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GASEOUS DETECTORS WITH PARALLEL ELECTRODES
AND ANODE MESH PLANES

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ABSTRACT

The amplification of electron avalanches in a uniform electric field between parallel electrodes can be used in single or multistep structures for a great variety of applications in fields such as charged-particle tracking, X-ray imaging, ultraviolet photon detection for ring imaging of Cherenkov light, beta autoradiography, and gamma-ray astrophysics. In this article some observed properties of parallel-electrode structures are analysed and compared with those of wire chambers. Parallel electrodes have advantages over wire chambers in their better energy resolution, better timing resolution, and the fact that they are easier to construct and are more durable. It is now possible to construct proportional gaseous detectors without the need to string wires, with readout options using either electronic charge signals or optical light imaging. For either of these methods the position and energy of the avalanches can easily be determined.

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1. INTRODUCTION

The multiplication of charges in a gaseous medium through a succession of inelastic ionizing collisions building up a Townsend avalanche is one of the oldest detection techniques in nuclear physics [1, 2]. Detectors based on amplification around wires have long been preferred since they permit larger gains before breakdown, which was a decisive advantage in the early days. However, it was a routinely used technique in the field of heavily ionizing particles, because there the required gains were much smaller. The limitation to the amplification came mainly from the onset of disruptive sparks when the avalanche reached a given threshold, this threshold being much lower than with wires. In a wire chamber the electric field is intense only around the wires and after the avalanche grows beyond a certain level; the decreasing electric field away from the wire is not favourable for the propagation of avalanches by ultraviolet (UV) photons which leads to disruptive streamers.

However, electronics has evolved, providing low-noise, low-cost, spark-resistant amplifiers permitting work with much smaller gains and greater safety. More importantly the understanding of the parallel-electrode structures has increased. It is now possible to use multistep structures with gains so large that avalanches from single electrons liberated by UV photons can be detected with nearly 100% efficiency. Even the single-gap structures have evolved, with a better understanding of factors limiting the gain. The readout of the position of avalanches in parallel gaps has also progressed. It can be done in two dimensions by a variety of electrical methods and very conveniently by observation of the light emitted by the excited atoms in the avalanche. This last technique can provide an advantage in some applications, in particular when events of high complexity have to be analysed.

After the initial work on multistep chambers in 1979 [3, 4] several groups started to adopt amplification between parallel gaps for soft X-ray imaging, demonstrating sizeable advantages over pro-

portional wire chambers, with essentially the same energy resolution. There is at present some confusion concerning the limitation in energy resolution or local counting rates. In this work we present some observations on the properties of the amplifying gaps between parallel electrodes, with particular emphasis on the construction where the anode plane is made of a mesh or wires since this is the condition for electron transfer to successive gaps. The parallel-plate avalanche chambers (PPACs) constructed in this way work in conditions equivalent to uniform field amplification.

Some observations are presented here on the relationship between charge amplification and light production using multiwire proportional chambers (MWPCs) and uniform electric fields such as in PPACs. A study of energy resolution, timing resolution, and feedback was performed in an effort to determine which of these amplification techniques was most suitable for certain needs. A study of light production in different electric fields, use of anode meshes under conditions of symmetric electric fields similar to those applied to wire planes in MWPCs, and a description of the set-up and operation of a single-gap chamber that has two steps of amplification -- in the uniform gap and on the wires of the limiting anode grid -- is presented. Although the work described here deals mostly with the properties of single-gap amplification structures, it has implications for multi-gap structures; these have the advantage of permitting the gating of the events and can thus be used in high-rate environments.

2. PROPERTIES OF A SINGLE AMPLIFICATION GAP

LIMITED BY MESH PLANES

When a voltage is applied to a mesh plane in order to produce a uniform electric field, the field is uniform in most of the gap but is increased near the wires. The strength and distribution of the field lines depend on the wire diameter, the wire spacing, and the electric field on either side of the mesh. The case of a grid made of

parallel wires has been extensively described in many articles on wire chambers [5]. Therefore, we limit ourselves to the case of wire meshes with wires stretched and interwoven in two orthogonal directions: these mesh structures have a mechanical advantage over wires in that they are quicker to make and stronger. We have worked with anode planes made of meshes and wires, in single-step and multistep modes, in order to make comparisons.

