INVESTIGATION OF DED INDUCED MHD ACTIVITY WITH ECE DIAGNOSTIC AT TEXTOR

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The Electron Cyclotron Emission (ECE)–diagnostic at TEXTOR was upgraded during the last year to match the conditions and plasma parameters for the operation with the new installed Dynamic Ergodic Divertor (DED). The DED can be operated in the 3/1 and 12/4 mode. The standard electron temperature diagnostic is upgraded by another 6 channels to cover the operation at $B_t = 1.9$ T. The sampling rate of several radiometer systems is enhanced to 1 MHz. Depending on the performed task they are connected to a hog horn antennae or an elliptical mirror, respectively. The magneto hydrodynamic (MHD) activity in the plasma due to DED operation is monitored by the ECE–diagnostic. Analysis techniques in the frequency domain were used to characterize the effects of the DED on MHD–modes. Special interest is focused to the $m/n = 2/1$ mode and the precursor mode of the sawtooth crash. The influence of the DED on both modes is studied for different plasma parameters as well as for DC and AC operation of the DED at different currents. With DED in 3/1 operation a threshold for the onset of the $m/n = 2/1$ mode is found and the influence of the DED operation on transport properties is investigated.

The DED concept at TEXTOR

The dynamic ergodic divertor (DED) consists of 16 coils wrapped toroidaly around the torus [1]. Since the DED is planned to influence the $q = 3$ surface, each single coils is wrapped around the torus in that way that it coincides with the field line pitch of the $q = 3$ surface. The coils can be operated in 12/4, 6/2 and 3/1 mode. For the 12/4 mode the current in two neighboring coils is in opposite direction. In that case the radial decay of the magnetic perturbation is strong and the DED in 12/4 mode influences only the plasma edge. In the case of the 3/1 mode the coils are grouped in bundles of 4 coils having all the same phase. In this configuration the magnetic perturbation is much larger and expected to influence the plasma core. The current in the coils can be varied up to 3.75kA in 3/1 mode and 15 kA in 12/4 mode. Furthermore the frequency can be varied within $0.5 \leq f \leq 10000$ Hz. Different slopes for the ramp up of the DED current are possible.

With the installation of the DED the ECE-diagnostic has been upgraded, too. Since the largest effects with the DED in 12/4 mode are expected at $B_T = 1.9$ T one of the ECE spectrometers has been modified in that way that the local oscillator can be switched between the operation at $B_T = 1.9$ T (observation of the low field side (LFS)) and at standard $B_T = 2.25$ T (observation on the high field side (HFS)). The video amplifiers allow a sampling up to 1MHz. In the vessel additional elliptical mirrors are installed. They are connected via switches to the existing wave guides. The ECE diagnostics are located at different toroidal positions. The standard T_e diagnostic and two spectrometers for the gradient region enclose an angle of 110^o for the estimation of low m number MHD modes.

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Observations from DED in 12/4 mode

For the operation in 12/4 mode the target plasma was shifted to the HFS by 0.03 m to enlarge the effects of the DED on the plasma, so that the magnetic axis coincides with major radius. The toroidal magnetic field is reduced since the theoretical model calculation predict an increased influence of the DED on the plasma at $B_T = 1.9$ T. To extend the resonant q surface, the plasma current is set to $I_p \geq 400$ kA yielding a cylindrical $q_a = 2.8$. Experiments are conducted for DC DED at $I_{DED} = 7$ kA for a duration of one second. In fig. 1 temperature profiles and density profiles (fig. 2) are compared for ohmic discharges with and without DED at a low and a medium line averaged electron density ($\overline{n_e}$). The profiles are averaged for 200 ms each to exclude minor effects as the sawtooth instability. At $\overline{n_e} = 2.0 \cdot 10^{19}$ m^{-3} the density profiles during the DED and non DED phase are nearly the same. In the case of $\overline{n_e} = 3.5 \cdot 10^{19}$ m^{-3} an increase of the local density for $1.5 \leq R \leq 2.0$ m is observed. For $R \geq 2$ m the local density is decreased. For the T_e–profiles a decrease of the electron temperature is found during the DED phase at low density. At $\overline{n_e} = 3.5 \cdot 10^{19}$ m^{-3} T_e is increased in the center whereas the outermost LFS channel displays a drop in the temperature, yielding an increased ∇T_e. The electron pressure profile for the medium density is therefore slightly increased, pointing towards an increased confinement in the DED phase.

