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FINAL REPORT FOR DOE GRANT NO. DE-FG02-88ER53263

Project Title:	Fundamental Studies of Fusion Plasmas
Principal Investigator:	Richard E. Aamodt
Period Covered by Report:	11/1/93 through 10/31/97
Date of Report:	January 30, 1998
Recipient Organization:	Lodestar Research Corporation 2400 Central Ave., P-5 Boulder, CO 80301
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DISCLAIMER

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I. EXECUTIVE SUMMARY

In the past four years, Lodestar has carried out a vigorous research program in the areas of rf, edge plasma and divertor physics. In accordance with the DOE priority during these years on fusion energy development, Lodestar's emphasis was largely geared towards improving the understanding and performance of ion-cyclotron heating and current drive (ICRF) systems. Additionally, a research program in the field of edge plasma and divertor modeling was initiated.

Much of the ICRF work focused on the important question of understanding and learning how to mitigate potentially deleterious edge-plasma interactions. Theoretical work on high power rf sheath formation for multi-strap rf arrays was developed and benchmarked against recent experimental data from the new JET A2 antennas. Sophisticated modeling tools were employed to understand the sheath formation taking into account realistic three-dimensional antenna geometry. A novel physics explanation of an observed anomaly in the low power loading of antennas was applied to qualitatively interpret data on DIII-D in terms of rf sheaths, and potential applications of the idea to develop a near-field sheath diagnostic were explored. Several theoretical mechanism of far-field rf sheath formation were developed for application to situations with poor single rf absorption. A number of additional mechanisms for edge power absorption in these low absorption cases were examined in the context of DIII-D current drive experiments. Finally, in ongoing work, the perplexing JET data on poor heating efficiency in some low wavenumber phasing experiments was tentatively explained in terms of edge interactions involving far-field rf sheaths. ICRF edge physics and IBW experiments on TFTR were also supported, but under a separate grant.

Other rf-wave related topics were also investigated. Full wave ICRF modeling studies were carried out in support of ongoing and planned tokamaks experiments, including the investigation of low frequency plasma heating and current drive regimes for IGNITOR. In a cross-disciplinary study involving both MHD and ICRF physics, ponderomotive feedback stabilization by rf was investigated as a potential means of controlling external kink mode disruptions. In another study, the instability of the ion hybrid wave (IHW) in the presence of fusion alpha particles was studied. This work showed that external driving of the IHW in the context of alpha-channeling may be enhanced on time scales small compared to slowing-down times by an anisotropic and/or population-inverted velocity-space distribution of immediate post-birth alphas. Finally, a formalism for extending the eikonal approximation to treat rf diffraction effects was developed and shown to be important for highly focused ECH beams.

In the field of edge plasma and divertor modeling studies, Lodestar began the development of a theory of generalized ballooning and sheath instabilities in the SOL of divertor tokamaks. This ongoing work began as a natural follow-on to the rf-motivated sheath studies. Preliminary investigations of the effect of neutrals on SOL stability have also been undertaken. In a separate study, which was also a natural follow-on to the work on rf-driven convection, a simple model for SOL profile modifications by convective cells was formulated in which the interaction of convection and diffusion was treated. In collaboration with MIT, sophisticated codes for kinetic divertor modeling have been developed and applied to experiments to fill a large gap in physics that cannot be addressed by the fluid codes in current usage by the divertor modeling community.

A detailed summary of our technical progress in these areas during the contract period is included in the following sections, where references to our published work can also be found. A separate listing of publications, meeting abstracts, and other presentations is also given at the end of this final report.

II. THEORETICAL ISSUES FOR RF PHYSICS

A. Instability of the Ion Hybrid Wave in the Presence of Fusion Alpha Particles†

We used a simple model distribution function for the alpha particles to investigate the stability of the ion hybrid wave (IHW) in a deuterium-tritium plasma.[1] The stability of the ion hybrid wave is relevant to the alpha-channeling proposal[2] and to ion cyclotron emission[3] observed from fusion products in JET and TFTR.

The possibility of channeling some portion of the energy available in fusion-born alpha particles back to the reactant ions in order to achieve enhanced fusion reactivity[4] and/or enhanced confinement by improved current drive[5] is an exciting fresh topic in the fusion community nowadays. In the usual formulation of the problem, an externally driven wave serves as the conduit: having been amplified by the alphas, the wave propagates into a region of increasing absorption by reactant ions and deposits its energy remotely or the wave is simply damped by the ions even as it is amplified by fusion alphas, thus catalyzing the fusion reaction *in situ*. In either case, sustained population inversion of the alphas in space (more high-energy alphas at the core than at the edge) has been invoked[6] to drive the wave amplification. We have demonstrated the feasibility that, on time scales small compared to slowing-down times, external driving of the candidate wave may be enhanced by an anisotropic and population-inverted velocity-space distribution of immediate post-birth alphas.

We considered an infinite homogeneous plasma with equal concentrations of deuterium and tritium. Both of the ion species and the electrons were given isotropic Maxwellian distributions in velocity space. A small population of alpha particles, typically 1% of the electron concentration, was assigned the following highly anisotropic ("barrel-hoop") velocity space distribution function.

$$f_{o\alpha} = \left(2\pi^{3/2} v_{\perp 0} v_{T\parallel\alpha}\right)^{-1} \exp\left\{ -\left(v_{\parallel} - v_d\right)^2 \Big/ v_{T\parallel\alpha}^2 \right\} \delta\left(v_{\perp} - v_{\perp 0}\right)$$

Such a highly nonthermal distribution of alpha particles is relevant to their condition before they have slowed down and to the behavior of large-excursion orbit alpha particles which give rise to ion cyclotron emission in the edge region of a tokamak. Our results are most relevant to the alpha-channeling application for which it is appropriate to take $v_d = 0$ and $v_{T\parallel\alpha} \lesssim v_{\perp 0}$. (For the ion cyclotron emission study a non-zero value of v_d is assumed.) Parameters were chosen to be typical of the TFTR plasma, and we sought instability in the complex-ω plane for real-k.

The dielectric tensor elements implied by this distribution function are well known. We have studied the full 3x3 electromagnetic dispersion relation and compared it with the far simpler dispersion relation, commonly adopted, which results from the neglect of the parallel electric field. We found that the latter approximation is not well justified in general, but does allow an algebraically tractable perturbation expansion in the alpha particle density that makes explicit, for example, the coupling of the IHW with the compressional Alfvén wave. We found that instability is obtained well away from this coupling for fusion-reactor parameters.

Based on the analytic approximation to the dispersion relation we were able to identify a parameter regime for which the destabilizing effects of the alpha particles on the IHW were maximized. This came from recognizing two classes of terms in the above mentioned perturbation expansion, one provoking instability in the same sense as an isotropic delta-shell distribution and the other related to the instability caused by an anisotropic distribution and similar to the Alfvén ion cyclotron instability. Both types of destabilizing effect can operate simultaneously in the present case, and demanding this gave us a good approximation to the most unstable regimes in parameter space. We have studied these regimes numerically using the full 3x3 electromagnetic dispersion relation.

We showed that the IHW can indeed be driven unstable by immediate post-birth alpha particles so modeled, with maximum growth rates of O(10) kHz for parallel wavelengths of the order of 1 meter and longer, and perpendicular wavelengths on the order of 1 cm, in a regime where the IHW frequency is about 23 MHz, for parameters typical of TFTR. For the most unstable waves, instability is observed in bands of $k_\perp$-values, owing to the J-type Bessel functions that occur in the dispersion relation thanks to the barrel-hoop distribution function.

The discovered instability suggests an *internal* enhancement of driven-wave amplification for early times. (An externally driven wave would be more effective than an internally excited wave since it could operate at a higher amplitude and so channel alpha-particle energy at a greater rate.) Our work provides some guidance on the conditions required to amplify a driven wave or just to ensure that energy flows from the alpha-particles to the wave even if, overall, the wave is damped. (To determine this latter property it was necessary to identify the irreversible reduction of alpha particle kinetic energy, i.e., alpha cooling.)

Since we were working solely with the dispersion relation in a homogeneous plasma we did not address the question of whether such an internally amplified wave might damp on reactant ions remotely. The implications of a spatially-localized region of amplification sustained by a superthermal distribution of alpha particles has yet to be explored, to our knowledge. Our work to date suggests some interesting possibilities. For example, in the homogeneous plasma and for equal concentrations of deuterium and tritium, the IHW is most unstable near a hybrid frequency lying midway between Ω_T and Ω_D, well removed from cyclotron absorption by either reactant ion. With increasing $k_\perp$ the IHW frequency moves toward Ω_T for larger values of $k_{//}$ and toward Ω_D for smaller values and so is eventually stabilized by cyclotron absorption, suggesting the possibility of preferentially heating one or the other reactant species remotely by tuning $k_{//}$ at the antenna. This might be used to compensate the fusion cross section for an imbalance in reactant ion number densities. To investigate this possibility properly it is necessary to study the IHW characteristics in the inhomogeneous plasma, a problem we will study in the near future.

