Importance of turbulence and of its control for plasma performance in the optimized stellarator Wendelstein 7-X

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In the optimized stellarator Wendelstein 7-X (W7-X)[1], neoclassical (NC) transport losses have been minimized by design through magnetic field optimisation, which is expressed by a significant reduction of the effective magnetic ripple ε_{eff} and hence, of the NC heat diffusivity. Such a NC optimization is necessary for stellarators due to a strongly unfavourable scaling of the NC transport with temperature $\chi_{1/\upsilon} \sim \varepsilon_{eff}^{3/2} \cdot T^{7/2}$ that would otherwise prohibit fusion operation. In this contribution we show, using a wide experimental data base from the last divertor campaign, that the NC optimization alone may not be sufficient and that the energy transport in W7-X is in fact dominated by turbulence for the vast majority of discharges with electron cyclotron resonance heating (ECRH) and gas fuelling. This fact is manifested in global performance markers, such as the energy confinement time and clamping of the central ion temperature at 1.5 ± 0.2 keV, and in missing power in the NC power balance. All in all, performance of such plasmas is significantly below neoclassical expectations[2] and does not vary with the effective helical ripple (ε_{eff}=0.8% - 2.5%). Nonlinear GENE[3] simulations show that ITG turbulence is indeed unstable for the typical experimental conditions, and is further exacerbated as the T_e/T_i ratio increases with ECRH heating power[4].

The plasma performance in W7-X is strongly improved in the case that the ion-scale turbulence is suppressed by a density gradient. The most prominent, though transient, improvement of this type is found after injection of a series of frozen hydrogen pellets[5], where record plasma parameters are achieved, confirming the success of the NC optimization. The T_i-clamping is removed and T_i values around 3 keV are obtained; the energy confinement time exceeds the empirical ISS04[6] scaling and the NC heat fluxes become significant, or even dominant, in the power balance. This favorable behaviour has been explained theoretically by the transition from the ITG driven turbulence to the Ion Trapped Electron Mode (iTEM) turbulence excited by the trapped electrons[7,8]. The latter type of turbulence emerges through the combined effect of ion temperature and density gradients, and is particularly mild in W7-X thanks to the optimization. Other examples that confirm the beneficial effect of density gradients are: laser impurity blow-off, impurity pellet injection, boron powder dropper experiments[9], plasmas with NBI heating[10].

Although a more detailed analysis of the experimental data is still ongoing, we may already conclude that a strong reduction of turbulent losses, possibly using various approaches, is necessary to achieve the designed performance values in W7-X. Several options will be tested in the next experimental campaign, including increased ECRH heating power, enhanced NBI heating, ICRH heating, newly installed cryopumps for the edge density control and a new steady state pellet injector.

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