Effect of pellet shots on edge plasma density fluctuations in the Wendelstein 7-X stellarator

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Abstract: The pellet fuelling potential was studied at Wendelstein 7-X (W7-X) stellarator in the OP1.2b campaign. Unusual observation was made by the PCI diagnostics[1], showing sudden drop of fluctuation level in the core after pellet fuelling. The decreased fluctuation level was accompanied by improved energy confinement. In this paper the edge behaviour was studied in details in this period. The decreased turbulence level was clearly observed in the edge region with the Alkali Beam Emission Spectroscopy (ABES) diagnostic. The spatio-temporal structure of fluctuations were calculated using correlation functions in various periods of the discharge. Multiple diagnostics were used to complete and confirm the results from the analysis of the ABES diagnostic. The time evolution of fluctuation behaviour was characterized by calculating cross-correlations of ABES signals with Phase Contrast Imaging (PCI), H-alpha, Mirnov coil diagnostics signals.

Introduction: In stellarators the radial heat diffusivity and particle exhaust are regulated by various transport effects. The W7-X is optimized for neoclassical transport, but turbulent transport is also expected to play a significant role. As an example: one of the great surprises of the 2017/18 campaign was that after the pellet injection series (which increases the core plasma density), improved energy confinement was observed.

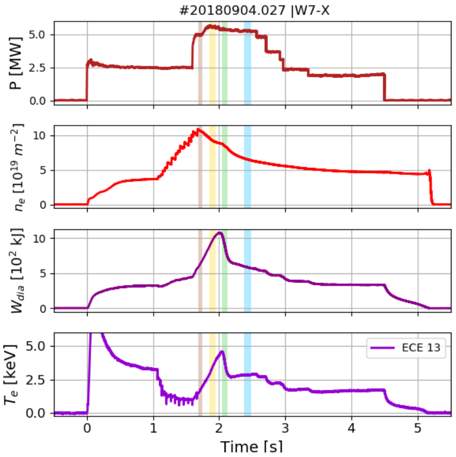

Figure 1 - Overview of main plasma parameters of #20180904.027

The second plot of Figure 1 shows the evolution of the line-integrated density from interferometry diagnostics. During pellet shots, the density gradually increases in multiple steps from 4 to $11\cdot 10^{19}\, m^{-2}$. After the injections, the density is slowly decreasing with a slight flattening at t = 2.1 s.

During this period, and distinctly after the end of the pellet sequence, the plasma stored energy increases sharply from W_{dia} = 0.3 MJ to a peak exceeding 1 MJ, indicating improved plasma confinement which lasts for a few hundred ms. After approximately t = 2 s this improved confinement collapses, and the plasma returns to a steady state. The temperature drops during the pellet injection series; after that it starts to grow. The growth can be explained partly by the change in the heating power. But the core temperature drop after t = 2 s cannot be explained by external effects or drives, as the heating power was constant during this period.

These transient periods were observed in multiple discharges and are extensively studied by both experiments and modelling. The primary candidate for the explanation is that the ITG turbulence is reduced by the steeper density gradient, which is built by the pellet fuelling. According to the modelling, the turbulence suppression occurs in the core. Whether it has any effects on the edge plasma has not been addressed yet in details.

The primary diagnostic for the detection of core turbulent density fluctuations is the phase contrast imaging (PCI) diagnostic at W7-X. The amplitude of the measured signal with PCI is proportional to the absolute, line-integrated density fluctuations along a line of sight, so the localization of the fluctuation is difficult.

1. Alkali Beam Emission Spectroscopy diagnostic (ABES): ABES is capable of the measurement of both the edge plasma density profile, and its fluctuations. The diagnostics has 40 channels with a radial spatial resolution of 5 mm. The observation is from the vertical direction, and the APDCAM-10G detector system collects data with 2 MHz sampling rate. The beam can be deflected by applying advanced beam modulation techniques, so background corrected density profiles can be reconstructed with up to 100 kHz frequency.

2. Temporal evolution of density fluctuation amplitude in the edge: The fluctuation amplitude was calculated in the edge plasma from the ABES signal. It was derived from the photon peak corrected autocovariance function normalized with the average signal. By calculating the fluctuation amplitude in every 10 ms, a time series is constructed, which is shown Figure 2a. This plot can be compared with the signal measured by PCI diagnostics. Figure 2b shows the line-integrated fluctuation measured by PCI. During pellet injection series transient peaks are visible in the fluctuation amplitude. If we look at the ratio of measured fluctuation amplitude to density, the proportionality factor is usually constant through a variety of densities and configurations. After pellet injections the level of fluctuation drops until $t_2 = 1.9$ s where it reaches its lowest value (~50 % drop). After t_2 the fluctuation starts to raise until t_3. Between t_1 and t_3 the previously seen proportionality factor changes. But after t_3 the plasma returns to a steady state and the above described proportionality recovers. Figure 2a. shows the fluctuation amplitude calculated from the ABES signal. Suppression after the series of pellet injection, can be seen from 4% to 2% in the inner channels. After t_2 the fluctuation raises from 2% to 12% on a ~100 ms wide time interval. The overall behaviour of the PCI signal is similar to the temporal evolution of the fluctuation calculated from ABES.

