Transport Studies with ECRH Power Modulation in ASDEX Upgrade

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1. Introduction

Understanding transport is essential for future fusion devices. Perturbative transport experiments using power modulation are useful to investigate energy transport physics, complementary to power balance analysis. In fact, the transport coefficients deduced from power balance (χ^{PB}) and from modulation (χ^{HP}) are of different nature and comparing them should yield precious information on the underlying physics [1]. Such experiments are performed in the tokamak ASDEX Upgrade (R = 1.65 m, a = 0.5 m, $\kappa = 1.7$) using ECRH power modulation to study the electron transport.

2. Experiments

An ECRH system, (4 $\times$ 0.5 MW / 2s, at 140 GHz, 2^{nd} harmonic X-mode), was built at ASDEX Upgrade. This scheme provides central deposition at $B_T = 2.5$T and single-pass absorption of 100% under the plasma conditions presented here. The power is injected into the tokamak with 4 separate narrow-focused Gaussian beams, permitting localised ($\Delta r \leq 5$ cm).

The essential diagnostic is the 60 channel ECE radiometer which provides the electron temperature (T_e) over the whole plasma radius with a time resolution of ≈ 30 kHz. The radial resolution of each channel is about 1 cm and the distance between channels 1 to 3 cm. The ion temperature profiles are gained from charge exchange neutral energy spectra in the Ohmic cases and from CXRS in cases with NBI heating.

The results presented here are based on ECRH on/off power modulation experiments in Ohmic or NBI heated plasmas ($P_{NBI} \leq 5$ MW). The plasma current was varied between 0.6 MA and 1.0 MA and the magnetic field between 2.2 T and 2.5 T. The line averaged density was around 4 $10^{19} m^{-3}$. The working gas was either hydrogen or deuterium.

For the analysis of heat pulse propagation amplitude and phase of the modulated T_e versus radius, provided by Fourier transform, are used. Good quality results require a high signal to noise ratio of the measured T_e modulation. The amplitude of the signal at a given radius depends of course upon the distance to ECRH deposition and also upon the modulation frequency: low frequency provides a larger signal.

In tokamaks the major source of noise is generally caused by the sawteeth, particularly with NBI heating where sawteeth with low frequency (down to 10 Hz) and large amplitude create a strong noise. This noise has a broad frequency spectrum due to the jitter of the sawtooth frequency over the time of the analysis. The choice of the ECRH modulation frequency for good quality data, typically 30 Hz to 100 Hz, results from a compromise between low frequency for large signal and higher frequency to place the modulation where the noise caused by the sawteeth is lower.

A possible way of decreasing the noise caused by the sawteeth is to reduce their jitter in frequency such that the ECRH modulation can be placed between 2 harmonics of the sawtooth spectrum. This is possible due to the property of sawteeth which often lock their frequency to heat modulation if it is near enough to their natural frequency. We stabilised the sawtooth frequency by applying short NBI pulses at the top of the 2.5 MW background heating at the frequency of the sawteeth, measured in a previous discharge. In the example of Fig. 1, the ECRH modulation at 45 Hz was placed between the 3rd and 4th harmonic of the sawtooth frequency ($\approx$ 12 Hz). Thus the signal to noise ratio could be improved from 8 to 30. Using NBI pulses is not the best method because of the smoothing due to the slowing down time ($\approx$ 20 ms) of the beam ions. We observed that ECRH modulation provides a more accurate frequency locking of the sawteeth, but this requires 2 independent ECRH systems, not available at that time.

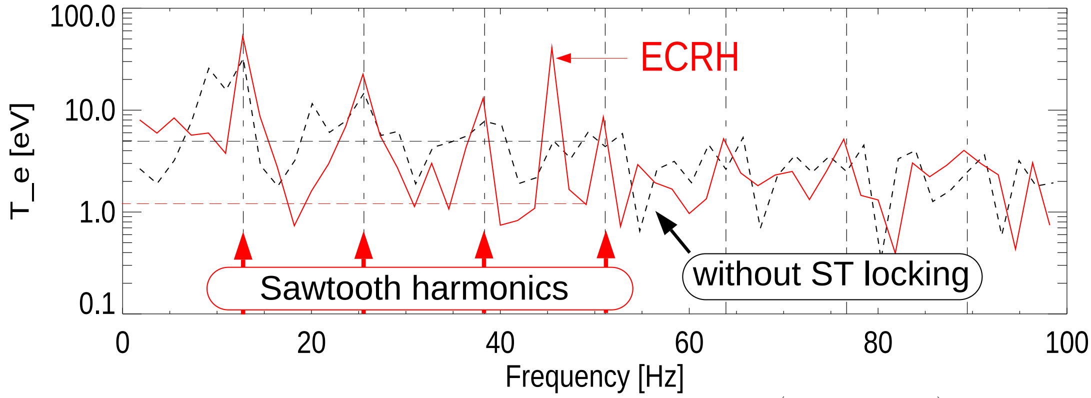

Figure 1: *Comparison of the frequency spectra without (dotted line) and with frequency locking of the sawteeth (solid line). The reduction in noise is shown by the difference between the two curves at 45 Hz.*

