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ABSTRACT

In order to achieve the stated objectives of key future experiments such as CIT, it will be necessary to maintain plasmas with confinement properties significantly improved over those observed in auxiliary-heated L-mode-type tokamak discharges. This underscores the importance of understanding the physics responsible for the favorable trends exhibited, for example, by "supershot" discharges in TFTR and by H-mode-type divertor plasmas. In addressing this general issue, the present paper reports results of theoretical investigations dealing with: (1) the onset conditions of the microinstabilities most likely to influence enhanced confinement behavior; (2) gyrokinetic particle simulations and analytic studies of the saturation and transport properties of the most persistent forms of these instabilities; and (3) detailed comparisons of experimental results with predictions from transport codes using appropriate microinstability-based diffusivities and with local diffusivities from various theoretical models.

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MASTER

MICROINSTABILITIES IN ENHANCED CONFINEMENT TOKAMAK DISCHARGES

Previous studies [1-4] have established that drift-type microinstabilities driven by trapped-electron dynamics and by ion temperature gradients could account in large part for the anomalous thermal transport observed in Ohmic- and auxiliary-heated L-mode-type tokamak discharges. The present analysis emphasizes that their threshold conditions as well as spectral properties can be significantly different when the distinct features of the equilibrium distributions and profiles characteristic of enhanced confinement plasmas are incorporated in the calculations. For the supershot-type discharges, the non-Maxwellian response of the hot beam ions has now been included in the eigenmode equation for η_i -instabilities. Analytic estimates have been obtained from a simplified sheared slab model using a slowing-down-type distribution for the hot beam ions, the usual Maxwellian-type ion response for the target and thermalized beam populations, and the familiar Boltzmann response for the electrons. For the moderate wavelength modes most difficult to stabilize [i.e., $b_s(1+\eta_i)(T_i/T_e) \geq 1$ with $b_s \equiv k_{\perp}^2 \rho_s^2$, $\rho_s \equiv c_s/\Omega_i$ and c_s being the sound speed], the threshold (η_{ic}) is roughly estimated to be

$$\eta_{ic} \approx \eta_{ic}^{(0)} \left[1 + c_1 \frac{(2\lambda+1)}{b_s^2} \left(\frac{\tau}{1+\tau} \right) \frac{L_{ne}}{L_s} + \frac{c_1}{b_s} \left(\frac{\tau}{1+\tau} \right) \frac{(\eta_b)_{eff}}{n_{i0}} (c_e \eta_e - c_b \delta_b) \right] \quad (1)$$

with $\tau \equiv T_e/T_i$, $\eta_e \equiv (L_n/L_T)_e$ with L_n and L_T being the density and temperature gradient scale lengths, L_s is the shear scale length, c_1 , c_e , and c_b are numerical coefficients of order unity, λ is the radial mode number, $\delta_b \equiv (L_n)_i/(L_n)_b$, $(L_n)_b = -d \ln (\eta_b)_{eff}/dr$, $(\eta_b)_{eff}$ is the unthermalized beam density [with $(\eta_b)_{eff}/n_{i0}$ assumed small]. Here $\eta_{ic}^{(0)} = b_s(1+\tau)/(\tau-b_s)$ is the threshold value assuming no unthermalized beam effects. Equation (1) indicates that the threshold for η_i modes (η_{ic}) tends to be improved (i.e.,

these modes become more difficult to excite) if T_i/T_e is increased. However, if radially nonuniform toroidal rotation effects are taken into account, η_{ic} is found to be lowered with respect to Eq. (1) [5]. The first condition is easily satisfied in supershots while the latter is best avoided with balanced beam operation. The analytical trends just described are supported by numerical results from a comprehensive toroidal kinetic stability code whose features are given in detail in Ref. [6]. For supershots, appropriate anisotropic distributions computed by the BALDUR transport code are used in calculating the unthermalized beam ion response. The results generally indicate that for the computed values of η_i typical of the confinement region of supershot discharges (i.e., $\eta_i \lesssim 1$), the dominant modes are the collisionless trapped-electron instabilities driven by unfavorable magnetic drifts [7]. Since the η_i -type modes are apparently not excited in supershots and since the η_e effects (which further destabilize the trapped-electron modes) are also weak in such discharges, the observed improvement in the confinement properties appears to be consistent with the theoretical trends calculated.

