PLASMA DYNAMICS

XX. PLASMA DYNAMICS

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XX. PLASMA DYNAMICS

A. Basic Plasma Research

1. NONLINEAR WAVE INTERACTIONS

National Science Foundation (Grant ENG79-07047)

Abraham Bers, Robert H. Berman, Kwok C. Ko, Vladimir B. Krapchev,
Abhay K. Ram, Kim S. Theilhaber, Maria Elena Villalon

Progress is reported in theoretical and computational work aimed at understanding the behavior of large-amplitude coherent waves in a plasma. Three specific research projects are briefly described.

(a) Nonlinear Waves in a Vlasov Plasma

The one-dimensional Vlasov equation for the electrons has been solved for a general form of the potential and to all orders in the field amplitude.[1] The distribution function is determined uniquely in terms of the action, which is the adiabatic invariant in the problem. In our approach the system evolves to its nonlinear state, in contrast to the stationary BGK solution.[2] The theory predicts the existence of a trapped-particle mode above a certain threshold for the field amplitude. Recent experimental observations confirm this prediction.[3]

(b) Stochasticity in Plasma Dynamics

Many problems involving the change from ordered to chaotic motion in Hamiltonian systems can be reduced to a simple two-dimensional mapping on a unit torus. The local work of Chirikov and Greene[4,5] on the standard mapping is extended to provide global measures of stability. Our local and global studies of difference equations with periodic coefficients show that well-developed stochastic behavior is observable below the Chirikov threshold.[6,7] We have obtained preliminary results on the onset of stochastic particle motion in a finite-amplitude wave packet.

(c) Space-Time Evolution of Wave-Wave Interactions

Resonant parametric instabilities can occur when a large amplitude lower hybrid wave is excited in a tokamak plasma. We study the decay into a low sideband of the pump and a low-frequency mode. During the past years an effort has been made to understand the effects of wave-numbers mismatch and finite spatial extent of the pump.[8-10] These works have focused mainly on numerical solutions. We have carried out an analytical study and reported the results.[11]

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2. RENORMALIZATION METHODS IN PLASMA TURBULENCE THEORY

National Science Foundation (Grant ENG79-07047)

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 ENG79-07047)
U.S. Air Force — Office of Scientific Research (Grant AFOSR-77-3143)

George Bekefi

During the past year our major experimental and theoretical effort has been in the generation of coherent microwave and submillimeter radiation using intense relativistic electron beams. Our interest was concentrated on free-electron lasers and magnetrons. Below we describe four pieces of research in which we have been active.

a. A Free-Electron Laser Pump Produced by Magnetic Diffusion

An efficient, quasi-static magnetic wiggler for use in free-electron lasers is produced by diffusing a time-varying magnetic field through a spatially periodic conductor, such as an assembly of copper rings or a copper helix. In our experiments, the magnetic field is generated in a 2275 turn, 1-m-long solenoid driven by a 3750-μF, 4-kV capacitor bank. At full capacitor charging, and in the absence of the periodic conductor, the solenoid current peaks at 720 A in a time of 17 ms, producing a uniform axial magnetic field $B_z = 21$ kG.

When a set of uniformly spaced copper rings (see Fig. XX-1) is used as the diffusive medium, the resulting magnetic field has the desired spatially periodic radial component B_r, together with a spatially modulated axial field B_z. The left-hand side of Fig. XX-1 shows the magnetic field components measured at a distance $r = 0.86$ cm from the solenoid axis when the capacitor bank is fully charged to 4 kV and the wiggler periodicity $\ell = 4$ cm. The right-hand side of Fig. XX-1 gives the dependence of B_r on the periodicity ℓ, and shows that large pump amplitudes can be achieved by this technique.

In FEL applications, it is desirable to gradually increase B_r as the electron

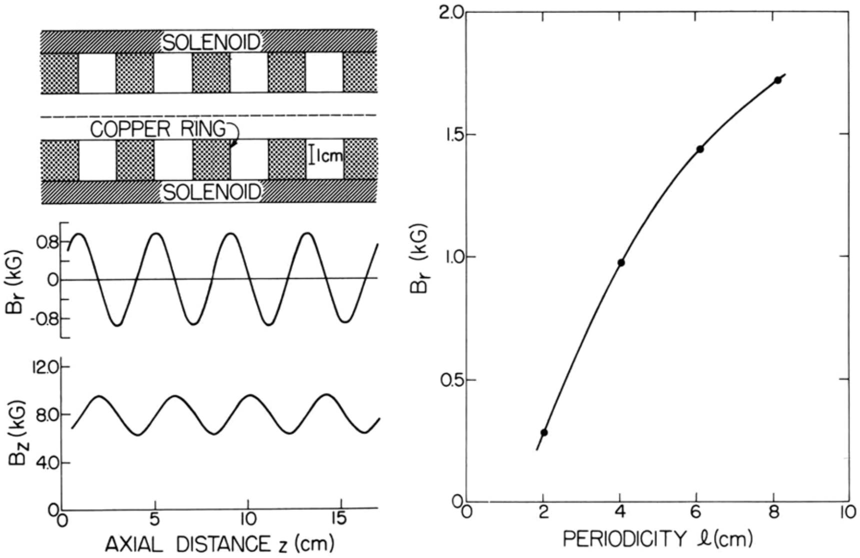

Fig. XX-1.

beam enters the interaction region. This is readily done by increasing the radial thickness of the rings as one moves away from the electron gun. Approximate calculations were carried out which allow one to optimize the thickness of the rings and estimate the values of B_r and B_z.