The frequency locking of the sawteeth was not used routinely because the sawtooth frequency must be known in advance within $\approx$ 10%. However, this confirmed our other results and indicated that those are valid in the region between the ECRH deposition and the plasma edge, where the effect of sawteeth is weak, but generally not in the region between centre and ECRH deposition where the signals are strongly distorted by the sawtooth pulses.

ECRH modulation performed in a few shots with flat shear ($q_0 \geq 1$) created by NBI applied early in the current ramp-up and which do not exhibit sawteeth [2] confirms this observation.

3. Results on transport

As mentioned above, the analysis of the ECRH modulation is based on the Fourier transform of the electron temperature. Amplitude and phase allow to determine directly the electron diffusivity for heat pulses (χ_e^{HP}) using a slab model approximation with corrections for geometry and density profile effects [3]. This provides a quick analysis of the heat pulse propagation, with acceptable accuracy. In addition we used the ASTRA transport code [4] for power balance analyses and also for time-dependent modelling of the discharges with ECRH modulation. The full transport equations are solved in toroidal geometry, the ECRH modulation is taken into account according to the experiment. Amplitude and phase of the modelled T_e are compared with the experimental ones. This

yields a precise comparison with experimental data and generally confirms χ_e^{HP} from direct Fourier analysis. Of course, modelling allows to test different physics assumptions as described below.
As example, the amplitude and phase of T_e in the shot from Fig. 1, L-mode with 3 MW of total heating power, are shown in Fig. 2.

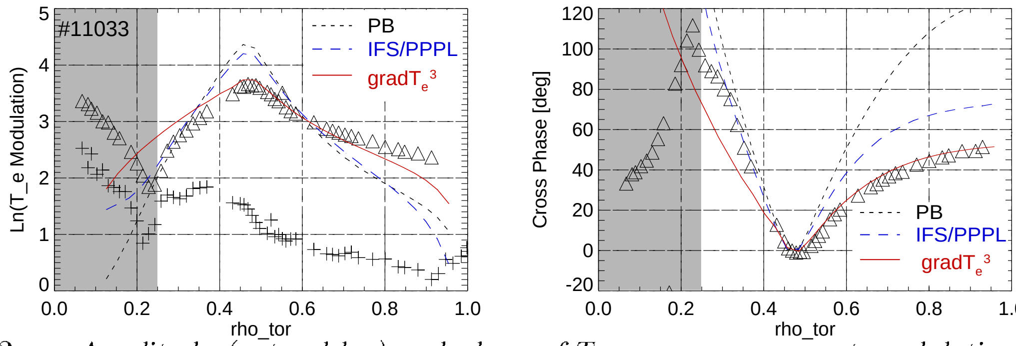

Figure 2: *Amplitude (natural log) and phase of T_e versus $\rho_{toroidal}$, at modulation frequency (45 Hz). Triangles are experimental data, lines are models as indicated in the figure and described in the text. The ECRH deposition is clearly seen at $\rho_{toroidal} \approx 0.47$. The crosses(+) at the lower part of the left figure indicate the noise, the shadowed parts indicate regions where the sawtooth noise is strong. In the other regions the signal to noise ratio is good.*

