Detachment physics of the W7-X divertor

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Wendelstein 7-X (W7-X) is the world's largest highly optimized stellarator and explores its own reactor path on which the development of a viable plasma exhaust concept is essential. W7-X employs a so-called island divertor, utilizing inherent low-order magnetic islands. First divertor experiments have demonstrated great success in accessing and stabilizing detachment – a SOL plasma scenario that is of high reactor-relevance. The detachment achieved in W7-X exhibits many features that differ from those seen in its predecessor W7-AS and tokamaks. Most of these features have been captured by the 3D edge plasma transport code - EMC3-Eirene. With the help of the EMC3-Eirene code and in conjunction with the first experimental results, this paper provides a detailed physical analysis of how the W7-X island divertor plasma self-regulates to maintain the particle, momentum, and energy balance under detached conditions.

Compared to the partial character of W7-AS detachment, the detachment achieved in W7-X is complete in the sense that the heat flux on targets decreases more homogeneously with rising radiation. The typical radiation pattern predicted for W7-X differs fundamentally from that for W7-AS. In W7-AS, the inboard side was favorable for impurity radiation, while the outboard side was nearly radiation-free, allowing enough heat to escape to leave a permanent hotspot on the targets. By contrast, the radiation distribution in W7-X exhibits a multiband structure. The radiation bands are poloidally broad and helically continuous and form a cooling layer at the edge with a large surface coverage. There are no large gap areas through which a significant amount of heat can escape without being effectively removed by radiation. The completeness of radiative heat removal results in homogeneous unloading of the targets – complete detachment.

The reduction of recycling flux at high radiation levels is understood as a constraint of the total power balance, which is machine-independent. However, how a divertor plasma regulates itself to adjust the recycling flux to keep a detached plasma thermally stable is controlled by momentum balance, which largely depends on the divertor configuration. In the W7-X divertor, the reduction in recycling flux at detachment is mainly due to a drop of the plasma pressure at the LCFS and a steepening of the pressure profile there. Viscous momentum transport into the confinement region plays a supporting role as the parallel particle flow channels expand toward the LCFS. In contrast, plasma-neutral friction, which plays a crucial role in the detachment of tokamaks, does not contribute greatly to the reduction of the recycling flux in the island divertor.

The decrease in the upstream plasma pressure is primarily a temperature effect resulting from an interplay between cross-field conduction and an inward shift of the radiation zone. A radial 1D analysis of each heat transport process reveals that cross-field conduction forms the main heat channel across the island under detached conditions. When the radiation fraction f_{rad} exceeds ~0.5, the radiation zone begins to detach from the target and gradually moves inward as f_{rad} continues to increase, shortening the perpendicular distance between the heat source (LCFS) and heat sink (radiation zone). Consequently, the plasma temperatures at the LCFS drop almost linearly while the radiation layer approaches the LCFS until the radiation front intrudes into the closed confinement region.

Both experiments and modeling consistently show that the W7-X divertor has good compatibility between particle and heat exhaust, in the sense that the maximum divertor neutral pressure is obtained under a deeply detached condition with f_{rad} ~80%, where the recycling flux has significantly decreased. The causes have been understood as follows: first, intensive carbon radiation cools the downstream plasma to an ionization-inactive state, opening up an ionization-free channel for the recycling neutrals toward the divertor gap. Second, momentum transfer between neutrals and ions through charge-exchange or elastic collisions generally hinders the neutrals from directly penetrating the ionization zone, which is shifted from the target and is usually located near the LCFS at high radiation levels of interest. These scattering processes tend to retain the recycled neutrals in the near-target region, increasing their probability of being captured by the divertor chamber