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

We report on theoretical and computational work related to studies of waves in plasmas. This group's work is aimed at understanding large-amplitude, coherent waves in a plasma in general, and their use in plasma heating in particular. Progress on four research topics is described.

(a) Nonlinear Waves in the Presence of Collisions

The one-dimensional adiabatic theory[1,2] for a high-frequency wave is extended to include electron-ion collisions. The corresponding Fokker-Planck equation is analytically solved to first order in the collisional frequency. Modifications to the trapped and the untrapped electron distribution function are found.[3] The bulk-electron distribution function is significantly different from a Maxwellian and is approximately that as given by the adiabatic theory.[1] The power dissipated in the plasma is then evaluated.

(b) Parametric Resonance Electron Heating by a LH Wave

The dynamics of the electrons in a two-dimensional electrostatic lower-hybrid (LH) wave has been studied. For the bulk electrons ($k_{\parallel}v_t/\omega < 1$, $k_{\perp}v_t/\Omega < 1$) it is found that the motion perpendicular to B_T is described by the Mathieu equation. Every particle with longitudinal velocity $v_{\parallel}$, such that $2\Omega/\omega - k_{\parallel}v_{\parallel} \simeq n$ (integer) will belong to an unstable resonant zone.[4] Typically, there are more than 50 such zones in the bulk of the electron distribution function. In these zones the particles are nonadiabatic, i.e., their gyroradii exponentially diverge in time. When the wave potential is large enough, so that $k_{\perp}^2 e\phi/m\omega\Omega \gtrsim 1$, the width of the zone and the growth rate in it are large and an appreciable electron heating can take place. This mechanism may explain experimental results of LH electron heating when the launched wave will not be Landau damped.[5]

A more comprehensive study of the nonlinear dynamics will be undertaken to establish the saturation mechanism and the possible impact on electron transport.

(c) Stochasticity and Random Behavior in Plasma Dynamics

The standard mapping on a unit torus is a model problem illustrating the change of ordered to chaotic motion. A global measure of stochasticity is used to analyze the effect of subharmonic resonances on the transition to stochasticity. In particular, the thresholds for resonances to occur are characterized by rapid changes in the global measure.[6] This work so far has ignored self-consistency. Preliminary calculations of self-consistent orbits show important differences from the nonself-consistent ones.

Current generation and plasma heating by electrostatic wave packets is being studied in a 1d self-consistent particle code with a stationary ion background. We are carrying out a study of the effects of varying the driving wave spectrum — its amplitude and phase velocities. We have performed one set of experiments formulated as a stochastic acceleration problem which show significant trapping effects that cannot be neglected.[7] Next, we have also treated the trapped particles self-consistently. Quasi-linear theory is found to be inadequate to predict or describe this problem. Two distinct fully stochastic regimes are evident. The first has a moderate driving field amplitude; when the spectrum of waves is narrow, one can be selective towards the excitation of waves in the plasma; when it is broad, a wide spectrum of plasma fluctuations develops. The second regime has large field amplitude and can excite a wide spectrum, both directly and indirectly, through nonlinear coupling. Preliminary results on heating and current generation show a broad driving spectrum can create and maintain a superthermal electron tail while a narrow one produces a "bump-on-tail." A standing wave gives little current but can produce significant heating.

(d) Mode-Coupling in Inhomogeneous Vlasov Plasmas[8,9]

The theory of pair-wise coupled modes excited at a real frequency ω in a plasma which is weakly inhomogeneous in one spatial dimension x, is developed on the basis of local Vlasov dispersion relations $D(k,z) = 0$, which define a many-valued mapping of the real axis $x = \mathrm{Re}z$ onto the complex plane of the wavenumber k. Mode coupling is, by definition, the analytical continuation of a branch of the mapping, and only occurs at the branch points. This requires that the z-plane be cut along contours C_b given by $D(k_c,C_b) = 0$, $\partial D(k_c,z)/\partial k = 0$, where z traces a contour passing through the branch points. The coupled modes can be analyzed by expanding the dispersion relation to second-order in k around the saddle points and along the lines $k_c(x)$, yielding a system of embedded dispersion relations corresponding to second-order differential equations possessing turning points at the appropriate branch points of the dispersion relation.

