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Performance estimates for cooled silicon photomultipliers

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1 Background

There are presently several light sensors that are being considered for the barrel calorimeter (Bcal) readout [1]. Silicon photomultipliers (SiPMs) has long been considered the nominal choice for use in the inner region. SiPMs are a natural fit to this application because their performance is unaffected by magnetic fields and the Bcal is located in a 2 T magnetic field. However, the light collection must cover a relatively large area and SiPM arrays of sufficient size ($\sim$1.4 cm^2) have only recently become available in test quantities. Furthermore, the SiPM arrays operating at room temperature do not currently meet our combined specifications simultaneously. In this note we estimate the performance improvement, relative to our requirements, when SiPMs are cooled below room temperature. We note that for the moment we are not attempting to distinguish one manufacturer from another, as the general characteristics are common, but rather to estimate the improvement due to cooling.

2 Parameters at room temperature

The parameters for the SensL SiPMs at room temperature have been reported by SensL for several of their cell configurations [2]. In cases where we have made measurements of similar devices, we have verified their results. Therefore, for the present purposes, we simply use their measurements as nominal at room temperature (i.e. 20° C). The PDE is plotted vs. DR in Fig. 1. where we have taken the DR for a 16-cell array to be 16 time higher than the measured DR for a single cell. An additional point is plotted for the Photonique 4.4mm^2 SSPM-0606BG4-PCB from Ref. [3] taking a DR of 6 MHz/cell at 20°, scaled by an area factor of 2 for comparison to the 3×3mm^2, and again 16 for an array. It follows the trend of the SensL sensors. The black curve is the Bcal minimum specification. Combinations of PDE and DR above the curve satisfy the Bcal requirements. There is agreement that the SiPMs operated at room temperature do not meet our readout specifications.

3 Dependence on temperature

The Hall D group has investigated the temperature dependence of SiPMs from SensL [4] and from Photonique [3]. We have not yet measured the temperature characteristics of SiPM arrays, but we expect that the photon detection efficiency (PDE) and dark current (DR) is determined by the intrinsic properties of the silicon itself. Therefore the measured temperature dependence of the single cells should be representative of the arrays.

3.1 PDE

The temperature dependence of the PDE was specifically measured only for the Photonique light sensors. However, the gain dependence was measured for both SensL and Photonique sensors, and we assume its temperature dependence is primarily due to changes in the PDE. The measurements of both the PDE and the gain showed a linear dependence on temperature, increasing as the temperature decreased. We have parameterized this dependence as follows:

$$\begin{aligned} \mathrm{PDE(T)} &= \mathrm{PDE(20^\circ)\ (1 + c\Delta T)} \qquad (1) \\ c_{\mathrm{SensL}} &= -0.075 \\ c_{\mathrm{Photonique}} &= -0.025 \end{aligned}$$

where $\Delta T = T - 20^\circ$ and T is the temperature of the sensor in degrees Centigrade. For the Photonique sensors, we have taken the measured dependence of the PDE which is steeper than the measured dependence for gain. But this dependence is still shallower than the one measured for the gain of SensL sensors.

3.2 Dark Rate

The dark rate as a function of temperature was measured for the Photonique sensors and increases exponentially. The dark rate was measured for the SensL sensors at 20° and −20°, showing there is a order of magnitude decrease at the lower temperature. With this input we parameterize the dark rate as follows:

$$\begin{aligned} \mathrm{DR(T)} &= \mathrm{DR(20^\circ)\ \exp(k\Delta T)} \qquad (2) \\ k_{\mathrm{SensL}} &= 0.057 \\ k_{\mathrm{Photonique}} &= 0.038 \end{aligned}$$

4 Extrapolations

With the parameterizations for the PDE and DR as a function of temperature given by Eqs. 1 and 2, we can estimate the predicted performance of the SiPMs at other operating temperatures. We show the expectations for PDE and DR at the operating temperatures of $T = 5^\circ$ and $T = 10^\circ$ C assuming the measured dependence for the SensL SiPMs in Figs. 2 and 4. The extrapolations using the dependence of the Photonique sensor are shown in Figs. 3 and 5 . The extrapolation has been done for all sensors for both parameterizations, as there are uncertainties in how various measurements are applied, especially to the SensL devices. We note that the measurements of the Photonique sensor are self-consistent, so the extrapolation of the SSPM-0606BG4-PCB using the "photonique" constants is likely the most reliable.

