FIRST INDICATIONS FOR A TRANSPORT BARRIER INDUCED BY THE DYNAMIC ERGODIC DIVERTOR AT TEXTOR

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1   The DED concept at TEXTOR

The dynamic ergodic divertor (DED) consists of 16 coils wrapped toroidaly around the inner side of the torus [1]. The DED coils are parallel to $q = 3$ magnetic field lines. The coils can be operated in 12/4, 6/2 and 3/1 configuration. In the case of the 3/1 configuration the coils are grouped in bundles of 4 coils having all the same phase. In this configuration the penetration depth of the magnetic perturbation is large and influences the plasma core. The current in the coils can be varied up to 3.75kA in 3/1 mode and the frequency can be varied within $0.5 \leq f_{DED} \leq 10000$ Hz. Different ramp up rates for the DED current are also possible.

With the installation of the DED at TEXTOR the O–mode reflectometry [2] has been upgraded, too. The antennae set up, consisting of three antennae in a poloidal cross section, was extended by two additional antennae in the equatorial plane, so that in total 5 antennae at the same toroidal location but different poloidal angles are available, allowing to measure cross correlations at 4 different angles. The emitting antenna is localized at the equatorial plane. Two receiving horns are placed poloidally below and above the equatorial plane, enclosing a poloidal angle of 11.5^o. The two additional horns, enclosing a poloidal angle of 5.7^o, are placed next to them. The heterodyne reflectometer is operated in the frequency range $26 \leq f \leq 37$ GHz. The reflected waves are measured by quadrature detection at 500 kHz sampling rate.

From the 2D full wave modelling with the TAMIC RτH code [3] the sensitivity in k_Θ yields reasonable values for $k_\Theta \leq 3$ cm^{-1} for plasma conditions at TEXTOR as well for the used antennae set up. It could be demonstrated that the a curved reflection layer increases the sensitivity in k_Θ of the reflected wave.

2   Effects of the DED on the plasma

For the results discussed in the next sections the DED is operated in DC mode. The DED pulse starts at 1.2 s. The current is ramped up to 2 kA. After an interval $\Delta t = 500$ ms where I_{DED} is kept constant, the current in the DED coils is ramped down fast (fig. 1a). The ohmic plasma conditions are $\overline{n_e} = 2.0 \cdot 10^{19}$ m^{-3}, $I_P = 300$ kA and $B_T = 2.25$ T. In addition for charge exchange measurements $P_{NBI} \approx 300$ kW (fig. 1d) was injected in co–direction.

With the onset of the DED we observe a decrease of the sawtooth precursor frequency. However both density and electron temperature profiles are not changed. The toroidal plasma rotation at $R = 2.05$ m ($q \approx 2$) increases by ≈ 30 % while in the plasma center a slight increase is observed. If the DED current overcomes a threshold of $I_{DED} \geq 800$A a short drop in the line averaged density $\overline{n_e}$ is observed (fig. 1b). However with an additional gas puff $\overline{n_e}$ is kept at its preprogrammed value. The dip in $\overline{n_e}$ is accompanied by a drop in the electron temperature (fig. 1c) as observed across the whole profile. Also the density profile is significantly changed
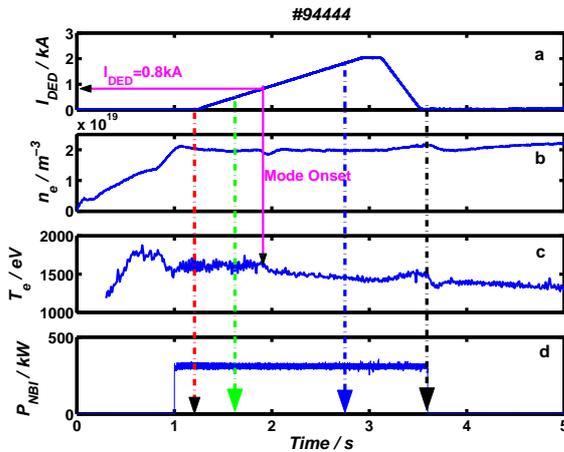

Figure 1: (a) DED current (b) Line averaged density (c) Central electron temperature (d) Power of tangential neutral beam. The onset of the locked mode is displayed by the magenta arrow. Colored arrows mark the times for the Ω estimation in fig. 4.
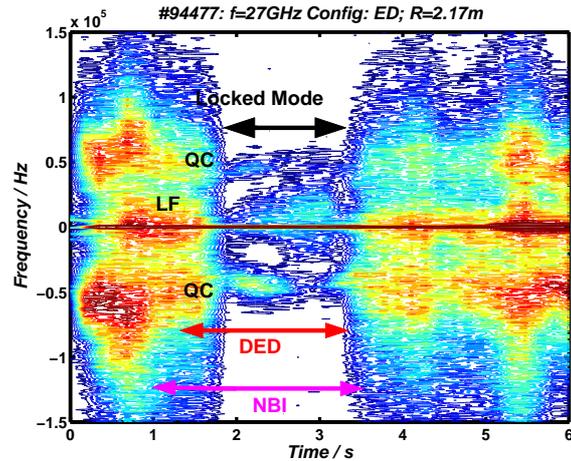
Figure 2: Contour plot of the coherency at $R = 2.17$ m displaying the change in the frequency of the QC mode and the onset of a low frequency structure rotating in ion diamagnetic drift direction

