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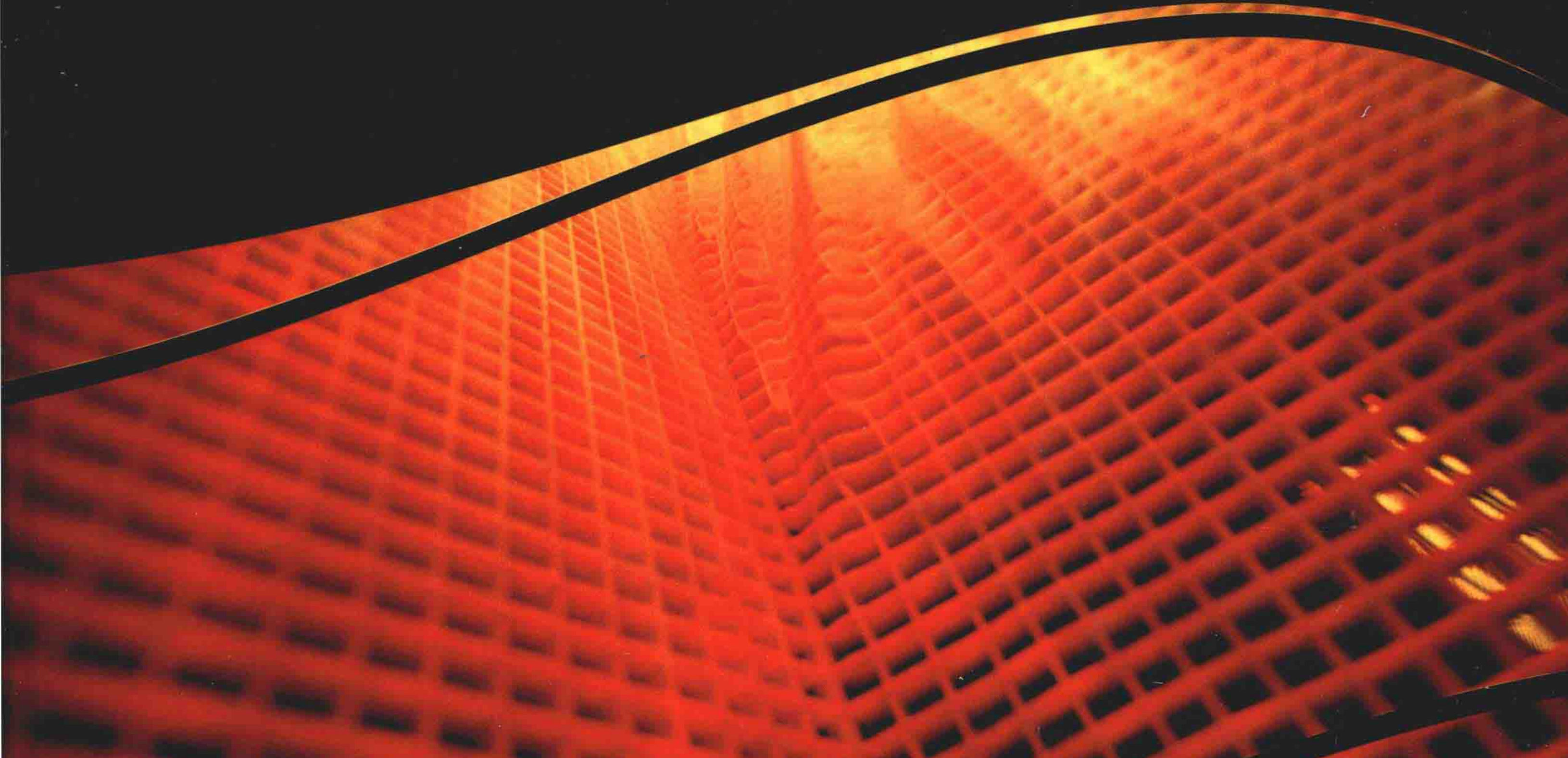
Innovative Applications and Developments of Micro-Pattern Gaseous Detectors



Tom Francke and Vladimir Peskov

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Innovative Applications and Developments of Micro-Pattern Gaseous Detectors

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A volume in the Advances in Chemical and Materials Engineering (ACME) Book Series

