§27. Geometry Changes Transient Transport in Plasmas

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Role of ballooning effect in toroidal plasmas on the transient transport problems is investigated. Due to the mode localization along the magnetic field line, a meso scale appears in a radial correlation length of fluctuating fields. This long radial correlation of the fluctuating field causes a fast propagation of response against a rapid transient perturbation.

It is shown that the turbulent fluctuations, which have short poloidal wave lengths ("micro scale", being of the order of ion gyroradius or collisionless skin depth) can have a long radial correlation length owing to the ballooning effect ℓ_E , $\ell_E \simeq \sqrt{s^{-1} a\rho_i}$, where s is the magnetic shear.

The plasma flux by the ballooning mode has been obtained. The particle flux at radius r by the kinetic ballooning mode has been derived as [1] $\Gamma_r(r) = \frac{nq}{B_0 r}\frac{e}{T_e}\sum_{n,M} F_{M,n}(r)$ wher

$$F_{M,n}(r) = \sum_{|m|<m_*} \Im m\left(\frac{\omega-\omega_*}{\omega}\xi_e Z\right)\phi_m\phi_m^*$$
$$+\sum_{|m|<m_*}\frac{r}{2R}\frac{L_n}{R}\frac{\omega_*}{\omega}\frac{\omega-\omega_*}{\omega} m\Re e\left(\xi_e Z + 2\xi_e^2\left(1+\xi_e Z\right)\right)$$
$$\times \Im m\left(e^{-i\theta_0}\phi_{m-1}\phi_m^* + e^{i\theta_0}\phi_{m+1}\phi_m^*\right) ,$$

Z is the plasma dispersion function, the argument of which is given as $\xi_e = \omega/|k_\parallel| v_{\mathrm{th\,e}}$, $k_\parallel = (M+m-nq)/qR$, $v_{\mathrm{th\,e}}$ is the electron thermal velocity, L_n is the density gradient scale length, and an abbreviation $\phi_m = \phi_{n,M}(r-m\Delta)$ is used. Here, n is the toroidal mode number, M is the central poloidal mode number, $M = n\,q(r_{M,n})$ at $r = r_{M,n}$, and $\Delta = 1/nq'$. This result shows that the transport by the (M,n) -mode, $F_{M,n}(r)$, is extended in the region $r_{n,M} - \ell_E < r < r_{n,M} + \ell_E$. The summation over M is approximately replaced by the integral over $r_{M,n}$ as

$$\Gamma_r(r) = \frac{nq}{B_0 r}\frac{e}{T_e}\sum_n \int_{r-\ell_E}^{r+\ell_E} \mathrm{d}r_{M,n}\,\Delta^{-1}\hat{F}_{M,n}\left(r - r_{M,n}\right)$$

where we rewrite as $F_{M,n}(r) = \hat{F}_{M,n}\left(r-r_{M,n}\right)$. Each flux $\hat{F}_{M,n}\left(r-r_{M,n}\right)$ is contributed from the plasma parameters at $r = r_{M,n}$. A similar integral form is also derived for the energy flux. The turbulence level of $e\tilde{\phi}/T_e \simeq 1/k_\perp L_n$ with $k_\perp\rho_i \simeq 1$ and the decorrelation rate of $\gamma_{dec} \simeq c_s/L_n$ have been obtained. For this level of fluctuation amplitude, the Kubo number, the ratio between deccorelation time to the eddy-turn-over time, is given as

$$\mathcal{K} \simeq \rho_i/\ell_E \simeq \sqrt{s\rho_i/L_n}$$

and is much smaller than unity. This result means that the one-time autocorrelation length of fluctuation fields (Euler's view) is much longer than the autocorrelation length of fluctuating motion of plasma elements.

The transient response of transport is analyzed based on the nonlocal expression of fluxes. A transient response of the form $T(x,t) \propto \exp\left(-i\Omega t\right)$ is studied for the transport equation. We obtain the equation for $k(\Omega)$ as

$$i\Omega = \chi\, k^2 \exp\left(-k^2\ell_E^2/4\right)$$

where χ is the value in the stationary state. By use of $\Re e\, k(\Omega)$, χ_{eff} is formally given as $\chi_{eff} = \Omega\left(\Re e\, k\right)^{-2}/2$. In the case of larger Ω , $\Omega > \chi\ell_E^{-2}$, numerical solution provides a relation

$$\chi_{eff}/\chi \simeq 3\Omega\,\ell_E^2/4\chi \, .$$

We have an upper bound of the effective thermal conductivity is rewritten as [2] $\chi_{eff}/\chi \le \mathcal{K}^{-2}$ in the case of $\mathcal{K} << 1$. For the case of the ballooning mode, one has $\chi_{eff}/\chi \le a/s\rho_i$.

This result is compared with experiments. One time correlation length is measured as $\ell_c \simeq 0.1m$,. When one uses a typical value of the L-mode of $\chi \simeq 10\, m^2/s$, one has a relation $\chi_{eff}/\chi \sim 10^{-3}\,\Omega$. For the sudden change with the time scale of the order of $100\mu s$, such as the L/H transition, the effective transport coefficient deduced from the transient response is given as $\chi_{eff}/\chi \sim 60$. This enhancement factor is in the range of experimental observations in large tokamaks at L/H transitions. This analysis gives a basis of the nonlocal transport model for the study of transient transport [3].

References

1) Itoh S-I, et al.: J. Phys. Soc. Jpn. **50** (1981) 3503
2) Itoh K and Itoh S-I: NIFS-705 (2001)
3) Iwasaki T, et al.: Nucl. Fusion **39** (1999) 2127