As an alternative to the rings, a helical copper bar has been used as the diffusive structure. This yields a helical magnetic pump whose properties are also being investigated.

b. A Study of Field Emission Diodes for FEL Applications

Relativistic electron beams exhibiting laminar, monoenergetic electron flow are required for use in free-electron lasers (FEL). Experimental[1] and computer simulation[2] studies indicate that foilless field-emission diodes used in stimulated Raman FEL systems do not possess the desired performance characteristics. One manifestation of poor beam quality (which we in fact use as a diagnostic) is the copious emission of microwave radiation. Power levels of 100-1000 kW have been observed when the beam emanating from the gun is guided by a uniform magnetic field ($B \sim 10$ kG) down a smooth cylindrical waveguide (no FEL pump). This radiation, which grows in amplitude with distance traversed, is probably generated by the cyclotron maser (gyrotron) instability, and would thus be an indication of transverse energy in the beam electrons.

Experiments are under way to study the power and frequency characteristics of millimeter wave (λ = 1-10 mm) radiation generated by a high-current electron beam propagating in a 1.9-cm diameter cylindrical stainless steel pipe. The REB diode is energized by a Physics International Pulserad 110-A electron-beam generator capable of delivering 20 kA of current at 1.5 MV. Both the pipe and the diode region are immersed in the uniform axial magnetic field of a 1-m-long solenoid.

We compare microwave power and spectra from beams produced in two diode configurations: foilless and with anode foil. In each case, the dependence of microwave emission on beam current, anode-cathode gap spacing, cathode shape, and (when applicable) foil thickness is investigated. Titanium foils, 0.5, 1 and 2 mils thick, have been used. In addition, limiting apertures placed between the diode and the pipe have been used to collect up to 90% of the beam current, allowing us to study microwave emission from the inner portion of the beam. In this way we are able to eliminate electrons emitted from the cathode edge where the diode electric field is not oriented parallel to the guiding magnetic field. Current measurements made with a series of such apertures also allow us to estimate the radial current-density profile in the beam under different diode conditions.

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c. Electrically Pumped, Relativistic, Free-Electron Wave Generation

Stimulated scattering induced by the longitudinal electric field of a pump wave is studied theoretically for the case of dense, relativistic electron beams traveling in cylindrical metal waveguides. Two processes are examined. In one, the pump wave decays parametrically into a slow and a fast space-charge wave. In the other, it decays into a slow space-charge wave and a TM wave of the guide. The dispersion

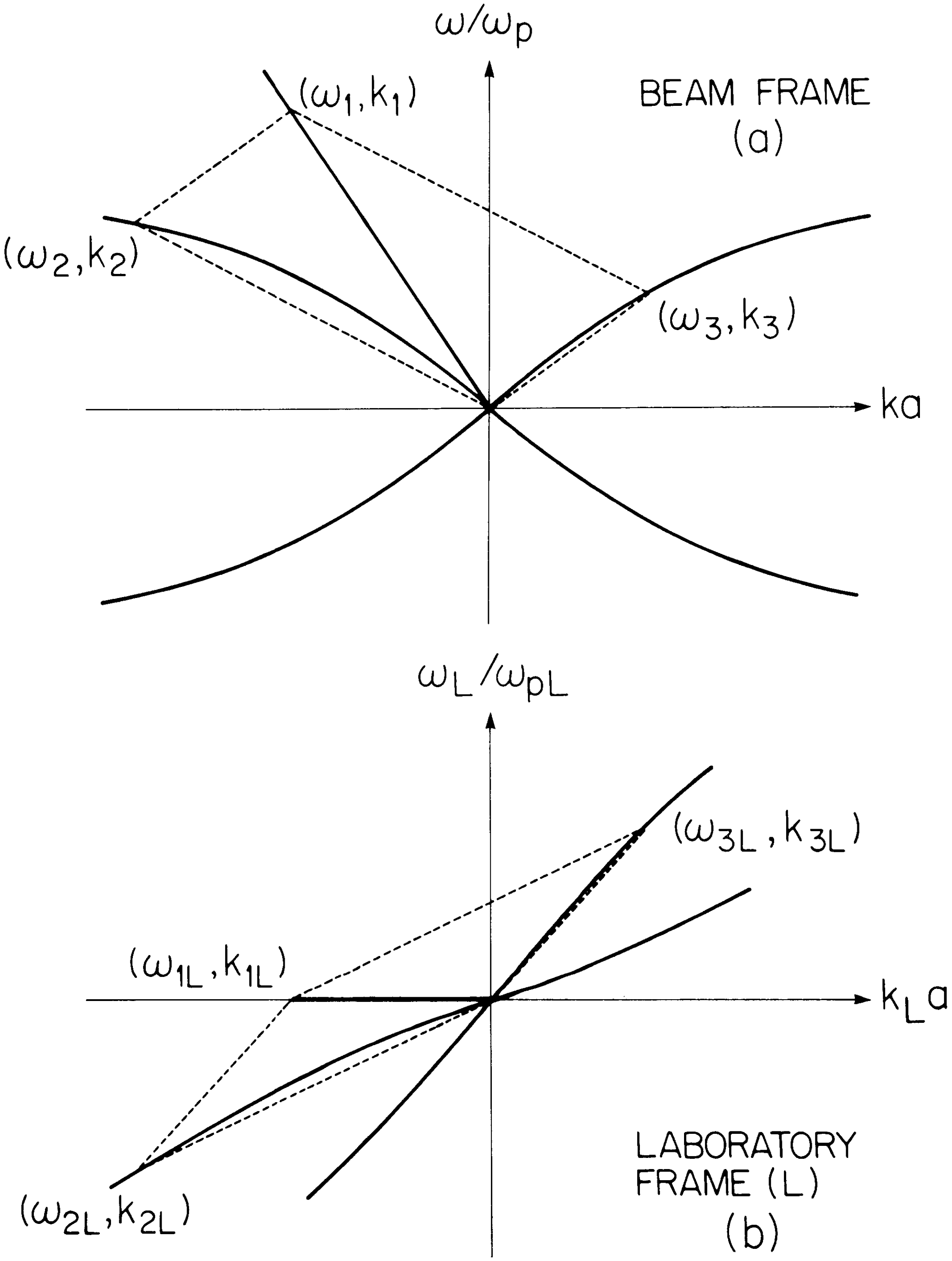

Fig. XX-2a. Schematic dispersion diagrams illustrating the coupling between a static pump wave (1), a slow space-charge wave (2), and a fast space-charge wave (3), as observed in the beam frame (top) and the laboratory frame (bottom). For clarity, the two figures are drawn to different scales.

