Nonlocal Transient Transport and Thermal Barriers in Rijnhuizen Tokamak Project Plasmas

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In the Rijnhuizen Tokamak Project plasmas, a transient rise of the core electron temperature is observed when hydrogen pellets are injected tangentially to induce fast cooling of the peripheral region. High-resolution Thomson scattering measurements show that the T_e rise is associated with large temperature gradients in the region $1 < q < 2$. This region acts as a layer of transiently increased thermal resistivity (transport barrier) when probed by fast heat pulses from modulated electron cyclotron heating. [S0031-9007(99)09366-7]

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A widespread observation in transient transport experiments in tokamak plasmas is the so-called "nonlocal" response of the plasma core to a fast perturbation of the electron temperature (T_e) in the outer layers of tokamak plasmas [1]. Most commonly, a core T_e rise is observed in response to fast edge cooling (cold pulse) by laser ablation or oblique pellet injection [1]. As reported in the literature, the central T_e response contradicts local transport predictions in that (a) the core response is of opposite polarity and of larger magnitude than the edge perturbation; (b) the response takes place before the edge perturbation diffuses in. The phenomenon cannot be ascribed to Ohmic power redistribution according to [1–3]. Therefore it is interpreted in terms of a fast change of the core electron heat diffusivity (χ_e) in response to a change in some plasma parameter elsewhere [1].

A common feature is a density (n_e) dependence of the nonlocal response. At low n_e, the nonlocality is strongest as the T_e perturbation reverses its polarity in the plasma core. As n_e is increased, the core T_e variation is reduced and can be replaced by a fast response of the same polarity [1].

Another common feature is a change, on the same time scale as the central T_e variation, of the sawtooth period and amplitude, which has suggested a possible link between nonlocal transport and MHD behavior of the plasma [3].

In this Letter we report new experimental results on the issue of nonlocal transport, obtained in the Rijnhuizen Tokamak Project (RTP). They are based on high-resolution measurements of T_e with Thomson scattering and on the use of modulated electron cyclotron heating (MECH) on top of cold pulses. These experiments show that the central T_e rise following edge cooling takes place through the formation of a large temperature gradient (thermal barrier) in a radially localized region of the plasma. Such a barrier acts as a layer of transiently increased thermal resistivity when probed by MECH heat pulses.

RTP (major radius $R = 0.72$ m, minor radius $a = 0.16$ m) is dedicated to transport studies and equipped with advanced diagnostics. Time resolved measurements of T_e and n_e are taken, respectively, with an electron cyclotron emission (ECE) radiometer covering the entire profile with 15 channels and with a 16 chord microwave interferometer. High spatial resolution is obtained with a double pulse Thomson scattering system measuring T_e and n_e on a vertical chord with a spatial resolution $\Delta z = 2.6$ mm. MECH is provided by a 110 GHz, 350 kW gyrotron (2nd harmonic X-mode).

Oblique injection of hydrogen pellets is used to cool the plasma outer region (impact parameter $r/a = 0.7$). A typical time evolution of T_e at different radii at low density is shown in Fig. 1. The most striking feature of nonlocal transients can be immediately seen: The T_e perturbation reverses its polarity in the plasma core. The relative increase of T_e amounts to $\Delta T_e/T_e = 27\%$ at $r/a \approx 0$. Nonlocal transients in RTP have been studied for a range of plasma parameters [4]. A clear scaling with n_e is observed. The T_e rise is reduced for increasing n_e and disappears for

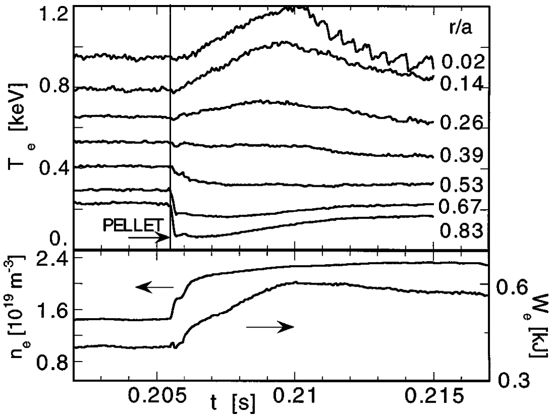

FIG. 1. Time evolution of T_e (measured with ECE), $\overline{n}_e$, and W_e for RTP discharge r19970224.024. A hydrogen pellet is injected at $t = 0.2054$ s in a target plasma with $q_a = 5.23$.

line averaged density $\overline{n}_e > 2.7\ 10^{19}\ \mathrm{m}^{-3}$. In this Letter, only low n_e results are considered.

