Turbulence in L-H transitions on MAST

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For a tokamak shot to transition into H-mode, the net power must cross a threshold $P_{net} \geq P_{LH}$. The power threshold P_{LH} has many complex parameter dependencies, which are mostly not well captured by empirical scaling laws. The predicted P_{LH} is usually much lower than the observed P_{LH} for low densities [1], and in general for spherical tokamaks in all conditions [2]. The net power vs density parameter space for double null shots with $I_p \approx 750$ kA on MAST has been mapped in a dedicated L-H transition experiment. All the shots were heated with NBI, and the net power is taken as $P_{net} = P_{nbi} + P_{ohm} - P_{rad} - dW/dt$. The radiated power P_{rad} is returned by the bolometry diagnostic, the stored energy W is given by the equilibrium code EFIT, and the captured NBI power and the ohmic power are determined by running the transport code TRANSP. The shots in the experiments and time periods within the shots have been categorised as clear H-modes, dithery H-modes, L-modes with intermittent periods of regular oscillations of a few kHz (possibly i-phases [3]), and clear L-modes. Examples for the four categories are shown in Fig. 1. Since the heating power could not be scanned during a shot at MAST, the (n_e, P_{net}) combination for L-H transitions correspond to H-mode accessible values, not necessarily the actual P_{LH}, and the $P_{LH}(n_e)$ curve should be determined

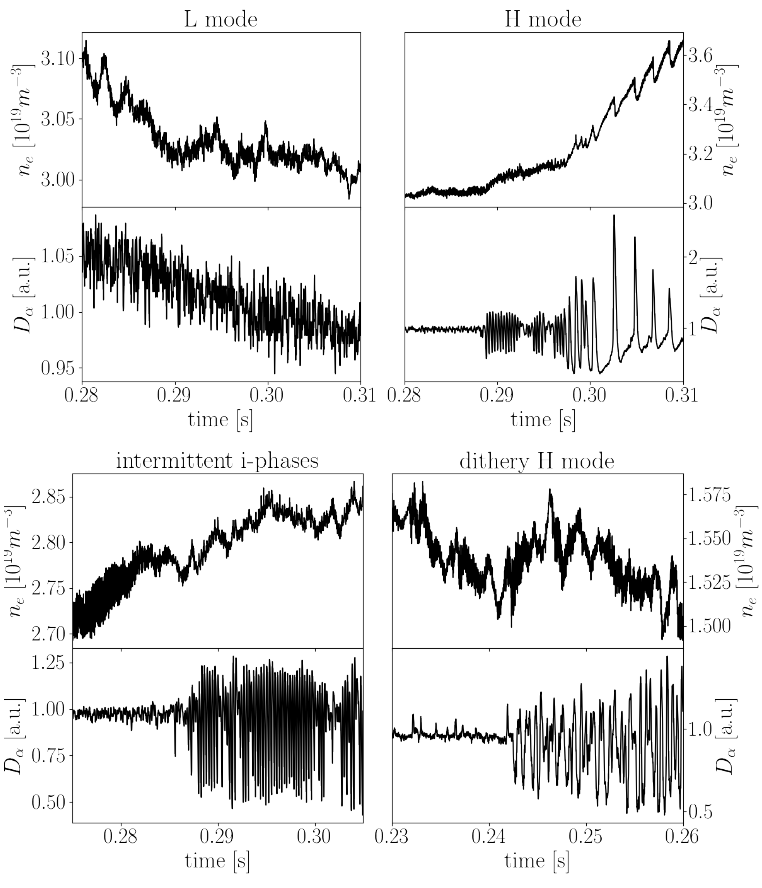

Figure 1: *Line averaged n_e and upper tangential D_α traces of examples of the four categories used in the power threshold studies.*

from the boundary between the H-mode-accessible and -inaccessible regions in the plot. The results (shown in Fig. 2) indicate that P_{LH} for conditions explored in the experiment follows the U-shaped density dependence observed in other tokamaks [1, 4, 5], with densities away from minimum P_{LH} region of $2-2.5\times10^{19}$ m^{-3} requiring increasingly higher powers to access H-mode. From the distribution of the two boundary behaviour types, dithery H-modes and intermittent i-phases, the low-density branch appears to show a broader boundary region mostly consisting of dithery H-modes, while the rest of the boundary appears narrower and populated with intermittent i-phases. The predicted P_{LH} from the empirical scaling law by Martin and Takizuka [2] was evaluated, but not included in Fig. 2 as it remained below 0.5 MW for the entire density range.

