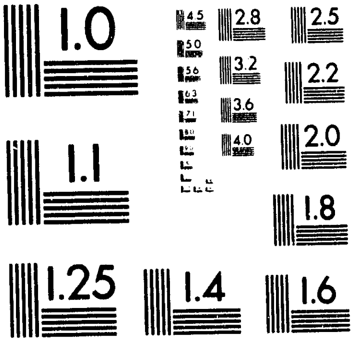
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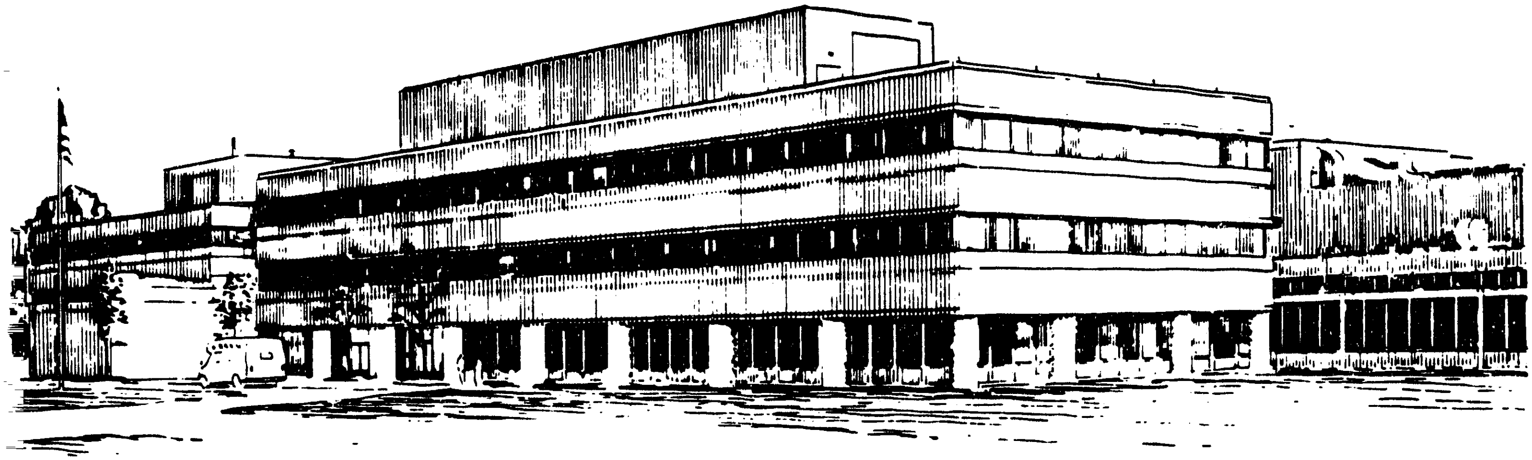
BY

M.W. KISSICK, E. D. FREDRICKSON, J.D. CALLEN, ET AL.

AUGUST, 1993

PPPL PRINCETON PLASMA PHYSICS LABORATORY



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TRANSIENT ELECTRON HEAT DIFFUSIVITY OBTAINED FROM TRACE IMPURITY INJECTION ON TFTR

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ABSTRACT. A new method for obtaining a transient ("pulse") electron heat diffusivity (χ_e^p) in the radial region $0.38 < r/a < 0.56$ in TFTR [Plasma Phys. Controlled Nuc. Fus. Research 1, 51 (1986)] L-mode discharges is presented. Small electron temperature perturbations were caused by single bursts of injected impurities which radiated and cooled the plasma edge. An iron injection case by laser ablation was found to be more definitive than a supporting helium gas puff case. In this new "cold pulse" method, we concentrate on modeling just the electron temperature perturbations, tracked with ECE (electron cyclotron emission) diagnostics and on being able to justify separation in space and time from the cooling source. This χ_e^p is obtained for these two cases to be $\chi_e^p = (6.0\text{m}^2/\text{s} \pm 35\%) \sim 4\chi_e(\text{power balance})$ which is consistent with, but more definitive than, results from other studies that are more susceptible to ambiguities in the source profile.

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1. INTRODUCTION

Understanding the transport of energy in tokamaks is a central concern for the development of a future fusion reactor. By making small and local perturbations in the electron temperature profile, it is possible to obtain a local and transient estimate of the electron heat diffusivity. However, this transient value is often different from an "equilibrium" or power balance derived electron heat diffusivity [1], and this difference is very important for understanding the transport processes in tokamaks.

A new method is presented here for obtaining a transient electron heat diffusivity in tokamaks from the "cold pulse" T_e (electron temperature) perturbations resulting from the injection of radiating and cooling impurities that are introduced at the plasma edge and that transport inward. This new method provides an independent comparison with results obtained from other transient methods which in general give similar results. The perturbations in T_e seem to travel faster in many cases than expected from power balance calculations. Beyond providing an independent comparison, this new method has significant advantages over sawtooth heat pulse propagation [2] since it does not result from a change in the magnetic topology. This paper both stresses the general concepts of this new method as well as results from its application to the TFTR [3] tokamak.

The next section of this paper provides a description of the physics involved in this method and emphasizes the logic scheme needed to determine where the T_e perturbations can be separated from their source in space and time. In the radial region where the source is negligible, the T_e perturbations can be analyzed directly to obtain the transient electron heat diffusivity. Emphasis is placed on a type of impurity injection termed "laser blow-off" [4] which in Section 3 is shown to be a good method of impurity injection for this heat transport study. The major strength of this method is that the effects of a locally transporting source on the T_e perturbations are well characterized, but the source itself does not need to be precisely characterized beyond demonstrating that it transports locally relative to the T_e perturbation: slower than the ensuing T_e perturbations for the safe application of this method. The source in this case is any cooling and transporting impurity introduced at the plasma edge. The magnitude and time behavior of the electron temperature perturbation itself indicates the presence of a local source (within certain source contraints discussed in Section 2).

After the general logic is discussed in Section 2, it is applied in Section 3 to TFTR T_e data from impurity injection and transport experiments already performed [5,6]. Iron injection is emphasized in this study; however, a supporting case of helium gas puff [7] induced T_e perturbations is also analyzed, discussed, and shown to be in good agreement with the results from the iron injection case. Analysis of the T_e perturbations in a small region where the source is insignificant shows rigorously that the transient electron heat diffusivity is about four times the expected electron heat diffusivity from power balance calculations. The ensemble of discharges used for this study have been extensively analyzed. The diffusion and very small convection coefficients for the trace iron, trace helium, and electron density perturbations have all been obtained [5,6] along with careful equilibrium analysis. Even though the method presented here does not require a precise knowledge of these trace impurity and perturbative electron transport coefficients, these coefficients do indicate local diffusive transport which is also slower than the T_e perturbation transport. Therefore, the method presented in Section 2 can be applied safely.

In Section 4, the relevance of the results obtained here to other methods is discussed along with a brief discussion of its possible implications for theory. The transient electron heat diffusivity and its relation to the power balance electron heat diffusivity are important quantities to measure. The new measurement method presented here has the desirable aspects of using raw and unmanipulated data for individual (or averaged) discharge data and a simple, rigorous scheme for showing separation of the T_e perturbation from its source.

