ONLINE TOTAL IONISATION DOSIMETER (TID) MONITORING USING SEMICONDUCTOR BASED RADIATION SENSORS IN THE ISIS PROTON SYNCHROTRON

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Abstract

During routine operation, the radiation levels in the ISIS proton synchrotron become high enough to permanently affect systems and electronics. This can potentially cause critical components to fail unexpectedly or denature over time, causing disruption for users of the ISIS facility or a loss of accuracy on a number of systems. To study the long term effects of ionising radiation on ISIS systems and electronics, the total dose received by such components must be recorded. A semiconductor based online Total Ionisation Dosimeter (TID) was developed to do this, using pin diodes and Radiation sensing Field Effect Transistors (RadFETs) to measure the total ionisation dose. Measurements are made by feeding the TIDs with a constant current, with the threshold voltage on each device increasing in relation to the amount of radiation that it has received. This paper will look at preliminary offline results using off the shelf Field Effect Transistors (FETs) and diodes, before discussing the development of the RadFET online monitor and the results it has gathered thus far. Finally the paper will look at future applications and studies that this type of monitor will enable.

INTRODUCTION

ISIS is a pulsed spallation neutron and muon source facility, consisting of a H^- linear accelerator (Linac) and a proton synchrotron. The Linac accelerates H^- ions up to an output energy of 70 MeV, these ions then have their electrons removed with a stripping foil on injection into the synchrotron. The protons (H^+ ions) are then accelerated up to 800 MeV before being extracted and directed to one of two target stations. ISIS runs in user cycles, during these cycles the accelerator runs for 24 hours a day for 6-8 weeks, this is when scientists use the neutrons and muons created by the facility to study materials in the target station beam lines. Maintenance operations are carried out during shutdown periods between these cycles, it is best to change components and systems during these shutdown periods, to avoid disrupting the users of the facility.

When the accelerator is being operated, some areas like the synchrotron, become off limits due to the amount of radiation produced. While radiation exposure to personnel has always been monitored at ISIS, historically it has not been done for systems and components. To try and predict when components or systems may fail due to radiation damage, an online TID monitor has been developed, using off the shelf FETs, pin diodes, and application specific RadFETs. The developed TID monitor allows for a number of studies to take place, such as component characterisation, however this paper will primarily focus on the development of the monitor.

Semiconductors are permanently affected by ionising radiation [1]. As high energy particles travel through the gate of a FET, the radiation induced charges get trapped in the gate and create electron hole pairs (see Fig. 1) [1, 2]. Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) have been shown to be more susceptible to radiation effects than the more generic FETs, due to this, they will be the type of FETs used in these experiments.

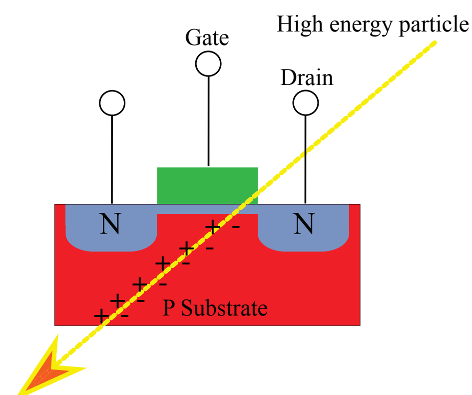

Figure 1: High energy particles creating electron hole pairs and trapping charges in the gate of a Field Effect Transistor (FET) as they travel through.

When biasing a FET or diode that's been irradiated with a constant current the voltage measured back will be proportional to how much radiation the component has been subjected to [2]. This allows for these components to be used as dosimeters. Organisations like the Tyndall Institute have made specific FETs, called RadFETs for just this type of application [3].

The RadFETs used in this experiment were the Tyndall TY1004 [3]. The thicker metal oxide gates of RadFETs have a larger exposed surface area. They are thus by design more susceptible to radiation damage. The TY1004 RadFETs have an 400 nm oxide gate, whereas typical off the shelf FETs will only have an oxide gate of a few nm. FETs with a thinner metal oxide gate will result in components that are less sensitive to radiation damage, but can measure a larger dose capacity. The voltages produced from the TY1004 RadFETs are factory calibrated against precise dose measurements and can be converted using a supplied transfer function Eq. (1) [3].

