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Single Electron Amplification in a "Single-MCP + Micromegas + Pads" Detector

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***Abstract*—We have tested a new gaseous detector structure based on a tandem of two parts, the first one is a single MCP plate (sometimes called the Microchannel plate or Capillary plates), and the second one is a Micromegas with pad readout. The new detector responds very well to a single electron signal, both in helium-based and Argon-based gases, and it can reach a very large gain. Our overall aim is to couple the proposed electrode structure to a Bialkali photocathode. The main advantage of this avenue of research is that such a detector would operate easily in a very large magnetic field, and it could achieve excellent position resolution and large pixelization, compared to existing vacuum-based MCP-PMT detectors.**

I. Introduction

We have a strong R&D in our group to develop Focusing DIRC [1-4]. This is a Cherenkov imaging detector, which will attempt to remove the chromatic error contribution to the Cherenkov angle error by precise timing on each single photon. As the total timing spread due to "color" of photons in Focusing DIRC with 4m-long Fused Silica bar with a photon detector equipped with a Bialkali photocathode is only 0.5 to 1.5 ns at most (depending how far the photon travels on the fused silica bar), one needs a timing resolution of 100 ps or better for each Cherenkov photon to be able to "color-tag" photons. The chromatic error is typically the dominant error. So far, there is no Cherenkov detector which has ever corrected the chromatic error. If one would succeed to eliminate the chromatic error, and if one could have the small pixel size at the same time, one could push the π/K separation in the Focusing DIRC up to 6-8 GeV/c compared to present DIRC in BaBar, where the limit is up to 3-4 GeV/c.

Presently, the strongest photon detector candidate for this task is a vacuum-based Multi-MCP-PMTs, for example, one made by Burle Co.[1] This device has two MCPs with 25 μm hole diameter. We have achieved a timing resolution of 50-60ps with the vacuum-based MCP-PMT – see Fig. 1. This device works very well, however, it is not yet suitable for 1.5 Tesla operation because the hole diameter is too large. Future devices will have 5 or 10 μm hole diameters, and they will operate in high magnetic field. One drawback of the vacuum-based MCP detectors is aging due to the ion bombardment of the photocathode. According to Burle Co., the photocathode aging of their devices has improved by a factor of ~10 compared to previous generation of such devices. This was accomplished by improvement of vacuum to remove residual gases. It will be interesting to see MCP results with smaller hole diameters as the scrubbing is more difficult. I should add that we have not yet performed the aging tests with it. Another potential problem with all MCP vacuum-based devices is rather large major photoelectron losses: (a) 30-40% due to geometrical collection efficiency of the 1-st MCP, (b) ~20% due to recoils of the photoelectrons from the 1-st MCP surface, contributing to the timing tail.

We have asked a question if a gaseous device could compete with a vacuum MCP-PMT. This would require solving a number of challenging tasks. The most challenging one is to solve a gas purity to such a level that the Bialkali photocathode would have a reasonable life time. A similar challenge would be to obtain a timing resolution in a gaseous device below 100ps. One also has to reduce the positive ion backflow to the photocathode to limit the production of secondary photoelectrons, which could trigger the positive feedback. Although ions in the gaseous detector are thermal, which is an advantage, there is a large number of them compared to the vacuum-based devices.

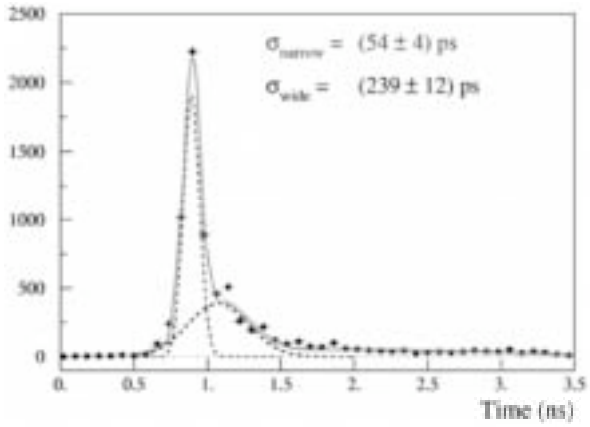

Fig. 1. Single electron timing resolution obtained with a vaccuum-based Burle MCP-PMT, and PiLas red laser diode. The MCP-PMT has Two micro-channel plates (MCP or Capillary). This measurements indicates that there is a good transit time distribution in the vacuum-based capillary. A long tail is explained by the recoil photoelectrons from the front MCP surface.

