Overview on high frequency quasi-coherent modes at Wendelstein-7X

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Motivation

Wendelstein 7-X (W7-X) is the world's largest stellarator and optimized to minimize neo-classical transport. Turbulent transport governs heat- and particle-transport, driven mainly by the gradients in the electron-, ion- and density profiles. The ratio of the gradients, defined by $\eta_e = L_n/L_{T_e}$ and $\eta_i = L_n/L_{T_i}$, where L denotes the gradient scale length, is found to be of particular importance in determining which type of turbulence dominates. Certain constraints on η_e and η_i determine which kind of turbulence dominates. The two most important types are the ∇T_i driven turbulence (ITG) and the trapped electron mode (TEM) driven turbulence. The latter is excited within magnetic wells along a magnetic field line and becomes stabilized with increasing collisionality. TEM activity splits into electron-temperature-gradient-driven TEMs (∇T_e-TEMs) and density-gradient-driven TEMs (∇n_e-TEMs).

From the observation of turbulence diagnostic mode structure and phase velocity can be determined which give information on the wave number and the $k_\perp \rho_s$ which allow separating ITG and TEM turbulence. The latter is observed for $k_\perp \rho_s \geq 0.7$ and the ITG driven turbulence for $k_\perp \rho_s \leq 0.5$. Together with the profile analysis it is possible to determine the type of turbulence. This paper classifies high-frequency quasi-coherent modes (QCMs) observed at W7-X for different plasma parameters

Diagnostic

Electron temperature and density profiles are measured by Thomson scattering [1]; ion temperature (T_i) profiles by XICS [2]. For the identification of the mode structures the poloidal correlation reflectometer (PCR) [3] and the phase contrast imaging diagnostic (PCI) [4] are used, which also yield the poloidal rotation of the plasma and the determination of a possible phase velocity of the modes with respect to the $E \times B$-velocity. The PCR probes 6 different poloidal distances suppressing with the correlation condition between antenna pairs the uncorrelated background turbulence.

Experimental observations in standard configuration

During power scan experiments (5 MW to 1 MW) at a medium line integrated density of $n_e \approx 6 \times 10^{19}\,\mathrm{m}^{-3}$ and low collisionality, strong coherent structures appear in the PCR within $0.4 \leq \rho \leq 0.7$ ($\rho = r_{eff}/a$). A reflectometer scan across the gradient region reveals a broad coherent structure (fig.1) with a centre frequency of 230 kHz and a width of $\Delta f = 130$ kHz. The centre

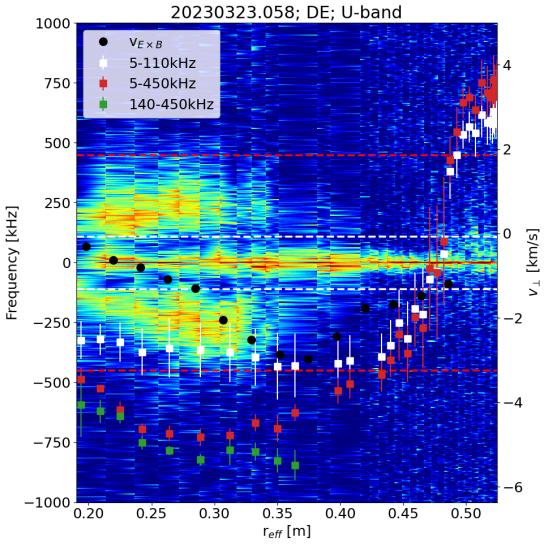

Figure 1: *Coherence spectrogram for* $s \approx 17$ mm*, with quasi coherent modes for* $r_{eff} \leq 0.35$ m*. Rotation for different filter intervals and the neoclassical* $E \times B$ *-rotation are overlaid*

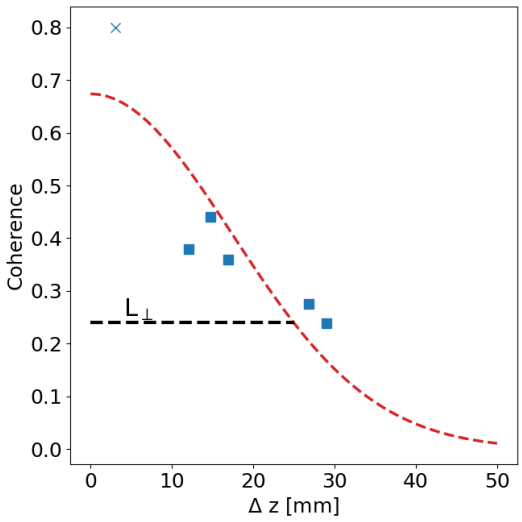

Figure 2: *Estimated* $L_\perp$ *for QCM. Only those combinations can be considered, where both, QCM and LF-turbulence are visible. Contributions of broad band turbulence showing up at short time scales are neglected.*

frequency increases with P_{ECRH} and ∇T_e, respectively [5]. Due to the large half width of the structure they are called quasi coherent modes (QCMs). For the different frequency components (i) 5 kHz to 110 kHz corresponding to the low frequency turbulence (LF) and (ii) 140 kHz to 450 kHz the QCM range, a cross-correlation analysis yields the time delay of the propagation. Applying the elliptical model yields the poloidal velocity ($v_\perp$) which is estimated to 3.5 km s^{-1} and 5.5 km s^{-1} for the different frequency intervals and for $r_{eff} \leq 0.35$ m. The agreement between the LF turbulence and the neoclassical rotation outside the QCM region, confirms a sufficiently low phase velocity of the LF-turbulence to serve as a proxy for the $E \times B$-rotation. For the interval with QCMs, the increased $v_\perp$ compared to $E \times B$-rotation indicates a propagation in electron diamagnetic drift direction, as expected for TEMs.