ENGINEERING SCIENCE REFERENCE
An Imprint of IGI Global

Managing Director: Lindsay Johnston
Production Editor: Jennifer Yoder
Development Editor: Allison McGinniss
Acquisitions Editor: Kayla Wolfe
Typesetter: John Crodian
Cover Design: Jason Mull

Published in the United States of America by
Engineering Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

Francke, Tom, 1964-
Innovative applications and developments of micro-pattern gaseous detectors / by Tom Francke and Vladimir Peskov.
pages cm
Includes bibliographical references and index. Summary: "This book focuses on the analysis and use of various gas detection systems, providing a detailed description of some of the most commonly used gas detectors and the science behind them"-- Provided by publisher. ISBN 978-1-4666-6014-4 (hardcover) -- ISBN 978-1-4666-6017-5 (print & perpetual access) -- ISBN 978-1-4666-6015-1 (ebook) 1. Gas detectors. I.Peskov, Vladimir. II. Title.
TP754.F73 2014
622'.159--dc23

2014001599

This book is published in the IGI Global book series Advances in Chemical and Materials Engineering (ACME) (ISSN: 2327-5448; eISSN: 2327-5456)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

All work contributed to this book is new, previously-unpublished material. The views expressed in this book are those of the authors, but not necessarily of the publisher.

For electronic access to this publication, please contact: eresources@igi-global.com.

Advances in Chemical and Materials Engineering (ACME) Book Series

J. Paulo Davim
University of Aveiro, Portugal

ISSN: 2327-5448
EISSN: 2327-5456

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To Kerstin and Tatiana

Preface

THE HISTORY OF GASEOUS DETECTORS

The importance of gaseous avalanche detectors in physics research cannot be overemphasized. After more than 100 years of detector development, they are still the dominant and most successful type of detectors capable of detecting the smallest amount of charge or light, a single electron, or a single photon. It is the ultimate amplifier.

Currently, a revolution is taking place in the development of gaseous detectors of photons and particles. Parallel plate-type and wire-type gaseous detectors, which dominated for decades in high energy and space experiments, are now being replaced by recently invented micropattern gaseous detectors.

Historically, gaseous detectors were the first devices allowing to detect charged particles and high-energy photons. The early gas ionization chambers were only able to measure the current produced inside its volume by ionizing particles, and could detect only high-intensity/high-energy radiation. These ionization chambers consist of two electrodes, an anode and a cathode arranged either in the form of parallel-plates or as coaxial cylinders. When the gas between the electrodes is ionized by the radiation, a current is generated. A sufficiently high voltage applied between the electrodes ensures that the ionization current is fully collected and the current reaches a saturated value. The sensitivity of this detector is limited by the electrometer circuit used, and consequently, it is quite low. At the end of the 19th and the beginning of the 20th centuries, these ionization chambers were widely used in various radiation measurements.

The breakthrough in the ionization measurement technique happened when the avalanche multiplication process was discovered by John Townsend in the early 1900s (Townsend, 1901, 1903a, 1903b). In a strong enough electric field, free electrons in a gas are subject to strong acceleration, and during collisions with atoms and molecules, they can produce secondary electrons via impact ionization. These released secondary electrons are in turn also accelerated and collide with the gas atoms and molecules releasing more even electrons. In this way, an avalanche of electrons is produced from a single primary electron. This avalanche of electrons is collected on the anode of the detector. If n_0 is the number of primary electrons in the gas, An_0 electrons are collected on the anode, where A is the multiplication factor or the gas gain.

The very first avalanche gaseous detectors had a cylindrical cathode and a thin anode wire in the center where a narrow region of strong electric field is created around the wire. The electron avalanches are developed in this region with a radius of a few wire diameters (Rutherford, 1908). These early detectors could reach a multiplication factor of up to 10^8. At the beginning, these detectors were not position sensitive (i.e. they were not able to determine the position of the created primary electrons). Later, some advanced designs of single-wire counters were constructed capable to detect where along the wire the primary electron was liberated, which in some designs gave a position resolution better than 1 mm.

