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Study of the Radiation-Hardness of VCSEL & PIN Diodes

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We investigate the feasibility of using VCSEL and PIN arrays in the optical links for the planned upgrades of the detectors at the LHC, CERN. We irradiated high-speed VCSEL (Vertical-Cavity Surface-Emitting Laser) and PIN arrays with 24 GeV/c protons at CERN and 300 MeV/c pions at PSI up to the equivalent dose of a few 10^{14} 1-MeV $n_{\mathrm{eq}}/\mathrm{cm}^2$. The arrays irradiated were fabricated by Finisar, Optowell and ULM Photonics. The irradiation using two species of particles allows us to test the hypothesis that the damage is proportional to the non-ionizing energy loss (NIEL) in a device. The results from the irradiations will be presented.

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1. Introduction

The High Luminosity LHC (HL-LHC) is designed to increase the luminosity of the LHC by a factor of five to 5×10^{34} cm^{-2}s^{-1}. Accordingly, the radiation level at the detector is expected to increase by a similar factor. The increased data rate and radiation level will pose new challenges for a tracker situated close to the interaction region. The silicon trackers of the ATLAS experiment at the LHC use Vertical-Cavity Surface-Emitting Laser (VCSEL) diodes to generate optical signals at 850 nm and p-i-n (PIN) photodiodes to convert back into electrical signals for further processing. The devices have been proven to be radiation-hard for operation at the LHC. In this paper, we present a study of the radiation hardness to HL-LHC fluence of PIN and VCSEL diodes.

In the past few years, we irradiated VCSEL and PIN diodes in several rounds with smaller statistics using 24 GeV protons [1]. Based on that study, in 2009, 7 VCSEL arrays manufactured by Finisar and 20 PIN arrays manufactured by Optowell were irradiated with protons. In 2010, twelve VCSEL arrays manufactured by Finisar and twenty PIN arrays manufactured by ULM were irradiated with protons and one VCSEL and two PIN arrays were irradiated with 300 MeV pions. We concentrate here the irradiation of arrays[1]. Each array has a common cathode and contains 12 channels. The VCSEL arrays manufactured by Finisar[2] have a bandwidth of 10 Gb/s and the PIN arrays by Optowell[3] and ULM[4] have a bandwidth of 3.125 and 4.25 Gb/s, respectively. We studied the effect of proton irradiation on the optical power and threshold current of VCSEL diodes and the current responsivity of PIN diodes to determine their radiation hardness. We also compared the effect of proton and pion irradiation on VCSEL power and PIN responsivity as a test of the NIEL hypothesis of radiation damage. Furthermore, we found some evidence of radiation damage affecting the leakage current of PIN diodes.

2. Radiation Hardness

We evaluated the radiation hardness of VCSEL diodes using their optical power and threshold current, defined as the minimum current through the diode required to induce lasing. These properties degrade under irradiation; the threshold current increases, resulting in decreased optical power. Thus, by irradiating the VCSEL diodes to the HL-LHC dose, we are able to determine whether the power levels and threshold currents remain within acceptable limits (i.e. whether the optical power remains sufficient for the signal to be read-out and whether the threshold current remains low enough that the system can be operated).

We evaluated the radiation hardness of PIN diodes using their responsivity, defined as the ratio of response current in Amperes to the level of incident light in Watts. The responsivity was evaluated at a benchmark input light level of 1 mW (i.e. 0 dBm). PIN responsivity degrades under irradiation; thus, by irradiating the PIN diodes to the HL-LHC dose, we are able to determine whether the responsivity remains within acceptable limits (i.e. whether it is high enough to convert optical signals into intelligible electrical signals).

[1]For results on single channel devices, see, for example, C. Soós et al., *JINST* **7** (2012) C01094.

[2]The part number of the Finisar VCSEL array is V850-209x-002.

[3]The part number of the Optowell PIN array is AP85-2M112.

[4]The part number of the ULM PIN array is ULMPIN-04-TN-U0112U.

