GA–A22988

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FEBRUARY 1999

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This is a preprint of a paper to be presented at the 17th International Atomic Energy Agency Fusion Energy Conference, October 19–24, 1998, Yokohama, Japan.

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Work supported by
the U.S. Department of Energy
under Grant DE-FG03-95ER54309

GA PROJECT 3726
FEBRUARY 1999

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Abstract

A comparison of two types of DIII–D plasmas with improved core ion thermal transport is made. One is an H–mode edge weak magnetic shear discharge and the other is an L–mode edge negative central shear plasma. It is found that the region of reduced ion thermal transport is consistent with the region where theory predicts stability of ion temperature gradient modes in both cases. The electron thermal transport remains anomalously high throughout the plasma. The electron transport may be caused by the presence of electron temperature gradient modes in the outer part of the plasma. The modes are found to be linearly unstable even into the region of high E×B shear. In the central core no drift-ballooning modes are found to be unstable. The negative central shear case is predicted to be unstable to resistive interchange modes in the reversed shear region.

The stabilization of ion temperature gradient (ITG) modes by E×B velocity shear has been quite successful at explaining the ion thermal transport reduction observed in the core of tokamaks [1,2]. However, the electron thermal transport does not show the same improvement that the ions experience. It has been proposed [2] that the electron temperature gradeint mode [3] (ETG) could supply the anomalous electron thermal transport within the region of reduced ion thermal transport. The ETG mode is the electron analog to the ITG mode. In the electrostatic limit, with no trapped particles and with the Debye length smaller than an electron gyroradius, the linear growth rates for the pure ETG mode with adiabatic ions are exactly scaled from the ITG mode growth rate with adiabatic electrons by the square root of the ion/electron mass ratio. The poloidal wavenumber must also be scaled up by the same factor. This exact isomorphism has been used in a transport code to compute an approximate ETG mode electron energy flux [2]. The predicted electron temperature profile has been shown to agree well with the experimental one in a plasma with an internal ion thermal barrier [2]. The exact isomorphism between ITG and ETG modes is broken by the full kinetic theory. Both species are non-adiabatic, trapped particles and electromagnetic effects are important and the Debye length exceeds the electron gyroradius in low density tokamak plasmas. Therefore, it is necessary to go beyond the ITG-ETG isomorphism to determine if ETG modes are indeed linearly unstable in tokamaks.

A comprehensive gyrokinetic linear stability code is used in this paper. The original code [4] had a shifted circle model equilibrium. A new local equilibrium model [5], which includes elongation and triangularity, has been added to the code and has compared well to an independently programmed version [6]. A fully electromagnetic kinetic response has been implemented. With the new geometry, the magnetohydrodynamic (MHD) ballooning mode beta limit can be computed. It is found that there can be a large increase in the ITG mode growth rates due to electromagnetic effects even in some weak positive magnetic shear regions, which have no ideal MHD ballooning mode limit.

In previous work with the original code [4], the ETG mode was shown to be unstable in an L–mode plasma [7]. It was discovered that the ETG mode growth rates are reduced strongly if the kinetic response of impurity ions is included. The reduced electron thermal transport in plasmas with impurity injection is consistent with this mechanism combined with ExB shear reduction of ITG modes [7]. It has also been found that electron heating by fastwaves [8], or electron cyclotron waves [9], causes an increase in ETG mode growth rates in L–mode edge negative central magnetic shear discharges with core ion thermal barriers. In this paper we compare the linear drift-ballooning mode stability of a high beta weak central magnetic shear discharge with an H–mode edge to a high beta negative central magnetic shear plasma with an L–mode edge. Both discharges have reduced core ion thermal transport.

The first discharge to be analyzed (#87977) has a weakly positive magnetic shear in the core and an H–mode edge. The measured profiles of ion and electron temperature, electron, and carbon 6 densities, safety factor and carbon toroidal rotation are shown in Fig. 1. This discharge produced a record

*Work supported by the U.S. Department of Energy under Grant No. DE-FG03-95ER54309.