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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-77-3143D)

George Bekefi, Alan Palevsky

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. This is a continuation of the work described last year in RLE Progress Report No. 122 (January 1980).

B. Plasma Research Related to Fusion

1. PHYSICS OF THERMONUCLEAR PLASMAS

U.S. Department of Energy (Contracts DE-AC02-78ET-51013 and DE-AC02-78ET-53073.A002)

Bruno Coppi

The combined experimental and theoretical investigation of plasmas where the nuclear fusion reaction products give a significant contribution to the global energy balance is the long-term goal of our program.

In view of their attractive confinement properties, we consider, in particular, plasmas with relatively high densities, in the range 10^{14} to 10^{15} particle/ cm^3, and temperatures of several kiloelectron volts. The line of experimental devices that we have developed for this is presented by its prototype, the Alcator A machine, and is characterized by toroidal plasma columns that can sustain both high currents and current densities. This characteristic, that leads to adoption of toroidal magnet configurations of compact size and relatively high fields, has made it possible to achieve and maintain the record values for the confinement parameters "$n\tau$", the product of the peak particle density and the energy replacement time. In addition, a sequence of plasma regimes of basic physical interest, in terms of the different characteristics of the electron distribution in velocity space and of the collective modes that are excited, has been produced. Plasma regimes of thermonuclear interest that are nearly impurity-free have been realized at the same time.

By combining these experimental results with the theoretical analysis of the global transport properties in the plasma regimes that have been attained and the available theory of deuterium-tritium plasmas where the produced α-particles contribute substantially to their heating, it has been possible to formulate a research program directed toward achieving thermonuclear ignition by a series of compact devices (called Ignitors or Alphators).

A considerable design effort on experiments of this type has been developed with a team of European collaborators. This has been particularly encouraged by the final announcement made by the U.S.S.R. delegation at the 1980 International

Atomic Energy Agency in Brussels that it had undertaken the construction of a compact deuterium-tritium burning device with general characteristics similar to those of the present Ignitor design.

Further encouragement has come from the experiments carried out on the Frascati Torus device that have extended the energy confinement times obtained by the Alcator A device.

As a related development, we have found that experiments leading to testing of the ignition conditions for advanced fuels reactors (that is, not involving tritium) can be undertaken on the basis of present-day technologies.[1]

Until recently, the realization of a D-He^3 or a D-D burning reactor has been considered a goal to be achieved in the next century, since a near-term experiment to test the possibility of igniting these kinds of plasmas could not be foreseen. In fact, in order to achieve this goal, it is necessary to have a plasma-confinement configuration that can attain, for instance:

(a) Values of $n_o\tau_E$ (with n_o the peak plasma density and τ_E the energy replacement time) higher than 5×10^{14} sec/cm^3;

(b) Values of $\langle\beta\rangle = 8\pi\langle p\rangle/\langle B^2\rangle$ (with $\langle p\rangle$ the average plasma pressure and $\langle B^2\rangle/8\pi$ the average magnetic pressure of the confining magnetic field) around 10 percent or higher;

(c) Plasma currents around 5 MA or higher, in order to generate the magnetic fields needed to confine the 14.7 MeV protons produced; and

(d) Peak plasma temperatures around 65 keV or higher.

These objectives can be achieved simultaneously in an axisymmetric toroidal configuration in which:

(i) Goal (a) is pursued on the basis of presently known scalings for the plasma thermal conductivity that exhibit a favorable dependence of τ_E on n. Thus it is proposed that peak particle densities, exceeding 10^{15} cm^{-3}, can be obtained in a high-field (120 kG) confinement having a sufficient area of its transverse cross section meet the desired $n_o\tau_E$ criterion. Well-confined plasmas with peak density values higher than 10^{15} cm^{-3} have, in fact, been produced in the Alcator device at M.I.T.

