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DIGITAL CAMERA PERFORMANCE IN A HIGH-RADIATION ACCELERATOR TEST BEAM FACILITY*

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Abstract

Digital cameras are critical diagnostics at test beam facilities. At FACET-II, there are over 100 digital cameras in operation. Scattered electrons from the 10 GeV beam cause high levels of ionizing radiation, which makes profile monitors susceptible to two types of failures: single-event upsets (SEU) and permanent death. We developed software infrastructure to detect camera failures and track SEUs over time. Additionally, we installed digital radiation monitors (RADFETs) at the locations of 10 cameras to measure local dosage. We find strong correlations between the SEU rate and local dose. This information is used to optimize camera placement and predict failure rates in the experiment.

INTRODUCTION

FACET-II [1] positions SLAC as a world leader in developing cutting-edge plasma wakefield acceleration (PWFA) [2] technology for future accelerators by providing 10 GeV electron beams optimized for PWFA experiments. However, producing extremely high-energy beams poses some challenges. Scattered electrons from the beam cause high levels of ionizing radiation, which creates concerns for the electronic equipment in the accelerator. Digital cameras at FACET-II are susceptible to failures in the form of single-event upsets (SEU) and permanent death. In the case of an SEU, the camera is disconnected from the camera server, but it can be recovered by power cycling the device. High radiation doses can also lead to permanent death, which is more costly and disruptive to experimental programs.

A study was conducted to understand radiation effects and investigate ways to mitigate damage to digital cameras. Digital radiation monitors have been installed at the locations of 10 cameras. They provide useful information about local radiation dosage during experiments. Additionally, a new software tool known as Camera Watchdog was deployed to monitor and automatically power cycle cameras in the case of an SEU. The Camera Watchdog also updates the total number of reboots executed for each camera, which is used as a proxy for the SEU rate. In this paper, we show that a combination of camera monitoring software and digital radiation monitors can provide valuable information about the longevity of digital cameras, which allows us to optimize camera placement and predict camera failures.

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RADIATION IN THE FACET-II ACCELERATOR

Past data have shown that radiation is highest near the beam dump. Additionally, there are hot spots, or locations where radiation is most concentrated. Hot spots have been identified through radiation dose measurements and trial and error. Where possible, cameras were moved away from hot spots to prevent further damage. Previously recorded data from radiation monitors have also shown that radiation levels are higher during PWFA experiments as a result of plasma interactions. Another source of radiation is beam tuning, which can lead to large beam losses. Reducing the time electronics are exposed to the radiation environment is an effective way to protect cameras from radiation; however, it is not possible to install cameras for just one experiment. It is also not possible to replace a camera in the middle of an experiment, so it is very important to keep track of radiation damage to equipment.

Table 1: Digital Cameras with RADFETs at FACET-II

Camera Name	Region	Model and Sensor
FrontView	IP Area	Allied Vision Mako CCD
IPOTR1	IP Area	Allied Vision Mako CCD
IPOTR2	IP Area	Allied Vision Mako CCD
DSOTR	IP Area	Allied Vision Manta CCD
DTOTR2	Dump	Allied Vision Mako CCD
CHER	Dump	Hamamatsu Orca CMOS
LBG LFOV	Dump	Hamamatsu Orca CMOS
GAMMA1	Dump	Allied Vision Mako CCD
LFOV	Dump	Allied Vision Mako CCD
GAMMA2	Dump	Hamamatsu Orca CMOS

HARDWARE

Digital cameras are critical diagnostics because they measure non-scalar parameters, such as beam energy spectrum and spot size. There are more than 100 cameras in operation at FACET-II, and about half of these are in the experimental area where radiation levels are highest. Most profile monitors at FACET-II are Allied Vision Mako or Manta CCD cameras. There are also a few Hamamatsu Orca CMOS cameras near the beam dump.

We placed radiation-sensing field-effect transistors (RADFETs) at the locations of 10 cameras in the experimental area, as depicted in Fig. 1. Table 1 shows the name, region in the linac, and model and sensor type for each camera included in the study.

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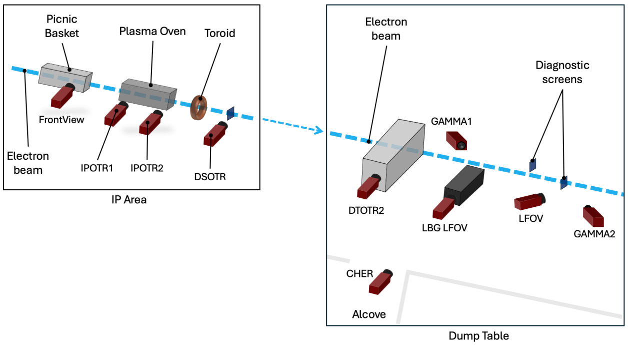

Figure 1: Map of camera placements in the experimental area.