Gaseous chambers containing vapours such as triethylamine (TEA) or tetrakis(dimethylamine)ethylene (TMAE) can be made to produce observable light in the UV and visible regions, respectively. This light production is the result of de-excitation of excited states formed by electron impact collision with the molecules during the amplification process [6]. Previously it was shown that the ratio of the amount of light produced to the amount of charge present was a function of the charge gain [7]. These relationships have a peak at low charge gain (5 to 10) indicating that to produce light most efficiently it is best to have a low charge gain close to the peak of this curve (see fig. 1). In this work these observations were extended and also now include measurements with intense electric fields and the effects of their geometry.

2.1 Multistep chamber with an optical-fibre readout

A multistep chamber [3, 4] is a device combining a PPAC with either another PPAC or a MWPC. If the PPACs are constructed using meshes, the electrons produced by the Townsend avalanche mechanism in one PPAC can be transferred out through the mesh plane and drifted into a second amplification step, which is either another PPAC or a MWPC; higher gains can thus be achieved. These types of devices can be of interest in high-energy physics because they permit high-rate operation ($> 10^7$ Hz) when gated; this also allows event selection from a high background [5].

Since the electrons produced are drifted perpendicularly to the mesh planes, such a device can be used with complex events, having a

large multiplicity, provided the means for reading out such a large multiplicity can be found. One method of handling these events is by optical imaging of the secondary light produced from the charge-multiplication process. The first multistep light chamber [8] had a geometry identical to that of the first multistep chambers used with charge-readout methods; they both used a MWPC as the second step of amplification, and initially it was assumed that most of the light was produced in the MWPC final amplification step. However, after some measurements with a multistep light chamber composed of a PPAC as the first step of amplification and a MWPC as the second, there was an indication that the light was mainly produced in the PPAC and not in the MWPC. The chamber construction is shown in fig. 2. It was a multistep chamber with the first amplification gap being a PPAC made with meshes, and the second amplification gap was either another PPAC made only of meshes or a classical MWPC. The chamber had thin Aclar^{*}) windows to allow X-rays to penetrate, and to permit UV light produced in the chamber to be imaged. Located on the outside of the exit window was an array of ten wavelength shifting optical fibres^{**}), 1 mm in diameter; these shifted TEA emission to 450 nm and were connected to a photomultiplier tube (PMT); the amount of light produced by the chamber, measured by this system, is shown in fig. 3. Two types of measurements were made: first the gain in the first step of amplification was kept constant, while that in the second MWPC step was varied; this was done for several different gains in the first step of amplification and the results are shown as the solid curves in fig. 3. The second type of measurement was done keeping the gain in the second MWPC step constant while that in the first step, a PPAC, was varied; the result is shown as the dashed curve in the figure. From a comparison of these curves, the fact that the slope of the dashed curve is much steeper indicates that light was produced

^{*}) Polychlorotrifluoroethylene (PCTFE).

^{**}) Fibres provided by M. Bourdinaud, CEA, Saclay (France).

most efficiently when the gain in the first amplification step was increased.

The light source could be determined by using only one optical fibre connected to the PMT, and moving the radioactive source perpendicularly to the optical fibre in order to measure the light distribution. This was done with only the first amplification step turned on (dashed curve in fig. 4), and with only the MWPC turned on (solid curve in fig. 4). The widths of these two curves are due to the different distances of the optical fibres from the light source. When the chamber was operated as a multistep light chamber, with a high gain in the first stage, the distribution of light after normalization was identical to that shown by the dashed curve in fig. 4; this indicates that most of the light was produced in the first step of amplification, the PPAC, and not very much in the second step, the MWPC. With the experience obtained in using optical fibres for these tests, it is now possible to suggest using an array of optical fibres close to the light source in order to determine the position of the avalanche. Both dimensions could be obtained by having two layers of optical fibres perpendicular to each other, their readout being achieved by using a linear charge-coupled device or a pin diode string. If the optical fibres are placed close to the light source, then the distribution of the light will be much smaller than shown in fig. 4. Although this method would only be able to handle the same multiplicity as the MWPC charge readout, it does have other advantages of the light-readout methods, which can be useful in some applications. When using optical-fibre readout in a gas scintillation detector for astronomy applications [9], difficulties arise from insufficient light; here, with stimulated light emission by electron multiplication, this is not a problem.

This work was our first indication that the light yield was dramatically greater in a uniform electric field amplification process, such as that taking place in a PPAC. After determining that the MWPC was hindering the maximum possible amount of light, the MWPC

was replaced by a second PPAC using meshes. To understand the limiting factors in the maximum light achievable, a comparison of light output for different charge gains was performed, using a single-gap PPAC, and multistep chambers with two PPACs. The results are shown in fig. 5. Here it is seen that the maximum charge gain achieved has some upper limit dependent upon the gas mixture, but independent of the method used to obtain it. The most striking feature of this figure is that the light produced with a multistep chamber using two PPACs is at a maximum when the gain in the first PPAC is at a maximum, with the second step at a lower gain; the light was then observed to originate almost completely from the second PPAC. This should be compared with the lower light output, when the chamber was operated with maximum gain in the second PPAC and moderate gain in the first. Under these conditions, even though the final charge gains were identical, 200 times less light was observed than with the more favourable operating conditions. This effect is related to the decaying tail in the light-to-charge ratio at high charge gains.

