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ANOMALOUS TRANSPORT AND CONFINEMENT SCALING STUDIES IN TOKAMAKS

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ANOMALOUS TRANSPORT AND CONFINEMENT SCALING STUDIES IN TOKAMAKS*

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Abstract

In addressing the general issue of anomalous energy transport, this paper reports on results of theoretical studies concerning: (1) the characteristics and relative strength of the dominant kinetic instabilities likely to be present under realistic tokamak operating conditions; (2) specific nonlinear processes relevant to the saturation and transport properties of drift-type instabilities; (3) the construction of semi-empirical models for electron thermal transport and the scaling trends inferred from them; and (4) the application of specific anomalous transport models to simulate recent large-scale confinement experiments (TFTR and JET) and current drive experiments.

KINETIC STABILITY PROPERTIES IN TOKAMAKS

In order to identify physical processes most likely to affect anomalous electron thermal transport, attention is focused on: (a) the relative strength of high- n MHD ballooning modes compared to other short-wavelength instabilities; and (b) the basic characteristics of instabilities which should persist in the "H-mode" tokamak discharges. Concerning the first topic, a comprehensive stability code [1] has been developed to analyze the appropriate kinetically generalized form of the ballooning modes together with the usual electrostatic microinstabilities (such as trapped-particle drift modes). The calculations here are fully electromagnetic and include the relevant dynamics associated with compressional ion acoustic waves. Trapped-particle effects together with all forms of collisionless dissipation (bounce, transit, and drift resonances) are taken into account without approximations. The influence of collisional dissipation is estimated by employing a model Krook operator. A detailed description of the resultant system of integral equations and the numerical procedure used to solve them are given in Ref. 1. Application of these calculations to both model and numerical MHD equilibria for parameters appropriate to existing tokamaks lead to the typical results given on Fig. 1. The general indication is that unstable short-wavelength modes with significant growth rates can extend from

$\beta \approx 0$ to values above the upper ideal-MHD-critical-beta (β_c) associated with the "second stability" regime. Although the strength of the dominant modes increases above the first β_c and begins to drop as the second β_c is approached, the transitions in magnitude are relatively gradual. Hence, the results here support a "soft" beta limit picture involving a continuous (rather than abrupt or "hard") modification of anomalous transport already present in low-beta tokamaks. However, the increasing dominance of the electromagnetic component of the perturbations at higher beta could lead to significantly different transport scaling properties. With regard to the "H-mode" confinement characteristics, analytic estimates show that for the relatively flat density profiles common to these discharges, electrostatic microinstabilities driven by temperature gradients and unfavorable magnetic curvature effects can persist. As noted earlier, for moderate values of beta, the kinetic ballooning modes could also be significant. Since the strength of these instabilities scales with the total pressure gradient, they too should persist in "H-mode" cases. These trends are consistent with experimental observations in that the electron thermal transport, while reduced, clearly remains strongly anomalous. In addition, detailed numerical calculations for "H-mode" conditions in the PDX tokamak yield kinetic instability growth rates which are typically about 30% smaller than corresponding cases for "L-mode" conditions. This is again consistent with the observed improvement in the energy confinement time in that the strength of the relevant instabilities is significantly reduced here.

NONLINEAR PROPERTIES OF DRIFT INSTABILITIES

For the moderate to low-beta conditions typical of most present generation tokamaks, the drift-type electrostatic modes (including trapped-particle instabilities) appear to be the most important. In order to gain some insight into the nonlinear processes likely to influence their saturation and transport properties, gyrokinetic particle simulations as well as analytic and numerical methods have been applied to the model problem of collisionless and collisional drift instabilities in a shearless slab system. In particular, it is found that the dominant saturation process need not always follow the conventional "source and sink" picture involving a coupling of energy from linearly unstable modes to those which are damped. Instead, it appears that in many cases saturation occurs when the nonlinear $\mathbf{E} \times \mathbf{B}$ advection of the electrons (rather than the ions) acts to eliminate directly the flow of energy from the electrons to the waves. In the collisionless limit, the saturation amplitude for the most unstable modes ($k_{\perp} \rho_s \ll 1$) is found to be $e\phi/T_e = (\gamma_L/\Omega_i)/(k_{\perp} \rho_s)^2$, where γ_L is the linear growth rate, $\Omega_i \equiv eB/M_i c$, $\rho_s \equiv v_s/\Omega_i$, and $v_s \equiv (T_e/m_i)^{1/2}$. Generally, these modes dominate the initial phase of the instability. In the second stage of development, the effect of the nonlinear $\mathbf{E} \times \mathbf{B}$ advection for the ions becomes important and is responsible for the energy cascade from modes with $k_{\perp} \rho_s \ll 1$ to modes with

