Local Physics Basis of Confinement Degradation in JET ELMy H-Mode Plasmas and Implications for Tokamak Reactors

The JET Team 1), presented by R.V. Budny 2,3)
JET JOINT UNDERTAKING, Abingdon, UK

1) Listed in contribution of C. Gormezano (IAEA-CN-77/OV1/2)
2) Permanent address: PPPL, Princeton Univ., P.O. Box 451, Princeton, NJ 08543, USA
3) Contributions of W. Dorland, D.R. Ernst, T.S. Hahm, G. Hammett, and E. Synakowski, and support of the US DoE Contract No. DE-AC02-76CH03073 are acknowledged

e-mail contact of main author: budny@princeton.edu

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 appears to be favorable. It will be necessary to sustain low Z_{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 ELMy H-mode plasmas: one with an intense gas puff, and the other with a spontaneous transition at the heating power threshold from Type I to III ELMs. Gyrokinetic analysis gives the linear growth rate, γ_{lin} of the fastest growing mode. The flow-shearing rate $\omega_{\text{E}\times\text{B}}$ and γ_{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 power reactors may require toroidal or poloidal torque input to maintain sufficiently high $|\omega_{\text{E}\times\text{B}}|/\gamma_{\text{lin}}$ 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 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, $\omega_{\text{E}\times\text{B}}$ 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 $\omega_{\text{E}\times\text{B}}$, with magnitude significantly larger than the computed maximum growth rate, γ_{lin} of high n-toroidal modes associated with microturbulence. An example of results for a JET plasma with an internal transport barrier is given in Ref. [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 $(\chi_{\text{i}}/(\Omega_{\text{i}} L_{Ti}^2))$ normalized by the local ion gyrofrequency Ω_{i} and T_i scale length L_{Ti}, indicate a reduction with increasing Mach number, further suggesting that $\omega_{\text{E}\times\text{B}}$ plays a role.

This paper studies the energy transport, $\omega_{\text{E}\times\text{B}}$, and γ_{lin} in JET ELMy H-mode plasmas with NBI heating and degradation of confinement. A more detailed report has been submitted for publication [4]. Evidence is presented that, at least in the NBI-heated ELMy plasmas, $\omega_{\text{E}\times\text{B}}$ plays a role in the degradation of confinement at high density. Energy confinement degradation occurs, in this picture, as a consequence of changes in the beam-induced rotation at high density causing the reduction of $|\omega_{\text{E}\times\text{B}}|/\gamma_{\text{lin}}$. Gyrofluid

simulation 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
χ_i, χ_{eff}	slight increase near pedestal	factor 2-3 increase