(ii) Goal (b) is pursued by adopting a combination of magnetic and geometric parameters, such as the torus aspect ratio, in such a way that during the heating cycle the plasma is maintained in one of the macroscopically stable regimes that have been identified in recent theoretical developments.[2]

(iii) The adoption of high magnetic-field technologies will make it possible to induce plasma currents exceeding 5 MA without violating any of the known criteria against macroscopic instabilities.

(iv) Goal (d) can be achieved by adopting an rf heating system to supplement ohmic heating in order to bring a deuterium-tritium plasma to ignition conditions. Thus, tritium is used as a "match" to raise the plasma temperature, and, as this temperature increases, is gradually replaced by He^3. The most convenient frequency for the auxiliary heating system appears to be that corresponding to the first harmonic of the cyclotron frequency of He^3, and, at the same time, to the second harmonic of the cyclotron frequency of tritium.

We note that the effectiveness of ion cyclotron heating in plasmas with two species of ions has been well demonstrated in several experiments carried out on the most advanced existing toroidal devices.

The usually-known ignition conditions, based on the assumptions that (1) the distributions of all components of the background plasma are Maxwellian, and (2) the slowing-down of the charged fusion-reaction products is due to Coulomb scattering only, are relaxed when considering the following effects:[3]

(a) Nuclear scattering collisions ("knock-on" events) modify the fraction of energy transferred to the background ions and electrons during the slowing down of the fast-charged fusion products in the background plasma;

(b) The fuel particles promoted in energy by their interaction with the fusion-reaction products have a nonnegligible self-interaction probability ("tail-tail" events); and

(c) Fast fuel particles that are promoted in energy by a large energy-transfer nuclear scattering event, or intermediate fusion-reaction products, can fuse with other fuel particles belonging to the Maxwellian part of their distribution ("fast-fusion" or "propagating reaction" events).

We have carried out an analysis of the heating cycles[4] that are appropriate for these experiments (we call them "Candor"), and consequently, an approximate evaluation of all the main forms of energy loss. These evaluations have been verified, by sophisticated numerical codes, such as the one developed by S. Tamor of S.A.I. for the electron-cyclotron emission.

As is traditional with our mode of operation, during 1980 we have had a system of close collaborations with national and overseas institutions for both our theoretical and experimental programs. Our contributions have been presented at major national and international meetings.

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2. RF HEATING AND NONLINEAR WAVES IN TOROIDAL PLASMAS

U.S. Department of Energy (Contracts DE-AC02-78ET-51013 and DE-AC02-78ET-53074)

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

The objective of this group's theoretical and computational work is to explore specific aspects on the use of externally applied rf power for the heating and confining of toroidal fusion plasma. Much of this group's work of the past was summarized at last year's international conference on plasma physics and controlled nuclear fusion research in Bruxelles.[1] Progress on four topics is reported here.

(a) Nonlinear Coupling of RF from Waveguides to a Plasma

(1) Temporal evolution of the coupling problem

We are studying nonlinear effects in the coupling of lower hybrid waves from a waveguide array into a tokamak plasma. The nonlinear effect considered is the ponderomotive density depression which is considerable at the high power levels (several kW/cm^2) needed for supplementary heating. The method of solution is integrating numerically the evolution equation for lower hybrid waves, in time and in two space dimensions, with a small waveguide array as a source. A steady state is reached, and we then determine the reflection coefficient in the waveguides and the nonlinear wave spectrum generated inside the plasma. The following effects have been observed.[2,3] (i) A traveling-wave excitation couples according to previous analytic theory.[4] Furthermore, inside the plasma the spectrum is well behaved. We do not see the large nonlinear reflections predicted by a less general evolution equation.[5] This is important in connection with current-drive schemes. (ii) The numerical reflection coefficient agrees qualitatively with the results of some high-power experiments.[6] Reflection for the in-phase waveguides, large at low powers, decreases sizeably with increasing power, while on the other hand the out-of-phase array experiences larger reflection. At large powers the reflection curves may cross, with the in-phase array coupling as much power as the out-of-phase array. (iii) As the waves penetrate the plasma the spectra are considerably shifted and broadened, with smaller n_z's depleted to larger ones. We are presently extending the power of the numerical scheme, to allow for a more complete description of the waveguides and a finer computational mesh.

