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Novel Photon Detectors for RICH Applications[+]

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Abstract

The paper describes recent developments in Photon Detectors useful for the Cherenkov Ring Imaging Applications (RICH). We discuss the Multi-anode PMTs, HPDs with PIN and APD diode readout, APDs working in a Geiger mode, and the gaseous multi-pattern detectors. The paper emphasizes their timing properties. We give equal chance to fragile, not yet entirely proven ideas.

1. INTRODUCTION

The important issues for the future Photon Detectors used in RICH applications are high detection efficiency, rate capability, aging problems, reliability and most recently also a timing resolution capability in the range of σ~100-200ps. The reliability is especially important for the new accelerators such as B-factories where running periods are long and the access for repairs is limited. The 100-200ps resolution became a goal recently for the new applications such as new DIRC-like devices [1], Aqua RICH [2] and new cosmic ray telescopes [3] operating at high background rates due to moonlight, etc. Finally, there has been a very strong effort to push the RICH detectors to work in the visible wavelength region to limit the chromatic error contribution.

Examples of two DIRC-like novel devices are shown in Fig. 1. Figure 1a shows a version of the Time of Propagation (TOP) counter [4]. It has a fused silica bar Cherenkov radiator equipped with a mirror and the multi-anode PMTs measuring the Φ-angle and time of each photon, which is a bare minimum from point of view of redundancy. Figure 1b shows one of several possible ideas for SLAC DIRC upgrade with a mirror and the Flat Panel multi-anode PMTs measuring x,y and time of each photon. Another possible geometry for the DIRC upgrade was already mentioned in Ref. 4. These new concepts would lead to a reduction of the chromatic error if a 100ps timing resolution were achieved [1].

This paper discusses various candidates for a 100ps-resolution detector. They include vacuum-based devices such as the Multi-anode PMT, Hybrid Photodiode (HPD), Micro Channel Plates (MCP) or Avalanche Photodiode (APD) working in a Geiger mode (SiPM). The best transit time distributions (σ) are ~60ps (MCP, SiPM), ~70ps (multi-anode PMT), ~150ps (Photonis XP2020/UR PMT) and ~170ps (Flat Panel H-8500). The paper also discusses the novel micro-pattern gaseous detectors. Their advantages are that they could operate at a very high magnetic field of ~4 Tesla, and that we would control the geometry. If one would be able to couple them to the Bialkali photocathode, one could still create a strong competitor to the vacuum-based devices. This requires a development of ultra-pure gases and clean materials. As A. Bream of CERN pointed out, to make a permanently sealed gaseous device is only one more additional step in a process to make an HPD. So far, the best single photoelectron timing resolution in a gaseous detector was "only" σ ~ 680psec. However, there was no attempt to optimize geometry or timing strategies, or to play with different gases.

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To perform the timing resolution studies in the σ~100ps range, one needs a special laser diode pulser. The Nagoya group uses a Hamamatsu pulser (395nm, light spread of ~35ps FWHM, ±10ps jitter) coupled to a 2m-long 2mm diameter fiber with diffuser at the end. The SLAC DIRC group has opted for a PiLas pulser (535nm, light spread of ~34ps FWHM, ±2ps jitter) coupled to a 5m-long multi-mode50μm diameter fiber with a lens at the end.

2. THE MULTI-ANODE PMTs

The Hamamatsu multi-anode PMT concept has already established itself in the RICH applications such as HERA-B. The most recent addition to this family, the 64-channel Flat Panel Hamamatsu H-8500 PMT, is the least understood because very few groups had a chance to obtain it. SLAC DIRC group received one sample. An average gain of this tube is 20-50 times smaller than that of other typical PMTs. Therefore it is necessary to use amplifiers with H-8500. Because these tubes are very fast (the charge arrives with a spread of FWHM ~300ps, resulting in the pulse rise time of ~700ps), one can use very fast amplifiers. For example, the SLAC group uses the Elantec 2075C amplifier with a gain of 40 (its bandwidth is 2GHz at gain of one). The group has developed a high-density amplifier package coupled directly to the 64 channels PMT. The resulting tube/amplifier rise time is ~1.4ns at an amplifier gain of 40. Figure 2 shows the author's own measurements of the timing resolution of the H-8500 tube using the PiLas Light pulser for (a) ADC-sliced single-threshold TDC timing and (b) double-threshold TDC timing. Figure 2a shows that one can approach ~100ps timing resolution only at high gain above ~10^6. At low gain, near ~10^5, the resolution gets rapidly worse ($\sigma > 250$ps). Figure 2b shows a double-threshold TDC timing, which makes a cut on the pulse height by requiring two thresholds of 15 and 20mV. The data was fitted with a double-Gaussian and quadratic background of a form G1 + G2 + a + bx + cx^2, resulting in σ_1 = 125ps and σ_2 = 193ps. These results are slightly better than a simple ADC-corrected single-threshold TDC timing, because the double threshold technique makes a cut on small pulses. The reason why the timing resolution is worse than that of other Multi-anode PMTs is that this tube has a low average gain of ~10^6 at –1kV, and its cathode-to-dynode maximum voltage is limited (at the time of this test, Hamamatsu strictly allowed only a linear resistor chain 1:1:…:1:1 for this tube). On the other hand, the geometrical packing efficiency of this tube is 97%, which is excellent. This is, however, offset by worse PMT response across its face. Hamamatsu has measured a relative response of this tube in a current mode (this method integrates the quantum and the photoelectron transfer efficiencies, and gain variation all together), and found 20-30% variation [5]. Initial SLAC scanning tests confirm also a similar variation in response.

