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K.W. Gentle, R.V. Bravenec, G. Cima, G.A. Hallock, P.E.
Phillips, D.W. Ross, W.L. Rowan, and A.J. Wootton

Fusion Research Center
The University of Texas at Austin
Austin, TX 78712

T.P. Crowley, A. Ouroua, P.M. Schock
Rensselaer Polytechnic Institute, Troy, NY 12180

C. Watts
Auburn University, Auburn, AL 36849

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The Evidence for Non-Local Transport in TEXT

K.W. Gentle, R.V. Bravenec, G. Cima, G.A. Hallock, P.E. Phillips,
D.W. Ross, W.L. Rowan, A.J. Wootton
Fusion Research Center,
University of Texas at Austin,
Austin, Texas 78712

T.P. Crowley, A. Ouroua, P.M. Schoch
Rensselaer Polytechnic Institute,
Troy, NY 12180

C. Watts
Auburn University,
Auburn, AL 36849

The electron temperature response of a tokamak to rapid edge cooling has characteristics difficult to reconcile with local transport analysis. The initial observations in TEXT have been extended to a wider range of plasma and perturbation parameters, including auxiliary heating, and the associated turbulence changes have been measured across the plasma radius. The fast edge temperature drops and core temperature increases are quantified by more extensive analysis. A perturbation complementary to edge cooling, edge heating by a fast current ramp, evokes a completely complementary plasma response.

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I. Introduction

The paradigm in nonequilibrium thermodynamics is a set of relations for conserved quantities in which the flux of each quantity is a function of the local thermodynamic variables. The flux is generally expressible as a sum of products of transport coefficients and (local) thermodynamic forces. The transport coefficients are likewise functions of the local variables. Such relations can be derived for systems near thermodynamic equilibrium, and they have proved to be generally useful even in high temperature plasmas to describe both equilibrium¹ and transient² processes. However, several recent experiments have produced observations of time

evolution that are either inconsistent with local transport models or would require implausible forms for local transport coefficients.

Among the first observations of anomalous behavior were those of the propagation of large sawteeth by Fredrickson *et al*³. A typical enhanced transport coefficient as usually inferred for sawteeth was inadequate to account for the results. A nonlocal effect has been explicitly invoked by Cordey *et al*⁴ to explain the interior temperature evolution in the Joint European Torus⁵ (JET) following the transition from "low" to "high" confinement modes (L-H transition). The time evolution implies a prompt reduction in energy transport over a broad region of plasma in the absence of any significant change in local parameters.

The nonlocalities suggested by these experiments and implied by the results here are a very restricted class. These nonlocalities do not alter the picture of a local thermodynamic equilibrium with variables generally constant on flux surfaces and fluxes across magnetic surfaces proportional to local thermodynamic forces. The question is only whether the transport coefficients are solely functions of the local variables or whether some form of nonlocal influence or communication renders the transport coefficients sensitive to changes remote from the immediate vicinity. There is no implication of drastic nonlocality, as might occur, for example, with large, strong convective cells that could preclude definition of useful thermodynamic variables on a flux surface.

This paper greatly extends the initial observations of nonlocal effects^{6,7} observed on TEXT⁸ in the temperature response to impurity ablation. The range of plasma parameters, especially q , over which the cold pulse is observed has been increased. In addition to the high q non-sawtooth discharges originally reported, lower q , sawtooth discharges are now included, and some significant interactions with sawteeth are observed. Nevertheless, all the qualitative features remain: the core temperature rises promptly in response to edge cooling, and the edge cooling greatly exceeds that produced by the direct radiative loss. More systematic observations of the effect of perturbation amplitude have been obtained, the effect of electron cyclotron auxiliary heating has been more extensively studied, and alternative interpretations of the observations have been more precisely evaluated. The changes in turbulence and plasma potential have been examined over the plasma cross-section.

The most novel addition has been the use of a fast current ramp to increase edge heating within milliseconds -- a time short compared with current penetration and thermal transport times. The fast current ramp also evokes a nonlocal transport response, the complete complement of the cold pulse case. The central temperature drops promptly in this case, while the edge temperatures rise more rapidly than can be explained purely by the increased ohmic dissipation at the edge.

The analysis and inference of nonlocal effects is based on a conventional transport equation posed in cylindrical coordinates

$$\frac{3}{2} n \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r n \chi \frac{\partial T}{\partial r} \right) + P_{in} - P_{rad} - P_{ei} \quad (1)$$

where P_{in} includes the ohmic as well as any auxiliary heating power input, P_{rad} is the radiative loss, and P_{ei} is the coupling to ions. At the low densities of these experiments, the weak coupling to ions is simply included with the radiative losses. The equation is often linearized about the equilibrium to give two equations

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r n \chi_{eo} \frac{\partial T_o}{\partial r} \right) = -P_{in}^{(o)} + P_{rad}^{(o)} + P_{ei}^{(o)} \quad (2)$$

$$\frac{3}{2} n \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r n \chi_e^{pert} \frac{\partial \Delta T}{\partial r} \right) + \Delta P_{in} - \Delta P_{rad} - \Delta P_{ei} \quad (3)$$

where Eq.(3) specifically assumes that the density is not perturbed, which is also a good approximation in these experiments. Many transient experiments, especially sawteeth, use Eq.(3) for the analysis with a $\chi_e^{pert} \sim (3-5)\chi_{eo}$. Although Eq.(3) will be used to provide some comparisons to the observations, most of the analysis here uses Eq.(1) directly.

To illustrate the sorts of phenomena that strongly suggest nonlocal transport effects, consider the cartoon of Fig. 1. The time development of the temperature, $T_e(t)$, at two radii is given by solid lines. For a transport analysis using Eq.(1), the temperature, temperature gradient, and time derivative of temperature at an intermediate radius are sketched as dashed lines. For a short time after t_0 , no significant changes in any of the local parameters (T , ∇T , etc.) will have developed; the right hand side of Eq.(1) as a function of local thermodynamic variables is continuous. However, the left hand side has jumped; the time derivative has a step at t_0 . Either the P or the χ must therefore be discontinuous in time. If a jump in P can be excluded, a jump in χ is required, *ipso facto* a nonlocal effect. Although experiments are never as simple as Fig.1, the figure does illustrate the sorts of observations that would imply nonlocal transport coefficients. Nonlocal effects will only be required or revealed in transient experiments on time scales fast compared with the transport time. Otherwise a local explanation would be most difficult to exclude.

