Turbulence in Alcator C-Mod and Wendelstein 7-AS plasmas during controlled confinement transitions

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At certain values of the edge rotational transform, $\iota_a = 1/q_a$, the confinement time of plasmas in the Wendelstein 7-AS (W7-AS) stellarator was found to be very sensitive to small modifications of ι_a. Since ι_a could be changed reproducibly by e.g. a small plasma current, these transitions provided a means to perform systematic investigations of differences in turbulence during 'good' ($q_a = 2.91$) and 'bad' ($q_a = 2.76$) confinement phases [1].

The macroscopic changes of confinement in W7-AS were attributed to the presence of internal transport barriers (ITBs) close to low-order rational ι-surfaces in the plasma and the fact that W7-AS had small magnetic shear [2]. Related empirical and theoretical models on thermal electron transport around low-order rational surfaces can be found in e.g. Refs. [3]. Due to larger shear in the Alcator C-Mod tokamak, confinement transitions associated with low-order rational q-values would therefore be expected to be local instead of global, i.e. a localized temperature flattening.

To study the effect of the presence or absence of low-order rational surfaces in C-Mod, we designed discharges where the current was ramped slowly up to lower q_a in a controlled fashion. If an ITB is associated with the $q = 3$ surface, this barrier would be removed from the plasma resulting in a (local) worsening of confinement. Fig. 1 (a) shows flux surfaces of the discharge we analyse in this paper. The L-mode, inner wall limited shot shown had low elongation $\kappa \sim 1.3$, low upper and lower triangularities $\delta_{\mathrm{U}} \sim \delta_{\mathrm{L}} \sim 0.2$ and a toroidal magnetic field $B_\phi = 5.5$ T. It was heated on-axis by 1.2 MW of ion cyclotron radio frequency power. The bottom trace in Fig. 1 (b) shows the reduction of q_a in response to a slow current ramp-up from 1.1 to 1.3 MA. Since global confinement in C-Mod is seen not to be affected by the current ramp, we name the time intervals shown in Fig. 1 (b) 'higher q_a' (HQA) and 'lower q_a' (LQA).

Line integrated fluctuations in the electron density of C-Mod plasmas parallel to the major radius were measured using the recently upgraded phase-contrast imaging (PCI) diagnostic [4]. The 32 vertical chords of the PCI system (see Fig. 1 (a)) enables the calculation of wavenumber-frequency spectra from 2D Fourier transformations. In Fig. 2 (a) we show wavenumber spectra vs time for fluctuations in the [250 kHz, 2 MHz] range. It is observed that the fluctuation amplitude increases as q_a is lowered, and that

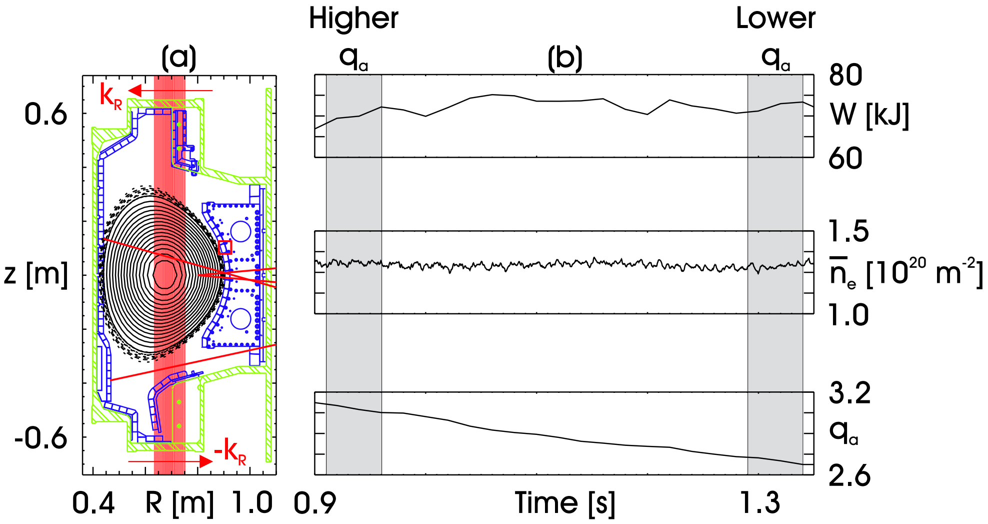

Figure 1: Left: Flux surfaces from EFIT and diagnostic sightlines, right: Traces of main plasma parameters for C-Mod current ramp discharge 1040319018. Top to bottom: Stored energy, line integrated density and q_a. The 50 ms time intervals used for cross correlation analysis are indicated by semi-transparent rectangles.

the characteristic wavenumber decreases. Two features in the turbulence exist, one at lower frequencies ([50 kHz, 250 kHz]), the other at higher values ([250 kHz, 2 MHz]). The low frequency feature does not develop markedly as current is ramped, in contrast to the high frequency feature seen in Fig. 2 (a).

