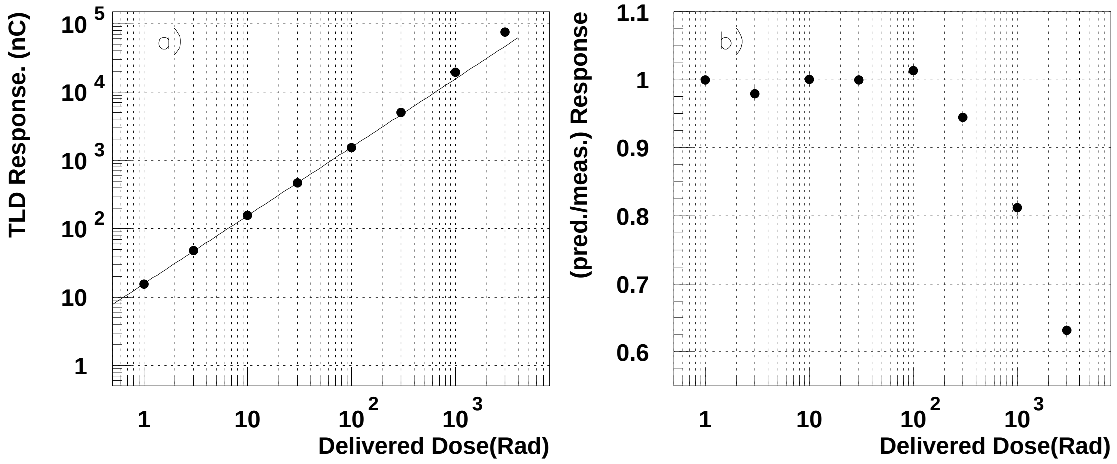


Figure 5: a) TLD-700 response measured in nC as a function of delivered dose. The line indicates the response predicted assuming a linear response model described in the text. b) Ratio of TLD-700 predicted/measured response as a function of delivered dose. The predicted dose assumes the linear response model described in the text.

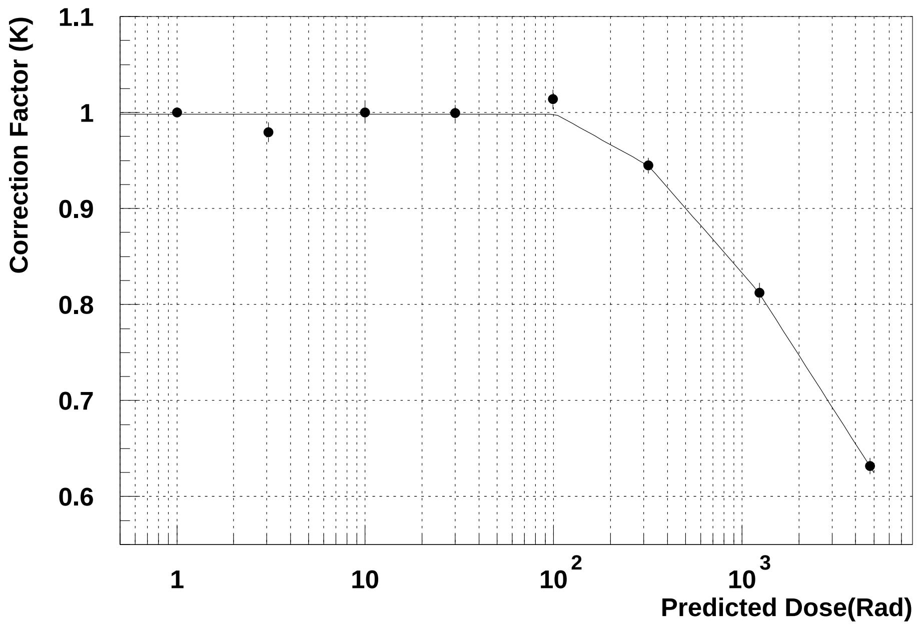


Figure 6: Linearity correction factor ($K$) as a function of the dose predicted assuming a linear TLD response model. The solid curve shows the factor used to correct the raw TLD data.

