IAEA
International Atomic Energy Agency

20th IAEA Fusion Energy Conference
Vilamoura, Portugal, 1 to 6 November 2004

IAEA-CN-116/IT/P3-37

TRANSPORT MODELING AND GYROKINETIC ANALYSIS OF ADVANCED HIGH PERFORMANCE DISCHARGES

J.E. KINSEY,[1] F. IMBEAUX,[2] G.M. STAEBLER, R. BUDNY,[3] C. BOURDELLE,[2] A. FUKUYAMA,[4] X. GARBET,[2] T. TALA,[5] and V. PARAIL[6] for the ITPA Topical Group on Transport Physics and the ITB Database Working Group

General Atomics
San Diego, California 92186-5608
United States of America

[1]Lehigh University, Bethlehem, Pennsylvania 18015, USA
[2]Association EURATOM-CEA, Cadarache F-13108 Saint-Paul-lez-Durance Cedex, France
[3]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA
[4]Kyoto University, Department of Nuclear Engineering, Kyoto, Japan
[5]Association EURATOM-Tekes, VTT Processes, FIN-02044-VTT, Finland
[6]EURATOM/UKAEA Fusion Association, Culham Science Center, Abingdon, Oxon, United Kingdom

Transport Modeling and Gyrokinetic Analysis of Advanced High Performance Discharges

J. Kinsey,[1] F. Imbeaux,[2] G. Staebler[3], R. Budny,[4] C. Bourdelle,[2] A. Fukuyama,[5] X. Garbet,[2] T. Tala,[6] and V. Parail[7] for the ITPA Topical Group on Transport Physics and the ITB Database Working Group

[1]Lehigh University, Bethlehem, Pennsylvania 18015 USA; At General Atomics, P.O. Box 85608, San Diego, California, 92186 USA
[2]Association EURATOM-CEA, Cadarache F-13108 Saint-Paul-lez-Durance Cedex, France
[3]General Atomics, P.O. Box 85608, San Diego, California 92186-5608 USA
[4]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543 USA
[5]Kyoto University, Department of Nuclear Engineering, Kyoto Japan
[6]Association EURATOM-Tekes, VTT Processes, P.O. Box 1608, FIN-02044 VTT Finland
[7]EURATOM/UKAEA Fusion Assocation, Culham Science Centre, Abingdon, Oxon UK

Email contact of the main author: kinsey@fusion.gat.com

Abstract. Predictive transport modeling and gyrokinetic stability analyses of demonstration hybrid (HYBRID) and Advanced Tokamak (AT) discharges from the International Tokamak Physics Activity (ITPA) profile database are presented. Both regimes have exhibited enhanced core confinement (above the conventional ITER reference H-mode scenario) but differ in their current density profiles. Recent contributions to the ITPA database have facilitated an effort to study the underlying physics governing confinement in these advanced scenarios. In this paper, we assess the level of commonality of the turbulent transport physics and the relative roles of the transport suppression mechanisms (i.e. ExB shear and Shafranov shift (α) stabilization) using data for select HYBRID and AT discharges from the DIII-D, JET, and AUG tokamaks. GLF23 transport modeling and gyrokinetic stability analysis indicates that ExB shear and Shafranov shift stabilization play essential roles in producing the improved core confinement in both HYBRID and AT discharges. Shafranov shift stabilization is found to be more important in AT discharges than in HYBRID discharges. We have also examined the competition between the stabilizing effects of ExB shear and Shafranov shift stabilization and the destabilizing effects of higher safety factors and parallel velocity shear. Linear and nonlinear gyrokinetic simulations of idealized low and high safety factor cases reveals some interesting consequences. A low safety factor (i.e. HYBRID relevant) is directly beneficial in reducing the transport, and ExB shear stabilization can win out over parallel velocity shear destabilization allowing the turbulence to be quenched. However, at low-q/high current, Shafranov shift stabilization plays less of a role. Higher safety factors (as found in AT discharges), on the other hand, have larger amounts of Shafranov shift stabilization, but parallel velocity shear destabilization can prevent ExB shear quenching of the turbulent transport, and only ExB suppression is achieved.

