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Priscilla Cushman and Brian Sherwood

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Along with quality assurance of ~1000 hybrid photodiode tubes for CMS, a subset were subjected to long term testing of their properties over time. Over the course of several years, the tubes were operated under non-uniform illumination at rates up to 3.75 nW per pixel and for total integrated charges of up to 7 C at the anode. In-situ measurements of quantum efficiency and gain, coupled with periodic photocathode uniformity scans, dark current and cross talk, provide information on expected time-dependent changes in the tube photo-sensitivity and some indication of possible failure modes.

1. Introduction
A 19 channel hybrid photodiode (HPD) was developed in collaboration with DEP[1] to read out CMS HCAL. This HPD, shown in figure 1, is a proximity-focused device using an applied voltage (V_{gap} ~ 10 kV) across a 3.3 mm gap to produce a gain of around 2000. When photons strike the photocathode, electrons are ejected and accelerated across the gap to create electron-hole pairs upon impact on a silicon photodiode. The photodiode, which is produced by Canberra[2], is segmented into an array of 5.4 mm hexagonal pixels with extremely low crosstalk. Each channel is read out individually through a bump-bonded vacuum feedthrough under a reverse bias which drifts the charges across the junction.

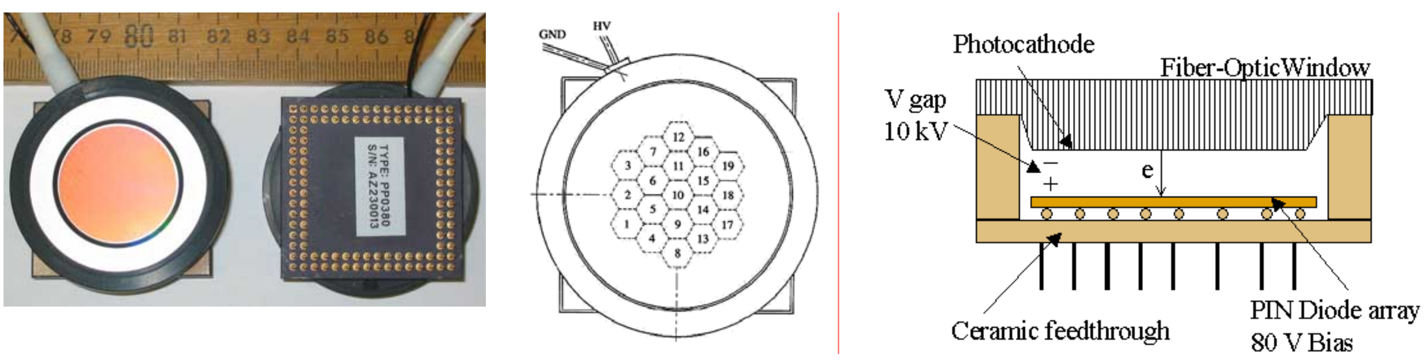


Figure 1. The custom CMS hybrid photodiode design. At the left is a photograph of the front and back sides. The pixel arrangement of the interior photodiode array is shown in the center and a schematic of the HPD structure is on the right.

Light from 520 nm wavelength-shifting (WLS) fibers coiled inside the HCAL scintillating tiles is introduced into the HPD via long ribbons of 1 mm diameter clear plastic fibers, which are rebundled at the HPD location. The fiber bundles are glued into holes in a polyethylene terephthalate faceplate, which is registered to 50 microns for each pixel via a custom alignment jig produced during the initial scanning and quality assurance steps.

The HPDs must be able to operate for 10 years in the CMS experiment, corresponding to an integrated charge of 3 C/pixel at the highest pseudo-rapidity locations. Extended lifetime tests must evaluate the long-term stability of the tubes under high voltage and measure any degradation in response over time and integrated charge. Since this must be done in a time shorter than the duration of the experiment, accelerated tests are used to reproduce the total integrated charge and lower intensity tests evaluate the rate of change expected in normal CMS running.

[1] B.V. Delft Electronische Producten, Roden, Netherlands
[2] Canberra Semiconductor N.V., Lammerdries 25, B2250, Olen, Belgium

2. Lifetime Tests under Illumination

2.1 Experimental Setup

In order to replicate the wavelength spectrum at HCAL, a blue light-emitting diode (LED) was used to illuminate a 10 cm long scintillator stick (Figure 2). The stick was formed from two 4 x 7 mm^2 tiles, grooved lengthwise and then epoxied together with a 1 mm diameter green WLS fiber running down the groove through the center. A reference photodiode read out one end of the fiber, and an HPD the other. On the HPD end, the fiber protruded into a channel on the cookie which was flared such that nearly one entire pixel was illuminated. The HPD was operated at gap voltages ranging from V_{gap} = 10 kV to 13 kV with the diode reverse-biased at V_{bias} = 80 V. Every two hours, the LEDs were switched off for a dark current reading, which was then subtracted from the light response for both the HPD's and the reference photodiodes. The quantum efficiency (QE) of the reference photodiodes was assumed to remain constant during each test, and they were used to calibrate the light source. Since the response from the HPD is temperature-dependent, a temperature sensitive transistor in the setup was also recorded every 2 hours.

