NEW DEVELOPMENTS IN HYBRID PHOTON DETECTORS[a]

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New developments in HPD design are presented, triggered by applications in high energy physics and astrophysics. The presented HPD designs are based on three innovations. (i) In order to achieve the highest possible surface coverage in a RICH detector, we introduced a photoelectron focussing method which is efficient to the periphery of the photocathode. (ii) To prevent positive ion feedback in HPDs, we introduced a permanent potential barrier in front of the anode. (iii) To replace a transmittive by a reflective photocathode, we arrived at a conceptually new HPD design with surprisingly good imaging characteristics, high quantum efficiency and low cost.

1 Introduction

With the onset of new technologies, Hybrid Photon Detectors (HPDs) became the most favourable option for detection of Cherenkov photons in large area Ring Imaging Cherenkov (RICH) detectors. Modern HPD detectors comprise high quantum efficiency, high photoelectron collection efficiency and sharp image reproduction. We present some new developments in HPDs, of particular importance for applications in RICH detectors. The goals achieved in the presented HPD designs are:

1. minimized dead area of individual HPDs, and consequently maximized active area of a RICH detector, 81% in a hexagonal HPD packing,
2. protection against the positive ion feedback, particularly important in gamma ray astronomy, and
3. application of a low cost and high quantum efficiency reflective photocathode in an HPD.

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For all the electron optics simulations presented, the SIMION 3D software [1] has been used. In the figures presented, only functional elements (conductors) are shown. Electrons are simulated with the initial energy of 0.25 eV and emission angles +45°, -45° and 0° relative to the normal.

2 "Killing the dead area"

The most important problem in the integration of HPDs into a matrix of a large-surface RICH detector is the low overall photon-sensitive surface coverage, caused by a typically high HPD dead area. HPDs have usually been designed as stand-alone devices, and very little, if any care has been taken of the relationship between the physical and the sensitive surface areas. In those applications when the Cherenkov photon detection pixel size of 1-2 cm is sufficiently small, one can use single-pixel HPDs (without internal imaging) and take care of the large dead area by focussing the light to the sentive area by the means of lenses or Winstone cones. In the applications which require a smaller pixel size (e.g. 1 mm), one has to use large diameter HPDs with internal imaging.

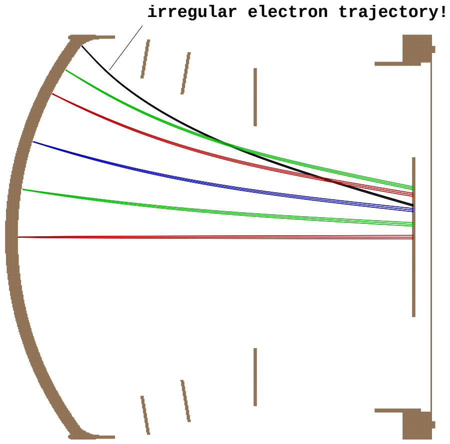

Figure 1: Proximity-focussing 5 inch diameter pad-HPD. Photons enter HPD from the left side, photoelectrons are focussed onto the silicon-pad detector on the right side. Photoelectrons emerging from the periphery of the photocathode are incorrectly focussed. Electrodes are kept at the following potentials, from left to right, respectively: -20 kV, -15 kV, -11 kV, -4.7 kV and 0 V. Electrons are simulated with an initial energy of 0.25 eV and an emission angle of +45°, -45° and 0° relative to the normal.