smaller $k_{\perp} \rho_s$. Finally, the fully nonlinear stage (steady state) is characterized by the energy exchange between these competing modes due to the nonlinear parallel acceleration of the electrons. It results in a broad and rather flat wavenumber spectrum and broad frequency spectra with $\Delta \omega_k \sim \omega_k$. Here, the maximum amplitude for each individual k mode does not deviate appreciably from the saturation amplitude for the most unstable modes. The diffusion in the simulation resembles more of a random walk process and is smaller than the quasilinear estimate of $D_{q2} = (\gamma_L/\omega_*)^2 (\gamma_L/k_{\perp}^2)$ with γ_L being the growth rate of the fastest growing linear mode in the system. Note here that the usual ambient gradient argument gives $e\phi/T_e = (\omega_*/\Omega_i)/(k_{\perp} \rho_s)^2$ and $D_{q2} = \gamma_L/k_{\perp}^2$. In the collision dominated regime ($v_{ei} > |\omega|$), the saturation amplitude becomes $e\phi/T_e = (\omega_*/\Omega_i)/k_{\perp} \rho_s$ for the most unstable modes. Nonetheless, the nonlinear development of the instability appears to be qualitatively similar to those of the collisionless cases. Although the diffusion in the simulation is significantly enhanced, its measured coefficient is still smaller than the quasilinear estimate of $D_{q2} = v_{ei} \rho_s^2$. It is particularly interesting to note that even when collisions are quite weak ($v_{ei} \ll |\omega|$), the nonlinear behavior of the steady-state fluctuations follows closely that of the collision dominated cases. On the other hand, the linear evolution for such cases remains unaltered from the collisionless limit. These observations serve to illustrate that general conclusions about the nonlinear properties of drift waves based on collisionless models could in fact be quite limited.

SEMI-EMPIRICAL MODELS FOR ANOMALOUS TRANSPORT

Since usable anomalous transport models based on self-consistent theoretical calculations still remain to be developed, it is necessary to turn to "semi-empirical" approaches which use experimentally observed trends to help select the dominant "first principles" physics features modeled. To deal with the anomalous energy confinement properties of low-beta ohmically heated plasmas, a microinstability-based model for the electron thermal transport coefficient (χ_e) is proposed in which its radial dependence is determined by a "profile consistent" constraint [2]. In particular, this involves assuming that anomalous processes in the plasma tend to maintain current profiles consistent with MHD stability to long-wavelength modes (e.g., low- n tearing modes near the $q = 2$ surface). Also incorporated in this model are the following experimentally observed features of ohmic discharges: (a) the region of effective thermal confinement lies between the $q = 1$ and $q = 2$ surfaces [3]; (b) the electron temperature profiles are well approximated by Gaussian shapes [4]; (c) the location of the $q = 1$ surface is well represented by $r_1/a = 1/q_a$ with a denoting the plasma edge [5]; and (d) the density profiles are roughly parabolic, $n_e(r) = n_{e0}(1 - r^2/a^2)^n$ [4]. The current profile is related to the electron temperature profile by a form of Ohm's law, and the steady-state energy balance equation (without radiation) is solved to give the basic

constraint condition which determines the radial profile of χ_e . Its magnitude and scaling characteristics are governed by the properties of the dominant anomalous mechanism. The fact that trapped-electron drift type microinstabilities are predicted to be strongly unstable in low- β ohmic cases [6] then motivates the choice of the simple $\gamma/k_{\perp}^2$ strong turbulence estimate [7] for the magnitude of χ_e . Using this with the constraint condition from the aforementioned solution to the energy balance equation leads to:

