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Heat Transport Barriers in RTP: Diffusive or Convective?

P.Mantica[1], G.Gorini[2,1], G.M.D.Hogeweij, N.J.Lopes Cardozo, A.M.R.Schilham and the RTP team

FOM Instituut voor Plasmafysica 'Rijnhuizen', Associatie Euratom-FOM, Trilateral Euregio Cluster, P.O.Box 1207, 3430 BE Nieuwegein, The Netherlands

[1] Istituto di Fisica del Plasma, Euratom-ENEA-CNR Association, Milano, Italy

[2]INFM and Dipartimento di Fisica 'G.Occhialini', Università degli Studi di Milano-Bicocca, Milano, Italy

In Rijnhuizen Tokamak Project (RTP, R/a=0.72m/0.16m, B_T<2.4 T, I_p<150 kA), experiments in conditions of dominant Electron Cyclotron Heating (P_{ECH}/P_{OH} >3) have shown that the central electron temperature (T_{e0}) reacts discontinuously to continuous changes of the ECH resonance location, ρ_{dep} (Fig.1) [1]. Regions where T_{e0} shows little variations with ρ_{dep} have been labelled with letters from A to E, and the rapid transitions from one plateau to the next have been observed to be correlated with the loss from the plasma of one low order rational magnetic surface (in A the innermost magnetic surface is q=1, in A' q=1.5, in B q=2, in C q=2.5, in D q=3, in E q=3.5). This evidence has been interpreted in terms of the existence in the plasma of layers of reduced electron thermal transport ("transport barriers") associated with the main rational magnetic surfaces and whose width is determined by the local magnetic shear (shell model) [2].

Modulated ECH (MECH) has been applied to these plasmas, with the purpose of probing the transport properties of such barriers, as a complement to the steady-state evidence. Since only one gyrotron (110 Ghz, 350 kW, 2nd harmonic X-mode, perpendicular launch from the low field side) was available both for sustaining the heating and for the perturbative transport studies, this experiment was performed by applying high duty-cycle MECH ($\omega/2\pi$=310 Hz, d_c=0.87) at different values of ρ_{dep}. Such MECH shots are marked in Fig.1. By applying standard Fourier analysis to the T_e time traces (about 50 cycles) measured by the 15 channels ECE heterodyne radiometer, one obtains the radial profiles of the amplitude (A) and phase (φ) of the induced T_e perturbation at 3 harmonics of the MECH frequency.

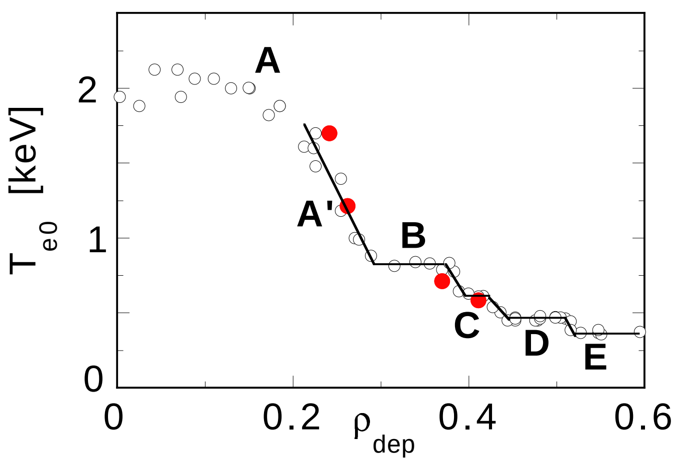

FIG.1. Central electron temperature vs. ρ_{dep} for a set of similar discharges (I_p=80 kA, q_a~5, $n_e(0)$=4 $10^{19} m^{-3}$) in which ρ_{dep} is increased in small steps from shot to shot. The full dots mark the discharges where the ECH power was modulated (duty cycle d_c=0.87, modulation frequency $\omega/2\pi$=310 Hz). The line is a guide to the eye.

