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**APPLICATIONS OF GASEOUS DETECTORS IN ASTROPHYSICS, MEDICINE
AND BIOLOGY**

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ABSTRACT

This paper gives some examples of use of gaseous position-sensitive detectors in applied fields other than elementary particle physics. The applications are grouped by family of devices: optical imaging chambers, conventional and unconventional multiwire chambers, microstrip gas chambers, and span over a wide range of applications, from astrophysics to biology and medical research.

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1. Introduction

Gaseous detectors of various kinds (ionization chambers, proportional and Geiger counters) have been in use for decades for detection of radiation. In the early seventies large area, fast position-sensitive gaseous detectors based on the Multiwire Proportional Chamber (MWPC) [1] were developed, primarily to satisfy the stringent demands encountered in elementary particle experimental physics. The spread of these new technologies in other applied fields, relatively slow in the beginning, has considerably increased in the recent years; often, original developments of the devices have been necessary for a better match to the specific experimental needs.

While remaining rather frail and complex instruments, and therefore requiring dedicated operators, MWPCs and their offsprings represent in many cases unique tools for detection and localization of radiation in advanced applied research. The continuing efforts towards an increase of the ruggedness and reliability of the devices, the introduction of performing wireless detectors (as for example parallel plate and microstrip gas chambers) permit to foresee an increasing use of gaseous detectors in astrophysics, medicine, biology.

The present review describes some representative examples of use of gaseous devices in various fields. The applications have been grouped according to the type of detector used, and in each section a short description of the detector itself is provided. For more details the reader is referred to the contributions in this volume and to the quoted literature.

2. Operation and applications of the Optical Imaging Chamber

Avalanche charge multiplication is exploited in gaseous counters for amplification of the ionization signal. Together with the production of electrons and ions, photons are also emitted in the avalanche in a wide range of wavelengths as a result of molecular excitation and recombination processes. While in charge detecting devices the operating conditions are optimized to reduce secondary effects induced by photon emission and reconversion (for example by the use of large fractions of a photon-absorbing or quencher gas), in imaging chambers one tries to detect and visualize the emitted photons. It has been shown [2] that addition of low ionization threshold vapors such as TEA* and TMAE⁺, together with the use of a parallel plate geometry (as against a MWPC structure), largely enhance the emission in a spectral region convenient for optical detection.

The structure of an Optical Imaging Chamber (OIC) is shown schematically in Fig. 1. Electrons released in a gas for example by cosmic rays tracks drift under the influence of an electric field towards a region of very high field between two semi-transparent grids. In the ensuing avalanche development, photons are copiously emitted and emerge from the detector through a suitable window. An image intensifier with suitable optics is used to bring the signal up to a level compatible with the sensitivity of a solid state camera (CCD); the image can be

* TEA: Triethylamine, $(C_2H_5)_3N$

+ TMAE: Tetrakis (dimethylamine) ethylene $[(CH_3)_2N]_2C = C[N(CH_3)_2]_2$

recorded directly or after digitization. To obtain high gains, one can use instead of a single amplification gap a multistep avalanche chamber [3]; to better tune the spectral emission to the sensitivity of the photon detector a thin foil wavelength shifter can be mounted in contact with the last electrode.

The simplicity and the high granularity of the device has sprouted the application of the OIC in various fields where these performances largely compensate for the modest data acquisition rate obtainable [4]. The most pictorial of these applications is the visual detection in real time of cosmic rays. As the chamber is continuously active, even a modest sensitive volume (a few liters of gas) shows tens of tracks per second due to natural radiation; an example is shown in Fig. 2. A device of this kind is to be operated at the Universal Exhibition in Sevilla to illustrate technological developments at CERN [5]. A similar detector with the gain pushed to very high values, installed at the CERN permanent exhibition "Microcosm", allows direct visualization with naked eyes of tracks produced by 5 MeV alpha particles [6].