Table 1: Table of TLD-700 linearity corrections.

| Dose (Rad) | | Correction Factor |
|---|---|---|
| Delivered | Linear Model | K |
| 1.00 | $1.00 \pm 0.00$ | $1.0000 \pm 0.0000$ |
| 3.00 | $3.06 \pm 0.03$ | $0.9794 \pm 0.0103$ |
| 10.00 | $10.00 \pm 0.10$ | $1.0002 \pm 0.0104$ |
| 30.00 | $30.02 \pm 0.26$ | $0.9993 \pm 0.0086$ |
| 100.00 | $98.66 \pm 1.00$ | $1.0137 \pm 0.0101$ |
| 300.00 | $317.57 \pm 2.73$ | $0.9447 \pm 0.0082$ |
| 1000.00 | $1231.57 \pm 16.30$ | $0.8121 \pm 0.0107$ |
| 3000.00 | $4751.48 \pm 64.17$ | $0.6315 \pm 0.0085$ |

the measurement and recompute the holder dose with two chips. We kept a control sample of several chips which were not exposed. The dose from our control sample was then subtracted from the individual holder doses. Only the TLD-700 data were analyzed for this note. Analysis to try and extract neutron doses from the TLD-600 chips lead to nonsensical results [1]. Table 2 summarizes the holder doses as a function of TLD holder location.

# 4 Analysis

With the doses of individual holders calculated, the spatial distribution of the radiation field can now be considered. We model the spatial distribution of the radiation field assuming cylindrical symmetry about the beam axis and a power law in $1/r$ motivated by previous measurements of silicon damage patterns in CDF [4] If one allows for an overall $(x, y)$ offset of the beam relative to the detector axis, the 2-dimensional dose can be parameterized as:

$$D(x,y) = A\left[(x-x_0)^2 + (y-y_0)^2\right]^{-\frac{\alpha}{2}}, \tag{5}$$

where $D(x, y)$ is the 2-dimensional dose, $A$ is the dose normalization, $(x_0, y_0)$ is the offset of the beam relative to the detector symmetry axis and $\alpha$ is the exponent in a power law.

For the analysis presented here, the data were split up into three regions:

1. negative side ($z = -86$ cm)

[1] The TLD-600 chips are sensitive to both neutron and photon radiation. However, we find that many TLD-600 chips had combined doses significantly less than the TLD-700 chips in the same holder. This effect is not completely understood at this date.

Table 2: Raw dosimetry data for the barrel-4 silicon during the 2000 engineering run. The bottom 3 measurements are from unexposed (control) dosimeters used to estimate natural backgrounds.

| TLD | Location | | | $\gamma$ Dose (Rad) | | n Dose (Rad) | |
|---|---|---|---|---|---|---|---|
| ID | r(cm) | $\phi$ (rad) | z(cm) | mean | rms | mean | rms |
| 1 | 2.995 | 3.141 | 15.0 | 1724.2 | 50.0 | 0.0 | 0.0 |
| 2 | 4.570 | 3.141 | 15.0 | 1086.7 | 31.3 | 0.0 | 0.0 |
| 3 | 7.020 | 3.141 | 15.0 | 668.5 | 11.0 | 0.0 | 0.0 |
| 4 | 8.720 | 3.141 | 15.0 | 519.3 | 6.5 | 0.0 | 0.0 |
| 5 | 10.645 | 3.141 | 15.0 | 418.0 | 8.7 | 0.0 | 0.0 |
| 6 | 2.995 | 3.141 | -15.0 | 1823.5 | 54.3 | 0.0 | 0.0 |
| 7 | 4.570 | 3.141 | -15.0 | 1097.1 | 18.0 | 0.0 | 0.0 |
| 8 | 7.020 | 3.141 | -15.0 | 668.4 | 11.2 | 0.0 | 0.0 |
| 9 | 8.720 | 3.141 | -15.0 | 523.9 | 6.8 | 0.0 | 0.0 |
| 10 | 10.645 | 3.141 | -15.0 | 403.2 | 5.0 | 0.0 | 0.0 |
| 11 | 16.400 | 4.167 | 0.0 | 251.3 | 4.6 | 0.0 | 0.0 |
| 12 | 16.400 | 3.113 | 0.0 | 257.9 | 3.2 | 0.0 | 0.0 |
| 13 | 16.400 | 2.030 | 0.0 | 277.6 | 3.0 | 0.0 | 0.0 |
| 14 | 16.400 | 1.015 | 0.0 | 288.1 | 4.6 | 0.0 | 0.0 |
| 15 | 16.400 | -0.029 | 0.0 | 285.1 | 3.9 | 0.0 | 0.0 |
| 16 | 16.400 | 5.211 | 0.0 | 258.3 | 8.9 | 0.0 | 0.0 |
| 17 | 16.400 | 3.113 | 86.7 | 268.2 | 8.1 | 0.0 | 0.0 |
| 18 | 16.400 | 3.113 | -86.0 | 236.4 | 3.0 | 0.0 | 0.0 |
| 19 | 37.700 | 3.141 | 84.5 | 66.9 | 0.8 | 0.0 | 0.0 |
| 20 | 37.700 | 3.141 | 0.0 | 91.4 | 1.0 | 0.0 | 0.0 |
| 21 | 37.700 | 3.141 | -83.8 | 100.4 | 1.5 | 0.0 | 0.0 |
| 24 | 16.400 | 2.030 | 86.7 | 274.8 | 11.6 | – | – |
| 25 | 16.400 | 1.015 | 86.7 | 288.1 | 5.6 | – | – |
| 26 | 16.400 | -0.029 | 86.7 | 309.0 | 5.7 | – | – |
| 27 | 16.400 | 5.211 | 86.7 | 268.2 | 2.8 | – | – |
| 28 | 16.400 | 4.167 | 86.7 | 259.2 | 5.1 | – | – |
| 29 | 16.400 | 2.030 | -86.0 | 245.6 | 5.0 | – | – |
| 30 | 16.400 | 1.015 | -86.0 | 256.1 | 3.6 | – | – |
| 31 | 16.400 | -0.029 | -86.0 | 273.1 | 13.3 | – | – |
| 32 | 16.400 | 5.211 | -86.0 | 208.2 | 3.4 | – | – |
| 33 | 16.400 | 4.167 | -86.0 | 226.9 | 5.1 | – | – |
| 22 | – | – | – | $< 0.03$ | 0.0 | 0.0 | 0.0 |
| 23 | – | – | – | $< 0.03$ | 0.0 | 0.0 | 0.0 |
| 34 | – | – | – | $< 0.03$ | 0.0 | 0.0 | 0.0 |

