GA–A22617

CORE TURBULENCE AND TRANSPORT REDUCTION IN DIII–D DISCHARGES WITH WEAK OR NEGATIVE MAGNETIC SHEAR

by
G.M. STAEBLER, C.M. GREENFIELD, D.P. SCHISSEL, K.H. BURRELL,
T.A. CASPER,[†] J.C. DeBOO, E.J. DOYLE,[‡] R,.J. FONCK,[△] L.L. LAO,
E.A. LAZARUS,[◊] G.A. NAVRATIL,[#] C.L. RETTIG,[‡] T.L. RHODES,[‡]
B.W. RICE,[†] H.E. St. JOHN, B.W. STALLARD,[†] E.J. STRAIT, R.E. WALTZ,
and the DIII–D TEAM

JUNE 1997

GA–A22617

CORE TURBULENCE AND TRANSPORT REDUCTION IN DIII–D DISCHARGES WITH WEAK OR NEGATIVE MAGNETIC SHEAR

by
G.M. STAEBLER, C.M. GREENFIELD, D.P. SCHISSEL, K.H. BURRELL,
T.A. CASPER,[†] J.C. DeBOO, E.J. DOYLE,[‡] R.J. FONCK,[△] L.L. LAO,
E.A. LAZARUS,[◊] G.A. NAVRATIL,[#] C.L. RETTIG,[‡] T.L. RHODES,[‡]
B.W. RICE,[†] H.E. St. JOHN, B.W. STALLARD,[†] E.J. STRAIT, R.E. WALTZ,
and the DIII–D TEAM

This is a preprint of a paper to be presented at the Twenty-Fourth European Conference on Controlled Fusion and Plasma Physics, June 9–14, 1997, Berchtesgaden, Germany, and to be published in the *Proceedings*.

[†]Lawrence Livermore National Laboratory
[‡]University of California, Los Angeles
[△]University of Wisconsin, Madison
[◊]Oak Ridge National Laboratory
[#]Columbia University

Work supported by
the U.S. Department of Energy
under Contract Nos. DE-AC03-89ER51114, W-7405-ENG-48,
DE-AC05-96OR22464, and Grant Nos. DE-FG03-86ER53266,
DE-FG02-92ER54139, and DE-FG02-89ER53297

GA PROJECT 3466
JUNE 1997

CORE TURBULENCE AND TRANSPORT REDUCTION IN DIII–D DISCHARGES WITH WEAK OR NEGATIVE MAGNETIC SHEAR*

G.M. Staebler, C.M. Greenfield, D.P. Schissel , K.H. Burrell, T.A. Casper,† J.C. DeBoo,
E.J. Doyle,‡ R.J. Fonck,◊ L.L. Lao, E.A. Lazarus,Δ G.A. Navratil,# C.L. Rettig,‡
T.L. Rhodes,‡ B.W. Rice,† H.E. St. John, B.W. Stallard,† E.J. Strait, R.E. Waltz
and the DIII–D team

General Atomics, P.O. Box 85608, San Diego California, 92186-5608 U. S. A.

Core turbulence fluctuation levels have been suppressed in DIII–D discharges with weak or negative magnetic shear (NCS) near the magnetic axis. In some weak magnetic shear discharges the ion thermal transport has been reduced to neoclassical levels throughout the whole plasma. The cause of the transport reduction is investigated by calculating the stability of toroidal drift waves i.e. ion temperature gradient modes (ITG) and trapped electron modes (TE), with a comprehensive gyrokinetic linear stability code. It is found that the ITG modes and TE modes are stabilized by E×B velocity shear. The E×B velocity shear is primarily responsible for the spontaneous growth of a region of suppressed ion thermal transport. Surprisingly, the negative magnetic shear and Shafranov shift are only weak stabilizing influences for the ITG and TE modes in the DIII–D cases studied. Negative magnetic shear does eliminate the ideal magnetohydrodynamic ballooning mode instability which is a necessary access criteria for these improved core confinement regimes. Dilution of the thermal ions by fast ions from the heating beams and hot ions compared to electrons are found to be important stabilizing influences in the core.