A delay of $\approx$0.6 ms is observed between the T_e drop in the outer plasma and the core T_e rise in Fig. 1. This delay, which is common to other tokamaks [5], implies that the central T_e response is fast but not instantaneous with respect to edge cooling, and may cast some doubts on the widespread picture of a nonlocal dependence of core transport on edge parameters [1]. Another observation is the absence of sawtooth instabilities before and during the T_e rise in Fig. 1. Clearly, sawteeth cannot be the cause of the T_e rise. The opposite is true: due to the T_e rise, the plasma current diffuses in, eventually leading to the occurrence of sawteeth.

One difference to be discussed between laser ablation and pellet cooling experiments is the increase of n_e present in the second case. In Fig. 1, the increase in $\overline{n}_e$ is 60% at the top of the T_e rise. Comparing the electron energy stored in the plasma (W_e) before and after the nonlocal T_e transient, an increase of about 40% is observed which agrees with confinement scalings of low density Ohmic plasmas. During the nonlocal transient, however, the time evolution of n_e and T_e is quite different: T_e falls back to prepellet levels while n_e is still rising. It is therefore not possible to provide a phenomenological interpretation of the T_e rise as due to a density dependence of confinement. More generally, the qualitative similarity of the RTP and, for example, Texas Experimental Tokamak (TEXT) results based on radiation cooling [2] indicates that neither the n_e rise in RTP, nor the rise in radiated power in TEXT can play a direct role in the nonlocal transients.

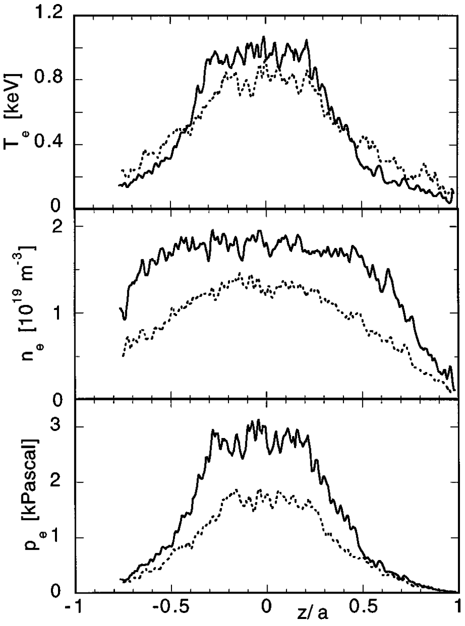

FIG. 2. Thomson scattering T_e, n_e, and p_e profile for two low density discharges (r19980303.005–006, $\overline{n}_e = 0.85 \times 10^{19}\ \mathrm{m}^{-3}$, $q_a = 4.7$) without (dashed line) and with (continuous line) pellet injection. The measurements are taken at the top of the rise for the case with pellet ($t = 210$ ms).

To investigate the changes in the T_e profile during the nonlocal transient, Thomson scattering measurements have been taken at different times in repeated discharges. Figure 2 compares two discharges, with and without oblique pellet injection. We see that during the nonlocal transient the plasma develops a sharp T_e gradient in the layer $0.3 < r/a < 0.5$ (the profile remains flat in the region $r/a < 0.3$). In Fig. 2 ∇T_e is observed to change by a factor 2, from 7 to 14 keV/m.