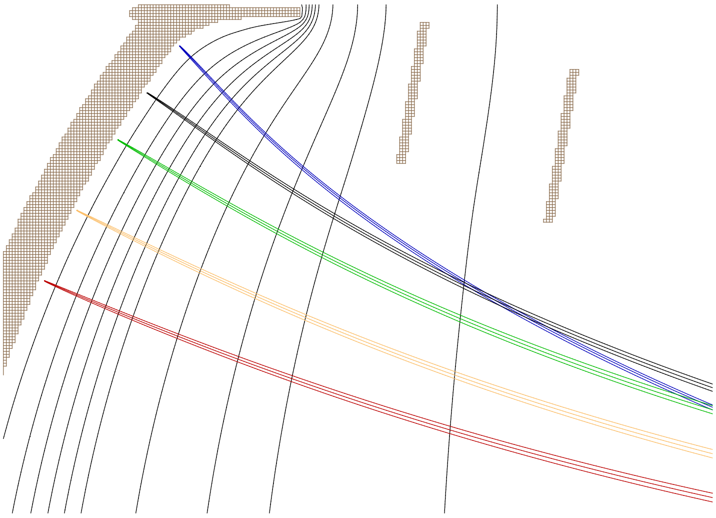

Figure 2: Incorrect electron focussing close to the periphery of the photocathode is due to the small radius of curvature of equipotential lines.

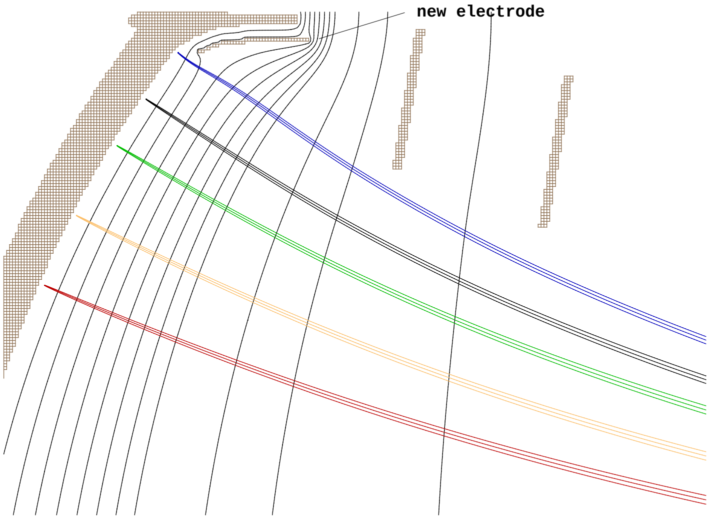

Figure 3: The new electrode allows the potential lines to be conducted out from the HPD through the created slot, curing the unwanted strong curvature of the equipotential lines seen in Fig. 3.

Proximity-focussing HPD designed for the LHCb experiment [2], is an example of a large imaging HPD (Fig. 1). It has been conceptually designed to have a small dead area, for close hexagonal packing.

Photons enter the HPD detector from the left side, and photoelectrons (emerging from the photocathode on the internal surface of the entrance window) undergo acceleration and (electrostatic) focalization onto the silicon-pad detector on the right side. There is a good mapping between the image on the photocathode and the projected image on the pad detector, except for the region close to the periphery of the photocathode. Although the physical shape of this HPD is optimized for close packing (the photocathode has been extended towards the periphery as much as possible), there is still a rather large *functionally* dead area.

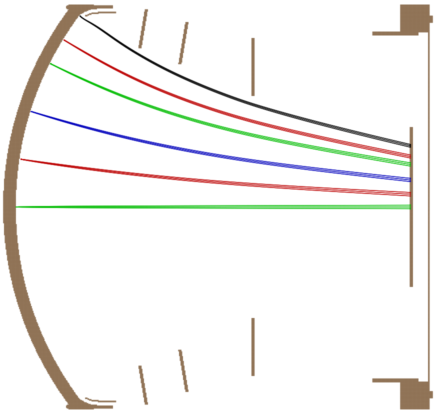

Figure 4: An appropriate focussing of all electrons, including those from the edge of the photocathode, results from the application of a new electrode. Potential lines are "conducted" out from the tube through the slot between this electrode and the window support. Electrodes are kept at the following potentials, from left to right, respectively: -20 kV, -19.45 kV, -15 kV, -11 kV, -4.7 kV and 0 V.

The reason for the failure becomes evident from Fig. 2. Equipotential lines have a rather small radius of curvature close to the edge of the photocathode. Photoelectrons emitted from that region are therefore too strongly accelerated along the potential gradient, i.e. towards the center of the HPD.