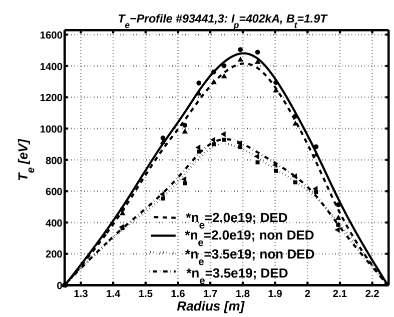

Figure 1: T_e-profiles for low and medium line averaged density

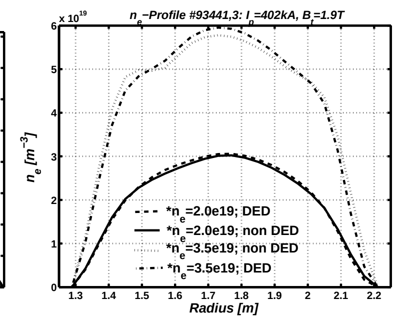

Figure 2: n_e-profiles for low and medium line averaged density

An effect of the DED on the precursor $(m/n = 1/1)$ mode was a priori not assumed. However the analysis of the precursor frequency (f_{PC}) in ohmic plasmas and those heated by tangential neutral beam injection (NBI), shows a change in the precursor frequency during DED operation (fig. 3), obtained after a sliding Fourier transformation. In general the mode frequency of any magneto hydrodynamic mode f_{MHD} can be expressed by:

$$f_{MHD} = n\frac{v^{\Phi}}{2\pi R} \pm m\frac{v^{\Theta}}{2\pi r} + f_e^* \qquad (1)$$

The change in the mode frequency can be due to a change in the toroidal rotation velocity of the bulk plasma, measured by Charge eXchange Recombination Spectroscopy, as well as by the change of the poloidal rotation velocity. Also the diamagnetic frequency f_e^* can influence the measured f_{PC}, since

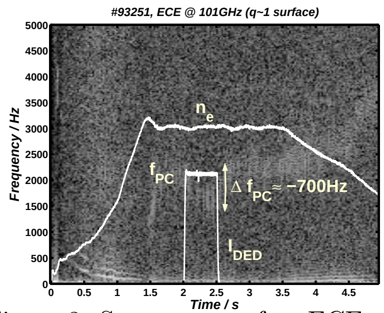

Figure 3: Spectogram of an ECE channel near to the $q = 1$ surface showing the decrease of f_{PC} caused by the DED at $I_{DED} = 7$ kA for an ohmic plasma.

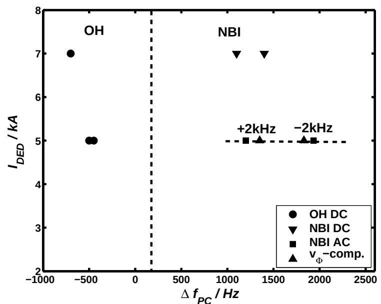

Figure 4: Δf_{PC} for ohmic and NBI heated plasmas for DED at DC and AC operation. In addition Δf_{PC} from the increase of the toroidal rotation velocity is displayed.

$f_e^* \propto \nabla p_e$ and therefore changes in ∇T_e and ∇n_e are responsible for changes in f_e^* [2]. At TEXTOR f_e^* acts like an additional counter–current rotation which has to be subtracted in the case of a plasma rotating in co–current direction. The analysis of the precursor frequency is performed by a cross correlation technique of two adjacent ECE–channels close to the $q = 1$ surface. The DC operation of DED with $I_{DED} = 7$ kA yields in ohmic plasmas a decrease of f_{PC} by $\Delta f_{PC} \approx 700$ Hz (*circles in fig. 4*). A decrease of the DED current by 2 kA reduces the shift in Δf_{PC} to 400 Hz, only. In neutral beam heated plasmas an increase of $\Delta f_{PC} \approx 1200$ Hz is found (*down triangle in fig. 4*). The change of the sign in Δf_{PC} is due to the fact that the tangential neutral beam injection reverses the direction of the mode rotation.