2.2 Light and charge measurements with a single amplification gap

Figure 6 shows the field lines in a gap limited by meshes, made of 50 μm diameter wires spaced every 500 μm , which are common and commercially available^{*)}. The electric fields are calculated in three dimensions using the actual geometry of a perfect mesh. The black dots are the wires of the mesh, perpendicular to the plane of the paper; this plane is half way between two of the mesh wires that are parallel to the plane of the paper (and thus perpendicular to the other wires). Figure 6a shows a mesh plane with non-symmetric fields, as is commonly found in multistep structures; fig. 6b shows an anode mesh plane with symmetric electric fields (similar to those fields used in MWPCs, but here with a mesh replacing the wire plane). It is clear that if the electric field is large enough for inelastic

^{*)} Manufactured by Gantois, Saint-Dié, France.

collisions to occur in the uniform field region, such collisions will also occur close to the wires, with an increased probability per unit length since the fields are slightly higher there. The gain may depend upon the different paths taken by the lines of force guiding the electrons, which may differ as a function of the initial position of an initially converted electron. The gain may be variable, thus spoiling energy resolution if such a gap is used for X-ray imaging when compared to an amplification gap with a perfectly uniform electric field. The electrons produced in the uniform field may either go to the wire at various angles, thus traversing different electric fields, or be transferred into the region beyond, which has a different electric field. This may affect the electronic gain and also the photon yield. This is best illustrated by the following experiments, performed on a double gap where the electronic signal is collected on the anode mesh and there is a simultaneous measurement of the light intensities with a photomultiplier.

The experimental system consisted of a ^{55}Fe X-ray source placed in front of the chamber. The chamber had thin Aclar windows, transparent to light of wavelength larger than 280 nm, on both sides so that the UV photons emitted from the excited TEA molecules could be observed with a PMT that had a quartz window. The chamber was constructed with mesh planes mounted onto fibre-glass-epoxy frames. The schematic of the chamber construction and experimental set-up is shown in fig. 7. The electrode mesh planes were constructed out of 50 μm diameter stainless-steel wires spaced 500 μm apart. The anode plane was changed according to the tests being performed, but it was either the same as the electrode mesh planes, or another mesh made of 30 μm stainless-steel wires with the same spacing, or wires of different diameter and spacing. The thickness of the conversion gap was 17 mm; the thickness of the amplification gap and the back gap could be changed to investigate the dependence of charge and light output. The gas mixtures used were mainly 90% argon and 10% methane, or 90% argon, 8% methane, and 2% TEA; also other gases were occasionally used.

The initial tests were started after calculating the electric field for an anode mesh plane at high voltage between two cathode ground planes; these electric-field conditions are similar to those in the MWPC, but with the wire plane replaced by a mesh plane. We were interested in measuring the relation between the charge and light produced as a function of the electric fields in the two gaps. In the past, the PPACs with mesh electrodes were operated with a high electric field on one side of the charge-collection mesh and zero electric field on the other; these conditions are referred to as antisymmetric fields. Figure 8a shows the electronic charge signal and fig. 8b the light signal as the electric field is changed from an antisymmetric to a symmetric field around the mesh anode. The results are at first sight surprising: whilst the charge signal increases when the field is made symmetric, the light signal decreases. The explanation lies in the fact that practically no light is produced in regions of intense electric fields such as those found around wires, and a careful study of fig. 6 provides the answer. The upper half of fig. 6 shows the antisymmetric case and the lower half the symmetric case. It is clearly seen from a comparison of these two figures that the electric field in the gap decreases when the electric field around the mesh plane is made symmetric. With the electric field lower in the gap and higher on the mesh wires, there is less amplification in the gap. Even though the charge signal increases, the light production is less, indicating that the latter comes mostly from the gap and not from amplification processes in intense electric fields. Another example of this effect will be described later in the paper. This work also shows that an anode wire plane may be replaced by an anode mesh, which is much stronger and easier to manufacture, and the detector still acts like a proportional wire chamber, as shown by measurements of pulses produced by X-rays (fig. 9). Other experiments have proposed the use of metal strips or pads, for the last electrode, to carry out the charge collection [10, 11]. There have been some difficulties with this technique owing to charge

buildup on the insulators between strips or pads, and spark discharges to the charge-sensitive pads destroying the electronics. After seeing that it was possible to use anode mesh planes as the charge-collection electrode in a symmetric electric field we are led to suggest the use of cathode pads as the back electrode, see fig. 10. This would have the advantage of a highly segmented pad readout for high-multiplicity events, as in the other cases, but it would not create the difficulties encountered when the pads are used as the last electrode for charge collection as mentioned above.

