# Dose Rate Response of MOS and Bipolar Devices: A Comparison between Flash Protons and Electrons

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*Abstract*

For the first time, dose rate responses of MOS and bipolar devices are characterized to 20-ns pulses of protons (flash protons) at the Indiana University Cyclotron Test Facility using a cooler injector synchrotron. The flash proton responses of these devices are then compared to the responses of similar devices that were characterized to 20-ns pulses of electrons at the NAVSEA-Crane linear accelerator test facility. This paper demonstrates that the use of flash protons generated with a synchrotron provides distinct advantages to the use of electrons generated with a linear accelerator. These data strongly suggest that protons are a viable radiation source for simulation of transient type environments.

## I. INTRODUCTION

There continues to be a need to validate space and weapons systems in a nuclear weapons environment in case of a nuclear weapons event. However, without the capability to perform nuclear underground testing, several national simulator facilities have been developed to test twenty-first century space and missile systems and their components to validate system performance.

In an earlier study [1] the Cooler Injector Synchrotron (CIS) at the Indiana University Cyclotron Facility (IUCF) was demonstrated to be a potential weapons environment simulator, where 20-ns burst of protons was correlated to 20-ns burst of electrons. If this type of source is demonstrated to provide a valid response for this type of environment, it may lead to the development of a high intensity, proton synchrotron specifically designed for high dose rate radiation effects testing. Details concerning the design and operation of the CIS can be found in that earlier study [1].

This paper provides the first measured dose responses of MOS and bipolar devices characterized to 20-ns pulses of flash protons using the IUCF CIS. The flash proton responses of these devices are then compared to the dose responses of similar devices that were characterized to 20-ns pulses of electrons using a linear accelerator located at NAVSEA-Crane, Indiana. This paper will demonstrate that flash protons provide advantages to electrons and is likely a viable radiation source for transient type environments.

## II. DOSIMETRY METHODS

The CIS beam was tuned using a removable copper Faraday stop mounted in air upstream from the test site. The Faraday stop could be moved in and out of the beam remotely from the data acquisition area. The pulse repetition rate was set up to provide a pulse every few seconds. A wall gap monitor located just upstream from the test site in the evacuated portion of the transfer line was used to monitor the quality and time structure of the beam pulses. Beam positioning monitors located upstream were used to monitor the beam position and profile. Quadrupole magnets in the transfer line were used to adjust the beam spot size. GafChromic films were used to physically locate the beam position, to determine a spot size, and to ascertain a dose profile. A laser alignment tool was then used to position the PIN diode and thermoluminescence dosimeters (TLDs) to the approximate beam center. The PIN diodes and TLDs are similar to the dosimeters used to monitor and measure electron pulses at the NAVSEA Crane Linac test facility. A schematic of the Flash Proton Experiment at the IUCF CIS is shown in Figure 1.

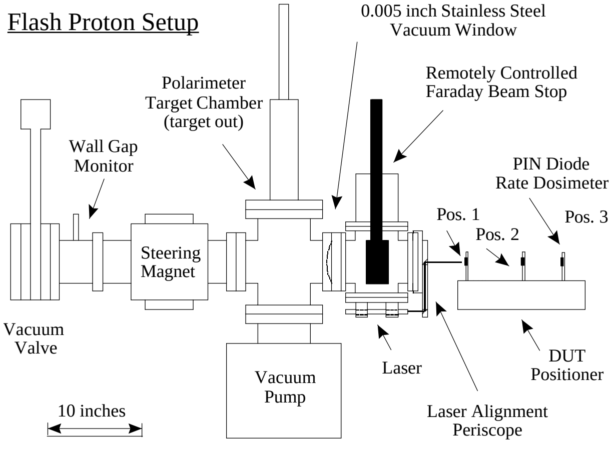


Fig. 1. Schematic of the beam line setup between CIS and the Cooler used. The proton beam went from left to right.

