DOE/ER/53263--28

DE93 013144

Annual Performance Report

Grant No. DE-FG02-88ER53263

"Fundamental Studies of Fusion Plasmas"

by R. E. Aamodt (P.I.), P. J. Catto, D. A. D'Ippolito, J. R. Myra, and D. A. Russell

27 April 1993

DOE/ER/53263-28 LRC-93-41

LODESTAR RESEARCH CORPORATION

2400 Central Avenue
Boulder, Colorado 80301

PERFORMANCE REPORT
TABLE OF CONTENTS

I. EXECUTIVE SUMMARY

Over the past three year contracting period Lodestar has played a key role in understanding ICRF antenna environments and helped develop the ability to credibly extrapolate existing results into new design regimes. As ICRF is expected to play a key role in advanced tokamak scenarios on ITER, TFTR, TPX, C-Mod, JET, JT60U, and Ignitor, these successes have been highly relevant to the world's fusion program. In this performance report we summarize our results to date, emphasizing the ICRF topics.

Lodestar has continued and extended work on ICRF interaction with the edge plasma. ICRF generated convective cells have been established as an important mechanism for influencing edge transport and interaction with the H-mode, and for controlling profiles in the tokamak scrape-off-layer. Power dissipation by rf sheaths has been shown to be significant for some misaligned ICRF and IBW antenna systems. Near-field antenna sheath work has been extended to the far-field case, important for experiments with low single pass absorption. Impurity modeling and Faraday screen design support has been provided for the ICRF community.

In the area of core-ICRF physics, the kinetic theory of heating by applied ICRF waves has been extended to retain important geometrical effects relevant to modeling minority heated tokamak plasmas, thereby improving on the physics base that is standard in presently employed codes. Both the quasilinear theory of ion heating, and the plasma response function important in wave codes have been addressed. In separate studies, it has been shown that highly anisotropic minority heated plasmas can give rise to unstable field fluctuations in some situations.

A completely separate series of studies have contributed to the understanding of tokamak confinement physics. Fast electron transport has been studied both by first principles theory, and by modeling transient perturbation experiments on TEXT. The spatial diffusion coefficient, important in current profile control schemes, and as a diagnostic of tokamak fluctuations, has been evaluated. The results of these studies are consistent with the interpretation that magnetic fluctuations control runaway but not thermal electron transport in TEXT.

Additionally, a diffraction formalism has been produced which will be used to access the focusability of lower hybrid, ECH, and gyrotron scattering antennas in dynamic plasma configurations.

II. SUMMARY OF TECHNICAL PROGRESS

A. ICRF-Edge Physics Studies

1. Introduction

There has been substantial progress recently in understanding the interaction of high-power ICRF waves with the tokamak edge plasma.[1] A large body of experimental results and theoretical modeling has shown that controlling the ICRF-edge interaction plays a crucial role in the success of ICRF heating and current drive experiments. The ICRF-edge plasma interaction can generate low and high-Z impurities with associated edge and core radiation, anomalous loading (i.e. power dissipation) and decreased heating efficiency, and DC edge electric fields and $E \times B$ drifts yielding enhanced edge transport and profile modification. Both the impurities generated at the Faraday screen (FS) and the ICRF-driven transport have been shown to influence the ability to achieve H-modes on JET with ICRF heating alone, with the remarkable result that the H-mode threshold power, global confinement, and duration depend on the phasing of the antenna. Our recent work has shown that many of these effects can be attributed to the existence of rf sheaths, which have therefore been the major focus of the Lodestar edge physics research program in recent years. Our theoretical work has been done in close collaboration with M. Bures and J. Jacquinot of the Joint European Torus (JET) experimental ICRF group, who have accumulated a large database on ICRF-edge physics and have played an active role in the development of rf sheath modeling. We are beginning a collaboration with J.R. Wilson and R. Majeski of the TFTR group, to apply this work on TFTR in order to optimize ICRF operation for D-T operation. We have also kept in touch with relevant developments in the experimental ICRF programs on DIII-D, Alcator C-Mod, Phaedrus-T, ASDEX and TEXTOR.

The interaction of ICRF waves with the material boundaries in the tokamak leads to the formation of rf sheaths when closed circuits linking substantial rf magnetic flux are formed by the magnetic field lines and various conducting surfaces (Faraday screen, limiters, etc.).[2-12] Equivalently, one can regard rf sheaths as being driven by the component of the rf electric field parallel to the equilibrium B field, i.e. the slow wave component. Thus, rf sheaths are driven quite strongly by slow wave couplers, such as ion-Bernstein-wave antennas, and also by fast wave antennas which are imperfectly aligned to the local magnetic field. A model[9] based on the theory of rf sheaths has been successful in explaining many experimental dependences[8-11] of the metal impurity generation in JET (see Sec. 2). These models also predict substantial power dissipation in the sheaths when the induced voltage across the sheath and the local plasma density are sufficiently large.[4] This effect has been observed in JET (as a significant reduction in heating efficiency) by reversing the toroidal field and using monopole phasing to create unusually large rf sheath voltages.[11] Sheath-driven parallel currents in the scrape-off-layer (SOL), which flow along field lines from the rf-sheath-biased antennas into limiters, have been measured on TEXTOR.[12] Similar SOL modifications (sheath-induced impurities, currents, and DC potentials) were measured on Phaedrus-T for three antenna phasings (0, 90 and 180 degrees) and it was shown that the presence of an insulating limiter on each side of the antenna greatly reduced the edge modifications in agreement with the predictions of rf sheath theory.[13] Thus, there is a growing body of experimental evidence supporting the importance of rf sheath effects in the SOL, and a growing effort to understand and control them.

Another important effect predicted by rf sheath theory is the generation of ICRF-driven convective cells in front of the antennas.[14,15] The spatial variation of the DC sheath potential $\Phi_0(r,\theta)$ drives a convective flow pattern, which can penetrate a substantial radial distance into the SOL. This convection may explain the observed density profile flattening with monopole phasing on JET (see Sec. A 4) and the observed phasing sensitivity of the ICRF-induced H-mode (see Sec. A 5). It is particularly important to understand the physics of the monopole ICRF H-mode, and to discover whether the extended duration and reduced impurity radiation characteristic of this regime is applicable to reactor operation.

In large tokamaks, such as JET and TFTR, the typical heating regime has good single pass absorption, and the amount of reflected or transmitted wave energy impacting the SOL is small. Thus, rf sheaths driven by the *near fields* of the antenna are the most important concern in these experiments, and most of our work to date has concentrated on various aspects of this problem (Secs. A 2 - A 5). However, there are a number of interesting conditions where the single pass absorption can be low (ICRF current drive or direct electron heating, heating with a low minority concentration, or heating in smaller tokamaks). In the multiple-pass regime, *far field* rf sheaths driven by ICRF wave energy far from the antenna become important (see Sec. A 6). Like the sheaths near the antenna, far field sheaths can generate impurities, increase recycling, give rise to enhanced edge convection, etc. With the increasing emphasis on ICRF current drive (DIII-D, JET and TFTR) and ICRF heating in high-density machines (Alcator C-Mod, Ignitor), it is expected that this problem will be of increasing interest in the next few years.