These experiments have provided unexpected experimental evidence that was preliminarily presented in [3]. Let us first compare (Fig.2) two MECH discharges with identical parameters, but with a very different MECH d_c (d_c =0.15 and d_c =0.85). In both cases ρ_{dep} =0.25. The low d_c case is a standard off-axis MECH experiment in a quasi Ohmic plasma, the d_c =0.85 case is off-axis MECH in a ECH dominated plasma in sub-plateau A' (see Fig.1). Plotted in Fig.2 are for the two cases: a) the steady-state T_e and q profiles (the latter calculated assuming neoclassical resistivity and correcting for the bootstrap current); b) the A profiles at 3 harmonics; c) the φ profiles at 3 harmonics. There is a clear difference in the T_e and q profiles, as expected. The striking point is however the difference in MECH data.

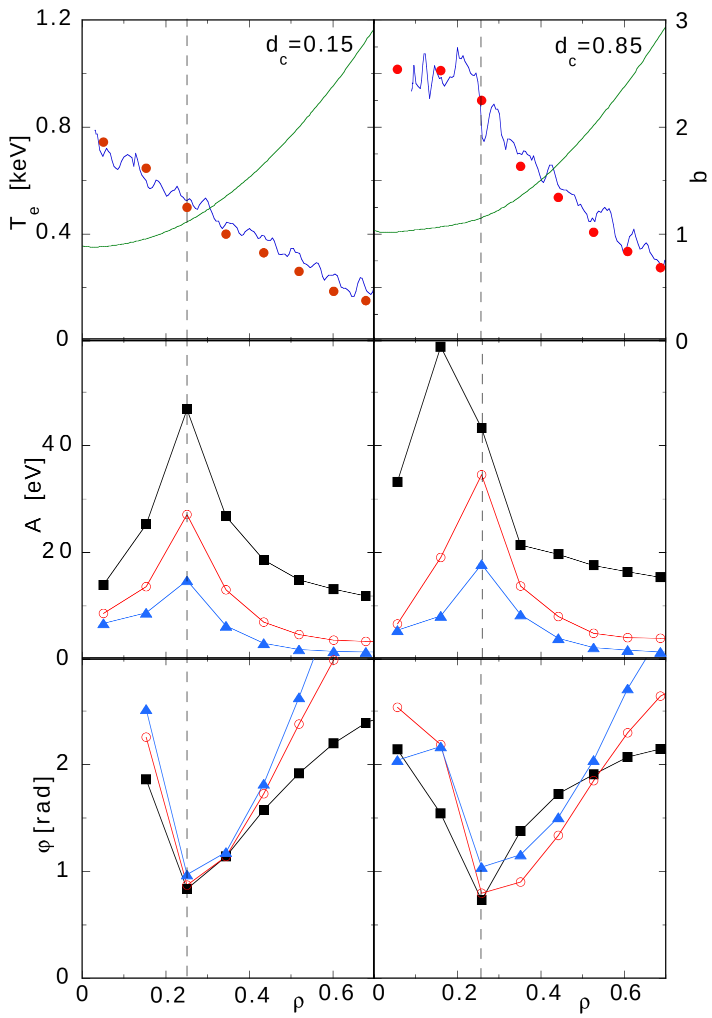

FIG.2. T_e and q profiles and MECH amplitude and phase profiles at 3 harmonics for two similar discharges with different MECH d_c: d_c=0.85 (r19980616.024, right column) and d_c=0.15 (r19980616.025, left column). Plasma parameters: I_p=80 kA, q_a~5, $n_e(0)=5\ 10^{19} m^{-3}$, ρ_{dep} =0.25

