PLASMA DYNAMICS

XVII. PLASMA DYNAMICS

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XVII. PLASMA DYNAMICS

A. Basic Plasma Research

1. NONLINEAR WAVE INTERACTIONS

National Science Foundation (Grants ENG77-00340)

Abraham Bers, Kwok C. Ko, Vladimir B. Krapchev, Kim S. Theilhaber,
Hossein Baghei, Abhay K. Ram, Thomas M. O'Neil

This research group concerns itself with theoretical studies of large-amplitude waves in a plasma. Thus it impacts on problems of wave propagation, plasma heating, and turbulence in plasmas. The following is a brief summary of accomplishments:

(a) We have completed our study of the nonlinear evolution in space-time of three interacting wavepackets, including the effects of dephasing due to inhomogeneity in the medium. This problem appears in many branches of physics and engineering, and not just in plasma physics. Two comprehensive papers on this work are now completed and scheduled to appear in Reviews of Modern Physics this spring.[1,2]

(b) We have initiated a new kinetic (Vlasov) description of ponderomotive effects in a plasma, and were able to solve some simple problems to all orders in the electric field. These results are particularly applicable to intense laser-plasma interactions, and they predict a new mechanism for the generation of magnetic fields in such interactions.[3-6]

(c) We have achieved a detailed understanding of self-modulation for electrostatic waves in a plasma, including the effects of plasma inhomogeneity. These results are of importance to wave propagation and RF heating of plasmas.[7]

(d) We have completed our study of the linear evolution of the three-wave interaction in a finite-width pump, including the effects of three-dimensional geometry and inhomogeneity.[8] In addition, we have completed the study of the nonlinear evolution of the convective quasi-mode parametric interaction in two and three dimensions.[9] This, like the three-wave problem, is also a universal nonlinear wave-interaction problem. Unlike the three-wave problem which is a second-order wave-wave interaction, the quasi-mode interaction is a third-order interaction (like self-modulation) describing the nonlinear coupling of waves through scattering off of particles.

In the past two years, three Ph.D. theses were completed (A. H. Reiman, J. L. Kulp, and C. C. F. Karney; the last two shared support from DOE). Two postdoctoral research associates (Drs. A. Sen and G. L. Johnston) completed their two-year stay. One foreign postdoctoral research associate (Dr. G. Leclert, University of Nancy, France) spent one year with us, and another one (Dr. M. E. Villalon, University of Madrid, Spain) is currently with us; both are supported primarily by their governments. This year, Professor T. M. O'Neil of the University of California at San Diego, is spending his sabbatical within our group.

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2. RENORMALIZATION METHODS IN PLASMA TURBULENCE THEORY

National Science Foundation (Grant ENG77-00340)

Thomas H. Dupree

Plasma fluctuations with velocities of the order of or less than the thermal velocity are being studied. In the stationary case these fluctuations are known as B. G. K. modes. In the turbulent case, they have been referred to as clumps. A clump is an excess or deficiency in the local phase density as compared with the local average density. We can picture the deficiency case as a hole and it has the interesting property of being gravitationally bound. These structures persist on a long time scale in the plasma and have important effects on a variety of plasma phenomena. The earlier theory of these fluctuations is being improved and a more rigorous theory developed. In particular, the new theory conserves both the electric energy of the fluctuations and the kinetic energy of the particles.

3. INTENSE RELATIVISTIC ELECTRON BEAMS

National Science Foundation (Grant ENG77-00340)
U.S. Department of Energy (Contract EY-76-S-02-2766)
U.S. Air Force – Office of Scientific Research (Grant AFOSR-77-3143)

George Bekefi

Three areas of research are now being studied, making use of our pulsed high-voltage facilities, Nereus (voltage 500 kV, current 70 kA, pulse duration 30 nsec) and Pulserad 110A (voltage 1.5 MV, current 20 kA, pulse duration 30 nsec).

Magnetron Design

We are continuing with our studies of the relativistic electron-beam magnetron. These studies include optimization of magnetron design, studies of its frequency spectra, and scaling with voltage and magnetic field. The experimental program goes hand-in-hand with a particle-in-cell computer code developed by us in collaboration with Dr. Adam Drobot at the Naval Research Laboratory.