Table 1: *Summary of plasma parameters*
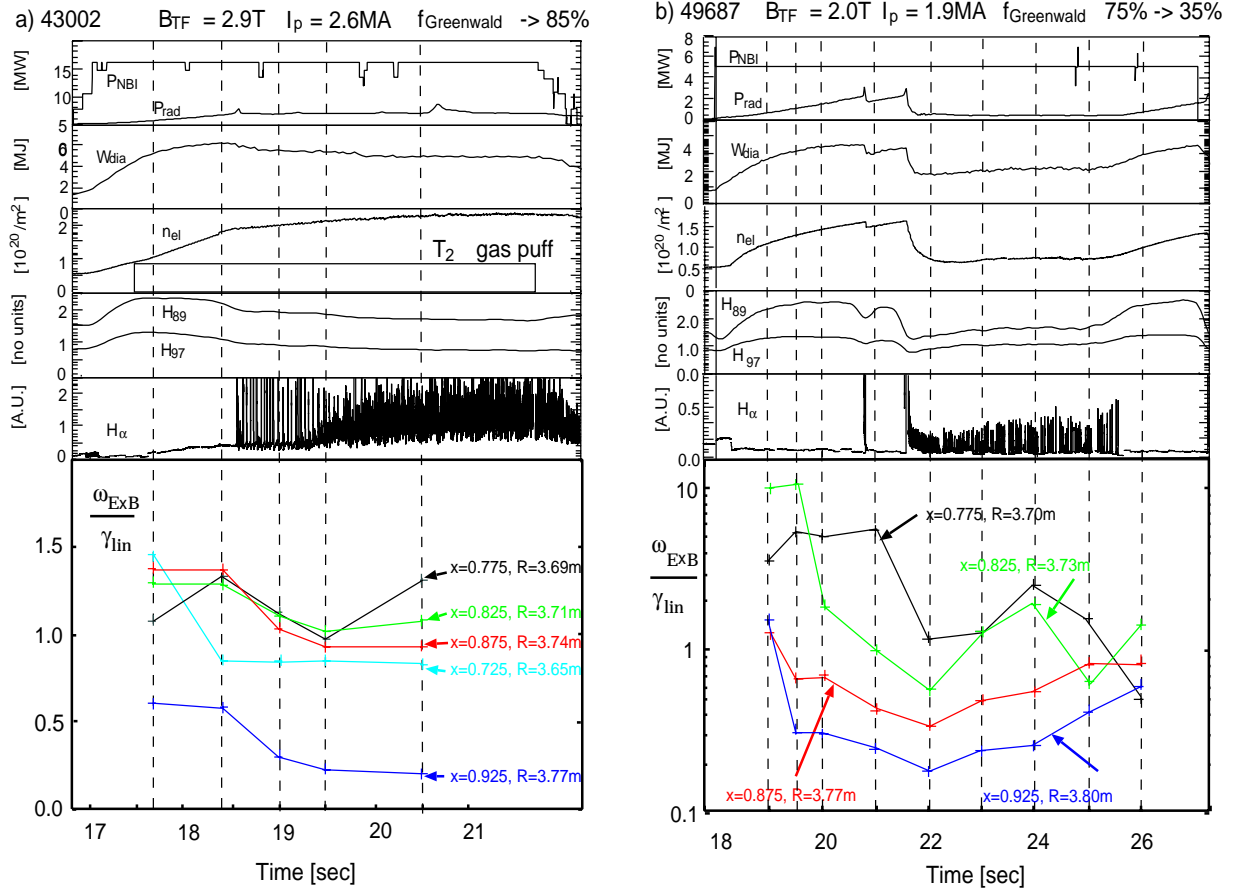
Figure 1: Top: waveforms of a) 43002 with intense gas puff and b) 49687 with a spontaneous Type I → III ELM transition; bottom: microturbulence suppression ratio as several radii near the top of the pedestal. Vertical dashed lines indicate analysis times.

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 was dominantly tritium, with intense gas puffing to achieve high density, making it the more reactor relevant of the two. The other was 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 connection between of the suppression ratio $|\omega_{E\times B}|/\gamma_{lin}$ and confinement degradation. The times chosen for the gyrokinetic analysis are indicated by the vertical dashed lines. The time evolution of $|\omega_{E\times B}|/\gamma_{lin}$ 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 χ_i (Fig. 2) and the effective heat conductivity χ_{eff} tend to increase as the confinement decreases. For 43002, χ_i shows a moderate increase, especially
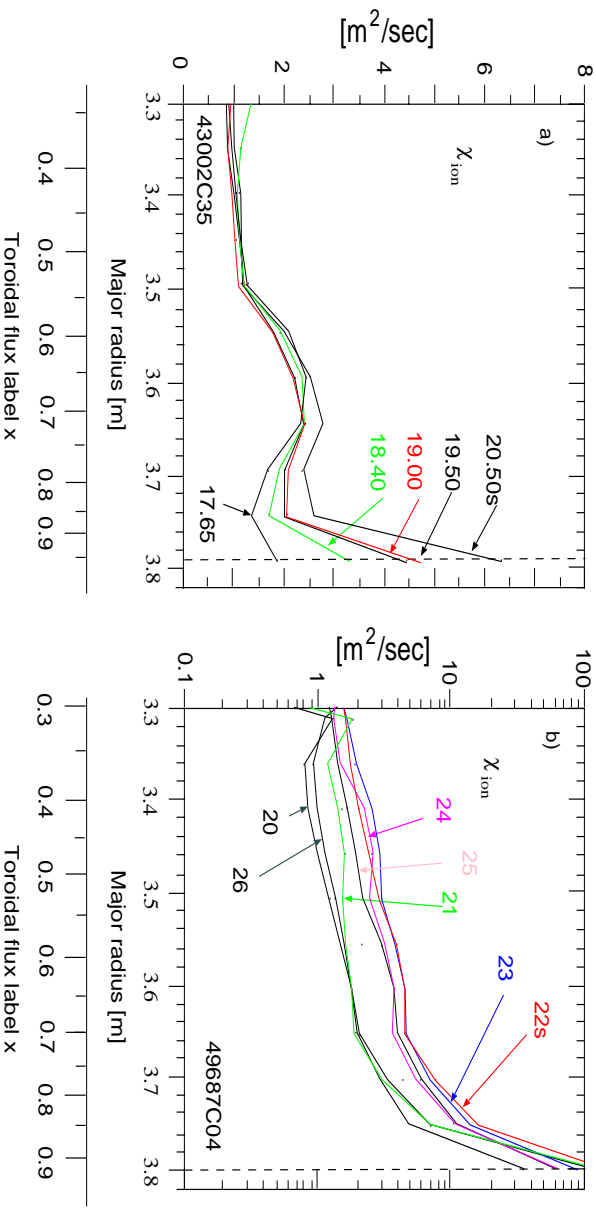