In the low d_c case, the behavior of A and φ has the usual 'diffusive' features: the amplitude decays and the modulation phase lag increases moving away from the heat source (ρ_{dep}) so that the locations of the peak amplitude and minimum phase coincide. In the high d_c case, in contrast, the data show an inward shift of the amplitude peak at 1st harmonic. This feature gradually disappears at higher harmonics, the 3rd one presenting a standard 'diffusive' pattern. Even the 1st harmonic phase profile is not immune from non-diffusive features: diffusive transport requires φ to increase with frequency at ρ_{dep} and elsewhere; instead, a larger 1st harmonic φ value relative to the other harmonics is found in the region just outside ρ_{dep}. These observations are in qualitativeagreement with the presence of a heat pinch (convective) component in the modulated heat flux [4]. Alternative explanations have been considered: spurious ECH power inside ρ_{dep} has been excluded as it would affect in the same way all harmonics; a strong χ_e gradient would yield convective-like features in MECH data [4], however quantitative simulations have shown that a χ_e gradient still compatible with the high harmonic data would yield a much lower convective-like effect at low harmonics than measured. The cause of the heat pinch does not seem to be the ECH power since the low d_c

case is immune from the effect. Rather, there are important modifications induced by ECH power in the plasma parameters that may be responsible for the heat pinch; in particular, the T_e and q profiles are rather flat inside ρ_{dep}. The time evolution of the T_e oscillations after switch on of the MECH shows that the time scale for the onset of the heat pinch is longer than the energy confinement time (≈3 ms) but comparable to the current diffusion time (≈10 ms). This suggests that the magnetic shear may in fact be a key factor for the onset of the heat pinch.

The signatures of the heat pinch in MECH data just discussed are present in all four discharges in different plateaux marked in Fig.1, as was shown in [3]. Moreover, a closer inspection of the steady-state T_e profiles (also reported in [3]) reveals that a heat pinch component must be present also in the time averaged heat flux. In fact in all T_e profiles the maximum T_e value is always located inside ρ_{dep} (note that ρ_{dep} is determined consistently from modulated ECE data, thus ruling out systematic errors in ρ_{dep} relative to the ECE profile), which cannot be accounted for by power balance analysis with diffusive transport only.

Quantitative simulations of the MECH experiments presented have been performed using the transport code ASTRA [5]. Fig.3 shows such a simulation for the MECH discharge in Fig.1 with the innermost value of ρ_{dep} (plateau A).

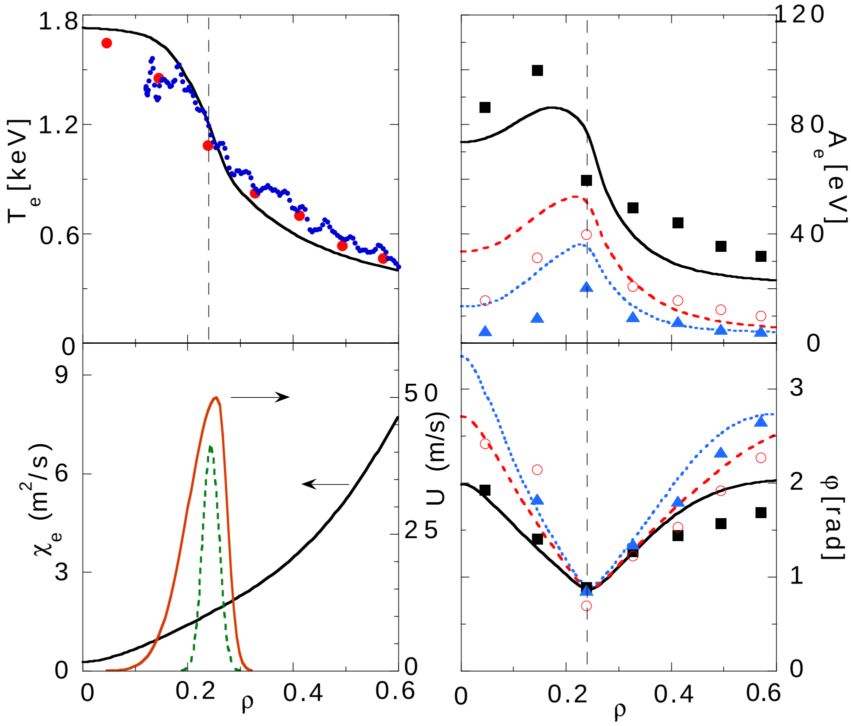

FIG.3. Simulated (lines) and experimental (symbols) profiles of T_e, MECH amplitudes and phases at 3 harmonics for the ρ_{dep} =0.24 (plateau A). The χ_e, U and P_{ECH} profiles (dashed, in a.u.)used in the simulation are also shown.