For comparison, we mention a multi-anode Hamamatsu R-5900-U-L16 PMT, which was used in the early TOP counter test [6]. This tube has more than ~10 times larger average gain than the H-8500. During the tests of the TOP counter, the tube was run at –1kV with an average gain approaching 2x10^7. In addition, the resistor divider was modified to increase the cathode-to-first dynode voltage (Hamamatsu allows a resistor chain 2:1:…:1:1 for this tube), the amplifier was driving TDC and ADC branches actively without a factor of two loss, and the TDC timing was corrected with an ADC information. This resulted in an excellent single photon timing resolution close to σ_T ~83ps, which is a value not far from the tube's transit time spread of σ_{TTD} ~70ps. This tube is, however, not suitable for this particular RICH application because (a) the geometrical packing efficiency is only ~40%, (b) the collection efficiency between cathode and the 1-st dynode is only ~50%, and (c) it is not able to work in high magnetic field.

The requirement to reach a σ_T ~100ps single-photon timing resolution at 1.5 Tesla motivated the Nagoya/Hamamatsu group to push a development of the multi-anode multi-mesh PMT R-6135-L24-α,β,γ [7] (Greek letters indicate tuning of the cathode-to-first dynode distance, and the mesh parameters – see Table 1). They have achieved a collection efficiency between the cathode and the first dynode of ~85%, a geometrical packing efficiency of ~90%, pulse rise time of 1ns, gain of 5x10^6 at 1.5 Tesla, and a single photon timing resolution close to σ_T ~150ps at 1.5 Tesla. The conclusion of the work in Ref. 6 is that to reach σ_T ~100ps, one needs a gain of ~5x10^7 at 1.5 Tesla, which requires more R&D work.

Table 1 shows a summary of various parameters of the above-mentioned Multi-anode tubes. The main attraction of these tubes is compactness, small operating voltage, and good timing resolution. A disadvantage is the relative non-uniform response of the gain and the variation in the cathode-to-first dynode collection efficiency.

3. THE HPDs WITH PIN DIODES

Table 2 shows parameters of three electrostatically focusing HPD tubes equipped with PIN diodes, which were recently developed at CERN and at DEP. The electron-focusing scheme, which was studied in great detail by D. Ferenc [8], is chosen to be either fountain

(CERN tube [9]) or cross-focusing (DEP [10] and BTEV [11] tubes). The main advantage of the cross-focusing optics is the ability to trap the positive ions created in the silicone by electron impact, a feature important at high rates. The gain in a HPD with a PIN diode is ($V_{cathode}$-$V_{threshold}$) q_e/3.62eV ~5000 electrons for $V_{cathode}$ = –20kV and $V_{threshold}$ ~2.1 kV (the last is due to energy loss in the aluminum contact layer), i.e., it is very small compared to a typical PMT. At present, the PIN diode arrays in all existing HPDs collect hole charges in a typically ~300μm-thick silicone, which makes them relatively slow devices (the collection time for holes is ~2.2ns per 100μm path in silicone for a bias voltage of 150 Volts). The corrected HPD photoelectron transit time distribution in vacuum $\sigma_{TTD}(e^-)$ is believed to be very small, i.e., less than ~100ps, provided that all distortions within the HPD, for example, due to stray magnetic field or incorrect electrostatics, are understood [8]. With a typical pixel capacitance of 4-10pF, the HPD has typically a noise of σ_{amp} ~ 400-500 electrons with a charge amplifier of 1-2 μsec shaping time. However, one should say that the LHC-b experiment is planning to use a shaping time of 25ns with a noise of 250e^-. This shaping time is still by a factor of ~20 too long compared to the Flat Panel PMT used in the SLAC tests (see chapter 2).

The main attraction of this concept is a superb pulse height distribution (so far, demonstrated for long shaping times only), and a uniformity of the response across its face. However, significant disadvantages are: high voltage, low gain, poor rise time, poor timing resolution, need for relatively long shaping times to cope with a poor signal-to-noise ratio, and a significant sensitivity to the magnetic field. Its geometrical packing efficiency is also worse than that of the Flat Panel PMT.

