2D temperature profiles of DED structures using ECE-Imaging in TEXTOR

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Direct 2D measurements of the edge electron temperature during operation of the Dynamic Ergodic Divertor (DED) at TEXTOR are presented. These high resolution ECE Imaging measurements reveal the temperature structure of the so called ergodic and laminar zones of the plasma edge, giving insight in the edge transport properties during the DED perturbation field experiments. A comparison of the observed structures with simulations (Atlas code) is given.

The Dynamic Ergodic Divertor

The Dynamic Ergodic Divertor [1,2] experiment on TEXTOR (circular limiter Tokamak, R_0=1.75m, a=0.47m) is designed to control the plasma edge properties by introducing a helical magnetic perturbation field. By manipulating the edge transport of heat and particles, heat loads on the plasma facing components can be controlled. In fig. 1 a schematic representation of the DED and the main plasma regions is shown. The DED consists of 16 helical coils on the high field side (HFS), aligned with the q=3 field lines. In the so called 12/4 DED mode, the currents through the DED coils are arranged such that they introduce a perturbation field with a base m=12, n=4 mode structure, with strong side bands at other m values close to 12. Only the plasma edge is affected due to the shallow penetration of the field in the 12/4 coil configuration. Both DC and AC DED currents are possible.

When the DED is switched on, the magnetic topology changes drastically. At the resonant surfaces (q=10/4, 11/4…) island chains build up. Where neighbouring island chains overlap (Chirikov parameter >1), the field lines become stochastic. This plasma region is referred to as an ergodic region. Close to the edge, open field lines with a very short wall-to-wall connection length arise. This plasma region is referred to as a laminar zone. In terms of field line topology, the laminar and ergodic regions can be defined by the ratio of the connection length L_C to the Kolmogorov length L_K (a characteristic length for the separation of neighbouring field lines). In the ergodic region L_C is long compared to L_K, making the magnetic topology stochastic. In the laminar zone $L_C < L_K$, inhibiting stochastic field line behaviour.

The topology of the DED induced structures and the level of ergodisation are mainly determined by the q-profile (positions of the resonant surfaces) and the plasma pressure, expressed in β_{pol}. With increasing β_{pol} the Shafranov shift enlarges the distance between resonant surfaces on the HFS near the DED coils. This leads to less overlap between the DED induced island chains (smaller Chirikov parameter), and hence less ergodisation. Also, β_{pol} influences the pitch angle of the field lines.

Edge transport during DED

The transport of heat and particles in the laminar region is a balance between perpendicular (collisional or turbulent) transport and parallel transport (convection/conduction along field lines). The collision length is typically larger than the wall-to-wall connection length in this region, so particles that (diffusively) enter the laminar zone almost certainly flow to the wall, making the laminar zone an effective heat sink.

In the ergodic region, where the collision length is comparable to or smaller than the connection lengths, perpendicular diffusive transport is important. But also the parallel transport along stochastic field lines enhances radial transport (field line diffusion).

The plasma edge during DED has a complicated (fractal) magnetic structure with entwined field lines of short and long connection length. In particular, long thin ergodic ‘fingers’, surrounded by laminar regions, connect the ergodic region with the wall. Numerical modelling using the 3D plasma edge transport code EMC3-EIRENE [4], predicts that electron temperature and density follow the connection length profile, so in the fingers a higher T_e is expected. Also the heat deposition profile on the divertor target plates follows the structure of these long connection length fingers.

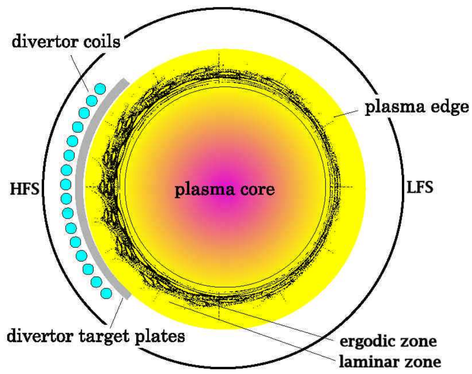

Fig. 1: Schematic representation of the DED coils and the main plasma regions. (Adapted from [5]).

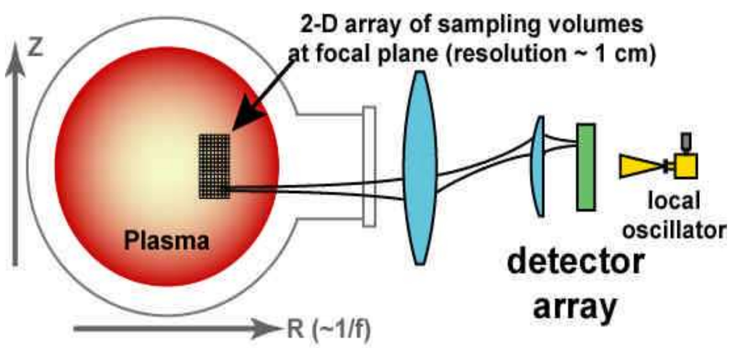

Fig. 2: Schematic representation of the ECE-Imaging system.