The RADFETs are transistors with an insulating layer that changes resistivity with radiation dose. Exposure to radiation causes a permanent change in the sensor's voltage output. This measurement allows us to maintain a history of local cumulative radiation dose. The RADFETs are placed inside plastic straws and attached to the camera mount with zip ties, as shown in Fig. 2. In addition to the RADFETs, there are film badge dosimeters at select camera locations. After the dosimeter is removed, the measurement can be used to verify the RADFET data. The RADFETs have a maximum threshold voltage of approximately 28 V, at which point it must be replaced.

Toroidal charge monitors are another important diagnostic because they measure the beam charge in the linac. The toroid used in this study is located at the Interaction Point (IP) Area, as shown in Fig. 1.

FACET-II uses the EPICS control system to control and collect data from diagnostic equipment and devices. Each camera and RADFET maps to a channel in an EPICS Input/Output Controller (IOC). Through EPICS, we can retrieve data from various Process Variables (PVs). For example, we can remotely monitor the connection status of each camera and the RADFET voltage. The data from the PVs are stored in an archive for later use in analysis.

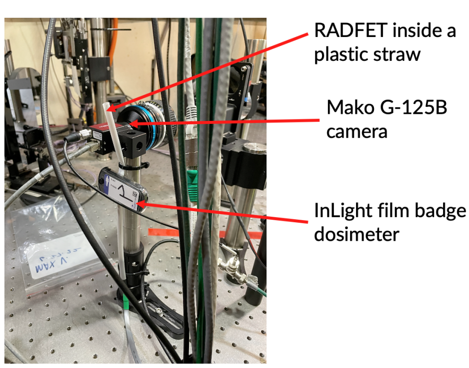

Figure 2: Setup of a RADFET and a dosimeter at the location of a camera at FACET-II.

CAMERA WATCHDOG SOFTWARE

Cameras can experience SEUs frequently during experiments. The Camera Watchdog software tool was developed to automate the task of monitoring and rebooting digital cameras at FACET-II during experiments. The software is written in MATLAB R2020a. The program gets data from EPICS PVs through labCA, a MATLAB wrapper for Channel Access developed at SLAC. The Camera Watchdog monitors the cameras at FACET-II by initializing objects for each camera. Each camera is then assigned a state based on several variables, including connection status, acquisition status, and trigger mode. The Camera Watchdog listens for changes in the PVs, and it updates the state accordingly. There are 6 possible states for a camera (see Table 2). The Camera Watchdog also monitors Power Over Ethernet (POE) Hubs, and Soft Input/Output Controllers (SIOC), and updates the camera to an alarm state if a POE Hub or SIOC is offline.

Table 2: Camera Watchdog States

State	Description
0	Camera is in a good state
1	Camera is disconnected
2	Camera is not acquiring
3	Camera is using an internal trigger
4	Array rate is equal to 0
5	Alarm state

If a camera is disconnected from the server, implying the camera experienced an SEU, the Camera Watchdog attempts to power cycle it. If the camera does not reconnect to the server after the initial reboot attempt, then the camera could have experienced permanent death. In this case, the Camera Watchdog does not continue to power cycle the camera. If the camera later recovers on its own or with manual troubleshooting, then the Camera Watchdog will continue monitoring it and rebooting it as necessary. The total number of reboot attempts for each physical camera is tracked in a PV and is used as a proxy for SEUs. The reboot count must be reset each time a camera is replaced.

RESULTS AND ANALYSIS

We observed a correlation between SEU counts and radiation levels for each camera using reboot counts and local radiation dosage data. As shown in Fig. 3 (left), there is a strong correlation during a period of normal operation (i.e., no plasma). This demonstrates that the Camera Watchdog is successful at recovering cameras from SEUs despite exposure to some ionizing radiation. However, there is less correlation during PWFA experiments, meaning the camera was unable to recover quickly enough to keep up with higher radiation levels. During the PWFA run depicted in Fig. 3, a camera at the IP Area (not pictured here) and its RADFET died after the local dosage spiked.