The following sub-sections describe our work in these areas in more detail.

2. ICRF Impurity Studies

One of the critical problems for ITER and other reactor-relevant machines is the control of impurities caused by auxiliary heating and by power flow in the scrape-off layer. Recently, an international effort has shown that the dominant ICRF-specific impurity generation mechanism is sputtering and self-sputtering by ions accelerated to hundreds of eV energies by rf sheaths.[2-11] Our work on this subject with M. Bures and J. Jacquinot of JET has resulted in a detailed model[9,10] of the metal impurity generation at the Faraday screen (FS) for the JET antenna geometry. An extensive comparison has shown good agreement with JET impurity influx data for a variety of limiter and FS materials and for different operational scenarios.[8-10] This effort culminated in the analysis of the data from operation with the new Be Faraday screens on JET.[11] The previous Be-gettered nickel screens were replaced by screens manufactured from solid Be with a more open design. The elimination of the residual Ni influx (from the gaps of the old gettered screens) allowed coupling to the H-mode for the first time in monopole phasing, emphasizing the importance of eliminating even trace amounts of high-Z impurities (see Sec. 3). The Be influx was less than 10^{19} atoms MW^{-1} s^{-1} (comparable to that with the previous screens) in agreement with the theoretical predictions. Another interesting aspect of the experiment was the investigation of the operating regime where the direction of the equilibrium magnetic field is reversed, so that the mismatch angle θ between the magnetic field and the screen bars increases from about 5 to 22 degrees. The model predicts that the voltage drop across the sheaths (and hence the energy dissipated by the sheath-accelerated ions) is proportional to $\sin\theta$. No change was observed for dipole phasing, where the rf sheath voltage vanishes by symmetry for either direction of B. With monopole phasing, it was found that the efficiency of ICRF heating is substantially degraded (about a 40% drop in central stored energy) when the direction of the toroidal field is reversed. The drop in coupled rf power was comparable to the theoretically predicted dissipation in the rf sheaths.[11]

The beryllium screen experiments, especially the ICRF H-mode results, confirm the usefulness of the JET-Lodestar prescription[9,10] for reducing ICRF-specific impurities to *negligible* levels in heating experiments. First, regimes with poor single pass absorption should be avoided, if possible, to prevent rf sheath formation away from the antenna which can pollute the SOL with limiter and wall impurities. Second, rf sheath formation at the antenna should be inhibited by proper antenna and Faraday screen design. A properly designed antenna for ICRF heating should include the following features:

1) FS elements should be aligned as closely as possible to the local equilibrium magnetic field;

2) the density at the FS should be minimized by the use of close-fitting side protection tiles;

3) the antennas should be designed with two symmetric current straps and operated with the straps out of phase (toroidal dipole phasing);

4) the antenna voltage (and hence power per antenna) should be minimized;

5) a low-Z material, such as beryllium, should be used for the Faraday screen material because it has a relatively low self-sputtering coefficient in the energy range 0.5 - 1 keV.

The adaptation of these rules for ICRF current drive, where single-pass absorption is low and typical antennas have 4-6 straps with $\pi/2$ phasing, will be a subject of future research.

In the past year, we have rewritten the Lodestar FS impurity code to make it more modular and more easily applicable to other machines than JET, and have applied it to evaluate the recently proposed ICRF antenna design[16] for Ignitor. We found that the high-density SOL characteristic of Ignitor has such good screening of impurities by ionization that the impurity influx inside the LCFS in dipole phasing is entirely negligible. The calculated influx in monopole phasing appears not to be negligible from the viewpoint of edge radiation or impurity avalanche for high-Z materials, but may very well be acceptable for low-Z materials such as C or Be.[17] This question will be settled more quantitatively using the thermal energy balance model described in Sec. A 3. One reason for the interest in monopole phasing for ICRF heating in Ignitor is the possibility that the rf sheath-driven convection (see Sec. A 4) can spread the heat load by increasing the "wetted surface area" on the first wall. Finally, as mentioned above, impurity influx and rf sheath parasitic heating calculations are in progress for TFTR.

3. Impurity Radiation Model

ICRF-specific impurity influxes can be computed from rf sheath theory as one aspect of evaluating the design of an ICRF antenna system. Although these impurities can be reduced to negligible levels in heating experiments, this is not necessarily the case for other applications of ICRF antennas, such as fast wave current drive. Therefore, criteria are needed to determine tolerable levels of impurities for future tokamaks, including current drive and ignition experiments. We have formulated a model[18] of the confined plasma thermal equilibrium, including a simple 1D impurity transport[19] and radiation[20] model, which can be used to establish quantitative radiation limits on ICRF-specific and other impurities. The model is simple enough to do extensive surveys of the tokamak parameter space for our specific purposes, and is meant to be complementary to detailed 2D transport codes.

The model was first applied[18] to understand the role of radiation from trace nickel radiation in the Be-gettering experiments on JET.[10] In these experiments with Be-gettered Ni screens, ICRF H-modes with dipole phasing were obtained, but no monopole H-modes were obtained. It was thought[21] that edge radiation due to the Ni influx coming from the uncoated gaps of the FS, combined with the increased edge convection[15] in monopole phasing, prevented the monopole H-mode. In a later experiment with solid Be screens, a similar influx of Ni atoms was introduced by laser ablation of a Ni pellet in the plasma edge during an H-mode, resulting in a transition to the "low particle confinement" H-mode.[22] To understand the role of Ni radiation in these experiments, we have simulated a JET discharge with similar rf power and Ni influxes and confirmed that the impurity radiation at the edge was large enough to inhibit the formation of an edge temperature pedestal. These and other calculations we have carried out with the power balance model clearly explain the superiority of low-Z Faraday screen materials for coupling to the H-mode.

The present version of the model is applicable to tokamaks in which impurity ionization occurs mainly inside the last closed flux surface. A number of modifications are in progress, including a new particle transport model to allow treatment of the high-density regime (with high impurity screening) appropriate to C-Mod and Ignitor. The model will be applied to establish quantitative limits on the ICRF-specific impurities in these machines.

