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Introduction

In the late 1950s as part of the International Controlled Thermonuclear Fusion Research Program, several small independent groups started investigating the possibility of using microwave power to create magnetically confined, hot-electron plasmas. This process became know variously as *electron cyclotron heating* (ECH) or *electron cyclotron resonance heating* (ECRH) in recognition of the key role played by resonant absorption of the microwave power at the electron gyrofrequency (often called the "cyclotron frequency"). Of these, the group under R.A. Dandl at the Oak Ridge National Laboratory was unique in using continuous wave (cw) microwave power and large DC magnets to produce steady-state plasmas. Unlike pulsed discharges, this steady-state operation permitted ongoing adjustments of the gas pressure, microwave power, and magnetic field strength as well as extensive diagnostic measurements of the plasma properties. By the early 1960s, it was clear that these plasmas could be operated in regimes that exhibited some remarkable properties. Although the plasmas were confined in simple magnetic mirrors and theoretically predicted to be susceptible to large-scale plasma instabilities, it was found that if the ambient gas pressure was suitably adjusted they could be operated in completely stable, steady-state regimes. Moreover, they contained two or more distinct populations of electrons: a low-temperature group with temperatures of some 10s of electron volts together with high-temperature populations with temperatures in excess of 100 keV and kinetic pressures of at least 5% of the magnetostatic pressure of the confining magnetic field. Dandl's group devoted the next two decades to an intense study of a sequence of increasingly powerful and sophisticated embodiments of these remarkable ECH plasmas.

In the ELMO magnetic mirror device, they achieved stable, steady-state, relativistic-electron plasmas with average hot-electron temperatures in excess of 3 MeV and kinetic pressures comparable to the confining magnetostatic pressure. Thirty years after they were created, these plasmas remain unique in many respects, particularly as regards their copious emission of neutrons apparently resulting from the electron dissociation of deuterium nuclei, as well as the plasma diamagnetic modification of the confining magnetic field to yield substantial localized depressions in the magnetic intensity. The relativistic-electron shells produced in ELMO were subsequently used successfully by Dandl to stabilize toroidal plasmas confined in the ELMO Bumpy Torus.

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At roughly the same time, a group under T. Consoli in Saclay, France, was investigating, among other things, the possible use of ECH plasmas to achieve the collective acceleration of plasma ions through space-charge electric fields. This group later moved to Grenoble and continued an active research program lasting over two decades. The goal of collective acceleration remained elusive, but the ECH techniques developed within this effort were to be influential in the design of sources of multiply charged ions and ultimately in sources of high-density plasma of interest for commercial applications in plasma processing. In particular, Consoli's group pioneered the use of whistler-wave heating to produce high-density albeit low-temperature plasmas. This technique, which later came to be known as high-field launch, coupled microwave power into the plasma electrons via whistler waves launched in the high-field region of the magnetic-mirror fields to propagate along the magnetic lines of force into the resonance region.

A vigorous ECH research program under H. Ikegami began in Nagoya, Japan, in the late 1960s, starting with magnetic-mirror experiments and subsequently progressing to experiments in the bumpy torus magnetic configuration. In the Soviet Union, ECH was investigated first in magnetic mirror devices and then in tokamaks, following the advent of gyrotrons, remarkable sources of high-frequency microwave power first developed in the former Soviet Union.

More recently ECH has found widespread use as a means of providing auxiliary heating in tokamaks and stellarators, as well as a means of stabilizing particular modes of instabilities and driving noninductive currents in tokamaks. In particular, early predictions that ECH could be used to stabilize neoclassical tearing modes of plasma instability in tokamaks were subsequently confirmed experimentally, and further applications became possible with the continuing development of high-power, long-pulse, and cw sources of microwave power at frequencies well above 100 GHz and, therefore, in the electron gyrofrequency range for major tokamak installations. Contemporary tokamaks routinely use several megawatts of 140 GHz microwave power to break down the gas and initiate the plasma discharge, to ameliorate the deleterious effects of plasma instabilities, and to carry out research on plasma and energy confinement. Large stellarators now use ECH to achieve current-free operation and exploit their unique advantage as a steady-state toroidal approach to fusion.

In several large tokamak installations, most notably the Joint European Tokamak (JET), deuterium–tritium plasmas have been heated to ignition temperatures and net fusion energy has been released. Encouraged by such achievements, the major fusion research programs have undertaken a broad collaboration including the United States, Japan, Russia, and the European Community to design, construct, and operate the International Thermonuclear Experimental Reactor (ITER). It appears likely that ECH will perform several important functions in ITER, including startup, auxiliary heating, and suppression of tearing modes. It is also possible that ECH could be used to drive the noninductive plasma currents required for steady-state operation, if that type of tokamak is deemed to be advantageous. Sources of microwave power and low-loss distribution systems have been under intensive development in recent years and gyrotrons in the required frequency and power range are now in operation at several tokamak and stellarator facilities.

These government-funded ECH research programs stimulated advances in various aspects of microwave technology that were essential to fusion applications, particularly the high-power cw millimeter microwave sources mentioned earlier; but the recognition of potential commercial applications of ECH plasmas led to entirely different directions for development. Rather than seeking to create plasmas with extremely high energy density, the developers of commercial ECH technologies typically sought to create large volumes of quiescent plasma with highly uniform densities and temperatures that were typically no greater than 10 eV. Increasingly, arrays of permanent magnets were employed in ECH plasma sources to replace the water-cooled or super conducting DC magnets typical of fusion experiments. Innovative coupler designs were eventually developed to facilitate the use of the ubiquitous and inexpensive 2.45 GHz microwave power sources in commercial ECH plasma devices.

