

Nonlinear Effects and Anomalous Transport in RF Plasmas

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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

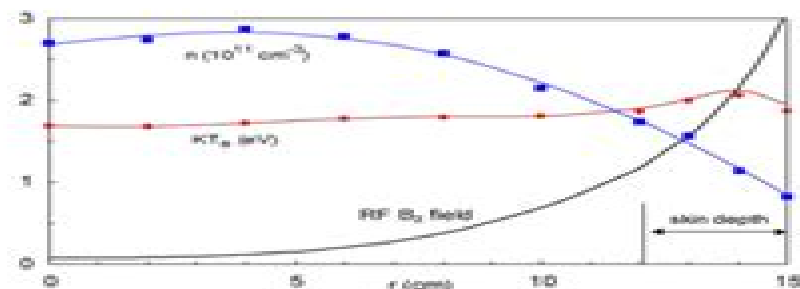


Fig. 1. Radial profiles of density, electron temperature, and the RF B_z field in the apparatus of Fig. 2 [1]. (Color version available online at <http://ieeexplore.ieee.org>.)

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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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

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 homogenous 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 deals with plasmas

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

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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 Documentation of Plasma Physics. Pt. 1, Experimental Plasma Physics [and] Theoretical Plasma Physics ,1981 **Plasma Physics Index** ,1982 **Asymptotic Methods in Nonlinear Wave Theory** Alan Jeffrey,Takuji Kawahara,1982 The Interaction of Strong Electromagnetic Fields with Plasmas Ivan Romanovich Gekker,1982 The range of plasma conditions considered here is intentionally broad systematic and relevant to such areas as plasma heating plasma acceleration laser plasma interaction and plasma confinement This volume presents the principle concepts of plasma physics with an account of the linear theory of electromagnetic wave interaction and then covers nonlinear processes with extensive treatment of the pondermotive force Related experimental work is thoroughly reviewed

Index of Conference Proceedings Received 1974-1978 British Library. Lending Division,1979 Oscillations and Noise in Low Pressure DC Discharges F. W. Crawford,Gordon S. Kino,1961 This analysis is concerned mainly with oscillations and fluctuations which occur either spontaneously or as a result of deliberate excitation in low pressure hot cathode plasmas Experimental observations on high and low frequency effects occurring spontaneously are discussed and speculations are made on the possible gener ATION MECHANISMS In many cases theories of these mechanisms have been treated in experiments involving deliberate excitation of oscillations and comparisons are made where relevant For device applications and to relieve the difficulties which occur in quantitative experiments in plasma physics it is important that the sources of spontaneous oscillations should be understood and suppressed if possible The analysis includes a discussion of work which has been carried out to reduce these effects and concludes with some suggestions for further lines of attack on the problems Author *Theoretical and Computational Plasma Physics* International Centre for Theoretical Physics,1978

Electromagnetic Fluctuations in Plasma Alekseï Grigor'evich Sitenko,1967 *BLL Conference Index, 1964-1973* British Library. Lending Division,1974 **Index of Conference Proceedings Received** British Library. Lending Division,1977

Energy Research Abstracts ,1991 **Physics, Uspekhi** ,1995 Solar Wind Nine: Proceedings of the Ninth International Solar Wind Conference Shadia Rifai Habbal,Ruth Esser,Joseph V. Hollweg,Philip A. Isenberg,1999-06-24 The Solar Wind Nine Conference was the ninth in the series of solar wind conferences established in 1964 by Dr Marcia Neugebauer to provide a forum for the interaction between solar physicists and space physicists interested in the origin and evolution of the solar wind One of the scientific goals of the conference was to reflect the importance of the synergistic interaction between theory numerical modeling and simulations in situ measurements and remote sensing observations in the exploration of the solar wind Indeed the opportunity provided by the many concurrent missions Ulysses Yohkoh SOHO TRACE SPARTAN WIND and ACE which probe the Sun and interplanetary space from different vantage points provided very rich material for the contributions The presentations included invited reviews and contributed talks as well as poster

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Table of Contents Nonlinear Effects In Plasmas Proc

1. Understanding the eBook Nonlinear Effects In Plasmas Proc
 - The Rise of Digital Reading Nonlinear Effects In Plasmas Proc
 - Advantages of eBooks Over Traditional Books
2. Identifying Nonlinear Effects In Plasmas Proc
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Nonlinear Effects In Plasmas Proc
 - User-Friendly Interface
4. Exploring eBook Recommendations from Nonlinear Effects In Plasmas Proc
 - Personalized Recommendations
 - Nonlinear Effects In Plasmas Proc User Reviews and Ratings
 - Nonlinear Effects In Plasmas Proc and Bestseller Lists
5. Accessing Nonlinear Effects In Plasmas Proc Free and Paid eBooks
 - Nonlinear Effects In Plasmas Proc Public Domain eBooks
 - Nonlinear Effects In Plasmas Proc eBook Subscription Services
 - Nonlinear Effects In Plasmas Proc Budget-Friendly Options

6. Navigating Nonlinear Effects In Plasmas Proc eBook Formats
 - ePub, PDF, MOBI, and More
 - Nonlinear Effects In Plasmas Proc Compatibility with Devices
 - Nonlinear Effects In Plasmas Proc Enhanced eBook Features
7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Nonlinear Effects In Plasmas Proc
 - Highlighting and Note-Taking Nonlinear Effects In Plasmas Proc
 - Interactive Elements Nonlinear Effects In Plasmas Proc
8. Staying Engaged with Nonlinear Effects In Plasmas Proc
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Nonlinear Effects In Plasmas Proc
9. Balancing eBooks and Physical Books Nonlinear Effects In Plasmas Proc
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Nonlinear Effects In Plasmas Proc
10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
11. Cultivating a Reading Routine Nonlinear Effects In Plasmas Proc
 - Setting Reading Goals Nonlinear Effects In Plasmas Proc
 - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Nonlinear Effects In Plasmas Proc
 - Fact-Checking eBook Content of Nonlinear Effects In Plasmas Proc
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning
 - Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
14. Embracing eBook Trends
 - Integration of Multimedia Elements

- Interactive and Gamified eBooks

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