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Kinetic effects on particle flux induced by ECRH in TJ-II stellarator

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Introduction.

Fast transport phenomena in plasmas are usually denoted as non-local transport to show that the perturbation is propagated much faster than the background diffusive transport. Both heat and cold pulse propagation have exhibited this kind of behaviour. As it seems that the perturbations propagate almost instantaneously, the fluxes must depend on the plasma characteristics of points far from the one where the transport is estimated [i]. Beyond the formal description of the non-local transport, it would be necessary to give its dynamical explanation, which is done here for the heat pulse propagation.

Heat wave experiments have been used in tokamaks and stellarators (see e. g. [ii] and [iii]) to study electron heat transport and to estimate the power deposition profile. In such experiments, several effects that cannot be attributed to a diffusive behaviour were observed: namely convective transport and a systematic widening of power deposition profile in comparison with the predicted by WKB theory for a Maxwellian distribution function [iii]. The former results are related to the appearance of an extra outward electron flux induced by ECRH both in tokamaks and stellarators. Some experimental features of the existence of this flux are the hollow density profiles and the increase of H_α emission when the gyrotron is switched on, as well as the onset of a suprathermal component in SXR spectra and an increase of SXR flux emissions observed at the vacuum vessel and at the limiters [iv]. Such a convective transport has been observed in heat wave experiments on the TJ-II flexible heliac.

The Convective Flux

This non-diffusive, ECRH-induced extra particle flux cannot be attributed to the existence of thermo-diffusion that relates particle flux with the temperature gradient, although this term could be playing some role due to the steep temperature gradients that appear in ECRH plasmas. Kinetic effects are necessary to explain the obtained results.

An extra positive electric field is triggered when this outward electron flux appears due to the ambipolar condition: ions are not affected by ECRH and a positive electric field must be increased to restore the charge flux balance (see e. g. [v]). The positive electric field plays a key role in creating an enhanced heat confinement, due to the appearance of the electron root in the centre of the (see e. g. [vi]).

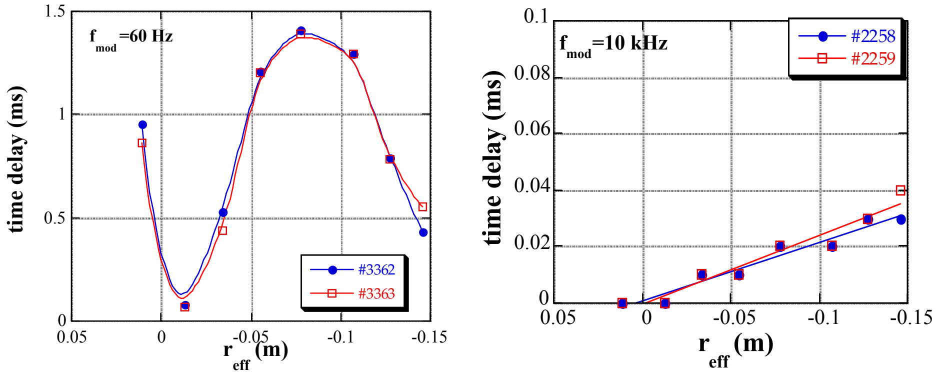

Figure 1: Time delay in several modulation experiments on TJ-II. a) Two shots with modulation frequency 60 Hz. b) Two shots with modulation frequency 10 kHz.

Low modulation frequency experiments, typically 30-70 Hz, are performed to estimate heat diffusivity in TJ-II while fast frequency (several kHz) modulation is used to probe the power deposition profile, assuming that transport phenomena are too slow to follow this fast modulation. This latter assumption is not justified, as will be shown below. Electron Cyclotron Emission (ECE) measurements are used to study the heat wave propagation in TJ-II. Eight channels with a sampling frequency of 50 kHz are located in the high field side (HFS) and allow us to measure the radiative temperature with good enough time resolution. Figure 1a shows the time delay of the pulse propagation from the central ECE outwards, during power modulation experiments. It can be seen that this time delay, obtained from phase shift, is not monotonic with radius (The same result is obtained for modulation frequency of 0.5 kHz, not shown here). These effects cannot be attributed to the downshifted emission of high energy electrons, since full reabsorption of the power emitted by those electrons at lower frequencies is expected. The weak optical thickness cannot be either the cause since it is avoided by the existence of multiple reflections. These features of the phase delay have been observed in other experiments performed in tokamaks [i], showing that this it is a universal effect that happens in many devices.

