Two-Dimensional Model Including the Mechanism of a Poloidal Shock Structure and Geodesic Acoustic Mode in Toroidal Plasmas

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In H-mode plasmas, two-dimensional steep structures of the electrostatic potential and density are formed when a large poloidal flow exists, whose formation mechanism has been studied to obtain a quantitative understanding of the particle transport in H-mode transport barriers. The previous two-dimensional model is extended to investigate parallel flow dynamics when potential and density distributions do not satisfy the Boltzmann relation. The extended model includes the generation mechanism of a poloidal shock structure and geodesic acoustic mode, whose competitive formation can be studied.

Keywords: poloidal shock structure, geodesic acoustic mode, H mode, poloidal asymmetry, toroidicity

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1. Introduction

A variety of structures are formed in toroidal plasmas, and their formation mechanism is one of the keys to understanding transport phenomena. The typical example appears in a high-confinement mode (H mode) [1]. A steep radial electric field plays an important role in turbulent suppression in H-mode transport barriers [2]. In addition, a poloidally steep structure can be formed in association with a large poloidal flow. Theories have predicted that a poloidal shock can appear in H-mode plasmas [3, 4]. The poloidal shock structure is a steady density or potential jump in the poloidal direction, resulting from the plasma compressibility and inhomogeneity of the magnetic field by the toroidicity. It is important, because it helps radial particle fluxes accelerate the density pedestal formation in L/H transition [5]. Some experiments have indicated the existence of poloidal asymmetry [6, 7]. Therefore, it is important to understand the formation mechanism of H-modes by analyzing the two-dimensional (2-D) electric field structure.

We have extended the one-dimensional (1-D) model for tokamak H modes to create 2-D structures by considering the coupling between different magnetic surfaces by shear viscosity, and obtained 2-D potential and density structures in edge transport barriers [5]. The previous quasi-1-D model [8] shows that the existence of viscosity at the shock makes the shock position to evolve to the inner mid plane, and then the shock to vanish. This is because the position of the shock is arbitrary in 1-D models. Our model is 2-D, and the position of the shock, which is stationary, is determined by the radial boundary constraint. Our evaluation clarifies the non-negligibility of the particle transport arising from poloidal asymmetry, and the self-consistent mechanism of the density pedestal formation in the L/H transition [9].

In this study, the previous 2-D model is extended to investigate two effects on the structural formation, i.e., the deviation from the Boltzmann relation and the parallel flow dynamics. The distribution of the potential and density difference from the Boltzmann relation contributes to the induction of a particle pinch [9], and the parallel flow dynamics is important to obtain the flow pattern, which contributes to the structural formation [2]. These extensions enable the analysis of the geodesic acoustic mode (GAM) [10], which is an oscillatory zonal flow caused by compressibility of the $E \times B$ flow in the presence of geodesic magnetic curvature [11]. The zonal flow interacts nonlinearly with turbulence and determines the transport level. Therefore, many experimental observations have been made to clarify the role of the zonal flow in plasma confinements [12]. Both the poloidal shock and geodesic acoustic mode induce density asymmetry in the magnetic flux surface; therefore, their competition must be examined to deepen our understanding of transport barrier physics.

In an edge transport barrier, a large poloidal flow with a poloidal Mach number (poloidal flow velocity normalized by the poloidal sound velocity) ~ 1 is generated, resulting in a poloidal shock. Therefore, a model applicable to both the subsonic and sonic regimes is necessary to describe the formation process of the edge transport barrier during L/H transitions. The aim of this paper is to present a comprehensive model for both the regimes. The paper is organized as follows. The derivation of the model equations is provided in Sec. 2. The formation mechanism of the poloidal shock or GAM can be deduced from the limiting cases of our new model with a large or small poloidal flow. Previous models [4, 5], [13] describing the poloidal

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shock or GAM are presented in Sec. 3. The summary is presented in Sec. 4.