4. ICRF Convective Cell Simulation

The radial and poloidal structure[9] of the rectified or time-averaged rf sheath potential[4] Φ_{rf} produces E × B convection in front of ICRF antennas.[14] The qualitative picture is as follows: the sheath potential Φ_{rf} has a maximum value at the FS and decays radially in the SOL on the scale of the electron skin depth; it varies poloidally, and drives E × B convective cells, with the periodicity of the Faraday screen structure and also on the scale length of the antenna. Convection on the scale of the antenna would have the greatest interaction with the plasma edge, and would be present even if the screen were removed. The smaller convective cells generated by the FS periodicity have less penetration, but increase the poloidal asymmetry of the equilibrium and give the strongest modification of the SOL density and temperature profiles. As discussed in Sec. A 5, the ICRF convection is a strong candidate to explain several interesting features of the JET ICRF H-modes.[15]

We have derived a generalized "convective cell" equation to describe the spatial variation of the electrostatic potential in the global SOL, and written a 2D fluid simulation code (CC2) to solve a model problem representing ICRF edge convection.[14,15] The model consists of an equation for the slow-time evolution of the field-line-averaged electrostatic potential $\Phi(x,y)$ in the SOL, assuming fixed density and temperature profiles. The convective cell equation includes the physics of advection, viscosity and parallel current flow into sheaths at material boundaries. It is solved subject to periodic B.C.'s in y and radial B.C.'s that model the sheath-induced driving flows at the antenna tile tangency surface (ATTS) and at the last closed flux surface (LCFS). In particular, we demand that $\Phi=\Phi_0$ at the ATTS and LCFS, where $\Phi_0 = \Phi_{rf}(x,y) + 3T_e(x)$ is the DC sheath potential and x,y denote the radial and poloidal coordinates. The model ensures no net parallel current $J_{||}$ leaving the plasma on field lines at the two radial boundaries of the SOL. In the SOL itself, a net $J_{||}$ flowing to the axial boundaries (limiters, diverter plates, etc.) is allowed and is balanced by $\mathbf{J}_\perp$ due to the ion polarization drift. The ratio $J_{||}/J_\perp \sim \lambda \equiv (\rho_s/L_{||})(L_y/\pi\rho_\phi)^4$ depends on the parallel connection length $L_{||}$, the poloidal scale length L_y, and the Larmor radii based on T_e (ρ_s) and Φ (ρ_ϕ). The limit of 1D sheath theory is recovered as $\lambda \to \infty$, and as $\lambda \to 0$ the convective cell equation reduces to the usual Navier-Stokes equation for 2D incompressible flow neglecting pressure gradients.

We solve the time-dependent coupled equations for the slow time evolution of the potential Φ and vorticity $\omega = \nabla^2\Phi$ using a combination of finite-differencing and spectral techniques and study the interaction of the two counter-streaming flows caused by spatial decay of the rf sheath potential Φ_{rf} near the antenna and the Bohm sheath potential ($\sim 3T_e$) near the LCFS.[15] For sufficiently small antenna-plasma separation Δx, the interaction is strong and the convective cell disrupts the poloidally-uniform flow near the LCFS. The flow contours reconnect giving birth to new vortices which connect the LCFS to the antenna tile surface. The convection time around these vortices is much smaller than the time for sonic flow along field lines, so that the density and temperature profiles would be essentially flattened across the vortices if these profiles had been evolved in the simulation.

The numerical results correspond to the experimental observations on limiter operation in JET as follows:

(1) the rf sheath potential driving the convective cells is large only in monopole phasing, in agreement with the profile flattening data on JET and other tokamaks;

(2) the rf-induced convection provides an explanation for the significant plasma density at the FS required in the modeling[8-11] to account for the experimental impurity data.

The comparison with JET H-mode data is given in the next section.

5. ICRF H-Mode Modeling

An important development in the JET ICRF program, made possible by the great reduction in impurities, was the achievement of H-modes induced by ICRF heating alone.[23] ICRF H-modes were obtained with both in-phase (monopole) and out-of-phase (dipole) operation of the 2 strap ICRF antennas. Dipole phasing yielded standard 3 MA H-modes of high quality with a threshold rf power of 5 MW and an energy confinement time $\tau_E = 2.5 - 2.8\ \tau_G$ (Goldston L-mode scaling). The plasma density and impurity concentration typically increased with time until radiative collapse in the X-point region terminated the H-mode. The dipole H-mode was very similar to the neutral-beam-induced H-mode on JET. By contrast, the H-mode obtained with monopole phasing had a larger threshold power (8 MW), smaller increase in confinement ($\tau_E = 1.7\ \tau_G$), a greatly reduced density rise, and an extended lifetime due to the absence of any radiative collapse. Thus, the early experimental results suggest that the monopole ICRF H-mode may provide a means of achieving density control and reducing the impurity accumulation in H-mode operation. The ICRF H-mode behavior suggests the existence of a phasing-dependent edge transport mechanism which degrades the effectiveness of the "transport barrier" but enhances the effectiveness of the divertor to withstand the power flow (perhaps by spreading out the heat load). The ICRF convection described in Sec. A 4 is such a mechanism.

In the simulation[15] rf-induced convective cells interact with the sheared flow layer at the plasma edge to produce secondary vortices which connect the last closed flux surface to the limiters, enhancing the edge transport and increasing the poloidal variation of the equilibrium density and temperature. All of these effects are likely to inhibit the formation of the highly-sheared, poloidally uniform H-mode transport barrier, although this effect is not yet in our simulation. In addition to the phasing dependence, the simulation yields two other promising quantitative predictions for the H-mode experiments:

(1) for typical JET parameters, the rf convective flow velocity near the ATTS ($v_E \sim 10 - 20$ km/sec) is comparable to that observed experimentally in the H-mode on machines such as DIII-D,[24] TEXTOR[25] and JFT-2M[26] and is rapid enough to broaden the density and temperature profiles;

(2) the computed antenna-plasma distance for strong interaction between the convective cell and the sheared flow layer at the LCFS ($\Delta x_{crit} \sim 1.5$ cm for JET parameters) is comparable with that measured during ICRF monopole H-modes.

Moreover, the scaling of $\Delta x = d_{a-p}$ (measured antenna-plasma distance) with rf power and antenna phasing has been analyzed[15] by means of a simple model of the plasma position control feedback system to compute the density scale length, λ_n, for dipole and monopole H-mode shots. Both the d_{a-p} and recycling (D_α) data imply that significant density profile flattening occurs for the monopole H-mode (as compared with dipole), and the degree of flattening increases with rf power. Thus, the simulation and data analysis suggest that ICRF-driven convection is a strong candidate to explain the absence of the radiative collapse in the JET monopole H-mode and may possibly be used as a technique to reduce the power load in a divertor.

Future work will extend the simulation in several important respects. We will investigate the correct boundary condition at the LCFS to connect the SOL simulation with the core plasma solution. Then we will extend the CC2 code to self-consistently evolve the density and temperature profiles using the new B.C.'s, and thus to compute the SOL profile flattening as a function of the rf convection. Finally, in a separate calculation a divertor radiation model will be developed to assess quantitatively the effect of the profile flattening on the carbon blooms and radiative collapse in the X-point region. As a first step to modeling the divertor performance on JET, we have documented and enhanced our impurity code to be more modular (so that it can be more easily adapted to divertor geometry), and we have developed the impurity radiation model described in Sec. 3.

