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by

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(presented by R.V. Budny)

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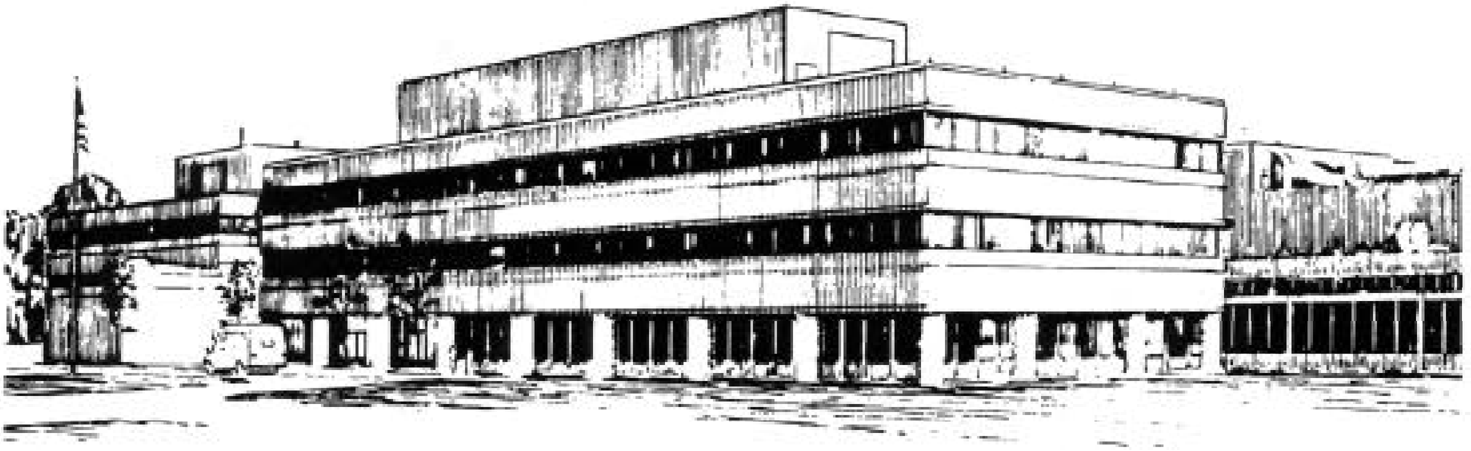

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Abstract ELMy H-mode plasmas form the basis of conservative performance predictions for tokamak reactors of the size of ITER. Relatively high performance for long durations has been achieved and the scaling is favorable. It will be necessary to sustain low $Z_{\rm eff}$ and high density for high fusion yield. This paper studies the degradation in confinement and increase in the anomalous heat transport observed in two JET plasmas: one in which the degradation occurs with an intense gas puff, and the other with a spontaneous transition at the heating power threshold from Type I to III ELMs. Linear gyrokinetic analysis gives the growth rate, $\gamma_{\rm lin}$ of the fastest growing mode. Our results indicate that the flow-shearing rate $\omega_{\rm E\times B}$ and $\gamma_{\rm lin}$ are large near the top of the pedestal. Their ratio decreases approximately when the confinement degrades and the transport increases. This suggests that tokamak reactors may require intense toroidal or poloidal torque input to maintain sufficiently high $|\omega_{\rm E\times B}|/\gamma_{\rm lin}$ near the top of the pedestal for high confinement.

