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(Received – Aug. 23, 1990)

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Modelling of Improved Confinements
- Peaked Profile modes and H-mode -

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Abstract

Theoretical models on improved confinement with peaked density profile and on H-mode are discussed. A model theory of inward pinch and peaked density profile of ohmic discharges in tokamak is presented. Ion anomalous viscosity in the presence of sheared toroidal rotation causes the drift across the magnetic field. The ratio of viscosity to diffusion coefficient, Prandtl number, determines structures of E_r and density profile in a stationary state. In viscous plasmas, peaked profiles of both density and rotation velocity are possible without central particle/momentum sources. Resultant rotation of the core relative to the edge is in the counter direction to plasma current. Reduction of edge neutrals can induce further density peaking.

H-mode transition model is further developed. The radial derivative of E_r, E_r', changes ion losscone loss through squeezing poloidal gyroradius and electron loss by affecting microinstabilities. Charge neutrality condition predicts cusp type catastroph in the relation between the gradient and flux at edge. At the transition, E_r' jumps to negative and fluctuations and anomalous fluxes reduce simultaneously. Combined model predicts that the core density profile is flattened during H-phase.

1. Introduction

Recently various improved modes have been found other than H-mode in tokamaks. In H-mode the steep gradient is established only near the edge[1]. Other improved modes are characterized by peaked density/ion temperature profiles[2,3]. We first present a model of peaked density profile of the core associated with radial electric field, $E_r(r)$, showing that anomalous viscosity in the presence of sheared toroidal rotation induces an inward flow of particles. The extended model of H-mode based on bifurcation of $dE_r(r)/dr$ associated with poloidal rotation is presented. Combining both models, the effect of edge pedestal to the core profile is discussed.

2. Peaked Profile Modes

Density continuity and charge conservation in the presence of the diffusion determines the structure of $E_r(r)$ and density profile, n(r). To obtain $E_r(r)$, electron and ion fluxes are assumed to be anomalous due to drift-type microturbulence of frequency, ω, and poloidal wave number, m. Applying quasilinear theory, we have[4],

$$\Gamma_{s,a} = -D_s n_s \left[\frac{n_s'}{n_s} (1+\alpha_s \eta_s) - \left(\frac{eE_r}{T_s} - \left\langle \frac{r\omega}{m} \right\rangle \frac{eB_t}{cT_s} \right) \right] \qquad (1)$$

where η =dlnT/dlnn, α; numeric and $\langle \omega r/m \rangle$; spectrum averaged phase velocity, suffix shows particle species, s. Radial ion flux includes an anomalous viscosity flow, $\Gamma_{i,v}=(qR/ZerB)n_i m_i \nabla\mu_\perp \nabla U_\phi$,($\mu_\perp$: viscosity)[5] and the momentum loss by charge exchange,

$\Gamma_{i,cx} = (qR/ZerB)n_i m_i U\phi n_0\langle\sigma_{cx}v\rangle$, where the toroidal rotation, $U\phi = (qT_i R/ZerB)[n_i'/n_i(1+c_i\eta_i)-ZeE_r/T_i]+ qRU_p/r$, is derived from the radial momentum balance. The charge conservation equation, $\Gamma_{e,tot} = \Gamma_{i,a}+\Gamma_{i,v}+\Gamma_{i,cx}$ and the continuity $\nabla\cdot\Gamma_{e,i,tot}=S_{e,i}$ are basic equations. $\Gamma_{e,tot} = \Gamma_{e,a}$ is assumed.

In the absence of beam or pellet, particle sources, $S_{e,i}$, and $\Gamma_{i,cx}$ are localized near the edge and we assume that $S_e = S_i$ ($S\equiv n_0 n_e\langle\sigma_i v\rangle$; where $\langle\sigma_i v\rangle$ is the ionization rate). We introduce the normalized electric filed, E ($=a^2 eE_r/rT_i$), and its shear part $\{E\}$ ($\equiv$E-const). We take $\eta=0$ with $T_e = T_i$ and $U_p\to 0$. D, $\mu_\perp$ and q are set to be numeric. In the core, where $n_0\sim 0$, $\Gamma_{e,tot} = 0$ gives the relation $-2(\ln n)' = \{E\}+ C_1$ in y ($=r^2/a^2$) coordinate. C_1 ($\propto\langle\omega/m\rangle$) is assumed to be constant, which is determined by boundary conditions. The condition, $\Gamma_{e,tot}=\Gamma_{i,tot}$ gives,

$$-\nu_a\{E\} + \nu_\mu \frac{1}{y}\frac{d}{dy} y \frac{d}{dy}\{E\} = 0 \qquad (2)$$

where $\nu_\mu=(1/Z+1)q^2R^2\mu_\perp/a^4$, $\nu_a=(1+Z)D_i/\rho_i{}^2$ and ρ_i is toroidal gyroradius.**

