GAS DETECTORS: RECENT DEVELOPMENTS AND FUTURE PERSPECTIVES

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ABSTRACT

Thirty years after the invention of the Multi-Wire Proportional Chamber, and twenty from the first Vienna Wire Chamber Conference, the interest and research efforts devoted to gas detectors are still conspicuous, as demonstrated by the number of papers submitted to this Conference. Innovative and performing devices have been perfected over the years, used in experiments, and still developed today. Introduced ten years ago, the Micro-Strip Gas Chamber appears to fulfill the needs of high luminosity trackers; progress in this field will be reported, followed by a discussion on discharge problems encountered and possible solutions. Recent and potentially more powerful devices such as the micro-gap, narrow-gap and micro-dot chambers will be described. A new generation of detectors exploiting avalanche multiplication in narrow gaps has emerged recently, namely MICROMEGAS, CAT (Compteur à Trous) and the Gas Electron Multiplier (GEM); whilst still in their infancy, they have promising performances with increased reliability in harsh operating conditions. I will describe also some “tools of trade” used to model the counting action and to analyze the properties of the detectors, discuss limitations to their performances, and suggest ways to improvement. Several still controversial subjects of study (as for example aging), and imaginative efforts of the experimenters ensure a continuing progress in the field of gas detectors, and new editions of this conference for years to come.

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1. INTRODUCTION

The scientific community celebrated last year the hundredth anniversary of the discovery of the electron by Sir J. J. Thomson; its the impact on science and technology need not be discussed here. Thomson's book on gas discharges, relating the work that led to the discovery and to the ensuing developments, remains a fundamental reference for the study of electron-molecule interactions in gases [1]. The single wire proportional counter, invented ninety years ago by E. Rutherford and H. Geiger [2], and its high gain offspring, the Geiger-Müller counter first described in 1928 [3], can be considered the ancestors of all modern gas detectors and were for many decades a major tool for the study of ionizing radiation; they are still in wide use for low-level radiation monitoring.

Thirty years ago the detectors' field was revolutionized by the invention of the Multi-Wire Proportional Chamber (MWPC) by Georges Charpak (Fig. 1 [4]). With its excellent position accuracy and rate capability, the MWPC became very soon a major tool in experimental set-ups used in particle physics. The picture in Fig. 2 shows Charpak and the writer with one of the first large size MWPCs. A large number of descendants, with novel geometry and exploiting various gas properties, was soon developed: drift, time projection, ring imaging Chambers are selected examples (see for example Ref. [5]).

Ten years ago, in 1988, Anton Oed introduced the Micro-Strip Gas Chamber (MSGC) [6], causing again turmoil in the physics community: the expected rate capability and position accuracy of the new device were indeed considerably better, a rather welcome feat at times when high luminosity colliders were close to be built. The picture in Fig. 3 shows the inventor with an unconventional T-shirt reproducing the MSGC structure. Again, a large amount of research was devoted to this new class of detectors, improving the original design and introducing variously named and more sophisticated devices (Micro-Gap, Micro-Dot, Small Gap Chamber....). Recently, and motivated by reliability problems encountered with MSGCs, new innovative devices have been developed; the most original will be described in what follows. For more details, the reader is referred to the literature and to the numerous topical contributions presented at this conference.

This year 1998 sees also the twentieth anniversary of the first "Vienna Wire Chamber Conference"; held in 1978, it attracted a large number of participants and scientific contributions, and was followed by regular new editions; Fig. 4 is a shot taken at one of the early conferences. From the conference proceedings, and quoting the organizers, "the number of contributions ... exceed all our expectations so that not all could be accepted". This comment applies well also to the present 1998 edition, demonstrating that the imagination and the interest of researchers in the field are far from being exhausted. It also implies that this review has to be very selective, neglecting many interesting developments; somewhat arbitrarily, the emphasis has been put on tracking devices, and the reader is referred to the abundant literature and to the other contributions for a more complete coverage of the subject.

2. USEFUL TOOLS

Once confined to bibliographic research, the quest for fundamental data on gaseous electronics is now eased by various computational tools; a list of interesting Internet sites is provided in Ref. [7]. Some of the most useful links cluster around the program GARFIELD [8], expanded from its original scope of computing equi-potential and drift lines in multi-wire structures to a more complete gas detector simulation that includes energy deposits and avalanche development. Connected to MAGBOLTZ [9] for the calculation of electron transport properties and, more recently, to MAXWELL [10] for the 3-D modeling of electric field in structures including odd-shaped electrodes and insulators, the set of programs permit to simulate drift and multiplication processes in complex detectors. A useful compilation of data on electron drift properties has been recently added [11]; an example is given in Fig. 5.

