Heat Pinches in Electron-Heated Tokamak Plasmas: Theoretical Turbulence Models versus Experiments

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Two fluid turbulence models, the drift wave based quasilinear 1.5D Weiland model and the electromagnetic global 3D nonlinear model CUTIE, have been used to account for heat pinch evidence in off-axis modulated electron cyclotron heating experiments in the Rijnhuizen Tokamak Project. Both models reproduce the main features indicating inward heat convection in mildly off-axis cases. In far-off-axis cases with hollow electron temperature profiles, the existence of outward convection was reproduced only by CUTIE. Turbulence mechanisms driving heat convection in the two models are discussed.

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Experimental observations have been reported in tokamaks DIII-D [1], FTU [2], and AUG [3] that, in conditions of localized off-axis electron cyclotron heating (ECH), inward electron heat convection [i.e., a contribution to the heat flux proportional to the temperature (T_e) rather than to its gradient] is required to explain the fact that the steady-state T_e profiles remain peaked even in the absence of a central power source. The first direct observations of such heat pinch were made using modulated ECH in tokamak RTP [4] and then in tokamak AUG [3]. In these experiments, a periodic T_e perturbation allowed the identification of convection from the distortion of the modulation amplitude profiles at low frequency.

On the other hand, theoretical investigation of turbulence predicts the possibility of turbulence-driven particle and heat convection [5–8]. Within the framework of "quasilinear theory," the two best known mechanisms for electrostatic turbulence to drive convective fluxes are the effect of the magnetic field curvature and a cross effect caused by the coupling between particle and heat transport (thermodiffusion, i.e., ∇T_e driven convection for particles, and density gradient, ∇n_e, driven convection for electron heat). Recently, more detailed bounce averaging has revealed the existence of a ∇q-driven (where q is the safety factor) contribution to the curvature effect [6] of the same type as predicted by the principle of turbulent equipartition. The resulting total convection can take either sign depending on the specific plasma conditions. Nonlinear turbulence simulations [6,9] can, in principle, imply turbulent particle and heat fluxes of the type $\Gamma(r,t) = \langle \delta n_e \delta v_r \rangle$, $Q_e(r,t) = 3/2\langle \delta p_e \delta v_r \rangle$, where p_e is the electron pressure, the average is over flux surfaces (i.e., with respect to toroidal and poloidal angles, not over time [9]), the velocity v_r is normal to the flux surface, and delta indicates fluctuations. In general, such fluxes are due to both electrostatic and electromagnetic fluctuations and are not simply proportional to local gradients. Both fluxes and gradients may rapidly vary in both space and time (i.e., on length scales a few times the gyroradius and frequencies much larger than the inverse of the energy confinement time), providing a net average convective term.

The RTP (major radius $R = 0.72$ m, minor radius $a = 0.16$ m) experiments reported in Ref. [4] provide a comprehensive set of results on which theoretical models describing mechanisms for the generation of heat convection can be tested. They include scans in ECH deposition radius (ρ_{dep}) and comparisons between results in mainly Ohmic heating plasmas and in plasmas dominated by off-axis ECH. All experiments were performed in hydrogen, using a 110 GHz, 350 kW gyrotron (2nd harmonic x mode) to heat the electrons and induce a T_e modulation using a square wave on-off power modulation. The plasma current was $I_p \sim 80$ kA ($q_{\text{edge}} \sim 5$), the central electron density $n_{e0} \sim 5 \times 10^{19}$ m^{-3}, and the toroidal magnetic field $B_T \sim 2$ T, finely adjusted to obtain the desired ECH ρ_{dep}.