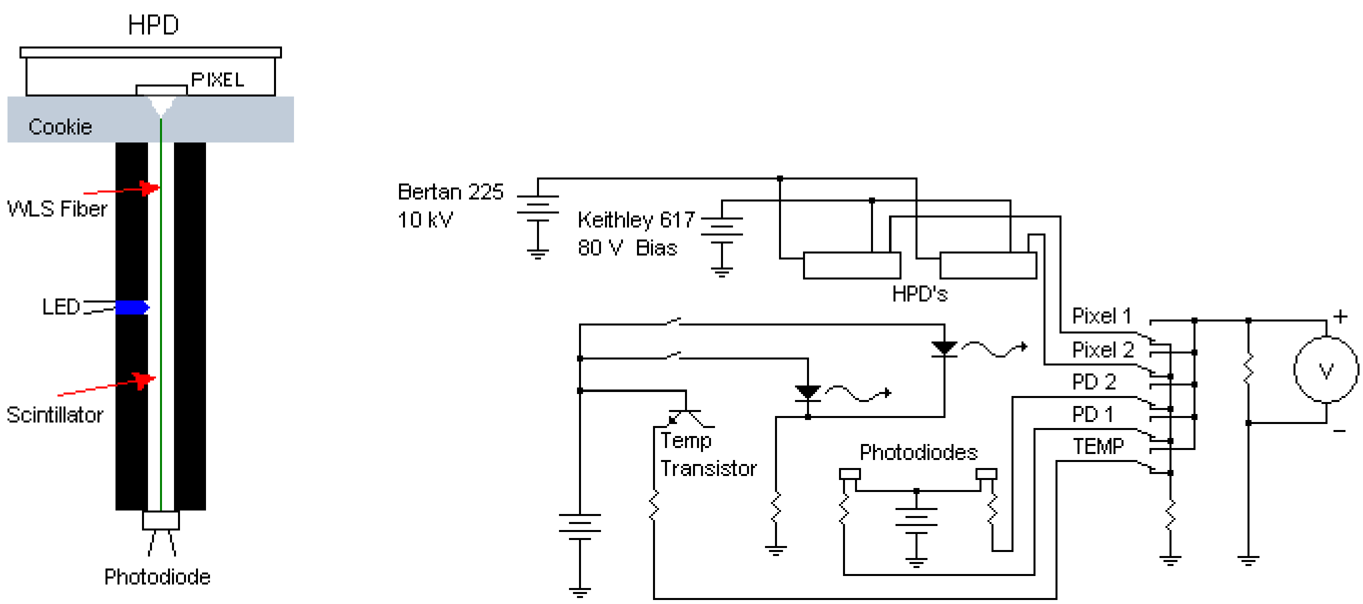


Figure 2. The Experimental Setup for the in-situ Lifetime Measurements. At the left is the light injection scheme reproduced for each tested pixel, and on the right is a simplified circuit diagram.

In order to normalize the HPD response to a known light source and to measure changes in portions of the tube that were not read out by the in-situ test, we periodically removed the tubes from the lifetime setup and installed them in the scanning setups used for quality assurance. The quality assurance setup, shown in figure 3, uses an Oriel[3] radiometric power supply (model 68831) with a light intensity controller (model 68850) to ensure a stable light source. The light is focused to a small dot, with a diameter of about 0.5 mm, and its intensity is calibrated using a calibrated Melles Griot[4] photo diode (Part #: 13DAS011/C). For an area scan, the two-dimensional nanomover is moved in 0.5 mm steps in the X and Y direction, and the combined dark and light response from all pixels is read at each position to create contour plots like the ones shown in figures 4 and 5. Since the light source for the quality assurance station is of known intensity, the photon flux can be divided out giving us the product of Gain x QE for the HPD. The QE data found in Table 1 and the individual pixel responses as a function of time in figure 6 uses data extracted from these contour scans to define an absolute normalization. Each pixel response was determined by averaging over a one mm square scan centered at each of the selected test pixels.

[3] Newport Corp-Oriel, 150 Long Beach Blvd, Stratford, CT 06615
[4] Melles Griot, 55 Science Parkway, Rochester, NY 14620

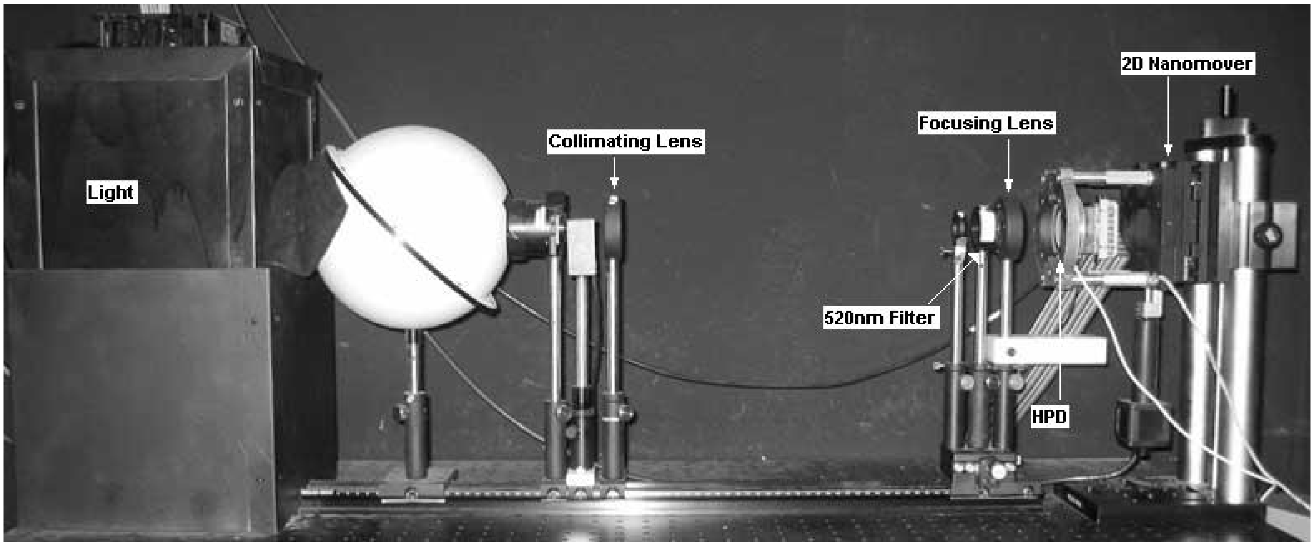


Figure 3: The quality assurance setup which performed calibrated area scans with attached HPD.

