CHAPTER 1

INTRODUCTION

1.1 Exordium

A nonneutral plasma[1,2] is a many-body collection of charged particles in which there is not overall charge neutrality. Such systems are characterized by intense self-electric fields, and in high-current configurations, by intense self-magnetic fields.[3] Nonneutral plasmas, like electrically neutral plasmas, exhibit a broad range of collective properties, such as plasma waves, instabilities, and Debye shielding. Moreover, the intense self fields in a nonneutral plasma can have a large influence on detailed plasma behavior and stability properties.

Since *Theory of Nonneutral Plasmas*[1] was first published in 1974, interest in the physics of nonneutral plasmas has grown substantially in such diverse areas as: investigations of basic equilibrium, stability and transport properties;[2] high-current electron induction accelerators[4,5] and alternating-gradient accelerators;[6,7] phase transitions[8,9] in strongly coupled, two- and three-dimensional nonneutral plasmas; coherent electromagnetic wave generation by free electrons interacting with applied magnetic field structures;[10–13] astrophysical studies of large-scale isolated nonneutral plasma regions in the magnetospheres of rotating, magnetized neutron stars;[14] and the development of positron[15] and antiproton[16] ion sources. In addition to developing a basic physics understanding of many-body charged-particle systems in which there is not overall charge neutrality, there are many practical applications of nonneutral plasmas. These include: coherent elecromagnetic wave generation by intense electron beams, as in free electron lasers,[10–12] magnetrons and cyclotron masers;[13] the development of advanced accelerator concepts,[5,6] including high-current accelerators such as the modified betatron,[17–19] and periodic focusing accelerators for heavy ions;[20,21] the equilibrium and stability of intense nonneutral electron and ion flow in high-voltage diodes,[22–24] with applications that include particle beam fusion;[25,26] and the stability and transport of intense charged particle beams[27–29] propagating through a background plasma or through the atmosphere, to mention a few examples.

The present volume on nonneutral plasmas has been prepared as a graduate-level text which covers a broad range of topics related to the fundamental properties and applications of nonneutral plasmas. The subject matter is treated systematically from first principles using a unified theoretical approach, and the emphasis is on the development of basic concepts that illustrate the underlying physical processes, which are often similar in different application areas. The statistical models used to describe the properties of nonneutral plasma are based on the fluid-Maxwell equations, the Vlasov-Maxwell equations, or the Klimontovich-Maxwell equations, as appropriate. The book also summarizes the results from several classic experiments illustrating fundamental processes in nonneutral plasmas.

1.2 Historical Background

The very early research on nonneutral plasma predated, by many decades, common usage of the terms "plasma" or "nonneutral plasma" in the lexicon of modern-day physics. [The term "plasma" was introduced by Tonks and Langmuir[30] in 1929 to describe collective electron plasma oscillations in an ionized gas, although widespread use of this descriptor did not occur until the 1950s and 1960s.] Indeed, the classic papers by Child (1911),[31] Langmuir (1923),[32] Lewellyn (1941),[33] Brillouin (1945),[34] McFarlane and Hay (1950),[35] Pierce (1956),[36] Kyhl and Webster (1956),[37] and Buneman (1957),[38] represent some of the earliest efforts to investigate theoretically and experimentally the equilibrium and stability properties of nonneutral electron flow in planar diodes and in geometries with crossed electric and magnetic fields. This research[31–38] and other early research[39–44] on nonneutral plasmas predated the major international development of the theoretical foundations of modern plasma physics, which occurred to a large extent during the 1960s. Moreover, advances in the understanding of nonneutral plasmas during this early period appear to have proceeded largely uninfluenced by the seminal works of Vlasov (1945),[45] Landau (1946)[46] and Bogoliubov (1946)[47] on collective interactions in many-body charged particle systems. This is due, in part, to the fact that the emphasis during this early period was mainly on the practical use and control of space-charge waves on nonneutral electron beams in microwave generation devices (such as klystrons, traveling wave tubes and magnetrons) and vacuum tube diodes. Excellent accounts of the early work on microwave devices and vacuum tube diodes are given by Slater[48] and Okress,[49] and Birdsall and Bridges.[50]