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[1] Burle Tecnologies Inc., http://www.burle.com

On the positive side, the gaseous detectors would easily work in a large magnetic field with large diameter MCP holes (1.5 Tesla), one could achieve small position resolution (<100 μm), and one could probably achieve larger gas gain (if the ion backflow can be reduced).

When considering what geometry to chose, a possible candidate was a single Micromegas [5]. A high gain was obtained in the He-based gases in this device. In addition, Giomataris has achieved a timing resolution of several hundred ps per single photon entering the Micromegas [6]. However, a single electron operation at gains above 10^5 is judged unsafe, especially if one expects a high ionization background caused by slow protons or ions. Similarly, Peskov has operated successfully single or double-MCP plates in gas up to gains of 10^5 [7]. However, based on our experience with the MCP-plates detector, operation near such gains is not very reliable. Therefore, we have decided to combine the two technologies together: a single-MCP plate followed by a single Micromegas with a pad readout. We find that this configuration works very well in the He-based gases, and one can achieve easily stable gains in excess of 10^6. One can operate the detector also in the Argon-based gases. The advantage of the Argon compared to helium is smaller photoelectron backscattering effects.

II. DETECTOR DESCRIPTION

Fig. 2 shows a geometry of our prototype, including spacers and G-10 rings necessary for mounting the components into our detector holder. The Micromegas gap between a s.s. mesh and pads is 100 μm. It is held presently by nylon lines of 100 μm diameter. The readout plane is formed by a 3 x 3 matrix of 1mm diameter round pins imbedded in a G-10 insulator.

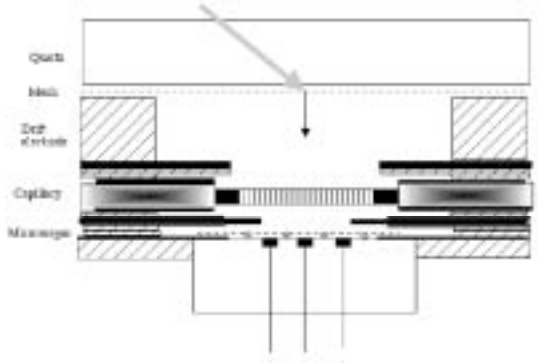

Fig. 2. Our detector is made by a combination of a single-MCP and a single-Micromegas. The Micromegas has 100 μm gap, and the Capillary has 50 μm hole diameter. The Micromegas gap is held by 100 μm diameter nylon lines in this particular test. Single electrons are produced by a UV light striking a dense s.s. mesh located at the entrance of the drift region.

Fig. 3 shows geometry of a s.s. mesh used in the Micromegas. It was made by Buckbee-Mears Co. by electro-etching. It has 1000 lines per inch, a square hole has a dimension of 17 x 17 μm^2, and a 9 μm wide wall separating them.

Fig. 4 shows geometry of the MCP, which was made by Hamamatsu Co. Its hole diameters are 50 μm, and a wall separating holes is 12 μm wide. The MCP is 1mm thick. In the present design, we are not using the angled holes, which is typically done in the MCP-PMT devices to limit the photocathode damage by ions.

The s.s. mesh, located next to a fused silica window (see Fig. 2) is our "simple" photocathode in this test, as we are producing photoelectrons by striking it with a focused UV light from a Hamamatsu Xe-filled UV lamp L2435. The UV light is attenuated appropriately to produce single electron pulses. This works well to measure single electron pulse height spectra, however, the lamp has a too large timing jitter for the precision timing measurements at a level of 100ps.