1. Introduction

While the Advanced Tokamak concept [1,2] has received considerable attention, another alternative to the ITER reference H-mode scenario [3] has emerged in recent years. A regime has been developed demonstrating high beta operation with the central safety factor maintained close to unity, a broad region of low magnetic shear, and the absence of sawtooth activity. This regime has been dubbed the ‘hybrid’ regime [4,5] by working groups of the International Tokamak Physics Activity [6] and offers the potential of achieving many of the performance goals of ITER including high fusion gain [2]. The hybrid regime is intermediate between conventional sawtoothing H-modes with a monotonic q-profile and reversed magnetic shear H-modes with internal transport barriers (ITBs). Hybrid (HYBRID) discharges have generally achieved higher beta than sawtoothing H-mode discharges at a reduced inductive current. The hybrid regime is distinct from the AT regime in that the current and pressure profiles have relaxed to a stationary state with values of the central safety factor maintained slightly above unity. However, a low bootstrap fraction limits the hybrid regime from being a candidate for steady-state operation. In any case, a predictive understanding of the transport and relative roles of the transport suppression mechanisms in both regimes is sorely needed. An overview of the confinement properties and operational limits in these two advanced scenarios utilizing data from the ITPA database is given by Sips et al. [7].

In this paper, we study the core transport properties of select HYBRID and AT discharges recently submitted to the ITPA Profile Database [6]. We compare the competition between stabilizing (i.e. ExB shear and Shafranov shift stabilization) and destabilizing (i.e. q and parallel velocity shear) transport effects in both regimes. Gyrokinetic stability analysis is performed using the GKS [8], GS2 [9], and KINEZERO [10] codes. Predictive transport simulations are also carried out with an emphasis on modeling the HYBRID discharges in the database. Here, we use the GLF23 driftwave model [11] and the mixed Bohm/gyro-Bohm semi-empirical model [12]. The GLF23 transport model uses drift-wave linear eigenmodes to compute the quasilinear energy, toroidal momentum, and particle fluxes due to ion/electron temperature gradient (ITG/ETG) and trapped electron modes (TEM). The model differs from other drift-wave-based transport models in that it includes kinetic effects through use of the gyro-Landau fluid equations. The model is intrinsically gyro-Bohm with the transport computed using a spectrum of eigenmodes with 10 wavenumbers for the ion temperature gradient (ITG) and trapped electron modes (TEM) and 10 wavenumbers for the short wavelength electron temperature gradient (ETG) modes. The fluxes were normalized to give the same ion thermal energy flux as non-linear gyro-Landau fluid simulations of ITG/TEM modes. Since publication of the 1996 model, it has been found that fully kinetic nonlinear simulations [13] predict a factor of 4 lower level of ITG transport than gyro-Landau fluid simulations for parameters used to normalize GLF23. Another recent revision involves a retuning to better describe the growth rates for reversed magnetic shear and MHD alpha values greater than unity [14].

The mixed Bohm/gyro-Bohm model is a semi-empirical model [12] that accounts for the effects of magnetic shear and ExB shear. Turbulence suppression by magnetic and ExB shear is taken into account by a smoothed Heaviside function. In the CRONOS [15] implementation of the Bohm/gyro-Bohm model, this function reduces the Bohm term when the stabilization criterion is locally met and takes the form : $F=1/[1+\exp(20(0.05 + \alpha_E\gamma_E/\gamma_{ITG}-\hat{s}))]$. Here, γ_E is the ExB shearing rate, α_E is a multiplier, and $\hat{s}$ is the magnetic shear. The Bohm term has a non-local scaling, and is inversely proportional to the electron temperature at the top of the pedestal. This non-local scaling allows the model to reproduce the reduced core heat diffusivity observed in H-modes [12].

2. Transport Modeling of HYBRID and AT Discharges

We have examined the role of ExB shear in transport simulations using the GLF23 and mixed Bohm/gyro-Bohm transport models. GLF23 transport modeling of DIII-D, JET, and ASDEX Upgrade (AUG) HYBRID and AT discharges indicates that ExB shear stabilization is an important ingredient in reproducing the experimental temperature profiles and therefore plays a major role in obtaining good core confinement in both regimes. The plasma parameters for the five discharges examined in the study are given in Table I. In the GLF23 and mixed Bohm/gyro-Bohm transport model simulations, the temperature profiles are predicted taking the density and toroidal rotation profiles from experimental data.

TABLE I: PLASMA PARAMETERS FOR THE AT AND HYBRID DISCHARGES.