2. Set of Model Equations

For analyzing the potential, density, and flow velocity, the following set of fluid equations consisting of the momentum conservation equation, the continuity equation of density, the charge conservation equation, and Ohm's law, are used:

$$m_i n \frac{d}{dt}\vec{V}_i = \vec{J}\times\vec{B} - \vec{\nabla}(p_i + p_e) - \vec{\nabla}\cdot\overleftrightarrow{\pi}_i, \tag{1}$$

$$\frac{\partial n}{\partial t} + \vec{\nabla}\cdot\left(n\vec{V}_i\right) = 0, \tag{2}$$

$$\vec{\nabla}\cdot\vec{J} = 0, \tag{3}$$

$$\vec{E} + \vec{V}\times\vec{B} = 0, \tag{4}$$

where m_i is the ion mass, $\vec{V}$ is the flow velocity, $\vec{J}$ is the current, p is the pressure, and $\overleftrightarrow{\pi}$ is the viscosity. We assume that density $n = n_i = n_e$ for simplicity, where n_i and n_e are the ion and electron densities, respectively. We also assume that $B_\phi \gg B_p$, i.e., low-β and electrostatic perturbations. Electromagnetic effects are not included because the main object of this paper is the poloidally-asymmetric structure in the edge transport barrier, where high-β effect is not significant. In the thin layer near the plasma edge, a large poloidal flow is generated and poloidal shocks are formed. Here, a large aspect ratio tokamak with a circular cross-section and the coordinates (r, θ, ϕ) are used (r: radius, θ: poloidal angle, and ϕ: toroidal angle). The magnetic field is expressed as

$$\vec{B} = \frac{1}{1+\varepsilon\cos\theta}\begin{pmatrix} 0 \\ B_{p0}(r) \\ B_{\phi 0}\end{pmatrix}, \tag{5}$$

where ε is the inverse aspect ratio. Using Eq. (4), the flow velocity can be written as

$$\vec{V} = \vec{V}_{/\!/} + \frac{\vec{E}\times\vec{B}}{B^2} = \begin{pmatrix} -\dfrac{1}{rB}\dfrac{\partial\Phi}{\partial\theta} \\ \dfrac{KB_p}{n} \\ \dfrac{KB_\phi}{n} - \dfrac{1}{B_p}\dfrac{\partial\Phi}{\partial r}\end{pmatrix}, \tag{6}$$

where

$$K \equiv \frac{nV_p}{B_p}, \tag{7}$$

V_p is the poloidal flow velocity, and Φ is the potential. Using Eqs. (6) and (2), the poloidal and parallel components of Eq. (1) are obtained as

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial r}\left(\frac{n}{rB}\frac{\partial\Phi}{\partial\theta}\right) + \frac{1}{r}\frac{\partial}{\partial\theta}\left(KB_p\right) = 0, \tag{8}$$

$$\begin{aligned}&B_p^2\frac{\partial}{\partial t}\left(\frac{K}{n}\right) - \frac{n}{KrB}\frac{\partial\Phi}{\partial\theta}\frac{\partial}{\partial r}\left[\frac{1}{2}\left(\frac{KB_p}{n}\right)^2\right] \\ &\quad + \frac{B_p}{r}\frac{\partial}{\partial\theta}\left[\frac{1}{2}\left(\frac{KB_p}{n}\right)^2\right] \\ &\quad = \frac{1}{m_i}\frac{JB_pB_\phi}{n} - \frac{1}{m_i}\frac{B_p}{r}\frac{\partial}{\partial\theta}\left(\frac{\bar{p}_e}{\bar{n}}\ln n + \frac{5\bar{p}_i}{2\bar{n}^{5/3}}n^{2/3}\right) \\ &\quad - \frac{1}{m_i}\left(\frac{\vec{B}_p\cdot\vec{\nabla}\cdot\overleftrightarrow{\pi}_i}{n}\right)_{\text{bulk}} - \frac{1}{m_i}\left(\frac{\vec{B}_p\cdot\vec{\nabla}\cdot\overleftrightarrow{\pi}_i}{n}\right)_{\text{shear}},\end{aligned} \tag{9}$$

