Strong Nonlocal Effects in a Tokamak Perturbative Transport Experiment

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(Received 26 September 1994)

A finite but small injection of carbon into the TEXT tokamak edge induces significant temperature perturbations throughout the plasma. Large, rapid temperature decreases are observed in the outer third, while temperatures in the inner third promptly begin to rise. The effects cannot be reproduced with transport coefficients that are functions only of local thermodynamic variables. A large increase in χ_e must occur within 100 μs in the outer region, and χ_e must simultaneously begin to decrease in the interior. Increases in local density fluctuation levels coincide with the increase in χ_e.

PACS numbers: 52.55.Fa, 52.25.Fi

Transport, even in physical systems as far from thermodynamic equilibrium as hot plasmas, is presumed to be a local phenomenon: The fluxes of particles, energy, etc., are determined by the local thermodynamic variables (e.g., density and temperature) and change only in response to changes in those variables. This is the premise of both equilibrium [1] and time-dependent [2] transport analyses, although nonlinearities permit differences between the two in the values for the coefficients. Only a few experiments have suggested that the premise is inadequate. Fredrickson *et al.* [3] found certain features of sawtooth heat pulse propagation inexplicable using purely local models, and more recently Parail *et al.* [4] have proposed a nonlocal model to explain the simultaneous onset of temperature increases over a broad region following the *L-H* transition in JET. Interactions of turbulence over long distances are conjectured to provide the nonlocal mechanism. Pellet injection experiments have also observed rapid temperature drops ahead of the pellet [5]. Since most transport theories are local, the existence of clear nonlocal effects would require fundamental modification to the conventional approaches.

The present experiment was designed to explore effects induced by rapid temperature changes, but with greater control. Carbon, as paralyene, is injected by laser ablation [6] in to the TEXT tokamak [7]. The optics of the laser ablation system may be adjusted to control the amount and insure gaseous, as opposed to solid fragment, injection. The temperature perturbations are measured with a multichannel electron cyclotron emission (ECE) heterodyne system at the second harmonic. The experiment is very similar to that reported by Kissick *et al.* [8] on TFTR, although the analysis and results are quite different. Carbon was chosen because its direct effect is well localized to the edge. Both modeling and spectroscopic measurements [9] confirm that C^{+2} actually peaks outside the last closed surface and that the multielectron, highly radiating states are found only near the edge. A typical perturbation is shown in Fig. 1, which shows the significant increase in a C^{+2} line as well as the smaller effects on total radiated power (represented by a chord at $\rho = r/a \sim 0.7$ to emphasize edge effects), line-averaged density, and D_α. Time is with respect to the start of the discharge; the perturbation is applied during a stable plateau with 1.7 T toroidal field, 110 kA plasma current, mean density of 1.6×10^{19} m^{-3}, and circular plasma radius of $a = 0.27$ m. The amount of carbon injected is less than the 5×10^{17} atoms vaporized from the target, to be compared with a carbon inventory of $\sim 5 \times 10^{18}$ and a total of $\sim 1.5 \times 10^{19}$ electrons. This is consistent with the magnitudes shown in Fig. 1. The edge density rises by a few percent and then decays, giving very small local density perturbations in the interior. In particular, the flatness of D_α implies that the temperature near $\rho \sim 1$ does not fall below the threshold for efficient ionization. For these experiments, q was maintained sufficiently large to avoid the appearance of sawteeth.

A representative temperature perturbation is shown in Fig. 2. The conditions were 2.1 T toroidal field, 125 kA plasma current, mean density of 1.6×10^{19} m^{-3}, and a slightly smaller carbon injection than in Fig. 1. The heavy lines show the ECE temperature measurements at the normalized radii indicated. The core is optically thick, and

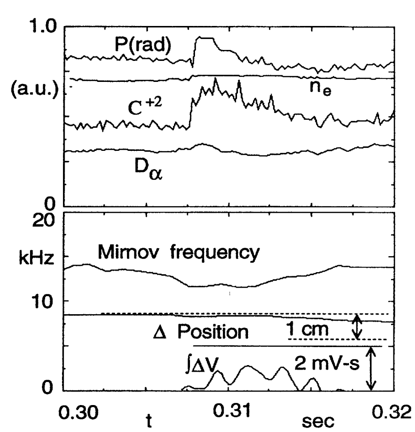

FIG. 1. Characteristics of carbon injection.