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3. NIEL Hypothesis

We compared the effects of the two types of beams to test the Non-Ionizing Energy Loss (NIEL) hypothesis. The NIEL hypothesis [2, 3] posits that radiation damage to a material caused by a particle is proportional to the energy lost by the particle through non-ionizing Coulomb interaction with nuclei in the material. The interaction results in displacement of nuclei from the lattice of the material. According to the NIEL hypothesis, a 300 MeV π should produce $\sim$1.5 times the damage of a 24 GeV p in a GaAs substrate. The PIN (VCSEL) arrays received a total pion dose of $4.3\ (4.1) \times 10^{14}\ \pi/\mathrm{cm}^2$. To compare the degradation to that due to protons, we interpolated the total proton dose of $1.0 \times 10^{15}\ (8.0 \times 10^{14})\ p/\mathrm{cm}^2$, assuming linear degradation with dose, to the equivalent dose of $6.4\ (6.0) \times 10^{14}\ p/\mathrm{cm}^2$.

4. Irradiation Procedure

We irradiated the VCSEL and PIN arrays using the proton beam supplied by the Proton Synchrotron at CERN and the pion beam at the PSI. The ambient temperature of the irradiation area was $\sim$ 30 C at CERN and 25.6 C at PSI. The actual operating temperature of the VCSEL and PIN arrays in the detector is still unknown at this time and the study must be repeated once the operating parameter is known.

Each VCSEL and PIN array that we irradiated was mounted in an optical package designed by The Ohio State University [4]. Each package was mounted on a PCB and wire bonded. The PCBs were stacked in a row along the beam-line. Aluminum foil was placed at both ends of the stack in order to determine the delivered dose. Each array coupled to a 12-channel radiation-hard fiber ribbon[5]. This allowed the measurement of the optical power of individual VCSEL channels and the responsivity of individual PIN channels by sending light only to the channel of interest. Each PIN array was reverse-biased at 10 V and the drive current (and hence the bias voltage) in each VCSEL channel was scanned during the irradiation, depending on the type of measurement conducted. On each VCSEL array, channels 1, 4, 8, and 12 were individually powered so that we could measure the LIV (light-current-voltage) curves during the irradiation. The remaining channels were powered in parallel. Consequently, we could only measure the optical power of these channels during irradiation. During the proton irradiation, the VCSEL arrays were periodically removed from the beam to allow for annealing to partially recover the optical power, as prior experience indicated that a prolonged period of intense radiation could irreversibly damage the arrays. This was not practical with the pion irradiation, complicating the interpretation of the results as will be discussed below.

5. VCSEL Irradiation Studies

5.1 VCSEL Optical Power

The study of VCSEL optical power was conducted in 2010 using a sample of 13 12-channel GaAs VCSEL arrays manufactured by Finisar. Most of the arrays were subjected to proton irradi-

[5]The fiber ribbons used were Infinicor SX+ by Corning with a 50 μm core and 125 μm cladding. The fiber has been discontinued.

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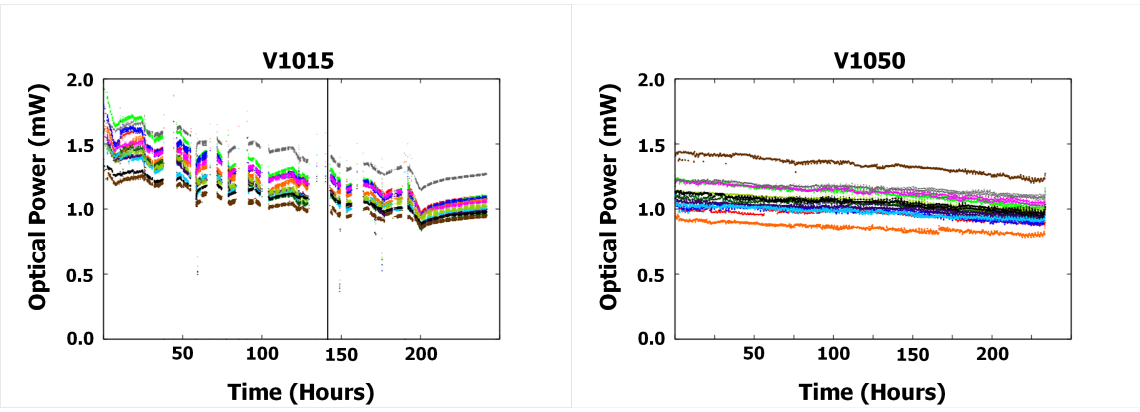