$$\begin{aligned}&B^2\frac{\partial}{\partial t}\left(\frac{K}{n}\right) - \frac{B_\phi}{B_p}\frac{\partial}{\partial t}\frac{\partial\Phi}{\partial r} \\ &\quad - \frac{n}{KrB}\frac{\partial\Phi}{\partial\theta}\frac{\partial}{\partial r}\left[\frac{1}{2}\left(\frac{KB}{n}\right)^2\right] + \frac{B_p}{r}\frac{\partial}{\partial\theta}\left[\frac{1}{2}\left(\frac{KB}{n}\right)^2\right] \\ &\quad + \frac{B_\phi}{rB}\frac{\partial\Phi}{\partial\theta}\frac{\partial}{\partial r}\left[\frac{B}{B_pB_\phi}\frac{\partial\Phi}{\partial r}\right] - \frac{KB_pB_\phi}{nr}\frac{\partial}{\partial\theta}\left[\frac{B}{B_pB_\phi}\frac{\partial\Phi}{\partial r}\right] \\ &\quad = -\frac{B_p}{m_i r}\frac{\partial}{\partial\theta}\left(\frac{\bar{p}_e}{\bar{n}}\ln n + \frac{5}{2}\frac{\bar{p}_i}{\bar{n}^{5/3}}n^{2/3}\right) \\ &\quad - \frac{1}{m_i n}(\vec{B}\cdot\vec{\nabla}\cdot\overleftrightarrow{\pi}_i)_{\text{bulk}} - \frac{1}{m_i n}(\vec{B}\cdot\vec{\nabla}\cdot\overleftrightarrow{\pi}_i)_{\text{shear}},\end{aligned} \tag{10}$$

respectively. Isothermal electrons and adiabatic ions are assumed. The viscosity of ions $\overleftrightarrow{\pi}_i$ is divided into two terms: bulk viscosity given by a neoclassical process [14] and shear viscosity given by an anomalous process [2]. The viscosity terms are presented in Ref. [15].

The 2-D structures of the potential, density, and flow velocity are obtained. The variable K is replaced by M_p, which corresponds to the poloidal Mach number, and is defined as

$$M_p \equiv \frac{KB_0}{\bar{n}v_{ti}C_r}, \tag{11}$$

where $v_{ti} = \sqrt{2T_i/m_i}$, $C_r^2 = 5/6 + T_e/(2T_i)$, and T_i and T_e are the ion and electron temperatures, respectively. Here, shock ordering, which is the perturbation, $O(\varepsilon^{1/2})$, is adopted. In the case of $M_p \sim 1$, a steep structure is formed in the poloidal direction, and the perturbations become larger than $O(\varepsilon)$. The variables are divided into average and perturbation parts, which are denoted by subscripts 0 and 1, respectively, as follows: $f = f_0(r) + f_1(r,\theta)$; here, f represents each quantity. The set of equations for obtaining M_{p0}, M_{p1}, Φ_1, and n_1 is derived from Eqs. (8–10) as follows, assuming $V_r/V_p \ll 1$, which is satisfied even if a strong poloidal shock exists:

$$\frac{\partial\chi}{\partial\tau} = -M_{p0}\varepsilon\sin\theta - \frac{\partial M_{p1}}{\partial\theta}, \tag{12}$$

$$\begin{aligned}&\frac{B_{p0}^3 v_{ti}^2 C_r^2}{B_0^2 r}\frac{\partial M_{p0}}{\partial\tau} \\ &\quad = \frac{1}{m_i}\left(\left\langle\frac{JB_pB_\phi}{n}\right\rangle - \left\langle\frac{\vec{B}_p\cdot\vec{\nabla}\cdot\overleftrightarrow{\pi}_i}{n}\right\rangle_{\text{bulk}} - \left\langle\frac{\vec{B}_p\cdot\vec{\nabla}\cdot\overleftrightarrow{\pi}_i}{n}\right\rangle_{\text{shear}}\right),\end{aligned} \tag{13}$$

