Radiation Tolerance Survey of selected Silicon Photomultipliers to High Energy Neutron Irradiation

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***Abstract*—A key feature of silicon photomultipliers (SiPMs) that can hinder their wider use in medium and high energy physics applications is their relatively high sensitivity to high energy background radiation, with particular regard to high energy neutrons. Dosages of 10^{10} n$_{eq}$/cm^2 can damage them severely. In this study, some standard versions along with some new formulations are irradiated with a high intensity ^{241}AmBe source up to a total dose of 5×10^9 n$_{eq}$/cm^2. Key parameters monitored include dark noise, photon detection efficiency (PDE), gain, and voltage breakdown. Only dark noise was found to change significantly for this range of dosage. Analysis of the data indicates that within each vendor's product line, the change in dark noise is very similar as a function of increasing dose. At present, the best strategy for alleviating the effects of radiation damage is to cool the devices to minimize the effects of increased dark noise with accumulated dose.**

I. INTRODUCTION

LIMITED Geiger-mode avalanche photodiodes, more commonly referred to as silicon photomultipliers (SiPM), are rapidly becoming a standard choice for current and next generation detector systems requiring a compact, low power, magnetically immune photodetector with the high gain and photodetection efficiency of vacuum photomultipliers. At the Thomas Jefferson National Accelerator Facility (Jefferson Lab or JLAB), the GLUEX experiment will have two principal detector systems using SiPMs: the barrel calorimeter (BCAL) that will use about 3,800 SiPM arrays (12×12 mm^2 active area per array) and the photon beam tagger with 3×3 mm^2 individual SiPM detector elements. In both cases, the positive characteristics of SiPMs [1] were a key factor in their choice as the technology.

Unfortunately, SiPMs also tend to have poor resistance to radiation damage. For the GLUEX case, studies indicated a relatively low intensity high-energy photon background (some tens of rads per year), but a neutron fluence of about $3{\times}10^8$ n$_{eq}$/cm^2 per year in the region where the BCAL SiPMs would be located. An extensive series of irradiation tests were carried out with both high energy gammas (^{137}Cs source) and neutrons (high intensity ^{241}AmBe source). Within the 10-year planned lifetime of the GLUEX experiment, it became clear that the proposed SiPMs would accumulate too much damage over that period. The implemented solution will be to operate the devices at a lower operating temperature (5°C) during beam operation, followed by accelerated annealing via air heating (40-60°C) of the SiPMs during beam off periods. (The temperature control also implements a necessity to maintain the SiPM arrays at a precise temperature resulting in a stable output performance from the SiPMs.)

The results of this study indicated a need for further research into the possibility of improving the radiation tolerance of SiPMs. Coincident with this is an ongoing study of the proposed Electron Ion Collider. Brookhaven National Laboratory, with funds provided by the DOE Office of Nuclear Physics, began an ongoing program to fund generic detector development work relevant to the proposed EIC facility. Here again, a strong high energy neutron background is the concern for the use of SiPMs. In addition, the DOE has funded JLAB with a one year program to study the applications of new detector technologies for Nuclear Physics. The Radiation Detector and Imaging Group at Jefferson Lab has a committed involvement in developing SiPMs as a useful technology for Nuclear Physics as well for bio-imaging applications. The group has received funds from both programs. The EIC project deals solely with the radiation tolerance of the SiPMs. The DOE application project includes, as a sub-project, an effort to improve the radiation tolerance of these devices. A survey of the literature also indicates an abiding concern with the radiation sensitivity issue with regard to continued use of the SiPM technology [2]–[6].

This study is a initial look at the relative radiation tolerance of a variety of SiPMs from two major vendors - Hamamatsu and SensL. Further studies are planned with a larger sampling of the products of different vendors, especially if they use substantially different processes for producing their version of SiPMs. It is also hoped that this initial study will allow for a more theoretical approach in which some modeling of the SiPM structure and operation will allow for the possible reconfiguration of current SiPMs to increase their radiation tolerance.

Being a pilot study, it was also decided to focus on the effects of high energy neutrons as it is clear that these devices show their greatest sensitivity to this background, and it will be this background that will have the greatest contribution at facilities based on electron accelerators. The specific affects from an intense gamma background (> 100 Gy/yr) will be left

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for a future study. Certainly some other studies have indicated that a gamma irradiation may have effects not found with a hadronic irradiation [2].