With the advent of modern plasma theory and improved instrumentation techniques, understanding the fundamental properties of nonneutral plasmas received new impetus in the late 1960s and early 1970s. Basic theoretical[51–54] and experimental[55–57] studies of one-component pure electron plasmas showed that many of the equilibrium, stability and collective oscillation properties[51–53] of nonneutral plasmas, including Debye shielding,[54] are directly analogous to the collective properties of electrically neutral plasmas, appropriately modified by equilibrium self-field effects due to the space charge. In addition, rapid advances in pulsed power technology during this period, and the improved ability to produce and accelerate high-current electron beams[58,59] led to increased research on nonneutral plasmas in such diverse areas as: the development of concepts for collective-effect acceleration,[60–62] such as the electron ring accelerator,[63–65] which utilizes the intense self fields of an electron cluster to trap and accelerate ions; novel approaches for the acceleration and stripping of heavy ions[66–68] in nonneutral electron clouds in toroidal magnetic field geometry; and the use of intense electron beams to generate high-power microwaves,[69,70] or to heat plasmas by collective two-stream instabilities.[71] A more complete bibliography of research in these areas prior to 1974 is given by Davidson.[1]

1.3 Technical Advances

In the short space of this introductory chapter, it is not intended to summarize the many technical advances that have occurred in the physics of nonneutral plasmas since *Theory of Nonneutral Plasmas*[1] was published in 1974. Nonetheless, it is useful to outline briefly the substantial progress in selected areas of research and to identify some of the key references. Many of these topics will be treated in more detail in subsequent chapters.

Experimental studies of the basic equilibrium and stability properties of nonneutral plasmas have ranged from investigations of plasma waves in a pure electron plasma,[72] to measurements of the laminar rotation velocity of a pure electron plasma column,[73] to studies of plasma waves in a pure ion plasma column,[74] to the identification of collective modes in a two-dimensional, nonneutral ion layer confined below a liquid-helium surface,[75,76] to studies of the linear and nonlinear evolution of the diocotron instability in an annular electron column,[77] to measurements of the collisional relaxation of anisotropic temperature in a pure electron plasma,[78] to observations of the transport of magnetically confined pure electron plasmas to global thermal equilibrium,[79] to mention only a few examples.

Theoretical studies of the basic equilibrium, stability and transport properties of nonneutral plasmas have ranged from analytical investigations of the influence of intense self fields on the filamentation instability,[80] to development of a confinement theorem for a low-density nonneutral plasma column,[81] to analytical and numerical investigations of the magnetron instability,[82–84] which is of considerable importance for intense nonneutral electron flow in crossed-field microwave devices[85,86] and magnetically-insulated high-voltage diodes,[22] to analytical and numerical-simulation studies of space-charge-induced transverse instabilities in nonneutral heavy ion beams,[87,88] to quasilinear studies of the nonlinear evolution of the diocotron instability for multimode excitation in a nonneutral electron layer,[89] to theoretical studies of collisional transport processes in pure electron plasmas,[90,91] to determination of the influence of intense self fields on the cyclotron maser instability in a relativistic, nonneutral electron beam,[92] to basic theoretical studies of the equilibrium and collective oscillation properties of a two-dimensional nonneutral ion layer confined below a liquid-helium surface,[93] again to mention only a few examples.

A particularly fascinating area of research on nonneutral plasmas relates to phase transitions[8] to the liquid and crystal states when the coupling parameter

$$\Gamma = \frac{e^2}{k_B T a} \tag{1.1}$$

is sufficiently large, which requires extremely low-temperature conditions. Here, Γ is the ratio of nearest-neighbor Coulomb energy (e^2/a) to the thermal energy $(k_B T)$ of a particle, $a = (3/4\pi\hat{n})^{1/3}$ is the Wigner-Seitz radius, and $\hat{n}$ is the average particle density. Similar to a neutral plasma, whenever $\Gamma \ll 1$ there are many particles in a Debye interaction sphere and the correlations are weak. For sufficiently large Γ, however, the plasma is strongly correlated. Research in this area ranges from experimental studies of the liquid-to-crystal phase transition in a two-dimensional nonneutral electron layer on a liquid-helium surface,[9] to the production and laser cooling of a strongly-coupled nonneutral ion plasma confined in a Penning trap with coupling parameter $\Gamma \sim 20 - 200$,[94–96] to computer simulation of the phase transition of bounded nonneutral ion plasmas to the liquid and crystal states both in Penning-trap confinement geometries,[97] and in heavy-ion storage rings.[98] Research on phase transitions in nonneutral plasmas has been further stimulated by continued advances in the theoretical understanding of strongly-coupled one-component plasmas.[99–102]