1. Introduction

The H-mode regime in the Edge Localized Mode (ELM) phase is favored for large, conventional tokamak reactors since it is the only regime which has obtained enhanced performance for long durations. Deuterium-tritium experiments in JET ELMy plasmas have achieved $Q_{dt} = 0.2$ [1]; however the confinement tends to degrade as the density is increased towards the Greenwald limit. This degradation is often associated with the transition from Type I to III ELMs. There is experimental evidence that the $E \times B$ flow shearing rate, $\omega_{\rm E\times B}$ can have an influence on the confinement. Some plasma regimes, such as those with weak or reversed magnetic shear in JET and other tokamaks, have achieved considerably lower transport transiently, with ion thermal and particle transport near the neoclassical level. Generally these regimes have relatively large $\omega_{\rm E\times B}$, with magnitude significantly larger than the computed maximum growth rate, $\gamma_{\rm lin}$, of high n-toroidal modes associated with microturbulence [2]. JET ELMy H-mode plasmas heated by neutral beam injection (NBI) have large toroidal rotation rates, f_{tor}, with Mach numbers near unity in the center. Empirical fits [3] to the dimensionless heat transport $(\Omega_{\rm i} L_{Ti}^2/\chi_{\rm i})$, normalized by the local ion gyrofrequency and T_i scale length, indicate a reduction with increasing Mach number, further suggesting that $\omega_{\rm E\times B}$ plays an important role.

This paper studies the energy transport, $\omega_{\rm E\times B}$, and $\gamma_{\rm lin}$ in JET ELMy H-mode plasmas with NBI heating and both with and without intense gas puffing to obtain high density. A more detailed report has been submitted for publication [4]. Evidence is presented that, at least in the NBI-heated ELMy plasmas, $\omega_{\rm E\times B}$ plays a role in the degradation of confinement at high density and possibly in the transition to Type III ELMs. Energy confinement degradation occurs, in this picture, as a consequence of changes in the beam-induced rotation at high density causing the reduction of $|\omega_{\rm E\times B}|/\gamma_{\rm lin}$. Theory indicates that when this ratio decreases below a value of approximately unity, degradation should occur [5].

2. Results

We study two JET plasmas with parameters summarized in the Table:

Shot No. (year):	43002 (1997)	49687 (1999)
Type I→III transition:	Forced by gas puff	Spontaneous at threshold
Time traces:	Fig.1-a	Fig.1-b
R / a [m]	2.88 / 0.95	2.94 / 0.90
B_{Tor} [T]	2.8	2.0
I_p [MA]	2.6	1.9
P_{NB} [MW]	8 (T^0)+3 (D^0)	5 (D^0)
n_e	increase	large decrease
$n_e(0)/ < n_e >$	$0.9 \rightarrow 1.1$	≈ 1.3
$\bar{n}_e/\bar{n}_{Greenwald}$	$\rightarrow 0.85$	$0.75 \rightarrow 0.35$
f_{tor}	increase	large decrease
τ_E	20 percent decrease	50 percent decrease
$\chi_{\rm i}, \chi_{\rm eff}$	slight increase near pedestal	factor 2-3 increase

Table 1: *Summary of plasma parameters*

Both plasmas were heated with NBI, and both experienced a decrease in confinement, as seen in the W_{dia}, H_{89}, and H_{97} traces in Fig.1. One plasma is dominantly tritium, with intense gas puffing to achieve high density, making it the more reactor relevant of the two. The other is dominantly deuterium, with sufficiently low NBI power to be at the threshold for the Type I→III transition. Although less reactor relevant, this plasma supports the theoretical understanding of confinement degradation. The times chosen for the gyrokinetic analysis are indicated by the vertical dashed lines. The time evolution of the suppression ratio $|\omega_{\rm E\times B}|/\gamma_{\rm lin}$ at several radii near the top of the pedestal are shown in the bottom of Fig. 1. There is a tendency for the ratio to decrease to low values (reduction of suppression) when W_{dia} and the energy confinement decreases.