II. RESULTS FROM A PREVIOUS RADIATION DAMAGE STUDY

During the time when the SiPM technology was being considered for use as the photodetector for the BCAL detector, it was decided to check the question of radiation damage. Simulations had indicated a low intensity high-energy gamma background, on the order of a few Grays per year. Studies in the literature [2] indicated that this should not pose a problem. In any case a study was done where the SiPMs were irradiated up to 200 Gy. No significant damage was detected. Subsequent simulations of the high energy neutron background indicated fluences of about 3×10^8 $\text{n}_{eq}/\text{cm}^2$ per year which the literature indicated could increase the dark noise to significant levels over the 10 year expected lifetime of the GLUEX experiment.

An initial study verified this problem and so a more careful study was performed using a JLAB calibrated high-intensity ^{241}AmBe source. The results of this study have been published [7]. Some results from it are worth mentioning as it influenced the methodology used in the present study.

1) A calibrated ^{241}AmBe source acted as the neutron source. Doses are reported in the accepted method of using the NIEL hypothesis of scaling to the fluence of 1 MeV equivalent neutron kinetic energy (units of $\text{n}_{eq}/\text{cm}^2$). For the GLUEX experiment, the expected fluence is 3×10^8 $\text{n}_{eq}/\text{cm}^2$ per typical operating year assuming a $1/3$ running efficiency. Based on previous work, it was decided to limit the total dose to a maximum of 5×10^9 $\text{n}_{eq}/\text{cm}^2$. The JLAB Radiation Control Group provided a calibration curve of the source detailing the dose rate as a function of the horizontal radial distance.
2) In the previous study, it became clear that some of the noise increase was transient and could be minimized by heating the samples (post irradiation) for some time. Whether this is purely a dose rate effect is unclear, but it seems reasonable to make the assumption that only the permanent residual damage should be considered as the quoted quantity. So for this study, after any irradiation, the samples were heated in air at 60°C for 24 hours to remove the transient damage.
3) As seen in the literature, the dominant change in performance is the increasing (linear with dose) rise in the dark noise, whether expressed as dark rate (frequency of pulse above 0.5 photoelectrons) or as dark current. The maximum dose in the study was 5×10^9 $\text{n}_{eq}/\text{cm}^2$ which is below the expected region where breakdown voltage, PDE and gain should be affected. These latter parameters did not change during the previous study. As with that previous case, these characteristics were also monitored during this study as it also provided a consistency check.
4) The increase in noise with dose was not found to different whether the device was powered or not. The linear behavior was same. This allows a simplification for the irradiations, namely the samples could be irradiated non-powered in air at the ambient room temperature.

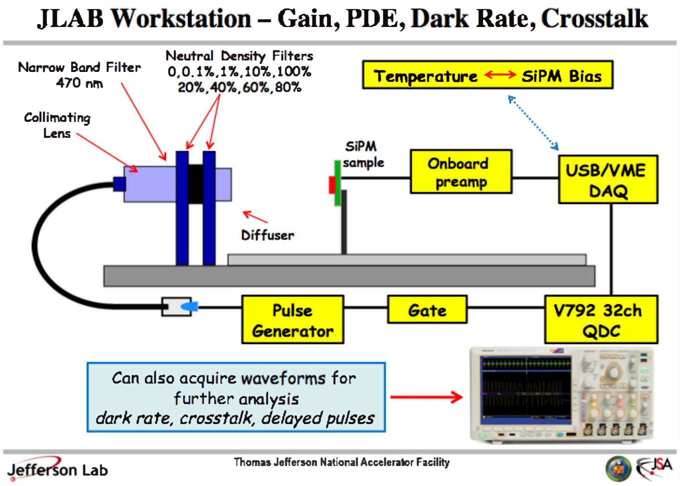

Fig. 1: Setup to characterize performance of SiPMs. The fast blue LED (470 nm) is run at constant amplitude with a dual set of neutral density filters controlling the intensity. A diffuser guarantees uniform illumination of the SiPM. Temperature was monitored so that the operational voltage for the SiPM could be adjusted.