1.4 Outline

As indicated in Sec. 1.1, an important motivation for the present treatise is to provide a unified theoretical treatment of a broad range of topics related to the fundamental properties and applications of nonneutral plasmas. In addition, the results of several classic experiments are summarized which illustrate fundamental processes in nonneutral plasmas. The subject matter is treated systematically from first principles, beginning in Chapter 2 with a review of the statistical frameworks for describing collective and discrete-particle interactions in nonneutral plasma based on the macroscopic fluid-Maxwell equations, the Vlasov-Maxwell equations, and the Klimontovich-Maxwell equations. Chapter 3 describes several fundamental properties of the nonneutral plasma state, ranging from the equilibrium rotation induced by space-charge effects, to thermal equilibrium properties of a nonneutral plasma column, to Debye shielding of the electrostatic potential surrounding a test electron, to phase transitions in strongly-coupled nonneutral plasma. In Chapter 4, the Vlasov-Maxwell equations are used to investigate the basic equilibrium and stability properties of nonneutral plasma in circumstances where both the configuration-space dependence and the momentum-space dependence of the one-particle distribution function $f_j(\mathbf{x}, \mathbf{p}, t)$ play an important role in determining the properties of the system. Such a kinetic description is shown to be remarkably tractable in geometries as diverse as: a nonneutral plasma column confined radially by an axial magnetic field $B_0\hat{\mathbf{e}}_z$; a spheroidal nonneutral plasma confined in Penning-trap geometry, where axial confinement is produced by applied electrostatic potentials on neighboring conductors; and a relativistic nonneutral electron ring confined by the combined toroidal and mirror magnetic fields in a modified betatron. In Chapter 5, the basic equilibrium and stability properties of nonneutral plasma are investigated in circumstances where the plasma is sufficiently cold that the evolution of the system can be described by a macroscopic model based on the cold-fluid-Maxwell equations. Such a model is particularly amenable to determining the detailed influence of boundary effects on collective oscillations and instabilities. Specific examples treated in this chapter include: electrostatic waves and instabilities in a nonneutral plasma column; two-stream instabilities in relativistic beam-plasma systems; the influence of self fields on the electromagnetic filamentation instability; and the equilibrium and collective oscillation properties of a two-dimensional nonneutral ion plasma confined below the surface of liquid helium. Chapter 6 investigates basic properties of the ubiquitous diocotron instability, which is driven by a shear in the flow velocity in low-density nonneutral plasma. In addition to investigating linear stability properties, the nonlinear evolution of the diocotron instability is analyzed for multimode excitation, and the stabilizing influence of electromagnetic and relativistic effects is examined.