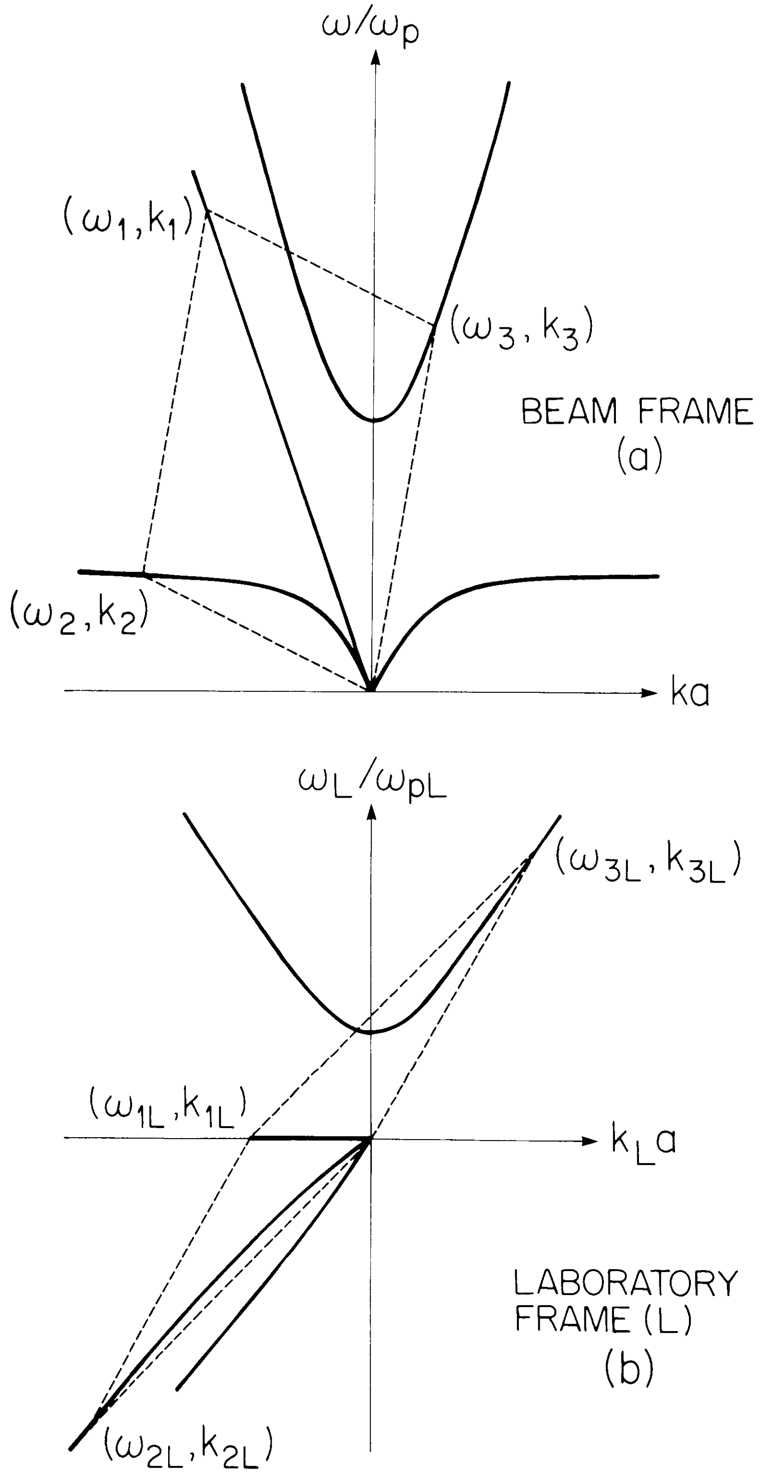

Fig. XX-2b. Schematic dispersion diagrams illustrating the coupling between a static pump wave (1), a slow space-charge wave (2), and a TM mode (3) of the waveguide, as observed in the beam frame (top), and the laboratory frame (bottom). For clarity, the two figures are drawn to different scales.

diagrams in Figs. XX-2a and XX-2b illustrate the two processes. The frequency characteristics and stimulated growth rates have been calculated for each process, as a function of beam diameter, velocity, and density.

d. Experiments and Computer Simulation of Relativistic Magnetrons

Experiments are in progress on the six-vane relativistic magnetron[1] operated in the 2π mode[2] at voltages in the range of 0.8-1.5 MeV. The microwave power is extracted from a single resonator through an iris-coupled waveguide; however, dummy loads are placed on the remaining resonators in order to insure uniform cavity loading and field symmetry.[3] Power spectra have been measured for a variety of field-emission cathode configurations.

A two-and-one-half-dimensional, electromagnetic, computer-simulation code has been tested on a coaxial relativistic magnetron[4] operating in the π mode. The code is coupled to an external lumped circuit simulating the voltage supply. The time evolution of the rf field is illustrated in the left-hand side of Fig. XX-3. Initially, an external "priming" field is imposed in order to speed up the time to saturation, which occurs after $\sim$8 nsec. The right-hand side of Fig. XX-3 shows the charged-particle distribution at saturation (time = 15 nsec), clearly illustrating the formation of a space-charge spoke.

