New Trends in Vacuum Based Photon Detectors

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Abstract. Recent progress on vacuum based photon detectors is reviewed. Even after rapid progress on various solid state detectors, vacuum based photon detectors such as photomultipliers still play a significant role in many high energy experiments where high speed detection of weak photon signals are critical. The latest development of hybrid devices such as HPD, HAPD, EBCCD and ISPA are reviewed and their advantage over conventional photon detectors is discussed in some detail.

INTRODUCTION

Recent and future high-energy experiments are becoming more demanding in photon detector performance in several areas:

1. Large sensitive area. For neutrino experiments such as Super-KAMIOKANDE, SNO or AMANDA, huge detector volume must be covered by a large numbers of large area, fast photomultipliers with single photo-electron sensitivity.
2. Immunity to the magnetic field. Operation under strong magnetic field requires special photon detectors. For example, CMS calorimeters are located under 4 Tesla.
3. Miniaturization and Pixelization. For RICH, Scinti-Fiber tracking and Fiber/Tile Colorimeter, Multi-pixel devices with $1 - 4mm$ pixel size are required.

As a result, various new photon detectors have recently been developed to satisfy these requirements. The purpose of this paper is to introduce and to compare these new developments in a systematic way, so that anyone in high energy experiments can decide the most suitable photon detector for their experiments in an unbiased manner.

In the following section, I first introduce various photon detectors, starting from the conventional ones. Once all the photon detectors are briefly introduced, resolutions on time measurement, energy measurement and position measurement are systematically compared for all photon detectors. Finally, as a critical ingredient of decision making, market prices of these detectors are shown.

Based on this analysis, advantages and disadvantages of various new types of photon detectors are discussed.

TYPE OF PHOTODETECTORS

A Conventional photo detectors

Generally speaking, there are two types of photon detectors: vacuum based and solid state. A vacuum based photon detector has a photocathode which converts photons to electrons. Photo-electrons are emitted into the vacuum and hit dynode structure for fast multiplication of signals. The first process, photo-electron conversion, has rather poor efficiency (so called Quantum efficiency is typically 20%), but the rest of the process has no additional noise factor. Thus we can count the number of emitted electrons. This process is extremely fast, which is the reason why conventional photomultipliers are still widely used in high energy experiments.

On the other hand, in solid state detectors, photons are absorbed by $p-n$ junction, where electron-hole pairs are created. The quantum efficiency is very high (close to 100%), but the intrinsic noise of the device itself limits the detection of low light signals. Recent development of fine lithographic technology allows one to develop finely segmented photo detectors like CCD, which are extremely powerful for imaging purposes.

The basic properties of typical conventional photon detectors such as photomultiplier, Photo Diode and CCD etc are summarized below.

1 Photomultipliers

As mentioned already, photomultipliers are sill one of the most widely used photon detectors in high energy experiments. Here, I briefly list the latest developments.

1. Improved magnetic-field immunity: For operation under strong magnetic field (up to 1.5 Tesla) fine mesh dynode has become the standard PMT. Examples of experiments using such PMT's are KLOE at DAFNE, H1 at ZEUS, BELLE at KEK B- Factory [1].

2. Larger sensitive area for neutrino experiments: New generation of neutrino experiments require huge detector volume, viewed by large PMTs (as large as 20 inch diameter.) A well known example is the Super-Kamiokande where

11,200 of 20 inch PMTs are installed in a 50k ton water tank. The rest of neutrino experiments have adopted 8 inch PMTs so far. There are many examples: AMANDA, MILAGRO, LSND, SNO etc.

3. Pixelization for tracking: As a replacement of drift chambers, the scintillating fiber tracker is becoming a mature technology. For readout of fibers, multi-pixel photomultipliers have been developed. Philips first developed XP1700 series using foil dynodes. Later Hamamatsu developed various types; starting from mesh dynode and Venetian blind, and recently metal channel plate [2]. But the quantum efficiency remains poor. This problem can be solved by using VLPC's, a solid state device descibed later. For the preshower or shower maximum detector, multi-pixel PMTs have been adopted. The CDF plug upgrade is such an example.

4. Position sensitivity for Particle ID: For particle identification, RICH (Ring Imaging Cherenkov) is becoming standard, in particular, for the CP violation experiments in the B decays. This requires, again, well segmented, pixelized photo detectors. There is no single standard photon detector yet, so multi-pixel photomultipliers are one of the most practical options. Such an example includes HERA-B.

In summary, even though the progress in this field has not been revolutionary but rather evolutionary, contributions of a variety of newly developed photomultipliers to the new generation of high energy experiments are quite impressive. Part of the reason is their extremely reliable, maintenance-free operation, thanks to high quality control by the venders.