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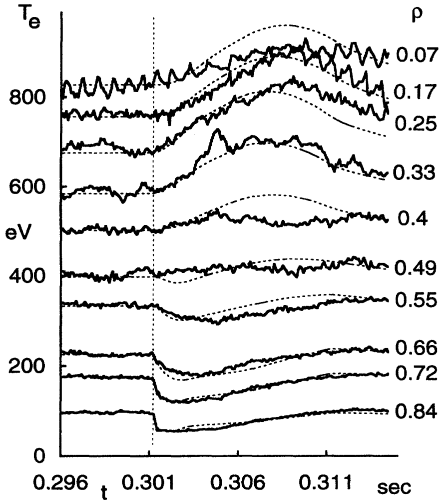

FIG. 2. Temperature variations $T_e(\rho, t)$ in solid heavy lines. Light dashed lines are calculated from the nonlocal model $\chi_e(\rho, t)$ shown in Fig. 3.

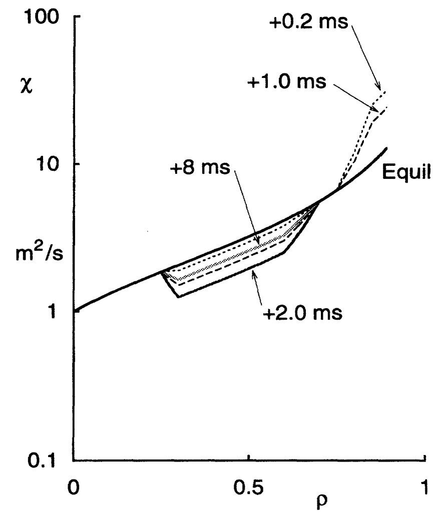

FIG. 3. Model $\chi_e(\rho, t)$ used in Fig. 2.

the outer channels shown are still accurate, considering the effect of wall reflections as inferred from other calibration experiments. The temperature falls very rapidly at $\rho = 0.84$, $\Delta t_{\text{step}} \sim 100\ \mu\text{s}$. In contrast, the central temperatures begin to rise immediately; a clear change is evident within 1 ms of ablation. An intermediate region, $0.4 \leq \rho \leq 0.5$ in this instance, appears almost unaffected—neither temperature nor temperature gradient change significantly. This is the obstacle, both physical and figurative, to a local transport model. Such an invariant region, in which none of the local thermodynamic variables changes perceptibly, precludes an effect in the interior, and in no case can the sign of the effect invert. The most plausible interpretation of the core temperature rise is a reduction in χ_e within 1 ms of ablation mediated by some nonlocal process. The indicated positions of the ECE channels are based on the initial magnetic configuration, which for these high q, low β_p circular plasmas is very simple—circular flux surfaces with a 1 cm Shafranov shift. The signals of Fig. 2 are on the low field side except for $\rho = 0.07$, which is on the high field side. (If the phenomena were caused by a position shift, the data of Fig. 1 notwithstanding, that channel should have cooled, and none of the channels could rise above the initial central value.) The same results have been obtained with the channels moved to the high field side.

Even the rapid temperature drop in the periphery implies nonlocal effects, although the argument is not one of principle but of magnitude. The direct, immediate effect of the carbon injection is to increase radiation for $\rho \geq 0.9$. The radiation cools that region, and the cold pulse propagates inward. To produce the large, rapid temperature drops of Fig. 2 in a local model, the total radiated power would have to exceed the Ohmic input power for several milliseconds, the temperature in the region $\rho > 0.9$ would drop below 10 eV, and a "χ_e^{HP}" $\sim 20\chi_e^{\text{PB}}$ would have to be invoked in the outer quarter of the plasma to propagate the perturbation inward. Such large radiated powers and low edge temperatures are totally inconsistent with Fig. 1. If the radiation were adequate to reduce the temperature transiently below 10 eV, that would quench the radiation, not even permitting a self-consistent picture. Based on the maximum amount of carbon actually injected, one would expect a temperature reduction of only ~20 eV at $\rho = 0.9$, which would then propagate inward with decreasing amplitude. The injected carbon is insufficient to produce the magnitude of the temperature reductions in Fig. 2. The nonlocal model posits that the impurity injection triggers an increase in χ_e everywhere in the outer region; the effects are largely the indirect effects of changing χ_e rather than the direct effects of edge cooling.