2. GENERAL METHOD AND CONCEPT

The small and local (in both space and time) nature of the electron temperature perturbations considered here allow for a linearization of the electron energy conservation equation [2,8-11]. If the source is not locally significant to the local T_e perturbation, then the T_e perturbation can be directly analyzed locally to obtain a transient electron heat diffusivity.

After doing a small perturbation $T_e \rightarrow T_e(r) + \delta T_e(r,t)$ in the electron energy conservation equation, one obtains a general electron temperature evolution equation for the perturbation:

$$\frac{3}{2} n_e \frac{\partial \delta T_e}{\partial t} - n_e \chi_e{}^p \nabla^2 \delta T_e + V_e{}^p \nabla \delta T_e + S_e{}^p \delta T_e \approx \delta S \ , \qquad (1)$$

which is a valid linearization if $\delta T_e / T_e << 1$. The right side term, $\delta S = \delta S(r,t)$, represents the inducing source of the perturbation which is time-dependent, yet independent of $\delta T_e(r,t)$. The terms $\chi_e{}^p$, $V_e{}^p$, $S_e{}^p$ represent the effective perturbed diffusivity, effective perturbed pinch (or convection), and effective perturbed source, respectively. The terms involving $n_e \nabla \chi_e$ and $\chi_e \nabla n_e$ appear in $V_e{}^p$, where χ_e is the power balance derived equilibrium electron heat diffusivity. It is not the same as the transient electron heat diffusivity, $\chi_e{}^p$ [1]. In this discussion, no electron density (n_e) perturbation is considered. Terms related to ion temperature perturbation effects through collisional electron-ion power coupling appear in $S_e{}^p$. The terms in Eq. (1) have a natural ordering due to the fact that a small localized perturbation excites much larger changes in the higher spatial derivatives on $\delta T_e(r,t)$ (the scale length of the perturbation is much smaller than the equilibrium scale length). Therefore, the terms are ordered by

$$\frac{\partial \delta T_e / \partial t}{T_e / \tau_E} \sim \frac{\nabla^2 \delta T_e}{\nabla^2 T_e} >> \frac{\nabla \delta T_e}{\nabla T_e} >> \frac{\delta T_e}{T_e} \ . \qquad (2)$$

The quantity τ_E is the electron energy confinement time: $\tau_E \approx a^2 / 4\chi_e$ where a is the minor radius. Equation (2) is a typical approximation used in most of the sawtooth heat pulse propagation studies [2,8-11] where local diffusive transport is assumed. For a single spatially sharp perturbation, one can ignore the perturbed source, perturbed pinch or convective terms in the initial part of the pulse, $t << \tau_E$ (near the maxima or minima in the pulse for instance). To a good approximation in the short time, $t << \tau_E$, Eq. (1) can thus be expressed as

$$\frac{3}{2} n_e \frac{\partial \delta T_e}{\partial t} - n_e \chi_e{}^p \nabla^2 \delta T_e \approx \delta S \ . \tag{3}$$

A key question that arises when the electron temperature perturbation is induced by a time-dependent source is the degree to which the inducing source (independent of $\delta T_e(r,t)$ to lowest order) influences the analysis of the ensuing electron heat transport. In particular, consider the inducing source, δS, to be a high atomic number impurity injected by laser blow-off [4] that generally introduces a very small amount of highly radiating impurities which can transiently and locally cool the plasma edge ($\delta T_e / T_e$ < 10%). In this case, the electron density perturbation is negligible, and all of the cooling is due to radiating impurities that are introduced only at the edge and that transport inward. The inducing source (not the "perturbed source") in this case is a locally transporting source: transient radiation power loss from a specific injected impurity. The functional form of this transient radiation power loss is to lowest order [12]:

$$\delta S \equiv -\delta Q_{rad}(r,t) \approx -n_e(r,t)\,\delta n_{imp}(r,t)\,L_{imp}(r,t) \quad , \tag{4}$$

where $L_{imp}(r,t)$ is a factor that represents the rates of ionization and recombination and the energy released per reaction of the various charge states for a given impurity as well as the charge state spatial distribution. The dependence in $\delta Q_{rad}(r,t)$ on $\delta T_e(r,t)$ occurs through L_{imp} and is small since $\delta T_e / T_e < 10\%$: this dependence occurs in $S_e{}^p\,\delta T_e(r,t)$ of Eq. (1) and is dropped via Eq. (2). Therefore, $\delta Q_{rad}(r,t)$ is independent of $\delta T_e(r,t)$ to lowest order. If the locations of the charge states do not change, then L_{imp} is only a function of r, and the impurity is said to be in "coronal equilibrium." The factor $L_{imp}(r)$ is generally weighted strongly towards the edge of a tokamak plasma where the highly radiating lower impurity charge states are located. With laser blow-off, $n_e(r,t) \rightarrow n_e(r)$. The equation representing the transport of the trace impurity, $\delta n_{imp}(r,t)$, can be written as follows [5,6,13,14]:

$$\frac{\partial \delta n_{imp}}{\partial t} - \nabla \cdot (D_{imp} \nabla \delta n_{imp} - V_{imp}\delta n_{imp}) = S_{imp} \quad , \tag{5}$$

where D_{imp} and V_{imp} represent the effective impurity diffusion and convection coefficients respectively, and S_{imp} represents the spatially sharp injection of the impurities at the plasma edge. Equation (5) together with Eqs. (3), (4) represent the set of equations needed to describe the entire T_e perturbation to first order where Eq. (2) applies.

Solving for $\delta T_e(r,t)$ with Eq. (3), regardless of the exact form of the radiation power loss from the transporting impurities injected at the plasma edge, one in general arrives at

$$\delta T_e(r,t) = -(\frac{2}{3})\int_{Vol} d\xi \int_0^t d\tau \{\frac{\delta Q_{rad}(\xi,\tau)}{n_e(\xi)} G(r-\xi, t-\tau)\} \,, \tag{6}$$

where G is the appropriate cylindrical diffusion Green's function of the electron temperature perturbation, Eq. (3): $\nabla G(0-\xi, t-\tau) = 0$ is the only internal boundary condition. Assuming that all of the relevant physics has been included here, the question of whether the electron heat diffusivity can be obtained from analyzing just the $\delta T_e(r,t)$ pulses amounts to asking whether the locally transporting inducing source is insignificant in some region.

Analysis of diffusive properties of small localized T_e perturbations concentrates mainly on characterizing the timing and magnitude of the peak perturbation. This peak (in this case a negative peak) is defined by

$$\left.\frac{\partial \delta T_e(r,t)}{\partial t}\right|_{t=t_p} = 0 \,. \tag{7}$$

The quantity, t_p, is defined as the time-to-peak for some position, r. Both the magnitude and the time-to-peak need to be characterized with a single homogeneous diffusion equation in order to justify the claim that the diffusion process is not affected by the locally transporting inducing source (within certain restrictions). The logic behind this statement has to do with the way a locally transporting (relative to the T_e perturbation) inducing source affects the timing and the magnitude of the pulse peak.