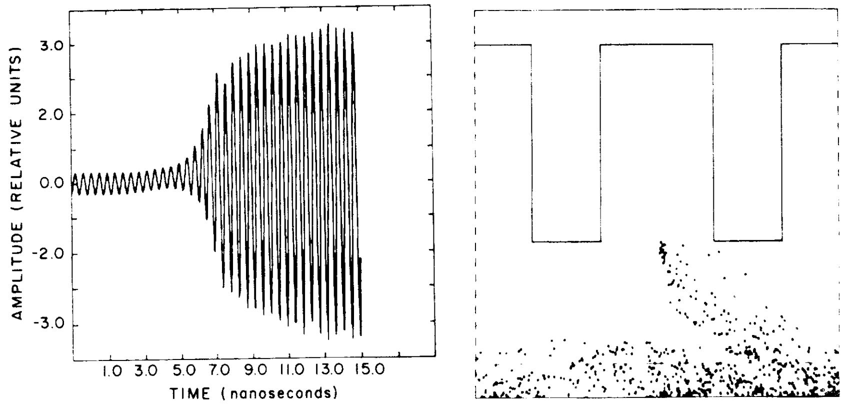

Fig. XX-3.

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XX. PLASMA DYNAMICS

B. Plasma Research Related to Fusion

1. PHYSICS OF THERMONUCLEAR PLASMAS

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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.

The primary focus of our activities 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 and relatively high density regimes.

Alcator's unique properties, high current and particle densities and relatively low impurity concentration, have made it one of the most successful confinements in terms of achieving the highest known values of the confinement parameter "$n\tau$," of producing for the first time near impurity-free plasmas of thermonuclear interest, and of realizing a sequence of plasma regimes of basic physical interest.

In particular, during 1979, 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 has been brought to regular operation with well-confined plasmas and plasma currents of approximately as high as 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 has been developed 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 and a series of relevant experiments has been prepared to be carried out on the Alcator A device. 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 theoretica effort for the numerical simulation of the plasma regimes that we hope to obtain.

The analysis of a relatively large variety of experiments (including among other the Alcator A and C, the Frascati Torus and the Princeton Large Torus where the most interesting plasma regimes have been obtained) has allowed us to formulate analytically a transport model which reproduces consistently the electron-density profile, the electron-energy confinement time, and the particle-density profiles that have been observed experimentally over a wide range of conditions.

This model that presupposes the excitation of microscopic plasma collective modes arrives at the identification of the relevant transport coefficients for the electron thermal energy and the particle density on the basis of global conditions involving particle and energy balance, criteria for the macroscopic stability of the plasma column, etc. This has strengthened the basis for the transport model and the codes that have been developed as part of our program, and that have been used both to predict the performance of Alcator C and to formulate a research program on ignition experiments by a series of compact devices. These are generally called Ignitor 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 has been undertaken.

Other theoretical achievements involve the identification and the analysis of new regions of stability, in the relevant parameter space, for magnetically confined toroidal plasmas with plasma pressure comparable to the effective magnetic-field pressure that are of importance for the possible realization of net power-producing fusion reactors. Another area where noticeable progress has been made is in the investigation of collective modes that can produce a change of topology (so-called magnetic reconnection) in the magnetic-confinement configuration. Modes of this type are of considerable interest also for space and astrophysics.

The Rector experiment, which was originally developed to study the confinement properties of toroidal plasmas with elongated cross sections, was employed to obtain remarkable results, in terms of improved equilibrium and stability conditions, by converting its basic axisymmetric magnetic configuration into a Stellarator-like configuration with helical symmetry. A novel distribution of coils has been adopted for this and, given its favorable construction characteristics, a series of higher performance relevant experiments is being considered.

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. Our contributions have been presented at major and international meetings.

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

James E. McCune, George M. Svolos

This work focuses on the analysis of drift and related low-frequency electrostatic (low-β) modes, in the "collisionless" and low-collisionality (banana) regime of large toroidal systems.

In our approach we make use of a drift kinetic equation with appropriate choices of the relevant parameters of the problem, and we keep finite Larmor radius and toroidal geometry effects from the outset.

In the linear treatment of the problem we abandon the traditional local approximation. Instead, we attempt an assessment of the stability properties of the system from the properties of the dispersion relation differential equation. We try to be as general as is analytically tractable in our treatment of this equation and we pay special attention to the effects of temperature gradients, the shear and the toroidal features of the magnetic field on the stability and localization properties of the modes and on the cross-flux eigenvalue problem. We also solve the dispersion relation analytically using a method of asymptotic matching. The solution and the eigenvalues so obtained, although approximate in this treatment, bear the qualitative features expected from the analysis of the dispersion relation differential equation.

In addition, we consider nonlinear turbulent electron behavior. We will examine the effects that nonlinear stochastic cross-flux electron diffusion, close to the mode rational surfaces, may have on the properties and ultimate nonlinear development of the modes.

b. Drift Modes in Tandem Mirror Systems

Daniel E. Hastings, James E. McCune

The linear theory of low-frequency drift wave is well understood in a low-β (where $\beta = 8\pi p/B^2$) plasma. However, in new experiments like the TMX, the plasma β is expected to be $O(1)$. This represents a significant change to the physics of drift waves. In the Ph.D. thesis of Hastings we present an analysis of the physics of two prototypical drift waves when $\beta = O(1)$. First, we derive the low-frequency dispersion relation with all high-β effects included. These fall into three categories: effects due to perpendicular magnetic fluctuations, effects due to parallel magnetic fluctuations, and effects due to ∇B drifting particles. We reduce the dispersion relation to a form suitable for numerical analysis by finding a basis set of functions in which the dispersion relation can be easily expressed.

