DE-FG05-80ET-53088-732 IFSR #**732**

Ion Transport Analysis of a High Beta-Poloidal JT-60U Discharge

W. HORTON, T. TAJIMA,[a] J.Q. DONG,[b]
Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712 USA
and Y. KISHIMOTO and J-Y. KIM
Japan Atomic Energy Research Institute
Naka Fusion Establishment, 311-01 Japan

[a]also at Advanced Science Research Center, JAERI, Japan
[b]Southwestern Institute of Physics, Peoples Republic of China

November 1995

Ion transport analysis of a high beta-poloidal JT-60U discharge

W. Horton, T. Tajima,[1] J.Q. Dong[2]

Institute for Fusion Studies
The University of Texas at Austin
Austin, Texas 78712, USA

Y. Kishimoto and J.-Y. Kim

Japan Atomic Energy Research Institute
Naka Fusion Establishment
311-01 Japan

Abstract. The high beta-poloidal discharge number 17110 in JT-60U that develops an internal transport barrier is analyzed for the transport of ion energy and momentum. First the classical ion temperature gradient stability properties are calculated in the absence of sheared plasma flows to establish the L-mode transport level prior to the emergence of the transport barrier. Then the evolving toroidal and poloidal velocity profiles reported by Koide *et al* [Phys. Rev. Lett. **72**, 3662 (1994)] are used to show how the sheared flows control the stability and transport. Coupled momentum-energy transport equations predict the creation of a transport barrier.

1. Introduction

The ion temperature gradient driven turbulent transport model is applied to a particular high beta-poloidal JT-60U discharge. The theory of the stability and transport reduction in the presence of sheared flows is taken from the works of Sugama and Horton (1994), Waelbroeck *et al* (1994), and Su *et al* (1994). These works show that poloidal sheared ion mass flows are strongly stabilizing, particularly in regions of weak magnetic shear, and that strong parallel shear flows are destabilizing. Both shear flows are measured in JT-60U and appear to be important aspects of the transport analysis for the high beta poloidal discharges.

[1] also at Advanced Science Research Center, JAERI, Japan
[2] present address: Southwestern Institute of Physics, P.O. Box 432, Chengdu 610041, Peoples Republic of China

2. Transport parameters for discharge 17100

Here we restrict the analysis to the time interval defined as phase I in Koide *et al* (1994). The evaluation of the polynomial fit to the electron density and ion temperature profiles are shown in figure 1

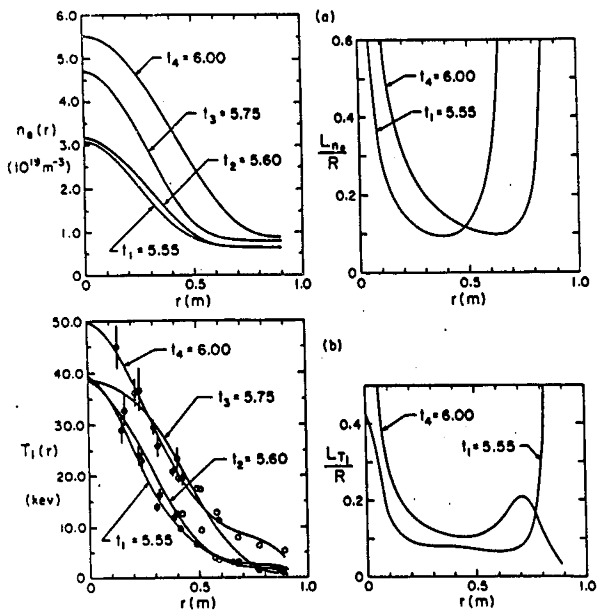

figure 1: Smoothed density and ion temperature profiles used to compute the gradient scale lengths at the four reference times. (a) density profile and the insert gives $\epsilon_n = L_n/R$. (b) ion temperature profile and the insert shows $\epsilon_{T_i} = L_{T_i}/R$.

at the time slices $\{t_i\} = \{5.55, 5.60, 5.75, 6.00\,\text{sec}\}$ labeled $\{1,2,3,4\}$ in figure 1 of Koide *et al* (1994). The inserts in figure 1 show the dimensionless transport parameters $\epsilon_n = L_n/R$ and $\epsilon_T = L_{T_i}/R$ computed from these profiles. The ratio $\eta_i = \epsilon_n/\epsilon_{T_i} = L_n/L_{T_i}$ as a function of minor radius and time varies from 1 to 3. The polynomial fitting to the diagnostics yields smoothed profiles suitable for computing the mean gradients but eliminates the radial structure that shows the location of the transport barrier. In figure 2