Use of the imaging chamber is being considered for an experiment aimed at detection of weakly interacting massive particles (WIMPs) [7, 8]. Originally proposed making use of a conventional time projection chamber, the experiment will profit from the greatly increased granularity of the optical device to improve background rejection. The apparatus consists in a very large volume of gas (tens of cubic meters) where recoil protons ejected off hydrogen or methane can be detected through amplification of the ionization trail in a geometry similar to the one shown in Fig. 1. To improve background rejection, the detector is operated at low pressures (1/10 to 1/20 of the atmospheric) to obtain measurable ranges for the low energy recoil protons (few KeV); in order to decrease the dispersing effect of diffusion on the drifting electrons, particularly large at low pressures, it is foreseen to operate the device in a strong magnetic field parallel to the drift direction. Simulations show that a distribution of the end point of the recorded tracks, compensated for the daily rotation of earth, should be able to pinpoint galactic sources of the hypothetical WIMPs with a good degree of confidence (Fig. 3). One can foresee the use of the imaging chamber in other astrophysics applications, for example in the detection of extended air showers generated by very energetic gamma rays, a domain in which more conventional systems of drift chambers are already considered (see the next section).

Down to earth, the OIC is being used in biology to map the two-dimensional activity distribution in anatomical samples marked with radioactive labellers [9]. The main advantage of the gas detector over conventional contact auto-radiography with photographic plates is the linearity of the response over an extended range of activity, see Fig. 4 [10]; this allows quantitative analysis in a single exposure. Fig. 5 shows examples of color-coded activity distributions in anatomical samples (brain slices of male and female rats labelled with tritiated vasopressin*) recorded with the imaging chamber [10]. This study aims at ascertaining the effects of hormones release at the early stages of development on the sex of mature animals. Due to the sensitivity to individual radioactive decays, comparable contrasts are obtained with exposure times one or two order of magnitude shorter with the gaseous device as

* AVP, [^3H] vasopressin

compared to film. This obviously allows the realization of exposure-intensive studies.

3. Applications of conventional and unconventional MWPC systems.

In the classic MWPC structure electrons released by ionization in the gas are multiplied in the high field created around thin wires. Various methods can be used to obtain localization over extended surfaces: simple digital detection of pulses over threshold on anode wires, measurement of the center of gravity of signals induced by the avalanches on cathode strips, coupling of the signals to an external delay line, measurement of the collection or drift time of charges [11]. Each methods has its advantages and drawbacks, and the choice is therefore application-specific.

An example of direct use in astrophysics of technologies developed originally in high energy physics is given by the Cosmic Ray Tracking project, aimed at detection of extended air showers produced in the upper atmosphere by energetic photons [12]. The basic element of detection is shown in Fig. 6: it consists of a pair of large volume drift chambers separated by an iron plate-scintillator sandwich used for triggering and as muon filter. Tracking is realized measuring both the drift time and the induced signals on arrays of cathode pads in the central wire plane; muon identification is obtained by comparison of the tracks measured before and after the muon filter (electrons will either be absorbed or generate an electromagnetic shower). Fig. 7 shows an example of cosmic shower detected recording the time profile of signals detected on six adjacent wires. The project foresees the installation of around 400 detector modules arranged in concentric rings and covering an area of about $3 \cdot 10^5$ square meters. Due to the superior two-track resolution (a few mm) as compared to existing scintillation counters arrays, the project aims at extending downwards the sensitivity of the detector to extended air showers by two orders of magnitude in energy (from 10^{14} to 10^{12} eV for the incoming photon).

Classic MWPCs have been used for applications in medicine and biology. The most widely used readout method makes use of delay lines, that transform the space coordinate of the induced signals on cathodes into time delays (the anode wire plane being used to provide the reference time) [13]. The rate limitations and single hit capability of such readout method are compensated by the great simplicity and low cost.