and on the low and high field side two shoulders become visible. The toroidal angular velocity profile becomes flat in the center at values comparable to those at $R = 2.05$ m. With the onset of the mode the diamagnetic energy shows decreases by 10% to 20%. To resolve the structure induced by the DED the electron cyclotron emission (ECE) diagnostic and the soft x–ray diagnostic is used. Since the ECE is located at different toroidal positions (enclosed angle 110°) a toroidal distortion of the profile at half radius is observed. The mode number of the DED induced island could be estimated as an $m/n = 2/1$ mode. Also the calculations of the $q = 2$ surface performed with a standard TEXTOR current profile are in agreement with the observations and yield the $q = 2$ surface at $R = 2.05$ m. The width of the island as measured by ECE and confirmed by SXR [4] amounts to $w = 0.08$ m. Towards the plasma edge a steepening of the T_e–profile with the mode onset is observed. This mode modifies strongly the plasma edge. A decreased density scale length (L_n) is observed for $R \geq 2.13$ m with onset of the $m/n = 2/1$ mode. The investigation of the T_e profile at the plasma edge performed at $B_T = 2.38$ T and $I_P = 325$ kA, keeping the q–profile fixed, allows to estimate the temperature scale length up to $R = 2.2$ m after correction for the optical depth. While in the profile without DED the temperature scale length is estimate to $L_{T_e} = 0.045$ m at $R = 2.17$ m L_{T_e} decreases to $L_{T_e} = 0.034$ m during the DED induced $m/n = 2/1$ mode. This observation is essential for the postulation of a transport barrier and is also supported by experiments with argon injection which show a reduced inward transport with the DED induced locked mode [5].

3   Indication for a transport barrier

The plasma in the range $2.13 \leq R \leq 2.18$ m, outside the induced $m/n = 2/1$ island, is investigated with the O–mode correlation reflectometer. The frequency was changed on a shot by shot base and the density fluctuations are studied. For a detailed analysis correlation reflectometry is used. It yields information on the frequency and poloidal angular velocity of small scale structures and their radial and temporal evolution. For one combination of antennae, looking at reflection points poloidally separated by an angle α, the cross phase Φ
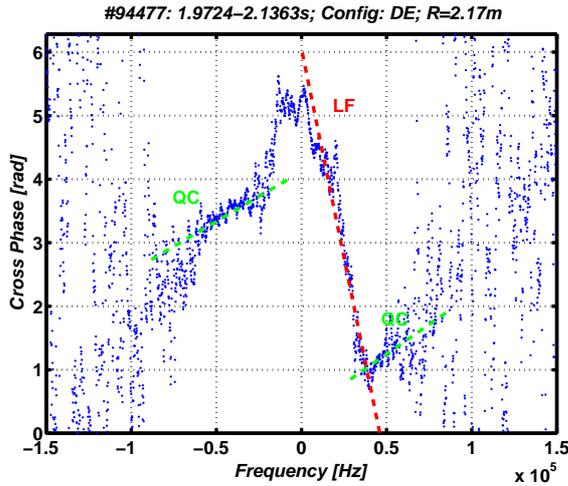
Figure 3: Estimated cross phase, showing that QC mode and LF mode rotate at different angular velocities at $R = 2.17$ m

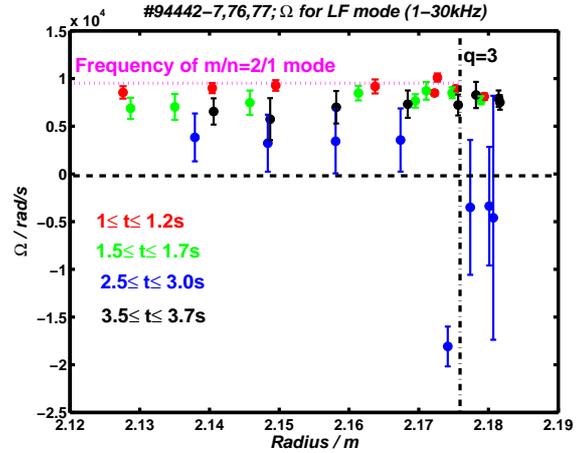Figure 4: Ω deduced for $1 < f < 30$ kHz. The different colors of the symbols denote different time intervals in the discharge corresponding to arrows in fig. 2.