The dispersion relation is specialized to the well-known universal drift instability. We examine the effect of each piece of high-β physics on the universal drift wave and then bring them all together. In particular, for the ∇B effects we find an analytical bound on the validity of the nonresonant approximation, and we show that it breaks down for small values of β, a result that had only previously been shown numerically. We show that universal's high-β behavior differs considerably from the electrostatic understanding. For most plasma and wave parameters, we find that the universal mode is stabilized by enhanced ion Landau damping, the enhancement arising from the reduction of the parallel phase velocity due to ∇B effects. For small β, we find that the behavior of the wave for the most part is dominated by the coupling to the Alfven wave. For large β, the behavior of the wave is dominated by the compression of the plasma flow induced by the ∇B particle drift. We find that, in contrast to the electrostatic case, the most unstable waves occur for phase velocities close to the ion thermal velocity, for long perpendicular wavelengths and for positive electron-temperature gradients. Also, we find that the high-β behavior of the wave is largely independent of the electron-to-ion temperature ratio. Finally, we compute some marginal stability curves and show that for electron-temperature gradients which are less than or equal to zero the universal drift wave is stabilized at a β_i of 0.07. For positive electron-temperature gradients, we show that a β_i of at least 0.44 is needed. The difference between the two regimes we ascribe to enhanced inverse transit-time damping for positive electron-temperature gradients.

We also examine the high-β behavior of the drift Alfven mode, and we show that when temperature gradients can be ignored the behavior of the mode for all β retains its compressionless character. We find that the mode always approaches marginal stability as β increases. However, temperature gradients change the mode behavior considerably. Electron-temperature gradients are found to be destabilizing at high β through their influence on the resonant energy transfer. Ion-temperature gradients cause a marked upshift in the oscillation frequency of the mode, and hence are strongly stabilizing.

We conclude that at high β, the Alfven mode will be stable and the universal mode may have a window of instability at long parallel and perpendicular wavelengths and positive electron-temperature gradients.

3. RF HEATING AND NONLINEAR WAVES IN TOROIDAL PLASMAS

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

Abraham Bers, Robert H. Berman, Vladimir Fuchs, Kwok C. Ko,
Vladimir B. Krapchev, Leo P. Harten, Abhay K. Ram, Kim S.
Theilhaber, Maria Elena Villalon

The general objective is to explore the use of external applied rf power for the supplementary heating and confining of toroidal plasmas. Particular studies are being carried out to determine the heating and steady-state current drive with microwave power in the lower hybrid range of frequencies. The results are applied to current experiments on Alcator C and Versator II, as well as to experiments in the near future on Alcator C.

a. Current Generation by Large-Amplitude Waves

RF power has the potential to continuously generate the confining current in a tokamak plasma. The exploration of these ideas was initiated within this group a few years ago. Since then we have actively participated in workshop studies.[1-3] Our theoretical efforts in this area have turned to understanding the full nonlinear dynamics of the plasma in large-amplitude fields. For a strongly magnetized plasma the one-dimensional Vlasov distribution function has been found to all orders in the field amplitude.[4-7] The lower hybrid-driven steady-state current has been calculate and the results have been applied to current experiments on Versator II.[8]

b. Studies in RF Heating to Ignition

It is well known that the plasma equilibrium near ignition is thermally unstable We have initiated a study to explore the advantages of using rf supplementary heating in reaching ignition. Specifically, the applied rf can be varied in time, and the potential for controlling the radial deposition of the power in the plasma also exists. We chose to study the plasma parameters of the High-Field Compact Tokamak Reactor (HFCTR).[9] We have studied the global[10] and radial[11] equilibria. The low-temperature (7-20 keV) equilibrium is unstable, but can be stabilized by a programmed rf heating source, which is gradually turned off near equilibrium.

c. Nonlinear Effects in Coupling of RF Power to a Plasma

For LH heating the nonlinear effects are prominent in the low-density and temperature region of the plasma edge. These effects have been seen experimentally over the past two years. We have proposed a nonlinear equation, which describes the nonlinear coupling of LH waves.[12] The Vlasov theory of spatially modulated waves[4-7] confirms this result. During the past year the analytical model was refined so that the nonlinear coupling problem could be solved in some detail. For a two-waveguide array, an approximate analytical solution was found. It exhibits the reduced dependence upon waveguide phasing and shows an upshift in the $n_{\parallel}$-spectrum, both consistent with experimental observations.[13] We have initiated two numerical schemes for solving the nonlinear equation; one attempts to find a steady-state solution for the fields, the other studies the time evolution of the coupling.

d. Linear Propagation, Mode Conversion, and Damping in Inhomogeneous Toroidal Plasmas

A full electrostatic, local dispersion relation[14] is used to numerically study the propagation characteristics of waves near the LH frequency in an inhomogeneous plasma ($\nabla n, \nabla B, \nabla T$). For relevant tokamak parameters and profiles, the results show significant differences from those previously obtained.[15] The linear mode-conversion process from LH to warm plasma wave is downshifted to lower $n_{\parallel}$, and is confined spatially to regions in between the ion-cyclotron harmonics.

e. Parametric Excitation in Lower-Hybrid Heating of Tokamak Plasmas

We have carried out a detailed linear and nonlinear analysis of quasimode type of parametric excitations relevant to the recent Alcator A heating experiment.[16] This quasimode excitation has been studied independently for the regions near the edge and the center of the plasma. The analysis near the edge shows that higher n_z's than predicted by linear theory are strongly excited, which may prevent the penetration of the rf power to the plasma center. Inside the plasma the power density is much lower than at the edge and is no longer confined to well-defined resonance cones; it is spread out across the plasma column.

Currently, we are in the process of evaluating the importance of resonant parametric excitations and contrasting them with the quasimode excitations.[17]

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4. NONLINEAR THEORY OF TRAPPED-PARTICLE INSTABILITIES

U.S. Department of Energy (Contract DE-AS02-78ET53074)

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. AN ADVANCED SCIENTIFIC COMPUTING ENVIRONMENT

National Science Foundation (Grant ENG79-07047)

Robert H. Berman, Thomas H. Dupree, John L. Kulp, Jr.