†Work done in collaboration with C. N. Lashmore-Davies, UKAEA Government Division, Fusion, Culham, Abingdon, Oxon, OX14 3DB, UK (UKAEA/Euratom Fusion Association).

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B. Fermi acceleration and parasitic heating of edge electrons by ICRF antennas

A theory of electron interaction with rf fields in the vicinity of conducting surfaces has been developed under the present contract, and applied to ICRF heating experiments on TFTR under a separately funded study. In the Boltzmann regime we recover the usual process of rf rectification, and its associated impurity release and convective cell generation, which we have studied previously. In the opposite limit, ponderomotive effects enter, and the rectification effect is reduced. In the transition region, the Fermi acceleration kick that the electrons receive from each interaction with the sheaths is computed and shown to yield strong electron heating. For TFTR, different field lines span the different regimes and the resulting heating mechanism is shown to provide a candidate explanation of observed glows on the antennas.[1]

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C. Edge Power Dissipation and Cavity Q for ICRF Eigenmodes

The central absorption of ICRF wave power in a tokamak can be weak due a variety of reasons. In the past, the smaller size and lower central density of confined plasma usually made good single pass absorption difficult, if not impossible. Present day and future generation machines are relatively large and dense, so that good absorption is generally possible for efficient heating scenarios. However, the importance of exploring new regimes of ICRF heating, and most importantly, current drive, often necessitate operation in regimes where the absorption per pass is small. In these cases, power dissipation at the edge must be examined as a possible competitive mechanism to central absorption. In general, power dissipated at the edge is not useful, and can be damaging to the first wall and ultimately the central plasma (through increased impurity radiation). The considerations motivate a treatment of ICRF edge dissipation processes.

In this work,[1] a number of edge dissipation mechanisms were surveyed, including wall resistivity, Coulomb and neutral collisions, parametric decay, and dissipation by far-field sheaths. Our work was motivated by current drive experiments on DIII-D which showed an anomalous loss of wave energy at the edge of about 4% per pass.[2] The results can be characterized in one of two equivalent ways: by the effective contribution to the cavity Q due to a specific process, or by the single pass absorption fraction that a ray would experience on a bounce through the edge region,

$$A_{sp} = \omega\tau/Q = \pi\nu/Q$$

where ω is the rf wave frequency, τ is the time for wave propagation across the minor radius of the tokamak, and ν is the radial mode number of the eigenmode. For weak dissipation ($A_{sp} << 1$), the A_{sp}'s and the Q^{-1}'s are additive for various dissipation processes, and the power loss per process is $P_j = PQ/Q_j$.

In low single pass current drive experiments, the edge power absorption determines the effective number of single passes a ray experiences before it is too weak to matter. Thus, when theoretically expected central absorption falls below a certain threshold level (typically of the order the edge absorption) the (heating or current drive) scenario becomes of limited use. To be more explicit, even if A_{sp} is small, say $A_{sp} \sim 4\%$, when central absorption is of the same order, then the ICRF power deposition for an eigenmode can be expected to be split between the core and edge roughly 50%-50%, resulting in significant power loss to the edge.

In the following we briefly summarize the results for A_{sp} and Q, for the five edge dissipation processes considered, using illustrative parameters from the DIII-D experiment.

Coulomb collisions

Both ion-electron and ion-ion collisions were considered. For ion-ion collisions, dissipation of an ICRF wave is not possible unless finite Larmor radius effects are retained.[3] Thus, ion-ion collisional dissipation tends to be small. Estimating the local damping decrement by $\gamma \sim \nu_{ii}(k_\perp \rho_i)^2$ we obtain $Q = \omega V/2\gamma V_{edge}$ where $V/V_{edge} = 2\Delta r/a$ is the fractional volume where collisions are significant. Our estimates show that for the DIII-D experiment ion-ion collisions are negligible, resulting in a Q_{ii} that exceeds 2×10^7, so further attention was not paid to this process.

For ion-electron collisions, we began out analysis with momentum moment of the ion kinetic equation, to obtain the current and hence the ion dielectric response, including collisions. Upon using conservation of total (i-e) momentum, and combining with the electron response, we obtained the collision form of the dielectric tensor relevant to ICRF propagation in the edge. Particularly simple and intuitive forms were found in the high frequency limit $\omega >> \Omega_i$ (where Ω_i is the ion cyclotron frequency), a regime relevant to the electron current drive experiments. In these cases, it was shown that the dominant modification to the conductivity is given by

$$\sigma \rightarrow \sigma + \frac{\nu_{ie}}{\Omega_i} \sigma \times \mathbf{b},$$

resulting in a enhanced local damping rate $\gamma = -\nu_{ie}\omega^2/2\Omega_i$.

Our esimates for ion-electron edge dissipation in DIII-D were shown to result in

$$Q_{ie} \sim 9.8 \times 10^3, A_{sp,ie} = 0.6\%.$$

Far field sheaths

To explore the relevance of the far field sheath mechanism[4] to edge power dissipation, a new analytical model of power balance in an rf sheath was developed. The model was employed both in the present work, and in the section of low power rf loading (where power dissipation in near field antenna sheaths was considered).

In this model, we calculated the electron and ion fluxes flowing into the sheath as a function of applied rf voltage. The time averaged particle flux was employed to obtain the usual sheath rectification effect[5] by applying quasineutrality. The particle and heat fluxes were then employed to obtain expressions for the sheath energy transmission factor in the presence of rf, and the power dissipated in the sheath. It was shown that a good approximation to the latter is

$$P = A n_e c_s T_e \, z I_1(z)/I_0(z),$$

where n_e is the presheath density, c_s the sound speed, T_e the presheath electron temperature, and $z = eV_0/T_e$, where V_0 is the applied rf voltage. Furthermore, an energy balance relation was constructed showing that the heat flux from the presheath, plus the above sheath power appears as particle fluxes at the material surfaces.

Far field sheaths (FFS) are sheaths that form on the walls and limiters of the tokamak due to wave energy at the plasma edge. Normally, the parameters are such that $eV_0/T_e << 1$ for far field sheaths, and small z expansion of P may be employed. This results in $P \sim z^2 \sim |E_{fw}|^2$ and hence leads to a Q_{FFS} that is approximately independent of power, and given in order of magnitude by

$$Q_{FFS} = \frac{\pi^2 a R c^2 T_e R_\psi}{8 n_e c_s e^2 w^2 \omega h^2 \lambda_n f_{rf}},$$

where a is the minor radius, R is the major radius, $R_\psi \leq 1$ describes the degree of edge evanescence, w and h are the poloidal and radial scale lengths of the flux surface to wall mismatch causing the far field sheaths,[4] λ_n is the density gradient scale length in the

SOL, and f_{rf} is the fraction of the edge exposed to rf. Our estimates for this mechanism in DIII-D imply one of the largest dissipations of all the edge mechanisms considered,

$$Q_{FFS} \sim 2.6 \times 10^3, A_{sp,FFS} = 2.3\%.$$

Other mechanisms

Other edge dissipations mechanisms have also been considered; however, in the interest of brevity a detailed description will not be presented here. These additional mechanisms include: ion and electron collisions with neutrals, (i.e. charge exchange, and electron impact excitation and ionization), classical resistive wall, and the parametric decay instability (PDI). Regarding PDI, it was estimated that PDI instability thresholds can probably be met in front of the antenna, but probably will not be met for waves reflecting off of the edge plasma, and thus the PDI would not impact Q or A_{sp} for eigen-modes. In cases where the PDI threshold is exceeded in the far field, estimates of Q or A_{sp} are exponentially sensitive to parameters and lead to the conclusion that the mechanism has a tendency to either be totally negligible or totally dominant (leading to pump depletion).

Summary

Our results indicate that of all the edge dissipation mechanisms examined to date, the dominant ones are likely to be ion-electron collisions, far field sheaths, and wall resistivity. The following table summarizes our estimates for DIII-D.

mechanism	A_{sp} (%)
ion-electron collisions	0.6
far field sheaths	2.3
ion-neutral collisions	0.01
wall resistivity	0.2
theoretical total	3.1
experimental	4

Thus, it appears that far-field sheaths may be the biggest contributor to the edge damping observed (inferred) from the DIII-D current drive experiments in the low single pass regime, but the uncertainty of the far-field sheath estimates is also largest. The best estimates to date predict a single pass edge damping of a few percent for the far-field sheath mechanism, consistent with what GA found was necessary to model the edge losses in the experiment.[2] More generally, our theoretical estimates indicate that edge dissipation processes do not result in substantial rf power dissipation except in very low single pass absorption cases.

