§14. An Assessment of Turbulent Momentum Transport

Itoh, K.

The 4th IAEA technical meeting (IAEA-TM) has been designed being motivated by the recent advancement in theoretical methodology, by the rapid progress in observations of laboratory and astrophysical plasmas, and by the evolution of fusion research of ITER era. The assessment is made based on the tide that '*knowledge must be developed into understanding*'[1]. In realizing this evolution, integration of the theory, simulation and experiments is crucial, and an emphasis is made on it as a key for the future progress. The key concepts in this summary that the way of thinking has evolved, from '*linear, local and deterministic*' models to '*nonlinear, nonlocal, statistical*' models.

The word 'non-diffusive transport' is used in many circumstances. When a flux of some quantity X, Γ_X, appears in the absence of the gradient of X, this flux is often called non-diffusive transport. One mechanism for this is that the transport is driven by gradients of quantities other than X. In this sense, one may analyze the 'off-diagonal elements of transport matrix'. It should also be noted, however, the concept 'transport matrix' itself is not well-defined in turbulent plasmas in many circumstances. Nonlinear combinations of gradients of various plasma parameters appear in the transport coefficients [2]. It is better to be formulated as 'interface of gradients' in transport. Other case where 'non-diffusive transport' is introduced is that the flux is driven by fluctuations, which have either long step sizes and/or long decorrelation times [3]. The latter case is discussed in elsewhere.

Keeping these clarifications first, assessment is made on the non-diffusive transport of toroidal rotation in plasmas. Symmetry of fluctuation spectrum must be broken, in order to generate the net radial transport of toroidal momentum. Various origins of momentum transport were discussed: up-down asymmetry, the effect of gradient of radial electric field on the asymmetry, electromagnetic effect and polarization drift and others. The momentum flux is symbolically written as

$$\Pi_{r,\zeta} = -m_i n_i \chi_\zeta \nabla V_\zeta + \Pi_{\text{others}} \qquad (1)$$

where ζ stands for the toroidal direction, V_ζ is the toroidal velocity, χ_ζ is the momentum diffusivity, and Π_{others} is the one which is independent of the gradient of toroidal velocity [4].

One can recall that the analysis of Π_{others} in Eq.(1) is associated with another tie between turbulence theory and neoclassical theory. For instance, Stringer spin-up in neoclassical theory has sensible analogy with the up-down asymmetry effect, and the polarization drift effect is related with neoclassical gyroviscosity. The partition between ZFs and GAMs has also relevant analogy with the Pfirsch-Schlueter transport in neoclassical theory. Thus, it is not surprising that the concept of neoclassical current-drive could be extended to the drive of toroidal flow by wave field.

From the consideration of the energy dependence of 'transportee' by turbulent motion, the difference is prominent between the 'passive quantities' (such as density and energy) and the 'active quantities' (e.g., poloidal velocity, magnetic flux) that constitute the turbulent motion. For the illustration, Eq. (1) is compared with the case of zonal flow drive. The momentum transport associated with ZFs may be symbolically written

$$\Pi_{r,\theta} = m_i n_i \chi_\theta \nabla V_\theta + \Pi_{\theta,\text{ others}} \qquad (2)$$

where the first term in the RHS indicates the drive of zonal flow by ambient turbulence (through modulational instability). In the quasilinear limit, the coefficient χ_θ is negative when zonal flows grow. (This shows a clear difference from energy and parallel momentum.) By renormalizing the nonlinear effect of ZFs, and summing up terms $m_i n_i \chi_\theta \nabla V_\theta$ and $\Pi_{\theta,\text{ others}}$, the evolution of mean poloidal flow is expressed in terms of positive viscosity. Experimental verifications of these essential nonlinear mechanisms are ongoing, and confidence is increasing [5]. Unifying analyses are emerging.

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