In addressing H-mode plasmas, ion transit resonances have been included in analytic and numerical calculations for a sheared slab geometry [8]. Results in the weak density gradient limit show that the threshold becomes independent of L_n and can be expressed by

$$\left(\frac{1}{L_{Ti}}\right)_c \approx 1.9 \times [1 + T_i/T_e]/L_s \quad (2)$$

For inverted gradients ($\eta_i < 0$), instability is found to occur for $\eta_i < \eta_{ic}^{(-)}$ with

$$\eta_{ic}^{(-)} \approx - \left(1 + \frac{T_e}{T_i}\right) \quad (3)$$

These analytically derived criteria are well supported by numerical results from WKB and Shooting Code programs. Equation (2) compares reasonably well with estimates for $(L_{T1})_c$ for toroidal n_1 -modes. It is also significant to point out that in contrast to the positive n_1 and flat-gradient modes, the growth rate is much smaller than the real frequency even far away from the threshold for the negative n_1 -modes given by Eq. (3). This feature, in turn, helps to justify the application of standard weak turbulence procedures for calculating the reduced anomalous transport associated with their presence. Examinations of profiles characteristic of steady-state H-mode plasmas [9] indicate that some discharges are near the threshold given by Eq. (2) and some are either near to or violate the threshold given by Eq. (3). These results are, therefore, suggestive that the theoretical picture presented could be consistent with the improved confinement observed in experiments such as DIII-D.

NONLINEAR GYROKINETIC STUDIES OF n_1 -INSTABILITIES

Realistic threshold studies such as those just described continue to affirm the importance of n_1 -type instabilities. In order to help formulate a sounder physics-based diffusivity, the nonlinear properties of these modes have been the focus of gyrokinetic particle simulations [10] using a newly developed 3D model and of improved analytic mode coupling investigations. A dual spatial scale expansion, which allows the background pressure gradient to be fixed in time, is employed in the simulations to represent the quasistatic profiles typical of tokamak discharges. Results have been obtained for a 3D sheared slab with multiple rational surfaces. Detailed studies of the radial structures of the unstable n_1 modes have revealed that the fundamental ($i=0$)

harmonics of the eigenmodes dominate the fluctuation spectra and remain localized near the mode rational surfaces due to Landau damping. On the other hand, higher radial eigenmodes tend to move away from the rational surfaces and saturate at a much lower level near their respective resonant points, $x_i(\approx \omega L_g / k_y v_{ti})$. With respect to global spectral features, the simulations show that while the fluctuation spectrum for the potential decreases rapidly for large poloidal wave numbers, the spectrum for the ion pressure remains relatively constant. This trend is supported by analytic estimates from nonlinear mode coupling calculations in which the real frequency for the dominant lowest harmonic radial eigenmode is taken to be finite, i.e., $|\text{Re}(\omega)| \geq \gamma$, with γ being the growth rate. The analytic predictions that the saturation level of the fluctuations and the corresponding diffusivity are only weakly dependent on L_g are also in broad agreement with the simulation results. More specifically, the steady-state thermal diffusivity x_i , which is found to be nearly an order of magnitude lower than the quasilinear value at saturation in these collisionless studies, scales as $(L_g)^\alpha$ with $\alpha=0.2-0.3$. The simulation results further indicate that the observed thermal flux is mainly caused by the fluctuations of the modes with moderate wavelengths. Based on the mixing length argument of $x_i \sim \gamma (\Delta_k)^2$ involving the linear growth rate and the radial eigenmode width, we can show that $x_i \sim (L_g)^C$ for these type modes if the linear mode width based on the fluid theory is used. By arguing that Landau resonances can actually determine the mode width in the kinetic limit, we may use $\Delta_k \approx x_i$ instead and obtain $x_i \sim (L_g)^{0.5}$. The effective mode width corresponding to the simulation results apparently lies somewhere in between. Thus, compared to the existing theories, the present analysis seems better suited for the interpretation of the simulation trend. Before progressing to fully toroidal simulations, it is appropriate to first gain

some insight into the influence of VB and curvature drift effects on electrostatic modes. Accordingly, investigations of drift-interchange instabilities in a cylindrical geometry with magnetic shear has been carried out. The growth rates, real frequencies, and radial mode structures observed in the simulations agree well with the linear stability analysis, and the saturation level for the density and electrostatic potential compare favorably with mixing length estimates.