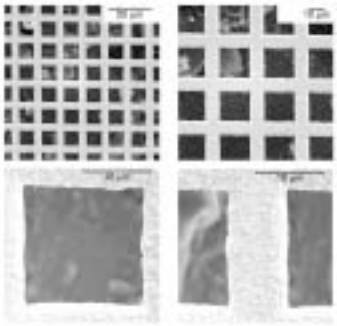

Fig. 3. Detailed pictures of Buckbee-Mears electro-mesh used to construct the Micromegas detector. The mesh has 1000 lpi,, has square holes of 17 x 17 μm^2, and a 9 μm wide wall separating them.

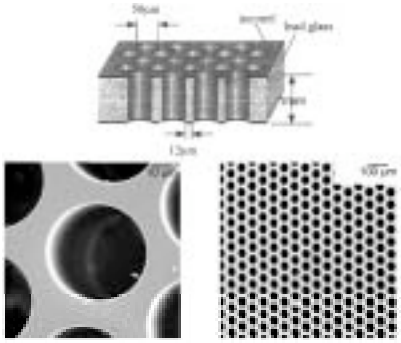

Fig. 4. A detailed picture of the MCP used in our detector. The MCP has holes of 50 μm diameter and 12 μm wall separating them.

III. EXPERIMENTAL SETUP

Fig. 5 shows the experimental setup including the detector vessel and the UV gun. Fig. 6 shows typical single electron pulses observed in the presented detector with an amplifier with 2.7 μV/electron gain and 65ns shaping time. We have used this amplifier only for the purposes to measure the gain and the pulse height spectra. In future, we plan to use the same electronics as is used for the MCP-PMT detector, which is based on Elantek 2075 amplifier, and the constant fraction discriminator [4].

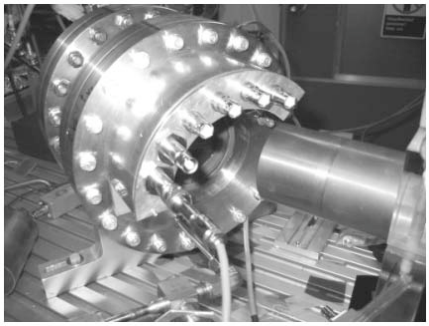

Fig. 5. Experimental setup with Hamamatsu UV Xe lamp L2435. The UV light is focused on a small spot on the dense s.s. mesh to produce the single electron source.

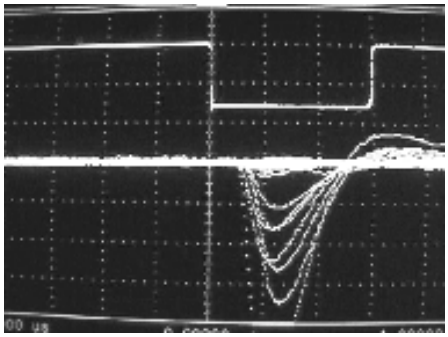

Fig. 6. Typical single electron pulses from this detector together with a QVT gate. A charge integrating amplifier has a gain of 2.7 V/electron, and a shaping time of 65ns.

IV. RESULTS

One can achieve a large gain in the He-based gas mixture in this device. For example, Fig. 7 shows single electron pulse height spectra in 89.1% He + 10.9% iC_4H_{10} for two major dependencies, one obtained by varying a voltage across the Micromegas and one across the MCP. Fig. 7a indicates a sign of turnover, which tends to increase with the Micromegas gain. This seems to happen only in He/iC_4H_{10} gas mix. For example, Giomataris has observed a very clear turnover in 70/30 He/iC_4H_{10} ratio – see Fig. 8.

Fig. 9 shows that the spectra become exponential as one reduces the admix of a quencher. In this case the mix is 94.5% He + 4.5% CH_4. However, this particular gas may suffer more from the photoelectron backscattering effect in which helium atoms return some photoelectrons back thus reducing the effective quantum efficiency. Argon gas is better in this respect. The detector does works, for example, with 96% Ar + 4% CH_4 gas mix as is shown in Fig. 10. However, the operation in pure Argon was found to be unstable.

