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NEOCLASSICAL CURRENT AND RELATED MHD STABILITY, GAP MODES, AND RADIAL ELECTRIC FIELD EFFECTS IN HELIOTRON AND TORSATRON PLASMAS

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Keywords : Neoclassical current, radial electric field, net toroidal current, Mercier criterion, TAE, HAE, poloidal shear flow, resistive and ideal interchange modes

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NEOCLASSICAL CURRENT AND RELATED MHD STABILITY, GAP MODES, AND RADIAL ELECTRIC FIELD EFFECTS IN HELIOTRON AND TORSATRON PLASMAS

ABSTRACT

By developing the neoclassical theory for parallel flow it is found out that if $\nu_e^* \neq \nu_i^*$ a parallel current directly generated by the radial electric field, which does not exist in axisymmetric systems, exists in the non-axisymmetric systems. This newly found current has a possibility to reduce the bootstrap current under a suitable condition even in the opposite direction in Heliotron/Torsatron. The differences between the rotations of bulk ions and impurities are discussed in the case where impurities are in the Pfirsh-Schlüter collisionality regime. In connection with the bootstrap current the effects of the net toroidal current on the ideal interchange instability are numerically studied taking the Large Helical Device (LHD) as an example. The direction of the current is crucial to the Mercier criterion. Helicity-induced shear Alfvén eigenmodes (HAE) attributed to the helicity of helical coils are considered for the first time in Heliotron/Torsatron and compared with TAE modes. Spectral gaps and eigenmodes significantly depend on the finite-β effects.

Radial electric field producing poloidal shear flow also plays a role for the edge anomalous transport in Heliotron/Torsatron. The electrostatic resistive interchange mode which is considered origin of the anomalous transport can be stabilized linearly by the poloidal shear flow. However, its effects on the turbulent state practically disappears by the nonlinear simulation for the resistive drift wave and interchange turbulence. It is pointed out that the poloidal shear flow destabilizes the electromagnetic ideal interchange mode.

Part A NEOCLASSICAL CURRENT AND RELATED MHD STABILITY AND GAP MODES (N.NAKAJIMA, K.ICHIGUCHI, Y.NAKAMURA, K.WATANABE, M.WAKATANI, C.Z.CHENG, M.OKAMOTO)

1. NEOCLASSICAL CURRNET AND ROTATION

Neoclassical theories for parallel flow are extended to a multispecies plasma in general toroidal systems, in which each species can lie in different collisionality regime [1]. As a result the bootstrap current is given by, for a simple plasma consisting of electrons and protons,

$$\begin{aligned}\left\langle BJ_{\|}\right\rangle &= L_{11}\left\langle G_{BS}\right\rangle_e\left(\frac{dP_e}{d\psi}+en_eE_\psi\right)+L_{11}\left\langle G_{BS}\right\rangle_i\left(\frac{dP_i}{d\psi}-en_eE_\psi\right)\\ &- L_{12}\left\langle G_{BS}\right\rangle_e n_e\frac{dT_e}{d\psi}+L_{11}L_{34}\left\langle G_{BS}\right\rangle_i n_e\frac{dT_i}{d\psi}\end{aligned} \tag{A.1}$$

where L_{ij}, $\left\langle G_{BS}\right\rangle_{e,i}$ and E_ψ are the transport coefficients, the geometric factor [2], and the radial electric field, respectively. The direction of the damping of the flows due to the parallel viscosities is given by, in terms of the geometric factor,

$$\nabla\theta_a^* \equiv \nabla\left[(I+\left\langle G_{BS}\right\rangle_a)\theta+(J-\iota\!\!\!-\left\langle G_{BS}\right\rangle_a)\zeta\right] \tag{A.2}$$

where θ and ζ are the poloidal and toroidal angles in the Boozer coordinates, respectively, and I, J, and $\iota\!\!\!-$ are the toroidal current inside the flux surface, the poloidal current outside the flux surface, and the rotational transform, respectively. In axisymmetric systems, as is seen from Eq.(A.2), the flow damps only in the poloidal direction regardless of the collisionality of each particle species, i.e., $\left\langle G_{BS}\right\rangle_e = \left\langle G_{BS}\right\rangle_i = J/\iota\!\!\!-$. Therefore, the current proportional to E_ψ vanishes in Eq.(A.1), which is the direct result from symmetry, the momentum conservation of friction forces, and the charge neutrality. On the other hand, in non-axisymmetric systems, lack of symmetry allows the flow in any direction to damp and the damping direction becomes to depend on the collisionality, which makes the current directly generated by E_ψ exist if $\nu_e^* \neq \nu_i^*$ ($\left\langle G_{BS}\right\rangle_e \neq \left\langle G_{BS}\right\rangle_i$). This newly found current can be comparable with the conventional pressure-driven neoclassical current since $e\phi \gtrsim T$ ($E_\psi = -d\phi/d\psi$). In the region where $|\left\langle G_{BS}\right\rangle_{e,i}|$ increases as $\nu_{e,i}^*$ decreases, if $\nu_e^* < \nu_i^*$, then $|\left\langle G_{BS}\right\rangle_e| > |\left\langle G_{BS}\right\rangle_i|$ and $E_\psi > 0$ would be realized according to the neoclassical theory. In such the situation the first term with $\left\langle G_{BS}\right\rangle_e$ in Eq.(A.1) dominates and the current proportional to E_ψ tends to cancel the conventional pressure-driven current. In the opposite case of $\nu_e^* > \nu_i^*$ where $|\left\langle G_{BS}\right\rangle_e| < |\left\langle G_{BS}\right\rangle_i|$ and $E_\psi < 0$ the resultant current would also be reduced. If $|E_\psi|$ is enough large we can expect even an inverted bootstrap current in Heliotron/Torsatron.

