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Waves in Plasma Sheaths and at Boundaries: Theory and Computer Experiments

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FINAL REPORT ON ONR AASERT AWARD TO DAVID C. COOPERBERG

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TITLE: MODELING AND SIMULATION OF HIGH FREQUENCY SURFACE WAVES IN BOUNDED PLASMAS

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ABSTRACT:

This report covers the ONR AASERT support at University of California at Berkeley for David J. Cooperberg from Fall 1993 until end of July 1997. During this time he did research on the material in the title, resulting in a Ph.D. thesis submitted to the University in July 1997.

High frequency waves which propagate at the edges of plasmas bounded by metal (conducting) boundaries are treated in great detail, in theory, and with many-particle simulations. There is no applied magnetic field; the plasma and waves are unmagnetized.

First, a linear theory and simulation are made, to include the sheath and the pre-sheath from first principles and self-consistently. The detailed structure of these waves, excited at small amplitudes (from noise in most cases), is obtained, specifically, the dispersion and eigenfields. These results are compared and contrasted with the well-known Tonks-Dattner (transverse, or dipole) resonances and Gould-Trivelpiece waves (longitudinal). The former are the cutoff frequencies for the latter waves.

Second, some of these plasma surface waves are driven by sufficient excitation to obtain a discharge (usually meaning sufficient plasma heating to obtain ionization by electrons). In a one-dimensional bounded planar slab model, the drive is near the series resonance frequency, allowing very low voltage drive (a few volts). (Such plasmas have been made in laboratories, for some time now.) Similarly, in two-dimensional models (both electrostatic periodic-bounded and electromagnetic fully bounded - a cavity), the waves are driven by low antenna voltages, at plasma resonance (not vacuum cavity resonance). Considerable information is provided as to the (new) wave heating mechanisms, reasons for seeking the resonance, drive frequency-density scaling, and more.

There are numerous practical applications of these plasma surface driven waves, especially the resonantly driven ones.

This thesis provides much more structure and details as to these high frequency waves than has been given heretofore.

This report provides the thesis Abstract, Contents, and Abstracts for the five chapters. The last have chapters have been submitted for journal publication.

Complete copies are available on written request to Prof. Birdsall.

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Modeling and Simulation of High Frequency Surface Waves in Bounded Plasmas

by

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M.A. (University of California, Berkeley) 1992

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Abstract

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"For many years plasma simulations were focused on the behavior of the bulk of the plasma, as there are many oscillations, waves, instabilities, and transport problems [to study] in the bulk... For many such models, periodic boundary conditions were acceptable, essentially ignoring boundaries."[1]. In the past decade accurate modeling of bounded plasma has advanced considerably motivated in part by a need to describe edge transport in fusion devices and in part by a desire to model DC, RF, and microwave discharges which are commonly used in plasma-assisted materials processing.

In the work presented here, we shall make a careful examination of an intrinsic property of bounded plasmas. Specifically, we will be studying a set of high frequency (electron) waves which propagate at the boundary of metal bounded plasmas. It will be shown that their existence and behavior requires an accurate model of the plasma edge and sheath regions.

This work has two main objectives. The first is to clarify the structure of these waves. While there has been considerable experimental and analytic work on electron surface waves in dielectric bound plasmas, there has been little or no investigation of the surface modes in a metal bound slab. Part of the reason for this is that metal bound plasmas are less accessible for some experimental techniques which include wave excitation and detection schemes (typically done with antennae positioned outside the dielectric bound plasma) and partly because it may have been believed that the electric fields of surface waves in metal bound plasmas would be shorted out by the conducting boundaries close to the plasma. This is not the case, as will be demonstrated. It is also hoped that this use of

simulation in the study of electron surface waves will further our general understanding of these waves in both metal and dielectric bound plasmas.

Our second objective is to study how these natural modes may be used to sustain a plasma discharge suitable for plasma processing. Current "surface wave plasmas" are produced in glass tubes with short-gap excitation[2]. Our analysis of surface waves in planar metal bounded plasma slabs enables us to demonstrate, through simulation, new types of surface wave sustained discharges which may operate at low pressures with low sheath potentials and may be scalable to large areas without compromising plasma uniformity.

This study of surface waves in metal bound plasmas also leads to speculation as to the use of such waves in controlling the plasma edge (and possibly the bulk). The application of microwave power at the plasma edges may be used to excite these surface modes and enhance plasma heating there. The effect might be enhanced plasma uniformity in traditional capacitively and inductively coupled discharges.

This work relies heavily on particle-in-cell simulation with Monte-Carlo collisions (PIC-MCC)[3][1][4] of unmagnetized, bounded $2d3v$ plasmas. Among the benefits of the PIC-MCC scheme are an adherence to first-principles, which allows a wide range of kinetic, non-linear, non-equilibrium, and non-local behavior to be accurately modeled, and an ease of collecting virtually any diagnostic that could be desired (at any and all positions in phase-space). The accuracy provided by PIC-MCC is of particular importance to this work because of a desire for an accurate representation of sheaths, non-linear effects, and kinetic effects such as Landau damping, stochastic heating, and wave-particle interactions. Also accurate modeling of the electron energy probability function (EEPF) is desired since the EEPF is known to depart from Maxwellian in low pressure discharges[5][6].

