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by

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This is a preprint of a paper to be presented at the 20TH EPS Conference on Controlled Fusion and Plasma Physics, July 26–30, 1993, Lisboa, Portugal and to be printed in the *Proceedings*.

Work supported by
U.S. Department of Energy
Contract DE-AC03-89ER51114

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GENERAL ATOMICS PROJECT 3466
MAY 1993

GENERAL ATOMICS

THE ROLE OF ELECTRIC FIELD SHEAR STABILIZATION OF TURBULENCE IN THE H–MODE TO VH–MODE TRANSITION IN DIII–D*

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VH–mode plasmas[1–5] exhibit energy confinement times up to 2.4 times the DIII–D/JET H–mode scaling relation and up to 3.9 times the value given by ITER89-P L–mode scaling. If this confinement improvement can be exploited in reactor plasmas, smaller prototype reactors with significantly lower unit cost can be produced. Accordingly, understanding and optimizing the confinement improvement is of significant interest. One of the possible explanations for this bulk confinement improvement is stabilization of turbulence by shear in the radial electric field,[2] similar to the present explanation for the confinement improvement at the extreme plasma edge at the L to H transition.[6] Preliminary measurements have shown that the region of the plasma where the electric field gradient is steepest broadens when the plasma goes from H–mode to VH–mode.[2] More recent measurements have confirmed this broadening and have shown that the change in the electric field gradient occurs prior to the change in the thermal transport. In addition, transport analysis shows that the electric field shear increases in the same region between magnetic flux coordinate $\rho = 0.6$ and 0.9 where the local thermal transport decreases.[5] Furthermore, far infra-red (FIR) scattering measurements have detected density fluctuations in the region around $\rho = 0.8$ which could be responsible for enhanced transport and which disappear at the time that the electric field shear increases.[5] These fluctuations appear as bursts of density fluctuations in the 0.5 to 1.5 MHz range.[5] The time between bursts increases as the electric field shear increases. Once these bursts disappear, the major change in confinement takes place in most discharges. When isolated bursts occur, the heat and angular momentum pulse connected with the burst are detectable on the plasma profile diagnostics.

The spatial correlation between increasing electric field shear and improved local transport is illustrated by the transport analysis results shown in Fig. 1. The transport analysis was carried out using the ONETWO transport code;[7] the electric field is inferred using the radial force balance equation and measurements from charge exchange recombination spectroscopy.[6] Local transport is assessed by considering the effective single fluid thermal diffusivity, $\chi_{\mathrm{EFF}} = -(q_e + q_i)/(n_e \nabla T_e + n_i \nabla T_i)$, where q_e and q_i are respectively the electron and ion heat flux. The greatest improvement in transport is between $\rho = 0.6$ and $\rho = 0.9$, which is the region where the shear in the radial electric field shows the greatest increase.

In order to determine whether the change in $E \times B$ velocity shear is big enough to affect the plasma turbulence, we use the Biglari, Diamond, Terry[8] expression for the magnitude of shear necessary for turbulence suppression $V'_{E\times B} \geq (\Delta\omega/k_\theta \Delta R) \equiv V'_{\mathrm{BDT}}$, where $\Delta\omega$ is the frequency spread of the turbulence and ΔR is the radial correlation length. Only the magnitude of the $E \times B$ velocity shear enters the theory, not the sign.

Measurements in the DIII–D edge region during L–mode[9] give $\Delta\omega \approx 2\pi\times$ (100 kHz) and $\Delta R \approx 1$ cm for $k_\theta = 2\ \mathrm{cm}^{-1}$, giving $V'_{\mathrm{BDT}} \approx 3 \times 10^5\ \mathrm{s}^{-1}$. This value is shown as the solid line in Fig. 1. The increased $E \times B$ velocity shear exceeds this value over much of the region of reduced thermal diffusivity, suggesting the increased shear is large enough to affect the turbulence.

