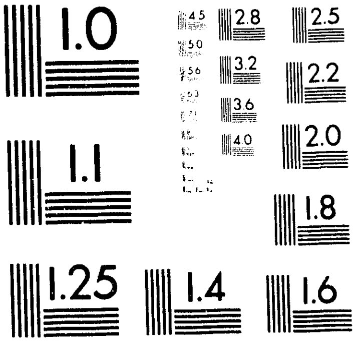
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DOMINANCE OF CONVECTIVE HEAT TRANSPORT IN THE CORE OF TFTR (TOKAMAK FUSION TEST REACTOR) SUPERSHOT PLASMAS

BY

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AUGUST, 1993

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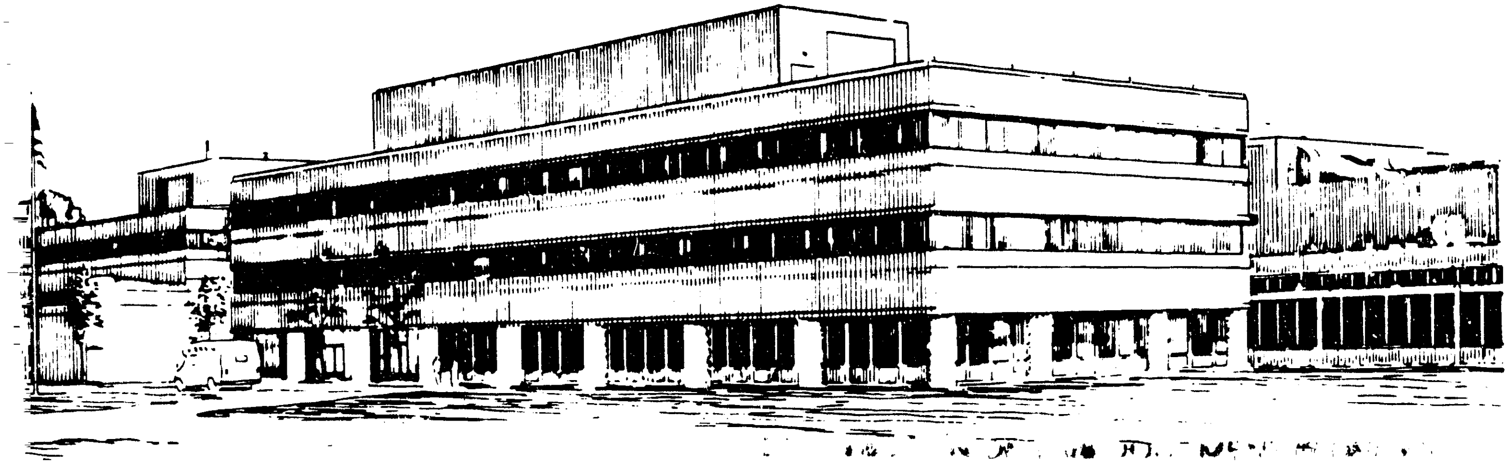

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Dominance of Convective Heat Transport in the Core of TFTR (Tokamak Fusion Test Reactor) Supershot Plasmas

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Using perturbations in electron density and temperature induced by small Helium gas puffs in TFTR (Tokamak Fusion Test Reactor) [Plasma Phys. Controlled Nuc. Fus. Research **1**, 51 (1986)], the dominance of convective heat transport in the core ($r/a < 0.4$) of supershot plasmas has been demonstrated in a new way. The TRANSP [Journal Comp. Phys. **43**, 61 (1981)] transport code was used to calculate the time-dependent particle and heat fluxes. Perturbations in the calculated convective and total electron heat fluxes were compared. They demonstrate that the conductive component decreases moving into the supershot core, and the convective component dominates in the supershot core. These results suggest a different transport drive in the supershot core compared to that in the rest of the supershot plasma.