Several problems in plasma dynamics concerning microturbulence and nonlinear phase-space structures[1,2] can be studied experimentally only by computer simulation techniques. These studies are essential to complement the theoretical studies that have been described in previous sections. These simulations for clumps, for example, require a fully kinetic, self-consistent description of the particles with high resolution in phase space that can represent discrete particle effects. Very effective algorithms have been developed to study these problems that will promote very efficient and cost-effective computer simulations.[3,4] The macrocell algorithm as originally envisioned will promote very accurate determination of short-range interparticle forces and, therefore, permit longer, more precise situations before numerical errors grow beyond reasonable bounds.

Our efforts to create an advanced scientific computing environment consisting of a LISP machine and array processor that supports interactive symbolic and numerical calculations are well under way.[5,6] The core of this project is the high-performance personal computer consisting of a LISP machine coupled with an arithmetic processor capable of a raw computing rate of $\approx$10 million floating-point (numerical) operations per second.

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6. TOKAMAK RESEARCH: RF HEATING AND CURRENT DRIVE

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

Introduction

The use of rf power near the lower hybrid frequency has long been considered as a means of heating ions in tokamak discharges.[1,2] More recently, experiments have shown that electron heating can also be obtained from lower hybrid wave injection.[3] In view of the apparent capability to modify the electron velocity distribution function by injection of a properly tailored wavelength spectrum of lower hybrid waves, it has been recently proposed that lower hybrid power injected with a net toroidal angular momentum should be capable of producing, via Landau damping, a steady-state toroidal current in tokamaks.[4] A fusion reactor driven in steady state with rf power has a number of attractive features distinguishing it from the commonly encountered transformer-driven pulsed machines. Lower hybrid experiments in progress on Versator II using phased-waveguide array, grill-type coupling structures are capable of studying all three aspects of current interest in the lower hybrid frequency range: ion heating, electron heating, and current drive.

In a second series of experiments to begin in mid 1980, microwave power will be injected into Versator II at the electron-cyclotron frequency. For this purpose, the newly developed gyrotron microwave source will be provided along with scientific and technical support from the Naval Research Laboratory. The NRL gyrotron will allow ECRH experiments to be carried out at significant power levels in the range of 100-120 kW at a frequency of 36 GHz.

To obtain a quantitative physics understanding of rf processes in tokamak plasmas, the target plasma must be capable of a well-controlled and flexible equilibrium state, and energy confinement and transport processes must be carefully monitored with a full array of tokamak plasma diagnostics. For this reason, a major effort is under way at Versator to implement a full range of plasma diagnostic experiments; and the plasma equilibrium and operation is being carefully studied and documented to provide a reliable benchmark for ongoing rf experiments.

Equilibrium Studies and Diagnostics

Equilibrium of the Versator II plasma is characterized[5] by plasma currents in the range of 30-50 kA, central density of 2×10^{13} cm^{-3}, toroidal field of 10-15 kgauss, major radius 40 cm, minor radius 13 cm, and flattop current pulse durations in normal operation in the range of 20-40 msec. Constant horizontal and vertical plasma positions needed for the rf experiments have been obtained with deviations not exceeding 0.5 cm. Low plasma impurity levels are indicated by the rapid density decay after initiation of the discharge.

Plasma density has been increased to 4.5×10^{13} cm^{-3} and sustained for a few milliseconds by gas puffing with consistent measurements with both 4-mm and 2-mm microwave interferometers. Extensive measurements of the density in the region between the edge of the plasma and the lower hybrid antenna structure have been made with Langmuir probes. The density is found to follow an exponential dependence in the edge region, and the density gradients in the region of the grill are found to be in the range of 10^{10} to 10^{11} cm^{-4} depending on the grill location.

Electron temperature during rf heating experiments is being monitored by a ruby laser Thomson-scattering system and supplemented by spectroscopic measurements in the ultraviolet, of impurity-line spatial profiles. Thomson-scattering temperature measurements indicate central electron temperatures in the range of 400-600 eV which is consistent with the observed relative intensities of the impurity lines O VII 1623 Å, N VI 1897 Å, CV 2271 Å, O V 2781 Å, and NV 1239 Å. In addition, two heterodyne detectors for observing fundamental and 2nd-harmonic cyclotron radiation are available for time-resolved, semiquantitative electron-temperature measurements.

The high-energy ion tail generated during lower hybrid heating is expected to be well confined in Versator in view of the small field ripple, $\Delta B_T/B_T \lesssim 2 \times 10^{-3}$ on axis; thus not only tail generation but bulk ion heating as well may be observed. The presence of the ion tail will be monitored by a neutral charge-exchange system, and bulk ion temperature by impurity atom spectral-line Doppler widths using an ultraviolet spectrometer.

Microwave scattering experiments have been carried out in the Versator II plasma with approximately 5 watts of power at 140 GHz.[6] Reliable measurements were obtained after installation of refractory microwave-absorbing material in the tokamak vacuum vessel in the region around the microwave horns. Measurements in this configuration show a spectrum of density fluctuations which is monotonically decreasing with ω for all values of $k_\perp$, with fluctuation activity in the drift-wave frequency range up to 300 kHz. This detector will be used to scatter from density perturbations associated with propagation of the high-power lower hybrid waves in the plasma during the heating and current-drive experiments.

