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New Developments in Photodetection for Particle Physics and Nuclear Physics

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Abstract

Photodetectors are widely used in particle and nuclear physics research. Since the beginning of the modern era of photoelectric transducers in the late 1930's, many types of devices have been developed and exploited for physics research. New performance requirements arising in physics experiments have often provided very interesting technological drivers for industry. New ideas for photodetection are rapidly adapted by the physics community to enable more powerful experimental capabilities. This report gives a sampling of new developments in photodetection for physics research in the period since the first conference in this series, Beaune 96. Representative examples of advances in vacuum devices, solid-state devices and gaseous photodetectors are described including, where appropriate, an indication of areas where technological improvements are needed or expected.

1. INTRODUCTION

Research in particle and nuclear physics relies heavily on photodetection methodologies for tracking, energy and particle identification detectors. Charged particles are detected either through the ionization produced by the particle's passage or through emission of photons produced by scintillation, fluorescence, Cherenkov or annihilation processes. Although the physics community does little basic research in photodetection, being very much application driven, any new developments in photodetection are rapidly evaluated and developed for physics experiments purposes. The pace of innovation in the past ten to fifteen years has far outstripped that of previous decades, particularly in solid-state photodetectors. A large part of the dynamic has been requirements from new experiments in which rather extreme conditions are present: magnetic fields up to 40 kGauss, radiation exposures up to 10 MRad, a linear dynamic range of 18 bits, single photon counting with more than 50% efficiency, and high stability over years of operation.

The first conference on new developments in photodetection, Beaune 96 [1], was created in recognition of this sudden flowering. This second conference three years later (dedicated to the memory of P. Besson who founded the series) marks the continuance if not acceleration of the pace of development in photodetectors for physics research. In this report, photodetection developments are grouped into three classifications, vacuum devices, gaseous photodetectors and solid-state devices. Representative examples from each have been selected that are illustrative of the progress and accomplishments since Beaune 96, and no claim of inclusiveness is made.

2. VACUUM DEVICES

A. Photomultiplier Tubes

In a global sense, one could say that progress since the invention of the photomultiplier tube at the RCA labs in 1936 has been incremental. However, further innovations such as fiberoptic faceplates, mesh and metal-channel dynodes, graded seals, microchannel plates, and electron bombardment anodes have all led to totally new capabilities and applications. Many of these new types of photomultipliers have come in response to the needs of physics research experiments. The physics market may be a risky one-shot business for industry, but the technology drivers from physics applications can lead to new types of photomultiplier tubes and open new market areas.

Today's global economy has resulted in a situation where developments are controlled by market considerations. The largest single market is for gamma cameras with 180,000 units sold annually [2]. Competitiveness here hinges on four performance areas; pulse height resolution, stability, reliability, and physical footprint. Physics applications which can benefit from these characteristics, particularly pulse height resolution, are then leveraging into a very large R&D effort. For example, studies at Jefferson Lab for the modest UV response of a silica aerogel Cherenkov radiator [3] have shown that the superior photoelectron collection efficiency of relatively inexpensive gamma camera tubes can provide performance figures as good as those of very expensive tubes with quartz windows and a high gain gallium-phosphide first dynode.

The photomultiplier tube developed for the time-of-flight detector in the CDF experiment illustrates the situation where a new device is realized as a variation of an existing standard device. In this detector, scintillators are located in a high magnetic field and light pipes to a field-free region are ruled out since timing resolution varies as the square root

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of the number of photoelectrons. Gain is essential as performance improves with pulse height up to the point where triggering is occurring on the first photoelectron. A modification of a mesh dynode tube [4] with an unprecedented 19 stages of gain with only a few hundred picoamps dark current was created for this application. Figure 1 shows the gain and dark current behavior of the tube in zero field along with the B-field dependence of the gain. The magnetic field reduces each dynode stage gain by a factor of 0.7 but the resultant gain surpasses the specification.