neutron flux for DIII–D [10,11]. The time chosen for analysis was very quiet both in externally measured magnetic fluctuations and in density fluctuations at 2 cm^{-1} [11]. However, there is coherent mode activity visible in the density fluctuation frequency spectrum. The power balance ion thermal diffusivity is near neoclassical across the whole plasma [10,11]. The electron thermal diffusivity is far above the electron neoclassical level. The measured E×B velocity shear [1] is compared to the computed maximum ITG mode growth rate in Fig. 2. When the E×B shear rate exceeds the maximum linear growth rate without E×B shear the ITG turbulence is predicted to be quenched [12]. This ITG quench rule was deduced from nonlinear simulations of ITG modes with adiabatic electron in the electrostatic limit. The growth rates in Fig. 2 have kinetic electrons, deuterons, carbon 6 and are fully electromagnetic. We will assume the quench rule is unchanged by the extended physics. The E×B shear rate exceeds the maximum ITG mode growth rate almost everywhere. The region $0.85 < r/a < 0.9$ where the growth rate exceeds the E×B shear rate has a pressure gradient above the ideal MHD limit.. Growth rate calculations have not been attempted beyond r/a=0.9 since the accuracy of the profiles at the edge is not sufficient. The linear growth rate spectrum at r/a=0.7 is displayed in Fig. 3. The low-k maximum is the MHD enhanced ITG mode. The high-k maximum is the ETG mode. Even though the local E×B shear (horizontal line in Fig. 3) is well above the ITG mode growth rates it is not above the ETG mode peak. Because the wavenumber of the ETG modes is higher than the inverse of the ion gyroradius (6.4 cm^{-1} at this radius) the ETG modes are expected to produce mostly an electron heat flux. Thus, the presence of ETG modes at this radius is a good candidate for explaining the anomalous electron thermal transport. The extent of the region unstable to ETG modes is shown in Fig. 4. Plotted in Fig. 4 are $a/LT_e = -a(dT_e/dr)/T_e$ (a = minor radius) measured and the minimum value $a/LT_{e\ crit}$ need for the ETG mode to be unstable. The ETG modes are predicted to be unstable from r/a=0.47 outwards. There is a gap between the point where the ETG modes become linearly stable and the center where we do not find any drift-ballooning modes linearly unstable. The gyrokinetic stability code uses the ballooning representation and cannot resolve interchange modes. The magnetic shear is close to the minimum needed for an ideal MHD instability to exist over much of the core. Thus, it is possible, within the experimental uncertainty in the q-profile, that MHD balloning modes could be controlling the electron pressure profile in the central core.

The second discharge (#87031) is a negative central shear plasma. The measured profiles are shown in Fig. 5. This plasma had an L–mode edge. The power balance thermal diffusivities of both electrons and ions are large in the outer half of the plasma [10]. The maximum ITG growth rate is compared to the E×B shearing rate in Fig. 6. There is a good correspondence between the crossing of the E×B shear rate and the ITG growth rate and the drop in ion thermal diffusivity [10]. Again it is found that the ITG mode growth rates have a substantial electromagnetic enhancement outside of r/a=0.6 in the positive magnetic shear region. The large ITG mode growth rates make it difficult to expand the transport barrier into the positive magnetic shear region. This provides an explanation for

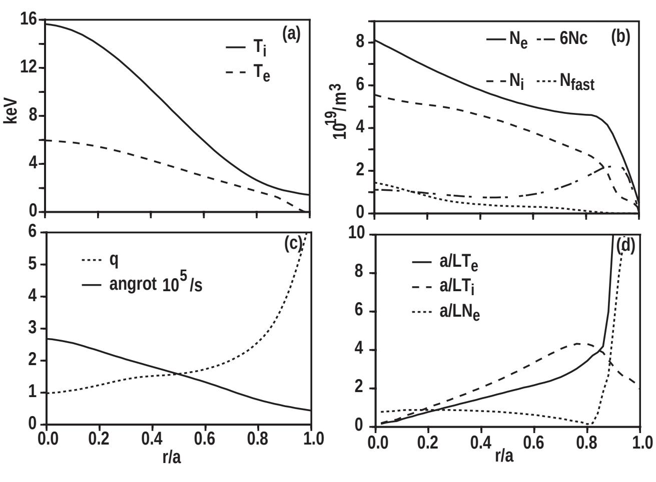

FIG. 1. DIII–D discharge #87977 at 2.5 s. (a) ion and electron temperatures, (b) electron, ion, carbon 6^+ (× 6) and fast ion densities, (c) safety factor (q) and carbon 6^+ toroidal angular rotation rate, (d) normalized logrithmic gradients. All profiles are measured except the fast ion density and deuterium ion densities which are computed by TRANSP.

