Particle Detection with Drift Chambers

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Preface to the First Edition

A drift chamber is an apparatus for measuring the space coordinates of the trajectory of a charged particle. This is achieved by detecting the ionization electrons produced by the charged particle in the gas of the chamber and by measuring their drift times and arrival positions on sensitive electrodes.

When the multiwire proportional chamber, or ‘Charpak chamber’ as we used to call it, was introduced in 1968, its authors had already noted that the time of a signal could be useful for a coordinate determination, and first studies with a drift chamber were made by Bressani, Charpak, Rahm and Zupančič in 1969. When the first operational drift-chamber system with electric circuitry and readout was built by Walenta, Heintze and Schürlein in 1971, a new instrument for particle experiments had appeared. A broad study of the behaviour of drifting electrons in gases began in laboratories where there was interest in the detection of particles.

Diffusion and drift of electrons and ions in gases were at that time well-established subjects in their own right. The study of the influence of magnetic fields on these processes was completed in the 1930s and all fundamental equations were contained in the article by W.P. Allis in the *Encyclopedia of Physics* [ALL 56]. It did not take very long until the particle physicists learnt to apply the methods of the Maxwell–Boltzmann equations and of the electron-swarm experiments that had been developed for the study of atomic properties. The article by Palladino and Sadoulet [PAL 75] recorded some of these methods for use with particle-physics instruments.

F. Sauli gave an academic training course at CERN in 1975/76, in order to inform a growing number of users of the new devices. He published lecture notes [SAU 77], which were a major source of information for particle physicists who began to work with drift chambers.

When the authors of this book began to think about a large drift chamber for the ALEPH experiment, we realized that there was no single text to introduce us to those questions about drift chambers that would allow us to determine their ultimate limits of performance. We wanted to have a text, not on the technical details, but on the fundamental processes, so that a judgement about the various alternatives for building a drift chamber would be on solid ground. We needed some insight into the consequences of different geometries and how to distinguish between the behaviour of different gases, not so much a complete table of their properties. We wanted to understand on what trajectories the ionization electrons would drift to the proportional wires and to what extent the tracks would change their shape.

Paths to the literature were also required – just a few essential ones – so that an entry point to every important subject existed; they would not have to be a comprehensive review of ‘everything’.

In some sense we have written the book that we wanted at that time. The text also contains a number of calculations that we made concerning the statistics of ionization and the fundamental limits of measuring accuracy that result from it, geometrical fits to curved tracks, and electrostatics of wire grids and field cages. Several experiments that we undertook during the construction time of the ALEPH experiment found their way into the book; they deal mainly with the drift and diffusion of electrons in gases under various field conditions, but also with the statistics of the ionization and amplification processes.

The book is nonetheless incomplete in some respects. We are aware that it lacks a chapter on electronic signal processing. Also some of the calculations are not yet backed up in detail by measurements as they will eventually have to be. Especially the parameter N_{eff} of the ionization process which governs the achievable accuracy should be accurately known and supported by measurements with interesting gases. We hope that workers in this field will direct their efforts to such questions. We would welcome comments about any other important omissions.

It was our intention to make the book readable for students who are interested in particle detectors. Therefore, we usually tried to explain in some detail the arguments that lead up to a final result. One may say that the book represents a cross between a monograph and an advanced textbook. Those who require a compendious catalogue of existing or proposed drift chambers may find useful the proceedings of the triannual Vienna Wire Chamber Conferences [VIE] or of the annual IEEE Symposia on Instrumentation for Nuclear Science [IEE].

Parts of the material have been presented in summer schools and guest lectures, and we thank H.D. Dahmen (Herbstschule Maria Laach), E. Fernandez (Universita Autonoma, Barcelona) and L. Bertocchi (ICTP, Trieste) for their hospitality.

We thank our colleagues from the ALEPH TPC group, and especially J. May and F. Ragusa, for many stimulating discussions on the issues of this book. We are also obliged to H. Spitzer (Hamburg) who read and commented on an early version of the manuscript. Special thanks are extended to Mrs. Heininger in Munich who produced most of the drawings.