For direct comparison of the dose at IUCF and the NAVSEA Linac, dosimetry at both facilities was performed using a PIN diode, calcium-fluoride manganese doped ($CaF_2$:Mn) TLDs, and GAF Type 55 films. The PIN diode was displaced but calibrated using TLDs and GAF films. The TLDs and GAF films were placed directly on each DUT. GAF films were only used at the IUCF.

### *A. PIN Diode Description*

For this experiment, a reverse biased 6202 PIN diode was used to monitor the intensity of each radiation pulse using the circuitry depicted in Figure 2. The PIN diode was mounted toward the ‘back’ of the test area, about 13.75 inches from the beam exit port and reversed biased at 200 volts. The DUT fixtures were placed at various distances between the exit port and the PIN diode. The PIN diode response determined the dose rate for each flash proton pulse. The 6202 was calibrated using films placed at the DUT and PIN positions, which determined the dose ratios for the DUT positions relative to the PIN.

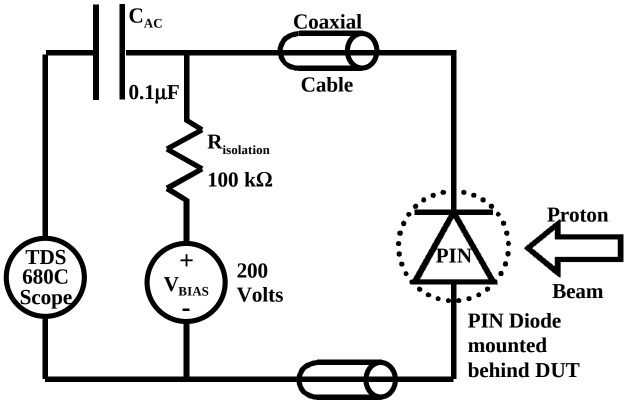


Fig. 2. Pin diode circuit used. Film is placed at the approximate DUT location to determine the dose of each pulse to calibrate the PIN diode.

Figure 3 shows a typical PIN diode response recorded using a high-frequency digital oscilloscope, a TDS 680C. The dose response was obtained by integrating the area of the PIN diode response at 10% of its peak response.

$$\text{dose} = (10)^{C1}(\text{area})^{C2} \qquad (1)$$

This integrated area was then subsequently used in Equation 1 to determine the variables, C1 and C2, by performing a least square fit of the measured dose (obtained with the TLDs) [2].

### *B. GAF Chromic Films*

The film was placed at the positions of each DUT and the PIN diode. The optical density of the film was then measured in gray (film). The data was then converted to gray (Si) or rad (Si). The conversion factor from rad (film) to rad (Si) is 0.813 at 205 MeV and is a weak function of beam energy. Corrections for actual beam energy losses were not made.

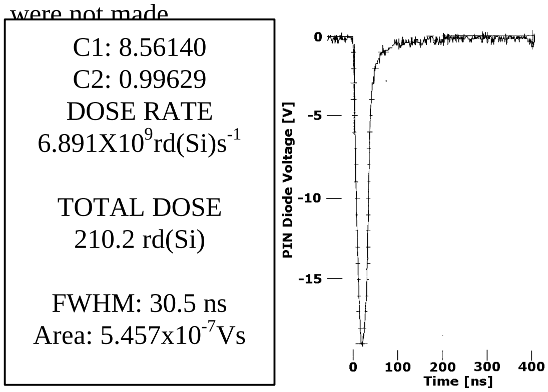


Fig. 3. Typical PIN diode response when subjected to a 30.5-ns proton pulse.

## III. TEST PROCEDURE

Numerous bipolar and MOS device types were selected for this study. Each device type was tested in a configuration using the same test boards that was used to test similar devices at the linear accelerator. A description of each device type and characterization are provided.

### *A. Response of Discrete Devices*

The photocurrent response of two bipolar transistors, three power-MOSFETs, and a Schottky diode were characterized to obtain their response to both flash electrons (NAVSEA LINAC) and flash protons (IUCF).