5 Summary and Conclusions

We have parameterized the temperature dependence of SiPMs based on measurements of the $2.1 \times 2.1\,\mathrm{mm}^2$ SSPM-0606BG4-PCB from Photonique and on measurements of the $3 \times 3\,\mathrm{mm}^2$ A20L device from SensL. The rate measurements were made on single cells and the rates extrapolated to a 16-cell array. The temperature dependence of the PDE (or gain) were assumed to be unchanged for an array compared to a single cell. The SensL cells have a steeper dependence on temperature for both quantities than do the Photonique cells. We estimate gains in cooling using both parameterizations. The measurements of the Photonique sensor are self-consistent, but Photonique has not yet produced any arrays of the required size. The parameterization of the SensL devices requires more assumptions, so without further measurements, the two extrapolations could be taken as a range of expectations for their arrays.

The extrapolations were made to the temperatures of $T = 5^\circ$ and $T = 10^\circ$ C, which could be considered for temperature stabilization at the ends of the Bcal modules. Both sets of parameters predict that the SiPMs operating at $T = 5^\circ$ will satisfy the requirements for the Bcal readout. The steeper parameterization for SensL predicts that these arrays would also satisfy our requirements at $T = 10^\circ$ C, but not for the Photonique parameterization. The parameterization of the SensL cells predicts considerable more headroom, but because of the large temperature dependence will also present tighter constraints on temperature stabilization.

References

[1] E.S. Smith. Specifications and evaluation of bcal readout options. GlueX-doc-795, February 2008.

[2] SensL, The Low Light Sensing Company. 080708_GlueX. Private communication, July 2008.

[3] I. Senderovich, C.R. Nettleton, and R.T. Jones. Prototype scintillating fiber tagger microscope design and construction. GlueX-doc-1074, Figures 15-17, June 2008.

[4] C. Zorn. Silicon photomultipliers for the GlueX barrel calorimeter. GlueX-doc-961, p. 38 and 50, February 2008.