The theoretical techniques and basic principles developed in Chapters 2 through 6 are used in Chapters 7 through 10 to investigate several important applications of nonneutral plasmas. Chapter 7 deals with coherent electromagnetic wave generation by the cyclotron maser instability and the free electron laser instability, which can occur when a relativistic electron beam interacts with a uniform magnetic field $B_0\hat{\mathbf{e}}_z$ or with a transverse wiggler magnetic field $\mathbf{B}_w(\mathbf{x})$, respectively. These instabilities exhibit a sensitive dependence on the detailed distribution of particles in momentum space, and therefore, the (kinetic) treatment in Chapter 7 is based on the Vlasov-Maxwell equations. In Chapter 8, a macroscopic cold-fluid model is used to investigate the equilibrium and stability properties of intense nonneutral flow in high power diodes. Particular emphasis is placed on: magnetically insulated electron flow; coherent electromagnetic wave generation by the magnetron instability; magnetically insulated ion diodes (also known as applied-B ion diodes); and the ion resonance and transit time instabilities. Chapter 9 deals with the propagation and stability of intense charged particle beams in a solenoidal focusing field $B_0\hat{\mathbf{e}}_z$. Here, the term "solenoidal" (or "solenoid") is used to indicate that the applied magnetic field $B_0\hat{\mathbf{e}}_z$ is in the axial direction, which is also the direction of beam propagation. The topics covered in this chapter include: the limiting electron current in a cylindrical drift cavity; laminar flow equilibria for an intense nonneutral electron beam; stability of nonneutral electron flow in a one-dimensional drift space; the transverse stability properties of an intense nonneutral ion beam; and the resistive hose, sausage and hollowing instabilities for an intense electron beam propagating through a dense background plasma. Finally, in Chapter 10, kinetic equilibrium and stability properties are investigated for an intense nonneutral ion beam propagating in an alternating-gradient focusing field (e.g., a periodic quadrupole field). The topics covered in this chapter include: analysis of the orbit and envelope equations including self-field effects; the average focusing force and phase advance for a periodic quadrupole field; the stability of the Kapchinskij-Vladimirskij equilibrium[103] for a uniform-density beam; and investigations of the emittance growth due to collective instabilities and space-charge homogenization. As would be expected, for sufficiently high beam current, self-field effects can have a large influence on detailed equilibrium and stability properties.

Chapter 1 References

1. R.C. Davidson, *Theory of Nonneutral Plasmas* (Benjamin, Reading, Massachusetts, 1974), reissued in the Advanced Book Classics Series (Addison-Wesley, Reading, Massachusetts, 1989).
2. *Nonneutral Plasma Physics*, eds., C. W. Roberson and C.F. Driscoll, AIP Conference Proceedings No. 175 (American Institute of Physics, New York, 1988), and papers therein.
3. R.C. Davidson, "Relativistic Electron Beam-Plasma Interaction with Intense Self Fields," in *Handbook of Plasma Physics—Basic Plasma Physics*, eds., M.N. Rosenbluth and R.Z. Sagdeev (North Holland, Amsterdam, 1984), Volume 2, pp. 729-819.
4. S. Humphries, Jr., *Principles of Charged Particle Acceleration* (Wiley, New York, 1986).
5. C.A. Kapetanakos and P. Sprangle, "Ultra-High-Current Electron Induction Accelerators," Physics Today **38** (2), 58 (1985).
6. J.D. Lawson, *The Physics of Charged Particle Beams* (Clarendon Press, Oxford, 1988).
7. M. Reiser, "Periodic Focusing of Intense Beams," Particle Accelerators **8**, 167 (1978).
8. J.H. Malmberg and T.M. O'Neil, "Pure Electron Plasma, Liquid, and Crystal," Phys. Rev. Lett. **39**, 1333 (1977).
9. G.C. Grimes and G. Adams, "Evidence for a Liquid-to-Crystal Phase Transition in a Classical, Two-Dimensional Sheet of Electrons," Phys. Rev. Lett. **42**, 795 (1979).

10. T.C. Marshall, *Free Electron Lasers* (Macmillan, New York, 1985).

11. C.W. Roberson and P. Sprangle, "A Review of Free Electron Lasers," Phys. Fluids **B1**, 3 (1989).

12. *Free Electron Laser Handbook*, eds., W. Colson, C. Pellegrini and A. Renieri (North Holland, Amsterdam, 1989).

13. *High-Power Microwave Sources*, eds., V. Granatstein and I. Alexeff (Artech House, Boston, Massachusetts, 1987), and papers therein.

14. C. Michael, "Nonneutral Plasmas in the Laboratory and Astrophysics," Proceedings of the Astronomical Society of Australia **6**, 127 (1985).

15. C.M. Surko, M. Leventhal, W.S. Crane, A. Passner, F. Wysocki, T.J. Murphy, J. Strachan and W.L. Rowan, "Use of Positrons to Study Transport in Tokamak Plasmas," Rev. Sci. Instrum. **57**, 1862 (1986).

16. G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas and W. Kells, "First Capture of Antiprotons in a Penning Trap: A. Kiloelectronvolt Source," Phys. Rev. Lett. **57**, 2504 (1986).