The ion heat conductivity $\chi_{\rm i}$ (Fig. 2) and the effective heat conductivity $\chi_{\rm eff}$ tend to increase as the confinement decreases. Details of the plasmas past the top of the pedestal, indicated by the vertical dashed lines in Fig. 2, are not modeled here. For 43002, $\chi_{\rm i}$ shows a moderate increase, especially at major radii R > 3.6m. For 49687, large changes are seen at all R. The measured thermal energy density profiles of JET ELMy H-mode plasmas generally are “stiff”, shifting up or down with the global W_{dia}. The measured profiles of T_i display two classes of behavior: they either shift by proportional amounts, as for 43002, or by equal amounts, as for 49687. In the first case, the heat conductivity appears to depend sensitively on T_i, and in the second, to be relatively independent of T_i. Near the mid-radius of both plasmas the major-radius normalized gradient, R/L_{Ti}, is close to the critical value, R/L_{crit} estimated by the IFS-PPPL model [6] (Fig. 3). For 43002, R/L_{Ti} exceeds the estimated critical value near the pedestal. For 49687, R/L_{Ti} is lower (sub-critical) near the pedestal. The measured toroidal rotation f_{tor} behaves very similarly to T_i. In the case of high density, the NBI heating and torque density decrease in the center as the beam penetration decreases. This correlates with the reduced T_i and

f_{tor} in the center. The radial electric field, E_r is calculated from the force balance for the trace carbon impurity, and the shearing rate $\omega_{\mathrm{E\times B}}$ is calculated from E_r [7].

Low frequency, electrostatic drift-type instabilities, driven by ion temperature gradient (ITG) and/or trapped-particle modes, are candidates for the anomalous transport generally observed in tokamak plasmas. We used the GS2 code [8] to calculate the linear growth rate γ_{lin} and the real part of the mode frequency ω_{lin} for the fastest growing mode. The GS2 code is a comprehensive initial-value electromagnetic code which solves the linearized gyrokinetic equation in a flux tube. We used up to eight species: thermal electrons, thermal hydrogenic ions, one impurity, and the fast ions from the NBI ions.

GS2 takes as input the product of the poloidal mode number k_θ (= nq/r in the circular approximation) and the ion gyro-radius ρ_i. We adjusted the value of $k_\theta \rho_i$ at each time-zone to find the value that maximizes γ_{lin}. Plots of the spectra at one time-zone are shown in Fig. 4. The mode frequency ω_{lin} is divided by ten for display in the plots. For 43002, ω_{lin} is positive (ion diamagnetic direction), and γ_{lin} has a broad peak versus $k_\theta \rho_i$ with a maximum value around $k_\theta \rho_i = 0.30\text{-}0.50$. This value is around the values typically found in other gyrokinetic simulations [9]. For 49687 with lower R/L_{Ti}, ω_{lin} is also positive near the midplane, but is negative close to the pedestal, typical of trapped electron modes (TEM), where γ_{lin} peaks at much higher $k_\theta \rho_i$. The "mixing length" estimate of χ_{i}, also in Fig.4, is given by $\gamma_{\mathrm{lin}}/(k_\theta^2 + < k_r^2 >)$, including the flux-tube average of the radial k_r. This peaks at low values of $k_\theta \rho_i$ for both cases, indicating that low $k_\theta \rho_i$ modes cause most of the anomalous transport. Because of this, for 49687 near the pedestal where the TEM dominates (as in Fig.4-b), we used a typical value of γ_{lin} near $k_\theta \rho_i \approx 0.5$ instead of the much higher values at large $k_\theta \rho_i$. Generally γ_{lin} is positive over a significant portion of the major radius near the outer midplane, with peak values in the region where $\omega_{\mathrm{E\times B}}$ peaks (Fig. 5). Deeper inside the plasma a state of marginal stability is maintained in the sense that γ_{lin} depends sensitively on R/L_{Ti}, which is close to its critical value. This is consistent with the observation that χ_{i} remains larger than approximately five times the neoclassical level over a wide range of densities and operating conditions.