The temporal correlation between the increased $E \times B$ velocity shear and the improvement in energy confinement can be most directly illustrated by comparing the time history of the ion temperature T_i and the plasma toroidal rotation speed v_ϕ. Over most of the discharge, v_ϕ is the dominant contribution to the radial electric field; only in the edge region outside of $\rho = 0.9$ are the poloidal rotation and pressure gradient terms important.[6] Accordingly, the time history of v_ϕ gives a direct picture of the change in the $E \times B$ velocity.

* This work was sponsored by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

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The most obvious feature in the v_ϕ time history given in Fig. 2 is the marked increase in velocity shear after 2400 ms. The rotation slows in the edge region of the plasma, but increases in the core. Measurements further into the plasma core, not shown in the figure, also show increasing v_ϕ. Closer examination of Fig. 2 reveals that v_ϕ in the region between $\rho = 0.82$ to $\rho = 0.93$ begins to decrease about 20 ms prior to the first detectable change in the thermal transport. The thermal transport change occurs at about 2395 ms on this particular shot and is indicated by the distinct change in slope of the ion temperature trace at $\rho = 0.67$ shown in Fig. 2. All shots examined to date which showed a definite transition from H-mode to VH-mode also showed this distinct slowing of the edge rotation prior to the thermal transport improvement.

Most VH-mode shots studied to date show a definite improvement in energy confinement part way through the ELM-free phase of the shot.[5] Less frequently, shots occur which do not manifest the distinct transition, but rather show a gradual, continuous confinement improvement. These shots, too, show a correlation between increasing $E \times B$ velocity shear and confinement improvement. As is illustrated in Fig. 3, v_ϕ in the plasma edge around $\rho = 0.9$ starts slowing within 50 ms of the L to H transition. It appears that this slowing gradually propagates into the plasma. Around 2450 ms, there is some sign of the more rapid velocity shear increase seen in Fig. 2, but it is much weaker here.

The rapid increase in velocity shear seen in Fig. 2 and, to some extent, in Fig. 3 is associated with the disappearance of a distinctive, bursting type of density fluctuations which have been dubbed momentum transfer events (MTE).[5] As is seen in Fig. 4, the overall level

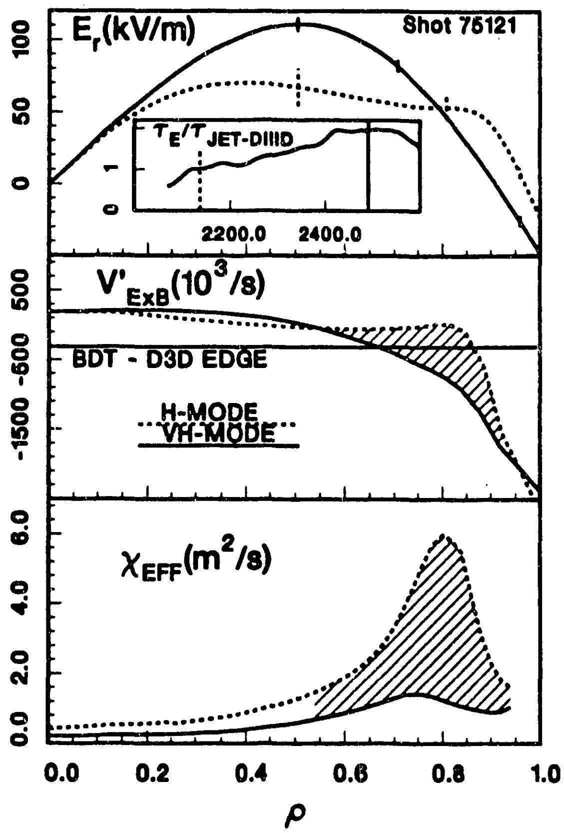

Fig. 1. Radial profiles of the radial electric field, the shear in the $E \times B$ velocity and one-fluid thermal diffusivity at a time in the H-mode and VH-mode phases of shot 75121. The inset in the top box shows the time behavior of the thermal energy confinement time normalized to the JET/DIII-D H-mode scaling result. Times for the radial profiles are indicated in the inset by vertical bars.

