Plasma Panel Sensors as Scintillation Detectors

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***Abstract*–A new type of highly-pixelated, photon counting radiation detector is described based on the integration of a photocathode into a plasma panel sensor (PPS). This device called a *plasma panel photosensor* (or PPPS) should be low cost as it can directly leverage off of the fabrication and materials technologies employed in plasma display panels (PDP's) and photomultiplier tubes (PMT's). When optically coupled to a scintillator, the device becomes a *PPPS-scintillation detector*. The PPS, PPPS and PPPS-scintillation detector all hold promise for high sensitivity with gains on the order of 10^{11}, high positional and pixel resolutions approaching 10 μm, and fast picosecond to nanosecond response times. Although the PPPS in some ways resembles a flat-PMT or a micropattern detector, it is not an analog device as it does not operate in the proportional region and in this sense resembles an avalanche photodiode. The PPS and PPPS, as plasma panel devices operating in the Geiger region, are digital detectors with the potential to expand beyond the capability of micropattern detector technology for a host of applications covering ionizing particles and photons, as well as non-ionizing photons. Key applications include medical imaging, homeland security and nuclear physics. Because of its thin form-factor (~ 1 mm) and highly-pixelated structure, the PPPS-scintillation detector should be capable of both good spectral and high directional/angular resolution.**

I. Introduction

A new kind of radiation sensor derived primarily from the technologies used in producing plasma display panels (i.e. PDP's) is described along with its projected capability and a few examples of depicted systems. These new radiation detectors called plasma panel sensors [1] or PPS, and plasma panel photosensors [2] or PPPS, are fundamentally low cost, large area devices, and should operate under the most challenging environmental conditions since they are inherently rugged and radiation resistant, and also insensitive to magnetic fields. They can also be configured in a wide variety of AC and DC structures and system arrangements such as Compton telescopes, laminated multilayer vertical stacks, etc. Although the PPS and PPPS share a number of similarities with micropattern gas detectors, they have the potential to expand well beyond the latter's capability for numerous applications over a wide intensity and energy range – i.e. from *low*-keV to *high*-MeV region and even into the GeV range. For example, micropattern gas detectors such as cascaded Gas Electron Multipliers or GEM's [3], which have been under development for many years in high-energy and nuclear physics, have many desirable properties as *proportional* gas detectors, but are limited to gains of ~ 10^6. The PPS and PPPS, which are digital in nature and therefore *not* analog devices, hold promise for much greater sensitivity, with gains on the order of 10^{11} and positional resolutions approaching 10 μm. They achieve this sensitivity because as plasma discharge panels, they operate at the *top-end* of the *Geiger* region (see Section II.B). It is emphasized that *unlike* GM-tubes, the gaseous layer in PPS-based devices does *not* function as the radiation interaction media, but only serves to provide electron multiplication/gain. For this reason, PPS/PPPS devices require only *minimal gas volume* (e.g. about a *picoliter* to *nanoliter* of gas per pixel) to perform their amplification function.

The plasma panel as a radiation detector was conceived in part to take advantage of the existing technology base and manufacturing infrastructure for PDP modules (selling *with* electronics for about $0.80 per square inch), which are being mass-produced for use in large area (i.e. 1 to 2 m^2), high definition, flat panel TV-sets. PPS devices, however, have shown little capability with respect to energy spectroscopy [1], [4]. To address this deficiency and other limitations, a *new* type of highly-pixelated, *light-sensitive* PPS detector was conceived – the PPPS [2], which is a PPS modified by the addition of an internal photocathode. When optically coupled to an appropriate scintillator, this new hybrid device which is called a *PPPS-scintillation detector*, should have enhanced potential (compared to a PPS) for high efficiency (from the stopping power and photon transmission range of the scintillation plate), good spectral energy sensitivity (by counting scintillation photons per event) and potentially excellent directional/angular resolution (from the highly pixelated nature of the PPS structure). This combination of attributes should allow the PPPS to have a capability somewhat similar to that of a flat-PMT (i.e. microchannel plate or MCP-PMT), or a silicon photomultiplier [5], or even an avalanche photodiode (APD), but with higher gain and with excellent positional resolution, and at far lower cost (it is estimated that PPPS detectors can be fabricated at a cost of a *few dollars* per square inch).

The feasibility of the basic PPS component has been demonstrated and the results described in late-2005 at NSS-MIC [1]. The PPPS, like the PPS, functions as a highly-integrated array of *parallel* pixel-sensor-elements or cells, each independently capable of detecting *single* "free-electrons" (i.e. *unbound* electrons such as photoelectrons, Compton electrons, β-particles, etc.) generated by incident radiation. Such free-electrons upon entering the panel gaseous region can undergo rapid electron multiplication resulting in an avalanche that can be confined to the local pixel cell-space. For all PDP commercial devices, this process is self-limiting and self-contained. The discharge current of an individual triggered pixel is unimportant, only the fact that a pixel is either *"on"* or *"off"*. All PPS and PPPS devices are therefore *intrinsically digital* (i.e. no A/D converters needed), and with a gain of ~ 10^{11} (see Section II.B) do not require amplification electronics. For PPPS-scintillation detectors, the enhanced energy resolution comes about from *counting* individual

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scintillation photons. The total number of such photons within a tight grouping (i.e. both spatially and temporally) being proportional to the incident radiation energy. With rise-times on the order of picoseconds to nanoseconds (see Section II.C), individual pixels should be able to light (i.e. turn on) *at least* 10^6 times per second, if not faster, and with a cell density of *at least* 10^4 pixels/cm^2, this yields a PPPS signal count rate *limit* of about 10^{10} cps/cm^2. PPPS-scintillation detectors should therefore be capable of responding *linearly* to almost any radiation source (assuming fast electronics to *individually* track separate, but temporally close, incident radiation "hits").