The first Two-Dimensional (2-D) position-sensitive gas detectors were the spark and streamer parallel-plate chambers introduced in 1950-1960. They consist of two parallel metallic electrodes between which a short pulse of high voltage is applied at the moment when the charged particles traverse the chamber (the trigger for this high-voltage pulse is generated by a separate triggering detector). The primary electrons can, depending on the applied high voltage, either produce avalanches or, at elevated voltages, streamers and sparks. A streamer and a spark is formed when the avalanche transits into plasma. The sparks and streamers were photographed or filmed, so that the position of the passing particles could be quite precisely determined (Bella, 1953; Chikovani, 1964; Dolgoshein, 1964). With a stack of such detectors, one could even visualize particle tracks in three dimensions. With further progress of this technique, electronic readout methods were developed, allowing one to obtain the coordinate information from the signals induced on segmented (or wire) electrodes. These detectors were complicated and operated at limited rates of high-voltage pulses, which restricted their applications.

The next impressive invention was the multiwire proportional chamber invented by Georges Charpak et al. in 1968 (Charpak, 1968). This device had an anode plane made of parallel wires with a pitch of 2-3 mm located between two metallic cathode electrodes. Later, the cathode planes were also made of wires or strips. This detector operated in avalanche mode, and the signals could be recorded on both the anode and the cathode planes, allowing one to accurately determine the 2-D coordinate of the avalanche.

This detector has had tremendous success since it operates "continuously" (a constant voltage is applied between the electrodes) and it is capable not only of measuring the position of primary electrons, but also of determining with some statistical accuracy their number, which gives information about the velocity and charge of the incoming radiation. Many important discoveries in high-energy physics have been done with the help of this powerful device.

In 1980s, the abandoned parallel-plate-type detectors were suddenly brought to life again by the developments triggered by the invention of the resistive plate chamber. It has resistive electrodes instead of the metallic ones (Parkhomenchuk, 1971). The resistive plate chambers were modified by Santonico et al. (Santonico, 1981) and can operate either in spark or avalanche mode and have become widely used as muon detectors.

In spite of the great diversity of the gaseous detector designs, all of them operate based on the same principle. The incoming radiation ionizes a gas and liberates primary electrons. These primary electrons trigger the formation of avalanches in the detector regions with a strong electric field. The resulting electrical signals produced are large enough to allow detection even of very weak primary ionization. Hence, these detectors are sometimes called "gaseous electron multipliers." Some detectors operate in even stronger electric fields where the avalanches transit into streamers or sparks producing even larger signals. The gap between the electrodes in all these detectors is typically between 2 and 10 mm. We will continuously name this family of detectors as "classical detectors."

These classical detectors are still actively used in various applications for visualization of charged particles tracks in high-energy physics and astrophysics experiments, for detection of X-rays and gamma rays, in medical and biological instruments, etc.

Micropattern detectors, which is the subject of this book, represent the latest generation of avalanche gaseous detectors. They were invented at the end of the 1980s (Oed, 1988) and are now in a blooming stage. The main advantage of these detectors is that they are produced by microelectronic technology, which offers high granularity and thus excellent 2-D position resolution (20-40 μm), which is impossible to reach with classical detectors. The gap between the anode and the cathode electrodes are reduced to 50 μm, enabling operation at significantly lower voltages than the classical detectors. These detectors strongly compete with classical detectors in many traditional applications. They also open avenues for new applications, which will be described at the end of this book.

THE CHALLENGES

Imagine a micropattern gaseous detector with an active of $1 m^2$ with a fine structure of anode and cathode electrodes separated by a gap of 50 – 100 μm. There are many challenges associated with the production and operation of such an amplification structure. For example:

1. The challenge to produce such a structure without or with a minimum of defects and imperfections.
2. The challenge to provide such a structure with sufficient mechanical stability and robustness.
3. The challenge to clean such structure form microparticles (dust, depositions, insertions) and dirt.
4. The challenge to achieve high enough gas gain uniformly over the whole area and a stable operation in time.
5. The challenge to protect such a structure from destruction in case of occasional sparks. In contrast to the robust classical detectors, the fine electrodes of micropattern detectors can easily be destroyed by discharges.
6. The challenge to develop appropriate multichannel front-end microelectronics capable of efficiently collecting and treating information about the energy, time, and the position of the recorded ionization events.
7. The challenge to achieve reliable operation in practical applications, for example in high-luminosity, high-energy physics experiments.

This list can be made even longer. These are the challenges solved during the years of development.

Most of these challenges are so difficult that they were only solved after a decade of efforts made by a huge number of researches and engineers. To efficiently coordinate this work, an international collaboration, RD51, was formed at CERN.