17. P. Sprangle and C.A. Kapetanakos, "Constant Radius Magnetic Acceleration of a Strong Nonneutral Proton Ring," J. Appl. Phys. **49**, 1 (1978).

18. N. Rostoker, "High-Current Betatron," Comments in Plasma Physics and Controlled Fusion **6**, 91 (1980).

19. J.J. Petillo and R.C. Davidson, "Kinetic Equilibrium and Stability Properties of High-Current Betatrons," Phys. Fluids **30**, 2477 (1987).

20. D. Keefe, "Research on High Beam-Current Accelerators," Particle Accelerators **11**, 187 (1987).

21. E.P. Lee and J. Hovingh, "Heavy Ion Induction Linac Drivers for Inertial Confinement Fusion," Fusion Technology **15**, 369 (1989).

22. R.V. Lovelace and E. Ott, "Theory of Magnetic Insulation," Phys. Fluids **17**, 1263 (1974).

23. T.M. Antonsen, Jr. and E. Ott, "Theory of Intense Ion Beam Acceleration," Phys. Fluids **19**, 52 (1976).

24. M.P. Desjarlais, "Impedance Characteristics of Applied-B Ion Diodes," Phys. Rev. Lett. **59**, 2295 (1987).

25. R.B. Miller, *Intense Charged Particle Beams* (Plenum, New York, 1982).

26. J.P. VanDevender and D.L. Cook, "Inertial Confinement Fusion with Light Ion Beams," Science **232**, 831 (1986).

27. E.J. Lauer, R.J. Briggs, T.J. Fessenden, R.E. Hester and E.P. Lee, "Measurements of Hose Instability of a Relativistic Electron Beam," Phys. Fluids **21**, 1344 (1978).

28. H.S. Uhm and M. Lampe, "Return-Current-Driven Instabilities of Propagating Electron Beams," Phys. Fluids **25**, 1444 (1982).

29. R.F. Fernsler, R.F. Hubbard, B. Hui, G. Joyce, M. Lampe and Y.Y. Lau, "Current Enhancement for Hose-Unstable Electron Beams," Phys. Fluids **29**, 3056 (1986).

30. L. Tonks and I. Langmuir, "Oscillations in Ionized Gases," Phys. Rev. **33**, 195 (1929).

31. C.D. Child, "Discharge from Hot CaO," Phys. Rev. **32**, 492 (1911).

32. I. Langmuir, "The Effect of Space Charge and Initial Velocities on the Potential Distribution and Thermionic Current Between Parallel Plane Electrodes," Phys. Rev. **21**, 419 (1923).

33. F.B. Lewellyn, *Electron Inertia Effects* (Cambridge University Press, London, 1941).

34. L. Brillouin, "A Theorem of Larmor and Its Importance for Electrons in Magnetic Fields," Phys. Rev. **67**, 260 (1945).

35. C.C. MacFarlane and H.G. Hay, "Wave Propagation in a Slipping Stream of Electrons; Small-Amplitude Theory," Proc. Phys. Soc. (London) **63B**, 409 (1950).

36. J.R. Pierce, "Instability of Hollow Beams," IRE Trans. Electron Devices **ED-3**, 183 (1956).

37. R.L. Kyhl and H.F. Webster, "Breakup of Hollow Cylindrical Electron Beams," IRE Trans. Electron Devices **ED-3**, 172 (1956).

38. O. Buneman, "Ribbon Beams," J. Electron. Control **3**, 507 (1957).

39. W.W. Rigrod and J.A. Lewis, "Wave Propagation Along a Magnetically-Focussed Electron Beam," Bell System Tech. J. **33**, 399 (1954).

40. G.R. Brewer, "Some Effects of Magnetic Field Strength on Space-Charge Wave Propagation," Proc. IRE **44**, 896 (1956).

41. J. Labus, "Space-Charge Waves Along a Magnetically Focussed Electron Beam," Proc. IRE **45**, 854 (1957).

42. W.W. Rigrod, "Space-Charge Wave Harmonics and Noise Propagating in Rotating Electron Beams," Bell System Tech. J. **38**, 119 (1959).