**footnote: If we evaluate $\langle\omega/m\rangle$ by the local dispersion relation, then we have $\{E\} = -2C_2(\ln n)'$ ($C_2=1/(1-\Lambda_0)$, $\Lambda_0=I_0 e^{-b}$, $b=k_\perp^2\rho_i^2$, I_0 being the 0-th order modified Bessel's function) and ν_μ is redefined as $(C_2/Z+1)q^2R^2\mu_\perp/a^4$. The qualitative nature of the solution in the following does not change.

The solution is given as, $\{E\} = A_1 I_0(\sqrt{\nu_a/\nu_\mu}\,y)$, and $\{E\}+C_1 = -$

$2(\ln n)'$. The profile of E_r is dictated by the parameter ν_μ/ν_α, which indicates the diffusion Prandtl number[6]. When the higher order derivative of the pressure is neglected, ν_μ/ν_a reduces to $(\mu_\perp/D_i)(q^2R^2\rho_i{}^2/a^4)$.

Neutrals in the outer region ($a-\Delta<r<a$, Δ: penetration length of neutrals) affect the momentum balance. For the boundary condition at $r=a$, $dn/dr/n\big|_{r=a} = 1/\lambda_n$, we obtain

$$\{E\} = \{(\frac{a}{\lambda_n} - \frac{a^2}{2D_e}\langle S\rangle\Big|_{r=a} - C_1)\frac{I_0(\sqrt{\nu_a/\nu_\mu}r^2/a^2)}{I_0(\sqrt{\nu_a/\nu_\mu})}\} \qquad (3)$$

in the limit of $\Delta \ll a$ where $\langle S\rangle = \int n_e n_0 \langle\sigma_i v\rangle dy/n_e y$.
We plot $n(r)$ for various values of ν_μ/ν_a in Fig.1a. For fixed line averaged density, ν_μ/ν_a is changed from 0.01 to 100. $A_0 = (a/\lambda_n - C_1 - a^2\langle S\rangle/D_e)$ is chosen to be 10. The more viscous plasma has the more peaked profile. Viscous frictional force to the toroidal rotation and the poloidal magnetic field causes the FxB drift of ions. Only if the rotation flow is counter to the current direction the inward drift occurs. The force differently acts on electrons, and E_r piles up. Electrons also drift inward. The peaked profile can be thus sustained without particle source. The peaking is expected if ν_μ/ν_a is large, i.e., if $\mu_\perp/D$, R/a, ρ_i/a is large or I_p is small. Radial profile of toroidal rotation is given by $U_\phi/v_{Ti} = (\rho_p/a)A_1 I_0(\sqrt{\nu_\mu/\nu_a}y)$+const. and is shown in Fig.1b. We plot the value of $(U_\phi - U_\phi(a-\Delta))/v_{Ti}A_0(\rho_p/a)$. The rigid rotation part is determined by the boundary condition. Associated with the density peaking, the rotation profile also

peaks. We show the effect of boundary condition on n(r) in Fig.1c. As A_0 becomes large, the density peaks. When gas-puff is reduced, edge source is expected to become small. The reduction of ⟨S⟩ reduces the momentum loss of the rotation, which can increase the density gradient at $r=a-\Delta$. And A_0 rises if λ_n remains similar. This causes the peaking of core density. The SOC/IOC transition[2] is attributed to this mechanism.[7] When ν_μ/ν_a is small (less viscous), the reduction of ⟨S⟩ is found to have little effect to cause density peaking. Actual value of ν_μ/ν_a is not known, however, if we apply a quasilinear theory to drift wave fluctuations[5] this ratio becomes order of unity to 10. Recent measurement of toroidal rotation[8] supports this estimate.