	DIII-D #99411	DIII-D #104276	JET #58323	JET #60933	AUG #17870
Regime	AT	HYBRID	HYBRID	HYBRID	HYBRID
Time (s)	1.80	5.71	12.0	12.0	6.0
I_p (MA)	1.2	1.2	1.4	2.0	1.0
B_T (T)	1.6	1.7	1.8	2.5	2.1
n_e (10^{19} m^{-3})	5.0	4.0	2.4	3.0	5.1
P_{NB} (MW)	9.2	5.5	15.7	15.7	7
P_{RF} (MW)	0	0	0.5	1.5	0

With ExB shear stabilization included in the GLF23 simulations, the measured ion and electron temperature profiles are well reproduced. Without ExB shear included in the simulations, the predicted core ion temperature profiles are approximately 40% lower for the DIII-D and JET HYBRID discharges modeled using GLF23 in the XPTOR [16] and CRONOS codes [15] (see Figs. 1, 2). The predicted transport is significantly reduced by ExB shear. In the XPTOR simulations, the ion heat transport is quenched to neoclassical levels near ρ=0.45 for DIII-D #104276 and near ρ=0.15 for JET #58323. Analysis of the simulations indicates that the DIII-D, JET, and AUG electron temperature (T_e) profiles are predicted to be unstable to ETG modes and limit the T_e profile across a substantial region of the core plasma.

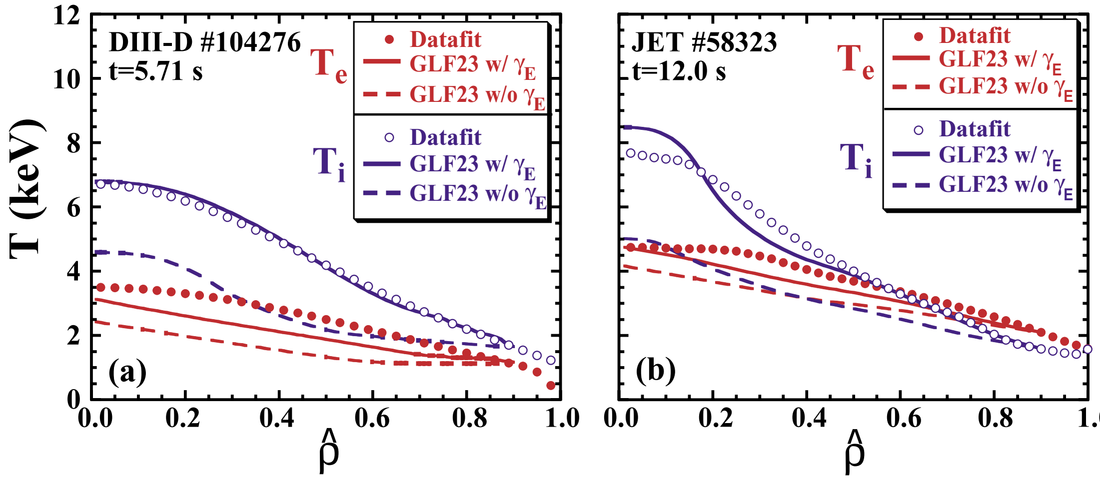


Fig. 1. Ion (blue) and electron (red) temperature profiles for HYBRID discharges (a) DIII-D #104276 and (b) JET #58323 with (solid lines) and without (dashed lines) ExB shear stabilization in GLF23 transport simulations using the XPTOR code. The dots indicate the experimental data and the lines indicate the model predictions.

Simulations using the GLF23 and mixed Bohm/gyro-Bohm transport models in the CRONOS code [15] show that ExB shear stabilization is also an important ingredient in reproducing the measured temperature profiles for AUG HYBRID discharge #17870 (see Fig. 2). The GLF23 predictions are more sensitive to γ_E than the mixed Bohm/gyro-Bohm predictions. When γ_E is not included in the simulation, the reduction in the central temperatures for AUG #17870 is similar to that found for the JET and DIII-D HYBRID discharges. We find that γ_E is also important in the JET HYBRID discharge #60933 (higher field companion to #58323).

