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Gain dispersion in Visible Light Photon Counters as a function of counting rate

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Abstract

We present measurements of light signals using Visible Light Photon Counters (VLPC), that indicate an increase in gain dispersion as the counting rate increases. We show that this dispersion can be understood on the basis of a recent observation of localized field reduction in VLPCs at high input rates.

Visible Light Photon Counters (VLPC) are silicon devices that detect single photons with a quantum efficiency (Q.E.) of $\approx 80\%$ and have high gain ($\approx 50,000$). Descriptions of these devices can be found in Refs. [1], [2] and [3]. A VLPC is composed of an undoped intrinsic silicon layer that overlays a weakly compensated arsenic-doped gain layer, as shown in Fig. 1.

A photoelectron produced in the intrinsic region drifts under applied bias to the positive contact and is collected. The hole moves across the intrinsic region towards the ground contact in a series of scatterings too weak to produce any impact-ionization. After reaching the gain layer, the positively ionized donor (called D^+ or hole) must acquire only about 0.05 eV to impact-ionize an As atom and generate an electron-D^+ pair. The liberated electron can impact-ionize other As atoms, generating new electron-D^+ pairs. As this process repeats, thousands of electrons and D^+ are created forming what is called an avalanche.

As a result of the slow movement of the D^+, the electric field is reduced in the region of the avalanche in the VLPC. Measurements [4] indicate that this field reduction lasts on the order of milliseconds. This temporary Localized Field Reduction (LFR) in areas of the VLPC produces a decrease in gain and quantum efficiency that has been observed when the device is operated at high counting rates [5].

We present measurements of the gain dispersion in the VLPC as a function of counting rate, and show how the observed increase in gain dispersion can be understood within the LFR model.

The DØ experiment [6] at Fermi National Accelerator Laboratory relies on approximately 100,000 channels of VLPC pixels to detect light from plastic scintillators. The gain, relative quantum efficiency and dark-current count rates were measured for each device under different operating conditions, and each detector was characterized using LEDs to illuminate optical fibers coupled to the VLPCs [7]. Since VLPCs have to be operated inside a cryostat at a temperature of about 9K, the optical fibers as well as the readout cables are routed into the cryostat using a VLPC cassette assembly as sketched in Fig. 2 [8]. Each cassette houses 1024 channels of VLPC readout. Two LEDs were used in our study, one was pulsed every few milliseconds and generated a signal that was read out with an ADC. An independent LED was pulsed at a much higher rate in order to simulate the background environment resulting from collisions at the DØ proton-antiproton interaction point. The particles produced in the collisions excite the surrounding scintillators at a rate equivalent to a photoelectron counting rate of 8MHz. The performance of each VLPC pixel was characterized at different background counting rates and different bias voltages. Figure 3 shows the charge distribution obtained from a single VLPC pixel, operated at a fixed bias voltage of 6.8 V and low counting rates (the background LED was turned off, and only the signal LED was flashing giving a counting frequency in the LED of approximately 100 Hz). As can be seen in Fig. 3, the LED signal yields a Poisson distribution with a mean of approximately 1.65 photoelectrons (pe). The distribution shows a remarkably clear separation of peaks corresponding to different numbers of pe. The reason for this clean separation is the relatively small fluctuation in the number of electrons produced in an individual avalanche. The gain dispersion δ_g is defined as the standard deviation in the number of electrons produced by a photon induced avalanche, as discussed in reference [9].

The charge distribution shown in Fig. 3 was fitted using a Poisson distribution convoluted with a Gaussian function:

$$P(q) = \sum_i (p_i^\mu/(2\pi\sigma_i)) \exp \frac{(q - ig)^2}{2\sigma_i^2} \tag{1}$$

where $P(q)$ is the probability of measuring a charge q in the ADC, p_i^μ is the probability for obtaining the integer i photon in a Poisson distribution with mean μ, g is the gain in units of ADC/e, and σ_i is the RMS of the i^{th} peak in the distribution, given by:

$$\sigma_i = \sqrt{\sigma_0^2 + ig^2\delta_g^2} \tag{2}$$

where σ_0 is the width of the pedestal peak, and δ_g is the gain dispersion of the VLPC.