Table 1 lists the many different chambers which were constructed to determine the optimal conditions for light and charge measurements. The data in table 1 were obtained at the maximum safe operating voltage for the given conditions, and the symbols refer to those in fig. 7. With one chamber we also investigated different gas mixtures under conditions of symmetric and antisymmetric electric fields around the anode mesh, and the results are listed in table 2. This has clear consequences for developments which aim at obtaining the maximum amount of light. It is more advantageous to split the amplification process into two steps: a first step aiming at the maximum electric charge multiplication which can be attained under stable conditions with respect to sparking, followed by a second step with a modest gain to optimize the light yield (see fig. 11).

We have found that there is more light with larger gaps between meshes, since there are then no regions of intense electric fields, and this is why the imaging optical chambers are now much easier to operate. In the early times when the final step of amplification was a wire chamber it was operated at extreme gains, such as those found in limited streamer mode, in order to observe satisfactory tracks. Conclusions drawn from these data indicate that the optimum chambers for light-imaging readout are with parallel electrodes made of meshes, and the best conditions for electronic charge readout are with wires having the spacing of the classical MWPC. However, for those experiments where it may be desirable to construct large

chambers out of meshes and still use electronic readout methods, because of the easier construction, it is still possible to do this if lower pulse-height signals are acceptable. Also the best gases for charge signals seem to be those of the MWPC.

It was suggested that the amount of light being observed was influenced by shadowing of the wires; in MWPCs most of the light could have been shadowed by the wires if the intense electric field concentrated the avalanche on one side of the wire, such that the light produced was hidden from the view of the PMT or camera. We have measured the amount of light being emitted on both sides of the chamber for MWPCs as well as PPACs and found no difference. We also measured the amount of light at varying angles with respect to the normal to the exit window and found the light emission to be isotropic.

2.3 Energy resolution

The initial work with multistep avalanche chambers [3, 4] had a surprisingly good energy resolution obtained from the first amplifying gap. Figure 12 illustrates this initial structure, which consisted of a conversion space for the X-ray photons, an amplifying gap between parallel grids, a drift space where the electrons from the amplifying gap were transferred and, finally, a multiwire chamber. The resolution was roughly the same as that of wire chambers, i.e. 18% FWHM for 5.9 keV X-rays. It was not the best which could be reached by a careful tuning of all the parameters contributing to the resolution, but it was sufficient for a number of applications. The fluctuations in uniform electric fields have been analysed by Alkhazov [12], and the attainable energy resolution should, in principle, be better than with single-wire proportional chambers.

The charge-signal energy resolution is shown in fig. 13a for our single-gap chamber filled with 90% argon, 8% methane (CH_4), and 2% TEA. It has 14% FWHM for the PPAC mode and 18% when the anode mesh plane is operated with a symmetric electric field. The light-signal

energy resolution, shown in figs. 13b and 13c, is 18% for the PPAC and 20% for the symmetric electric field mode. In the PPAC mode the charge-signal energy resolution is practically 1% short of the value reached by those groups who have strived to attain the best energy resolution, even though in our tests we have used low-cost electronics. These results are in agreement with Alkhazov's calculations that uniform electric fields produce better energy resolution. The energy resolution of our light measurements is worse than the charge-signal energy resolution, as would be expected from an additional fluctuation in the light-production mechanism on top of the charge fluctuations.

In this respect we can mention other work advocating the use of the 'Penning Imaging Counter', which was a normal multistep chamber filled with a Penning gas [13]. Such a mixture was used in the original multistep chamber, when it was thought that a Penning mixture was important for the uniform transfer of charge from the amplifying gap to the transfer gap. Indeed, studies with a LiF window between these two gaps showed that with these mixtures the transfer mediated by photons does exist. However, further studies showed that the transfer was also uniform with mixtures not exhibiting the properties of a Penning mixture, where the electrons produced in the avalanche simply moved along the lines of force going from one gap to the other.