II. Device Description

A. Capability of PPS-Based Detection Devices & Systems

The PPS and PPPS, as well as other associated configurations such as the PPPS-scintillation detector, are related to micropattern gas detectors, but have the potential to expand beyond the capability of this technology for a host of applications covering both ionizing photons and particles (i.e. charged and neutral), as well as non-ionizing "optical" photons (e.g. photons generally falling within the UV/visible – near IR range). Yet the development of micropattern gas detectors (such as cascaded GEM's) has in large part been held back due to avalanche-induced secondary effects associated with ion, electron, photon and metastable species feedback, and photocathode degradation caused by ion impact [3]. In contrast, the PPS and PPPS hold promise for much greater sensitivity gains and pixel resolution, while inhibiting avalanche-induced secondary effects (such as those described above) by, in part, being able to incorporate internal plasma panel barrier structures such as those used in PDP-TV-sets. Additionally, PPS and PPPS detectors are digital devices as compared to micropattern detectors which are analog. This combination of higher gain and direct digital output for plasma panel based devices can be exploited to achieve high directional, imaging and spectral capability in a low cost, large area, radiation detector. Also being plasma panel devices, they are extremely rugged and radiation damage resistant, as PDP's have been used by the military for more than 30 years, from underwater applications by Navy Seals to the vacuum of near-outer space [6]. Most importantly, plasma panel technology, which has benefited by 40 years of *commercial* development activity, provides a variety of solutions to many of the problems plaguing micropattern gas detectors and gaseous photomultipliers.

The technical basis for using plasma panels as radiation detectors lies in exploiting the device physics, yet also *requires* modifying the structure from that of a PDP. Previous research proved the utility of plasma panel based radiation sensors. For example, using modified gas mixtures in *existing* plasma *display* panels (i.e. PDP's ***not*** optimized for radiation detection), gamma radiation from ^{57}Co and ^{137}Cs sources was detected [4]. Yet these devices, while highly promising, faced a number of challenges. First, it was recognized that to fully exploit the technology, PPS-based devices must be built using different design parameters than PDP's. These design changes address challenges posed by charge storage and discharge spreading [1]. Also individual PPS devices have only a fair probability of detecting an incident photon passing through a given cell, as the cell attenuation layer must be thin enough to allow efficient electron transport to the gas. Additionally, since each pixel/cell operates in the Geiger region, individual discharges provide no energy information. By implementing a different technique for radiation detection – that is by using plasma panels incorporating a photocathode layer for detecting optical photons either directly or indirectly (e.g. via photon emitting luminescent materials such as scintillators, biologically tagged fluorophores, etc.) – these deficiencies can be addressed. The resulting PPPS device is similar in operation to a *photosensitive* Geiger-Mueller counter, a device used in the early days of scintillation detection [7]. Given the high counting rate capability and dense pixel structure of the plasma panel based photon detector, the number of discharging pixels should be proportional to the number of incident photons. In the case of a PPPS-scintillation detector, this means that the number of adjacent and near-adjacent pixels that discharge during a scintillation event should be proportional to the number of photons generated in the scintillator and hence to the energy deposited by the photon or particle, while the pattern of "adjacent" pixels can determine the position of the interaction in the scintillator.

In order to maximize sensitivity, plasma panel devices designed for radiation detection need to *minimize* all internal sources of free-electrons, and thereby be configured such that any and all electrons required to initiate the gas discharge are generated from an external radiation source – e.g. gamma-rays or neutrons. Thus in PPS/PPPS devices, the gas mixture, gas pressure, dielectric surfaces, etc., all need to be optimized to inhibit *internal sources* of free-electrons, while maximizing sensitivity to radiation-induced electrons entering the gas [1]. Some common sources of internal free-electrons to be minimized via gas-phase quenching and VUV absorbing molecules, include gas phase metastables as well as the lifetimes of gaseous excited state species and propagation of VUV emitted photons.

An important performance goal for some critical applications (e.g. medical tomography and homeland security) is that a radiation detection system be capable of achieving high image angular resolution. To test this feasibility, a numerical analysis was initiated in 2006 by Oak Ridge National Laboratory (ORNL) for the PPPS-scintillation detector integrated into a Compton telescope system (see Section II.F). The resulting simulation suggested that an angular precision / resolution of better than 2° is feasible for a reasonably configured PPPS system using NaI(Tl) and operating at room-temperature. More specifically, the Compton telescope arrangement modeled by ORNL was shown to have the potential to provide substantially better angular resolution than any system based on conventional PMT's, and that the efficiency can even be substantially better at much lower cost than arrays of semiconductor detectors

with similar angular resolution [8]. It was also recognized by ORNL that similarly configured PPPS systems could be valuable for detection of neutrons encountered in experiments with heavy ion beams from a few tens of MeV per nucleon up into the GeV range (note that both the time-of-flight and scattering angle of neutrons would need to be measured with enough precision to reconstruct the reaction in detail). Using such PPPS devices as inexpensive position and time detectors could permit building such arrays much more cheaply and estimating the neutron emission angles more precisely. Also, with a thickness of about 1.0 mm or possibly less, the proximity of the PPPS to the interaction sites could provide better timing resolution since the pixels are so close, thereby reducing dispersion in the light collection. The above characteristics should therefore result in the highly-pixelated PPPS-scintillation detector having good radiation source identification and radiological imaging capability via Compton scatter gamma-ray imaging, although such devices could also be incorporated into coded-aperture masked position-sensitive detectors for gamma-ray and neutron imaging [9], and/or double-scatter kinematics for neutron source imaging [10]. Finally for certain applications, radiation detectors often need to be placed in regions of high magnetic fields; fortunately both the PPS and PPPS should be insensitive to these fields. The above breadth of radiation detection possibilities, coupled with the wide spectral sensitivity, the potential to enhance the response to neutrons relative to gamma-rays via judicious selection of low-Z materials (e.g. low density glasses or metals coated with, or containing, Li or B), and the possibly of achieving improved performance in certain applications currently requiring GEM and/or position-sensitive ^{3}He wire-chamber devices [9], [11] should give broad transformational capability to PPS and PPPS devices.