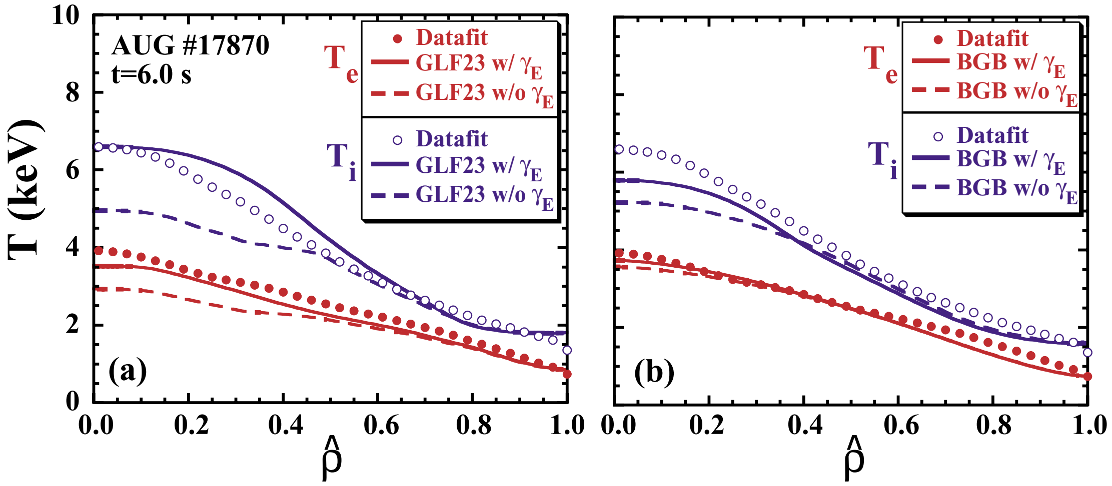


Fig. 2 (a) GLF23 and (b) Bohm/gyro-Bohm model predictions for the ion (blue) and electron (red) temperature profiles with (solid lines) and without (dashed lines) the effects of ExB shear (γ_E) in CRONOS simulations of AUG HYBRID discharge #17870 and fitted experimental profiles (dots).

3. Gyrokinetic Stability Analysis of HYBRID and AT Discharges

Gyrokinetic stability analysis for both the HYBRID and AT discharges already existing in the ITPA profile database has been performed using the GS2, GKS, and KINEZERO codes. GS2 analysis (electrostatic, collisions, real geometry) indicates that long wavelength ITG modes (ion branch) dominate over most of the core plasma with similar maximum linear growth rates in the DIII-D and JET HYBRID discharges (see Fig. 3a).

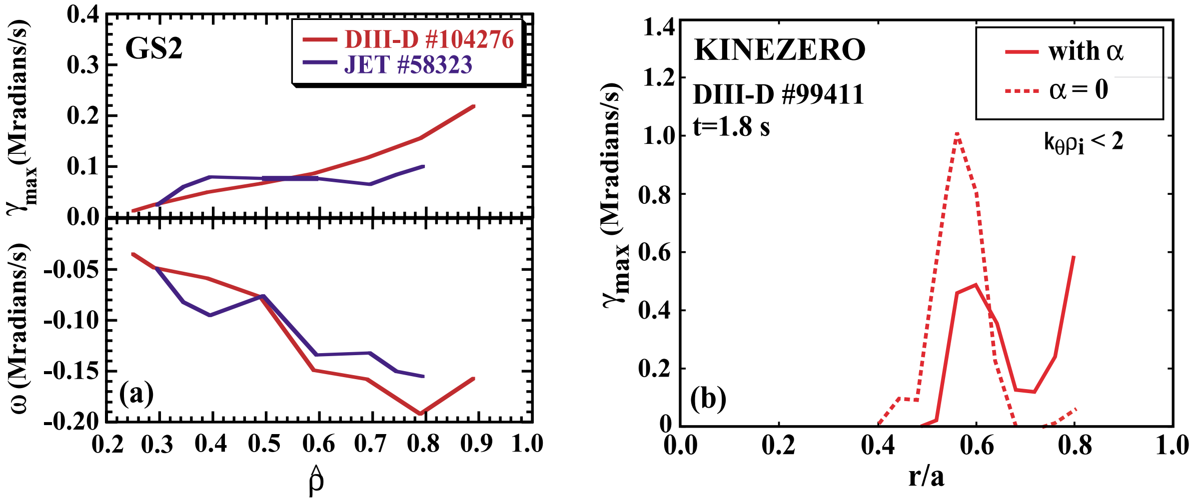


Fig. 3. (a) Maximum linear growth rates and mode frequencies for DIII-D #104276 (red) and JET #58323 (blue) HYBRID discharges using the GS2 gyrokinetic stability code. (b) Maximum linear growth rates for DIII-D #99411 AT discharge with (red solid line) and without (red dashed line) Shafranov shift (α) stabilization using the KINEZERO gyrokinetic stability code.