Similar effects are also observed for the AC operation of the DED. The negative AC operation acts like an additional counter rotation and the positive AC operation like an additional co rotation for the bulk plasma, with respect to the current direction in TEXTOR. The observed changes in the precursor frequency reported here are compiled in fig. 4. With the AC operation it can be checked if f_{PC} changes accordingly, which means if an additional torque is induced on the plasma. For the investigations plasmas with $\overline{n_e} = 2.0 \cdot 10^{19}$ m^{-3}, $I_p = 400$ kA, $P_{NBI} = 1.3$ MW and $I_{DED} = 5$ kA are used. Operating the DED at +2 kHz yields an increase of $\Delta f_{PC} \approx 1300$ Hz. For DED operation at -2 kHz a shift of $\Delta f_{PC} \approx 1900$ Hz (*squares in fig. 4*) is observed. In both cases the precursor frequency increases compared with ohmic ones, which is in agreement with the above considerations.

For an understanding of the changes in the precursor frequency the different components of equ. 1 are analyzed. The different observations in f_{PC} due to co and counter rotation of the DED cannot be caused due to the influence of f_e^* since the T_e and n_e–profiles show no significant change justifying a change in f_e^*. Since the measurements of the CXRS are only available during neutral beam heated plasmas the analysis is restricted to two discharges only. The measured rotation profiles for the both cases (± 2 kHz, $I_{DED} = 5$ kA) is shown in fig. 5. The toroidal angular rotation is not only increased at the plasma boundary but for the whole radial region, during DED operation. At the $q = 1$ surface the angular toroidal rotation (Ω_Φ) is increased by $\Delta\Omega_\Phi = 8500$ and $\Delta\Omega_\Phi = 11500$ rad/s respectively. According to the equ. 1 the change in Ω_Φ is translated to a frequency shift of $\Delta f_{PC} = 1300 \pm 600$ Hz in the case of co and $\Delta f_{PC} = 1800 \pm 700$ Hz in the case of counter–rotation (*up triangles and dashed line in fig. 4*). The measured shift in f_{PC} and the calculated ones from CXRS measurement are within the error bars in agreement. The shift in the precursor frequency is a first indication for an increased toroidal rotation velocity. However an indication for a change in Ω_Φ due to change in the direction of the DED AC operation cannot be confirmed since the error bar of the frequency shift from the measurement of the angular rotation is larger than the observed change in f_{PC}.

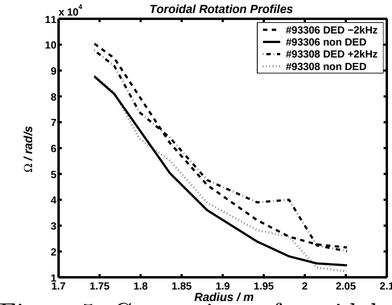

Figure 5: Comparison of toroidal rotation velocity profiles with and without DED operation at ± 2 kHz.

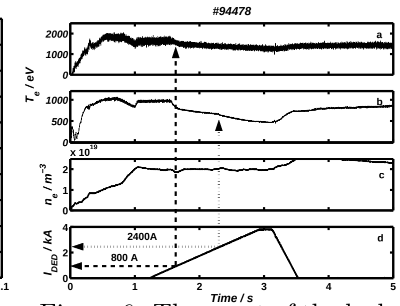

Figure 6: The onset of the locked mode as seen by center– (a), edge ECE channel(b), $\overline{n_e}(c)$ at a critical I_{DED} (d).

Observation from DED in 3/1 operation

With the DED in 3/1 mode most experiments are performed in DC and a few in AC operation. The target plasma for DED operation in 3/1 mode is characterized by $B_T = 2.25$ T, $I_P = 300$ kA. The horizontal plasma position was slightly shifted to the LFS by 0.03 m. Most of the experiments were performed with tangential neutral beam co–injection at $P_{NBI} \approx 300$ kW to allow CXRS measurement. For the experiments reported here the DED is switched on at $t = 1.2$ s and ramped up with 1.2 kA/s. At $t = 2.9$ s a flat top of 200 ms at $I_{DED} = 2$ kA is applied followed by a fast current ramp down (see fig. 6).