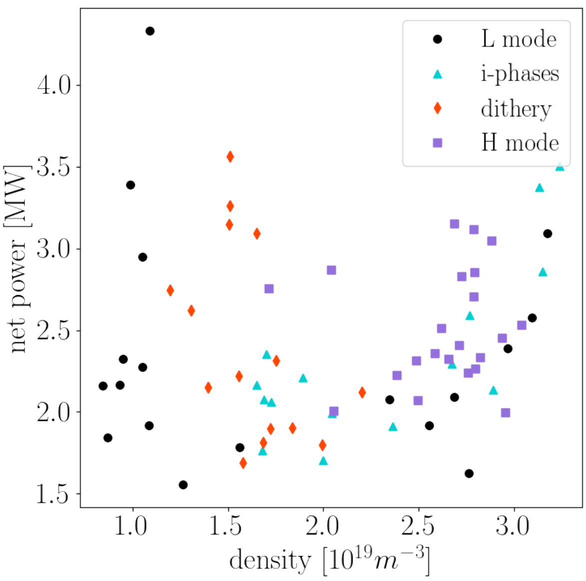

Figure 2: *Net power vs density plot, with a noticeable separation of the four categories and qualitative difference between the low density and high density branches.*

The L-H transition is characterised by the formation of an edge transport barrier and the suppression of turbulence. Though the exact mechanisms of the confinement transition are not yet fully established, research into the microscopic physics of the L-H transition trigger has demonstrated the significance of the depletion of turbulence power through nonlinear kinetic energy transfer to zonal flows experimentally, e.g. using gas puff imaging on C-Mod [6]. Results from several studies show that the nonlinear kinetic energy transfer from drift wave turbulence to shear flow (zonal flow) is consistent with the observed turbulence power loss during a confinement transition [6, 7]. Zonal flows are turbulence-driven while acting to deplete turbulence power, such that a certain amount of energy transfer can trigger a collapse of the turbulence and therefore a transition into H-mode. Understanding the parametric dependence of the L-H threshold requires study of the turbulence and flows before, during, and after a transition, as well as the contrasting behaviour of cases that did not transition. The power threshold studies of the first part are being complemented by analysis of edge turbulence using the beam emission spectroscopy (BES) diagnostic.

The BES system on MAST was an optical turbulence diagnostic using the south neutral heating beam to extract a 2D spatially localised image of density fluctuations [8]. The line of sight is oriented such that it points along the magnetic field where it intersects the beam, as the fluctuations are elongated in the direction of the field and spatial localisation of the measurement is thus optimised [9]. The viewing location of the 4×8 detector array was moved on a shot-by-shot basis to allow studies of core, edge or scrape-off-layer (SOL) plasma. The diagnostic had a high sampling frequency of 2 MHz, with a spatial resolution limited to 2 cm by the pixel size [9].

Since the BES was oriented to image core turbulence for the shots in the threshold power experiment, a sample of other MAST shots was selected for the edge turbulence studies. Calculations of the energy transfer between different spectral components requires estimation of poloidal and radial velocity fluctuations, so a velocimetry method based on cross-correlation time delay estimation (CCTDE) was developed. As an example for a typical result during the L-H transition, Fig. 3 shows the calculated poloidal projection of velocities in the edge and the SOL for a 650 kA lower single null shot.