The linear growth rates for toroidal drift waves are computed using a code written by M. Kotschenreuther [1]. This is an initial value code so it finds the most unstable mode (either ion or electron branch) at the given poloidal wavenumber. The code uses ballooning co-ordinates and has the full gyro-averaged kinetic linear response for both electrons and ions. The impurity ion species and the fast ion (from neutral beam heating) response were assumed to be adiabatic with only the effective charge (Z_{eff}) and ion dilution contributing to the growth rate calculation. The magnetic equilibrium is modeled by shifted circles ($\hat{s}$,alpha). Even though the stability code has a full electromagnetic response implemented, the ideal magnetohydrodynamic (MHD) ballooning mode limit for this model geometry is not accurate for the elongated double null DIII–D discharges. Thus, the growth rates computed for actual plasmas were done in the electrostatic approximation in order to avoid an unrealistically low MHD threshold. Parallel velocity shear was added to the original code by R.R. Dominguez and A. Brizard. Inclusion of the E×B shear in a ballooning co-ordinate code presents some technical difficulties which make a direct calculation of linear stability including E×B shear hard to interpret. It has been shown from non-linear simulations of toroidal drift wave turbulence that the turbulence quenches when the E×B shear rate is comparable to the maximum linear growth rate in the absence of E×B shear [2]. Furthermore, the saturated fluctuation intensity was found to be proportional to the net growth rate defined as the maximum growth rate minus the E×B shear rate:

---

*Work supported by U.S. Department of Energy under Contract Nos. DE-AC03-89ER51114, W-7405-ENG-48, and DE-AC05-96OR22464 and Grant Nos. DE-FG03-86ER53266, DE-FG02-92ER54139, and DE-FG02-89ER53297.

†Lawrence Livermore National Laboratory. ‡University of California, Los Angeles.
◊University of Wisconsin, Madison. ΔOak Ridge National Laboratory. #Columbia University.

$$\gamma_{\mathrm{net}} = \gamma_{\mathrm{max}} - \omega_{\mathrm{E\times B}}, \quad \omega_{\mathrm{E\times B}} = \frac{\mathrm{RB_p}}{\mathrm{B_T}} \frac{\partial}{\partial \mathrm{r}} \left(\mathrm{E_r} / \mathrm{RB_p} \right) \tag{1}$$

where B_p, B_t are the poloidal and toroidal magnetic field components, R is the major radius, r the minor radius and E_r the radial electric field. This is not an exact prescription. In general there is dependence on magnetic shear and other factors [2] which can be up to a twofold variation in the coefficient of the E×B shear rate. This should be kept in mind when comparing the E×B shear rate to the maximum growth rate in the figures to follow. In all the figures in this paper the linear growth rates have been maximized with respect to the poloidal wavenumber. The maximum growth rate can sometimes have a large poloidal wavelength shift as a parameter such as density gradient length is varied. This can result in a very different stability trend for the maximum growth rate than what would be inferred from the growth rate at fixed poloidal wavenumber. The gyrokinetic stability of NCS discharges has been studied using G. Rewoldt's eigenvalue code, with similar physics included [3]. Our findings are in accord with theirs. The ion temperature gradient (ITG) and trapped electron mode (TE) are the dominant instabilities in the core of NCS plasmas [3]. The ITG branch is dominant for flat density profiles. The three main drives are the density gradient length, the temperature gradient length and the parallel velocity gradient.

Peaking the density profile excites the TE mode. The Shafranov shift (α) is included in these parameter scans through the formula

$$\alpha = 2\,\beta \mathrm{q}^2 \left(\mathrm{a/L_T} + \mathrm{a/L_n} \right)\ \mathrm{R/a} \tag{2}$$

A large Shafranov shift has been proposed as the primary stabilizing mechanism in some reversed magnetic shear discharges [4]. We find that decreasing the density or temperature gradients lengths alone results in an increased maximum growth rate even though the Shafranov shift increases. However, increasing the pressure (β) is strongly stabilizing for reversed magnetic shear, as shown in Fig. 1, due to the electromagnetic coupling and the Shafranov shift. Of course, for positive magnetic shear the ideal MHD limit greatly enhances the growth rates with beta as shown in Fig. 1. Figure 1 also illustrates that there is nothing special about zero magnetic shear. Strong magnetic shear of either sign is stabilizing. But for comparable stabilization about twice as much positive magnetic shear compared to negatively magnetic shear is required. The other primary stabilizing influences found in NCS plasmas (besides β) are hot ions $T_i/T_e>1$ and fast ion dilution. The E×B shear causes a second stability of ITG and TE modes for large temperature, density or toroidal velocity shear. This is illustrated in Fig. 2. The density and temperature gradients are increased together and the E×B shear is taken to be due to the diamagnetic velocity (no toroidal momentum injection) by the formula

$$\omega_{\mathrm{E\times B}} = \rho_{\mathrm{i}} / \mathrm{a} \left(\mathrm{a/L_T} \right) \left(\mathrm{a/L_n} \right) \tag{3}$$

The ion gyroradius (ρ_i) was taken to be 0.01 times the minor radius (a) in Fig. 2. The E×B shear increases faster than the maximum growth rate with the gradients so the net growth rate γ_{net} has a second stability at large gradients. The first and second stability points (zero's of γ_{net}) are distinguished by two features. Both $\omega_{E\times B}$ and γ_{max} are small at the first stable point and both are large for the second. The derivative of γ_{net} with respect to $\omega_{E\times B}$ has opposite signs at the two zeros.

