The Role of Rotation in Tokamak Internal Transport Barriers*

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Abstract

Internal transport barriers have been observed in several tokamak operating regimes. A model of the energy, particle, and toroidal momentum transport due to drift wave turbulence is shown to form internal transport barriers due to $E \times B$ rotational shear. The power threshold for the transport barrier to form is found to be lowered by peaking of the power deposition or density profile near the magnetic axis in agreement with experimental trends. Toroidal momentum injection counter to the current is predicted to lower the power threshold if the thermal ion density is peaked on axis, but an internal transport barrier can form even without toroidal rotation in either direction due to the density and temperature gradient contributions to the $E \times B$ rotational shear.

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Recent experiments with negative central magnetic shear have strongly reduced turbulence and transport [1,2]. Earlier experiments with pellet fueling [3] or high beta poloidal [4] have also observed internal transport barriers. The suppression of sawtooth instabilities in all of these operational modes is a necessary condition for internal transport barrier modes, but there is also a power threshold. This is clearly demonstrated in the negative magnetic shear experiments [1,2]. One major difference between the DIII–D and TFTR experiments is that TFTR uses balanced neutral beam injection (NBI) with no net toroidal momentum injection whereas DIII–D uses only co-injected NBI. The radial electric field in TFTR is thus determined by the diamagnetic and neoclassical poloidal rotation contributions, but in DIII–D the toroidal rotation is the main contributor to the electric field. We will show in this letter that $E \times B$ rotational shear can cause a bifurcation to an internal transport barrier mode for either balanced or unbalanced NBI. The power threshold is predicted to be lowest for counter-injection when the thermal ion density is peaked on axis.

The transport model used for these calculations is an extension of a previous model of $E \times B$ shear suppression [5] to include more of the physics of ion temperature gradient (ITG) model turbulence assumed to be the dominant instability governing transport. The basic properties of internal transport barriers were discovered with the previous model [5,6] and only depend upon the $E \times B$ shear suppression. The introduction of a critical temperature gradient length for ITG modes in the present model increases the width of the transport barrier significantly.

The same physical model can be used to simulate H–modes, VH–modes, and internal transport barrier modes. The difference is in the distribution of the energy, particle, and toroidal momentum sources. If the main particle source is at the edge and the heating and/or toroidal torque profiles are broad then the local bifurcation condition is only satisfied at the edge for moderate heating and an H–mode results. A VH–mode naturally evolves from an H–mode at high power once the local bifurcation condition is met in the plasma interior [5]. A transport barrier forms in the interior, without an edge barrier, if the edge particle source is small and if the heating and/or toroidal torque and fueling profiles are strongly peaked on the magnetic axis [6,7]. The transport barrier grows from the edge inward in a VH–mode, and from the core outward for an internal transport barrier but they are otherwise very similar.

To evaluate transport due to ITG turbulence, the average intensity of the ITG mode fluctuations is evolved according to

$$\frac{\partial A}{\partial t} + \frac{1}{r}\,\frac{\partial}{\partial r}\,(r\Gamma_A) = \gamma A - \beta A^2 \quad , \tag{1}$$

$$A = \left|\frac{c k_\theta \widetilde{\Phi}}{B}\right|^2 \left(\frac{R}{V_{\mathrm{th_i}}\rho_\mathrm{i}}\right)^2 \quad , \tag{2}$$

where $V_{\mathrm{th_i}} = (2\,T/m_\mathrm{i})^{1/2}$, $R =$ major radius, ρ_i = ion gyroradius. The average linear growth rate is taken to retain the gross features of more exact ITG mode transport formulas [8]

$$\gamma = \gamma_0\,\frac{V_{\mathrm{th_i}}}{R}\left(\frac{R}{L_\mathrm{T}} - \frac{R}{L_\mathrm{T}^\mathrm{c}}\right)^{1/2} - |S_\perp| \quad , \tag{3}$$

where $L_\mathrm{T}^{-1} = -(\partial/\partial r)\ell\mathrm{n}T$, γ_0 is a constant, and the $E \times B$ velocity shear rate in toroidal geometry [9] is

$$S_\perp = \frac{B_\theta\,R}{B}\,\frac{\partial}{\partial r}\,(E_\mathrm{r}/RB_\theta) \quad , \tag{4}$$

with

$$E_\mathrm{r} = B_\theta\,V_\phi - B_\phi\,V_\theta + \frac{1}{e\,Z_\mathrm{i}\,n_\mathrm{i}}\,\frac{\partial p_\mathrm{i}}{\partial r} \quad . \tag{5}$$

The average growth rate vanishes when the $E \times B$ velocity shear rate $S_\perp$ equals the average growth rate in the absence of $E \times B$ shear, a prescription derived from nonlinear gyrofluid simulations of the toroidal ITG mode [10]. The critical temperature gradient length is taken to be

$$\frac{R}{L_\mathrm{T}^\mathrm{c}} = 0.3\,\frac{R}{L_n} + \frac{B_\theta}{B}\,10.0 \quad . \tag{6}$$

The factor B_θ/B is included *ad hoc* in order to ensure that $R/L_\mathrm{T}^\mathrm{c} \to 0$ as $r \to 0$, otherwise the temperature gradient always becomes less than the threshold near the axis. The nonlinear damping rate is determined from 3-D simulations [11] to be approximately

$$\beta = \left(\frac{V_{\mathrm{th_i}}}{R} \right) \frac{0.2}{q} \quad . \tag{7}$$