Figure 1: Optical power versus time under proton irradiation (left) to a dose of $8.0\times10^{14}\ p/\text{cm}^2$ and pion irradiation (right) to a dose of $4.1\times10^{14}\ \pi/\text{cm}^2$. The vertical line on the proton irradiation plot indicates the point of equivalent fluence to that from pion irradiation, assuming the NIEL hypothesis (viz. $6.0\times10^{14}\ p/\text{cm}^2$).

ation; one array was subjected to pion irradiation in order to test the NIEL hypothesis. The level of optical power produced in a typical array from each irradiation by an input current of 10 mA is shown in Fig. 1. During proton irradiation, the VCSEL diodes were alternated between periods of irradiation and beam-off annealing, which is visible in the figure as periods of decreasing and increasing optical power respectively. However, there was no beam-off annealing during pion irradiation. Due to the annealing during proton irradiation, it is difficult to compare the overall level of degradation produced by the different beams. As such it is difficult to evaluate the NIEL hypothesis for VCSEL diodes based on this round of proton irradiation. We plan to conduct another round of proton irradiation, this time without the beam-off annealing periods, to get a better comparison and therefore a better evaluation of the NIEL hypothesis. That notwithstanding, irradiation to the expected fluence of the HL-LHC left the VCSEL diodes with sufficient optical power to be considered usable. Therefore we conclude that the GaAs VCSEL arrays manufactured by Finisar are radiation-hard for operation at the HL-LHC.

5.2 VCSEL Threshold Current

The study of VCSEL lasing thresholds was conducted in 2009 using a smaller sample of 6 Finisar GaAs VCSEL arrays (one of the 7 irradiated arrays was excluded from this analysis due to issues with the wire bonds). The threshold current as a function of dosage was measured by fitting the optical power vs drive current for the four channels on each array with LIV curves. The fit function is a 2^{nd} order polynomial. The result for one array is shown in Fig. 2. The threshold current at which the VCSEL diode begins to lase increases under irradiation and partially recovers under annealing. As such, periods of irradiation and annealing are visible in the figure as periods of increasing and decreasing threshold current.

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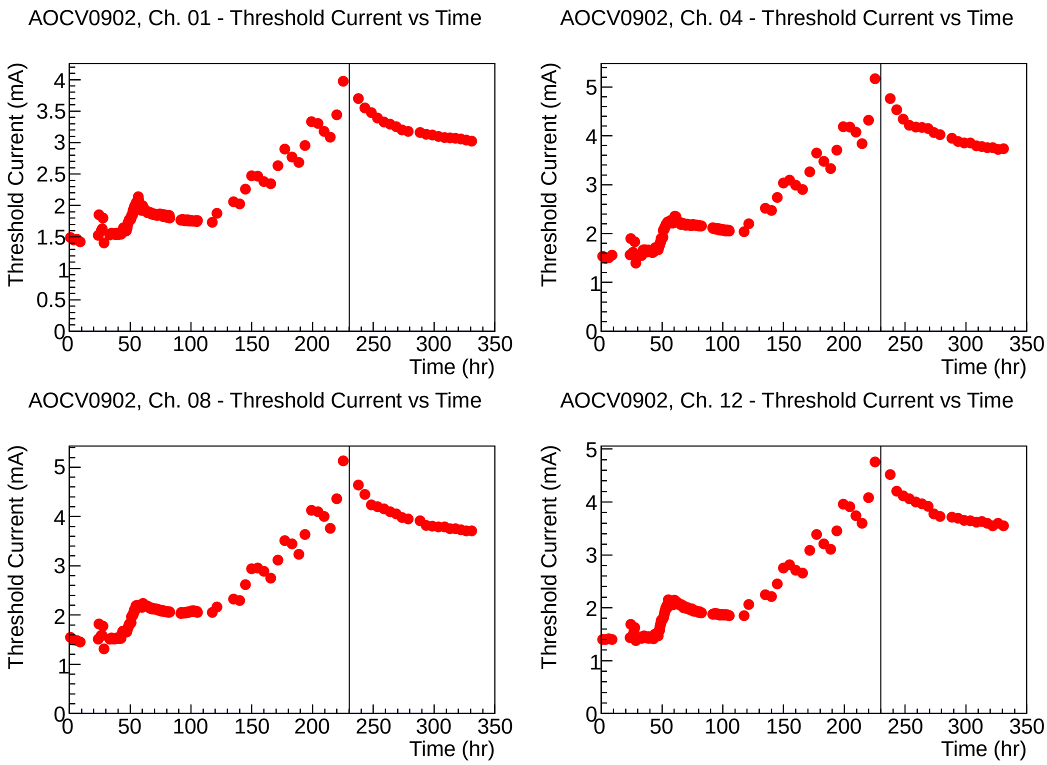