$\chi_e(r) = 2 \times 10^4 n_{eo}^{-1} a R^{-1.9} q_a^{-1.6} B_T^{0.3} Z_{eff}^{0.2} F(r)$ with
 $F(r) = \frac{\exp[(2\alpha_q/3)(r^2/a^2)] - \exp[-(\alpha_q/3)(r^2/a^2)]}{(r^2/a^2)^{1/2} [1 - (r^2/a^2)]^n}$ where $n_{eo}(10^{14} \text{ cm}^{-3})$, $B_T(\text{Tesla})$, $a(\text{m})$, $R(\text{m})$, and, typically, $\alpha_q \approx q_a + 0.5$ and $q_n \approx 1$. Application of this model to a representative set of ohmic cases from the PDX experiment yields good agreement with the empirically estimated values for χ_e . This model also leads to the following scaling for central electron temperature and volume-averaged-electron-temperature:
 $T_{eo} \propto B_T^{0.7} a^{0.4} R^{0.1} q_a^{-0.2} Z_{eff}^{0.3}$ and $\langle T_e \rangle \propto B_T^{0.7} a^{0.4} R^{-0.1} q_a^{-0.9} Z_{eff}^{0.3}$.
 With regard to the energy confinement time, if $\tau_E \propto \tau_{E,e}$, then the model yields $\tau_E \propto n_{eo} a R^{1.9} q_a^{0.6} B_T^{-0.3} Z_{eff}^{-0.2}$ or $n_{eo} a^{2.2} \times R^{1.3} B_T^{0.3} Z_{eff}^{-0.6} Z_{eff}^{-0.2}$. These results are in good agreement with the empirically determined scaling trends for $\langle T_e \rangle$ [8] and for τ_E [5] obtained from the general experimental data base for ohmic discharges.

To estimate the confinement scaling trends in auxiliary heated discharges, a low- β electrostatic drift wave turbulence model [9] applied in the collisionless regime ($\omega_{*e} > v_{ei} R/r$) gives $\chi_e = A(T_e^{3/2} M_i^{1/2} c^2 / e^2 B_T^2) (2\alpha_n/a^2) (1-r^2/a^2)^{-1} (R/r)^{1/2}$ with $A = \text{constant}$. Taking ignition conditions into account, this model leads to an electron heat balance equation of the form, $(A/r)(d/dr)[(T_{eo}^{2.5} r^{2.5} \alpha_n n_{eo}) / B_T^{2.0} a^2 (1-r^2/a^2) (1-\alpha_n)] (d\tau/dr) = n^2 \times \langle \sigma v \rangle E_n / 4 + P / 4\pi^2 R a r$. The neutral beam heating profile used here models recent PDX results [10]. Note that the temperature dependence of the loss term on the left side of this equation is almost the same as that of the thermonuclear cross section in the range $5 < T(\text{keV}) < 20$. This result implies that the ignition condition for tokamaks becomes independent of the temperature at which ignition occurs and takes the form [9], $B_T^2 \times n_{eo} R^{0.5} a^{2.5} \alpha_n^{-1} > 10^3$. Dimensional analysis of the energy balance equation here yields the scalings: $T_{eo} \propto B_T^{0.8} (P/n)^{0.4} \times (a/R)^{0.2} q_a^{0.1} \alpha_n^{-0.4}$ and $\tau_{E,e} \propto R^{0.9} a^{1.7} n^{0.6} B_T^{-0.6} a^{0.1} \alpha_n^{-0.4}$. The central electron temperature scaling is in good agreement with the empirical trend deduced from experimental data for neutral beam heated tokamaks [11]. With regard to confinement scaling, the observed improvement from L- to H-mode confinement can be interpreted in terms of the flattening of the density profile (i.e., a reduction from $q_n \approx 1$ to $q_n \approx 0.3$).

