THEORY OF ENHANCED CORE CONFINEMENT REGIMES IN TOKAMAKS*

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The cause of the enhanced core confinement in three regimes observed in tokamaks is investigated: pellet enhanced performance (PEP) [1], radiation improved (RI) [2], and internal transport barrier (ITB) modes with weak or negative magnetic shear [3,4]. Theoretical calculations of the linear stability and quasilinear transport of toroidal drift waves and high toroidal mode number electromagnetic instabilities are compared with experiments. Three theoretical tools are employed: a comprehensive gyrokinetic linear stability code [5] which has been extended to shaped magnetic equilibria, nonlinear 3-D gyrofluid simulations [6], and a reduced gyrofluid transport model [7]. A consistent picture of the transport of both ions and electron energy is found for all three experimental regimes. It is found that generally the low wavenumber part of the linear drift wave spectrum is partially or completely suppressed by E×B velocity shear. This includes trapped ion modes (TIM), ion temperature gradient modes (ITG) and trapped electron modes (TEM). The improvement in the ion thermal transport is explained by this E×B shear suppression. The high wavenumber electron temperature gradient mode (ETG) is not suppressed by E×B shear due to its high growth rate. This explains the generally smaller reduction in electron thermal transport observed. The ETG mode properties give rise to different levels of the electron transport in the three regimes.

The gyrokinetic growth rates (γ) are computed without E×B shear ($\gamma_{E\times B}$) for technical reasons. The measured $\omega_{E\times B}$ is then subtracted from γ to get a positive residual net growth rate. This method of including E×B shear is based on nonlinear simulations of ITG modes [6]. The simulations found that the turbulence was completely quenched when $\gamma_{E\times B} > \gamma_{max}$, where γ_{max} is the maximum linear growth rate. By comparison, nonlinear decorrelation theory [8,9] would only predict a small reduction in the fluctuation level when the E×B shear is at the quench point. The quench point also does not follow linear eigenmode stability (including E×B shear) in a torus but it does in a sheared slab magnetic geometry. Therefore, it is possible to distinguish the quench rule from the other two theories experimentally. The improved thermal confinement of the PEP mode has been ascribed to the stabilization of ITG modes by density peaking. However, density gradients drive the TEM unstable. Thus, density peaking alone cannot reduce ion thermal transport since the TEM mode produces ion heat flow. The ion thermal transport reduction requires E×B shear suppression of the TEM in PEP modes. Peaking the density increases the critical electron temperature gradient of the ETG mode which improves the electron energy confinement. For large enough particle source and high density a bifurcation to neoclassical electron transport, by complete ETG modes suppression, is predicted to be possible [10] but has not been reported.

The RI–mode has reduced transport after impurity injection. Analysis of a DIII–D discharge [11] with improved energy confinement after neon injection showed substantial E×B shear suppression of the ion transport. The electron transport is also found to be improved experimentally. The ETG modes have reduced growth rates in the outer part of the plasma due to the neon kinetic response. There is a good correlation between the measured electron thermal diffusivity and the ETG mode trends. Improved electron energy confinement persist in both the L– and H–mode phases of the discharge. The energy confinement reaches three times its pre-neon L–mode value during the improved H–mode (IH) phase. Sawteeth and

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edge localized modes (ELM) reduce the energy confinement to normal H–mode later in the discharge.

The weak and negative magnetic shear plasmas with a region of neoclassical ion thermal transport are commonly referred to as having an ITB. It has been demonstrated previously that the quench rule for E×B shear suppression is well satisfied for the ITG and TEM modes explaining the ion transport. However, the electron thermal transport is still well above neoclassical in the ITB. Linear growth rate analysis of several discharges has found that the electron temperature gradient is very close to the marginal stability point of the ETG mode in most cases. The quasilinear energy flux computed with the electron temperature gradient 10%–20% above the stability point is much larger than the experimental value. This is consistent with the temperature profile being marginally stable as observed.

The reduced gryofluid transport model (GLF23) approximates the transport due to toroidal drift waves (ITG, TEM, ETG) and uses the quench rule for E×B shear. The model fits the norm and scaling of nonlinear gyrofluid simulations and has been shown to reasonably predict the electron and ion temperature profiles in L– and ELMing H–mode plasmas over a multi-tokamak database of 60 discharges. If the calculated E×B shear agrees with the measured value, the model can predict the ion and electron temperature profiles well even in enhanced confinement regimes. The power threshold for an ITB can be computed with the model. The usual dimensionally similar scaling to a reactor yields an unfavorable scaling for the diamagnetic contributions to the E×B shear due to the magnetic field dependence. The toroidal rotation contribution has a more favorable scaling. Dimensional similarity scales the profile gradient lengths to the plasma size. Localized off-axis heating, fueling or momentum sources break this scaling and can greatly reduce the total power required to form an ITB. Modeling suggests that off-axis electron cyclotron (ECH) heating can move the leading edge of the ITB to the resonance absorption layer. ECH increases the electron temperature gradient at and outside of the resonance layer which excites electron turbulence. However, at smaller radii than the off-axis heating location, the electron temperature is higher than before the ECH heating but the power flow carried by the electrons is reduced. This is because the Ohmic and direct electron heating from the neutral beams is reduced The ion collisional heat exchange to the electrons is also lower. Thus, the free energy to drive electron turbulence is reduced in this region. If the electron turbulence reduction also reduces ion transport, then it becomes easier for the ITB to grow out to just short of the ECH heating radius.

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