The challenges 1-3 are mainly technological. In principle, micropattern detectors can be produced in any microelectronics workshops using the same technology as used for the production of modern printed circuit boards. A pattern of small pitch electrodes is usually produced on a metalized dielectric substrate using photolithographic methods. The surface is coated with a photosensitive layer (photoresist), which is irradiated by ultraviolet light through a mask having a corresponding pattern. This photoresist is then developed and non-exposed resist, and the metal below it is etched away. This leaves a fine pattern of conductive areas.

The main challenge is that in contrast to a standard electronic circuit, micropattern detectors operate with quite high voltages, 500-1500 V, applied between electrodes. This imposes additional requirements on the accuracy and quality of their production and cleanliness, since any defect, microparticles, or dirt can provoke discharges.

The challenge 4 in some degree depends on the success in solving challenges 1-3.

Another serious challenge, 5, is to protect the micropattern detectors from, or make it robust enough to withstand, sparks.

In principle, the position information from the micropattern detectors can be obtained with the existing multichannel electronics. For example, the electronics used to read out solid-state detectors can be used also for micropattern detectors. However, it should be properly modified to meet some new requirements, for example, the necessity to withstand violent sparks.

The main challenge is of course to achieve a reliable operation of the micropattern detectors in their applications. As an example, let us mention the experiments at the Large Hadron Collider (LHC) at CERN, where the detector should continuously operate during several years in extremely high rates of charged particles with a minimum sparking rate or, ideally, without any sparking at all.

SEARCHING FOR SOLUTIONS

The first three challenges are related to the detector technology and were solved systematically by the teams of physicists and engineers. A big contribution was done by specialists at CERN (European Center for Nuclear Research) and CEA (Commissariat a l'Enegy Atomique) Saclay, France. As a result of these collective efforts, we now have the technology to manufacture detector modules of up to 1x2 m^2.

The challenges 4 and 5 are more related to the physics of the detector operation. In this book, a special focus is put on these problems and their solutions. In great detail, it describes what causes the discharges, how to prevent them, and how to limit the energy released.

The reader will learn some practical measures to be taken to reduce the risk of the detector destruction by sparks. They include segmentation of the electrodes into smaller parts in order to reduce the capacitance involved in the discharge process, protection of the front-end electronics with input diodes, the use of resistive electrodes that restrict the discharge current in the case of sparks, etc.

Finally, we will make a few comments about electronics for micropattern detectors (challenge 6). To achieve high-position resolution, the charge signals are collected on segmented electrodes (e.g. strips or pads). In many applications, standard electronics used for the readout of solid-state detectors is adopted to micropattern gaseous detectors. The electronics is complemented with additional input circuits (e.g. diodes) for protection against destruction by sparks. There are also promising developments aiming to quickly diminish the voltage applied to micropattern detectors in the case of sparks. Another important development, which may lead to three-dimensional charged particle track reconstructions, is the use of modern front-end electronics directly coupled on the readout pads. Using this technology, the micropattern detectors can approach the level of integration, compactness, and resolving power typical of solid-state pixelated devices, but with areas of hundreds of square meters at a reasonable cost.

The studies described in this book show that as with any other devices, micropattern detectors have some limitations. For example, at low counting rate their maximum achievable gains are governed by the so-called Raether limit, and at high counting rates, due to other physical effects, the maximum achievable gain begins dropping with rate. To ensure a reliable operation, one has to carefully consider all these limits in order to find the best compromise between design parameters. Only this will ensure a reliable operation so that the challenge 7 can be successfully overcome.

FILLING THE GAP BETWEEN THE FAST DEVELOPMENT AND COMMON KNOWLEDGE

The objective of this book is to fill the widening gap between the fast development in the field of micropattern gaseous detectors and the available scientific publications and presentations at conferences.

We will review the main achievements in the field and discuss the most promising directions of future developments and applications. The main designs of micropattern detectors will be introduced (e.g. microstrip gas chamber, microdot counters, micromesh [usually called MICROMEGAS], Gas Electron Multipliers [GEMs]) as well as hybrid detectors that combine several of these detectors. The success for the user depends on a deep understanding of how these detectors work. For this reason, a strong focus will be on the physics behind the operation of micropattern detectors.

