Direct Observation of Non-locality of Non-diffusive Counter-gradient Electron Heat Transport

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Heat transport in fusion plasmas is often modeled as a temperature gradient. In contrast, when a narrow region away from the plasma center is heated to create a plasma with a peculiar hollow temperature profile and then a narrow region near the center is further heated, a transient phenomenon was observed in which the heat pulse propagates against the temperature gradient. Furthermore, by switching the heating on and off, it was experimentally evaluated that the driven heat flux is not determined by the temperature gradient alone.

To realize fusion power generation, it is necessary to generate high-temperature plasma. However, even if the heating power is the same, the temperature profile of the generated plasma will change if the heating location is different. Therefore, it is essential to study the mechanisms (confinement and transport) of how the different temperature profiles are formed.

Heat transport is usually considered in a diffusion model where the heat flux is driven by a temperature gradient. In the Large Helical Device (LHD), an external heating method called electron cyclotron heating (ECH) is used, which can heat a narrow plasma region. Normally, the plasma center is heated to produce a high-temperature plasma and a peaked electron temperature (T_e) profile. However, in this study [1], we observed for the first time that heating away from the plasma center produces a hollow T_e profile; in a quasi-steady state where the T_e profile does not change, it is possible to describe the non-diffusive outward heat flux in terms of heat convection. Such a model can reproduce the T_e profile of the LHD plasma.

Next, we experimentally investigated the response of the T_e profile to a plasma with a hollow T_e profile when an additional ECH is added to the center of the T_e profile. In other words, the transient response of how the heat pulse propagates outward from the center was investigated from the time evolution of the T_e profile. Figure 1 shows the flux-gradient diagram. The results showed that the heat pulse propagates transiently against the T_e gradient. In other words, net heat was found to flow transiently from lower T_e to higher T_e. Also, with central heating, the T_e profile changed from a hollow profile to a peaked profile over time, but there was a period when it just flattened out (the T_e gradient became zero). Even then, net heat flowed outward; direct experimental investigation of the relationship between the T_e gradient and the driven heat flux showed that the diffusion model could not explain the heat transport in this case.

We then stopped the central heating and examined the relationship between the T_e gradient and the driven heat flux when the T_e profile returned from the peak profile to the hollow profile. The results showed that the trajectory was different from that during central heating. This phenomenon is called transport hysteresis. We found that the transport at a given location is not determined by the T_e gradient or T_e at that location. This hysteresis was confirmed to be repeated by turning the central heating on and off; the non-local nature of the non-diffusive heat transport associated with heat convection was experimentally revealed as T_e moves back and forth between peak, flat, and hollow profile states. This finding is a new insight into transport phenomena in fusion plasmas.

References

[1] T. I. Tsujimura *et al.*, Phys. Plasmas **29**, 032504 (2022).

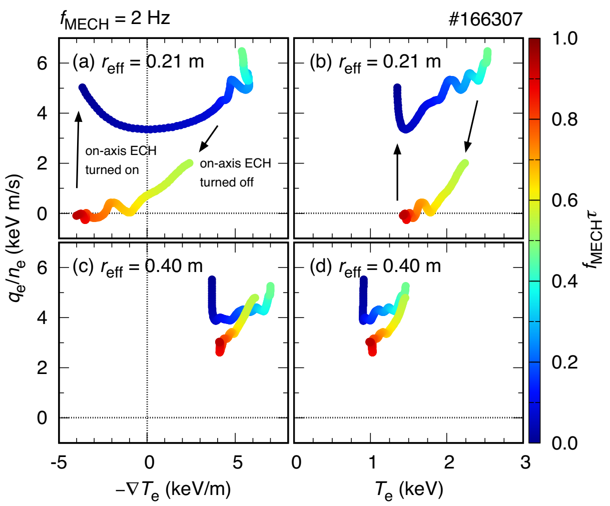

Figure 1. Diagrams of the flux-gradient relation at (a) r_{eff} = 0.21 m (between two ECH deposition locations) and (c) r_{eff} = 0.40 m (outside two ECH deposition locations) along with (b) and (d) the flux-temperature relation at same locations (from Fig. 8 in Ref. [1]).