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Investigation of the Heat Pinch by Low Frequency ECRH Modulation Experiments in Tore Supra

X.L. Zou, S.D. Song, W.W. Xiao[a], G. Giruzzi, J.L. Ségui, F. Bouquey, C. Darbos, M. Lennholm, R. Magne, E. Traisnel

CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

a) Southwestern Institute of Physics, P.O. Box 432, Chengdu, China

The heat transport in tokamaks is a key issue for research in controlled magnetic nuclear fusion. The existence of a heat pinch remains a controversy, but is an important subject of research. In tokamaks DIII-D and RTP, a heat pinch is invoked to explain the results of ECRH experiments [1] [2]. On the other hand, in other tokamaks like ASDEX-U, ECRH experiments did not succeed in reproducing these results [3].

ECRH modulation at low frequency (<*5 Hz*) presents some advantages relative to the high frequency modulation (> *10 Hz*). It allows to exploit a very wide time scale, from first harmonic to the high harmonics (up to 11^{th} harmonic), on the heat transport property. In addition, owing to the large amplitude of the temperature modulation and a very different frequency, the FFT analysis is less affected by the sawtooth and other perturbations. By analyzing the phase and the amplitude of the Fourier components of the modulated temperature, and using their different sensitivity to the transport coefficients, it is possible to separately determine the heat diffusivity χ, the heat pinch V, and the loss term which is characterized by a damping time τ_d [4]. In fact, the derivative of the phase is very sensitive to the diffusivity, less sensitive to the pinch and the damping time; the minimum of the phase is very sensitive to the damping time, less sensitive to the diffusivity and the pinch; the amplitude is sensitive to the diffusivity and the damping time, very sensitive to the pinch for low harmonics, and insensitive to the pinch for high harmonics. Thus it is more interesting to work with low frequency modulations for the investigation of the heat pinch.

A series of experiments with ECRH modulations at low frequency has been carried out in Tore Supra. The plasma parameters in the present ECRH modulation experiments are: the major radius R=2.40 m, the minor radius a=0.70 m, the toroidal magnetic field B_T=3.73 T, the plasma current I_p=0.7 MA. The electron temperature profile is measured by a 32-channel ECE diagnostic with a spatial resolution of 3 cm. Fig.1 displays, respectively, the phase and the amplitude of the 1^{st} harmonic of the Fourier transform of the modulated temperature with a modulation frequency of 1 Hz. These figures show that the maximum of the amplitude is clearly shifted toward the center compared to the minimum of the phase located at ρ=0.51, which indicates the heat source location. This is often considered as an obvious proof of a heat pinch in ECRH experiments.

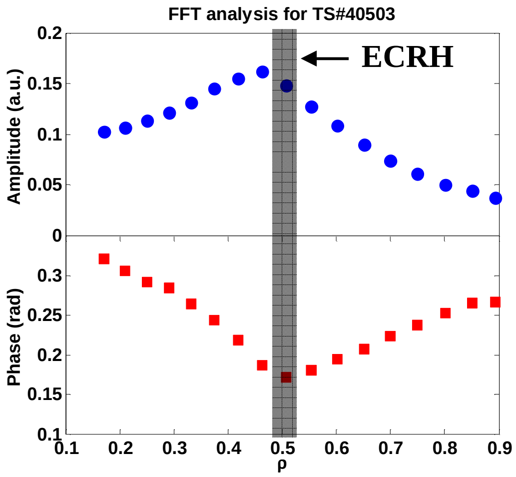

Fig.1 Phase and amplitude of the 1st harmonic of the Fourier transform of the modulated temperature.