6. Far Field Sheath Modeling

Experiments on many tokamaks indicate that fast wave (FW) interaction with walls and limiters can lead to increased impurity influxes in regimes of poor single pass absorption. On JET, before the introduction of a beryllium first wall, poor single pass absorption of the ICRF waves was found to lead to disruption in severe cases.[27] Direct measurements in the edge plasma also showed that both magnetic and electric fields in the edge were larger in regimes of poor single pass absorption.[27,28] In ASDEX[7,29] rf induced impurities were found in the plasma that could not have come from near field sheath[2-6] processes. These and similar observations have motivated some recent theoretical work.[30-32]

It is expected that far field sheath physics will be increasingly important in the next few years because of two developments in the fusion program. First, the new emphasis on ICRF direct electron heating and current drive experiments on DIII-D, TFTR and JET means that these experiments will be running in the low single pass absorption (multiple pass absorption) regime required for far field sheaths. Second, Alcator C-Mod will be also be operating in this regime for several of its advanced tokamak scenarios with ICRF. This has motivated the recent work at Lodestar on far field sheaths.[33]

We have studied the interaction of ICRF waves with a conducting wall or limiter of a tokamak, with attention focused on the generation of slow waves (SW) and subsequent formation of far field rf sheaths. The elements of the theoretical model[33] can be summarized as follows: i) A launched FW from the antenna is not completely absorbed on one pass and therefore encounters the inner wall or limiter on the high field side (HFS), perhaps after tunneling through the HFS FW cutoff. More generally, a FW encounter with a HFS or LFS surface could occur after multiple reflections from either FW or minority cutoffs. ii) Because the flux surfaces at the edge do not match the conducting surface exactly (due to the presence of bumper limiters or simply the effect of plasma shaping), a SW component is generated at the wall,[31] with concomitant $E_{||}$. iii) The $E_{||}$ is screened along the field line by the plasma in a characteristic penetration length resulting in a net rf voltage drop along the field line $V = \int ds\, E_{||}$. iv) This rf voltage V is the drive for rf sheaths which act to increase impurity sputtering and generate convective cells by the same mechanisms discussed in Sections 2 and 4.

An analytic scaling for the voltage V with plasma parameters, antenna spectrum and characteristic mismatch length scale (taken to be the height h of an idealized bumper limiter) has been obtained[33] and compared with the results of a 2D code solution for the same model problem. Surprisingly good agreement was obtained between the analytic formulas and the numerical treatment for parameters in which numerical resolution could be obtained. The large separation between FW and SW length scales creates resolution problems for a numerical treatment, and restricts the parameter regime which can be treated numerically. The success of the analytic model removes these restrictions and allows us to model experimental data.

The analytic model shows that three qualitative pieces of physics tend to dominate far field interactions for a given flux surface to conducting surface mismatch. The are the FW cutoff (which acts to protect the walls from the high $k_{||}$ part of the wave spectrum), the beneficial role of increased plasma dielectric screening of $E_{||}$ at high plasma edge densities (which reduces the induced voltage), and the single pass absorption (which determines the electric field amplitude incident on the wall). Preliminary results correspond qualitatively to the JET experiments as follows. i) Monopole operation produces more far field edge interaction than dipole. ii) Edge interaction is stronger in cases of poor single pass absorption than in cases of good absorption. Quantitatively, the far field processes result in $V \sim 40$ volts, and an enhanced sputtering energy $\sim Z(eV+3T_e)$ including the Bohm sheath, which exceeds typical sputtering thresholds of order 25 - 100 eV.

In future work, the analytic far field sheath model will be applied to understand relevant impurity, density control and transport issues for several ICRF experiments, as we have already done for near field sheath physics on JET.

B. ICRF-Core Physics Studies

1. Fast Wave Minority Heating with Off-Axis Tangency Interactions

Fast Wave (FW) heating by waves in the ion cyclotron range of frequencies (ICRF) is an important auxiliary heating method for reactor plasmas because of its ability to penetrate to the core, and thereby provide efficient central heating. While the basics of energy transfer from the waves to the ions at minority ion cyclotron resonance have been well understood for a long time,[34] some details of the quasilinear heating having to do with the tokamak geometry are still not well understood theoretically, especially in the high power density regime where extended ion tails form.

At Lodestar, we have developed[35] and implemented[36] a formalism which retains all geometrical effects known to be crucial to modeling minority heated tokamak plasmas. In particular, the singularity in the Stix theory which occurs for off axis tangency interactions (i.e. at the flux surface tangent to the resonant surface $\omega = \Omega_i$ when Ω_i is not on the magnetic axis) is properly resolved by an Airy function treatment.[35] This treatment effectively correlates pairs of interaction points $\omega = \Omega_i$ treated as independent stationary phase interactions in the pioneering work of Stix.[34] The evaluation of these tangency interaction modifications is thus mathematically similar to the more familiar treatment of the correlations that occur when the banana tips of trapped ions lie in the vicinity of the resonant layer.[37-41]

The Lodestar work on quasilinear heating has integrated well with separate grant work done under Small Business Innovative Research (SBIR) funding. In the SBIR study, a numerical implementation[36] of the Airy function representation for correlated tangency interactions was successfully completed.

The resulting Fokker-Planck code has been used to demonstrate that ICRF can be used to control the hot ion populations in trapped and passing particles by exploiting the off axis tangency interactions on the high field side (to heat passing and barely trapped particles preferentially) and on the low field side (to heat deeply trapped particles preferentially). Control of trapped/passing populations may be beneficial for optimizing hot ion stabilization of MHD modes. In addition, the code has been used to investigate the degree of perpendicular vs parallel energy anisotropy to be expected in FW heating. These results have contibuted to anisotropy stability studies, to be described separately in this report (Sec. B 3).

2. Kinetic Model of FW Propagation near Minority Ion Cyclotron Resonance

Fast wave heating of tokamak plasmas in the ion cyclotron range of frequencies (ICRF) is well established in both the minority and second harmonic regimes.[42-45] For both these schemes an understanding of the spatial dependence of the resonant interaction region is highly desirable since this would lead to greater control over the heating. Three important factors which influence the resonance width are the Doppler effect, the spatial variation of the equilibrium magnetic field (including the effects of trapped particles), and the anisotropy of the distribution function.

The model which has been used in most calculations of ion cyclotron absorption in a tokamak is that of an equilibrium magnetic field with straight field lines and a perpendicular gradient in strength.[46] This model has produced much useful information and includes the two essential ingredients of Doppler broadening and perpendicular magnetic field inhomogeneity. However, a straight field line model cannot properly account for effects due to a parallel variation of the magnetic field.