Figure 2: Ion heat conductivity vs major radius and toroidal flux label x. Vertical dashed lines indicate approximate location of top of pedestal.

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_{T_i}, is close to the critical value, R/L_{crit} estimated by the IFS-PPPL model [6] (Fig. 3). For 43002, R/L_{T_i} exceeds the estimated critical value by a factor of 2.5 near the pedestal. For 49687, R/L_{T_i} is lower (sub-critical) near the pedestal. The shapes and temporal behavior of the measured toroidal rotation f_{tor} are similar 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 in general toroidal geometry $\omega_{E\times B}$ is calculated from E_r [7].
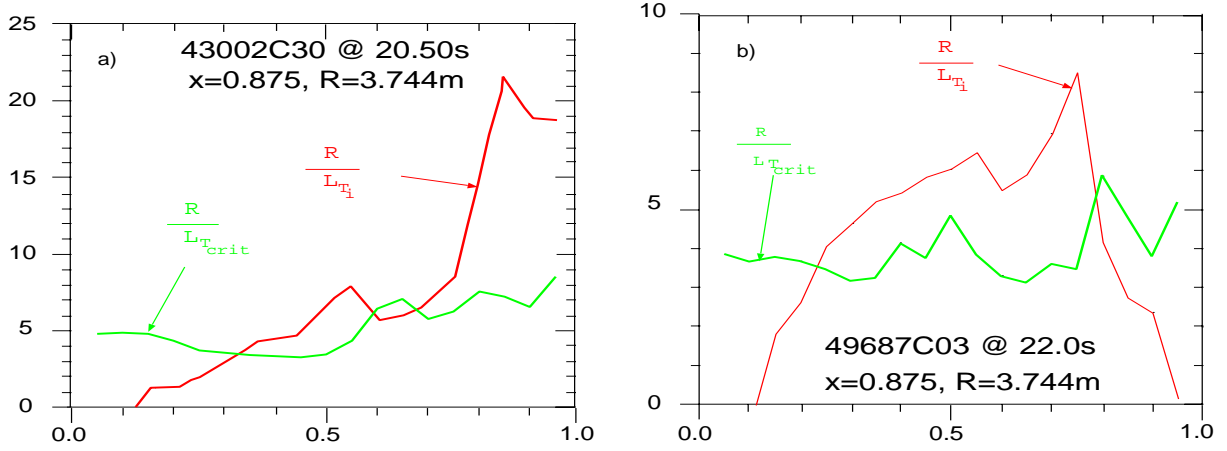
Figure 3: Comparison of normalized T_i gradients with the critical values estimated by the IFS-PPPL model vs toroidal flux label x

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.
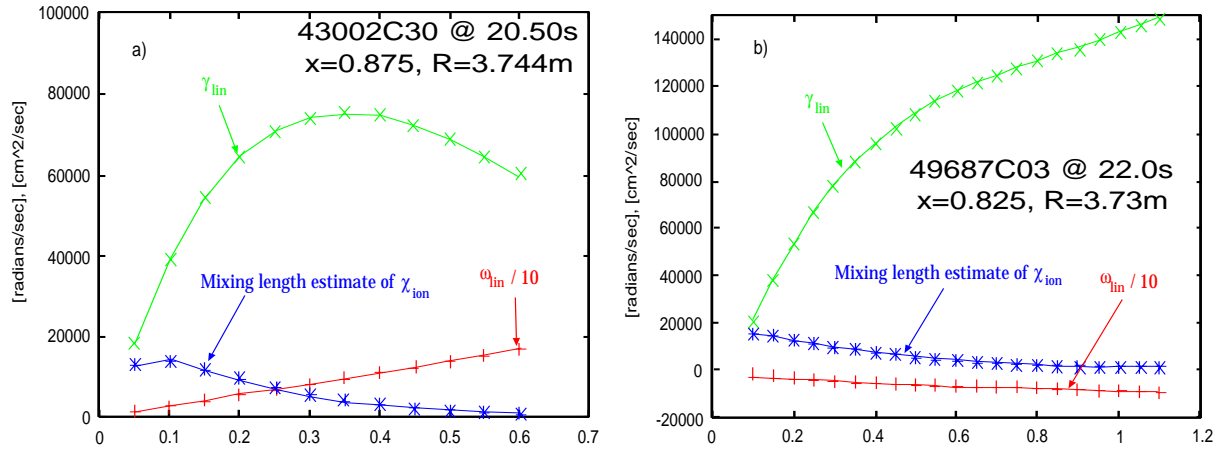