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D. Three Dimensional Analysis of Antenna Sheaths

It is by now well established that Ion Cyclotron Range of Frequency (ICRF) systems can heat fusion plasmas for a wide range of physics heating scenarios,[1] and efforts are well under way to employ ICRF systems for driving steady state current in tokamaks.[2] Experience has shown that while ICRF systems can be made robust and effective, attention must be paid to certain critical ICRF - edge interaction issues. Experiments have shown that under adverse conditions, ICRF systems can lead to increased impurity injection from the antennas and/or their limiters into the plasma,[3] the formation of "hot spots" and arcs on the antenna surface,[4] excessive power dissipation at the edge,[4] nonlinear loading[5] (i.e. loading that is a function of power), and modifications of the scrape off layer (SOL) plasma.[6] Many of these issues, while present in ICRF heating configurations, are expected to be even more critical for extended current drive arrays, which fill a substantial fraction of the SOL volume, and for which anti-symmetric (dipole, or 0-π) phasing cannot be employed. Furthermore, recent developments in the ICRF launcher design for ITER suggest that there will be a need for "in-port" designs capable of handling high voltages and power densities without breakdown, or severe impurity problems.

The importance of rf sheaths in determining the antenna - plasma interaction and the sensitivity of these sheaths to the complicated three dimensional structure of modern Ion Cyclotron Range of Frequency (ICRF) launchers motivated the work to be described below. While the work was mostly funded under a separate Small Business Innovative Research grant, it dovetailed well with ongoing ICRF edge physics investigations funded under the present contract, and in several instances simulated important improvements in our theory of rf sheaths and ICRF antenna - edge physics interactions.

To analyze rf sheaths on the plasma facing regions of the launcher (a conventional ICRF antenna, folded waveguide or combline), we first calculate the contact points of the tokamak magnetic field lines on the surface of the antenna Faraday screen and nearby limiters for realistic three dimensional magnetic flux surface and antenna geometries. Next, the rf voltage that can drive sheaths at the contact points is determined and used to assess the resulting sheath power dissipation, rf-driven sputtering, and rf-induced convective cells (which produce edge profile modification). The calculations are embodied in a computer code called ANSAT, (Antenna Sheath Analysis Tool).[7] One use of ANSAT is as a design tool, to assess the strengths and weaknesses of a given design with respect to critical voltage handling and edge plasma interaction issues. Additionally ANSAT has been useful in the analysis and interpretation of ICRF experiments on TFTR and JET (in progress).

In the course of this work, we also developed a new method for describing the effect of the SOL plasma on the slow waves (SW's) that occur in the vicinity of the Faraday screen (FS). These SW's have a short poloidal scale length (set by the Faraday screen bars) and decay on a scale length characteristic of the electron skin depth, c/ω_{pe}, consequently they are difficult to resolve in 3D antenna codes that use finite differencing techniques. In fact, most antenna codes (ARGUS being one noteable exception) do not treat the detailed structure of the FS at all. For the sheath and plasma interaction studies that are our focus, the SW effects are critical because their polarization drives $E_{\parallel}$, and ultimately the rf sheath voltages. Our method is described in detail in Ref. 7 (Report #LRC-50-DOE/ER/81799-1). It is based on the approximation that the FW radial scale length is long compared to scales of interest for the sheath studies. This allows the total field near the FS to be decomposed into an inert FW and an exponentially decaying SW branch.

Among the theoretical ICRF - edge physics advances stimulated by this work are: an improved method for calculating the particle influx to the Faraday screen (and other complicated plasma facing components) and the resulting sputtering,[7] the realization that flux surface mismatches of the *poloidal* curvature to the antenna face can increase sheath voltages by increasing the field line connection lengths,[7,8] an improved theory and treatment of convective cells[7,9] and of the effect of plasma loading of the antenna on the sheaths,[7] and an understanding of the generally beneficial effects of bumper tiles around and in between currents straps on the plasma facing surfaces.[7]

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E. Scrape-off-layer Profile Modifications by Convective Cells

The existence of convective cells in the SOL is expected to be generic, with drives arising both from low frequency instabilities in the edge plasma and well as by nonuniformities in the equilibrium potential of neighboring SOL field lines. For example, in the equilibrium problem, the potential of magnetic field lines inside the last closed surface (LCS) is established by different physics than lines in the SOL, resulting in radial electric fields and poloidal $\mathbf{E} \times \mathbf{B}$ flows. Furthermore, neighboring field lines in the SOL can have different termination points and sheath boundary conditions (as a function of both radius and poloidal angle) due to the presence of limiters (especially secondary limiters in a diverted plasma) and the irregular shapes of antennas, gas boxes and other hardware in the SOL plasma. Consequently, both radial and poloidal drifts are to be expected.

In the case of the interaction of ICRF with the edge plasma, which we have studied in detail,[1] theory predicts the existence of convective cells (CC's) in front of an antenna, due to the presence of rf-induced sheaths. In this case, the sheaths bias adjacent field lines to different dc potentials, depending of the spatial relationship of the field lines to the antenna box and Faraday screen, and this causes an rf-induced $\mathbf{E} \times \mathbf{B}$ plasma convection. Recently,[2-4] diagnostics of the scrape-off-layer (SOL) density profile in the first few cm's in front of the antenna have shown that high power ICRF can indeed modify the profiles, and this data has stimulated the present work, in which we examine the SOL transport and profile modification induced by both closed and open CC's.

The effect of closed cells on transport has been treated by other authors,[5] where it was shown in an asymptotic limit (large v, and large $L_n \equiv |n/n'|$) that an effective enhanced diffusion coefficient results, viz. $D^* = C\,(vLD)^{1/2}$, where C is a numerical constant, v is a typical convection velocity and D is the background diffusion coefficient. In this project we have examined the combined effect of diffusion and convection on the standard SOL density model. A new treatment is needed because i) L_n is not large compared to L, the dimensions of the cells, ii) end loss must be retained, and iii) we include the effects of both closed and open cells, where the latter have streamlines that connect directly to a wall. The feature of open cells is one which has been shown to be relevant to at least the ICRF application, by detailed analysis of convective patterns predicted by the ANSAT code (see Sec. IID).

Both Monte-Carlo (MC) and analytical techniques have been applied to understand the transport induced in this problem.[6] In the simple diffusive limit (standard SOL model) the MC code was first shown to give excellent agreement with theory. In the limit of strong convection, it was shown as expected, that the density profile is flattened in the region of the closed CC's. The open CC's carry particles directly into the wall, and thus lower the confinement time through the convection dominated region of the SOL ($v > D/L$, where v is a typical CC velocity). This strong pumping action reduces the SOL density and increases the particle flux.

In order to better understand the competition and interaction between convection and diffusion, we have developed a two-branch model[6] which yields a one-dimensional (1D) description of the SOL profiles. The difficulty in describing convection in 1D is that the mean y-averaged (poloidal) flow velocity is zero at each x (radius). To circumvent this, we introduce the notion of two branches (or sheets) for the density function in the CC regions. Calling the density $n_\pm$ on the respective branches, we have the physical density $n \equiv n_+ + n_-$ where $n_\pm$ obeys

$$\frac{\partial n_\pm}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial n_\pm}{\partial x} \mp v n_\pm\right) - \frac{n_\pm}{\tau_\parallel}$$

and $v \sim |v_x|$ is a typical CC velocity. The branches may be thought of as arising from averages over the regions in y where v_x is of one sign; n_+ (n_-) corresponds to right (left) going flow.

Using this two-branch model we have been able to make progress on several fronts. First, the model elucidates the relationship between full convection and the simpler, enhanced D model. It was shown that the two-branch model predicts the existence of two scale lengths which are very disparate in the strong convection limit. On the branch where the convective and diffusive fluxes add (+) the scale length become very long, whereas on the branch where they compete (-), the scale lengths become very short. When CC's are modeled by enhanced diffusion $D^* >> D$ with $v = 0$, the short scale length information is lost.

Second, of more practical importance is the fact that the two-branch model was shown to agree very well with the MC simulations. Consequently, it is suitable for general SOL modeling, and, because it is 1D, it is simple to employ either analytically, or numerically. Using it, we have shown that the particle flux diverted into an antenna (from end loss to a limiter) is a strong function of the distance of the convective cells to the LCS (last closed surface). We anticipate that the model will prove very valuable in analyzing the TFTR experimental data[2,3] in work funded by another contract.

The ICRF applications are of importance for several reasons. The particle flux to the antenna is directly responsible for impurity sputtering and erosion of the Faraday screen, as well as for sheath-induced power dissipation, as discussed in our previous work.[7,8] Also of importance is the fact that when convection modifies the density near the antenna, the loading resistance can change. Thus, the SOL density profile is a critical input to the loading codes employed by the ICRF community.