From the analysis of the coherence spectra for different distances the poloidal correlation length ($L_\perp$) is estimated (see fig. 2) to $L_\perp = 25(2)$ mm. With $\rho_s = 4$ mm to 5 mm, $L_\perp$ is in the range of $3 - 10\rho_s$, expected for ∇T_e-TEMs. Knowing the circumference of the flux tubes covering the radii with QCMs, the calculated poloidal mode number is estimated to range from

$80 \leq m \leq 120$, in agreement with ∇T_e-TEMs. Also, the mean calculated $k_\perp \rho_s$-value of 1.35 fulfils the condition for ∇T_e-TEMs. From the profile data a check of η_e and η_i for the radii with QCM-activity yields $8 \leq \eta_e \leq 10$ reflecting the impact of ∇T_e and confirms ∇T_e-TEMs (fig.3). In contradiction η_i shows almost no variation and $\overline{\eta_i} \approx 3.5$ is not sufficient for stabilizing ITG turbulence in low collisionality plasmas. Beside the QCM modes in the plasma core high frequency QCM modes are found in plasmas with steep density gradients [6]. These modes are observed in (i) NBI-fuelled or (ii) pellet fuelled plasmas. These QCMs are more located in the plasma edge at $0.67 \leq r_{eff}/a \leq 0.77$ and observed in PCR as well as in phase contrast imaging (PCI). In fig. 5 the grey rectangle show the QCM activity within a full scan of the PCR ranging from the edge to the core and back. The frequency of the mode is higher compared to QCMs driven by ∇T_e (see fig. 1) ranging from 700 kHz to 1100 kHz and increases with ∇n_e and ∇T_e (see fig. 6). At constant P_{ECRH} from 3 s to 8 s the density peaking is slowly increasing. With ramping up P_{ECRH} the peaking becomes significant as well as the increase of the QCM frequency. From the spectrogram the LF-turbulence and the QC-modes are well separated, and a cross-correlation analysis can be performed for the different frequency intervals. Compared to the LF-turbulence ($v_\perp = -5\,\mathrm{km\,s^{-1}}$) the QCM rotate at a higher velocity ($v_\perp = -7.5\,\mathrm{km\,s^{-1}}$) as expected for TEMs in general. An estimate of the $L_\perp$ yields $22\,\mathrm{mm} \leq L_\perp \leq 27\,\mathrm{mm}$, similar to the $L_\perp$ for QCMs from ∇T_e-TEMs. With $\overline{\rho_s} = 3.4\,\mathrm{mm}$ $k_\perp \rho_s$ is in the range of 0.8 to 1.0 and within the range for ∇n_e-TEMs. In addition, QCM activity goes along with an increase of the diamagnetic energy (W_{dia}) of the plasma, and the so-called T_i clamping is surpassed [7]. Analysing η_e- and η_i-profiles for the region with mode activity yields $\overline{\eta_e} = 1.4$, slightly above $\eta_e \lesssim 1.0$ ex-

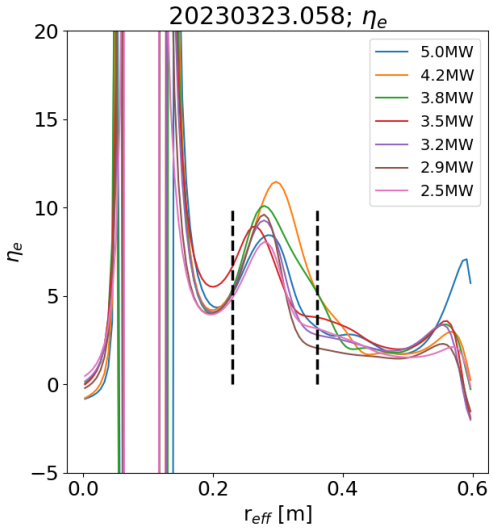

Figure 3: *η_e for different power levels showing the influence of ∇T_e. The dashed black lines mark the range with QCM activity.*