43. H.F. Webster, "Breakup of Hollow Electron Beams," J. Appl. Phys. **26**, 1386 (1955).

44. G.R. Brewer, "Some Characteristics of a Cylindrical Electron Stream in Immersed Flow," IRE Trans. Electron Devices **ED-4**, 134 (1957).

45. A.A. Vlasov, "On the Kinetic Theory of an Assembly of Particles with Collective Interaction," J. Phys. (USSR) **9**, 25 (1945).

46. L.D. Landau, "On the Vibrations of the Electronic Plasma," J. Phys. (USSR) **10**, 25 (1946).

47. N.N. Bogoliubov, *Problems of a Dynamical Theory in Statistical Physics* (State Technical Press, Moscow, 1946).

48. J. Slater, *Microwave Electronics* (Van Nostrand, New York, 1950).

49. *Cross-Field Microwave Devices*, ed., E. Okress (Academic Press, New York, 1961), Volume 1.

50. C.K. Birdsall and W.B. Bridges, *Electron Dynamics of Diode Regions* (Academic Press, New York, 1966).

51. R.C. Davidson and N.A. Krall, "Vlasov Description of an Electron Gas in a Magnetic Field," Phys. Rev. Lett. **22**, 833 (1969).

52. R.C. Davidson and N.A. Krall, "Vlasov Equilibria and Stability of an Electron Gas," Phys. Fluids **13**, 1543 (1970).

53. B.L. Bogema and R.C. Davidson, "Rotor Equilibria of Nonneutral Plasmas," Phys. Fluids **13**, 2772 (1970).

54. R.C. Davidson, "Electrostatic Shielding of a Test Charge in a Nonneutral Plasma," J. Plasma Phys. **6**, 229 (1971).

55. R.E. Pechacek, C.A. Kapetanakos and A.W. Trivelpiece, "Trapping of a 0.5 MeV Electron Ring in a 15 kG Pulsed Magnetic Mirror Field," Phys. Rev. Lett. **21**, 1436 (1968).

56. C.A. Kapetanakos, R.E. Pechacek, D.M. Spero and A.W. Trivelpiece, "Trapping and Confinement of Nonneutral Hot Electron Clouds in a Magnetic Mirror," Phys. Fluids **14**, 1555 (1971).

57. A.W. Trivelpiece, "Nonneutral Plasmas," Comments in Plasma Physics and Controlled Fusion **1**, 57 (1972).

58. D.A. Hammer and N. Rostoker, "Propagation of High Current Relativistic Electron Beams," Phys. Fluids **13**, 1831 (1970).

59. G. Benford and D.L. Book, "Relativistic Beam Equilibria," in *Advances in Plasma Physics*, eds., A. Simon and W.B. Thompson (Wiley, New York, 1971), Volume 4, p. 125.

60. V.I. Veksler, V.P. Sarantsev, A.G. Bonch-Osmolovskii, G.V. Dolbilov, G.A. Ivanov, I.N. Ivanov, M.L. Iovonich, I.V. Kozhuhov, A.B. Kuznetsov,

V.G. Mahankov, E.A. Perelstein, V.P. Rashevskii, K.A. Reshetnikova, N.B. Rubin, S.B. Rubin, P.I. Ryltsev and O.I. Yarkovov, "Collective Linear Acceleration of Ions," Atomnaya Energiya (USSR) **24**, 317 (1968).

61. J.D. Lawson, "Collective and Coherent Methods of Particle Acceleration," Particle Accelerators **3**, 21 (1972).

62. D. Keefe, "Collective-Effect Accelerators," Scientific American **226**, 22 (1972).

63. D. Keefe, G.R. Lambertson, L.J. Laslett, W.A. Perkins, J.M. Peterson, A.M. Sessler, R.W. Allison, Jr., W.W. Chupp, A.U. Luccio and J.B. Rechen, "Experiments on Forming Intense Rings of Electrons Suitable for Acceleration of Ions," Phys. Rev. Lett. **22**, 558 (1969).

