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Coupling between Particle and Heat Transport during Power Modulation Experiments in Tore Supra

X.L. Zou, G. Giruzzi, J.F. Artaud, F. Bouquey, S. Brémond, J. Clary, C. Darbos, S.P. Eury, M. Lennholm, R. Magne, J.L. Ségui

Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, 13108 St. Paul-lez-Durance (FRANCE)

1) Introduction

Particle transport is an important issue in magnetically confined fusion plasmas. Recently a significant peaking of the density profile has been observed on the Tore Supra tokamak in long discharges (> 4 mn) with fully non-inductive lower hybrid current drive [1]. In this regime the loop voltage remains zero over a time much longer than the current diffusion time, *i.e.* the toroidal electric field vanishes over the whole plasma volume, as well as the neoclassical Ware pinch. This suggests the existence of an anomalous particle pinch in the plasma. The anomalous pinch velocity is predicted by turbulent transport theories. For example, a 3D fluid model of ITG/TEM turbulence shows that there are two types of particle pinch [2]: the curvature driven pinch, which depends essentially on the magnetic shear and the plasma geometry, and the themodiffusion, which depends on the temperature profile and on its gradient.

Power modulations are a powerful tool often used to investigate heat transport processes in tokamaks [3]. In some situations, this could also be an interesting method for the investigation of the particle transport due to the anomalous pinch. Low frequency ($\approx 1\,Hz$) power modulation experiments, using both electron cyclotron resonance heating (ECRH) and ion cyclotron resonance heating (ICRH), have been performed in the Tore Supra tokamak. A strong and synchronous coupling has been observed between the density and temperature modulations. The aim of this work is to determine the driving source for this density modulation, and in particular the role played by the anomalous pinch.

2) ECRH and ICRH modulation experiments

A series of low frequency ECRH and ICRH modulation experiments have been performed in Tore Supra in order to investigate the coupling between the density and temperature modulations. Figures 1 and 2 show the time evolution of the temperature, chord averaged density and loop voltage during an ECRH and an ICRH modulation experiment, respectively. The plasma parameters in these discharges are: R=2.38 m, a=0.70 m, I_p=1 MA, B_0=3.8 T. For the ECRH modulation, a power of 0.7 MW (delivered by two gyrotrons) has been injected into the plasma with a modulation frequency of 1Hz. For the ICRH modulation, a power of 0.92 MW has been injected into the plasma with a modulation frequency of 0.67Hz. These figures show that for both heatings the temperature is perfectly modulated by the input power, and furthermore the chord averaged density is strongly and synchronously modulated with the temperature. Note that the loop voltage in both cases is inversely modulated with the temperature. This can be easily explained: when the temperature increases, the plasma resistivity decreases, as well as the loop voltage, since the plasma current is constant. The appearance of the density modulation in this kind of experiments mainly depends on two parameters: the input power and the modulation frequency. In our case, when the input power is less than 0.4 MW or the modulation frequency is larger than 4 Hz, the amplitude of the density modulation is strongly reduced and it is difficult to analyze the density modulation.

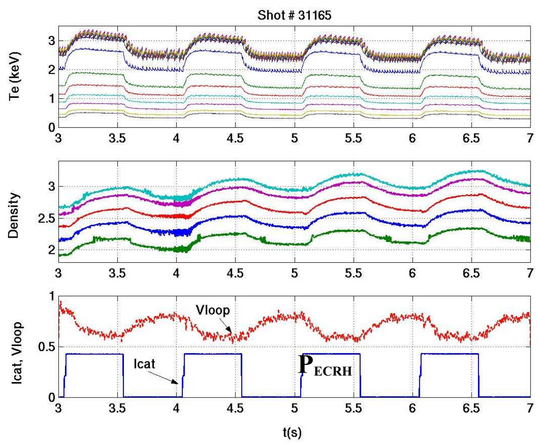


Fig.1 ECRH modulation experiment :
P_{ECRH}=0.7 MW, f_{mod}=1.0 Hz.