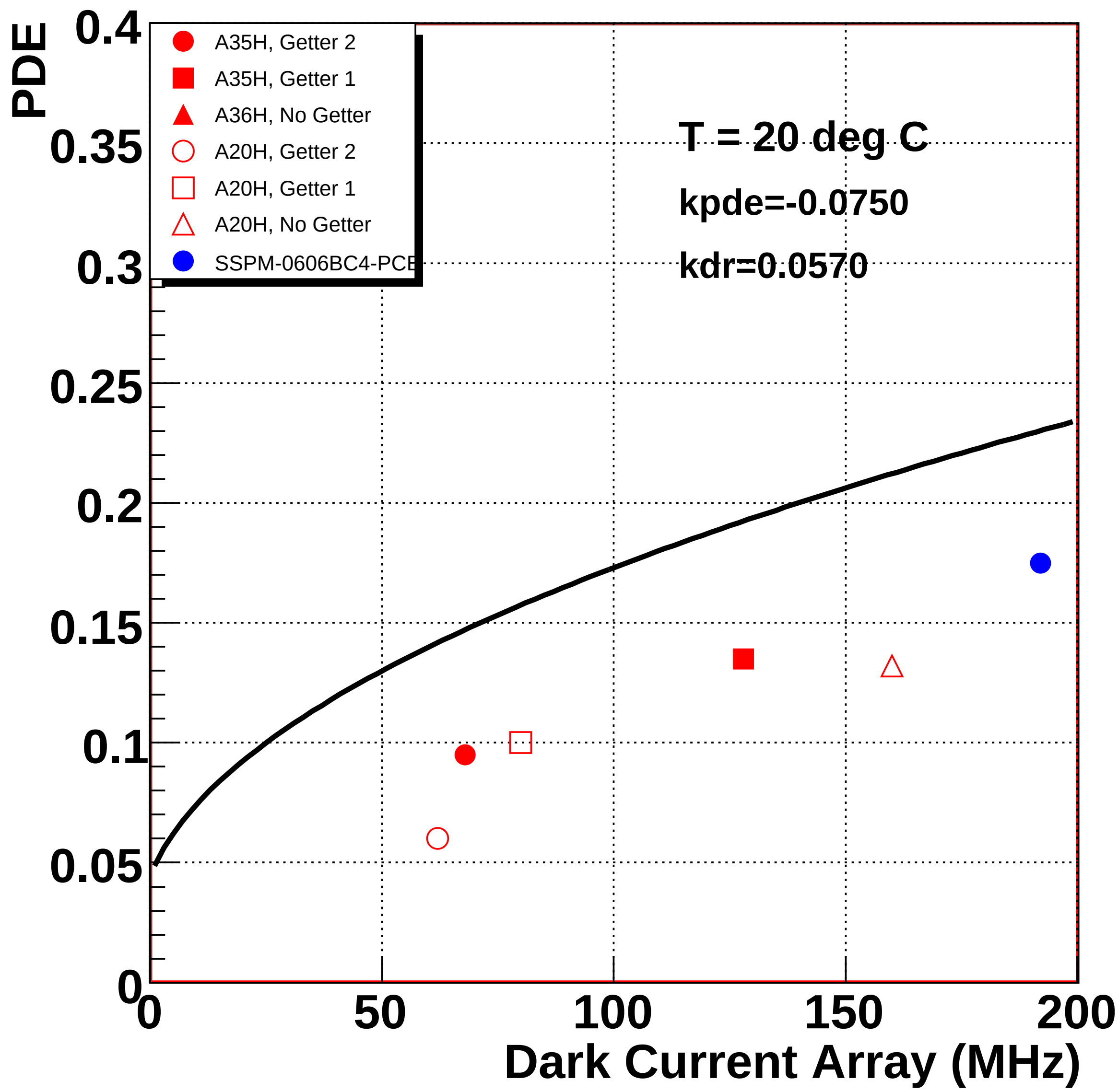

Figure 1: Photon detection efficiency vs dark rate for various cell configurations at $T = 20°$. The black line indicates the minimum requirements for the Bcal. Combinations of PDE and DR above the line meet our specifications.

