A Study of Silicon Photomultiplier Sensor Prototypes for Readout of a Scintillating Fiber / Lead Sheet Barrel Calorimeter

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Abstract: **The GlueX collaboration is designing a detector system to study exotic hybrid meson states at the upgrade beam line of Jefferson Laboratory. The hermetic detector includes a cylindrical electromagnetic calorimeter based on the scifi design used in KLOE, SPACAL, and JETSET. Since the calorimeter will be placed within a 2.24 tesla axial magnetic field, the optimal readout solution will include a solid state photodetector known as the silicon photomultiplier. This is an array of avalanche photodiode microcells operated in geiger mode with the output summed from all the microcells. The result is a photodetector with many of the same characteristics of vacuum photomultipliers such as high gain (10^6) and fast response, but with the additional advantage of immunity to high magnetic fields and superior quantum efficiency. This study is a report on the characteristics of a variety of prototype devices being developed by SensL of Cork, Ireland. The chief parameters being studied are photon detection efficiency (PDE), gain, dark noise, linearity, dynamic range, optimum operating voltage, and stability. This is a status report for an ongoing study.**

I. INTRODUCTION

As part of the 12 GeV upgrade to Jefferson Laboratory, the GlueX collaboration has designed a hermetic detector system for studying certain aspects of QCD confinement. Specifically, the spectrum of proposed exotic mesons will be investigated that include excitations of the gluonic states. Fig. 1 displays a schematic of the experimental setup. The initial 9-12 GeV electron beam will be converted to a polarized bremstrahlung photon beam that is optimal for creating the exotic meson states.

The overall detector system will use a refurbished superconducting magnet [1] to create a 2.2 tesla axial field. Within this magnetic field is a barrel calorimeter. It uses a design inspired by previous experiments such as KLOE, SPACAL and JETSET. In this design, scintillating fibers are laid into grooved lead sheets. Many layers are stacked and glued together onto a 2.5 cm thick aluminum plate, and the module is subsequently machined into the appropriate trapezoidal shape necessary to form one of 48 sectors of the barrel calorimeter. Some basic parameters of the planned device can be found in [2].

Detection of the light from the fibers will occur at both ends of the calorimeter. Analysis of the showers requires a large number of readout sectors on each face of a module. Although the outer half only needs a 2x2 array, the inner half will be split into a 4x6 array. Taking into account the overall dimensions, this implies small sectors of a few centimeters on the side. Small acrylic light guides will image each sector onto a 1.2 cm diameter area. For the upper sectors, larger acrylic light guides with a 90º bend can used to bring to light out to standard high performance (and relatively inexpensive) 5 cm diameter phototubes that can be efficiently shielded from the residual magnetic field. On the other hand, the inner sectors would require a large number of small area phototubes. Fine mesh phototubes, such as the Hamamatsu R5924-70, may be able to operate at such a high field, but are prohibitively expensive. Alternatively, one could use bundles of plastic light guide fibers to bring the light out to multichannel phototubes such as the Burle Planancon series or the Hamamatsu H8500. The preferred solution is to develop, in partnership with a commerical vendor, a new compact, magnetically immune solid-state photodetector with many of the high response speed and gain characteristics of traditional vacuum photomultipliers.

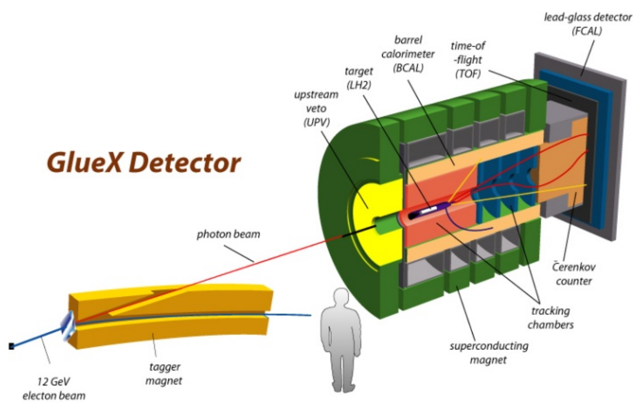

Fig. 1 Schematic of proposed Gluex experimental apparatus at Jefferson Laboratory.

