Scale-resolved Turbulence Studies in L- and H-mode Plasmas of TJ-II and ASDEX Upgrade

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Introduction

Since the L-H transition was discovered in 1982 [1], many questions regarding the physical mechanism of the turbulence reduction came up. Some of them could be answered satisfactorily, but others still remain as open questions to the fusion community. One important point, which has not been addressed intensely, is the scale-dependence of turbulence reduction. Furthermore, the identification of differences and similarities in different types of confinement devices (here: stellarator and tokamak) could yield important information on the processes associated with turbulence suppression.

Doppler reflectometry [2] has proven to be a powerful technique to measure the perpendicular velocity of density fluctuations and their fluctuation level on different spatial scales. The perpendicular velocity is obtained from the Doppler shift ω_{D} of the spectrum of the received signal through $\omega_{\mathrm{D}} = u_\perp k_\perp$. The perpendicular wavenumber $k_\perp$ is calculated after the discharge by ray tracing (TJ-II) or beam tracing (ASDEX Upgrade). From the perpendicular velocity, the radial electric field can be calculated. Both experiments (TJ-II and ASDEX Upgrade) are equipped with Doppler reflectometers [3, 4], which have been used to investigate L-H transitions with special emphasis on scale separation (TJ-II: $k_\perp = 3 - 15$ cm^{-1}, AUG: $k_\perp = 3 - 20$ cm^{-1}).

Experimental results

L-H transitions in TJ-II occur spontaneously, depending mainly on the combination of density, heating power and plasma current. Plasmas in TJ-II were co-NBI heated ($P_{\mathrm{NBI}} = 370$ kW) with line-averaged densities $\langle n_e \rangle \approx 2.8 \times 10^{19}$ m^{-3} and edge rotational transform $\iota(a)/2\pi = 1.63$, where a is the plasma minor radius.

The L-mode plasma in ASDEX Upgrade $\left(\langle n_e \rangle \approx 4.2 \times 10^{19}\ \mathrm{m}^{-3}\right)$ was heated by 1.1 MW NBI power. In H-mode, additional 1.5 MW ECRH and 2.6 MW NBI power were used, obtaining $\langle n_e \rangle \approx 6.0 \times 10^{19}$ m^{-3} with an edge safety factor is $q_{95} = 5.3$.

Radial Profiles of the Perpendicular Velocity Fig. 1 shows radial profiles of the perpendicular velocity of density fluctuations $u_\perp$ in L- and H-modes for TJ-II (a-b) and ASDEX Upgrade

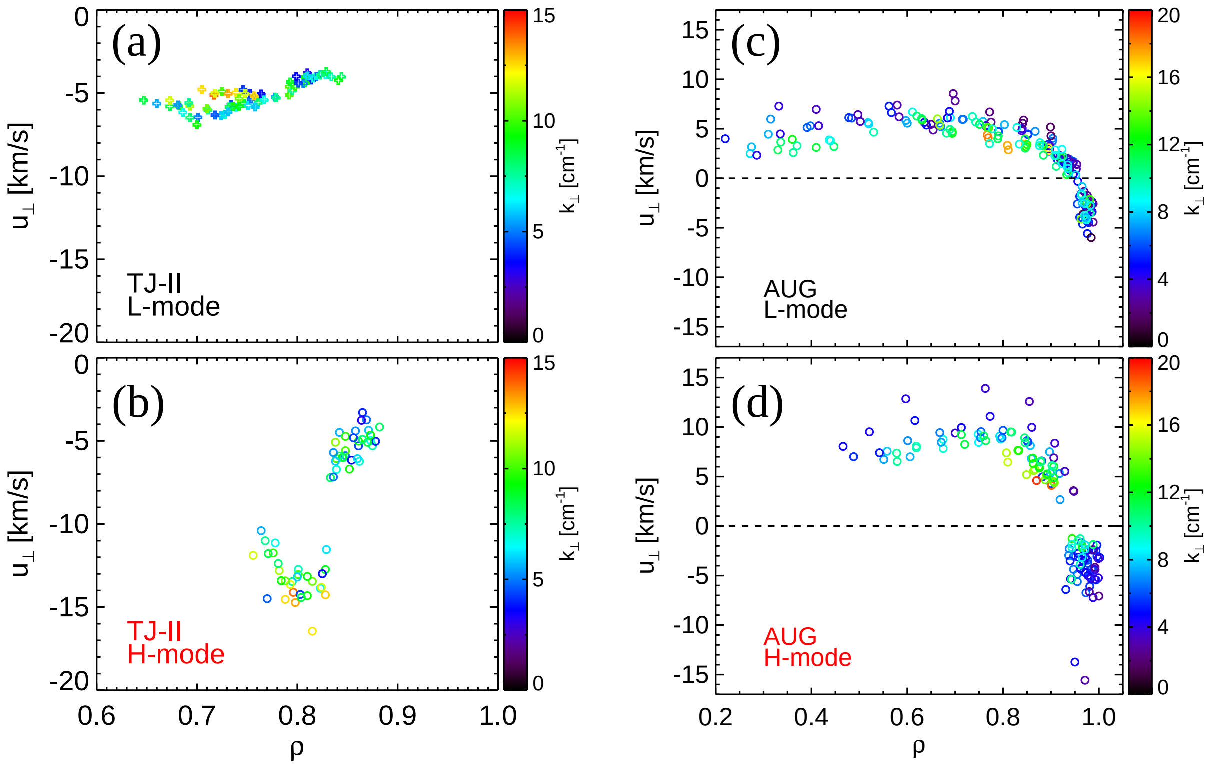

Figure 1: Perpendicular velocity profiles for TJ-II L-mode (a) and H-mode (b) and for ASDEX Upgrade L-mode (c) and H-mode (d) plasmas. For details refer to the text.

