Interplay between magnetic topology, density fluctuations and confinement in high-β Wendelstein 7-AS plasmas

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1.Introduction

Previous high-β experiments in the Wendelstein 7-AS (W7-AS) stellarator have shown that it was not possible to reach the stability β-limit; the discharges remained either power or radiation limited [1]. A central β (β_0) of 4 % and an average β ($\langle\beta\rangle$) of between 1.7 % and 1.8 % was achieved. To ameliorate this situation, the W7-AS neutral beam system has been reconfigured from balanced to unbalanced injection, totalling 4 MW power [2].
We analyse experiments that were performed at half field (1.25 T) with full beam power to ascertain the effects of the increased β-value. A moderate increase of $\langle\beta\rangle$ up to 2.2 % was obtained in this series, which was later improved to 3.1 % [3]. The main diagnostic used in the present paper is the CO_2 laser based LOcalised TUrbulence Scattering (LOTUS) instrument [4]. This measures electron density fluctuations in two toroidally displaced vertical measurement volumes - here we will only treat a single volume. The wavenumber of the fluctuations measured ($k_\perp$) was set to 20 cm^{-1}.

2.Magnetic topology

The three discharges we study had different net plasma currents I_p as produced by the Ohmic transformer. The effect of a larger current was to increase the edge rotational transform ι_a from 0.41 ($I_\mathrm{p} = 0$ kA) to 0.51 (-4 kA). We show some of the main time traces in figure 1, from top to bottom: Stored energy, line density, plasma current and density fluctuations integrated over negative/positive frequencies, respectively.
Negative/positive frequencies are due to fluctuations travelling inward/outward parallel to the major radius R. The density fluctuations are normalised to line density squared. Shot 51262 (0 kA) is represented by solid lines, 51265 (-2 kA) by dotted lines and 51266 (-4 kA) by dashed lines. The disturbance in the density fluctuations before 100 ms is due to the normalisation, and the discrete steps in the negative frequency turbulence at 150 ms (51265 and 51266) and 170 ms (51262) coincides with a doubling of the injected beam power.
We observe that the global quantities hardly change in response to the plasma current variation, but that significant differences are observed in the negative frequency density fluctuations. These density fluctuations decrease with increasing plasma current, and shot 51265 appears to be marginal in the sense that the fluctuation power decreases throughout the discharge. Surprisingly, this clear development is not mirrored in the positive frequencies as is usually the case [4].
We begin the analysis of flux surfaces by studying finite-β effects, see figure 2. The

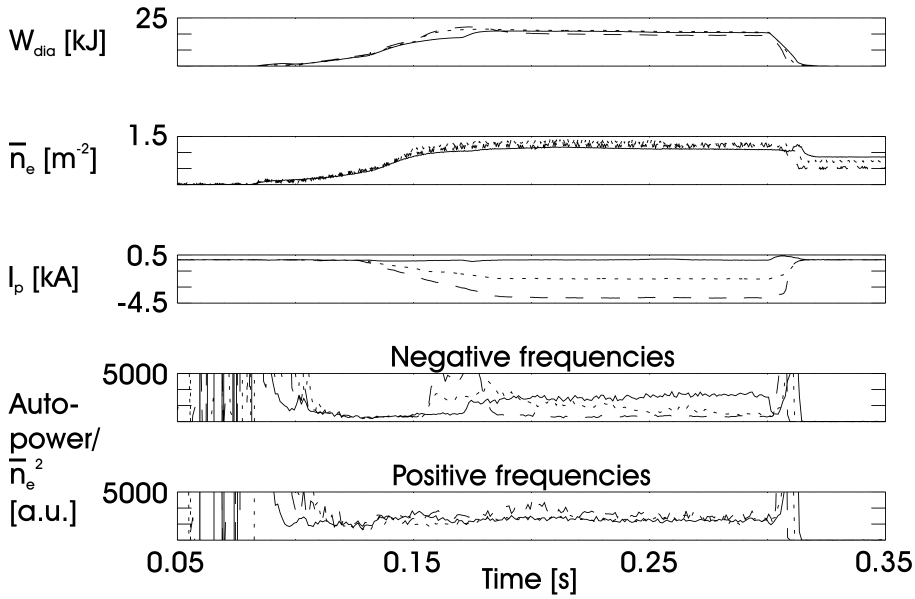

Figure 1: Waveforms of main plasma quantities for the three shots analysed. From top to bottom: Stored energy, line density (in units 10^{20}, central density about 3×10^{20} m^{-3}), plasma current, density fluctuations integrated over negative frequencies and density fluctuations integrated over positive frequencies. The density fluctuations have been normalised by line density squared.

left-hand plot shows the flux surfaces at a toroidal angle of 32 degrees, which is quite close to that of the LOTUS diagnostic (30 degrees). The measurement volume position at $R = 207$ cm is indicated by the vertical line. The structure shown in the bottom is the divertor baffles (two tilted lines) and the divertor target, where the measurement volume passes through. For this $\langle\beta\rangle = 0$ % case, we observe fluctuations slightly on the inboard side of the magnetic axis. The right-hand plot shows flux surfaces for $\langle\beta\rangle = 2.2$ %; we observe that the plasma column is Shafranov shifted about 5 cm outward and increases in size. The density fluctuations observed here originate far inside the axis.