The functionality of micropattern detectors will be discussed in great detail, including the factors that determine their maximum achievable gain, counting rate characteristics, energy, time and position resolutions, etc.

ORGANIZATION OF THE BOOK

The book is organized into 12 chapters:

Chapter 1 is focused on the fundamental properties of gaseous detectors in general. This includes the physics of their operation and their main designs, as well as examples of their wide use in high-energy and astrophysics experiments. The description of the various processes involved in the operation of the gaseous detectors, the interactions of charged particles and high-energy photons with gases and other media leading to the creation of primary electrons, the drift and diffusion of electrons on the their way to the region of strong electric field where they experience an avalanche multiplication, the physics of the avalanche process and the result of the avalanche in the form of electrons, ions, photons, etc. are described. The main designs of classical gaseous detectors, single-wire counters, spark and streamer chambers, parallel-plate avalanche chambers, multiwire proportional counters, and resistive plate chambers are reviewed. The physics of the breakdown mechanisms is described. This chapter is intended to give the reader a background knowledge necessary for better understanding the following chapters.

In chapter 2, the first micropattern gaseous detector, the Microstrip Gas Counter (MSGC) invented by Oed in 1988, is presented (Oed, 1988). It is a glass plate covered with alternating anode and cathode strips with a pitch of less than 1 mm. It resembles an array of two-dimensional proportional wire counters. The novelty is that for the first time microelectronic technology was used for its manufacturing, offering new possibilities for large-area planar detectors with small gaps between the anode and the cathode electrodes. The first prototypes of this detector suffered from several serious problems, such as charging up of the substrate, discharges that destroyed the thin anode strips, etc. Later, most of these child diseases were solved. Although nowadays this detector has limited applications, its practical importance is that it triggered the chain of developments that finally led to the creation of a new generation of gaseous detectors, the micropattern detectors.

Chapter 3 describes pixel, microdot, and micropixel detectors. Their invention was inspired by Oed's work on MSGCs. In these detectors, avalanche multiplication occurs in the strong electric field created near small anode dots or pixels. This naturally segments the detector into independent active cells, or pixels. For two-dimensional position measurements, the anode and cathode rows are connected to independent readout lines. One of the advantages with this pixel geometry is that it allows gas gains that are ten times higher than what is achievable with MSGCs. This is due to the geometry of the electric field lines, which near the anode cells are radial, which is a favorable factor for quenching of surface streamers (similar to the field geometry in a wire chamber). These early generation microdot and micropin detectors have recently gained new momentum after the introduction of spark-protected microdot detectors with resistive electrodes. These new detectors fit well with the requirements of some important applications, such as noble liquid time projection chambers (Peskov, 2013).

Chapter 4 is dedicated to one of the most successful micropattern detectors, the micromesh gas chamber (MICROMEGAS) invented in 1995 by Georges Charpak et al. (Charpak, 1995). This detector is a modified parallel-plate avalanche counter having a very small gap (50-100 μm) between a cathode micromesh and an anode plate made of a printed circuit. It has excellent position resolution, 30 μm in conventional gas mixtures and close to 14 μm in CF_4 based gas mixtures. The first prototypes of the MICROMEGAS had spacers between the mesh and the anode plate made of fishing lines. Later, a matrix of micro-spacers was manufactured by microelectronic technology, allowing one to build individual modules with active areas up to 40x40 cm^2. Studies of the main factors limiting the maximum achievable gain of this detector at various counting rates is presented, as well as measurements of the time, position, and energy resolutions of this detector. For completeness, a comparison of these parameters with a classical parallel-plate avalanche counter is done. Today, micromesh gas chambers are one of the most successful micropattern detectors, which conquer more and more applications in high-energy physics and other applications.

Chapter 5 introduces another popular micropattern detector, the Gas Electron Multiplier (GEM), which belongs to the family of hole-type avalanche detectors. Such a detector consists of a dielectric sheet, metallized on both sides, and with a matrix of holes through it. When a voltage is applied between the metalized electrodes, a strong electric filed is created inside the holes. The main feature of GEM is that it is easily manufactured by a photolithographic technology from a thin metalized Kapton sheet. Due to the small dimensions, avalanche amplification occurs in the holes even at relatively low voltages (500-600 V). This detector has several unique features. It can be formed to a curved shape, which is important for some applications. As with any other hole-type detector, GEM can operate in cascade mode, allowing one to increase the overall maximum achievable gain. Cascaded GEMs are used now in several experiments at CERN and elsewhere. A modified robust version of GEM, called a "thick GEM," can operate at gas gains ten times higher than ordinary GEM and is used in various photodetectors.