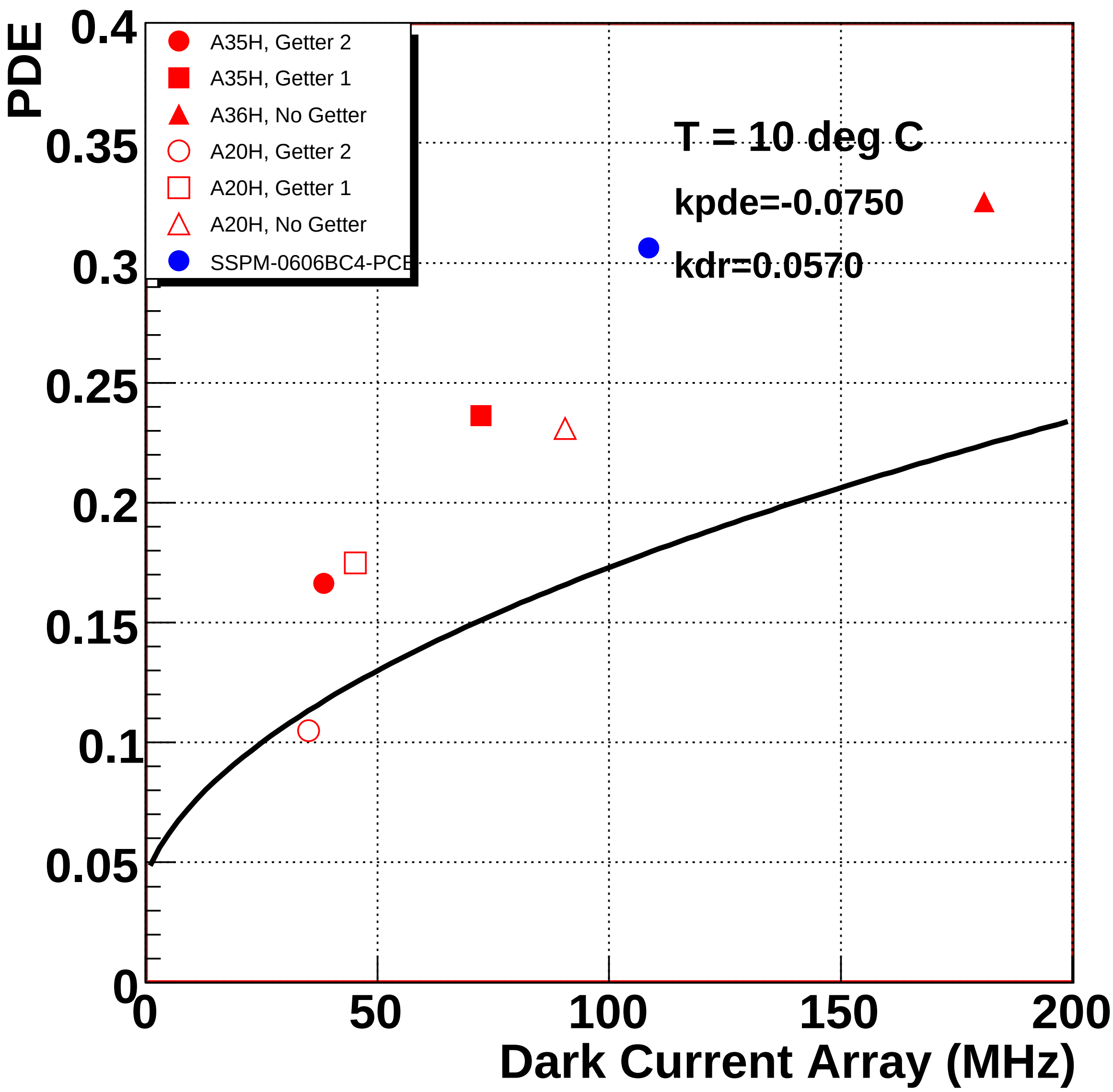

Figure 2: Photon detection efficiency vs dark rate for various cell configurations extrapolated to at $T = 10^{\circ}$ C using the parameterization of the temperature behavior for the SensL devices. The black line indicates the minimum requirements for the Bcal. Combinations of PDE and DR above the line meet our specifications.

