BUDGET-FRIENDLY DEFENSE AGAINST RADIATION-INDUCED CAMERA DAMAGE*

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Abstract

Cameras observing scintillating viewers provide a valuable tool for tuning heavy ion beams. The close placement of these cameras near intense stray neutron and ion radiation, particularly at elements intercepting the primary beam, presents a unique reliability challenge. Commercial solutions are sparse, expensive, and sometimes tightly regulated. We present common failure modes observed at FRIB and propose solutions to extend the lifespan of unspecialized industrial cameras using consumer-grade hardware and open-source software.

INTRODUCTION

Scintillating viewers are a straightforward way to qualitatively observe the alignment and shape of an ion beam. FRIB's primary uranium beam reaches up to 200 MeV/u uranium, and higher energies are achieved for lighter species. The current primary power on target is 20 kW, with the eventual goal of reaching 400 kW. The interaction of this beam with interceptive devices (*e.g.* the charge stripper [1], production target [2], and separator slits [3]) creates stray radiation fields that damage conventional electronics.

This work does not seek to advance any particular state of the art – rather, we present inexpensive, accessible strategies undertaken at FRIB to mitigate the detrimental effects of radiation on cameras, which might apply in equal measure to other sensitive electronic devices.

PROBLEM ANALYSIS

Reactions caused by beam interaction with solid materials induce stray radiation on the order of 1 – 10 Gy y^{-1} total ionizing dose (TID) [4, 5], neutrons and photons. High-energy photons (X-rays and γ-rays) can cause electrical effects by disrupting electron-hole pairs in silicon, and neutrons can physically displace atoms in semiconductor crystal lattices. Preliminary work [4] estimates the total soft error rate in silicon to be roughly $2 \cdot 10^7$ $\text{FIT} \cdot \text{MBit} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ at current beam power. That is, for a hypothetical device with a density of 1 Mbit in 1 cm^2 of area, a soft error latch-up would be expected every 50 hours of operation. Empirically, soft errors are seen once per 6 hours of operation at the liquid lithium charge stripper (LLCS), with hard errors and replacement during maintenance necessary after 500-1000 hours of operation on average. Figure 1 depicts typical performance during 20 kW operation.

This presents something of a gray area. Specifically designed radiation-hardened cameras are expensive with few existing options on the market, especially with respect to neutrons. Failures are mitigated, to a certain extent, with radiation-tolerant design (*e.g.* CMOS sensors vs. CCD). Other elements are just duplicated for redundancy, which extends the usable lifetime, but does not ultimately prevent radiation-induced failure. However, since these cameras are used primarily for qualitative measurements, sporadic failures are generally acceptable, *provided* the image remains legible and the latch-ups can be cleared remotely without operator intervention.

CONVENTIONAL DESIGN

Hardware

For general-purpose qualitative measurement and some thermographic applications in the near infrared, FRIB uses off-the-shelf general-purpose industrial cameras. Typically, FRIB uses The Imaging Source's 33GX265, featuring a 3.1MP monochrome Sony IMX265 CMOS sensor. It retails for about $550 USD[1]. Lenses are chosen from the Fujinon HF-XA-5M line, with no noticeable darkening in 3 years of operation. The cameras are generally aligned on kinematic mounts between 50 and 100 cm from the object.

Software

Incoming images from the cameras are handled by section of the linac on physical camera servers, with each camera's feed aggregated over a 10-Gigabit Ethernet fiber link. Camera control is accomplished with the camera's firmware implementing the GenICam control standard [6], with network communication implemented by Aravis [7], an open-source emulation of the GigE Vision protocol [8] Aravis, in turn, interfaces with the EPICS supervisory control system [9] via the AreaDetector ADAravis driver [10]. With the detector driver producing images, users may adjust the camera's raw feed and take statistics using the other AreaDetector plugins[2].

MITIGATING RADIATION DAMAGE

Dead Pixels

Depending on the placement of cameras with respect to interceptive devices, cameras on the beamline will develop dead or "hot" pixels due to radiation damage on the sensor. Visually, this can be mitigated by applying a median filter,

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[1] *cf.* similar radiation-hardened models well into the thousands.

[2] The state machine, along with a sample skeleton EPICS IOC, can be found at `https://github.com/daykin/HIAT25-MOP19`.

