Preface

This book is intended to provide the reader with an overview of the basics, the current experimental status, supporting theory and technology, and potential applications of Inertial Electrostatic Confinement (IEC) fusion.

The IEC is a unique approach to fusion in that electrically driven units offer a number of near-term “spin-off” applications. This is largely due to its simple construction and ability to provide a relatively high fusion rate in a small volume, i.e., at a low power level. Such operation is four or five orders of magnitude below energy “breakeven,” but the application justifies the cost of the electrical input required to drive the fusion. Examples include a small neutron source for Neutron Activation Analysis (NAA) to determine impurities in ores or coal at the mine. Extension of that technology discussed in this book includes land mine detection, neutron radiography, clandestine material detection at air- and seaports, medical isotope production, plasma space propulsion, subcritical fusion–fission hybrid reactors, and tunable x-ray sources, to name a few. The simplicity of the IEC has made construction of experiments, often called “fusors,” possible. A number of amateur scientists and high school students have built units in their garages. These garage-based “fusor” experiments typically used hydrogen or run at low voltages to avoid serious radiation (x-rays and neutrons) danger to the operator. These experiments are an important introduction to fusion for a number of young people, some of whom eventually make fusion science their careers. Devices with higher neutron rates have been studied at various universities and laboratories where radiation shielding and monitoring can be employed. Much of this work has been done in the United States and Japan and is documented in a long series of DOE-sponsored U.S.–Japan IEC workshops. Principle participants have been the Universities of Illinois and Wisconsin, Los Alamos National Laboratory (LANL), Kyoto University, Kobe University, and the Tokyo Institute of Technology. Other participants include researchers from the University of Maryland, University of Sydney, University of Missouri, along with the private company EMC^2. Much of the material in this book comes from presentations at these meetings, with emphasis on IEC studies at the Universities of Illinois and Wisconsin, which the authors are most familiar with.

To move the IEC from electrically driven units to fusion breakeven and a power producing fusion plant requires a basic change from beam–background neutral reactions to beam–beam fusion. While studies of magnetically insulated and actively cooled grids have been performed, the preferable approach is to replace physical grids with "virtual" electrodes, forming a deep potential well for ion confinement. Indeed this is along the lines originally proposed by Philo Farnsworth (the U.S. inventor of electronic television) in his IEC patent which discussed "poissors" (virtual electrodes). The feasibility for experimentally achieving such a state revolves around fundamental physics issues such as ion beam thermalization, ion upscattering out of the well, stability of this configuration, and the ratio of ion to electron "temperature" (average energy). Much work remains to resolve these issues. Still, if such an IEC mode can be achieved, the door would be opened to a highly non-Maxwellian fusion plant capable of using advanced fuels such as D–^{3}He and p–^{11}B as well as D–T and D–D. Due to its simple structure and theoretical capability to achieve breakeven and net power gain in small units, an experimental campaign to study this could be done faster and at much less cost than currently involved in the international effort to develop a Tokamak reactor based on magnetic confinement.

This book reviews some computational/theoretical studies focused on moving toward an IEC power unit, but many issues need more study to fully understand the physics involved. On the other hand, electronically-driven gridded devices for immediate applications are reasonably well understood. With that in mind, we have included chapters on the basic technology of such units, e.g., high-voltage stalk design, grid design and geometry, and other non-spherical geometries. Thus this book should be useful for developing IEC experiments in university laboratories for students as well as researchers. It is the hope of the authors that this book aid the growth of IEC fusion research aimed at near-term "spin-off" applications and ultimately a stand-alone fusion power plant.

Features of This Book

Chapter 1 discusses the background and basics of IEC fusion, as well as some experiments. IEC fusion offers many potential advantages, including simplified support structures and the ability to create non-Maxwellian plasmas that can be used with a variety of fusion fuels. The basic IEC approach is to create a potential well through electrostatic confinement of one of the plasma species in a dynamic (inertial) configuration. "Inertial" effects associated with dynamic motion of the confined species are essential to avoid plasma losses.

