INTRODUCTION TO

PLASMA PHYSICS AND CONTROLLED FUSION

SECOND EDITION

Volume 1: Plasma Physics

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This volume is based on Chapters 1–8 of the first edition of *Introduction to Plasma Physics,* published in 1974.

To the poet and the eternal scholar…

M. Conrad Chen
Evelyn C. Chen

PREFACE TO THE SECOND EDITION

In the nine years since this book was first written, rapid progress has been made scientifically in nuclear fusion, space physics, and nonlinear plasma theory. At the same time, the energy shortage on the one hand and the exploration of Jupiter and Saturn on the other have increased the national awareness of the important applications of plasma physics to energy production and to the understanding of our space environment.

In magnetic confinement fusion, this period has seen the attainment of a Lawson number $n\tau_E$ of 2×10^{13} cm^{-3} sec in the Alcator tokamaks at MIT; neutral-beam heating of the PLT tokamak at Princeton to KT_i = 6.5 keV; increase of average β to 3%–5% in tokamaks at Oak Ridge and General Atomic; and the stabilization of mirror-confined plasmas at Livermore, together with injection of ion current to near field-reversal conditions in the 2XIIB device. Invention of the tandem mirror has given magnetic confinement a new and exciting dimension. New ideas have emerged, such as the compact torus, surface-field devices, and the EBT mirror-torus hybrid, and some old ideas, such as the stellarator and the reversed-field pinch, have been revived. Radiofrequency heating has become a new star with its promise of dc current drive. Perhaps most importantly, great progress has been made in the understanding of the MHD behavior of toroidal plasmas: tearing modes, magnetic islands, and disruptions. Concurrently, the problems of reactor design, fusion technology, and fission–fusion hybrids have received serious attention for the first time.

Inertial confinement fusion has grown from infancy to a research effort one-fourth as large as magnetic fusion. With the 25-TW Shiva laser at Livermore, 3×10^{10} thermonuclear neutrons have been produced in a single pellet implosion, and fuel compressions to one hundred times liquid hydrogen density have been achieved. The nonlinear plasma processes involved in the coupling of laser radiation to matter have received meticulous attention, and the important phenomena of resonance absorption, stimulated Brillouin and Raman scattering, and spontaneous magnetic field generation are well on the way to being understood. Particle drivers—electron beams, light-ion beams, and heavy-ion beams—have emerged as potential alternates to lasers, and these have brought their own set of plasma problems.

In space plasma physics, the concept of a magnetosphere has become well developed, as evidenced by the prediction and observation of whistler waves in the Jovian magnetosphere. The structure of the solar corona and its relation to sunspot magnetic fields and solar wind generation have become well understood, and the theoretical description of how the aurora borealis arises appears to be in good shape.

Because of the broadening interest in fusion, Chapter 9 of the first edition has been expanded into a comprehensive text on the physics of fusion and will be published as Volume 2. The material originated from my lecture notes for a graduate course on magnetic fusion but has been simplified by replacing long mathematical calculations with short ones based on a physical picture of what the plasma is doing. It is this task which delayed the completion of the second edition by about three years.

Volume 1, which incorporates the first eight chapters of the first edition, retains its original simplicity but has been corrected and expanded. A number of subtle errors pointed out by students and professors have been rectified. In response to their requests, the system of units has been changed, reluctantly, to mks (SI). To physicists of my own generation, my apologies; but take comfort in the thought that the first edition has become a collector's item.

The dielectric tensor for cold plasmas has now been included; it was placed in Appendix B to avoid complicating an already long and difficult chapter for the beginner, but it is there for ready reference. The chapter on kinetic theory has been expanded to include ion Landau damping of acoustic waves, the plasma dispersion function, and Bernstein waves. The chapter on nonlinear effects now incorporates a treatment of solitons via the Korteweg–deVries and nonlinear Schrödinger equations. This section contains more detail than the rest of Volume 1, but purposely so, to whet the appetite of the advanced student. Helpful hints from G. Morales and K. Nishikawa are hereby acknowledged.

For the benefit of teachers, new problems from a decade of exams have been added, and the solutions to the old problems are given. A sample three-hour final exam for undergraduates will be found in Appendix C. The problem answers have been checked by David Brower; any errors are his, not mine.

Finally, in regard to my cryptic dedication, I have good news and bad news. The bad news is that the poet (my father) has moved on to the land of eternal song. The good news is that the eternal scholar (my mother) has finally achieved her goal, a Ph.D. at 72. The educational process is unending.

Francis F. Chen

Los Angeles, 1983

PREFACE TO THE FIRST EDITION

This book grew out of lecture notes for an undergraduate course in plasma physics that has been offered for a number of years at UCLA. With the current increase in interest in controlled fusion and the widespread use of plasma physics in space research and relativistic astrophysics, it makes sense for the study of plasmas to become a part of an undergraduate student's basic experience, along with subjects like thermodynamics or quantum mechanics. Although the primary purpose of this book was to fulfill a need for a text that seniors or juniors can really understand, I hope it can also serve as a painless way for scientists in other fields—solid state or laser physics, for instance—to become acquainted with plasmas.

Two guiding principles were followed: Do not leave algebraic steps as an exercise for the reader, and do not let the algebra obscure the physics. The extent to which these opposing aims could be met is largely due to the treatment of plasma as two interpenetrating fluids. The two-fluid picture is both easier to understand and more accurate than the single-fluid approach, at least for low-density plasma phenomena.

The initial chapters assume very little preparation on the part of the student, but the later chapters are meant to keep pace with his increasing degree of sophistication. In a nine- or ten-week quarter, it is possible to cover the first six and one-half chapters. The material for these chapters was carefully selected to contain only what is essential. The last two and one-half chapters may be used in a semester course or as additional reading. Considerable effort was made to give a clear explanation of Landau damping—one that does not depend on a knowledge of contour integration. I am indebted to Tom O'Neil and George Schmidt for help in simplifying the physical picture originally given by John Dawson.

Some readers will be distressed by the use of cgs electrostatic units. It is, of course, senseless to argue about units; any experienced physicist can defend his favorite system eloquently and with faultless logic. The system here is explained in Appendix I and was chosen to avoid unnecessary writing of c, μ_0, and ϵ_0, as well as to be consistent with the majority of research papers in plasma physics.

I would like to thank Miss Lisa Tatar and Mrs. Betty Rae Brown for a highly intuitive job of deciphering my handwriting, Mr. Tim Lambert for a similar degree of understanding in the preparation of the drawings, and most of all Ande Chen for putting up with a large number of deserted evenings.

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Los Angeles, 1974

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