Figure 4: Spectra of maximum growth rate, mode frequency, and mixing length estimate of transport versus $k_\theta \rho_i$

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 $k_\theta \rho_i = 0.30$-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 $\gamma_{\text{lin}}/(k_\theta^2 + < k_r^2 >)$, 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
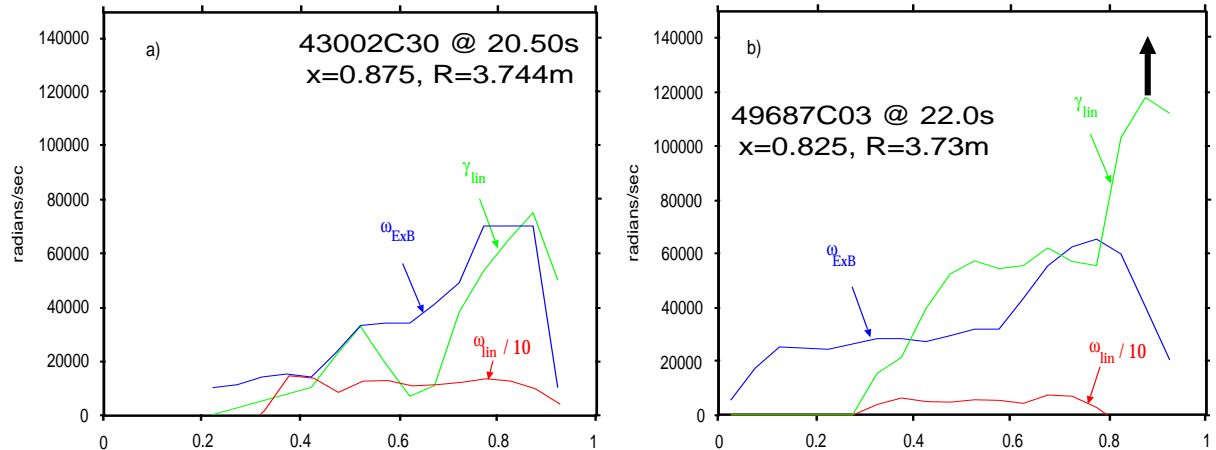

Figure 5: Profiles of the linear growth rate, mode frequency divided by 10, and flow shearing rate versus toroidal flux label x. The vertical arrow in b) indicates the region where much larger values of γ_{max} result from the TEM-branch.

of the major radius near the outer midplane, with peak values in the region where $\omega_{E\times B}$ 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 high density or the transition from the Type I to III ELMy phase. The heat conduction increases, especially near the top of the pedestal as the energy confinement degrades. For the plasma with intense gas puffing, γ_{max} remained relatively constant in time while $|\omega_{E\times B}|$ decreased. For the plasma near the Type I$\rightarrow$III transition, γ_{max} increased while $|\omega_{E\times B}|$ remained constant. Thus the criterion for reduction of the microturbulence, $\alpha_{\text{exb}} |\omega_{E\times B}| > \gamma_{\text{max}}$, with $\alpha_{\text{exb}} \simeq 0.5 - 2.0$ appears to be applicable to these plasmas within about 10 cm of the top of the pedestal. This suggests that tokamak power reactors relying on high density and high energy confinement in the ELMy H-mode may require a source of torque to maintain a high $|\omega_{E\times B}|/\gamma_{\text{lin}}$ near the top of the pedestal. It may prove more effective to drive poloidal rather than toroidal rotation since E_r and $\omega_{E\times B}$ 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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