The extended neoclassical theory is applied to the poloidal and toroidal rotations in a plasma consisting of electrons, ions, and impurity ions in the Pfirsh-Schlüter regime [3]. It is found that the differences between bulk ions and impurities come from the different diamagnetic flows and the ion temperature gradient in the $1/\nu$ regime, but depend strongly on the field structure in Heliotron/Torsatron in contrast to the tokamak cese [4]. For the experimental parameters of CHS (Compact Helical System) the differences are small and on the order of bulk ion diamagnetic flow.

2. IDEAL MHD STABILITY WITH NET TOROIDAL CURRENT

The currentless condition is often violated by the net toroidal current such as the bootstrap current. We first consider the effects of the net toroidal current on the Mercier criterion systematically using the three dimensional VMEC equilibrium code. As an example we take the standard configuration of the Large Helical Device (LHD), where $R = 3.9m$, $B = 3T$, $\gamma_c = 1.25$ (γ_c the pitch parameter of helical coils), $\alpha = 0.1$ (α the pitch modulation parameter), $\Delta_{axis} = -15cm$ (Δ_{axis} the magnetic axis shift in the vacuum field), and the toroidally averaged magnetic surfaces are nearly circular. We find the 2nd stability for the currentless equilibrium with a pressure profile of $P = P_0(1-\Phi_T)^2$, where Φ_T is the toroidal flux. The unstable region is so small that the growth rates of low-n interchange modes are expected to be very small. The additive current, which increases the central rotational transform ι_0^v and makes the magnetic well shallow in the vacuum field, is unfavorable to the MHD stability. On the other hand the subtractive current decreasing ι_0^v allows the large Shafranov shift to extend the well region and makes the shear strong near the edge as β increases. Thus subtractive current improves the MHD stability against interchange modes. For the same pressure profile as in the above currentless case the additive current of 50kA (the current density is $J = J_0(1-\Phi_T)^2$) expands the unstable Mercier region, but the 2nd stability persists for $< \beta > \gtrsim 3\%$. The subtractive current of 50kA can stabilize the plasma completely against the Mercier criterion, hence the configuration is stable to ideal low-n interchange modes.

3. GAP MODES (SHEAR ALFVÉN EIGENMODES)

In Heliotron/Torsatron and other helical systems the helicity of helical coils in addition to the toroidicity can cause the poloidal and toroidal mode couplings resulting in breakup of the shear Alfvén continuous spectra into small bands of continuous spectra. We first consider the high-n Helicity-induced shear Alfvén Eigenmodes (HAE) and the high-n TAE modes in Heliotron/Torsatron, where n is the toroidal mode number. The high-n HAE modes are identified in a low-β straight helical system and it is found that the polarity of the helical coil influences the structure of spectral gaps through the shape of the flux surface [5]. The existence of high-n HAE and TAE modes in the finite-β toroidal Heliotron/Torsatron is confirmed numerically. The continuous spectral gaps of high-n HAE and TAE modes are essentially determined by $|\nabla\psi|$ and the lowest ones appear, respectively, around $\Omega^2_{HAE} = [(L - M/\iota\!\!\!-)/2]^2$ and $\Omega^2_{TAE} = [1/2]^2$ where ψ is the flux function, $\Omega = \omega/\omega_A$, ω_A is the poloidal Alfvén transit frequency, and L and M are the polarity of helical coils and the toroidal pitch number of helical coils, respectively. The gap structure and the eigenvalues of high-n TAE modes widely change with the flux surface when the shearless region appears due to the finite-β effects. In the shearless region, a great deal of discrete eigenmodes exist with local or global structures along the magnetic field line. Although the localized high-n HAE modes appear independent of the β value, the localized high-n TAE modes appear only at a finite-β. The θ_k-dependences of Ω_{HAE} and Ω_{TAE} are stronger than the α-dependence, where θ_k and α are the radial wave number and the label of the magnetic field line, respectively. In Heliotron/Torsatron with $|L - M/\iota\!\!\!-| \gg 1$, high-$n$ HAE modes with high frequencies may be irrelevant to the alpha particle losses. The high-n TAE modes, however, may be relevant to them. We also consider the low-n TAE and HAE modes placing emphasis on the poloidal mode coupling. As well as the high-n TAE modes, the poloidal mode coupling makes the spectral gap in the shear Alfvén continuum in Heliotron/Torsatron.