In a tokamak magnetic field an ion experiences a parallel variation in the equilibrium magnetic field due to the rotational transform. This feature has a profound effect on resonant ions compared with the straight magnetic field model. For the latter case an ion if resonant along a particular field line will remain in resonance since the field lines are straight. Thus, for the straight field line case there are fewer resonant ions interacting strongly and locally with the wave, whereas in the curved field line model there are many more resonant ions interacting weakly and non-locally with the wave.

To date, there are very few treatments of the effect of parallel field variation and trapped ions on fast wave heating at the ion cyclotron resonance. Particularly insightful is the work of Faulconer[47] and Smithe et al.[48] in which the parallel field variation model employed is partially motivated by the earlier work of Itoh et al.[49] Their plasma response function is found by retaining the leading effect of the field inhomogeneity as well as Doppler broadening, but without introducing the full complications of tokamak geometry.

In recent work at Lodestar,[50] response functions for Maxwellian and bi-Maxwellian minority ions have been obtained which generalize and extend previous modified Z function forms, and which are valid for arbitrary minority concentrations. The plasma response function obtained for a Maxwellian minority includes both passing and trapped ions and, in the limit of small minority concentrations, is used to evaluate the transmission coefficient. The small minority concentration expression for the transmission coefficient is then shown to be valid for more general unperturbed distribution functions that are arbitrary functions of pitch angle and speed on each flux surface provided $k_{\parallel}\rho \ll 1$, where $k_{\parallel}$ is the parallel wavenumber and ρ the minority gyroradius. For the bi-Maxwellian distribution function an explicit and compact expression for the plasma response function has been derived for arbitrary minority concentrations, which for strong anisotropy substantially modifies the Maxwellian case.

These results show that a fully toroidal evaluation of the plasma response function is an essential step towards the construction of both one and two dimensional full wave theories of fast wave minority heating.

3. Anisotropic Minority Driven Instability

Motivated by the possibility that minority ICRF heating of tokamak plasmas may give rise to unstable field fluctuations and with an eye to studying mode conversion among unstable waves (i.e., waves that are temporally growing for real wave vectors and whose wave vectors are therefore complex for real frequencies), we have carefully delineated the unstable branches of the dispersion relation for a warm magnetized deuterium plasma to which has been added a small amount of extremely anisotropic ^3He ($T_\perp / T_{//} \equiv r = 400$). For parameters typical of JET, three waves are unstable at frequencies just below the ^3He cyclotron frequency. They are the Bernstein wave, fast magnetosonic wave and the 2-ion hybrid (2IH) wave.

Both of the low-frequency normal modes of the cold plasma, the Alfven-Ion Cyclotron (AIC) wave and the fast magnetosonic wave, may be destabilized by the helium. In the warm background plasma, the Bernstein wave, the 2IH wave and the ion acoustic wave may be unstable as well. However, the AIC wave and the ion acoustic wave are easily stabilized by Landau damping on the warm background electrons and deuterium. Only the fast wave, the Bernstein wave and the 2-ion hybrid wave are unstable for parameters typical of a fusion reactor.

The fast magnetosonic wave is unstable only for angles of propagation strictly between 0° and 90° to the magnetic field. For parallel propagation, the polarization is right-hand circular so that the wave cannot resonate with the left-hand gyrating helium ions. For perpendicular propagation, the fast wave corresponds to the extraordinary wave that is resonant at the lower hybrid frequency. It is easily shown from the dispersion relation that the anisotropy affects only the dispersion of the *ordinary* wave at 90°; the fast wave is unaffected. An instability of the perpendicular propagating ordinary wave can be provoked by anisotropy opposite to that considered here (i.e., $T_\perp < 2 \cdot T_{//}$ or $r < 1$) in the ion distribution function of a two-component plasma. So we restricted our attention to propagation strictly between 0° and 90° to the magnetic field.

Near the fundamental, the fast wave is destabilized by the helium over the widest range of angles of propagation - virtually all angles between 0° and 90°. As we seek instability at progressively higher harmonics, the dispersion relation forces us to use larger values of k so that Landau damping on the deuterium ions squelches the instability at all but the larger angles of propagation. At the tenth and higher harmonics, there is no instability for angles less than 50°. But at 85° the instability persists at least through the 70th harmonic. With increasing harmonic number, the instability is constrained to lie in a very narrow wedge (±2°) of **k**-space, approximately centered on 87°. The fast wave does not exist for frequencies greater than the lower-hybrid resonance. For canonical, JET-like parameters the (cold) lower-hybrid resonance is at $\omega_{LH} = 101 \cdot \Omega_{^3He}$ for propagation at 87°.

Near (just below) $\Omega_{^3He}$ and depending on the angle between the wave vector and the magnetic field, either the Bernstein wave or the fast wave may be unstable. These two waves are nearly indistinguishable when either one is unstable (their dispersion curves intersect in ($\underline{k}$,Re(ω))-space) and exchange roles as a function of angle and background temperature. For example, at 80° the fast wave is unstable if the background plasma is assumed cold, and the (helium) Bernstein wave is unstable if the background is assumed hot. Either wave is more easily stabilized by a warm background (i.e., more effective at heating electrons and deuterium) than is the 2IH wave. About one half of either wave's energy is in the longitudinal mode when the wave is unstable.

We found that the 2-ion hybrid (2IH) instability coincides with its resonance just below $\Omega_{^3He}$ and endures over a range of k that *increases* with increasing ^{3}He temperature, for fixed r. This is apparently because with increasing ^{3}He temperature the resonance moves further away from the instability cut-off at $(1 - 1/r) \cdot \Omega_{^3He}$. When unstable, the 2IH wave polarization is predominantly transverse. We have further discovered that the 2IH branch is accurately described by a reduced dispersion relation obtained by neglecting the component of the electric field vector along the magnetic field and solving the resulting 2x2 matrix dispersion relation for a cold background plasma.

To simulate the progressive stabilization of the fast wave by alpha particles in a burning plasma, we have solved the dispersion relation for successively greater concentrations of alphas using the (isotropic) slowing-down distribution function. For the slowing-down distribution, the anti-Hermitian part of the dielectric tensor vanishes for phase velocities greater than the birth velocity (for real frequencies); there is no Landau damping and therefore no enhanced stabilization of the fast wave. Since the fast wave phase velocity ~ cos(ϕ) at high frequencies, the alphas are most effective at stabilizing the higher harmonics where the instability is confined, without alphas, to $\phi \to 90°$. For example, the 70th harmonic is stabilized by $n_\alpha \geq 0.005\ n_e$ for all ϕ if $n_{^3He} = 0.01\ n_e$, whereas $n_\alpha \geq 0.07\ n_e$ is required to stabilize the 10th harmonic at $\phi = 80°$. No concentration of alphas that is reasonably weak, so as not to profoundly alter the zero-order dispersion relation, can stabilize the fast wave at the 10th harmonic if $\phi = 60°$, because the fast wave phase velocity exceeds the alpha birth velocity at this angle.

