

Nonlinear Effects and Anomalous Transport in RF Plasmas

Francis F. Chen, *Life Fellow, IEEE*

Abstract—Three examples are given of experiments which give evidence of nonclassical behavior in partially ionized, low-temperature, radio-frequency plasmas: anomalous skin depth in inductively coupled plasmas, transport by fluctuations in helicon plasmas, and parametric instabilities in helicon plasmas. A variety of physics puzzles have been found in industrial plasmas, and techniques learned from high-temperature, fusion research are used to solve them. Low-temperature plasma physics is becoming a precise, challenging discipline in the field of plasmas.

Index Terms—Anomalous skin depth, anomalous transport, drift wave instability, helicon discharges, helicon sources, inductively coupled plasma, Kelvin–Helmholtz instability, low-temperature plasma, nonlinear, parametric, radio-frequency plasma, transport barrier.

I. INTRODUCTION

ALTHOUGH plasmas were first studied in weakly ionized discharges such as glow discharges, the explosion of knowledge of how plasmas behave and how they can be diagnosed has come from the fusion effort. Hot, collisionless plasmas provide a certain degree of simplicity which allowed progress to proceed. Partially ionized plasmas, which add to the ions and electrons a neutral species with many energy levels were regarded as too complicated, leading to “dirty science.” This is not always true, of course. Partially ionized plasmas do not have to be in a confinement geometry and, indeed do not need a direct current (dc) magnetic field, so are in many ways simpler. Plasmas being what they are, even cold plasmas produce the anomalous and nonlinear effects seen in hot plasmas. Three examples of interesting problems are given here. These do not include sheaths, which are inescapably nonlinear (but may not be plasmas) and in any case are less interesting than these other problems.

II. ANOMALOUS SKIN DEPTH IN ICPs

Inductively coupled plasmas (ICPs) are plasma sources excited with an external antenna carrying a radio-frequency (RF) current, usually at the industrial frequency of 13.56 MHz. They are one of the main plasma devices used in producing computer chips and are, therefore, highly developed. But they were developed without a good understanding of how they worked. There are two basic types of antennas. The first is a spiral coil shaped like a stove-top heating element and placed on the dielectric top cover of a vacuum chamber. After breakdown, the RF field

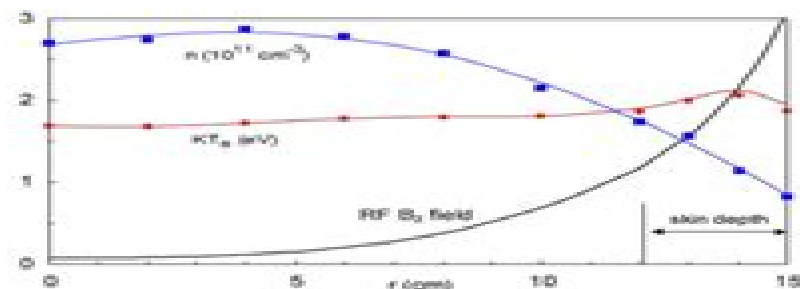


Fig. 1. Radial profiles of density, electron temperature, and the RF B_z field in the apparatus of Fig. 2 [1]. (Color version available online at <http://ieeexplore.ieee.org>.)

from the antenna current penetrates about a skin depth into the plasma and creates the ionization there. The plasma diffuses a short distance downwards to the substrate to be treated. There is no problem understanding this. The second type of antenna, however, is wound around the cylindrical sides of the vacuum chamber, with no elements near the axis. Since the skin depth is much smaller than the chamber radius, one would expect ionization to occur near the sidewalls, with the plasma diffusing toward the axis. Since particles are lost to the top and bottom by thermal motion while they are diffusing, one would expect the density to peak near the sidewalls and have a minimum on the axis. Fig. 1 shows that the opposite happens [1]. The RF field decays inward with the expected e -folding length, and kT_e peaks in the skin layer, as expected. The density n , however, has a minimum in the skin layer and peaks near the center. In commercial use, the parameters can be adjusted to produce a completely uniform plasma across the diameter.