In DC operation no effect on the averaged temperature profile is observed as long as $I_{DED} \leq 700A$. Once the threshold is overtaken a large island is formed at half radius. This goes along with a drop in the central plasma temperature by ≈ 200 eV. A small dip in $\overline{n_e}$ at the mode onset is found which recovers to the preprogrammed value because it is feedback controlled (fig. 6). In DED DC operation the island locks immediately. To estimate the mode number of the locked mode the toroidal separated ECE measurements are used. In fig. 7 two temperature profiles are presented taken at different phases of the discharge. For the profile, taken before the onset of the DED, a toroidal symmetric plasma is observed. The measurement of the spectrometer (*filled circles*) coincide with the spline fit obtained from the standard T_e measaurement (*open circles*). The blue profile during the DED phase shows a deviation between the toroidal different ECE measurements. The data for $R \leq 2.05$ m are shifted inward and data for $R \geq 2.05$ m are shifted outward, so that a shoulder in the profile at $R \approx 2.05$ m becomes visible. This structure agrees with a m/n=2/1 mode. In that case the standard T_e diagnostic measures near to the X-point of the island whereas the ECE diagnostic located 110^o toroidaly apart measures near to one of the O-points of the island. A calculation with a standard current profile is in agreement with the $q = 2$ surface at the position of the shoulder as obtained by the spectrometer. The unlocking of the mode after the DED phase allows to determine the mode number from the Mirnov coils. Again $m/n = 2/1$ is found. A further increase of the DED current yields another change in the edge ECE channels. At $I_{DED} = 2.4$ kA ($t = 2.3$ s) the observed temperature decrease at the plasma edge, becomes even steeper. No enhanced decrease of the central T_e is observed (fig. 6). The structure causing this behavior is not yet resolved.

The analysis of the sawtooth instability and the precursor activity yields in ohmic plasmas a decrease of the precursor frequency with the onset of the DED operation similar to those observed in 12/4 mode operation of the DED. Due to the stronger far field, f_{PC} decreases by 1.5 kHz until the mode stops the precursor activity at the threshold DED current (fig. 8). From the measurement of the sawtooth period and amplitude a decrease of both quantities up to 30 ms before the onset of the $m/n = 2/1$ mode is observed. From fig. 9 it can be seen that the reconnection process occurs earlier for subsequent sawtooth. The period decreases from $\tau = 14.1$ms to $\tau = 7.1$ms. Since the rate of temperature rise in the center is not changed after the crash, the amplitude of the sawtooth crash decreases from $\Delta T_e = 450$ eV to $\Delta T_e = 50$ eV. A stabilization of the sawtooth activity by reducing the sawtooth period and amplitude is observed. The estimation of the inversion radius shows no change. Since the inversion radius is related to central safety factor[3] by $r_{INV} = <j> / (j_0 q_0)$, where j_0 denotes the current density on axis and $<j>$ the total current, a change of the q on axis above one can be excluded and therefore a disappearance of the $q = 1$ surface as long as the sawtooth activity is observable. With the onset of the $m/n = 2/1$ mode a small 600 Hz T_e oscillation of ≈ 20 eV is observed, lasting for the rest of the DED period. With the DED switch off the observed structures stay for 100 ms. Then the $m/n = 2/1$ mode is unlocked and rotates at $f = 2.2$ kHz.