Section II presents the analysis of cold pulses over the range of observations, Section III treats the fast current ramp, and Section IV discusses the conclusions.

II. Cold Pulses

Impurities are often injected into a plasma by laser ablation to study impurity transport. Kissick *et al*⁹ first noted that the radiative cooling associated with the injection could produce a significant electron temperature perturbation suitable for transport studies. This perturbation was rather the inverse of a sawtooth and had the virtue of being independent of the complexities of sawtooth collapse. The initial experiments, injecting iron into strongly auxiliary-heated discharges, were consistent with normal diffusive time evolution of the temperature.

For TEXT, carbon injection was employed in a well-developed ablation system optimized to generate vapor and avoid cluster injection.¹⁰ The Z of carbon is sufficient to produce significant radiative cooling without significantly raising the density, but the Z is sufficiently low to restrict the radiation to the plasma edge, $\rho = r/a \gtrsim 0.9$. (For TEXT, $a = 0.27$ m, but the dimensionless and device-independent ρ will be used for all radial labels.) Spectroscopic studies have confirmed that carbon is stripped to the weakly-radiating helium-like state or below before it can penetrate further into the discharge.¹¹

The characteristics of a typical injection are shown in Fig. 2 for an ohmic discharge. The time of injection is selected in the middle of a good plateau period -- the $t = 0$ of Fig. 2 has been shifted for clarity. The injection clearly causes a large increase in a C^{+2} line. The effect on total radiated power is also measured with a fast bolometer array. A chord viewing with a tangent radius of $\rho = 0.85$ [$P_{\text{rad}}(0.85)$] sees a strong increase, confirming that the edge radiation is strong. The chord at the limiter radius [$P_{\text{rad}}(1.0)$] shows a much weaker effect; the scrape-off layer is not greatly affected. At $\rho < 0.85$, the chord-integrated effect again weakens, consistent with radiation restricted to the edge. The increase in edge radiation, $\sim 40\%$ for a few milliseconds, is typical, but it has been varied from 10% to almost 100% in some experiments. For these ohmic discharges, the total radiated power in equilibrium ranges from 40% to 60% of the ohmic input power. The effect of injection on line-averaged density is small, $\sim 3\%$ in this case. Edge chords of the interferometer show somewhat larger changes, but they decay promptly. The density change in the interior is quite small. The total plasma current does not change measurably and is not shown.

The effect on loop voltage cannot be shown directly. As with most tokamaks, the loop voltage on TEXT has a very large ripple from the power supply. To extract the injection effect, the $\int \Delta V(t) dt$ is shown, where the $\langle V(t) \rangle$ over several milliseconds before injection is subtracted and the integral begins shortly before injection. Two important implications may be drawn from this trace. The first is that the effect on loop voltage is modest at best. The integrated value of 5 mV-sec over 5 ms gives only a 1 V change in the loop voltage of ~ 1.5 V in the plateau. One cannot distinguish between resistive and inductive contributions to ΔV , but edge cooling suggests at least some resistive component. The upper bound for the increase in inductance from contraction of the current channel is $\Delta I_i \sim 0.1$. Second, the integrated effect over 15 ms almost vanishes. This is

less than one would get from a simple transient increase in Z_{eff} from carbon being injected and diffusing back out -- that would give a step in the integral. The carbon injection clearly has not produced a significant increase in Z_{eff} . This is quite consistent with the measurements of ablated carbon. The amount of carbon removed from the slide by the ablation laser, an upper bound for that injected into the plasma, is $\sim 5 \times 10^{17}$ atoms, small compared with the carbon inventory of $\sim 5 \times 10^{18}$ atoms in the plasma, which has a $Z_{\text{eff}} \sim 3.5$, largely carbon from wall and limiter tiles. Finally, the effect on the edge temperature, $T_e(0.8)$, is large. The temperature drops 60% in this case, and injections producing drops from 15% to 70% have been analyzed.

The full temperature evolution is measured with a multichannel heterodyne electron cyclotron emission radiometer. The instrument is regularly calibrated with reference to Thomson scattering temperature profiles and refined with plasma shift measurements to maintain good relative calibration between channels. Data is shown for $\rho \leq 0.9$. Opacity is poor for the outermost channel, but multiple reflections from the stainless steel vacuum vessel appear to give better results in calibration comparisons than would be expected from single-pass absorption. At the least, the outermost channels is qualitatively useful. The temperature evolution for a representative case is shown in Fig. 3 at a density of $1.8 \times 10^{19} \text{ m}^{-3}$, toroidal field of 2.1 T, and a plasma current of 120 kA ($q = 7.2$). The energy confinement time τ_E is ~ 10 ms for these conditions. The radiometer channels span the region from magnetic axis to larger major radius here, but similar results have been obtained at lower magnetic fields with the channels at smaller major radius. The characteristic features are the fast, large drops in temperature at large minor radii, the vanishing effect at mid radii, and the rather prompt rise in temperature at small minor radii. The later observation is the most obviously paradoxical, for a diffusion equation can never invert the sign of a perturbation. In fact, none of the features can be reasonably reconciled with a normal transport analysis.

The plasma position is carefully controlled in these experiments to prevent artifacts in the $T_e(t)$ data. The perturbation would normally drive a small change in equilibrium position before the feedback system could restore it. However, a programmed correction is added to the vertical field control circuit to anticipate the injection. The excursion is thereby reduced to $|\Delta\rho| < 0.01$, and comparisons of the slight remnant position variation $\Delta x(t)$ with various $T_e(t)$ have not indicated any correlation. Certainly the behavior of Fig. 3 is not that of a position shift, since different positions change in opposite directions. Experiments have also been run at slightly reduced toroidal field to place radiometer channels on both sides of the magnetic axis. The results are symmetric, and the peak temperatures reached after injection are higher than any temperatures present before injection.