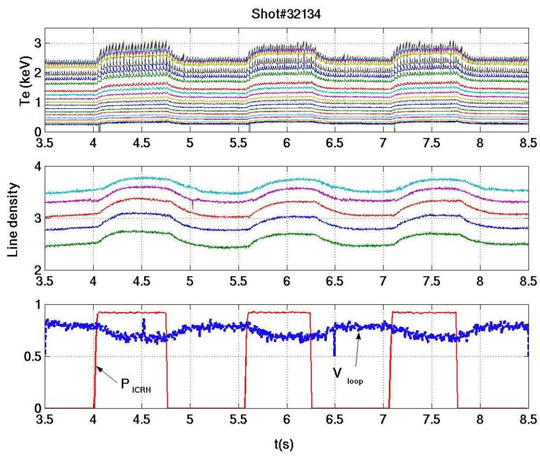


Fig.2 ICRH modulation experiment :
P_{ECRH}=0.92 MW, f_{mod}=0.67 Hz

3) Driving source for the density modulation

The particle transport equation can be written in the following form:

$$\frac{\partial n_e}{\partial t} = -\nabla\Gamma + S \tag{1}$$

where n_e is the density, Γ is the particle flux and S is the particle source. The particle flux is given by

$$\Gamma = -D\nabla n_e + \left(V_{ware} + V_{an}\right)n_e \tag{2}$$

where D is the particle transport coefficient, V_{ware} is the neoclassical Ware pinch velocity, and V_{an} represents the anomalous particle pinch or convection velocity. Turbulence driven transport theories show that the anomalous particle pinch velocity V_{an} can be decomposed in two terms [2]:

$$V_{an} = C_T D\frac{\nabla T_e}{T_e} - C_q D\frac{\nabla q}{q} \tag{3}$$

The first term in the RHS of Eq. (3) is the themodiffusion, which depends on the temperature and the temperature gradient; the second term is the curvature driven pinch, which depends essentially on the magnetic shear and on the plasma geometry of the plasma. In Eqs. (1-3), the driving source for the density modulation can be due to outgassing of plasma facing components caused by the input power, the Ware pinch effect V_{ware}, the curvature driven pinch, and the thermodiffusion. Now we try to determine by elimination this driving source.

3.1) Outgassing effect

Fig.3 shows a pure outgassing caused by an ECRH input power of 0.4 *MW*. In this configuration, because of misalignment of the polarisation of the incident EC waves, only 13% input ECRH power has been absorbed at the first pass, therefore the temperature is slightly affected during the ECRH phase, but a strong outgassing is observed for the density. It should be noted that the density raise and descent during the outgassing are much more prompt than that observed during the density modulations of Figs.1-2. Thus the outgassing can not be responsible for these density modulations. Note that during the *LH* power injection of 0.4MW, the density is slightly affected, thus no outgassing is present in this case.

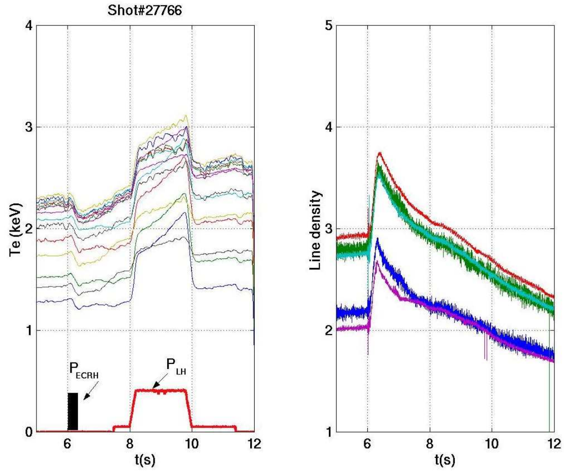


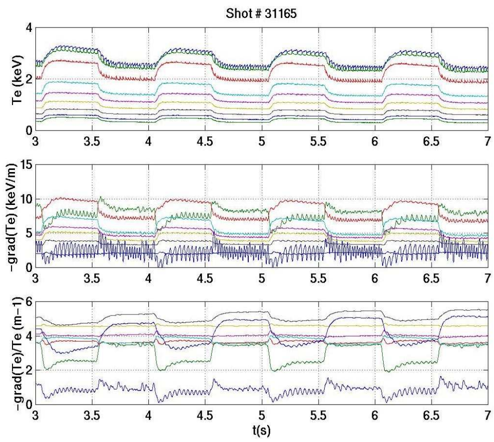
Fig. 3 Time evolution of the temperature (left) and the chord averaged density (right) during ECRH and LH power injection.