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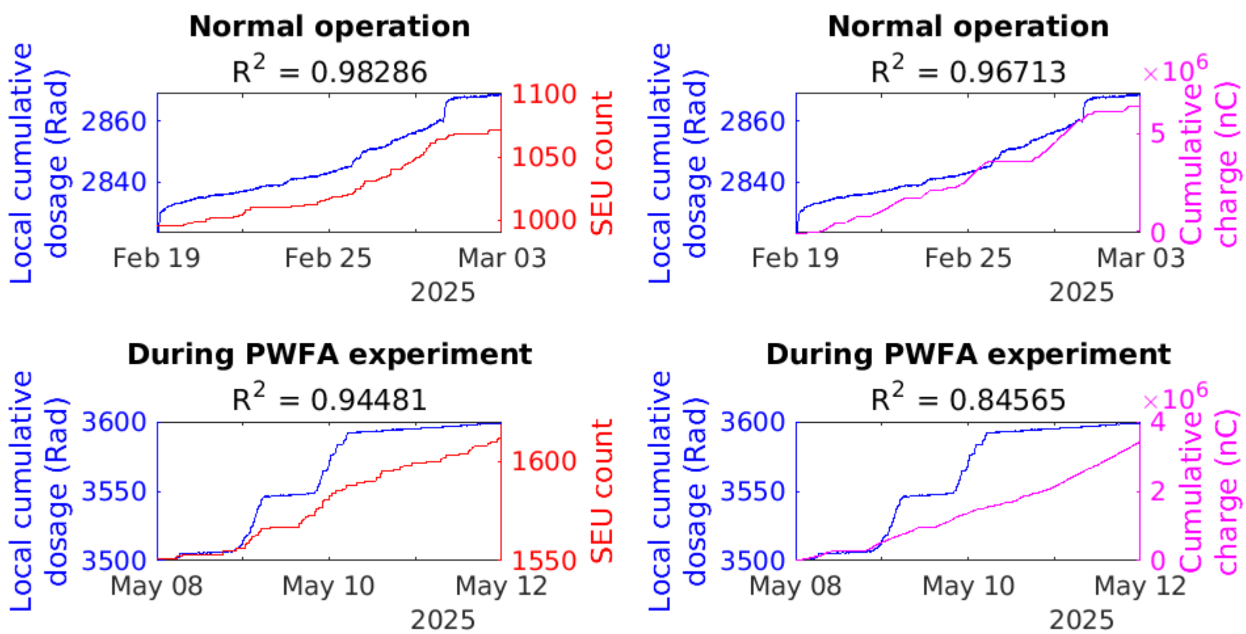

Figure 3: Correlation of local cumulative dosage with SEU count (left) and cumulative beam charge (right) during normal operations and during a PWFA experiment for one camera.

We also expect a strong correlation between local radiation dose at the camera and cumulative charge in the experimental area. As expected, Fig. 3 (right) shows a strong correlation between the two variables during normal operation, and there is less correlation during PWFA experiments. Although the charge delivered to the experimental area increased steadily, the radiation levels increased at a much faster rate. Radiation also increased by almost twice the amount during just 4 days of a PWFA run, compared to 10 days of normal operation. This suggests that there are more losses during PWFA experiments than during normal operation.

We can conclude that during PWFA experiments, there is significantly more radiation-induced damage to cameras. However, it is possible to lessen damage to diagnostics by strategically relocating cameras that are subjected to high radiation doses. An example is CHER, a camera that was previously located next to the beam dump. Since the camera was relocated to its current position in the alcove (see Fig. 1), the camera has seen less radiation and has experienced fewer failures. By increasing the distance from the radiation source to the camera, we have been able to extend the lifetime of critical diagnostics.

SUMMARY AND FUTURE WORK

The results of installing digital radiation monitors and deploying software infrastructure to monitor cameras demonstrate that there is a correlation between SEU rates and local radiation dosage at cameras in the experimental area of FACET-II. The correlation was lower during PWFA experiments, which suggests that the Camera Watchdog software tool is less efficient at recovering cameras from SEUs during plasma operations.

Further work is required to continue improving camera performance. This includes creating a model of the SEU probability for a given camera. Survival analysis will enable us to predict when a camera is nearing the end of its lifespan and prompt us to replace it before it fails.

Additionally, a Geant4 model of the FACET-II experimental area is being developed to simulate radiation effects during PWFA experiments. The results can help us find more optimal locations for cameras that are farther away from radiation hot spots. Radiation effects are a concern for other equipment in the linac as well. In particular, vacuum components such as roughing pumps are susceptible to failures caused by high radiation levels. Therefore, this work is critical to ensuring the success of PWFA research at FACET-II.

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