By way of summary, PPPS devices have three especially important potential attributes: fine positional resolution, high electron detection efficiency, and low cost. A number of structures are possible for the PPPS, many of which require an internal photocathode to make the device photosensitive and thus able to function as a scintillation light-sensor with PMT-like properties. Various electrode configurations are possible, including a number of *surface-discharge* type structures similar to those found on PDP's sold today (i.e. with the X- and Y-electrodes on the same substrate), and the *columnar* structure used on most PDP's sold through the early-1990's (see Fig. 1). With regard to the location of the photocathode, it can be either on the backside of the PPPS front substrate (i.e. transmissive mode), or on the top inside surface of the PPPS back substrate (i.e. reflective mode). To optimize performance and minimize plasma generated interference including ion-induced photocathode erosion, various structural/material options are available [1], [2] and can be employed including special gas mixtures, protective coatings, and physical barriers such as those used in commercial PDP's to isolate each pixel or cell from interfering photons, electrons, ions and metastables. In fact, such barriers could even be coated with a reflective-type photocathode layer. As a practical strategy, these physical solutions can be combined with electronic solutions (see below) to further enhance the likelihood of achieving a complete solution.

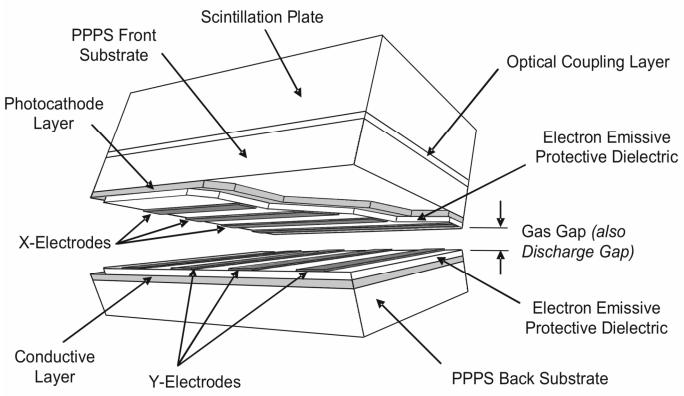

Fig. 1. Columnar-discharge PPPS-scintillation detector without barrier.

In terms of basic efficiency, the intrinsic efficiency of the PPPS-scintillation detector should be significantly greater than that of the PPS, because the radiation "absorption" function is separate and independent of the "electron conversion" function, and so each parameter can be individually optimized for the specific radiation of interest. Also the conversion layer thickness is no longer limited to the PPS free-electron range, so a far greater fraction of incident radiation can be captured by a PPPS-scintillation detector, and with the added number of information carriers the energy spectral resolution will improve accordingly. Finally, by vertically stacking PPPS-scintillation detectors (see Section II.F), a high efficiency, low cost, Compton imager/telescope could be developed for numerous applications covering medical imaging, homeland security, nuclear physics, etc. With regard to nuclear physics, it is noted that for accelerators, intensity profiles and emittance analyses are among the most critical tools used for optimizing beam transport. Thus profile measurement systems could benefit very significantly from improvements in performance and cost that might be provided by PPS and/or PPPS devices such as the PPPS-scintillation detector.

B. Device Energy Consumption & Internal Gain

In terms of PPS and PPPS energy consumption, this value should be low because the number of discharging pixels at any one time should normally be much less than for a PDP-TV, which is generally designed to handle about a 40% duty cycle (i.e. the panel and electronics can handle 40% of the pixels being "on" at the same time at full brightness). However under most circumstances the PPS and/or PPPS would not be expected to be in a radiation environment in which 40% of the pixels turn on *simultaneously*. And in any case, PDP-TV's generally consume less energy (and less *average* power) than equivalent size CRT's, but about the same energy as backlit, active-matrix LCD's (which can be run off of portable power supplies) even though the peak *pixel* discharge power can be rather high. However, *as a **reactive** light-emitting device that*

only consumes significant power for the instant that a pixel turns on, the PPS and PPPS would normally be expected to consume very little power. Additionally, plasma panels have a well understood and long development history relating to energy consumption as a function of scaling in both size (i.e. from ~ 1 to 250 cm in diagonal) and resolution (i.e. from ~ 10 dpi to more than 200 dpi), and have shown that to a first approximation, plasma panel energy consumption *per unit panel area* is essentially independent of panel size and pixel resolution. In other words, more pixels in a given area simply means that each pixel is smaller and proportionally consumes less energy per discharge – e.g. smaller pixels have less surface area and thus less capacitance (or a smaller RC-time constant), and therefore each discharge would have a shorter duration (see Section II.C), proportionally reducing both the energy and average power consumption, although peak pixel discharge power could remain about the same.

With regard to the repeated claim of PPS and/or PPPS devices having a gain on the order of 10^{11}, this value is based on *extrapolation* of PDP experimental data and so does *not* represent a direct measurement; it is therefore only an estimate. However by way of supporting data, Breskin has fabricated a variety of multi-GEM devices [3], all operating in the *proportional region*, and he has measured device gains up to about 10^6 (this limit is also true for silicon photomultipliers as well as vacuum PMT's, and higher than for APD's [16]). It is noted that from a design viewpoint, GEM's are *not* supposed to produce visible plasma discharges. By contrast, plasma devices by design operate at the *top-end of the Geiger region* producing *visible discharges* (e.g. for TV-sets), and should therefore have a gain that is *at least* ***several orders*** *of magnitude higher* than GEM devices. Yet whether the precise PPS/PPPS gain is 10^{10} or 10^{11}, or even 10^{12} is not particularly important, as the internal gain is certainly large enough to avoid having to use external signal amplification electronics, especially considering that the plasma panel radiation detector is a digital counter and therefore required only to count, rather than measure, discharge pulses.

