Clamping of the ion temperature at 1.5 keV in electron heated plasmas with a ~ 0.5 m in ASDEX Upgrade, the Large Helical Device and Wendelstein 7-X

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The ion temperature is clamped around 1.5 keV in electron heated L-mode plasmas of three magnetic confinement devices of similar cross section, virtually irrespective of heating power, plasma density and magnetic geometry. This clamping is caused by turbulence driven transport, exacerbated by the electron and ion temperature ratio (T_e/T_i). Turbulence suppression mechanisms are required to boost the performance of such plasmas

The magnetic configuration of the ASDEX Upgrade tokamak (AUG), the Large Helical Device heliotron (LHD) and Wendelstein 7-X stellarator (W7-X) differ strongly, not only in their aspect ratio, but also in their 3-D geometry, see table 1. The neoclassical transport is benign in a tokamak with heat diffusivity $\chi_{NC,tok} \sim n/\sqrt{T}$, but can be very significant at reactor relevant collisionality ν and temperatures for a heliotron/ stellarator with $\chi_{1/\upsilon} = \varepsilon_{eff}^{3/2} \cdot T^{7/2}/n$. (An important criterion for good neoclassical energy confinement is the reduction of the magnetic ripple $\varepsilon_{eff.}$). However in all three devices turbulent transport dominates over the neoclassical transport in the current experiments. The central density and electron heating power were varied as in Table 1, with electron cyclotron heating, ECRH, available for all three devices and in addition for LHD up to 10 MW of negative neutral beams (nNBI), predominantly heating the electrons.

Power balance analyses as well as (non)-linear gyrokinetic simulations show that for electron heat transport, either ETG or TEM turbulence are most unstable whereas for the ion heat transport ITG or TEM modes dominate. The T_i clamping stems from a vicious cycle where the electron heating increases T_e/T_i, which in turn drives TEM/ITG turbulence which enhances the ion heat transport, etc. Thus, effectively clamping is profile stiffness convolved with the T_e/T_i enhancing effect on TEM/ITG turbulence. As a result the ion heat transport experiences an effective strong stiffness of the transport with $a/L_{Ti} \sim 2$ regardless of exchange heat flux.

This vicious cycle can be overcome, or even broken in experiments. In a tokamak, H-mode operation can lift the core T_i by means of an edge pedestal (also found in LHD). Moreover, thanks to a high degree of quasi-isodynamicity in W7-X the core ITG and TEM turbulence can be suppressed by introducing strong density gradients, achieved after e.g. pellet injection, with $a/L_n \sim a/L_{Ti} >> 2$, to achieve $T_{i,0}$ = 3keV with electron heating only. Possible other beneficial mechanisms are e.g. fast ions stabilization, or to design turbulence-resilient-stellarator-configurations from scratch. In any case the T_i clamping issue sets strict design requirements for future electron heated fusion plasmas through alpha-heating.

Table 1: Covered density and electron heating power ranges. As well as aspect ratio and effective ripple.

	AUG	**LHD**	**W7-X**
$\mathbf{n_{e,0}}$	2-8·10^{19} m^{-3}	1-5·10^{19} m^{-3}	2-15·10^{19} m^{-3}
$\mathbf{P_e}$	< 5MW (ECRH)	< 2 MW (ECRH) + 10 MW (nNBI)	< 7 MW (ECRH)
$\mathbf{R/a_{eff}}$	1.5/0.6 = 2.5	3.6/0.6 = 6	5/0.5 = 10
$\mathbf{\varepsilon_{eff.}}$	-	0.2- 3%	~ 0.8%