2 Photo Diode and APD

PIN photo diodes are also widely used in precision calorimeters, where the number of photons is large enough. Examples are BGO in L3, CsI(Tl) in CLEO-II, BaBar and BELLE. It is shown in Section E that once the number of photons become greater than 10^6, a photo diode gives better energy resolution than a PMT. Besides, it is totally immune to the B-field.

In the future experiments, radiation hardness of crystals is another important issue. $PbWO_4$ was chosen by the CMS for the EM calorimeter for this reason. Photon yield of this crystal is quite low, so additional intrinsic gain is required for photon detection. Due to strong magnetic field (4 Tesla), conventional vacuum photon detectors are no longer allowed. Avalanche Photo Diode (APD) is currently under development [6–8]. Making a large area, yet stable APD is unfortunately non trivial, and it may take another year or two to develop reliable ones for use in the high energy community.

3 CCD and ICCD

A CCD itself has much wider applications not only in scientific but also in commercial applications as a standard imaging device of today's digital world. In high energy, it is primarily used as a tracking device by directly detecting ionization (in the SLD for example.) Once it is combined with an Image Intensifier, it can serve as a readout for high resolution scintillating fiber tracker, as long as the readout speed is not an issue. Neutrino oscillation experiments such as CHORUS and K2K adopted this approach.

B New photo detectors

In this section, several recently developed photon detectors are reviewed.

1 VLPC/MRS

The Visible Light Photon Counter (VLPC) is an impurity conduction band device [11], which generates an avalanche like APD, But the avalanche region is very limited and due to space charge effect, the signal is saturated after $\sim 10^5$ electrons are generated. This mechanism quantizes the output pulse charge unlike APD, allowing photon counting. In other words, it has high quantum efficiency of a solid slate device as well as high gain and small excess noise of a photomultiplier. This ideal performance, however, requires low temperature ($\sim 6^o K$) operation.

Similar conditions can be realized at room temperature, if saturation can be achieved locally. The Metal Resistive Semiconductor(MRS), recently developed by Russian groups, has needle structure in PIN junction where electric field is locally realized to generate saturated avalanche [9,10] This device, however, seems to have rather large thermal noise and poor rate capability.

2 HPD/HAPD

Conventional vacuum photon detectors have metallic dynode structure where secondary electrons are emitted from the surface. Instead of metal, one can incorporate solid state devices as a dynode, where photo-electrons are directly captured internally. Such a device, HPD (hybrid Photo Diode) was originally proposed by R. Desalvo in late 80's and finally it has become a mature technology to be adopted by some of the major high energy experiments [3,4]. DEP is leading this effort and several different types are now commercially available. The current version has either single or pixelized photo diode. By pixelizing photo diode, the cost per channel can be reduced. Major advantages of such a device are as follows.

1. Immunity to magnetic field. As long as the tube axis is aligned to the B-field axis, this device is not sensitive to the field at all.

2. Very small ENF(excess noise factor). As shown later, due to large (> 1000) multiplication factor of photo electrons, ENF is almost unity.
3. Wide dynamic range. It has the same dynamic range as photo diode. Unlike PMT, there is no space charge effect which limits the linearity.
4. Uniform Gain. The gain of this device is given by the number of electron-hole pairs produced by the kinetic energy of a photo electron. Since the energy is simply given by electric potential for acceleration, gain uniformity is guaranteed.

One should however note that it still suffers from poor quantum efficiency as a vacuum device, and rather low gain makes detection of single photo-electron very difficult, unless long shaping time is allowed.

Once the photo diode is replaced by the APD, single photo-electron detection can be easily achieved, even with modest gain. Such a device is called HAPD (Hybrid APD), described below.

3 EBCCD

The electron bombarded CCD (EBCCD) is another type of the hybrid device where photo-electrons are directly bombarded into the CCD [14]. Compared to the conventional Image Intensifier where photo electrons are multiplied by the MCP and captured by the phosphor screen, there is no extra materials between photo cathode and CCD. Therefore, distortion of image and loss of linearity can be minimized.

4 ISPA

Although the EBCCD has a good image resolution, the speed is still limited due to slow readout of the CCD. This can be overcome the ISPA (Imaging Silicon Pixel Array) which incorporates a silicon pixel detector in the vacuum instead of the CCD [13]. The Silicon Pixel detector has parallel readout chain, so this would be an ultimate photon detector for fast, precise imaging.

SYSTEMATIC COMPARISON

The primary purpose of a photon detector is to convert information carried by light to electric signals. Generally speaking, a light signal carries the following pieces of information: time, intensity (the number of photons), position, and wave length.

In most of high energy applications, wave length is not important, as it is not related to the property of particles to be measured. Therefore, I will focus in this section on three quantities, time(T), intensity(I) and position(X).

Attention must be paid to the choice of units before we go further. A wide variety of photon detection is done in frequency domain, where signal is modulated by carrier waves. To make the analysis method simple, I will only consider time domain approach, where signal is assumed to be produced and detected as an event in time.