C. Device Resolution, Response Time & Lifetime

For most applications the PPS and/or PPPS will generally consist of a highly integrated array of about 10^4 to 10^6 micro-detection cells per cm^2, each of which has the capability of acting as an independent, position and intensity sensitive, radiation sensor. However, attaining a pixel pitch of between 10 to 100 μm (i.e. 10^6 to 10^4 pixels/cm^2) in an affordable PPS and/or PPPS product depends largely on being able to fabricate such devices utilizing low cost manufacturing technology. Certainly achieving high pixel resolution is almost always a desirable feature, but perhaps even more so for this device because it is enabling *to prevent signal pileup* and to achieving sufficiently high angular and energy (i.e. spectral) resolution. From a materials, fabrication, and theoretical point of view, a device pixel resolution of ~ 10 μm is eminently feasible, much more so than for a PDP-TV product. This is because the preferred device configurations generally resemble *DC*-PDPs (see Section II.E), as opposed to the *AC*-PDP structures used in PDP-TV products. More specifically, the electrode resolution in a DC-PDP can be much higher and much better controlled than in an AC-PDP, because DC-PDP electrodes are not encapsulated under a highly reactive and chemically corrosive thick-film dielectric which tends to undercut and undermine the AC-PDP electrode-material linewidth during fabrication. As an important collateral benefit, minimizing electrode-width to enhance the pixel resolution of PPS and/or PPPS devices could also raise the intrinsic firing voltage, thereby increasing the local-pixel, electric-field strength, and hence the device sensitivity. However, even with the above advantages regarding easier fabrication of ***DC*** plasma panel electrodes, it is noted that in 1994, Photonics Systems initiated production of 21-inch diagonal ***AC***-PDP's (i.e. with internal pixel barriers and RGB phosphor patterns) having a cell resolution of 108 μm [12]. The pixel structure of these AC-PDP's was significantly complex, much more so than that for the described PPS and/or PPPS devices, as these *display* panels (i.e. AC-PDP's) required phosphor patterning and alignment via screen-printing and were fabricated on a high coefficient of thermal expansion (i.e., 90 x 10^{-7}/ °C) float glass substrate [13]. By comparison, PPS and PPPS devices will not require difficult-to-control, thick film, screen-printing and phosphor pattern alignment within a pixel constructed on a rather unstable glass substrate. For most PPS and/or PPPS applications, a pixel pitch of 50-100 μm should be more than sufficient [8], which is only slightly higher in resolution than AC plasma panels *produced more than a decade ago*. In addition, PPS and/or PPPS substrates, if glass, will likely have a much lower coefficient of thermal expansion of ~ 30 x 10^{-7}/ °C, as compared to the 90 x 10^{-7}/ °C for the above 21-inch AC-PDP's. Finally more than a decade has passed since 1994 and photolithographic technology has significantly progressed. For the above reasons, the ability to manufacture PPS and/or PPPS devices with a pixel pitch approaching 10 μm should be achievable. In terms of electrode fabrication, it is noted that Samsung has developed a 2-inch active-matrix LCD mobile phone display product on a glass substrate with a 21 μm pixel pitch [14]. For the described PPS and PPPS devices, the electrode fabrication process could utilize similar active-matrix LCD technology.

In terms of the referenced PPS/PPPS picosecond to nanosecond rise-times, this estimate reflects the response characteristics of the plasma panel sensor specifically, and not the decay constant of the scintillation plate. It has been noted that each plasma panel pixel can in some ways be thought of as a miniature Geiger-Mueller (GM) counter, and Geiger tubes have very long recovery times, so why would plasma panel based detectors have far faster response times than GM-tubes? The answer primarily has to do with geometry, which directly relates to field gradients and space-charge. In both the GM-tube and plasma panel detector, the operating voltage is similar – approximately 600 volts for the plasma panel, and about 500-1500 volts for GM-tubes. However, the anode to cathode gap in a GM-tube is typically about 10-20 mm,

whereas in a plasma panel it is on the order of 0.15 mm, a reduction of ***two orders**-of-magnitude*. All other things being equal, this would translate into a field gradient that is 100 times greater for the plasma panel. But the result is much bigger than this, because although the cathode *"wire"* in a plasma panel is a narrow electrode, as is the anode, the cathode *"area"* actually is restricted to the common *overlap* between the two orthogonal electrodes. For a "typical" medium resolution plasma panel radiation detector, the effective cathode dimensions might be 100 μm x 100 μm, or 10^{-2} mm^2. This is in comparison to a GM-counter in which the cathode comprises the entire inner surface of the cylindrical tube, which could easily be 10^4 mm^2. The difference between the cathode area for a *medium size* GM-tube, and a *medium resolution* plasma panel detector, could thus be ***six orders**-of-magnitude* (i.e. 10^6). It follows that the "slow-moving" ions in a plasma panel can be "cleared-out" very quickly, because they need only travel ***tens of microns*** to the cathode and are being pulled by a very strong electric field. Contrast this to the GM-tube, where the cathode field strength is ***many orders**-of-magnitude* smaller than for the plasma panel, and where the ions have a much longer distance to travel to reach the cathode – perhaps *10 mm*. The bottom line is that for all gas discharge devices (i.e. GM-tubes or plasma panels), the rise-time primarily reflects the electron efficiency in going from the cathode to the anode, whereas the fall-time primarily reflects clearing-out the space-charge volume of slow moving ions from the region located approximately midway between the anode and cathode. Because of the very weak field in the vicinity of the GM-cathode, the ion movement towards the cathode almost represents a *random-walk* in comparison to the movement of ions near the plasma panel cathode. In summary, the geometric differences in the discharge volume dimensions and field gradients for the plasma panel versus the GM-tube ultimately result in huge, ***orders***-of-magnitude differences in pixel response time. For example, the GM-tube which functionally acts as a *single* pixel, has a typical discharge volume of 10^{-1} to 10^{-2} liters, whereas the PPS and/or PPPS pixel discharge volume is in the range of 10^{-9} to 10^{-12} liters (i.e. nanoliters to picoliters). Of course, the gas discharge physics are more complicated than just comparing the gap dimensions or volume between anode and cathode, or the nominal field gradients. In practice there are many complicating factors, including all kinds of charge recombination events and field-shielding effects, etc. But the above geometric comparisons are very useful and provide insight, at least semi-quantitatively, as to why there should be such tremendous differences in the response times for these two kinds of gas discharge detection devices.

In support of the above arguments relating to the fast response of plasma panel radiation detectors, it is noted that AC-PDP's have been operated at refresh rates of 900 kHz, corresponding to a pixel "on/off" time of 1.1 μs (data obtained using a 2% Xe / 98% Ne gas mixture and a pixel pitch of 325 μm [15]). In order to continuously switch or recycle at 1.1 μs, the pixel rise-time should be at least an order of magnitude faster – i.e. approximately 100 ns. However as the percent Xe increases, so does the gas discharge response speed. Additionally, as the pixel pitch gets smaller, the discharge gap decreases, raising the field gradient and further reducing the rise-time. For many PPS and PPPS devices, gas mixtures containing ~ 99% Xe would probably be used (i.e. similar to that for the plasma panels tested under the DTRA program), along with a pixel pitch of 50-100 μm. Nominally, the gas discharge rise-time would be expected to shorten accordingly with increased Xe content and reduced pixel pitch, in other words by *at least* two orders-of-magnitude to about ***1 ns*** or even less.