3.2) Ware pinch

The Ware pinch velocity is directly proportional to the toroidal electric field, thus to the loop voltage. As shown in Fig.1, the loop voltage during the power modulation experiments is inversely modulated with the temperature because of the resistivity, thus the Ware pinch cannot be responsible for the density modulation.*3.3) Curvature driven pinch*

As shown in [2], the coefficient C_q is essentially function of the magnetic shear and of the plasma geometry, and does not depend on the temperature except when $T_e \approx T_i$. On the other hand, the modulation of $\nabla q/q$, if it exists, is too small. Thus the curvature driven pinch can not be responsible for the density modulation.

3.4) Thermodiffusion driven effect



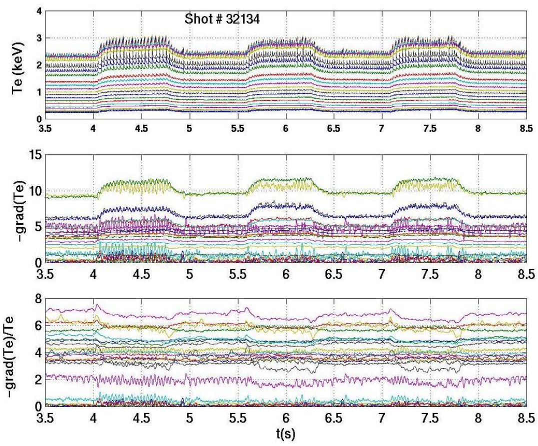


Fig.4 Time evolution of T_e, $-\nabla T_e$, $-\nabla T_e / T_e$ during the ECRH power modulation experiment.

Fig.5 Time evolution of T_e, $-\nabla T_e$, $-\nabla T_e / T_e$ during the ICRH power modulation experiment.

Figures 4 and 5 show the time evolution of the temperature, $-\nabla T_e$ and $-\nabla T_e / T_e$ during the ECRH and the ICRH modulation experiments, respectively. The temperature gradient is synchronously modulated as the temperature for both heatings. On the other hand, $-\nabla T_e / T_e$ is inversely modulated with the temperature for the ECRH modulation, while it remains nearly constant for the ICRH modulation. This difference of behavior can be explained by the input power deposition: strongly localized in ECRH, and much broader in ICRH. Thus the temperature gradient length or $\nabla T_e / T_e$ is not responsible for the density modulation. As the coefficient C_T is generally a function of the temperature or the temperature gradient [2], the thermodiffusion can be the driving source for the density modulation.

3.5) Simulation

From the above analysis, the thermodiffusion appears the most serious candidate as a driving source for the density modulation. Thus the corresponding density modulation driving source can be written as

$$S_m = -\nabla\left(C_0\, T_e\, D\left(\frac{\nabla T_e}{T_e} \right) n_e \right) \tag{4}$$

where C_0 is a factor defined by $C_T = C_0 T_e$.

Fig. 6 shows a simulation of the density modulation with the density modulation source given by Eq. (4).
The simulation has been done with an analytical model [4] for the solution of the diffusion/convection equation. The particle transport coefficient D is determined by the density profile analysis, and found to be D=0.5 m^2/s in the present case. Excellent agreement has been found between the experiment and the numerical simulation for $C_0 \approx 0.2$. This value of C_0 or C_T is compatible with that obtained on JET by density profile analysis [5].

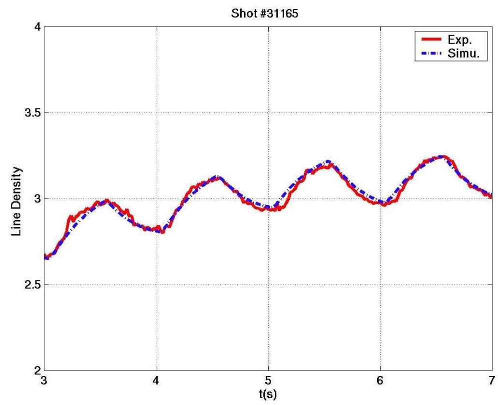


Fig.6 Simulation of the density modulation by an analytical model.

4) Conclusions

Strong coupling has been observed in Tore Supra between the temperature and density modulations during the low frequency ECRH and ICRH modulation experiments. It has been shown that mechanisms as outgassing, Ware pinch effect, curvature driven pinch are not likely to be responsible for this density modulation. Because of its dependence on temperature or temperature gradient, the thermodiffusion is a serious candidate to be the driving source for this density modulation. This analysis shows that low frequency power modulation experiments have a great potential for the investigation of the anomalous particle pinch in tokamaks. Future plans will include the use of more precise density profile measurements using X-mode reflectometry.

References

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