The shape of the time delay for $\rho < 0.4$ (<r> < 0.075 m) shows a clear diffusive behaviour in Fig. 1a, since the propagation of heat wave is described by $r \sim t^{1/2}$. A decreasing time delay is observed at outer positions, showing that these points react to the heating before the closer ones. Such decreasing delay has to be due to the presence of fast electrons at those external positions. The value of the magnetic field corresponding to the ECE channel with maximum delay behaviour (ρ≈0.4) is B≈1.0403 T, therefore the energy of resonant electrons is K ≥ 20 keV. A single modulation cycle takes 1/(60 Hz)=16.6 ms (and 1/(0.5 kHz)=2 ms), which are time intervals long enough for fast electrons to travel to the edge. The fact that the amplitude of the modulation is much larger in the inner than in the outer ECE channels, T_w (ρ>0.5) << T_w (ρ<0.5) [iii], shows that the population of fast electrons must be small, but they are able to leave a footprint on the delay signal.

As the modulation frequency is increased, the shape of time delay becomes more and more monotonic, showing again that the former effect cannot be attributed to downshifted emission or weak optical thickness. For very high modulation frequency (≥5kHz) the delay is totally monotonic, showing a clear ballistic behaviour, since r(t) ~ t, as can be seen in Fig. 1b: transient transport induced by ECRH is convective.

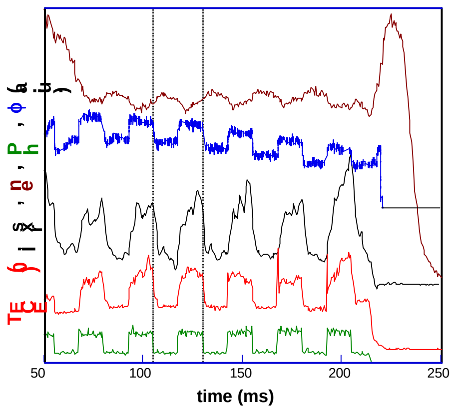

Figure 2: Time evolution of central potential and temperature, SXR intensity and line density in a discharge with f_{mod}=40 Hz and a modulated power of 200 kW over a 200 kW continuous heating power.

The heat pulse velocity (v_r ≈ 4500 m/s for f_{mod}=10 kHz and v_r ≈ 3100 m/s for f_{mod}=5 kHz) is of the same order as the drift velocity for the high energy resonant electrons in TJ-II, about 3300 m/s. The non-monotonic behaviour disappears for some frequency between 5 and 0.5 kHz, therefore, the maximum time scale for which diffusive effects are still present has to be between 0.2 ms and 2 ms.

When the modulated power is similar to the steady heating power, plasma density suffers the effect of heating and the pump-out is strong enough to modify plasma density profile. A power of P=200 kW has been modulated with f_{mod} =40 Hz in a plasma sustained by a constant P=200 kW. Line density is also modulated in counter phase with power and temperature, as expected. Fig. 2 shows that the central temperature and line density evolution during high power modulation experiments are in counter phase. As density is reduced, the potential is increased and the central electron heat confinement is improved. Fig. 2 also shows the evolution of central potential, which is found in phase with temperature. We have studied the possible existence of a delay between the central temperature channel and the potential signal, having found that both are simultaneous within our time resolution (<10 μs). The evolution of plasma potential profile during a modulation cycle shows that the potential slope is the same everywhere in the profile but in the plasma centre, where an enhanced electric field appears during the upper modulation cycle.

The fast particle flux is monitored by SXR. Power modulation experiments at f_{mod}=60 Hz with 100% modulated power have shown the existence of fast electron losses roughly in phase with ECE. The spectra tipically show that the average energy of superthermal electrons is duplicated (from 1.5 keV to 3 keV). These fast electrons react to the modulation power and reach the limiter faster than the bulk plasma does. The SXR signal reacts between 10 and 20 μs before ECE signal does.

The induced particle flux can be obtained comparing two Thomson scattering density profiles, acquired during the gyrotron switch-on and off phases, and considering the time-scale, given by ECE, $t \approx 1 - 5 \cdot 10^{-3}$ s. The flux is $\Gamma^{ECH} \approx 3.5 \times 10^{12}$, in agreement with [v].

Conclusions

The main consequences of these findings are: 1) Thermo-diffusion must be estimated carefully in ECRH plasmas since the outward particle flux cannot be explained only by the existence of such non-diagonal transport coefficient [vii], since the pump-out is usually dominant. 2) These phenomena can produce an apparent widening of the power deposition profile when this is measured using fast modulation experiments. The extra widening was traditionally explained in terms of the non-Maxwellian features of the electron distribution function (see e. g. [viii]), but one has to take into account fast transport phenomena that can make the power deposition profile wider. The distance reached by fast electrons in a modulation cycle gives the extremes of power deposition area in the minor radius, which can be obtained from the radial velocity of convective heat pulse and the modulation frequency: $\Delta r \approx v_r / f_{\mathrm{mod}} \approx 3000\, m/s / 5\, kHz \approx 6 cm$ (in agreement with [iii]). 3) Finally, the dynamics of fast electrons is a feasible explanation for non-local transport phenomena.

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