Ballooning Mode Instability due to Slowed-Down α-Particles and Associated Transport

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Microscopic instabilities of toroidal plasmas have been subject to intensive studies since these are considered to be possible candidates to cause the anomalous cross-field transport and to impose the upper limit of the β-value of the confined plasmas. The studies have to be extended to cover the stability of the burning plasmas since the pressure gradient and the non-maxwellian distribution of the α-particles can yield additional free energy sources of the instability mode, which is generally called to be the thermonuclear instability1). This instability may limit the total β-value as well as the density of the α-particles produced by nuclear reactions. The other aspect of the problem is that the fluctuations which are enhanced by the instabilities affect the transport of the plasmas and α-particles; the energy deposition of α-particles and the radial flux can become different from the estimation based on the (neo)classical theory. This fact can give rise to the change in the thermal equilibria of burning plasmas and serious reconsiderations may become necessary with respect to the thermal stability, burn control and ash exhausting.

Alpha-particles experience three typical stages during their presence in the plasma column. The first is the birth through the reaction and the associated physics issue is the effects of the direct loss. The second is the slowing down by the host plasma. The main mechanism in this stage is the binary collision and the α-particles can also be affected by collective modes in the plasma. In the third stage, α-particles are already slowed-down and constitute thermalized distribution function. The main part of the energy of confined α-particles in the steady state are carried by the thermalized α-particles, which give a free energy source to the unstable modes.

We here study the microscopic stability of tokamak plasmas which are containing slowed-down α-particles2,3,4) and the anomalous fluxes enhanced by the fluctuations3,5,6).

We choose local maxwellian distribution with the density inhomogeneity as equilibrium distributions for electrons, ions and α-particles. It is emphasized that the kinetic interactions between wave and particles are kept into account for electrons, ions and α-particles, because these play essential role for stability in high temperature plasmas.

In the zero-β limit, we obtain two branches of eigenmodes which are electrostatic. The electrostatic ballooning mode becomes unstable by the ∇B drift of particles in the toroidal plasmas. The growth rate of this mode increases (linearly if

$n_\alpha/n_e \ll 1$) as the number density of confined α-particles increases. It should be noted that there is no critical α-particle density and no critical β-values for the onset of the instability in toroidal plasmas even in the presence of the magnetic shear. The mode is excited by electrons, ions and α-particles. The drift branch, which continues to the Pearlstein-Berk mode in the slab limit, is stabilized by the magnetic shear (or remains to be a weak instability) even in the presence of the toroidal coupling. The existence of the α-particles does not change the stability.

As β-value increases, the electrostatic mode turns out to be the electromagnetic one. The growth rate of the ballooning mode increases with β-values. If the β-value exceeds the critical β-value of the MHD ballooning mode, the growth rate approaches to that of the MHD mode and the modestructure becomes very close to that of the MHD mode. The α-particles enhance the growth rate for fixed values of other parameters. The drift-Alfven mode appears in the finite-β plasma. The mode has been suspected to be excited by the α-particle resonance when the β-value becomes high enough that the Alfven velocity v_A is less than the thermal speed of α-particles v_α.[1] However the shear stabilization is very strong and prominent even in the torідal plasma, and the mode remains to be marginally stable at most in high-β cases; the α-particles cannot destabilize this mode even if $v_A < v_\alpha$.

As β-value becomes higher, the magnetic well and the toroidal shift of the magnetic axis become large, and the "second stability region" appears for the MHD modes. The ballooning mode remains to be unstable in the second stability region due to the wave particle interactions.

The unstable mode in the toroidal plasma is the ballooning mode and is unstable for all plasma parameters. The existence of the α-particles enhances the growth rate. The mode may be called to be "thermonuclear ballooning mode" in the presence of the α-particles.

We next consider the associated cross-field transport by the ballooning mode. One mechanism[3,5] to cause the cross-field flux is the E × B diffusion. The flux is proportional to the momentum exchange rate with the wave. The exchange of the momentum in the poloidal direction results a net force in the same direction, and the force F gives rise to the F × B drift of particles, which appears as a net flux in the radial direction. Since both ions and α-particles destabilize the mode, the force acting on the ions and α-particles are in the same direction. The particle fluxes of ions and α-particles are in the same direction. In a steady state, we have

$$\Gamma_e = 2\Gamma_\alpha + \Gamma_i \tag{1}$$

and the ratio of Γ_α and Γ_i is given approximately as

$$\Gamma_i : \Gamma_\alpha \sim \nabla p_i : \nabla p_\alpha \tag{2}$$

($p = nT$). If the static electric field, which, for instance, is expected as the consequence of the direct loss of the high energy α-particles, is not much piled up in the plasma, the electron flux Γ_e is given by the same representation in terms of $\hat{E}$ as in the slab calculations[5]. As shown by Eq.(2), after being thermalized, α-particles tends to flow out faster than host ions. One does not see the trend that the slowed-down and thermalized α-particles tends to accumulate near the center of the plasma. This fact is important and favourable from the view point of the ash exhausting. We have also studied the α-particle flux induced by the trapped ion instability comparing the cases of the slowed-down distribution and the birth distribution before the slowing down. We have found that if one assumes the distribution function to be the birth distribution, the loss rate is very slow and slower than the slowing down time.

These results on the radial transport in one hand seem favourable from the view point of the ash exhausting. However, the thermal and MHD equilibrium itself changes due to this radial loss, so that there appear problems to be solved, how the deposition profile is affected, and consequently, whether the thermal stability is improved or deteriorated.

Another key issue is the effect of the α-particles on the large scale MHD activity of the plasma. The birth, direct loss and piling-up of α-particles cause influences on the toroidal current and pressure distributions, changing the stability of low-n helical modes, which then induce the changes of orbits and confinement region in a phase space of α-particles.

The comprehensive studies on the stability and transport are left for further analyses.

References

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