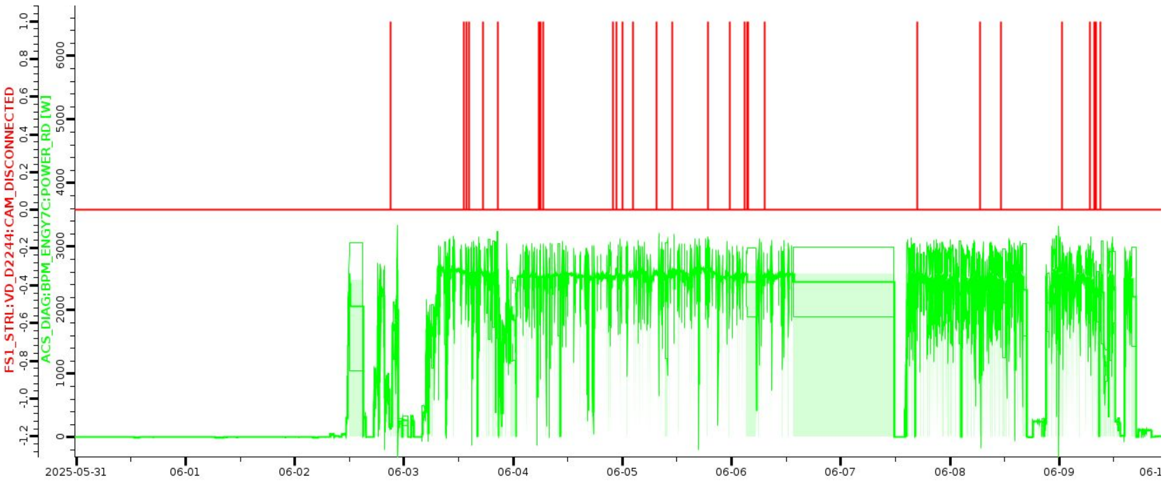

Figure 1: Strip chart of detected soft errors on the LLCS camera during a week-long experiment. The upper trace depicts 27 latch-ups, the lower trace depicts beam power in the area, in Watts.

in which each pixel of the image is replaced by the median of the surrounding 5×5 kernel. OpenCV implements this efficiently with a sliding window and heap strategy, which can accomplish the filtering in $O(nk)$ time, as opposed to $O(nk\ log\ nk)$ for n pixels on a $k \times k$ kernel. Figure 2 shows the difference between the raw and filtered image[3]. We wrap the OpenCV median filter for use in the control system using a fork of the ADCompVision AreaDetector plugin [11].

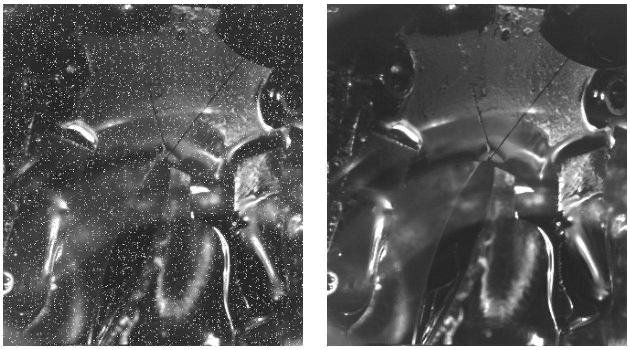

Figure 2: Comparison of the LLCS film image before (left) and after (right) median denoising.

Physical Countermeasures

In areas of particularly high radiation, it becomes reasonably likely that a camera will experience a hard error during active operation, resulting in downtime if it is needed and cannot be brought back up. The only solution, in this case, is to shield and distance the critical components of the camera. This is accomplished by creating a 'periscope' of various form factors depending on the environment. This places the active components in shielding away from the most intense radiation. Figure 3 shows an exploded view of one of these assemblies, placed in this case at the Carbon-foil charge stripper (CCS) used before the LLCS came online. For more complex devices where scale must be preserved, the infrared thermal imaging camera at the target dump features a telecentric lens focused on the dump by a moving series of mirrors, which lengthen or shorten the optical path such that the image is properly focused on the camera's focal plane array (FPA). This "trombone" assembly is shown in Fig. 4.