Part B **RADIAL ELECTRIC FIELD EFFECTS ON HELIOTRON AND TORSATRON PLASMAS** (M. WAKATANI, Y. NAKAMURA, K. WATANABE, H. SUGAMA)

1. INTRODUCTION

Recently it is recognized that the radial electric field plays an important role in tokamak confinement from the study for L/H transition phenomena [6,7]. We study the radial electric field effects on heliotron and torsatron plasmas from several points of view of trapped particle confinement [8], neoclassical ripple transport [9], ideal and resistive MHD stability, and the resistive drift wave and interchange turbulence [10]. The latter two subjects are discussed in this paper.

2. POLOIDAL SHEAR FLOW EFFECTS ON LINEAR MHD STABILITY

Since the most probable candidate for the anomalous transport in Heliotron/Torsatrons is the resistive interchange turbulence, we have studied effects of the poloidal shear flow, driven by the radial electric field, on the electrostatic resistive interchange mode in the slab model [11]. From the linear stability analysis (i) $k_y v_0 > \gamma_g L_E/\Delta$ and (ii) $\Delta < L_E$ are required for suppressing this instability, where the flow velocity profile is assumed to be $v_E = v_0 \tanh(x/L_E)$, k_y is a wave number in the poloidal direction, γ_g is a growth rate at $v_0 = 0$ and Δ is a radial mode width at $v_0 = 0$. The origin $x = 0$ corresponds to a mode resonant surface. According to these conditions a stabilizing effect is expected in Heliotron E for $v_0 \gtrsim 3 \times 10^5$cm/sec and $L_E \simeq 0.5$ cm. Experimentally $v_0 \lesssim 5 \times 10^5$cm/sec was already observed; however, the shear flow width was not clear in the experiment. When v_0 is sufficiently large, the usual Kelvin-Helmholtz (K-H) instability appears.

Next we study the poloidal shear flow effect on the ideal interchange mode or the Suydam mode. By using the slab model the stability criterion becomes $D_v = -k_y^2 P'\Omega'/((k_{\parallel}')^2 - (k_y v_E')^2) < 1/4$, where the primes denote the derivative with respect to the radius, P is an equilibrium pressure, Ω' is related to the average curvature of heliotron and torsatron, and $k_{\parallel}$ is a parallel wave number [12]. Here v_E is normalized with the Alfven velocity. Usually Ω' is positive and destabilizing. If $v_E' = 0$, this criterion reduces to the Suydam criterion. The linear growth rates of the $(m, n) = (1, 1)$ mode in the Heliotron E model configuration [13] are shown in Fig. 1 for various poloidal shear flow cases, where $\omega_{E0} = k_y v_0$ is normalized with the Alfven transit time, and L_E is normalized with the radius. The pressure profile is assumed $P(r) \propto (1 - r^2)^2$. For $v_E' \neq 0$, the shear flow has a destabilizing tendency to reduce the beta limit. Thus, the poloidal shear flow is unfavorable to obtain a high beta stable plasma. For $\omega_{E0} = 0.2$ and $L_E = 0.1$, the K-H instability clearly appears, and the growth rate becomes finite even at $\beta_0 = 0$. When $\beta < \beta_c^o = 1.62\%$, the instability destabilized by the poloidal shear flow has characteristics similar to the K-H instability where β_c^o is determined by $D_v = 1/4$ for $v_E' = 0$.

3. RADIAL ELECTRIC FIELD EFFECT ON RESISTIVE DRIFT WAVE AND INTERCHANGE TURBULENCE

When $\Omega' > 0$ or the average curvature is unfavorable, both the resistive drift wave and the resistive interchange mode become unstable. We studied the non-linear evolution of these instabilities in a cylindrical plasma with magnetic shear by using two field model equations for the density fluctuation and the potential fluctuation [14]. We showed that the radial electric field is self-generated from the turbulent fluctuations and this electric field affects the particle transport.