III. IRRADIATION METHODOLOGY

Characterization is done with a SiPM test station shown in Figure 1. Excepting the measurement of the device IV curves, all characterizations were done in pulsed mode. The SiPMs were powered and the signal readout with JLAB designed board (for 1×1 mm^2 samples) specifically optimized for the Hamamatsu SiPMs. SensL provided their own board for their devices. Bias voltage was the standard operational voltage modified to account for the actual room temperature (typically 23-24°C) using the temperature coefficients provided by the vendor. A fast blue LED (mean wavelength = 470 nm) was used as the light source. Calibration of the source (via a calibrated photodiode) allowed the measurement of the PDE, and analysis of the charge spectra was used to monitor the gain and the dark rate as a function of the total dose. Dark rate was measured as the mean photoelectron count of the device when the charge spectrum was measured in total darkness. This quantity μ_{dr} is defined as

$$\mu_{dr} = -\ln\left({}^{N_0}\!/_{N_t}\right)$$

where N_0 is the number of pedestal counts and N_t is the total number of counts in the spectrum. A Keithley 6487 picoammeter was used in DC mode to measure the IV curve of the SiPMs. The dark current and dark rate are considered complementary measurements. The dark rate is measured for a specific acquisition gate time which is sufficient to encompass the SiPM pulse. However, limiting the gate width also tends to minimize the effect of additional noise caused by crosstalk and afterpulses. The dark current is a DC measure of all the