In the simulation we assumed that the electron heat transport consists of two components: $-q_e=n_e\chi \nabla T_e+n_eUT_e$. For both components an empirical description has been adopted, which was optimized to reproduce the data (Fig.3). It is found that a heat pinch velocity with peak value *U*≈50 m/s and localized in a rather narrow region of the plasma can match the gross features of the data, the most important one being the inward shift of the amplitude peak at low frequency. Similar agreement is obtained for the simulation of the other MECH discharges. Note that some features in the data are not perfectly reproduced, in particular the fast decay of the amplitudes at higher harmonics inside ρ_{dep}. This is due to the restrictive assumption in the χ_e model that the ratio χ^{pert}/χ^{PB} =1 [6]: allowing more elaborated models for χ_e would cure the discrepancy. This feature, however, is not related to the heat pinch issue on which this paper is focussed (it is present also al low d_c, see Fig.2). Therefore we decided to adopt the simplest model for χ_e yielding the heat pinch velocity profile.

Having shown that a strong and radially localized heat pinch is found in RTP plasmas with high ECH power, we can now address the question raised in the title of this paper: what is the relation between such heat pinch component and the transport barriers evidenced by the staircase behaviour in Fig.1? In fact, the Gaussian shaped heat pinch component required to reproduce the MECH data in Fig.3 acts as a powerful heat pump and can completely replace the main diffusive transport barrier located in the low shear region near ρ_{dep} in the shell model [2]. On the other hand, the diffusive barriers featured in the shell model cannot account for the non-diffusive MECH evidence, but could account for the staircase behavior of Fig.1 rather accurately. The question then rises whether a shell model based on narrow layers of strong heat pinch embedded in a smooth diffusive plasma background could reproduce the staircase behavior of Fig.1. It was an obvious step to test a simple model obtained by replacing in the shell model the low χ_e regions with layers of inward pinch (leaving all barrier prescriptions untouched) and using for χ_e the profile shown in Fig.3. Indeed, it was possible to recover with such model the staircase behaviour of T_{e0} as function of ρ_{dep}. In fact, the mechanism underlying the transitions is essentially the same as with the old shell model: a transition occurs when a rational q value and its accompanying pinch layer are lost. Note that, even if several pinch layers are simultaneously present in the shell model, only the one near ρ_{dep} (which is the largest due to the low magnetic shear in that region) is responsible for the discontinuous plasma response of Fig.1; it is also the only one detectable with MECH. Such a test can be regarded as a proof of principle that a shell model based on convective barriers could indeed explain at the same time the staircase evidence in Fig.1 and the MECH evidence in Fig.2. However, an optimization of the model to fit quantitatively all the experimental observations has not been attempted as the number of free parameters in the model is too large with respect to the small data set of MECH dicharges available.

In summary, MECH experiments in RTP dominant ECH plasmas have indicated the presence of a significant heat pinch component pumping heat against the T_e gradient. Such heat pinch is observed at different values of ρ_{dep} , and appears to show up (or at least become large enough to be measurable) in the low magnetic shear region created by off-axis ECH near ρ_{dep}. Previous observations of a heat pinch component in off-axis ECH plasmas were performed on DIII-D [7], but in a quite different plasma scenario. In order to simultaneously account for the MECH evidence (Fig.2) and the steady-state evidence of discontinuous plasma response to variations of ρ_{dep} (Fig.1) one has to assume that the heat transport barriers in RTP are mainly of convective rather than diffusive nature. This result opens a series of questions regarding what could be the physical mechanism underlying the heat pinch, which have not been addressed here. It certainly constitutes a stimulating result for theoretical research working towards a full understanding of electron heat transport.

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