For reference in Fig. 3, the observations in heavy lines are compared with a standard model, shown in light dashed lines. This standard model uses a χ_{e0} adjusted to match the initial equilibrium temperature profile with enhanced transport for perturbations of $\chi_e^{\text{pert}} = 3 \chi_{e0}$, typical

of sawtooth results. For the model calculation of Fig. 3, ΔP_{rad} is determined from experiment: the amplitude and time dependence are taken from data like Fig. 1, and the spatial distribution is uniform over the region $0.85 < \rho < 1.0$, consistent with the bolometer arrays and independent spectroscopic studies of carbon in TEXT. One significant feature of the model solution in Fig. 3 is that the edge temperature drop is far smaller than that observed, a result insensitive to the χ_e^{pert} choice. The modest increase in edge radiation for $\rho > 0.85$ is not sufficient to drive a large drop in edge temperature at $\rho \leq 0.8$. In addition, the temperature drops at interior radii are too slow.

To quantify this effect, the edge radiation was increased to obtain a satisfactory temperature drop at $\rho = 0.89$, with the result shown in Fig. 4. For this case, $\Delta P_{\text{rad}} = 1.3 P_{\text{rad}}$, more than twice the observed increase in radiation. The total radiated power rises to 40% more than the ohmic input, and yet the perturbation does not extend into the plasma as required. Even at $\rho = 0.79$, the model produces less than half the observed temperature drop. There are two possibilities one might consider to model the temperatures for $\rho > 0.5$ more accurately. One is a purely radiative model in which the amplitude, time dependence, and radial extent are all adjusted to fit the data. Such a model is illustrated in Fig. 5. The time dependence of the total radiation in this model is shown in Fig. 6. This *ad hoc* radiation model fits the temperature data for $\rho > 0.5$ reasonably well, but it requires that carbon penetrate the outer half of the plasma within ~ 0.1 ms in sufficient quantity to produce $\Delta P_{\text{rad}} = 8 P_{\text{rad}}$, as shown in Fig. 6. Such radiation levels are totally inconsistent with the observations. Figure 6 disagrees strongly with the direct P_{rad} measurements. The amplitude of ΔP_{rad} presumed is almost twenty times that observed, and the model radiation must continue at elevated levels for 10 ms to keep the edge temperature depressed, compared with observed levels that return to normal within a few milliseconds. Such radiation levels would also require amounts of carbon injection far greater than available from the ablation source. Furthermore, there is neither evidence nor mechanism for transporting carbon over the whole $\rho > 0.6$ region so rapidly.

A second possibility is to restrict the enhanced radiation to the edge, but invoke a large χ_e^{pert} (at large ρ) to propagate the disturbance inward. This possibility is shown in Fig. 7. This model still requires an unreasonably large $\Delta P_{\text{rad}} = 3 P_{\text{rad}}$ and $\chi_e^{\text{pert}} = 20 \chi_{e0}$. Values of $\chi_e^{\text{pert}} > \chi_{e0}$ are usually explained by a nonlinearity in χ_{e0} , but such a nonlinearity sufficient to produce this effect would be inconsistent with the response to small or slow changes to the equilibrium. Furthermore, any of these assumptions that produce the large drops in edge temperature also imply significant core cooling, as seen in Figs. 5,7. The observations of P_{rad} and T_e for $\rho > 0.5$ are not compatible with any conventional treatment of Eq. (1).

To explain the temperature rise in the core with a conventional Eq.(1), a change in the source terms is needed. The inwardly-diffusing perturbation can only decrease T_e . Lacking any plausible mechanism for decreasing P_{rad} in the core, a small quantity in any case, P_{in} must be

presumed to increase. With $P_{in} = \eta j^2$, either η must increase from Z_{eff} , the current density j must increase, or some combination may develop. To evaluate effects, the model of Fig. 5 with *ad hoc* radiation was modified by increasing P_{in} in the core. The effect (Z_{eff} or j) was presumed to increase over some characteristic time to its new level. Several alternatives were examined. One is shown in Fig. 8. The core heating ($\rho < 0.5$) is presumed to rise over 3 ms to a level sufficient to increase the core temperatures by approximately the observed amounts. The deficiency is immediately apparent: the temperature rise in the model is significantly delayed with respect to the observations. The fault cannot be remedied by a larger increase in the core power, as shown in Fig. 9. Changes over the first few milliseconds are still not well represented, and the model temperatures then exceed the observations.

In fact, the observations somewhat resemble the data from Cordey *et al.*,⁴ in which the derivative of T_e changes abruptly, e.g. at $\rho = 0.29$, at the time of injection. The rapid change in $\partial T/\partial t$ implies an equally rapid change in P_{in} . Such a model is the third possibility in Fig. 9 and is extended as Fig. 10. The net core power is assumed to increase by 70% within 0.5 ms of injection. This provides a plausible fit to the data, but it is not consistent with any possible mechanism. The time scale of 3 ms used for the model of Fig. 8 is much faster than any characteristic impurity diffusion time observed on TEXT and is even faster than heat propagation at $\chi_e^{pert} = 3 \chi_{e0}$ as can be inferred from Fig. 3, for example. Current penetration times are slower still. Changes of P_{in} on submillisecond time scales are quite implausible. The magnitude of ΔP_{in} is likewise problematic. Changing the entire core plasma to fully-stripped carbon (by some unknown mechanism) would barely suffice, and $Z_{eff} = 6$ would have to appear as a large increase in the loop voltage eventually. The injected carbon is not sufficient to make such a change in Z_{eff} .

To provide the heating by j^2 is also difficult. In general, it is hard to increase $\int j^2 r dr$ subject to the constraint of constant current $\int j r dr$. In this case, the local current density would have to increase rapidly by 50% over much of the confinement region in defiance of the magnetic diffusion equation. For this high- q discharge with strongly peaked temperature, there is little current in the periphery that one might suppose is redistributed to the core ($\rho < 0.6$). To demonstrate this, Fig. 11 gives the results of a model with *ad hoc* edge radiation to produce the edge cooling as in Fig. 5 and the transfer of all current from $\rho > 0.6$ (the region of significant cooling) to the region $0.2 \leq \rho \leq 0.6$. As Fig. 11 shows, this is not sufficient to drive the core heating; it suffices only to balance the inward diffusion of the cool wave. This peaking of the current profile would increase the internal inductance $\Delta I_i \sim 0.1$, the maximum permitted by the observations in Fig. 2. The increased ohmic dissipation requires additional V-sec. The model of Fig. 11 requires 8-10 mV-sec over ten milliseconds, more than permitted by the loop voltage measurements, but less than the temperature rise requires.