A more quantitative estimate of response time can be obtained from the pixel RC-time constant. For a "*low resolution*" PPS or PPPS pixel (e.g. 1 mm^2 area), the capacitance would be expected to be in the range of 0.1 to 1 pF (depending upon specific discharge-cell geometry and materials). However, the 1 pF value should be considered an *upper limit* as most likely a "slightly conductive" (i.e. leaky) dielectric would be used to minimize stored-charge. In addition, the cell area for a *medium to high resolution* pixel pitch device (i.e. 10-100 μm) would be 10^{-2} to 10^{-4} mm^2, or ***two to four** orders-of-magnitude smaller*. Thus the *predicted pixel capacitance should be on the order of ~ **0.01 to 10 fF***. By using a current-limiting, in-line resistor of about 100 kΩ, with a voltage of 600V, the discharge current per pixel should be limited to about 6 mA, which is manageable (unless a relatively big area of the PPS or PPPS were to light up, in which case a larger impedance would be used). The shortest time (τ) required to discharge the capacitance would be just the RC-time constant, or about ***1 picosecond*** to ***1 nanosecond*** (e.g. $\tau = RC = 100\ k\Omega \times 0.01\ fF = 1\ ps$), which can be ***three orders-of-magnitude faster*** than the *1 ns* rise-time estimated above. In conclusion, although none of the above arguments are proof-certain, the three independent estimates provided, convincingly suggest device pixel rise-times on the order of ***picoseconds to nanoseconds***.

An issue that should not be a problem, but which might be construed as such, is that of gas purity and possible gas contamination. Plasma panels are hermetically-sealed, gas-filled devices, and once installed have remarkably *long lifetimes* (e.g. better than CRT's). For example, AC-PDP's sold in the 1970's, and operating 24/7, are still functioning today, 30 years later. One reason for this extraordinary lifetime is that ***plasma panels are not vacuum devices***, and as such are fairly impervious to normal out-gassing and so do *not* require getters. In fact, plasma panels are notoriously tolerant of small amounts of gas contaminants (e.g. gas evacuation is generally done within the range of 10^{-3} to 10^{-6} torr, depending upon processing conditions). In addition, PDP discharge gases are monoatomic, so *there should be no significant aging due to radiation-induced gas breakdown*. Finally, a large, constant pressure, reservoir of panel gas can be conveniently stored in the panel tip-off tube, which would significantly dilute whatever few contaminants might be present. In summary, for

the above reasons, PPS and PPPS devices should enjoy long lifetimes and be essentially maintenance free.

As mentioned previously, the most serious *anticipated* problem is that of excited state species (e.g. photons, ions, electrons and metastables) generated in the gas discharge causing secondary discharges of time-delayed new avalanches. These secondary discharges could occur at either the original gas discharge pixel site or at neighboring pixel sites. The classical method for preventing this in GM-tubes is to employ quenching components in the gas mixture. For the PPS and PPPS, a number of *physical* solutions exist to address this problem. These solutions include: "enclosing" each pixel within a *barrier wall structure* similar to those used in *all* commercial PDP's; adding a *quenching agent*(s) to the gas mixture to "absorb" high energy photons emitted by the gas discharge as well as acting as an energy sink for gas-phase metastables, electrons and ions; and depositing a *protective coating* over the photocathode (see Fig. 1). It should be noted that by adapting one or more of these solutions, the above problem should at the very least be effectively reduced to a manageable level if not altogether eliminated. In fact, by simply adding a diatomic quenching agent (which also served as a Penning gas dopant) to the DC-PDP's tested under the prior DTRA program, the problem of secondary avalanches was essentially eliminated in an "open-structure" device with the discharge apparently confined to the pixel closest to the initial radiation induced electron emission site [1], [4].

In addition to the above three *physical* methods for preventing secondary discharges, two different electrical methods can be employed to supplement this strategy. One method would be to take advantage of the time-delayed nature associated with the onset of secondary discharges. This could be accomplished by design of appropriate circuitry to cut off power to the effected pixel(s) as soon as the discharge event(s) begins. The required response time for the reactive circuitry must be fast enough to sense the leading-edge of the initial discharge pulse; fortunately this technology is available and the general approach is one that has been successfully used in other applications, such as the use of leading-edge discriminators with silicon photomultipliers [16]. Another approach would be to use buffer circuitry to prevent feedback of an avalanche across one set of electrodes from coupling into another. The second method is to fabricate (using LCD or PDP technology) *quenching resistors within each pixel* that could serve the dual function of both limiting the discharge and decoupling one pixel from another. This method has been used for silicon photomultipliers [5], and also by Japanese companies in the early-1990's when DC-PDP's were considered to be possibly the leading technology for PDP-TV-sets.

D. Device Operation

The PPPS is designed to function as a direct, high-gain, position and intensity sensitive, digital counter of optical photons. Generally speaking, a single solitary photoelectron (i.e. free-electron) upon entering the high-field pixel space of a suitably designed plasma panel cell, should experience almost instantaneous electron amplification with a gain of about eleven orders-of-magnitude (i.e. 10^{11}), without *external* amplification and without loss of spatial resolution. The resulting electron avalanche, which can be both confined and self-contained within the region that defines each pixel's cell space, should occur on the picosecond to nanosecond time-scale. It is noted that the PPPS does *not require* the use of scintillation plates or crystals, although a number of device configurations can employ such materials (e.g. PPPS-scintillation detector). Similarly, the PPS and/or PPPS device does not require the use of high-pressure, expensive, high-purity isotopic gases such as ^{3}He or $^{10}BF_3$, although such gases might be useful for certain applications.