Figure 2: VCSEL threshold current versus time under proton irradiation. The vertical lines indicate the final dosage of 1.0×10^{15} (8.0×10^{14}) p/cm^2.

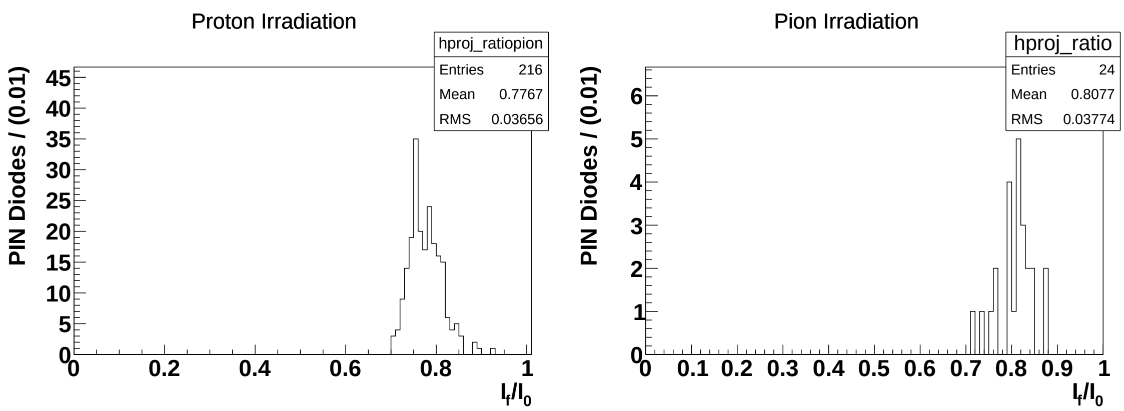

Figure 3: Fractional remaining PIN responsivity after proton irradiation (left) to a dose of 6.4×10^{14} p/cm^2 and pion irradiation (right) to a dose of 4.3×10^{14} π/cm^2.

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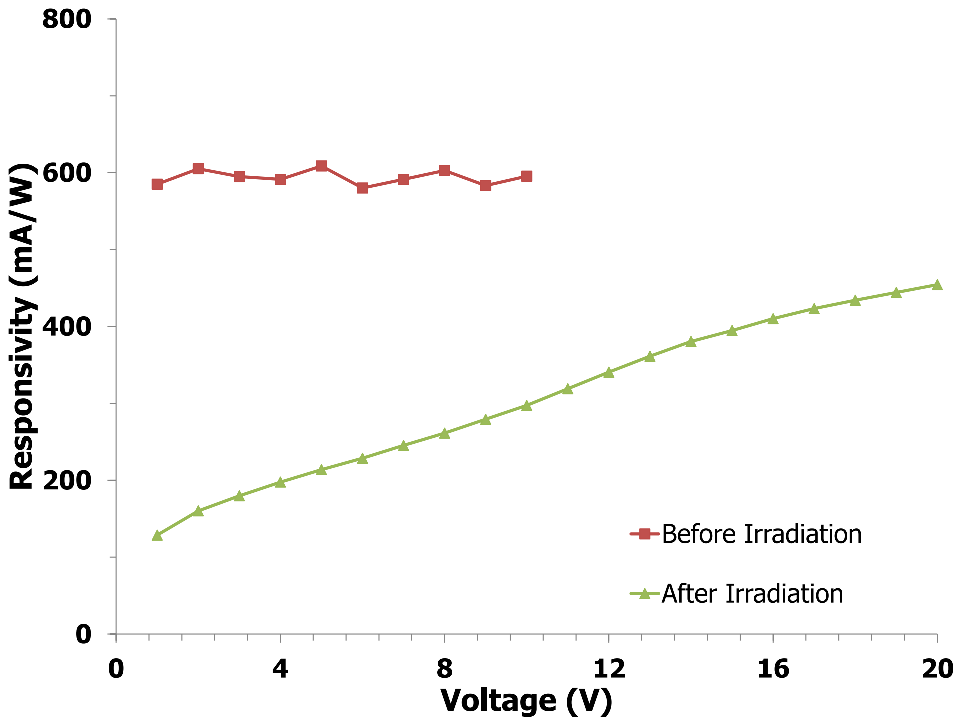