To fix this problem, one should reduce the curvature of the potential distribution. One is tempted to redesign the window supporting structure and let potential lines leave the tube, but for constructional reasons (related in fact to the maximal exclusion of the mechanical dead area), this was not possible. Therefore we searched for another solution with the basic idea to reduce the field curvature by “conducting” some of the potential lines out from the tube, around the metallic window support. The solution was found in the creation of a slot which acts as a “potential-conductor”, see Fig. 3. The slot was created by the insertion of a specially shaped new electrode. The unwanted potential lines are indeed conducted away through the slot between the new electrode and the body of the tube, and the resulting field in the problematic peripheral region has evidently lost its strong curvature, see Fig. 3, Fig. 4.

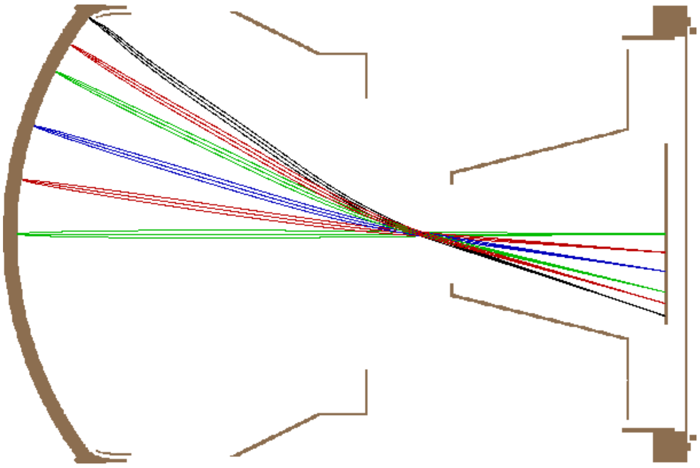

Figure 5: A cross-focussing 5-inch diameter HPD, with superior imaging characteristics. Electrodes are kept at the following potentials, from left to right, respectively: -20 kV, -19.97 kV, -19.4 kV, +100 V, and 0 V.

The same method has been successfully applied in a different design, the so called cross-focussing HPD design, shown in Fig. 5. This HPD can also be hexagonally packed with the same surface coverage of 81% .

Apart from providing a much narrower spread of photoelectrons on the silicon pad detector, and thus a superior imaging performance, this design also provides a simple way to apply the protection against the positive ion feedback [5], which is the subject of the following section.

3 Potential barrier - protection against the ion feedback

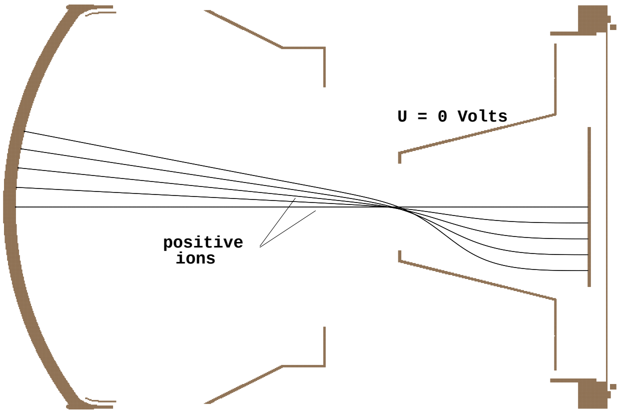

Figure 6: Positive ion trajectories, when the conical electrode is set to the anode potential (0 V). Ions emerge from the surface of the anode (right) and become accelerated towards the photocathode (left), eventually producing damage and operational noise.

Air Cherenkov Telescopes (ACT) have been considered the ultimate instruments for the ground based detection of high energy cosmic gamma rays [3,4]. In order to lower the energy threshold for the detection of cosmic gamma rays down to 20 GeV – to explore the only unexplored window in cosmic electromagnetic spectrum (20 GeV to 300 GeV) – one should both increase the detector area, and achieve an unprecedented photon detection with single photon sensitivity and very high efficiency. Considering photon sensors, HPDs currently present the most promising solution. However, commercial devices have still some serious drawbacks and need further improvement. In particular, it is very important to reduce the internal instrumental noise below the present limits, because other sources of noise in imaging air Cherenkov detectors (like the night sky background) are irreducible.