ANOMALOUS TRANSPORT IN THE PRESENCE OF IMPURITIES

Up to the present, the plasmas produced and confined in large scale experiments (TFTR and JET) have been characterized by values of $Z_{eff} > 1$ and radiation losses in the current-carrying part of the plasma column which are significant in the overall energy balance. Another characteristic of these discharges is that the $q = 1$ surface extends out to a significant fraction of the plasma radius. In order to simulate these operating conditions, a specific 1D radial transport code, which was successful in simulating smaller scale experiments, has been employed. In this code both the impurity radiation and the MHD sawtooth oscillations inside the $q = 1$ surface are taken into account. The anomalous transport properties are governed by a model based on the "profile consistent" constraint [2] described earlier together with a modified form of the Coppi-Mazzucato prescription for the loop voltage [12]. Specifically, the electron heat flow can be expressed as $Q_e = -K_e dJ_{||}/dr$ where $J_{||} = J_0 \exp(-r^2/a_1^2)$ represents the current density and $K_e = (\epsilon_s/24\pi)(I_p/8\pi e)(a_1 T_e/r^2)W_N(r)C_s^{2/5}$ with $a_1 \equiv$ radius of the current carrying channel, $C_s \equiv (v_s/v_{Te})(v_{ee}/v_{Te}^2)w_{pi}d_e^2$, and $W_N(r) \equiv \int_0^r dr (J_{||}E_{||} - L_R)/[(E_{||}I_p/2\pi) - L_R(r=0)a_1^2/2]$. Here L_R is the impurity radiation energy loss, w_{pi} is the ion plasma frequency, $d_e \equiv c/\omega_{pe}$ is the electron inertial skin depth, and the free parameter ϵ_s is about 1.3 (as suggested by a fit of the results from previous small scale experiments). The factor C_s was constructed to reflect the presence of current-driven magnetic reconnecting modes. An alternative choice [13], which would introduce a stronger scaling with R , is to replace C_s with $C_N = (v_s/L_R)(a_1/R)^{3/2}(v_{ee}d_e^2/v_{Te}^2)$ with L_p being the pressure gradient-scale-length associated with the presence of instabilities driven by the combined effects of the pressure gradient and unfavorable magnetic field curvature. Proceeding with the calculations using C_s , it is found that the presence of impurities can influence transport in two ways: (a) the presence of heavy impurities in the current-carrying part of the plasma column may increase the loop voltage above that associated with a clean plasma; and (b) the presence of light impurities can cause T_e to be raised above the values that would be predicted by assuming a clean plasma. In the latter case, increasing Z_{eff} does not appreciably affect the loop voltage but does increase the electrical resistivity. Consequently, $T_{eo} \propto Z_{eff}^{2/3}$ and $T_{ee} \propto Z_{eff}^{2/3}$. This tends to indicate that at equal densities, cleaner discharges will tend to be cooler. The code described here has been applied to a TFTR discharge exhibiting strong radiation from light ion (primarily carbon) impurities. For this case the total radiated power was roughly 60-90% of the ohmic power while the impurity radiation during the current flat-top was characterized by a fairly flat emissivity profile. Typical parameters were $I_p = 1.4$ MA, $B_T = 2.7$ T, $n = 2.3 \times 10^{13} \text{ cm}^{-3}$, $R = 2.55$ m, $a = 0.82$ m, $V_{loop}(\text{meas.}) = 1.2$ V, and $Z_{eff}(\text{meas.}) = 4.5 \pm 0.9$. During a sawtooth

oscillation experimental values of the maximum/minimum central temperatures (keV) were $T_{eo} = 1.9/1.6$ and $T_{io} = 1.6/1.5$. Results of the simulation using the modified transport coefficient with $Z_{eff} = 3$ and neoclassical resistivity [14] indicate good agreement with the observed values of the relevant parameters when the impurity radiation profile was assumed to be flat and to constitute 60-75% of the ohmic power.