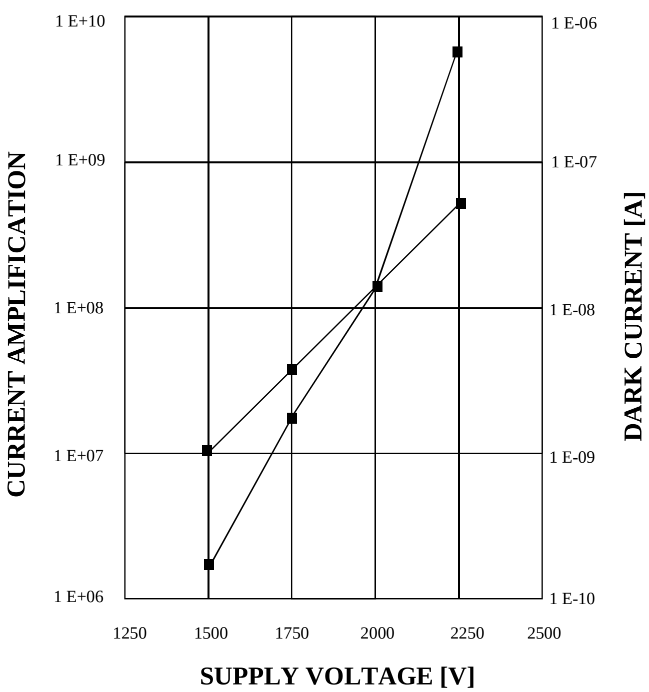

Figure 1a. Gain and dark current response for zero magnetic field.

An example of the exceptional situation where a new photomultiplier development is not application driven is provided by the recent announcement of the "flat panel pmt" concept. This device is projected to have a 5 cm by 5 cm active area in a rectangular package only a few mm thick with less than one mm dead area around the periphery to allow dense packing. The enabling technologies are seen in the company's rectangular flangeless tubes and micromachined metal-channel dynodes. The performance parameters expected for this technology [5] are summarized below:

photocathodes - standard evaporated types not transfer technology
gain - at least one million at a bias around one kVolt
dark current - the normal value for metal-channel dynodes
frequency response - sub nanosecond, intrinsically very fast
window - standard glass faceplates at first
pixels - all devices expected to be position sensitive with at least 64 pixels.

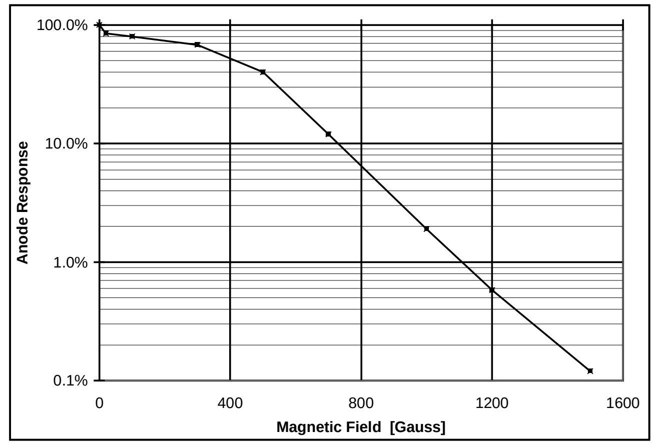

Figure 1b. B-field dependence of gain.

B. Hybrid Photodiodes

The hybrid photodiode [6,7] is a variation of long-standing industry products, image intensifiers and night vision tubes. Photoelectrons, in this case, bombard a depleted silicon diode instead of a gain-staged phosphor screen. The resultant electrical signal is amplified to provide the photodetection function which is characterized by both single photoelectron detection capability and a very large linear dynamic range. Position sensitive response is realized by patterning the diode electrodes and both proximity focused and electrostatically demagnified versions are available. Physics researchers have pioneered practical development of this type of device [8] for calorimeter applications. There has been significant progress since Beaune 96 in applications for high magnetic field calorimetry and for ring-imaging Cerenkov detectors.