The predictions of a simple nonlocal model embodying these elements are shown as the light, dashed lines in Fig. 2. The transport coefficient $\chi_e(\rho, t)$ of this model is shown in Fig. 3. The equilibrium profile is typical of power balance results. During the perturbation, the edge diffusivity increases rapidly, relaxing back to equilibrium within 2 ms, while the core diffusivity decreases steadily for 2 ms and then returns to normal after 12 ms. The region of improved confinement is inferred to be *at somewhat larger radii* than the region within which temperatures actually rise. Some mechanism must cause the signals to vanish in the region $0.4 \leq \rho \leq 0.5$. In this model, a null region occurs where the inward propagating cold pulse balances the heating from improved confinement. In a local model, a pulse vanishes only if $\chi_e^{\text{HP}}(r) \to 0$ in

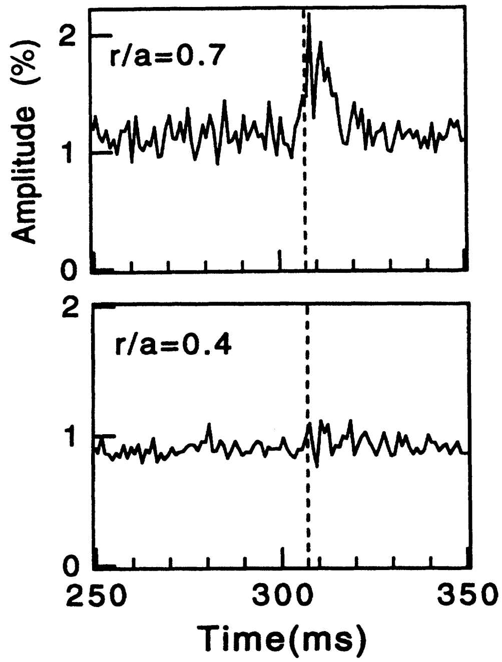

FIG. 4. Time dependence of density fluctuation amplitude at two representative radii. The dashed line indicates the injection time.

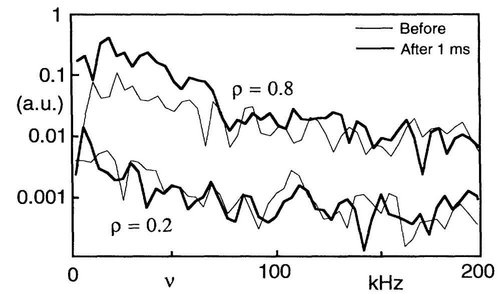

FIG. 5. Frequency spectra of density fluctuations. Spectra using 1 ms window before and starting 1 ms after injection.

the direction of propagation. For the case of Fig. 2, a $\chi_e^{\rm HP} \sim 0.2\chi_e^{\rm PB}$ would be required to reduce the cold pulse below the observable limit.

The increase in χ_e is accompanied by a strong increase in local density fluctuations, as shown in Fig. 4 for the conditions of Fig. 1. The measurements are made with a heavy ion beam probe (HIBP) [10] having a spatial resolution of $\sim$1 cm. The fluctuation amplitude $\tilde{n}/n$ (an rms value) includes frequencies above 5 kHz with $k \lesssim 2$ cm^{-1} and a time window of 1 ms. The amplitude increases immediately with the arrival of the carbon and lasts several milliseconds. The increase of $\tilde{n}/n$ is consistent with an increase of χ_e by factors of 3 to 4 as used in the model. There is no clear decrease in $\tilde{n}/n$ over the region of confinement improvement. The changes in χ_e there are somewhat smaller, but $\tilde{n}/n$ is only an index of turbulence, not the sole determinant of energy flux. The convected flux is proportional to $\langle \tilde{n}\tilde{E}_\theta \rangle$, but the conducted flux depends on $\langle \tilde{T}_e\tilde{E}_\theta \rangle$, which has not been measured in these experiments. Changes in phase angle between the fluctuating components could also reduce the flux without changes in amplitude. The frequency spectra of the density fluctuations are shown in Fig. 5. Again, there are no significant changes in the core. Toward the edge, the increase occurs over a broad frequency range, but it is especially marked at low frequencies, generally associated with low k, long wavelength modes.