Since interpreting the observations of T_e in the context of Eq.(1) using conventional forms of χ requires unreasonable and unphysical assumptions for P_{in} and P_{rad} , terms in which one has some physical confidence, alternate models for χ warrant consideration. A minimal modification is to permit $\chi_e(r,t)$, where the time dependence could reflect effects at other locations, not merely implicit time dependencies through local variables. Although there are no full theories for such transport, there are many waves propagating at speeds high compared with transport time scales that could communicate information and perhaps mediate the process.¹² Some marginal stability theories and self-organized criticality models do imply non-local transport in this sense.¹³ Two forms of phenomenological analysis are employed here. Both use the experimental data for P_{in} and P_{rad} . Since the results of Fig. 5 indicate that large changes in P_{in} are needed to effect significant changes in T_e , whereas the injected carbon is insufficient to increase Z_{eff} greatly and there is neither time, mechanism, nor evidence in l_i of changes in j , $\Delta P_{in} = 0$ is assumed. In one approach, simple forms for $\chi_e(r,t)$ are explored to find reasonable fits to the $T_e(r,t)$ observed. The $\chi_e(r,t)$ is adjusted to simulate $T_e(r,t)$.

In the second approach, the $T_e(r,t)$ are subjected to direct transport analysis to extract $\chi_e(r,t)$. Although this approach might seem more accurate, the results are rather crude. Since fast effects are being analyzed, little smoothing may be applied to $T_e(r,t)$, and especially noisy results appear in the derivatives needed to infer $\chi_e(r,t)$. Furthermore, $\chi_e(r,t)$ is obtained only between channel radii and no inferences about the edge region are possible. In contrast, the requirement for a globally consistent result in the simulation approach requires a reasonable model of $\chi_e(r,t)$ everywhere. Nevertheless, the two approaches are consistent.

In the context of nonlocal models, the large, prompt decreases in edge T_e , much larger than those implied by the increased radiation, suggest prompt increases in local χ_e . Similarly, the increase in core temperatures suggest a decrease of χ_e in this region. These two effects are included in a comparatively simple separable phenomenological model as

$$\chi_e(r,t) = \chi_{e0}(r) \{ 1 + f_{core}(t) g_{core}(r) + f_{edge}(t) g_{edge}(r) \} \quad (4)$$

to allow suitable space and time dependence for the core and edge changes. Each of the four functions -- $f_{core}(t)$, $g_{core}(r)$, $f_{edge}(t)$, and $g_{edge}(r)$ -- has a simple piecewise linear form and is 0 outside the affected interval. The models used here typically have three space and time points for each function and three adjustable magnitudes. A fit using this model to the data of Fig. 3 is shown in Fig. 12. This model reproduces all the qualitative features of the data and provides a semi-quantitative fit, with a mean fitting error of less than 10%. To depict the nonlocal effects

invoked, a contour plot of a somewhat unconventional quantity, η_{rth} , the relative thermal resistivity is useful as shown in Fig. 13. The quantity has the straightforward definition

$$\eta_{rth} = \frac{\chi_{eo}(r)}{\chi_e(r,t)} = \frac{1}{1 + f_{core}(t) g_{core}(r) + f_{edge}(t) g_{edge}(r)} \quad (5)$$

in terms of Eq. (4). The choice of a relative quantity removes the radial variation of χ_{eo} and emphasizes the changes in χ_e , while the choice of resistivity means that larger values are associated with improved confinement.

Figure 13 illustrates the changes in transport implied by the cold pulse results. In the outer region of the plasma, $\rho > 0.6$, the resistivity drops immediately ($\Delta t < 0.1$ ms) by as much as a factor of five and remains there for some extended time. In contrast, the resistivity increases in the confinement region by about 50%. The improvement must begin rather soon after injection ($\Delta t < 0.5$ ms), but it may take a millisecond to reach full value. Although this model for $\chi_e(r,t)$ has a number of adjustable parameters, it is clear from Fig. 13 that it is far from a general $\chi_e(r,t)$. The parameters in the model are reasonably well defined in the sense that changing any of them would measurably increase the fitting error, but more complex forms of $\chi_e(r,t)$ could certainly produce better fits. However, the model is strictly phenomenological with a phenomenological purpose -- to indicate the sorts of effects that must be triggered by the cold pulse.

Although there is no reasonable alternative to increasing χ_e in the edge to account for the temperature drops there, a nonlocal heat pinch could be introduced instead of the reduction in core χ_e . The fit from a simple model is shown in Fig. 14, and the pinch velocity $v(r,t)$ used to produce the fit is plotted in Fig. 15. The velocities are somewhat large, larger than those measured in particle transport experiments on TEXT, for example, but a heat pinch is a conceptually viable off-diagonal alternative to a nonlocal change in χ_e . The fit in Fig. 14 is certainly not as good as that of Fig. 12, but only because the $v(r,t)$ has not been refined as much as the $\chi_e(r,t)$. The important implications are that the qualitative features can be reproduced and that the $v(r,t)$, like the $\chi_e(r,t)$ of Fig. 13, develops in the confinement region at intermediate radii. Although a $v(r,t)$ is a possibility, the phenomenology will be described in terms of a single transport coefficient χ_e in the remainder of the discussion.