The RF energy has apparently penetrated beyond the classical skin depth and has produced ionization in the interior of the discharge. This problem of anomalous skin depth in plasmas has been known for many years since it was reported by Demirkhanov *et al.* [2] and Kofoed and Dawson [3], and later by Joye and Schneider [4], Weibel [5], and later Sayasov [6], proposed theoretically that electron thermal motions could transport RF energy past the skin layer. With the advent of ICPs, the subject was revived in the 1990s. This literature has been summarized in three long review articles by Kolobov and Economou [7] (theory), Kolobov and Godyak [8], and Godyak [9] (experiment). Most papers [10]–[13] consider ICPs with flat-coil antennas. Since these impose RF fields on axis, the problem of peaked density profiles does not arise, as with

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Jan Weiland



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Nonlinear Effects in Plasma V. Tsytovich, 2012-12-06 For some time now there has been an interest in the non linear interaction of electromagnetic waves in plasma 1 2 But only in the last few years has the theory of nonlinear wave interaction effects undergone such vigorous development as to result in the formulation of clear physical concepts regarding the mechanisms of interaction This development has been engendered by attempts to solve many of the plasma physical problems accompanying the tremendous growth of experimental research 3 The importance of nonlinear effects in modern plasma physics is discussed in detail in Chap I At this point we merely stress the fact that today the analysis of nonlinear effects is a practical necessity in any experiment involving plasma instabilities We should also point out that plasma instabilities can assert themselves extensively in solids solid state plasma and play an important part in the study of cosmic plasma Consequently the problems of nonlinear wave interaction in plasma are of concern to those working in widely different areas of physics Yet it is difficult to assimilate the results of investigations on nonlinear effects owing to the complicated way in which the results of original research are presented In the present book the author hopes in some measure to fill the need for a text on the physics of non linear effects that is accessible to a fairly general audience

Cosmic Ray Interactions, Propagation, and Acceleration in Space Plasmas Lev Dorman, 2006-09-02 Chapter 1 briefly describes the main properties of space plasmas and primary CR Chapter 2 considers the problem of CR propagation in space plasmas described by the kinetic equation and different types of diffusion approximations Chapter 3 is devoted to CR non linear effects in space plasmas caused by CR pressure and CR kinetic stream instabilities with the generation of Alfvén turbulence In Chapter 4 different processes of CR acceleration in space plasmas are considered The book ends with a list providing more than 1 300 full references a discussion on future developments and unsolved problems as well as Object and Author indexes

Fluctuations and Non-Linear Wave Interactions in Plasmas A. G. Sitenko, 2016-09-20 Fluctuations and Non linear Wave Interactions in Plasmas talks about a theory of fluctuations in a homogeneous plasma The title takes into consideration non linear wave interactions The text first presents the statistical description of plasma and then proceeds to covering non linear electrodynamic equations Next the selection deals with the electrodynamic properties of magnetized active plasma and waves in plasma The text also tackles non linear wave interactions along with fluctuations in plasmas The next chapter talks about the effect of non linear wave interaction on fluctuations in a plasma Chapter 8 details fluctuation dissipation theorem while Chapter 9 discusses kinetic equations The tenth chapter covers the scattering and radiation of waves and the last chapter tackles wave interaction in semi bounded plasma The book will be of great use to scientists and professionals who deal with plasmas

Principles of Plasma Mechanics Bishwanath Chakraborty, 2007 This Book Presents A Systematic Exposition Of The Fundamental Principles Involved In Plasma Mechanics It Also Highlights Some Of The Recent Developments In The Area The Book Emphasises The Following Topics Magnetization By Inverse Faraday Effect

Ionospheric Cross Modulation Relativistic Vlasov Equations For Waves In Plasmas Kinetic Theory Of Vlasov For Plasmoidal Equilibrium Structures Formalism Of Transformation From Laboratory Frame To A Space Independent Frame For Study Of Dispersive Wave With Its Comprehensive Approach And Detailed Treatment The Book Would Serve As An Excellent Text For M Sc Physics Students As Well As Research Scholars **Perturbation Methods** Ali H. Nayfeh, 2008-09-26 The Wiley