It is also worth mentioning that the transfer of charge does not always lead to a loss of energy resolution. This may be due to the fact that the lateral spread of the avalanche is very favourable for proportional amplification at the anode mesh of the final stage. The anode mesh limits the effect of space charge from the positive ions, which is strongest when they are in concentrated avalanches such as those found around wires. Such an effect was observed with the spherical drift chambers [14], where the energy resolution from the charge gain improved after the ionization electrons had drifted by as much as 15 cm, with respect to that obtained by direct detection in the wire chamber.

2.4 Feedback measurements from mesh planes

A useful way of reducing the secondary effects produced by the UV photons emitted from TEA vapour was found when the stainless-steel mesh wires were gold-plated. The chamber used in these tests was similar to that shown in fig. 3, with a 3 mm amplification gap but with a gold-plated drift electrode. Since the electronics used to observe the charge signal was not fast enough, it was not possible to measure the photon feedback from a mesh plane other than that of the drift electrode. The time delay between the drift electrode and the anode plane was 180 ns. The electronics circuit used to measure the feedback is shown in fig. 14; the main idea in the measurement of the feedback was to determine for each event the time until the next event. The threshold of the electronics for detection was on the level of 5 primary electrons; hence our measurement was not sensitive to secondary single photoelectrons. If all of the observed signals were originating from the source, then the time spectrum should be flat, owing to the random time process of the decaying source. If there was feedback from the TEA molecules in the gas there should be an observed increase in the time spectrum for times corresponding to gas drift distances when compared to the longer times which are purely due to statistics. For feedback from the mesh plane the time spectrum should have a bump related to the drift-time needed for the electrons extracted from the mesh plane to drift back to the anode mesh. The threshold of electron extraction for stainless steel is 4.5 eV, lower than that for gold, which is 5.1 eV. The light-emission spectrum of TEA was previously measured [15], and is shown in fig. 15. Because less photons emitted from TEA reach the threshold of gold than that of stainless steel, we observed a sharp decrease in feedback pulses, from 0.7% with stainless-steel meshes to 0.05% for gold-plated meshes, for the same observed charge pulse height, as shown in figs. 16a and 16b respectively.

Such a dramatic drop in the number of photoelectron feedback pulses from the gold-plated mesh and the lack of observable feedback

from the TEA molecules in the conversion gap show that the main source of photon feedback in avalanches is photon emission by the TEA and not the vacuum ultraviolet (VUV) photons from the Ar or other gases used in the detector. Feedback effects, caused by the reabsorption of photons produced in the avalanche, may also affect the energy resolution. If the feedback effects are reduced, higher gains and better energy resolution could be achievable. Since the secondary effects leading to feedback or discharges are dependent on the light intensity, it is most favourable that the first step of electron multiplication be reached under conditions of large electric fields. Also for any chamber where it is wished to observe light, regions of intense electric fields such as those found around wires should be eliminated to avoid feedback from VUV photons.

2.5 Combining uniform-field amplification with wire amplification

We wished to construct a chamber that had two steps of amplification in a single gap. Our first attempt was a chamber that used an anode plane of wires with 10 μm diameter and 1 mm spacing; the chamber construction is shown in fig. 7; the amplification gap thickness is $d = 3 \text{ mm}$ and the back-gap thickness is $b = 5 \text{ mm}$. The aim was to have uniform electric field amplification in the gap and additional amplification on the wires. For the detection of X-rays or single UV photons it is possible to remove the parallax error by obtaining a knowledge of the depth of conversion.

The charge gain in an amplifying gap between parallel electrodes, $G = e^{\alpha x}$, is a function of x , the distance between the initial electron and the anode, and of α , the first Townsend coefficient (a function of the electric field and the gas). If the initial electrons from a drift space are injected into the gap through a cathode grid, this gain is constant. If the initial conversion electrons are created inside the amplifying gap the gain will be variable. This variable gain may be exploited to advantage in some applications: it is useful to enhance those events that occur very

near to the cathode, such as in autoradiography [16] or slow neutron imaging [17] with gadolinium converting foils. It is also an advantage for applications where the pulse heights of the avalanches from low-energy X-rays are used to obtain information about the depth of absorption in order to overcome parallax error.

The most direct proof of combined amplification came when we used an 8 keV X-ray generator, collimated to a 300 μm diameter beam, which was directed at an angle of 45° to the mesh planes (see fig. 17). For this measurement only one anode wire signal was read out. The X-ray beam was moved in 0.5 mm steps so as to change the average depth of conversion with respect to the readout wire, and the average pulse height was recorded. The geometry was taken into consideration and the depth of conversion calculated for each point. The pulse height as a function of the depth of conversion is shown in fig. 18. Although this was not the largest amplification possible in the uniform electric field, it was the best linearity that could be achieved with the electronics at hand. Depth of conversion was measured away from the anode plane so that the largest pulse height occurred when the X-ray converted 3 mm away from the anode plane. The saturation of the amplifier is starting to dominate at large pulse heights.