The presence of positive ions in a vacuum tube is particularly devastating because the acceleration and subsequent dumping of positive ions into a photocathode leads both to creation of noise through electrons released, and to a damage of the photocathode [6,7]. In the high-vacuum tubes the vast majority of positive ions do not originate from residual gas, but rather from the impact of accelerated photoelectrons on the surface of the anode. Cesium ions

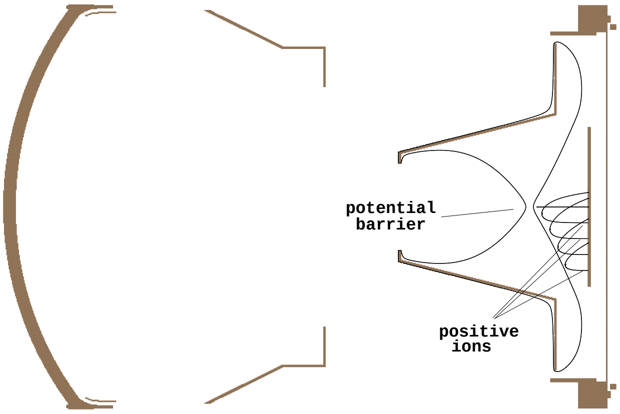

Figure 7: HPD design with a conical barrier–electrode at +100 V. Between the barrier–electrode and the anode a potential barrier is established (see Fig. 8) to repel back the positive ions emerging from the anode surface.

are particularly abundant because they usually spread inside tubes during and after the manufacturing of photocathodes.

Trajectories of singly charged positive ions are shown in Fig. 6, emerging from the anode at normal incidence with energy 44 eV. Note that the angular and energetic distributions of positive ions are at this point unknown. We have worked out a measurement scheme, but at the time being we are using only a very rough estimate that the ions could reach an energy of about 30 eV.

It has been previously demonstrated [5] that the insertion of an electrostatic potential barrier close to the anode solves the ion feedback problem. Apart from being complete, this solution is easy to implement and it preserves cylindrical symmetry of the device.

As demonstrated in Fig. 7, the functionality of the conical barrier–electrode is simple: being kept at a potential somewhat higher than the anode potential, it breaks down the monotonous decrease of the potential for positive particles towards the photocathode, and creates a potential barrier in front of the anode. The barrier prevents positive ions from penetrating further towards the photocathode. The potential distribution in front of the anode plane is shown in a magnified view in Fig. 8. Trajectories of singly charged positive ions are simulated with identical initial conditions like before.

The precision of the potential on the barrier–electrode, required for stable electron focussing, is not a critical issue – variations of even 10% on the potential will leave the electron focussing essentially unchanged [5,8]. The most common voltage supply may be therefore used to bias the barrier–electrode, while a separate, unipolar and very stable voltage supply could be used to bias the focussing electrodes.

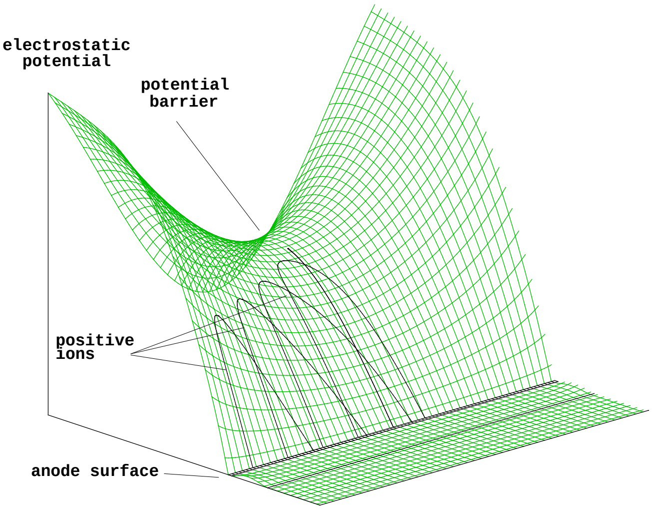

Figure 8: Potential distribution in front of the anode plane of HPD from Fig. 7. Positive ions of energy E_{ion}=44 eV and emission angle normal to the anode surface start "climbing" the potential barrier (E_b=45 eV) but eventually become repelled.