Figure 4: PIN diode responsivity versus bias voltage before and after irradiation with $1.0 \times 10^{15}\ p/\mathrm{cm}^2$.

6. PIN Irradiation Studies

6.1 PIN Responsivity

The current responsivity (i.e. the ratio of induced current to incident optical power) of PIN diodes decreases under irradiation. We fit responsivity versus time of the 22 ULM PIN diodes irradiated in 2010 to determine the initial and final responsivities. The distribution of the ratio of final to initial responsivity is shown in Fig. 3. The average loss of responsivity under pion irradiation at $4.3 \times 10^{14}\ \pi/\mathrm{cm}^2$ was 19%. The average loss of responsivity under proton irradiation, interpolated to $6.4 \times 10^{14}\ p/\mathrm{cm}^2$ for testing the NIEL hypothesis, was 22%. Therefore, we see similar levels of degradation in responsivity under both proton and pion irradiation, as the NIEL hypothesis predicts. Furthermore, irradiation to the expected fluence of the HL-LHC left the PIN diodes with sufficient levels of responsivity to be considered usable. Therefore we conclude that the GaAs PIN arrays manufactured by ULM are radiation-hard for operation at the HL-LHC.

6.2 PIN Bias Voltage

In the process of conducting the study of PIN responsivity, the responsivity of each PIN diode used in the irradiation study was characterized as a function of bias voltage both before and after

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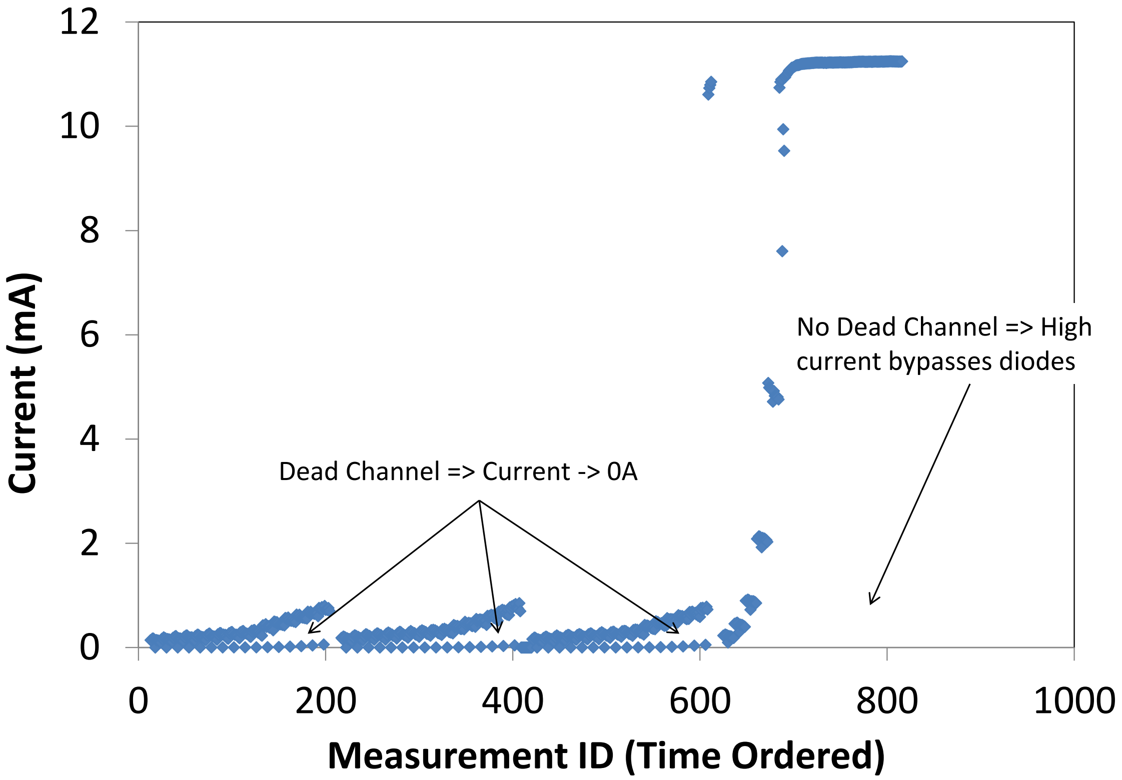