### *(1) Bipolar Transistor Photocurrent Response*

Two bipolar transistor types have been extensively characterized to obtain their peak photocurrent responses when exposed to electrons using a linear accelerator and when exposed to flash protons using the IUCF CIS. The selected devices were the 2N3468 (1W) PNP switch and the 2N3019 (1W) NPN switch. Both of these devices were characterized using a specific bias condition and a load-sensing resistor to monitor the photocurrent response.

In both Flash Proton and Linac environments the transistors were configured so that a specified reverse bias (12 volts) was applied across the collector region of the transistor with the emitter and base tied together. Selected current sensing resistors were used to monitor Ipp across the collector junction. In Figures 4 and 5, the peak photocurrent response of the 2N3468 and the 2N3019 are compared showing the observed response for flash protons and electrons over a range of dose rates. The observed photocurrent responses show a displacement in device response between flash Protons and electrons, however both flash Protons and electrons show the same trend with dose rate. There are several possible reasons for this displacement in device response, some of which will be provided in the discussions section.

### *(2) Power MOSFETs Photocurrent Response*

Three power MOSFET types were characterized for their peak photocurrent response using flash protons (IUCF synchrotron) and electrons (NAVSEA LINAC). The three part types were the FRF150D, FRF250D, and FRF450D. The FRF150 is a 100-volt power MOSFET, the FRF250 is a 200-volt MOSFET, and the FRF450 is a 500-volt MOSFET. All three are radiation-hardened power MOSFETs Manufactured by Intersil Corporation. For reference, more in-depth dose rate responses of these devices types and other power MOSFETs types can be found in two recent studies [3]-[4].

The peak photocurrent responses of all three, device types were obtained under three off-state bias conditions over a range of dose rates when exposed to flash protons and electrons. Figure 6 and 7 show a comparison of the observed photocurrent response of the FRF150 and FRF250, respectively when exposed to flash protons and electrons. In Figure 8 the ratio of peak photocurrent and the dose rate versus applied drain voltage of the FRF450 at a dose rate of 9.5 x $10^9$ ± 5 x $10^8$ is shown. Those figures indicate that both radiation sources (electrons or protons) provide similar device response. A more detailed explanation is provided in the discussions section.

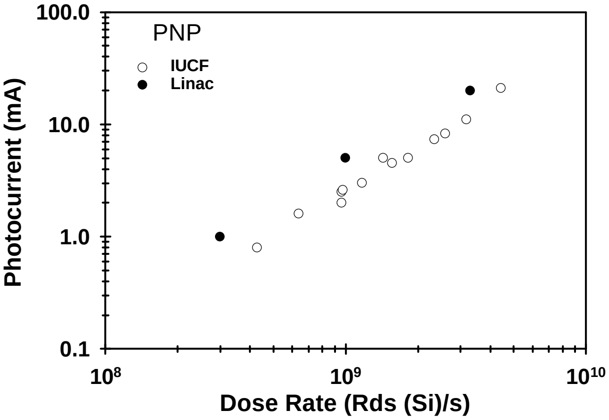


Fig. 4. The Photocurrent response in Flash Proton and Linac environments of the 2N3468 (1w) PNP switch

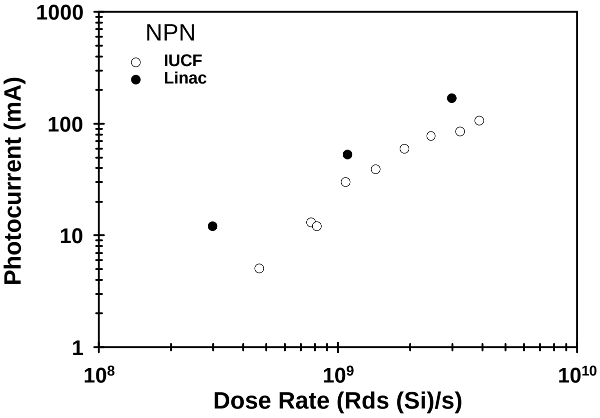


Fig. 5. The Photocurrent response in Flash Proton and Linac environments of the 2N3019 (1w) NPN switch