The fast wave is strongly absorbed between adjacent harmonics of $\Omega_{^3He}$. Therefore, if low-frequency fluctuations are responsible for saturating the instability by scattering unstable waves into nearby sinks in (ω,$\underline{k}$)-space, we anticipate that a sharp stationary power spectrum of fast waves concentrated near the ^{3}He cyclotron harmonics will result from the instability. As the plasma burns, spikes in the power spectrum diminish first at the higher harmonics and larger angles of propagation. This could prove useful as an alpha particle diagnostic, for example, in the context of gyrotron scattering off electric field fluctuations.

In conclusion, as a first step in studying the stability of ICRF-heated fusion plasmas, we have demonstrated the destabilizing effect of a tenuous, highly anisotropic bi-Maxwellian distribution of ^{3}He ions on the low-frequency normal modes of a warm magnetized deuterium plasma. For parameters typical of a fusion reactor, we find that the AIC wave is always stable due to strong Landau damping on the deuterium. However, for the degree of anisotropy assumed, the fast magnetosonic wave is unstable near each of (at least) the first 70 helium cyclotron harmonics at angles of propagation that approach 90° with increasing harmonic number. We have also discovered that for the same parameters, the Bernstein wave and the 2-ion hybrid wave are unstable just below the helium cyclotron frequency and we have studied these unstable waves in considerable numerical detail. We have demonstrated the stabilizing effect that slowing-down alphas can have on fast waves with phase velocities less than the birth velocity.

A by-product of our research is the code STAB which solves the dispersion relation for wave propagation in a warm, uniformly magnetized multi-component plasma using Newton's method in the complex ω-plane. Once two poles are isolated starting from cold-plasma or Born-approximate first guesses, STAB bootstraps along a branch of solutions of the full dispersion relation. We anticipate generalizing STAB to handle anisotropic minority distribution functions other than bi-Maxwellians, consistent with our evolving understanding of the nature of ICRF heated plasmas, as described elsewhere in this report.

C. Fast Electron Transport

An understanding of the diffusion of fast electrons in a tokamak is of importance for a number of reasons. In current drive schemes, fast electron confinement competes with collisional slowing down to establish the spatial profile of fast electrons and hence the local fast electron density and current. This competition of confinement vs slowing down is particularly critical in schemes where localized control of the current profile is desired (e.g. for reasons of plasma stability). A separate, but related, practical reason necessitating an understanding of energetic electron confinement is in the context of runaway production during major disruptions in a tokamak reactor plasma. Runaways are a concern because of the damage they cause to plasma facing components. It is believed that runaway electrons are produced by parallel electric fields during an MHD disruption. The ultimate energy attained by these runaways is a function of their confinement time in the vicinity of the accelerating fields. Finally, when regions of stochastic magnetic fields exist in a tokamak, it has been shown[51,52] that fast electron transport provides a useful diagnostic of the magnetic fluctuations, and is therefore important to characterize the turbulence conditions in a tokamak.

In previous work, done in collaboration with TEXT group, it was shown that TEXT data was consistent with the idea that magnetic fluctuations control runaway but not thermal electron transport near the edge.[51,53,54] These results were obtained by deriving expressions for the transient response of the runaway flux (technically the hard x-ray flux produced by the runaways) to various edge perturbations. In a related, but separately funded study[55] under a Small Business Innovative Research (SBIR) grant, the sawtooth crash was employed as an internal perturbation which could be used to determine the ratio of thermal to fast electron transport. Again, with certain caveats, it was concluded that data was consistent with magnetic fluctuations controlling runaway but not thermal electron transport.

In all of the above studies, the diffusion of fast electrons could be related to the magnetic fluctuation levels in the plasma once the effect of drifts on runaway diffusion had been calculated. As pointed out by Mynick et al,[52] for sufficiently energetic electrons and sufficiently small turbulent scale lengths, finite orbit width corrections act to reduce the net diffusion. Although the results of our calculations[56] had been mostly consistent with the original work of Mynick et al.[52] a small discrepancy remained which has now been fully reconciled in a joint publication.[57] Specifically, this recently completed work notes the relevance of a previously unexplored inequality which involves the spectral width of the turbulence relative to a finite Larmor radius parameter. The original works[52,6] treated two different limiting cases of this parameter.

Although much progress has been made by employing runaway electrons as test particles in these transport studies, a fundamental difficulty that remains is the lack of an accurate knowledge of the "equilibrium" spatial and velocity space distribution of the fast electrons.[53] This is a consideration of some importance because this equilibrium provides the source distribution in transient response transport experiments.[51,53,54] This deficiency has motivated the development of an analytic model for the runaway distribution function in the presence of spatial diffusion, acceleration by the tokamak electric field and Coulomb collisions. An equation for the one dimensional distribution function $f(v_{||})$ (velocity parallel to B) has been derived and solved in terms of parabolic cylinder functions which are matched smoothly to a Maxwellian f at low velocities by means of a WKB technique. The theory includes the usual critical speed at which drag and acceleration balance[58] as well as a characteristic velocity of the highest energy runaways for which spatial confinement and acceleration balance.[59] In addition to improving our interpretation of transient response experiments, the results are expected to be useful in understanding the long time scale evolution of runaways, and in pellet ablation studies by fast electrons[60] where a better knowledge of the runaway distribution is also required. A technical report describing this work is in progress.

D. Diffraction Effects for Focussed Electromagnetic Waves

Most quantitative analyses of electromagnetic wave propagation in plasmas are formulated using the geometric optics or equivalently the ray approximation description. This formalism is very powerful, giving tremendous insight into complicated wave propagation problems in inhomogeneous magneto-plasmas. This technique has several important limitations however; it requires not only long wavelengths compared to the background medium's inhomogeneity scale lengths but additionally the waves must satisfy the condition that focal lengths are long compared to propagation distances of interest. This latter condition is typically violated because focussed wave energy deposition is usually desirable and thus focal lengths are inherently smaller than or comparable to system size. Additionally ray tracing solutions are sometimes known to self focus, or develop a caustic, and here again the geometric optics method breaks down. In both instances diffraction effects must be retained. Additionally, a geometric optics treatment of fluctuation scattering of the propagating waves is inherently incomplete because broadening of a narrow beam is commonly dominated and limited by diffraction effects.

In all of these mentioned cases diffraction effects must be retained for a quantitatively correct description of wave propagation. These diffraction modifications are essential for determining energy deposition profiles, scattering volumes, and the scattered signal details for long wavelength resonant plasma wave detection schemes. While determination of these modifications requires solving second order partial differential equations for the electric field amplitude, these reduced equations have averaged out the short scale length behavior and hence usually have rapidly converging numerical solutions.

