MICROWAVE BREAKDOWN IN GASES

A. D. MacDONALD

LOCKHEED PALO ALTO RESEARCH LABORATORY

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MICROWAVE BREAKDOWN IN GASES

WILEY SERIES IN PLASMA PHYSICS

SANBORN C. BROWN, ADVISORY EDITOR
RESEARCH LABORATORY OF ELECTRONICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

BEKEFI · RADIATION PROCESSES IN PLASMAS
MacDONALD · MICROWAVE BREAKDOWN IN GASES
HEALD AND WHARTON · PLASMA DIAGNOSTICS WITH MICROWAVES
McDANIEL · COLLISION PHENOMENA IN IONIZED GASES

PREFACE

It is now nearly twenty years since I first became interested in electrical breakdown in gases while a member of the group of graduate students working with Professors S. C. Brown and W. P. Allis at Massachusetts Institute of Technology. During the intervening years much work has been done on the interaction of microwaves with gases in general and on breakdown phenomena in particular. Though there are books covering many aspects of this interaction, and though there is considerable interest in breakdown phenomena in connection with propagation of microwaves to and from high-flying vehicles, none of the books has dealt in a substantial way with high-frequency and microwave breakdown phenomena. This book was written in order to provide a unified treatment of both the experimental and theoretical aspects of microwave breakdown in gases. The text is, to a considerable extent, self-contained and should be readily comprehensible to senior undergraduate and first-year graduate students in physics and electrical engineering.

One of the interesting features of this subject is the manner in which theoretical analyses based on the kinetic theory of electrons in the gas can be related to experimental results. This relationship is discussed at some length, and an attempt has been made to present the theoretical derivations based on the Boltzmann transport equation in such a manner that conclusions can be drawn about relationships among the experimental parameters.

A brief account of dimensional analysis is included in the introductory chapter to explain the combinations of experimental variables customarily used in describing gas discharge phenomena. The second chapter is devoted to the processes involved in electron collisions with neutral particles; the concepts considered are essential in the development of breakdown theory.

The Boltzmann equation for an ionized gas is treated as a phase space continuity equation for electrons, and series expansions in both space and time are derived. With these expressions a second order differential equation for the electron energy distribution function is obtained. The range of validity of the expressions used is treated in some detail. Breakdown theory based on the distribution functions is considered in detail in Chapters 4 and 5. The extent of the theoretical development for a given gas is limited by the complexity of the energy variation of the electron-atom collision frequencies, but for a number of gases meaningful comparisons of theoretical predictions with experimental data are possible. The agreement which is found provides a verification of the validity of the breakdown theories.

Chapter 7 includes a description of the methods by which data are obtained as well as details of microwave measurements and modern vacuum and gas-handling systems.

Because of the present interest in breakdown in the atmosphere and in the ionized shock region in the neighborhood of missiles, the final chapter covers breakdown in air and in atmospheric gases. Although the precise distribution function approach does not seem to be feasible for these gases, useful theories have been devised and both theory and experiment are described in detail.

It is a pleasure to acknowledge the help of many people in the preparation of this book. I wish particularly to thank Professor Sanborn C. Brown for his aid and encouragement throughout the whole project, for reviewing the manuscript, and for making many valuable suggestions. Much of the writing was done while I was at Dalhousie University. Professor Forbes Langstroth of the Dalhousie Physics Department read most of the manuscript, and I appreciate his useful advice. Finally, for many stimulating discussions of the subject matter, I am indebted to Dr. R. F. Whitmer and other staff members of the Electronic Sciences Laboratory at Lockheed.

A. D. MacDonald

Palo Alto, California
June 1966

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CHAPTER 1

Introduction

The many interesting things that happen when an electric field is applied across a gas have occupied the attention of physicists for more than a century. Study of "electrical discharges in gases" or "gas discharges," as the phenomena have generally been called, has led to many fundamental discoveries. During the latter half of the nineteenth century and much of the twentieth century this field of research has been closely connected with the mainstream of progress in physics. Though the understanding of the phenomena was not always complete, the studies have led to such fundamental discoveries as cathode rays and x-rays, properties of electrons and atoms, and optical and mass spectrometry. Gas discharge phenomena are now often thought of as part of the field of plasma physics, which occupies the attention of increasing numbers of physicists as it becomes apparent that a large fraction of the matter in the universe is in the plasma state, a fourth state of matter.

