TRANSPORT WITH ON-AXIS AND OFF-AXIS ECRH IN ASDEX UPGRADE

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1. Introduction

An ECRH system (4×0.5 MW, 2s, 140 GHz, 2nd harmonic, X-mode) is being built for the ASDEX Upgrade tokamak. which provides central deposition at 2.5T and single-pass absorption of 100%. The power is injected into the tokamak with 4 separate mirror systems, which allow poloidal and toroidal varaition of the injection angle of the narrowly focused Gaussian beams, permitting localised on-axis or off-axis deposition at fixed magnetic field. So far, 2 gyrotrons have been put into operation providing a maximum of 700 kW ECRH power deposited in the plasma.

Experiments with on-axis or off-axis heating allow to investigate transport, in particular the question of temperature profile resilience. Previous experiments in DIII-D with off-axis ECRH exhibited a peaked electron temperature profile, explained by an inward heat pinch [1]. Recent experiments in RTP showed flat or even hollow temperature profiles in the off-axis cases [2]. Similar experiments are described in this paper.

2. Experiments

The results are based on experiments in which the off-axis deposition was in general at about mid-radius ($0.35 \leq \rho_{toroidal} \leq 0.55$). The ECRH pulse was applied for several confinement times and the results are taken at steady state. Small changes in l_i are observed with respect to which the plasma is also steady-state at the time of the analysis. The results presented here are restricted to ECRH applied to Ohmic phases, with $P_{Ohm} \leq 1$ MW. The ECRH power was continuous (CW) with a small amplitude modulation (10%) to allow the experimental determination of the deposition and study transient transport (section 4).

The main diagnostic is the 60 channel ECE radiometer which provides the electron temperature (T_e) over the whole plasma radius with a high time resolution (≈ 30 kHz) and in good agreement with that from the Thomson scattering. The radial resolution of each channel is about 1cm and the distance between channels 1 to 2 cm. The density profile is provided by a deconvolution of the interferometer and edge density from Li beam.

3. Steady-state analysis of on-axis and off-axis cases

We compare two discharges ($I_p = 1$ MA, $B_T = 2.35$ T, $\bar{n}_e = 3.0 \ 10^{19}$ m^{-3}, $P_{ECRH} \approx 600$ kW) in which only the ECRH deposition was changed from on-axis ($\rho_{toroidal} \approx 0.1$) to off-axis ($\rho_{toroidal} \approx 0.5$) by changing the injection angle. In the on-axis case, l_i increase weakly (by about 5%) whereas it decreases (by about 10%) in the off-axis case as expected. The profiles of the electron temperature and of the temperature change caused by the ECRH with respect to the Ohmic phase are shown in Fig. 1. The temperature profiles remain peaked for both on-axis

and off-axis heating. The temperature change ($T_e^{ECRH} - T_e^{OH}$) clearly shows the difference between the two cases. Note the similarity of the profile outside the off-axis deposition. No influence of the ECRH position on the density profile is detectable.
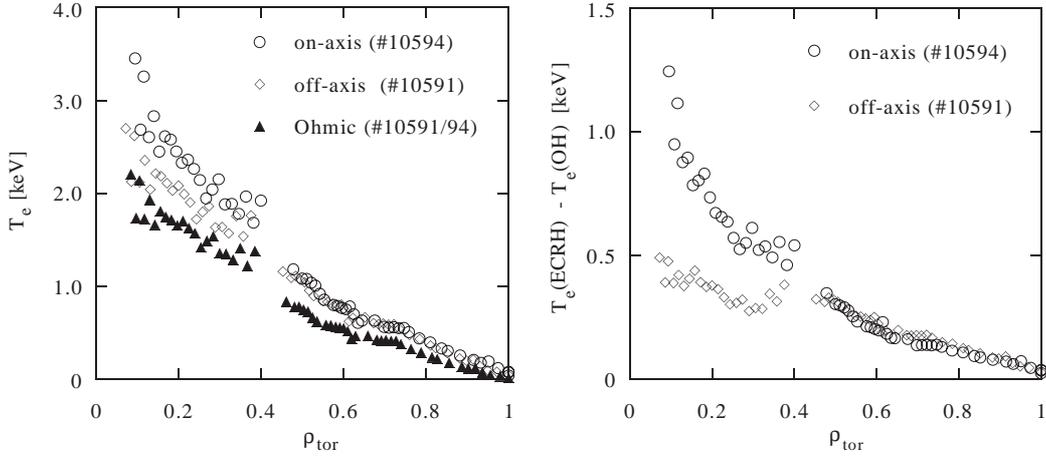

Figure 1. Electron temperature profile and difference for on-axis and off-axis ECRH.