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II. SILICON PHOTOMULTIPLIERS (SiPM)

A. Introduction

The silicon photomultiplier is an array of micro-sized (20-100 μm) avalanche photodiodes operated in geiger mode. Each pixel has a recovery resistor associated with it to quench the resultant avalanche. In the geiger mode, each pixel acts like a digital switch as any number of photons activating a pixel during the period of the avalanche will produce the same output as one photon. By ganging the pixels together via the associated resistors, one produces a summation device whose output is proportional to the number of detected photons.

Details of the operational characteristics of a SiPM can be found in the literature [3-4],but some salient aspects can be noted. First, these devices have a distinct breakdown voltage under reverse bias where the probability of creating an avalanche becomes significant above this threshold. As the voltage is increased above breakdown (the overbias), the probability increases and results in an increased gain. The intrinsic gain should be linear with the overbias where typical gains are in the range of 10^5-10^6. The breakdown voltage is a function of temperature. Along with an overall lessening in noise at lower temperatures, the breakdown voltage will also decrease. The avalanche process also results in an intrinsic dark noise factor where single photoelectron pulses are created even in the complete absence of light. Furthermore, there are also events where the occurrence of a dark noise pulse can trigger a time coincident second dark noise pulse in an adjacent microcell. This is a crosstalk factor and can affect the linearity of the device. Indeed, it is creation of light by the initial avalanche that creates this secondary pulse. (In other words, this is a device that should literally "glow in the dark".) Finally, there are delayed avalanches that result in extended (over time) dark noise pulses. It is claimed that these would be more common at low temperatures [5]. Fig. 2 is an example oscilloscope display of the dark noise pulses.

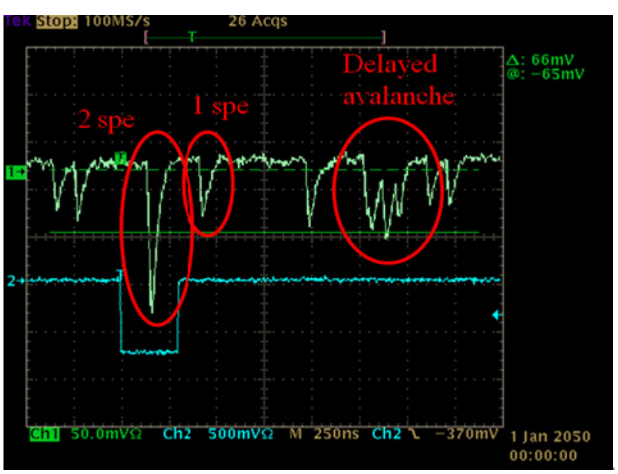

Fig. 2 Oscilloscope picture of typical dark pulses in a silicon pmt.

B. SensL SiPM

At the time when this project was begun, the standard physical size of a SiPM was 1 mm^2, although larger sizes were being developed. Jefferson Laboratory, on behalf of GlueX, contracted with SensL [6] to begin working towards a more realistic size using its patented CMOS-based technology. A 3x3 mm^2 has become a standard size, and it is this type that is the subject of this paper.

In order to make the final device, a square array of the 3x3 mm^2 can be used to make to 12x12 mm^2 device needed to readout each of smaller sectors. Eventually the goal is to produce a monolithic design with the corners omitted so as to make a better match to the circular output of the light guide.

Some initial studies comparing the performance of 1 mm^2 samples with traditional vacuum phototubes have been published [7]. This report concerns itself with the evaluation of the initial sample set of 3x3 mm^2 devices. The dark noise is the usual concern when scaling up the device size since it tends to rise at least as fast as the area. Tests of 1 mm^2 samples indicated that it would be wise to include an onboard Peltier cooler. Again, initial tests indicated that an operating temperature of -20ºC would be best choice for the initial evaluation tests.