3. H-mode

We consider the edge of circular plasma. Particle flux can be bipolar near edge[9]. The relation $\Gamma_{e,NA}=\Gamma_{i,NA}$ determines the ambipolar electric field, E_r. The bipolar flux of ions $\Gamma_{i,NA}$ comes from losscone loss. In the presence of E_r', the banana width changes by the factor $G\equiv 1/\sqrt{1-u_g+C\varepsilon}$[10,11], where $u_g=\rho_p E_r'/v_{Ti}B_p$. Taking u_g corrections, we have $\Gamma_{i,NA}=(Fn_i\nu_i\rho_p G/\sqrt{\varepsilon})\exp[-X^2]$, where ν_i is the ion-ion collision frequency, $X=\rho_p eE_r/T_i$ and F is a numerical coefficient($\sim O(1)$).

The microscopic mode stability is affected by E_r'. The collisionless trapped particle drift instability, for example, is stabilized if the condition $u_g<-u_c$ is satisfied,($u_c^2=8\sqrt{2\varepsilon}(4-u_c)$). We employ an analytic estimation of the growth rate and transport coefficient as $\gamma \sim \gamma_0 \sqrt{1+u_g/u_c}$ and $D_e = D_{e0}\sqrt{1+u_g/u_c}$, where suffix 0 denotes cases of $E_r' = 0$. The bipolar electron flux near edge, $\Gamma_{e,NA}$, being originated from the convection of excited waves[9], is $\Gamma_{e,NA} = n_e D_{e0}\sqrt{1+u_g/u_c}(\lambda - X)$, $\lambda = -(T_e T_i)\rho_p (n_e'/n_e + \alpha T_e'/T_e + eBr/T_e\langle\omega/m\rangle)$. Equating $\Gamma_{e,NA}$ and $\Gamma_{i,NA}$, we have the refined equation,($d \equiv \sqrt{\varepsilon} D_e/\nu_i F \rho_p^2$)

$$d\sqrt{1+u_g/u_c}(\lambda - X) = G\exp[-X^2]. \qquad (4)$$

The poloidal bulk viscosity gives the relation as $U_p/v_{Ti} \propto \rho_i \nabla T_i/T_i$[12], i.e., $X = -\lambda_i - U_\phi/v_{Ti}$, where $\lambda_i = -\rho_p(n_i'/n_i + c_i T_i'/T_i)$ and c_i is a numerical coefficient(O(1)). Since the toroidal flow in the scrape-off layer is damped[13], we neglect U_ϕ/v_{Ti} and have $X = -\lambda_i$. The solution is obtained only in the negative E_r region.

In Fig.2, the solution of E_r', the relative transport coefficient and the resultant flux are shown for $\lambda = \lambda_i$. At the threshold value of λ, λ_{c1}, E_r' jumps from positive to negative, and D_e/D_{e0} and Γ/Γ_0 show transitions to smaller values.

Combining the models in Sec.2 and 3, we finally note the effect of the H-mode to the core density profile. The transport barrier effectively increases $\langle S\rangle/D_a$ (i.e., local diffusion is reduced) and reduces A_0. Profile of the density and U_ϕ of the core plasma are flattened owing to the decrease of A_0. The reduced momentum loss increases the rigid toroidal rotation.

4. Summary and Discussions

We have presented a model of the improved confinement with peaked density profile and that of the H-mode transition.

Inward pinch induced by the ion viscosity is studied; it is predicted that the peaking occurs by the reduction of the edge source if the values of ν_μ/ν_a is large enough. This mechanism explains SOC/IOC transition. The bifurcation of E_r' at the edge is predicted. The anomalous diffusivity and the associated flux reduce simultaneously. E_r' turns to negative and the negative E_r becomes more negative. Combining these models, the core density profile is predicted to be flattened in H-mode.

The inward pinch is studied in the absence of the external momentum source and ∇T_i. The extension of the present model to the various peaked profile modes are left for future study.