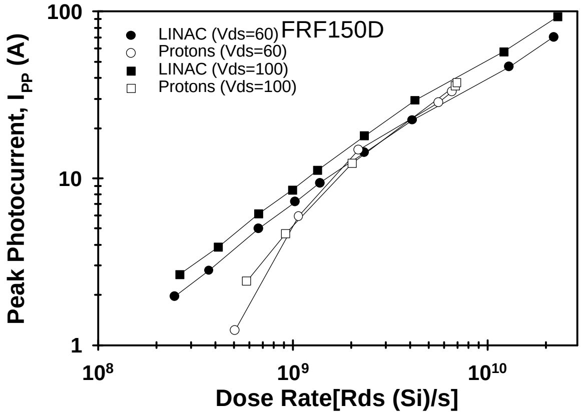


Fig. 6. Peak photocurrent response of the FRF150D Power MOSFET showing a comparison between flash electrons and protons with a drain bias of 60 and 100 volts over a range of dose rates.

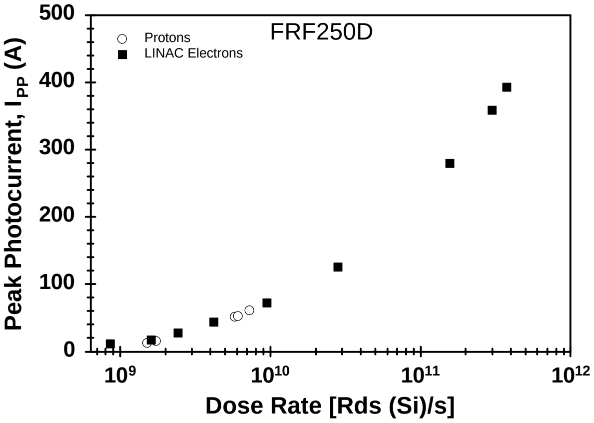


Fig. 7. Peak photocurrent response of FRF250D showing a comparison between flash electrons and protons at a $V_{DS}$ of 200 volts over a range of dose rates.

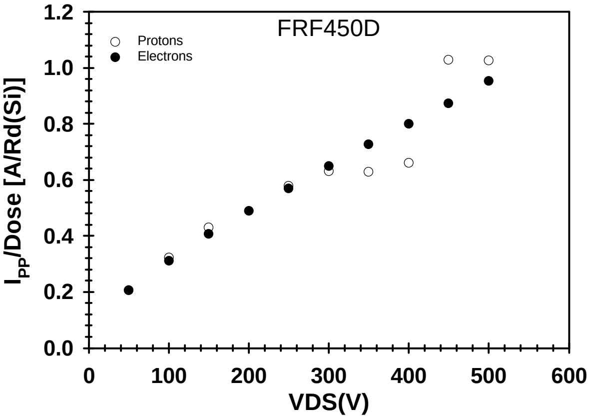


Fig. 8. Normalized peak photocurrent (Ipp / dose rate) response of FRF450D

as a function of applied drain voltage ($V_{DS}$) showing a comparison between the flash electrons and protons at a fixed dose rate of 9.5 x $10^9$.

*(3) Power Schottky Diode Photocurrent Response*

Another device type, a power Schottky diode (15CGQ100), has recently been characterized for its dose rate response using 20-ns pulses of electrons in a linac environment along with several other schottky diode types [5]. The 15CGQ100 is a 100-volt, schottky diode and it is manufactured by International Rectifier.

The peak photocurrent responses of the IR 15CGQ100 were obtained under three off-state bias conditions over a range of dose rates when exposed to flash protons. Figure 9 shows a comparison of the observed photocurrent response of the IR 15CGQ100 when exposed to flash protons and electrons. This figure indicates that both radiation sources (electrons or protons) provide similar device responses. A more detailed explanation is provided in the discussions section.