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F. RF Diffraction

Focusing rf beams to heat, drive currents, and diagnose plasmas in fusion devices is normally described by the geometric optics approximation. We have shown that this approximation is not adequate for highly focused waves, but requires a diffraction operator correction which is anisotropic in magnetized plasmas. This formalism has been evaluated for high frequency, i.e. ECH and microwave scattering systems, and shown to give important corrections to the usual eikonal approximation. Additionally the result is in general agreement with actual tokamak measurements. This diffraction formalism has presently been extended to describe fluctuation scattering of focused rf beams which heretofore have been described only by scattering effects added to the geometric optics approximation.

III. EXPERIMENTAL APPLICATIONS OF RF PHYSICS

A. JET ICRF Sheath Modeling

1. Analysis of Near Field Antenna Sheaths for JET A2 Antenna

Over the past several years, Lodestar has collaborated with both JET (on this contract) and TFTR (on another contract) in the area of ICRF-edge plasma interactions. This work began by studying the rf sheath physics responsible for the observed impurity generation, [1-3] SOL modifications, [4] and reduced heating efficiency[4] during high-power ICRF heating experiments on JET. Recently, on another contract we have developed a quantitative sheath analysis code, ANSAT[5] (see Sec.IID). ANSAT is useful both for quantitative data analysis and for testing the design of ICRF antennas. We have applied this code to analyze the rf sheath distribution on the JET A2 antenna in an effort to help improve its power handling and heating efficiency in 0-0-0-0 ("monopole") and current drive phasings. Operation in monopole phasing is essential to increase the A2 antenna loading sufficiently to allow coupling of the full ICRF power in D-T operation next year. It is also essential for various physics experiments of interest to us and to other ICRF researchers.

The A2 antenna, unlike its predecessors, has had a number of problems. These include limiter hot spots and arcing in various phasings (which limit the antenna voltage and rf power) and greatly reduced heating efficiency in 0-0-0-0 phasing.[6] The phasing dependence of the heating efficiency, and the increased efficiency when the density at the FS is lowered by inserting an additional bumper limiter, are consistent with an rf sheath-related explanation. It is likely that these problems are caused, at least in part, by near-field sheaths forming on the Faraday screen (FS) and poloidal limiter surfaces. In collaboration with M. Bures of JET and P. Ryan of ORNL, we are making quantitative estimates of the effect of the near-field sheaths on the heating efficiency. (We are also investigating the effects of far-field sheaths in collaboration with P. Moroz, as described subsequently.) The idea behind this work is that there is a power dissipation in the rf sheaths given by the product of three factors: the ion flux into the sheaths, the area covered by the sheaths, and the energy gain of the ions in the sheaths. This effect was demonstrated using the old (A1) antenna in reversed-field experiments on JET with monopole phasing, which ensured that the rf sheath potentials were extremely large. In these experiments, the rf sheath power dissipation resulted in a 40% decrease in heating efficiency.[3] A similar effect seems to be happening for the A2 antenna, but now for normal operation in monopole phasing.

The first step in the rf sheath analysis is to obtain the rf fields. These are computed by P. Ryan using the ARGUS 3D antenna code for a model antenna based on the JET A2 flatbed mockup antenna. The ARGUS files describing the antenna structure and rf electric field distribution are input to the ANSAT code which calculates the 3D rf sheath distribution and integrates over the antenna/limiter surface to obtain the sheath power dissipation. This analysis has been carried out for several antenna phasings (0-0-0-0, 0-π-0-π) and with several variations in antenna structure (with and without endplates and flux excluders, etc.) to identify ways of minimizing rf sheaths on the A2 antenna. This work was carried out as part of the JET-ORNL-Lodestar collaboration on ICRF physics in order to help in the re-design of the JET antennas.

This work led to several qualitative and quantitative conclusions. The calculations show that the A2 antenna has larger sheath voltages than was the case for the previous JET antennas, partly because of changes in the antenna design and partly because of the greater mismatch between the antenna and flux surface shape, particularly the mismatch in the poloidal curvature. Other differences which serve to increase the importance of rf sheath effects are the larger number of current straps (4 instead of 2), the reduced loading, and the increased parallel connection length (which increases the density at the FS and hence increases the rf power dissipation for a fixed rf sheath voltage). Our calculations indicate that rf magnetic flux from the radial parts of the feeders and current straps drives large rf sheaths on field lines passing near the corners of the A2 antenna, as was also the case for the TFTR Bay-M antenna.[7] A result which is not yet understood is that the calculated sheath voltage distribution is not affected much by closing off the antenna side-slots with flux excluders. The position of the largest sheath voltages on the JET antenna coincide with the location of the hot spots and arcs on the poloidal limiters. The observed arcing on the poloidal bumper inserted in the middle of the JET antenna has been interpreted as the result of nickel self-sputtering avalanche on a metal plate attached to the limiter mounting. Calculations comparing cases with small and large poloidal curvature mismatch between the plasma and the antenna shapes show that this mismatch greatly increases the sheath voltages and affects the locations of the "hot spots". The results of these calculations have been used in redesigning the JET A2 antenna.

The physics significance of these calculations is that good ICRF coupling without intense edge interactions requires careful matching of the flux surfaces to the antenna, both in terms of radial position and in terms of the flux surface shape (toroidal and poloidal curvatures). One cannot arbitrarily deform the plasma shape for other reasons (MHD stability, neutral beam optimization, etc.) and still expect the ICRF antennas to perform adequately. This physics point must be appreciated in designing the antennas for ITER.

We have also studied the effect of removing the FS on the JET A2 antenna (an experiment proposed for ITER). The sheath analysis for this case showed that removing the screen changes the symmetry of $E_{\parallel}$, the component of the rf electric field parallel to B and therefore increases the rf sheath voltages. (One of the main effects of the FS is to screen out the toroidal component E_z of the rf electric field, which has the opposite toroidal symmetry to the poloidal component E_y.) With a FS, $E_{\parallel}$ has the same symmetry as the poloidal rf field E_y, and the rf sheath voltage $V = \int ds\, E_{\parallel}$ (integrated along the field line between contact points) nearly cancels for anti-symmetric phasings of the current straps (0-π or 0-π-0-π). Without the FS, $E_{\parallel}$ has no definite symmetry and the rf sheath voltages are not so different in 0-0-0-0 and 0-π-0-π phasings. For antennas with many current straps (and hence potentially large sheath voltages), this effect reduces the attractiveness of screenless antenna operation.

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2. Full Wave modeling of ICRF Edge Fields and Far-Field Sheaths in JET

ICRF experiments on JET[1] clearly show that the loading resistance and heating efficiency of the 4-strap antennas are strongly dependent on phasing. At the lower $k_{\parallel}$ phasings, the coupling is good but the heating efficiency is dramatically reduced from the values typical of the higher $k_{\parallel}$ cases. An understanding of the cause of the reduced heating efficiency is important both to the JET program and to the ICRF program generally, because low $k_\parallel$ (quasi monopole) operation is often employed both to increase coupling (hence reduce antenna voltages) and to favor ion heating over electron heating. The important issues of sheaths, parasitic damping and impurities due to the near fields in monopole operation are discussed in the previous section. Here, we consider full wave modeling of the ICRF fields on the scale of the whole tokamak, paying special attention to the possibility of far field sheath (FFS) formation due to the presence of large wave fields in the edge plasma, and the concomitant sheath interactions with walls and limiters. Our goal is to determine whether we can understand the observed anomalous power dissipation that would explain the JET reduced heating efficiency observations.

Using the 3D distribution of rf fields from the ALFA code,[2] we investigated several possible mechanisms relevant to the JET observations. Calculations for various phasings show that the antenna loading resistance decreases as the dominant toroidal mode number increases (in correspondence with JET data). The field distribution is also significantly different for different phasings and suggests strong FFS interactions with walls and limiters for strap phasings corresponding to low toroidal mode numbers.

The basic idea we investigated is that rf wave energy at the plasma edge gives rise to an rf parallel electric field $E_\parallel$ which penetrates the SOL. An equilibrium magnetic field line in the SOL is by definition not closed, but rather contacts limiting surfaces at two contact points. When the rf $E_\parallel$ is integrated between the two contact points, it drives an rf voltage $V = \int ds\, E_\parallel \approx L_\parallel E_\parallel$. If the external electrical circuit between the contacts is complete, the original rf driving voltage V appears in sheaths near the surfaces, while the plasma between the contact points is maintained at an elevated dc potential $V_{dc} \sim 0.6$ V, which can substantially exceed $3T_e$.[3] This rectification effect is responsible both for the near field rf sheath effects[3-6] that have been studied previously, and is also closely related to the rf edge power dissipation[7] for far-field sheaths.