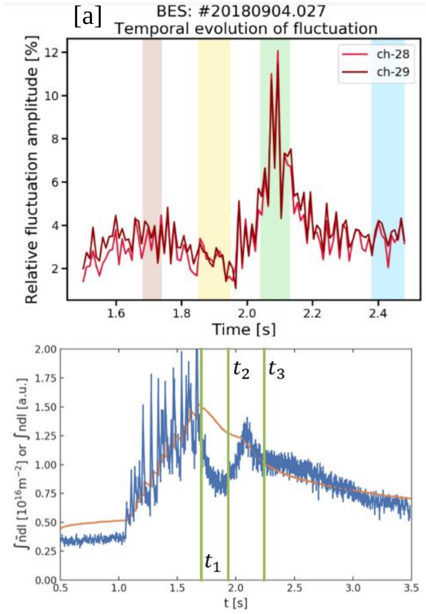

Figure 2 Temporal evolution of fluctuation amplitude from [a] ABES and [b] PCI

In the selected shots 4 characteristic time intervals were selected for further analysis of the fluctuation evolution: the first interval comes right after pellet shots, the second interval belongs to a 100 ms interval when the level of the fluctuation amplitude is the lowest, the third is when the level is the highest, the fourth interval is from the stage when the plasma has reached a steady state. This last interval is used as baseline in the comparison.

3. Density: The light intensity values measured on the ABES channels are a non-local function of the plasma density. The density therefore can be reconstructed from the radial light profile. On Figure 3 the temporal evolution of the reconstructed density is plotted with the density on channel 22 highlighted. The line-integrated density continuously drops after pellet injection from 11 to $6 \cdot 10^{19}\, m^{-2}$. At channel 22 (radial position: R = 6.19 m) the density drops from 3.4 to 2.9 $\cdot 10^{19}\, m^{-3}$ when the energy confinement improves (~ 15 % drop). The density raises during fluctuation peak from 2.9 to $5 \cdot 10^{19}\, m^{-3}$ (~ 170 % raise).

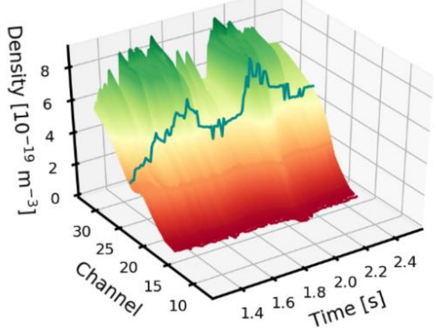

Figure 3 - Temporal evolution of the edge plasma density profile (ABES)

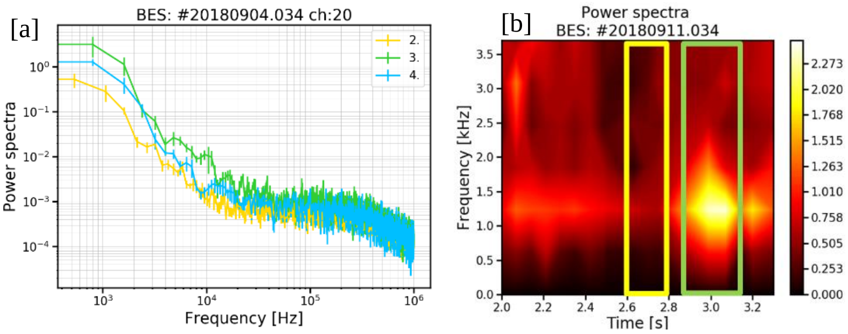

Figure 4 - Power spectra of a „slow chopping" mode shot [a] and a „fast chopping mode" shot [b] on the selected intervals

4. Analysis of edge turbulence from ABES: The power spectra of the chosen intervals were calculated. When the ABES diagnostic was operated in "slow chopping" beam modulation mode, the spectra can be calculated up to 1 MHz, however in "fast chopping" mode the spectra could only calculated up to 30-100 kHz depending on the settings. Compared to the power spectra of the steady state, the suppression of low frequencies up to 10 kHz was observed on the second interval as it can be seen on Figure 4a and Figure 4b. When the fluctuation amplitude peaked (3. interval) the power of low frequencies (~ kHz) increases tenfold compared to the second phase. On higher frequencies, no changes can be observed. The spectrogram of the PCI [1] shows visible changes in the power of high frequencies (f > 50 kHz), which indicates that these high-freqency fluctuations are originated from the core.