Then the unit of intensity can be given by the number of photons per event per unit area, where unit area is typically the sensitive area of the given photo detector. The unit of time can be the typical width of the signal, and the unit of position is the typical size of photon bucket when it arrives at the surface of photon detector.

C Sensitivity and Dynamic Range

Let's move on to the sensitivity and the dynamic range of each photon detector in Time(T), Intensity(I) and Position(X). Table 1 summarize various photon detectors and their range of detection capabilities. Here I categorized devices into three groups; vacuum, solid state and the hybrid which is the combination of the both.

Name	T(Min)	T(Max)	X(Min)	X(Max)	I(Min)	I(Max)
Human Eyes	$100msec$	$10sec$	$0.1mm$	$10cm$	10^{4}	10^{10}
Picture Film	$100msec$	$100sec$	$1\mu m$	$30cm$	10^{2}	10^{5}
Vacuum						
PMT	$300psec$	$1sec$	$5mm$	$50cm$	5	10^{7}
Pos. Sens. PMT	$300psec$	$1sec$	$1mm$	$5mm$	5	10^{7}
MCP PMT	$30psec$	-	$1mm$	$3cm$	10	10^{4}
Image Intensifier	$100psec$	$1sec$	$10\mu m$	$1cm$	10	10^{4}
Streak Tube	$1psec$	-	$0.1mm$	$2mm$	10	10^{4}
Solid State						
Photo diode	$1nsec$	$1sec$	$1mm$	$5cm$	10^{4}	10^{15}
APD	$1nsec$	$1sec$	$0.1mm$	$5cm$	10	10^{12}
CCD	$10msec$	$10^{3}sec$	$10\mu m$	$1mm$	10	10^{5}
Silicon Strip	$1nsec$	$1\mu sec$	$10\mu m$	$1mm$	100	10^{6}
Silicon Pixel	$1nsec$	$1\mu sec$	$10\mu m$	$0.1m$	10	10^{5}
Hybrid						
Photo diode	$1nsec$	$1sec$	$2mm$	$2cm$	5	10^{10}
APD	$1nsec$	$1sec$	$0.5mm$	$5mm$	5	10^{8}
CCD	$10msec$	$10^{3}sec$	$10\mu m$	$1mm$	5	10^{4}
Silicon Strip	$1nsec$	$1\mu sec$	$10\mu m$	$1mm$	5	10^{5}
Silicon Pixel	$1nsec$	$1\mu sec$	$10\mu m$	$0.1mm$	5	10^{4}

TABLE 1. Summary of some important properties of photon detectors.

The rest of this paper is devoted to a more detailed analysis of why each detector has the sensitivity shown in Table 1. Here, as an introduction, I just summarize several key characteristics of each detector.

1. Vacuum based detectors are generally more sensitive to weak light signals and

better in time resolution, thus, more suitable for detecting photons in high energy experiments.

2. Conventional solid state photon detectors are more suited for large photon signals. CCD is particularly optimized as a replacement of human eyes.
3. Hybrid devices have better dynamic range in detecting wide range of photon intensity.

Since various photon detectors and their covered ranges in three dimensional phase space in (T,I,X) is described, it is time to compare their resolution on these three dimensions. In the following sections, time, energy (i.e. intensity) and position resolutions are systematically compared.

D Time Resolution

One of the biggest advantage of the vacuum devices over solid state ones is their fast response. Thanks to the long distance between photo cathode and dynode structure, time jitter due to the intrinsic capacitance is almost negligible. The time resolution is mainly limited by the transit time spread (TTS). For large area photomultiplier, it is important to optimize photoelectron trajectory so that all electrons arrive at the dynode at the same time. In addition, time variation may be introduced by secondary electrons' spread inside of the dynode structure. This effect can be minimized by the fine dynode structure.

Such fine structure also allows to maintain position information as well. At the same time, since secondary electrons are well contained in a small area, the effect of external magnetic field can be minimized. Based on the above observations, many types of finely segmented dynode structures have been developed. Table 2 summarizes various dynode structures.

Name	Pitch	Max. B	Company
Box and Grid/Linear Focus	$1cm$	$0.1Gauss$	Many
Venetian Blind	$2mm$	$1Gauss$	Many
Foil Dynode	$0.5mm$	$100Gauss$	Philips
Metal Channel	$0.5mm$	$100Gauss$	Hamamatsu
Fine Mesh	$20\mu m$	$1Tesla$	Hamamatsu/Russia
Micro Channel Plate(MCP)	$10\mu m$	$5Tesla$	Many
Hybrid(PD/APD/CCD)	$1cm - 10\mu m$	$> 10Tesla$	DEP/Hamamatsu/API

TABLE 2. Various dynode structures.