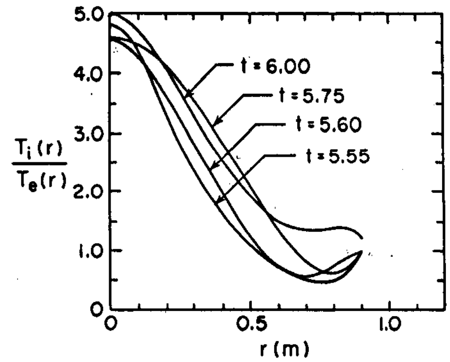

figure 2: Profiles of the ion-to-electron temperature ratio at the four reference times.

we show the ratio of T_i/T_e for the reference times. The growth rate of the ITG mode decreases strongly with increasing T_i/T_e which contributes to the first phase of lowering of the central ion thermal conductivity $\chi_i(r,t)$.

The values of ϵ_T below 0.2 to 0.3 are unstable to a broad range of wavenumbers, and thus we conclude that the profiles are unstable to drift wave microinstabilities in the absence of sheared flows. Using the full kinetic toroidal dispersion relation for a local, static Maxwell-Boltzmann distribution function with $n_i(r,t), T_i(r,t), T_e(r,t)$ gives the growth rate

$$\frac{\gamma^\ell}{|\omega_{*e}|} = (0.2)(2\epsilon_n + s)\epsilon_n(\eta_i - \eta_c), \quad \eta_c \simeq \frac{2}{3} + \frac{4\epsilon_n}{3}\left(1 + \frac{T_i}{T_e}\right) \tag{1}$$

for $\epsilon_n < 0.3$. In the rapidly rotating frame of the plasma the mode frequency is $\omega_k \simeq \omega_{Di}$. In the region $r/a > 0.7$ where L_n is comparable to R, we define $\mu = R/L_{T_i} = 1/\epsilon_{T_i}$, the flat density profile applies and $\gamma^\ell/|\omega_{Di}| = 0.3(\mu - \mu_c)$ with $\mu_c \simeq 2(1 + T_i/T_e)$ as in Horton *et al* (1992) analysis of TFTR pellet injection discharges.

Turbulence theory and simulations based on the ion temperature gradient driven instabilities leads to formulas for the ion thermal flux

$$q_i = -n_i\chi_i(W)\left(\frac{dT_i}{dr}\right) \tag{2}$$

and the nonlinear growth rate $\gamma(W) = \gamma^\ell - 0.3(L_s u'_\perp/c_s)^2 - \gamma^{n\ell}W$ where the quantity $W(r,t)$ is the fractional turbulent energy density. Here we use the weak turbulence approximation so that $W \ll 1$ and thus $\chi_i(W) = \chi_0 W$. The parametric dependence of χ_0 and $\gamma^{n\ell}$ are known for specific transport models, e.g., Horton-Choi-Tang (1981). The shear flow stabilization and ITG transport reduction is given in Hamaguchi and Horton (1992) and Dong and Horton (1993) and applied to DIII-D. Here the magnetic shear length $L_s = qR/s$ where $s = rq'/q$ and $c_s = (T_e/m_i)^{1/2}$ in the ion acoustic speed.

2.1. Energy-momentum injection and sheared flows

In addition to the energy injection $P_E(r,t)$ (MW/m^3) and its normalized radial gradient $P'_E = \partial_r(2P_E(r,t)/3n_i(r,t))$ per ion, the seven neutral beams lines in JT-60U impart toroidal and poloidal momentum densities $P_\phi(r,t)$ and $P_\phi(r,t)$. Again, it is the normalized radial gradients of these momentum sources that would seem to be the critical control parameters for the generation of sheared flows providing the best plasma confinement.

Plasma flow velocities of the magnitude (50 to 150 km/s) measured in the discharge 17110 will affect the plasma ITG turbulent transport. Here we describe the transport based on drift wave turbulence taking the equilibrium provided by the parametric fits of the diagnostic data in figures 1 and 2.