An outline of this work is as follows. Chapter 1 presents an overview of past and current work on electron surface oscillations and waves in bounded plasmas. In Chapter 2 we initiate our study of waves in the metal bound slab using a matrix sheath model. A linearized Vlasov treatment for this model is derived and compared to simulation. Next a more realistic model for the plasma and sheath is developed in Chapter 3. The result is the identification of a new set of surface modes which exist only in the non-uniform, thermal, bounded plasma. We then move from the study of surface wave characteristics to a study of surface wave sustained discharges. In Chapter 4 we consider the 1d3v plasma which is sustained at the series resonance frequency (which will be shown to be the cut-off frequency for the main asymmetric surface wave). The 2d3v surface wave sustained slab will be treated in Chapter 5.

Contents

Chapter 1

Brief History of Electron Resonances and Surface Waves in Bounded Plasmas

Plasmas bounded by conducting or dielectric walls provide regions near the plasma edge in which the permittivity, ϵ, changes sign. This sign change takes place at the plasma/dielectric interface in the dielectric bounded case, at the plasma/sheath interface for a uniform metal bounded plasma with a matrix sheath, and at some intermediate point inside the plasma (where the local plasma frequency equals the excitation frequency) for non-uniform plasmas. A consequence of this sign change in ϵ is the introduction of surface wave modes. The field strength in these modes is greatest at a point near the plasma boundary and decays exponentially away from this point. One dimensional simulations of a plasma slab show: (a) plasma oscillations at high frequencies ($\omega \gtrsim \omega_{pe}$), associated with the bulk; and (b)resonances (main or series, and secondary or Tonks-Dattner) on the order of but less than ω_{pe}, associated with the edges. Two dimensional simulations of a plasma slab similarly show modes associated with the bulk and waves which propagate along the walls (in $\hat{y}$) which are localized in the edge (analogous to Gould-Trivelpiece and Tonks-Dattner waves in a plasma column). The resonances found in 1d are the cut-off frequencies ($k_y = 0$) in 2d. Evidence of the series resonance in a parallel plate discharge is demonstrated by the measurement of plasma impedance which approaches a pure resistance when driving at or near $f_{series} = f_{pe}(2s/L)^{1/2}$ (where s is the sheath width and L is the total system width). In 2d thermally excited waves can be detected via spectral analysis and also can be driven to sustain a plasma. Before proceeding with a further description of the current work on surface modes found in the metal bounded slab, we present a history of the experimental and theoretical advances made in understanding high frequency surface waves in bounded plasmas, and advances in the area of surface wave produced plasmas.

Chapter 2

Electron Surface Waves in a Plasma Slab with Uniform Ion Density

2.1 Abstract

Electron surface waves in a metal bound plasma slab have been detected and analyzed. In this work we show that the presence of a matrix sheath (fixed ions, no electrons) between the central quasi-neutral region and the metal walls allows for the propagation of surface waves analogous to those found in dielectric bound plasmas. Measurements of the dispersion relations and eigenfunctions of asymmetric and symmetric, electrostatic, surface and body waves are made via particle-in-cell simulation of a plasma slab with sheaths. The plasma slab has finite temperature electrons and fixed ions of uniform density. The sheaths consist of electron free, fixed, uniform ion regions ("matrix sheath")of thickness $\sim \lambda_{De}$. A linearized Vlasov theory is developed for comparison with the simulation. It is shown that the long wavelength approximation is not valid even for long wavelengths in the propagation direction. Collisionless damping of both surface and body waves is measured which compare well with theoretical estimates.

Chapter 3

Electron Surface Waves in a Nonuniform Plasma Slab

3.1 Abstract

Electron surface waves in a nonuniform, metal bound, thermal plasma slab have been analyzed and detected. The time averaged densities and potentials are wholly self-consistent, with physical sheaths and pre-sheaths. Measurements of the dispersion relations of these waves, as well as the eigenstructure of the perturbed electron density, reveal a spectrum of waves with frequencies above and below the peak electron plasma frequency in the slab. These waves are analogous to the Gould-Trivelpiece and Tonks-Dattner waves found in dielectric bound plasma columns. Measurements have been made using particle-in-cell simulation of an argon plasma and are compared with linear fluid theory in which the adiabatic approximation is made for the perturbed pressure and the experimental (simulation) zero order electron density is used. The presence of the metal boundary leads to regions near the plasma sheaths in which the fluid theory breaks down; we explore the differences between theory and measurement in this region.

Chapter 4

Series Resonance Sustained Plasmas in a Metal Bound Plasma Slab

4.1 Abstract

The characteristics of series resonance sustained collisional argon plasmas are measured by particle-in-cell Monte-Carlo simulation and analyzed with various theoretical models. These measurements include discharge gap impedance which is shown to be nearly pure resistive, EEPFs, electron heating profiles, electric field structure, and electron density profiles over a range of applied frequencies ($110MHz$ to $470MHz$) and neutral gas pressures ($2mT$ to $300mT$). The scaling laws, which predict the density and sheath width dependency on operating frequency as ω_{rf}^3 and ω_{rf}^{-1} respectively, are verified. These resonant discharges are driven with low applied voltages ($\sim T_e$) and are shown to produce low-voltage plasmas. A heating mode transition between a high pressure collisional regime and a low pressure collisionless regime is discussed. Also the self-tuning of the discharges, needed to maintain resonance, is explained.

Chapter 5

Surface Wave Sustained Plasmas in a Metal Bound Plasma Slab

5.1 Abstract

Standing electron surface waves have been used to naturally sustain a resonant plasma discharge. The surface waves are excited in a metal bound collisional plasma and propagate along the plasma/sheath boundary. Our experimental results are obtained from fully electromagnetic particle-in-cell simulations with Monte-Carlo collisions of a 2d3v plasma. Results are analyzed for discharges operating over a range of frequencies, neutral gas pressures, and antennae design.