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$$Dose = (a\Delta V)^{\frac{1}{b}} \text{ Rads} \quad (1)$$

where:

$$a = 0.06594$$
$$b = 0.41169$$

PRELIMINARY EXPERIMENTS

Offline Setup

To test that standard FET based devices would record dose measurements like RadFETs, preliminary tests were carried out using off the shelf IRF9530 FETs and BPW34 pin diodes [4, 5]. BPW34 diodes have been used in similar applications before and will measure the non ionising energy loss [6], whereas the FETs will measure the total ionisation dose [2]. To take the voltages, the FETs were placed in a reader circuit configuration (see Fig. 2) and driven with a 8.6 µA current. A similar circuit was used to test the diodes where they were driven by a 1 mA current instead.

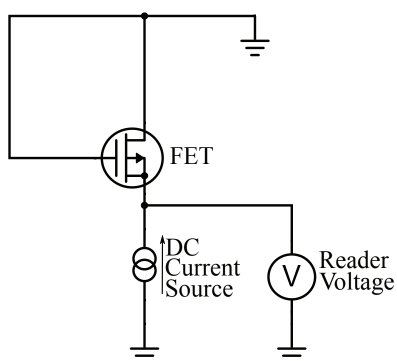

Figure 2: FET Reader circuit configuration.

Irradiating the Components

To test and irradiate the diodes and FETs, they were placed in aluminium die cast boxes with three of each component to a box (see Fig. 3) to increase the sample size.

Figure 3: BPW34 Pin diodes and IRF9530 FETs in die cast box.

Four of these boxes were placed at different locations around the synchrotron, while another box was kept in an office as the control. The box locations were chosen so that the radiation levels measured in each one would be varied, with the higher doses expected near the injection beam dump, and the beam collimators.

Preliminary Results

The boxes were exposed for one user run, and voltage measurements were taken at three points: before installing the boxes, during the mid cycle off day, and at the end of the user cycle. The results show (see Fig. 4) that after an entire user cycle the reader voltage from the FETs located near the injection beam dump and collimators had increased by approximately 0.8 V and 0.1 V respectively. When testing the FETs in the straights, and the control, the results show that they stayed very close to their initial values.

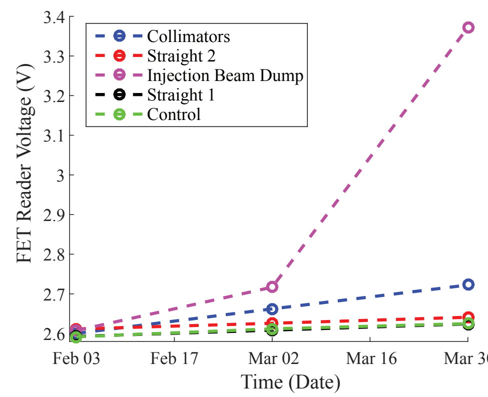

Figure 4: Reader voltage vs time for IRF9530 FETs placed in different locations.

The BPW34 diode results (see Fig. 5) were similar to the FETs, with the diodes located by the injection beam dump and collimators increasing by approximately 0.9 V and 0.2 V respectively. Much like the FETs the diodes located in the straights and control box also stayed relatively close to their initial values.

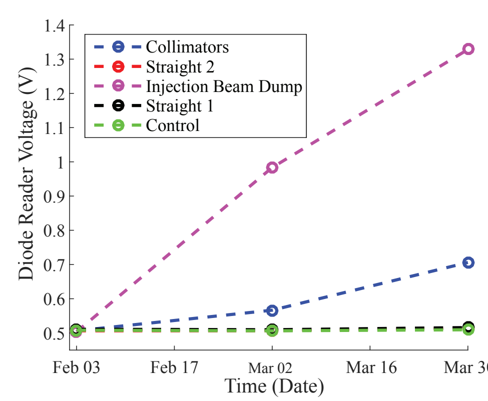

Figure 5: Reader voltage vs time for BPW34 diodes placed in different locations.

