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[REGULAR POSTER TWIN] Confinement in electron heated plasmas in Wendelstein 7-X and ASDEX Upgrade; the necessity to control turbulent transport

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Wendelstein 7-X (W7-X) is an optimized stellarator of the HELIAS type. ASDEX Upgrade is a medium sized tokamak. In electron cyclotron heated (ECRH) hydrogen plasmas the central ion temperature is clamped at Ti,0 ~ 1.5 keV in both W7-X (Figure-1) and AUG. These findings are found to be virtually independent of heating power and electron density, and for W7-X, independent of magnetic configuration. In both devices ion scale turbulence (ITG/TEM) is thought to be responsible for the enhanced turbulent transport. In combination with the off-axis ion heating profile that stems from the electron-to-ion energy transfer-profile, the enhanced turbulent transport leads to the observed clamping of Ti,0. For future fusion reactors with dominant electron (i.e. α-particle) heating, of either stellarator or tokamak type, these W7-X and AUG experiments expose the potential performance limiting ion-temperature-"clamping"issue. Active turbulent suppression may then become a necessity.

The clamped ion temperature has been studied in an AUG deuterium plasma with high central density (1.10^20m-3) and high plasma current (1 MA) in H-mode, and Pecrh=4 MW. Central ECRH deposition yielded Te,0 = 3.4 keV and Ti,0 =1.9 keV. Moving Pecrh = 3.3 MW off-axis to r/a =0.6 and keeping only 0.7 MW in the core, resulted in unchanged pedestal parameters Te = Ti = 1 keV. However, central Te,0 = 2.3 keV significantly reduced while Ti,0 remains at 1.9 keV within error bars, whereas the total heat flux to the ions is reduced by a factor of two. This behaviour has been predictively modelled with the trapped-gyro-Landau-fluid model (TGLF) for turbulent transport, and relates to the result that in tokamaks the ratio Te/Ti has a strong effect on ITG stability. In a direct comparison to W7-X, in AUG experiments in hydrogen were conducted with 122 different heating and density variations between Pecrh = 0.5-5MW and ne,0 = 2-8 10^19m-3, in which Ti clamped at 1.5 keV, independent of confinement H- or L-mode. Turbulence suppression in these scenarios would be required to obtain enhanced Ti.

In W7-X, neoclassical transport losses have been minimized through a reduction of the effective ripple down to εeff ~ 0.8%. Its design aims are steady state operation up to a pressure <β> ~ 5% with mainly dominant electron heating. Neoclassical (NC) transport predictions show that this may be achievable with Pecrh ~ 10MW, and would have an energy confinement fISS04 = τe / τISS04 > 2, compared to the ISS04 confinement scaling. Assuming Pecrh ~ 4.5MW in such simulations, ion temperatures of up to Ti=2.8-3.5 keV may be achieved, depending on the configuration chosen (Figure-1). In experiments after wall conditioning by means of boronization and with divertor operation, a wide operational window with Pecrh = 0.5-6MW and ne,0 = 0.2-1.4 10^20m-3 in four different magnetic configurations with <εeff> 0.8% - 2.5%, was obtained. In contrast to the NC predictions, a confinement of only fISS04 = τe / τISS04 < 0.7 was found, virtually independent of Pecrh and εeff, and degrading with density compared to the scaling. Most notably, in W7-X the achieved central ion temperature across the standard ECRH database was at maximum Ti ~1.5 ± 0.2 keV, independent of configuration, whereas the electron temperature could vary more widely as Te ~ 1 to 10 keV (Figure-1). Radiation losses and charge exchange losses have been excluded beyond reasonable doubt as the cause of the increased core transport losses.

For W7-X, various candidate turbulent mechanisms are investigated using non-linear and linear gyrokinetic flux surface averaged simulations. At low-density gradients with a/Ln $\leq$ 1, ion temperature gradients (ITG) are thought to dominate the ion heat transport, whereas trapped electron modes (TEMs) drive the electron heat transport. At high-density gradients a/Ln > 3-4 and low temperature gradients a/LT $\leq$ 1, TEMs dominate the overall transport. However, the so-called maximum-J property of W7-X entails that when the temperature and density gradients align like a/LTi ~ a/Ln, the turbulence growth rates are strongly reduced and improved confinement may be the result. This leads to the so called "stability valley", as is thought to be observed in e.g. the post-pellet plasmas.

A power balance on a selected dataset (Pecrh = 2-6MW) and plasma density (3.5-7·10^19 m-3) shows that, focussing on r/a = 0.5-0.7, the electron heat diffusivity remains virtually unchanged at χe,exp ~ 0.7 ± 0.1 m^2/s despite a large variation of Pecrh. The electron transport therefore has a low degree of stiffness as seen in Figure-2a, as well as seen in separate heat pulse propagation experiments which show Se= $\chi\epsilon^{HP}/\chi\epsilon^{PB} \leq 2$. The ion heat diffusivity ranges from 0.5-2 m^2/s, with an average χi,exp ~ 1.1 ± 0.5 m2/s, see Figure-2b. The low variation of a/LTi and moderate variation of χi,exp for a given radius, may imply some degree of ion profile stiffness S=$\Delta\chi/\chi$ consistent with ITG turbulence, but the variation of ion heatflux Qi in gyrobohm units, is too small compared to experimental errors to be conclusive. Also, although the variation of Te/Ti =1-5 in the plasma center and Te/Ti =1-2 at mid radius, is expected to affect ITG turbulence, we have thus far not found

any evidence for this in our heat transport studies. The possible role of ITGs on transport, and its suppression, has however been experimentally shown by introducing a significant density gradient by e.g. hydrogen ice-pellet injection. In the post pellet phase, density and ion temperature gradients transiently increase and align as a/Ln ≈ a/LTi =3-5. Consistent with our gyrokinetic modelling given the maximum-J property of W7-X, transport is reduced and higher central Ti,0 $\approx$ Te,0 $\sim$ 3keV are achieved (green stars in Figure-1). A power balance analysis at the highest Ti indeed shows that the ion heat transport drops to neoclassical levels χi,exp ≈ χi,NC (stars in Figure-2b), implying (ITG) turbulence suppression. Simultaneously a reduction in density fluctuations is seen from our phase contrast imaging diagnostic, also implying reduced turbulence levels.
Extrapolating the performance of W7-X plasmas for enhanced ECRH power is difficult. However, assuming the averaged experimental heat diffusivities, χe = 0.7 m2/s and χi = 1.1 m2/s, in our NTSS predictive transport model, one would require Pecrh > 50MW to approach the design aim of <β> = 5%. Therefore, turbulence suppression (through e.g. induced density gradients) is essential for future high performance electron heated scenarios in W7-X. New tools for scenario development in W7-X are: cryo-pumping; a continuous pellet injector; and enhanced ECRH power (8MW). The PNBI $\sim$ 7MW may yet reveal other venues to high performance.

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