The energy, particle, and toroidal momentum transport equations for the primary ions are

$$\begin{aligned}
&\frac{\partial p}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (rQ) = S_p \quad , \\
&\frac{\partial n}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r\Gamma) = S_n \quad , \\
&\frac{\partial m_\phi}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r\Pi_\phi) = S_{m\phi} \quad ,
\end{aligned} \tag{8}$$

where

$$\begin{aligned}
Q &= -\, n\chi \frac{\partial T}{\partial r} \quad , & \Gamma &= -\, D \frac{\partial n}{\partial r} \quad , \\
\Pi_\phi &= -\, n\mu \frac{\partial V_\phi}{\partial r} \quad , & \Gamma_A &= -\, D_A \frac{\partial A}{\partial r} \quad , \\
\chi &= \left(\chi^{\mathrm{H}} + A\chi^{\mathrm{L}}\right) V_{\mathrm{th_i}}\, \rho_{\mathrm{i}}^2/R \quad , & \mu &= \left(\mu^{\mathrm{H}} + A\mu^{\mathrm{L}}\right) V_{\mathrm{th_i}}\, \rho_{\mathrm{i}}^2/R \quad , \\
D &= \left(D^{\mathrm{H}} + AD^{\mathrm{L}}\right) V_{\mathrm{th_i}}\, \rho_{\mathrm{i}}^2/R \quad , & D_A &= \left(D_A^{\mathrm{H}} + AD_A^{\mathrm{L}}\right) \quad .
\end{aligned} \tag{9}$$

All of the transport coefficients have a part due to ITG modes proportional to A and a background contribution which is unaffected by $E \times B$ shear (representing neoclassical or high frequency turbulent transport).

The poloidal ion velocity is taken to be neoclassical in the banana regime [12]. The ion poloidal rotation almost completely cancels the temperature gradient term in the diamagnetic contribution to E_{r} [Eq. (5)]. The calculated evolution of an internal transport barrier with no toroidal momentum source (balanced NBI) is shown in Fig 1. There are five time slices (labeled 1 through 5) at 25 ms intervals. The curves labeled 1 are L–mode before the power has been increased tenfold, exceeding the threshold for transport barrier formation. The electric field is negative everywhere being dominantly due to the density gradient term in the diamagnetic velocity. Note that while E_{r} must vanish on axis E_{r}/B_θ does not [Fig. 1(d)] and the shear in E_{r}/B_θ is positive throughout the core region. For $r < 0.3\,a$ the turbulence intensity vanishes for the last time slice. This is the transport barrier. The shear rate $S_\perp$ [Eq. (3)]

vanishes on axis. Very near the axis the turbulence is suppressed [Fig. 1 (c)] because R/L_{T} drops below the critical temperature gradient $a/L_{\mathrm{T}}^{\mathrm{c}}$ for the ITG mode after the transport barrier is initiated by $S_{\perp}$ off-axis. Thus, the presence of a critical temperature gradient length in the model broadens the region of suppressed transport.

It can be shown that the power threshold for the internal transport barrier to form is strongly reduced by peaking of the density and/or the power deposition profile on axis for this model.

Toroidal rotation gives a positive contribution to E_{r} for co-rotation ($B_\theta V_\phi > 0$) and negative for counter-rotation ($B_\theta V_\phi < 0$). In Fig. 2 are shown the evolution of the toroidal flux ($M_\phi = nV_\phi$), E_{r}/B_θ, and pressure profiles for counter- [Fig. 2 (a), (c), (e), (g)] and co-momentum [Fig. 2 (b), (d), (f), (h)] injection for the same model parameters as we used in Fig. 1. For counter-toroidal momentum injection, the power threshold to form the internal barrier is lower as evidenced by the fact that the barrier forms sooner [compare Figs. 1 (c) and 2 (c)] when the power flow reduced by the derivative of the stored energy is smaller. The width of the barrier with counter-rotation also increased. The reason for these effects is that counter-toroidal rotation shear has the same sign as the shear in the ion poloidal diamagnetic velocity $[(1/Z_{\mathrm{i}}en_{\mathrm{i}}B_\theta)(\partial p/\partial r)]$ which peaks on axis for the strongly peaked ion pressure profiles of Fig. 2 (g). However, for broader ion pressure profiles, the ion poloidal diamagnetic velocity peaks off-axis and its shear becomes negative near the axis, subtracting from the counter-toroidal rotation shear term in $S_{\perp}$. This is the case for VH–modes. The VH–mode power threshold is lowered by co-rotation [5]. For internal transport barriers near the axis, co-rotation is predicted to be less favorable than counter since the ion poloidal diamagnetic velocity shear subtracts from the co-rotation shear. If the thermal ion density is hollow near the axis then the co-rotation is more favorable for E_{r}/B_θ shear near the axis.

For the co-rotation case the transport barrier is not fully formed near the axis even after 100 ms [curve 5 of Fig. 2 (d)]. This is due to the competition between the diamagnetic and perpendicular velocity contributions to the E_{r}/B_θ shear. Notice that the fluctuation intensity is somewhat suppressed near the edge for the co-rotation case [Fig. 2 (d)] where the diamagnetic and perpendicular velocity gradients add together. At high power or high unbalanced torque the plasma evolves to a state where the turbulence is suppressed across the entire profile just like the ultimate state of a VH–mode [5]. The energy, momentum, and particle deposition profiles determine where the transport barrier initially forms.

In conclusion, we have shown that $E \times B$ rotation shear is capable of producing an internal transport barrier with balanced or unbalanced NBI. Magnetohydrodynamic stability is necessary for access to improved confinement but negative magnetic shear is not essential for the transport barrier formation. Counter momentum injection is predicted to lower the power threshold for transport barriers near the axis, if the thermal ion poloidal diamagnetic velocity is peaked on axis. An important caveat to this conclusion is that we have not considered the parallel velocity shear drive which can overcome the $E \times B$ suppression especially near the magnetic axis [13]. Very large toroidal rotation (approaching the sound speed) in either direction could destabilize the ITG mode.

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