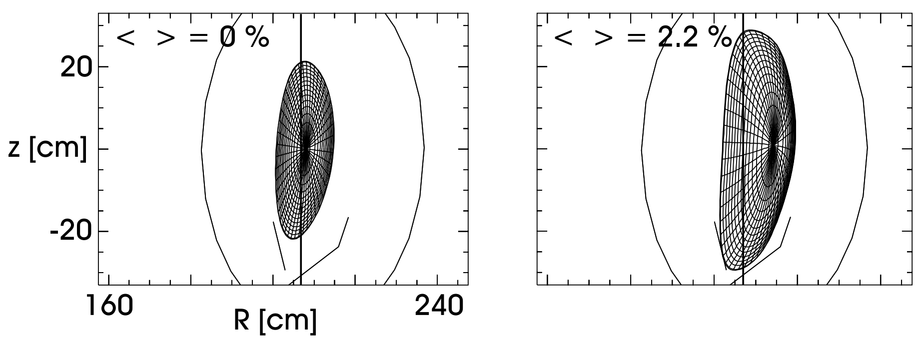

Figure 2: Equilibria calculated using the NEMEC code for a toroidal angle of 32 degrees, shot 51260 (had settings identical to shot 51262). The vertical lines show the measurement volume position.

The varying plasma current introduces differences in the magnetic edge topology. Due to the five-fold toroidal symmetry of W7-AS, natural islands exist for $\iota = 5/m$, where m

is the number of islands in a poloidal cross section. These islands can be visualised using Poincaré plots, see figure 3. The left-hand boxed plot shows flux surfaces for shot 51262 ($I_{\rm p}$ = 0 kA, $\iota_{\rm a}$ = 0.41) and the three plots on the right-hand side show flux surfaces for configurations having m = 10, 11, 12 natural islands. Note that the flux surfaces have a slight tilt with respect to the measurement volume.
The major problem in studying flux surfaces is the following: (i) If one makes finite-β calculations, the islands are not treated (figure 2) and (ii) if one makes Poincaré plots to investigate the islands, they are made for vacuum (figure 3). The actual flux surfaces are a combination of both effects.

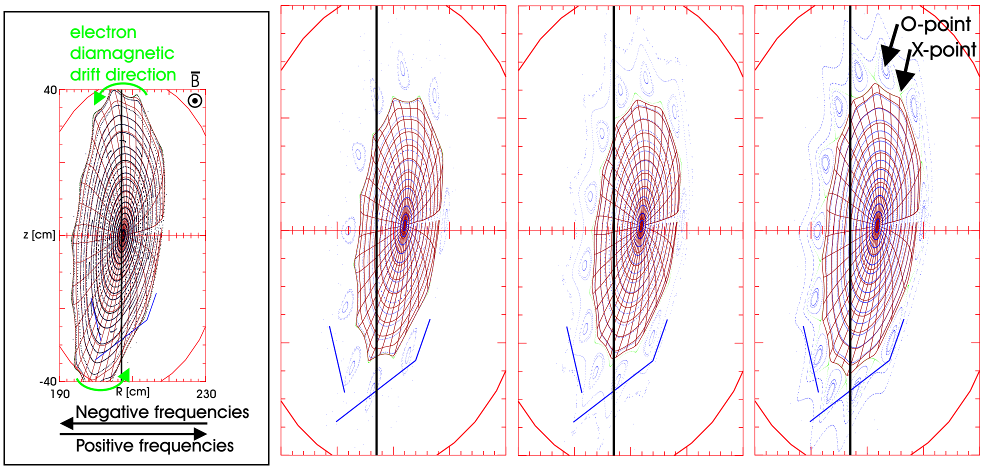

Figure 3: (Colour) Poincaré plots for $\langle\beta\rangle = 0$ %. The vertical lines show the measurement volume position. The green arrows at the top and bottom of the left-hand boxed plot show the electron diamagnetic drift direction. The right-hand sequence of plots shows m = 10, 11 and 12 natural islands.