$$
\begin{aligned}
&\frac{\partial M_{\mathrm{p1}}}{\partial \tau} \\
&= -\frac{1}{2}\frac{\partial}{\partial \theta}\left((1-\chi)\left(M_{\mathrm{p0}}+M_{\mathrm{p1}}\right) - M_{\mathrm{p0}}\varepsilon\cos\theta + \frac{\chi^2}{2}M_{\mathrm{p0}}\right)^2 \\
&\quad -\frac{1}{2}\varepsilon\cos\theta\frac{\partial}{\partial\theta}\left(M_{\mathrm{p0}}+M_{\mathrm{p1}}-\chi M_{\mathrm{p0}}\right)^2 \\
&\quad -\frac{B_0^2}{B_{\mathrm{p0}}^2}\left[\frac{\partial}{\partial\theta}\left(\chi+\frac{5}{18}\frac{1}{C_{\mathrm{r}}^2}\chi^2+\frac{5}{84}\frac{1}{C_{\mathrm{r}}^2}\chi^3\right)-\varepsilon\cos\theta\frac{\partial\chi}{\partial\theta}\right] \\
&\quad +M_{\mathrm{p0}}\frac{\partial\chi}{\partial\tau}+(\chi+2\varepsilon\cos\theta)\frac{\partial M_{\mathrm{p0}}}{\partial\tau}+\frac{B_0^2 r}{B_{\mathrm{p0}}^3 v_{\mathrm{ti}}^2 C_{\mathrm{r}}^2} \\
&\quad \times\frac{1}{m_{\mathrm{i}}}\left[\frac{JB_{\mathrm{p}}B_{\phi}}{n}-\left(\frac{\vec{B}_{\mathrm{p}}\cdot\vec{\nabla}\cdot\overleftrightarrow{\pi}_{\mathrm{i}}}{n}\right)_{\mathrm{bulk}}-\left(\frac{\vec{B}_{\mathrm{p}}\cdot\vec{\nabla}\cdot\overleftrightarrow{\pi}_{\mathrm{i}}}{n}\right)_{\mathrm{shear}}\right],
\end{aligned}
\tag{14}
$$

$$
\begin{aligned}
\frac{\partial E_1}{\partial\tau} &= -\hat{\mu}\,r^2\frac{B_0}{B_{\mathrm{p0}}}\frac{\partial^2}{\partial r^2}\left\{M_{\mathrm{p0}}\left[\exp(-\chi)-1\right]\right\} \\
&\quad +\frac{2}{3}D\exp(-\chi)\frac{\partial^2\chi}{\partial\theta^2}+\left(1-M_{\mathrm{p0}}^2\right)\frac{\partial\chi}{\partial\theta} \\
&\quad +2A\frac{\partial\chi^2}{\partial\theta}+\frac{\partial}{\partial\theta}\left[(1-2\chi)M_{\mathrm{p0}}M_{\mathrm{p1}}+\frac{1}{2}M_{\mathrm{p1}}^2\right]-M_{\mathrm{p0}}\frac{\partial E_1}{\partial\theta} \\
&\quad -\varepsilon\left\{D-\hat{\mu}\frac{B_0}{B_{\mathrm{p0}}}\left[2r^2\frac{\partial^2 M_{\mathrm{p0}}}{\partial r^2}+4r\frac{\partial M_{\mathrm{p0}}}{\partial r}-2M_{\mathrm{p0}}\right]\right\}\cos\theta \\
&\quad +2\varepsilon M_{\mathrm{p0}}^2\sin\theta+\frac{\partial M_{\mathrm{p1}}}{\partial\tau}-M_{\mathrm{p0}}\exp(-\chi)\frac{\partial\chi}{\partial\tau} \\
&\quad -\left(\chi-\frac{\chi^2}{2}+2\varepsilon\cos\theta\right)\frac{\partial M_{\mathrm{p0}}}{\partial\tau},
\end{aligned}
\tag{15}
$$