Free Electron Laser

Experimental and theoretical works are in progress on a novel free-electron laser. In this device the low-frequency pump wave is a spatially periodic, quasi-static electric field obtained by rippling the wall of the drift tube containing the relativistic electron beam.

Reflex Diode

We are studying the dynamics of the electrons in the reflex diode. This diode is comprised of a pinch cathode and a thin-foil anode. The system is immersed in a strong axial magnetic field of 10-20 kG.

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B. Plasma Research Related to Fusion

1. PHYSICS OF HIGH-TEMPERATURE PLASMAS

U.S. Department of Energy (Contracts ET-78-C-01-3019
and ET-78-S-02-4681)

Bruno Coppi

An understanding of the physics of high-temperature plasmas is of primary importance in the solution of the problem of controlled thermonuclear fusion. One of our goals is the magnetic confinement and heating of plasmas with densities in the interval 10^{14} to 10^{15} particles/cm^3 and thermal energies in the few kiloelectronvolt range. The macroscopic transport properties (e.g., particle diffusion and thermal conductivity) of plasmas in these regimes are weakly affected by two-body collisions between particles. The relevant transport coefficients, in fact, are influenced significantly by the type of collective modes that can be excited, such as density and temperature fluctuations caused by microinstabilities.

Relevant theoretical and experimental contributions have been presented at national and international conferences or published in professional journals. The primary focus has been on the experimental effort involving the Alcator A and C devices. Our purpose has been to realize plasmas that can sustain very high current densities without becoming macroscopically unstable, in order to achieve the highest possible rate of resistive heating of the plasma.

Alcator's unique properties, high current and particle densities and relatively low impurity concentration, have made it one of the most successful confinement experiments in terms of achieving the highest known values of the confinement parameter "$n\tau$" and of realizing a sequence of plasma regimes of basic physical interest. In particular, during 1978 a series of experiments carried out with record low values of the so-called "safety factor" has led to regimes with relatively high plasma currents and modest magnetic fields where the confinement time is improved in comparison to that obtained at the higher values of the "safety factor" that characterize the conventional operation of most toroidal confinement devices.

Experiments on the injection of microwaves at the lower hybrid frequency, which for the system adopted on Alcator A is 2.45 GHz, have been undertaken systematically at power levels of approximately 100 kW. One of the most striking observable effects has been the enhancement of the rate of fusion-neutron emission in deuterium plasmas, by approximately a factor of 30 when compared to the case where there is no injection of microwave power. Therefore it has been possible to verify the dependence of microwave penetration and energy deposition on different macroscopic parameters, such as the magnetic field, the particle density, and the plasma current.

The Alcator C device was formally dedicated in April 1978, and is now operating with well-confined plasmas and plasma currents of approximately 300 kA. We recall that the reference design value of the total plasma current is 1 megampere and that one of the objectives of Alcator C is to achieve values of the confinement parameter $n\tau$ around 10^{14} sec/cm^3.

A major program on microwave heating of Alcator C was undertaken with the goal of realizing a system for injection of up to 4 megawatts at a frequency of 4.6 GHz. This is in the range of the lower hybrid frequency for the values of the plasma density that are expected to be realized. A parallel program of heating at the ion cyclotron frequency has also been undertaken. The objectives of these efforts are to be able to raise the maximum temperature of plasmas with peak densities of approximately 10^{15} particle/cm^3 above 2 keV and to study their basic confinement properties in conditions where the effectiveness of ohmic heating begins to degrade. The experimental program is integrated with a theoretical effort for the numerical simulation of the plasma regimes that we hope to obtain.

A series of experiments carried out on the FT device at Frascati and on the PLT machine at Princeton have confirmed and extended the results that had been obtained on the Alcator A device since 1974 concerning the nature of the diffusion coefficient for the electron thermal-energy loss. This was, in fact, one of the bases for the transport model and codes that have been developed as a part of our program, and that have been used both to predict the performance of Alcator C and to formulate a research program on α-particle heating by the realization of a series of compact devices. These are generally called Ignitors or Alphators, and represent the natural evolution of the Alcator program into a generation of high particle density, relatively small-dimension fusion reactors. A design study of an Alcator D device along the same line is being undertaken.