The purpose of this Letter is to report on theoretical modeling of two sets of RTP experiments [4]. First, the case of weakly off-axis ECH deposition ($\rho_{\text{dep}} \sim 0.25$, $\rho = r/a$ indicating the normalized radial coordinate) is considered, where the T_e profile is peaked on-axis. For this case, results in "almost Ohmic" plasmas, with modulation duty cycle (i.e., the ratio of the duration of on phase to the total period) $d_c \sim 0.15$ are compared with results using high average ECH power ($d_c \sim 0.85$) where an inward shift of the peak amplitude of the first harmonic component of the variation of T_e (not present in the higher harmonics) indicates the existence of an inward convective heat flux just inside ρ_{dep} [4]. Second, the case of high d_c far-off-axis ECH ($\rho_{\text{dep}} \sim 0.44$) is considered where the T_e profile becomes significantly hollow. Since the core electron heat flux estimated from the experimental profiles is either positive or close to zero, the sustainment of a strongly inverted T_e gradient can be ascribed only to the presence of an outward convective heat flux in the plasma core [10,11]. Given that the modulation amplitude profiles still indicate the existence of the inward convective term localized just inside ρ_{dep}, this experiment constitutes a challenge for theoretical modeling.

The experimental profiles of T_e, n_e, q, as well as those of the amplitudes (A) and phases (φ) of the T_e variation at three harmonics of the modulation frequency ($\omega/2\pi = 310$ Hz), together with the estimated power source profiles are compared with the simulation results in Figs. 1–3 for the above two cases. All quantities are time averaged over several modulation cycles. T_e and n_e were measured with a 15 channel electron cyclotron emission (ECE) radiometer and a 16 chord microwave interferometer. High spatial resolution for T_e and n_e was obtained with a double pulse Thomson scattering system. Theoretical modeling of the data has been performed using both the drift wave based quasilinear fluid 1.5D Weiland model [5] and the electromagnetic global 3D nonlinear fluid code CUTIE [9,11], with time dependent simulations covering several modulation cycles in steady-state conditions.

The Weiland drift wave model includes ion temperature gradient (ITG), trapped electron (TE), kinetic ballooning, and magnetohydrodynamic ballooning modes [5]. For the ITG mode, the instability mechanisms present in slab as well as those due to toroidal geometry are considered, while for the TE mode the instabilities caused by the T_e gradient (compressional) and by the n_e gradient (ubiquitous mode) are taken into account. In these RTP discharges, the density is so peaked that the ubiquitous mode dominates. In the present version of the model, one impurity species is included (carbon in these simulations), treated with the same accuracy as the main ion species (H), and thus also an impurity ITG mode may be excited. The full transport matrix and convective fluxes are retained. In the matrix, effects of the dynamic variables, i.e., temperatures and densities, are included. In the convective fluxes, the gradient of the confining magnetic field is taken into account. Magnetic drifts usually dominate the off-diagonal elements. Important magnetic drift effects arise from the diamagnetic heat flow. Thus, inclusion of the fluid resonance is important. The overall trend of the off-diagonal elements is to make the different length scales of densities and temperatures comparable. The convective fluxes, although not directly dependent on the length scales, do not seem to change this trend. The effects of all unstable modes are summed up to yield the transport coefficients. The model uses a non-Markovian mixing length assumption, leading to a larger contribution to the ion thermal conductivity from modes propagating in the ion drift direction and vice versa for electrons. In combination with off-diagonal and convective transport fluxes, this can lead to different transport properties for different physical quantities, although in the model only electrostatic (mediated by $E \times B$, as opposed to magnetic flutter dependent) transport fluxes are considered.