Geneva *W. Blum*
1 April 1993 *L. Rolandi*

Preface to the Second Edition

The first edition has continuously served many students and researchers in the field. Now we have enlarged and improved the book, essentially in three ways: (1) The chapter on electronic signal processing was added, and (2) the chapter on the creation of the signal was rewritten and based on the principle of current induction. This was made possible because our team was complemented with a new young co-author (W.R.). (3) Also there are various modernizations throughout the book including some of the recent chambers capable to measure tracks at very high fluences that one could not imagine 15 years ago. Four of the chapters were left untouched. The development of drift chambers in the last 15 years was driven by the idea that their performance should be pushed towards the limits of the laws of physics. The concept of the book matches very well this trend because it is the basic principles of drift chambers rather than their technical design solutions that are in focus. The most modern design solutions, among them the ones developed for the experiments of the Large Hadron Collider, can be found e.g. in the proceedings of the IEEE Symposia [IEE] and of the Vienna Wire Chamber Conferences [VIE].

During the last two decades, the development and optimization of drift chambers has increasingly relied on simulation programs, which in some sense ’encode’ the physics processes described in this book. The program GARFIELD, written by Rob Veenhof, is the most widely used tool for drift chamber simulation. It allows calculation of electric fields, electron and ion drift lines, induced signals, electrostatic wire displacements and many more features of drift chambers. For calculation of the primary ionization of fast particles in gases, the program HEED, written by Igor Smirnov, is widely used. A very popular program for calculation of electron transport properties in different gas mixtures is the program MAGBOLTZ, written by Steve Biagi. MAGBOLTZ and HEED are directly interfaced to GARFIELD, which therefore allows a complete simulation of the drift chamber processes, from the passage of the charged particle to the detector output signal. Clearly a thorough understanding of drift chambers, which is subject of this book, is a necessary precondition for efficient use of these simulation programs.

Despite the development of the fine grained silicon detectors which now outperform the wire chambers near the interaction point, the large detector volumes surrounding modern experiments have to rely on drift chambers because of their simplicity and also because their measurement accuracy in relation to their size is better than it is in any other instrument. Time Projection Chambers with electron drift lengths up to 2.5 m are the most important tools for studying heavy ion collisions, because of their very low material budget, channel number economy and particle identification capabilities. TPCs are also studied as principle detectors for future electron colliders. 36 years after the first working drift chamber, these instruments are still going strong.

Geneva
April 2008

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[IEE] The symposia are usually held in the fall of every year and are published in consecutive volumes of the *IEEE Transactions in Nuclear Science* in the first issue of the following year

[PAL 75] V. Palladino and B. Sadoulet, Application of classical theory of electrons in gases to drift proportional chambers, *Nucl. Instrum. Methods* **128**, 323 (1975)

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[VIE] The Vienna Wire Chamber Conferences were held in February of the years 1978, 1980, 1983, 1986, 1989, 1992, 1995, 1998, 2001, 2004, 2007, and they were published mostly the same years in *Nuclear Instruments and Methods* in the following volumes: **135, 176, 217,** A **252,** A **283,** A **323,** A **367,** A **419,** A **478,** A **535.** Since 2001 they are called *Vienna Conference on Instrumentation*.

Contents

Chapter 1

Gas Ionization by Charged Particles and by Laser Rays

Charged particles can be detected in drift chambers because they ionize the gas along their flight path. The energy required for them to do this is taken from their kinetic energy and is very small, typically a few keV per centimetre of gas in normal conditions.

The ionization electrons of every track segment are drifted through the gas and amplified at the wires in avalanches. Electrical signals that contain information about the original location and ionization density of the segment are recorded.

Our first task is to review how much ionization is created by a charged particle (Sects. 1.1 and 1.2). This will be done using the method of Allison and Cobb, but the historic method of Bethe and Bloch with the Sternheimer corrections is also discussed. Special emphasis is given to the fluctuation phenomena of ionization.

Pulsed UV lasers are sometimes used for the creation of straight ionization tracks in the gas of a drift chamber. Here the ionization mechanism is quite different from the one that is at work with charged particles, and we present an account of the two-photon rate equations as well as of some of the practical problems encountered when working with laser tracks (Sect. 1.3).