Figure 5: PIN current during post-irradiation thermal cycling.

irradiation. The responsivity before and after proton irradiation versus bias voltage for a typical PIN diode measured using 1 mW of incident light is shown in Fig. 4. Before irradiation, the responsivity was in a plateau for typical values of the bias voltage (i.e. < 10 V). After irradiation, the responsivity is no longer in a plateau, but, rather, increases with increasing bias voltage. The effect of this phenomenon is that operating at a higher bias voltage enables us to partially recover the responsivity lost due to radiation damage. However, it should be noted that the bandwidth and long-term reliability of the PIN arrays at such higher bias voltage after irradiation are still to be evaluated.

6.3 PIN Leakage Current

The test of PIN responsivity was also conducted using the 20 Optowell PIN diodes that were irradiated in 2009. In the process of characterizing the post-irradiation responsivity, it was determined that the characterization should be conducted at multiple temperatures, since the operation temperature in the detector is still unknown, while the pre-irradiation characterization had been conducted at room temperature (20 C). Since the diodes were to be thermal cycled, it was additionally decided that we could test the bounds of the operating temperature range (viz. -25 C and 50 C). The diodes were thus thermal cycled (20 C$\rightarrow$-25 C$\rightarrow$10 C$\rightarrow$50 C) and ramped to the manufacturer specified maximum bias voltage (0-10 V in 1 V increments and then 10-40 V in 5 V increments) at

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each temperature. Their responsivities were characterized at each bias voltage step by supplying 1 mW of light to each channel on the array successively and measuring the response current through the array.

During this procedure, it was discovered that near the top of the ramp at 10 C, after the full ramp at -25 C, 15% of arrays ($\sim$ 1% of diodes, assuming one channel per array) suddenly have high leakage current. The high leakage current was reset by removing the bias voltage, but returned when the bias voltage was returned. The initial current spike (to 10 mA), the reset to low leakage ($\sim$1 mA) and the subsequent current spike (again to 10 mA) are visible in Fig. 5. One of the diodes on the array was disconnected due to a broken wire bond when this test was conducted, visible in the figure as having 0 mA leakage current before the spike. Since there is no measurement with 0 mA leakage current during the spike, we conclude that one of the diodes not being supplied light is spiking to high leakage, thereby bypassing the dead circuit. Based on a limited sample size (only 6 arrays), we were unable to reproduce this behavior using non-irradiated devices. Nevertheless, based on this potential form of radiation damage, a different manufacturer (viz. ULM) was chosen for the PIN arrays to be irradiated during the subsequent round of the study in 2010. Also, all ULM PIN arrays in the subsequent round were subjected to the same thermal cycle, both before and after irradiation, to check against this phenomenon, however, it was only exhibited by the Optowell PIN arrays.

7. Conclusions

The optical power and threshold current of VCSEL diodes are degraded when irradiated but partially recover when annealed. The responsivity of PIN diodes is degraded when irradiated. Overall, Finisar 12-channel GaAs VCSEL arrays and ULM 12-channel GaAs PIN arrays are radiation-hard for operation at the HL-LHC. The NIEL effect on VCSEL damage is difficult to test with the current round of proton irradiation data due to beam-off annealing periods. Irradiation by 300 MeV π causes $\sim$ 1.5 times as much degradation in the responsivity of PIN diodes as does irradiation by 24 GeV p, in accordance with the NIEL hypothesis. Some Optowell PIN diodes exhibit large leakage current post-irradiation; however, due to limited statistics, it is unclear whether this is an effect of radiation damage.

References

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