The presence of a locally transporting inducing source has the effect of adding to the pulse magnitude (always true if $\delta Q_{rad}(r,t) > 0$) and delaying the time-to-peak, t_p, in most situations. Both of these effects taken together are incompatible with a single diffusion process. The important time-to-peak delay can be seen as follows. Applying Eq. (7) to Eq. (6), one obtains

$$0 = \int_{Vol} d\xi [\lim_{\tau \to t} \{ \frac{\delta Q_{rad}(\xi,\tau)}{n_e(\xi)} G(r-\xi,t-\tau)\}] \Big|_{t=t_p}$$

$$+ \int_{Vol} d\xi \int_0^t d\tau \{ \frac{\delta Q_{rad}(\xi,\tau)}{n_e(\xi)} \cdot \frac{\partial G(r-\xi,t-\tau)}{\partial t} \} \Big|_{t=t_p} . \qquad (8.a)$$

The first term in Eq. (8.a) reduces to $\delta Q_{rad}(r,t_p) / n_e(r)$ since G must be from a "delta function family" [15] as $\tau \longrightarrow t$. Thus, one can further simplify Eq. (8.a) to

$$0 = \frac{\delta Q_{rad}(r,t_p)}{n_e(r)}$$

$$+\left\langle \frac{\partial G}{\partial t}(r,t_p) \right\rangle \int_{Vol} d\xi \int_0^{t_p} d\tau \{ \frac{\delta Q_{rad}(\xi,\tau)}{n_e(\xi)} \} \; , \tag{8.b}$$

where the brackets indicate an average over the evolving profile $\delta Q_{rad}(\xi,\tau)\,/\,n_e(\xi)$ for times up to t_p:

$$\left\langle \frac{\partial G}{\partial t}(r,t_p) \right\rangle \equiv \frac{\int_{Vol} d\xi \int_0^{t_p} d\tau \{ \frac{\delta Q_{rad}(\xi,\tau)}{n_e(\xi)} \cdot \frac{\partial G(r-\xi,t-\tau)}{\partial t} \}}{\int_{Vol} d\xi \int_0^{t_p} d\tau \{ \frac{\delta Q_{rad}(\xi,\tau)}{n_e(\xi)} \}} \; .$$

Since $\delta Q_{rad}(r,t) > 0$ or $\delta Q_{rad}(r,t) \approx 0$ everywhere at any time, in order for the above equation to be satisfied at $t = t_p$, the following condition must hold:

$$\left\langle \frac{\partial G}{\partial t}(r,t_p) \right\rangle \leq 0 \; . \tag{9}$$

The equality sign applies to the case of $\delta Q_{rad}(r,t) = 0$ locally for $t \leq t_p$, and in this case, the average peak of the Green's functions yields the $\delta T_e(r,t)$ peak. Since the diffusion Green's function is a positive definite with only a single peak and is solved for with no internal zero order boundary conditions, Eq. (9) essentially indicates that the average peak of these Green's functions has already occurred at the time of the $\delta T_e(r,t)$ peak where $\delta Q_{rad}(r,t) \neq 0$ locally for $t \leq t_p$. Therefore, the time-to-peak is delayed for the case $\delta Q_{rad}(r,t) \neq 0$ relative to the case $\delta Q_{rad}(r,t) = 0$.

The function $\delta Q_{rad}(r,t)$ is specified to be positive and time-dependent, yet independent of $\delta T_e(r,t)$ to lowest order. These arguments also only hold if $\delta Q_{rad}(r,t)$ is spatially localized such that Eq. (2) holds. However, even if $\delta Q_{rad}(r,t)$ is spatially localized, there may still be exceptions to the above discussed time-to-peak delay. These exceptions occur when $\chi_e{}^p$ is very small relative to the transport of the radiating impurities such that Eq. (3) with Eq. (4) becomes to lowest order for all $t << \tau_E$:

$$\frac{3}{2} n_e \frac{\partial \delta T_e}{\partial t} \approx -\delta Q_{rad}(r,t) \ , \tag{10}$$

even though Eq. (2) may still be satisfied. Equation (10) is consistent with $G(r-\xi, t-\tau) \rightarrow \delta(r-\xi)$ as $\chi_e{}^p \rightarrow 0$ in Eq. (6) [15]. In this extreme situation, the time-to-peak may shorten, which would occur at the time when $\delta Q_{rad}(r,t)$ returns to zero at r: Eq. (7) applied to Eq. (10). An extremely fast locally transporting inducing source mimics near global source behavior relative to the $\delta T_e(r,t)$ response: this makes Eq. (10) potentially valid near the pulse peak. By characterizing the transport of the inducing source as slower than the $\delta T_e(r,t)$ transport, the above situation cannot occur and the significance of the $\chi_e{}^p$ term in Eq. (3) is guaranteed for all $t << \tau_E$. With this guarantee, Eqs. (8) through (9) hold which in turn implies a definite time-to-peak delay due to the local significance of the inducing source.

The key concept is that when a significant locally transporting inducing source within the constraints described above is present at a given locality, it is not possible to characterize or model the $\delta T_e(r,t)$ pulses at that locality with a single homogeneous diffusion equation. The time-to-peak delay indicates a lower $\chi_e{}^p$, yet the lack of as much peak magnitude decay from one position to another indicates a higher $\chi_e{}^p$ (the inducing source only adds to the pulse magnitude). Therefore, the extent to which one can model or characterize the $\delta T_e(r,t)$ pulses with a single homogeneous diffusion equation in the short time ($t << \tau_E$) is the extent to which one can claim separation from the inducing source, δS, which must transport locally relative to the $\delta T_e(r,t)$ response.

Characterization of the inducing source beyond assuming or demonstrating local transport independent of $\delta T_e(r,t)$ is mostly avoided since its effects on the $\delta T_e(r,t)$ pulses cannot be indicative of a single diffusion process described by $\chi_e{}^p$. The situation described by Eq. (10) occurs in the extreme situation where the inducing source is more global than local relative to the $\delta T_e(r,t)$ pulses. As long as Eq. (10) is never valid for $t << \tau_E$, the quantities D_{imp}, V_{imp}, and L_{imp} do not need to be characterized or calculated to justify the time-to-peak delay due to the inducing source. The time-to-peak delay together with the lack of magnitude decay due to the significant presence of an inducing source allows for a rigorous separation of the inducing source from the $\delta T_e(r,t)$ pulses. The transport of the inducing source should be demonstrated as slower than the transport of the $\delta T_e(r,t)$ pulses to ensure that the inducing source can be separated from the $\delta T_e(r,t)$ pulses by modeling only the $\delta T_e(r,t)$ pulses: Eq. (10) is never valid for $t << \tau_E$.

3. APPLICATION TO TFTR

The method of obtaining the χ_e^p for electrons as described in Section 2 has been applied to some L-mode discharges on TFTR. All of the L-mode plasmas examined here were designed to examine trace iron and helium transport [5,6] and perturbed electron transport [5,6,7] and have the following basic parameters: approximately 12.5MW of balanced neutral beam power, major radius $\approx$ 2.45m, minor radius($\equiv a$) $\approx$ 0.80m, $B_T \approx$ 4.8T, $I_P \approx$ 1.0MA, $q_a(cyl) \approx 6$, $T_e(0) \approx$ 4.0keV, $n_e(0) \approx 4.5 \cdot 10^{19}\mathrm{m}^{-3}$, and sawtooth inversion radius $\approx$ 0.10m.