Inclusion in the program of electron-molecule inelastic cross sections permits to simulate the avalanche process, and to estimate the gain of a gas detector in a wide range of conditions. Fundamental physical parameters such as the field dependence of the Townsend coefficient, the avalanche width, the two-track resolution can be evaluated and compared with the data. Fig. 6 provides an example of good matching between computed and measured gain dependence from voltage for a MSGC [12]. In some cases, an analytical or monte-carlo calculation using phenomenological data for the ionization and multiplication statistics can provide very useful indications for the understanding and optimization of detectors; an example is the analysis of the time resolution and efficiency of parallel plate counters discussed recently [13].

3. LIMITATIONS OF GAS DETECTORS AND POSSIBLE IMPROVEMENTS

The low density of gaseous media sets basic limitations to the performances of detectors. In a typical noble gas-quencher mixture at STP, fast particles experience around 40 primary ionizing encounters per cm, releasing in average 100 electron-ion pairs. Statistical fluctuations result in a wide, asymmetric energy loss spectrum (the Landau distribution), and, for the thin layers required for fast response, in poor efficiency and position accuracy. In MSGCs, the position accuracy is around 40 μm rms for tracks perpendicular to the detector, but degrades rapidly with the incidence angle. Several solutions have been envisaged to improve on this point. Operation at pressures higher than atmospheric is possible, but implies the use of containment vessels adding unacceptable amount of material to the experiment. Filling gases containing large fractions of high density quenchers such as isobutane, dimethylether (DME) or the more recently introduced heavy freons ($\text{C}_2\text{F}_4\text{H}_2$, $\text{C}_2\text{F}_5\text{H}$ [14] and C_3F_8 [15]) also improve on primary ionization but usually require inconveniently high operating voltages; electro-negativity and aging properties of these gases are still open questions. The primary ion pairs released per cm in DME is 55 (as compared to 25 for argon), and a value close to 100 has been quoted for C_3F_8 .

A very interesting possibility is to exploit secondary electron emission from solids, a well known process in vacuum, hindered however by back-scattering in presence of gas molecules. Good secondary emitters are low density layers of KCl, KBr, LiF, CsI [16, 17]. In a gas counter having the cathode coated with a columnar CsI layer, around 200 μm thick (Fig. 7), the authors of ref. [18] have demonstrated a substantial enhancement of the detected charge signal. In a more tantalizing device, realized with wires embedded in a thick low-density emitter and operating in vacuum, a large secondary emission coefficient followed by multiplication has been observed [17]; despite the marginal efficiency obtained so far for minimum ionizing particles, exploiting the secondary emission process with its intrinsic independence from the incidence angle and sub-nanosecond timing remains a very challenging possibility and is being explored by several authors [19, 20].

3. MICROSTRIP DETECTORS AND DESCENDANTS

The original concept of the MSGC has been perfected by many authors in view of the use of the detector in a high flux environment. Operating instabilities observed in early devices, essentially due to the rate-dependent charging-up of the insulating support, have been eliminated using bulk or surface-conditioned controlled resistivity supports. Fig. 8 shows a comparison of gains measured for various operating conditions in MSGCs manufactured on bare boro-silicate (dashed curves) and on a diamond-coated support with surface resistivity $\sim 10^{14} \Omega/\text{square}$ [21]. Other conditioning methods have been studied and are reviewed for example in Ref. [22].

The operating characteristics of a MSGC are described by correlated efficiency-noise plots such as the one in Fig. 9, obtained for minimum ionizing particles detected in a 3 mm gap and using a fast electronics recording [23]. The lowest operating voltage corresponds to the separation of signal from noise, and the onset of micro-discharges (revealed by the increase in the noise rate) determines the upper boundary. Although not very wide, the efficiency plateau is acceptable. It has been found however by several authors [24-27] that in realistic operating conditions, with a high flux of particles over all the active area and occasional heavily ionizing tracks generated by neutrons, gamma and nuclear fragments, the maximum safe operating voltage is drastically reduced, in some cases below the beginning of the plateau. Long-term operation of the detector in critical conditions results in a slow degradation of performances and a substantial increase with time of the discharging and dead channels, as shown in Fig. 10 [28].