The Rector experiment, which was originally developed to study the confinement properties of toroidal plasmas with elongated cross sections, was moved to new and more appropriate quarters. Regular plasma operation has restarted with a series of new diagnostic systems. Remarkable results, in terms of improved equilibrium and stability conditions, have been obtained by converting the basic axisymmetric magnetic configuration of Rector into a Stellarator-like configuration with helical symmetry. A novel distribution of coils has been adopted for this and, given its favorable construction characteristics, we expect that a series of higher performance experiments will evolve from this.

As is traditional with our mode of operation, we have maintained a system of close collaborations with national and overseas institutions for both our theoretical and experimental programs.

2. DYNAMICS OF TOROIDAL DISCHARGES

U.S. Department of Energy (Contract ET-78-S-02-4682)

James E. McCune, Daniel E. Hastings, George M. Svolos

a. Drift Modes in Tori

George M. Svolos, James E. McCune

Our study is focused on the analysis of drift modes and other related low-frequency modes in low-collisionality, "banana" regime, large toroidal systems.

In our approach we will make use of an inertial drift kinetic equation with appropriate choices for the relevant physical parameters of the problem. Insofar as a straight cylinder, even with a helical field, is not the true natural limit of a toroidal magnetic field configuration, toroidal effects are included from the outset.

The systematic study of the cross-flux eigenvalue problem, the effects of shear on the stability of the modes, their localization and the toroidal effects are the central parts of this research. In addition, special attention is given to nonlinear turbulent electron behavior. In particular, we examine the effects that nonlinear stochastic cross-flux electron diffusion close to mode rational surfaces may have on the stability properties and ultimate fate of these modes.

b. Drift Modes in Tandem Mirror Systems

Daniel E. Hastings, James E. McCune

The central cell plasma in the tandem mirror is expected to be high-beta. Hastings (FY '79) developed a general formalism to describe small fluctuations in the high-beta plasma including finite ion Larmor radius effects and has since then set up the corresponding radial eigenmode problem. This has been solved in a WKB sense giving (in the no-shear case) the so-called 'local' approximation. Work in this area is now directed to writing computer programs to numerically locate and track the various low-frequency drift waves as beta is increased.

A complete study of low-frequency drift waves (universal drift mode, temperature-gradient drift mode, etc.) will be made available with the important high-beta physics included.

3. RF HEATING AND NONLINEAR WAVES IN TOROIDAL PLASMAS

U.S. Department of Energy (Contract ET-78-S-02-4682)

Abraham Bers, Kwok C. Ko, Vladimir B. Krapchev,
John L. Kulp, Jr., Kim S. Theilhaber, Maria Elena
Villalon, Thomas M. O'Neil

The general objective of this research is to explore the use of externally applied electromagnetic power (generically, "RF power") for the supplementary heating and confining of toroidal plasmas. Particular studies are being carried out to determine the heating of tokamak plasmas with microwave power in the lower hybrid range of frequencies, with the results applied to current experiments on Alcator A and Doublet II-A, as well as to experiments in the near future on Versator II and Alcator C.

Our studies have continued to focus on problems relevant to lower hybrid heating of tokamak plasmas in general, and to understanding the recent results of lower hybrid heating on Alcator A in particular. The two most prominent results from Alcator A are the observed nonlinear effects in the coupling of the RF power and the strong ion heating observed in a narrow range of plasma densities.