where

$$\chi = \ln\left(\frac{n}{\bar{n}}\right), \tag{16}$$

$$E_1 = \frac{1}{B_{\mathrm{p0}}v_{\mathrm{ti}}C_{\mathrm{r}}}\frac{\partial\Phi_1}{\partial r}, \tag{17}$$

$$D = \frac{4\sqrt{\pi}}{3}\frac{I_{\mathrm{ps}}K_0B_0}{\bar{n}v_{\mathrm{ti}}C_{\mathrm{r}}^2}, \tag{18}$$

$$A = \frac{M_{\mathrm{p0}}^2}{2}+\frac{5}{36}\frac{1}{C_{\mathrm{r}}^2}, \tag{19}$$

$\hat{\mu}$ is the shear viscosity coefficient, and the form of I_{ps} is shown in Eq. (10) of Ref. [4], which depends on M_{p} and the collision frequency [16]. The variables n_1 and Φ_1 are replaced by χ and E_1 in this set, respectively. Equations (14) and (15) are obtained by considering the terms up to $O(\varepsilon)$ with the perturbation of each variable as $O(\varepsilon^{1/2})$ (shock ordering) and $O(\varepsilon)$ (small perturbation). This is because poloidal shocks and GAMs provide $O(\varepsilon^{1/2})$ and $O(\varepsilon)$ perturbation, respectively; therefore, an intermediate parameter region must be considered to study their competition. Time t is normalized as $\tau = t\big/t_{\mathrm{p}}$, where

$$t_{\mathrm{p}} = \frac{B_0 r}{B_{\mathrm{p0}}v_{\mathrm{ti}}C_{\mathrm{r}}}. \tag{20}$$

Equations (13) and (14) are the flux surface average and the 2nd order of Eq. (9), respectively. Current J is obtained from Eq. (3), which includes polarization current $\varepsilon_0\varepsilon_\perp\partial E_r/\partial t$ and external components driven by an electrode, orbit losses, etc. [17]. Here, ε_0 is the vacuum susceptibility, and $\varepsilon_\perp$ is the perpendicular dielectric constant of a toroidal plasma, which depends on the flow pattern and is of the order of $c^2/\mathrm{v}_{\mathrm{A}}^2$, where v_{A} is the Alfvén velocity [2].

3. Formation Mechanisms of Poloidal Asymmetry

Equations (12–15) form a set of model equations. This extended model includes the generation mechanism of the poloidal shock structure and the GAM. In this section, some limiting cases, where a similar set of equations have been provided by previous studies [5], [13], are described to depict the fundamental mechanisms in our model.

3.1 Poloidal shock structure

The key mechanism for poloidal shock formation is in the momentum conservation Eq. (1). When a large poloidal flow exists, nonlinear effects in the convective derivative and the density gradient generate the poloidal shock structure by coupling with toroidicity. Assumption of Boltzmann relation

$$n = \bar{n}\exp\frac{e\Phi_1}{T_{\mathrm{i}}}, \tag{21}$$

and strong toroidal flow damping

$$V_\phi = 0, \tag{22}$$

which results in M_{p} being proportional to the radial electric field, provides a simplified set of equations [5]. Equation (15) is written as