COMPARISONS OF EXPERIMENTAL RESULTS WITH MICROINSTABILITY-BASED MODELS FOR ANOMALOUS THERMAL TRANSPORT

Profile-constrained microinstability-based thermal diffusivities implemented in the BALDUR transport code have previously produced results demonstrating favorable agreement with transport properties from a large number and variety of discharges on TFTR [11,12]. These investigations have now been extended to the analysis of (i) improved-confinement pellet-fueled discharges on ALCATOR-C and ASDEX, (ii) the TEXT experiments exhibiting ion fluctuation features, (iii) T-10 plasmas with high central electron temperatures produced by strong ECH, and (iv) balanced-beam supershot cases in TFTR. For the peaked-density profile, pellet experiments on ALCATOR-C and ASDEX, the resultant low values of n_1 kept the n_1 -mode feature in the code from being activated. Since the results indicate good correlations with the observed enhanced confinement properties, they lend support to the theoretical picture that n_1 -modes are indeed suppressed in these cases [13]. Furthermore, in TEXT discharges where ion fluctuations were observed (and where $n_1 > n_{1c}$ was satisfied), the simulations are found to be in good agreement with the associated confinement data only when the n_1 -mode feature is activated in the code [14,15]. With regard to T-10 experiments, the simulations of Ohmic

discharges and steady-state, ECRH-heated, collisionless plasmas were found to be within 20% of measured temperatures [16]. In carrying out the simulation for collisionless cases, the model used was based on the presence of collisionless trapped-electron modes (CTEM) [7]. The radially local form of the associated anomalous ion diffusivity is related to the local electron diffusivity by

$$\chi_i = 1.5(1+1/\eta_i) (L_n/R) \chi_e . \quad (4)$$

In Table I are shown preliminary results for several TFTR supershots for which ion temperature profiles have been measured. The supershots are all in the collisionless regime with simulated values of η_i (in the confinement region between $q=1$ and $q=2$) falling below the critical thresholds discussed earlier in this paper. Simulated temperatures were found to be in agreement with experiment within about 20%. Table I also indicates reasonable correlations between the thermal confinement times simulated by BALDUR and those evaluated from experimental data by the TRANSP code for each of these deuterium discharges.

Local χ_e formulas from a number of theoretical models [17] have been tested against a TFTR data base derived from measured T_e , n_e , P_{rad} profiles and calculated heat depositions using the SNAP and TRANSP analysis codes. The data base consists of full aperture L-mode and Ohmic discharges ($R \approx 2.5$ m, $a \approx 0.8$ m, $B_T \approx 5.0$ T). Several different prescriptions for the ion heat conductivity have been used in the SNAP analyses. Ohmic discharges (0.8 MA $< I_p < 2.2$ MA) are constrained to be consistent with measured central values of T_i or neutron flux, and L-mode discharges (1.0 MA $< I_p < 2.5$ MA, $P_b < 15$ MW) are consistent with magnetic measurements of the stored energy. Fifty-seven

Ohmic and 131 L-mode cases have been analyzed with x_i set equal to x_e . Values for x_e from five supershots were obtained from time-dependent TRANSP analyses using measured T_i profiles. Comparisons between local x_e for the Ohmic and L-mode data sets (with $x_i=x_e$, $1 < q < 2$) and some theoretical formulas taken from Ref. [17] are shown in Table II. For the supershots, the fits were taken between the $q=1$ and $q=3$ surfaces. The correlation coefficient, R^2 , and the slope, C , are tabulated for drift wave models assuming profile constraints [x_e^{anom} (DTEM, CTEM)], local trapped-electron models [x_{eTP1} , x_{eTP2}], models based on skin-depth scaling arguments [x_{eKP2} , x_{eMd}], a local collisional drift wave model [$x_{e,DW2}$], and a prescription, $x_{e,RL}$, given by Rebut and Lallia [18]. As indicated in Table II, the profile-constrained models yield the best fit to the data. Similar results were obtained for a larger TFTR data base with either measured central T_i values or magnetic data used to constrain the analysis. This data set has also been fit to a power law, x_e^{PL} , using a set of seven dimensionless parameters [19]. The correlations for these fits are tabulated here to show the optimal level of agreement achievable for this data set assuming a power-law form for x_e .