In order to model this physics, the $E_\parallel$ component of the rf field from the ALFA code runs at the last closed surface (LCS) was used to calculate the rf sheath driving voltage $V = \int ds\, E_\parallel$ as a running integral V(s) along various typical field lines. Characteristic values of this voltage could then be used to estimate the power dissipation in far-field sheaths, as discussed below.

It was found that V increases linearly with s for a distance $L_\parallel \sim \pi R$ and then begins to saturate. The characteristic values of V are strongly phasing dependent, e.g. $V_c \equiv V(L_\parallel = \pi R)$ is of order 1-2 KV for 0-0-0-0 phasing while it is only 100-200 V for 0-π-0-π phasing. This work showed that a strong mechanism for edge sheaths in the case of low single pass absorption scenarios on JET was the generation of surface waves by edge mode conversion.[8] Related work was done by Brambilla and coworkers as an explanation of the observed metal impurities in ASDEX.[9] The surface wave mechanism exists in additional to a mechanism for $E_{\parallel}$ generation by geometrical mismatches of the vacuum chamber and flux surfaces (e.g. due to curvature differences and limiters) which was developed under this contract in a previous year.[10] For JET parameters, it would appear that the surface wave mechanism is dominant.

Perhaps the most significant observation from our numerical work is that the computed values of V_c are anticorrelated with the observed heating efficiencies[1] on JET. If power absorption by rf sheaths, P_{sh}, is playing a role, we would expect the heating efficiency H to scale like $H \propto 1 - P_{sh}/P_{rf}$ where P_{rf} is the launched power and $P_{sh} \propto V_c$ is the power dissipated in the far field sheaths (see below). The experimental data shows that H is a minimum for the smallest $k_{\parallel}$, and the theoretical calculations yield the result that V_c is a maximum for the smallest $k_{\parallel}$. Thus, power dissipation in the far-field sheaths may be a plausible mechanism for explaining the JET heating efficiency data.

Sheaths driven by rf fields consume power because, in the high voltage limit, the rf sheath causes a dc plasma-wall potential difference of order $V >> 3\ T_e$.[3] Ions impacting the wall gain an energy of order ZeV, which ultimately comes from the rf wave driving the sheath.[3] It can be shown[7] that

$$P_{sh} = A_{\perp} n_e c_s e \langle V_{dc} \rangle$$

where $A_{\perp}$ is the area of the sheaths projected normal to the flux tubes ($\sim 2\pi a \lambda_n$ with a the minor radius and λ_n the density gradient scale length), n_e and c_s are respectively the edge density and sound speed, and $\langle V_{dc} \rangle$ is the rectified sheath voltage ($V_{dc} \sim 0.6\ V_c$) averaged over the surface of the torus. Employing typical JET SOL parameters ($n_e = 3 \times 10^{12}$ cm^{-3}, $T_e = 50$ eV, $\lambda_n = 2$ cm, and taking as illustrative the cases $V_c = 100$ volts and 1 kV we obtain the very rough order of magnitude estimates $P_{sh} \sim 300$ kW and 3 MW respectively, corresponding to a launched power of 4 MW. These estimates are consistent with significant edge power absorption by far-field sheaths for low $k_{\parallel}$, but negligible edge losses at high $k_{\parallel}$.

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B. Low Frequency Plasma Heating and Current Drive Regimes for Ignitor.

The powerful system of ICRF heating is an essential part of the Ignitor design.[1-3] It allows to shorten substantially the time to ignition and save valuable Volt-sec (up to 6 Vs)[3] of the ohmic current transformer. Also, it allows the attainment of ignition at relatively low plasma current of 10 MA and to obtain high levels of performance at lower than standard fields and currents.[3] An ICRF system with a frequency range, 100 MHz < f < 210 MHz, has been considered in Refs. 1-4.

Using the 2D full-wave code, ALFA,[5,6] we extended the analysis to lower frequencies, 40 < f < 100 MHz. Also, we extended the analysis to the current drive problem. This code features general toroidal geometry with the poloidal magnetic field included, and uses Bessel functions in the hot plasma dielectric tensor to correctly account for the large Larmor radius effects.

The total input RF power of up to 24 MW was suggested. The 6-strap phased antenna is required to produce the narrow spectrum of excited toroidal wave numbers, n, which is necessary for high CD efficiency. For plasma heating, however, there is no need in so narrow spectrum and more simple 4-strap antenna works satisfactorily. Normally, in Ignitor (as well as, in the other large tokamaks with the hot and dense plasma) fast waves do not penetrate far in toroidal direction from the antenna. As a result, neighboring antennae practically do not "feel" each other, and can be considered separately.

The low frequency region considered includes frequencies corresponding to the ion cyclotron resonances for all ion species: for deuterium, $\omega = \Omega_D$, for tritium, $\omega = \Omega_T$, and for α-particles, $\omega = \Omega_\alpha$. As a result, a variety of essentially different plasma heating regimes can be identified which have the potential for various applications in Ignitor. One can find the heating scenarios when RF power is absorbed preferentially by any particular ion component: D, T, or α-particles. Also, the ion-ion hybrid resonance is usually present in the plasma, which extends the possible heating and current drive schemes to ones that include mode conversion to the ion Bernstein wave (IBW). For example, at frequencies, $f \approx$ 60-70 MHz, it is easy to find scenarios when most of RF power goes to T-ions, and at frequencies, $f \approx$ 80–90 MHz, -- to D-ions or α-particles.

The steady-state operation of a fusion reactor is, probably, absolutely necessary to make the electricity production cost competitive. RFCD together with the bootstrap current is one of the possible means to reach the steady operation. We showed that low frequency current drive methods can be used for high density plasmas, $n_{eo} = 10^{21}$ m^{-3}, typical for Ignitor.

An interesting regime was found at Alfven frequencies, i.e. $\omega < \Omega_i$ for all plasma species (f = 42 MHz). The single-pass absorption in this case is about 50% and RF power is absorbed by electrons alone. The toroidal Fourier spectrum of the 6-strap antenna with phasing $\Delta=\pi/4$ between adjacent straps has a peak at $n \approx 5$ corresponding to the strongest electron absorption ($\zeta_e \approx 1$, where $\zeta_e = \omega/k_{\|} v_e$). In this regime, most RF power is absorbed in the central plasma region. However, some power is absorbed near the plasma edge on the high-field-side (HFS) via the Alfven resonance. This parasitic absorption is small, however, because of the narrow antenna spectrum chosen.

The total driven current was found to be 360 kA for $n_{eo} = 10^{21}$ m^{-3}. This is a significant result if one takes into account that CD efficiency usually scales as $1/n_e$. The current drive efficiency factor, $\gamma = \langle n_e \rangle R_o I_{rf} / P_{in}$, found in our calculations for Ignitor, is about 20 times larger than that reported in the DIII-D FWCD experiments.[7] This RF driven current, although is not enough to sustain the plasma equilibrium by itself, is important as a seed for the bootstrap current. Also, it can be used for the current profile control.

There are other regimes at higher frequencies, $f \approx$ 66 MHz and $f \approx$ 90 MHz, also efficient for current drive (antenna strap phasing or/and spacing has to be changed with frequency to satisfy the requirement, $\zeta_e \approx 1$). In those cases, the D-T hybrid layer plays the role of a reflecting wall. Better CD results are obtained for smaller T-concentrations when the ion-ion hybrid layer is located further on HFS leaving more space for wave penetration and electron absorption. The main competitor to the electron absorption at $f \approx$ 66 MHz is T-ion absorption, and at $f \approx$ 90 MHz it is D-ion absorption. At T-concentrations of around 25% the power absorbed by electrons in these regimes can reach 70%, and the CD efficiency is acceptably high.

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C. Low Power Fast Wave Antenna Loading as an RF Sheath Diagnostic

As discussed elsewhere in this report, radiofrequency sheaths induced by the rf $E_{||}$ component are a ubiquitous feature of ICRF heating and current drive, and rf sheaths cause several important edge plasma interactions, including impurity generation, power dissipation, and SOL modifications. Thus, it is important to diagnose a new antenna in its various operating modes (different phasings, antenna-plasma gaps, etc.) to determine under which circumstances its edge interactions are acceptable. Simply operating the antenna at high power in its various modes is not a practical way of doing this; rf-sheath-driven arcs and impurities can, in extreme cases, result in serious contamination of the tokamak. For this reason, it is difficult on most experiments to obtain enough run time to explore rf sheath formation in phasings such as monopole (0-0-0-0). It would therefore be desirable to have a low-power, non-perturbative diagnostic of rf sheath formation to help assess the safe operating boundaries of the rf system. The present section describes our proposal for such a diagnostic.

The immediate motivation for this work was to understand the DIII-D experimental data on low-power antenna loading with and without a Faraday screen (FS).[1,2] It is generally observed on all ICRF experiments that the fast wave (FW) loading has a peak at very low rf power (< 20 kW). The curve $R_L(P_{RF})$ has a maximum at $P_{RF} = 0$ and rapidly decreases with power until saturating at the usual FW loading. The interesting feature of the DIII-D data is that the loading peak was much larger when the FS was removed.