4. PROSPECTS FOR A 100 PS TIMINIG RESOLUTION WITH HPDs

For the Si detectors, followed by charge sensitive amplifier, the expected timing resolution is σ_T ~σ_{amp}/(dV/dt), where σ_{amp} is the amplifier noise, and dV/dt is the slope of the leading edge of the pulse taken at the threshold V_0 [12]. This can be approximated as $\sigma_{amp}T_r/V_{peak}$, where T_r is the rise time and V_{peak} is the amplitude of the pulse. From here it follows that to minimize σ_T, one should minimize the amplifier noise, reduce the pulse rise time, maximize the gain and set the threshold at a point of maximum slope. R. DeSalvo has shown experimentally that this equation is valid to ~10% for applications involving HPDs with PIN diodes [13].

All PIN diode arrays used in present HPDs drift holes in the silicone. The combined rise time of the HPD with the PIN diode array is a result of a convolution of (a) the amplifier rise time, (b) the electron transit distribution in vacuum $\sigma_{TTD}(e^-)$, (c) the hole transit time distribution σ_{TTD}(h), which is driven by hole mobility, diffusion and electric field profile in silicon, and (d) the diode circuit contribution, controlled by the pixel capacitance and the diode series resistance. There is not much point to push the amplifier rise time much below the major limiting factor σ_{TTD}(h), which is 3-4ns at present. The value of σ_{TTD}(h) can be dramatically improved by increasing the diode bias voltage to 500-600 Volts [14]; however, this requires manufacturing robust diodes out of a high resistance silicone. The result of the above convolution is a HPD rise time of 3-4ns at best in the present available designs. If the HPD is coupled to a charge integrating amplifier with a noise of σ_{amp} ~400-500 electrons, one can expect σ_T ~ $\sigma_{amp}T_r/V_{peak}$ ~300-400ps at best. Figure 3 shows the best attempt so far to use the HPD for timing purpose with the short shaping time [15], and indicates that a ~100ps timing resolution can be achieved with a signal of ~20 photoelectrons, which is not very useful for RICH. If one is allowed to extrapolate using a power law function, one would obtain 400-500ps for N_{pe} =1. However, up to this point, nobody has achieved a single photoelectron sensitivity with a short shaping time of 3-4ns, not to speak of ~100ps resolution (Fig. 3 represents the best effort so far).

What can be done to improve the timing resolution? Probably, the most practical way to speed up the HPD rise time is to increase the diode's bias voltage to ~500 Volts, i.e., ask the manufacturer to make more robust diode design. Another possible option is to convince the manufacturers to design the PIN diode arrays with the electron drift, and gain a factor of ~2.75 in the drift speed. One could then probably achieve ~1ns rise time, however with a gain of ~5000 and not 10^6. It would appear that yet another way is to increase the shaping time to 20-25ns, and digitize the single electron waveform. However, to get to the 100ps regime one needs to come up with an improvement factor of ~200, which seems an unrealistic goal in the noisy environment [16]. To make the silicon thinner, which would reduce the overall time spread, also seems to be the wrong direction, as it would increase the PIN diode capacitance.

5. HPDs WITH APD DIODEs

I believe that the right way to reach the 100ps timing resolution with the HPD is to combine it with the avalanche photodiode (APD). The reason is that one can get <1ns rise time and a total gain almost as high as that of the Multi-anode PMT. The noise of the HPD/APD combination is worse than that of HPD/PIN diode, primarily driven by much larger APD capacitance and very short shaping time to take advantage of its speed. This leads to a pulse height spectrum, which is not as spectacular as in the case of the HPD with the PIN diode. However, the pulse height is not as important a parameter for the RICH applications compared to parameters such as the timing resolution or the rate capability.

Intervac Company made one of the first HPD/APD. It had a GaAs photocathode, less than 10 kV cathode voltage and ~40pF pixel capacitance. It was the basis of many later developments in this field. Another example of early development was the VAPD tube made by Advanced Photonics (APD) and Litton Electron Devices[1] (vacuum enclosure) [17]. VAPD achieved a gain of 10^6 with a few ns rise time.

Examples of more recent HPD/APD tubes are Hamamatsu HPD/APD R7110U-07, developed together with Nagoya University [18]. They have achieved a timing resolution of σ_T ~ 150ps at a total gain of 1.5×10^5. The detector can work in a field of 1.5 Tesla. The tube rise time was ~1.1ns. The authors conclude that a 100ps resolution can be reached if the total gain can be increased to $\sim 5 \times 10^5$. The test used a 300 MHz BW amplifier with a 60dB gain (MITEQ). Another Hamamatsu tube is R7110U-01MOD, developed together with E. Lorenz from MPI [19]. It has a GaAsP photocathode, which has a quantum efficiency extending into a visible range. Its pixel capacitance is only 24pF, which is small for an APD, and enables a rise time of only ~0.8ns, pulse width of 2.1ns, and fall time of 1.9ns. Such parameters make the HPD/APD suitable for very high rate operations with performance close to the Multi-anode PMT. Figure 4 shows a schematic view of this new tube, which is similar to old Intervac design. Table 3 shows a summary of the parameters of these two tubes.