As an alternative to adjusting a model $\chi_e(r,t)$ to fit the observed $T_e(r,t)$, the $T_e(r,t)$ data can be run through an analysis procedure to infer $\chi_e(r,t)$. The inference is based on the first integral of Eq. (1) and the same values of P_{in} and P_{rad} as used in the modeling.

$$n\chi = \frac{\int_0^r \left(\frac{3}{2} n \frac{\partial T}{\partial t} + P_{\text{rad}} - P_{\text{in}} \right) r' dr'}{r \frac{\partial T}{\partial r}} \quad (6)$$

As is clear from Fig. 3, *et seq.*, there is noise in the $T_e(t)$ data; some smoothing is needed to avoid excessive noise in $\partial T/\partial t$. This limits the time resolution in the inference. Although Eq. (6) is evaluated between each pair of $T_e(r)$, a spline fit is used rather than a simple difference estimate of $\partial T/\partial r$ to reduce noise. Nevertheless, the results show considerable time variation in the steady conditions preceding injection. The results for several radii are shown in Fig. 16, along with the values used in the model of Fig. 13 for comparison. The agreement, especially in the critical features of timing and duration, is excellent. At $\rho = 0.84$, χ_e rises rapidly and remains elevated for some time before relaxing toward its original value. The effect is smaller at $\rho = 0.75$. Further in, one recovers the prompt drop in χ_e inferred from the simulation for $0.57 \geq \rho \geq 0.33$. Although there is no indication of improvement in χ_e at $\rho = 0.18$, sawtooth oscillations are dominant contributors in the analysis, and the improvement used in the model is weak.

The edge temperatures are observed to drop precipitously. This is reproduced in the model and analysis by an immediate increase in χ_e over that region, but the precise time development is important in deciding among possible mechanisms. For example, Cordey *et al*⁴ argue that the speed with which $\partial T/\partial t$ changes in JET is not consistent with any reasonable purely nonlinear dependence of χ_e on local $\partial T/\partial r$. To examine the timing in TEXT, Fig. 17 shows the edge T_e channels for a strong injection with fast sampling (0.05 ms) of the radiometer. The effects are simultaneous, at least to within 0.1 ms, for $\rho \geq 0.6$. There is no indication of propagation delay or diffusive relaxation of the slope in this region. This places a significant constraint on possible mechanisms, because the dominant electrostatic turbulence has characteristic frequencies of order 100 kHz or less, and growth or relaxation times are generally slower.

To explain the enhanced χ_e associated with sawteeth, nonlinear turbulence models with $\chi_e \propto (LT_e)^{-\alpha}$ are often suggested. To test whether such models could explain effects like those of Fig. 17, the time histories of LT_e at various radii were compared with the relative thermal resistivities used in the model. The turbulence hypothesis implies $\eta_{\text{rth}} \propto (LT_e)^{\alpha}$. As illustrated in Fig. 18, this hypothesis totally fails. At $\rho = 0.9$, where the drop in η_{rth} is maximum, LT_e decreases only slightly and briefly before rising. A strong, sustained drop in LT_e occurs at $\rho = 0.6$, where the thermal resistivity only increases. In the center, $\rho = 0.1$, LT_e does increase, but there is no change in η_{rth} there. This experiment provides an excellent test of the LT_e hypothesis,

for LT_e changes significantly in both directions, but there is no correlation between changes in LT_e and χ_e .

The speed with which the core responds is equally significant from the view of possible mechanisms. Figure 19 illustrates the timing for a high q discharge ($q = 8.4$) with at most weak sawteeth. The temperatures, particularly at $\rho = 0.22$ and 0.29 , clearly begin to rise within 0.5 ms of the onset at $\rho = 0.8$. This is an effect over a spatial distance of half the minor radius and a time scale of $\tau_E/20$, very fast compared with the transport time scale. Discharges with sawteeth can be more or less informative, depending upon the timing of the injection with respect to the sawtooth crash. One useful example is shown in Fig. 20 for $q = 5.6$. The effect on the temperature at $\rho = 0.31$ clearly begins within 0.5 ms. Whereas the temperature rise from the sawtooth normally relaxes quickly, after injection the temperature ratchets up with each heat pulse. The behavior suggests an improvement in confinement (and no sawtooth-enhanced χ_e) in this region. A strongly sawtoothed discharge with $q = 4.2$ is shown in Fig. 21. The same prompt improvement at $\rho = 0.31$ is again apparent, and the effect on sawteeth becomes clear. The sawtooth slope, $\partial T/\partial t$, generally considered indicative of the core heating rate, does not change, as indicated by the guide lines of constant slope in Fig. 21. The core temperature rises because the sawtooth period lengthens but the crash amplitude does not increase. This is fully consistent with the model used here in which heating rates remain fixed, but confinement improves promptly at middle radii.

Although these effects have been found in ohmic discharges at all values of q and even in discharges with distinct $m=2$ activity and no sawteeth, the effect of auxiliary heating warrants special consideration. The first experiments by Kissick *et al*⁹ in L-mode discharges with high levels of beam heating did not show these effects. Injection of the same amount of carbon as used in the previous examples into a discharge heated by 500 kW of Electron Cyclotron Heating (ECH) gives the result shown in Fig. 22. The qualitative features are similar, although the fractional amplitudes are smaller and the speed with which the edge temperatures drop is somewhat less. The auxiliary heating is approximately three times the initial ohmic level for this case. Lower heating levels are almost indistinguishable from the ohmic case. However, the response to auxiliary heating is complex. If injection occurs while the temperature is still rising -- before the steady state of Fig. 22, one can obtain phenomena like that shown in Fig. 23. Although the carbon injection remains the same and the measured increase in radiation is just as large, the effect on temperature almost vanishes. The fact that the effect turns off under these circumstances provides one of the strongest arguments that the drops in edge temperature are caused primarily by an increase in χ_e and not directly by radiation. The nonlocal effects seem to be controlled by time derivatives. When the increased cooling is balanced by increasing heating, nothing is triggered.

Unfortunately, no results for the core temperatures could be obtained at full ECH power. The frequency difference between two of the gyrotrons overlapped the **if** frequency band of the radiometer and overwhelmed it.