Two different impurities were injected by very different techniques. Iron was injected by the laser blow-off technique which introduced only a minuscule number of electrons (about 10^{18} atoms ablated versus $\sim 10^{21}$ electrons in the TFTR plasma) and cooled the plasma by radiation of the inward transporting iron atoms. In the other case, small puffs of helium (3.5 torr·liters over 0.015s to 0.02s) cooled the electrons mainly through the addition of cold electrons but probably also from some helium radiation as well. Both of these sources for transient, perturbative local cooling of the plasma involve transport into the plasma from the edge, but are weighted heavily toward the edge for the short time scale of concern here ($t << \tau_E$). A 20 channel ECE (electron cyclotron emission) grating polychromator [16] (time resolution of ~0.2ms and radial spatial resolution of ~0.03m with channel separation of ~0.06m) was used to track the T_e perturbation induced in both injection cases. The polychromator, however, does not provide the absolute electron temperature and each channel must be calibrated relative to another T_e diagnostic such as Thomson scattering or the Michelson interferometer. The relative T_e perturbation ($\delta T_e / T_e$) in the region $0.38 < r/a < 0.56$ is ~3% for the iron injection case and < 2% for the helium puff case.

The first characteristic to notice about the ECE data of the $\delta T_e(r,t)$ pulses is that in 0.015s, the pulse peak propagates most of the way through the plasma (see Fig. 1). However, the power balance electron energy confinement time, τ_E~0.09s. In addition to this very fast propagation of the pulse peak, the magnitude of the pulse peak actually grows for both cases (especially for the iron injection case) in the outer part of the plasma (see Fig. 2). This magnitude behavior can be explained in both cases mainly by the time integral over the locally significant presence of the inducing source (radiation in the iron injection case) in the outer radial region. However, the very fast propagation can only be due to a large χ_e^p since a locally significant inducing source, which transports slower in this case [5,6], only delays the time-to-peak (see Section 2). Where the radiating iron source is significant, a clear time-to-peak (t_p) delay is seen in the data (see Fig. 3).

Using a homogeneous cylindrical diffusion simulation, driven by using the data at r=0.45m as a time-dependent boundary, a χ_e^p has been obtained for both cases in the region where there is no locally significant inducing source ("region of interest" in Figs. 2 and 3). The iron injection case is more definitive, yet both cases agree. In the region $0.38 < r/a < 0.56$, both cases require $\chi_e{}^p = 6.0\mathrm{m}^2/\mathrm{s} \pm 35\%$ to match the timing and the magnitude of the pulses (see Figs. 4 and 5). The error in this quantity was determined mainly from the iron injection case by varying the $\chi_e{}^p$ and determining the range of acceptable agreement with the data. Also shown in Figs. 4 and 5 are the simulations using a highest possible estimate of the power balance χ_e for comparison; careful analysis indicates χ_e(power balance) $\approx 1.5\mathrm{m}^2/\mathrm{s}$ in the region $0.38 < r/a < 0.56$. This χ_e(power balance) was obtained just prior to the injection and given by the 1-D time-independent transport code SNAP (using $T_e(r)$ determined by Thomson scattering averaged and smoothed over 7cm) for "identical" discharges.

The highest possible χ_e(power balance) $\approx 2.5\ \mathrm{m}^2/\mathrm{s}$ corresponds to the use of the Michelson interferometer for $T_e(r)$ and is comparable to the upper bound of the uncertainty in χ_e(power balance) using the Thomson scattering $T_e(r)$. The Thomson scattering $T_e(r)$ and the Michelson interferometer $T_e(r)$ disagree (~10% at r=0) on the $T_e(r)$ magnitude for these discharges. The choice of which electron temperature diagnostic to trust was made by using both diagnostics on neighboring Ohmically heated discharges and then calculating an effective ion charge, Z_{eff}, with the assumption of neoclassical resistivity. This method of checking Z_{eff} is more definitive in the Ohmic case [17]. The Thomson scattering values produce a $Z_{eff} \approx 1.2$-1.5 which matches the visible Bremsstrahlung obtained Z_{eff}. However, the Michelson interferometer values produce $Z_{eff} \approx 0.75$ (< 1 is unphysical). Because enhancement in χ_e^p over χ_e(power balance) is being illustrated in Figs. 4 and 5, the highest possible χ_e(power balance) is used for illustration, even though it is not the accepted power balance value for these discharges. It is then clear from Figs. 4 and 5 that even the upper bound of the power balance calculation underestimates the fast diffusion of the perturbation in electron temperature.

Unfortunately, the radial "region of interest" is too small to provide information on the radial dependence of χ_e^p. The χ_e^p obtained here is larger than a factor of three times the diffusion coefficients for trace iron and helium in this region (D_{Fe}~1-2m^2/s, V_{Fe}~ -(1-3)m/s, D_{He}~1.5-2.5m^2/s, and $|V_{He}| < 2$m/s) [5,6]. It is also about twelve times larger than the electron particle diffusion coefficient determined from equilibrium analysis which is itself in agreement with the transient electron particle diffusion coefficient (negligible convection of the transient electron density) in this region for these discharges [5,6]. These injected impurities transport much slower than the T_e perturbation so that the method presented in Section 2 can be applied safely. Perturbations in the electron temperature seem to travel faster than any other cross-field diffusion process, even bulk ion heat diffusion which is only half as fast in this region [5,6].

The reasons why the iron case is more definitive are that: 1) Laser blow-off produces a spatially sharp, nearly instantaneous injection versus a gas puff which produces a time integral effect at the start of the T_e perturbation due to the gas line valve being open for up to 0.02s (see Fig. 6). 2) The cooling source for the iron injection case is unambiguously the radiating iron, whereas in the helium case, it is probably both the addition of cold electrons and the small amount of radiation from the helium. 3) For these discharges, the T_e perturbation in the helium case is so small that the data needed to be averaged over four "identical" shots, whereas in the iron case, the unmanipulated raw data for each of the nine good shots can be analyzed directly. 4) The helium puff case has complications due to the changing equilibrium caused by helium's very low pump-out rate which complicates the $\delta T_e(r,t)$ pulse magnitude determination (see Fig. 6).

In examining these discharges, the injections and perturbations did not appear to perturb the current (< 1%) on these time scales, nor was there any plasma vertical movement (< 0.001m) or plasma contraction (Δa < 0.004m). The temperature perturbation was the same on the inside as well as the outside of the torus. There was no detectable MHD activity (beyond small sawteeth). The sawtooth inversion radius for these discharges was quite small, but sawteeth are mostly responsible for the inner radial range limit of this analysis (see r/a < 0.31 channels in Fig. 1). A sharp decrease in χ_e^p is perhaps present close to the sawtooth mixing radius, however, the less definitive pulse peaks preclude accurate determination of this. Using the line integrated 10 channel far-infrared interferometer [18] data, the less than 5% increase in the line-integrated electron density through the plasma edge due to the injected iron atoms was observed to be poloidally symmetric. However, following this small electron density rise, there was an unexplained subsequent transient drop in the electron density of about the same magnitude as the rise over 0.05s. These phenomena were, however, very local to the plasma edge (outer 10 cm), and they do not seem to have any effect on these results. Specifically, in the region $0.38 < r/a < 0.56$, the electron density perturbation is negligible: by Abel inverting [19] the line-integrated data, no change at all (< 1%) in the local electron density is observed in the region of interest, $0.38 < r/a < 0.56$.