(c-d). $\rho = r/a$ is the normalized poloidal flux radius. Since Doppler reflectometry is a scale-selective diagnostic, the perpendicular wavenumber $k_\perp$ can be scanned. The respective values of $k_\perp$ are color-coded in the velocity plots (see colorbar).

The $u_\perp$-profile in L-mode plasmas in TJ-II (a) is almost flat with values of about -5 km/s. When going into H-mode (b), the profile changes substantially, and a strong radial velocity shear layer is formed at $\rho \approx 0.83$. Velocities inside this shear layer (towards the plasma core) take on values of up to -15 km/s, while in the edge plasma, the values almost show no changes compared to the L-mode plasma. In ASDEX Upgrade (c-d) $u_\perp$ is negative in the edge and positive towards the core. A strong velocity shear exists in L- and H-modes, while generally in H-mode the absolute velocity values are higher, resulting in a stronger shear as well.

In both experiments no $u_\perp$-dependence on $k_\perp$ is observed, in all plots of fig. 1 red points are found amongst dark ones. It can be concluded that either the phase velocity of turbulence is small compared to the $E \times B$-velocity, $v_{\text{ph}} \ll v_{E\times B}$, or that v_{ph} does not depend on $k_\perp$, i.e. $v_{\text{ph}} \neq v_{\text{ph}}(k_\perp)$. For TJ-II, $v_{\text{ph}} \ll v_{E\times B}$ has been shown by comparison with Heavy Ion Beam Probe measurements for ECRH and NBI L-mode plasmas [5].

Perpendicular Wavenumber Spectra Fig. 2(a-b) shows wavenumber spectra for L- (black) and H-modes (red) in TJ-II. Two different radial regions are shown, $\rho = 0.73 - 0.78$ (a) and

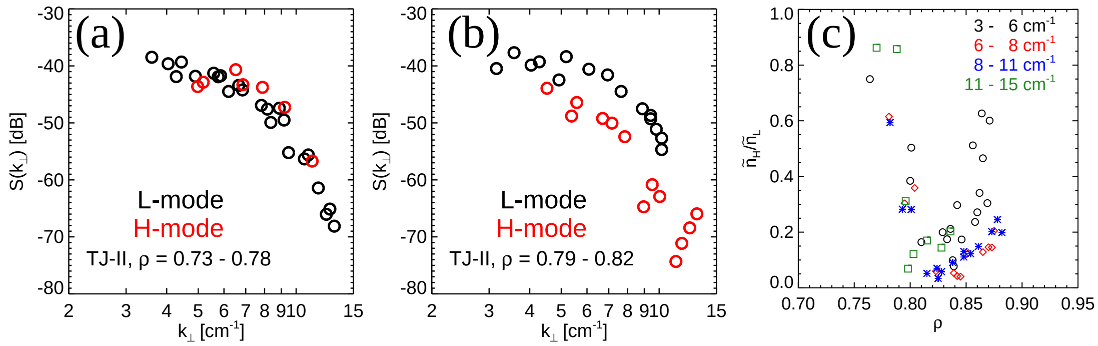

Figure 2: (a-b) Density Wavenumber spectra in TJ-II at two different radial regions for L- (black) and H-modes (red). (c) Radial profile of fluctuation level in H-mode normalized to L-mode for different scales. For details refer to the text.