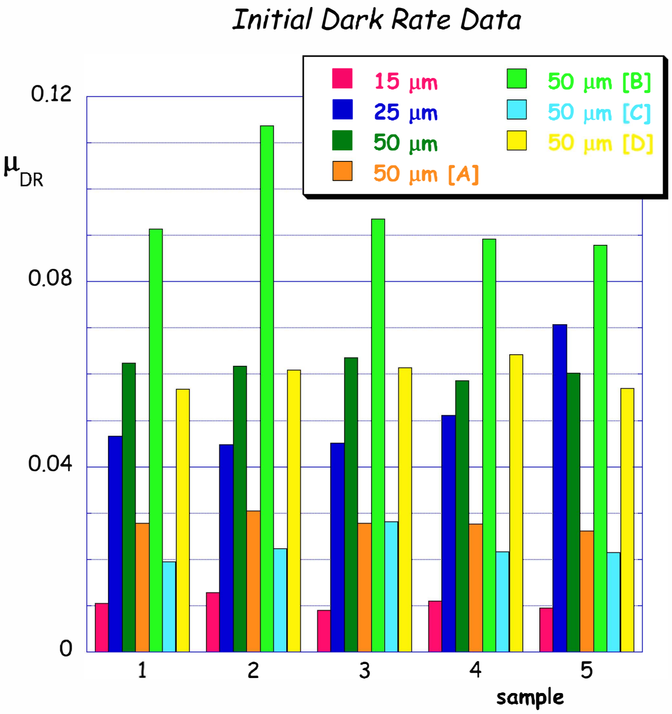

Fig. 2: Initial dark rate for Hamamatsu samples

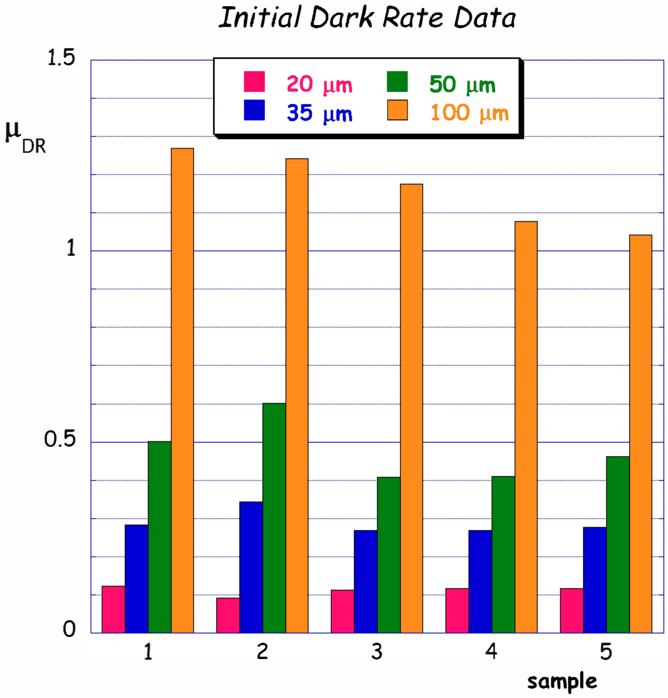

Fig. 3: Initial dark rate for SensL samples

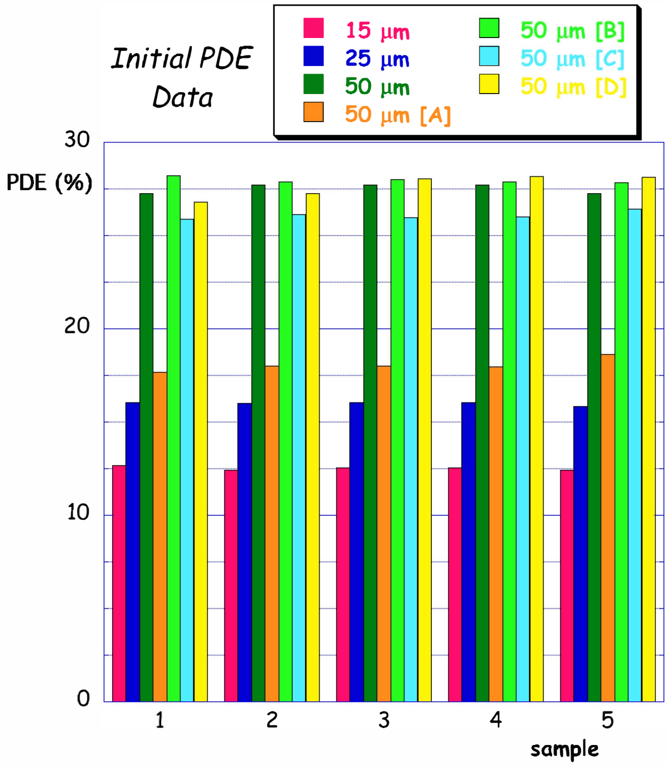

Fig. 4: Initial PDE values for Hamamatsu samples

noise effects taken together. Using longer gate widths and more elaborate parametrization of the charge spectra, one can separate the effects of simple dark rate from crosstalk and afterpulsing. The much simpler method of monitoring dark rate and dark current was chosen for this study. The dark current measurement is also useful when the noise rate becomes so high that the dark rate cannot be measured from the pulsed ADC spectra.

Using the pulsed mode and DC measurements, the following quantities could be monitored during the irradiation tests: Voltage Breakdown V_{br}, Dark Current I_{dc} (as a function of applied bias), Dark Rate μ_{dr}, Photon Detection Efficiency PDE, and Gain. Figures 2-3 displays the initial values of the Dark Rate for the samples (both vendors) before irradiation. Figures 4-5 similarly displays the initial PDEvalues.

IV. RESULTS

A. *Hamamatsu*

As with other researchers, it was seen that, for the dose levels of this study, Voltage Breakdown, PDE and Gain remained constant, at least for the samples where quantification of the charge spectra were possible. The main effect of the irradiation is the increase of noise in the devices. Figures 6-7 displays the incremental changes in Dark Rate μ_{dr} with increasing dose. The photoelectron peaks were well-resolved for all the samples throughout all the dosages. Linear fits indicate that the change in Dark Rate for all the devices fits within a narrow range of 0.05-0.06 yr^{-1}. This is clearly a sign that although the initial Dark Rates cover a wide range of values, the damage rate is very similar among all the device types. Translating this into rates for a 200 ns ADC gate, the rate of increase is 80-100 kHz mm^{-2} for a fluence of 10^8 $\text{n}_{eq}/\text{cm}^2$. Given that most of the samples have initial rates below 400 kHz mm^{-2}, this implies a rapid increase of noise rate per year. In essence, all of the devices would be equally disadvantaged after several years of exposure