The purpose of this book is to describe a small segment of this field—a segment which for the most part dates back only to the end of World War II, but which is important for an understanding of the whole field—that of electrical breakdown at high frequencies. The term "breakdown" as applied to the initiating process seemed reasonable to those studying the phenomena in which a dc voltage across a gas tube was gradually increased until the gas suddenly started to glow and became conducting. The voltage at which the gas "broke down" or at which sparking began was naturally studied early and extensively, and such studies have occupied a central place in gas discharge phenomena over the years.

Quite a number of years ago the relatively low-frequency voltages that were available were tried, but these first extensions of the dc to ac voltages did not disclose new phenomena. When relatively high frequencies were used, interesting effects were observed, however. The term "high frequencies" requires some explanation because it is convenient to use it, in connection with breakdown theory, to include all frequencies above a few megacycles per second. The concepts and theories in this book are based mostly on experiments in the microwave region of the frequency spectrum, but they are applicable to a much wider range of frequencies under some conditions. For this reason some of the theories considered are applied to breakdown studies for frequencies ranging from as low as 2 or 3 Mc/sec to as high as those in the optical part of the spectrum.

In this chapter we outline in a general way the experimental data for which it was necessary to develop the experimental and theoretical models that we now call high-frequency breakdown theory.

Microwave Studies

When an electric field of sufficient strength to produce breakdown is applied across a tube containing a gas, the electrons and ions are accelerated to very high speeds. Unless the frequency of the field is high enough so that the direction of the force on a charged particle is changed before the particle traverses the tube, impact with the wall is likely to produce other charged particles, thus multiplying the electron or ion concentration. When the rate at which electrons are thus produced exceeds the rate at which they disappear, the resultant rapid increase in concentration causes sparking or breakdown. The electrons generally play a dominant role because they are accelerated so much more by a given electric field than are the ions. Secondary electron and ion production by means of impact on the electrodes or walls are characteristic of dc fields, and we may have what are effectively dc phenomena for some alternating voltages. In this case there is a separate dc discharge during each half cycle of the electric field, and under some conditions this may happen for frequencies as high as hundreds of kilocycles per second. This dc breakdown may be much more dependent on the material and condition of the electrode surfaces than on the properties of the gas and, because of this, progress in understanding the basic phenomena in the gas was slow. As a result, by the end of World War II there was little satisfactory theory that would enable one to predict breakdown fields in a gas, in spite of extensive efforts over many years.

The development of radar during World War II led to the improvement of microwave techniques and widespread use of microwave equipment. This opened up new possibilities in many fields of science and in particular in studies of gases. The very high frequencies involved mean that when fields are applied across a gas, electrons move only short distances before the direction of the field changes. Therefore electrons are not swept out of

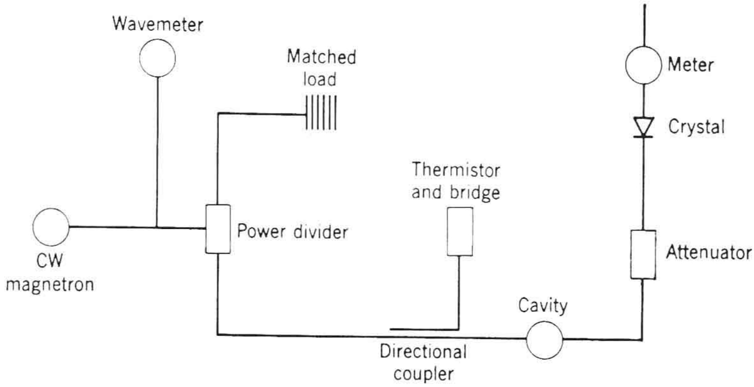

Figure 1-1 Simplified schematic diagram of a typical arrangement for measuring microwave breakdown fields.

the discharge region by the field, but leave with relatively low speeds and produce essentially no secondary effects at the surfaces of the container. For this reason microwave techniques made it possible to study interactions between electrons, atoms, and ions without the disturbance of electrode phenomena, in a manner that had not been practical previously.