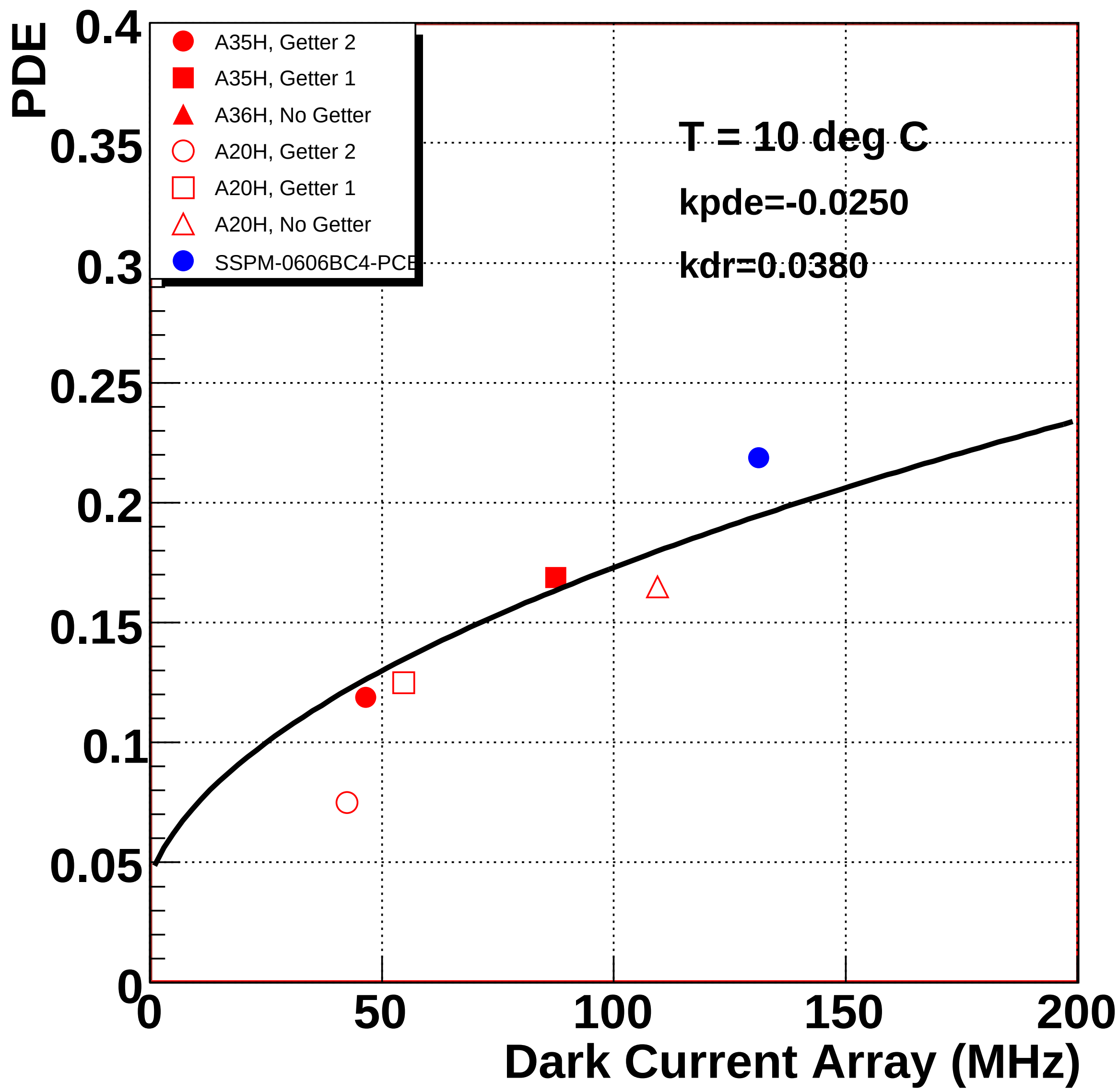

Figure 3: Photon detection efficiency vs dark rate for various cell configurations extrapolated to at $T = 10^{\circ}$ C using the parameterization of the temperature behavior for the Photonique devices. The black line indicates the minimum requirements for the Bcal. Combinations of PDE and DR above the line meet our specifications.