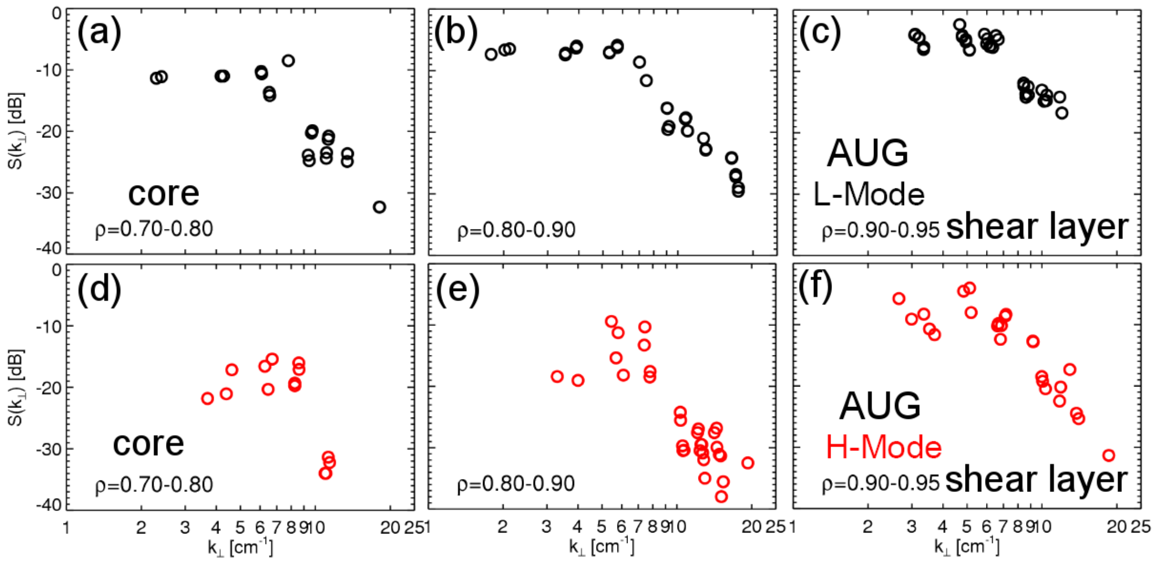

Figure 3: Density wavenumber spectra in ASDEX Upgrade. (a-c) L-mode and (d-f) H-mode plasmas in different radial regions indicated in the respective plots.

$\rho = 0.79 - 0.82$ (b), corresponding to the respective parts of the velocity profiles in fig. 1(a-b). In particular, the spectrum from fig. 2(b) is measured in the $u_\perp$-shear vicinity in H-mode. For the inner positions, no change between L- and H-modes is observed, while close to the $u_\perp$-shear, the density fluctuation level is reduced on all scales, which points to a decorrelation of the turbulence due to strong velocity shear. Apart from that, a *knee* – defined by an abrupt change of the spectrum slope [6] – is observed in the spectrum at inner radii, while the spectra close to the velocity shear do not show any clear knee.

In fig. 2(c) the radial fluctuation level profile in H-mode normalized to the L-mode values is depicted. Close to the maximum $u_\perp$ gradient (cf fig. 1(b)) the fluctuation reduction is maximum. Towards the edge and core, the fluctuation reduction is less pronounced. Furthermore, the reduction of intermediate-scale turbulence (6 – 11 cm^{-1}) is strongest, even in the edge plasma. No interpretation for this effect has been found yet.

Perpendicular wavenumber spectra of density turbulence in the ASDEX Upgrade tokamak are plotted in fig. 3. The L-mode spectra for different radial regions (a-c) reveal a knee at about $k_\perp = 6$ cm^{-1}, which corresponds to structure sizes of about 1 cm. Furthermore, the density fluctuation level is decreasing with decreasing plasma radius (from (a) to (c)).The H-mode plasmas (d-f) show a more pronounced radial decrease of fluctuation amplitude.

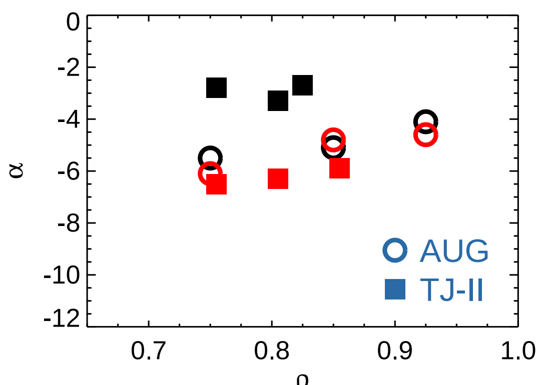

Figure 4: Spectral indices in TJ-II (squares) and ASDEX Upgrade (circles) in L- (black) and H-mode (red).

Fig. 4 shows the radial evolution of the spectral index α for small-scale turbulence in L- ($k_\perp \rho_s = 0.7-1.6$, black) and H-modes ($k_\perp \rho_s = 1.0-4.0$, red) of TJ-II (squares) and ASDEX Upgrade (circles). In TJ-II in H-mode, $\alpha \approx -6$, about twice as large as in L-mode where $\alpha \approx -3$. For ASDEX Upgrade, the values in H-mode are comparable to the TJ-II values. However, no change between L- and H-modes can be observed. Since the radial variation of α is small in all cases, no radial change in turbulence characteristics can be concluded.

Summary

Perpendicular velocity profiles and wavenumber spectra have been compared between the TJ-II stellarator and the ASDEX Upgrade tokamak. From L- to H-mode, the changes in perpendicular velocity profiles are more pronounced in TJ-II. No observable dependence of the perpendicular velocity on wavenumbers has been detected on either experiment. This means that either the phase velocity of turbulence is small compared to the $E \times B$-velocity or that the phase velocity of turbulence is independent of the turbulence scale. In H-mode, both experiments exhibit a strong perpendicular velocity shear close to the plasma edge, in the respective maximum pressure gradient region.

Wavenumber spectra show a reduction of fluctuation level on all scales from L- to H-mode. In TJ-II, the turbulence reduction in the perpendicular velocity shear region is strongest. Furthermore, intermediate scales are reduced most effectively in TJ-II. The spectral indices for small-scale turbulence are comparable in both experiments in H-modes.

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