Of course, the RICH applications require multi-pixel devices, and all the above examples are single-element devices. Hamamatsu offers a 4 x 4 array of R7110U-07. However, such a solution has still too much dead space between individual APDs, which leads to either individual Winston cones or lenses, which means some photon losses. Perhaps a better way is to replicate the single-cell focusing structure shown on Fig. 4 many times without the individual ceramic boundaries, thus forming the multi-pixel detector with a common vacuum envelope. One should mention that there was already a fairly advanced solution available during the early "SSC era" by Advanced Photonics and Litton Electron Devices, which developed an 8 x 8 APD array placed into a proximity focusing HPD [20] (see Fig. 5). Unfortunately, this device was another casualty of the SSC loss…

6. THE RE-FERENCE HPD

D. Ferenc has come up with an ingenious combination of the Winston cone and HPD shown in Fig. 6 [21], being developed in collaboration with ITT Night Vision Company. The advantage of this concept is a large demagnification factor, excellent timing resolution even with a flat photocathode, efficient magnetic shielding in the region where photoelectrons are slow, and use of the reflective photocathode, which has higher quantum efficiency. The detector can be, for example, an APD diode. One can envisage expanding a single device into a mosaic of many such units, thus forming the multi-pixel detector. The challenge is the vacuum-compatible reflective material on the Winston cone because it cannot be, of course, conducting surface. An interesting possibility is a foil by 3M [22], which has a superb reflectivity capability, far better than commonly used reflecting materials.

7. APD OPERATING IN A GEIGER MODE

It is well known that an APD diode can be operated in a single photon detection regime if one drives the gain into the Geiger mode. To prevent damage one provides a protection resistor, which lowers the bias voltage when the current exceeds a breakdown limit, thus extinguishing the avalanche. This leads to a dead time associated with the voltage recovery. Example of a new development in this area is work described in Ref. 23. The authors developed a monolithic chip with an array of tiny APD diodes, called silicone photomultiplier (SiPM). Each APD diode pixel has the protecting 100-200kΩ resistor implanted on the chip. The pixel size is 42 μm x 42 μm (one can place up to ~4000 pixels per mm^2), the pixel capacitance is only ~100fF, and a single pixel gain is $\sim 1.5 \times 10^6$. The authors have already achieved a timing resolution of 60ps, without a need of pulse height correction, which means that the pulse height spectrum is superbly good. The detector is insensitive to magnetic field, the bias voltage is only 25 Volts, and the dark noise rate is a few MHz/mm^2 at room temperature. However, the device has a poor geometrical packing efficiency of only ~30% and it is realized in very small sizes so far ($\sim 1 \times 1 mm^2$).

[1] Litton Electron Devices purchased the Intervac Co.

A US company RMD[2] has been offering APD arrays operating in the Geiger mode [24]. The active area of each diode is 30-40 μm, with a single pixel gain 10^8 and a quantum efficiency of 50% at 400nm. However, again there is a significant dead space between diodes.

8. THE MCP DETECTORS

The MCP is a well-known concept, which is clearly capable of achieving 50-100ps timing resolution per single photon. So why did we not build DIRC using it ? Up to now, it was believed that these devices do have considerable aging rate. For example, work of Anashin et al. [25] has indicated that a 50% degradation of either Bi-alkali photocathode or the micro-channel's tube wall coating occurs after an anode charge dose of only 20-30mC/cm^2. The authors did not determine which is the dominant factor[3]. However, recent data from Burle Company hint that a 50% degradation occurs after ~200mC/cm^2. The company is developing a 2 inch square MCP-PMT with an 8x8 anode array, Bi-alkali photocathode, ~10^5 gain, ~0.75ns rise time, active area of 67% (initially), <10% cathode uniformity, the anode uniformity ~1.5:1 over the 2" active area, and with acceptable cost for the RICH imaging [26]. Author obtained a very good timing resolution of σ~59ps with a constant fraction discriminator. A version of this tube with the GaAs photocathode would offer the excellent quantum efficiency up to ~900nm, which would improve the chromatic error enough so that the overall gain in terms of the particle identification is significant. If this concept proves to be successful, this may be a major contribution to our field, and the most significant novel detector concept of this paper.