A striking feature of this figure is the strong asymmetry between the regions $\rho < \rho_{ECRH}$ and $\rho > \rho_{ECRH}$ of both amplitude and phase data. The analysis yields $\chi_e^{HP} \approx 1m^2/s$ in the region $\rho < \rho_{ECRH}$ and $\chi_e^{HP} \approx 7m^2/s$ for $0.6 < \rho < 0.8$. Whereas the former is close to the power balance χ_e, the latter value is about 4 times higher than the power balance χ_e. Other shots indicate that the asymmetry and the values of χ_e^{HP} for $\rho > \rho_{ECRH}$ clearly increase with total heating power. The asymmetry in Ohmic cases is weak and $\chi_e^{HP} \approx 2 \times \chi_e^{PB}$. However, at all values of the total heating power, these features seem to be independent of the amplitude of the modulation within our range: ECRH peak power from 50 kW to 700 kW. The propagation of sawteeth exhibits properties similar to the ECRH cases $\rho > \rho_{ECRH}$, with higher values of χ_e^{HP}.
To interpret these results we made simulations with different models, indicated with the lines in Fig. 2. The first simulation, as reference, is made with the time averaged power balance χ. The agreement with the data is poor, as expected. As physics-based model we used the IFS/PPPL [5] model based on ITG physics which is a very stiff transport model for ions. The agreement with experimental time-averaged temperature profiles (not shown here) is satisfactory with however a trend to provide flatter T_e and T_i profiles, the difference in the central temperatures being 10 % to 30 % , depending on the conditions. In the comparison between modulation simulations, it is important that the time-averaged χ are about equal. For this model we reduced both χ_e and χ_i by 20%. For the phase the agreement with the data is better with the IFS/PPPL model than using the power balance χ, however the asymmetry of both amplitude and phase is not reproduced with the desired magnitude and the value of χ_e^{HP} in the region $\rho > \rho_{ECRH}$ is too low by a factor of about 2. This model is expected to describe the ion physics but probably does not include all properties of the electron transport, which may be a reason for the lack of agreement. Other physics based models were not tested so far.
We also investigated the effect of a ∇T_e^{α} dependence of χ_e: $\chi_e = \chi_e^{PB} \times (\frac{\nabla T_e}{<\nabla T_e>})^{\alpha}$, where $< \nabla T_e >$ is the time-averaged gradient. This assumption yields $\chi_e^{HP} = (1+\alpha)\chi_e^{PB}$ [6].

Adjusting α allows to reproduce phase and generally amplitude with a good accuracy in the region $\rho > \rho_{ECRH}$. However the asymmetry is not reproduced by this model and thus χ_e^{HP} is much too high in the region $\rho < \rho_{ECRH}$. Note also that the amplitude at the ECRH deposition is well reproduced. The ECRH power was not adjusted but was taken according to the experiment. The value of α must be increased with heating power from ≈ 1 in the Ohmic case to ≈ 4 with 5 MW NBI.

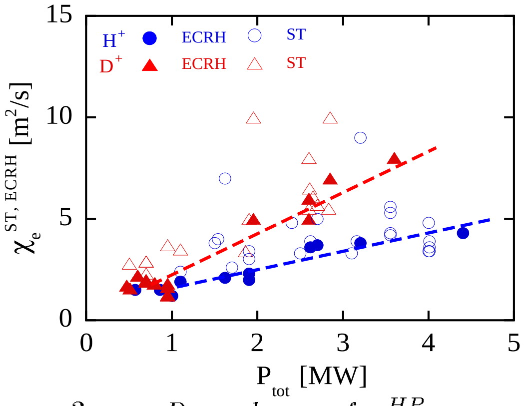

Figure 3: *Dependence of χ_e^{HP} versus heating power for ECRH and sawteeth (ST) in hydrogen and deuterium.*

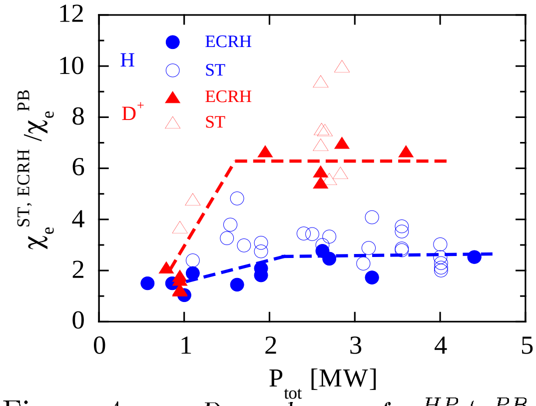

Figure 4: *Dependence of χ_e^{HP}/χ_e^{PB} versus heating power for ECRH and sawteeth in hydrogen and deuterium.*

The overview of our results for χ_e^{HP} in the region $\rho > \rho_{ECRH}$ ($0.6 \leq \rho_{tor} \leq 0.8$) for several shots are summarised in Fig. 3 and 4. They clearly show the increase of χ_e^{HP} for both ECRH modulation and sawteeth with heating power, as well as that of χ_e^{HP}/χ_e^{PB}. The lines are supposed to only guide the eye. Some values for sawteeth at high heating power reaching 30 are outside the frame of the figures. Fig. 3 and 4 also show that χ_e^{HP} is *lower* in hydrogen plasmas than in deuterium plasmas, in contradiction to the well-known isotope effect and to our power balance results. It must be added that, correlated with the lower values of χ_e^{HP}, the asymmetry is weaker in hydrogen than in deuterium. These results support the indications that heat pulse propagation does not directly reflect the power balance χ.

Acknowledgement
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