$$
\begin{aligned}
&M_{\mathrm{p0}}\exp(-\chi)\frac{\partial\chi}{\partial\tau} \\
&= -\hat{\mu}\,r^2\frac{B_0}{B_{\mathrm{p0}}}\frac{\partial^2}{\partial r^2}\left\{M_{\mathrm{p0}}\left[\exp(-\chi)-1\right]\right\} \\
&\quad +\frac{2}{3}D\exp(-\chi)\frac{\partial^2\chi}{\partial\theta^2}+\left(1-M_{\mathrm{p0}}^2\right)\frac{\partial\chi}{\partial\theta}+2A\frac{\partial\chi^2}{\partial\theta} \\
&\quad -\varepsilon\left\{D-\hat{\mu}\frac{B_0}{B_{\mathrm{p0}}}\left[2r^2\frac{\partial^2M_{\mathrm{p0}}}{\partial r^2}+4r\frac{\partial M_{\mathrm{p0}}}{\partial r}-2M_{\mathrm{p0}}\right]\right\}\cos\theta \\
&\quad -\left(\chi-\frac{\chi^2}{2}+2\varepsilon\cos\theta\right)\frac{\partial M_{\mathrm{p0}}}{\partial\tau}+2\varepsilon M_{\mathrm{p0}}^2\sin\theta.
\end{aligned}
\tag{23}
$$

In this case, an iterative process can be considered to obtain the solution, i.e., time evolution of the 2-D structure is calculated from Eq. (23) by substituting M_{p0} obtained by Eq. (13). Then, using the Boltzmann relation (21), the potential profile is obtained. We are interested in the structure in the edge transport barrier, and a boundary condition that there are no perturbations outside of the barrier. Then, 2-D partial differential equation can determine the poloidal position of the shock. An example of the 2-D structure is presented in Ref. [9]. With a prescribed inhomogeneous density profile, a steep gradient of the radial electric field is formed in a critical layer, and the 2-D structure of the potential perturbation, including a poloidal shock structure, is obtained.

3.2 Geodesic acoustic mode

The GAM is formed in toroidal plasmas by coupling the $(m, n) = (0, 0)$ electrostatic potential and (1, 0) sideband density perturbation, where m and n are the poloidal and toroidal mode numbers, respectively [11]. Considering that perturbations have $O(\varepsilon)$ with a small poloidal flow, Eq. (12), the flux surface average of Eqs. (13) + (14), and that of Eq. (15) with $D = 0$ and $\hat{\mu} = 0$, are obtained as

$$\frac{\partial \chi}{\partial \tau} = -M_{\mathrm{p0}} \varepsilon \sin\theta - \frac{\partial M_{\mathrm{p1}}}{\partial \theta}, \tag{24}$$

$$\frac{\partial M_{\mathrm{p0}}}{\partial \tau} = \frac{B_0^2}{B_{\mathrm{p0}}^2} \left\langle \varepsilon \cos\theta \frac{\partial \chi}{\partial \theta} \right\rangle, \tag{25}$$

$$\frac{\partial M_{\mathrm{p1}}}{\partial \tau} = -\frac{\partial \chi}{\partial \theta}, \tag{26}$$

respectively [13]. This set of equations describes the GAM oscillation. If the density perturbation has a $\sin\theta$ dependency

$$\chi = \chi_{\mathrm{r}}(r, t) \sin\theta, \tag{27}$$

Eqs. (24–26) provide the dispersion relation

$$\Omega^2 - \frac{\varepsilon^2}{2} \frac{B_0^2}{B_{\mathrm{p0}}^2} - k_\theta^2 = 0, \tag{28}$$

where Ω is the oscillation frequency, and k_θ is the wave number in the poloidal direction. The time is normalized by t_{p} shown in Eq (20), and the frequency in real unit is given by

$$\omega = \frac{C_{\mathrm{r}}}{\sqrt{2}} \frac{v_{\mathrm{ti}}}{R} \sqrt{1 + \frac{2k_\theta^2}{q^2}}, \tag{29}$$

where q is the safety factor.

4. Summary

An extended set of fluid equations, which consists of the momentum conservation equation, the continuity equation of the density, the charge conservation equation, and Ohm's law, is derived to obtain 2-D structures of the potential, density, and flow velocity in H-mode transport barriers. This model includes the generation mechanism of the poloidal shock structure and the GAM, and their competitive formation can be studied. Derivation is the first step in analyzing the multi-dimensionality of transport in toroidal plasmas, which provides a quantitative understanding of the transport barrier physics.

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