The soft-x-ray data for the iron injection case shows a 50-60% increase in the line-integrated data. Because these detectors are not sensitive to the low energy photons from recombination radiation of the lower charge states which radiated much of the power, 50-60% is probably an underestimate of the actual $\delta Q_{rad} / Q_{rad}$. Quantities which are perturbed < 10% (T_e, T_i, n_e, etc.) will have a negligible effect on $\delta Q_{rad}(r,t)$ which is dominated by the positive impurity particle injection. In fact, the iron and helium atoms were tracked directly from their radiation, $\delta Q_{rad}(r,t)$, in the particle transport study of these discharges [5,6] by neglecting $\delta T_e(r,t)$.

Attempts were made to model the entire $\delta T_e(r,t)$ pulse behavior in the outer regions of the plasma by using the impurity transport code MIST [12] to provide the $\delta Q_{rad}(r,t)$ profile for these shots. However, at this stage, it appears that MIST is underestimating the degree of plasma edge weighting of $\delta Q_{rad}(r,t)$ for short times and is not consistent with the T_e perturbation observed. Even though MIST shows a very strong degree of edge weighting in the $\delta Q_{rad}(r,t)$ profile, it is not edge weighted enough to provide an inner region where $\delta Q_{rad}(r,t)$ is insignificant as the T_e data shows (see Figs. 2 and 3). One possibility is that MIST may be underestimating how long the lower charge states (at the edge) continue to radiate.

Radiation data from various diagnostics presently is not local enough and has too high of a noise to signal ratio for accurately comparing to the MIST calculation of $\delta Q_{rad}(r,t)$ for this application (short time scale and local). None of these concerns, however, affect the main results of this paper, because there is no significant $\delta Q_{rad}(r,t)$ in the region 0.38 < r/a < 0.56 as evidenced by the ECE T_e data analyzed relative to the arguments given in Section 2.

4. DISCUSSION OF RESULTS

The enhancement, $\chi_e{}^p \sim 4\chi_e$(power balance), obtained here is a somewhat familiar result. Sawtooth heat pulse propagation studies generally show these types of enhancements [2,9,10,20]. Other studies [20] also seem to show the same behavior. Most of the already proposed physics models [1,2,9,10,21] that purport to explain this perturbative transport enhancement also apply here.

Most of the work in the past with T_e perturbations involved sawtooth heat pulse propagation which lately has been shown to involve complications due to a ballistic effect [22] beyond the m=1 surface during a sawtooth crash. This effect seriously complicates the analysis, but it is controversial [23] just how much of any heat pulse $\chi_e{}^p$ is due to this effect. Sawtooth heat pulse propagation is also potentially complicated by the proposed coupling [10,11] to electron density perturbations resulting from the sawtooth crash. Moreover, different machines seem to give different degrees of coupling [24]. Because the new method presented here does not have a significant associated electron density perturbation (iron injection case) away from the outer 10cm, and does not involve ambiguities about sawtooth or MHD activity in the region r/a > 0.38, the relevance of the above complications can be evaluated.

Most of the other methods used for inducing transiently localized electron temperature perturbations rely on modulating heating sources and fueling sources [20]; often the perturbations are not small or other quantities get perturbed as well. Particularly when Fourier methods are used, the whole pulse in time must be analyzed, and in this case, the perturbed pinch and perturbed source terms cannot be neglected. The laser blow-off method used for this study produces a single sharp (in time and space) perturbation which shortens the scale length of the perturbation and magnifies the role of the perturbed diffusion terms above all others in the short time scale of the pulse peak.

There are three main classes of models proposed to explain enhancements $\chi_e^p > \chi_e$(power balance). Any pinch behavior [9,25] in the electron energy conservation equation would be much more relevant to power balance calculations and would not be significantly accessed in a spatially localized perturbation. Therefore, if a pinch was not correctly included in the power balance, the χ_e(power balance) would be artificially low. Secondly, if there were other coupled diffusion processes [10,11] such as electron density or current, terms related to these could show up in χ_e^p. However, in this study, no other such perturbations occurred in the iron injection case. Moreover, the helium injection case also gives the same χ_e^p with a significant electron density perturbation (~ 5-6%). Thirdly, a dependence of χ_e on the electron temperature gradient (nonlinear electron "diffusive" heat flux), when perturbed, could place this exponent as a multiplier in $\chi_e{}^p$: an electron heat flux, $q_e \sim \chi_e(\nabla T_e) \sim (\nabla T_e)^\beta$ gives $\delta q_e \sim \chi_e{}^p(\nabla \delta T_e) \sim \beta(\nabla T_e)^{\beta-1}(\nabla \delta T_e)$ so that to first order, $(\chi_e{}^p / \chi_e) \sim \beta$. This third possibility is attractive since for a long time the T_e profile in tokamaks has been observed to be stiff or "resilient" to the heating profile [26,27]. A nonlinear electron "diffusive" heat flux could account for this [27,28]. However, none of the above mechanisms are mutually exclusive. It has long been a hope that local perturbative measurements such as this one, when compared to global equilibrium or power balance calculations, could uncover the relevance of the various mechanisms discussed above.

In using the injection of impurities to cool the plasma and induce $\delta T_e(r,t)$, laser blow-off seems to be the best method. This instantaneous injection of very small amounts of radiating impurities produces predominantly perturbations in the plasma temperature which can be as small as desired. Any coupling to perturbations in the ion temperature would probably only occur through the perturbed source terms in Eq. (1) and therefore only affect the long time tail of the pulse. Depending on the type of impurity, the plasma needs to be hot enough to mostly ionize the impurity atoms near the edge so that there is an inner region in which $\delta Q_{rad}(r,t)$ is insignificant. In addition, the sawtooth inversion radius needs to be small and MHD activity low enough.

5. CONCLUSION

The work in this paper represents a new and different way to obtain a transient electron heat diffusivity. The advantages of this method include the fact that the source's local impact on the $\delta T_e(r,t)$ pulses can be rigorously determined by looking at both the timing and magnitude (within the constraints discussed in Section 2). The timing information alone sets the lowest possible value of χ_e^p in most cases. If, then, the magnitude as well can be modeled with a single homogeneous diffusion equation in some region for $t << \tau_E$, then χ_e^p can be obtained with a high level of confidence. Laser blow-off is a very good method for producing T_e perturbations. Disadvantages include the need for high temperature plasmas that are relatively quiescent with regard to their MHD and sawtooth activity. In addition, a diagnostic like ECE which measures only T_e and not the radiation causing the T_e perturbations needs to be used. The high temporal and spatial resolution of the ECE grating polychromator makes possible analysis of the unmanipulated data.

Secondly, but just as important, these concepts applied to TFTR L-mode discharges gave χ_e^p = (6.0m^2/s ± 35%) ~ 4χ_e(power balance). In this case, no sawtooth or MHD ambiguities or simultaneous electron density perturbations (in the iron injection case) affect this result. Helium puff induced T_e perturbations, while more complicated and less definitive, require the same χ_e^p to model the pulses in the same region on the same discharges. The dominant similarity between these two cases is the equilibrium plasma itself.

As with other studies giving qualitatively similar results [20], this χ_e^p enhancement over χ_e(power balance) may indicate heat pinches in the power balance and/or nonlinear T_e transport which are not mutually exclusive possibilities. As a final note, $\chi_e^p \sim 6\mathrm{m}^2/\mathrm{s}$ is seemingly the fastest cross-field diffusion process in these discharges [5,6]. Any possible macroscopic or nonlinear thermodynamic theories [29] would put considerable weight on the fastest communication between the system boundary and the core. In addition, perhaps the plasma may seem to be overly sensitive to the wall conditions if the perturbed T_e transport is not considered and its short time scale not appreciated.