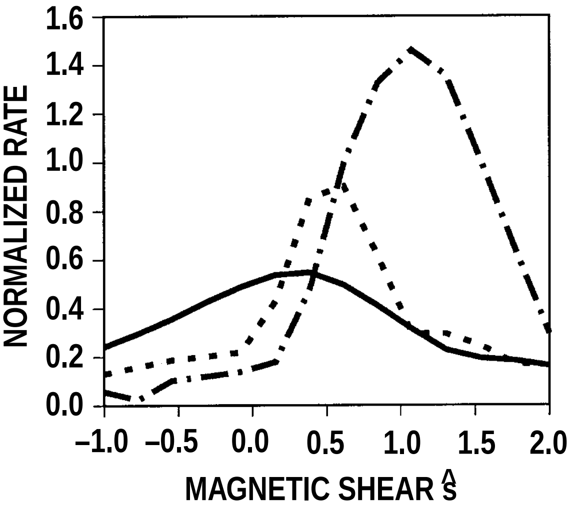

Fig. 1. Maximum growth rate vs. magnetic shear for β=0.0 (solid), β=0.005 (dashed), β=0.01 (dot-dashed). Rates are nomalized by $\left(\sqrt{T_e/m_i}\right)/a$.

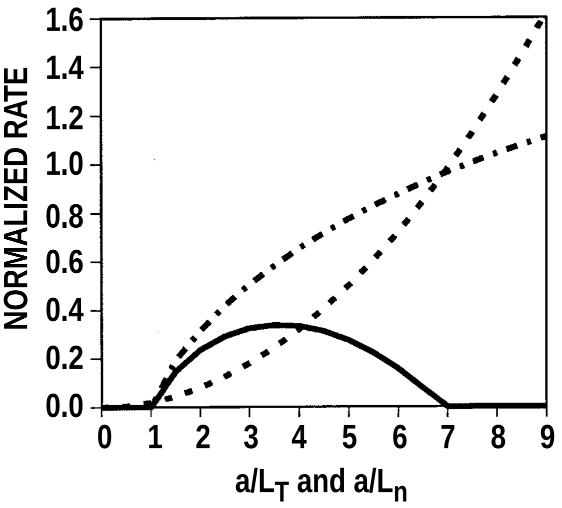

Fig. 2. γ_{net} (solid), $\omega_{E\times B}$ (dashed) and γ_{max} (dot-dashed) variation with a/L$_T$=a/L$_n$.

$$d\gamma_{net}/d\omega_{E\times B} > \text{ first stable,} \qquad d\gamma_{net}/d\omega_{E\times B} < 0 \text{ second stable.} \qquad (4)$$

This suggests a way of determining if the E×B shear has caused the stabilization of the turbulence or is just an effect of the improved confinement. If the point where γ_{net} vanishes is of the second stable type, then reducing the E×B shear would cause a return of the instability and hence the E×B shear is required for stability. If the zero of γ_{net} is of the first stable type, then increasing the E×B shear would make the toroidal drift modes unstable. An example from a DIII–D shot is shown in Fig. 3. This is a high power NCS discharge with a well established region of suppressed ion thermal transport out to r/a=0.5 [5]. The point at r/a=0.5 where $\gamma_{max}=\omega_{E\times B}$ is clearly a second stable point since γ_{net} is decreasing in the direction in which $\omega_{E\times B}$ increases. It is very typical of the dozen or so NCS discharges which have been analyzed in this way that the leading edge of the region of transport improvement is near a second stable point. This shot also shows another typical feature which is that farther into the region of improved transport, near the magnetic axis, the toroidal drift waves, in the ion gyroradius wavelength range, are linearly stable even without the E×B shear. Looking now at the low power formation phase of this same discharge in Fig. 4 we find that the region of improved confinement is smaller (r/a<0.3) [5]. The zero of γ_{net} at r/a=0.3 is ambiguous since $d\omega_{E\times B}$=0 showing that our classification scheme does not always work. The maximum growth rate was computed without the Shafranov shift to evaluate the importance of this factor in stability. As shown in Fig. 4 the maximum growth rate is only weakly affected. The maximum growth rate with the fast ion dilution removed and with $T_i=T_e$ is also shown (Shafranov shift as measured). In the center of the plasma these two effects have about the same stabilizing effect on γ_{max}. With both ion dilution and hot ions turned off the maximum growth rate exceeds the E×B shear in the center. Thus, the way in which this plasma was formed, with low target density and early neutral beam injection during the current ramp phase, greatly stabilized the plasma in the center due to the fast ion dilution and the hot ions. To a lesser extent the Shafranov shift was also stabilizing. The lower growth rate reduces the E×B shear required to initiate the transport barrier. Even after the E×B shear has formed a transport barrier, the effect of the leading edge of the barrier on the plasma within favors linear