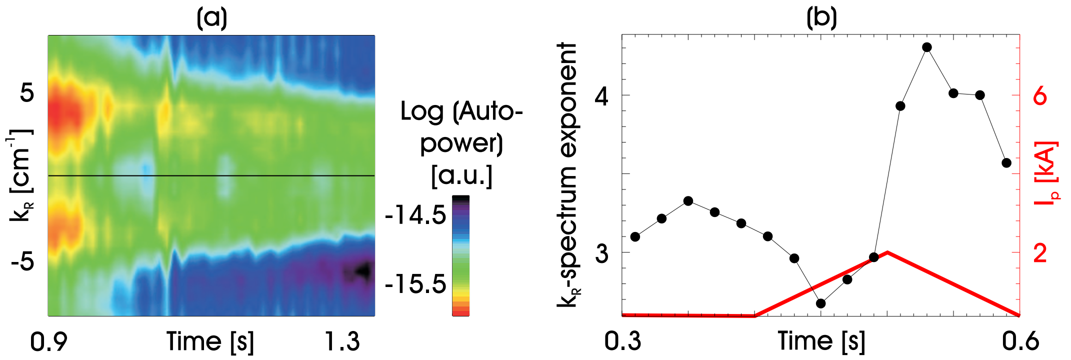

Figure 2: Left: Wavenumber spectra vs time for C-Mod, time resolution 10 ms, right: Exponent of wavenumber spectra vs time in W7-AS for k_R = [25, 61] cm^{-1} (connected black dots) and current (red trace): 0 (2) kA corresponds to good (bad) confinement.

Density fluctuations in W7-AS at wavenumbers ranging from 14 to 62 cm^{-1} were measured using small-angle collective scattering. Fitting wavenumber spectra assuming a power-law dependence showed that the slope of these spectra increased during bad confinement, see Fig. 2 (b). In other words, the relative weight of smaller wavenumbers increases for degraded confinement. Further, the amplitude of turbulence at small wavenumbers (k_R = 15 cm^{-1}) rose. Both trends follow the ones found in C-Mod from

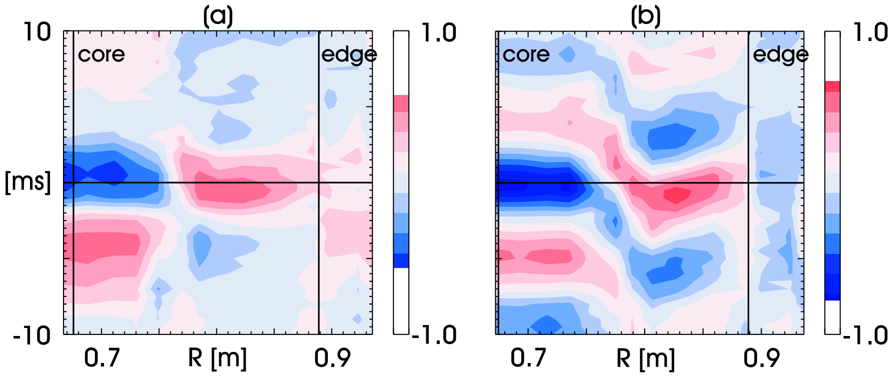

Figure 3: Cross correlation between a core PCI channel (17) and GPC2 vs R for HQA (left) and LQA (right). A positive time lag τ means that PCI fluctuations occur before ECE changes. The time resolution is 0.5 ms.

HQA to LQA: Small wavenumbers dominate and the strength of turbulence increases in bad confinement. Two features separated by frequency in C-Mod were also observed in W7-AS: The high frequency feature rotated in the electron diamagnetic drift (DD) direction inside the separatrix, whereas the low frequency feature rotated in the ion DD direction and was localized in the scrape-off layer.