Linear stability analysis shows that Shafranov shift (α) stabilization can have a strong impact on the growth rates. Figure 3b compares the maximum linear growth rate γ_{max}, as computed by the KINEZERO code, for DIII-D AT discharge #99411 with and without α-stabilization.

In the weak magnetic shear region, the effect of α is stabilizing with γ_{max} being approximately two times smaller with α-stabilization than the rate computed without α-stabilization. In the strong positive magnetic shear region to the outside, the effect of α is actually destabilizing. The KINEZERO calculations were electrostatic, collisionless, and with s-α geometry.

Gyrokinetic stability analysis of the AT and HYBRID discharges indicates that the destabilizing effect of parallel velocity shear can also be important. Figure 4 shows the maximum linear growth rates from the GKS code for JET #58323 and DIII-D #99411 with and without parallel velocity shear γ_P [$\gamma_P=(Rq/r)\gamma_E$]. When γ_P is included, the growth rates are somewhat larger. For discharge #58323, the marginal point also shifts deeper into the core region. In both cases, the ITG/TEM modes are predicted to be stable inside $\rho=0.35$. Analysis of DIII-D #104276 yields similar changes in γ_{max} when γ_P is included. The GKS calculations were performed including kinetic electrons, electromagnetic effects, collisions, and real geometry (Miller equilibrium).

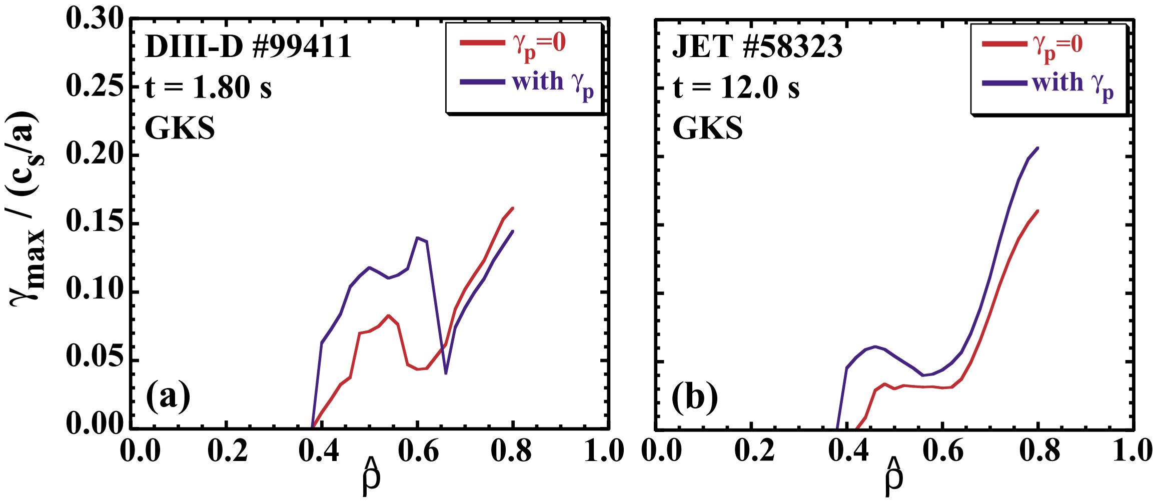
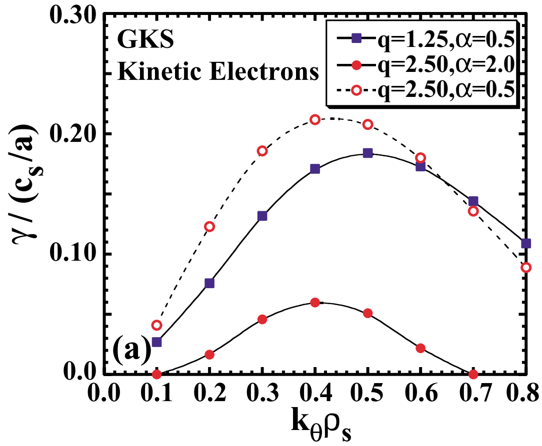


Fig. 4. Maximum linear growth rates for (a) DIII-D #99411 AT discharge and (b) JET #58323 HYBRID discharge with (blue) and without (red) parallel velocity shear γ_P using the GKS gyrokinetic code with real geometry, kinetic electrons, electromagnetic effects, and collisions.