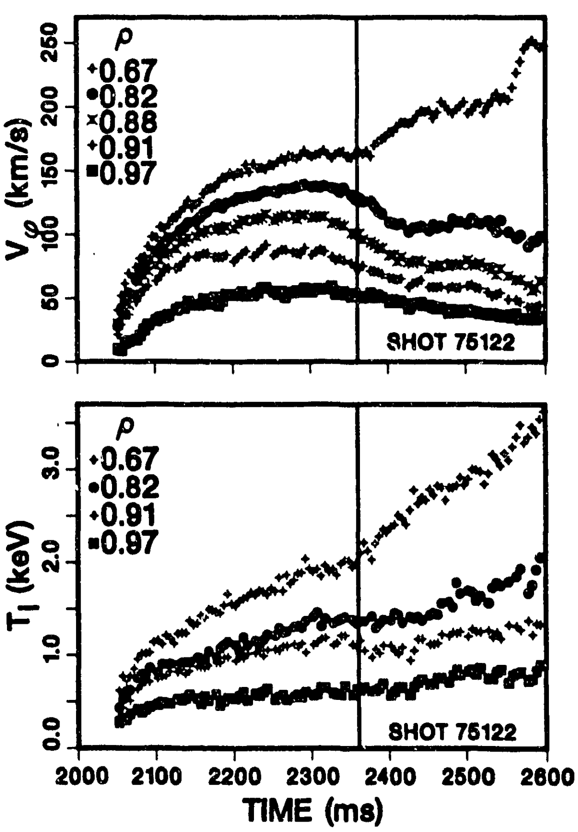

Fig. 2. Time history of ion temperature and toroidal rotation speed at various radial locations for shot 75122. The vertical bar in both boxes indicated the time of the first detectable change in the thermal confinement. Note that the toroidal rotation changes outside of $\rho = 0.8$ prior to the first detectable change in the thermal confinement.