The global MHD activity, observed with the ECE and soft X-ray diagnostics, is quite different in the two cases. The off-axis heating exhibits almost no change in presence of ECRH: the sawtooth frequency and amplitude remain constant within 10%, the (1,1) sawtooth precursors are quite comparable, no other modes are detected. In contrast, in the on-axis case, the central MHD activity increases dramatically: strong (1,1) modes appear and the sawtooth frequency becomes erratic, however no non-central modes such as (2,1) or (3,2) are observed. It must be underlined that this strong MHD activity appears very quickly after the onset of the ECRH. It is therefore directly linked with effects caused by the local temperature increase and is not related with changes in global current profile which has a longer time scale as shown by l_i. The influence of the strong MHD activity on the temperature profile is not clear: the dependence of the central electron temperature just before a sawtooth crash on P_{ECRH} is weaker than linear. This is also the case of the plasma energy content. In contrast, the central temperature just after a sawtooth crash increases linearly with P_{ECRH}. This suggests that the maximum electron temperature in the center for on axis heating is limited by the MHD activity which probably causes an enhanced transport in the core. The power scan also shows that the increase of the MHD activity is visible at a power as low as 100 kW. For off-axis heating the temperature at the deposition and in the center increase linearly with the ECRH power with almost the same slope.

Transport simulations were made with the ASTRA transport code for the 2 discharges of Fig. 1, to estimate the possible change of the electron heat diffusivity (χ_e) occurring in the on-axis and off-axis cases, compared to the Ohmic one. The results of the analysis for the steady state is shown in Fig. 2. For this purpose, the power balance heat conductivity profile (χ_e^{PB}) is adjusted such that the time-averaged temperature profile in the 3 cases (Ohmic, on-axis, off-axis) is well reproduced. The electron density is that of the experiments. The ion temperature profile is determined by using neo-classical transport multiplied by a factor (close to 1) which is chosen such that the measured central ion temperature (passive CX measurement) and the plasma energy content are matched within their uncertainties. The radiative power, low in these discharges, is not considered and would only play a role at the very edge.

The results from the transport simulation of the electron temperature, shown in Fig. 2,
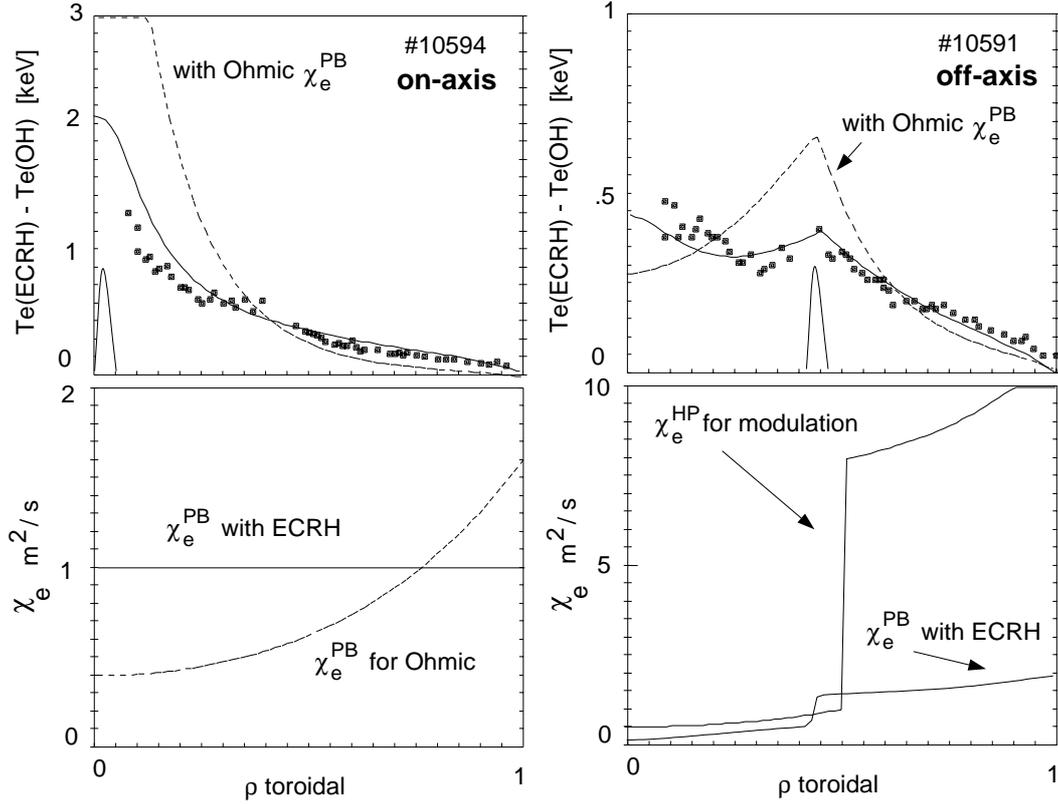
Figure 2. Transport simulation: points are data, dashed line model using Ohmic χ_e, solid lines ECRH χ_e^{PB}. χ_e^{HP} for modulation (Sect. 4) also shown.

clearly indicate that χ_e^{PB} changes quite significantly when ECRH is applied and that its profile shape must be different for off-axis or on-axis. Note the strong disagreement for both the on-axis and off-axis case when the Ohmic χ_e^{PB} profile is tentatively used to simulate the ECRH phases. It is not clear however to which extend the MHD activity in the on-axis situation contributes to the value of (χ_e) in the central part of the plasma. For the off-axis case, the χ_e^{PB} profile with a step around the position of the ECRH deposition is absolutely necessary to obtain a good agreement with the data. In principle such a step in transport could also be achieved by an adequate convective term (heat pinch), as convection and diffusion cannot be distinguished in steady-state analyses. The modulation allows to separate them as described in the next section.