The CMS hadron calorimeter application requires operation in a 40 kGauss magnetic field, a large linear dynamic range, and a high degree of position sensitivity with very low cross talk to maximize utilization of the photocathode surface. Three years ago, proximity focused devices from DEP had demonstrated adequate magnetic field immunity, cross talk isolation, and dynamic range and rate capability [9]. The remaining challenges were to reduce the occurrence of noisy pixels (bump bonding replacing wire bonding) and to improve the time response. Figure 2 shows the improvement in time response achieved by reducing the diode thickness to 200 microns and Figure 3 shows the typical gain and leakage current characteristics of these devices. Backscattering of electrons from the silicon diode is an unavoidable physical property leading to cross talk and a reduced response for a fraction of photo-electrons[10,11]. In the presence of a strong axial magnetic field, the backscatter area is limited to micron dimensions and cross talk is eliminated.

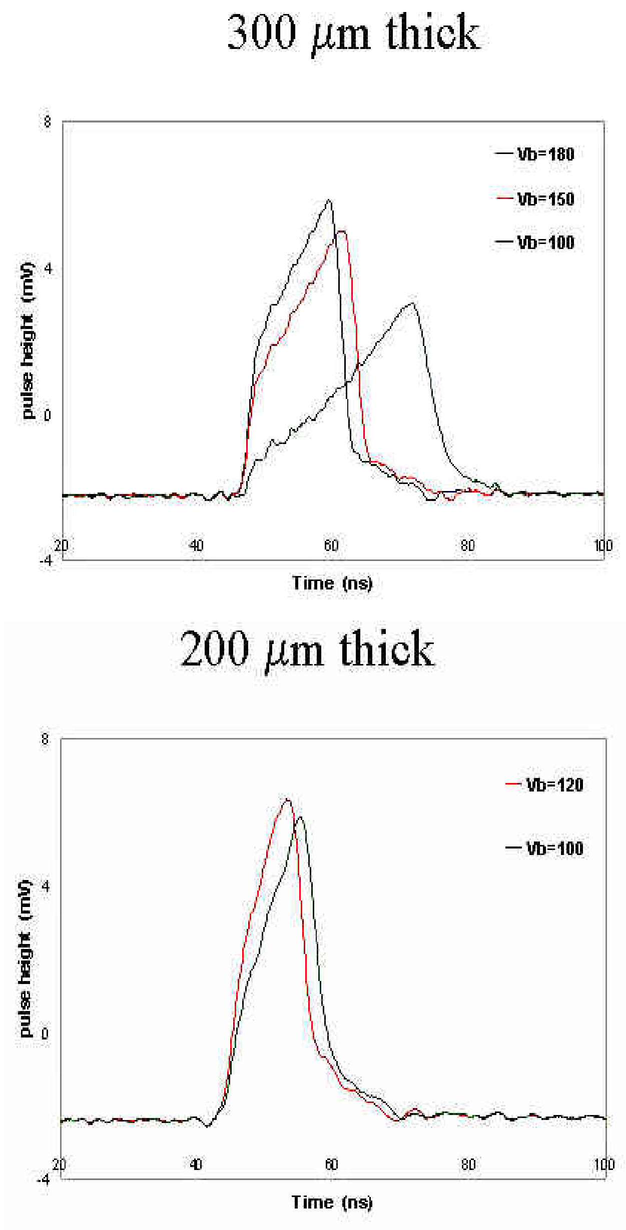

Figure 2. Time response for 200 and 300 micron thick diodes.