64. D. Keefe, "Research on the Electron Ring Accelerator," Particle Accelerators **1**, 1 (1970).

65. R.C. Davidson and J.D. Lawson, "Self-Consistent Vlasov Description of Relativistic Electron Rings," Particle Accelerators **4**, 1 (1972).

66. G.S. Janes, R.H. Levy, H.A. Bethe and B.T. Feld, "New Type of Accelerator for Heavy Ions," Phys. Rev. **145**, 925 (1966).

67. J.D. Daugherty, L. Grodzins, G.S. Janes and R.H. Levy, "New Source of Highly Stripped Heavy Ions," Phys. Rev. Lett. **20**, 369 (1968).

68. J.D. Daugherty, J.E. Eninger and G.S. Janes, "Experiments on the Injection and Containment of Electron Clouds in a Toroidal Apparatus," Phys. Fluids **12**, 2677 (1969).

69. M. Friedman and M. Herndon, "Microwave Emission Produced by the Interaction of an Intense Relativistic Electron Beam with a Spatially Modulated Magnetic Field," Phys. Rev. Lett. **28**, 210 (1972).

70. J. Nation, "On the Coupling of a High Current Relativistic Electron Beam to a Slow Wave Structure," Appl. Phys. Lett. **17**, 491 (1970).

71. C.A. Kapetanakos and D.A. Hammer, "Plasma Heating by an Intense Relativistic Electron Beam," Appl. Phys. Lett. **23**, 17 (1973).

72. J.H. Malmberg and J.S. deGrassie, "Properties of Nonneutral Plasmas," Phys. Rev. Lett. **35**, 577 (1975).

73. A.J. Theiss, R.A. Mahaffey and A.W. Trivelpiece, "Rigid-Rotor Equilibria of Nonneutral Plasmas," Phys. Rev. Lett. **35**, 1436 (1975).

74. G. Dimonte, "Ion Langmuir Waves in a Nonneutral Plasma," Phys. Rev. Lett. **46**, 26 (1981).

75. M.L. Ott-Rowland, V. Kotsubo, J. Theobald and G.A. Williams, "Two-Dimensional Plasma Resonances in Positive Ions Under the Surface of Liquid Helium," Phys. Rev. Lett. **49**, 1708 (1982).

76. S. Hannahs and G.A. Williams, "Plasma Wave Resonances in Positive Ions Under the Surface of Liquid Helium," Japanese Journal of Applied Physics **26-3**, 741 (1987).

77. G. Rosenthal, G. Dimonte and A.Y. Wong, "Stabilization of the Diocotron Instability in an Annular Plasma," Phys. Fluids **30**, 3257 (1987).

78. A.W. Hyatt, C.F. Driscoll and J.H. Malmberg, "Measurement of the Anisotropic Temperature Relaxation Rate in a Pure Electron Plasma," Phys. Rev. Lett. **59**, 2975 (1987).

79. C.F. Driscoll, J.H. Malmberg and K.S. Fine, "Observation of Transport to Thermal Equilibrium in Pure Electron Plasmas," Phys. Rev. Lett. **60**, 1290 (1988).

80. R.C. Davidson and B.H. Hui, "Influence of Self Fields on the Equilibrium and Stability Properties of Relativistic Electron Beam-Plasma Systems," Annals of Physics **94**, 209 (1975).

81. T.M. O'Neil, "A Confinement Theorem for Nonneutral Plasmas," Phys. Fluids **23**, 2217 (1980).

82. J. Swegle and E. Ott, "Instability of the Brillouin-Flow Equilibrium in Magnetically Insulated Diodes," Phys. Rev. Lett. **46**, 929 (1981).

83. T.M. Antonsen, Jr., E. Ott, C.L. Chang and A.T. Drobot, "Parametric Scaling of the Stability of Relativistic Laminar Flow Magnetic Insulation," Phys. Fluids **28**, 2878 (1985).

84. R.C. Davidson and K.T. Tsang, "Influence of Profile Shape on the Extraordinary-Mode Stability Properties of Relativistic Nonneutral Electron Flow in a Planar Diode with Applied Magnetic Field," Phys. Fluids **28**, 1169 (1985).