Differences between the HQA and LQA phases are also observed when we cross correlate power detected in a core PCI channel (17) integrated over the [250 kHz, 2 MHz] interval with electron cyclotron emission (ECE) measurements using the grating polychromator 2 (GPC2) system, see Fig. 3. GPC2 has 14 channels spanning the outer half of the plasma cross section. The correlations for HQA (Fig. 3 (a)) are separated into two regions, one where $R \leq 0.76$ m (IR), the other where 0.76 m $\leq R \leq$ 0.89 m (OR). In the IR, density fluctuations and temperature are anti-correlated at a time lag τ = 0.5 ms and correlated at τ = -4 ms, meaning that the fluctuations detected by PCI occur 4 ms after the changes are observed in the electron temperature. The OR feature is correlated at τ = -0.5 ms. The shot analysed is sawtoothing throughout the discharge, and has a central temperature of 2 keV. The explanation for the (anti-)correlated signals around zero time lag is that as the temperature drops in the core and rises towards the edge at a sawtooth crash, the line integrated fluctuations of the core PCI channel increases. So the R separating the two regions is the sawtooth inversion radius associated with the $q = 1$ surface. The delayed IR feature implies that density fluctuations begin to rise after the electron temperature has risen a while (4 ms). Comparing the correlations to those for LQA (Fig. 3 (b)) several differences are observed: (i) Correlations in the IR have shifted towards negative τ, so the rise in density fluctuations at a sawtooth crash now happens almost instantaneously. (ii) The inversion radius moves slightly outwards because the $q = 1$ surface is closer to the edge due to the current ramp. (iii) A periodic structure becomes clear both in the IR and the OR. The time between two maxima or two minima is 9 ms, corresponding to the sawtooth frequency. (iv) The periodic correlations are connected across the sawtooth inversion radius, indicating a propagating core-edge link between thermal transport and turbulence.

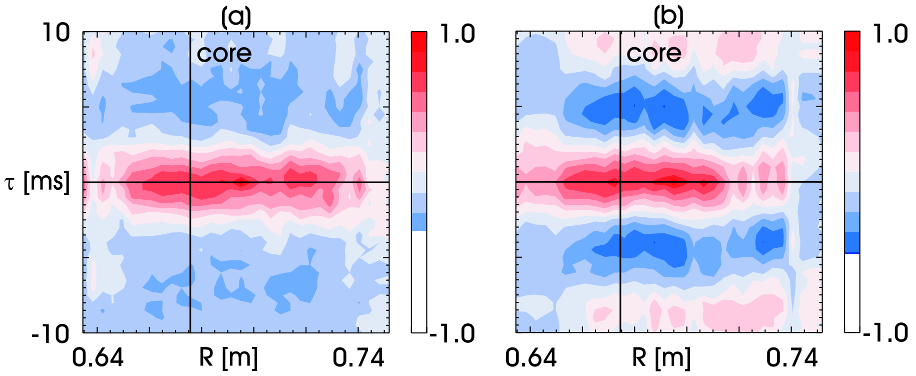

Figure 4: Cross correlation between a reference core PCI channel (17) and 31 PCI channels vs R for HQA (left) and LQA (right). A positive time lag τ means that the reference PCI signal occurs after changes in the other channels. The time resolution is 0.5 ms.

In Fig. 4 we use power detected in a core PCI channel (17) integrated over the [250 kHz, 2 MHz] range as a reference, and correlate this signal with corresponding measurements from 31 PCI channels (1 channel was left out because of a bad detector response). Note that all chords pass through the $q < 1$ region, so they detect a mixture of fluctuations inside and outside the sawtooth inversion radius. The correlations for HQA (Fig. 4 (a)) show that the core measurements are correlated for $\tau = 0$, extending further towards the low-field side. The R-calibration for PCI was not very exact, the uncertainty in R is 1-2 cm. Apart from the strong $\tau = 0$ correlation, there are broad, weak anti-correlations at $\tau = 6/\text{-}7$ ms. The correlations for LQA (Fig. 4 (b)) are different in several respects: (i) The core correlation increases (decreases) towards small (large) R. (ii) The anti-correlations become stronger and move to $\tau = 5/\text{-}4$ ms. (iii) The appearance of a periodic structure is similar to the results shown in Fig. 3 (b) and the distance between the prominent minima, 9 ms, is the approximate sawtooth frequency.

To conclude, there is a global change in confinement at low shear (W7-AS) and a local change in heat transport and turbulence at high shear (C-Mod) as a function of q_a.

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