Divertor detachment and core plasma transport with RMP application in LHD

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Compatibility of divertor heat load mitigation with high performance core plasma confinement is of critical importance for realization of a nuclear fusion reactor. The divertor heat load mitigation is realized with energy dissipation via impurity radiation often accompanied by divertor detachment. Because of the strong nonlinearity of the energy transport and impurity radiation against temperature, the divertor detachment is a bifurcation between high and low temperature branches [1]. On the other hand, high performance core plasma confinement is also achieved through a transition from a low confinement mode to a high confinement mode, where the transition is also bifurcation between the two branches in the nonlinear system. In Large Helical Device (LHD), the impact of edge magnetic field structure/topology on the divertor detachment and core plasma confinement have been studied [2]. In this contribution, we present current understanding of these issues in the 3D edge magnetic configuration of LHD.

Magnetic topological effect on the thermal condensation instability, which triggers detachment, is studied by creating edge magnetic island with RMP (resonant magnetic perturbation) field application. A magnetic island introduces a X-point, where field line connection length becomes infinity due to the singularity. In such case, a stabilization term in the instability by energy transport along magnetic field is disabled due to $k_{//} \rightarrow 0$. This means that the X-point is most unstable against the thermal condensation instability. This was experimentally confirmed by impurity radiation measurement that selective cooling occurs around the X-point, indicating onset of the instability there [3]. Analysis with numerical simulations show that at the onset of the instability, a feedback loop takes place between the X-point cooling, pressure gradient from O-point to X-point, and impurity flow drive toward X-point [4]. Afterwards, the impurity radiation propagates toward the O-point, which is consistent with the observation in the experiment.

In the recent experiments, it has been found that combination of the edge island, Ne impurity seeding, and ECRH heating realizes high radiation fraction of more than 90% of the input power. In this operation, it is indicated that there is optimum radial position of the edge island to achieve the high radiation fraction. With NBI heating, however, only 60% radiation was achieved in the same magnetic field configuration. The reason for the difference owing to the heating scheme is under investigation.

The application of RMP introduces sharp boundary in the magnetic field structure between the confinement region (closed magnetic flux surface) and the edge stochastic layer (open field line). At the onset of the detachment, it has been found that edge transport barrier develops at the boundary, where steep gradient forms in both electron temperature and density profiles. One of the possible mechanisms for the ETB formation is strong flow shear caused by the parallel flow localized at the island separatrix, which is driven to supply particles to the X-point where density condensation takes place due to the thermal instability as mentioned above. The ETB is more pronounced in deuterium plasmas than in hydrogen plasmas. As the detachment deepens, the ETB becomes stronger and edge temperature decreases. This leads to excitation of pressure gradient resistive MHD mode, such as resistive interchange mode. When this mode is excited, the ETB collapses. But at the same time, core transport coefficient decreases, as analyzed by heat transport analysis code, to compensate the ETB degradation, showing clear core-edge coupling. As a result, the plasma stored energy is kept unchanged. It is also noted that during this phase, the adiabaticity parameter estimated at the pedestal top is far above unity, which is in contrast the confinement degradation observed around density limit as observed in HL-2A tokamak. During the MHD mode excitation, turbulence starts to spread into the edge stochastic layer, which leads to further widening of the divertor heat load. Then, spontaneous increase of the stored energy and of recovery of the ETB occurs. This recovery is accompanied by spin up of the MHD mode frequency and reduction of density fluctuation. Later the coherent MHD mode ceases to change to ELM like bursts. In this improved confinement mode, impurity decontamination occurs as indicated by reduction of carbon high charge state emission (CVI). Similar decontamination during improved mode was observed in W7-AS experiments. The divertor heat load, however, slightly increases in this improved mode due to the reduction of radiated power down to 40% because of the impurity decontamination and to the ELM pulses.

These results provide insight into the interplay between cold edge plasma with enhanced impurity radiation and the ETB to sustain core plasma performance in the 3D edge magnetic configuration inherent to the helical devices.

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