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Combatting turbulent transport in the Wendelstein 7-X stellarator; a comparison to the ASDEX Upgrade tokamak.

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Turbulent transport plays a dominant role in magnetically confined fusion plasmas where high ion temperatures of T_i >10keV and densities $n > 10^{20}$ m^{-3} are required. For state of the art tokamaks, such as ASDEX Upgrade (AUG), this has long been established and has resulted in a vast knowledge base on the turbulent transport mechanisms. Stellarators initially suffered from their relatively high magnetic ripple producing a strong magnetic mirror with enhanced neoclassical transport losses.

The Wendelstein 7-AS (W7-AS) [1] and its successor Wendelstein 7-X (W7-X) [2] are stellarators increasingly optimized - beyond other criteria - to provide strongly reduced effective magnetic ripple (ε_{eff}) and hence a reduction of the neoclassical heat diffusivity $D \sim \varepsilon_{eff}^{3/2} \cdot T^{\frac{7}{2}} \cdot n^{-1}$ at medium collisionality in the 1/ν regime. This reduction means that in these devices turbulent transport, at least initially, remains the dominant transport channel. In W7-AS this could only be overcome in the so-called "optimized" confinement scenario, where strong E_r and steep density gradients helped to suppress the ion turbulent transport. This scenario could not be reproduced in W7-X but has been used to extrapolate to a best-case confinement scaling with only neoclassical heat transport in the core $\tau_{e,W7\text{-}X} > 2 \times \tau_{iss04}$ [3], following the ISS04 confinement scaling.

This can be reviewed with data from the latest W7-X experimental campaign, where divertor operation and boronization opened up a large operational space in hydrogen plasmas with densities ranging from $2 \cdot 10^{19}$ to $1.4 \cdot 10^{20}$ m^{-3} and electron cyclotron heating power P_{ECRH} up to 7 MW. To test the remaining influence of neoclassical transport, the average effective ripple has been varied by using four magnetic configurations from $\langle\varepsilon_{eff}\rangle = 0.8$ to 2.5%.

Firstly we find that the level of transport in the experiments is much above the neoclassical heat transport: the experimental ion and electron heat fluxes are up to 10 times the neoclassical fluxes calculated with the neoclassical transport code NTSS [3]. Moreover, the confinement time for the entire operational space of standard ECRH plasmas with flat density profiles is $\tau_e < 0.7 \times \tau_{iss04}$. Secondly, we observe no or only a small effective ripple dependence of the confinement. Therefore, under the present accessible conditions turbulence dominates the W7-X confinement.

A comparison with this W7-X database is conducted with ECRH heated L-mode hydrogen plasmas in AUG. Figure 1 shows that the electron temperature T_e was varied from 1.5 -10 keV in both AUG and W7-X with P_{ECRH} < 6MW in both devices. However the ion temperature is clamped at $T_i \sim 1.5$ keV. The exchange power P_{ei} was varied by over a factor of 3 in both devices, but the normalized flux P_{ei}/n only varies by a factor of ~2. Whereas this complicates the evaluation of ion profile stiffness in these experiments, similar ion turbulence processes are likely dominant in both experiments.

Just like in tokamaks, simulations with the non linear gyrokinetic code GENE [4] show that electrostatic micro-instabilities dominate the particle and heat transport in W7-X core plasmas. For particles, this is evidenced by the presence of flat to slightly peaked density profiles, where otherwise hollow profiles are expected [5]. Also, experiments in W7-X using tracer-impurities by laser blow off (LBO) injection [6] show that indeed the impurity confinement time is well below that of neoclassical predictions and scales up with the ratio of electron and ion temperature (T_e/T_i), a signature of ITG turbulence. Transiently improved energy confinement is found for W7-X using ice pellets injections. After an initial cooling phase in which steep density gradients are generated, both ion and electron temperature transiently rise to 3keV and $\tau_e \sim 1.4 \times \tau_{iss04}$ [7]. The density gradients suppress ITGs, whereas thanks to the maximum-J property of W7-X ion driven TEM type of turbulence is avoided [8.9]. This mechanism is not responsible for the "optimized" confinement plasmas in W7-AS in absence of the maximum-J property. Here the strong radial electric field may be responsible for stabilizing the turbulence. The challenge for W7-X is now to find stationary high confinement scenarios.

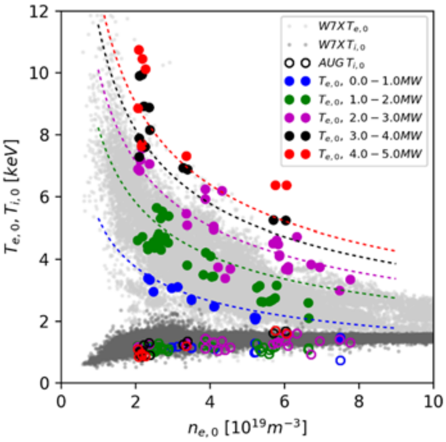

Figure 1: T_i-clamping in ECRH plasmas in AUG and W7-X

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