2.2 Time-dependent Pixel Response under Illumination

For the first test 1(a), pixels 9 and 11 from HPD-1, were illuminated. As this was an accelerated aging test, the light into pixel 9 was very bright, characterized by an anode current (at normal operating voltages) of 12.1 C/yr. Pixel 11 was operated at a tenth of this rate, or 1.48 C/yr. Since the expected integrated charge into any one pixel after 10 years of CMS running is 3C at the worst location, these rates correspond to 40 and 4 times the CMS exposure rate respectively. After 8 months of continuous operation, HPD-1 was removed from the setup and stored in a dark drawer for 7 months while the experimental setup was debugged and updated. The computer interface circuit, which was made using an 8-bit prototype card from JDR Microdevices[5] (#JDR-PR2) was found to be overheating and causing a drift in our in-situ current readings. Over the break it was replaced with a more reliable Keithley[6] 7001 system with a 7111-S switch card. The light intensity was also adjusted slightly. With the new computer interface, the same HPD was then operated for another 6 months with the same pixels illuminated in test 1(b). Next, to test recovery modes, the light was turned off for 2 months with the HPD left at bias and high voltage. This concluded the first test and HPD-1 was then stored for 3 months while new hardware for the second test was constructed.

For the second test, pixel 10 on a new HPD-2 was illuminated at the dimmer 1.35 C/yr rate, while HPD-1 was re-installed, this time with a different pixel illuminated at a brighter 9.15 C/yr rate. Since HPD-1 had already experienced damage in pixels 9 and 11 from the first test, switching to pixel 3 allowed us to look for any shifting in the damage profiles both near (11) and far (9) from the illumination point, as well as for signs of photocathode recovery. This test ran for about 7 months and ended on June 30, 2005.

Table 1 summarizes the conditions for the set of all lifetime tests and pauses in testing. It is grey-scale coded to match figure 6, which contains the same information in graphical form. The black line in Table 1 represents the start of the second test. The absolute light intensity in nW is measured by taking a previously calibrated HPD and using it to measure the light at the HPD end of the fiber and in the calibrated area scan setup described in the next section. The “Signal” column in Table 1 is the initial pixel signal from HPD-1 or HPD-2 in the place of the calibrated HPD. It represents a simple conversion from nW to nA for that pixel’s particular initial QE and gain, and does not change from test to test, even though the tube response changes.

[5] JDR Microdevices, 1850 South 10th St., San Jose, CA 95112
[6] Keithley Instruments, Inc., 28775 Aurora Road, Cleveland, OH 44139

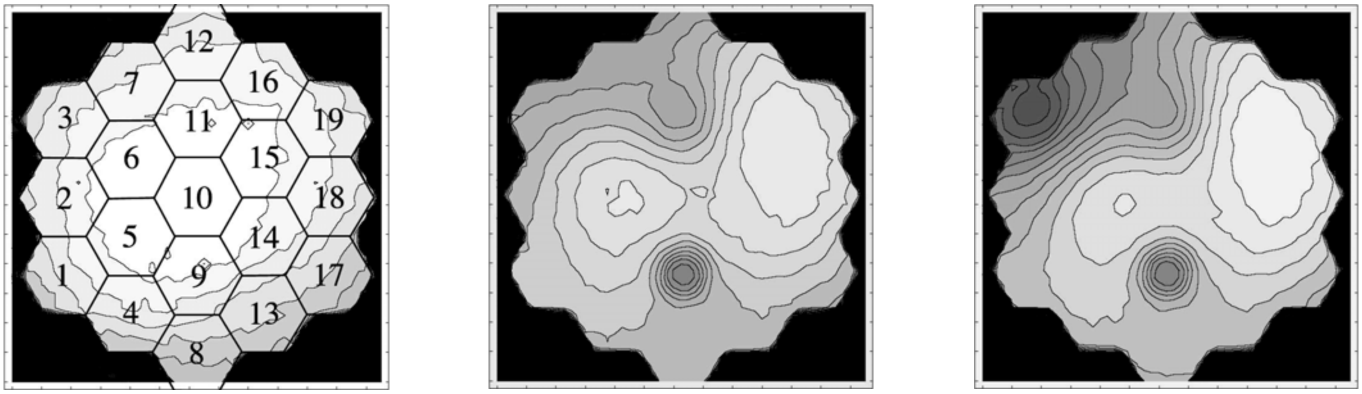
Test Length	HPD	Pixel	Light (nW)	Signal (nA)	C/Year	C_{int}	ΔQE (%)	ΔQE / Year (%)
TEST 1(a) (Start Date: 2002-09-04)								
250 days 13 kV	1	9	3.30	385	12.1	6.96	-28	-41
		11	0.392	47	1.48	1.09	-23	-34
		19					-9	-13
BREAK 1 (2003-05-12) - Stored, No Light								
232 days 0 V	1	9					-2	-3
		11					-1	-2
		19					+4	+6
TEST 1(b) (2003-12-30)								
186 days 13 kV	1	9	3-4	360	4	7.85	-12	-24
		11	0.5	40	0.44	0.86	-10	-20
		19					-4	-8
TEST 1(c) (2004-07-03) - No Light, High Voltage Only								
55 days	1	All					-2	-13
BREAK 2 (2004-08-27) - Stored, No Light								
89 days 0 V	1	All					+1	+4
TEST 2 (2004-11-24)								
218 days 10 kV	1	3	2.8	300	2.8	4.69	-30	-50
		7 (near 3)					-12	-20
		19 (far)					-3	-5
		All Other					-3 to -11	-5 to -18
	2	10	0.34	40	0.45	0.75	-3	-5
		All Other					0 to -1	0 to -2
BREAK #3 (2005-06-30) - Stored, No Light								
140 days 0 V	1	3					+1	+3
		1 All Other					+1 to +2	+3 to +5
	2	10					+1	+3
		All Other					+1	+3

Table 1. Summary of lifetime test conditions and overall response degradation. HPD-1 is the 37th production tube with serial number AZ0230019. HPD-2 is the 189th production tube with serial number AZ0308004.