Chapter 6 describes the progress of the development of glass capillary plates, which also represent the family of the hole-type detectors. In some applications, capillary plates have advantages over the GEM, since they are compatible with vacuum technology, allowing them to be used in sealed gaseous detectors. Prototypes of capillary plates combined with solid photocathodes sensitive to ultraviolet and visible light have been developed and successfully tested. This demonstrates the potential to build large-area, position-sensitive photomultipliers, since at atmospheric pressure there are no serious mechanical constrains of the window size as compared to conventional vacuum-based photodetectors (e.g. photomultiplier tubes). If the glass capillary plate is made of lead glass, which has high density, it can be used as both an efficient convertor of X-rays as well as a detector of the liberated electrons. Such a device is attractive for X-ray and gamma imaging, and the results of the first successful tests of such a detector are described.

Chapter 7 describes the interesting development between 1998 and 2003, when many new designs of micropattern detectors were invented, including a microwire detector, a microslit detector, a so-called LEAK multiplication structure, a microgap parallel-plate chamber, a micro-hole strip plate gaseous detector, etc. Some of them were used in practice. For example, mammographic scanners based on microgap parallel-plate chambers were developed, allowing one to obtain high-quality X-ray images at a reduced radiation dose delivered to the patients. Micro-wire detectors are used in plasma diagnostics, micro-hole strip plate gaseous detectors are used in photodetectors, allowing one to efficiently suppress ion feedback to reach the high gas gains necessary for the detection of single photoelectrons, etc.

Chapter 8 is focused on the physic of operation of micropattern detectors. We will analyze in more detail what can cause discharges in these detectors. It will be shown that at low counting rates, the breakdowns appear when the total charge in the avalanche reaches some critical value, the Raether limit. It will also be shown that in some particular detectors (e.g. microdetectors combined with high-efficient photocathodes) or operating in pure noble gases, the discharges may appear via a feedback mechanism. In all cases, the maximum achievable gain drops with the counting rate due to avalanches overlapping in space and time, and also due to contribution from the explosive electron emission. Detailed studies of the problems these detectors may experience when operating in cascade mode, in particular in GEMs, are presented. The understanding of these effects has allowed researches to make a further step in the development of micropattern gaseous detectors in recent years.

In Chapter 9, the exciting developments in micropattern detectors in recent years are described. This includes GEM and MICROMEGAS detectors combined with micropixel readout, some special designs of GEM and GEM-like detectors sensitive to the ultraviolet and visible light, large area GEM and MICROMEGAS developed for the upgrade experiments at the large hadron collider (~$1 m^2$ modules), etc. A new generation of spark-proof micropattern detectors, using resistive electrodes instead of traditional metallic ones, is introduced. In these detectors, the current of the sparks is limited by the resistivity of the electrodes so that the energy of the discharge is reduced by several orders of magnitude. Various designs of such detectors, resistive GEM, resistive MICROMEGAS, and resistive MSGC, etc., are described. Among this family of detectors, a special place belongs to resistive parallel-plate micropattern detectors achieving at the same time excellent spatial (38 μm) and time (77 ps) resolutions.

In Chapter 10, the unique ability of some micropattern detectors, in particular GEM, MHSP, COBRA, and MICROMEGAS, to suppress the positive ion flow from the multiplication region of the detector back to the drift space is discussed. This feature makes these detectors attractive for innovative applications, such as photodetectors combined with highly efficient solid photocathodes, where positive ions may trigger undesirable false signals, or time projection chambers for the tracking of a high flux of charged particles where the backflow of the avalanche ions into the drift region may strongly disturb the detector operation.

In Chapter 11, a comparison between various designs of micropattern detectors is given, allowing the reader to better evaluate their specific advantages and disadvantages and hence properly determine the optimum fields of their applications. The diversity of micropattern detectors makes them attractive for many applications. For example, in measurements requiring simultaneously excellent time and position resolutions, mutigap-multistrip detectors can be used in high rate applications and hole-type structures are advantageous in detection of visible photons. In some commercial applications, where reliability and robustness are important, spark protected detectors with resistive electrodes could be useful.