Table I is a list of the initial samples indicating pixel size, number of pixels and the overall fill factor. (The last is the percentage of actual photosensitive surface.) One exception is the 1 mm^2 version of type C20. This had no Peltier cooler and was used in the initial tests to measure the photon detection efficiency.

This initial set also included a amplifier board (gain = *x*20) with an additional board to control the Peltier cooler. The latter was set to produce a temperature of -20ºC. The SiPM chip and cooler were mounted within a standard TO-8 can. Fig. 3 is a picture of the system. DC power requirements were +5, -5, and a positive DC bias for the SiPM.

TABLE I

Type	# pixels	Microcell size	Fill Factor
C20 (1 mm^2)	620	20 μm	17.8 %
C20	4496	20 μm	17.8 %
A20L	6744	20 μm	34.2 %
A20H	8640	20 μm	42.7 %
A35L	2452	35 μm	30.5 %
A50H	1930	50 μm	70.3 %

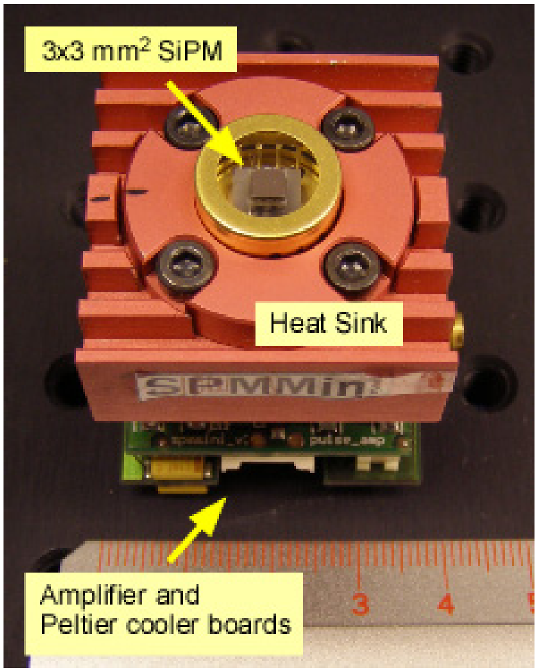

Fig. 3 Photograph of module used to house and test SiPMs. The Peltier unit is place directly behind the SiPM chip within the TO-8 housing.

C. Photon Detection Efficiency

The first task was to measure the photon detection efficiency. The expression for this is the product of the following terms:

$$PDE\left(\lambda, \Delta V_{br}\right) = Q_E\left(\lambda\right) \times F \times \alpha_p\left(\Delta V_{br}\right)$$

where $Q_E\left(\lambda\right)$ = intrinsic quantum efficiency, $\alpha_p\left(\Delta V_{br}\right)$ = avalanche probability and F = the fraction of photosensitive surface. The parameters λ and ΔV_{br} are the wavelength and overbias (voltage above breakdown) respectively. Due to nature of the device, $Q_E \times \alpha_p$ is the actual quantity measured as α_p is proportional to the overbias voltage set for the measurement.

The initial tests of PDE were made with the 1 mm^2 C20 device (at room temperature) as this had the lowest noise level. The measurement was made in pulse mode and followed many of the principles described in reference [8]. Fig. 4 is schematic of the basic measurement setup used for the measurements in this report. Two LEDs (blue and green) are used as pulsed light sources. Their light is delivered via a bifurcated glass fiber bundle to a beam collimation unit that creates a uniform illumination. A manual filter wheel equipped with narrow band filters (width = 10 nm) is used to select one of two wavelengths – 450 or 520 nm. A dual set of remotely controlled filter wheels equipped with UV-VIS neutral density filters is used to control the light intensity over a broad range. One of the filter wheels controls the overall magnitude – 0, 0.1, 1, 10, or 100% while the other provides a finer control – 20, 40, 60, 80, 100%. Finally, the output light can be further diffused (and lowered in intensity) via a UV-VIS diffuser element. In this way, a large dynamic range of light intensities (including single photoelectron level) can be utilized while maintaining a highly uniform illumination of the photodetector.