When the adiabatic parameter $(\Omega_e/\nu_e)(\rho_s^2/R^2)/(\kappa\rho_s)$ is small, a trend of dual cascade, normal cascade of the density fluctuations and inverse cascade of the potential fluctuations, is seen in the wave number spectra producing a large particle flux proportional to $\nu_e^{1/3}$. Here R is the major radius, ρ_s the ion Larmor radius at the electron temperature, Ω_e the electron cyclotron frequency, ν_e the electron ion collision frequency and κ is an inverse scale length of the background density gradient. Parallel wave numbers are represented by $1/R$. In this case deviation from the Boltzmann relation is clearly seen [10]. For large $(\Omega_e/\nu_e)(\rho_s^2/R^2)/(\kappa\rho_s)$, the electrons become adiabatic, with a significant reduced particle flux proportional to ν_e.

We have also studied the externally imposed radial electric field on the ambipolar electric field on the turbulence. We assume $E_r(r) = \pm 4r^2$ and $\nu_e/\Omega_e = 2.1 \times 10^{-4}$ here. The background density is taken as Gaussian and fixed in the nonlinear calculation. Figure 2 shows the time evolution of the energy of the electric field fluctuation, $E_k = \int |\nabla_\perp \tilde{\phi}|^2 dv$, and the energy of the density fluctuation, $E_n = \int |\tilde{n}|^2 dv$, for both cases with the positive and negative radial electric field. The case with $E_r = 0$ lies between the two lines. In the presence of this type of electric field with a negative (positive) polarity, $E_r < 0$ ($E_r > 0$), the poloidal velocity shear in the $\mathbf{E} \times \mathbf{B}$ drift motion suppresses (enhances) the fluctuation level in the growth phase; however, these effects practically disappear in the saturated state. Here we note that the polarity of the electric field affects the result, since our model equation includes the electron drift frequency ω_{*e} [15]. This result suggests importance to include the mechanism of the radial electric field generation self-consistently in the turbulence study as shown in Ref. [14].

It may be possible to find the poloidal shear flow induced by the radial electric field to suppress the electrostatic resistive interchange modes and not to excite the electromagnetic interchange modes. The next subject is to find a way to produce such a radial electric field consistently.

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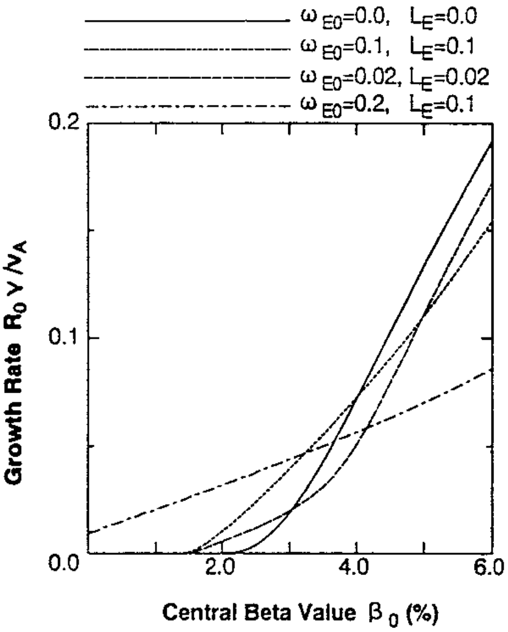

Fig.1 Growth rate of ideal interchange mode with poloidal mode number $m = 1$ and toroidal mode number $n = 1$ versus central beta value β_0 in the presence of poloidal shear flow. $\omega_{E0} = k_y v_0$ and L_E is a characteristic length of velocity shear layer.

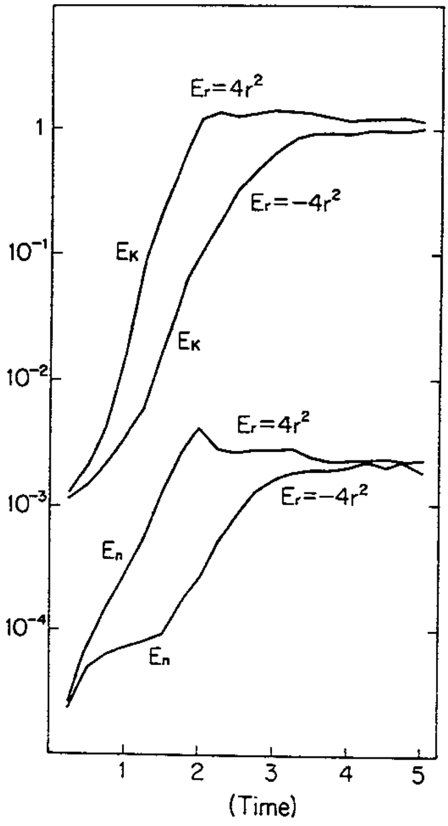

Fig.2 Time evolution of the energy of electric field fluctuation, E_k, and the energy of density fluctuation E_n for $E_r(r) = -4r^2$ and $E_r(r) = 4r^2$.

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