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Stuart, 2013-10-22 Proceedings of the International Symposium on Plasma Wall Interaction **Electromagnetic Fluctuations In Plasma** A Sitenko, 2012-12-02 Electromagnetic Fluctuations in Plasma focuses on the theoretical investigation of the electromagnetic properties of a plasma an ionized gas The manuscript first takes a look at the general theory of fluctuations and electromagnetic fluctuations in media with space time dispersion Discussions focus on spectral distribution of the fluctuations and energy dissipation in the medium dielectric and magnetic permittivities in a medium with spatial dispersion current charge and field fluctuations in a medium and inversion of the fluctuation dissipation theorem The text then examines the electrodynamic properties of an electron plasma and electromagnetic fluctuations in an electron plasma The publication ponders on fluctuations in an electron ion plasma and electron plasma in a magnetic field Topics include plasma dielectric permittivity tensor in a magnetic field longitudinal plasma oscillations in a magnetic field

fluctuations in charge and current densities in an equilibrium electron ion plasma and electron and ion density fluctuations in an equilibrium plasma The text also tackles the passage of charged particles through plasma and dynamic friction and diffusion coefficients in a plasma The book is a dependable reference for readers interested in the study of the

electromagnetic properties of a plasma **Electrodynamics of Density Ducts in Magnetized Plasmas** I G Kondratiev, A V Kudrin, T M Zaboronkova, 1999-07-23 Providing a systematic and self contained treatment of excitation propagation and re emission of electromagnetic waves guided by density ducts in magnetized plasmas this book describes in detail the theoretical basis of the electrodynamics of ducts The classical dielectric waveguide theory in open guiding systems in magnetoplasma is subjected to rigorous generalization The authors emphasize the conceptual physical and mathematical aspects of the theory while demonstrating its applications to problems encountered in actual practice The opening chapters of the book discuss the underlying physical phenomena outline some of the results obtained in natural and artificial density ducts and describe the basic theory crucial to understanding the remainder of the book The more specialized and complex topics dealt with in subsequent chapters include the theory of guided wave propagation along axially uniform ducts finding the field excited by the source in the presence of a duct excitation of guided modes the asymptotic theory of wave propagation along axially nonuniform ducts and mode re emission from a duct The full wave theory is used throughout most of the book to ensure consistency and the authors start with simpler cases and gradually increase the complexity of the treatment *Coherent Non-linear Interaction of Waves in Plasmas* Jan Weiland, Hans Wilhelmsson, 1977

Physics Of New Methods Of Charged Particle Acceleration A G Bonch-osmolovsky, 1994-03-30 Contents Introduction Historical Review Some Quasistatic Effects of Space Charge Collective Effects in the Charge Particle Ensembles The Foundation of the Physics and Schemes of Collective and Coherent Methods of Acceleration Veksler Problem Impact Method of Acceleration The Problems of Equilibrium of Relativistic Electron Rings On a Stability of Electron Rings Beam Wave Collective Methods of Acceleration The Physics of Resonance Doppler Interaction Its Mathematic Description Readership High energy physicists keywords

Laser Interaction and Related Plasma Phenomena Helmut J. Schwarz, Heinrich Hora, 2012-12-06 Since the third Workshop on Laser Interaction and Related Plasma Phenomena in 1973 one area within the scope of this conference received increased attention laser fusion This possibility was emphasized in February 1977 in a Seminar on US energy policies at The Hartford Graduate Center by John F O Leary Head of the Federal Energy Administration who said that by the year 2100 laser fusion will be coming along giving us a new age of choice Efforts in research and development were stepped up to investigate new concepts of laser ignition of controlled nuclear reactions Here one expects no radioactive waste from fuel Th deuterium tritium reaction the only one which may be possible with magnetic field confinement in tokamaks has a highly radio active tritium cycle while in principle laser reactions are possible with pure deuterium hydrogen boron or others The worldwide progress in laser compression was not only stimulated by the energy crisis but also by its advancements In

our first Workshop in 1969 F Floux of the French Limeil Laboratories described his experiments which led only one month later to the production of fusion neutrons in such large numbers as had not been achieved up to then see appendix of Vol I these Proceedings