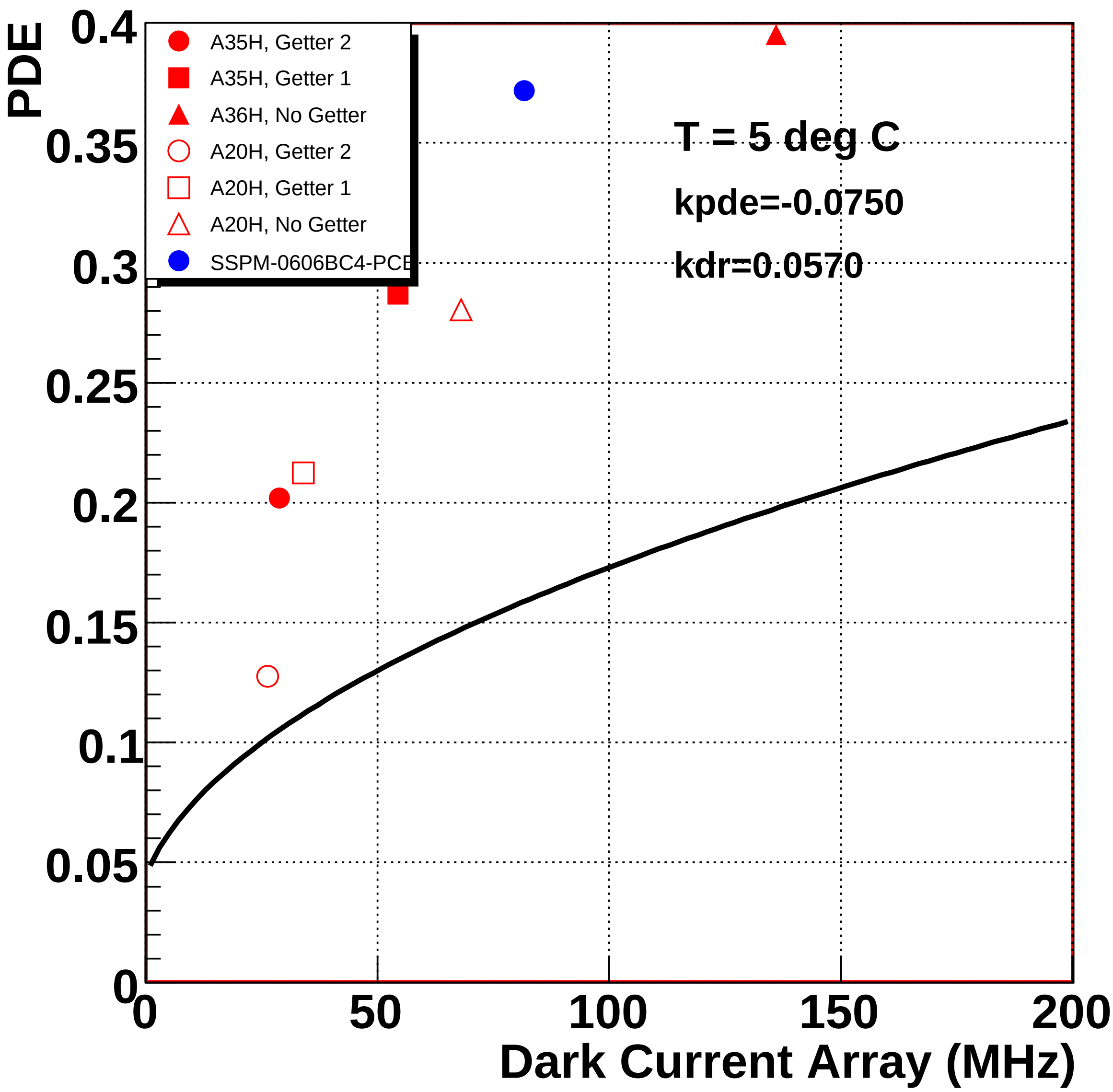

Figure 4: Photon detection efficiency vs dark rate for various cell configurations extrapolated to at $T = 5°$ C using the parameterization of the temperature behavior for the SensL devices. The black line indicates the minimum requirements for the Bcal. Combinations of PDE and DR above the line meet our specifications.