1.1 Gas Ionization by Fast Charged Particles

1.1.1 Ionizing Collisions

A charged particle that traverses the gas of a drift chamber leaves a track of ionization along its trajectory. The encounters with the gas atoms are purely random and are characterized by a mean free flight path λ between ionizing encounters given by the ionization cross-section per electron σ_{I} and the density N of electrons:

$$\lambda = 1/(N\sigma_{\mathrm{I}}). \tag{1.1}$$

Therefore, the number of encounters along any length L has a mean of L/λ, and the frequency distribution is the Poisson distribution

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$$P(L/\lambda,k)=\frac{(L/\lambda)^k}{k!}\exp(-L/\lambda). \tag{1.2}$$

It follows that the probability distribution $f(l)\mathrm{d}l$ of the free flight paths l between encounters is an exponential, because the probability of finding zero encounters in the interval l times the probability of one encounter in dl is equal to

$$\begin{aligned} f(l)\mathrm{d}l &= P(1/\lambda,0)P(\mathrm{d}l/\lambda,1) \\ &= (1/\lambda)\exp(-l/\lambda)\mathrm{d}l. \end{aligned}$$

From (1.2) we obtain the probability of having zero encounters along a track length L:

$$P(L/\lambda,0)=\exp(-L/\lambda). \tag{1.3}$$

Equation (1.3) provides a method for measuring λ. If a gas counter with sensitive length L is set up so that the presence of even a single electron in L will always give a signal, then its inefficiency may be identified with expression (1.3), thus measuring λ. This method has been used with streamer, spark, and cloud chambers, as well as with proportional counters and Geiger–Müller tubes. A correction must be applied when a known fraction of single electrons remains below the threshold.

Table 1.1 shows a collection of measured values of $1/\lambda$ with fast particles whose relativistic velocity factor γ is quoted as well, because λ depends on the particle velocity (see Sect. 1.2.6); in fact, $1/\lambda$ goes through a minimum near $\gamma = 4$.

Table 1.1 Measured numbers of ionizing collisions per centimetre of track length in various gases at normal density [ERM 69]. The relativistic velocity factor γ is also indicated

Gas	$1\,\mathrm{cm}/\lambda$	γ
H_2	5.32 ± 0.06	4.0
	4.55 ± 0.35	3.2
	5.1 ± 0.8	3.2
He	5.02 ± 0.06	4.0
	3.83 ± 0.11	3.4
	3.5 ± 0.2[a]	3.6
Ne	12.4 ± 0.13	4.0
	11.6 ± 0.3[a]	3.6
Ar	27.8 ± 0.3	4.0
	28.6 ± 0.5	3.5
	26.4 ± 1.8	3.5
Xe	44	4.0
N_2	19.3	4.9
O_2	22.2 ± 2.3	4.3
Air	25.4	9.4
	18.5 ± 1.3	3.5

[a] [SÖC 79].

Table 1.2 Minimal primary ionization cross-sections σ_{p} for charged particles in some gases, and relativistic velocity factor γ_{min} of the minimum, according to measurements done by Rieke and Prepejchal [RIE 72]

Gas	$\sigma_{\mathrm{p}}(10^{-20}\,\mathrm{cm}^2)$	γ_{min}	Gas	$\sigma_{\mathrm{p}}(10^{-20}\,\mathrm{cm}^2)$	γ_{min}
H_2	18.7	3.81	i-C_4H_{10}	333	3.56
He	18.6	3.68	n-C_5H_{12}	434	3.56
Ne	43.3	3.39	neo-C_5H_{12}	433	3.45
Ar	90.3	3.39	n-C_6H_{14}	526	3.51
Xe	172	3.39	C_2H_2	126	3.60
O_2	92.1	3.43	C_2H_4	161	3.58
CO_2	132	3.51	CH_3OH	155	3.65
C_2H_6	161	3.58	C_2H_5OH	230	3.51
C_3H_8	269	3.47	$(CH_3)_2CO$	277	3.54