We have recently pointed out that at the plasma edge ponderomotive effects parallel to $\overline{B}_o$, coupled with the nonlinear bunching of the electrons there, can explain the experimentally observed nonlinear effects in the external coupling of lower hybrid energy to the plasma, as seen, for example, in Petula, JFT II, and Alcator A.[1] The ponderomotive force in the direction of $\overline{B}_o$ produces plasma density modifications in that direction that are independent of the phasing of the waveguides. In addition, the applied electric fields at the edge are such that the electron bunching is nonlinear; thus one finds that $(\omega_B/\omega) = (k_{\|}v_{tr}/\omega) = (v_{ind}/v_{ph})^{1/2} \sim 0.3$. This, together with the ponderomotive rippling of the plasma surface, leads to a shift of the applied $k_{\|}$-spectrum to larger $k_{\|}$ by a factor of 2-3, which is consistent with observations of heating and CO_2 laser scattering in Alcator A.[2, 3]

In relation to the observed ion heating in Alcator A there exist three possible mechanisms: (a) by the parametrically excited waves; (b) by stochastic heating of the lower hybrid wave or its parametrically excited waves; (c) by linear ion-cyclotron harmonic damping of the lower hybrid wave or its parametrically excited waves. (Enhanced collisional damping at mode conversion can no longer be relied upon.[4]) The theory of stochastic heating by lower-hybrid waves is by now relatively well advanced.[5] In the recent past we have concentrated on understanding the possible relevance of linear ion-cyclotron-harmonic damping in an inhomogeneous magnetic field, and the nonlinear heating aspects of quasi-mode parametric excitations. The first requires $(k_\perp \rho_i)^2 \gtrsim (\omega/\Omega_i)$ which can only be satisfied near or beyond wave conversion occurring at the center of the plasma. At the large field amplitudes of interest, however, and with the above condition satisfied, stochastic heating is effective and linear theory is not appropriate. The relevance of parametric excitations in ion heating is less clear. Parametrically excited spectra are observed in all tokamak heating experiments utilizing externally applied power in the lower hybrid range of frequencies. These are detected, however, at the plasma wall, and hence can not necessarily be assumed to occur in the plasma where the heating occurs. In the recent past, we have undertaken a detailed study of the nonlinear (heating) aspects of the quasi-mode parametric excitation in an inhomogeneous plasma. This parametric excitation is a prominent one since it is nonresonant, and it has a low threshold. In the past it was thought that the lower frequency sideband (also a lower hybrid wave) is mainly excited by scattering of the pump (the applied lower hybrid wave) off the electrons.[6] We have recently shown that for the parameters of Alcator A (but also, in fact, for any tokamak-type plasma) the dominant scattering is off the ions by Doppler-shifted ion-cyclotron-harmonic resonance of the low-frequency fields.[7] This may explain the ion-cyclotron-harmonic structure which one observes on the sideband signal at low frequencies.[2,8] Furthermore, nonlinearly, the quasi-mode excitation may be strong near the edge of the plasma. In that case, the pump depletes mainly to the sideband which propagates farther into the plasma but in a different direction, and has a wave conversion point that is farther out in the density gradient. Ion heating can then occur near wave conversion of the sideband by either linear ion-cyclotron-harmonic damping or induced stochastic ion motion, as before. A small fraction of the pump power (ω_{LF}/ω_s), where LF ≡ low frequency, and s ≡ sideband, goes directly to the ions via the low-frequency fields of the quasi mode.

Two projects have been completed. The first was related to current generation by RF fields.[9] The second involves a study of group velocity rays in toroidal geometry. The results of the latter have been written up in the Ph.D. thesis of John L. Kulp.[10] As a result of this work, we now have a sophisticated (symbolic and numeric) computer program and display for following RF energy propagation in a toroidal plasma, including all of the linear effects due to plasma and magnetic-field inhomogeneity, and toroidal geometry. The most important new result is the discovery that the applied $n_{||} = (ck_{||}/\omega)$ can be reduced by as much as 30-50% when $\omega \sim \omega_{LH}$ and $(\omega_{pe}/\Omega_e) \gtrsim 1$. This can have important consequences, especially in electron heating which is sensitive to $k_{||}$.

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4. NONLINEAR THEORY OF TRAPPED-PARTICLE INSTABILITIES

U.S. Department of Energy (Contract ET-78-S-02-4682)

Thomas H. Dupree, David J. Tetreault

The phenomenon of clumps is being studied in a plasma with a magnetic field. In particular, the effect of clumps on the drift and trapped particle mode instabilities is being studied. Clumps in the ion phase space density produce an enhanced ion viscosity which appears to be very effective in damping these modes and providing a nonlinear stabilization.