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Figure Captions:

FIG. 1. Example ECE grating polychromator data for TFTR shot 49971 (same iron injection case as analyzed in Fig. 4). Note the fast propagation of the "cold pulse" in from the edge. The magnitudes of these pulses are presented in Fig. 2.

FIG. 2. Example "cold pulse" T_e magnitudes for the discharge in Fig. 1 and one of the helium puff discharges (TFTR shot 49990) averaged into the data analyzed in Fig. 5. These particular pulses could only be analyzed for diffusive electron heat transport in the small region $0.38<(r/a)<0.56$. The helium puff case magnitudes are much smaller and have complications presented in Fig. 6.

FIG. 3. Time-to-peak (t_p) delay for averaged TFTR shots 49970,71,72 which have been smoothed over 0.003s. In the region $0.38<(r/a)<0.56$, this delay disappears consistent with the iron injection magnitude behavior in Fig. 2 (see Section 2), and the slope indicated is responsive to only to χ_e^p [2]. The source reference position r=0.74m was used rather than r=a=0.80m because of possible plasma edge physics complications.

FIG 4. Driven simulation from iron injection case T_e data at r=0.45m (TFTR shot 49971) showing good agreement with $\chi_e^p=6.0m^2/s$. The highest possible χ_e(power balance) of $2.5m^2/s$ is still much too small to model either the timing or the magnitude of the pulses at r=0.31,0.38m. Each of several discharges "identical" to this one give the same result.

FIG. 5. Driven simulation from smoothed (over 0.003s) and averaged (TFTR shots 49990,91,94,95) T_e *data for the helium puff case showing the same* $\chi_e^p = 6.0 m^2/s$ *models the pulses better than the highest possible* χ_e*(power balance) of* $2.5 m^2/s$ *as in Fig. 4. This case is less definitive but supportive of the inference of* χ_e^p *obtained in Fig. 4.*

FIG. 6. The δT_e *pulse for a helium puff discharge (TFTR shot 49990) at r=0.60m. This shows the complications caused by helium's low pumping rate which changes the equilibrium. The helium gas line valve being open for ~0.02s causes an additional time integral effect at the start of the pulse.*

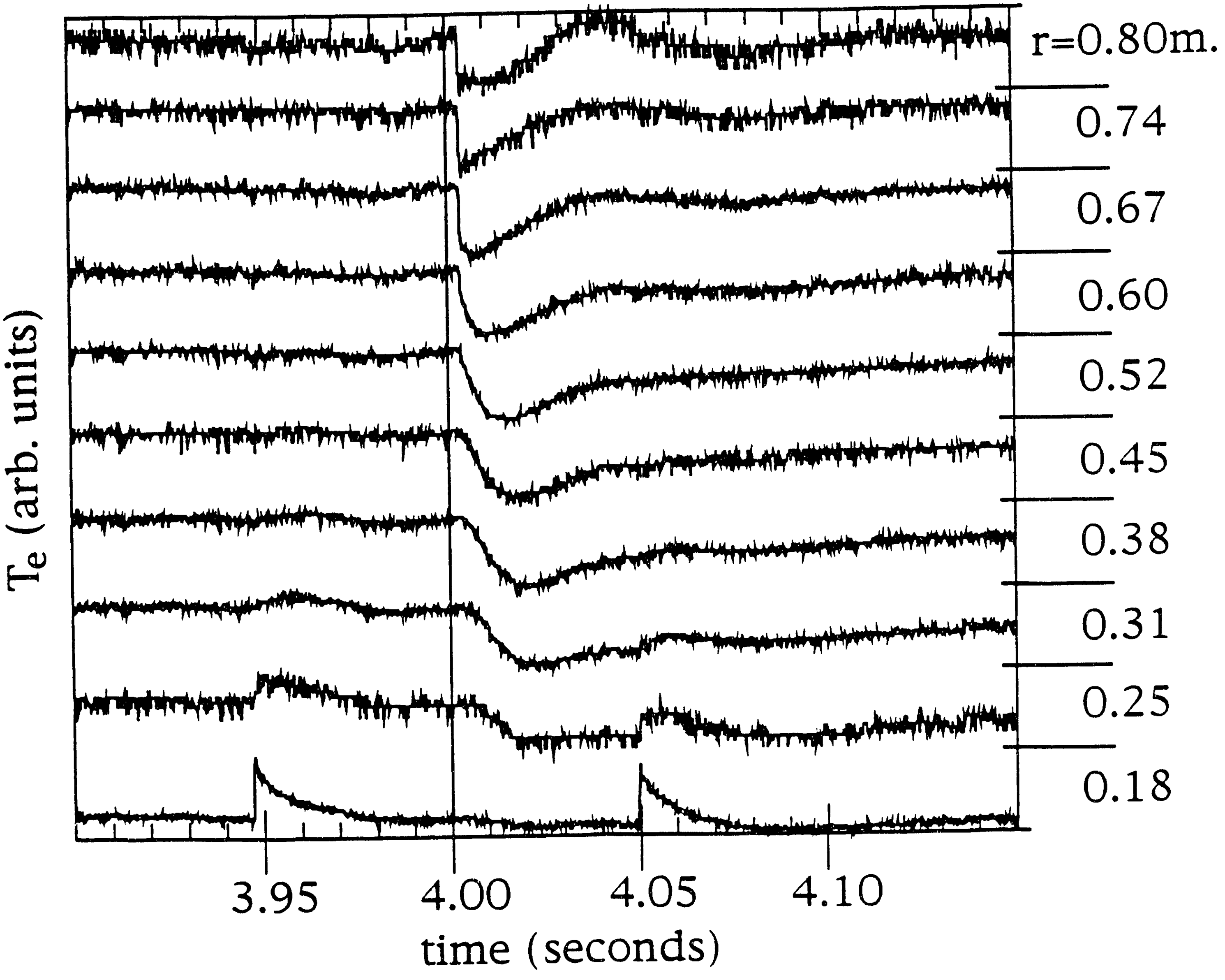
r=0.80m.
0.74
0.67
0.60
0.52
0.45
0.38
0.31
0.25
0.18
Te (arb. units)
3.95
4.00
4.05
4.10
time (seconds)

