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

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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.

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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.

![Graphs showing density and temperature profiles](image)

**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 $\epsilon_T = L_T/R$.

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 $\epsilon_T = L_T/R$ computed from these profiles. The ratio $\eta_i = \epsilon_n/\epsilon_T = L_n/L_T$ 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

![Graph](image)

**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 $\epsilon_T$ 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

$$\frac{\gamma'}{\omega_{ci}} = (0.2)(2\epsilon_n + s)\epsilon_n(\eta_k - \eta_e), \quad \eta_e \approx \frac{2}{3} + \frac{4\epsilon_n}{3} \left(1 + \frac{T_i}{T_e}\right)$$

(1)

for $\epsilon_n < 0.3$. In the rapidly rotating frame of the plasma the mode frequency is $\omega_k \approx \omega_{Di}$. In the region $r/a > 0.7$ where $L_n$ is comparable to $R$, we define $\mu = R/L_{Ti} = 1/\epsilon_{Ti}$, the flat density profile applies and $\gamma'/\omega_{Di} = 0.3(\mu - \mu_e)$ with $\mu_e \approx 2(1 + T_i/T_e)$ 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

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

(2)

and the nonlinear growth rate $\gamma(W) = \gamma' - 0.3(L_s u'_i/c_s)^2 - \gamma^{le}W$ 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 $\chi_i(W) = \chi_0W$. The parametric dependence of $\chi_0$ and $\gamma^{le}$ 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 $s = qR/q$ 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 $P_\theta(r,t)$. 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 con-
finement.

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 $\mathbf{u}$ 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 $\nu^a$ and mean
beam injector energies $\frac{1}{2} m_i (u^a)^2$ in the poloidal and toroidal directions as $P_\theta$ and $P_\phi$. In
the absence of any neoclassical and turbulent viscosities these charge exchange forces
$P_\theta, P_\phi$ 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 $u^{nc}(T_i, T'_i)$ in the
absence of accelerating forces according to $\dot{u}_\theta = -\nu^{nc} (u_\theta - u^{nc})$ with the well-known
formulas for $\nu^{nc}(T_i)$ and $u^{nc}(T_i, T'_i) \approx 1.17 c T_i / 2 e B L T_i$ 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 unit of ion mass ($m_i$) by

$$
\begin{align*}
P'_E &= \frac{\partial}{\partial r} \left( \frac{2 P_E(r)}{3 n_i(r)} \right), \\
P'_\theta &= \frac{\partial}{\partial r} \left( \frac{P_\theta}{m_i n_i} \right), \quad \text{and} \\
P'_\phi &= \frac{\partial}{\partial r} \left( \frac{P_\phi}{m_i n_i} \right).
\end{align*}
$$

Thus the model dynamical system has three control parameters $P'_E, P'_\theta, P'_\phi$. 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 $u'_\phi \lesssim 4 \times 10^5$/s in the region $r/a \approx 0.4$ and at time $t_3 (= 5.750$ s) the steep gradient
region has moved outward to $r/a = 0.7$ and steepened to $u'_\phi \approx 7 \times 10^5$/s. At time $t_4$ the
velocity is more uniformly high at over 100 km/s across the region $r/a \approx 1$ except for a
dip to 70 km/sec 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 $r/a \leq 1$. During this time
poloidal velocity profile is known to increase from velocities of order $5 - 10 \text{ km/s}$ to up to $50 \text{ km/s}$. 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 $v_\theta' \sim (0.7 - 1.6) \times 10^5 / \text{s}$.

From the toroidal $v_\phi$ and poloidal velocity profiles $v_\theta$, the $q(r)$ profile, and the density profiles we derive the dimensionless stability parameters defined by $\tilde{u}'_\perp = L_n / c_s du_{\perp} / dr$, $\tilde{u}_\parallel' = L_n / c_s du_{\parallel} / dr$, $S = L_n / L_s = (L_n / qR)(r_{df} / q)$. For example at $t_3$, from $L_n = 0.25 \text{ m}$, $L_s = 8.3 \text{ m}$, $q = 3$, $R = 3.05 \text{ m}$, and $\tilde{S} = d\ln q / d\ln r = 1.1$, we obtain the following dimensionless transport parameters

$$\tilde{u}'_\perp = \frac{(0.25 \text{ m})(1 \times 10^5 / \text{s})}{220 \text{ km/s}} = 0.11, \quad \tilde{u}_\parallel' = \frac{(0.25 \text{ m})(6 \times 10^5 / \text{s})}{220 \text{ km/s}} = 0.68, \quad S = \frac{0.25 \text{ m}}{8.3 \text{ m}} = 0.03$$

and thus $L_s u'_\perp / c_s = \tilde{u}'_\parallel / s = 3.6$. 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 $(L_s u'_\perp / c_s)_{\text{crit}} \approx 2 \sqrt{T_i / T_e} (\eta_i - \eta_e)$ which at $t_3$ we estimate as $2 \sqrt{4 \text{ kev} / 2 \text{ kev}} (3 - 1) \approx 4$ 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 $P_{L \rightarrow H}$ for this internal L to H transition is estimated from the surface area $4\pi^2 r_s R$ and the values of $P'^*_{\phi}$ and $\nu^{ac}$ at the $W_H = W_L$ bifurcation. When $P'^*_{\phi} = P'^*_{\phi} = 0$ the bifurcation condition is $\nu_{ac} < \chi_L / \Delta^2 \propto W_L$. Taking $R_0 = 3 \text{ m}$, $r_s = 0.7 \text{ a} = 0.5 \text{ m}$, $n = 1.1 \times 10^{13} \text{ m}^{-3}$, $T_i = 3 \text{ kev}$, we estimate $\nu_{ac} \sim 10^{-2}$ and derive $P_{L \rightarrow H} = 18 \text{ MW}$. The threshold is substantially lowered by the increase of $u'_\perp$ associated with $P'_\phi$. Including $P'_\phi$ as indicated we estimate $P_{L \rightarrow H}$ drops to 10 MW. These estimates show the importance of the momentum deposition profiles in determining the core transport barrier power threshold.

3. Conclusions

The high $\beta_p$ 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.

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