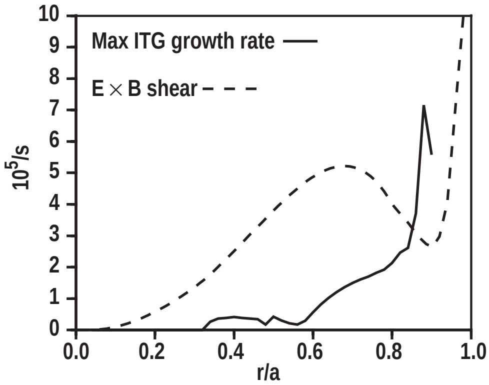

FIG. 2. Computed ITG mode growth rate profile maximized over poloidal wavenumber and E × B shearing rate from carbon 6^+ data for DIII–D discharge #87977 at 2.5 s.

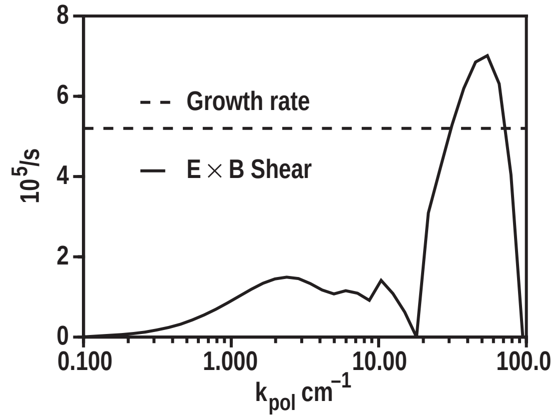

FIG. 3. *Growth rate spectrum for discharge #87977 at 2.5 s at r/a = 0.7. The local E × B shearing rate is shown as a horizontal line.*

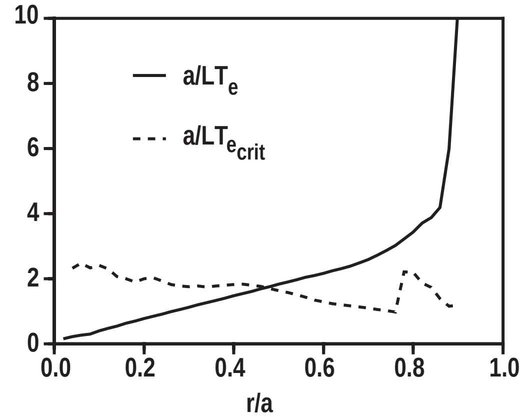

FIG. 4. *Measured a/LT_e for discharge #87977 at 2.5 s and computed critical value a/LT_{ecrit} for ETG modes to be unstable.*

the common observation that the leading edge of the "transport barrier" tends to not exceed the radius of zero magnetic shear [1]. The concept of a maximum ITG mode growth rate breaks down beyond r/a=0.7 in most L–mode edge plasmas that have been analyzed. The linear growth rate spectrum at r/a=0.8 is shown in Fig. 7. The maximum in this spectrum is an ETG mode. Since there is a continuous spectrum of unstable ion and electron modes, non-linear simulations need to be extended to include the both ITG and ETG modes in order to accurately predict the transport. The measured a/LT_e is at or above the minimum required for ETG mode instability into r/a=0.35 as shown in Fig. 8. The electron temperature gradient a/LT_e in Fig. 8 starts to rise at r/a=0.50. This is inside of the location (r/a=0.54) where the E×B shear exceeds the maximum ITG mode growth rate. The rise in a/LT_e follows the critical gradient for ETG modes into the ion thermal barrier region until r/a=0.35. Something, which does not show up as a linear drift ballooning mode, suppresses the electron temperature profile from this point inward. The local stability condition for resitive interchange modes [13] D_R is also shown in Fig. 8. The region of positive D_R is unstable to interchange modes. Note that this corresponds to the region with negative magnetic shear [Fig. 1(c)] and a strong pressure gradient. In this case there is a good agreement between the region where the ETG modes become stable and the interchange modes become unstable. However, in lower power plasmas, a similar flattening of the electron temperature gradient below the ETG mode threshold occurs near the plasma center but D_R is computed to be negative. A kinetic version of the interchange mode may have a lower threshold. High wavenumber tearing modes [14] are another candidate. Resolution of these modes would have required larger grids than where used.