4. Competing Effects on Driftwave Turbulence for Low and High Safety Factors

The competition between the stabilizing effects of ExB shear and Shafranov shift (α) stabilization and the destabilizing effects of intrinsic q-dependence and parallel velocity shear changes going from low-q (i.e. HYBRID) to high-q (i.e. AT) scenarios. First, we examine changes in α coupled with changes in the safety factor (α scales like q^2) at fixed gradients and other local quantities using the GKS [8] and GYRO [17] gyrokinetic codes. Two idealized cases (HYBRID-like and AT-like) are created using the same set of standard parameters from Ref. [11] but with values of the safety factor, magnetic shear, temperature gradients, and T_i/T_e taken from HYBRID discharge #104276 near the half-radius. Here, we assume the parameters: R/a=3.0, r/a=0.5, s=0.25, $a/L_n=1.0$, $a/L_{Ti}=1.75$, $a/L_{Te}=1.25$, Ti/Te=1.5, $\gamma_E=0$, $\gamma_P=0$, $\nu=0$, and $\beta=0$. The HYBRID-like case uses q=1.25 and $\alpha=0.5$ (reference values from #104276). The AT-like case uses q=2.50 and $\alpha=2.0$. The only difference between the two idealized cases is in the safety factor and MHD α. Figure 5a shows that a strong reduction in the linear growth rates occurs when α increases from 0.5 to 2.0 as the safety factor value is changed from q=1.25 (HYBRID-like) to q=2.50 (AT-like).

Due to the intrinsic q-dependence of the ITG/TEM turbulence, the growth rates increases when the safety factor doubles from 1.25 to 2.5 at fixed magnetic shear and MHD alpha, α. However, if α increases as q^2 (α=-$Rq^2(d\beta/dr)$ for circular geometry), then the growth rates are significantly reduced for the HYBRID-like case with q=1.25 and α=0.5 compared to AT-like case with q=2.5 and α=2.0.



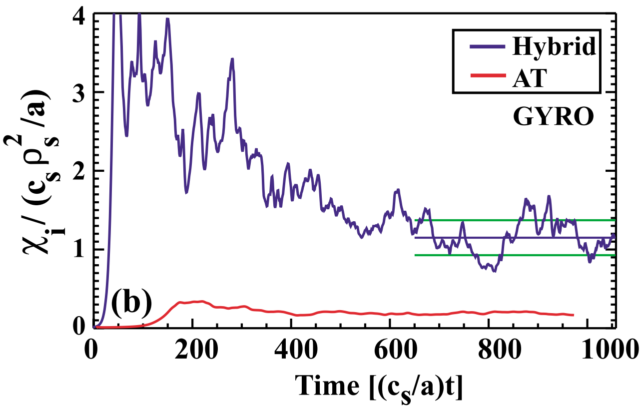


Fig. 5. (a) Linear growth rate versus $k_\theta\rho_s$ for the HYBRID-like (solid line with blue squares) and AT-like (solid line with red circles) idealized cases using the GKS gyrokinetic stability code and (b) Turbulent ion heat diffusivity from GYRO nonlinear simulations of the q=1.25 (α=0.5, blue line) and q=2.5 (α=2.0, red line) cases. In Fig. 5a the dashed line with hollow red circles indicates the growth rates for the case where q is increased from 1.25 to 2.5 but with α held fixed at 0.5.

For weak positive magnetic shear, the effect of α-stabilization is strongly stabilizing for the idealized AT case despite having a larger safety factor compared to the low-q HYBRID-like case. Nonlinear gyrokinetic simulations using the GYRO code [17] also show a strong reduction in the turbulent heat diffusivities for the AT-like case compared to the HYBRID-like case (see Fig. 5b). The turbulent ion and electron heat diffusivities are reduced by a factor of 6.0 and 4.7, respectively, going from low-q to high-q. The GYRO simulations were performed assuming s-α geometry, flat profiles within the annulus, and included kinetic electrons. The simulations included 16 toroidal modes with a maximum $k_\theta\,\rho_s$=0.75, $(m_i/m_e)^{1/2}$=60, and a box size of $[L_x/\rho_s, L_y/\rho_s]$=[107,125]. Electromagnetic effects and collisions were not considered. It is worth noting that the observed q-scaling in DIII-D discharges which varied the safety factor while maintaining the same magnetic shear found that the effective heat diffusivities scaled as $\chi_{eff} \propto q^{2.3}$ in H-mode [18] and as $\chi_{eff} \propto q^{0.8}$ in L-mode [19]. With the exception of the inner core plasma, the magnetic shear in these discharges was strongly positive (i.e. s > 0.5) resulting in α-destabilization going from low-q to high-q. Thus, it is desirable to maximize the radial extent in which the magnetic shear is negative or weakly positive in order to take advantage of α-stabilization in high-q AT scenarios. In any case, it is clear that the scaling of the core heat transport cannot be simply explained in terms of the safety factor. Variations in the MHD α can be an important ingredient when comparing low-q to high-q discharges with similar magnetic shear profiles, gradients, T_i/T_e, ExB shear, and parallel velocity shear.