PACS: 52.25.Fi, 52.55.Fa, 52.25.Vy

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I. Introduction

The supershot is an enhanced confinement regime in TFTR[1] (Tokamak Fusion Test Reactor) that is associated with peaked density profiles. In addition to supershot confinement being independent of I_p and P_{inj},[2,3] it has been inferred that supershots exhibit a high degree of convective heat transport in the core region.[2,4] We have a new method for demonstrating this convective heat transport dominance in the core region by using perturbation techniques. Previous analyses inferred this convective dominance in the core of supershot plasmas using "equilibrium" (long-time) results from interpretive transport codes such as the TRANSP[5] (1.5-D time-dependent) code.[2,4] In this study, we used perturbations in the TRANSP calculated electron heat and particle fluxes to observe this convective dominance in the cores of an ensemble of "identical" supershots. These perturbations were caused by small gas puffs (3.5 torr•liters over 0.02 seconds) of Helium from which small perturbations in electron temperature and density propagated inward.[3]

II. Measurement of Convective Domination

The He was puffed during energetic neutral beam injection (13MW of balanced co- and counter- tangential injection) from a single valve located on the top of the torus. The TRANSP code was used to calculate the energy and particle balance equations from the average of 6 reproducible shots on TFTR with the following basic parameters: R_0=2.45 m, a=0.80 m, B_T=4.8 T, I_p=1.0 MA, q_a(cyl.)=6, $T_e(0)$=6.5 keV, $n_e(0)=4.5\times10^{19}$ m^{-3}, Z_{eff}=4.0, and profile peakedness,

$n_e(0)/\langle n_e \rangle = 2.4$. Measurements of $T_e(r,t)$ were made using ECE (Electron Cyclotron Emission) radiometry[6] (4 msec time resolution). A 10 channel infrared interferometer[7] array was used to measure $n_e(r,t)$ and to confirm poloidal symmetry of the injected helium into the edge plasma (transport parallel to the magnetic field is much faster than perpendicular transport). These line-integrated raw density data were Abel inverted[8] and smoothed (over 3 msec). TRANSP calculations with various time resolutions (2 to 10 msec) and numbers of Monte Carlo beam particles produced no significant changes in these results. The TRANSP calculated heat fluxes were smoothed in time over 10 msec.

The inference of convective heat transport dominance was previously demonstrated by using the equilibrium results from TRANSP calculated power balances. For electrons, this balance gives Q_e, the electron heat flux, subsequently separated into its conductive and convective parts:

$$Q_e = -n_e \chi_e \nabla T_e + (3/2) T_e \Gamma_e, \tag{1}$$

where T_e, n_e, and χ_e are the electron temperature, density, and effective heat diffusion coefficient respectively. The quantity Γ_e is the electron particle flux calculated through TRANSP by a particle balance. The multiplier 3/2 was chosen rather than 5/2 in order to keep the effective ion heat diffusion coefficient positive in the supershot regime.[2,4] It was observed for both ions and electrons that the quantity $2Q/3T\Gamma$ was greater than but close to unity which indicated that a large component of the heat transport was due to the convective term.

In this study, we used He gas puff induced perturbed electron quantities:

$$\delta Q_{total} = \delta Q_{conductive} + \delta Q_{convective}, \quad (2)$$

where $\delta Q_{convective} = 3/2\ \delta(T_e \Gamma_e) \approx 3/2\ T_e\ \delta\Gamma_e$ is observed. Any change $\delta Q_{conductive}$ in the conductive electron heat flux, which is not assumed to have a specific form as in Eq. 1, is imperceptible above the approximately 10% relative noise level in the fluxes coming from the Monte Carlo energy source (beam) calculations both inside and outside of the core. In fact, near the plasma core, the only reliable δQ_{total} measurement results from $\delta Q_{convective}$ (see Figure 1). The *induced* $\delta Q_{total} \approx \delta Q_{convective}$ and needs to be of a larger magnitude than $10\%(Q_{total})$ in order to be observed. This happens in the core region where convective heat transport is dominant such that the noise in $Q_{conductive}$ does not obscure the induced $\delta Q_{convective}$. The quantities δQ_{total} and $\delta Q_{convective}$ were measured in the same 20 msec time window (4.05s to 4.07s in the core region) within the initial perturbation. This time window was chosen such that the noise in $\delta Q_{conductive}$ was at a minimum and there was simultaneously a large negative drop in $\delta Q_{convective}$ concurrent with the local initial rise of the electron density.