4. Analysis of the power modulation for off-axis

The power modulation (10%, 30Hz) applied "on the top" of the ECRH pulse in the above experiments allows to analyse simultaneously the propagation of the heat pulses with a Fourier transform method, yielding χ_e^{HP} [3,4]. The on-axis cases are not adequate for such analysis because of the strong MHD activity. The off-axis cases, however, yield interesting information because the modulation is expected to differentiate between diffusive and conductive (e.g. heat pinch) transport.

We consider again the off-axis case presented above (discharge 10591) with its 30 Hz 10% power modulation. The amplitude and phase yielded by Fourier transformation are shown in Fig. 3. Both phase and amplitude are strongly asymmetric which clearly indicates a strong transport difference between the sides with radii larger and smaller than that of the ECRH

deposition (ρ_{dep}). The fact that *both* amplitude and phase exhibit such an asymmetry proves that the transport difference between both sides is *not* due to a heat pinch. In fact a heat pinch is strongly visible on the amplitude but not on the phase. In the present case, the inward pinch required for the profile peaking would cause an asymmetry opposite to that of Fig. 3.
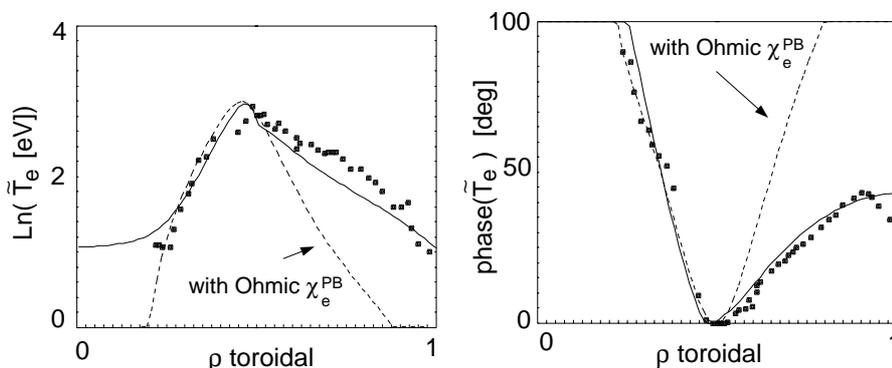

Figure 3. Amplitude (Log) and phase of Fourier transformation for both data and ASTRA modelling: dashed line with Ohmic χ_e^{PB}, solid line χ_e^{HP} from Fig. 2.

A simple approach using a χ_e^{HP} profile with step (shown in Fig. 2), provides a reasonable agreement between experimental and modelled amplitude and phase (Fig. 3). Note the large discrepancy when the Ohmic χ_e is used. It must be underlined that χ_e^{HP} used in the simulation is time-independent and in such a situation it is generally larger than χ_e^{PB} [3,4]. Here, as shown in Fig. 2 $\chi_e^{HP}/\chi_e^{PB} \approx 5$ which is a rather large value and suggests a strong dependence of χ_e on plasma parameters in this heating situation. Earlier modulation experiments in ASDEX Upgrade with less time-averaged ECRH power (about 200 kW instead of 600 kW) gave $\chi_e^{HP}/\chi_e^{PB} \approx 2$, compatible with $\chi_e \propto \nabla T_e$ [4]. Using physics based models was not yet attempted but clearly reproducing the results requires a strong χ_e dependence on profile changes, or power flux. The adequate model should allow χ_e to increase for $\rho \geq \rho_{dep}$ whereas the tendency of the off-axis heating to produce a flatter profile in the center should be counterbalanced by a decrease of χ_e for $\rho \leq \rho_{dep}$. A model based on a critical gradient assumption might have these properties.

5. Summary and conclusion

The on-axis and off-axis experiments performed in ASDEX Upgrade with ECRH, which has a narrow deposition width (w/a $\leq$ 0.1) and 100% single-pass absorption, clearly show that the electron temperature profile has a strong tendency to remain peaked: profile resilience. This is provided by the change in electron heat conductivity which strongly reacts to the position of the ECRH deposition. The existence of a heat pinch in these experiments has been ruled out by simultaneous power modulation experiments simultaneously in the same discharges. This effect is clearly visible owing to the scheme used here: larger time-averaged ECRH power, but keeping a small modulation, as compared to previous experiments in ASDEX Upgrade. Physical models should now be compared to the experimental data.

References

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