The signal column is also used to define the units of C/year in the next column, a rate characteristic of the amount of light delivered (which would also correspond to constant illumination under constant HPD response). In contrast, the integrated charge is an actual measurement of the charge passing through the HPD over time using the in-situ data, and thus includes the degradation in response of the tube. Both the percent overall change in QE, as well as the slope of the loss in units of percent loss per year is listed in the last two columns of Table 1.

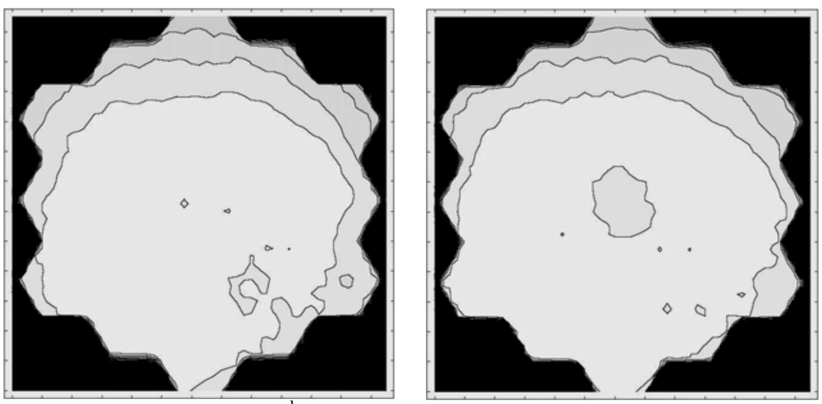
Snapshots of the progress of localized damage on the photocathode under bright illumination are shown in the area contour maps taken of HPD-1 (figure 4) and HPD-2 (figure 5). Each contour line represents a 4% difference in calibrated response. The initial scan (4-a) is shown with a grid overlay which indicates where the 19 hexagonal pixels are located. In this scan the HPD is locally uniform with a gradual 20 % falloff toward the edges, which is within CMS specification. By the end of test 1 (4-b), corresponding to 33 years of CMS running into one pixel, damage to illuminated pixels 9 (bright) and 11 (dim) are clearly visible. Although damage is local to the pixel, degradation of the photocathode is also seen in the outer edges closest to the illuminated pixels and in the region bridging the two pixels. Figure 4-c shows the same HPD at the end of the second test in which pixel 3 was illuminated. Again the damaged region extends to neighboring pixels, but previously damaged regions further away maintain the same damage pattern, while slowly degrading as a whole (see details in figure 6).

The area scans from HPD-2 before and after illumination of the center pixel (pixel 10) are found in figure 5, showing only a 3% reduction in calibrated response, for a much less aggressive illumination rate of 1.35 C/year (still more than 4 times that expected at the worst CMS location). The integrated charge of 0.46 C represents approximately one and a half years of CMS running at high η. None of the non-illuminated pixels were affected significantly by illumination of pixel 10 at this lower rate.



a) 2002-08-08 (Beginning)   b) 2004-08-26 (End of first test)   c) 2005-10-14 (End)

Figure 4. Area scans (4% contours) of HPD-1 (AZ0230019) upon receipt of the tube (left), after illumination of pixels 9 and 11 (center), and after additional illumination of pixel 3 (right). The center picture represents 11 C delivered to pixel 9 in the course of 436 days (excluding breaks). The right picture represents 2.83 C delivered to pixel 3 in the course of 218 days.



a) 2004-11-14 (Start of 2nd test)   b) 2005-10-13 (End)

Figure 5. Area scans (4% contours) from HPD-2 (AZ0308004) at the start of the test (left) compared to after illumination of pixel 10 by 0.46 C over 218 days.

The progress of selected pixels, ranging from worst affected (pixel 7) to least affected (pixel 19), are shown in figure 6 as a function of time, using data from the periodic area scans. The curves are normalized to the first data point for each pixel, which is set to 100 %. Here, the change in an illuminated pixel is relative to a “control” pixel which was not illuminated during the test, thereby eliminating the several percent absolute calibration uncertainty which applies to the tube as a whole. While this smoothes out the individual curves, it also removes any overall drift in the tube response. The measured drift corresponds to a 10% decrease from start to finish in HPD-1 for all pixels which are far from the illumination, and which we assign to overall tube degradation during such high rate operation. Thus, while the ΔQE column in Table 1 accurately shows the absolute changes in QE (see pixel 19 of HPD-1), figure 6 represents only the degradation due to local illumination damage. In general, it can be seen that the total tube response degrades monotonically during illumination and then recovers slightly during dark storage.

