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Critical particle circulation caused by high-performance steady-state plasma discharge

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Steady-state operation focused on the fusion reactor has been investigated in magnetic confined fusion devices, and plasma performance and duration time are steadily extended by the improvement of the quality of plasma heating and sophisticating plasma operation using the understanding of long-pulse plasma experiments. When higher-performance helium steady-state plasma discharges with duration time over 40 min, electron density of 1.2×10^{19} m^{-3}, ion and electron temperatures over 2 keV and heating power of 1.2MW were repeatedly achieved in LHD, time-evolution of the wall-pumping and increasing frequency of impurity contaminations around the plasma edge clearly occurred. These are strongly related to the increasing mixed-material layer caused by continuous divertor erosion around geometrical dense divertor plates, which consists of carbon ($> 90\%$) and iron ($<$ a few %) with amorphous structure, that can retain the helium particles and affect the particle balance in long-pulse discharges. The mixed-material layer is easily exfoliated by the thermal stress and helium explosion in the layer, and small pieces of exfoliation enter the plasma edge in all toroidal sections. Uncontrolled flake contamination was one of the causes of plasma termination in long-pulse experiments. Increased plasma performance using higher heating power (~ 3.3 MW) with high quality makes robust plasma against impurity contaminations, and then a small amount of contamination of mixed-material does not terminate the helium plasma. Carbon impurity was circulated from the divertor plates and around the plates to the plasma edge in long-pulse plasma discharges, and the circulation was increased by the plasma duration and performance. The eroded material plays an important role in degrading the plasma performance as an impurity source and in the controllability of particle fueling in long-pulse discharges.