Concepts from strong plasma turbulence are being used to investigate magnetic islands in tokamaks. Turbulent magnetic fluctuations induced by drift waves as well as those formed through self-consistent currents are being studied. The purpose is to determine how the resulting turbulent destruction of magnetic surfaces affects tokamak plasma confinement.

Work is also beginning on computer simulations of the structure of clumps in plasma.

5. TOKAMAK RESEARCH: RF HEATING AND CURRENT DRIVE

U. S. Department of Energy (Grant EG-77-G-01-4107 and
Contract ET-78-S-02-4714)

George Bekefi, Miklos Porkolab, Kuo-in Chen, Stanley C. Luckhardt

Wide-ranging experimental investigations involving injection of high RF power levels are in progress or planned for the near future on the Versator II Tokamak. To accommodate these experiments, Versator II has been upgraded in toroidal field strength from 8 to 15 kG. This project was completed in late 1978, and after initial studies of plasma equilibrium in the upgraded machine, improved discharge parameters now achieved include plasma currents of 30-50 kA, central densities of $2\text{-}3 \times 10^{13}$ cm and pulse durations of 20-40 ms.

Currently, first RF injection experiments were initiated at the lower hybrid frequency using up to 150 kW of power at 800 MHz from an RF system supplied by the Princeton Plasma Physics Laboratory. In these experiments lower hybrid waves are injected with a phased array of waveguides (grill) designed to produce a favorable power spectrum of injected waves for heating ions or modifying the electron-velocity distribution so that a net toroidal current is driven. This later effect, investigated theoretically by Fisch and Bers,[1,2] could lead to the possibility of achieving a steady-state fusion reactor driven by microwave power.

In a second series of experiments to begin in late 1979, microwave power will be injected into the torus at the electron-cyclotron frequency. For this purpose, the newly developed gyrotron microwave generator will be supplied by the Naval Research Laboratory; the NRL gyrotron will allow ECRH experiments to be carried out at significant power levels in the range of 100-200 kW at a frequency of 35 GHz.

In support of the basic physics experiments, a large number of plasma diagnostic experiments are available or in preparation. These include: vacuum ultraviolet spectroscopy, 90-GHz microwave scattering, first-harmonic electron-cyclotron emission measurement, 35-GHz microwave interferometry, charge-exchange neutral-atom energy analysis, and ruby laser Thompson scattering.

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6. MIRROR-CONFINED PLASMAS

U. S. Department of Energy (Contracts ET-78-S-02-4886 and
ET-78-S-02-4690)

Louis D. Smullin

We have two systems in operation, Constance I and II. Constance I is devoted, this year, to the study of electron-cyclotron-resonance-heating (ECRH) as a means of damping the drift-cyclotron-loss-cone (DCLC) instability that limits the lifetime of highly ionized mirror-confined plasmas. This problem is being studied by M. E. Mauel.

Constance II is a larger version of Constance I. When completed (about June 1979) it will be used to compare DCLC stabilization by ECRH with stabilization by electron-beam plasma interaction (a technique demonstrated last year on Constance I). K. Rettman is the engineer in charge of building Constance II.

The target plasma we are attempting to stabilize is produced by the self-trapping of a plasma stream emitted from a plasma gun located outside the mirror region. Although this is an effective technique used by others before us, virtually nothing is known about the trapping mechanism nor about the detailed characteristics of the plasma stream. This problem is being studied by J. P. Rymer.

7. NEUTRAL BEAM RESEARCH

U.S. Department of Energy (Contract ET-78-S-02-4690)

Louis D. Smullin

High-current, negative ion (H^- or D^-) sources are needed to produce the high-energy ($\gtrsim$300-keV) neutral beams needed for heating of tokamak reactors. The Dimov magnetron source has been shown to be capable of emitting $\gtrsim 1$ amp of H^-. Peter Kenyon has been studying the high pressure ($\rho \approx 0.5$ T) magnetron discharge that characterizes these devices. His particular interest is to understand the noisy (turbulent) behavior of the discharge; he is comparing experimental results with a linear theoretical model of the onset of a drift instability driven by radial gradients of density and electrostatic potential.