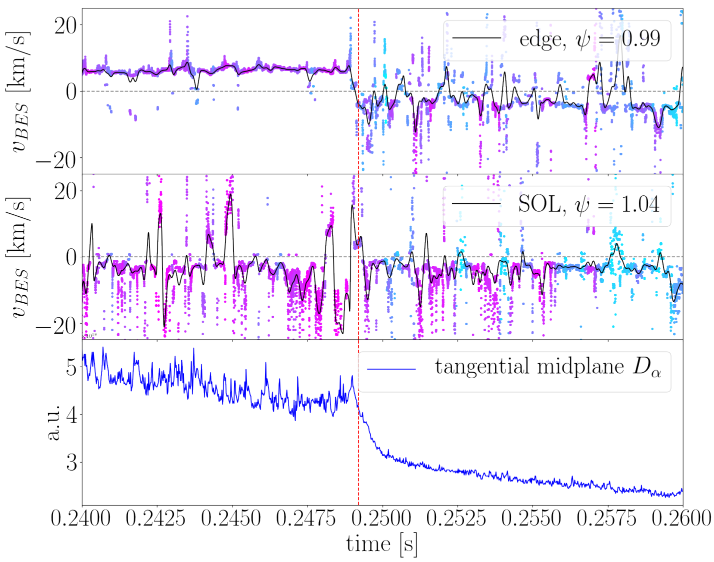

Figure 3: *Poloidal velocities of two selected channels (in the edge and SOL) during the transition. The black line is smoothed over the correlation window, while the colours of the individual points correspond to the average correlation, with cyan being low and magenta being high.*

For every transition where velocities could be extracted from BES, the L-mode leading up to the transition (before 248 ms in Fig. 3) showed a steady poloidal velocity of around $5-10$ km/s in the edge, while the SOL was more noisy with intermittent fluctuations, but showing a general trend of a velocity of a few km/s in the opposite direction to the edge, consistent with the velocity shear expected at the separatrix. The edge velocity reverses as the shot transitions into H-mode, though the timing of this reversal is not always consistent, with some occurring a few ms before the transition markers in D_α and n_e while others occur at the same time. H-mode velocities are more difficult to capture, as the reduced levels of turbulence result in fewer tracers.

To aid understanding of the physics of the transition and to verify models [7] and experimental results from other machines [6], determining the nonlinear energy transfer from turbulence to low-frequency shear flow and its evolution during the transition is of interest. The energy transfer between spectral components f and f_1 can be evaluated from the cross-bispectrum [6]

$$T_v(f,f_1) = -\mathrm{Re}\left(\langle \widetilde{v}_\theta^* \widetilde{v}_r(f-f_1)\partial_r \widetilde{v}_\theta(f_1)\rangle\right)$$

where $\widetilde{v}$ is the Fourier transform of the velocity, and the angled brackets represent an average over a large number of realisations, the necessary number of which can be established with convergence studies. As an intermediate step to generating full bispectra, bicoherence spectra can reveal information about the strength of the phase coupling between spectral components. Fig. 4 shows the auto-bicoherence of fluctuation data during a steady L-mode period, with a phase coupling between a low-frequency f component and a broadband f_1 component. For the next step in this analysis process, the poloidal and radial velocities determined from the CCTDE analysis will be included in the above energy transfer calculations.

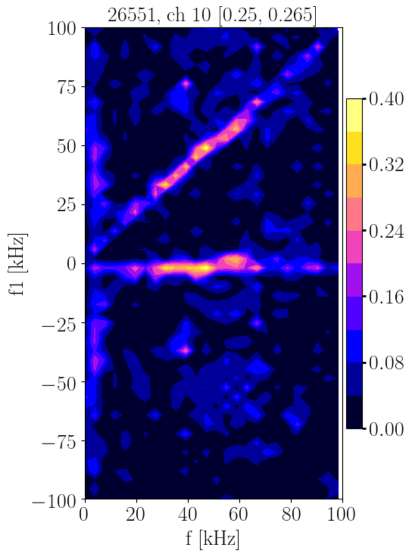

Figure 4: *Auto-bicoherence of an L-mode showing phase coupling.*

Upcoming experiments: The power threshold has been shown to vary significantly when aspects of the divertor configuration are changed [10, 11]. Which divertor geometry parameters are relevant and the exact nature of the underlying physics responsible for this change have not been identified. Experiments to compare the L-H transition for a conventional and Super-X (with elongated outer legs) divertor configuration are scheduled to take place this experimental campaign on MAST-U. The power and density parameter space of the transition will be mapped for both configurations, and the edge turbulence behaviour will be probed using the BES and DBS (Doppler Backscattering) diagnostics.

References

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