We have also attempted to measure the absolute total gain in both the MCP and the Micromegas. Fig. 11 shows a gain measurement in the MCP alone using a strong Mercury UV lamp, and the structure operating as an ionization chamber, where a picoammeter was connected between the pads and the ground. The gas gain in 94.5% He + 5.5% CH_4 increased by a factor ~15 for every 100 Volts across the Capillary. A similar result was obtained when measuring the gain in the Micromegas alone.

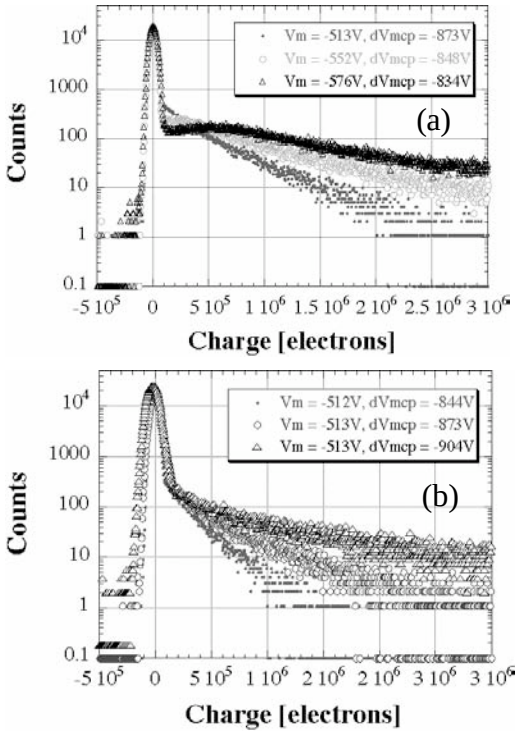

Fig. 7. Single electron pulse height spectra in 89.1% He + 10.9% iC_4H_{10} gas: (a) vary the "bottom" power supply, which controls both the Micromegas and MCP gain, and (b) vary voltage dVmcp across the MCP.

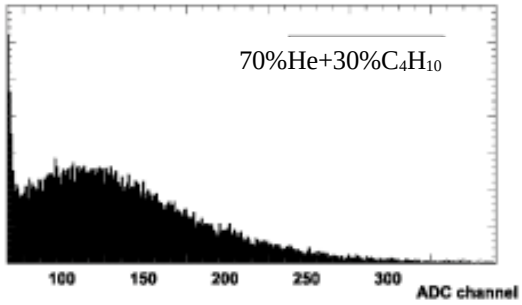

Fig. 8. Single electron pulse height spectrum measured in a Micromegas in 70% He+30% iC_4H_{10} [8].

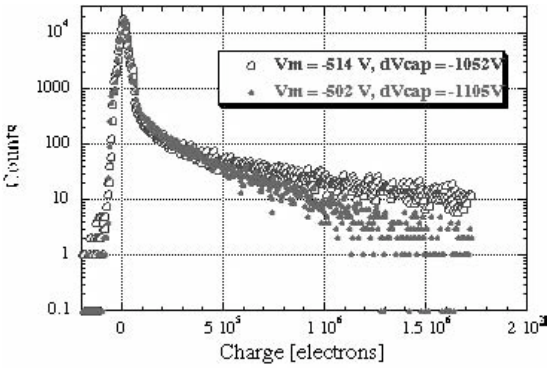

Fig. 9. Single electron pulse height spectra in 94.5% He + 4.5% CH_4 gas.