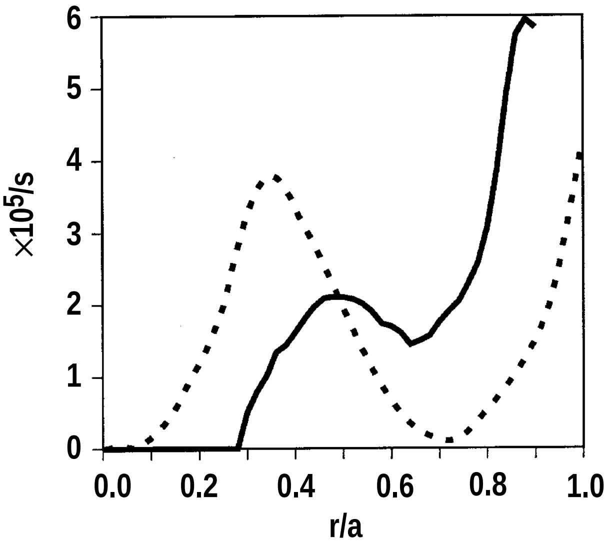

Fig. 3. γ_{max} (solid) and $\omega_{E\times B}$ (dashed) profiles for DIII–D discharge 87031 during the high power phase (1760 ms).

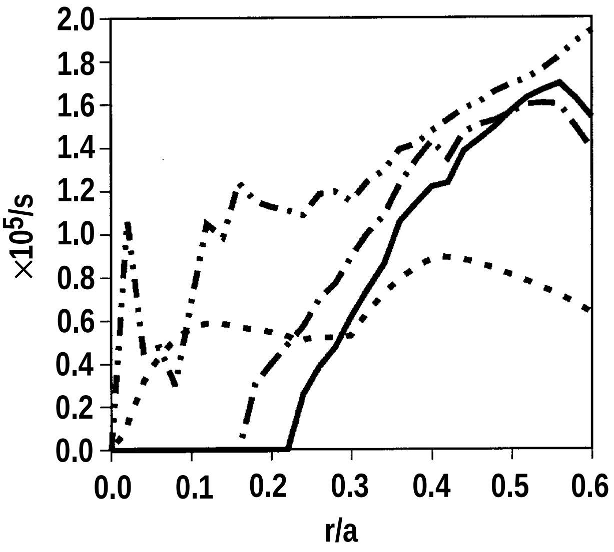

Fig. 4. γ_{max} (solid) and $\omega_{E\times B}$ (dashed) profiles for the same discharge as Fig. 3 during the low power phase (1590 ms). Also shown are γ_{max} with no Shafranov shift (α=0) (dot-dashed) and γ_{max} with T_i=T_e and no fast ion dilution (dot-dot-dashed).

stability near the axis. In many DIII–D NCS discharges the ion thermal transport improves much more than the electron thermal transport or the particle transport. This favors hot ions and fast ion dillution because the low densities and high temperatures result in a long slowing down time for the neutral beam ions. The high beta near the axis and the higher safety factor *q* on axis also increase the Shafranov shift behind the transport barrier initiated by the E×B shear. These stabilizing influences extend the region of reduced transport inward to the magnetic axis where the E×B shear vanishes. This extension of the suppressed transport region to the axis has been seen in modeling of internal transport barriers with E×B shear and ITG mode turbulent transport [6].

REFERENCES

[1] M. Kotschenreuther *et al.*, comput. Phys. Commun **88**, 128 (1995).

[2] R.E. Waltz *et al.*, Phys. Plasmas **1**, 2229 (1994).

[3] L.L. Lao *et al.*, Phys. Plasmas **3**, 1951 (1996).

[4] M.A. Beer and G.W. Hammett, Bull. Am. Phys. Soc. **40**, 1733 (1995).

[5] D.P. Schissel, *et al.*, Proc. 16th IAEA Fus. Eng. Conf. Montreal, October 1996, Paper F1-CN-64/A5-3.

[6] G.M. Staebler, *et al.*, Nucl. Fusion **37**, 287 (1997).