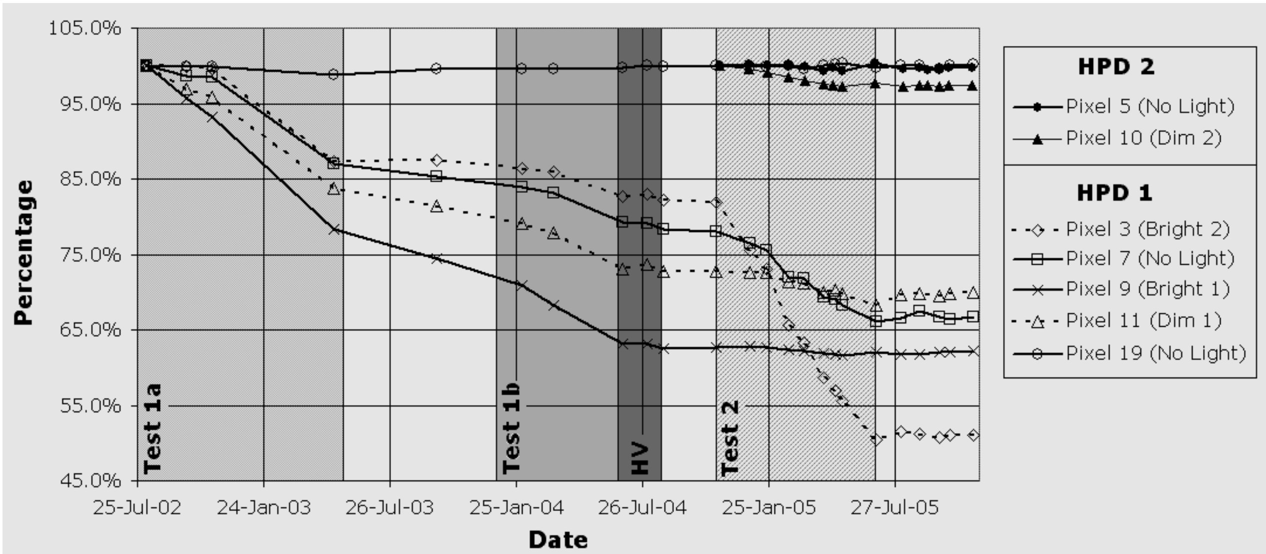


Figure 6. Pixel signal compared to a control pixel (pixel 18). Data extracted from the calibrated area scan measurements.

The in-situ data of the second test provides a more detailed and continuous time-dependent response curve. A log plot of the in-situ data taken during the second test are shown in figure 7, including the temperature, dark current, and signal (light minus dark) of the two illuminated pixels, where any variation in the source intensity is normalized out using the reference photodiode at the other end of the scintillator stick. Changes in the dark current due to temperature fluctuations are at the same level as the noise from the setup, but can be distinguished when compared to the temperature sensor data. Since the range of the temperature fluctuations was only around 3˚ C, the temperature effects on the HPDs were insignificant, so they were neglected rather than corrected for. Running the tube under illumination caused a monotomic degradation of the tube response which can be characterized by the slope in the lines labeled *signal*. During this test, the response from the brightly lit pixel 3 lost 40% of the signal after 2.8 C of integrated charge, while the dim pixel 10 would have lost only 19% at its projected rate (it lost 3% over 0.46 C), indicating that the intensity, not just the total charge, affects the rate.

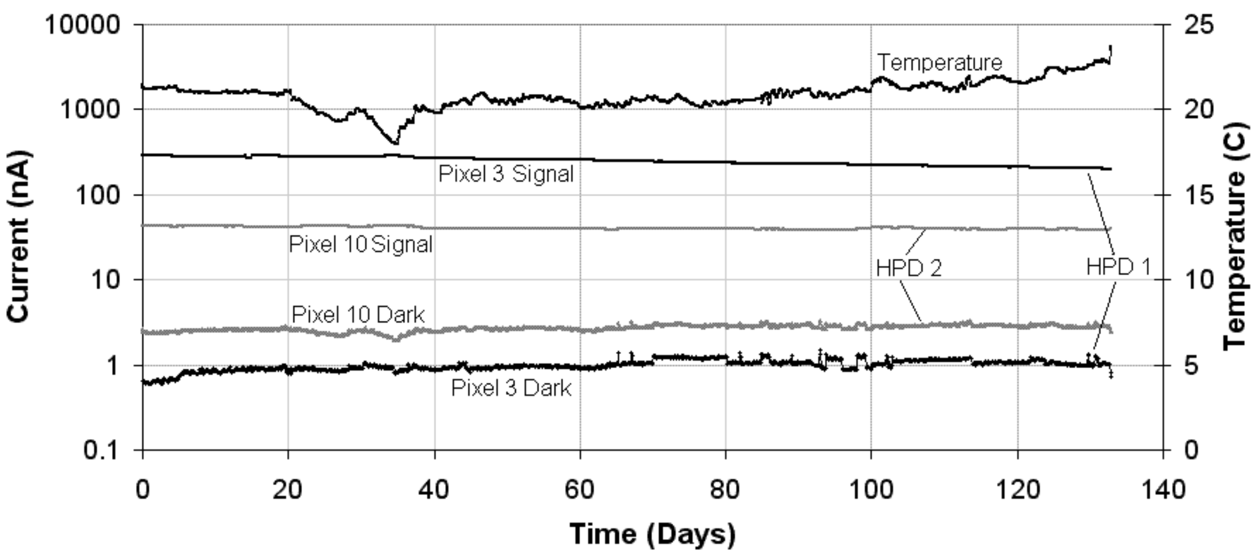


Figure 7. In-situ measurements for the second test period: one pixel per HPD. Temperature, pixel dark current, and light (signal-dark) are recorded automatically every 2 hours.

3. High Voltage Aging Tests

In a similar test, a set of 8 HPDs were operated at V_{gap} between 8-10 kV for 18 months to test the effect of high voltage alone. Four of the HPD's (B1, B2, B3, B4) were chosen because they had known voltage breakdown problems above V_{gap} > 10 kV, while the other four "good" HPD's (G1, G2, G3, G4) did not.

Bad Tube Number	Production Number	Good Tube Number	Production Number
B1	80	G1	147
B2	85	G2	182
B3	95	G3	189
B4	163	G4	193

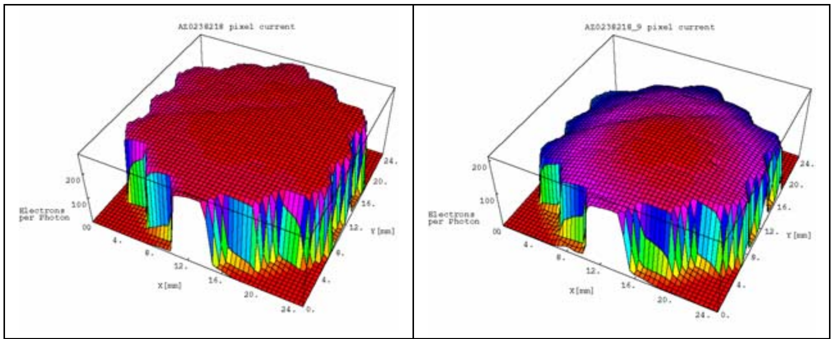
The purpose of this test was to check if the "bad" HPD's would have more problems just remaining at high voltage than the HPD's that appeared normal. Although subjected to no light injection or diode bias while on high voltage, they were periodically removed from the setup to undergo area scans, gain curve, and other measurements in our quality assurance stations. Table 2 summarizes the results, using the variables which were recorded in the HPD database: http://hcal-up.hep.umn.edu/ (click "search" for the database, "statistics" then "histograms" for trending diagrams). The first set or rows in the table applies to all the tubes, whereas in the second set, only the tubes which experience a change are mentioned. The standard deviation of the change for all affected tubes is in the righthand column.