and the coherency is calculated. From the slope of the cross phase

$$\frac{d\Phi}{df} = 2\pi\Delta t, \quad \Delta t = \frac{\alpha}{\Omega}, \quad \Omega = \frac{2\pi \cdot \alpha}{d\Phi/df} \tag{1}$$

in a given frequency range the angular velocity Ω is obtained and the coherency gives the center frequency of the structure. As already mentioned in reference [6] different structures can be distinguished in the coherency and cross phase presentation, a broad band structure (BB) with a small decorrelation time τ_{DC} and a quasi coherent structure (QC) with $\tau_{DC} \gg \Delta t$. Also low frequency structures (LF) are observed. The investigation of the coherence level of two poloidally separated antennas at $R = 2.17$ m (fig. 2) show that the correlation for the BB fluctuations breaks down completely as soon as the $m/n = 2/1$ mode is generated. Furthermore the coherence for the quasi coherent (QC) mode decreases as soon as the locked mode is generated. Also the frequency of the QC mode is decreased and the coherence disappears completely at $t \approx 2.5$ s. This is an indication for a transport barrier. At the same time the asymmetry in the coherence spectrum, due to the plasma rotation, changes from negative frequencies to positive ones, indicating a change in the rotation direction for the low frequency structures in the range $5 \le f \le 20$ kHz (fig. 3). However when the DED induced mode locks the LF structures and the QC mode rotate at different Ω and different direction. This indicates the different underlying physics of both modes.

With the cross correlation technique Ω is deduced for different time intervals (see figs. 4 and 1). Without DED $\Omega = 9 \cdot 10^4$ rad/s is measured (red symbols) independent of the radial position of the measurement. With the applied DED field, but still below the threshold for the locked mode, nearly no change in Ω is obtained (green symbols). Note that the poloidal angular velocity for the QC mode for these time intervals is constant for the investigated radial range. Also the $m/n = 2/1$ mode [7] rotates at the same frequency as the QC mode [8] (see fig. 4). For the time the locked mode is generated (blue symbols) a clear decrease in the angular velocity is observed and when reaching the $q = 3$ surface the velocity even changes its direction. For $R > 2.17$ m Ω becomes negative, this corresponds to a changed angular rotation in the ion diamagnetic drift direction. It is interesting to note that for this time interval the QC mode is still rotating in the same direction and with nearly the same Ω, whereas the $m/n = 2/1$ mode is already locked. After the DED pulse the measured Ω is again in agreement with those values measured before the DED pulse. The radial map of the coherency (fig. 5) shows the
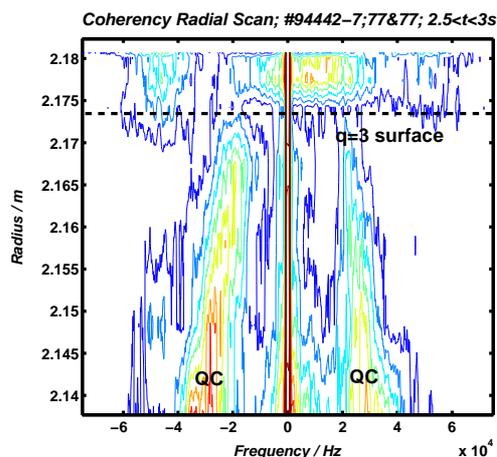
Figure 5: Radial map of the coherency obtained during DED operation above the threshold for the locked mode. The frequency of the QC mode is decreasing and LF modes show up for $R \geq 2.17$ m
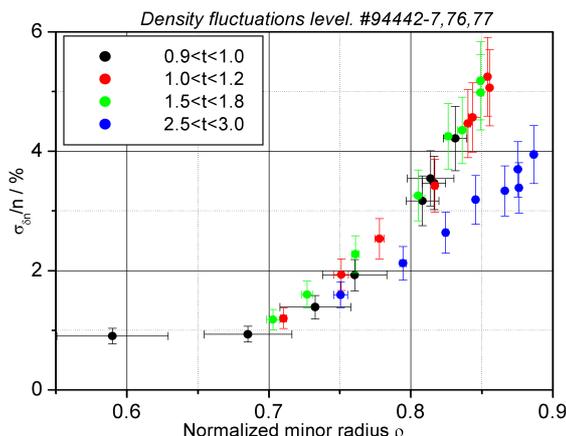

Figure 6: Density fluctuation for different time intervals, showing a decrease in the vicinity of the $q = 3$ surface during the DED induced island

disappearance of QC mode and the appearance of new low frequency (LF) structures quite well. The radial position of the of the $q = 3$ surface is well in agreement with the radius where the QC mode disappears. A decrease of the central frequency of the QC mode starting at $f \approx 35$ kHz towards $f \approx 20$ kHz is found. Outside the $q = 3$ surface LF modes with a high coherency are found. Furthermore the investigation of the RMS level of the density fluctuation for all channels is performed. In fig. 6 the averaged RMS level is shown in a phase without DED where an increase towards the plasma edge is observed and with the locked mode, due to DED operation, where density fluctuation level is decreased in the vicinity of the $q = 3$ surface.

4   Conclusion

With the DED a tool for the study of fluctuations under controlled conditions is available.
The experiments at TEXTOR with the DED show interesting features at the $q = 3$ surface ($R = 2.17$ m), due to an induced $m/n = 2/1$ mode. The QC mode vanishes at $R = 2.17$ m and the fluctuation level is strongly reduced, indicating the existence of a transport barrier. The LF mode rotates in ion diamagnetic drift direction whereas the QC mode at smaller radii rotates in electron diamagnetic drift direction. Also the electron temperature gradient is slightly increased and a retarded impurity transport is observed.
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