ECE Imaging

Direct 2D measurements of the electron temperature with a high spatial and temporal resolution are possible with the ECE Imaging (ECEI) diagnostic [3] on TEXTOR. ECEI uses wide aperture optics to image a vertical slice of the plasma onto an array of 16 receivers. Each receiver is treated as a conventional 2^{nd} harmonic X-mode ECE radiometer with 8 frequency channels, giving an 8 (radially) by 16 (vertically) array of sampling volumes in the poloidal plane, representing about 8 by 16 cm^2 in the plasma centred on the equatorial plane. The position of the observation volume can be shifted radially (the system is wideband tuneable from 85 to 130 GHz to match a wide variety of magnetic field conditions). With the ECEI system one can directly explore the two-dimensional nature of plasma structures in a single measurement with a time resolution of up to 500 kHz. Fig. 2 gives a schematic representation of the ECEI system.

Experimental results

In figures 3a-d ECEI measurements at the LFS plasma edge during a shot with DC DED (I_{DED}=11.5 kA, B_T=1.91 T, $n_{e,line\ av.}\approx 4\cdot 10^{19}$ m^{-3}) are presented. During this shot the plasma current was ramped down from I_p=450 to 200 kA (only I_p=390-365 kA shown). The data is normalised to the temperature profile just before switching on the DED, and hence reflects the relative change in temperature during DED and the current ramp. After switching on the DED, the temperature drops over the entire observation volume of ECEI (all normalised temperatures below 1), which is a clear sign of an enhanced transport level. The measurements also show structures that evolve with the changing plasma current, in particular ‘hot spots’ (less-cold spots) that approximately stay at the same poloidal position, but migrate radially inward with decreasing plasma current (fig. 3a-c). Due to the changing q profile the DED induced structures are expected to evolve. The resonant q surfaces migrate inward during the ramp, and major changes in the DED structure appear when a new resonant surface enters the plasma and becomes dominant (fig. 3c-d show such a transition). Figures 3e-h give the corresponding ‘laminar plots’, as calculated with the Atlas code [5]. A laminar plot is a contour plot of the wall-to-wall connection length in units of poloidal turns. The laminar zone consists mostly of the 1 and 2 poloidal turn field lines. The field lines with connection length longer than 4 poloidal turns belong to the ergodic region. The black contour indicates the observation volume of ECEI (although these measurements indicate the position is probably a few degrees more to the left). The Atlas calculations also show a long connection length structure (red coloured region in the upper left, where two ‘fingers’ cross) which migrates inward. In fig. 3h the structure connects to the main ergodic region, and a new structure arises just right of the ECEI observation volume.

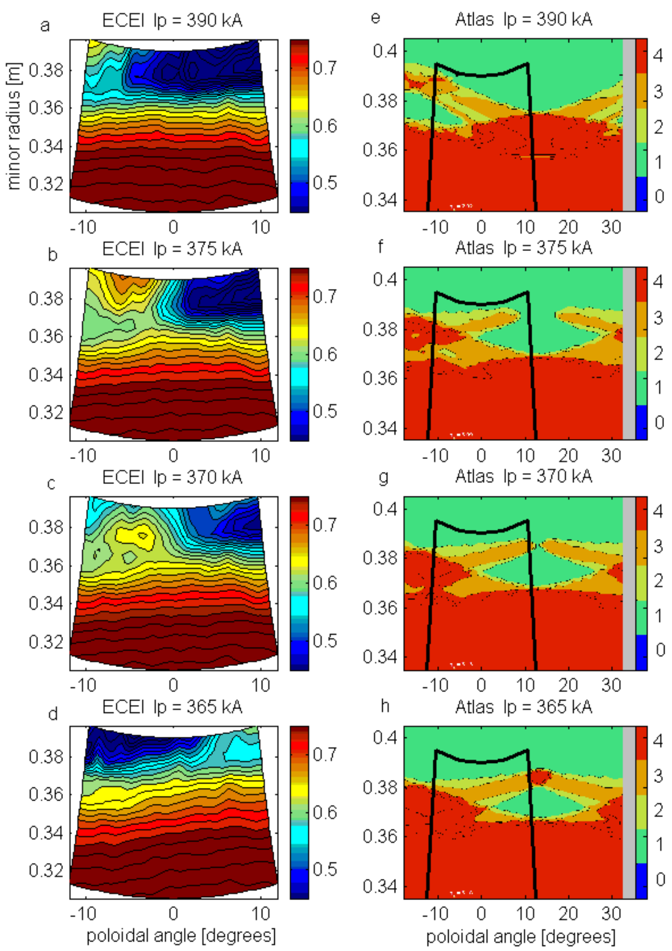

Fig 3Comparison of ECEI temperature measurements with Atlas calculations of the connection length (laminar plots) during a plasma current ramp.