The AC crosstalk measures the capacitively-coupled crosstalk, while the DC crosstalk is optical crosstalk (the electron backscatter component has been removed by application of a 0.3 T axial magnetic field). The Bias Curve test is sensitive to the shape of the tube response curve as a function of reverse bias, essentially determining whether there was a change in the breakdown voltage of the diode itself. The HV Curve measures the linearity of the HV curve by forming a ratio of the slope from 8-12 KV to the slope from 6-8 kV. An upturn in the slope at higher voltages indicates possible low level sparking. The Viking test measures the resolution of the single photoelectron peaks at very low light levels. It can detect the onset of ion feedback due to poor vacuum, but in these cases, it fails because the current out of at least one pixel is too high or fluctuating, thus loading the system preamp. E/P stands for Electrons/Photons and is the number of Coulombs out the anode divided by the number of photons in the front. It is therefore the calibrated tube response. Once the gain is factored out, it gives the QE.

Scan	**Change (Average)**	**Comments**	**st dev**
AC Crosstalk	0.18% decrease per year	Better	0.13%
DC Crosstalk	0.26% decrease per year	Better	0.21%
Bias Curve	None	30% variation due to temperature	
Area Scan (B1, B3)	19% decrease in uniformity	Worse, leveled off after ~ 1 year	5%
Area Scan (G2)	10 - 30% Variation	Damaged then recovered	
Dark Currents (B1, B3)	Large increase in one pixel near 12 kV	Worse, (B1 pixel 9, B3 pixel 15)	
HV Linearity (B1, B3, G1)	18% decrease in linearity	Worse	10%
HV Linearity (B2)	3% increase in linearity	Better	
Viking (B1, B3)	Bad after 2 – 3 months	worse	

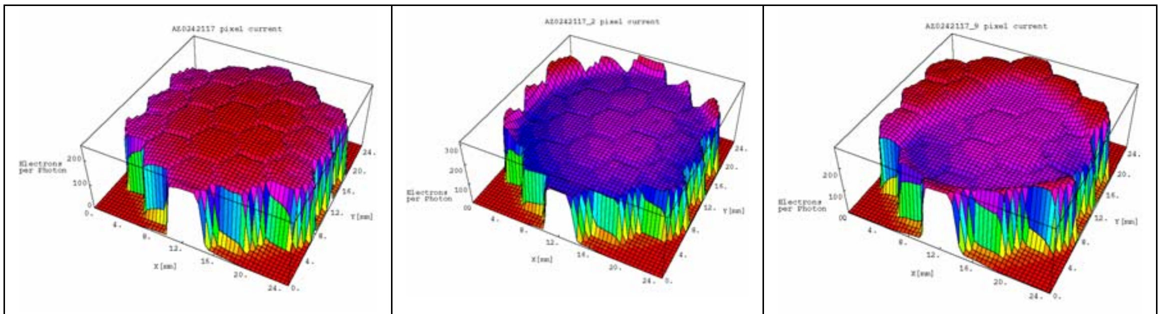
Table 2. 18 month voltage stability test for 8 HPDs, 4 with suspected HV problems

The gain of the tubes is a stable quantity over time. The overall dark current decreased for most of the HPDs during the HV-only test, as did the optical crosstalk and capacitively-coupled crosstalk. This effect has been seen for many other HPDs as well during routine operation. The QE can be affected by operation (even without light injection) if the tubes have HV instabilities. For three of the HPD's (B1, B3, G2), area scans show large changes in QE during the test, but all three appear to have been affected differently. B1 and B3 both decreased somewhat in QE and their surface response became non-uniform (see figures 8 and 9). G2 actually redistributed its response over time (figure 10). The area scans are calibrated and the QE of just the center pixel (pixel 10) is tracked in figure 11, demonstrating that G2 actually lost QE on the edges, then gained QE back again (rather than becoming uniform at a lower QE). For the last few months of the test it was operating within CMS specification.



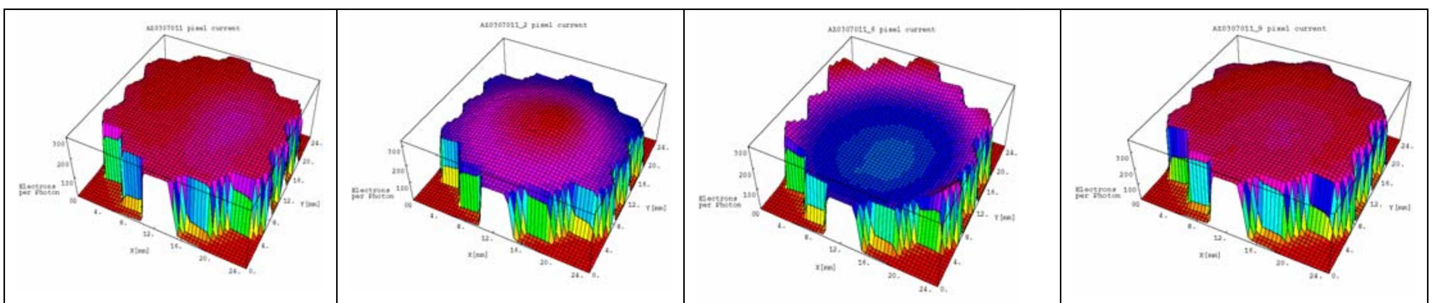
2003-05-18	2005-10-18

Figure 8. B1 area scans for selected times during HV-only test



2003-05-18	2003-12-02	2005-10-18

Figure 9. B3 area scans for selected times during HV-only test



Initial Scan 2003-05-18	Edge QE is falling off 2003-09-29	Edge QE rises, Center falls 2004-06-23	Center QE rises 2005-10-18