9. THE GASEOUS DETECTORS

To some, the gaseous detectors are dead for the future RICH applications. However, would we not consider a multi-pixel photon detector with an internal geometry defined by us, capable of operating in a field of up to 4 Tesla, with a Bi-alkali photocathode, and with a sub-nanosecond timing resolution, if we are offered such a device? It is possible that the permanently sealed multi-pattern gaseous detectors will evolve into such a candidate. This is assuming that the amplifying structure can also be made clean. In the following, we will consider only the micro-pattern detectors, which have demonstrated a single electron detection capability and fit into this overall vision. However, one should remember that, unlike the case of a MWPC, all these new detectors are too linear to limit the gain by the saturation effect, i.e., when the avalanche reaches the Raether limit of ~10^8 electrons, the detector will spark. Since single electron detection with a good timing resolution requires a gas gain in excess of 10^5, the Raether limit can be easily reached. This is a drawback in a high background environment, such as the HERA-B experiment, unless a device is robust enough to tolerate a certain sparking rate, or has resistive meshes or GEM electrodes to limit a local capacity going into a spark (as is done in a RPC).

The most interesting development in this area is the work of A. Breskin and his group from the Weizmann Institute, reported at this workshop by R.Chechik [27]. They created a permanently sealed structure filled with Ar and containing a Bi-alkali photocathode of a quantum efficiency peaking near ~3%, which stayed stable for 6 months. Then they repeated the process, this time inserting a double-GEM amplifying structure, which was baked to 200^{o}C for a few days. They reached a total gas gain of $2x10^3$ with 95%Ar+5%CH_4 gas at 1 bar. The quantum efficiency remained stable for weeks. After further optimization of the process, their latest value on the quantum efficiency peak is now at 13%. This is a remarkable result, indeed. This work follows their previous work with a triple-GEM amplifier and a CsI photocathode in CF_4 gas at 1 bar [28]. A remarkable observation of this work was that this structure would support a maximum total gas gain of ~$6x10^6$ before onset of the secondary effects. Considering the fact that CF_4 gas is known to scintillate very efficiently [29], it speaks very well for the shielding power of the triple GEM structure preventing the avalanche photons from reaching the semi-transparent CsI film (in this case evaporated on the window), which would create secondary photoelectrons. One should mention that this effort made it possible to propose a hadron-blind detector shown in Fig. 7 for the PHENIX experiment at RHIC [30]. In that particular case, proponents would evaporate a thick CsI film directly on the top surface of the first GEM, making the photocathode reflective, which increases the quantum efficiency and reduces the photon feedback. The group already demonstrated a high gain of >10^5, timing resolution of 2.1ns, a good 2D resolution of σ ~ 100 μm, and no photon feedback. Perhaps, one may worry about the corrosive features of the CF_4 gas.

J. Va'vra and A. Sharma [31] opted for the quadruple-GEM with pad readout. The additional GEM

[2] Radiation Monitoring Devices, Inc., 44Hunt Street, Watertown, MA 02472, USA.

[3] J. Va'vra has found that the DIRC PMT cathode is still functioning well after a charge dose of 6500 μC/mm^2 caused by UV photons from the Mercury lamp. In this test the PMT operated without the gain, only in current collection mode.

foil reduces the gain per GEM, and thus improves the device's lifetime. The original motivation was to make it compatible with the CRID geometry and electronics, which uses a charge-integrating amplifier with a 65ns shaping time. The detector reached a maximum total gain of ~10^6 in ethane at 1 bar, a good operation at ~$2x10^5$ with exponential pulse height spectra. Another interesting simulation result by A. Sharma, related to the charge flow through the structure, was that the fraction of the transmitted electron charge is only ~36%, and ion deposition on the GEM Kapton hole sides in the last GEM foil is about 6%. That is a non-negligible amount of trapped charge, which will have to leak out with some finite time constant. Indeed, the measurements interrupting the light flux indicate a time constant of the order of minutes. This may be relevant at high rates. One should add that a detector operating with a Bi-alkali photocathode requires extremely low levels of water, which may further enhance the Kapton resistivity. More work in this area is needed.

A single-stage Micromegas detector with pad readout was used in Ref. 32 to demonstrate a single-photon detection capability, with a Polya-shape pulse height spectrum with a turnover, excellent timing resolution of 680ps, and reaching a maximum gain of 10^6. The maximum reachable gain, driven by the sparking rate, decreased with increasing rate, being down to ~10^4 for rate of ~10^3 mm^{-2} sec^{-1}. One possible way to help the problem, though to a limited extent, is to add an additional amplification stage, for example additional Micromegas or GEM.

The last detector concept I want to mention is a multi-capillary structure with pad readout. The capillary plate is a similar structure to a micro-channel plate; however, the channels have larger diameter and it is made of glass without any special wall coating, which is not necessary, because the amplification occurs only in the gas and not on the walls. The amplification mechanism is similar to GEM, which uses Kapton foil, but the capillary plate can be made cleaner. The first to succeed using this structure was Peskov [33], who used double capillaries with an amplifier connected directly to the bottom's capillary's end electrode (an ideal coupling). A single capillary reached a gain of ~10^4 in 95%Ar+5%CH_4 gas at 1 bar with a SbCs photocathode, the double capillary only ~10^5. The study was performed with an Fe^{55} source, and some signs of the pulse height broadening was noticed at highest gains close to 10^5, which may indicate signs of poor quenching. Although this avenue, and this includes also the author's effort, has not yet demonstrated a solid single electron detection performance, it is nevertheless an interesting avenue to investigate.