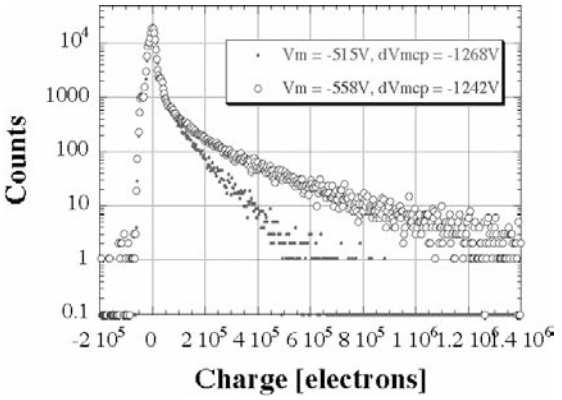

Fig. 10. Single electron pulse height spectra in 96% Ar + 4% CH_4 gas

The conditions in the above tests vary, but typically we would run the detector with the following electric fields: $E_{Capillary\text{-}entrance}$ ~350V/cm, $E_{Capillary\text{-}exit}$ ~1.25kV/cm, $E_{Capillary}$ up to 10kV/cm, and $E_{Micromegas}$ up to 50kV/cm, corresponding to an average gain of a 2-3x10^5.

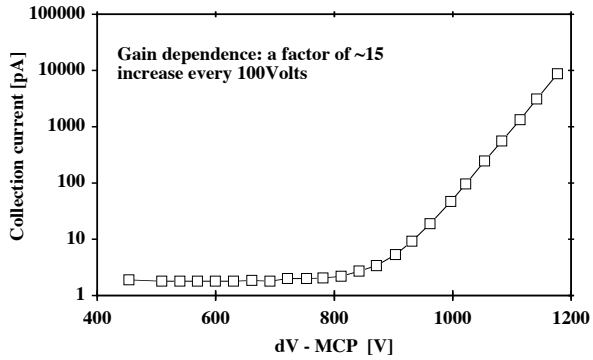

Fig. 11. Absolute gain measurement in MCP in 94.5% He + 4.5% CH_4 gas. The MCP was in collection mode and the light source was a strong Mercury lamp. A gain increase by a factor of ~15 every 100 Volts was observed. A similar gain was measured in the Micromegas in the same gas.

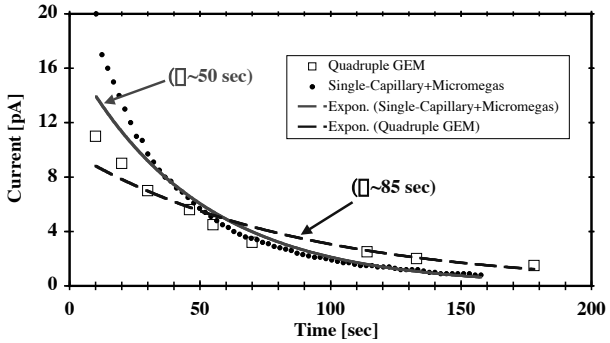

Fig. 12. The charging effects in the structure was measured using a strong Mercury lamp creating a standing current of 350nA, which was suddenly interrupted to measure the discharging time constant. We measure a time constant of ~50sec for the presented detector, and this is to be compared to ~85 sec, which was measured for the Quadruple-GEM detector [9].

The charge can stay on insulators, such as glass or Kapton, for a long time. Therefore we wanted to know how long it takes to bleed it away after the detector was subject to a strong light from a Mercury lamp creating a current of ~350nA. The discharge time constant was measured by interrupting the light, and following the current decay with a picoammeter connected between the pads and the ground. Fig. 12 shows that the discharge time constant is ~50 sec. For comparison, the same measurement with the Quadruple-GEM yielded a time constant of ~85sec [9]. The discharge time constant is dominated by the resistivity of the glass or Kapton, i.e., for example, the effect of the resistance divider is negligible. In both cases, no pumping was done to remove water from the insulator surfaces, and the detector was typically under a gas flow 1-2 weeks only.