Figure 10. G2 area scans for selected times during HV-only test

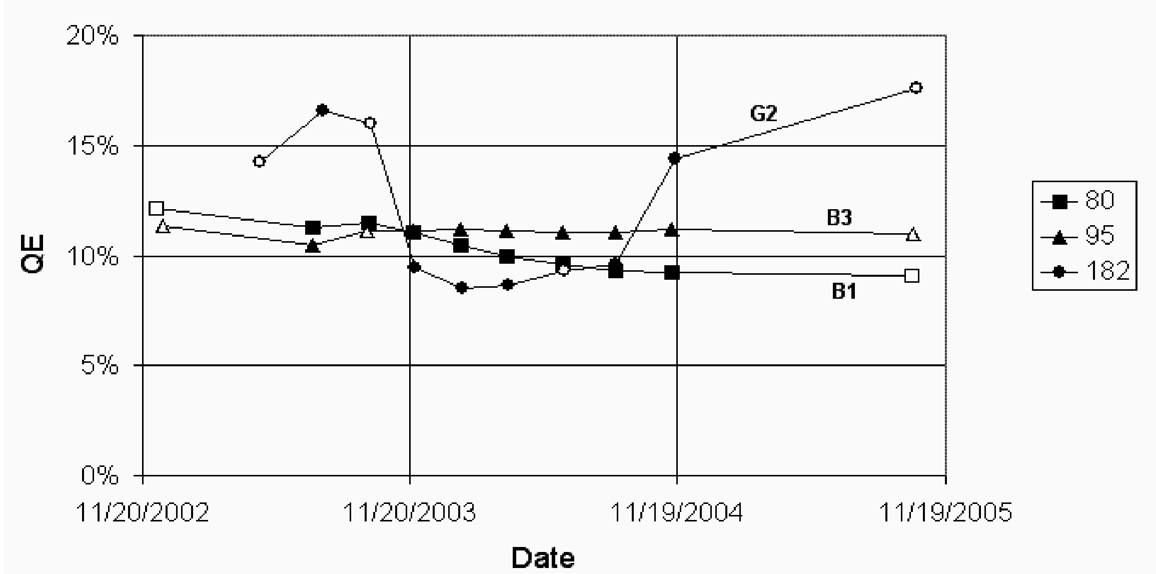


Figure 11. The QE of the center pixel as a function of time during the HV-only tests. The open circles correspond to the dates of the plotted area scans in figures 8-10.

The two "bad" tubes (B1, B3) have pixel leakage currents that are now dependent on V_{gap}. This is connected to the observed non-linearities in the HV response curve. Since we have observed light from the fiber optic faceplate (using both an APD and a PMT facing the tube window), we believe this to be due to glow discharge across the window. We observed such unstable tubes over periods of hours and noted that the response above 10 kV would vary as much as 10% from measurement to measurement within that timescale. It is also worth noting that with many other HPDs that we have tested, large variations in area scans are almost always accompanied by an upturn in the HV curve above 10 kV, indicating that the area scan non-uniformity is due to the onset of HV breakdown. The converse is not true, however. Many HPDs with a non-linear slope above 10 kV have good area scans. B2 was the only HPD with a non-linear HV at the start of the test, and it appears to have healed during the 18 months on high voltage, such that it is hardly noticeable in the scans taken at the end of the test. Figure 12 shows the non-linearity of the HV curve.

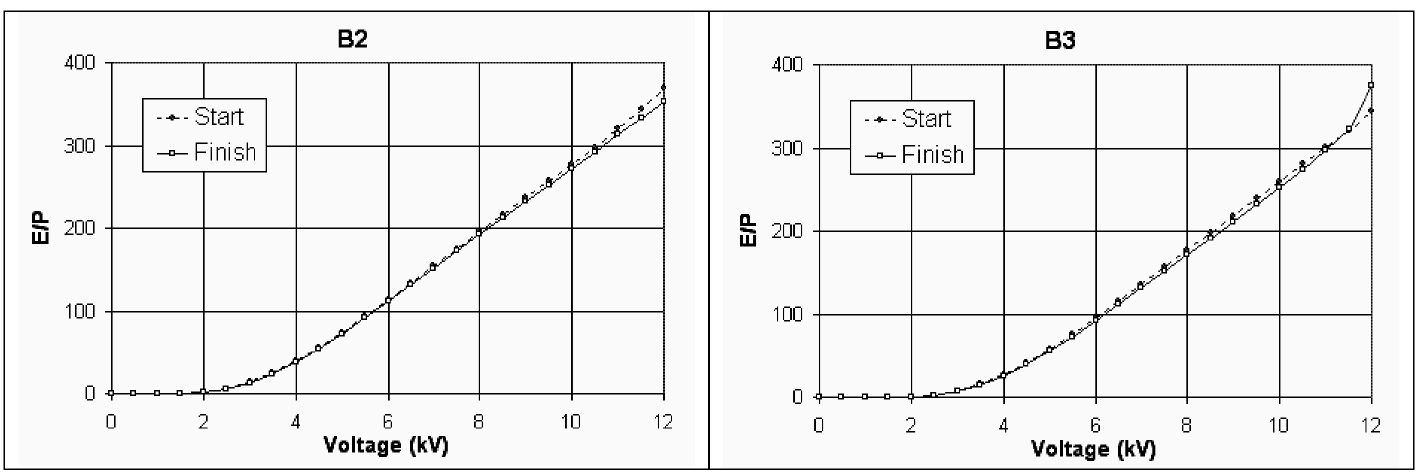


Figure 12. Linearity of HV response curve. B2 (left) linearity improved with time and B3 (right) became worse. This is related to HV instabilities which also manifest as the dark currents in some pixels becoming elevated when the tube is operated higher than 10 kV. Since this is an instability, the HV curve can fluctuate from day to day; the fact that it appears to be "cured" on the test date should not be trusted.