In Table 1.2 we present additional measurements of a larger number of gases that are employed in drift chambers. These primary ionization cross-sections σ_{p} were measured by Rieke and Prepejchal [RIE 72] in the vicinity of the minimum at different values of γ and interpolated to the minimum $\gamma_{\mathrm{p}}^{\mathrm{min}}$ at γ^{min}, using the parametrization of the Bethe–Bloch formula (see Sect. 1.2.7). The mean free path λ is related to σ_{p} by the number density N_{m} of molecules:

$$\lambda = 1/(N_{\mathrm{m}}\sigma_{\mathrm{p}}).$$

The measurement errors are within ±4% (see the original paper for details). In comparison with the values presented in Table 1.1, the measurements are in rough agreement, except for argon.

1.1.2 Different Ionization Mechanisms

We distinguish between primary and secondary ionization. In primary ionization, one or sometimes two or three electrons are ejected from the atom A encountered by the fast particle, say a π meson:

$$\pi\mathrm{A} \rightarrow \pi\mathrm{A}^+\mathrm{e}^-,\ \pi\mathrm{A}^{++}\mathrm{e}^-\mathrm{e}^-,\ldots \tag{1.4}$$

Most of the charge along a track is from secondary ionization where the electrons are ejected from atoms not encountered by the fast particle. This happens either in collisions of ionization electrons with atoms,

$$\mathrm{e}^-\mathrm{A} \rightarrow \mathrm{e}^-\mathrm{A}^+\mathrm{e}^-,\ \mathrm{e}^-\mathrm{A}^{++}\mathrm{e}^-\mathrm{e}^-, \tag{1.5}$$

or through intermediate excited states A^*. An example is the following chain of reactions involving the collision of the excited state with a second species, B, of atoms or molecules that is present in the gas:

$$\pi\mathrm{A} \rightarrow \pi\mathrm{A}^* \tag{1.6a}$$

or

$$e^- A \rightarrow e^- A^*, \tag{1.6b}$$

$$A^* B \rightarrow AB^+ e^-. \tag{1.7}$$

Reaction (1.7) occurs if the excitation energy of A^* is above the ionization potential of B. In drift chambers, A^* is often the metastable state of a noble gas created in reaction (1.6b), and B is one of the molecular additives (quenchers) that are required for the stability of proportional wire operation; A^* may also be an optical excitation with a long lifetime due to resonance trapping. These effects are known under the names of *Penning effect* (involving metastables) and *Jesse effect* (involving optical excitations, also used more generally); obviously they depend very strongly on the gas composition and density.

Another example of secondary ionization through intermediate excitation has been observed in pure rare gases where an excited molecule A_2^* has a stable ionized ground state A_2^+:

$$A^* A \rightarrow A_2^* \rightarrow A_2^+ e^-. \tag{1.8}$$

The different contributions of processes (1.5–1.8) are in most cases unknown. For further references, we recommend the proceedings of the conferences dedicated to these phenomena, for example the Symposium on the Jesse Effect and Related Phenomena [PRO 74].

A pictorial summary of the processes discussed is given in Fig. 1.1.

1.1.3 Average Energy Required to Produce One Ion Pair

Only a certain fraction of all the energy lost by the fast particle is spent in ionization. The total amount of ionization from all processes is characterized by the energy W that is spent, on the average, on the creation of one free electron. We write

$$W \langle N_\mathrm{I} \rangle = L \left\langle \frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle, \tag{1.9}$$

where $\langle N_\mathrm{I} \rangle$ is the average number of ionization electrons created along a trajectory of length L, and $\langle \mathrm{d}E/\mathrm{d}x \rangle$ is the average total energy loss per unit path length of the fast particle; W must be measured for every gas mixture.

Many measurements of W have been performed since the advent of radioactivity, using radioactive and artificial sources of radiation. The amount of ionization produced by particles that lose all their energy in the gas is measured by ionization chambers or proportional counters. The value of W in this case is the ratio of the initial energy to the number of ion pairs. The energy W depends on the gas – its composition and density – and on the nature of the particle. Experimentally it is found that W is independent of the initial energy above a few keV for electrons and a few MeV for alpha-particles, which is a remarkable fact.