CONCLUSION

HPD detectors have made a huge progress since the last RICH workshop. Their pulse height spectra with an amplifier with a long shaping time are simply spectacular. The next challenge is to reach the ~100ps resolution limit. We believe that the right path toward this goal is to make a combination of HPD and APD diodes. This requires creating a new interest in the relevant companies, which was unfortunately lost during the demise of SSC.

Now that the RICH imaging with more than 10000 PMTs is accepted, the next challenge is to achieve the ~100ps resolution for each pixel. We believe that the right choice at present is the Hamamatsu H-8500 multi-anode PMT structure, if the magnetic field is not an issue. However, the new Burle square MCP-PMT tube is very attractive because it would operate in high magnetic field and provides excellent timing resolution. Nonetheless, one needs to show that it is indeed resistant to anode aging as the manufacturer claims.

The gaseous detectors would allow operation up to 4 Tesla. The real challenge is to combine the Bi-alkali photocathode with such a detector structure. This requires development of the ultra-pure gases and clean electrodes. The multi-pattern detectors are possible candidates.

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Table 1: Basic parameters of the Hamamatsu Multi-anode PMTs. The mesh PMT has 2000 (α,β) or 2500 (γ) lines/inch, pitch 9 (γ) or 12.5 (β) μm, and cathode to the 1-st dynode distance of 2.5-3 (α) or 1 (β,γ) mm.

PMT parameter	**Flat Panel H-8500 ***	**Multi-anode R-5900-U-L16 [6]**	**Multi-anode mesh R-6135-L24-α, β, γ [7]**
Geometrical packing efficiency	~97%	~40%	~90%
Collection efficiency of the 1-st dynode	~70-80%	~50%	52%(α) & 63%(β) & 85% (γ)
Operating voltage (max.)	-1 kV	-900 V	-3.4 kV (γ)
Pixel size	5mm x 5mm	16mm x 0.8mm	5mm x 5mm
Matrix	8 x 8	16 x 1	26.5 x 0.8
Number of pixels	64	16	24
Gain (Hamamatsu)	$\sim10^6$ @ –1 kV	$\sim10^7$ @ –900 V	$\sim5\times10^6$ @ –3.4 kV (γ) @ 1.5 T
Worst cross-talk	4% *	3%	-
Number of stages	12	10	24 (α) 19 (β,γ)
Resistor chain (K - D1 - D2 - -> A)	1-1-….-1-0.9-0.1	2-1-….-1-0.9-1	1-1-….-1 (α) & 2-1-….-1 (β,γ)
Transit time distribution (Hamamatsu)	σ_{TTD} ~170 ps	σ_{TTD} ~70 ps	σ_{TTD} ~100 ps @G~5×10^7 (β,γ)
Timing resolution per single photon	σ ~125 ps *	σ ~83 ps	σ ~150 ps at B = 1.5 Tesla

* Author's own measurement with a double threshold timing with 15 & 20 mV thresholds. This may cut small pulses and improve the timing resolution compared to the transit time distribution at the expense of efficiency.

Table 2: Basic parameters of the HPD equipped with silicone PIN diode detector.

HPD parameter	**CERN tube [9]**	**LHCb [10] (DEP tube)**	**BTEV [11] (DEP tube)**
Operating voltage	-20 kV	-20 kV	-20 kV
Geometrical packing efficiency	~80%	~80%	~80%
Pixel size	1mm x 1mm	1mm x 1mm	1.4 mm flat-to-flat, hex
Matrix	16 x 128	320 x 32	
Number of pixels	2048	1024	163
Pixel size (at the photo-cathode plane)	1 mm x 1 mm	2.5 mm x 2.5 mm	6.5 mm flat-to-flat, hex
Electron optics	Fountain focusing	Cross focusing	Cross focusing
Demagnification	4	5	4.1
Gain ~$(V-V_{th})\, q_e / 3.62$ eV, V_{th} ~2.1kV	~5000 @ –20kV	~5000 @ –20kV	~5000 @ –20kV
Electronics	Internal	Internal	External
Type of amplifier	Viking VA3	New development	Viking VA2
Measured electronics noise	~400 electrons	~250 electrons	~500 electrons
Shaping time	1.3 μs	25 ns	2 μs (at present)

Table 3: Basic parameters of the Hamamatsu HPD equipped with an APD diode detector.