The low-power peak in the FW loading was previously regarded as a curiosity by most experimentalists, and it was thought that ponderomotive density expulsion would account for the effect. Recent loading calculations at ORNL suggest that the density profile changes measured by the reflectometer on DIII-D cannot account for the observed shape of the loading curve.[2] We have proposed[3] a different explanation for the data based on the different scalings of the rf sheath power dissipation and the FW propagation with the antenna voltage.

The starting point of our argument is that power coupled to the core plasma via the fast wave, P_{FW}, and the power dissipated in the RF sheaths are independent loss channels driven by the antenna current. Thus, the lumped circuit resistances of these two channels should be taken in series giving the antenna loading resistance $R_L = 2(P_{FW} + P_{sh})/(V_a/Z_o)^2$, where V_a is the antenna voltage and Z_o is the antenna impedance. The power radiated into the FW is approximated by $P_{FW} = A_{FS} S_x$,where $A_{FS} = L_y L_z$ is the FS surface area, S_x is the Poynting flux, and the coordinates x, y, z denote the radial, poloidal, and toroidal directions, respectively. The voltage scaling for the FW power coupling is $S \propto |E_y|^2 \propto V_a^2$, where $|E_y| \approx V_a/L_y$. The sheath power dissipation P_{sh} scales linearly with the sheath voltage in the limit $eV/T_e >> 1$, and Vis directly proportional to the antenna voltage, so that $P_{sh} \propto V_a$. At very low RF power, or equivalently low V_a, these scalings imply that the dominant power loss mechanism is the sheath power dissipation. The FW loading scales as $R_L \propto V_a^{-1} \propto P_{RF}^{-1/2}$ at low power where $P_{sh} > P_{FW}$, and $R_L \approx$ constant at higher RF power where P_{FW} gives the dominant contribution. This behavior is consistent with the usual ICRF antenna loading curve. Moreover, our calculations[3] based on this rf sheath model qualitatively reproduce the DIII-D loading data[1,2] for the experiments with and without the FS, when either a larger sheath voltage or larger SOL density is assumed in the screenless case. To give a convincing explanation of the data, it remains a subject for future work to determine the dominant class of sheaths for the cases with and without FS and to identify the parameters controlling the rf sheath distribution.

With proper calibration of the low-power loading measurements, this effect can be used as a non-perturbative diagnostic for rf sheaths.[3] (At rf power levels below 50 kW, the rf modifications of the SOL and core plasmas are negligible.) The ratio $R_L(0)/R_L(\infty)$ is a direct measure of the average rf sheath voltage on the antenna and nearby limiter surfaces. This technique could be used to compare the sheath properties of different antennas or operational regimes (e.g. different phasings) without perturbing the SOL plasma. Also, since $P_{sh} \propto n_i$, the low-power loading might be used as a density diagnostic, if the rf sheath distribution could be accurately calculated by the ARGUS-ANSAT codes[4]. In effect, one would use the antenna as an extended Langmuir probe. We intend to refine our calculations and explore the diagnostic application further in the coming year.

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D. Alcator C-MOD ICRF Sheath Modeling

In early 1994, at the request of M. Porkolab, we performed a preliminary analysis of the impurity influx for the single strap ICRF antenna experiments using data supplied by S. Golovato of MIT. The point was to understand whether the predictions of rf sheath theory agreed or disagreed with the observed good performance of the antenna in a high-Z (molybdenum limiter), high-density environment. The antenna/magnetic geometry was analyzed to determine the driving sheath voltages and approximate connection points, and impurity influxes calculated taking into account rf-enhanced convection. It was found that rf sheath theory gives good agreement with the experimental impurity data assuming a Mo-coated Faraday screen (FS) and a reasonable value of the Mo concentration in the SOL. The impurity influx from the C-MOD FS calculated from our model is comparable to that measured on JET in monopole phasing, but is more heavily screened by ionization in the SOL. The associated impurity radiation is a substantial fraction of the rf power and may account for the reduced heating efficiency in these experiments. The 2-strap antennas installed subsequently are typically run in dipole phasing to minimize rf sheaths, so we have not analyzed any later C-MOD data.

E. Survey of Antenna Sheath Issues for ITER

In the Fall of 1993, at the request of the U.S. and European ITER Home Teams, we collaborated with M. Bures of JET in surveying critical ICRF edge physics issues for ITER. The survey included all rf-sheath related issues including rf impurity generation, power dissipation, and ICRF-induced edge convection. This work extended our previous analysis of the JET database to include antennas with an arbitrary number of straps and arbitrary phasing between straps. (The improved model is thus relevant to JET and DIII-D current drive experiments.) An analysis of a preliminary ITER antenna design was carried out to illustrate the physics issues. As a result of this work, we were requested by the ITER Joint Central Team to carry out a more detailed studies of the evolving ITER ICRF antenna design in collaboration with ORNL and JET. This work was funded separately by small contracts from ITER.

IV. EDGE AND DIVERTOR STUDIES

A. Kinetic divertor modeling

The development of sophisticated techniques for divertor modeling is one of the important challenges facing the theoretical/modeling community. Many new plasma physics regimes and phenomena are asociated with the divertor, and the importance of edge and divertor physics for successful operation of the tokamak cannot be overstated. An important aspect of divertor physics is to develop an understanding of the role of kinetic effects in divertor plasmas.

Because of their relative simplicity, one and two dimensional plasma fluid codes are routinely employed for edge plasma modeling. However, fluid plasma descriptions are not always adequate for edge plasma modeling since they require that the charged particle mean free path be small. This assumption is not valid in the vicinity of material surfaces (limiter or divertor targets) which absorb and recycle plasma ions and thereby cause a strong departure of the distribution function from Maxwellian. To deal with this complication, approximate boundary conditions for fluid equations are derived from crude guesses about distribution functions adjacent to material interfaces. These approximate boundary conditions sometimes imply very strong restrictions on plasma parameters at the boundary, for example the Bohm condition that the parallel plasma velocity becomes sonic.

Fluid descriptions can also fail in the presence of very strong plasma gradients along the magnetic field lines; a situation that occurs for detached divertor operation and that is very attractive for the ITER divertor design since it is characterized by a reduced heat load on the target. Indeed, the detached divertor regime observed on most diverted tokamaks is the one most sensitive to the kinetic modifications of a fluid plasma description. These gradients are associated either with neutral recycling near targets or with impurity energy radiation losses. It is known[1,2] that the Braginskii plasma transport coefficients begin to fail even at rather small values of the ratio γ which we define as the Coulomb mean free path of a thermal particle $\lambda(cm) \approx 10^{12} T^2(eV)/n(cm^{-3})$ (T and n are the plasma temperature and density) to the parallel temperature scale length L. In particular, the Spitzer-Harm[3] heat transport coefficient fails for $\gamma > 1/100$. The breakdown of fluid treatments occurs at these surprisingly large values of collisionality because the Coulomb collision frequency falls off as $1/v^3$. The rapid fall off causes the Spitzer heat conduction to be dominated by charged particles with energies on the order of seven times the thermal energy and energy weighted mean free paths roughly 50 times larger than that of the thermal particles. The typical value of γ for the current tokamaks Alcator C-Mod and Doublet-III-D, as well as the expected value for ITER, is about 1/10. As a result, the weakly collisional energetic particles are expected to result in non-local behavior that has a strong influence on parallel plasma transport.

To investigate non-local plasma transport in the regimes of interest requires kinetic descriptions and codes. The adaptive grid Fokker-Planck code ALLA and particle-in cell (PIC) codes W1 and W2 are being developed by O. Batishchev (Lodestar) in collaboration with the MIT Plasma Fusion Center.[4-12] Also involved in the W1 collaboration are J. Byers, R. Cohen, T. Rognlien, and X. Xu of LLNL.

ALLA, W1, and W2 are being used to model divertor operation in regimes in which non-Maxwellian features can make short mean free path fluid treatments invalid. The ALLA and W1 codes are currently being used to interpret Alcator C-MOD data from experimental probe measurements to provide insight into the electron temperature at the divertor plates. The kinetic codes W1, W2 and ALLA are described in the following sections.

Kinetic PIC Codes W1 and W2. We have developed and obtained the first kinetic results of modeling detached divertor regimes using the fully kinetic particle-in-cell (PIC) code W1.[4,5,9,12] W1 avoids the disadvantages of the short mean free path expansion approach used in the fluid plasma codes. W1 retains two velocity (2V) components (parallel and perpendicular), and spatial variation along the magnetic field (1D). In the W1 code we treat Coulomb collisions between all plasma species, the ambipolar electric field, and neutral transport with plasma-neutral interactions including ionization, excitation by electron impact, and ion-neutral charge exchange. The self-consistent ambipolar electric field is determined from the plasma quasineutrality condition. The higher dimensionality associated with kinetic modeling of the SOL plasma makes it much more difficult than fluid modeling so normally only parallel spatial variation is retained. However, a higher dimensionality PIC code W2 removes this restriction in some special circumstances, resolves the additional physics associated with sheath structure in two dimensions in real space (besides 2V or 3V), and can be run on a massively parallel computer platforms as discussed in a subsequent paragraph.