To quantify the effects of auxiliary heating and to assess the linearity of the nonlocal processes, experiments were conducted over a range of ECH power, plasma current, and quantity of injected carbon. The injection is described by the fractional increase in edge radiation, $\Delta P_{\text{rad}}/P_{\text{rad}}$, as shown in Fig. 2. The response is described by two quantities in the model, which is adjusted for best fit to the data. The quantities are the maximum value of the relative thermal conductivity $\chi_{e(r,t)}/\chi_{e0(r)}$ in the outer region and the minimum value in the inner region. These provide dimensionless measures of the prompt confinement degradation near the edge and the improvement in the interior. The results are summarized in Fig. 24. The lines are linear fits to the ohmic data. For the ohmic discharges, there is a fairly consistent linear relation between the strength of the perturbation and the change in transport. There is also considerable scatter over the discharges at various q and density, although no systematic variations have been found for either parameter. More important, the fitting lines and data points indicate a threshold for transport effects. For values of $\Delta P_{\text{rad}}/P_{\text{rad}} < 0.1$, no change in transport is discernible. Such small amounts of carbon have been injected and are easily seen spectroscopically, but the effects on T_e are quite small and characteristic of a pure ΔP_{rad} driven effect. The edge temperature falls steadily for ~ 0.5 ms before recovering, and the perturbation diffuses inward. The signal-to-noise ratio does not justify detailed analysis. The threshold for changes in edge transport may be lower than the threshold for changes in core transport, but the apparent difference may be an artifact caused by the comparative ease of discerning sharp drops in edge temperature.

The transport effects are clearly attenuated by auxiliary heating, despite the increased values of $\Delta P_{\text{rad}}/P_{\text{rad}}$ for those cases. There are some instances in which no core effect is apparent; these are cases for which the injection occurs during the temperature rise to the heated equilibrium. The range of auxiliary heating power in these experiments was insufficient to determine a criterion for the vanishing of the transport effect in steady state.

Although $\Delta P_{\text{rad}}/P_{\text{rad}}$ is a convenient experimental parameter to describe the perturbation as used in Fig. 24, the correct physics parameter must be more general. For the L-H transition in JET⁴, the edge temperature or temperature gradient proved a useful parameter. However, Fig. 3 shows that for the cold pulse, the edge temperature as well as the interior temperatures are largely the result of the nonlocal processes and not easily inferred from ΔP_{rad} or other direct measure of the size of the perturbation. Temperature is thus not a suitable control parameter for cold pulses.

As might be expected from the change in transport, the level of plasma turbulence clearly changes upon injection. Density fluctuations were measured as a function of position and time with a Heavy Ion Beam Probe (HIBP)¹⁴ for conditions similar to those of Figs. 2,3. The level,

expressed as a root-mean-square value of $\Delta n/n$, is shown in Fig. 25. The value represents an integral over all frequencies above 10 kHz, the range considered significant for transport effects, and the instrument is sensitive to all $k \leq 2 \text{ cm}^{-1}$. As can be seen in Fig. 25, the turbulence increases promptly in the outer regions where χ_e is presumed to increase, and the elevated level persists for $\sim 10 \text{ ms}$, as does the enhanced χ_e . However, there is no reduction of Δn in regions where χ_e is presumed to reduce, nor is any change in core turbulence discernible. The data in Fig. 25 is plotted as a function of minor radius, and it represents points along the HIBP primary beam. The data at the left are at small major radius below the midplane. The data continue through the magnetic axis to larger major radius above the midplane, but extend only to $\rho \sim 0.6$. The increase in χ_e is associated with an increased level of turbulence, but the reduction in χ_e must be a more complex effect. It might be caused by a change in phase relation between fluctuating components, or it might reflect a reduction in $\tilde{T}$ with no change in $\tilde{n}$.

The plasma potential or radial electric field is also a possible mechanism of communication or control of turbulence, but measurements with the HIBP have shown no changes in plasma potential associated with these injections. Potential measurements across the plasma, made simultaneously with the data of Fig. 25, showed no changes at any point greater than the resolution of ± 50 volts with a 1 ms time average. These observations would still allow a fast oscillation in potential as a transmitter of information, but they exclude a radial electric field-driven shear flow as the mechanism for transport suppression. There are no significant changes in radial electric field over millisecond time scales.

Another possible process is magnetic turbulence. The spectrum of magnetic fluctuations before and after the cold pulse (1 ms window) is shown in Fig. 26. There is no increase in turbulence, and the higher frequencies are actually reduced. Since these have been shown to originate near the plasma edge, the reduction is probably a simple consequence of edge cooling.¹⁵

III. Fast Current Ramp

Because the cold pulse observations clearly suggest that the nonlocal effects are initiated by fast changes in parameters, this conjecture should be tested by examining other fast changes. Although ECH can be turned on and off quickly, the power available is not sufficient to produce large $\partial T/\partial t$. One alternative is the use of a capacitor to raise the loop voltage, and hence the edge heating rate, quickly. The process is shown in Fig. 27. The loop voltage jumps to almost 20 V and the current ramps up more than 50% in 10 ms. The current cannot penetrate the core on this time scale; the result is a large increase in edge heating. There is a small, slow density increase. The remarkable effect appears in the core temperature in Fig. 27. The temperature begins to drop promptly with the increase in loop voltage, certainly within 1 ms. The temperature recovers after 10 ms as the heating and current penetrate. The initial discharge is a low current, high q , non-

sawtooth discharge. The 40 ms delay in the onset of sawteeth gives a direct indication of the time required for full current penetration.

Lacking direct measurements of the current profile, the first step in the analysis was solution of the magnetic diffusion equation. The analysis is based on Spitzer resistivity and constant Z_{eff} . The value of Z_{eff} is determined by the initial current, loop voltage, and temperature profile. Thereafter the solution is determined from the constraint of measured $I(t)$. The solution for $j(\rho, t)$ is shown in Fig. 28. The analytic form of $I(t)$ that was used to represent the data of Fig. 27 is plotted along with the current density at several radii. As surmised from the sawtooth activity, it does require ~ 40 ms for the current density on axis to reach its new equilibrium value. Equally important for the transport analysis, the edge j more than doubles, giving a large, fast increase in the ohmic heating rate ηj^2 . This solution provides the $P_{\text{in}}(r, t)$ to be used in Eq.(1).