It should also be noted that the strange shape of this perturbation for a single gas puff is still not yet understood. Specifically, the observed and expected transient drop in $\delta Q_{convective}$ in response to the locally initial increase in electron density seems to be superimposed on a longer time transient rise occurring in all three heat fluxes (see r=0.15m of Figure 1). Supershot plasmas are observed to be very dynamic (large gradients in density and temperature and heavily driven by beams)[1] which could be responsible for small flux surface movements that would affect both the conductive and convective heat flux components similarly and result in the strange transient rise mentioned above. The small gas puff did not seem to have a significant effect on the plasma globally: magnetics diagnostics, which are sensitive to the plasma edge where the largest induced perturbations occur, show δR_0, $\delta a < 1.5$cm, $\delta I_p <$ 3%, and $\delta q_a < 1\%$. It should be stressed, however, that fundamentally our major observation is that a clearly significant and induced $\delta Q_{convective}$ occurs unaccompanied by a significant or induced $Q_{conductive}$ perturbation between 4.05s and 4.10s in the core region (see Figure 1). The degree to which this exclusively convective heat flux perturbation gets expressed in the power balance (or total heat flux) is the basic measurement here.

The electron particle flux changes by factors of about 30-50% due to the perturbation, but the total electron heat flux follows the dynamics of the particle flux only in the core of supershot plasmas. Essentially, this large response of the particle flux to the small gas puff locally increasing the electron density ($\delta n_e/n_e \approx +6\%$) is in contrast to the negligible conductive heat flux response. From a localized transient perturbation in which the scale length of the perturbation is much smaller than the equilibrium scale length, the following is expected and observed:

$$\frac{\delta\nabla^2 n_e}{\nabla^2 n_e} >> \frac{\delta\nabla n_e}{\nabla n_e} >> \frac{\delta n_e}{n_e} , \qquad (3)$$

where the inequalities represent factors of about six. The relative electron temperature perturbation is < 2% and its gradient changes are likewise negligible relative to the large changes in the electron density gradient. This provides for a good indication from this transient method of the convective heat flux dominance.

This perturbed convective dominance can be quantified by forming the following ratio R of perturbations (see Figure 2):

$$R = \delta Q_{total}/\delta Q_{convective}. \qquad (4)$$

The ratio R increases with minor radius and approaches unity near the plasma center, or equivalently, the ratio $\delta Q_{total}/T_e\delta\Gamma_e$ approaches 3/2 near the plasma center. The estimated uncertainty in R does not include uncertainty in the convective multiplier (i.e., 3/2 vs. 5/2) which was set at 3/2. This perturbed measurement has the advantage of not involving source calculations since the beam deposition of particles and energy were not perturbed as a result of the puff. However, possible anomalous electron-ion heat exchange processes have not been considered. Classical electron-ion heat exchange perturbations were not observed in the TRANSP output on these time scales and were small as expected since they are perturbed source terms that respond to δn_e and not $\delta\nabla n_e$ (see Eq. 3) and can only significantly affect the longer time behavior of the perturbations.

III. Discussion

In considering the possible implications of these results (Fig. 2), it is important to realize that the formal definitions of "conductive" and "convective" are blurred especially in the case of turbulence. In the context of electrostatic microinstability theories, $2Q/3T\Gamma$ approaching unity is really a measure of the dominance of drives other than ∇T that link Γ and Q. In these supershots, there is a sharp decrease in η_i at $r \approx 0.40$ m. to a value below $\eta_{i\ \mathrm{crit}} \approx 1.5$ for $r < 0.30$ m ($\eta_e < 1.0$ for $r < 0.30$ m). This is qualitatively consistent with the supershot not being dominated by ∇T-driven modes in the core region. In the region $r > 0.40$ m, $\eta_i >> \eta_{i\ \mathrm{crit}}$ which is qualitatively consistent with the dominance of ∇T-driven modes[9] in the outer regions of supershots. However, perturbations in η_i (through dn_i/dr but not dT_i/dr) in L-mode plasmas in TFTR produced no change in the local heat transport,[10] in apparent contradiction with such an interpretation.

Results from this study are apparently in contradiction to critical electron temperature gradient conductive models[11] which seem to break down in the convectively dominated supershot core. These models assume that the conductive electron heat flux is proportional to the difference between ∇T_e and some $(\nabla T_e)_{\mathrm{critical}}$. Calculations[12] using a typical form[11] of $(\nabla T_e)_{\mathrm{critical}}$ show that it is significantly smaller than ∇T_e. This magnitude difference implies a larger conductive component to the electron heat flux than is actually observed in the supershot core.