To model the energy flux coming into the SOL plasma from the bulk in the W1 code we employ an energy source in the kinetic equations. To model plasma particle sources we assume complete recycling at the target so that no particle flux enters from the bulk. As a result, the plasma flux onto the target equals the neutral outflux from the target. Since the regimes of interest are high recycling regimes in which the main particle source is associated with plasma recycling at the targets this is reasonable approximation. Neutral trasnport is described by two different geometric models that retain the main features of the Knudsen (long mean free path) neutral transport regimes.

For C-Mod and ITER like conditions we have found a strong enhanced tail on the electron distribution function near the target for energies > 3T, resulting in an effective temperature about twice that of the background electron temperature. This finding shows that experimental probe measurements of the electron temperature, which actually determine tail electron temperature, can differ the actual background temperature. This important result means that real plasma temperature of Alcator C-Mod in the detached regime might be as low as 1 eV.

W2 is a 2D, 3V kinetic PIC code which can be used to model magnetic sheath structure in rectangular geometry. The angle between the magnetic field and the target can be arbitrary. The target plate operates at the self-consistent or biased potential and the electric field is obtained from Poisson equation. A typical spatial domain size is 100-1000 Debye lengths. A Boris algorithm is used to trace the finite ion gyro-motion and permits the **E**×**B** drifts to be evaluated correctly. A neutral background with a fixed temperature and specified spatial behavior is assumed in W2 and ionization via electron impact is included. Under special circumstances a two stream instability is found to be excited in the long ion and neutral mean free path limit.

Adaptive, Non-Uniform Grid, Fokker-Planck Code ALLA . A 1D, 2V Fokker-Planck plasma kinetic code called ALLA is being developed and benchmarked with exact analytical solutions of the collisional kinetic equation.[6,7,8,10,11] This code employs adaptive spatial meshes and a nonuniform velocity grid. It allows us to investigate, over an extremely wide plasma parameter range, multi-species plasmas (including heavy impurities) having very strong plasma gradients. The ALLA code will ultimately treat Coulomb collisions between all plasma species, the ambipolar electric field, and plasma-neutral interactions including ionization, excitation by electon impact, and ion-neutral charge exchange. The numerical solution method is based on a conservative, cubic spline interpolation scheme with a fast solver for the Rosenbluth potentials. We find the ambipolar electric field from the plasma quasineutrality condition. To model energy flux coming into the SOL plasma from the bulk we employ an energy source in the kinetic equations. ALLAp is the massively parallel version of ALLA.[8]

To verify that the ALLA Fokker-Planck code under development is working properly in less collisional plasmas, we use analytic and semi-analytic models to benchmark the code. We use a self-similar technique[13] to reduce the dimensionality of the kinetic equation for the time dependent and isotropic velocity space case to find an analytic solution for Maxwellian Rosenbluth potentials over a greatly extended range of collisionality.[6,10] Indeed, the ALLA code is able to reproduce these temporal self-similar analytic solutions out to energies of 50 or more times the thermal energy (corresponding to the limits of machine accuracy!). M. Shoucri and I. Shkarofsky of CCFM in Canada are collaborators for this work.

The benchmarking work considers simple models of ELM propagation in a SOL plasma in which the distribution function is unable to equilibrate during the ELM bursts. During the cooling phase of the ELM burst, the distribution function has an elevated tail causing the short mean free path heat conduction coefficient to exceed its Maxwellian value by an order of magnitude in the region between the heat front and target.

The ALLA code is being used to simulate the parallel electron flow in the SOL's of Alcator C-Mod and TdeV.[7] We find that the actual electron distribution function is asymmetric in the direction parallel to the magnetic field and its tail starts to depart from Maxwellian at energies around 2T, where T is the plasma temperature. This feature can substantially affect probe measurements, and modify reaction rates and plasma transport properties. The ratio of the electron Coulomb mean-free path to the connection length in TdeV is around 1/10 and for C-Mod is around 1/40. As a result, the electron distribution function is almost Maxwellian for thermal particles with energies near or below T, but not for suprathermal electrons because of the quadratic dependence of mean-free path on energy. These higher energy electrons strongly influence the parallel heat conduction and impurity excitation rates. In addition, they determine the electron temperature measured by Langmuir probes since the floating potential of a deuterium plasma is almost 3T. As a result, probe measurements can mis-estimate the electron temperatures. Also the non-

Maxwellian tail can be responsible for the experimentally found variation of upstream and downstream temperatures as measured by reciprocating probes on C-Mod.

Fokker-Planck kinetic simulations with the ALLA code using plasma profiles that match the experimental data show significant departures of the electron distribution from Maxwellian and result in an overestimate of the plasma temperature at the divertor probes by an average of 60%. Simultaneously, fast scanning probes underestimate it by 20%. Our results are also consistent with the measured difference between the upstream and downstream temperatures of 30% measured experimentally by reciprocating probes. Plasma reaction rates can be 50% higher near the target and 20% lower at midplane, than Maxwellian values. The heat conduction coefficient can be an order of magnitude greater than its Maxwellian value in the divertor because of the strong dependence on suprathermal particle contribution.

B. Generalized Ballooning & Sheath Instabilities in the SOL of Divertor Tokamaks

Understanding the stability of the scrape-off-layer (SOL) of divertor tokamaks is important for many reasons. One is the necessity of controlling edge localized modes (ELM's) to achieve good confinement. Another is because an understanding of turbulent SOL widths is needed to address heat load considerations for divertors, and to provide a proper boundary condition for core transport studies. Because field lines in the SOL terminate in sheaths, SOL modes must be treated with appropriate sheath boundary conditions (BC's). This fact can profoundly influence their stability.[1-3] In the present work, we have incorporated sheath effects into a study of high-n ballooning-type modes. The high-n modes are a good starting point because they are localized to a field line; therefore the sheath BC's can be applied one line at a time. Our initial goal is to compare the stability (and importance of various drives) for different experiment divertor equilibria (e.g. varying degrees divertor attachment).

This work has followed naturally from Lodestar's previous interest in both edge ballooning stability[4,5] and plasma sheaths[6,7] in the context of ICRF waves. Sheath boundary conditions were found to play a critical role in understanding the interaction of rf waves with surfaces, both near launching structures and when unabsorbed waves interacted with limiters and walls in the tokamak. These rf sheath interactions occur in the frequency regime $\omega \sim \Omega_i$. Additionally, on the slow (dc) time scale for the rf problem, we found that plasma convection was driven by the spatial variations of the sheath potential.[8] The sheath instability discovered by Ryutov is basically the perturbed version of the nonlinear convective cell equation[8] that we obtained in the rf case.

An important feature of the present study was the use of divertor geometry for the equilibrium magnetic field. We employed an analytical two-wire model for a magnetic X-point, adding toroidal curvature in the small inverse aspect ratio limit. Equilibrium profiles of density and temperature were provided as input to the model, corresponding to i) a collisionless SOL (T_e constant along a field line), and ii) a collisional attached divertor (with moderate variations T_e but negligible neutral pressure). The completion of our neutral physics work (see the following topic) will also permit the study of detached divertors (with large variations T_e and neutral pressure). The equilibrium electrostatic potential Φ in each case is obtained on a field-line by field-line basis, from a parallel integration of Ohm's law. The procedure requires that $\eta J_{\parallel}$ be negligible, and is typically valid throughout the SOL except very near the X-point. The Φ thus obtained has both parallel and perpendicular variations (i.e. it has non zero $\nabla_{\parallel}\omega_E$ where ω_E is the E×B drift frequency) that are driven by the variations of density and temperature. Thus the $\nabla_{\parallel}\omega_E$ drive for instability[5,9] is self-consistent with the pressure weighting of curvature and the sheath boundary condition for the modes.

A generalized ballooning equation was derived including parallel variations of density, temperature and potential, plasma resistivity (important at high mode numbers), and the sheath boundary condition in the X-point divertor geometry. These features had not previously been incorporated into the same study, although other authors[2,3,5,9,10, 11] had considered them separately in simpler models. The equation was solved numerically for the eigenfunction ψ, and it was shown that integrals of equilibrium quantities weighted by $|\psi|^2$ could be constructed to ascertained the physics dominating the modes. The integrals give instability drive terms corresponding to E×B axial shear ($\nabla_{\parallel}\omega_E$), MHD (curvature) and the sheath boundary condition; and stability terms corresponding to line bending, finite Larmor radius (FLR), and the sheath line tying effect.