(2) Steady-state solution

The steady-state electromagnetic coupling problem of lower hybrid waves with self-consistent density modulation is considered.[7,8] The exciting structure is a two-waveguide array and in the absence of rf the plasma is assumed to have a linear density profile. The governing nonlinear Klein-Gordon equation is formulated as a system of coupled Airy equations in Fourier space. Numerical solutions to the nonlinear system compatible with radiation conditions are obtained. Spectral broadening and bending of resonance-cone trajectories are observed with increase of incident power with these nonlinear effects being more pronounced for the π phasing at the same power level. Calculations of reflectivities and power coupled are in progress, and comparison with predictions of recent theory[8] will be made.

(b) Linear Mode-Conversion and Damping in the Presence of Ion-Cyclotron Harmonics

The linear mode conversion of lower hybrid to warm plasma waves is studied taking into account all plasma inhomogeneities (∇n, ∇B, ∇T).[9-12] Numerical solutions of the full dispersion relation for Alcator A parameters and profiles show that the presence of the ion-cyclotron harmonics introduces significant modification to the wave-propagation characteristics, and portions of the incoming lower hybrid wave spectrum can undergo successive but partial mode conversions into warm plasma waves. The process is well modeled by a second-order dispersion relation derived under a vanishing group velocity condition.[11] The corresponding wave equation is solved numerically, and power-flux calculations indicate that a considerable amount of power can be dissipated in the mode-conversion region.

(c) Current Generation by Nonlinear Waves

The lower-hybrid steady-state current has been calculated[13] using the Vlasov distribution function derived for a strongly magnetized plasma.[14] The analytical results have been applied to the study of the current that can be generated in the Versator II experiment. A numerical integration of the Vlasov equation confirms the analytical predictions.[15]

In order to study the feasibility of the current-drive scheme, the Vlasov equation has been modified to include the electron-ion collisions. The corresponding Fokker-Planck equation has been analytically solved up to first order in the collisional frequency. The distribution function for the trapped and the untrapped electrons is determined. Preliminary results indicate that the ratio of the power dissipated (in watts) to the current generated (in amperes) for the Versator II is between 20 and 50 depending on the density and the parallel wavelength (along the toroidal magnetic field).

(d) Thermal Stability for Steady-State Tokamak Reactors

We are studying methods of operating a tokamak reactor near ignition in a thermally stable manner. Most of the computations have been done with the High-Field Compact Tokamak Reactor (HFCTR)[16] design, without and with line averaging of profiles. We have investigated the use of temperature-programmed supplemental heating[17] in order to create thermally stable tokamak reactor equilibria with high-Q in a subignited state.[18] We consider a time delay between the measured temperature and the power input to the controlled plasma and find that time delays of order 1 second still preserve stable operation.[19] RF-power is a very attractive method for supplying the varying heating power needed for such operation.

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3. NONLINEAR THEORY OF PLASMA INSTABILITIES

U.S. Department of Energy (Contracts DE-AC02-78ET-51013 and DE-AC02-78ET-53074)

Thomas H. Dupree, David J. Tetreault

Concepts from strong plasma turbulence are being used to investigate magnetic islands in tokamaks. Turbulent magnetic fluctuations 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. A nonlinear instability due to the regeneration of ion and electron clumps is being studied. The effect of self-gravitating phase space holes on the regeneration of clumps is being investigated.

4. TOKAMAK RESEARCH: RF HEATING AND CURRENT DRIVE

U.S. Department of Energy (Contracts DE-AC02-78ET-51013 and DE-AC02-78ET-53076)

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

Introduction

Heating tokamak plasmas with rf power has a large theoretical literature and has attracted wide interest over the years; however, experimental work is just beginning to scratch the surface of the problem, and as yet relatively few careful experimental investigations have been carried out in this field. The purpose of experimental work going on at the Versator II tokamak is to study the detailed physical processes involved in rf heating of a tokamak plasma.