THEORETICAL INTERPRETATION OF CURRENT DRIVE EXPERIMENTS

The interpretation of results from current drive experiments [15,16] in the lower hybrid frequency range at relatively low density has been undertaken with attention focused on the upshift of the parallel wave number (i.e., reduction of phase velocity) caused by toroidal effects on the waves launched at the plasma edge. If multiple reflections of wave energy at low density cutoffs are included, this mechanism enables waves with small initial $k_{||}$ to interact with a large number of electrons and thus generate substantial current. In addition, the anomalous electron energy transport here is associated with the thermal electrons (with little contribution from the current carrying superthermal electrons). These processes are taken into account in a combined analytic and numerical model comprised of a 1D radial transport code, a toroidal ray tracing code, and a relativistic quasilinear calculation of the longitudinal electron distribution function. The distribution of launched wave energy as a function of $k_{||}$ for a lower hybrid wave grill is obtained with a linear Brambilla code. In the transport code block of this numerical model, conservation equations for the time evolution of the bulk electron and ion temperatures and the magnetic stream function ($B_{\theta} \equiv \partial\psi/\partial r$) are solved for a particular choice of transport coefficients. In addition, diffusion equations for the rf-generated current densities parallel and antiparallel to the toroidal magnetic field are also solved [17]. The ray tracing code uses the ray equations of geometric optics to follow the propagation of individual lower hybrid waves for a dispersion relation that includes electromagnetic and warm plasma effects and a Shafranov equilibrium. The assumed absorption mechanisms are electron and (unmagnetized) ion Landau damping and nonresonant collisional damping. A quasilinear diffusion coefficient D_{q1} is found by summing ray amplitudes for multiple passes through a magnetic surface. The quasilinear calculation of the longitudinal electron distribution function consists of the numerical solution of a relation obtained by integrating a relativistically correct, 2D steady-state-Fokker-Planck equation over perpendicular momentum with appropriate simplifying assumptions. Included here are the effects of the waves (via D_{q1}), a DC electric field, a large effective perpendicular temperature, and a particle loss time that increases monotonically with energy. The model described is found to reproduce adequately many of the results of the PLT and Alcator-C steady-state current drive experiments. At "optimal" waveguide phasing (60° for PLT, 67.5° for Alcator-C)

and "maximum" B_T (3.1 T for PLT, 10 T for Alcator-C), the simulations can be summarized by a figure of merit of the form $C \equiv n(10^{19} \text{ m}^{-3}) I_{RF}(\text{kA}) R(\text{m}) / P_{RF}(\text{kW}) \approx 1$, in reasonable agreement with observations. The code does not predict a sharp drop in efficiency above the density limits of $\bar{n} \approx 7 \times 10^{18} \text{ m}^{-3}$ and $\bar{n} \approx 2 \times 10^{20} \text{ m}^{-3}$ for PLT and Alcator-C, respectively. Increasing the waveguide phasing angle and thereby decreasing the energy launched in high phase velocity waves brings about a decrease in the calculated value of C. Lowering B_T also reduces the calculated C due to poorer accessibility of high phase velocity waves to the center of the plasma. The experimental observations mirror both of these trends. It should also be noted that the present model effectively reproduces the time dependent behavior observed at the beginning of otherwise "steady-state" experiments and throughout runs where the plasma is overdriven and the current ramps up at a rate which is a fraction of the pre-rf inverse L/R time. In the former case, the rapid drop in the loop voltage to the value near zero (≤ 50 msec for PLT, ≤ 15 msec for Alcator-C) is a consequence of the spatial diffusion of the rf current density mentioned above. In the latter case, a slow current rise results from the restraining influence of a negative DC electric field on the magnitude of the rf current.

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FIGURE CAPTIONS

FIG. 1. Typical linear growth rates for short wavelength instabilities as a function of beta for a model tokamak equilibrium. The curves represent: (a) the usual ideal MHD estimate for ballooning modes without coupling to compressional ion acoustic waves; (b) kinetic collisionless estimate in the same limit; (c) and (d) full kinetic collisionless results for the ballooning modes and the trapped-electron drift modes, respectively; and (e) a "hybrid" of (c) and (d) when collisional dissipation is modelled with a Krook operator. All frequencies are normalized to ω_{*e} .

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Fig. 1

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