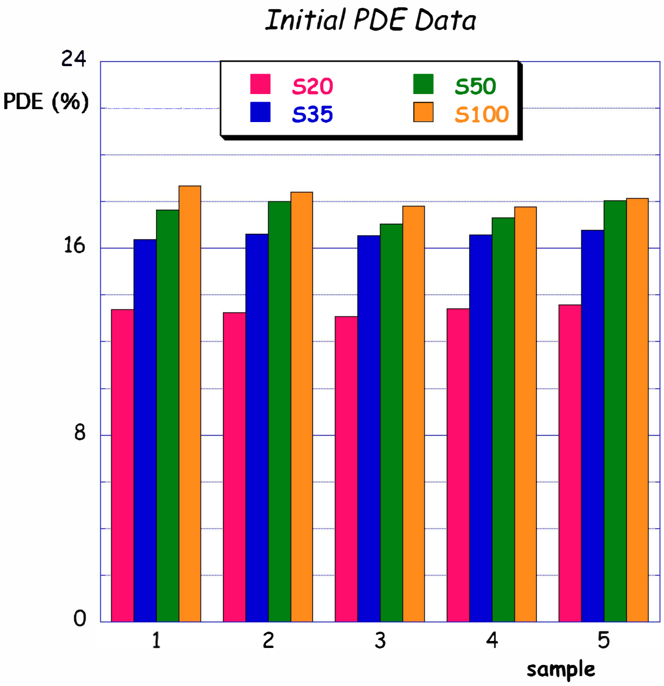

Fig. 5: Initial PDE values for SensL samples

To provide a measure of performance, it is proposed that a Quality Factor be defined that quantifies the relative effect of Gain, PDE and the Dark Rate. As seen experimentally, Gain and PDE seem to be unchanged with dose and one only needs to use the values defined at the standard operational voltage. The Quality Factor (QF) will be defined as follows:

$$QF = \frac{\langle PDE\rangle * \langle Gain\rangle}{\mu_{dr}}$$

where $\langle PDE\rangle$ is the fractional PDE$(0-1)$, $\langle Gain\rangle$ is the gain renormalized to 10^6 to provide a fractional value $(0-1)$, and μ_{dr} is the fractional Dark Rate $(0-1)$. Figure 8 shows both the pre-irradiation values of QF and the expected value at the maximum dose. Although 50C starts with the highest relative quality factor, the performance decreases rapidly with dose to the point where it only has a marginal advantage over the other 50 micron devices. The small pixel types, 15 and 25 microns, seem poor in performance, but may in fact be desirable in cases where the higher pixel densities are required for a larger dynamic range.

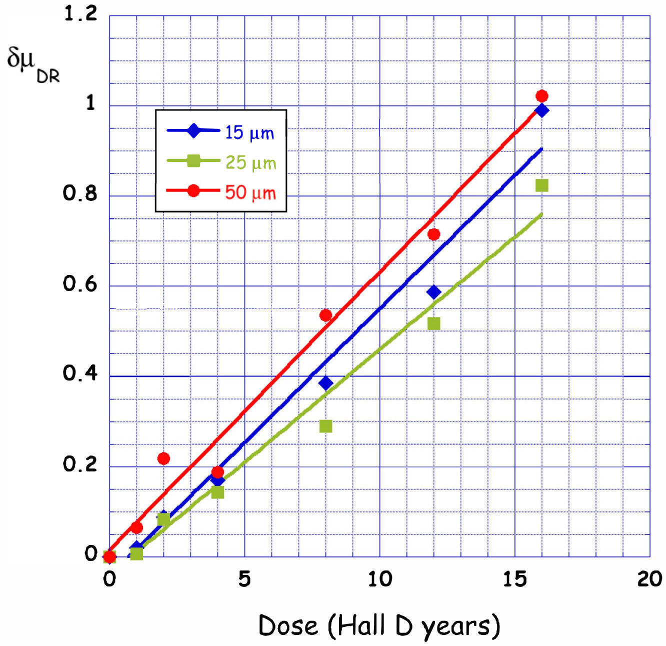

Fig. 6: Incremental dark rate changes in the Hamamatsu 15, 25, and 50 (standard) micron types.