The use of RF power near the lower-hybrid frequency ($\omega_{LH}^2 = \omega_{pi}^2/(1+\omega_{pe}^2/\omega_{ce}^2)$, 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 via 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 recently been proposed[4] that lower-hybrid power injected with a net toroidal angular momentum should be capable of producing, via Landau absorption, a steady-state toroidal current in tokamaks.

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 devices. In particular, steady-state operation would eliminate the problems of peak loading of reactor output-power equipment and the thermal cycling of the reactor walls inherent in pulsed operation.

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.

Recently, a second series of experiments has begun at Versator in which high microwave-power levels at the electron-cyclotron frequency are employed. These experiments in cooperation with the Naval Research Laboratory use the gyrotron source developed at the Naval Research Laboratory. The NRL gyrotron provides power of 100 kW at a frequency of 35 GHz for 10 msec-duration pulses.

To understand the physics 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 plasma diagnostic experiments. For this reason, a major part of the Versator effort involves implementation and maintenance in reliable operation of plasma diagnostic experiments.

Equilibrium Studies and Diagnostics

The Versator II tokamak as a facility for rf heating experiments provides a well-diagnosed target plasma for these experiments. The operation of Versator II without rf injection is similar to many other experimental tokamak devices, thus the basic ohmically heated plasma operation is phenomenologically well-understood and well known.

The ohmic heating discharges are characterized by good repeatability of basic discharge parameters shot-to-shot with typically only a few percent variation. Plasma position is controlled to within 0.5 cm, and plasma density is controlled by programmable gas puffing. The basic parameter ranges characteristic of Versator operation are shown in Table XX-1.

Impurity levels are maintained at low levels by titanium sublimation pumping before plasma operation. With titanium gettering, discharges with $Z_{eff} \cong 1$ are obtained.

A full array of plasma diagnostic experiments are in operation or planned for operation in the near future. The ion component is routinely monitored using a charge-exchange spectrometer; and spatially and time-resolved measurements of the bulk ion temperature are reliably and routinely obtained with a VUV spectrometer.[5] Electron-temperature measurements are routinely obtainable by a ruby laser Thomson-scattering experiment. This laser system has been upgraded over the last six months for high-energy operation, up to 10 joules/pulse, and the system now has the capability of making temperature-profile measurements. Nonthermal and high-energy tail features of the electron distribution will be monitored in the near future with a second-harmonic cyclotron emission detector and

Table XX-1.

VERSATOR II PARAMETERS

Major Radius	40 cm
Minor Radius	13 cm
Ohmic Heating	30-100 kW
Plasma Current	25-50 kA
Toroidal Field	8-15 kG
Pulse Duration	20-50 msec
Ion Temperature	120-160 eV
Electron Temperature	∿250-350 eV
Confinement Time	∿1 msec (Est.)
Density $\bar{n}_e$	∿0.2-3×10^{13} cm^{-3}
Z_{eff}	1-3

a soft x-ray pulse-height spectrometer. These two experiments are currently under construction.

Microwave-scattering experiments have been carried out in the Versator II plasma with a 2-mm Extended Interaction Oscillator power source. Coherent scattering from electron-density fluctuations in the drift-wave frequency range has been observed. The spectrum of density fluctuations is generally decreasing with ω for all values of $k_\perp$, with fluctuation activity observed from 10 kHz up to 300 kHz. More recently, coherent scattering from injected lower-hybrid waves has been observed and the spectral density has been measured as a function of $k_\perp$.[6] These are the first tokamak experiments in which the lower-hybrid wave has been detected by microwave scattering.

Lower-Hybrid Experiments

The problems addressed in the Versator lower-hybrid experiments include:

Technology: Improvement of power transmission in waveguides.

Coupling: Physics of wave excitation by waveguide array.

Wave propagation: Measurements of wave trajectories in plasma with probes and microwave scattering.