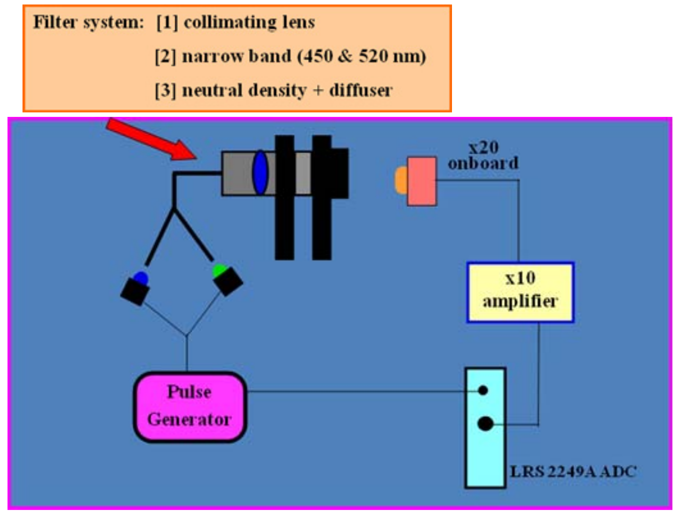

Fig. 4 General setup for testing SiPMs

The measurement of the PDE involved the following prescription:
1. Use a calibrated photodiode [9] to calibrate the neutral density filters.
2. Given this calibration, use the photodiode to calibrate a reference PMT.
3. Using the calibrated PMT, switch to pulse mode and compare the response (at equal gain) of the PMT and SiPM at low light intensities where crosstalk effects are kept minimal.

The photodiode was used in DC mode. In this case, the LEDs were also operated in DC mode to maintain maximum stability. Using a voltage divider circuit, a current of 1 mA through the LEDs was found to be sufficient and gave a very stable output. The phototube's photocathode (XP2262) had all but a central 6 mm diameter hole masked. This allowed comparable photosensitive areas to be used and also avoided the problem of incomplete photoelectron collection efficiency across the entire 5 cm diameter surface. This phototube had been used in previous studies of PMT/base linearity and rate studies, so it was possible to gauge a range of currents that maintained linear response. A variety of intensities and distances were used to minimize systematic errors. The PDEs were determined to be (3.4±0.5)% and (4.4±0.5)% at 450 and 520 nm for an overbias of 1.2 volts and a fill factor of 18%. This was consistent with the SensL data. Their method of measurement is similar and can be found in their technical documentation [4].

D. SiPM Gain

Measuring the PDE requires that the single photoelectron spectrum from the SiPM can be resolved to set the gain at a given overbias voltage. In subsequent work with the larger

3x3 mm^2 devices, photoelectron spectra were resolved when the devices were operated at -20ºC. The noise levels were too high at room temperature to allow this possibility. Figure 5 shows the gain data for this set of 3x3 mm^2 devices. The best device was the A20L for which a variety of gains were measured. This data verified that they operated at a overall gain level of 10^6 or better. Linear variation of the gain with overbias voltage was also observed. One can also see that the 35 micron microcell device produced a significantly higher intrinsic gain although a higher level of noise prevented a broad range of measurements from being made.