4 HPD with a reflective photocathode

Semi-transparent photocathodes, commonly used in photon detectors, present a problem *per se*: they need to be opaque for photons, but at the same time transmittive for photoelectrons.

An alternative solution is to use a photocathode in a reflective mode, i.e. in a configuration when photoelectrons emerge from the same surface through which photons enter. A considerably higher quantum efficiency is granted, but perhaps equally important, the photocathode manufacturing process is not any more strictly constrained to extremely high tolerances. In particular, there is no need to perform some of the most complicated stages in the processing of the III-V photocathodes (like e.g. GaAsP), namely the attachment of the

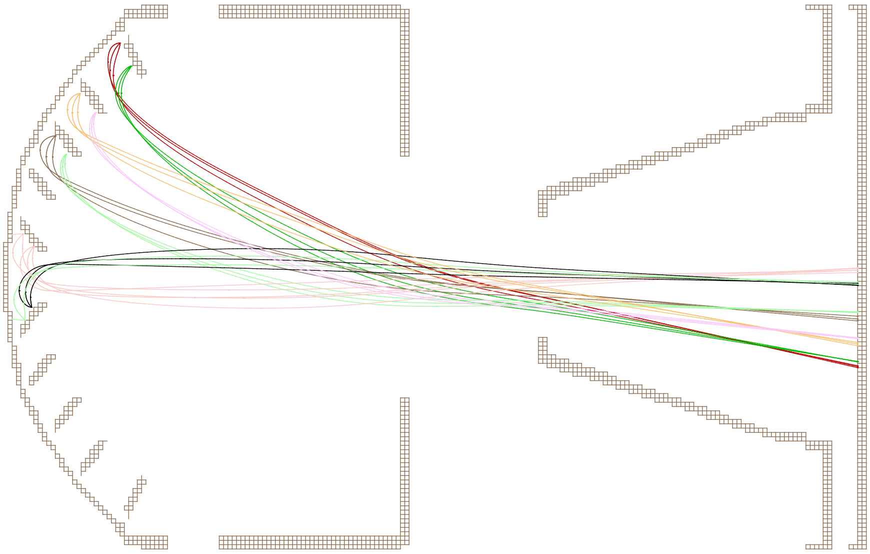

Figure 9: Imaging HPD with reflective photocathode. Photoelectrons emerge from the photocathode attached to the surface of conical "blinds". Note the surprisingly good imaging performance! Electrodes are kept at the following potentials, from left to right, respectively: -20 kV, -19.4 kV, +100 V, and 0 V.

epitaxially grown surface onto the entrance window of the phototube, and then the removal (usually by etching) of the substrate from the opposite side.

Motivated by these considerations, we have developed a conceptually new HPD device - the imaging HPD with reflective photocathode, see Fig. 9. This cylindrically symmetric device converts photons into photoelectrons in the photocathodes mounted on the surface of the conical “blinds”, attached mechanically and electrically to the entrance window. After a detailed electron optics optimization, this device provided a surprisingly good imaging quality, see Fig. 9. Note that two imaging operational modes are possible: (i) a mapping of each individual blind electrode into a single “point”, in which case the silicon detector surface should be placed slightly closer towards the photocathode than in Fig. 9, and (ii) a point-to-point mapping, as shown in Fig. 9.

Among the drawbacks of this particular design, one should note a compromised photon angular acceptance and a relatively large difference in the time of flight of photoelectrons emitted from different points on the same blind.

Acknowledgments

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