The charge distribution from the VLPC pixel is shown in Fig. 4 for a background rate of 4MHz (as in Fig.3, the signal LED is flashing at approximately 100Hz, and now the background LED is flashing at 4MHz). The reduction in the mean number of pe reflects the decrease in quantum efficiency of the device at the higher rate. The fit shows that the variation in the number of electrons in an avalanche is larger at this rate. Although Figs. 3 and 4 show examples for a single channel, the 100,000 channels tested at DØ display similar behaviour. In this article, we concentrate on the measured increase in gain dispersion as a function of rate shown in Fig. 5.

A model to describe the degradation in quantum efficiency and gain has been developed recently [4] and its main feature are sketched in Fig. 6. It assumes that, after an avalanche, the gain of a cell is reduced by 50%, and recovers with a characteristic time of 3.75μs. The

Q.E. of the cell recovers as the second power of the gain, predicting that at high rates the photon will have a non-negligibe probability of being absorbed in a region of the VLPC where the electric field is reduced. This leads to a smaller average gain, as discussed in Ref. [4], but also to an increase in the variation in the number of electrons in an avalanche. Some regions of the VLPC will have full gain, while other regions will have no gain at all. Using a numerical simulation of the model proposed in Ref. [4], we calculate the expected increase in δ_g as a function of operating rate. The open points in Fig. 5 show the calculated gain dispersions for a VLPC operating at different frequencies.

In conclusion, we have presented measurements of gain dispersion as a function of counting rate observed in VLPCs. A clear increase in gain dispersion is seen as the counting rate in the device goes up to 8 MHz. This increase is reproduced by a model that was developed to accomodate the reduction in VLPC gain and quantum efficiency as a function of rate.

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Figures

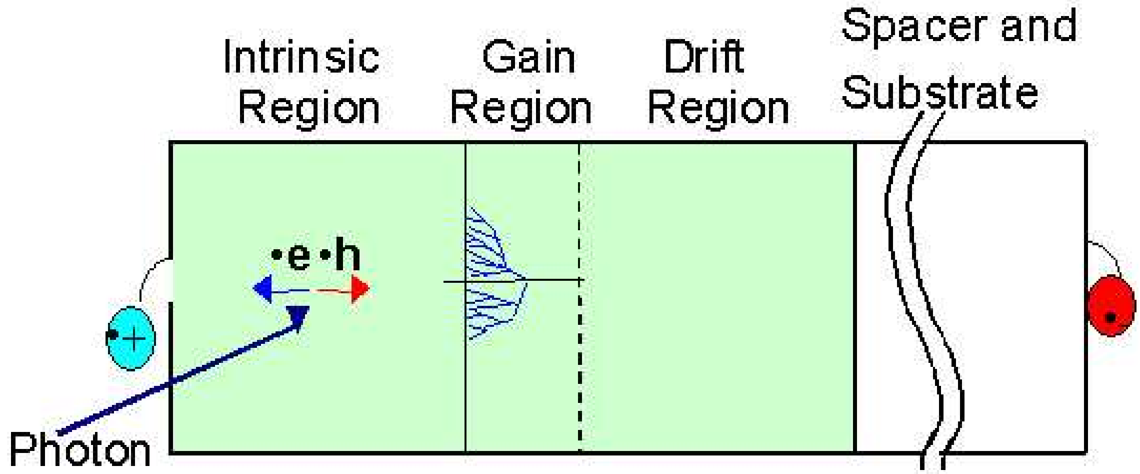

Figure 1: Sketch of a VLPC detector. The incident photon is absorbed in the intrinsic (1.12 eV band gap) or in the gain region (0.05 eV band gap), creating an electron-hole pair.