Considerable experimental and theoretical work was undertaken, some

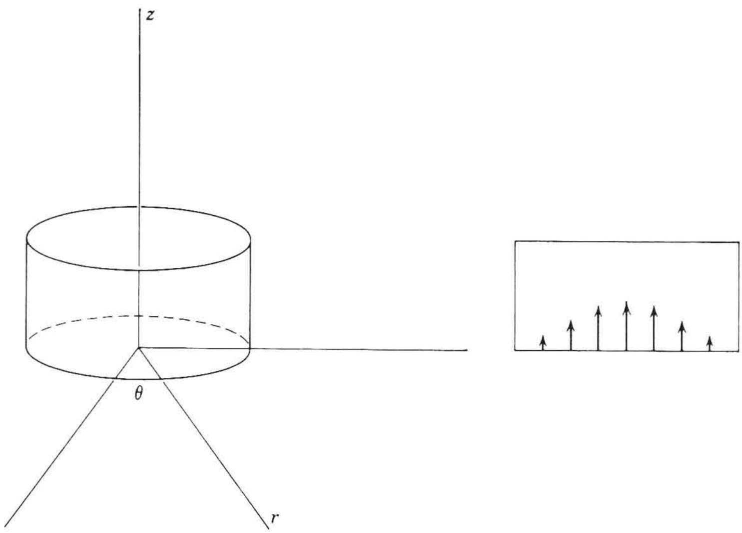

Figure 1-2 Shape of resonant cavity showing direction of electric field in TM_{010} mode.

of which we describe now in order to indicate in a general way the kind of experiments which were done. We will reserve details of experimental procedures until a later chapter and indicate only enough at this point to make the experimental methods understandable.

Experiment. Figure 1-1 illustrates schematically a simplified version of a typical experimental arrangement. Power generated in a very stable CW magnetron is coupled to a resonant cavity. A wavemeter samples a small fraction of the power to measure the frequency. A thermistor bridge connected by a directional coupler monitors the power flow which is controlled by the power divider. A small fraction of the power in the cavity is coupled out through a calibrated attenuator to a crystal and meter. For a particular cavity and frequency, the attenuator and meter combination is calibrated in terms of the thermistor and bridge, and is used during the breakdown measurements to indicate the power in the cavity, because the bridge measurements are very time-consuming.

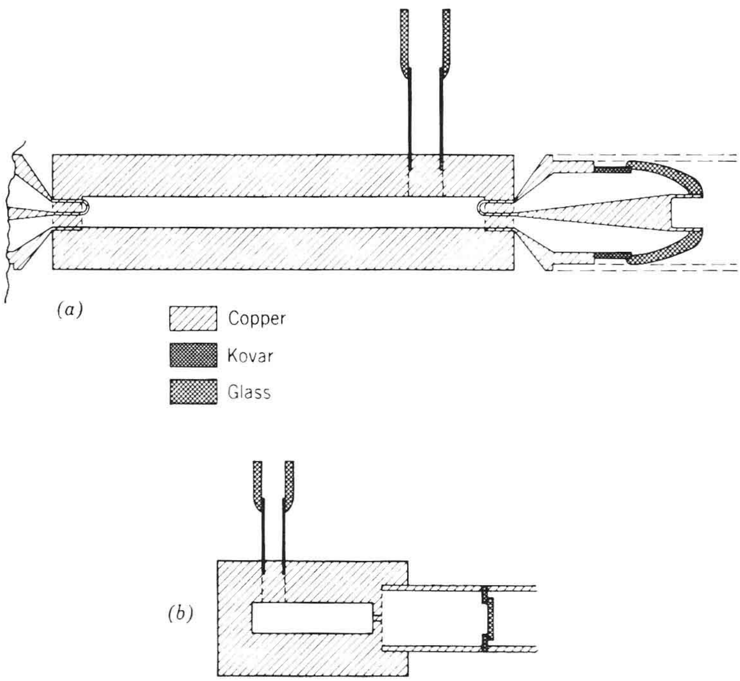

Figure 1-3 Cross sections of typical cavities of $\frac{1}{4}$-inch height. (*a*) Cavity is coupled by loops to coaxial lines—approximately 3 Gc/sec; (*b*) cavity is coupled by an iris to wave guide—10 Gc/sec.

The properties of the resonant cavity are critical in the measurements, and there are differences between the microwave measurements and the low-frequency measurements because, in the microwave region, the wavelength of the field is of the order of magnitude of the container's dimensions. Therefore the region over which the electric field is uniform is limited, and care must be taken to make measurements in a region in which the field is effectively uniform. The type of resonant cavity generally used is a cylindrical TM_{010} cavity, that is, one that is resonant in the lowest magnetic mode. In this mode the resonant frequency is independent of cavity height and the electric field is in the direction of the axis of the right circular cylinder as indicated in Fig. 1-2. A cross-sectional view of the cavity indicating the variation of the electric field with radius is also shown in Fig. 1-2. The field is a maximum at the center, and is proportional to $J_0(2.405r/R)$, the zero order Bessel function of the radial variation. The zero order Bessel function is slowly varying when r is small so that there is a significant region in which the field is almost uniform. Breakdown will take place at the center of the cavity where the field is a maximum. Figure 1-3 shows cross sections of typical cylindrical cavities, one of which is coupled to coaxial lines by loops and the other to a wave guide system by an iris.