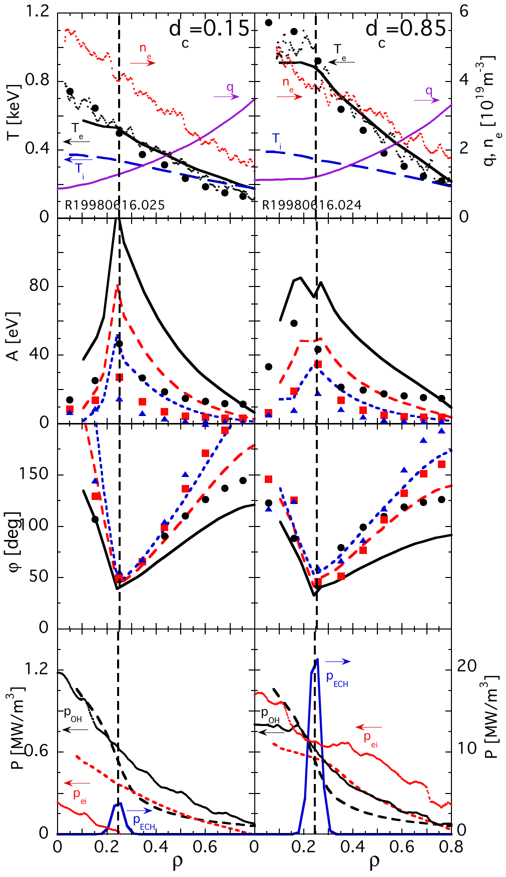

FIG. 1 (color online). 1st row: Profiles of T_e (black), T_i (blue), n_e (red), q (violet). Dots are experimental data: T_e from ECE and Thomson scattering, n_e from Thomson scattering, q calculated from the measured T_e and n_e profiles, and loop voltage, assuming neoclassical resistivity and correcting for the bootstrap current. Lines are simulations using the Weiland model (q and smoothed n_e profiles are taken from experiment). 2nd and 3rd rows: Profiles of 3 harmonics of A and φ: dots are experimental data (1st: black circles, 2nd: red squares, 3rd: blue triangles), lines are simulations using the Weiland model (1st: black full line, 2nd: red dashed line, 3rd: blue dotted line). 4th row: Profiles of ECH (blue), Ohmic (black), and e-i exchange (red) power density [for the latter two, profiles from experimental determination (small dots) and from simulation (dashed lines) are plotted]. All profiles are time averages over the modulation cycles. Two similar discharges with $\rho_{\mathrm{dep}} = 0.25$ with different duty-cycle: $d_c = 0.85$ (R19 980 616.024, right column) and $d_c = 0.15$ (R19 980 616.025, left column) are compared.

The CUTIE code is an electromagnetic, global two-fluid model for saturated plasma turbulence in tokamaks. The equations used to evolve $T_{e,i}$, $n_e \sim n_i$, the ion parallel velocity v, the electrostatic potential Φ, the parallel vector potential Ψ, and the potential vorticity Θ are described in detail in Refs. [9,11]. The heat flux includes neoclassical, turbulent convective $E \times B$ and magnetic "flutter" contributions. CUTIE models tokamaks on "mesoscales": In time, these range between the Alfvén time [$t_A = qR/V_A$, with $V_A = B_T/(4\pi m_i n_e)^{1/2}$] and the resistive time ($t_{\mathrm{res}} = 4\pi a^2/c^2 \eta_{\mathrm{nc}}$, where η_{nc} is the neoclassical resistivity), and

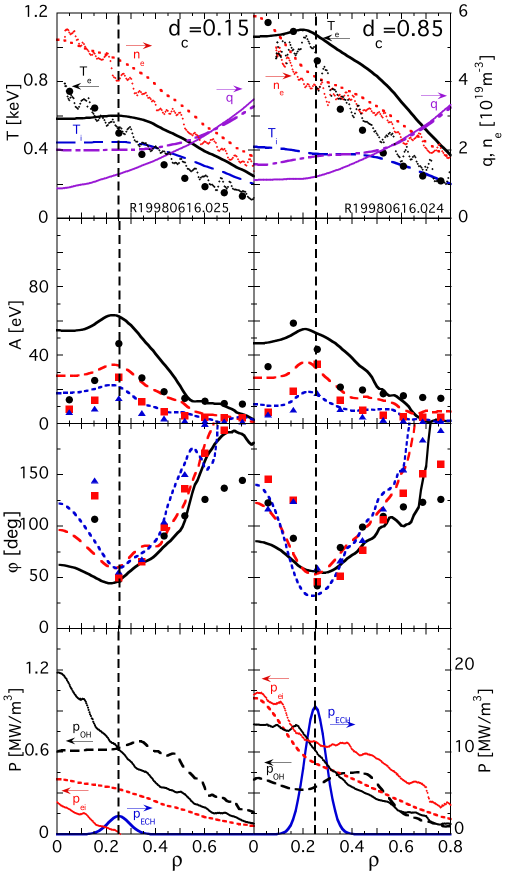

FIG. 2 (color online). Same as in Fig. 1 with simulations using the CUTIE code. Here n_e is also simulated, and q (and P_{ohm}) evolved consistently.