In the absence of apparent changes in core turbulence, one should examine alternative explanations of the temperature rise. Either the confinement must improve or the Ohmic heating rate must increase. An increase in $Z_{\rm eff}$ is not a tenable hypothesis. As noted above, the amount of carbon is insufficient to provide the doubling of $Z_{\rm eff}$ needed for the heating observed. Furthermore, normal impurity transport rates are inadequate to explain the time scales: The rapid onset of heating would require almost a step function in core $Z_{\rm eff}$. Finally, a large increase in $Z_{\rm eff}$ would have to be accompanied by a change in loop voltage, which is not observed. These carbon injections produce no obvious change in the loop voltage signal. To be sure, the loop voltage has a strong ac component, making small changes impossible to discern, but the integrated signal $\int \Delta V\, dt$ shown in Fig. 1 bounds the change at $\sim$1 mV s, vanishing within $\sim$6 ms. This is sufficient to account for the edge reheat but not the central heating, which would consume roughly 10 times that amount.

If $Z_{\rm eff}$ does not change, increased heating requires increased current density j. Since the current is constant, only redistribution is possible. There is no direct evidence of increased central j, such as onset of sawteeth, nor is it consistent with standard current penetration analysis. A step function in surface voltage penetrates only to $\rho \sim 0.3$ in 5 ms, and times greater than 30 ms are required for full relaxation. Even if the current that flowed in the regions which cool were totally transferred inward, it would be insufficient to produce the heating. Moreover, any significant redistribution of current would change the internal inductance significantly. The observed bound of $\sim$1 mV s limits the $I\Delta L$ effect to an $\sim$2% change in internal inductance.

There is no other indication of peculiar magnetic or magnetohydrodynamic effects. The plasma radial position, as shown in Fig. 1, varies by $\Delta\rho < 0.01$. The frequency of low-level Mirnov oscillations remains near 15 kHz, implying no change in rotation, a conclusion confirmed by the lack of change in plasma potential seen by the HIBP. Internal magnetic coils see only a decrease in high frequency components, a likely consequence of the drop in T_e near the edge.

The observations and arguments imply that the core temperature behavior represents a reduction of χ_e for $\rho \leq 0.6$. The effect is clearly nonlocal, because it occurs in advance of any change in local thermodynamic variables—n or T_e. Even the increase of χ_e toward the outside appears nonlocal insofar as the observations cannot be reproduced by a local model χ_e $(n, T_e, dT_e/dr$, etc.) with plausible dependencies. These results do not prescribe the nonlocal mechanism. Causality is not a consideration. The times are quite long compared with Alfven times for information transfer and probably long compared with times for drift-type wave communication, the mechanism proposed by Parail *et al.* [4]. Determining the mechanism and the principle that couples improved core confinement with enhanced edge effects will require much additional work. The effect requires a minimum injection amplitude but is robust above that size over a range of plasma currents, toroidal fields, and densities, although the parameter range free of obscuring sawteeth is limited. The effect seems to weaken with auxiliary electron cyclotron heating, which is consistent with the absence of the effect in TFTR L-mode discharges [8] and the presence of the effect in recent Ohmic experiments on TFTR [11].

More generally, the existence of nonlocal effects means that conventional local theories are missing an important physical element. Furthermore, even gyro-Bohm turbulence—fluctuations with scale and correlation lengths small compared with the plasma size—as is generally observed and subjected to theoretical analysis, can easily lead to global scalings that differ qualitatively from gyro-Bohm if nonlocal effects enter.

This work was supported by the U.S. Department of Energy under Grant No. DE-FG05-88ER-53267. The authors are indebted to Dr. Kissick for sharing the results of recent experiments on TFTR.

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