Generally speaking, the smaller the photosensitive area is, the better is the time resolution. For fair comparison of time resolution, in Figure 1, time resolution of various photon detectors are plotted as a function of sensitive area.

As one can see from Figure 1, per unit area, time resolution of a typical vacuum device is an order of magnitude better than that of a typical solid state device. That is why the old-time photomultiplier is still alive today.

Next, Figure 2 shows the effect of magnetic field on various photon detectors.

Conventional photomultipliers can be operated in magnetic fields of up to 10 Gauss or so. In stronger magnetic fields, finer dynode structure is required. The finer the structure is, the less sensitive is their performance to the magnetic field. Needless to say, a solid state device is completely unaffected by a magnetic filed. A hybrid device is also insensitive to the magnetic field as long as its axis is aligned with the direction of the field.

E Energy Resolution

In the ideal case, energy resolution is governed by the simple Poisson statistics of the number of incident photons (N), given by,

$$\frac{\sigma}{E} = \sqrt{\frac{1}{N}} \tag{1}$$

In reality, several modifications to this equation are need.

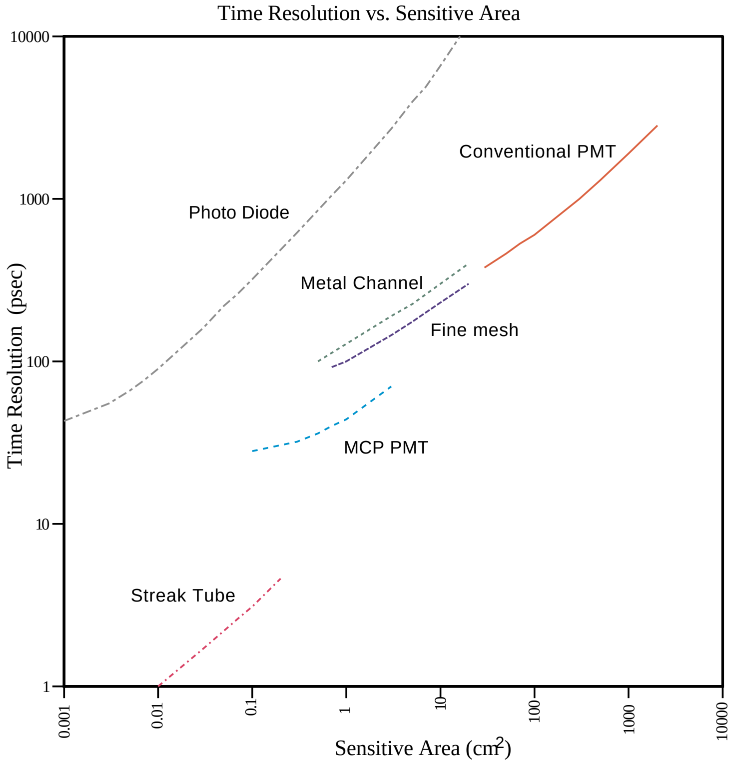

FIGURE 1. Time resolution of various photon detectors as a function of sensitive area.

1. We must take the Poisson statistics of photoelectrons, not photons. The number of photoelectrons (N_{pe}) is given by the following formula:

   $$N_{pe} = N \cdot QE \cdot \eta \qquad (2)$$

   Here, QE is the quantum efficiency of the device and η is the collection efficiency for photo electrons.

2. The Poisson statistics is further modified by the Excess Noise Factor (ENF). In general, the ENF is given by the following formula:

   $$ENF = 1 + \frac{1}{\delta_1} + \frac{1}{\delta_1 \cdot \delta_2} + \cdots + \frac{1}{\delta_1 \cdot \delta_2 \cdots \delta_N} \qquad (3)$$

   Here δ_N stands for the the multiplication factor of the N'th dynode. For typical PMTs, δ_N is $5 \sim 10$, While it is about two for the fine mesh and MCP. As for solid state device, the photo diode is one, but the APD has two or greater than two.

3. Lastly, there is an additional contribution from the Equivalent Noise Charge (ENC). A typical amplifier has about 1000 e^- of ENC. This factor must be normalized by the effective output signal level, given by $N_{pe} \cdot G$, where G is the gain of the photo detector,