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Table I. COMPARISON OF DRIFT WAVE MODEL RESULTS WITH DATA FOR TFTR SUPERSHOTS

Shot	$\bar{n}_e$	P_B	T_e^{sim}	T_e^{exp}	T_i^{sim}	T_i^{exp}	$\tau_{E,th}^{sim}$	$\tau_{E,th}^{exp}$	v_{*e}^{sim}	η_i^{sim}
	($10^{19}/m^3$)	(MW)	(keV)	(keV)	(keV)	(keV)	(sec)	(sec)		
22014	3.2	11.3	6.7	6.9	15	--	.14	--	.07	0.7
26762	2.5	11.6	6.8	7.4	20	20	.12	.10	.06	0.9
28813	2.4	12.0	6.5	6.0	22	17	.11	--	.06	0.8
29917	2.5	13.6	6.8	7.3	23	25	.11	.11	.05	1.0
29918	2.6	13.6	7.2	7.8	23	22	.12	.15	.05	0.9
30640	2.6	14.3	7.3	7.7	24	21	.11	.11	.05	0.9

TABLE II. CORRELATION COEFFICIENTS FOR THEORETICAL MODELS FROM ANALYSIS OF TFTR DATA

	OHMIC			L-MODE			SUPERSHOT		
	residual/variance	R ²	C	res/var	R ²	C	res/var	R ²	C
$\chi_e^{\text{anom}}(\text{DTEM})$	0.87	0.94	0.82	0.30	0.89	1.35	---	---	---
$\chi_e^{\text{anom}}(\text{CTEM})$	0.81	0.95	1.01	0.58	0.79	1.80	0.50	0.80	1.23
$\chi_{\text{ETP1}}^{\text{DTEM}}$	8.40	0.43	0.58	1.49	0.46	1.10	---	---	---
$\chi_{\text{ETP2}}^{\text{CTEM}}$	3.46	0.77	0.61	1.13	0.59	0.78	1.93	0.26	0.06
χ_{ekp2}	2.51	0.83	2.14	0.90	0.68	5.04	0.69	0.73	5.50
$\chi_{\text{e,DW2}}$	6.46	0.56	22.5	1.44	0.48	33.7	---	---	---
$\chi_{\text{e,Md}}$	6.95	0.22	0.01	1.32	0.52	0.26	0.86	0.66	0.22
$\chi_{\text{e,RL}}$	9.50	0.68	7.91	1.14	0.61	0.46	1.27	0.46	0.11
χ_e^{PL}	0.23 ^a	0.98 ^a	1.00 ^a	0.82 ^a	0.70 ^b	1.00 ^b	0.08 ^c	0.97 ^c	1.00 ^c
^a $\chi_e^{\text{PL}} B^2 / T_e^{3/2} \approx (L_n/R)^{1.3} (L_n/L_T)^{-1.2} (T_{e0}/T_{i0})^{-2.0} \beta^{-1.5} v_*^{0.81} q^{0.45} (r/R)^{-0.86}$									
^b $\chi_e^{\text{PL}} B^2 / T_e^{3/2} \approx (L_n/R)^{0.59} (L_n/L_T)^{-0.70} (T_{e0}/T_{i0})^{-0.02} \beta^{-0.58} v_*^{0.42} q^{1.2} (r/R)^{1.2}$									
^c $\chi_e^{\text{PL}} B^2 / T_e^{3/2} \approx (L_n/R)^{0.54} (L_n/L_T)^{-0.27} (T_{e0}/T_{i0})^{0.10} \beta^{-0.68} v_*^{1.3} q^{1.3} (r/R)^{0.58}$									

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