Table 3: Results of fitting the data to the model discussed in the text. For the results at the ends of the SVX space tube, the exponent ($\alpha$) was fixed to the result obtained from the data $|z| < 16$ cm.

| $z$ (cm) | A (Rad) | $\alpha$ | $x_0$(cm) | $y_0$(cm) | $\chi^2$/DOF |
|---|---|---|---|---|---|
| $\lvert z\rvert < 16$ | $8890 \pm 280$ | $1.253 \pm 0.070$ | $0.745 \pm 0.010$ | $0.750 \pm 0.120$ | 33.97/13 |
| $z = 86$ | $9150 \pm 88$ | (fixed) | $0.86 \pm 0.19$ | $0.60 \pm 0.14$ | 13.48/3 |
| $z = -86$ | $7748 \pm 57$ | (fixed) | $-0.05 \pm 0.14$ | $1.22 \pm 0.13$ | 26.34/3 |

2. center ($|z| < 16$ cm)

3. positive side ($z = 86$ cm)

We fit the data in the central region to the model presented above allowing all parameters to float. For the data in the negative/positive regions we fixed the exponent ($\alpha$) to the value found in the fits for the central regions and allowed the overall scale and offset to float. The results of these fits are found in table 3. Figures 7 and 8 show the same results graphically.

From these data we can draw a few qualitative conclusions. The radial dependence appears to follow a power law in the distance from the beam with an exponent of $\alpha = 1.253 \pm 0.070$. The $\phi$ distributions away from the center of the detector show features which do not fit the strict cylindrical symmetry used in our model. The data collected here are insufficient to distinguish additional components in any fits.

# 5 Discussion and Conclusions

The dosimetry data taken during the CDF 2000 commissioning run yeilded information of a very high quality. From these data we were able to measure the integrated radiation dose due to ionizing radiation in many places giving a good measurement of a power law radial dependence with an exponent $\alpha = -1.253 \pm 0.070$. The quality of the data were such that we observed an offset of the beam relative to the axis of the detector.

However, the success of this test is qualified by several conditions unique to the commissioning run. The silicon beam monitoring system was not installed or working during a large portion of the run. Tevatron tune studies accounted for a large portion of the CDF running as can be seen by the number of protons/antiprotons accumulated compared with the integrated luminosity reported in an earlier section. Finally, energizing the CDF solenoid magnet is expected to significantly modify the radial dependence of radiation field due to the curved path of charged particles moving perpendicular to the magnetic field.