85. A. Palevsky and G. Bekefi, "Microwave Emission from Pulsed, Relativistic Electron Beam Diodes II: The Multiresonator Magnetron," Phys. Fluids **22**, 986 (1979).

86. D. Chernin and Y.Y. Lau, "Stability of Laminar Electron Layers," Phys. Fluids **27**, 2319 (1984).

87. I. Hofmann, L.J. Laslett, L. Smith and I. Haber, "Stability of the Kapchinskij-Vladimirskij Distribution in Long Periodic Transport Systems," Particle Accelerators **13**, 145 (1983).

88. J. Struckmeier, J. Klabunde and M. Reiser, "On the Stability and Emittance Growth of Different Particle Phase-Space Distributions in a Long Magnetic Quadrupole Channel," Particle Accelerators **15**, 47 (1984).

89. R.C. Davidson, "Quasilinear Theory of the Diocotron Instability for Nonrelativistic Nonneutral Electron Flow in Planar Geometry," Phys. Fluids **28**, 1937 (1985).

90. T.M. O'Neil, "A New Theory of Transport Due to Like-Particle Collisions," Phys. Rev. Lett. **55**, 943 (1985).

91. D.H.E. Dubin and T.M. O'Neil, "Two-Dimensional Guiding-Center Transport of a Pure Electron Plasma," Phys. Rev. Lett. **60**, 1286 (1988).

92. H.S. Uhm and R.C. Davidson, "Influence of Intense Equilibrium Self Fields on the Cyclotron Maser Instability in High-Current Gyrotrons," Phys. Fluids **29**, 2713 (1986).

93. S.A. Prasad and G.J. Morales, "Equilibrium and Wave Properties of Two-Dimensional Ion Plasmas," Phys. Fluids **30**, 3475 (1987).

94. J.J. Bollinger and D.J. Wineland, "Strongly Coupled Nonneutral Ion Plasma," Phys. Rev. Lett. **53**, 348 (1984).

95. L.R. Brewer, J.D. Prestage, J.J. Bollinger and D.J. Wineland, "A High-Γ, Strongly Coupled, Nonneutral Ion Plasma," in *Strongly Coupled Plasma Physics*, eds., F.J. Rogers and H.E. DeWitt (Plenum, New York, 1987), p. 53.

96. S.L. Gilbert, J.J. Bollinger and D.J. Wineland, "Shell Structure Phase of Magnetically Confined Strongly Coupled Plasmas," Phys. Rev. Lett. **60**, 2022 (1988).

97. D.H.E. Dubin and T.M. O'Neil, "Computer Simulation of Ion Clouds in a Penning Trap," Phys. Rev. Lett. **60**, 511 (1988).

98. A. Rahman and J.P. Schiffer, "Structure of a One-Component Plasma in an External Field: A Molecular-Dynamics Study of Particle Arrangement in a Heavy-Ion Storage Ring," Phys. Rev. Lett. **57**, 1133 (1986).

99. W.L. Slattery, G.D. Doolen and H.E. DeWitt, "Improved Equation of State for the Classical One-Component Plasma," Phys. Rev. **A21**, 2087 (1980).

100. S. Ichimaru, "Strongly Coupled Plasmas: High-Density Classical Plasmas and Degenerate Electron Liquids," Rev. Modern Physics **54**, 1017 (1982).

101. H. Totsuji, "Static and Dynamic Properties of Strongly Coupled Classical One-Component Plasmas: Numerical Experiments on Supercooled Liquid State and Simulation of Ion Plasma in the Penning Trap," in *Strongly Coupled Plasma Physics*, eds., F.J. Rogers and H.E. DeWitt (Plenum, New York, 1987), p. 19.

102. S. Ichimaru, H. Iyetomi and S. Tanaka, "Statistical Physics of Dense Plasmas: Thermodynamics, Transport Coefficients and Dynamic Correlations," Physics Reports **149**, 91 (1987).

103. I.M. Kapchinskij and V.V. Vladimirskij, "Limitations of Proton Beam Current in a Strong-Focusing Linear Accelerator Associated with the Beam

Space Charge," in *Proceedings of the International Conference on High Energy Accelerators and Instrumentation* (CERN Scientific Information Service, Geneva, 1959), p. 274.