3.Density fluctuations

To study the spectral characteristics of the density fluctuations in more detail, figure 4 shows autopower spectra versus frequency and time for the discharges. The left-hand plot is shot 51262, center 51265 and right 51266. The central line at 0 ± 100 kHz is our carrier frequency and noise due to mechanical vibrations. We show frequencies up to 2 MHz with a time resolution of 1 ms. Fluctuations having opposite frequency signs are observed to behave disparately: Positive frequency (outward moving) fluctuations decrease at high frequencies with increasing current, while they increase at lower frequencies. The negative (inward moving) high frequency component disappears completely, while the low frequency fluctuations remain at an approximately constant level.
Treating 30 ms time windows, we can calculate 2D cuts of the autopower spectra, see figure 5. The left-hand plot shows initial plasmas; they are identical and the positive frequency fluctuations have the largest amplitude. In the right-hand plot the negative high frequency component dominates for shot 51262, decreases for shot 51265 and is small for shot 51266. The positive fluctuations develop a slightly steeper slope.
It is of interest whether a given spectral shape is due to measurements through an island O- or X-point. Work on this topic has recently been presented in [5], which deals with reflectometry measurements of rotating MHD-modes. For high frequencies (above 200 kHz) it was shown that the fluctuation amplitude inside the O-point is larger than

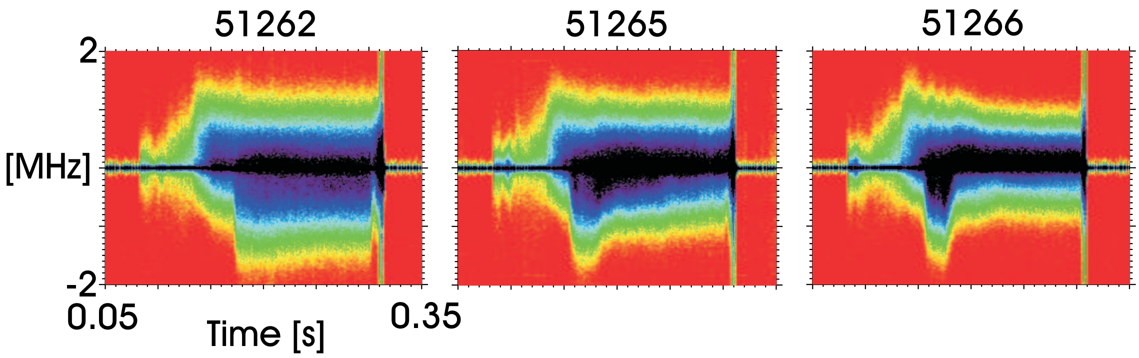

Figure 4: (Colour) Autopower versus frequency and time. Left to right: 51262, 51265 and 51266. The autopower scale is logarithmic and identical for the three shots; the time resolution is 1 ms.

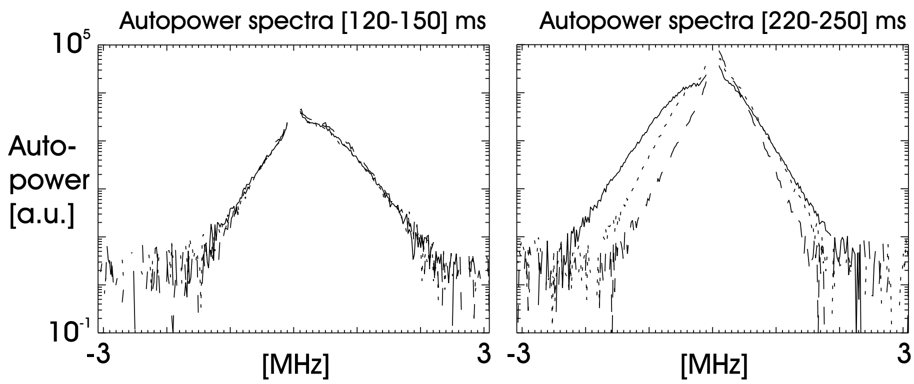

Figure 5: 2D representations of autopower versus frequency averaged over 30 ms, left: [120, 150] ms, right: [220, 250] ms. The linestyles have the same meaning as those in figure 1.

from behind the X-point. Assuming that this observation can be transferred to density fluctuations in natural islands, we conclude the following: Positive frequencies dominate in the initial phase and remain rather constant throughout all discharges, indicating that they are measuring O-point fluctuations. In the late phase, the negative frequencies seem to go through an O- to X-point development, where shot 51265 is the transitional discharge.

Combining this with the usual observation that high frequency fluctuations travel in the electron diamagnetic drift direction, an island O-point is positioned at the bottom of the measurement volume. The top of the volume develops from O- to X-point. The reason for the up-down asymmetry is probably the tilt of the flux surfaces at the toroidal angle where LOTUS is situated.

References

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