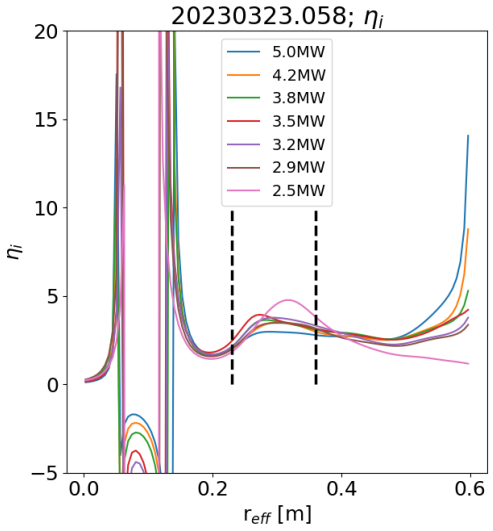

Figure 4: *η_i for different power levels: no change in L_n/L_{T_i}. η_i is too large in the QCM region to stabilize ITG turbulence.*

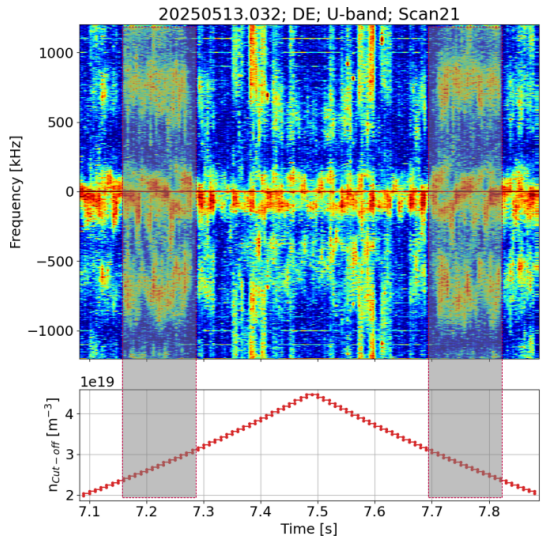

Figure 5: *Coherence spectrogram for* $s \approx 17\,\mathrm{mm}$*, with QCMs in the greyish rectangles.*

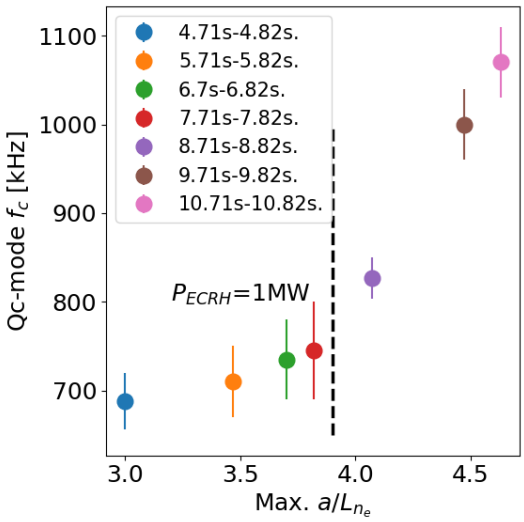

Figure 6: *Scaling of* f_{QCM} *with* a/L_{n_e} *showing a strong increase with* P_{ECRH}*.*

pected for purely ∇n_e driven TEMs in the plasma edge and suggest that both gradients ∇T_e and ∇ne contribute. For these conditions ITG-turbulence is stabilized for $\eta_i \leq 2/3$ and $\overline{\eta_i} = 1.2$ is 3 times smaller than the value for the ∇T_e-TEMs (see above), suggesting partly stabilized ITG-turbulence, in agreement with the increased W_{dia} and the observed reduced turbulence level [8]. Experiments with an $5/5$-island inside the last closed flux surface, show similar QCMs with increased W_{dia}, suggesting a relation between the appearance of ∇n_e-TEMs and the suppression of ITG-turbulence.

Conclusions

Density fluctuations in W7-X are monitored with PCR and PCI. Two distinct classes of quasi-coherent modes driven by trapped particles are identified. In purely heated ECRH-plasmas, ∇T_e **TEMs** are located at mid-radius and the η_e increase with ∇T_e. T_i-profiles stay below the clamping limit and η_i suggest no reduction of ITG-turbulence. In contrast to ∇T_e-TEMs, the ∇n_e**-TEMs** are observed when the density profile shape is varied due to NBI-fuelling or pellets. Saturation of η_e-values at low levels and $\eta_i = 1.2$ suggest partly stabilized ITG turbulence, being a possible reason for the increased W_{dia} and a reduction in the turbulence level.

References

[1] E.Pasch et al., Rev. Sci. Instrum. **87** (2016) 11E729
[2] A.Langenberg, Rev. Sci. Instrum. **89** (2018) 10G101
[3] A.Krämer-Flecken et al., Nucl. Fusion 57 (2017) 066023
[4] E.M.Edlund et al., Rev. Sci. Instrum. **89** (2018) 10E105
[5] A.Krämer-Flecken et al., Plasma Phys. Control. Fusion **67** (2025) 025014
[6] A.Krämer-Flecken et al., 25th Int. Stellarator–Heliotron Workshop, Cordoba (2026)
[7] M.N.A.Beurskens et al., Nucl. Fusion **61** (2021) 116072
[8] S.A.Bozhenkov et al., 2026 Plasma Phys. Control. Fusion **68** (2026) 055015