Plasma Physics K. Nishikawa, M. Wakatani, 2013-04-17 Plasma Physics Basic Theory with Fusion Applications presents a thorough treatment of plasma physics beginning at an introductory level and including an extensive discussion of applications in thermonuclear fusion research The physics of fusion plasmas is explained in relation to recent progress in tokamak research and other plasma confinement schemes such as stellarators and inertial confinement The unique and systematic presentation and numerous problems will help readers to understand the overall structure of plasma theory and will facilitate access to more advanced literature on specialized topics This new edition has been updated with more recent results

Strongly Coupled Plasmas Gabor Kalman, Paul Carini, 2013-06-29 The Advanced Study Institute on Strongly Coupled Plasmas was held on the campus of the Universite d Orleans Orleans la Source France from July 6th through July 23rd 1977 15 invited lecturers and 50 other participants attended the Institute The present Volume contains the texts of most of the lectures and of some of the numerous seminars presented at the Institute The topic of strongly coupled coulomb systems has been an area of vigorous activities over the last few years Such systems occur in a great variety of physical situations stellar and planetary interiors solid and liquid metals semiconductors laser compressed plasmas and gas discharges are some of the most important examples All these systems have the common feature that for one or more of their constituent charged particle liquids the potential energy to kinetic energy ratio is not small and therefore the application of the traditional plasma perturbation techniques is not feasible Many ingenious theoretical schemes have been worked out in order to attack both the related equilibrium and nonequilibrium problems and also various methods have been borrowed from areas where problems not dissimilar to the ones arising in coulomb systems had already been tackled At the same time computer simulations have led to a probably unparalleled accumulation of data on the behavior of an ensemble of classical charged particles For the first time the Institute assembled workers from various disciplines who had been involved with diverse aspects of the strongly coupled plasma problem

Stability and Transport in Magnetic Confinement Systems Jan Weiland, 2012-06-27 Stability and Transport in Magnetic Confinement Systems provides an advanced introduction to the fields of stability and transport in tokamaks It serves as a reference for researchers with its highly detailed theoretical background and contains new results in the areas of analytical nonlinear theory of transport using kinetic theory and fluid closure The use of fluid descriptions for advanced stability and transport problems provide the reader with a better understanding of this topic In addition the areas of nonlinear kinetic theory and fluid closure gives the researcher the basic knowledge of a highly relevant area to the present development of transport physics

Publications of Los Alamos Research Los Alamos National Laboratory, 1983

Microwave Discharges Carlos M. Ferreira, Michel Moisan, 2013-11-21 Proceedings of a NATO ARW held in Vimeiro Portugal May 11 15 1992

Nonequilibrium Atmospheric Pressure Plasma Jets

XinPei Lu,Stephan Reuter,Mounir Laroussi,DaWei Liu,2019-04-23 Nonequilibrium atmospheric pressure plasma jets N APPJs generate plasma in open space rather than in a confined chamber and can be utilized for applications in medicine This book provides a complete introduction to this fast emerging field from the fundamental physics to experimental approaches to plasma and reactive species diagnostics It provides an overview of the development of a wide range of plasma jet devices and their fundamental mechanisms The book concludes with a discussion of the exciting application of plasmas for cancer treatment The book provides details on experimental methods including expert tips and caveats covers novel devices driven by various power sources and the impact of operating conditions on concentrations and fluxes of the reactive species discusses the latest advances including theory modeling and simulation approaches gives an introduction overview and details on state of the art diagnostics of small scale high gradient atmospheric pressure plasmas covers the use of N APPJs for cancer applications including discussion of destruction of cancer cells mechanisms of action and selectivity studies XinPei Lu is a Chair Professor in the School of Electrical and Electronic Engineering at Huazhong University of Science and Technology Stephan Reuter is currently Visiting Professor at Universit Paris Saclay In a recent Alexander von Humboldt research fellowship at Princeton University he performed ultrafast laser spectroscopy on cold plasmas Mounir Laroussi is Professor of Electrical and Computer Engineering and director of the Plasma Engineering and Medicine Institute at Old Dominion University He is a Fellow of IEEE and recipient of an IEEE Merit Award DaWei Liu is Professor in the School of Electrical and Electronic Engineering at Huazhong University of Science and Technology Inventory of Current Energy Research and Development Oak Ridge National Laboratory,1972 *Plasma Physics Index* ,1982 Energy Research Abstracts ,1992-05

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