Particle identification by means of ring imaging Cherenkov detectors is an application where a large photocathode area is required along with image recognition through position sensitive response. Large area demagnified hybrid photodiodes are under development now for experiments planning ring imaging detectors such as LHCb. At CERN, one team [12] is working on a 5-inch tube with demagnification factor 2.7 onto a diode pixel array with 1mm pixels that are readout by standard silicon strip detector multiplexed electronics. A very high value of the accelerating voltage, 25 kV, is planned to benefit single photoelectron sensitivity. Figure 4 shows the pulse-height spectrum from a single pixel in a development tube illustrating the excellent signal-to-noise performance.

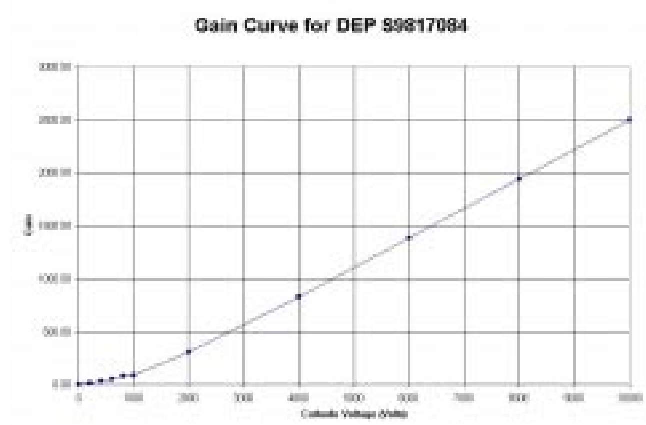

Figure 3a. Gain characteristic of a 19-pixel HPD.

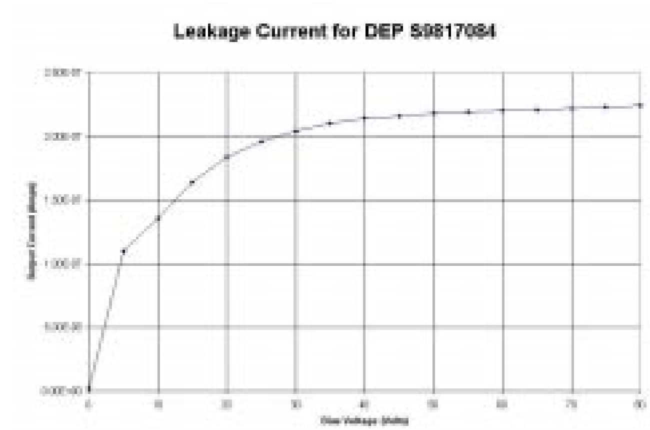

Figure 3b. Leakage current characteristic of a 19-channel HPD.

3. GASEOUS PHOTODETECTORS

Gaseous detectors are based on photoconversion and subsequent photoelectron charge multiplication in a gas avalanche or gas amplifying device. Large area applications are involved as no other technique is cost competitive for square meters of coverage. There is a significant body of work utilizing photosensitive vapours and wire proportional chambers resulting in devices which have unfortunate limitations in many important parameters including gain, temperature range, rate and stability. Attention recently has shifted from photosensitive vapours to solid photocathodes such as cesium iodide. Since Beaune 96 when the approach was still under active investigation, the fabrication of large area CeI photocathodes has been demonstrated and this technology has been selected for several experiments.

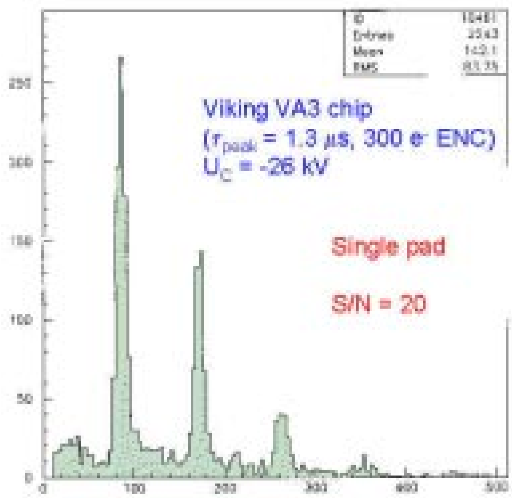

Figure 4. Low light level response of a 1 mm HPD pixel.

