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THE EFFECT OF CURRENT PROFILE CHANGES ON CONFINEMENT IN THE DIII–D TOKAMAK*

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Experiments in the DIII–D tokamak have demonstrated that the effect of changes in the current profile on plasma confinement varies with the discharge shape. The results are similar in many respects to those from other tokamaks.[1–3] In all cases, a rapid change in the plasma current in an L–mode, circular or moderately elongated, discharge has been used to produce a transient change in the current density profile. Although the detailed results vary among tokamaks, it is generally observed that during and immediately following a negative plasma current ramp, the stored energy does not follow the L–mode scaling that predicts that confinement should be proportional to the total plasma current. The stored energy changes on the time scale of the relaxation of the current density profile rather than the shorter time scales of the energy confinement time or the change in the total current. Because of the discharge shaping capability of the DIII–D tokamak it has been possible to extend these current ramp experiments beyond the L–mode, moderate elongation case ($\kappa \leq 1.5$) to highly elongated ($\kappa \leq 2$) double-null divertor discharges in H–mode. In separate experiments, a rapid change in the discharge elongation has also been used to vary the current density profile. This paper shows that the dependence of the plasma confinement on the current profile changes when the discharge shape is changed. This variation with discharge shape provides evidence for a model that predicts that changes in the local magnetic shear resulting from the changes in the current profile can result in decreased local transport.

In L–mode, nearly circular, inside-wall-limiter discharges in DIII–D the plasma confinement varies approximately linearly with the internal inductance, ℓ_i. To demonstrate this, a rapid decrease in the plasma current has been used to induce transient changes in the current density profile. Higher values of ℓ_i result from a more peaked current density distribution and from a region of zero or negative current density in the outer portion of the discharge produced by the negative surface voltage that drives the current ramp. With a factor of 2 decrease in the current and a current ramp rate of $dI/dt \approx -4$ MA/sec, ℓ_i increases from 1 to as high as 2.75. The time evolution of this type of discharge is illustrated in Fig. 1 along with the evolution of a comparison discharge for which the plasma current was constant. Here, $\kappa = 1.2$, the neutral beam power is constant at 10 MW and $n_e \approx 6 \times 10^{19}\,\mathrm{m}^{-3}$. The thermal stored energy shown in the figure is obtained by subtracting the calculated value of the energy of the unthermalized fast ions from the total stored energy calculated from the MHD equilibrium reconstruction. The thermal stored energy changes by less than 10% during the current ramp. If the confinement time depended only on the total plasma current the stored energy would be expected to decrease by a factor of 2 on the time scale of the current ramp, a period of approximately $3\,\tau_E$. Instead, about one second is required before the factor of 2 decrease is complete, the same time scale as the relaxation of the current profile, or the decay of ℓ_i.

The observed changes in the thermal stored energy occur because of changes in the electron temperature and density. On the time scale of the current ramp, there is no measurable change in the electron density or ion and electron temperature profiles. After the current profile relaxation, both n_e and T_e have decreased by 20% to 30% while there is still no change in the ion temperature. The data in Fig. 2, obtained from several discharges during the current profile relaxation, show that there is an approximately linear relation between ℓ_i and the confinement time. The figure shows the confinement time normalized to the JET/DIII–D scaling law for

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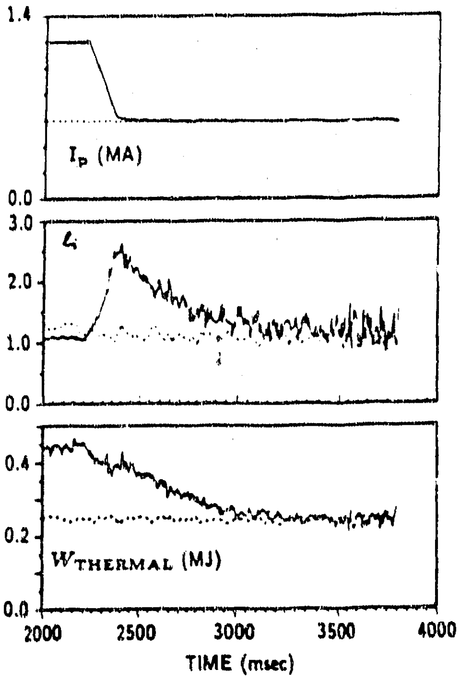

FIG. 1. The time evolution of an L–mode, $\kappa = 1.2$ discharge during and after a rapid current ramp (solid lines). The dashed lines show a comparison discharge for which the plasma current was constant.