There was also a 20 – 25% decrease in the dark current of the HPDs over the winter. This is due to temperature fluctuations in the room, since the dark current changes by about 20% for a 10^{o}C temperature shift. The gain, on the other hand, is less sensitive to temperature fluctuations, increasing by approximately 1.5 % over 10^{o}C. Both the in situ scan of figure 7 and the temperature scan of figure 13 quantify this effect.

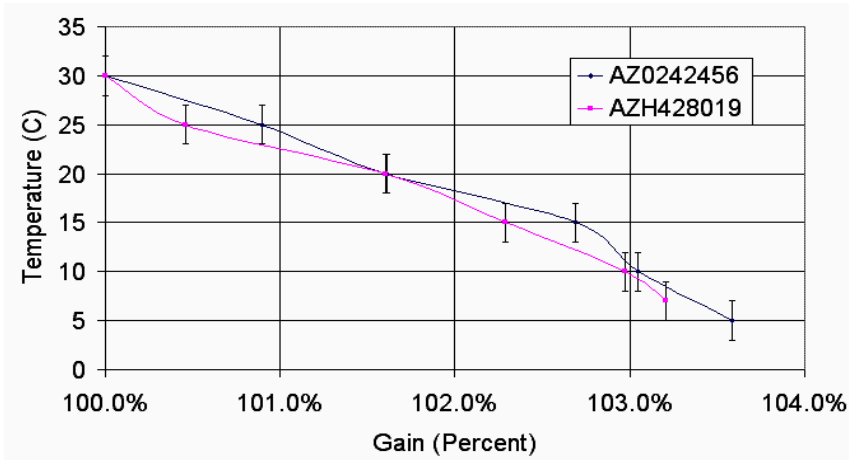


Figure 13. Gain increases as Temperature decreases at approximately 0.15% per degree C.

4. Conclusion

Figure 14 summarizes rate dependent effects by plotting the rate of QE degradation as a function of the rate at which the light was delivered. The details of the damage were displayed in the contour plots, showing that the damage covers an area of several pixels, thus forcing the dimmer pixel to be damaged at the rate determined by incident light into both itself and the close brighter pixel. Thus, for pixels 9 and 11 of HPD-1, it is the sum of the light into both which is plotted on the x-axis. If plotted this way, the slope seems to remain the same for all rates of illumination and a rule of thumb would be that the quantum efficiency is reduced by about 2% every C through the anode. For CMS tubes running at 0.3 C/yr over 10 years, one might expect a 6% reduction. Pixel 3 of HPD-1 in the second test does not fall along this curve, experiencing a much steeper rate of damage. However, this is probably because it is an edge pixel in an already highly-damaged tube. We did not observe any evidence of photocathode redistribution to other pixels during damage. Even the non-illuminated pixels showed some decrease during the tests. In addition, there is very little annealing of the photocathode when the HPD is not in use. The non-uniformity in QE caused by light injection does not appear to decrease during storage in a darkened environment.

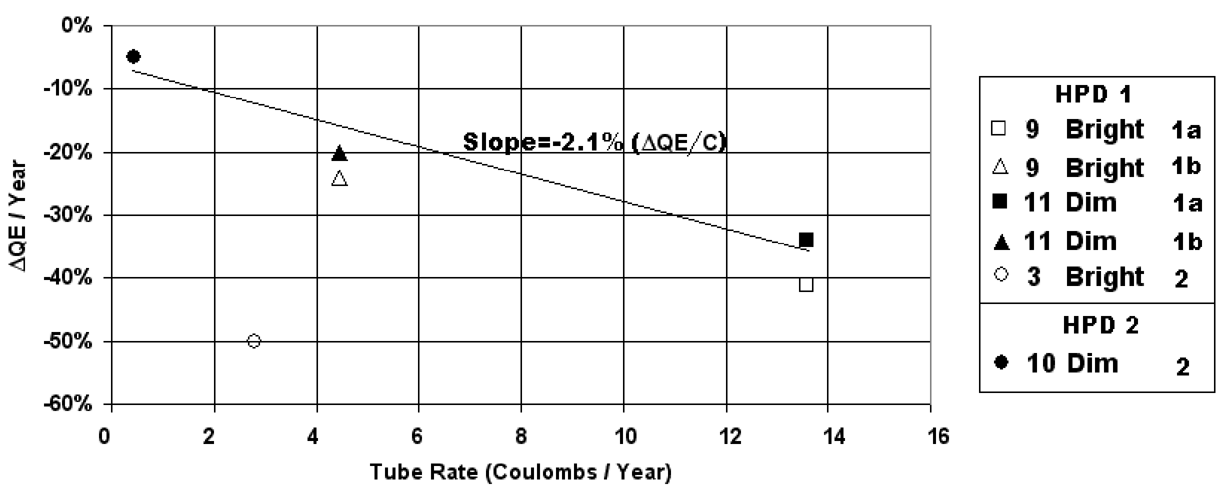


Figure 14. Change in %QE per year as a function of the brightness of all illuminated pixels. In other words, the rate by which QE is reduced as a function of the total rate of charge through the tube anode due to illuminating the pixels. Recall that the highest rate CMS tubes will be subjected to rates of approximately 0.3 C/yr, corresponding to HPD-2, pixel 10 in test 2.