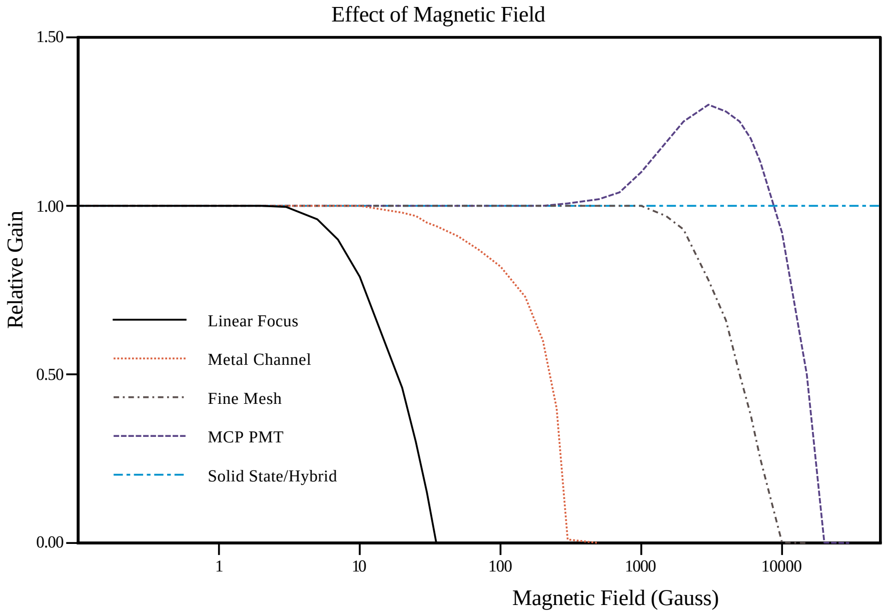

FIGURE 2. Relative gain of various photon detectors under magnetic field.

Taking all these factors into account, the energy resolution is given by,

$$\frac{\sigma}{E} = \sqrt{\frac{ENF}{N_{pe}} + \left(\frac{ENC}{N_{pe} \cdot G}\right)^2} \tag{4}$$

Table 3 summarizes the energy resolution calculated by this formula, assuming the typical ENC level. The results are given as a function of the number of photons (not photoelectrons).

Type	Name	Q.E.	δ_i	ENF	Gain	Energy Resolution
Vacuum	Conventional PMT	0.3	10	1.2	10^6	$\sqrt{\frac{4}{N}}$
	Fine Mesh PMT	0.3	2	2.0	10^6	$\sqrt{\frac{7}{N}}$
	MCP PMT	0.2	-	1.5	10^6	$\sqrt{\frac{7}{N}}$
Solid State	PIN Photo Diode	0.8	-	1	1	$\sqrt{\frac{1.4}{N} + (\frac{1000}{N})^2}$
	APD	0.8	2	2	100	$\sqrt{\frac{3}{N} + (\frac{14}{N})^2}$
	MRS	0.2	-	1.1	10^6	$\sqrt{\frac{5}{N}}$
	VLPC	0.8	-	1.1	10^5	$\sqrt{\frac{1.6}{N}}$
Hybrid	HPD	0.3	1000	1.0	10^3	$\sqrt{\frac{3}{N} + (\frac{3}{N})^2}$
	HAPD	0.3	1000	1.0	10^5	$\sqrt{\frac{3}{N}}$

TABLE 3. Comparison of Energy resolution.

The energy resolution of various devices is plotted in Figure 3 as a function of number of incident photons.

Based on this analysis, I would like to list several important conclusions.

1. Thanks to its high gain($> 10^4$), the vacuum devices can reduce the electric noise contribution to completely negligible level. This makes photon counting possible.

2. On the other hand, the photo diode (PD) achieves the best energy resolution, if the number of photons exceeds 10^6, thanks to its high QE and low ENF.

3. The characteristics of APD fall between the PMT and the Photo diode. It has better energy resolution than the PMT and the PD in the range of 100 and 10^6 photons. This is because the APD has higher QE than PMT and higher gain than the PD, but lower gain than PMT and worse ENF than PMT and PD.

4. The HPD is somewhat similar to the APD. It's poor QE can be compensated by the excellent ENF. The gain is higher than APD, which makes the resolution better than the APD in the region of $10 \sim 100$ photons. The HAPD can cover

even fewer photon numbers, down to single photon because of its high gain. However both HPD and HAPD still suffer from poor QE, which is an intrinsic property of the vacuum device.

5. The VLPC is the ideal device for photon counting with high QE (as a solid state device), high gain and low ENF (similar to the PMT).

As one can see from this analysis, the major advantage of solid state devices at the large number of photons comes from their high quantum efficiency (QE). In order to further improve the energy resolution of the vacuum devices, increased QE is essential. To achieve this, solid state photo cathodes such as GaAs and GaAsP have been under development [12]. Figure 4 shows the quantum efficiency of various photo cathodes as a function of wave length. As shown here, the newly developed GaAsP photo cathode by Intevac has achieved the QE as high as 50%.