Fig. 8 shows the beta activity distribution recorded with a MWPC with delay line readout in anatomical samples (slices of a dog's heart) labelled with tritiated deoxyglucose [14]. The experiment aims at studying the regional uptake of sugars in the heart under different stimulation conditions. Animals are open-chested after anesthesia, and selected efferent axons of cardiopulmonary nerves stimulated after injection of tritiated deoxyglucose. After excision, the distribution of the labeller is detected with the chamber and compared to normal distributions. The interest of the work resides in the large number of experimental animals used (around 20) with several hundred of preparations analyzed, again a rather time consuming exercise when using photographic methods.

With a similar apparatus, optimized for the detection of x rays in the range between 20 and 60 KeV, the same group has demonstrated the superior qualities

of digital methods over photography in the clinical measurement of bone mineral content in the peripheral skeleton [15]. A pressurized (3 bars) xenon-filled MWPC with delay line readout is used to detect and localize the photons at rates up to 220 kHz. Single photon absorption (SPA) transmission images are obtained using radioactive sources emitting photons at 27.4 KeV (^{125}I) and 42 KeV (^{153}Gd); the limb to be imaged is immersed in a water bolus, and the contribution of soft tissues can be subtracted making a transmission image of the bolus alone. In Double Photon Absorption (DPA), the soft tissue contribution is cancelled recording two images at different energies (27.4 KeV from ^{125}I and 60 KeV from ^{241}Am) and logarithmically subtracting the two after weighting. Fig. 9 shows an example of absorption radiography with the corresponding bone density distributions computed along selected lines.

MWPC of conventional design are limited in their use to moderate acquisition rates, several hundred kHz or so over the whole detector, mostly because of the time necessary for transferring and recording the coordinate information; this is particularly the case for the most accurate localization methods (as for example the center-of-gravity) requiring numerical elaboration of the recorded information. A simple counting of the hits on a wire can be done at much higher rates, but does not provide two-dimensional localization in conventional MWPC. An ingenious geometrical construction has been used to fully profit from the high intrinsic rate capability of the gas detectors for x-ray transmission radiography [16]. With reference to Fig. 10, the object is exposed to a fan beam of x rays from a point source (a collimated x-ray generator); the position detector, a pressurized xenon MWPC, is built with a particular geometry having non-parallel anode wires pointing to the source. All x-rays with the same angle are therefore detected by the same wire, and the counting rate on wires provides the absorption profile in the slice. Successive slices are obtained scanning through the body with the generator-detector system.

To compensate for the variable distance between anodes (affecting the gas gain) the anode to cathode distance is increased correspondingly. The system can acquire data at a rate in excess of 300 kHz per wire, with a typical position accuracy around 0.8 mm fwhm. The requirement of a coincidence between adjacent wires, while reducing the efficiency, allows an improvement of the resolution (to 0.64 mm fwhm). Fig. 11 shows an example of transmission digital radiography of the chest obtained with the described apparatus in clinical conditions. The low exposure dose (few mREM skin value) allows to foresee the use of the device in radiation-sensitive areas of the body.

4. Microstrip Gas Chambers

This recently introduced gaseous detector [17] may overcome some of the restrictions met in the classic multiwire structures, in particular the resolution and rate limitations resulting from the practical minimum wire pitch (a mm or so). As shown in Fig. 12, a Microstrip Gas Chamber (MSGC) consists in a set of thin parallel metal strips on an insulating substratum, alternately connected as anode and cathode; an upper electrode defines the sensitive volume of the chamber. Typical dimensions are given in the figure. Electrons released in the gas drift to the anode strips, where the high electric field induces avalanche multiplication much as in a wire counter. A suitable potential applied to the back

plane prevents the collection of ions on the insulating substratum and minimizes gain-perturbing charging up processes.

The MSGC allows to reach gas gains around 10^4 with remarkably good energy resolutions (12% fwhm for the 5.9 keV x-rays [18]). The fast collection of most of the ions produced in the avalanche by the neighboring cathode strips imply also a very high rate capability, close to a MHz/mm² (in fact limited by the acquisition electronics [19]).