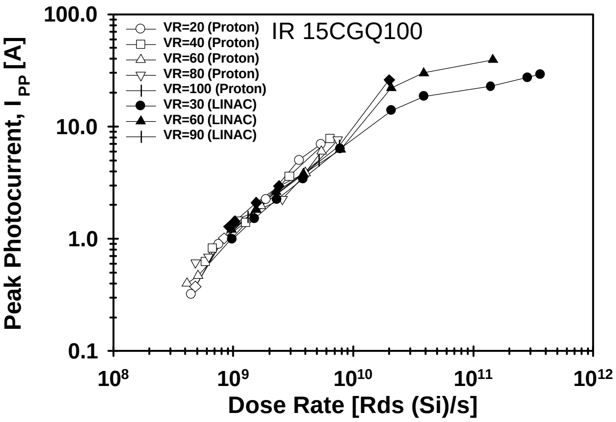


Fig. 9. Peak photocurrent response of the 15CGQ100 power schottky diode showing a comparison between flash protons and electrons under various bias conditions over a range of dose rates.

*B. Response of Integrated Circuit*

The photocurrent response of a CMOS circuit was characterized to obtain its dose rate response to both flash electrons (NAVSEA LINAC) and flash protons (IUCF).

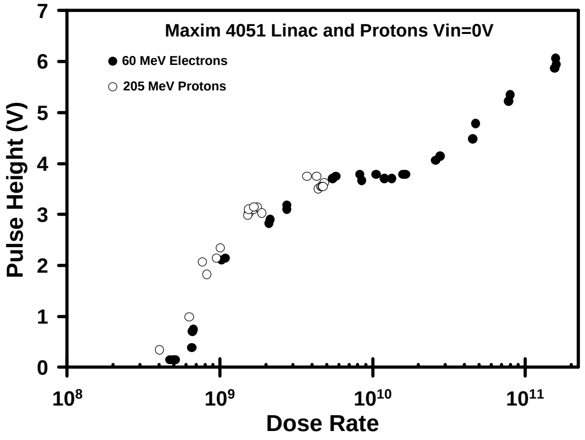
*(1) CMOS Circuit Function*

A Maxim 4501 CMOS analog switch was included as an evaluation circuit. The MAX4501 is a single-pole/single-throw (SPST), low-voltage, single-supply, CMOS analog switch with a normally-open (NO) contact. The circuit contains 17 CMOS transistors. A 5-V bias was applied to the power pin ($V_{pp}$) and the input was controlled using input levels of 0 and 3 volts. The dose rate response of the circuit was evaluated in two operating modes the normally-open (NO) position, which used an input level of 0 volts and the closed position, which used an input level of 3 volts. The output response for each condition was recorded. The same test fixture was used for both proton and LINAC evaluations.

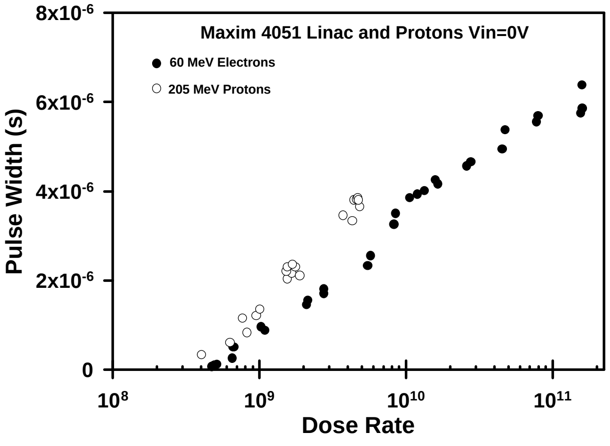
The output dose rate upset response was characterized by two factors:

1) peak voltage of upset transient (Pulse Height) and
2) time period of the upset transient spike (Pulse Width).