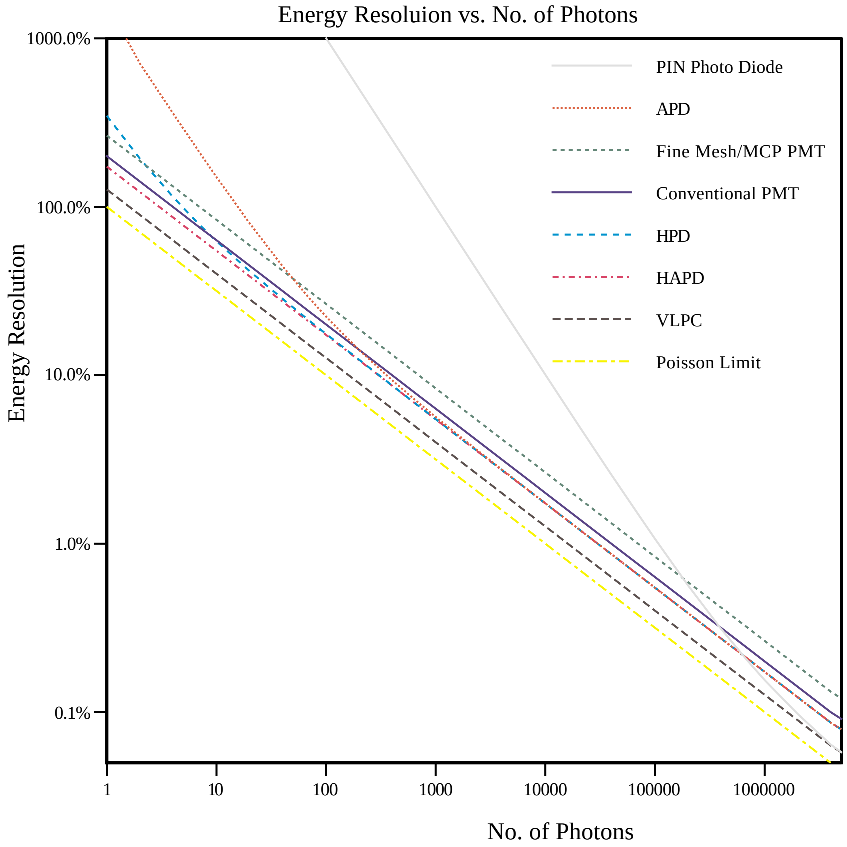

FIGURE 3. Energy resolution of various photon detectors as a function of sensitive area.

F Image Resolution

Traditionally, Image resolution is given by the Signal to Noise Ratio (SNR). However, by taking the inverse of the SNR, one can define the image resolution as a natural extension of the energy resolution as shown below.

$$\begin{aligned}
(\text{Image Resolution}) &= (\text{Energy Resolution}) \cdot (\text{Position Resolution}) && (5)\\
&= \frac{\sigma}{E} \cdot \frac{1}{MTF} && (6)\\
&= \frac{1}{SNR} && (7)
\end{aligned}$$

Here, MTF is so-called Modulation Transfer Function at the given spatial frequency.

Table 4 summarizes the image resolution calculated by this formula. For simplicity, the MTF at $10lp/mm$ is given here. The image resolution is given as a function of the number of photons (not photoelectrons).

The image resolution of various devices is plotted in Figure 5 as a function of the number of incident photons. Based on this analysis, I can conclude the following:

1. In general, by using vacuum devices, one can reduce the electric noise to negligible level. This is the common feature of ICCD, EBCCD and ISPA.
2. Among these three, EBCCD has the best image resolution, thanks to its excellent ENF and MTF. ICCD is the worst due to its poor ENF and MTF. ISPA is not as good as EBCCD, simply because of larger pixel size. But the main advantage of ISPA over EBCCD is readout speed.

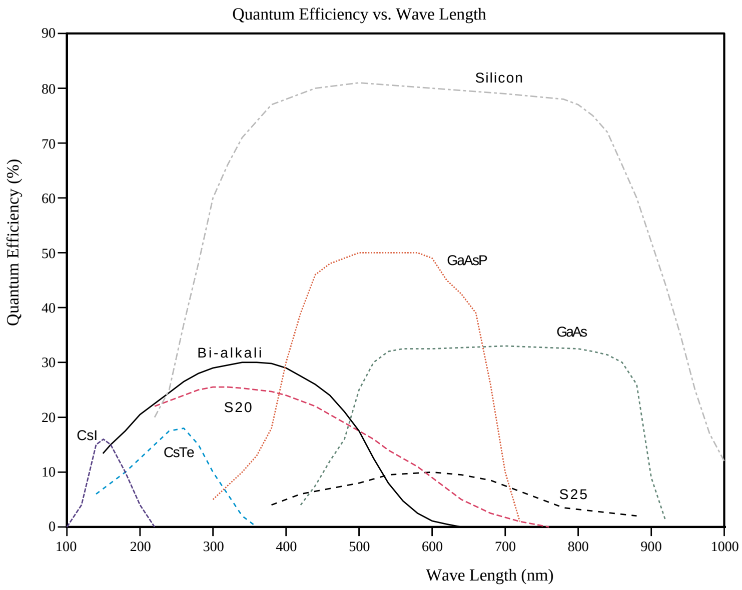

FIGURE 4. the quantum efficiency of various photo cathode as a function of wave length.