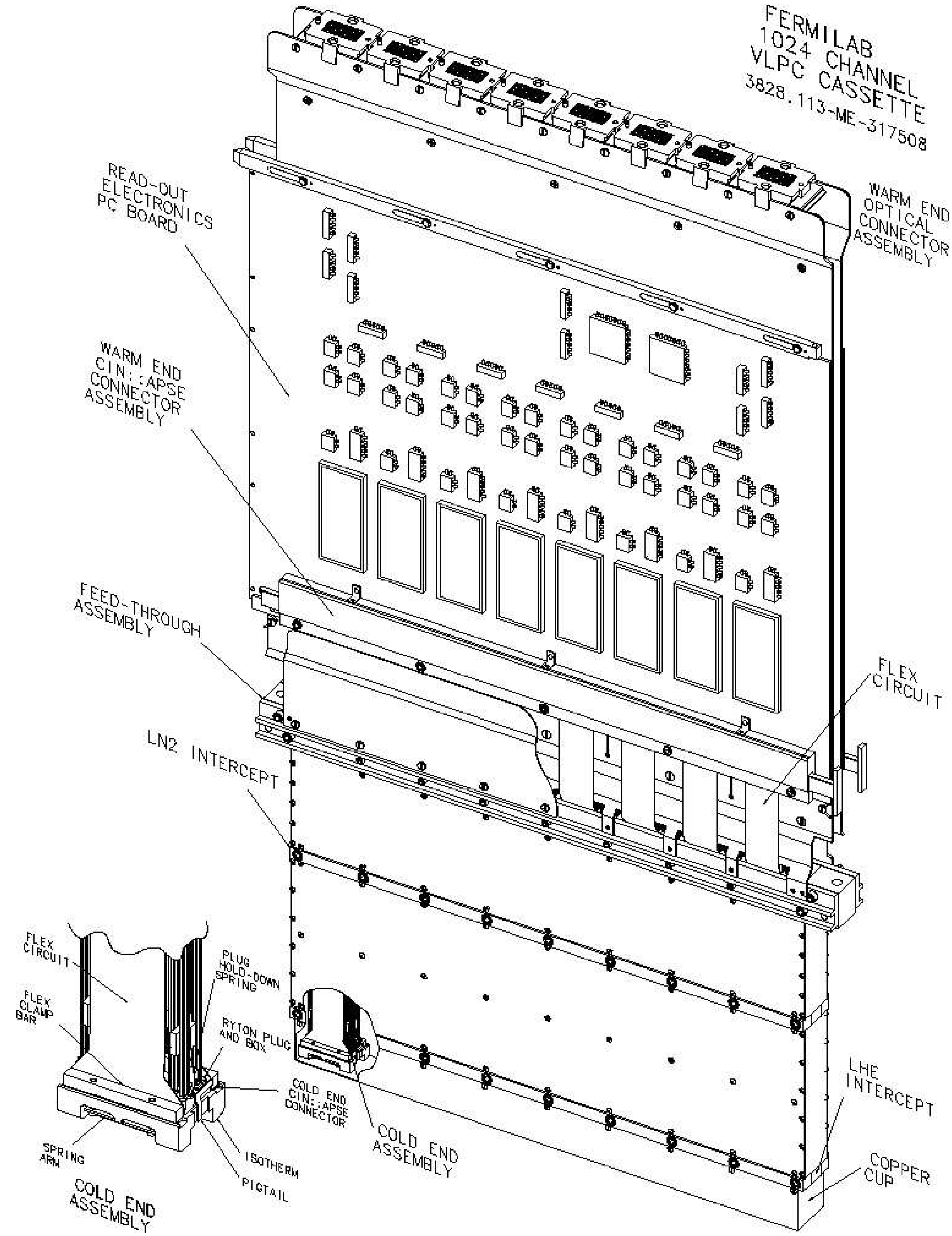

Figure 2: VLPC cassette assembly

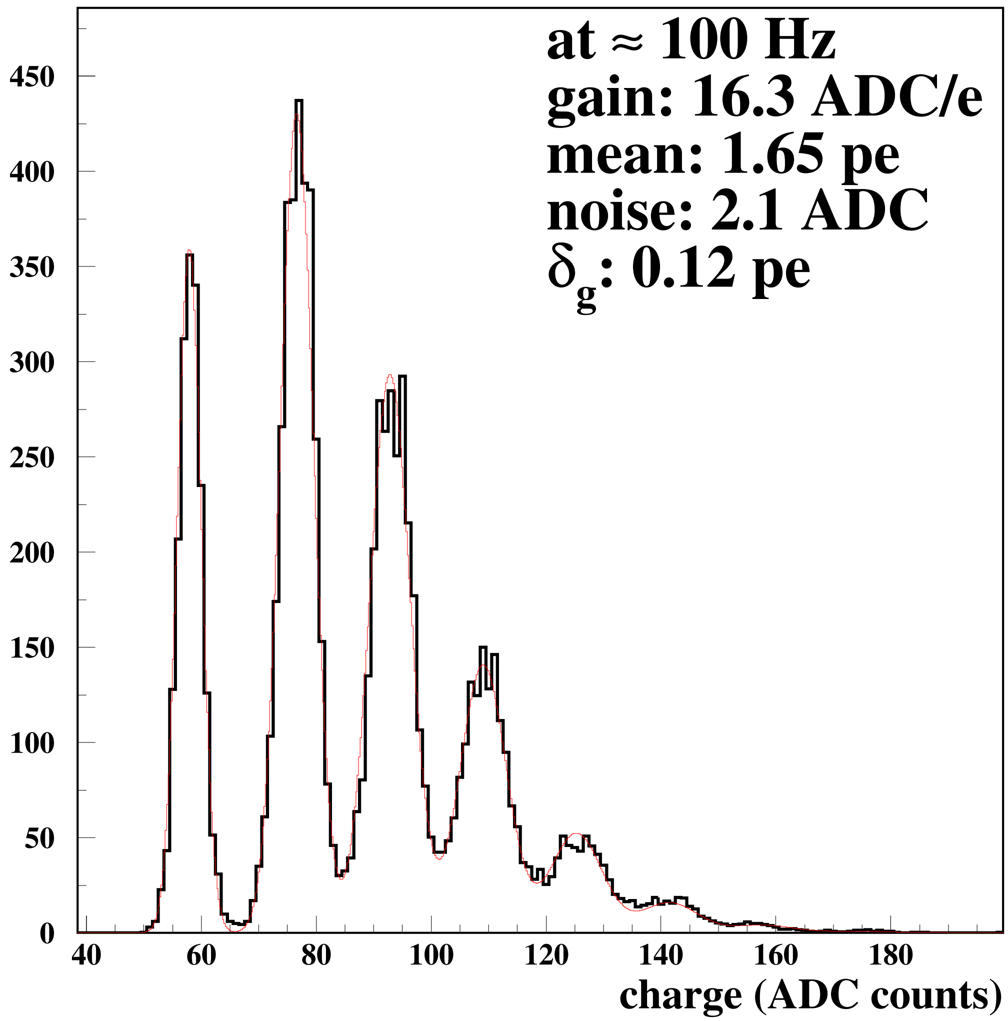

Figure 3: Charge distribution from a VLPC pixel operated at 6.8 V at a small counting rate (≈ 100 Hz). The open histogram corresponds to data (10,000 entries) and the curve corresponds to a fit using a Poisson distribution convoluted with a Gaussian (see text for details).