V. DISCUSSION

Our primary goal was to see if we can achieve the timing resolution of less than 100 ps per single photon. We have attempted to create the single electrons with either red or blue Pilas laser diode striking the dense s.s. mesh at the beginning of the drift filed, hoping to trigger the double-photon Photoelectric effect. We have not accomplished this, presumably because the laser diodes were not powerful enough. In absence of the direct measurement, we will attempt to argue at least theoretically. Let's assume that the capillary has an average gain of 5. We will use a simple formula expressing the expected timing resolution as $\Delta t \sim (1/N)\,\lambda_{coll}/v_{drift}$, where N = 5, $\lambda_{coll} = 1/\alpha$ is the mean free path (α is the Townsend coeff.) and v_{drift} is the electron drift velocity in the Micromegas at ~50kV/cm. Using the Magboltz-Monte program [10], one obtains $\Delta t < 100$ps for a 95%He+5%CH_4 gas. However, the avalanche fluctuations, which are not included in the simple formula, will make the resolution worse. Nevertheless, this simple theoretical argument seems to be consistent with a measurement using a single Micromegas, which achieved a timing resolution of 200-300ps per single photon with a simple leading-edge electronics [6].

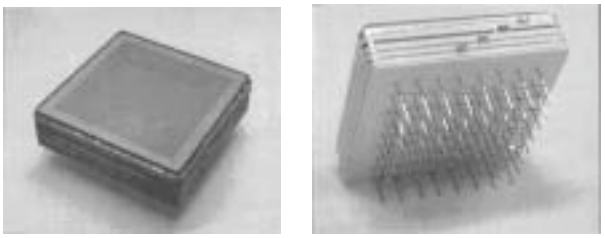

Fig. 13. A possible future step is to build the proposed detector in the already well proven structure, for example, in the Burle MCP-PMT enclosure.

Immediately after the IEEE presentation, Bo Yu (BNL) suggested in a private discussion to eliminate the Micromegas by creating a small gap between the MCP and the pads, and operate this gap as a parallel-plate chamber [11]. This would definitely increase the charge transfer from the MCP to the Micromegas, and also simplify the structure. However, it would also increase the ion backflow to the photocathode. This is actually a critical issue, as the gaseous detector produces

much larger ion backflow compared the vacuum-based MCP-PMT, where the ions are created on the electron collisions with the residual gas molecules. The ions in the gaseous detector are less energetic, but nevertheless also capable of extracting the secondary photoelectrons at the cathode surface [12], which tend to trigger secondary avalanches. A probability to extract a secondary electron is at a level of ~10^{-6} per ion. Therefore it is probably necessary to suppress the ion backflow to a level of less than 1%.

Our goal is to try the proposed detector in the already well established detector structure, for example, as shown in Fig. 13, which is presently used for the Burle MCP-PMT. The main attraction is the operation in a large magnetic field, and possible extrapolation to even large detector sizes. However, the timing resolution (<100ps) and the detector longevity when running with a Bialkali photocathode are still obvious questions yet to be answered.

VI. CONCLUSIONS

We have tested a new gaseous detector structure based on a tandem of two parts, the first one is a single MCP plate (sometimes called the Microchannel plate or Capillary plates), and the second one is a Micromegas with pad readout. The new detector responds very well to a single electron signal, both in helium-based and Argon-based gases, and it can reach a very large gain.

We have asked a question if this gaseous detector could compete with a vacuum-based MCP-PMT. On the positive side, the gaseous detectors would easily work in a large magnetic field (1.5 Tesla), one could achieve small position resolution using the pad readout (<100 m), and one could probably achieve larger gas gain. However, there are many new questions to be answered. The most challenging one is to solve a gas purity to such a level that the Bialkali photocathode would have a reasonable life time. A similar challenge would be to obtain a timing resolution in a gaseous device below 100ps. The last but not the least is to reduce the positive ion backflow to the photocathode to limit the production of secondary photoelectrons, which could trigger the positive feedback. Although ions in a gaseous detector are thermal, which is an advantage compared to a vacuum device, there is much more of them. At the end this effect would limit a maximum achievable gas gain, which would in turn affect the timing resolution.

VII. ACKNOWLEDGMENT

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