Table 3 lists the voltages used on this special chamber when it is operated in classical multiwire chamber mode, in PPAC mode, and in a combined mode. The standard gas mixture of 90% argon and 10% methane was used in the experiments described below. By applying a low symmetric electric field around the anode wire plane, the chamber operated as a classical MWPC, exhibiting 20% FWHM energy resolution for ^{55}Fe . At slightly higher symmetric electric fields, amplification in the gap started to become more important, and with small increases in the electric field the energy resolution quickly degraded. After seeing this degradation it was obvious that the same effect must have been seen 20 years ago when other experimenters, including some of the present authors, tried to make MWPCs with very small wire

spacing. Our conclusions are that care must be taken, when operating an MWPC with 1 mm wire spacing, in the choice of the gap distance between the anode and the cathode planes, as well as in the use of the correct gas mixtures, so that uniform field amplification combined with wire amplification does not destroy the energy resolution at high gains. Parallel-plate amplification was when there was an electric field across the gap in front of the anode wire plane and zero electric field across the back gap, but it was far from being pure PPAC operation because the thin wires always added some contribution to the amplification. These two modes of amplification were combined by first finding the proper operating voltage for classical MWPC mode and then adding amplification in the front gap by increasing the electric field across this gap. There was an additional conversion gap preceding the uniform field amplification gap. When the conversion gap had a reversed voltage across it, so that the electrons produced there were not collected by the anode wire plane, then the dominant signal came only from those X-rays that converted in the uniform field amplification gap. The conversion gap was also operated so as to drift the electrons towards the anode wire plane; in this case almost all of the electrons had the same amount of amplification in the uniform electric field. The pulse-height spectra for combined amplification mode with the conversion drift on and off are shown in fig. 19. The difference in pulse-height spectra for these modes is a second proof of combined amplification. Differences in the amplification factors of wires and of uniform fields were between 3 and 100, but the amplification in the gap was probably higher. When the conversion gap was turned off, the good energy resolution was destroyed by the varying amplification coming from the different depths of conversion for the X-rays. The charge amplifier used had a sensitivity of 230 mV/pC, as calibrated with the capacitance of the chamber included. Average maximum pulse heights in proportional mode were 820 mV for ^{55}Fe X-rays, which indicated a gain above 10^5 .

Using a gas mixture of 90% argon, 8% methane, and 2% TEA vapour, the light output was measured with a photomultiplier. Large amounts of light were seen when the chamber was operated in PPAC mode and in combined mode, but very little light was observed when the chamber was operated in classical MWPC mode. This agrees with the measurements with the other chambers described in section 2.1, which are summarized in table 1. The amount of light was measured when the chamber was operated at maximum gain in the gap for combined amplification mode and the charge-signal pulse height noted. The electric field across the front amplification gap was lowered, but that across the back gap was raised, in order to keep the same charge-signal pulse height as before, and the amount of light was measured. This was continued as much as possible and the amount of light output as a function of electric field across the front gap was measured, as shown in fig. 20. It is seen from this figure that as the electric field across the amplification gap was decreased, the amount of light also decreased, even though the charge signal remained the same. This indicates that the light is produced mainly from the uniform electric field region and that there is very little light production in intense electric fields.

2.6 Timing measurements

The test chamber with the combined amplification described in section 2.4 was operated without the conversion region, using a ^{106}Ru beta source. Others who have worked with low-pressure PPACs [18] have noticed that the timing resolution was extremely good. They attributed this to the property of two steps of amplification, one from the uniform-field amplification and another from the wires or mesh. Their good timing resolution and electric-field calculations were their main arguments for two-step combined amplification. We were interested in knowing if our combined amplification chamber described above would have better timing resolution than a normal PPAC or a MWPC with 1 mm wire spacing. The experimental set-up for the timing

measurements consisted of a time-to-amplitude converter; the start signal was provided by a scintillator-photomultiplier at the back of the chamber and the stop signal by the anode-wire plane. Simple threshold timing electronics was used for the anode wire signal [19], and a standard discriminator for the scintillator signal. The timing measurements were made using a gas mixture of 90% argon and 10% methane for classical MWPC, PPAC, and combined-amplification modes with the voltages given in table 3. The measured timing resolutions in FWHM are: 34 ns for the classical MWPC mode, 26 ns for the PPAC mode, and 42 ns for the combined-amplification mode. These measurements have the expected timing resolution for the MWPC mode, but it is our conclusion that the PPAC mode is better for timing measurements than the combined-amplification one.