Chapter 2 discusses the theory of potential well traps in the IEC. It might seem that the two injection methods are similar. However, important differences occur due to the mass difference in the particles that are then effectively providing the inertia to electrostatically confine the other species. This difference is discussed through the analyses presented in this chapter. This chapter focuses on potential well formation and fully ionized spherical IECs. Other geometries have also been studied to see whether such wells could be formed. One example is a gridded cylindrical device that can be viewed as a two-dimensional version of the spherical IEC. However, a spherical geometry has generally been favored due to the three dimensional convergence of the ion beam in the central core.

Chapter 3 discusses gas discharges in gridded IECs. Many experimental IEC devices employ a gas discharge between the grid and vacuum vessel wall (or outer grounded grid) as an ion source. In this chapter we examine some of the basic physics of such discharges and the resulting voltage–current characteristics in the IEC.

Chapter 4 discusses high-voltage stalk design for IECs. Stalk design is crucial for successful internal source IEC device operation. This is particularly true for applications where very high voltages are desired. The requirements for an "ideal" stalk design are listed.

Chapter 5 discusses IEC grid materials and construction. This chapter concentrates on grids for spherical IEC systems. The construction of the IEC grid is complex in that a number of factors contribute to grid performance relative to key issues such as neutron production and ion confinement times. In this chapter we discuss issues that affect the selection of the grid materials and methods for assembling a grid.

Chapter 6 covers effects of grid design and geometry in more detail. Grid geometry plays an important role in the performance of a gridded spherical IEC device because the ion recirculation, hence the reaction rate, is strongly affected by the orientation and size of openings in the cathode in grid design. Several aspects of the effect of grid design on IEC operational performance are discussed.

Chapter 7 discusses studies of space charge limited flow analysis. The classical analyses presented in this chapter are of interest for several reasons. First, these analyses are historic in providing initial insight into space charge effects in diodes carrying large currents. Second, they illustrate techniques originally employed to solve the equations involved. Third, to some extent, the limiting current prediction as a function of applied voltage and anode–cathode spacing roughly apply to the IEC behavior prior to the point where, with combined ion–electron currents, virtual electrodes are formed. The application of space charge limited flow concepts to an actual IEC experiment is discussed. In that case, issues of plasma flow convergence and the high density converged core become important aspects of the problem.

Chapter 8 discusses ion and electron current scaling issues related to how the fusion rate scales with the ion current in the ion-injected type IEC.

Chapter 9 discusses cylindrical and other IEC geometries. Spherical geometry has been widely used following Farnsworth's original studies that stressed the possibility of three-dimensional compression of recirculating beams in the central core of this geometry. This becomes a very important feature if the goal is net power production. However, in many other applications, less compression (e.g. two-dimensional compression in a cylindrical geometry) may be adequate. Indeed, a unique feature of the IEC is that we can adapt its geometry to a number of important near-term applications short of power production. In this chapter we consider cylindrical, Jet extraction, dipole-assisted, and magnetically-coupled IEC geometries. These provide unique capabilities for various near-term commercial applications.

Chapter 10 discusses other IEC concepts and experiments. Here we have chosen a few experiments that have received attention and supplement discussions in Chaps. 1, 2, and 9, in order to explain some issues and status relative to gridded devices for near-term applications such as neutron sources and also to address some issues such as ion injection related to future fusion power units.

Chapter 11 discusses IEC diagnostics. A wide variety of plasma diagnostics can be applied to an IEC. However, the specific diagnostics incorporated are usually selected based on the objective of the research or application involved. The most common of diagnostics used in IEC research are discussed in this chapter. Emphasis is placed on how these diagnostics are modified for use in the IEC and on the interpretation of the measurements made.

Chapter 12 discusses potential applications. The ability to use the IEC for practical applications with operation well below energy breakeven is a unique attractive feature of this device. In this chapter we discuss some NAA applications, along with medical isotope production. With some increase in energy gain and power, an IEC neutron driven subcritical fission assembly for student labs seems feasible. We discuss that use in this chapter, along with more demanding use in future fusion–fission hybrid reactors. IEC fusion space propulsion, another future application, is discussed to stress the potential for high power-to-weight systems using the IEC.

Chapter 13 discusses reactor confinement theory and visions for an IEC power reactor. Various semi-analytic and computer simulations of plasma confinement in the potential traps created by various IEC devices are discussed, and key issues such as ion thermalization times, energy balances, and instabilities caused by deviations from equilibrium conditions are addressed.

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