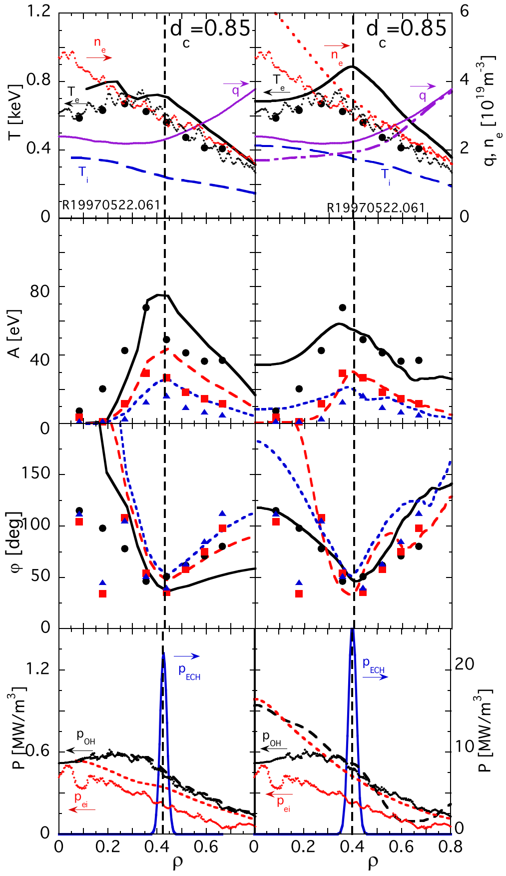

FIG. 3 (color online). Same quantities as in Fig. 1 for discharge R19 970 522.061 with $\rho_{\mathrm{dep}} = 0.44$ and $d_c = 0.85$. The left column presents simulation with the Weiland model; the right column presents simulation using CUTIE.

in space, the meso length scales L_{meso} satisfy $r_s < L_{\mathrm{meso}} < a$ [where $r_s = C_s/\Omega_i$; $C_s^2 = (T_e + T_i)/m_i$; $\Omega_i = eB_T/m_i c$; m_i is the mass of the main ion species, and e is the elementary charge]. The model includes the physics of shear Alfvén, drift tearing, and ballooning modes [11]. When subject to external sources (i.e., modulated ECH power), the system gives rise to turbulence with regions of mesoscale variations of the profiles called "corrugations," which interact nonlinearly with the turbulence.

Figures 1 and 2 show that, as in the experiments, both in the Weiland and in the CUTIE simulations at high d_c an inward shift of the 1st harmonic A component is present, which gradually disappears at higher harmonics. In the low d_c case, instead, the locations of maximum A and minimum φ at all harmonics coincide with each other and with ρ_{dep}, as expected from diffusive transport. Overall, the quantitative agreement of simulations and data is far from perfect. For example, the Weiland model overestimates the amplitudes in the low d_c case, while in CUTIE the electron heat diffusivity (χ_e) in the core is too high, leading to broad profiles of A and φ around ρ_{dep}. However, we stress here that the simulation of modulation data is much more demanding than that of steady state and that the CUTIE results are the first ever made turbulent simulations of a T_e modulation experiment. In fact, the overall agreement is surprisingly good. In particular, the features that indicate the existence of a heat pinch in the high d_c case but not in the low d_c one are clearly seen in both simulations.

Figure 3 refers to the far-off-axis ECH case ($\rho_{\mathrm{dep}} = 0.44$). We note that in the CUTIE simulation ρ_{dep} has been set to 0.4 because the simulation with $\rho_{\mathrm{dep}} = 0.44$ led to strong MHD activity at a frequency coupled with the modulation frequency, which seriously distorted the modulation profiles. The simulation with $\rho_{\mathrm{dep}} = 0.4$, which is close to the experimental conditions, does not exhibit strong pollution by MHD activity. Again both models reproduce the experimentally observed inward shift of the first harmonic component of A.