All PPS and PPPS devices operate as highly-pixelated radiation detectors by turning "on" their pixels (which are normally "off") in direct proportion to incoming radiation, and so at their most basic level functionally behave as *digital* radiation *counters*. On both an operational and functional basis, all such radiation induced pixel discharges begin (i.e. are turned "on") by initially maintaining the panel at a voltage just below its spontaneous discharge setting, such that any free-electron upon entering the gas can "immediately" set off a discharge (i.e. avalanche) at the nearest pixel site. In the case of a PPS, the initiating free-electron(s) is generated by incident ionizing radiation directly interacting with the device conversion layer (or within the gas itself). In the case of a PPPS, the free-electron can be generated by incident radiation first interacting with a top scintillator plate (or crystal, or other such top luminescent material layer or coating) which emits optical photons that can interact with the photocathode layer *within* the PPPS, which in-turn emits photoelectrons into the gas. The actual pixel sensing mechanism is straight-forward and can be perhaps most directly accomplished by utilization of standard digital (i.e. photon-counting) acquisition electronics to store time-tagged pixel discharge information and correlated X-Y events. Recording of X-Y positions and histogramming counting rates versus positional locations can be implemented, for example, via field programmable gate array (FPGA) logic devices. Discriminators will likely be needed to condition the signals for the FPGA processors; however, since the PPPS signal integration is inherently digital, with a huge electron gain on the order of 10^{11}, *no A/D converters* or amplification electronics are required. Also the duty cycle should be a few orders-of-magnitude *less* than for a PDP video monitor, thus the power requirements should be modest (see Section II.B). Local information processing, however, for all electronic devices is limited at some point by the number of I/O lines. Thus a relatively small PPPS (or PPS), or an equivalently-sized sectored area within a larger PPPS, can easily have more than a million distinct cells, which requires 2000 or more processor input lines. This number is not so great, however, when compared to a typical, *low-cost* (i.e. commercial), high definition PDP-TV which has about six million cells and about 8000 processor input lines.

E. AC versus DC Structures

The PPPS (as well as the PPS) can be structured to function as either an AC or DC device (e.g. AC-PPPS or DC-PPPS). In comparing AC to DC configurations, the latter (i.e. DC) has a basic structure and mode of electronic operation much more akin to that of a GM-tube than the former. In particular, like the GM-tube, the DC-PPPS in its simplest embodiment of a "columnar-discharge" configuration (see Fig. 1) is structured with its "bare" cathode facing a "bare" anode (i.e. no dielectric layer in-between), separated by a gap and filled with a discharge gas. In this structure, the DC electrodes, like those of the GM-tube, are normally kept at a constant "ready-to-discharge" voltage via direct connection to a steady, well-regulated DC power supply circuit. Such is not the case with AC structures which constantly cycle back and forth between two effectively opposite voltage plateaus and are therefore in a receptive (i.e. ready-to-discharge) state for only some portion of each cycle. For the transition periods during which the voltage is changing, the device will be unresponsive (i.e. experience dead-time) and radiation generated free-electrons in the gas will essentially be "lost" (i.e. not counted). In addition to this problem, "conventionally structured" AC-PPPS devices (i.e. having a dielectric coating over the X- and Y-electrodes) require significantly more complex drive-waveforms incorporating dielectric wall-charge erase functions (for neutralizing accumulated charge stored from previously lit "on" pixels), which can never be totally 100% effective. However, if the stored wall-charge from the top dielectric layer can effectively be erased, then the dielectric-coated AC-PPPS structure might offer some benefits. For example, a top-layer MgO refractory coating on an AC-PPPS device could provide perhaps a more stable and possibly more efficient electron emissive surface than a metallic DC-PPPS electrode. Also the above AC-PPPS emissive thin-film overcoat might be improved upon in terms of its direct interaction with X-rays or gamma-rays (i.e. absorption and/or inelastic scattering), by replacing the "standard", low-Z, MgO coating with a higher-Z, electron emissive oxide such as La_2O_3, Eu_2O_3, etc. However all such candidate secondary-electron emitter materials must, like MgO, be chemically and thermally stable, sputter-resistant, and thermally activated at process-compatible temperatures. As an alternative to the above described, so-called conventional AC-PPPS structure, a *"bare-electrode"* AC-PPPS could also be developed without a charge-storing dielectric over the X- and Y-electrodes; such a structure could look identical to Fig. 1. Yet regardless of whether or not a top dielectric layer is employed over the electrodes, all AC structures will suffer the previously mentioned efficiency disadvantage associated with the "lost" AC voltage-changing transition time (i.e. dead-time).

Fig. 1 is a perspective view of a columnar-discharge PPPS-scintillation detector without barriers, and under "normal" circumstances would operate in the DC mode, but could also be made to operate non-conventionally (as described immediately above) in the AC mode. The detector in Fig. 1 consists of a PPPS device optically coupled through a coupling media to a scintillation plate. The PPPS device includes a first (front) substrate, and a second (back) substrate, separated by a gas-filled gap. However, for some materials the scintillation plate could also serve the dual function as front substrate, in which case the optical coupling layer would be eliminated. The shown detector includes both column ("X") electrodes, and row ("Y") electrodes. The PPPS detector further includes a photocathode layer, a back substrate conductive layer, and an electron emissive protective dielectric layer for the front and back plates respectively that electrically isolates the X- and Y-electrodes. It is noted that both the photocathode and conductive layer could also be used to bleed off stored charge that tends to accumulate on the two respective dielectric layers. With regard to the materials to be employed on the back plate in Fig. 1, the configuration and materials can mirror those chosen for the front plate as appropriate. Some variations of the PPPS as described above might utilize a conductive or partially conductive back substrate which would eliminate the back conductive layer.

F. Vertically Stacked Configurations

To enhance the positional or angular resolution of a PPPS-scintillation detector, the uncertainty of the reaction site location (for a particular radiation absorbing or scattering event) in a *"thick"* scintillation plate (or crystal) can be reduced by vertically-stacking an "equivalent" number of *"thinner"* scintillation plates, each optically coupled to a PPPS (see Fig. 2). The thinner the scintillation plate, the greater the number of vertically-stacked PPPS-scintillation detectors required to achieve a given level of radiation interaction (e.g. absorption or scattering). However, the thinner the scintillation plate, the smaller the uncertainty with respect to reaction site location, hence the better the overall positional and/or angular resolution of the integrated PPPS-scintillation detection system. In other words, achieving improved positional and/or angular resolution in this type of vertical-stacked detection system requires thin, flat, PPPS devices. The availability of such a thin, low cost, radiation detector thus provides the system designer with a new degree of freedom, allowing the optimization balance to shift towards using *thinner* scintillation plates (i.e. less absorption), with each plate having higher positional resolution, and making up for the reduced radiation absorption per plate, by vertically-stacking (or even laminating) more PPPS-scintillation detector plates on top of each other. Fig. 2 is a conceptual, perspective view of the above described vertically-stacked PPPS-scintillation detector apparatus. It is noted that the practicality of the solution provided by the above system design is dependent upon the required large area, flat PPPS devices being affordable, which plays directly into the low cost advantage of plasma panel based radiation detectors. Additionally, the vertically-stacked conceptual design applies to all types of PPPS structures, including: photon and particle PPPS detection devices, AC and DC structures, columnar-discharge and surface-discharge electrode configurations, etc. Finally, the extra degree of freedom associated with vertical-stacking also allows for a number of innovative *hybrid*

structures, such as different spectral response optimized devices on top of each other, or integrating gamma-ray detectors with neutron detectors, etc.