It was known that low-pressure operation has a large transverse diffusion as the avalanche develops [20], and so it was postulated that this might be the origin of the good timing resolution in the low-pressure PPAC mode. To test this hypothesis, helium or neon gas was used in our chamber, because the diffusion for these gases is larger than for argon [21]. Also, from this same report it is known that as the percentage of quencher is decreased the diffusion increases. Measurements for timing resolution with either argon, neon, or helium, combined with different percentages of methane, are shown in fig. 21. The best timing resolution, i.e. 12 ns FWHM, was obtained in the PPAC mode with 90% neon and 10% methane, as shown in fig. 22. All the measured points in fig. 20 are for the same observed pulse height, and the curves cannot be extrapolated because the PPAC mode could not be reached at lower concentrations of methane for this chamber. These measurements encouraged our belief that the good timing resolution was originating from the larger dispersion of the avalanche. To confirm this belief we used a gas mixture of argon and TEA, where the transverse spread of the avalanche is known, smaller for a higher TEA concentration [22]. We measured an improvement in the timing resolution as the percentage of TEA was decreased; however

it was not better than any of our measurements with helium or neon. This improvement in timing resolution can mainly be attributed to a large avalanche size, which helps to remove the geometry effects of the anode signal plane. A side effect of this might be an increase in the spot size of the light produced for easier optical imaging.

3. SUMMARY AND CONCLUSION

The process of amplification in gaseous wire chambers is sufficiently well documented that it was not discussed here, and we refer the reader to the many places where its description may be found (see for instance refs. [23] and [24], and references therein). The process of gaseous amplification in a uniform electric field, and characteristics of this amplification, can be found in refs. [1, 2], and a detailed description of the fluctuations in gaseous amplification was given by Alkhazov [12].

Above some minimum electric field, depending on the gas, the drifting electrons are accelerated and then undergo inelastic collisions. These collisions, if sufficiently energetic, may lead to the liberation of free electrons by ionizing collisions, or to the emission of photons by the excited atoms or molecules if the electric field is low [7], and more often to a mixture of these two processes. Gaseous amplification processes produce photons which can be generated by atomic excitation or complex molecular effects; we do not want to analyse these here, referring the reader to the work where they are used in gaseous detectors with good energy resolution [25]. The emission of photons plays a great role in the maximum amplification attainable in the avalanches since they are the main contribution to the propagation of discharges; they generate fresh electrons outside the initial avalanche, either in the gas or on the electrodes. This generation of further avalanches leads to streamers or sparks if the gain is extremely high. In photosensitive gases, such as TMAE or TEA, feedback effects are enhanced because of their low ionization potential. Avalanches reaching a size of the order of

10^5 electrons are usually followed by a spark. However, it should be emphasized that such high gains are usually impossible to reach. Even at modest gains, such as 10^4 or 10^5 , it always happens that a rare event, produced for instance by an alpha particle emitted from a contaminant gas such as radon, often present in gases, or a very ionizing reaction produced by cosmic rays, leads to a destructive spark. A non-negligible point, in the progress of parallel-plate amplification structures, has been the availability of cheap amplifiers, well protected against such occasionally large energy sparks.

We have made a comparison between uniform field amplification and MWPCs to study energy resolution, timing resolution, feedback, and maximum charge and light production. The best energy resolution and timing resolution were found in uniform electric fields in a PPAC structure. Feedback from the mesh planes was reduced by an order of magnitude in mixtures containing TEA by gold-plating the mesh planes. Although the wire chamber is a popular device it seems that the future of high-intensity beams, or those events covering a large surface with high multiplicity, can better be dealt with by using multigap structures with either charge-signal or light-imaging readout. The past few years have seen the light-imaging chambers develop from a novel idea into many possible applications. Although the work presented here was an academic study aimed at optimizing the light production for imaging, without any particular application in mind, it is now clear that light is best produced in uniform electric fields that lack regions of high electric fields such as those around wires. Meshes made of $50\text{ }\mu\text{m}$ diameter wires $500\text{ }\mu\text{m}$ apart are favourable. Use of wire-grid planes or meshes with smaller wires produces less light. The PPACs are more favourable for light emission because they have no concentrated intense electric-field regions. A two-step process of first producing maximum charge, which is then transferred into a large gap suitable to produce the maximum light yield, can aid in light-imaging applications. In this work we have also constructed a chamber that has combined the uniform field

amplification process with that of wire amplification. This type of chamber can be used to remove parallax errors in some applications such as the imaging of X-rays or VUV photons.