The position of the high ∇T_e region is found to depend on the plasma current, or the safety factor q. This is shown in Fig. 3 for two discharges with different $q(r = a)$ values. The figure shows the two T_e profiles at the top of the T_e rise along with the two q profiles taken in the Ohmic steady-state phase just prior to pellet injection. They can be computed from the measured T_e and n_e profiles assuming neoclassical resistivity and correcting for the bootstrap current. In both cases the barrier lies in the q range $1 < q < 2$. Note that, in the discharge with $q_a = 6.6$, $q > 1$ at all radii. No sawteeth are observed even in the fall phase of the central T_e rise.

A likely explanation for the large ∇T_e values observed is a transient decrease of the underlying electron thermal transport. We therefore provisionally call this layer of reduced transport a "transient thermal barrier" and set out to investigate its nature.

To this purpose, oblique pellet injection was performed on plasmas in which the MECH power (frequency $\omega/2\pi = 750$ Hz, duty cycle $= 0.3$) was deposited at different radial locations with respect to the position of the thermal barrier. The inward/outward propagation of the heat pulses and its change during the cold pulse was investigated. Figure 4 illustrates the changes in the inward propagating heat pulses for a case where the resonance was set at $r/a = 0.15$ (within the thermal barrier region,

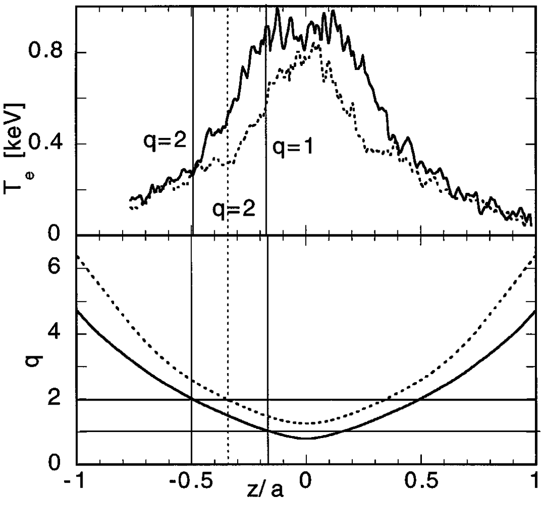

FIG. 3. T_e profiles at the top of the rise (measured with Thomson scattering) and calculated propellet q profiles for two discharges at $\overline{n}_e = 1.4 \times 10^{19}\ \mathrm{m}^{-3}$ with different q_a: shot r19980303.015, $q_a = 6.55$ (dashed line), and r19980303.026, $q_a = 4.7$ (continuous line).

near its inner side). We note that in this case the edge cooling was slower than in Fig. 1 because the pellet was evaporated before entering the plasma. Nevertheless, a central T_e rise is still observed.

A large reduction in the MECH amplitude is observed in Fig. 4 in the T_e time trace at the plasma center on the same time scale as the T_e rise. The MECH amplitude in the other time traces is almost unaffected. The change in heat pulse propagation lasts only for the duration of the barrier, i.e., about four MECH cycles. In this case the outward propagating signal becomes too weak to be a useful probe of transient behavior at the other side of the barrier. In cases with resonance at $r/a = 0.33$ (within the thermal barrier region, near its outer side) we observe that the outward propagating heat pulses feature a similar drop as they leave the barrier region.

The observed variation in the heat wave propagation is the first direct evidence that electron transport is indeed changing in cold pulse experiments with central T_e rise. In fact, Ohmic power redistribution alone would not affect heat wave propagation. Moreover, the change must involve diffusive transport, since it is observed through high frequency MECH, which is rather insensitive to convection (not to mention that inward convection to heat the center would not be able to cause an amplitude drop in the plasma center). Therefore we can conclude that a substantial decrease in χ_e in the barrier region is required to explain the observations.

These conclusions are based on a qualitative analysis of the experimental evidence. A more detailed analysis of the experiment of Fig. 4 was performed on the basis of time dependent simulations. For this purpose, we used the ASTRA [6] transport code. The code solves the coupled force balance and transport equations of tokamak plasmas; see [6] for details. Of relevance for these experiments are the electron heat transport and the current diffusion equations. The n_e evolution is taken from the experiment. Electron-ion energy exchange is negligible in RTP at these low densities. Neoclassical resistivity and bootstrap current are taken into account. The main plasma parameters are taken from experiment, together with the ECH power deposition profile. A model for electron heat transport must be prescribed.

