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Increased power operation with water-cooled divertors at Wendelstein 7-X

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The plasma exhaust concept of the Wendelstein 7-X (W7-X) stellarator is based on the island divertor configuration, which exploits the interaction of magnetic islands with ten discrete carbon targets. These targets are designed to cope with multiple magnetic configurations featuring different island chains at the edge of the machine. They are therefore in an 'open' configuration with minimal baffling.
During the initial experimental campaigns, the concept was tested using inertially cooled targets. Due to the open nature of their geometry, these experiments revealed low neutral pressures behind the divertors (well below 0.2 Pa). However, no significant issues were encountered in terms of heat load handling within the explored power and density range (≤ 6 MW and ≤ 10.5 10^{19} m^{-3}), for both attached and detached scenarios. In fact, the inertially cooled targets were robust and could reach high surface and bulk temperatures. The high material temperatures resulted in the release of a high number of particles, leading to power-starvation detachment through the radiation of intrinsic impurities (mostly carbon), with line-averaged densities well within the operational range for optimal electron cyclotron resonance heating (ECRH).
After two experimental campaigns, the targets were replaced with water-cooled ones, suitable for long pulse operation, but with a lower surface temperature limit. This hindered the ability to achieve high radiated power fractions (f_{rad}) with intrinsic impurities: higher line-averaged densities were required to reach the same level of f_{rad} at the same power as with the uncooled divertor. The densities necessary for detached operation increased further when the power entering the scrape-off layer rose above 5 −6 MW. Thanks to improvements made to the main heating systems (ECRH and neutral beam injection), input powers up to 13 MW were achieved, pushing the line-averaged density required for f_{rad} > 0.8 closer to the limit of optimal ECRH absorption ($2 \cdot 10^{20}$ m^{-3}).
Additional differences in divertor operation were observed in the high power experiments. The density profiles measured by multiple diagnostics (multi-purpose manipulator probes, Alkali beam, He beam) showed steeper radial gradients, both inside and outside the magnetic islands. Bolometer measurements revealed increased toroidal variation in plasma radiation at higher power levels, exacerbating the already existing discrepancy with EMC3-Eirene predictions. The high powers entering the scrape-off layer, now sustaining higher divertor densities, led to higher neutral pressures, stronger impurity flow velocities, and increased perpendicular transport. This change in transport resulted in heat loads being deposited on plasma-facing components that were not designed to withstand them. This prevented safe attached operation (f_{rad} < 0.75) within the mid-density range (6 to $9 \cdot 10^{19}$ m^{-3} line-averaged density) in some of the most commonly used W7-X magnetic configurations for heating powers above 4 −5 MW, highlighting the need for reliable scenarios featuring seeded impurities (e.g. with a dedicated feedback controller).

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