Also potentially relevant are some theories of nonlinear thermodynamics[13,14] which predict a correlation between driver power and transport near the stationary states of conductively dominated nonlinear systems. The facts that supershot transport is independent of auxiliary power and that supershots have a convectively dominated core, in this context, is qualitatively consistent with the supershot being a departure from an L-mode "stationary state."

IV. Summary

Perturbation techniques provide an alternative method to power balance approaches for inferring the relative amount of convective heat transport. In particular, these small gas puffs produced mainly particle flux perturbations without perturbing any heat source terms, the beam fueling, or the conductive heat flux. Therefore, when the perturbed heat flux is proportional to the perturbed particle flux, the relative amount of convective heat transport can be directly demonstrated. As shown in Fig. 2, convective heat transport dominates the perturbed heat flux response in the core of supershot plasmas in TFTR.

The evolution from L-mode to supershot is continuous and strongly correlated to the peakedness in the density profile[2] which results from the primary particle source from intense neutral beam injection being in the core rather than from recycling at the plasma edge. Results from this short study and others in the past suggest that another distinguishing feature between L-mode and supershot confinement is the degree of dominance of convective heat transport in the plasma core. In fact, in similar L-mode plasmas with these same gas puffs, we can measure no direct correspondence between δQ_{total} and $\delta\Gamma$ which would be needed to form the ratio, R, in Eq. (4). This indicates that, in contrast to supershots, L-mode plasmas are dominated by heat conduction throughout the plasma. Theories which predict separate transport drives for the core versus the rest of the supershot plasma would seem to be in better agreement with these results than theories which consider only a single transport drive throughout.

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Figure Captions:

FIG. 1 Representative measurements of δQ_{total} and $\delta Q_{convective}$ in the core region, r=0.15 m. contrasted with the outer region, r=0.45m. In the outer region, no reliable measurement of δQ_{total} is possible due to the strong conductive dominance there. Note the similarity of the Q_{total} and $Q_{convective}$ plots at r=0.15m. and the similarity of the Q_{total} and $Q_{conductive}$ plots at r=0.45m. (TFTR shots 49855-49860)

FIG. 2. The ratio, R in Eq. (3), of perturbed heat flux components, $\delta Q_{total}/\delta Q_{convective}$, approaches unity in the core region of a supershot ensemble. Beyond r=0.40 m, δQ_{total} seems unresponsive to $\delta Q_{convective}$, indicating dominance by the conductive heat flux there. Inside r=0.30 m, $\delta Q_{total}/\delta Q_{convective} < 2$, indicating convective dominance.