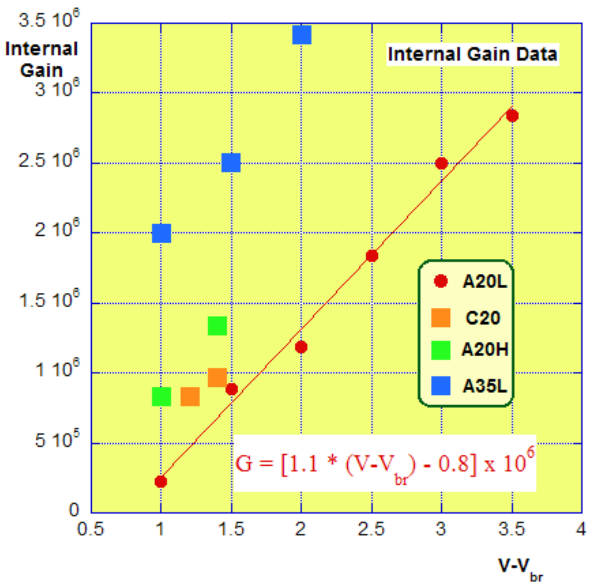

Fig. 5 Gain data for SiPMs where the photopeaks could be resolved at -20ºC. The equation is a fit for the A20L sample. Note the significantly higher gain possible with the 35 µm pixels.

E. SiPM Dark Noise

Noise measurements can be expressed in two ways – as a dark count rate, that is, the rate of single (and higher) photoelectron pulses, or as a DC current. The latter is often a matter of necessity if the actual count rate exceeds the capability of the instrumentation. The same can also happen if the noise level is high enough that the photoelectron peaks cannot be resolved. In this case, no plateau counting level corresponding to the single photoelectron can be found and only a smoothly falling curve in rate can be plotted.

For this set of devices, it was decided to measure the actual count rate for the A20L device at -20ºC, as the photoelectron peaks could be resolved at a wide variety of gain settings. Dark current measurements would be made for all devices at both -20ºC and room temperature (21ºC) so as to ascertain relative differences in dark noise. The actual quantitative relationship between the two methods of measurement remains to be determined.

The setup in Fig. 4 is modified for measuring dark rate. The light sources are extinguished, and the dark pulses are amplified and then sent through a discriminator to create standard NIM pulses that are counted by a scalar. Due to the timing characteristic of the pulse, it was estimated that a maximum count rate of 10 MHz was quantifiable. Fig. 6 is the rate data for the A20L sample while Fig. 7 is the dark currents for all the samples. Fig. 8 is the dark current for the A20L sample at -20ºC and room temperature. In figure 7, the behavior for the samples A20H and A50H was later realized to be anomalous and indicative of a problem in the device. The standard behavior is to have the dark current slowly approaching a plateau at higher voltages. The data from the cooled A20L device falls within the guidelines established for successful operation of the calorimeter. The next set of improved samples indicate that we are approaching such behavior at room temperature as is desired.

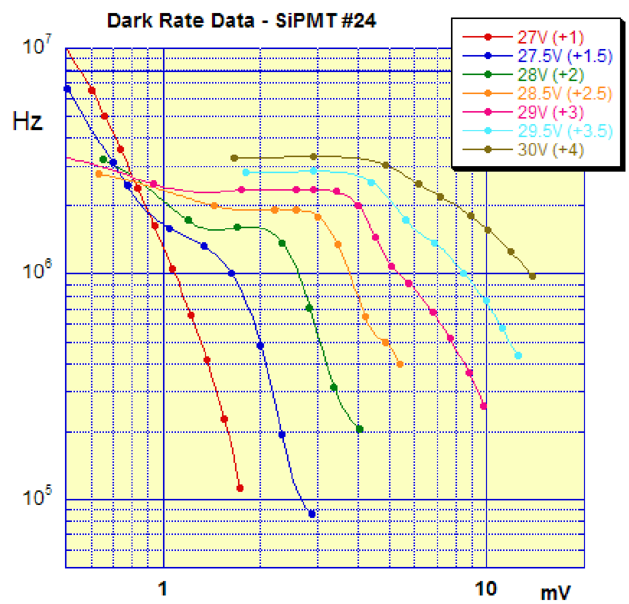

Fig. 6 Dark rate data for the A20L sample at -20ºC. The plateau is the rate of > 1 pe dark pulses. Note the unresolved data at the lowest overbias of 1 volt. The rates are consistent with what is expected for the calorimeter at room temperature.