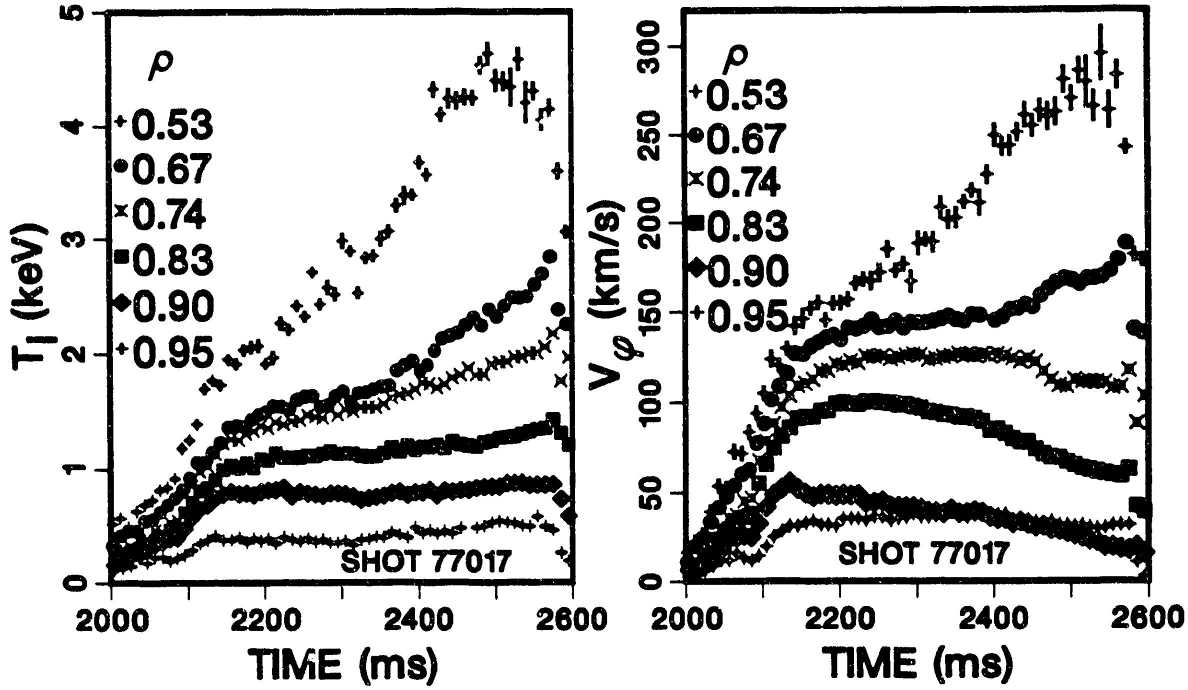

Fig. 3. Time history of ion temperature and toroidal rotation speed at various radial locations for shot 77017. The confinement improvement and toroidal rotation evolution are much more gradual than that shown in Fig. 2. The sudden decrease in temperature and rotation after 2570 ms is due to the MHD event that ends this VH–mode.

of core density fluctuations detected by the FIR scattering system[10] decreases with time into the H–mode. This decrease in the overall level is associated with the core confinement improvement that occurs when the plasma goes from L–mode to H–mode.[11] Riding on top of this overall level are repetitive bursts of density fluctuations. The frequency of the bursts slows as the velocity shear increases and the bursts slow dramatically and basically cease prior to the confinement improvement. This decrease is associated with the decrease in v_ϕ outside of $\rho = 0.82$.

The MTEs are more visible on the FIR scattering and the soft X-ray fluctuation diagnostics than they are on the profile diagnostics.[5] The bursting frequency is usually so rapid that the profile diagnostics simply average over the effect of the MTEs. When the MTEs occur as an isolated event, as in Fig. 4 near 2490 ms, the effect on v_ϕ can be distinctly seen. We believe that the MTEs are responsible for increased thermal and angular momentum transport. Their suppression leads to the improved confinement. However, shots like those in Fig. 3 illustrate that the MTEs are not always the dominant effect on confinement near $\rho = 0.8$ and that the association between velocity shear and confinement improvement occurs even prior to the suppression of the MTEs in discharges where the MTEs are weak.

Although transport bifurcation models[12] of the L to H transition have not been successful to date,[6] the change in v_ϕ and T_i over 10's of milliseconds after the H–mode to VH–mode transition suggests that such a model might be more successful in explaining the VH–mode. Our data suggest a model in which an unknown drag mechanism (possibly increased ion orbit loss[13]) causes v_ϕ around $\rho = 0.9$ to slow. This slowing produces a transient increase in v_ϕ and $E \times B$ shear just inside this region. Since the plasma is already in H–mode and the $E \times B$ shear is already large enough to affect transport,[6] this increase in shear leads to reduced angular momentum transport from the core plasma, which then forces v_ϕ in the edge to drop further. In addition, the reduced angular momentum transport allows v_ϕ deeper into the plasma to increase. Both of these changes increase the $E \times B$ velocity shear. This process can feed on itself until the $E \times B$ velocity shear has reduced fluctuation-driven transport significantly and some other process sets the limiting transport. The increase in $E \times B$ velocity shear also leads to a reduction in thermal transport. Since $E \times B$ velocity shear is capable of stabilizing many types of turbulence,[8] stabilization of MTEs by this process also appears possible.

Four main observations support the model that electric field shear stabilization of turbulence explains the confinement improvement from H–mode to VH–mode. First, the electric field shear changes most in the region where the dominant change in local transport takes place. Second, the magnitude of the electric field shear is large enough to affect turbulence according to theory.[8] Third, the electric field shear changes prior to the first detectable change in the thermal transport. Finally, there is a correlation between the change in density fluctuations and increased $E \times B$ velocity shear.