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Figure captions

- Fig. 1: Relation between charge gain and light gain. Amplification gap width $d = 1.5$ mm, for a gas mixture of 88% argon, 10% methane, and 2% TEA [7].
- Fig. 2: Multistep chamber construction with either a PPAC or a MWPC as the second step of amplification, and an optical-fibre readout.
- Fig. 3: The multistep chamber with a MWPC as the second step of amplification, showing the light output as a function of the charge gain. See text for an explanation of the curves.
- Fig. 4: Light distributions as viewed with the optical fibres. See text for an explanation of the curves, which have been normalized to each other.
- Fig. 5: Light output as a function of charge gain, using either a single PPAC with gaps of different thicknesses, or a multistep chamber with two PPACs.
- Fig. 6: a) Equipotentials for a mesh plane with the amplification gap on the right, and zero electric field on the left; these are the conditions referred to as PPAC mode.
b) Equipotentials for a mesh plane with a symmetric electric field similar to those in MWPCs; in the case of a wire plane, the ovals would be circles.
The slices shown in both these figures are half way between the mesh wires parallel to the plane, and the solid circles are the mesh wires perpendicular to the plane. Notice should be taken of how the electric field in the gap is reduced when a symmetric electric field is applied around the anode mesh plane.
- Fig. 7: Experimental set-up for the measurement of light and charge from the test chamber: the charge signal was taken from the plane labelled A and the light signal was recorded by the PMT.

Fig. 8: Measurement of the charge signal (a) and the light signal (b), as the electric field around the anode mesh plane is made symmetric.

Fig. 9: The charge-signal pulse height for different energy X-rays, showing that the anode mesh plane with a symmetric electric field is proportional to energy.

Fig. 10: A suggested chamber design for the anode mesh plane with symmetric electric field and a back plane made of cathode strips or pads to localize the shower.

Fig. 11: A multistep chamber followed by a light production gap which is optimum for maximum charge production and maximum light emission.

Fig. 12: A schematic of the original multistep chamber with MWPC readout.

Fig. 13: a) The energy resolution of the charge signal for ^{55}Fe X-rays: the black spectrum is 14% FWHM for PPAC operation, and the white spectrum is 18% FWHM with a symmetric electric field around the anode mesh plane.

b) The energy resolution of the light signal is 18% FWHM with ^{55}Fe for PPAC operation.

c) The energy resolution of the light signal is 20% FWHM with ^{55}Fe for symmetric electric field around the anode mesh plane.

Fig. 14: Schematic of electronics used for measuring the amount of feedback pulses due to the reabsorption of UV photons emitted in the avalanche. PA is a preamplifier, TFA a timing filter amplifier, and TAC a time-to-amplitude converter.

Fig. 15: Light-emission spectrum from mixtures containing TEA [13].

Fig. 16: Time spectra showing the time between pulses in the chamber. The large peak on the left of both figures indicates those events that have no stop for a given start within the range setting of the time-to-amplitude converter. This peak is highly suppressed so as to enhance the background level.

a) The feedback pulses from the stainless-steel mesh plane;
b) the feedback pulses with the gold-plated mesh plane. The measured feedback from the mesh plane in (a) is 0.7%, clearly seen above the background, and the feedback in (b) is 0.05%.

Fig. 17: Experimental set-up with the X-ray beam to measure pulse height as a function of the depth of conversion.

Fig. 18: A measurement of the pulse height as a function of the depth of conversion, using the X-ray beam collimated to 300 μm as described in fig. 17.

Fig. 19: The black (light, superimposed) spectrum is the pulse-height distribution with the conversion gap on (off); this is additional proof of the amplification in the gap and on the wires.

Fig. 20: Using the combined-amplification chamber, the amplification in the gap was lowered and that from the wires increased, keeping the same charge pulse height; the amount of light decreased, proving that light comes only from the uniform field amplification region.

Fig. 21: Timing measurements for different gases and different percentages of methane for the chamber operated in the PPAC mode. The curves should not be extended downwards since the PPAC mode was not possible with lower percentages of quencher.

Fig. 22: The best timing measurement of 12 ns FWHM for a gas mixture of 90% neon and 10% methane. The horizontal scale is 17 ns per box.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

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Fig. 9

Fig. 10

Fig. 11

Fig. 12

a)

b)

c)

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22