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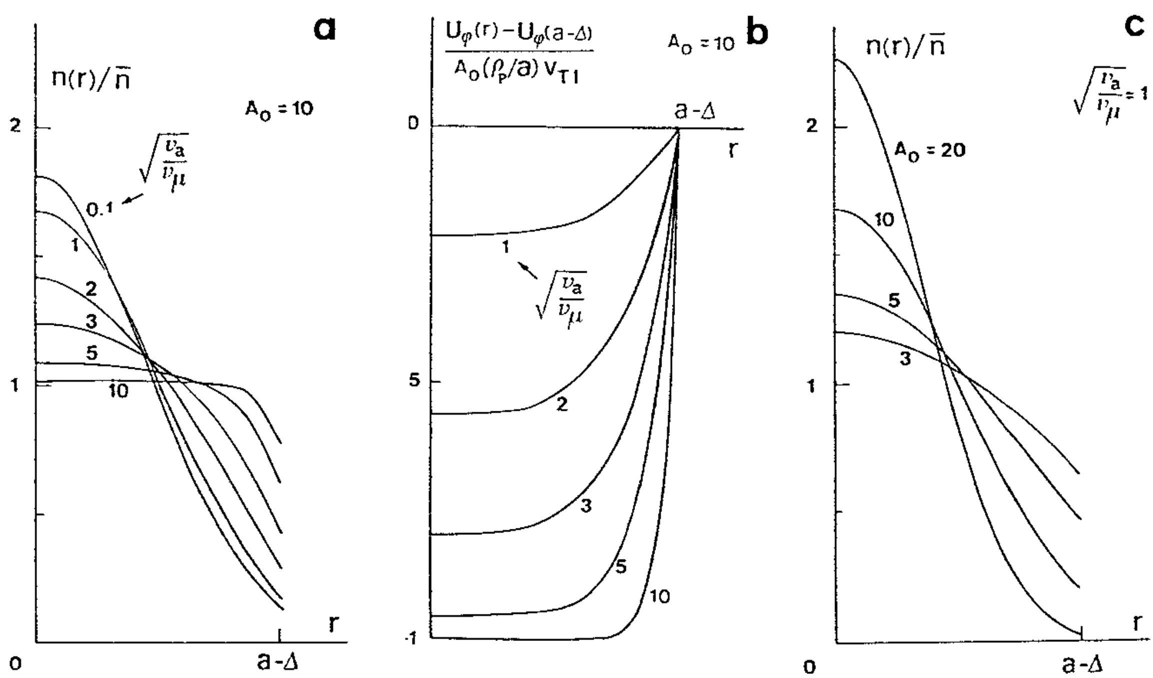

Fig. 1 Density profiles for various values of $\sqrt{\nu_a/\nu_\mu}$ (from 0.1 to 10)(1a), and flow velocity (normalized to $v_{Ti}\rho_p/a$) (1b) for fixed value of A_0(=10)(1a).
Density profiles for various values of A_0 (3, 5, 10, 20)for the fixed values of ν_a/ν_μ(= 1)(1c).

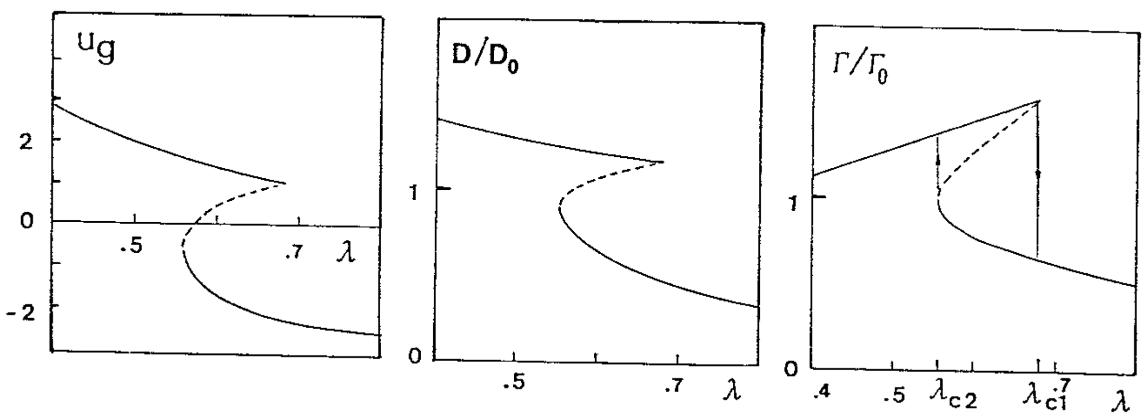

Fig. 2 Radial gradient of $E_r(u_g)$, transport coefficient(D_e/D_{e0}) and flux (Γ/Γ_0) are shown as a function of λ. In the region of $\lambda_{c2}<\lambda<\lambda_{c1}$, solutions become multi-valued. Transition takes place at $\lambda=\lambda_{c1}$(L→H) and $\lambda=\lambda_{c2}$(H→L).

Key words : Peaked profile, Inward pinch, H-mode, Improved mode
Radial electric field