Fig. 1

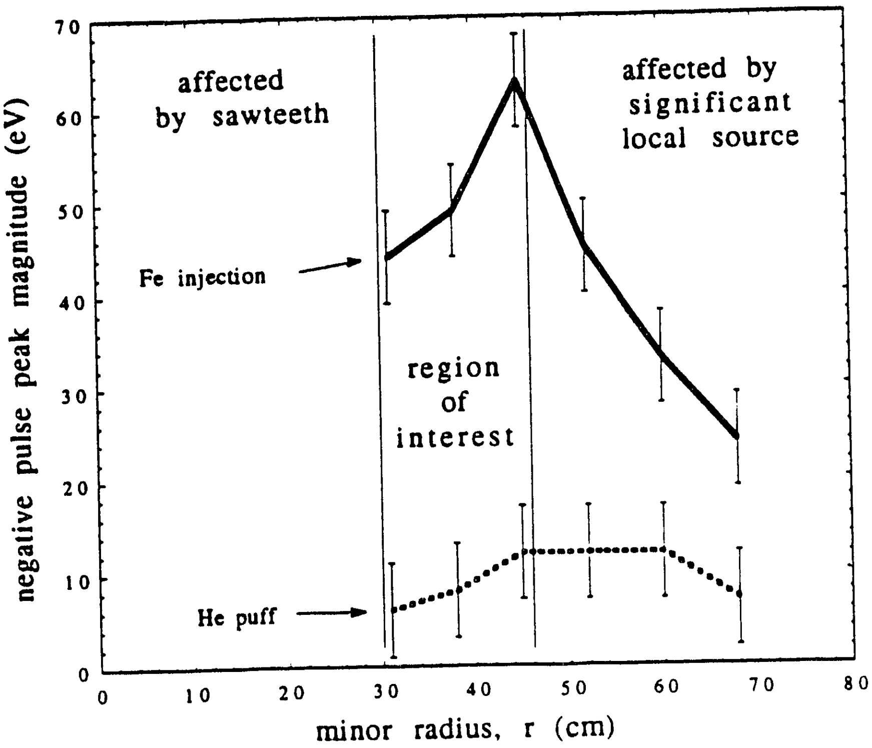
70
60
50
40
30
20
10
0
negative pulse peak magnitude (eV)
0
10
20
30
40
50
60
70
80
minor radius, r (cm)
affected by sawteeth
affected by significant local source
region of interest
Fe injection
He puff

Fig. 2

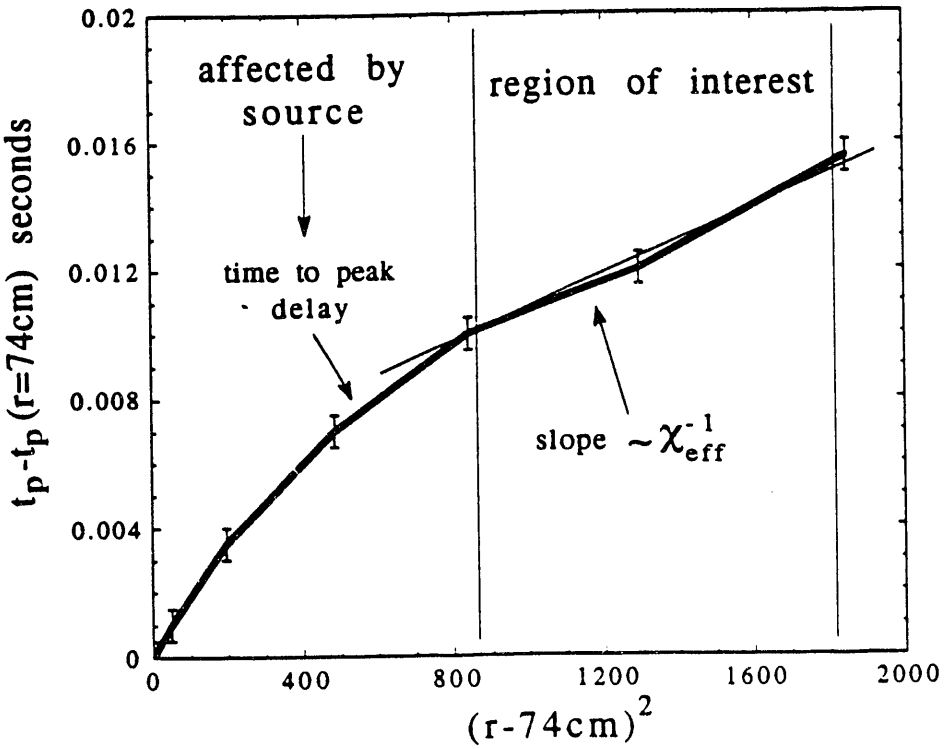
0.02
0.016
0.012
0.008
0.004
0
0
400
800
1200
1600
2000
$t_p - t_p\,(r=74\text{cm})$ seconds
$(r-74\text{cm})^2$
affected by source
region of interest
time to peak delay
slope $\sim \chi_{eff}^{-1}$

Fig. 3

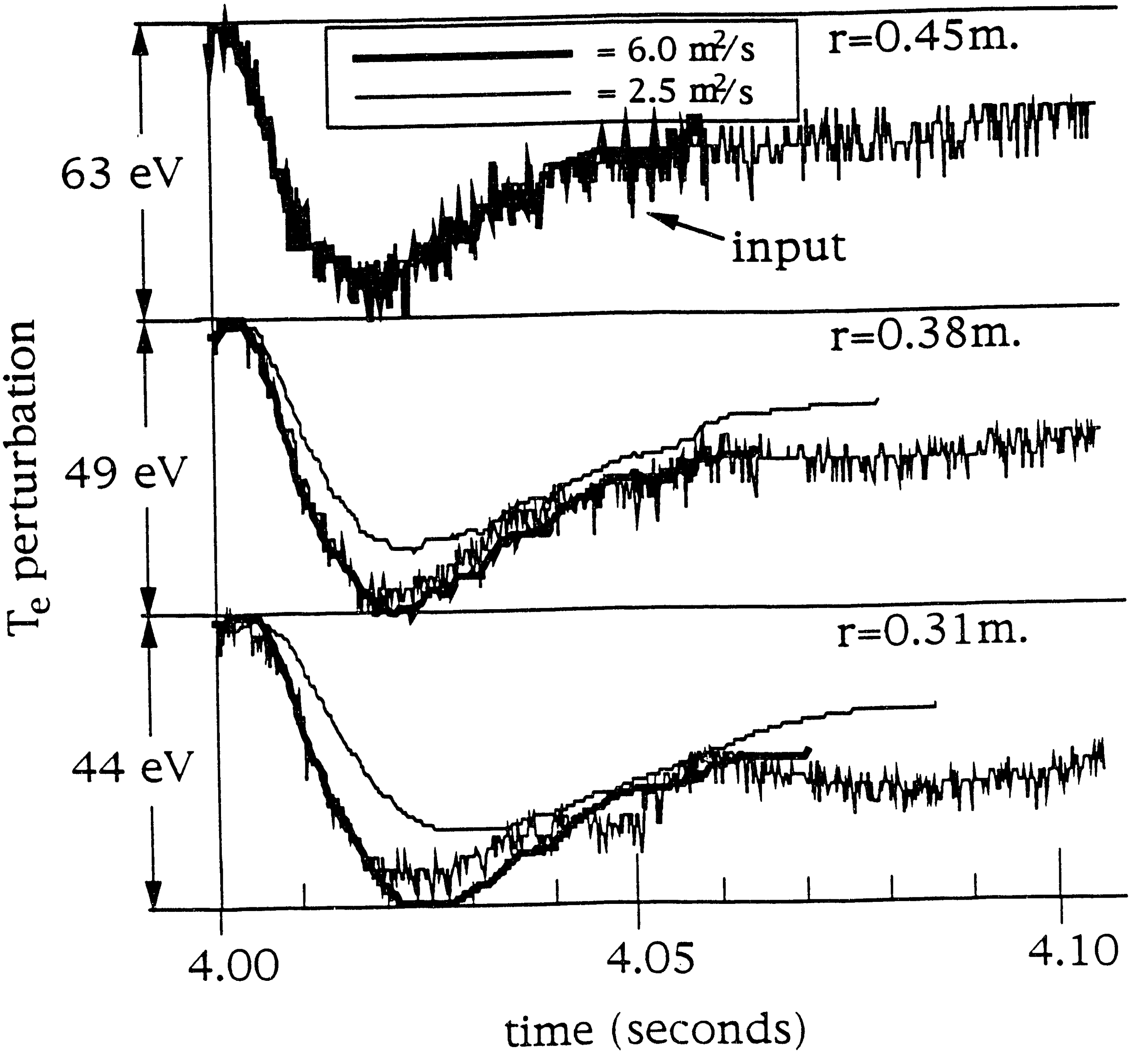
= 6.0 m^2/s
= 2.5 m^2/s
r=0.45m.
63 eV
input
r=0.38m.
49 eV
r=0.31m.
44 eV
T_e perturbation
4.00
4.05
4.10
time (seconds)