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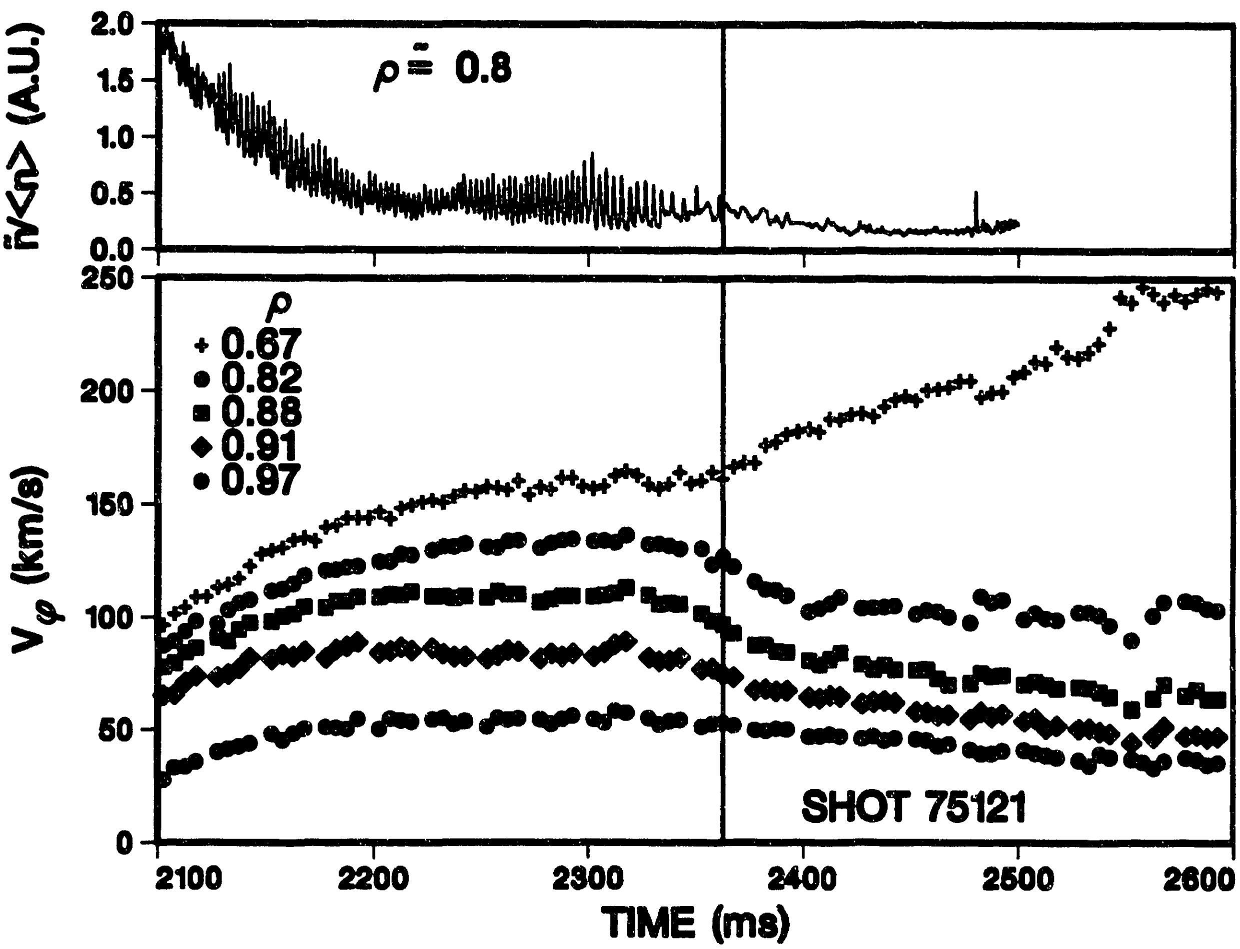

Fig. 4. Time history of the amplitude of electron density fluctuations near $\rho = 0.8$, determined from FIR scattering, and toroidal rotation at several radial locations for shot 75121. The density fluctuations are integrated over the 0.5 to 1.5 MHz range. The vertical bar indicates the time of the first detectable change in the thermal confinement.

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