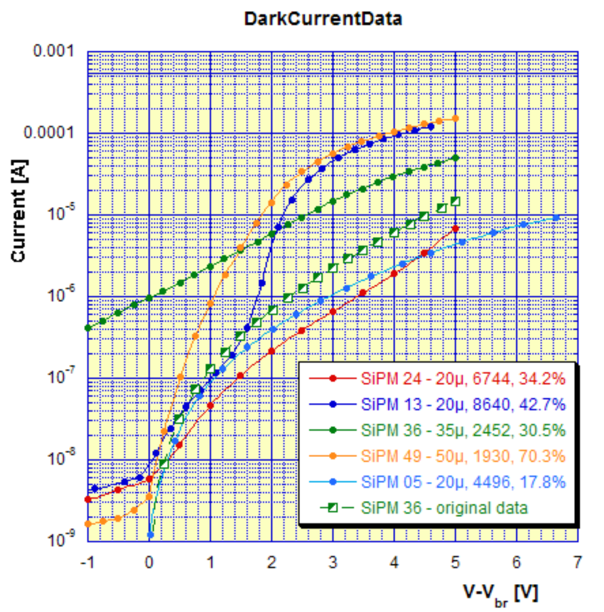

Fig. 7 Dark currents for cooled SiPM samples. The 35 µm sample became unstable after about 1 day of operation and showed a substantial increase in dark current. It is now understood that samples #5 and #49 have anomalous current behavior at higher biases.

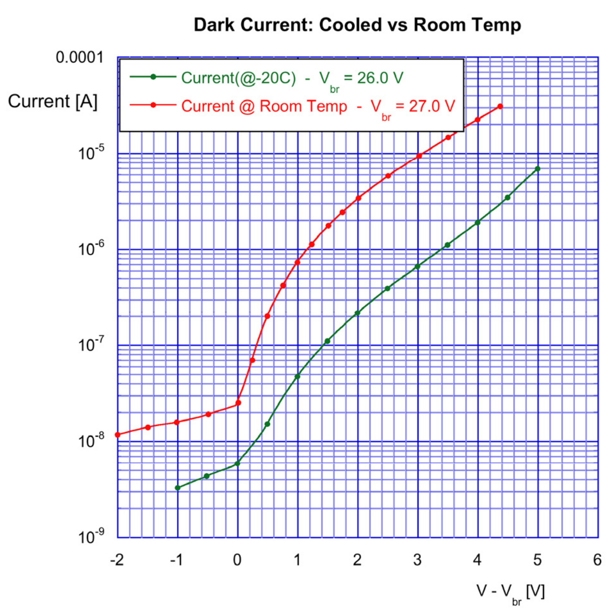

Fig. 8 Comparsion of dark current for A20L sample at -20ºC and room temperature (21ºC). Note the 1 volt increase in the breakdown voltage. Data is presented in terms of overbias – voltage above breakdown.

F. Latest Lower Noise Samples

The most recent samples have been based upon several evolving improvements particularly in the noise levels. We have a set of devices based upon a A35H design (3640 pixels, 60% fill) that includes 5 samples of a 4x4 array of 3x3 mm^2 devices in a summed array (Fig. 9). This is a first order prototype of the kind of device needed for the calorimeter. We also have a set of ten 3x3 mm^2 devices, some of which are intended for long term stability tests. Figure 10 shows pulses of the array in comparsion to the individual devices. For the latest A35H samples, the pulse width is too wide especially for the array. The aim is to achieve something comparable to what a standard phototube would give from a plastic scintillator with decay times below 5 ns as is seen in the A20L sample. SensL is actively working to improve the decay time.