Also in the case of AC DED operation with $f = 1$ kHz the onset of the m/n=2/1 island is observed at a certain thresholds of I_{DED}. In the AC case the $m/n = 2/1$ island locks to the DED frequency and from the contour plot of the electron temperature the island width is estimated to $w \approx 0.10$ m. With the formation of the island also the electron heat transport in the plasma within the $q = 2$ is enhanced. This was observed in experiments with modulated ECRH (MECH), deposited at half radius ($P_{ECRH} = 600$ kW, $t_{mod} = 20$ ms), where a propagation of the heat wave into the plasma center is observed (fig. 10) with

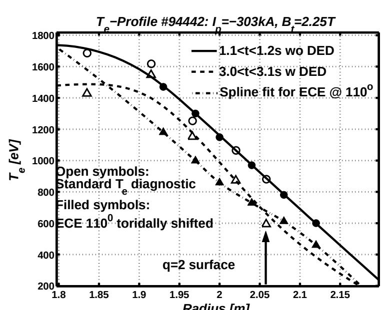

Figure 7: T_e–profiles with and without DED. The filled symbols denote measurements observed 110^o apart.

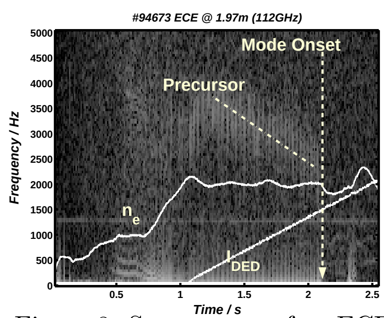

Figure 8: Spectogram of an ECE channel showing the decrease of the precursor frequency with increased I_{DED}.

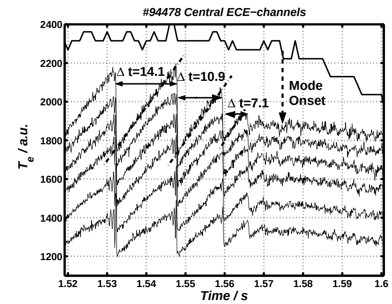

Figure 9: Central ECE channels showing the decrease of the sawtooth period and amplitude before the onset of the mode

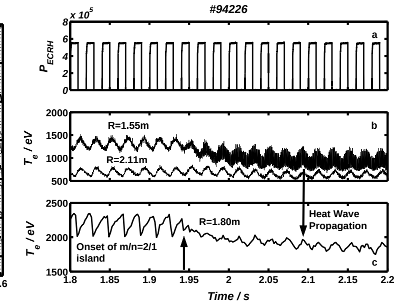

Figure 10: (a) MECH deposited at half radius. (b) Edge ECE showing the response of the MECH. (c) Core ECE showing the heat wave caused by MECH.

the onset of the $m/n = 2/1$ island. Before the island is formed the heat wave is not able to penetrate the $q = 1$ surface and the sawtooth instability as well as the precursor are still observed in the plasma center. Similar observations of an enhanced radial transport in the plasma core are found by Argon spectroscopy. A possible locking of the $m/n = 1/1$–mode to the $m/n = 2/1$–mode could not be confirmed. The ECE channels located inside the $q = 1$ surface show no $m/n = 1/1$ activity. Transport experiments and models [4] suggest the coexistence of regions with reduced radial transport and rational surfaces. In that sense the observations are an indication for the decoupling of rational surface and a region of decreased radial transport. However an additional proof for the existence $q = 1$ surface from the measurement of the current density profile is still missing.

Summary

The first experimental campaigns with DED in 12/4 and 3/1 mode showed interesting results. Within this paper first MHD effects are described and discussed. In plasmas with low $\overline{n_e}$ the confinement becomes worse. Indications for an increased confinement and a increased edge gradient are observed for $\overline{n_e} \geq 3.5 \cdot 10^{19}$ m^{-3}. A change of the precursor frequency in the 12/4 as well as in the 3/1 mode is observed caused by the change of the toroidal angular velocity of the bulk plasma during DED operation. The calculated changes in the precursor frequency due to the change in the angular velocity are within the error bars in agreement with the observations from the ECE diagnostic.

In 3/1 mode DC operation a large locked $m/n = 2/1$ island is formed at a critical DED current. Several tenth of milliseconds before the onset of the island the sawtooth instability vanishes, because of a decrease in the re–heating of the plasma core. The inversion radius is not changed as long as sawteeth are observable. In AC DED operation the transport barrier at the position of the $q = 1$ surface disappears. The whole plasma core acts like a short circuit and the radial electron heat transport is enhanced.

References

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