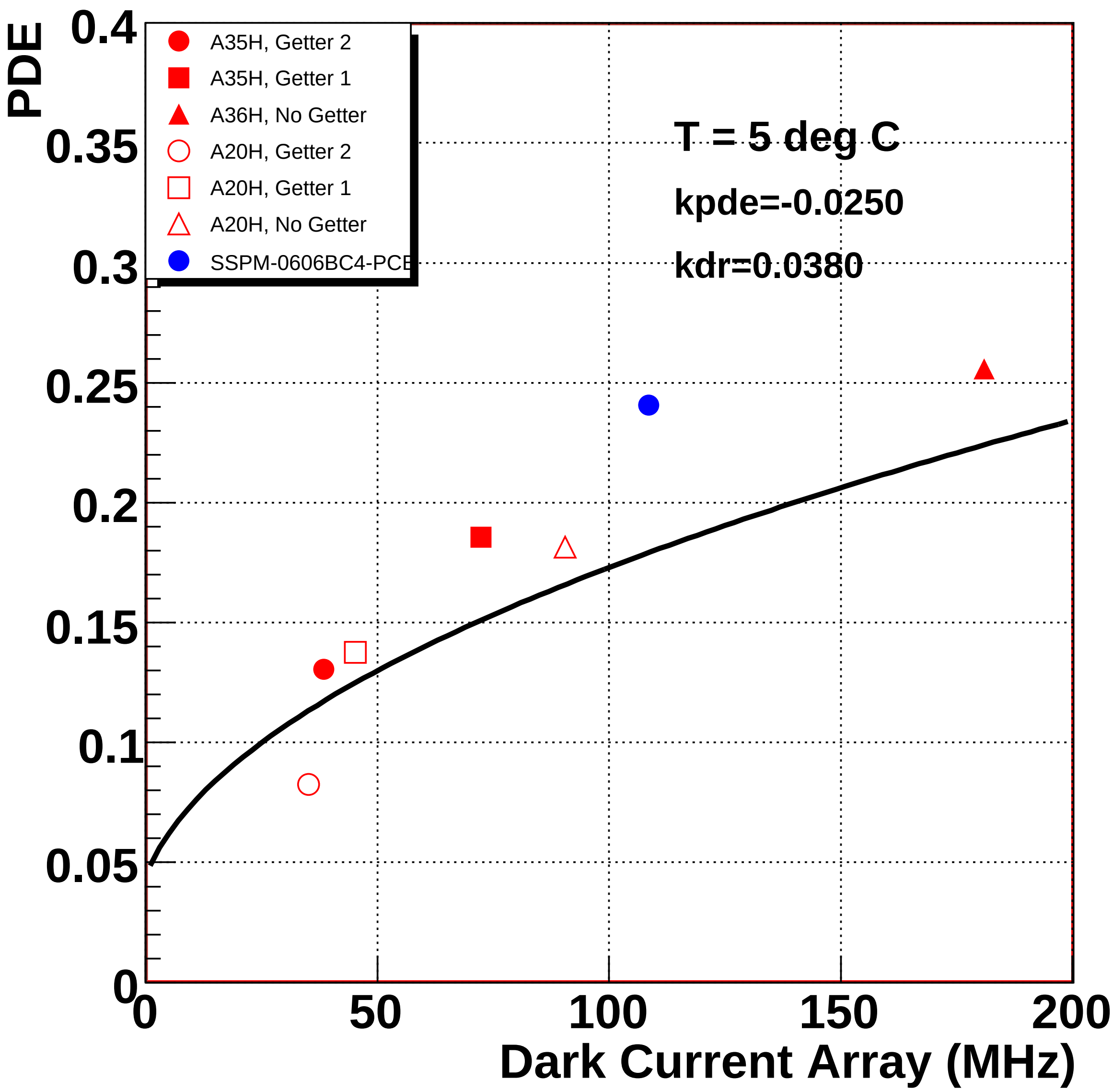

Figure 5: Photon detection efficiency vs dark rate for various cell configurations extrapolated to at $T = 5^\circ$ C using the parameterization of the temperature behavior for the Photonique devices. The black line indicates the minimum requirements for the Bcal. Combinations of PDE and DR above the line meet our specifications.