Initial dark current measurements, when compared to that of the previous set indicate that a substantial improvement (> x10) has been made in lowering the noise level. It should be possible to obtain resolvable photopeaks at room temperature either with this device or perhaps one of the type A20L where the smaller pixel size and lower fill factor should give even larger improvements in lower noise levels.

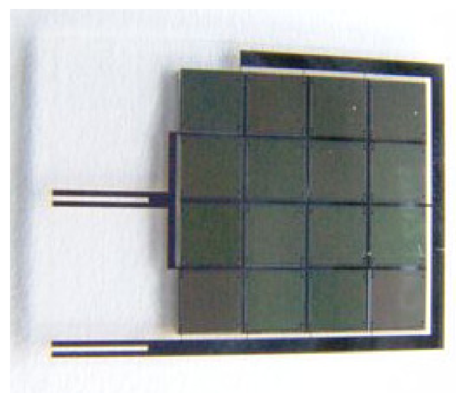

Fig. 9 Photograph of one of the 4x4 prototype SiPM arrays made from 16 of the 3x3 mm2 sensors (type A35H).

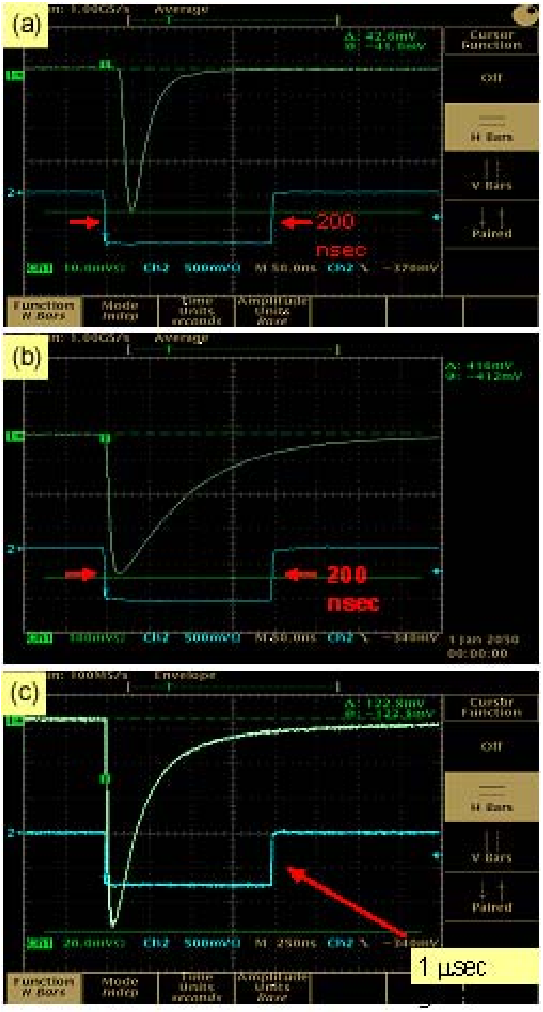

Fig. 10 Comparison of pulse shapes of (a) A20L, (b) A35H, and (c) A35H 4x4 array when pulsed by a fast blue LED.

III. SUMMARY

In order to readout a scifi calorimeter set within a high magnetic field, a research program has been initiated to create practical versions of silicon photomultipliers that can readout areas of 1.2 cm diameter. The present course is to create 3x3 mm^2 devices which can be placed into summed arrays (4x4) that will act as the photodetector. In this paper, measurements were made of the first set of 3x3 mm^2 devices in order to verify noise levels, gain capabilities and photon detection efficiency. Due to initially high noise levels, the measurements had to be made at a temperature of -20ºC. These measurements showed that the devices could operate as hoped. In the next phase, a new set has been made with much lower noise levels, including a first set of prototype arrays. Finally, a 1 mm^2 sample has been made with trenching technology in order to reduce the crosstalk factor. Measurements will continue on such issues as long term stability, linearity, room temperature behavior, temperature sensitivity, PDE, and gain uniformity (across the array).

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