The magnitude of the field within the resonator is found by measuring the voltage standing wave ratio on resonance, the cavity Q, and the incident power at the instant of breakdown, by techniques which are now

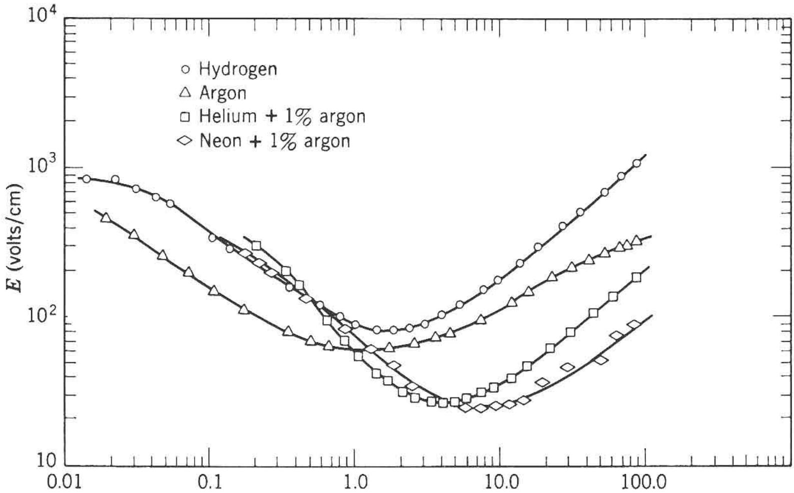

Figure 1-4 Breakdown fields as a function of pressure for different gases (frequency 992 Mc/sec—characteristic diffusion length 0.631 cm).

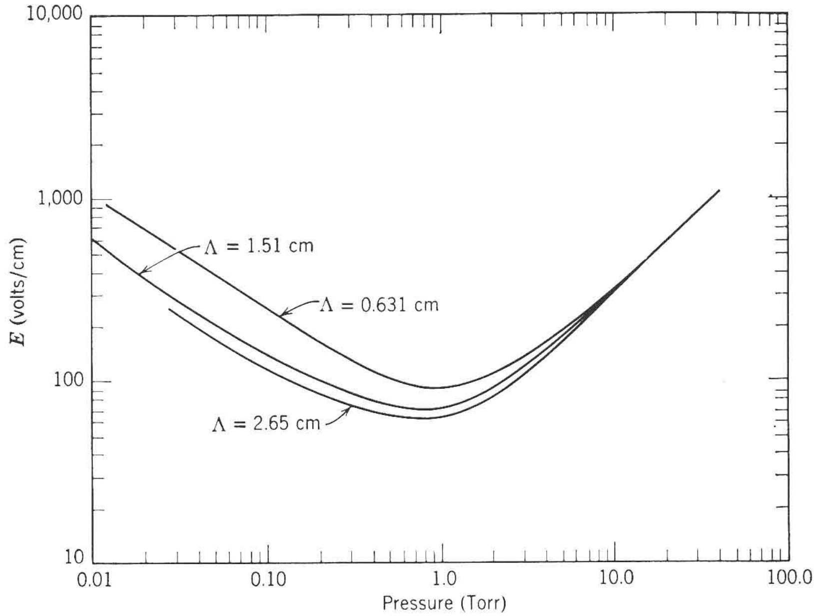

Figure 1-5 Breakdown fields as a function of pressure for different container sizes (gas, air—frequency 992 Mc/sec).

standard and are described briefly in Chapter 7. The cavity itself is made in such a way that it can be evacuated and clean gas samples introduced at any desired pressure. The details of the vacuum techniques are also described in Chapter 7. Several workers, using these or similar techniques, made measurements on a number of gases under various conditions. Figures 1-4, 1-5, and 1-6 show the manner in which the breakdown field varies with pressure when other parameters are also varied. The electric field at breakdown varies with pressure in each of the three cases, and in each there is a further variation, first with the type of gas used, second with the size of the container as represented by the characteristic diffusion length Λ, and third with the frequency of the applied field. These curves, then, illustrate four different variables which affect the breakdown field and also illustrate the types of variation which must be explained theoretically.