The specification of the equilibrium of the plasma being analyzed requires that the mean flow velocity $\boldsymbol{u}$ and magnetic field shears be treated on equal footing (Su *et al* , 1994; Yushmanov *et al* , 1994). From the condition of incompressible flow the two contravariant components of the surface velocity are flux functions. The description of the total system of neoclassical collisional viscosity and the drift wave fluctuations is given in Su *et al* (1994) and Sugama and Horton (1995b). The result is to obtain evolution equations for $u_\phi(\psi,t)$ and $u_\theta(\psi,t)$ that are driven both by the momentum density absorbed from the neutral beam lines and from the turbulent transport of the momentum densities. The accelerating forces from the unbalanced neutral beam injection are written in terms of the charge exchange ionization collision frequency ν^a and mean beam injector energies $\frac{1}{2}m_i(u^a)^2$ in the poloidal and toroidal directions as P_θ and P_ϕ. In the absence of any neoclassical and turbulent viscosities these charge exchange forces P_θ, P_ϕ would accelerate the plasma on the time scale $1/\nu^a$ to high velocities. In the axisymmetric torus the neoclassical viscosity is a frictional drag that acts only in the poloidal direction taking the mean velocity to the neoclassical value $u^{\rm nc}(T_i,T_i')$ in the absence of accelerating forces according to $\dot{u}_\theta = -\nu^{\rm nc}(u_\theta - u^{\rm nc})$ with the well-known formulas for $\nu^{\rm nc}(T_i)$ and $u^{\rm nc}(T_i,T_i') \simeq 1.17cT_i/2eB\,L_{T_i}$ well below the measured poloidal velocity.

The ion energy-momentum density transport equations determine the gradients $T_i', u_\perp', u_\parallel'$ for the ITG dispersion relation through the gradients of the energy-momentum input per ion per unit of ion mass (m_i) by

$$P_E' = \frac{\partial}{\partial r}\left(\frac{2P_E(r)}{3n_i(r)}\right), \quad P_\phi' = \frac{\partial}{\partial r}\left(\frac{P_\phi}{m_i n_i}\right), \quad \text{and} \quad P_\theta' = \frac{\partial}{\partial r}\left(\frac{P_\theta}{m_i n_i}\right). \tag{3}$$

Thus the model dynamical system has three control parameters P_E', P_ϕ', P_θ'. Since it is principally the *gradient* of $T_i(r,t)$ and $u_\perp(r,t)$ that controls the growth of W and the resulting transport, we made a reduced model by neglecting the evolution of $n_i(r,t)$.

2.2. *Transport parameter and power threshold for barrier formation*

The profiles of the toroidal plasma velocity at the four-time slices in phase I are given in Koide *et al* (1994). At time t_1 and t_2 the velocity profile has a steep radial gradient with $v_\phi' \lesssim 4\times 10^5$/s in the region $r/a \simeq 0.4$ and at time t_3 (= 5.750 s) the steep gradient region has moved outward to $r/a = 0.7$ and steepened to $v_\phi' \simeq 7\times 10^5$/s. At time t_4 the velocity is more uniformly high at over 100 km/s across the region $r/a \lesssim 1$ except for a dip to 70 km/seç at $r/a = 0.8$. During the period between t_2 and t_3 the gradient of T_i and n_e increase from a radial position that moves outward from $r/a = 0.6$ to 0.8. At time t_4 the entire profiles of T_i and n_e are lifted upward for all $r/a \le 1$. During this time poloidal velocity profile is known to increase from velocities of order $5-10\,\mathrm{km/s}$ to up to $50\,\mathrm{km/s}$. The radial profile of the poloidal velocity in this region of the transport barrier is not so well known but an estimate implies gradients of order $v_\theta' \sim (0.7-1.6)\times 10^5/\mathrm{s}$.

From the toroidal v_ϕ and poloidal velocity profiles v_θ, the $q(r)$ profile, and the density profiles we derive the dimensionless stability parameters defined by $\widehat{u}_\perp' = L_n/c_s\, du_\perp/dr$, $\widehat{u}_\parallel' = L_n/c_s\, du_\parallel/dr$, $S = L_n/L_s = (L_n/qR)(rq'/q)$. For example at t_3, from $L_n = 0.25\,\mathrm{m}$, $L_s = 8.3\,\mathrm{m}$, $q = 3, R = 3.05\,\mathrm{m}$, and $\widehat{s} = d\ell n\, q/d\ell n\, r = 1.1$, we obtain the following dimensionless transport parameters

$$\widehat{u}_\perp' = \frac{(.25\,\mathrm{m})(1\times 10^5/\mathrm{s})}{220\,\mathrm{km/s}} = 0.11,\ \widehat{u}_\parallel' = \frac{(.25\,\mathrm{m})(6\times 10^5/\mathrm{s})}{220\,\mathrm{km/s}} = 0.68,\ S = \frac{.25\,\mathrm{m}}{8.3\,\mathrm{m}} = 0.03$$