Figures 10 and 11 show the peak voltage and transient pulse response for both linac and flash proton sources for the dose rate range with input levels of 0 and 3 volts, respectively. These figures show that there is general agreement in device response between flash protons and linac electrons. This will be revisited in more detail in the discussions section.



a) Pulse Height

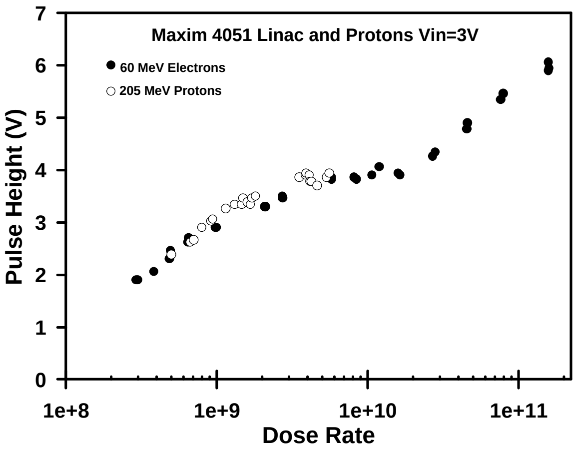


b) Pulse Width

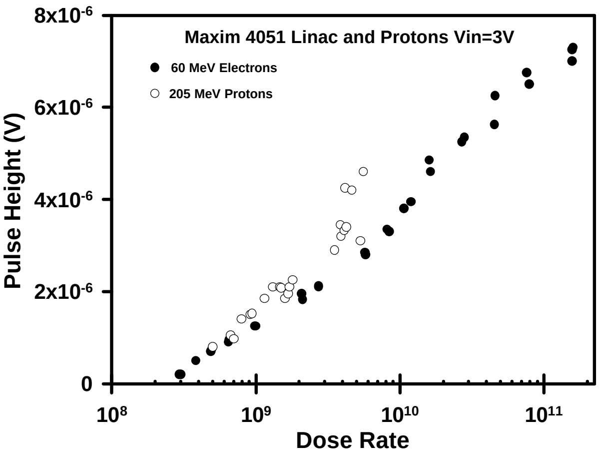
Fig. 10. The Responses, a) Pulse Height And b) Pulse Width, Of The Maxim 4501 To 205 MeV Protons And 60 MeV Electrons At An Input Of 0 V(Open State).

## IV. ADVANTAGES

The use of the IUCF Synchrotron provides advantages over conventional Linac testing. One of these advantages is the low noise test environment when using the synchrotron. Some of these noise issues were addressed in our earlier



a) Pulse Height



b) Pulse Width

Fig. 11. The Responses, a) Pulse Height And b) Pulse Width, Of The Maxim 4501 To 205 MeV Protons And 60 MeV Electrons At An Input Of 3 V(Closed State).

study [1]. This section examines the noise issue again as well as examines the effect of other beam issues.

### *A. Noise Example of Linac vs Synchrotron*

It is difficult to describe all the noise issues with respect to dose rate testing. Experimenters expend a significant amount of time and money addressing these issues. Figure 12 shows a photocurrent response taken at IUCF CIS test facility using a 1GHz Bandwidth limited scope. The EMI in the upper trace illustrates a 1.3GHz RF signal generated by the CIS LINAC. This RF signal is common with linac type facilities: it occurs at the DUT simultaneously with the electron pulse, and it commonly interferes with the test measurement as noise. Figure 12 also shows in the bottom trace the capacitive pickup of the faraday cup, which indicate when the protons arrive at the test fixture. In the CIS the protons arrive after the RF signal has already decayed to a very manageable level. This demonstrates that the flash proton source has an inherent advantage over a LINAC facility in shielding RF noise.

### *B. Dose Rate Modulation*

As described by Foster et al. [1] the methods to modulate the exposure dose rate differ between synchrotron protons and Linac electrons. The proton dose rate is varied by changing the beam flux directly, while maintaining a fixed DUT position. The electron dose rate is varied by changing the DUT position, which modulates the beam flux incident on the DUT indirectly. This approach for protons offers a distinct advantage in that it simplifies the test requirements.