Attention now has shifted from the photoconverters to the gas amplification devices themselves with the newest entrant, the gas electron multiplier film [13], under close scrutiny [14]. This technique has shown much promise against the three principal difficulties of gaseous photodetection; ion feedback, photon feedback and suppression (only for solid photocathodes) of photoelectron emission. Gain is accomplished through microscopic shaped pores in a metal-insulator-metal laminate film. A multistage film structure was used with a CeI photocathode and the indicated gas mixtures to produce the single photoelectron pulses shown in Figure 5. The next

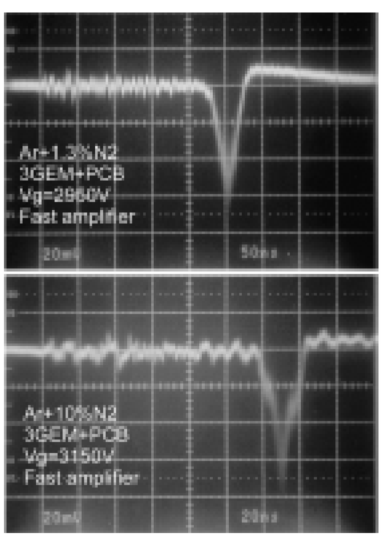

Figure 5. Single photoelectron pulses from a GEM photodetector.

conference in this series, Beaune 02, can be expected to reveal the ultimate capabilities of these new devices.

4. SOLID-STATE DEVICES

Although the progress in solid-state detectors using microelectronic technology has been greatest in high resolution imaging devices for X-rays and particle tracking, photosensitive devices with internal gain operating in the visible region have recently found widespread application. The advantages include high quantum efficiency, fast response, and immunity to magnetic fields.

A. Avalanche Photodiodes

Applications for avalanche photodiodes in physics experiments emphasize very different characteristics than those found in telecommunications devices. In calorimetry, the important characteristics are a low excess noise factor, large area (25 mm^2 or larger), good efficiency for blue light, a small direct response to traversing minimum ionizing particles, negligible gain change with neutron and ionizing exposures, and very special packaging for direct optical coupling. Readout of fibers or fiber bundles as individual detection elements places emphasis on position sensitive APD arrays where low noise, high gain and good efficiency for green light are important.

In the CMS experiment, a development project was started for the demanding requirements provided by the crystal calorimeter. A report in these proceedings [15] shows that two new APD structures were created during the development work, and the specifications were eventually met. The quantum efficiency curve in Figure 6 is for the new Hamamatsu APD type with a radiation hard silicon-nitride passivation layer which also serves as the anti-reflection coating that flattens the central part of the response.

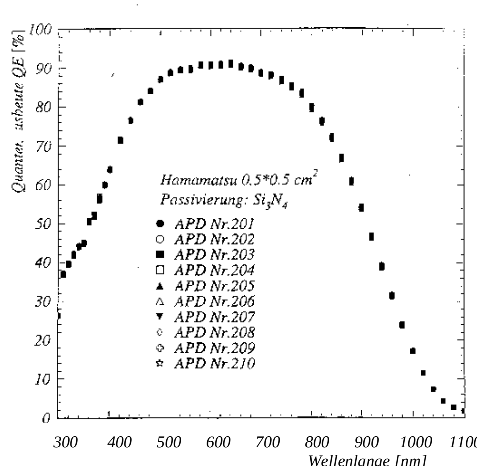

Figure 6. Spectral response of a CMS crystal calorimeter APD.