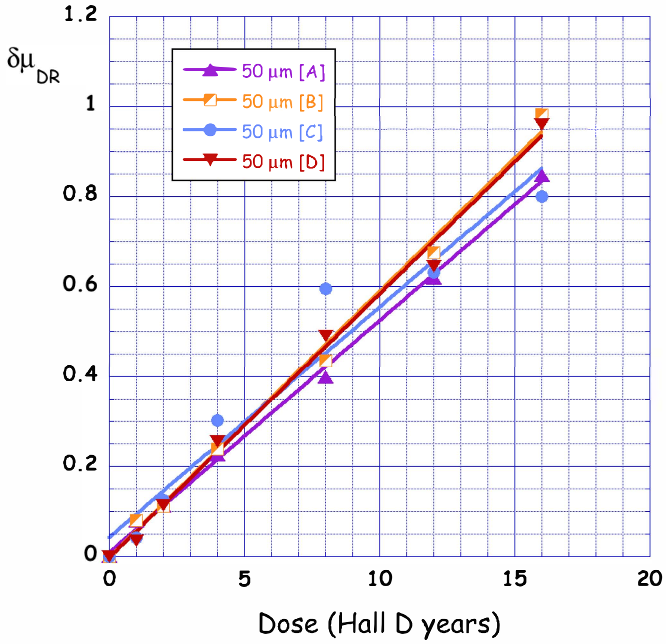

Fig. 7: Incremental dark rate changes for new Hamamatsu 50 micron types.

B. SensL

Figure 3 shows the initial dark rates for the SensL devices. In this case, the large range of pulse timing characteristics precluded any attempt to use a common ADC gate width. Moreover, even if the gate width is factored out, these devices still have a much higher noise rate than the Hamamatsu ones. It was found that the photoelectron resolution dropped rapidly with dose and microcell size to the point where only the dark rates for the 20 micron model could be measured for all dosages. The 35 micron had a limited range of measurement. This is shown in Figure 9 where the dark rate data is only shown for these two models. As an alternative, the change in dark current is followed in Figure 10. Unlike the Hamamatsu case, it is the relative ratio to the device's pre-irradiation value that is plotted. Again, as with the Hamamatsu devices, it is seen that the rate of change in the noise is similar in all the device types. However, the rate is much higher than in the Hamamatsu case. Using the slope from Figure 9 and the initial rate for the 20 micron model from Figure 3, the noise rate increases at about 0.3 MHz mm^{-1}for each additional dose of

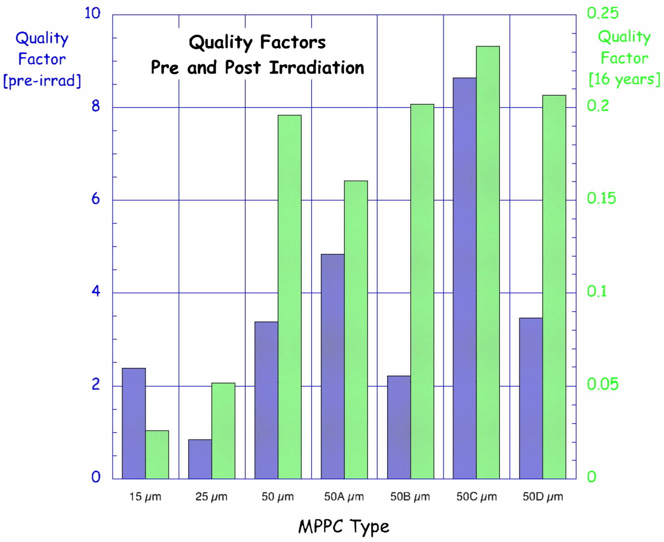

Fig. 8: Changes in the initial and post irradiation quality factor among the SiPMs. Note how the relative standing tends to equalize at the maximum dose indicating the overwhelming influence of the dark noise on the eventual performance of the device.