We have formulated the complete explicit set of equations which retain all of the terms needed to correctly describe diffraction effects of electromagnetic waves in a general background linear medium where the WKB conditions are satisfied. These equations are expressed in terms of functionals of the medium's dielectric tensor and the amplitude of electric field and hence have general applicability to hot plasmas. For special, but realizable, boundary conditions we have shown that the general diffraction solutions are straightforward generalizations of ray solutions. However, as these equations and special solutions can be algebraically complicated as examples we have considered the case of cold magnetoplasma propagation and study the diffraction effects on X and O mode gyrotron propagation in modeled inhomogeneous equilibrium plasmas.

A DOE report on this work to be submitted to The Physics of Fluids is in final stages of preparation[61] and will be completed before the end of this contract period.

E. Ignitor ICRF Antenna Design Studies

The Ignitor machine can optimally use ICRF for maintaining MHD stability during the current and field ramping and increase the fusion reactivity early in the ramp to save valuable volt-seconds in an ignition sequence. Additionally ICRF advanced tokamak scenarios can give the device enhanced flexibility to explore the physics of $Q_{fusion} \lesssim 5$ regimes. To identify possible critical issues for the Ignitor ICRF antennas Lodestar took on the job of investigating the then existing designs and using the newest state of the art physics and design guidelines recommended changes in the machine to maximize its rf characteristics. We were ably aided by J. Jacquinot of JET and P. Colestock of Fermi Lab in this endeavor. The effort resulted in a completely new antenna/Faraday screen design with an attendant change in the port configuration to accommodate the increased rf coupling considerations. These features have been incorporated into the Ignitor design and as such have given great confidence to the major role that Ignitor can play in the international fusion energy program.

F. Boulder ICRF Antenna Design Workshops

Every year during this contract Lodestar has sponsored a workshop emphasizing the newest experimental and theoretical design considerations. These workshops have successfully brought together a significant fraction of the world's ICRF expertise to update, in detail, the ICRF design data base. The 1993 workshop specialized in Ignitor design issues and found no show stoppers. A detailed program to finalize the design was recommended to DOE.

G. References

1. J.-M. Noterdaeme, in Proceedings of the Ninth Topical Conference on Radio Frequency Power in Plasmas, Charleston, S.C., (AIP, New York, 1992), p. 71.
2. F. W. Perkins, Nucl. Fusion **29**, 583 (1989) .
3. R. Chodura and J. Neuhauser, in Controlled Fusion and Plasma Heating, Proc. 16th European Conf., Venice, Vol. **13B**, Part III, 1089 (1989).
4. J. R. Myra , D. A. D'Ippolito , and M. J. Gerver Nucl. Fusion 30, 845 (1990).
5. R. Van Nieuwenhove, Doctoral Thesis, University of Antwerp (1989); R. Van Nieuwenhove and G. Van Oost, J. Nucl. Mater. **162-164**, 288 (1989).
6. D. A. D'Ippolito, J. R. Myra , M. Bures, M. Stamp, and J. Jacquinot, in Proceedings of the IAEA Technical Committee Meeting on ICRH/Edge Physics, Garching, published in Fus. Eng. and Design **12**, 209 (1990).
7. M. Brambilla, R. Chodura, J. Hoffmann, J. Neuhauser, J.-M. Noterdaeme, R. Ryter, R. Schubert, and F. Wesner in Proc. 13th IAEA Conf. on Plasma Phys. and Contr. Nuclear Fusion Res., paper IAEA-CN--53/E-2-5 (1990).
8. D. A. D'Ippolito, J. R. Myra , M. Bures, J. Jacquinot , and M. Stamp in Proc. 13th IAEA Conf. on Plasma Phys. and Contr. Nuclear Fusion Res., paper IAEA-CN-53/E-3-1-1 (1990).
9. D. A. D'Ippolito, J. R. Myra, M. Bures, and J. Jacquinot, Plasma Phys. Contr. Fusion **33**, 607 (1991).
10. M. Bures, J. Jacquinot, K. Lawson, M. Stamp, H. P. Summers, D. A. D'Ippolito, and J. R. Myra , Plasma Phys. Contr. Fusion **33**, 937 (1991).
11. M. Bures, J. Jacquinot, M. Stamp, D. Summers, D.F.H. Start, T. Wade, D. A. D'Ippolito, and J. R. Myra , Nucl. Fusion **32**, 1139 (1992).
12. R. Van Nieuwenhove and G. Van Oost, Plasma Phys. Contr. Fusion **34**, 525 (1992).
13. R. Majeski et al., in Proceedings of the Ninth Topical Conference on Radio Frequency Power in Plasmas, Charleston, S.C., (AIP, New York, 1992), p. 322.
14. D. A. D'Ippolito, J. R. Myra, J. Jacquinot, and M. Bures, in Proceedings of the Ninth Topical Conference on Radio Frequency Power in Plasmas, Charleston, S.C., (AIP, New York, 1992), p. 177; the JET team, presented by J. Jacquinot, Plasma Phys. and Contr. Fusion **33**, 1657 (1991).
15. D. A. D'Ippolito, J. R. Myra, J. Jacquinot, and M. Bures, in Proc. 14th IAEA Conf. on Plasma Phys. and Contr. Nuclear Fusion Res., paper IAEA-CN-56/E-3-9 (1992); Lodestar report #LRC-92-34 (1992), submitted to Phys. Fluids.
16. J. Jacquinot, presented at the Sixth Boulder Workshop on High Power ICRF Antenna Design and Physics, January 20-22, 1993.