and thus $L_s u_\perp'/c_s = \widehat{u}_\perp'/s = 3.6$. The parameter combination $L_s u_\perp'/c_s$ is identified in transport analysis of Hamaguchi and Horton (1992) and Dong and Horton (1993) as the key parameter for the onset of shear flow stabilization. The critical condition given is $(L_s u_\perp'/c_s)_{\mathrm{crit}} \cong 2\sqrt{T_i/T_e\,(\eta_i - \eta_{ic})}$ which at t_3 we estimate as $2\sqrt{4\mathrm{kev}/2\mathrm{kev}\,(3-1)} \cong 4$ which is close (10%) to the value of 3.6 estimated above. Thus, the steep ion temperature gradient can be established by the combination of the sheared perpendicular mass flow and the magnetic shear found in the profiles.

The low-dimensional dynamical model for the evolution of the transport barrier is given in Kishimoto *et al* (1994) and Sugama and Horton (1995a).

The power threshold $P_{L\to H}$ for this internal L to H transition is estimated from the surface area $4\pi^2 r_s R$ and the values of P_E' and ν^{nc} at the $W_H = W_L$ bifurcation. When $P_\theta' = P_\phi' = 0$ the bifurcation condition is $\nu_{\mathrm{nc}} < \chi_L/\Delta^2 \propto W_L$. Taking $R_0 = 3\,\mathrm{m}$, $r_s = 0.7\mathrm{a} = 0.5\,\mathrm{m}$, $n = 1.1\times 10^{13}\,\mathrm{m}^{-3}$, $T_i = 3\,\mathrm{kev}$, we estimate $\nu_{*i} \sim 10^{-2}$ and derive $P_{L\to H} = 18\,\mathrm{MW}$. The threshold is substantially lowered by the increase of $u_\perp'$ associated with P_θ'. Including P_θ' as indicated we estimate $P_{L\to H}$ drops to $10\,\mathrm{MW}$. These estimates show the importance of the momentum deposition profiles in determining the core transport barrier power threshold.

3. Conclusions

The high β_p discharge in JT-60U that develops an internal transport barrier is analyzed with the ion temperature gradient driven turbulence theory with and without plasma flow shears. It is demonstrated that the dimensionless plasma parameters $\eta_i, T_i/T_e$ and $L_s u_\perp'/c_s$ for this discharge are well inside the regime where the theories predict that a large T_i' can be maintained. A four-dimensional state space analysis shows that the evolution and the profiles of the plasma are controlled by the profiles of the energy and momentum deposition.

Acknowledgments

This work was supported in part by the U.S. Dept. of Energy contract No. DE-FG05-80ET-53088, and in part by JAERI Naka Fusion Establishment and Advanced Science Research Center. The authors thank H. Shirai and T. Fukuda for assistance with the analysis.

References

Dong J Q and Horton W 1993 *Phys. Fluids* B **5** 1581

Hamaguchi S and Horton W 1992 *Phys. Fluids* B **4** 319

Horton W, Choi D-I and Tang W M 1981 *Phys. Fluids* **24** 1077

Horton W, Lindberg D, Kim J Y, Dong J Q, Hammett G W, Scott S D, Zarnstorff M C and Hamaguchi S 1992 *Phys. Fluids* B **4** 953

Kishimoto Y, Tajima T, LeBrun M J, Kim J Y, Horton W, Tokuda S, Kawanobe M, Dong J Q, Waelbroeck F L and Fukuda T (15th International Atomic Energy Agency Conference, Vienna 1994)

Koide Y, Kikuchi M, Mori M, Tsuji S, Ishida M, Asakura N, Kamada Y, Nishitani T, Kawano Y, Hatae T, Fujita T, T Fukuda T, Sakasai A, Kondoh T, Yoshino R and Neyatani Y 1994 *Phys. Rev. Lett.* **72** 3662

Su X-N, Yushmanov P N, Dong J Q and Horton W 1994 *Phys. Plasmas* **1** 1905

Sugama H and Horton W 1994 *Phys. Plasmas* **1** 345

—— 1995a *Plasma Phys. Cont. Fusion* **37** 345

—— 1995b *Phys. Plasmas* **2** 2989

Waelbroeck F L, Dong J Q, Horton W and Yushmanov P N 1994 *Phys. Plasmas* **1** 3742

Yushmanov P N, Dong J Q, Horton W, Su X-N and Krasheninnikov S I 1994 *Phys. Plasmas* **1** 1583