Power Absorption: Mechanism of power absorption — do the waves heat ions, electrons or drive current?

In the past year experimental results have been obtained in all of the above areas.

A lower-hybrid antenna system operating at 800 MHz with peak power levels of P = 150 kW has been in operation on Versator over the past year. The system has the flexibility to employ either a four-waveguide array grill launching high-parallel-phase-velocity waves appropriate for ion heating, or a six-waveguide array launching low-phase-velocity waves appropriate for electron absorption.

Injection of rf power into tokamaks with phased-array waveguide grills is known to be advantageous from a reactor standpoint. The stainless-steel components should be relatively damage-resistant in the reactor environment with its consequent neutron and heat fluxes. However, the presence of plasma in or near the waveguide, neutral gas, ionizing radiation, and a strong field in the waveguides leads to the possibility of a power-transmission limit due to waveguide breakdown. One of the important questions addressed in the Versator lower-hybrid experiment is the technology involved in power transmission in this nonideal situation.

Progress in these techniques over the past year has led to injection-power levels in the range of 60-100 kW with power densities of up to 0.8 kW/cm^2 without evidence of plasma formation or breakdown. To reach these power levels, care must be taken in the surface preparation and vacuum cleanliness of the waveguide array. In-situ vacuum baking at 100-150°C, and in-situ titanium coating have been found useful in addition to rf pulse processing of the system. Furthermore, it is found that rf power transmission is seriously degraded in tokamak discharges with high impurity levels. As surface preparation techniques are further refined, we expect further improvement in the power-handling capability of the waveguide systems. However, progress in this area has allowed high-power experiments to begin on Versator during the past year.

Results of lower-hybrid injection at high-power levels occur in two broad parameter ranges shown in Fig. XX-1. In high-density, high-current discharges, charge-exchange spectroscopy shows the formation of a high-energy ion tail (Fig. XX-2). So far, Doppler width measurements of ion-impurity spectral lines has shown no bulk ion heating.[7] Further experiments are planned to study the parameter dependence of the ion tail formation, and an upgrade of the charge-exchange spectrometer is planned to allow detection of high-energy ions in the interesting energy range of 1-10 keV.

In the low-density, low-current regime, rf injection causes loop-voltage decreases and current increases not seen at high density.[8] These effects are shown in Fig. XX-3. These experiments have also shown a clear dependence of the effects on array phasing. On general grounds, these effects could be caused by

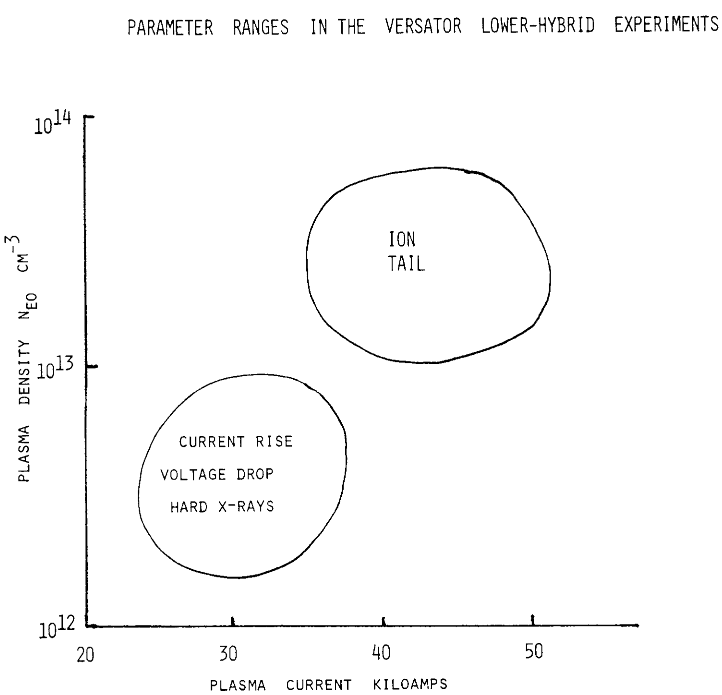

Fig. XX-1. Parameter ranges of Versator lower-hybrid experiments.