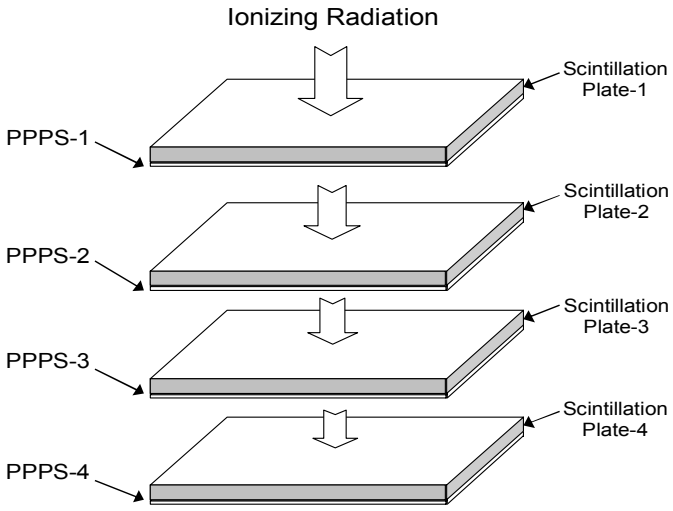

Fig. 2. Vertically-stacked PPPS-scintillation detector composed of four (4) "thin" scintillation plates as opposed to one (1) "thick" scintillation plate.

A variety of vertically-stacked PPPS-scintillation detector designs are possible. For some configurations an important benefit is the potential to realize significantly enhanced system efficiency. To improve system efficiency as well as angular resolution for radioactive source directional determination, and/or to improve energy spectroscopic resolution for source isotope identification, a different embodiment of the vertically-stacked PPPS-scintillation detector configuration can be employed, such as the Compton telescope arrangement [8], [17] shown in Fig. 3.

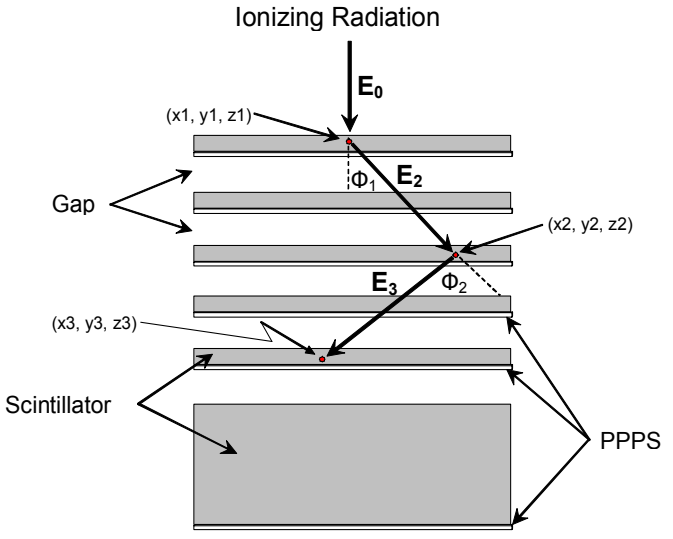

Fig. 3. Vertically-stacked Compton telescope PPPS-scintillation detector utilizing 3-Compton technique.

One advantage of the Compton telescope configuration shown above is the ability to improve system efficiency and angular resolution by the elimination of collimation optics, although other system configurations such as coded-apertures [18] could also accomplish this with a different set of trade-offs using the PPPS-scintillation detector. Several different Compton telescope arrangements utilizing vertically-stacked PPPS-scintillation detectors can be implemented, however the one which Oak Ridge National Laboratory has modeled (see Section II.A, and Fig. 3) is known as the 3-Compton technique [8], [19].

G. "Positive" Gas Pressure

For all gas discharge type devices, a simple relationship known as the Paschen curve gives the firing or breakdown voltage as a function of the product of gas pressure and discharge gap. Based on this classical relationship, the PPPS internal gas pressure should be increased as the device pixel pitch decreases. For very high pixel resolutions, it could thus be advantageous to increase the internal panel gas pressure above one atmosphere. However, from a mechanical design viewpoint, maintaining a uniform gas gap while holding a positive internal gas pressure in a plasma panel having a total thickness of only about 1 mm, could be considered a significant engineering challenge. Fortunately, one can take advantage of the fact that for PPPS-scintillation detectors, many candidate scintillation plate/crystal materials are hydroscopic and therefore require some sort of encapsulation package or mechanical housing to maintain an inert or dry atmosphere. Since an external housing might be required anyway to maintain an inert environment, it should add very little additional cost to the apparatus if the gas atmosphere within the mechanical housing was adjusted such that it effectively matches the PPPS positive gas pressure, thereby eliminating any significant pressure differential acting upon the PPPS structure. In summary, by utilizing an integrated system-level housing design, the PPPS should be able to maintain a uniform gas gap at positive pressure, regardless of how thin the device might be.