Theory. A number of different theories have been developed for different gases, and these will be described in later chapters. The degree of sophistication in the various theories depends on how fully the collision processes involving electrons, ions, and atoms are taken into account. In the simplest

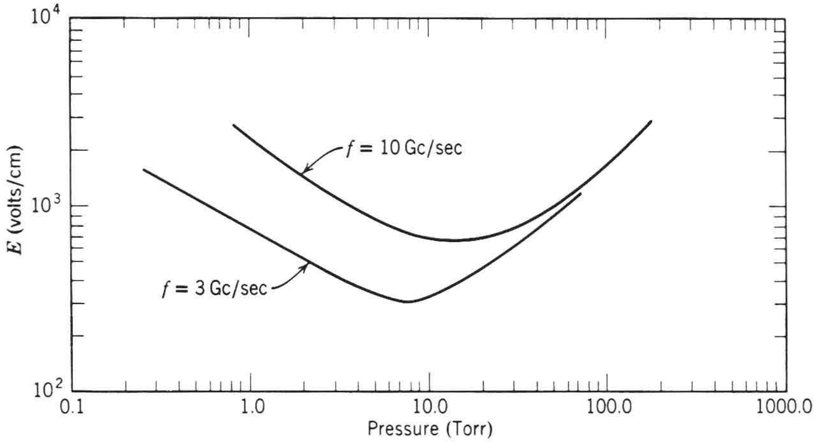

Figure 1-6 Breakdown fields as a function of pressure for different frequencies (gas, Heg, a mixture of He and Hg—characteristic diffusion length 0.6 cm).

theory a model in which all electrons have the same speed is used, and by analyzing the average electron it is possible to describe breakdown phenomena with a fair degree of accuracy. Theories that take account of the fact that the electrons are moving at random with many different velocities have also been developed. Manipulations with functions describing the distribution of electron velocity and energy have made possible calculations of breakdown fields which are accurate within the experimental error, when the parameters range over several orders of magnitude. Such theories have been successful for certain gases, in particular some of the noble gases; but the difficulties of mathematical analysis have prevented development of similar theories for all the gases for which there are experimental data and in which there is interest. One of the gases which does not yield readily to the exact analytic treatment is air. There is considerable interest in microwave interaction in the atmosphere, and so the final chapter is devoted to it. Along with experimental results, we include a phenomenological theory which has been reasonably successful in predicting breakdown for a wide range of variation of pressure and frequency.

Dimensional Analysis

It may be appropriate at this point to discuss the question of dimensional analysis. Although it has seldom been explicitly stated, the use of the results of dimensional analysis has had considerable effect on the development of concepts in microwave breakdown theory, and an understanding of these results gives an insight into the reasons for the particular modes of presentation of the experimental and theoretical data in this field of physics. These reasons seem sufficient justification for taking this diversion before tackling the principal topics with which this book is concerned.

Dimensional analysis, or the principle of similitude as it is sometimes called, is based on two very simple and perhaps obvious principles.

1. Whenever a functional relationship is found expressing one physically measurable variable A in terms of other variables $B, C, D, \ldots$, including dimensional constants such as the velocity of light, the value of A must be independent of the choice of units used to specify the other variables.
2. Any equation representing a relationship between physically measurable variables must have the same units on the left-hand side and the right-hand side of the equation. This is known as the principle of dimensional homogeneity and is discussed at length by Bridgman.[1]

The results which can be obtained on the basis of these simple principles are clearly no substitute for the setting up and solving of the appropriate differential equations in a given situation. On the other hand, the power of the methods that will be illustrated should not be underrated, and many important results have been obtained by dimensional methods. Two noted physicists who made considerable use of the methods were Lord Rayleigh and Sir James Jeans.

A simple example. Consider first a very simple example in mechanics. Suppose we wish to find the way in which the time of oscillation of a simple pendulum consisting of a mass m, suspended on the end of a light string of length l, is related to other variables. We first write out all the variables and dimensional constants that might be involved, as well as their dimensions—in this case those of mechanics, length, mass, and time, designated by L, M, and T.

Quantity	*Dimensions*
Period of oscillation, t	T
Length of pendulum, l	L
Mass of pendulum, m	M
Angle of oscillation, θ	No dimensions
Acceleration of gravity, g	LT^{-2}

If we now write out the period in terms of other variables, assuming that each may appear with any unknown exponent,

$$t = l^{\alpha} m^{\beta} \theta^{\gamma} g^{\delta},$$

or dimensionally

$$T = L^{\alpha} M^{\beta} L^{\delta} T^{-2\delta}.$$