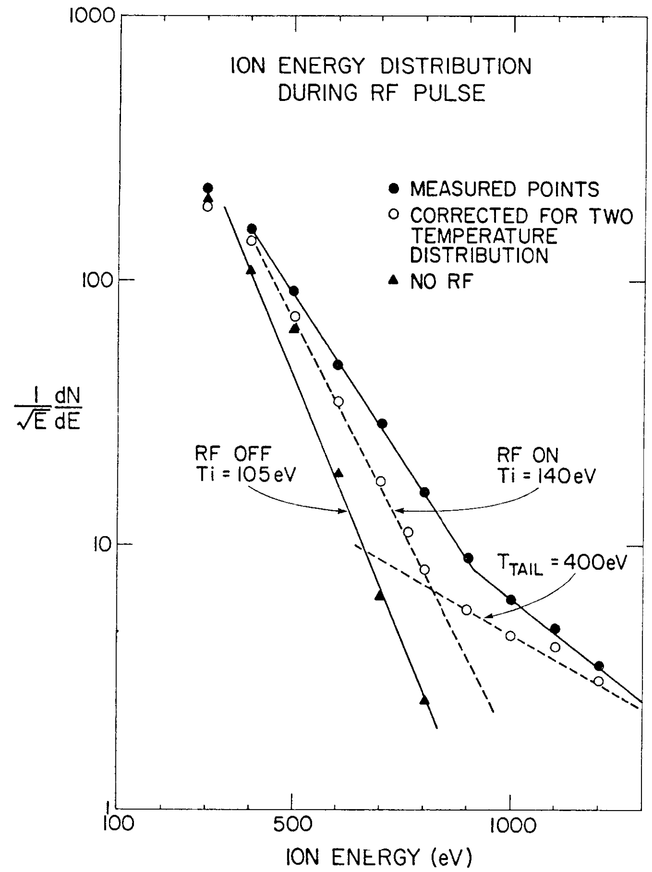

Fig. XX-2.

Charge-exchange spectroscopy shows formation of high-energy ion tail during lower-hybrid rf injection at high density.

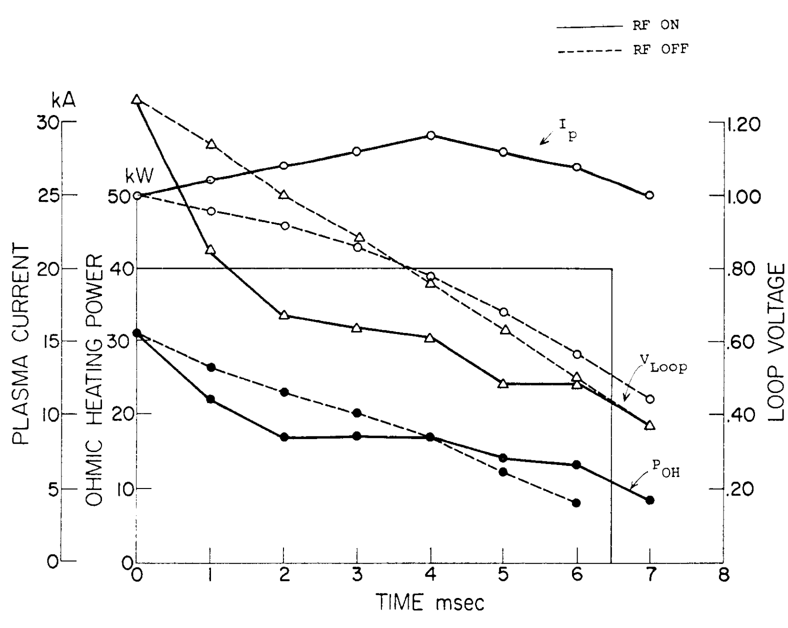

Fig. XX-3.

Loop-voltage drops and plasma-current increases are observed in low-density plasmas during lower-hybrid injection.