These problems have been corrected since the start of CDF run II data taking. We've expanded our original program to include dosimeters in more locations to

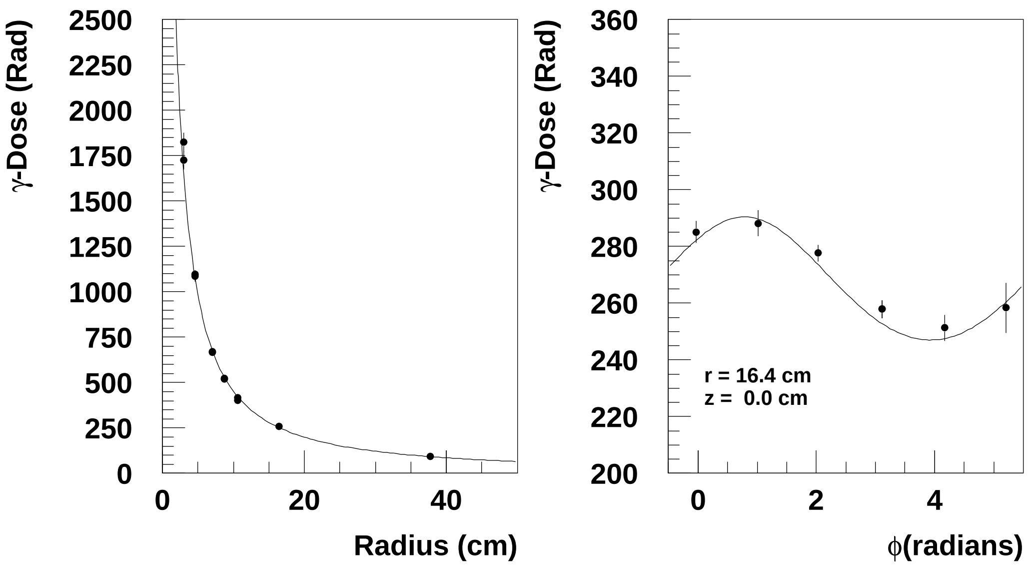


Figure 7: Photon dose as a function of $r$ (left) and $\phi$ evaluated at $r = 16.4$ cm (right). The solid curves are the result of fitting the data to the model discussed in the text.

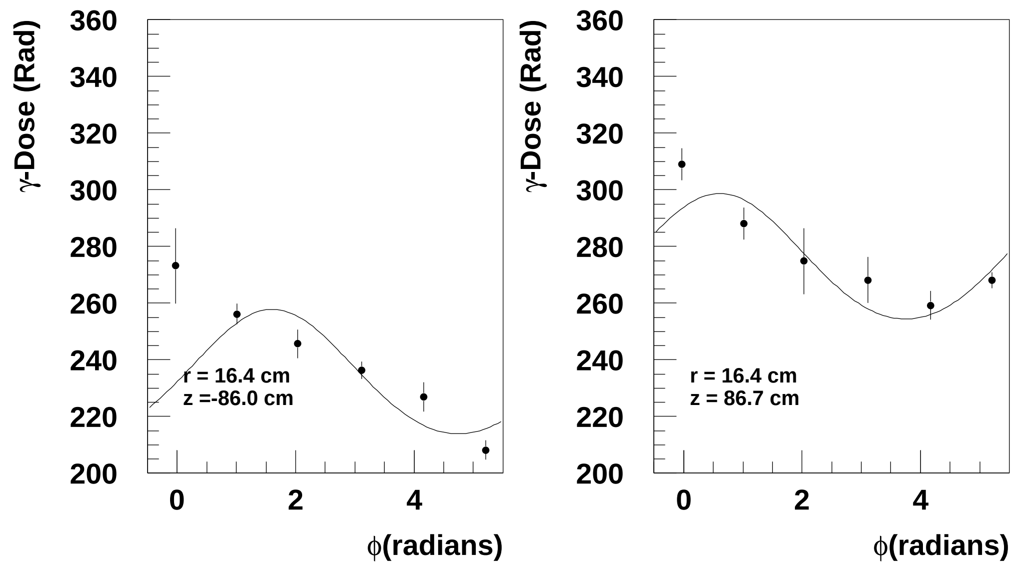


Figure 8: Photon dose as a function of $\phi$ for the negative (left) and positive (right) sides of the SVX space tube. The solid curves are the result of fits to the data to the model discussed in the text.

better map the radiation field inside the tracking volume. We look forward to better and more data to come.

# References


[1] "The CDF II Detector Technical Design Report," **FERMILAB-Pub-96/390-E**, November 1996.

[2] Reference for the Radiation Physics Calibration Facility Cs137 source.

[3] Reference for the Harshaw Model 4000 TLD reader.

[4] D. Amidei, *et al.* Nucl. Instr. and Meth. **A350** (1994) 73.

[5] Jaco Konigsberg, Song Ming Wang, *private communication.*