17. D. D'Ippolito and J. R. Myra, presented at the Sixth Boulder Workshop on High Power ICRF Antenna Design and Physics, January 20-22, 1993.
18. D. A. D'Ippolito and J. R. Myra, presented at the 10th Topical Conference on Radiofrequency Power in Plasmas, Boston, Massachusetts, April 1-3, 1993.
19. W. Engelhardt and W. Feneberg, J. Nucl. Mater. **76 & 77**, 518 (1978).
20. D. E. Post, R. V. Jensen, C. B. Tarter, W. H. Grasberger, and W. A. Lokke, Atomic Data and Nucl. Data Tables **20**, 397 (1977).
21. M. Bures, private communication.
22. M. Bures, D. J. Campbell, N. A. C. Gottardi, J. J. Jacquinot, M. Mattioli, P. D. Morgan, D. Pasini, and D. F. H. Start, Nucl. Fusion **32**, 539 (1992).
23. V. P. Bhatnagar et al., in Proceedings of the Ninth Topical Conference on Radio Frequency Power in Plasmas, Charleston, S.C., (AIP, New York, 1992), p. 115.
24. R. J. Groebner, K. H. Burrell, and R. P. Seraydarian, Phys. Rev. Lett. **64**, 3015 (1990); R. J. Groebner et al., in Proc. 13th IAEA Conf. on Plasma Phys. and Contr. Nuclear Fusion Res., paper IAEA-CN-53/A-6-4 (1990).
25. R. R. Weynants et al., in Proc. 13th IAEA Conf. on Plasma Phys. and Contr. Nuclear Fusion Res., paper IAEA-CN-53/A-6-6 (1990).
26. Y. Miura et al., in Proc. 13th IAEA Conf. on Plasma Phys. and Contr. Nuclear Fusion Res., paper IAEA-CN-53/A-4-6 (1990).
27. M. Bures, K. Avinash, H. Brinkschulte, G. Devillers, J. Jacquinot, S. Knowlton, A. Pochelon, D. Start, J. Tagle, Bul. APS **33**, 2032 (1988).
28. J.A. Tagle, M. Laux, S. Clement, S.K. Erents, H. Brinkschulte, M. Bures, and L. DeKock, Fusion Eng. Des. **12**, 217 (1990).
29. J.V. Hofmann, et al., Fusion Eng. Des. **12**, 185 (1990).
30. E. Berro, B. Fried, D. Holland, G. Morales, presented at the First Boulder Workshop on ICRF/Edge Physics, March 30 - April 1, 1988 (unpublished).
31. F.W. Perkins, Bull. Am. Phys. Soc. **34**, 2093 (1989) paper 6S6.
32. J.R. Myra and D.A. D'Ippolito, presented at the Fifth Boulder Workshop on High Power ICRF Antenna Design and Physics, April 9-11, 1992.
33. J.R. Myra and D.A. D'Ippolito, presented at the 10th Topical Conference on Radiofrequency Power in Plasmas, Boston, Massachusetts, April 1-3, 1993.
34. T. H. Stix, Nucl. Fusion **15**, 737 (1975).
35. P. J. Catto and J. R. Myra, Phys. Fluids **B4**, 187 (1992).
36. P. J. Catto, J. R. Myra and D.A. Russell, Lodestar Research Corporation Report LRC-92-36 (December 1992); submitted to Phys. Fluids.
37. I. B. Bernstein and D. C. Baxter, Phys. Fluids **24**, 108 (1981).
38. M. E. Mauel, Phys. Fluids **27**, 2899 (1984).

39. D. Anderson, M. Lisak, and L.-O. Pekkari, Phys. Fluids **28**, 3590 (1985).
40. G. Kerbel and M. McCoy, Phys. Fluids **28**, 3629 (1985).
41. G. W. Hammett, Ph.D. dissertation, Princeton University, 1986.
42. The JET Team (presented by D. F. H. Start), in Plasma Physics and Controlled Nuclear Fusion Research 1990 (IAEA, Vienna, 1991), Vol. 1, p. 679; and D. F. H. Start, et al. , in Plasma Physics and Controlled Nuclear Fusion Research 1988 (IAEA, Vienna, 1989), Vol. 1, p. 593.
43. J. Jacquinot, V. Bhatnagar, H. Brinkschulte, M. Bureš, S. Corti, G. A. Cottrell, M. Evrard, D. Gambier, A. Kaye, P. P. Lallia, F. Sand, C. Schueller, A. Tanga, K. Thomsen, and T. Wade, Philos. Trans. Roy. Soc. London, Ser. A322, 3 (1987); and The JET Team - presented by J. Jacquinot, Plasma Phys. and Controlled Fusion, **30**, 1467 (1988).
44. J. C. Hosea, et al., in Plasma Physics and Controlled Nuclear Fusion Research 1990 (IAEA, Vienna, 1991), Vol. 1, p. 669; and J. R. Wilson, et al., in Plasma Physics and Controlled Nuclear Fusion Research 1988 (IAEA, Vienna, 1989), Vol. 1, p. 691.
45. PLT Group, in Proceedings of the 12th European Conference on Controlled Fusion and Plasma Physics (E.P.S., Budapest, Hungary, 1985), Vol. 9F, Part 2, p. 120; and D. Q. Hwang, J. Hosea, H. Thompson, J. R. Wilson, S. Davis, D. Herndon, R. Kaita, D. Mueller, S. Suckewer, C. Daughney and C. Yamanaka Phys. Rev. Lett. **51**, 1865 (1983).
46. D. G. Swanson, Phys. Fluids **28**, 2645 (1985) and references therein.
47. D. W. Faulconer, Plasma Phys. Controlled Fusion **29**, 433 (1987).
48. D. Smithe, P. Colestock, T. Kammash and R. Kashuba, Phys. Rev. Lett. **60**, 801 (1988).
49. S.-I. Itoh, A. Fukuyama, K. Itoh, and K. Nishikawa, J. Phys. Soc. Jpn. **54**, 1800 (1984).
50. P.J. Catto, C.N. Lashmore-Davies and T.J. Martin, submitted to Phys. Fluids.
51. J.R. Myra, P.J. Catto, A.J. Wootton, R.D. Bengtson and P.-W. Wang, Phys. Fluids. **B4**, 2092 (1992).
52. H.E. Mynick and J.D. Strachan, Phys. Fluids **24**, 695 (1981); H.E. Mynick and J.A. Krommes, Phys. Fluids 23, 1229 (1980); H.E. Mynick and J.A. Krommes, Phys. Rev. Lett. **43**, 1506 (1979); R.E. Duvall, Ph. D. thesis, Princeton Univ., 1990.
53. P.J. Catto, J.R. Myra, P.W. Wang, A.J. Wootton, and R.D. Bengtson, Phys. Fluids **B3**, 2038 (1991).

54. R.D. Bengtson, M.R. Freeman, G.G. Castle, K.W. Gentle, S.C. McCool, A.J. Wootton, P.J. Catto, J.R. Myra, H.E. Mynick, P.-W. Wang, in Plasma Physics and Controlled Nuclear Fusion Research 1992 (IAEA, Vienna, 1993), paper IAEA-CN-56/A-7-18; R.D. Bengtson, M.R. Freeman, A.J. Wootton, P.-W. Wang, J.R. Myra, P.J. Catto, Rev. Sci. Instr. **63**, 4595 (1992).
55. P.J. Catto, J.R. Myra, R.D. Bengtson, A.J. Wootton, Phys. Fluids **B5**, 125 (1993).
56. J.R. Myra and P.J. Catto, Phys. Fluids **B4**, 176 (1992).
57. J.R. Myra, P.J. Catto, H.E. Mynick and R.E. Duvall, Phys. Fluids **B5**, 1160 (1993).
58. R.M. Kulsrud et al., Phys. Rev. Lett. **31**, 690 (1973); J.W. Conner and R.J. Hastie, Nucl. Fusion 16, 415 (1975); R.H. Cohen, Phys. Fluids 19, 239 (1976).
59. C.S. Liu and Y. Mok, Phys. Rev. Lett. **38**, 162 (1977).
60. S.C. McCool, G.C. Castle, et al. Cont. Fusion and Plasma Phys. **15C**, I, 325 (1991).
61. R. E. Aamodt, "Diffraction Effects for Focussed Electgromagnetic Waves in a Plasma," Lodestar Research Corporation Report # LRC-93-40, to be submitted to Phys. Fluids.

END

DATE FILMED

6/3/93