A new technique for fabricating traditional deep diffusion APD types has been developed at Radiation Monitoring Devices [16]. Previously, each diode was cut individually from the wafer and polished with a bevel to reduce the electric field at the edge. The new technique for passivating the edges also can be used anywhere on the surface to create independent pixels. This fabrication advance allows for mass production of deep diffusion APDs and APD arrays free of the costly beveling and polishing steps needed heretofore. Any standard power semiconductor fabrication facility can now produce APDs. The gain and normalized noise curves in Figure 7. are for a single 1 mm^2 pixel in an eight by eight array. The optimum signal to noise performance is seen to occur at a gain of about 200.

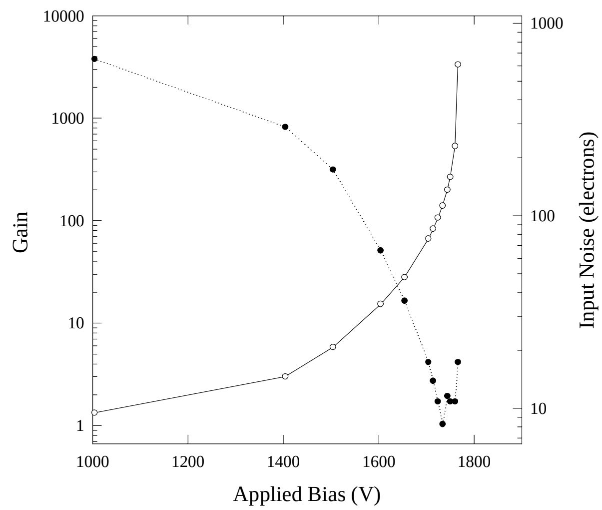

Figure 7. Noise and gain vs. Voltage for one 1-mm pixel of a 64 element array.

B. Metal-Resistive-Silicon Devices

Quite high gain devices have been demonstrated using metal resistive layer structures with built-in high field n+ type inclusions. The technology originated for night vision and is being modified for visible light applications. The challenge has been to develop a version which is sensitive in the visible region and can be position sensitive. Recent work [17] has yielded single pixel devices and 4 pixel arrays with very high gain, Figure 8, and also has shown that the linear dynamic range is limited. Other efforts have produced a new MRS structure [18], the limited Geiger mode microcell in which high gain avalanches are confined to a 10 micron by 10 micron region. Single photon counting is a natural application for MRS and technological improvements are needed to achieve lower noise and higher quantum efficiency devices.

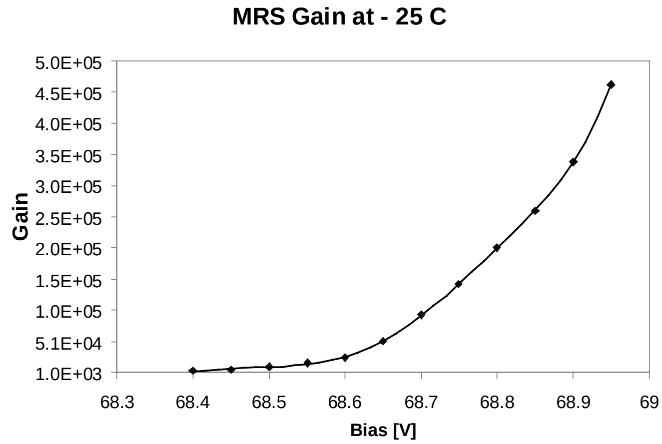

Figure 8. Gain characteristic of a 1mm MRS pixel.

C Visible Light Photon Counters

Visible light photon counter devices (VLPC) are based on impurity band-gap structures which offer excellent single photon counting capability [19] due to the high gain and low noise. Originally created for night vision applications, development of a visible light sensitive version was begun for SSC applications and then continued by the D-Zero experiment for readout of their scintillating fiber tracking detector. VLPC devices operate at cryogenic temperatures, 6 to 10 K, as the band gap is only 50 milli-eV, and at that temperature the saturated avalanche gain is about $3x10^4$. At Beaune 96, the VLPC development work was concentrated on optimizing quantum efficiency and improving the space charge characteristics to allow high rate operation. As is evident from Figures 9 and 10, the work has been successful. Production and testing were recently completed with 140 k devices fabricated at 87% yield.