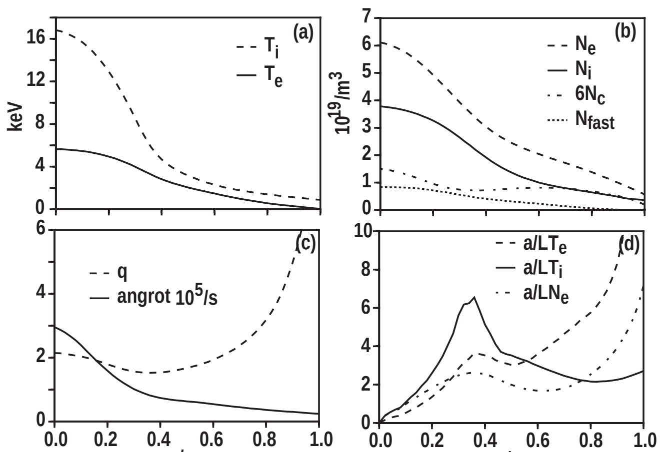

FIG. 5. *DIII–D discharge #87031 at 1.82 s. (a) ion and electron temperatures, (b) electron ion, carbon 6^+ (×6) and fast ion densities, (c) safety factor and carbon 6^+toriodal angular rotation rate, (d) normalized logarithmic gradients.*

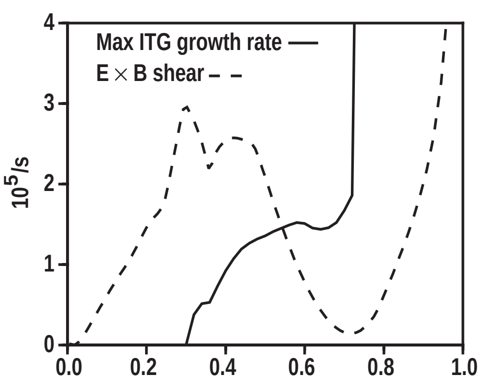

FIG. 6. *Computed ITG mode growth rate profile maximized over polodial wavenumber and E×B shearing rate from carbon 6^+ data for DIII–D discharge #87031 at 1.82 s.*

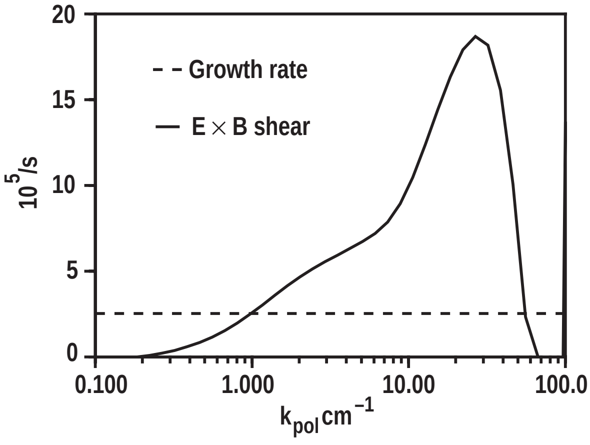

FIG. 7. Growth rate spectrum for discharge #87031 at 1.82 s at r/a = 0.8.

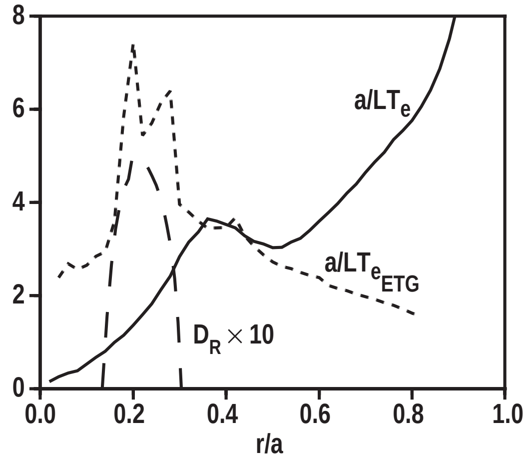

FIG. 8. Measured a/LT_e for discharge #87031 at 1.82 s and computed critical value of $a/LT_{e\ crit}$ for ETG modes to be unstable. Also shown is the computed resistive interchange stability parameter D_R.

Linear growth rate analysis of two enhanced core confinement discharges have been presented in this paper. In both the weak positive magnetic shear H–mode and the negative magnetic shear L–mode there is a region of reduced ion thermal transport consistent with E×B shear quenching the ITG modes. High wavenumber ETG modes remain unstable from the edge of the plasma well into the region of reduced ion transport. The anomalous electron thermal transport shows little reduction in this region. Only electron thermal transport is expected to be enhanced by ETG modes. In the high-pressure core, another mechanism takes control of the electron transport. The electron temperature gradient drops below the threshold for ETG modes. For the negative magnetic shear case resistive interchange modes are predicted to be unstable. Thus, even though negative magnetic shear and a large Shafranov shift are stabilizing to ETG modes an electron thermal confinement improvement is not realized in the negative shear region. The cause of the anomalous electron transport in the central core of the weak magnetic shear discharge is unexplained by linear drift-ballooning mode stability in the wavenumber range studied.

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