3. Discussion

We presented transport and micro-instability results for two JET ELMy H-mode plasmas with degradation of confinement associated with the transition from the Type I to III ELMy phase. The heat conduction coefficient increases, especially near the pedestal as the global and local energy confinement degrades. For the plasma with intense gas puffing, γ_{max} remained relatively constant in time while $|\omega_{\mathrm{E\times B}}|$ decreased. For the plasma near the Type I→III transition, after the spontaneous transition, γ_{max} increased while $|\omega_{\mathrm{E\times B}}|$ remained constant. Thus the criterion for reduction of the microturbulence, $\alpha_{\mathrm{exb}}\ |\omega_{\mathrm{E\times B}}| \simeq \gamma_{\mathrm{max}}$, with $\alpha_{\mathrm{exb}} \simeq 0.5 - 2.0$ appears to be applicable to these plasmas within about 10 cm of the top of the pedestal. This suggests that tokamak reactors which rely on high density and high energy confinement in the ELMy H-mode may require a source of torque to maintain a high $|\omega_{\mathrm{E\times B}}|/\gamma_{\mathrm{lin}}$, at least near the top of the pedestal. It may prove more effective to drive poloidal than toroidal rotation since E_r (and indirectly $\omega_{\mathrm{E\times B}}$) are generated by the sum $v_{Pol}B_{Tor} + v_{Tor}B_{Pol}$. It may be sufficient to apply a torque dipole near the top of the pedestal.

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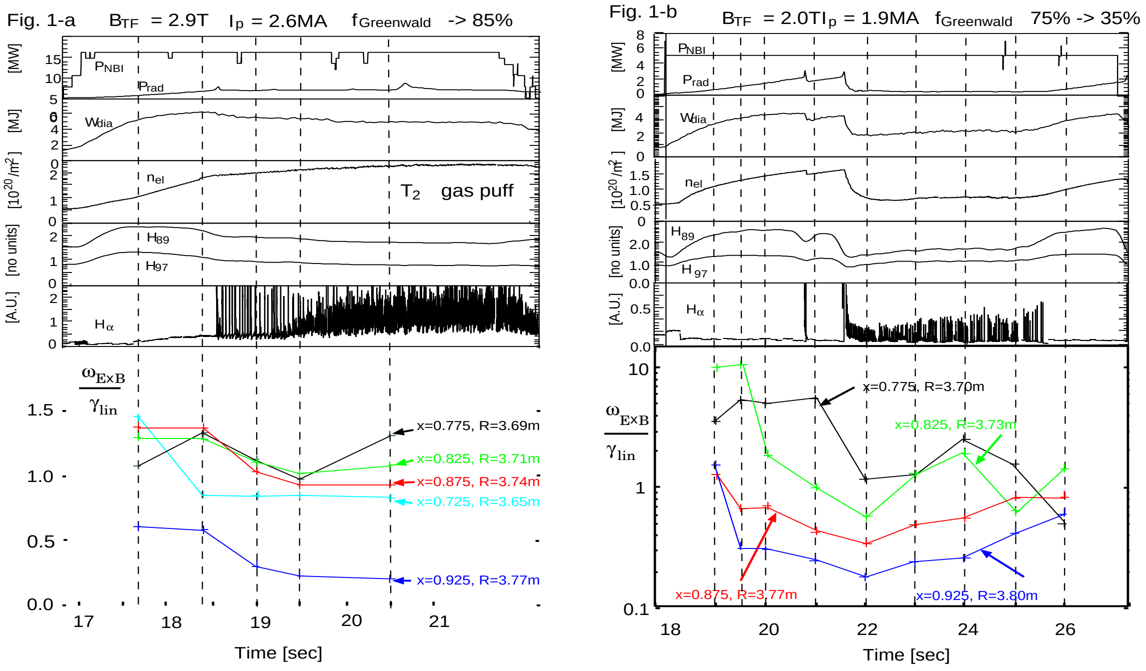

Fig. 1 Waveforms a) 43002 with intense gas puff b) with spontaneous Type I → III transition