Transport modeling has demonstrated that ExB shear (γ_E) stabilization is a strong effect in the hybrid discharges examined in this paper. For tokamak plasmas with significant toroidal rotation, an increase in toroidal velocity (accompanying an increase in γ_E) results in an increase in the destabilizing parallel velocity shear rate γ_P resulting in a Kelvin-Helmholtz instability. The balance between the competing effects of γ_E stabilization and γ_P destabilization changes with q and is of particular interest when comparing low-q (HYBRID) and high-q (AT) discharges. Linear stability analysis, including the results shown in the previous section, indicates that γ_P can be an important effect on the growth rates. For high values of q, parallel velocity shear can prevent ExB shear quenching of transport. Figure 6 shows that when the destabilizing effect of parallel velocity shear is included in GYRO nonlinear simulations, assuming purely toroidal rotation, the transport is not quenched by any level of ExB shear at q=2. The Kelvin-Helmholtz drive increases faster than γ_E increases for the standard parameters from Ref. [11]. Without parallel velocity shear included in the simulations, the transport is quenched by ExB shear near γ_E/γ_{max}=2. Here, γ_{max} is the maximum linear growth rate computed in the absence of γ_P. Also, $\gamma_P = (Rq/r)\gamma_E = 12\gamma_E$ assuming R/a=3, r/a=0.5, and q=2.

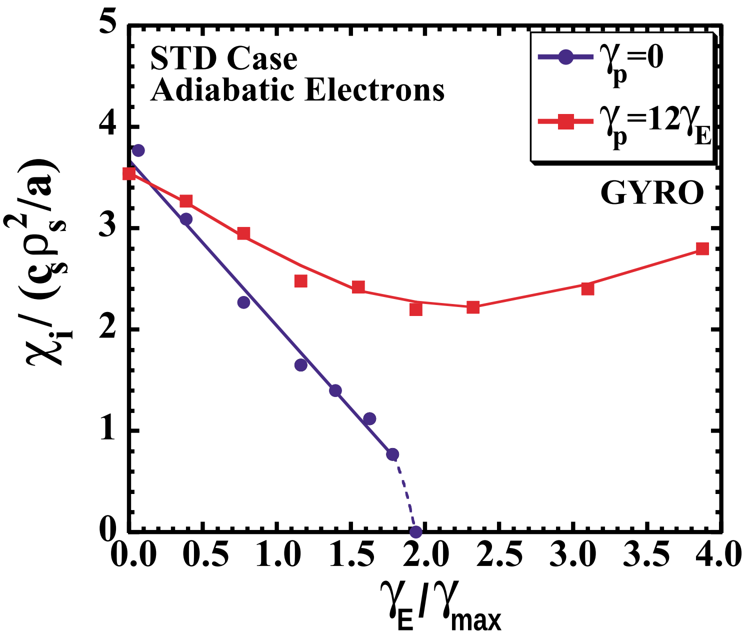


Fig. 6. Ion heat diffusivity versus γ_E/γ_{max} with (red squares) and without (blue circles) parallel velocity shear, γ_P for the standard case [10] with q=2. The points denote the GYRO results and lines denote curve fits.

This result suggests that low-q (e.g. HYBRID) discharges are potentially advantageous in that a low safety factor allows ExB shear stabilization to increase faster than the destabilizing parallel velocity shear, thus allowing the turbulent heat transport to be quenched. Our analysis indicates that AT discharges tend to have more Shafranov shift stabilization than HYBRID discharges with similar pressure gradients, however γ_P destabilization at larger safety factors can impose a lower bound on the level of ExB shear stabilization and constrain the transport to turbulent levels.