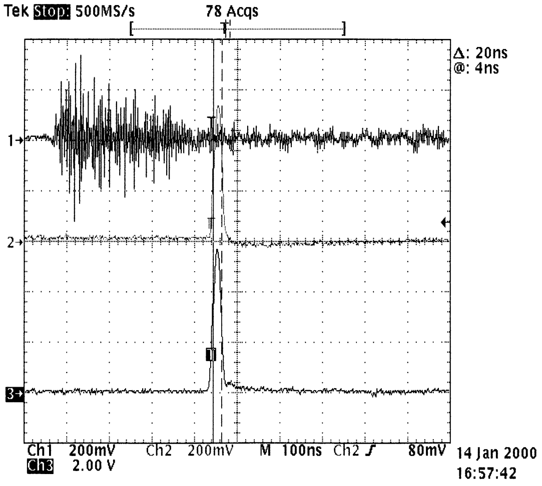


Fig. 12: Comparison Of Amplified (~ 37 Db) EMI Noise (Upper Trace) With The Beam Pulse Signal From The Capacitive Pickup Monitor (Middle Trace) And From The Faraday Cup (Bottom Trace) At The IUCF CIS. The Vertical Scales Are 200 Millivolts Per Division For EMI Noise And Capacitive Pickup And 2.0 Volts Per Division For The Faraday Cup. The Horizontal Scale Is 100 Nanoseconds Per Division.

### *C. Shielding issues*

Another common issue encountered with Linac test facilities is shielding. Generated electrons are easily scattered which requires sufficient shielding to protect circuit components. This is usually accomplished by encasing the test board with lead with a collimator hole to allow the DUT to be selectively exposed.

On the other hand, protons are 3 orders heavier than electrons and not as easily scattered by interaction with air and other materials. Therefore, the test board does not require elaborate shielding.

### *D. Penetration Depth (Modules and Multiple Boards)*

High energy protons are minimally ionizing. That means that they produce relatively few secondary electrons. Approximately one secondary electron is produced for every thirty protons that strikes a copper surface. High energy protons also have a relatively long range in most materials. For example, it takes nearly two inches of copper to stop a 200-MeV proton. In addition, as these protons traverse through a material multiple scattering causes the number of particles/cm$^2$/s (flux) to decrease while the stopping power increases as the protons lose energy. This means that the dose rate, which is proportional to the product of the stopping power and the flux, changes slowly as the proton penetrates a material. This effect continues until the proton energy falls below about 80 MeV. Below this energy, the stopping power begins to change more rapidly. These properties make high energy protons well suited for characterizing the response of integrated systems which can have numerous layers of material to traverse (exposure of black box or module) or test multiple boards. An example of a stacked DUT experiment is shown in Figure 13. In Table 1, the change in the stopping power an initial proton beam of 205 MeV as it passes through successive layers is illustrated.

Table 1.
Calculated Change in LET For Two Stacked Generic Boards

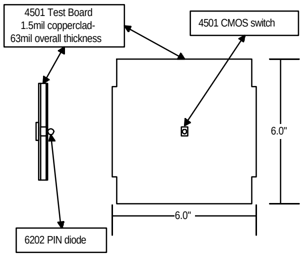
| Layer | Incident Energy (MeV) | Exiting Energy (MeV) | Thickness (cm) | LET $\left(\frac{\text{MeV}\cdot\text{cm}^2}{\text{g}}\right)$ |
|---|---|---|---|---|
| Air | 205.00 | 204.96 | 10 | 3.596 |
| DUT #1 | 204.96 | 202.35 | 0.33 | 3.597 |
| Air | 202.35 | 202.29 | 10 | 3.626 |
| DUT #2 | 202.29 | 199.69 | 0.20 | 3.627 |
| Air | 199.69 | 199.65 | 10 | 3.656 |