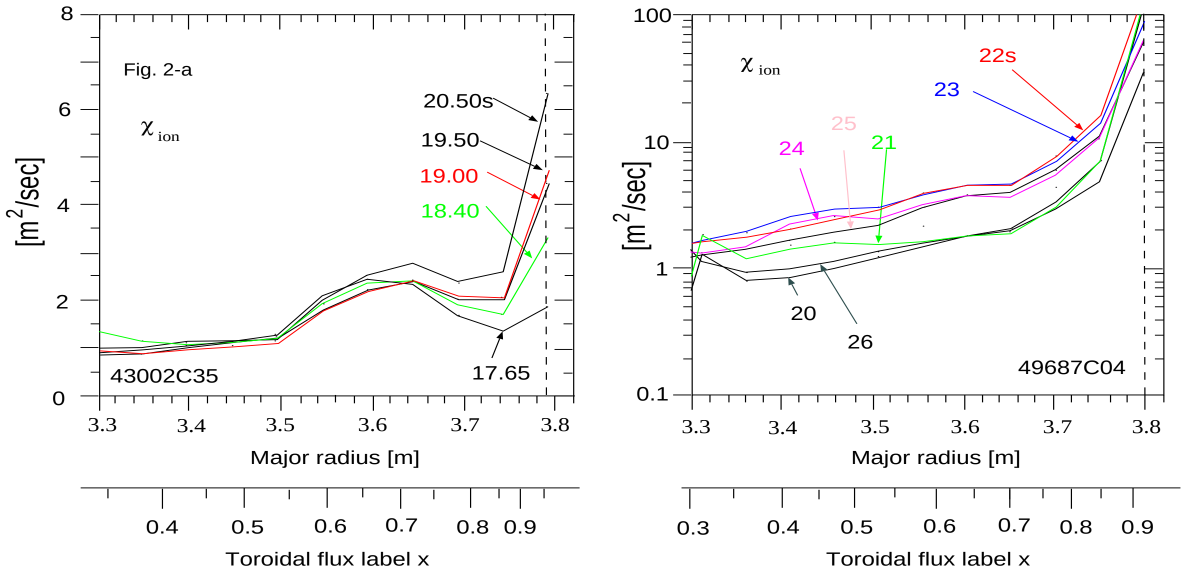

Fig. 2 anomalous ion heat conductivity vs major radius with conversion to toroidal flux label x

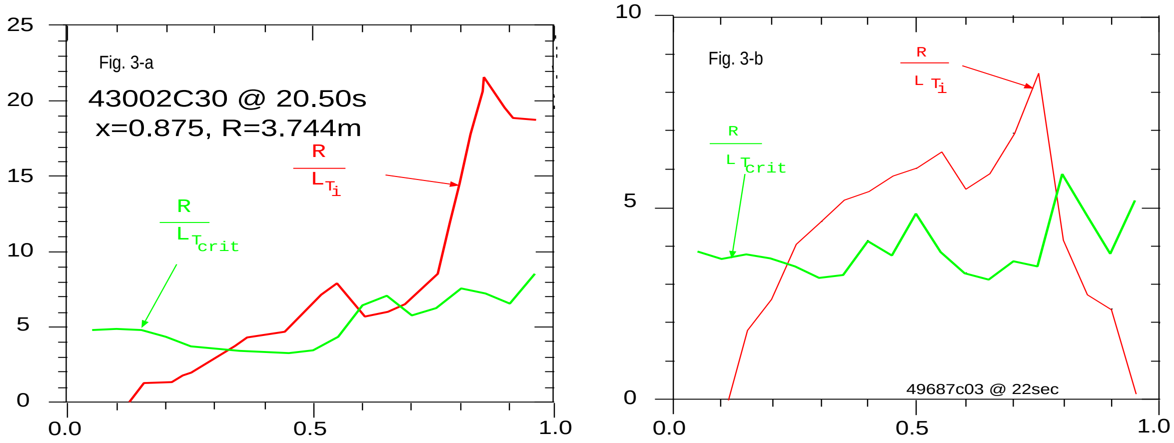

Fig 3 comparison of T_i gradiants with IFS-PPPL critical values vs toroidal flux label x