5. Summary

Using the ITPA profile database, transport modeling and gyrokinetic stability analysis indicates that ExB shear and Shafranov shift (α) stabilization play essential roles in producing the improved confinement in the plasma core of hybrid (HYBRID) and Advanced Tokamak (AT) discharges from the DIII-D, JET, and AUG tokamaks. GLF23 transport modeling shows that ExB shear stabilization is an important ingredient in reproducing the experimental temperature profiles in both HYBRID and AT discharges. Shafranov shift stabilization is found to be an important effect in AT discharges owing to the larger safety factor (compared to hybrid discharges) which tends to enhance the intrinsic ITG/TEM growth rates. Gyrokinetic stability analysis of a DIII-D AT discharge shows that the maximum linear growth rates are significantly reduced when α is included in the calculations. Linear stability analysis has shown that the destabilizing effect of parallel velocity shear γ_P increases the growth rates in both HYBRID and AT discharges. The change in the growth rates with γ_P is similar in magnitude to the change in the growth rates with safety factor. For the AT discharge, γ_P has less of an impact in comparison with Shafranov shift stabilization.

A comparison of low-q (i.e. hybrid) and high-q (i.e. AT) profiles has revealed some interesting consequences associated with the competition between the stabilizing effects of ExB shear and Shafranov shift stabilization and the destabilizing effects of intrinsic q-dependence and parallel velocity shear, γ_P. HYBRID discharges have a lower safety factor which is directly beneficial in reducing the transport but Shafranov shift stabilization then plays less of a role. At low-q, nonlinear simulations suggest that ExB stabilization can win out over γ_P destabilization and the transport can be quenched to neoclassical levels. While AT discharges tend to have larger amounts of Shafranov shift stabilization, parallel velocity shear destabilization can prevent ExB shear quenching of the transport resulting in only ExB shear suppression of the transport.

Acknowledgments

Work supported in part by U.S. Department of Energy under Grants DE-FG02-92ER54141 and DE-FG03-95ER54309. The authors would like to thank the ITPA Confinement Database & Modeling Topical Group and the various experimental teams for their many contributions in providing and maintaining the experimental profile data.

References

[1] Taylor, T.S., *et al.*, Plasma Phys. Control. Fusion **39**, B47 (1997).
[2] M.R. Wade, M. Murakami, T.C. Luce, *et al.*, Nucl. Fusion **43**, 634 (2003).
[3] ITER Physics Basis, Nucl. Fusion **39**, 2137 (1999).
[4] A.C.C. Sips, *et al.*, Plasma Phys. Control. Fusion **44**, A391 (2002).
[5] T.C. Luce, M.R. Wade, J.R. Ferron, *et al.*, Nucl. Fusion **43**, 321 (2003).
[6] T. Fukuda, Proc. 28th EPS Conference, Madeira, Portugal, paper P4.004 (2001).
[7] A.C.C. Sips, *et al.*, paper IT/P3-36, this conference (2004).
[8] M. Kotschenreuther, Bull. Am. Phys. Soc. **37**, 1432 (1992).
[9] see http://gs2.sourceforge.net
[10] C. Bourdelle, *et al.*, Nucl. Fusion **42**, 892 (2002).
[11] R.E. Waltz, G.M. Staebler, W. Dorland, *et al.*, Phys. Plasmas **4**, 2482 (1997).
[12] V. Parail, *et al.*, Nucl. Fusion **39**, 429 (1999).
[13] R.E. Waltz, J.M. Candy, M.N. Rosenbluth, Phys. Plasmas **9**, 1938 (2002).
[14] J.E. Kinsey, G.M. Staebler, R.E. Waltz, submitted to Phys. Plasmas.
[15] V. Basiuk, J.F. Artaud, F. Imbeaux, *et al.*, Nuc. Fusion **43**, 822 (2003).
[16] J. Kinsey, G.M. Staebler, and R.E. Waltz, Phys. Plasmas **9**, 1676 (2002).
[17] J. Candy and R.E. Waltz, Phys. Rev. Lett. **91**, 45001 (2003).
[18] C.C. Petty, T.C. Luce, D.R. Baker *et al.*, Phys. Plasmas **5**, 1695 (1998).
[19] C.C. Petty, J.E. Kinsey, T.C. Luce, et al., Phys. Plasmas **11**, 1011 (2004).