As for the cold pulses, the behavior of $T_e(0)$ is paradoxical. The temperatures at various radii are shown in Fig. 29, compared with a model using constant transport coefficients coupled with the current penetration of Fig. 28. The central temperature decreases promptly upon application of the increased loop voltage. This implies either an increase in radiative losses, a decrease in heating, or a (nonlocal) change in transport. There is no direct evidence of an increase in core radiation, and there is no plausible mechanism for moving radiating impurities to the core with the speed required. These discharges have very low levels of high-Z impurities and small radiative losses from the core. No decrease in core heating would be expected. Although the edge current density increases, Fig. 28 does not indicate a skin current or q inversion -- $\partial j / \partial r < 0$ always. The steep gradients of the initial state are merely reduced by the fast ramp. There is no increase in magnetic fluctuations. Nevertheless, a model with fast current redistribution was tested with the result shown in Fig. 30. This represents an extreme, nonphysical assumption that all the current for $\rho < 0.15$ is moved to $\rho > 0.5$ within 1 ms, leaving a hollow current profile that recovers over 10 ms. This extreme assumption reproduces the core cooling for $\rho = 0.12$, although the edge response remains below the observations. Most important, reaching $j = 0$ for $\rho < 0.15$ on the submillisecond time scale assumed would wreak havoc with the magnetic diffusion equation. The model of Fig. 30 is far stronger than an inversion of dj/dr in the core; the core heating rate must be set to 0 to model the results.

The only alternative is a nonlocal transport change, a prompt increase in core χ_e . The effect is nonlocal in the same sense as the $\chi_e(r, t)$ used to model the cold pulse -- the χ_e must change in the absence of a significant change in the local plasma parameters. Using the P_{in} from the current penetration calculation and a suitably adjusted model for core χ_e degradation gives results for comparison with the $T_e(r, t)$ data shown in Fig. 31. The model reproduces the core effects well in both magnitude and timing, but the edge temperatures rises more strongly than predicted by the model. One possible explanation for the edge would be underestimated or

anomalous heating, but heating rates much more than twice that inferred from current penetration would be required. This statement is not sensitive to the speed of current penetration. Anomalous current penetration would not improve the fit. For constant transport coefficients, the data require much larger dissipation for $\rho > 0.7$ than is available from ηj^2 . The total ohmic input only doubles during the ramp. The alternative is a reduction in χ_e near the edge, making the fast current ramp the complete complement of the cold pulse.

The results of such a fully complementary model are given in Fig. 32. It provides a satisfactory representation of the observations. The relative $\chi_e(r,t)$ used for this model is shown in Fig. 33. In keeping with the idea of complementarity, Fig. 33 plots the relative $\chi_e -- \chi_e(r,t)/\chi_{e0}(r)$ -- the inverse of the relative thermal resistivity η_{rth} , and thus resembles Fig. 13 rather closely. The magnitudes are also similar. In Fig. 33, the core χ_e increases by a factor of four, compared with the edge increase of six in Fig. 13. The reductions of χ_e in regions of improved confinement are approximately a factor of two in both cases.

Although the results of Figs. 27 and 29 are quite reproducible, having been the conditions used extensively for the development of current profile diagnostics, the effects are not as robust as the cold pulse phenomenology. Reducing the capacitor voltage by a factor of two or increasing the initial plasma current abolishes the peculiar effects. The maximum perturbation available in this case appears to be near the threshold for inducing nonlocal effects. It was not possible to measure effects of different magnitudes for various perturbation strengths and discharge conditions as was done for cold pulses.

IV. Conclusions

The extensive cold pulse observations and the complementary fast current ramp phenomena leave few reasonable alternatives to the hypothesis that transport is not purely a function of local variables but is influenced by the global state of the system. The effects are genuinely global. The increase in edge χ_e over an extended region in the cold pulse, like the reduction in edge χ_e following the L-H transition in JET⁴, implies merely a spatially extended region of influence from the primary cause. Those effects are continuous over a spatially connected region. However, the coupling of opposite effects -- increased edge χ_e with decreased core χ_e for a cold pulse and decreased edge χ_e with increased core χ_e for a fast current ramp -- is fully global and hints at some sort of invariant or conservation principle.

The nonlocal effects are caused by strong, fast changes. The characteristic time for the change [$\tau_{pert} = X(dX/dt)^{-1}$] must be short compared with the transport time scale τ_E . The relevant parameter X may be related to the local net power input, but the correct criterion is not prescribed by these experiments. For $X = P_{in} - P_{rad}$, $\tau_{pert} \sim 1.5$ ms for both typical cold pulses

and the fast current ramp. This is indeed short compared with $\tau_E \sim 10$ ms, by almost an order of magnitude. Large, but slow, changes have certainly been produced in other experiments without evidence of nonlocal effects. Impurity gas puffs can greatly increase P_{rad} , and the current is often doubled in slow current ramps. Fast changes are essential to trigger the effects.

Certain aspects of the nonlocal response are very fast. For the cold pulse, χ_e increases simultaneously over an extended region with a time resolution of 0.1 ms, a time scale typical of turbulence. The reductions in χ_e appear to be slower. They typically require 0.5 to 1.0 ms to manifest themselves, but this is still fast compared with the transport time scale.

The relaxation of the nonlocal changes back to the original equilibrium is consistent with the transport time scale τ_E . However, current and current profile effects (poloidal flux) cannot be excluded. Although the current penetration time (cf. Fig. 28) is clearly longer than τ_E , the relaxation times are not well defined and the differences not conclusive. In this context, cold pulse experiments on stellarators would be most useful. If similar phenomenology occurs, the effect would be unrelated to currents, whereas if different effects are found, the differences might reflect current-mediated effects.