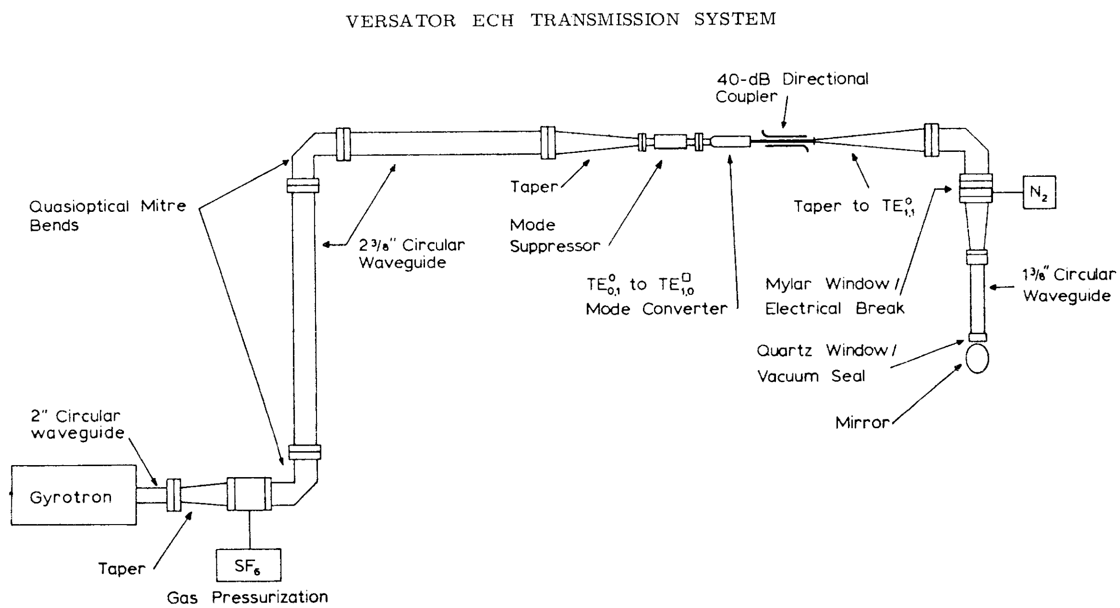

Fig. XX-4. ECH power-transmission system.

actual generation of a current by wave absorption; however, other interpretations cannot be ruled out as yet; in particular, heating and modification of the temperature profile could produce similar changes in plasma current and voltage. Experiments in the coming year will concentrate on distinguishing these possibilities and investigating other interpretations.

Electron-Cyclotron Heating

The electron-cyclotron heating (ECH) experiment at Versator II is a cooperative program with the Naval Research Laboratory. The microwave source developed and constructed at NRL is a gyrotron capable of producing 100 kW of rf power at 35 GHz with 10-msec pulse duration. For these experiments, an rf transmission system and injection antenna have been installed on Versator.[9] The system, shown in Fig. XX-4, will be used to study basic physics questions of ECH including: antenna design and optimization, and polarization and propagation-angle dependence of wave absorption; also, the possibilities of heating at the second-cyclotron harmonic and plasma preionization experiments can be investigated.

Preliminary experimental results have been obtained in the last month of

1980 showing a decrease in loop voltage and decrease in line average density injection of power at the fundamental cyclotron-resonance frequency.

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5. MIRROR-CONFINED PLASMAS

U.S. Department of Energy (Contracts DE-AC02-78ET-51002, DE-AC02-78ET-51013, and DE-AC02-78ET-53076)

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We produce a plasma with $T_i \gtrsim 150$ eV $n > 10^{12}$, in a min-B mirror system. The plasma is produced by a so-called "washer gun," located in a guide field about 2 m from the mirror. After, or during injection, we heat the plasma by ion cyclotron resonance (~100 kW at 4-5 MHz) to values of $T_i > 500$ eV. The fluctuations and instabilities of the resultant plasma are the objects of our study.

During the coming year we will investigate the production of a sloshing ion distribution by ICHR, and the properties of a hot-cathode plasma gun.