## V. DISCUSSIONS

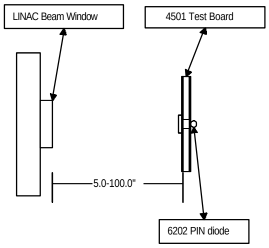
The use of synchrotron protons as an emulator for a Linac electron environment rests on the following observations. The CIS emits 200 MeV protons that have a stopping power of 3.637 (MeV cm$^2$)/g in silicon and a NEIL of 1.94 X 10$^{-4}$ (MeV cm$^2$)/g, yielding 2.33 x 10$^6$ electron-hole pairs per cm and 1.23 x 10$^3$ electron-hole pairs respectively. The NAVSEA-Crane Linac generating 50 MeV electrons with a stopping power of 3.802 (MeV cm$^2$)/g and a NEIL of .15 (keV cm$^2$)/g, yielding 2.44 x 10$^6$ electron-hole pairs per cm and 95 electron-hole pairs respectively. There are 2.33 x 10$^6$ and 2.44 x 10$^6$ electron-hole pairs generated by ionization for 200 MeV protons and 50 MeV electrons respectively. Therefore, there is equivalence in ionization between Linac electrons and synchrotron protons. In addition, in both environments, there is negligible displacement damage.

This experiment was designed as a demonstration of the viability of using flash protons to simulate an x-ray environment compared with using electrons generated with a Linac. Since the use of the IUCF synchrotron was limited, the experimental setup and procedures were somewhat fluid. This approach was employed because the test setup had to be quickly implemented. The IUCF had prior commitments for the proton beam allowing only a limited operating window (24 hours) to setup the necessary test hardware, beam tune-up, and finally make the necessary measurements. We felt this may have increased the possibility of error in alignment of the DUTs to the beam, which ultimately affected the overall dosimetry, notwithstanding normal dosimetry error.

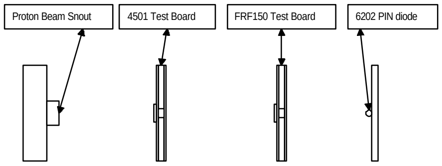
Figure 13 illustrates that the PIN diode was placed toward the rear of the test area. Figure 14 shows the dose profile of the beam measured with MD55 GafChromic film and shows that the beam spot is very narrow. A small displacement in the DUT board could easily result in an



a) DUT Board



b) LINAC Test Setup



c) IUCF Flash Proton Test Setup

Fig. 13: DUT Layout Showing, a) DUT Board b) LINAC Test Setup and c) Setup Used At IUCF With Multiple Board Stacking.

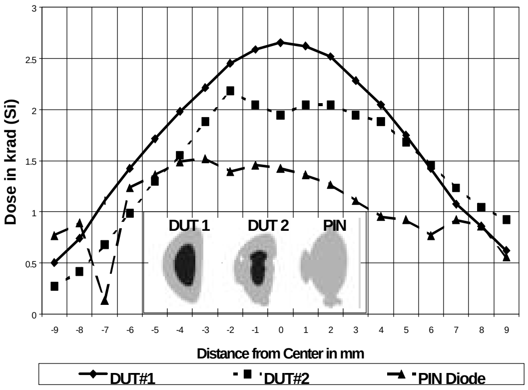


Fig. 14. Film measurements at the PIN diode and two DUT positions. Dose distributions were obtained from the change in optical density of MD55 GafChromic film, seen in the inset (not to scale).

overestimation of the dose rate, if not accounted for in the dosimetry measurements. In the future, this error will be minimized by placing a PIN diode directly behind each DUT, allowing on board dosimetry measurements.

In the majority of the test devices, the responses show good agreement between flash protons and Linac electrons, in both general trends and specific results. However, with the 2N3468 PNP switch in figure 4 and the 2N3019 NPN switch in figure 5 there is a displacement in the measured responses of about 20%. There are several possible explanations for this displacement. One explanation is that different devices were tested at each facility. It has been documented that response variations between devices can occur, due to inherent differences encountered during the fabrication process. Another explanation is that the dosimetry error may have been slightly higher as previously discussed. Despite these issues, there is very good agreement in the observed dose rate responses between Linac electrons and flash protons.

## VI. ACKNOWLEDGMENT

The authors would like to thank Lew Cohn, and acknowledge the support given to this project by the Defense Treat Reduction Agency (DTRA). The authors would also like to recognize and acknowledge the efforts of the individuals, manufacturers, and groups who have contributed to this project. We are particularly grateful to the personnel at the NAVSEA Crane Linac and the IUCF Facilities.

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