RF Experiments

A lower hybrid antenna system operating at 800 MHz with peak power levels of $P \sim 150$ kW has been constructed on Versator.[7] This system, shown in the schematic diagram in Fig. XX-4, has the flexibility to employ a four-waveguide grill designed

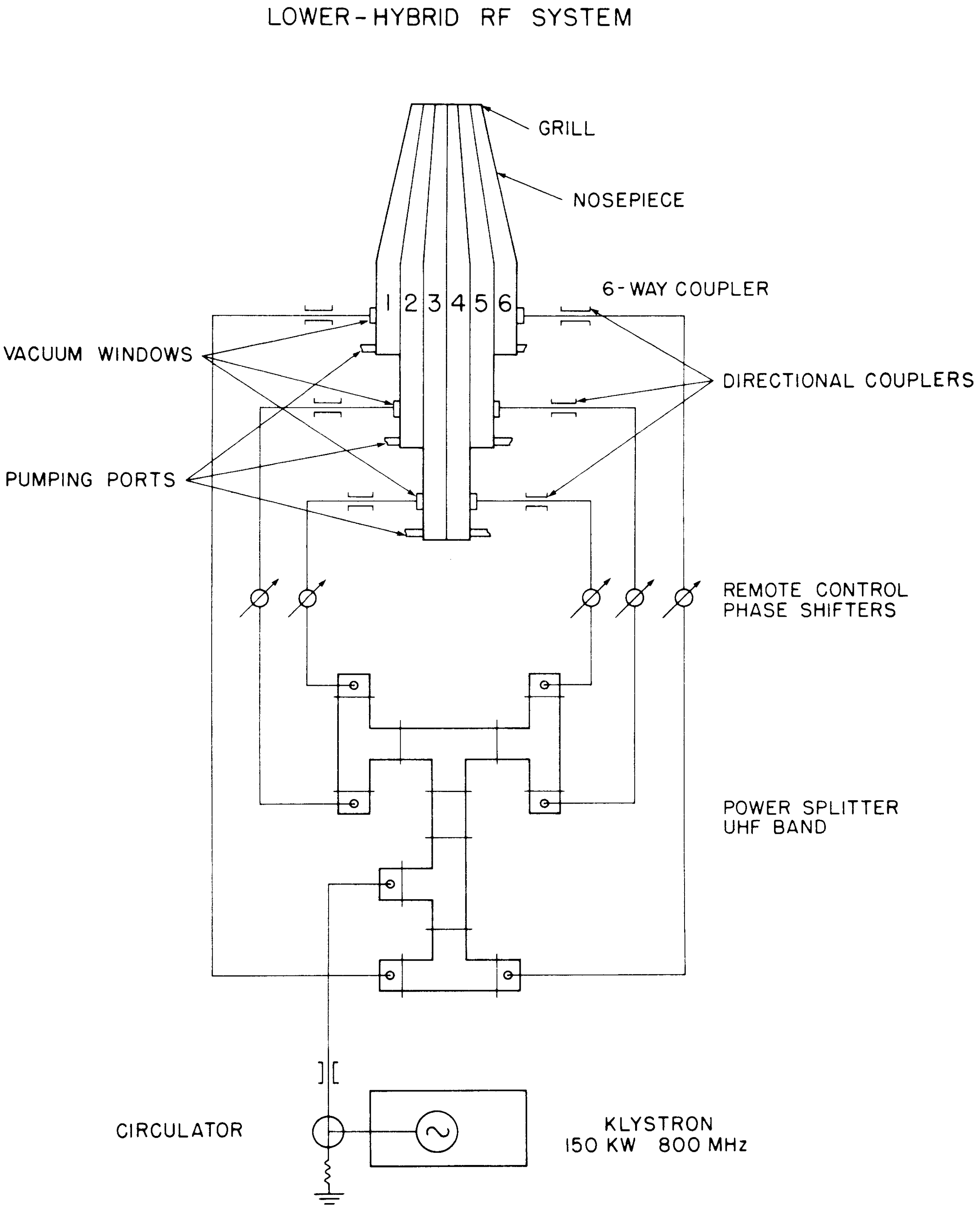

Fig. XX-4. RF system.

to produce a power spectrum favorable for ion heating studies, or a six-waveguide grill for electron-heating or current-generation studies. The rf system consists of a coaxial-fed, vacuum-pumped waveguide array with a tapered, interchangeable "nose-piece" section which is inserted into the tokamak vacuum vessel. The system can be used with both four- and six-waveguide grills, and the relative phases, ϕ, between adjacent waveguides are continuously adjustable. These features of the MIT RF system allow a wide range of lower hybrid power spectra to be produced either for ion or electron heating, or the unidirectional power spectrum desired for current-generation experiments.

To date, measurements of RF coupling to the plasma have been carried out in some detail. At the relatively low power levels investigated, P = 0.5-10 kW, S = 1-20 W/cm^2, the coupling efficiency is found to be strongly dependent on the relative phase of the waveguides and the position of the grill relative to the plasma limiter. In the four-waveguide experiment, minimum total-power reflectivities obtained are R = 17% with guide phasing in the range of ϕ = 90°-180°. As shown in Fig. XX-5, optimal coupling was obtained by positioning the grill 3.1 cm behind

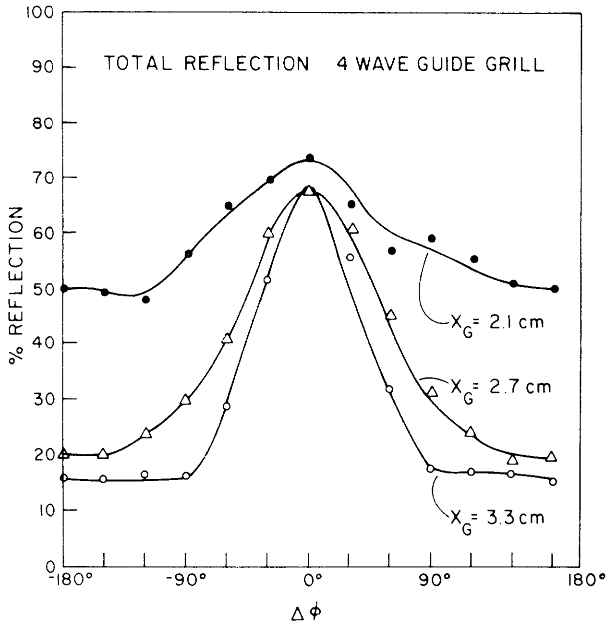

Fig. XX-5. Experimentally observed coupling (4-waveguide grill).

