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Detachment physics of W7-X island 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.[1] 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 [2, 3] – 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. With the help of the EMC3-Eirene code, this paper provides a detailed physical analysis of the main experimental results to reveal how the island divertor plasma self-regulates to maintain particle, energy, and momentum balance under detached conditions.[4]

Compared to the partial character of W7-AS detachment, the detachment achieved in W7-X is more 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, forming 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 a constraint of the total power balance, being machine-independent. However, how a divertor plasma regulates itself to adjust the recycling flux to keep a detached plasma thermally stable, does depend on the divertor geometry. For 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.

For the island divertor concept, particle removal is more challenging compared to power exhaust. In the island divertor, the target-core separation is limited by the radial island width. The long connection length and the high sensitivity of the island location to the plasma current do not allow very close positioning of the strike-line to the divertor gap. All these circumstances make it difficult for the recycling neutrals to enter the divertor chamber without being ionized in the island. Simulations have identified two beneficial effects that prevent the recycling neutrals from being readily ionized, thereby increasing the probability of the neutrals being trapped in the divertor chamber. 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.

References

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