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It was expected that the box placed by the collimators would have deteriorated more than the one by the injection beam dump, as there are more beam losses by the collimators. As the collimators are highly radioactive, access from personnel is restricted. This meant the box could not be placed directly by the collimators, but instead about 2 m away on top of the closest dipole magnet. This explains why the results from the injection beam dump are higher than the results from the beam collimators.

The two boxes placed on the straights are both about 3 m away from the beam pipe in areas with low beam losses, and thus the negligible change in voltage was expected. Overall the results from this user cycle demonstrated that the change in voltage measured from the FETs and diodes was positively correlated to the expected dose they had been exposed to.

MEASUREMENT SYSTEM

Based on the preliminary offline results obtained with the off the shelf components, an online monitor that can be sampled on demand was built using RadFETs along with BPW34 pin diodes. When the RadFETs and diodes are being irradiated they should have all terminals connected to ground, this is to prevent polarising the components and making them more sensitive to radiation. A custom circuit (see Fig. 6) and PCB was developed to supply and switch the constant current, as well as buffer the signals measured from the components.

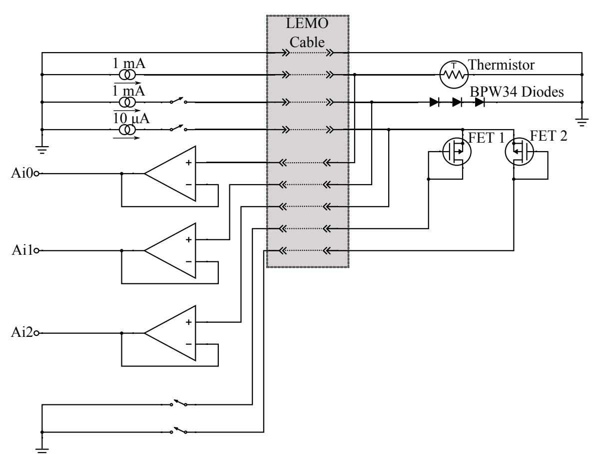

Figure 6: TID power switching and signal conditioning circuit.

The main controller used for the switching, data acquisition and analysis was a National Instruments cRIO [7]. The cRIO, the PCB, and associated power supplies were assembled inside in a custom Schroff chassis (see Fig. 7), and then installed in an area at the centre of the proton synchrotron, behind concrete shielding to protect from radiation damage.

For this experiment, a cable was fed from the inner synchrotron to a sensor board which housed three BPW34 pin diodes in series, a TY1004 RadFET, and a thermistor. The thermistor was used to gather temperature data, as readings from the diodes and RadFETs may be temperature depen-

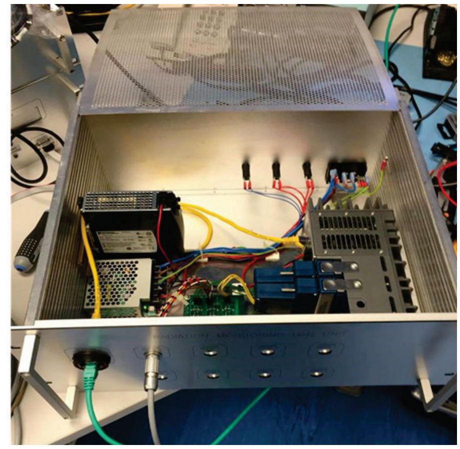

Figure 7: National Instruments cRIO measurement system in custom Schroff chassis.

dant. The cRIO sampled each sensor once every 10 seconds and recorded an average measurement every 30 minutes. For the online measurements, the pin diodes were driven with 1 mA current and the RadFETs 10 µA current. The cRIO's analogue input module was used to acquire the data from the sensors, it's DIO module was to switch the sensor supply to and from ground. At the time of writing this paper, the cRIO has been measuring from one sensor board that has been placed by the injection beam dump. This location was chosen as it yielded the highest increase in voltage in the preliminary results.