HAPD parameter	**R7110U-07 [19] (Hamamatsu)**	**R7110U-01MOD [20] (MPI/Hamamatsu)**
Photocathode	Multi-alkali	GaAsP
Max. recommended value of $V_{photocathode}$	-8.5 kV	-8 kV
APD diode bias voltage V_{APD}	~155 Volts	~338 Volts
Geometrical packing efficiency	~16 %	-
APD diameter	3 mm	-
Diameter of sensitive area	8 mm	18 mm
Pixel capacitance	120 pF	24 pF
Number of pixels	1	1
Total gain	~1.5×10^5	~5×10^4 at present
Rise-time [ns]	1.1	0.8
Fall-time [ns]	14.8	1.9
Pulse width [ns]	4.9	2.1
Electronics	External	External
Type of amplifier	MITEQ, 60dB, 300MHz BW	Fast amplifier
Timing resolution per single electron	150 ps	100 ps expect
Planned magnetic field operation	1.5 Tesla	-

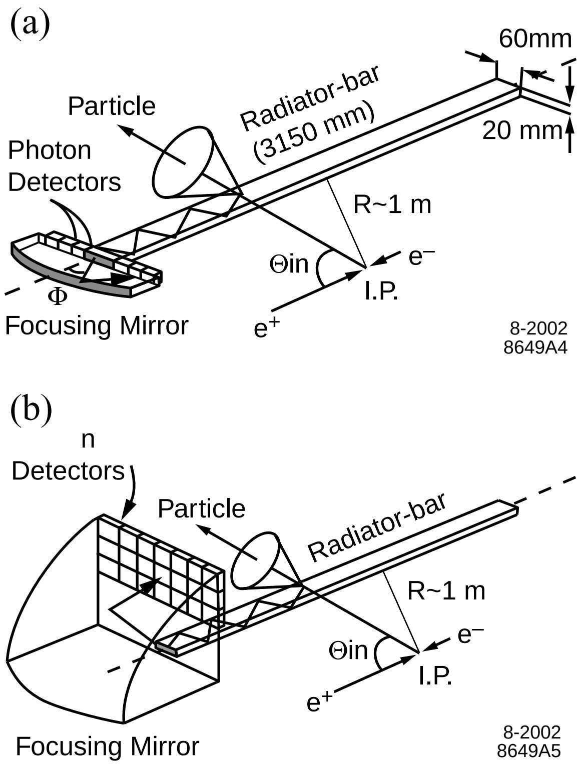

Figure 1. Examples of DIRC-like R&D efforts: (a) TOP counter, which in this example measures a Φ angle and time to ~100ps for each photon [6], and (b) a possible test with the modified version (no wedges) of the existing DIRC bar box with a new flat panel multi-anode H-8500 PMT, which would measure x, y and time to ~150 ps for each photon.

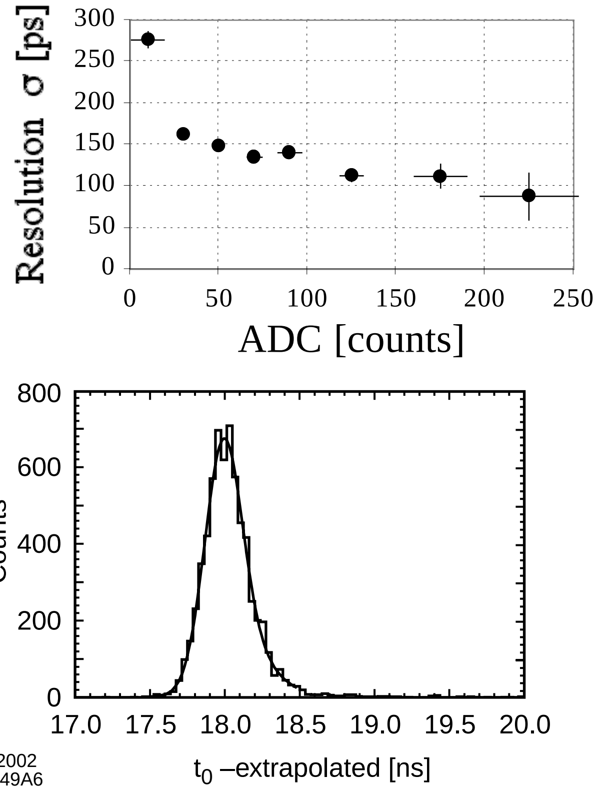

Figure 2. Author's own measurements of the timing resolution with the Hamamatsu Flat Panel Multi-anode H-8500 PMTusing the PiLas Light pulser for (a) ADC-sliced single-threshold TDC timing, and (b) double-threshold TDC timing with a passive splitter. The graph shows fitted parameters from a double-Gaussian fit of a form $G1 + G2 + a + bx + cx^2$ (σ_1 = 125ps, σ_2 = 193ps).