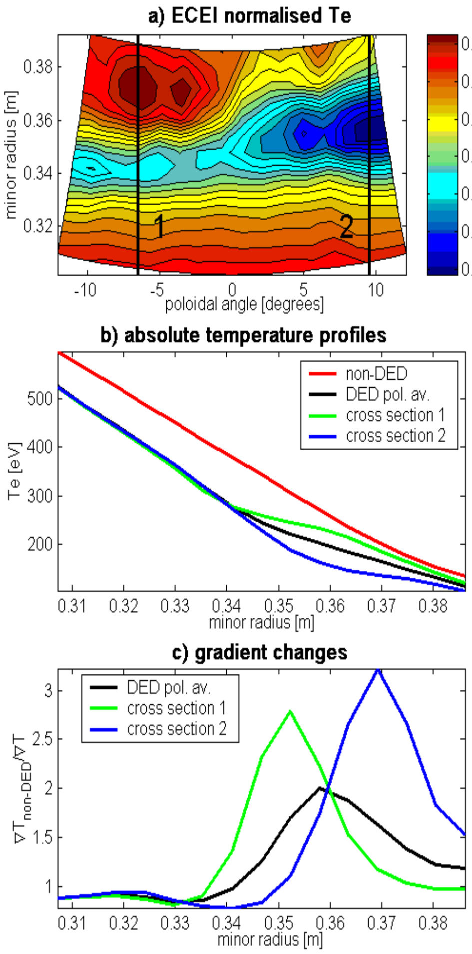

Fig. 4: Comparison of T_e profiles during DED with non-DED reference.

In fig. 4a (normalised) ECEI data from a shot with DC DED and constant plasma current (I_p=350 kA, I_{DED}=12kA, $n_{e,line\ av.}$≈$1.5\cdot10^{19}$ m^{-3}, B_T=1.9T) is shown. The constant plasma parameters enable a direct comparison of the DED phase with the (otherwise identical) non-DED phase. The data clearly shows a 'hot spot' separated from the main plasma by a colder region, similar to the structure in fig. 3. In fig 4b, estimates of the absolute temperature profiles at cross sections 1 and 2 indicated in fig 4a are shown, along with the poloidally averaged profile and the non-DED reference. ECEI is not absolutely calibrated and has to rely on cross calibration or profile shape assumptions. The absolute temperature values presented in fig. 4b are derived from measurements with a different, calibrated ECE system, and the edge profile shape (in the non-DED reference case) is estimated from He beam measurements. The profiles clearly show the overall drop in temperature and the large poloidal variation in profile shape during DED. The extent of the DED affected region is clearest seen in fig 4c, where the ratio between the temperature gradient in the non-DED reference case and the temperature gradient during DED is plotted. Assuming heat flux and density profiles stay the same (which is an oversimplification, certainly for the two poloidal cross section profiles due to poloidal redistribution of heat flux) this ratio is a measure for the enhancement of the heat transport during DED [4]:

$$\frac{\nabla T_{e,non-DED}}{\nabla T_{e,DED}} \approx \frac{\chi_{erg}}{\chi_{\perp}}$$

Where $\chi_{\perp}$ is the perpendicular diffusion coefficient in the unperturbed case and χ_{erg} is the effective heat diffusion coefficient in the perturbed magnetic field (containing both perpendicular and parallel transport and hence is not a true *diffusion* coefficient). Although not very accurately, fig 4c indicates a significant transport enhancement in the plasma regions where from Atlas calculations the laminar zone is expected. In the ergodic region (for example in the 'hot spot') transport levels are close to the unperturbed values.

Caution is needed in quantitatively interpreting the ECEI edge measurements due to two difficulties. First due to the lack of an absolute calibration and second, due to the low optical thickness near the edge, meaning that not only temperature, but also density changes are to some extent reflected in the measurements. Only a partial correction for this effect has been performed, probably leading to an overestimation of the relative temperature drop during DED. Qualitatively the presented results are not sensitive to these two difficulties.

Conclusion

The temperature structures seen in the edge plasma during DED are in agreement with the structures predicted by the Atlas code. The temperature follows the structures in the connection length (longer connection lengths corresponding to higher temperatures). The lower edge temperature profiles during DED confirm the enhanced transport levels due to the perturbation field, in particular in the laminar zone.

References

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