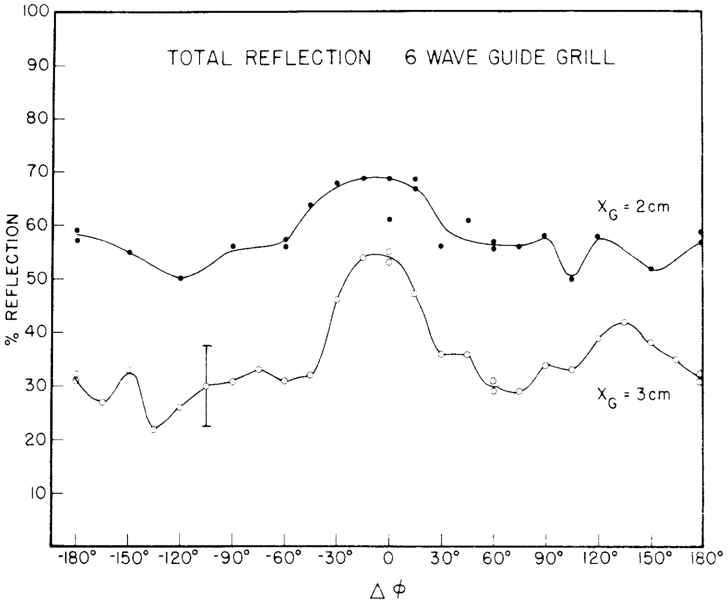

Fig. XX-6. Experimentally observed coupling (6-waveguide grill).

the limiter. In six-waveguide experiments, optimized total reflections of R = 25-35% are obtained with the grill located 3 cm behind the limiter, as shown in Fig. XX-6.

For comparison with the waveguide-coupling theory, the density profile in the region between the limiter and the grill mouth has been measured with Langmuir probes, yielding the parameter ∇n needed in the Brambilla waveguide-coupling theory.[2] The observed density gradients at the waveguide mouth are typically in the range of 10^{10} to 10^{11} cm^{-4} depending on the grill location. For such density gradients, waveguide-coupling theory predicts total reflectivities of R = 75-80% for the six-waveguide grill; thus the observed coupling is much better than the theoretical expectation. If density gradients 10-100 times larger than those measured are assumed, the theory yields semiquantitative agreement with the observations. This result, that agreement is obtained by assuming a large value of ∇n, has been found in other experiments;[8,9] however, in those works independent measurement of ∇n was not made, so our experiments are the first where such a discrepancy between the theory and experiment is documented.

In the coupling experiments, low power levels were used, S = 1-20W/cm^2, so that nonlinear effects are probably unimportant in explaining the discrepancy between theory and experiment. However, a number of improvements are suggested in the linear theory by the present experiments. A more realistic theory should contain boundary conditions, including the details of the tokamak port conducting wall shape, density gradients in the direction parallel to the magnetic field which have been observed in our experiment, the finite height of the waveguides, and the experimentally measured density profiles.

At high rf power levels, P = 100 kW, current-drive experiments with the six-waveguide grill are predicted by recent transport code calculations[10] to produce an additional toroidal current in Versator of $\Delta I = 20$ kA (initial conditions $T_{eo} = 300$ eV, $n_0 = 2 \times 10^{13}$ cm^{-3}, and $I_p = 40$ kA). Production of an rf-driven toroidal current in an ohmically heated toroidal discharge is also expected to produce a strong runaway electron component; so, in addition to electron temperature-measurements, a hard x-ray monitor is employed to detect the rf-produced high-energy runaway activity.

The high-energy ion tail generated during lower hybrid ion-heating experiments (4-waveguide grill) is expected to be well confined in Versator, in view of the small toroidal field ripple, $\Delta B_T/B_T = 2 \times 10^{-3}$ on axis; thus, bulk ion heating is also expected.

Experimentation in 1980 will concentrate on raising the rf power levels coupled into the plasma so that significant heating and current generation can be observed.

Klystron and power supplies on loan from Princeton Plasma Physics Laboratory.

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7. MIRROR-CONFINED PLASMAS

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Louis D. Smullin, Robert E. Klinkowstein

We are studying problems related to the physics of plasma confined in min-B magnetic mirrors. The system Constance II has a mirror field of 2:1 ratio, with a maximum value of $B_{max} \approx 10$ kG. A quadrupole coil mounted in the vacuum system, and excited by a capacitor bank, can produce a full min-B field configuration when the midplane field is 3 kG.

The facility was completed by December 1979, and we have been making detailed measurements of the plasma characteristics. Diagnostics now in place include: 4-mm interferometer, neutral-particle energy analyzer, vacuum-ultraviolet monochromator, probes, diamagnetic coils, and various probes. A Thomson-scattering laser system is under construction.

In the smaller facility, Constance I, we are studying the behavior of the "washer plasma gun." We have built a fast-acting (msec) gas valve for the 2-inch washer gun, and we are comparing the behavior of two guns: one using an H_2-saturated Ti washer, and the other with controlled, pulsed gas injection.

The behavior of the magnetron injection gun, used for beam-plasma interaction, is being studied with the help of a computer-simulation code. A program, originally developed at SLAC, for plotting electron trajectories in guns with very weak space charge, has been modified to handle full space charge of guns with perveance as high as 15×10^{-6} volts/amp$^{3/2}$.