Two physical processes responsible for discharges in presence of ionizing radiation have been proposed. Field emission of one or more electrons at the cathode strip edges, enhanced by the presence of ions produced in avalanches, has been studied in Ref. [24]. Once ejected, the electrons multiply in the high field around the cathode edges, before reaching the anode strips; overall anomalous multiplication factors above 10^5 have been estimated for a MSGC having a normal gain of a few thousand, see Fig. 11. The process can easily

become divergent, when the avalanche size approaches the well known Raether condition ($\sim 10^8$ electrons), leading to discharge. An alternative mechanism involving the transition from avalanche to streamer, occurring above a critical value of charge, is described in Ref. [29]. Once initiated, the streamer can easily propagate across the insulator. The presence of a thin resistive layer on the substrate, with the consequent increase of the field close to the surface, enhances the streamer propagation. Coating the cathode strips edges with a thin insulator (the so-called advanced passivation) increases the margin between operating and discharge voltage in MSGCs, probably by quenching secondary emission and opposing the flow of current in a discharge [30, 31]. The long-term effects of the introduction of a thin insulator in the MSGC structure remain to be verified.

Improved structures have been developed as alternative to the MSGC, such as the Micro-Gap [32] and the Small Gap Chamber [33]; promising in performances, they require multi-mask processing and are consequently limited in size.

Two-dimensional readout in standard MSGCs can be realized laying pick-up strips on the back side of the support; to obtain sufficient signals, the ratio between substrate thickness and inter-strip gap should be close to unity. For narrow gaps, this implies the use of sophisticated technologies for realization, such as the polyimide-on-silicon used by the authors of Ref. [30].

An elegant way to enhance the back side signal is to remove most metal from the cathode strips leaving only their contour for the application of potentials [34]. With the cathodes left floating, a pickup signal almost as large than the direct anodic one is detected, see Fig. 12. Going to the limit, as in the Virtual Cathode Chamber [35], cathodes have been removed altogether and the multiplying field is provided by the back plane potential. In both devices rate capability is severely limited, unless supports with sufficiently high electronic conductivity are used.

Perhaps the ultimate 2-D gas detector is the Micro-Dot Avalanche Chamber (MDC) developed by the Liverpool group [36]; realized on a silicon substrate, the device consists of metallic anode dots surrounded by circular field and cathode rings (Fig. 13) acting as individual proportional counters, and permits to reach very high gains (Fig. 14). Early instabilities due to substrate charging-up have been eliminated over-coating the device with a controlled resistivity layer. As demonstrated by the authors of Ref. [37], operating the MDC at low pressures and exploiting the parallel plate multiplication in the drift gap one can achieve single photoelectron detection. Applications as photon detectors and Cherenkov ring imagers are being developed.

5. NEW APPROACHES TO DETECTION

Several innovative detector designs have been proposed recently, and appear very promising in terms of performances and, even more important, reliability under harsh operating conditions. MICROMEGAS, a narrow gap parallel plate counter, is shown schematically in Fig. 15 [38]. It consists of a thin

metal grid (micro-mesh) stretched above a stripped readout electrode at a very small distance, 50 to 100 μm . Regularly spaced supports (insulating fibers or pillars) guarantee the uniformity of the gap, at the expense of a small localized loss of efficiency. A very high field is applied across the multiplying gap, typically above 60 kV/cm, and electrons released in the upper drift region are collected and multiplied. Essentially an avalanche counter with a Frisch grid, MICROMEGAS exploits the saturating characteristics of the Townsend coefficient at very high field to achieve a reduced dependence of gain from the gap variations thus improving the uniformity of response over large area. The main properties of parallel plate counters, i.e. rate capability and energy resolution, are maintained, and the authors have demonstrated operation at very high particle fluxes; Fig. 16 shows a measurement of current as a function of voltage, measured at increasing rates of a 20 MeV proton beam. Satisfactory efficiency plateaus have been measured for minimum ionizing particles, perpendicular to the chamber [39]; obtained with relatively slow, low noise amplifiers, the result needs to be confirmed using the faster amplifiers required for high rate operation.

Another interesting new device has been developed recently, the so-called “Compteur à Trous” or CAT [40]. In its basic form, it consists in a single hole drilled through a metal foil cathode and followed by an anode; similarly to the previous device, ionization electrons are drifted into the high field region, multiplied and collected by the anode [Fig. 17]. The authors have analyzed the collection and focusing properties of the field structure, and demonstrated good energy resolution and proportional gains up to 10^4 (Fig. 18). The detected signal has, as expected, a fast electron and a slower ion component; the time length of the ion tail depends from the gap (several μs for one mm), and can be reduced to few hundred ns for narrower gaps. Several variations of the CAT structure have been described, with multiple holes and an insulator plate between anode and cathode to improve mechanical stability.