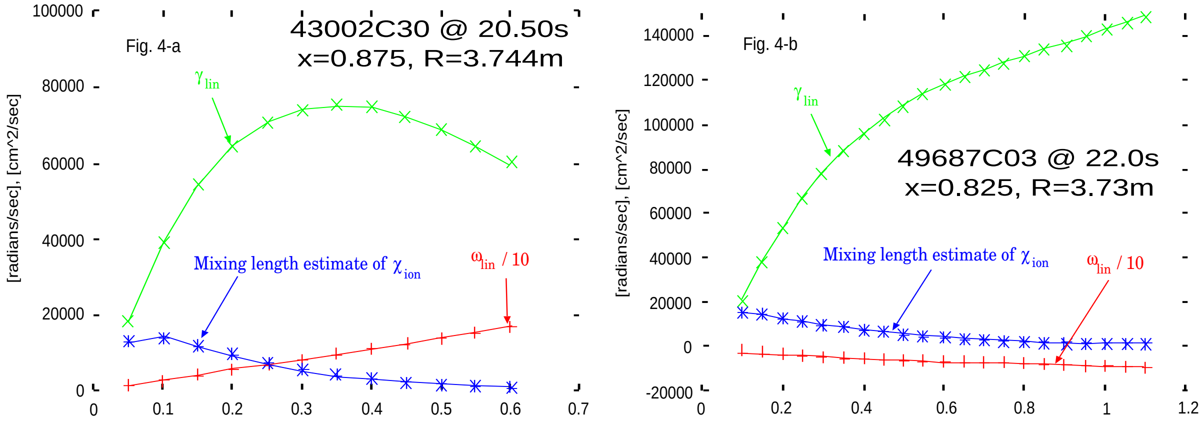

Fig 4 spectra of growth rates, mode frequencies, and mixing length estimates vs $k_\Theta \rho_i$

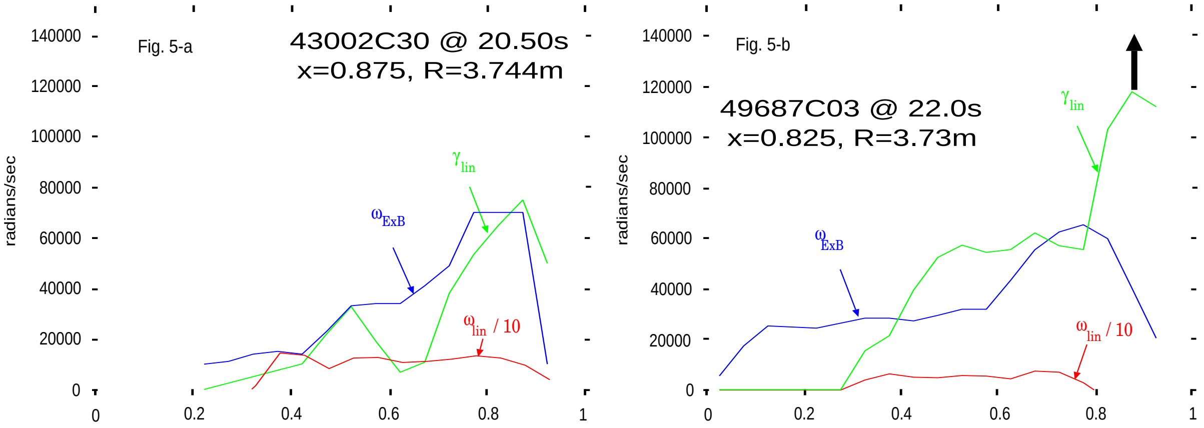

Fig 5 profiles of growth, mode frequency, and shearing rates vs toroidal flux label x

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