RESULTS

The results displayed (see Fig. 8) were taken between the 3[rd] of April until and the 20[th] of August. Over this time the accelerator went through two user cycles. The first user cycle was a typical cycle delivering proton pulses to both ISIS target stations with a repetition rate of 50 Hz. Due to maintenance and upgrades carried out on the first target station, for the second user cycle only the second target station was receiving proton pulses from the synchrotron at a repetition rate of 10 Hz. This drops the average synchrotron current from approximately 200 µA to 40 µA.

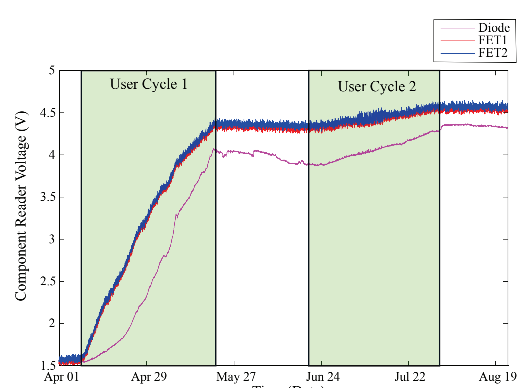

Figure 8: Component reader voltage vs time graph.

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The voltages from the components start to rise at the beginning of the first user run, before levelling off during the shut down period. The diodes showed some annealing during this time as the measured voltage drops off slightly, the RadFETs also show some annealing, though it is not as much as the diodes.

By processing the FET voltage readings through the function given by Eq. (1), a dose over time graph can be obtained (see Fig. 9). The graph is split, divided by the two user runs and accelerator shut downs. The increase in ionising dose for the first user run was about 8800 rads, whereas for the second user run it was approximately 1600 rads. Given the drop in synchrotron current and repetition rate for the second run this is to be expected, and it shows that the measured dose scales with accelerator intensity.

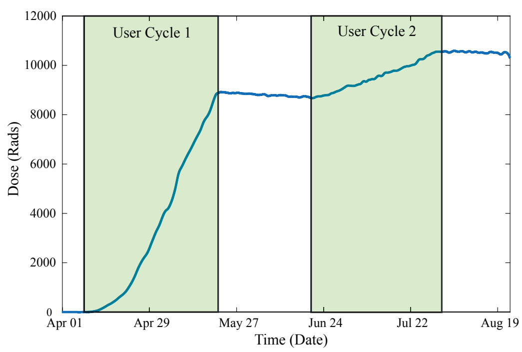

Figure 9: Dose vs Time Graph.

SUMMARY

Completed Work

Preliminary offline measurements have been carried out to test how off the shelf MOSFETs and pin diodes may react to ionising radiation. The theory that the more radiological dose a FET or diode has absorbed, the higher the threshold or reader voltage, has been reinforced with these experiments. Data gathered from these tests has been useful in building an online TID monitor that can be used for new studies, such as component characterisation.

The online TID monitor has successfully logged and recorded the total ionisation dose in a single location. The results gathered from the sensors track with not only the running schedule of the accelerator, but also the intensity of the run. During the shut down, there was annealing observed in both the BPW34 pin diodes, and the TY1004 RadFETs. As well as TID measurements, temperature data has been logged using a simple thermistor. During the user cycles the air conditioning is on, leaving the temperature flat during the runs but variable during shutdown periods.

Future Monitor Development

The TID monitor has been completed and is now functional, while this allows for more studies to take place, there is still some work that can be done to improve the monitor itself. Currently there is only one sensor board connected to the TID monitor, in the future more sensor boards can be added to monitor multiple locations at once.

It is believed that the readings from the RadFETs and the pin diodes are temperature dependant. As the synchrotron air conditioning has been active during the user cycles, it is believed this has not effected the readings a great deal. More analysis should be done on the temperature data acquired, as there may be a need in the future, to monitor radiation dose in non temperature controlled environments.

Future Studies

The monitor now allows for TID measurements of different components, systems, materials, and locations. By measuring the dose failure point of any of these parts, through long term testing, or accelerated testing, predictions can be made of when these parts need to be replaced or upgraded. Should these predictions be correct, these parts can be replaced during a shutdown period and not unexpectedly during an ISIS user cycle. This will result in less disruption to users, and an overall improvement in ISIS reliability.

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