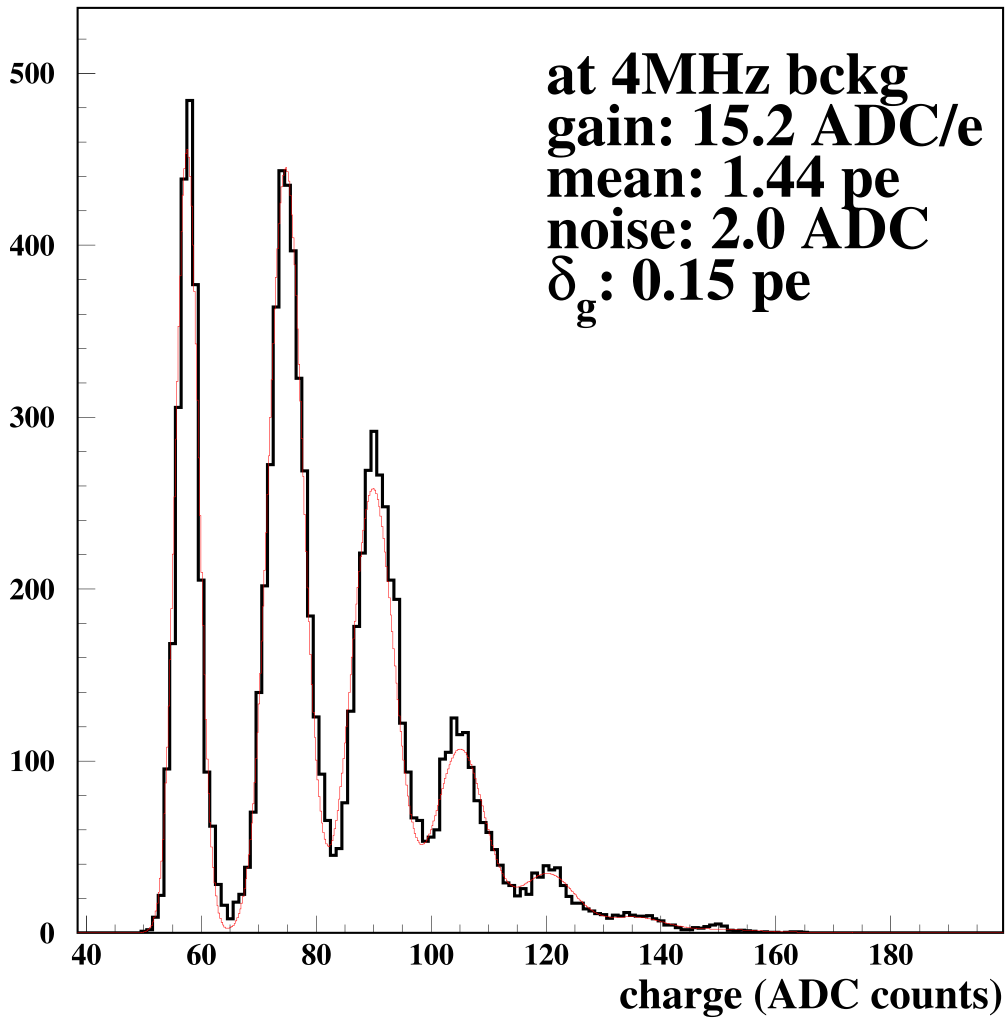

Figure 4: Charge distribution from the same VLPC pixel shown in Fig. 3, operated at the same bias voltage, but at a counting rate of 4 MHz. The open histogram corresponds to the data (10,000 entries) and the curve corresponds to a fit using a Poisson distribution convoluted with a Gaussian (see text for details). The mean pedestal was adjusted to match the value of Fig. 3 for the sake of comparison.