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Figure Captions

1. Hypothetical temperature measurements implying nonlocal transport. Temperatures at radii $a < b$ and values of T , $\partial T/\partial r$, and $\partial T/\partial t$ at $r = (a+b)/2$ for application of Eq. (1) are illustrated.
2. Characteristics of a typical laser injection of carbon.
3. Time evolution of electron temperature at various minor radii following impurity injection.
The observations are shown in heavy lines, and the light dashed lines show results of a model fitted to the initial equilibrium perturbed by the observed radiative loss with $\chi_e^{\text{pert}} = 3\chi_{e0}$.
4. Data of Fig. 3 compared with a model in which the radiative losses were increased (ΔP_{rad} twice the measured increment) to match the observed temperature drop at $\rho = 0.89$.
5. Data of Fig. 3 compared with a model in which the radiative losses were arbitrarily increased and distributed over all $\rho > 0.6$ as required to match the temperature drops for $\rho > 0.5$.
6. Time development of the total radiation used in the model of Fig. 5, to be compared with the $P_{\text{rad}}(0.85)$ observations of Fig. 2.
7. Data of Fig. 3 compared with a model using enhanced, but edge localized, radiation and $\chi_e^{\text{pert}} = 20\chi_{e0}$ to simulate the edge temperature drops.
8. Data of Fig. 3 compared with a model using the edge radiation of Fig. 5 coupled with core heating from inward-diffusing impurities.
9. Data of Fig. 3 compared with several models of core heating. Data shown as heavy solid, rough lines. Model of Fig. 8 is shown as short dashed lines, a model with the same time scale but stronger heating as long dashed lines, and a model with a very rapid increase in core heating as thin solid lines.
10. Data of Fig. 3 compared with the fast heating model shown in Fig. 9 with solid lines.
11. Data of Fig. 3 compared with a model of edge radiation (Fig. 5) and fast current redistribution.
12. Data of Fig. 3 compared with a nonlocal transport model
13. The relative thermal resistivity $\eta_{\text{rth}} = \chi_{e0}(r)/\chi_e(r,t)$ used in Fig. 12.
14. Data of Fig. 3 compared with a model using a nonlocal enhanced diffusivity in the edge as in Fig. 13 but an inward heat pinch to produce the core temperature rise.
15. The inward heat pinch velocity used for the model of Fig. 14.
16. Values of $\chi_e(t)$ at various radii obtained by direct analysis of the data (solid lines) compared with those used in the model of Fig. 12 (dashed). (a) Outer radii; (b) Inner region
17. Timing of edge temperature changes with 0.05 msec sampling rate.

18. Comparison of the evolution of the temperature gradient scale length LT_e (in units of a) at several radii (lower panel) with the relative thermal resistivity η_{rth} used in the model of Fig. 12 (upper panel).
19. Timing of core temperature changes.
20. Core temperature rise as a dam for the sawtooth heat pulses
21. Constant rate of sawtooth central temperature rise during core heating.
22. Effect of impurity injection during steady state with 500 kW of ECH heating. The amount of carbon injected is similar to that in Fig. 2.
23. Effect of impurity injection during temperature rise following start of 500 kW ECH pulse.
24. Transport changes needed to fit cold pulses. Magnitude of the relative increase in χ at the edge and decrease in χ in the core required in best fit models as a function of impurity injection amplitude, measured by relative increase in radiated power.
25. Amplitude of density fluctuations as a function of position and time following impurity injection from the HIBP.
26. Magnetic turbulence measured with a small coil just outside the limiter radius before and after impurity injection.
27. Characteristics of the fast current ramp
28. Calculated current penetration in the fast current ramp. Total current $I(t)$ as measured on left axis, and calculated current densities at several radii on right axis.
29. Temperature data observed during the fast current ramp at several radii (heavy lines) compared with an *ad hoc* model of constant transport coefficients, transient removing of current for $p < 0.15$, and otherwise classical current penetration (light dashed lines).
30. Temperature data observed during the fast current ramp compared with an *ad hoc* model of constant transport coefficients, transient displacement of current for $p < 0.15$, and otherwise classical current penetration (light dashed lines).
31. Data of Fig. 29 compared with a model of nonlocal transport increase at the center and classical current penetration.
32. Data of Fig. 29 compared with a full nonlocal model of χ increased in the core and decreased in the outer regions.
33. The relative $\chi_{e(r,t)}/\chi_{eo(r)}$ used in the full nonlocal model of Fig. 32.

Fig. 1 A temperature evolution suggesting nonlocal effects

Fig. 1 Characteristics of a typical injection of carbon.
(Time origin shifted for simplicity.)

Fig. 2 Measured electron temperatures at various radii (heavy lines) and calculation using measured radiation with standard transport coefficients (dashed lines).

Fig. 4 Data of Fig. 3 compared with a model using edge radiation intensified to reproduce edge temperatures

Fig. 5 Data of Fig. 3 compared with a model using intense radiation extending deep into the plasma.

Fig. 6 Radiation assumed for model of Fig. 5

Fig. 7 Data of Fig. 3 with a model of intense edge radiation and a large incremental transport coefficient.

Fig. 8 Radiation model of Fig. 5 with enhanced core heating from impurities diffusing in with a fast sawtooth transport coefficient

Fig. 9 Data and edge model of Fig. 5 with various core heating assumptions. Model of Fig. 8 shown as dashed line; stronger heating longer dashes; immediate penetration shaded.

Fig. 10. Model with an immediate 70% increase in core heating.

Fig. 11 Model using current redistribution

Fig. 12 Data of Fig. 3 with experimental radiated power and an optimized nonlocal transport coefficient

Fig. 13 Relative thermal resistivity of the nonlocal model

Fig. 14 Data of Fig. 3 fit with a model using nonlocal enhanced edge transport and nonlocal heat pinch in the core

Fig. 15 The heat pinch velocity used in the model of Fig. 14.

Fig. 16(a) Comparison of transport coefficients obtained from analysis of Fig. 3 with model of Fig. 12.

Fig. 16(b) Comparison of transport coefficients from analysis with model of Fig. 12.

Fig. 17. Timing of edge temperature changes

Fig. 18 Comparison of relative thermal resistivity with temperature gradient scale length

Fig. 19. Timing of core temperature changes

Fig. 20 Core change begins after next sawtooth crash

Fig. 21 Core heating rate remains constant

Fig. 22. Impurity injection in ECH discharge

Fig. 23. Impurity injection during temperature rise

Fig. 24 Magnitude of transport change as a function of perturbation amplitude

Fig. 25 Time variation of turbulent density fluctuations

Fig. 26 Magnetic fluctuations at edge

Fig. 27. Characteristics of the fast current ramp

Fig. 28 Current penetration in the fast current ramp

Fig. 29 Temperature evolution during a fast current ramp compared with a model using classical current penetration.

Fig. 30 Fast current ramp temperatures compared with a model of classical current penetration except $j(0)$ goes to zero.

Fig. 31. Temperature in a fast current ramp compared with a nonlocal core and calculated ohmic heating

Fig. 32. Temperature (heavy lines) in a fast current ramp compared with a fully nonlocal model.

Fig. 33 Nonlocal relative thermal conductivity used in model of Fig. 32.