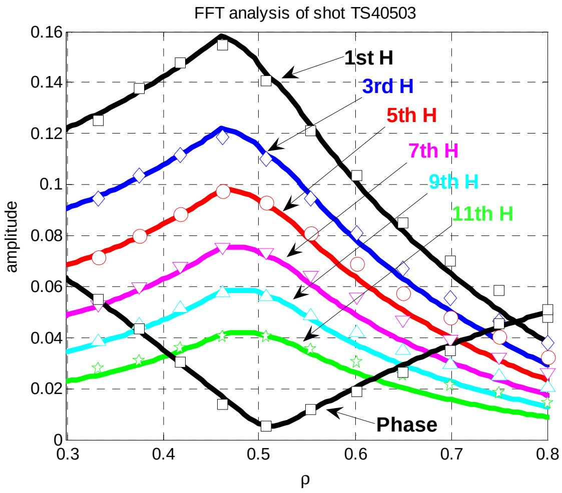

Fig.2 Amplitudes of harmonics 1, 3, 5, 7, 9, 11 of the Fourier transform of the modulated temperature. The points represent the experimental values, the solid lines represent the simulation.

Fig.2 shows the amplitudes of harmonics 1, 3, 5, 7, 9, 11 of the Fourier transform of the modulated temperature. The points on this figure represent the experimental values. The solid lines represent the simulation with the analytical solution of the following transport equation [5]:

$$\frac{\partial T_e}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\,k(r)\frac{\partial T_e}{\partial r} + r\,V\,T_e \right) - b\,T_e + S(r,t)$$

with the 3 control parameters, $k = 2\chi/3$, V, $b = 1/\tau_d$. S defines the heat source. We can observe that all the harmonics are well reproduced with the 3 parameters (diffusivity, damping time and pinch velocity). The pinch effect on the amplitude is maximum on the 1st harmonic, then decreases gradually, and disappears completely starting from the 7th harmonic. The decrease of the effect towards the high harmonics is a very strong signature of the pinch in modulation experiments. The parameters for the simulation are (see Fig.3): for the diffusivity $k_1 = 0.75m^2/s$ inside the ECRH deposition, $k_2 = 0.95m^2/s$ outside the ECRH deposition; for the damping time $\tau_d \approx 67ms$; for the heat pinch $V = 3.5m/s$ localized just inside the ECRH deposition with a width of 3.5 cm. This localized heat pinch, which moves following the ECRH deposition, is probably directly driven by the ECRH.

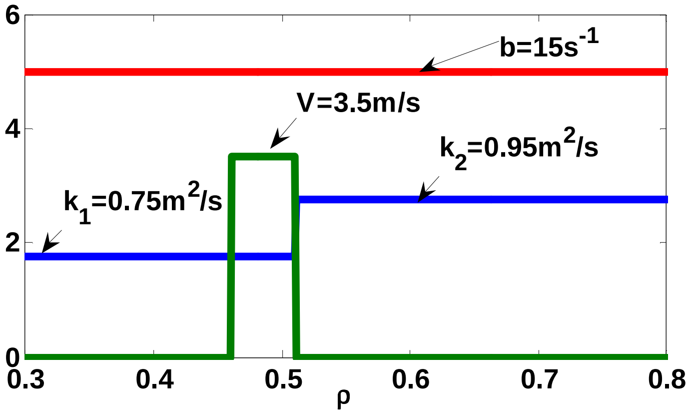

Fig.3 Radius profile of the diffusivity, the damping time, the pinch velocity.

Now the important question is the following: is the heat pinch always localized at the ECRH deposition? The following example shows a case with non localized pinch. Fig.5 display, respectively, the phase and the amplitude of the 1st, 3rd, 5th harmonics of the Fourier transform of the modulated temperature. The solid and dashed lines represent the simulation with and without pinch, respectively. For the phase of all 3 harmonics no significant differences are observed for the 2 simulations; for the amplitude of 1st harmonic, we have to introduce a non localized pinch of $V = 0.3 m/s$ in order to correctly reproduce the experimental points, while for the amplitude of 5th harmonic no difference is observed as for the phase. This indicates clearly the presence of a moderate heat pinch in the central region of the plasma. Fig.6 shows the corresponding parameters used in the simulation. A large jump has been obtained in the diffusivity, which can be explained by the critical gradient as shown in [3].