The described detectors, albeit ingenious and performing, suffer from the basic drawback of all parallel plate counters: a discharge initiated by any of the mechanisms discussed above can lead to a spark. Although the thick electrodes are not damaged, at least in the short term, the same may not apply to the sensitive amplifiers used for readout (one should remember that most modern high-density circuits have been developed for discharge-free solid state devices). The recently introduced Gas Electron Multiplier (GEM) [41] completely eliminates the problem by separating the multiplication and the read-out functions. As shown in Fig. 19, the detector consists of a conversion and a transfer gas volumes, separated by a composite mesh acting as amplifier; the GEM electrode itself is a thin polymer foil, metal-clad on both sides, and pierced by a high density of narrow holes (typically 70 μm at 140 μm pitch). A suitable difference of potential applied across the mesh generates the field structure shown in Fig. 20: electrons released in the upper conversion region drift into the holes, multiply in the high field and continue into the transfer region towards the lower electrode. Gains up to several hundred were achieved in the early GEMs, necessitating a second element of amplification for detection.

Fig. 21 shows combined gain curves for a GEM coupled to a MSGC [42]. Compared to the MSGC alone, the pair permits to obtain larger gains, or given the gain to operate the MSGC at a considerably lower and safer voltages. Extended efficiency plateaus, very good localization accuracy and time resolution (40 μm and 5 ns rms respectively) have been demonstrated in beam tests with prototypes equipped with fast readout electronics [43]. The combined device has been recently adopted as baseline for the HERA-B tracker.

Recent advances in the GEM manufacturing technology, optimization of the geometry and operating conditions have permitted to reach gains up and above 10^4 , sufficient for detection using as second element a simple printed circuit board (PCB) with pickup strips [44]; this mode of operation, where the signal is entirely produced by electrons and no ions are produced in the last gap, is intrinsically fast and safe since the moderate field in the transfer region prevents the propagation of a discharge in GEM (a rare but always possible event) to the readout lines. Fig. 22 shows the pulse height spectrum measured for fast electrons with the high-gain GEM with PCB read-out; fast amplifiers with 40 ns shaping time have been used for the measurement. The ratio signal over noise is around 60, and the efficiency plateaus are correspondingly very comfortable in non-flammable gas mixture of argon and carbon dioxide.

High gain operation of GEM has been demonstrated by the Weizmann group, operating the device at low pressures. A very attractive possibility is to use the upper GEM electrode, facing a transparent window, as photocathode, followed by a transfer of the photoelectrons through the holes to a following gas amplifying device [45, 46]. The strong suppression of photon and ion feedback in this reverse photocathode configuration should permit to obtain efficient single photon detection; various gain-limiting feedback processes are being analyzed in order to optimize the device [47]. Operation at high pressures and xenon filling has also been demonstrated, in view of applications in medical imaging [48].

6. CONCLUSIONS

Almost one century after its origin, and thirty years after the invention of the wire chamber, the field of gaseous electronics is far from being fully exploited, as demonstrated by the many innovative contributions submitted to this conference. In many instances, the observations are controversial; to quote from Thomson's foreword to his book, "In several cases the results obtained by different observers are contradictory, suggesting that some factors may themselves be complex and depend on unsuspected conditions which have not been specified". This statement remains true today, and is suggestive of yet more innovative and exciting developments in the future.

Although the name "Wire Chamber Conference" has since several years only historical meaning, with the appearance of wire-less detectors, there is no doubt that this conference will continue to be successfully organized and attended in the years to come.

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FIGURE CAPTIONS

- Fig. 1: The first MWPC (1968).
- Fig. 2: G. Charpak (left) and F. Sauli (center) with a large MWPC (1972)
- Fig. 3: A. Oed, wearing a strip T-shirt, at the time of the invention of the MSGC.
- Fig. 4: (Left to right): M. Regler, G. Charpak, W. Bartl and G. Neuhofer celebrating the successful conclusion of an early Wire Chamber Conference.
- Fig. 5: Comparison between computed and measured drift velocity for electrons.
- Fig. 6: Examples of computed and measured gains in a MSGC.
- Fig. 7: Columnar CsI growth, $\sim 200 \mu\text{m}$ thick, for secondary emitters.
- Fig. 8: Rate dependence of gain for MSGCs made on boro-silicate glass (open points, dashed curve) and on diamond-coated glass (full points).
- Fig. 9: Gain, efficiency and noise rate as a function of cathode voltage in a MSGC.
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- Fig. 20: Electric field structure in the GEM holes.
- Fig. 21: Combined gain of the GEM+MSGC detector.
- Fig. 22: Pulse height distribution for fast electrons in the GEM+PCB detector.

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