In chapter 12, some applications of micropattern detectors will be described. The classical application is tracking of charged particles in high-energy physics experiments. However, currently there are a lot of research and developments going on, which may open new exciting fields of applications, for example in dark matter search, medical applications, homeland security, etc. The chapter starts with the description of "traditional" applications, which are in high-energy physics and astrophysics, and then moves on to new promising developments oriented towards new applications.

THE IMPORTANCE OF GASEOUS DETECTORS

A century after John Townsend discovered the avalanche amplification process, gaseous detectors still represent the best choice whenever a large-area detector at a reasonable cost is required. The advantages of the photolithographic and microelectronic technology has led to a transition from "classical detectors" to micropattern detectors. This opens up a new page in state-of-the-art detector technology. Their applications are now rapidly expanding on several fronts, from the Large Hadron Collider (LHC), Future Linear Collider (ILC), and dark matter search experiments to medicine and homeland security.

Our book is intended to provide a comprehensive understanding of gaseous detectors and act as a selection guide for future applications.

It is oriented to a wide auditorium of readers, including students, researchers, university professors, engineers, medical physicists, technicians, etc.

We hope you find it useful and interesting.

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Acknowledgment

This book is based on our lifelong experience of developing gaseous detectors. During all these years, we have had the opportunity to meet and work with a large number of very skilled and fascinating people, with a common interest in gaseous detectors of all kinds.

We hope that this book reflects the hard work and interesting discoveries made by all these persons. We are grateful for all the knowledge they have shared with us and the memorable moments we have had together.

We would like to take the chance to specially thank some of those who opened our eyes to this fascinating field of research, and who have supported and encouraged us through the years: Amos Breskin, Per Carlson, Paolo Fonte, Robert Golden, Paolo Martinengo, Enrico Eugenio Nappi, Anton Oed, Panagiotis Pavlopulos, Fabio Sauli, Steve Stochaj, and many others.

Special thanks also for many discussions and technical support to Eraldo Oliveri, Leszek Ropelewski, Maxim Titov, and all members of the RD51 collaboration.

None of the work would have been possible without the professional hands of Jacob van Beelen, Roger Bouclier, Eric David, Daniel Lacroix, Rui de Oliveira, Juha Rantanen, Miranda van Stenis, and many more of the skilled engineers.

Finally, we are especially grateful to Martin Suffert and Georges Charpak, who introduced and trained us to the world of gases and electric fields.

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Introduction

Position-sensitive detectors of ionizing radiation (photons and elementary particles) play an important role in the study of our nature, universe as well as in many day-to-day applications. There are four main types of such detectors: vacuum, gaseous, liquid and solid. This book will focus on modern gaseous detectors.

The first gaseous detector, the single wire counter was invented in 1908 by Rutherford and Geiger. It was based on a very interesting phenomenon, Townsend avalanches, which appear in gases at high enough electric fields. Townsend avalanches are still the basis of all gaseous detectors.

From the old time of Rutherford and till now this detector passed through several steps of evolution. In 1992, it looked like the development of wire-type detectors had reached its culmination when the inventor of the Multiwire Proportional Chamber (MWPC), Georges Charpak, was awarded the Nobel Prize in Physics.

After a long and fruitful "wire detector era," two major breakthroughs occurred in the field of gaseous detectors which revolutionized detection of ionizing radiation, the development of resistive plate chambers and of micropattern detectors. These new fantastic detectors make it possible to detect single ultraviolet photons, X-rays, gamma rays, neutrons and any charged particle with a position resolution of better than 100 μm, a time resolution of better than 100 ps, and they can in some cases even be operated without amplifying electronics. They can be manufactured with simple methods in large areas and at low cost.

This book focuses on micropattern detectors. The first such detector, the microstrip gas counter, was invented in 1988 by Oed (1989). His invention triggered a chain of other similar developments performed by various groups. Due to the contributions from a large community of physicists, nowadays united by the CERN RD-51 collaboration, micropattern gaseous detectors are currently in a stage of very fast development and are starting to be used in many applications: from high-energy physics experiments to medicine and homeland security (Alfoncy, 2008; Pinto, 2009; Chefdeville, 2010).

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