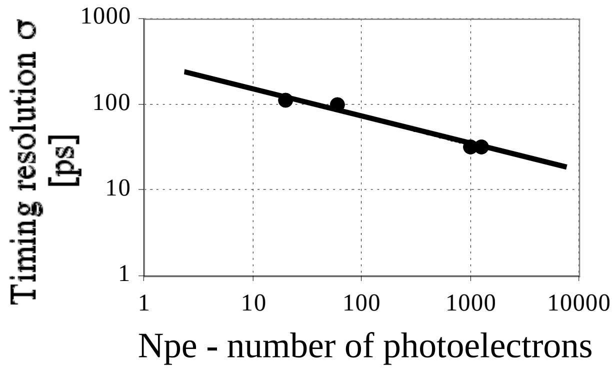

Figure 3. Earlier attempts to use HPD for timing purpose [15]. Data indicates that a ~100ps timing resolution was achieved for N_{pe} ~ 20 photoelectrons. If one can extrapolate using a power law function, one obtains 400-500ps for N_{pe} =1.

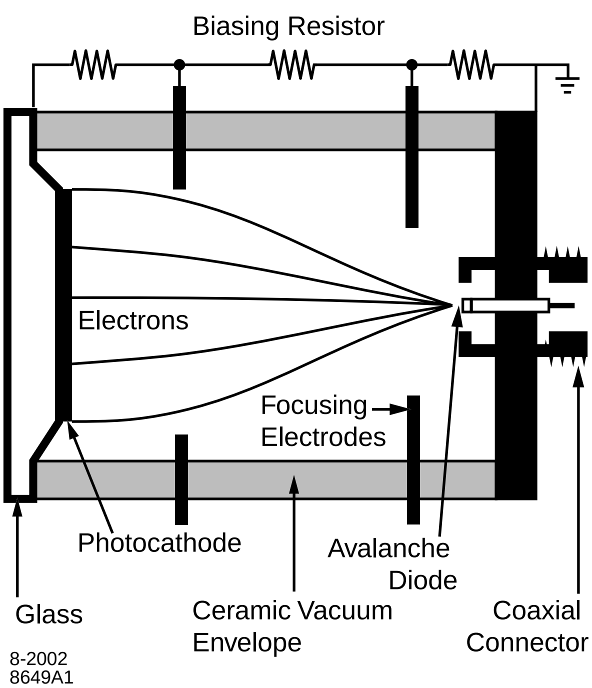

Figure 4. Hamamatsu tube HAPD R7110U-01MOD, developed together with E. Lorenz from MPI (Ref.19 and Table 3).

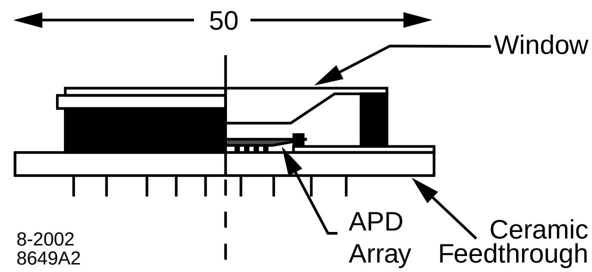

Figure 5. Advanced Photonics and Litton Electron Devices developed an 8 x 8 APD array placed into proximity focusing HPD [20].

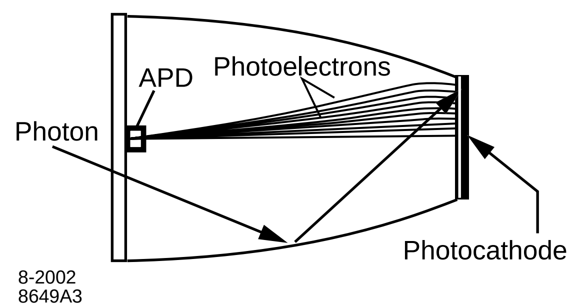

Figure 6. D. Ferenc has come up with an ingenious combination of the Winston cone and HPD shown in Fig. 5 [21].

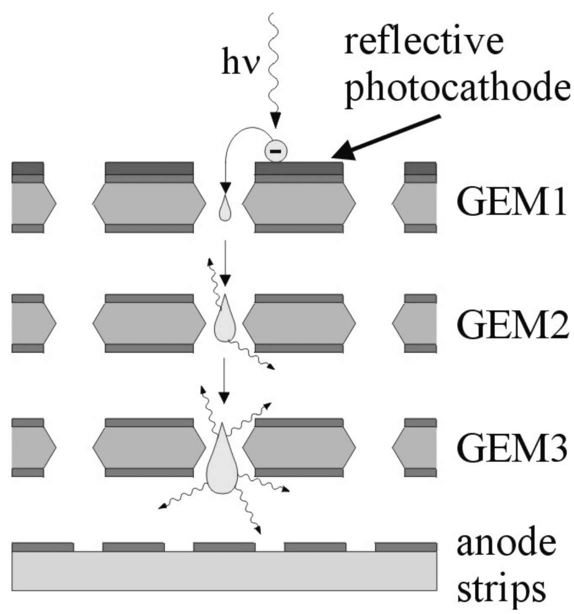

Figure 7. Hadron-blind detector intended for the Phenix experiment at RHIC [30].