In addition to these terrestrial laboratory investigations of ECH plasmas, there have been several efforts to explore possible applications of ECH to magnetospheric plasmas using ground-based antenna arrays to launch electromagnetic waves along various trajectories into the earth's magnetosphere. One goal of these active ECH experiments in space is a means of precipitating energetic electrons out of the magnetosphere to prevent damage to satellites, astronauts, and ground-based communications networks. There have also been suggestions that ECH could be used to model phenomena of astrophysical interest by employing laboratory experiments whose results can be scaled in size to provide useful insights into the behavior of the larger cosmic systems that seem to exhibit effects of nonthermal plasmas.

Thus, over the past five decades ECH has been employed in a wide range of circumstances encompassing microwave frequencies from 2 to 200 GHz and power levels ranging from less than 1 kW to 1 MW per microwave source. Magnetic configurations utilized in these applications have included simple magnetic mirrors, various types of open-ended magnetic wells, many toroidal devices, as well as magnetic geometries intended to produce unconfined plasmas for industrial processes. Much has been learned about the fundamental aspects of ECH although, regrettably, the pressure to apply ECH in large experiments has meant that some underlying phenomena still need more detailed theoretical and experimental research to resolve outstanding issues that remain. Nonetheless, much ECH physics is relatively mature – a claim that hopefully will be supported by the present work. In the future, the body of ECH science seems likely to find an increasingly wide range of goal-oriented applications. Furthermore, the remarkable achievements of ECH, particularly in regard to the generation of steady-state high energy density plasmas, are so strikingly novel and so rich in potential for further discovery that future basic research efforts are likely to be undertaken to examine phenomena that cannot readily be produced by other means and in other media.

The goal of the present work is to collect in one place most of the basic components of the science of ECH as a resource for present and future students and researchers in the physics of high energy density, relativistic-electron plasmas, as well as for scientists and engineers who are seeking to develop more utilitarian applications of ECH. In the early chapters of the book, emphasis is given to the underlying fundamental physics that governs the outcome of any particular ECH experiment. Later chapters use the published results from various experiments to examine the ways in which these underlying phenomena work in collaboration to determine the properties of ECH plasmas.

ECH of plasmas involves a number of fundamental plasma physics phenomena whose basic properties are relatively well established. These include the motions of individual electrons in various types of static magnetic fields as well as the propagation of electromagnetic waves in low-temperature magnetized plasmas. Chapter 2 deals with the analysis of illustrative types of magnetostatic fields with special emphasis on those properties that are critical to ECH. The motions of individual electrons in these magnetostatic fields are then discussed in Chapter 3. Chapter 4 addresses the coupling of microwave power into plasmas by employing highly simplified models of the plasmas and magnetic fields. Although simplified, these models are particularly applicable to the "quasioptical" plasmas in large contemporary tokamaks and stellarators as well as the ionosphere. The dynamical response of electrons to spatially localized resonant microwave electric fields, while less thoroughly documented, has been investigated by many workers with results that are presented in Chapter 5.

ECH also involves a number of plasma physics phenomena that are not as well established but are especially important, for example, in the generation of relativistic-electron plasmas with very high energy densities. Chapter 6 deals with applicable theories of plasma equilibria based, in the first instance, on simple transport models of plasma particles and heat and, in the second instance, on somewhat ad hoc microscopic models of the anisotropic equilibria confined in magnetic mirror configurations. Chapter 7 summarizes several theories of the stability of ECH plasmas in order to provide a basis for the interpretation of experiments which illustrate the dominant observable properties of specific archetypal ECH plasmas. Several such experiments in magnetic mirror devices are summarized in Chapter 8 and interpreted as fully as possible in the context of the basic ECH physics presented in the earlier chapters.

As was mentioned earlier, many of the present generation of tokamaks and stellarators use multimegawatt ECH power levels at frequencies as high as 157 GHz for several essential aspects of their functioning. Results from several of these as well as earlier tokamak experiments are interpreted in Chapter 9 using the basic physics developed in the earlier chapters.

The ELMO Bumpy Torus employed ECH in several unique roles and the key features of these are discussed in Chapter 10. Chapter 11 discusses some of the ongoing and potential future applications of ECH to space plasma phenomena, again emphasizing aspects of ECH physics that are of unique importance to these applications. Chapter 12 presents a brief overview of some of the technological aspects of the microwave sources and distribution systems that have permitted the dramatic increase in the applications of ECH to the large fusion installations.

Finally, Chapter 13 discusses the more speculative use of frequency-modulated microwave power with steady-state current drive in tokamaks as the main illustration.

As expected in a field that has been developing over five or more decades, much of the basic material in the early chapters of this book is available in many older works. Here this type of archival material is presented in as concise a form as possible and in a uniform notation and system of units (rationalized MKS) with references to much of the earlier work, particularly works that include copious references. The choice of topics covered was largely determined by the interpretative needs of the experiments to be discussed in the later chapters and readers may notice regrettable gaps. The experiments were chosen with the aim of permitting the reader to verify for himself the applicability of the basic ECH phenomenology and obviously many important experiments could not be included. In this regard, the present work differs fundamentally from a review of ECH. Fortunately, there are several excellent such reviews available to the interested reader [1, 2]. Exercises are included at the end of each chapter to encourage students to internalize and make concrete what otherwise might remain vague and intangible.

References

1 R. Prater, *Physics of Plasmas* **11**, 2349 (2004) and works cited therein.

2 V. Erckmann and U. Gasparino, *Plasma Phys. and Control. Fusion* **36**, 1869 (1994) and works cited therein.