Figure 1

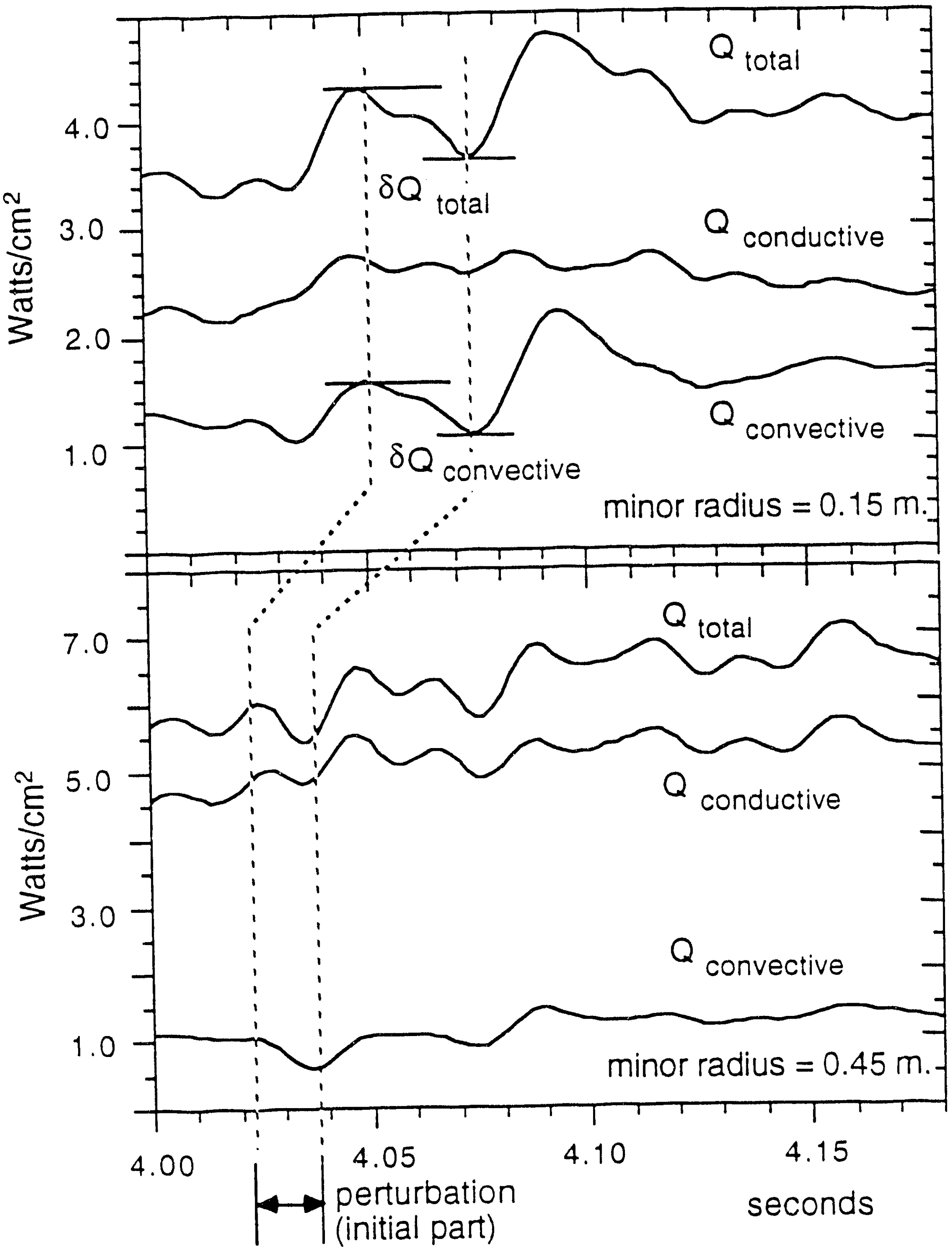
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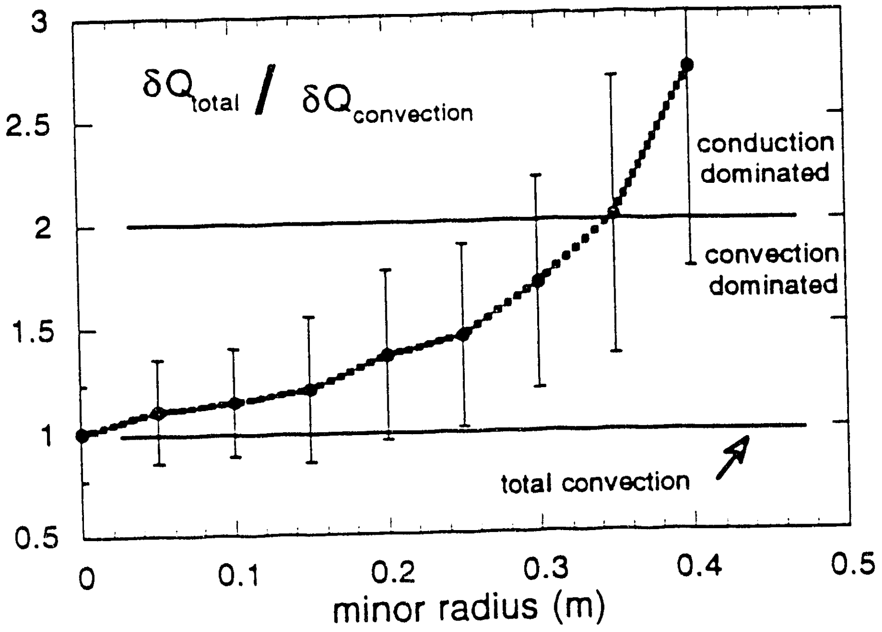
Figure 2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