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Non-local transport nature revealed by experiments in toroidal plasmas

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The non-local transport nature revealed by the research in transient phenomena of toroidal plasma is reviewed [1]. The following non-local phenomena are described: core temperature rise in the cold pulse, hysteresis gradient–flux relation in the modulation ECH experiment, and see-saw phenomena at the internal transport barrier (ITB) formation. There are two mechanisms for the non-local transport which cause nonlocal phenomena. One is the radial propagation of gradient and turbulence. The other is a mediator of radial coupling of turbulence such as macro/mesoscale turbulence, MHD instability, and zonal flow [2]. Non-local transport has a substantial impact on structure formations in a steady state. The turbulence spreading into the ITB region [3], magnetic island [4], and SOL [5] are discussed.

The non-local transport is one of the physical mechanisms of transport hysteresis in gradient–flux relation. The gradient–flux relation of heat transport is determined by the so-called hidden parameters as well as gradients. Therefore, there are multiple gradient–flux relations (transport curves) depending on the value of hidden parameters. The gradient of off-diagonal terms (e.g., density gradient or flow velocity shear in the heat transport) are standard hidden parameters. The other well-known hidden parameters are magnetic shear and radial electric field that is not explicitly included in the element of the transport matrix. The difference of hysteresis characteristics between local transport and non-local transport is whether the hidden parameter is a local parameter or not. In the case of hysteresis of local transport, the hidden parameters are local plasma parameters at the location the same as the gradient of the x-axis of the transport curves. In contrast, the hidden parameters of non-local transport hysteresis are the plasma parameters at a location different from that of the x-axis of the transport curves. In the steady state, it is impossible to find the hidden parameter of non-local transport. Therefore, the transient phenomena, either by the perturbation or by the transition, are necessary to identify non-local transport hysteresis.

The various observations have identified the existence of non-local transport. The core temperature rise is the most common phenomenon, which reveals the non-local transport by the hysteresis in gradient–flux relation. This phenomenon is characterized by the spontaneous increase of core electron temperature after the transient edge cooling produced by pellet injection or supersonic molecular beam injection (SMBI) in various toroidal plasmas. The modulation ECH is also a common technique to measure the hysteresis in gradient–flux relation at the mid-radius where there is no heat deposition. The heat flux starts to increase before the increase of temperature gradient after the ECH is turned on. In contrast, the heat flux starts to decrease before the decrease of temperature gradient after the ECH is turned off. Then, the heat flux in the time period for the ECH on-phase becomes larger than that in the time period for the ECH off-phase for the given temperature gradient. The heat flux at mid-radius increases due to the increase of temperature gradient near the plasma center not due to the increase of temperature gradient at mid-radius. This hysteresis clearly shows a coupling of heat flux at the mid-radius and temperature gradient near the plasma center, which is clear evidence of non-local transport. The abrupt spontaneous increase of temperature gradient at the mid-radius is called an internal transport barrier (ITB) formation. The non-local transport is also observed in the transient phase at the ITB formation. After the formation of ITB, the thermal diffusivity coefficient decreases inside the ITB region but increases outside the ITB region. This simultaneous decrease/increase of the thermal diffusivity coefficient is called see-saw transport.

In the mechanism causing the non-local transport, there are various types of propagation and types of mediators of radial interaction of turbulence. Turbulence spreading is a nonlinear coupling of fluctuation energy that redistributes the turbulence intensity field away from the regions where it is exciting. Avalanche is a ballistic front propagation of turbulence and gradient in the radial direction due to a strong nonlinearity of the growth rate of the micro-scale turbulence. Since the turbulence and gradient can be radially coupled at a distance much larger than the turbulence correlation length, this is categorized as turbulence spreading. The other radial propagation is due to the gradient propagation through the transient change in radial flux, which is an approach to explain the non-local phenomenon by the local transport model. There are various candidates for the mediator causing the radial interaction of micro-scale turbulence. Zonal flow is mesoscale shear flows driven by nonlinear interactions through energy transfer from micro-scale drift waves. Because of the energy transfer to and from the microscale turbulence, zonal flow can be one of the candidates for the mediator of turbulence coupling between two locations in the mesoscale. Macro-scale or mesoscale turbulence can also be a candidate for the mediator through the energy transfer by nonlinear interactions. Macro-scale or mesoscale MHD instability is another candidate for the mediator because of the interaction between MHD and micro-scale turbulence.

References

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