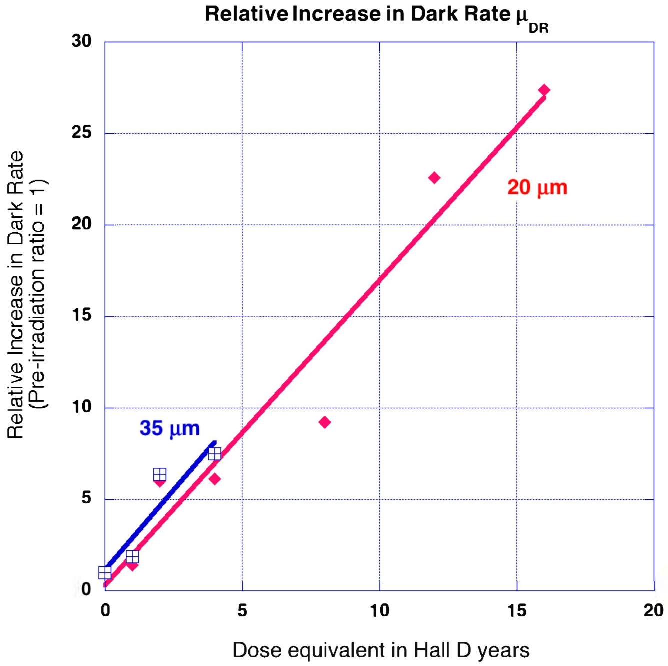

Fig. 9: Relative increase (ratio of post to initial value) of dark rate with exposure for the SensL samples. Only the 20 and 35 micron types were able to maintain sufficient photoelectron resolution.

10^8 n_{eq}/cm^2.

It should be noted here that at the time of the study, only the *L* series from Sensl was available. At the time of this writing, the improved *M* series has become available. These will evaluated in the near future.

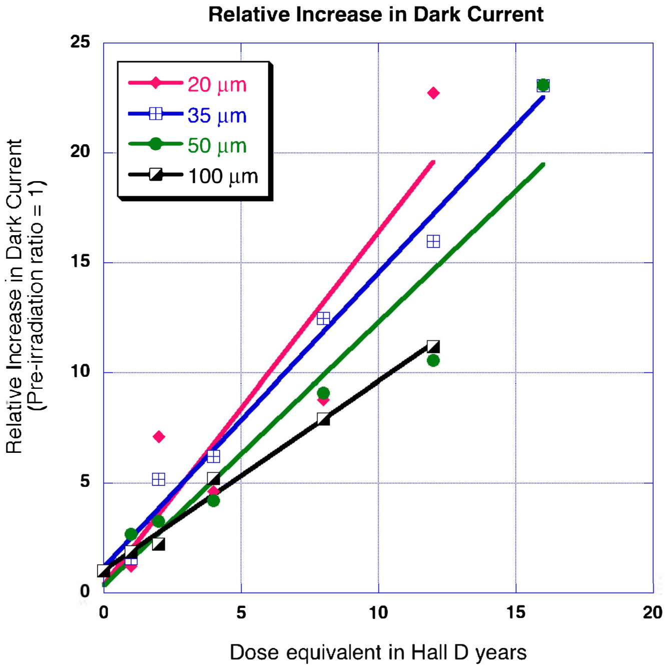

Fig. 10: Complementary to Figure 9, the relative increase (ratio) of the dark current measured at the standard operating voltage of 2 volts above the breakdown voltage. This also shows the similar increase in dark noise among all the microcell types although at a different rate from that of the Hamamatsu devices.

V. COMMENTARY

For neutron doses below 10^{10} n_{eq}/cm^2, no sign of any deleterious effect on voltage breakdown, PDE or gain has been seen. The increase in dark noise is significant and can be a limiting factor in the use of these devices. For a given vendor's product line, dark rate increases linearly the same rate regardless of microcell size. A combination of relatively high gain and PDE combined with low noise (as with the type 50C from Hamamatsu) can be an advantage, but the rise in noise level with dose tends to minimize this initial advantage. For now, it still seems best to cool these devices during exposure to background radiation to minimize the effect of the increased noise rates. The extent of this cooling will be dependent on the particular situation. It may also be necessary to heat the devices during beam down times to anneal the devices and minimize the amount of noise increase.

Plans are in place to continue these studies. This will include microscopic examination of the irradiated samples with an infrared camera, and testing a new variety of samples from a number of vendors, including the present ones. It is to be noted that in the proceedings of this conference, there are already claims of increased radiation tolerance from at least one vendor.

ACKNOWLEDGMENT

The authors wish to acknowledge the important role of the Jefferson Laboratory Radiation Control Group (RADCON) for providing support during the irradiations of the samples. The authors also wish to thank the representatives from Hamamatsu and SensL Corporations for their continued interest in this research program as well as for provision of the SiPM samples. W. Steinberger is presently an undergraduate at Rensselaer Polytechnic Institute, Troy, NY.

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