H. PPPS as a Large-Area Avalanche Photodetector

With its photocathode sensitivity suitably matched to a given photon spectral region of interest, a PPPS can function as a large area, direct digital, detector of optical photons, and given its huge gain and fast response, thus operate as an avalanche photodetector. Such a device could be fabricated by simply eliminating both the scintillation plate and the optical coupling layer (to the PPPS front substrate) for the PPPS-scintillation detector shown in Fig. 1. Such detectors could be used for many applications that currently require photomultipliers and other photodetectors, and could also prove useful for the detection of excited chemical and biological species via photo- and/or bio-luminescence, and for free-space DUVAP optical communication applications (i.e. deep ultraviolet avalanche photodetector). With regard to bioluminescence, this technique has been widely employed for monitoring bacterial contamination in clinical, food and

environmental settings. Therefore such detectors could potentially be used for everything from the testing of water treatment facilities and irrigation water, to foods (e.g. meat and vegetables), environmental air samples including aerosols and powders, and the general monitoring of numerous agents for chemical and/or bioterrorism. The theoretical basis behind the use of the PPPS as a photoluminescent chemical and/or biological agent detection device relies on being able to detect luminescent chemical and/or biological species that could be appropriately excited to emit characteristic optical photons that could then be captured and analyzed by a large area PPPS-type avalanche photodetector. The efficacy of such a detector could be significantly improved upon by adding (or directly coating) a narrowband transmission filter (on top of the PPPS front substrate) to enable only photons having a specific wavelength of interest to be passed through and detected by the PPPS device. Such an arrangement could be especially useful for DUVAP type applications.

III. Summary and Impact

Many useful applications, such as the detection of radioactive materials, computer-assisted tomography (CAT), digital radiology, optical detectors, etc., rely on the detection of ionizing radiation (e.g. photons and/or high energy particles – both neutral and charged), as well as non-ionizing photons. The latter, sometimes referred to as optical photons, are commonly detected by various types of devices such as CMOS, CCD's, photomultiplier tubes (PMT's), avalanche photodiodes (APD's), etc. The broad area of PPS-based devices described above, which constitute a new radiation detection technology, are capable of detecting ionizing and non-ionizing radiation for numerous applications and should be especially important for those applications requiring large area, low cost coverage, in an inherently rugged, thin cross-sectional device, with potentially high spatial, temporal and good energy resolution. In particular, the plasma panel photosensor (PPPS), which is the primary focus of this study, is a gaseous, solid state, hybrid device formed by coupling a PPS with an internal photocathode. The PPPS essentially constitutes a new family of radiation detectors involving the marriage of low cost, plasma display panel (PDP) TV-set technology with photomultiplier-type photocathode materials. A variety of designs are possible for this highly-pixelated and inherently-digital detector which requires little or no signal amplification and, when optically coupled with a scintillator plate (or crystal) to form a PPPS-scintillation detector, is capable of good spectroscopic sensitivity across an extremely broad energy range for most kinds of ionizing radiation.

A key performance goal for various imaging and/or tracking applications from medical tomography, to homeland security, to nuclear physics, is achieving high angular resolution. To evaluate this ability for the PPPS-scintillation detector, a numerical analysis was initiated by Oak Ridge National Laboratory (ORNL) for the Compton telescope arrangement [8]. The initial simulation results suggest that angular resolutions of less than 2° are feasible for a reasonably configured PPPS system operating at room-temperature with NaI(Tl). A second conclusion by ORNL was that ***this device has the potential to provide substantially better angular resolution than any system based on conventional PMT's, and further, that the efficiency can be substantially better at much lower cost than arrays of semiconductor detectors with similar angular resolution***. ORNL also concluded that such configurations should be valuable for detection of neutrons typically encountered in experiments with heavy ion beams from a few tens of MeV per nucleon up into the GeV range. Using such devices as an inexpensive position and time detector could permit building such arrays more cheaply and estimating the neutron emission angles more precisely. Also with a thickness of about 1 mm (or possibly less), the proximity of the PPPS to the interaction sites could provide better timing resolution (since the pixels are so close), thus reducing dispersion in the light collection. Additionally, such detectors often need to be placed in regions of high magnetic fields, and the PPS/PPPS should be insensitive to these fields. With respect to accelerators, intensity profiles and emittance analyses are among the most critical tools used for optimizing beam transport. According to the ORNL analysis, profile measurement systems could benefit from improvements in performance and cost that might be provided by PPS-type detectors. Improved radioactive ion beam (RIB) diagnostics for low-intensity beams is critical for the success of RIB facilities. Reliable, rugged, low-cost detectors are needed for the next phase of nuclear physics studies involving rare isotope beams. In this regard, the PPS/PPPS might be the next-generation detector.

Finally the intrinsic efficiency of the PPPS should be significantly greater than that of the basic PPS structure, because the radiation "absorption" function is separate and independent of the "electron conversion" function, and so each can be individually optimized for the specific radiation of interest. Also the conversion layer thickness is no longer limited to the free-electron range, so a greater fraction of incident radiation can be captured by the PPPS-scintillation detector, and with the added number of information carriers, the energy spectral resolution will improve accordingly. Finally, by vertically stacking the PPPS, a variety of high-efficiency, low-cost, Compton imagers/telescopes could be developed for numerous applications, from high-resolution medical imaging, to long-range, fast-neutron analysis for detection of high-explosives.

In summary, PPPS devices have the potential to offer a number of significant improvements to the current state-of-the-art in radiation detection technology, especially with regard to the following: (1) new apparatus and method for high-resolution digital radiography, radiation source imaging, computed tomography, source isotope identification, neutron activation spectroscopy, free-space optical communication, chemical and biological species detection, optical photon based chemical sensors and/or biosensors; (2) highly-pixelated, high-gain, digital detection without the use of A/D converters; (3) rugged, large area, flat panel form-factor with

excellent position-sensitive capability; (4) high-level performance in various challenging environments with insensitivity to magnetic fields; (5) order-of-magnitude cost reduction potential compared to existing detection techniques, especially for large area, fast response, radiation detection systems; (6) thin cross-sectional device profile facilitating operation in a variety of vertically-stacked configurations for enhanced efficiency and/or improved performance including system designs such as coded-apertures and Compton telescopes. With regard to the latter, the PPPS-device Compton telescope simulation study results at ORNL suggest that ***the use of scintillators coupled with the PPPS promises to approach the angular resolution of Si and Ge based semiconductor telescopes, for a very small fraction of the cost and a dramatic gain in detection efficiency. A fully-realized PPPS system could revolutionize any detection system in which position measurements with small detector mass are critical, such as for homeland security. Beyond this latter application, the PPPS could revolutionize medical tomography and high-energy neutron research*** [8].

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