Fig. 4

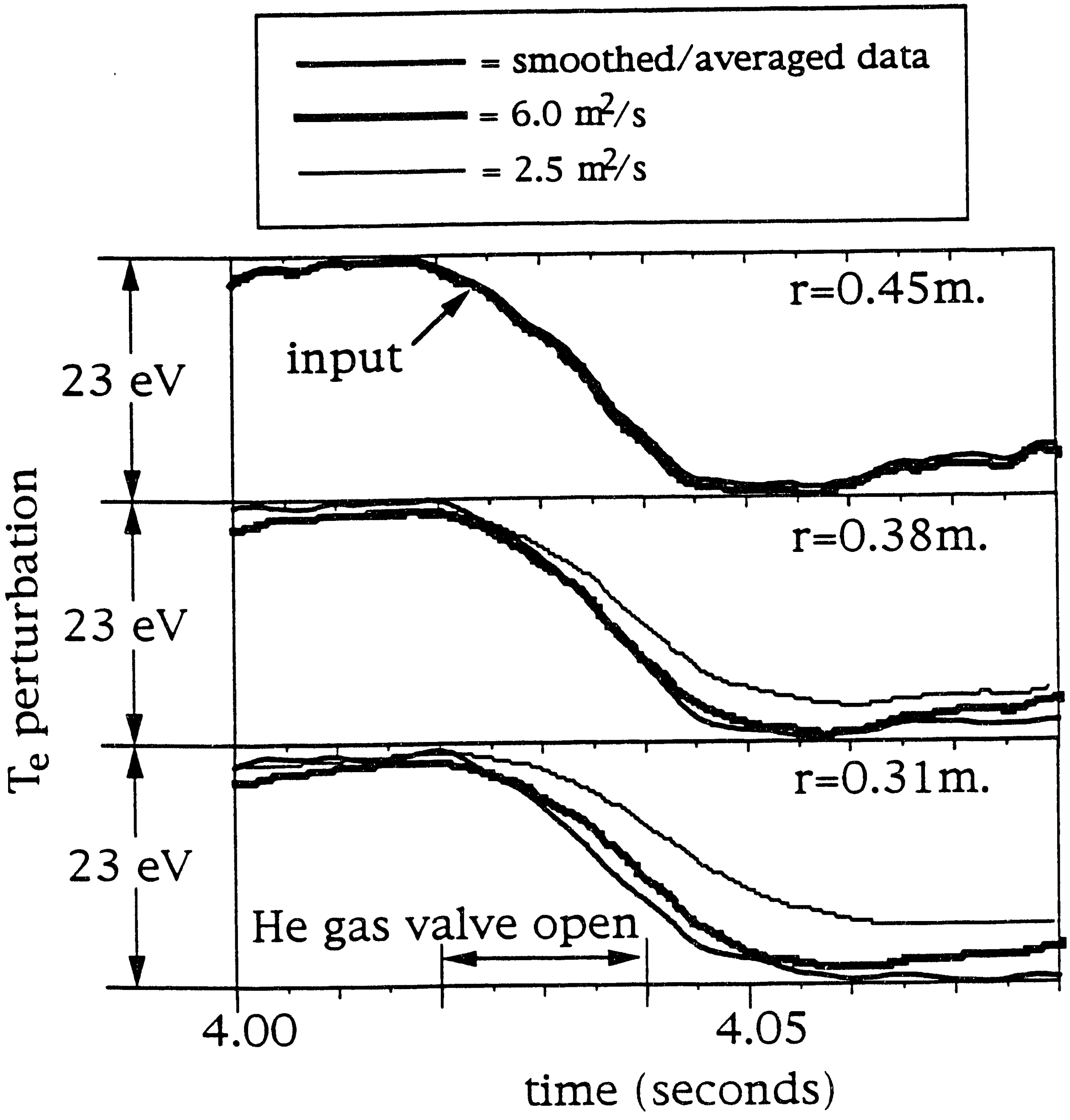
= smoothed/averaged data
= 6.0 m^2/s
= 2.5 m^2/s
r=0.45m.
input
r=0.38m.
r=0.31m.
23 eV
23 eV
23 eV
T_e perturbation
He gas valve open
4.00
4.05
time (seconds)

Fig. 5

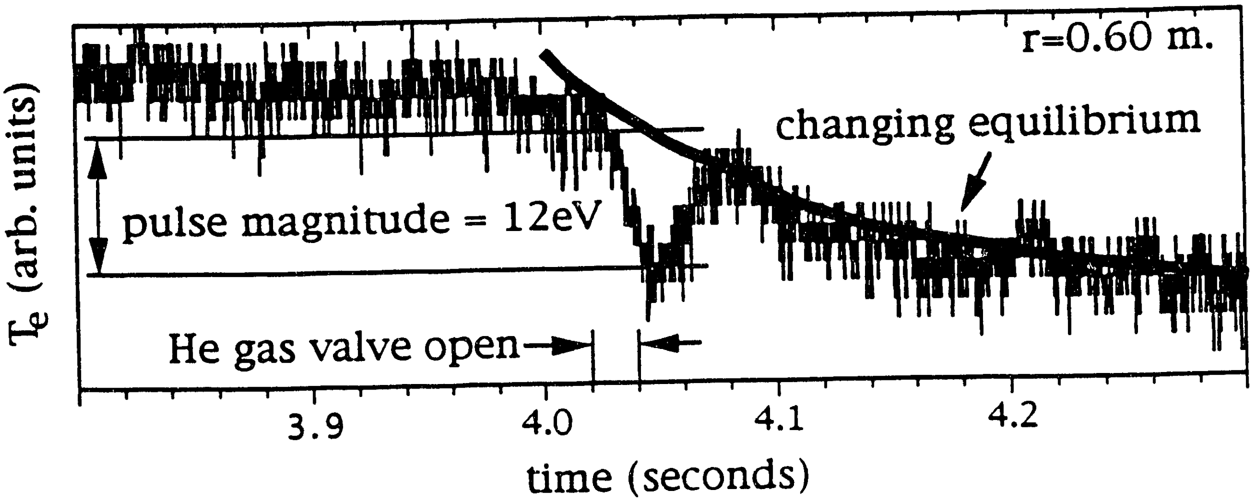
r=0.60 m.
changing equilibrium
pulse magnitude = 12eV
He gas valve open
T_e (arb. units)
3.9
4.0
4.1
4.2
time (seconds)

Fig. 6

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