Type	Meaning	Q.E.	ENF	Gain	MTF (at $10lp/mm$)	Image Resolution
CCD	Charge Coupled Device	0.3	1	1	0.8	$\sqrt{\frac{5}{N}+(\frac{200}{N})^2}$
BCCD	Back Illuminated	0.8	1	1	0.8	$\sqrt{\frac{2}{N}+(\frac{80}{N})^2}$
Cooled BCCD		0.8	1	1	0.8	$\sqrt{\frac{2}{N}+(\frac{10}{N})^2}$
ICCD	Intensified by MCP	0.2	2	600	0.3	$\sqrt{\frac{100}{N}+(\frac{1}{N})^2}$
EBCCD	Electron Bombarded	0.2	1.1	3000	0.6	$\sqrt{\frac{15}{N}+<(\frac{1}{N})^2}$
ISPA	Imaging Silicon Pixel Array	0.2	1.1	5000	0.4	$\sqrt{\frac{30}{N}+<(\frac{1}{N})^2}$

TABLE 4. Comparison of Image resolutions.

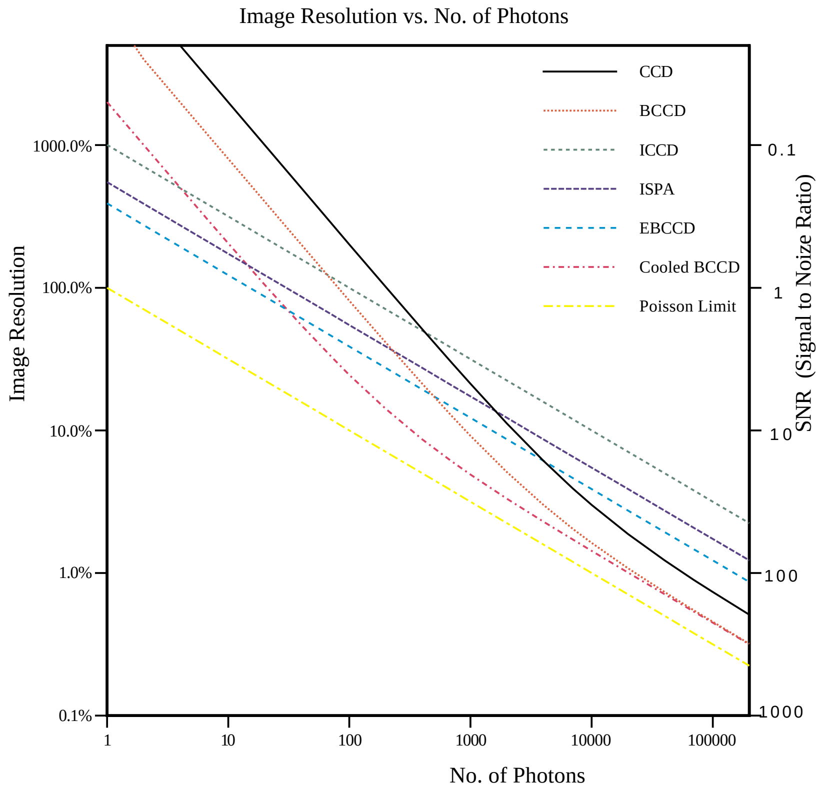

FIGURE 5. Image resolution of various photon detectors as a function of sensitive area.

3. Once the number of photons exceeds several hundreds, Back illuminated CCD (BCCD) shows the best image resolution, thanks to its high QE. Its electric noise level can be reduced by cooling the device to the level of less than 10 electrons. This is the reason why astronomical observations are performed by the cooled, back-illuminated CCD.

In summary, newly developed EBCCD or ISPA is a powerful device for the detection of photons in a range of < 10 photons. However, for most of scientific applications where one can collect more than 10 photons be integrating over time, the cooled BCCD is better suited and less expensive.

I MARKET PRICE AND FUTURE PROSPECT

A Comparison of Market Price

The market price is one of the most important factors to make a final decision on the choice of the photon detector to be used. So I would like to make some comments on this issue. Figure 6 shows the market price of various photon detectors as a function of dimension (diameter) of the sensitive area. The prices were taken from the large scale high energy experiments.