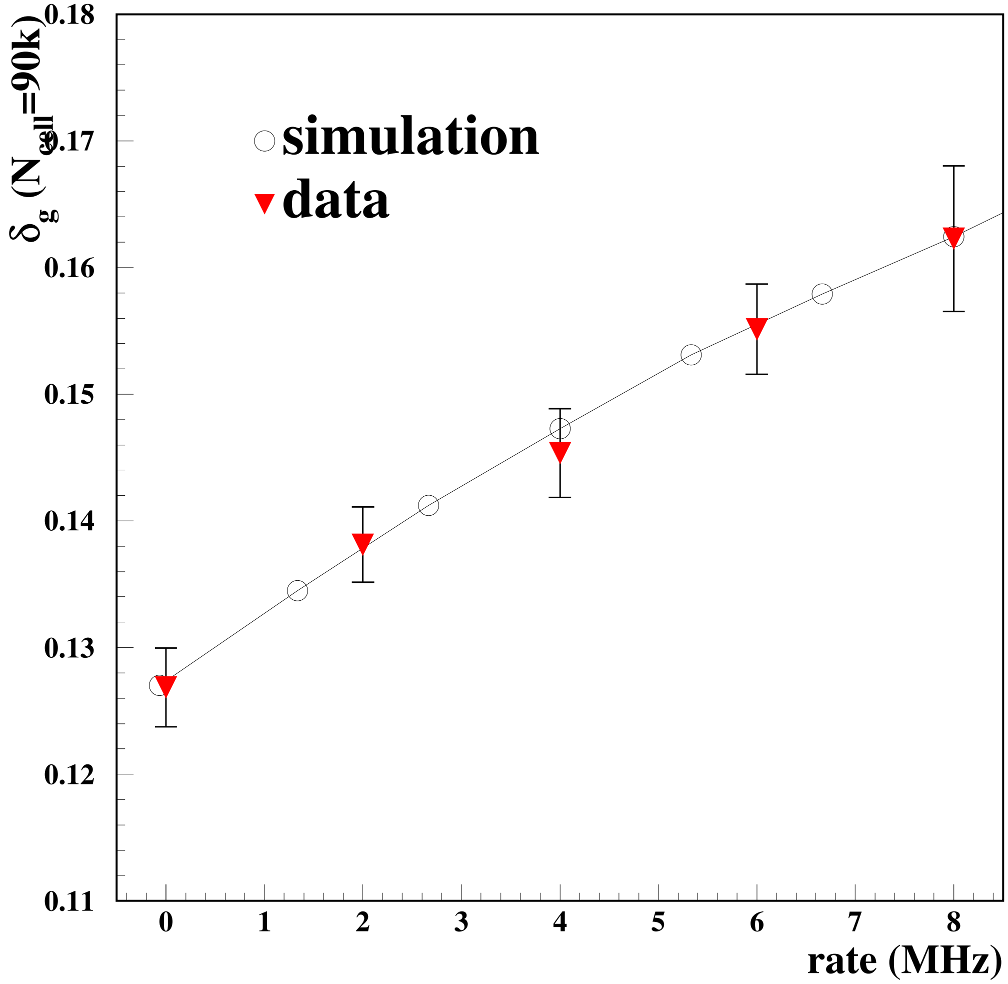

Figure 5: Gain dispersion as function of background rate. Data points are the mean values of 64 VLPCs, taken at a temperature off 9K and $V_{bias} = 6.8V$. Simulation points were obtained using 90,000 cells in one pixel, and k=2 (see text for details).

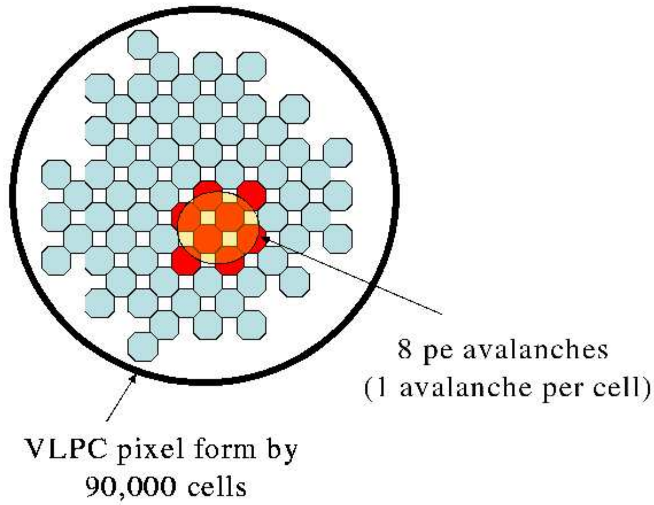

Figure 6: Sketch of the VLPC model used in the simulation. The area of the pixel is $1mm^2$. Up to 90,000 non-overlapping avalanches (one per isolated cell) can develop in each pixel.