Preliminary results[12] show that both the collisionless and collisional attached cases recover the usual MHD mode, now with a growth rate that is enhanced by the sheath boundary condition. The mode is stable at low n due to line tying, and stable at high n due to FLR, with maximum growth in between. Maximum growth occurs when the $k_{\perp}$ vector is oriented to be purely poloidal (and hence $k_{\perp}^2$ is a minimum) at the top of torus (when the X-point is at the bottom), in contrast to the usual MHD closed field line case where $k_{\perp}$ is poloidal at the outside of the torus where the bad curvature is. This result may be understood in terms of the mode attempting to minimize the stabilizing line-tying effect of the plates. Perhaps more importantly, in the collisional attached case the model finds E×B axial shear modes near the X-point. These modes are a generalization of the modes discussed by other authors. The axial shear modes are not FLR stabilized at large n (but have growth rate γ an increasing function of n) because they are driven by ω_E which like the FLR term ω_{*i} is proportional to n. For sufficiently large n, the growth rates ultimately become limited by plasma resistivity. In the highly resistive limit, the modes become localized, therefore they do not see either the shear, or the sheath BC's. The X-point geometry has an important influence on the E×B axial shear modes due to the parallel variation of $k_\perp$, (hence ω_E) near the X-point. This feature was exhibited by the present model for the first time.

Ongoing work on this topic includes several points. First we plan to complete the investigation of the effects of resistivity to determine which modes are likely to make the maximum γ/k^2 contribution to turbulent transport. This will allow an overall assessment of the various divertor operational scenarios with respect to the stability issue. The breakdown of the formalism near the X-point may also contain important clues about divertor behavior. This topic could lead to interesting generalizations of the work by Mattor and Cohen,[13] since the present modes appear to maximize their growth by seeking out rather than avoiding the X-point. Eventually, we hope to combine the present model with the neutral model described in the following section, thus enabling a stability treatment of detached divertors.

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C. Effect of Neutrals on SOL Stability

In an effort to reduce the loading of hot plasma streaming into the divertor target plates, present day experiments are investigating various methods to optimize divertor operation. Operating a divertor with a fully detached plasma appear to be a promising approach. In this case, the plasma flame becomes extinguished (i.e. it cools and begins to recombine) before it reaches the divertor plates, so that a layer of neutral gas separates the fully ionized plasma from the divertor target plates. The stability problem for waves in the SOL is expected to be somewhat different in this situation, not only because the field lines do not terminate in sheaths, but also because of the coexistence of a large neutral population with the plasma in the vicinity of the detachment layer.

The modification of the sheath boundary conditions in this situation is handled naturally in the model discussed previously, because the sheath disappears as $T_e \rightarrow 0$ at the sheath entrance. In this study, we have therefore focused on the effect of a large neutral population on the SOL stability. Previous work on this problem dates back several decades[1,2] to when cold partially ionized plasmas were routinely studied in the laboratory. There is not, however, much contemporary literature investigating the consequences of neutral collision physics for the stability of SOL divertor plasmas. One exception is Xu et al.[3] who consider the effect of ionization (electron-neutral collisions) in the sheath on sheath balance and sheath driven instabilities.

In our preliminary work on this subject, we began with fluid equations for plasma and neutrals including the effect of ion-neutral collisions in the momentum equation, i.e. an ion-neutral friction term proportional to the relative velocity of the plasma and neutrals. The hydrodynamic formalism for the neutrals is valid in the short mean free path limit, and is marginal for some divertor equilibria of interest, but provides a simple starting point for investigation. We have derived a high mode number (eikonal limit) flute-mode dispersion relation for this case. A key parameter turns out to be the ratio ν_{in}/Ω_i where ν_{in} is the ion-neutral collision frequency and Ω_i is the ion cyclotron frequency. In the case of detachment with high neutral density, this ratio can be 0.1 or larger.

When $\nu_{in}/\Omega_i \rightarrow 0$, so that the ion E×B motion is not disturbed, neutral collisions enter only through a modification of the usual MHD inertial term, viz. $\rho_i(\omega-\omega_E)^2 \rightarrow$

$\rho_i(\omega-\omega_E)^2 + i\rho_i\nu_{in}\rho_n\omega(\omega-\omega_E)/(\rho_n\omega+i\rho_i\nu_{in})$ where ρ_i and ρ_n are the mass densities of the ions and neutrals, ω is the mode frequency, and $\omega_E = \mathbf{k}\cdot\mathbf{v}_E$ is the E×B drift frequency. This term leads only to damping by the neutral drag, not instability. In the limit of large ν_{in} and $\omega_E = 0$ it corresponds to an increase in effective plasma mass, $\rho_i\omega^2 \rightarrow (\rho_i+\rho_n)\omega^2$ because the strong friction drags the neutrals along with the ions. A similar effect was noted in Ref. 4.

More interesting is the case of finite ν_{in}/Ω_i. In this case, the free energy of relative flow between plasma and neutrals ($\omega_E \neq 0$) combined with the neutral friction can lead to a class of neutral drag instabilities[1,2] which we are in the process of investigating for implementation in our divertor SOL stability code (see preceding topic). Preliminary estimates suggest that the growth rates of these instabilities can be comparable to SOL MHD growth rates in some cases.

One difficulty with the fluid formulation (other than its basic validity criterion for the equilibrium) is that it is difficult to argue for a valid closure scheme for the perturbed neutral pressure because the modes of interest typically have $\omega \sim \omega_E < kv_n$ where v_n is the neutral "thermal" velocity. This may motivate the consideration of kinetic treatments in the future. Additionally, the effect of electron-neutral collisions and their modifications to Ohm's law remains a topic for future work.

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D. Ponderomotive Feedback Stabilization

An important challenge facing the tokamak fusion concept is to develop active means of stabilizing magnetohydrodynamic (MHD) modes near their instability boundaries. Theoretical analysis[1] shows that there exist attractive "advanced tokamak" high beta regimes with a plasma-generated bootstrap current profile nearly aligned with the required plasma equilibrium current, giving second stability to all high-n ballooning modes. Such configurations are typically unstable only to the n=1 external kink mode. Stabilization of external kinks may also significantly decrease the frequency of plasma disruptions, which occur when thresholds in plasma density or in the plasma beta are exceeded. External kinks can be stabilized for short times by a conducting wall, but an active stabilization method may be required to achieve stability on times longer than the resistive-diffusion time of the magnetic field through the wall. We have analyzed a novel active feedback scheme for MHD mode control using the modulated ponderomotive force (PF) of an array of radiofrequency antennas as the active element to stabilize n = 1 external kinks. For a practical implementation of this scheme, it is envisaged that the stabilizing elements would be IBW antennas; these are slow wave couplers and therefore produce the greatest PF per unit rf power. Our calculations were motivated by the PBX-M tokamak which has both close-fitting metal plates (to maximize wall stabilization) and IBW antennas. In collaboration with S. Jardin, M. Chance and E. Valeo, we have also suggested and analyzed a preliminary n = 0 modulation experiment which could test the concept on PBX-M without additional hardware. This work was mainly funded by a Small Business Innovative Research (SBIR) grant, but some of the applications and the writing of a journal article[2] were funded by the present contract.

It was shown that the rf power required for PF stabilization of kinks[3] is greatly reduced if the rf intensity is modulated in response to a feedback detector system.[2] Two feedback systems were considered: (1) a local response (LR) system, in which each antenna responds to the local displacement ξ_k measured at the nearest detector; and (2) a Fourier mode response (FMR) system in which the available detectors are used to resolve a target Fourier mode, ξ_{mn}, and each antenna responds with the appropriate phase to stabilize this mode. The FMR system was shown to have many advantages (in particular, requiring fewer antennas) as long as the number of detectors was sufficient to resolve the mode structure of the targeted mode. The rf power required for n = 1 kink stabilization in PBX-M was estimated, and it was shown that the idea can be tested with the existing PBX-M antenna system (2 antennas) and power supplies (4 MW at 40-80 MHz) when a feedback system is developed (as planned for PBX-M). In collaboration with PPPL, we also suggested and evaluated a useful test of the PF coupling that can be carried out before the feedback system is installed. The idea is to modulate the vertical field coils to produce an n = 0 oscillation of the magnetic axis, and to simultaneously modulate the rf power to the IBW antennas, with the latter modulation shifted in phase by ϕ. By measuring amplitude and phase of the modulated rf power required to hold the magnetic axis in place, one can benchmark the PF required for stabilization of MHD modes. Simulations carried out by Jardin with the TSC code indicate that a useful experiment can be carried out with the present rf system.

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V. PUBLICATIONS, ABSTRACTS, PRESENTATIONS

A. OLEG V. BATISHCHEV

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