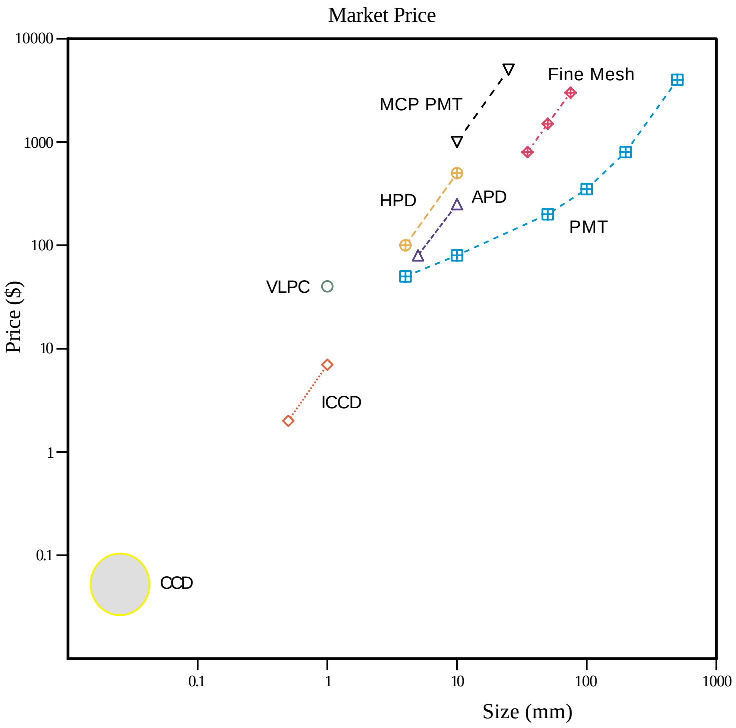

FIGURE 6. The market price of various photon detectors which have been used in large scale high energy experiments.

I can conclude the following from this figure.

1. Above $10mm$ diameter, the PMT is still the least expensive. Any other devices cost more. Therefore, unless there is a specific reason why PMT's can not be used, motivation for using other devices is not compelling. Fine mesh

PMTs have been used when the magnetic field is somewhere 0.1 - 1.5 Tesla, and the APD and HPD are under consideration by the CMS because of 4 Tesla environment. Otherwise, even though APD and HPD have slightly better performance in terms of energy resolution and linearity than the PMT, additional cost is hard to justify under today's market prices.

2. For small pixel size ($< 0.1mm$). CCD is the only practical solution, and it is cheap. For high energy applications, however, its slow readout speed and electric noise level make it difficult to use.
3. Between $0.1mm$ and $1mm$, there is no single solution. ICCD is OK if readout speed is not an issue. But this is not the case for most of high energy applications.
4. Between $1mm$ and $5mm$, again, there is no easy solution. Ideally the price should be an order of \$10 at 1 mm. In reality, the VLPC costs \$50 (including associated cryogenic and preamp), and the position sensitive PMT costs $\sim$ \$20 per channel. This is the area where future development of inexpensive photon detectors can contribute the most.

The market price is one of the most important parameters for the final decision. Developing a new detector with 10% better energy resolution or time resolution is an interesting R & D project. However, if it costs twice than the conventional one at the end, it is hard to justify such a new device for large quantities. Considering the fact that the cost of the photon detectors is a significant part of budget for today's large scale detectors, further competition and price reduction are more important than anything else in my opinion.

B Future prospect

In the past 10 years or so, many new types of photon detectors have been proposed and developed. From time to time, people thought that these new devices, such as APD and HPD would eventually replace all the PMTs in the world. As we know, this has not yet happened. In this paper, I tried to address this question by taking a systematic approach.

We have more variety of photon detectors than ever. However, as I demonstrated, there is no single device for general purposes, which makes our research more interesting.

As a conclusion to my paper, I would like to propose my dream photon detector for the scintillating fiber read out. It is a hybrid APD with GaAsP photo cathode. My specifications is given in Table 5.

REFERENCES

1. T. Iijima *et al.*, Nucl. Instr. and Meth. A **379** (1996) 457.

Item	Specification
Window	FOP (or Glass window)
Photo cathode	GaAsP (or InGaN) with $> 50\%$ QE
Inside	APD array: 64 pixels(4mm), 256 pixel(2mm), 1024 pixels(1mm)
Gain	$> 10^5$
ENF	1.0
Readout	Single optical fiber
Size	35mm × 35mm
Cost	$<$ \$2000

TABLE 5. Katsushi's dream detector.

2. Y. Yoshizawa *et al.*, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 33.
3. R. DeSalvo *et al.*, Nucl. Instr. and Meth. A **342** (1994) 558.
4. R. DeSalvo, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 92.
5. P. Cushman *et al.*, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 107.
6. J. P. Pansart, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 186.
7. Th. Kirn *et al.*, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 199, 202.
8. A. Karar *et al.*, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 205.
9. N. Bacchetta, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 225.
10. A. V. Akindinov, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 231.
11. M. R. Wange, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 278.
12. S. M Bradbury, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 45.
13. T. Gys *et al.*, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 131.
14. M Gruwa, Nucl. Instr. and Meth. in Phys. Res. A **387** (1997) 282.