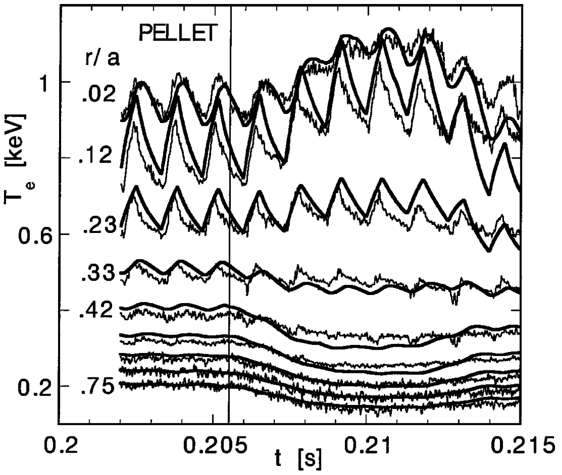

FIG. 4. Experimental (thin) and simulated (thick) T_e time traces for a discharge with combined pellet injection and MECH (discharge r19970522.020, $q_a = 5.3, \overline{n}_e = 1.77 \times 10^{19}$ m^{-3}). MECH resonance at $r/a = 0.15$. The simulation was performed with the transport model illustrated in Fig. 5.

The expert reader will immediately realize that simulating all the processes occurring in Fig. 4 is a rather difficult task. It entails the simulation of (i) the steady-state T_e profile preceding the pellet injection, (ii) the MECH induced perturbation to the T_e time traces before the pellet injection, (iii) the transient T_e evolution following the pellet injection, and (iv) the quasiperiodic MECH perturbation during the pellet injection transient.

A preliminary comment concerns the well-know observation that also in RTP, as in many tokamaks, the ratio between "perturbative" and "power balance" χ_e values is larger than 1. The most commonly proposed models to solve the discrepancy are a nonlinear or an offset linear relation between heat flux q_e and ∇T_e. On RTP, the second option seems more consistent with experimental

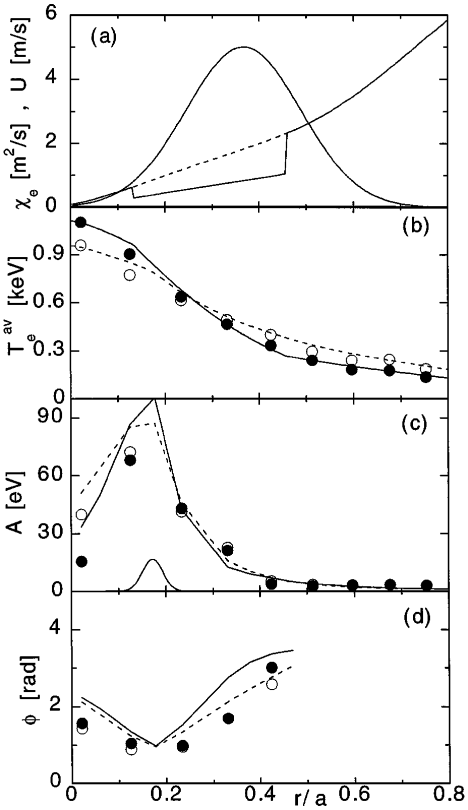

FIG. 5. Simulation of the experiment shown in Fig. 4: (a) χ_e and U profiles; (b) T_e profile averaged over MECH; (c), (d) amplitude and phase of MECH wave at 1st harmonic, obtained by standard Fourier analysis. In (c) the ECH power density profile is also indicated. Dashed and continuous lines refer to simulation before and during the cold pulse. Open and full circles refer to experimental data before and during the cold pulse. The T_e time traces for this simulation are shown in Fig. 4.