As anticipated earlier, the peculiarity of the $\rho_{\mathrm{dep}} = 0.44$ case is that the hollow T_e profiles can be explained only by the presence of an outward convective heat flux in the plasma core. In the Weiland simulation, it was not possible to obtain such an outward convection, and, consequently, the T_e gradient follows the sign of the heat flux (which oscillates around zero, leading to a double hump in the temperature profile). The CUTIE simulation generates instead a hollow T_e profile despite a slightly positive power balance of the electrons, indicating the existence of an outward convection in the simulation, in agreement with the experiment and in addition to the inward convection found on approaching ρ_{dep} from inside. Regarding this inward pinch, a closer inspection of the experimental time-averaged T_e profiles reveals that its maximum is located inside rather than at ρ_{dep}. Note that ρ_{dep} coincides with the minimum of the φ profile of the modulated ECE data, and the consistent use of the same diagnostic to identify both minimum φ and maximum T_e excludes that the discrepancy between the two comes from systematic errors in the spatial mapping of the measurements. The inward shift of the T_e maximum implies that the net convective heat flux is negative in a limited range inside ρ_{dep}. Thus, the outward convective flux in this spatial range must be smaller than the inward convection. The CUTIE T_e profiles, however, do not show this feature, i.e., the net convective heat flux, although being reduced by the inward pinch, still remains positive adjacent to ρ_{dep} (Fig. 4), indicating that the inward pinch is underestimated with respect to experiment.

Having assessed the capability of both models to reproduce the heat convection evidence, it is important to recall that the mechanisms providing the heat convection in the two models are completely different, but potentially both may be present in tokamak plasmas. In the Weiland simulations, the inward flux present just inside ρ_{dep} is due to a combination of curvature and off-diagonal terms related to the ubiquitous mode, with the curvature part playing the main role in determining the inward direction of the pinch. In CUTIE, instead, pinches in either direction are driven mainly by mechanisms of electromagnetic nature, predominantly an interaction of a low frequency MHD mode with turbulence. In CUTIE, this mechanism drives convective heat, particle and current fluxes which vary rapidly in space and time. This action is as follows: At the low order rational q surface closest to ρ_{dep}, a MHD mode ($m - nq \sim 0$) is driven by the heating. This electromagnetic mode tends to drive convective fluxes which have a minimum close to the radius of the rational q magnetic surface and maxima both in board and out board of it (Fig. 4). The local dynamo currents and the zonal flows driven by the mode tend to flatten the local magnetic shear but enhance the electric field shear and, thus, indirectly suppress the higher wave number instabilities close to the resonant surface. This is the result of strong nonlinear profile-turbulence interactions and self-organization and leads both to local inward heat pinches and to the core outward convective flux in the plasma core required to generate the hollow profiles [11]. The inverse cascades ubiquitous to drift Alfvén waves also play a role in the resultant MHD relaxation processes driven by the modulated ECH. Thus, in CUTIE all the convective effects arise from electromagnetic nonlinearities which are closely dynamically linked to the electrostatic perturbations [9], but the code does not include trapped-particle turbulence effects.

In summary, we have presented simulations, using two different turbulence models, of RTP ECH modulated discharges providing experimental evidence for the presence of heat convection. We have found that, indeed, the theoretical simulations provide the same qualitative features observed in the experiment. The physical mechanisms providing convective heat transport in the two models are different. We conclude that convection should, therefore, be regarded as a heat transport mechanism associated with turbulence and normally present in tokamak plasmas in addition to diffusive transport, although in many conditions not easily detectable. Further work is clearly needed to clarify the nature of the mechanisms dominant in specific cases.

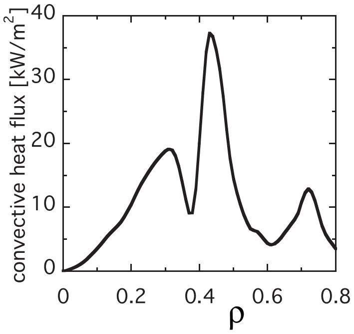

FIG. 4. Time-averaged convective electron heat flux for the CUTIE simulation of Fig. 3 (right column). Note the deep minimum just inside ρ_{dep} indicating the presence of a strong inward heat pinch component, although not strong enough to result in a negative convective heat flux as in the experiment.

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