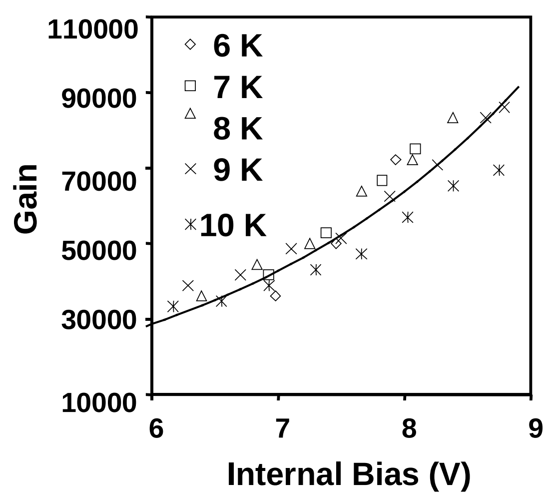

Figure 9a. Gain characteristic of VLPC pixels.

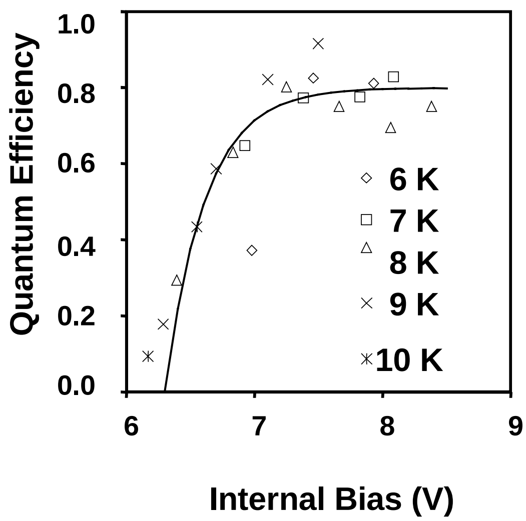

Figure 9b. Response characteristic of VLPC pixels.

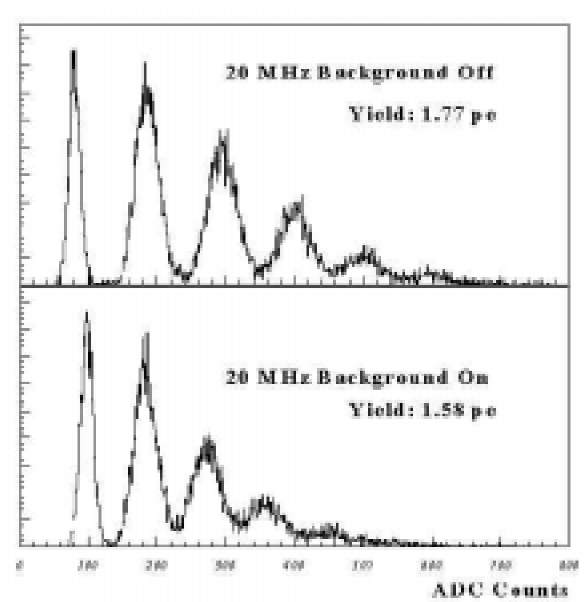

Figure 10. Rate capability of VLPC.

5. FINAL REMARKS

The application of photodetection techniques to particle and nuclear physics research is increasingly demanding yet growing in scope. Developments since the Beaune 96 meeting appear to indicate a trend towards devices with a high degree of position sensitivity. This is to either confront a pattern recognition challenge as in ring imaging detectors or to enable a much finer detection granularity through the efficiency of many independent photodetectors in one package. Also, new types of photodetectors have been created through innovations in processing technology, most notably deep-diffusion APD arrays, the limited Geiger mode microcell MRS device, and the flat-panel photomultiplier concept.

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