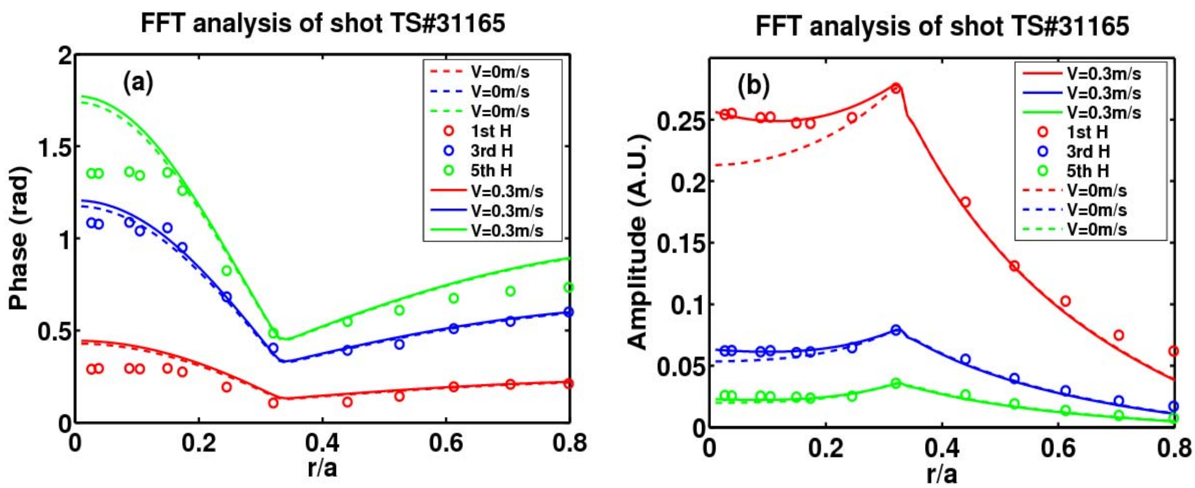

Fig.5 Phase (a) and amplitude (b) of the 1st, 3rd, 5th harmonics of the Fourier transform of the modulated temperature. Simulations with pinch (solid) and without pinch (dash).

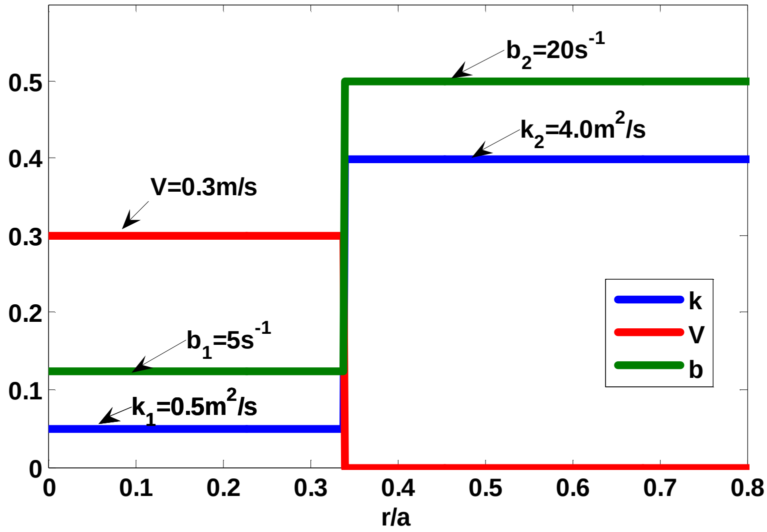

Fig.6 Radius profile of k, b and V.

In conclusions, two types (localized and non localized) of heat pinch have been observed in ECRH modulation experiments in Tore Supra. In the same time a large jump in the diffusivity (critical gradient) has been observed at the ECRH deposition. Decreasing effects of the heat pinch on all harmonics (from 1st to 11th) have been well reproduced. For moderate heat pinch, the modulation frequency should be lower than 5 Hz in order to detect the pinch effect on the amplitude. This possibly explains why different results have been obtained in different tokamaks with ECRH modulation experiments.

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