Several schemes can be used to readout the space coordinates of the detected radiation in the MSGC. A simple amplifier-discriminator on each anode strip will provide an accuracy corresponding to the pitch, while recording the profile of induced charge on cathode strips allows to get an accuracy of 30 μ m rms for minimum ionizing particles [18]. A charge division readout method has been developed for the x-ray detector of the Soviet-Danish Röntgen Telescope (SODART) [20], see Fig. 13. Groups of cathode strips are connected through a resistive chain, with pickup amplifiers in discrete positions. The second coordinate is provided by a similar system mounted on an induction grid above the amplifying structure.

Although limited to moderate rates, the scheme allows to reduce the number of electronics channels to a minimum, a stringent requirement for space applications. Operating the detector with a xenon-CH₄ mixture, the authors have demonstrated a position resolution around 340 μ m rms for 5.9 keV x-rays. In two detectors optimized to cover the low and the high energy x-ray region respectively, the energy spectra shown in Fig. 14 a) and b) have been obtained.

Use of the MSGC as detector for x-ray transmission radiography is appealing because of the very high rate capability of the device. It has been recently demonstrated that MSGC can reliably operate in xenon mixtures at pressures up to 6 bars, a necessary requirement for obtaining efficient detection of x-rays at the energies used for clinical applications [21].

It might be appropriate to mention here that MSGC are still experimental devices, and a lot of work remains to be done in order to fully understand their operating characteristics. Long-term gain drops due to charging up processes on the insulating support and ageing phenomena have been reported [19], and will have to be solved before one can think of widespread use of the devices in physics and in other applied fields.

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Figure captions

Fig. 1: Schematics of the imaging chamber. Electrons released in the gas volume drift to the parallel plate avalanche chamber. Photons emitted by the avalanches are detected by an image intensifier coupled to a solid state camera.

Fig. 2: An example of cosmic activity recorded in a single frame with the video digitizer.

Fig. 3: Simulated distribution of the end points of recorded track for signals and background, for a hypothetical source of WIMPs located in the galactic center (corrected for the earth rotation).

Fig. 4: Response of the imaging chamber (left) and of conventional film autoradiography to increasing activities of a tritiated polymer standard.

Fig. 5: Activity distribution in brain slices of a female and male rats labelled with tritiated vasopressin (the real size is about 10 by 5 mm²).

Fig. 6: Detector module for the cosmic ray tracking project. It consists of two independent chambers separated by a muon filter and scintillator.

Fig. 7: A cosmic shower recorded by six drift wires equipped with flash analogue-to-digital converters.

Fig. 8: Regional uptake of deoxyglucose under effort. The activity distribution in slices of a dog's heart is recorded following repeated stimulation of specific cardio-pulmonary nerves after injection of tritiated deoxyglucose.

Fig. 9: Transmission digital radiography of limbs. The histograms show examples of bone mineral content and density computed along selected lines.

Fig. 10: Scanning system for transmission radiography using a high rate digital MWPC.

Fig. 11: Absorption radiography of the chest obtained with the high rate digital MWPC.

Fig. 12: Schematics of the microstrip gas chamber.

Fig. 13: Schematics of the charge division system foreseen for the readout of a MSGC used in the soviet-danish Röntgen telescope (SODART).

Fig. 14: Measured energy resolution of the MSGC built for SODART in the low (a) and high energy (b) x-ray regions.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

FEMALE LONG

MALE LONG

0.0

0.007

0.014

1 mm

Fig. 5

Fig. 6

Fig. 7

EXPERIMENT: 0

SLICE: 4019

SLICE: 4001

SLICE: 3020

SLICE: 6001

SLICE: 5020

SLICE: 5001

SLICE: 7037

SLICE: 7018

SLICE: 6020

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14 a

Fig. 14 b