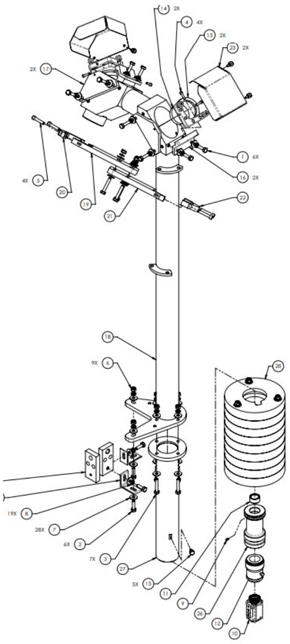

Figure 3: Exploded view of the CCS optical line. The camera itself is shown in the lower-right, and is surrounded by rings of cast iron or borated polyethylene.

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[3] Additional speckling was rendered onto 'before' image before processing to demonstrate effect in print.

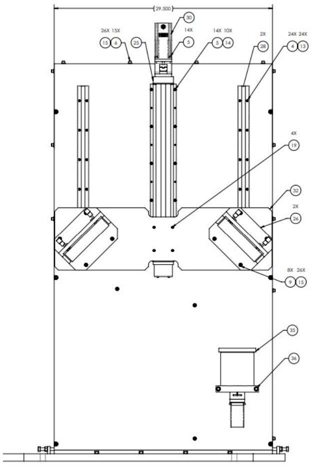

Figure 4: Forward view of the target dump optical line. The camera itself is shown in the lower-right. Angled mirrors move vertically to adjust the apparent distance to the FPA.

Soft Error Recovery

Radiation-induced corruption and latch-up is a more difficult issue to solve. Since the corruption of volatile memory on the device is random by nature, the exact characteristics seen by a remote user are varied. Thus, the device's network stack may still be functioning and the device driver may not recognize the malfunction. In this state, the only way to recover functionality is to physically power down the link.

To solve this, the camera link is shunted with an off-the-shelf Power-over-Ethernet (PoE) injector, powered by a network-controlled power distribution unit (PDU). A finite state machine is implemented on the camera control EPICS server. In short, if the device is nominally 'acquiring', but the frame counter is not incrementing for more than 10 acquisition periods, the server recognizes the camera to be malfunctioning. It will first attempt to send the GenICam a 'Reset' command. If the soft reset does not work (evidenced by the same symptom), it will command the PDU outlet off - first for 5 seconds, then exponentially backing off to 5 minutes switched off, to ensure volatile memory eventually clears. After power-cycling, the application will again check if the camera is successfully transmitting images. The process repeats as long as the state machine is enabled, at longer intervals due to the back-off mechanism.

DISCUSSION

Use-Cases

In the case of FRIB's first three years of operation, hard camera failures induced by radiation have not represented a significant fraction of unscheduled downtime, and maintenance intervals are frequent enough to allow for proactive replacement. However, before the introduction of the above-described methods, sensor damage and soft latch-ups became a significant nuisance. In this operating niche, it is feasible to use remarkably inexpensive methods to automate recovery from the most frequent failures.

Difficulties and Future Work

Some strategies, particularly that of using unspecialized camera hardware, must be carefully considered with respect to the environment in which they will operate. With any installation, it is important to design for the characteristics of stray radiation fields that will be encountered. From this information, a very rough estimate of the mean time between failures can be calculated to determine feasibility. This estimate can be refined on existing installations or test setups with empirical data from commissioning or operation. Failure rates, in turn, can be used to make informed decisions about camera installations in light of the sensor capabilities, operational lifetime, cost of replacement, and cost of related facility downtime.

A particular case in which these strategies are less effective is in the target dump thermal imaging system. This specialized mid-infrared (7–12 μm) camera requires a higher level of care in the harshest environment, due to its potential future role in identifying overheating and uncontrolled beam loss. Despite sitting atop 1.5 meters of cast-iron shielding and retrofitting with 15 cm borated polyethylene, soft failures are still observed between 100 and 1000 hours of operation. We would like to devote future work to in-house modification to relocate all components except the FPA entirely out of the target hot-cell.

CONCLUSION

Placing cameras near devices producing strong prompt radiation is a necessary, but challenging task. Ionizing radiation is particularly damaging to dense semiconductor components, including CMOS sensors and most common forms of volatile and non-volatile memory.

For constrained budgets, we present inexpensive methods of extending the longevity of these devices, and mitigating the most common errors without manual intervention. The most prefarable methods involve commercially available, relatively inexpensive hardware, open-source software. If necessary, shielding and distance enclosures are fabricated from commercially available parts and fabrication techniques accessible to most heavy-ion accelerator laboratories.

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