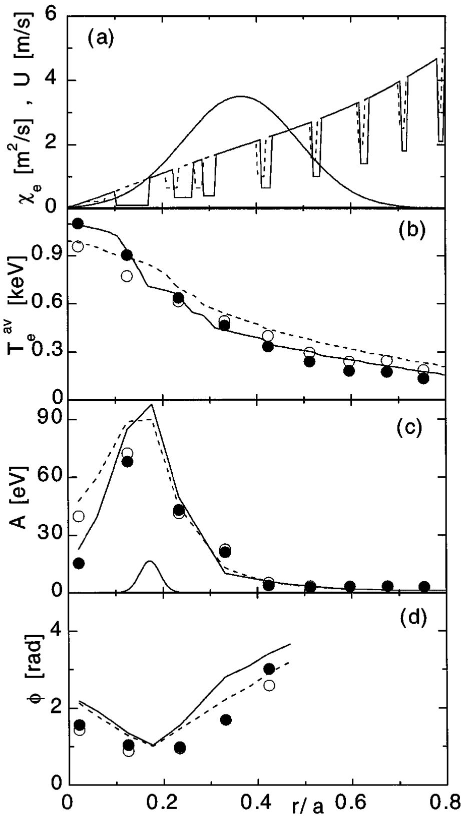

FIG. 6. Same as Fig. 5 but assuming the shell model for χ_e described in the text.

observations [7]. Therefore we have adopted a model with χ_e independent of ∇T_e and an inward convective term in the heat flux.

Figure 5 shows a simulation of the experiment of Fig. 4 using the heat flux model illustrated in Fig. 5a. During the steady state, the model features a heat pinch component and a radially increasing diffusivity. This allows good reproduction of the time averaged T_e profile (Fig. 5b) and of the amplitude and phase profiles of the T_e perturbation at 1st harmonic (Figs. 5c–5d). Following the pellet injection, a uniform reduction by a factor 2.2 is applied to χ_e in the $1 < q < 2$ layer (Fig. 5a). The time averaged T_e profile at the top of the rise is shown in Fig. 5b, the amplitude and phase of the heat wave corresponding to the 5 cycles during the rise are shown in Figs. 5c–5d. χ_e is ramped down and up again in 2 ms, staying at the low level for 3 ms. The resulting T_e time traces are compared with the experimental data in Fig. 4. The agreement with the experiment is quite satisfactory. This model allows also good reproduction of the discharge of Fig. 1 (Ohmic, proper pellet) by taking χ_e to decrease by a factor 5 in 0.6 ms.

The model adopted in the simulation of Fig. 5 lacks the physical explanation for the observed χ_e variation triggered by the cold pulse. In this respect, we have investigated an alternative χ_e model, based on the "shell model" for electron transport in RTP [8]. The main features of this χ_e model are thin layers of low thermal diffusivity (transport barriers) embedded in a high diffusivity background of standard parabolic shape. The transport barriers are located near low order rational q surfaces: $q = 1, 4/3, 3/2, 2, 5/2, 3, 7/2, 4$, etc. All barriers have the same width in q. In the shell model the χ_e profile has an implicit time dependence due to changes in the q profile. The question is then whether q profile modifications during a cold pulse can induce χ_e variations capable of inverting the sign of the T_e perturbation. We find that neoclassical current diffusion alone does not provide q profile modifications resulting in a central T_e rise. However, introducing an *ad hoc* time dependence of the barrier strength, a simulation can be obtained (Fig. 6) which is as good as the one in Fig. 5. The diffusivity profiles before and at the top of the T_e rise are plotted in Fig. 6a. Note that the barriers move outward following the neoclassical evolution of the current profile. This happens on the same time scale as the T_e rise and agrees with the observation of an expansion of the sawtooth inversion radius during the T_e rise in sawtoothing discharges. Such variation of the q profile is an effect, rather than a cause, of the T_e rise.

In conclusion, the core T_e rise observed during pellet edge cooling experiments in RTP is due to a reduction in the electron heat diffusivity, which can be probed by electron cyclotron heating heat pulse propagation. Although a link with the plasma magnetic structure has been identified, the physical mechanism causing the transport change remains unknown. Assuming a "shell model" for electron transport, one can speculate the cause of the transport change to be some nonlinear process enhancing the transport barriers. This could be triggered by small local variations of the q profile, possibly with the help of the high bootstrap current density driven by the large T_e gradient inside the barrier.

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