5. Spatio-temporal structure of fluctuations: 2D correlation maps are calculated and analysed to reveal spatio-temporal structure of the fluctuations. In this analysis the second period, measured in the turbulence suppression phase and third period measured in the fluctuation peak are compared. In these calculations all ABES channels are correlated with a reference channel and plotted in 2D map. The reference channel can be one ABES channel or signal from another diagnostic. Since the correlation functions were calculated from the measured light of all channels, due to beam attenuation, anti-correlation can be seen on the channels after the maximum of light profile on these 2D correlation maps. Figure 5 shows the cross-correlation between all ABES channels and a reference of ABES channel (Ch-20). Weaker correlation with a 2 ms wide structure can be seen on the 2. interval. On the 3. interval rapidly decaying wavelike structure is visible. During this period stronger correlation appears, with the increase in radial correlation length. Slight

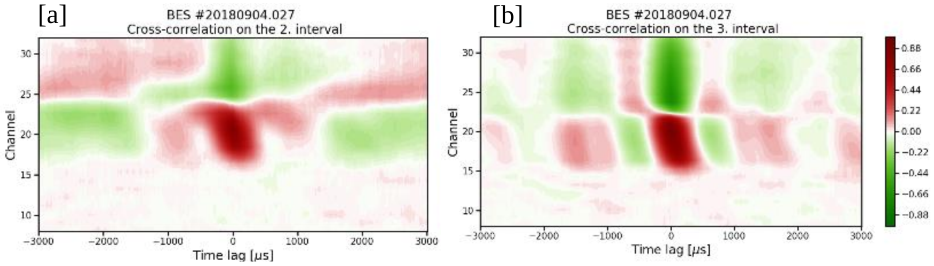

Figure 5 – 2D cross-correlation map on ABES during fluctuation suppression (2. interval) [a] and during fluctuation peak (3. interval) [b]

skew can be observed in the position of the correlation peak which can be connected to the outward propagation of the fluctuation (~100 m/s between ch:16 -19).

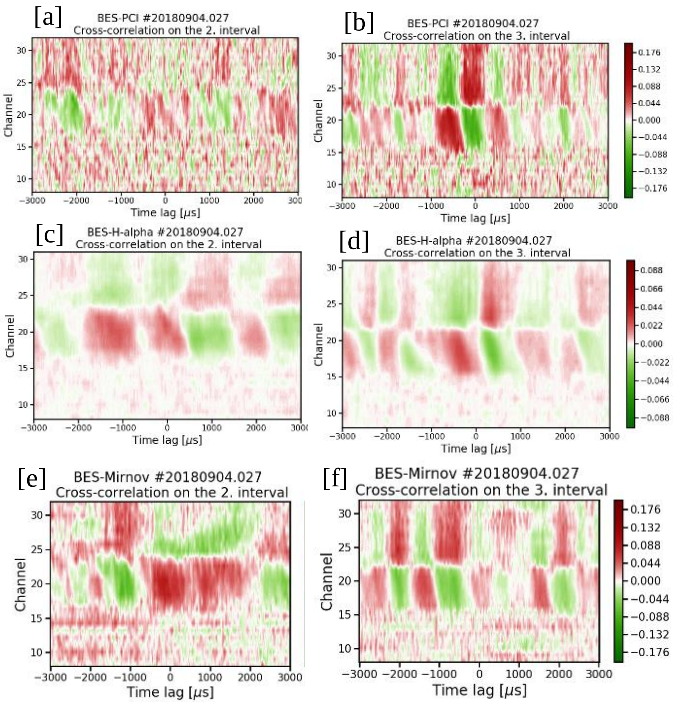

Figure 6 - 2D cross-correlation map between all ABES channels and multiple diagnostics ont he 2. and 3. interval

6.1 Correlation between PCI and ABES signal: Strong correlation can be seen on the 3. interval with 1 ms wide wavelike structures appearing, which was previously observed in ABES. During fluctuation suppression (2. interval) only weak correlation is found, with a significantly different temporal structure. Although usually PCI signal analyses is presented above 10 kHz, the cross-correlation with ABES reveals, that the signal also contains interesting information at ~kHz range frequencies.

6.2 Correlation between H-alpha and ABES signal: H-alpha signal indicates the magnitude of the edge plasma transport. During fluctuation suppression (2. interval) weaker correlation and lower frequency structures are appearing. Stronger correlation can be seen on the 3. interval with 1 ms wide wavelike structures dominating it.

6.3 Correlation between Mirnov coils and ABES signal: Strong correlation is observed between Mirnov and ABES signal. Similar differences are visible between interval 2. and 3. on the temporal structure of the correlation map as seen above. The difference in correlation amplitude is less pronounced.

Summary: Simultaneously to the suppression of core plasma fluctuations the level of edge plasma fluctuation also drops: The fluctuation amplitude measured by BES drops after pellet injection series then it raises transiently and recovers. The edge plasma density also drops during fluctuation suppression, then raises during fluctuation peak. After pellet injections suppression of <10 kHz fluctuations can be seen in edge plasma, comparing to the steady state. About 1 kHz frequency fluctuations are dominant during fluctuation peak, as a 1 ms wavelike structure can be seen in the correlation. Significant correlation can be seen between PCI, H-alpha, Mirnov and ABES signals which provides a coherent observation of edge plasma fluctuation suppression.

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