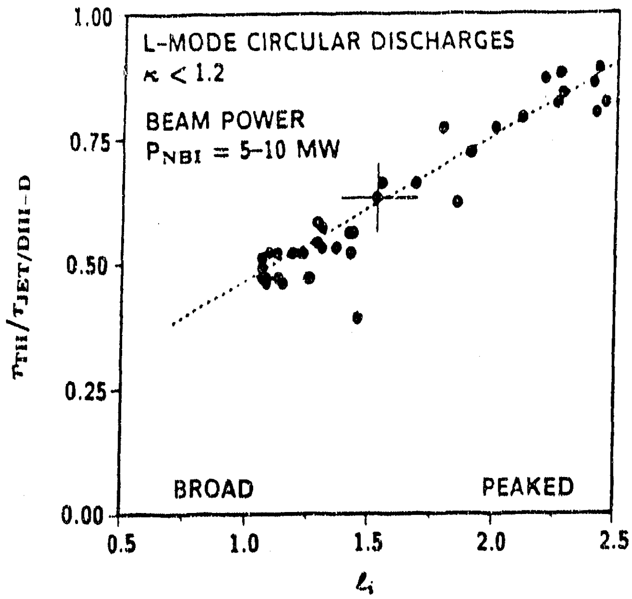

FIG. 2. The observed scaling of thermal energy confinement normalized to the JET/DIII–D H–mode energy confinement scaling as a function of ℓ_i.

H–mode[4] which has no ℓ_i dependence. There is nearly a factor of 2 improvement in confinement obtained through modification of the current density profile and the discharges with the highest values of ℓ_i have confinement close to that observed in H–mode.

In similar experiments with high elongation ($\kappa = 1.95$), high triangularity ($\delta = 0.85$), double-null divertor, H–mode discharges there is a large change in stored energy during the current ramp. The time evolution of this type of discharge is illustrated in Fig. 3. Here the neutral beam power is constant at 6.3 MW, $n_e = 1.1 \times 10^{20}\,\mathrm{m}^{-3}$, and the discharge is in a steady-state H–mode with ELMs by 2100 ms, well before the beginning of the current ramp. During the factor of 2 current ramp, the stored energy decreases to 65% of the value present before the ramp even though ℓ_i increases from 1 to 2.8. The current ramp is followed by a period of nearly constant stored energy, even as ℓ_i decays, which lasts until 3500 ms. The change in stored energy during the current ramp is accompanied by a drop in electron density of as much as 60%, primarily in the outer half of the discharge, and a 30% drop in electron temperature.

There is some variation with time of the ELM character in these H–mode discharges, but this variation has no effect on conclusions drawn about the connection between the current profile and confinement. During the ramp the elongation decreases from 1.95 to 1.75 because of the effect of the increase in ℓ_i on the control of the discharge shape. This results in a decrease in the ELM frequency which lasts until 3500 ms. The rapid drop in stored energy during the current ramp cannot, however, result from the change in ELM frequency since a decrease in ELM frequency would be expected to result in an increase in the confinement time. The period of constant stored energy before 3500 ms during which the ELM frequency is approximately constant and ℓ_i decays indicates a weak dependence of the confinement on ℓ_i. The slow drop in stored energy after 3500 ms coincides with a slow increase in the ELM frequency. A comparison of confinement in the period after 4000 ms with the confinement in the period before the current ramp agrees only approximately with the linear scaling of τ with total current that is commonly observed in H-mode because of the difference in ELM character in these two periods.

The observed changes in the global confinement are consistent with a model of the diffusivity which depends on both the plasma current and the local current profile. In both the low

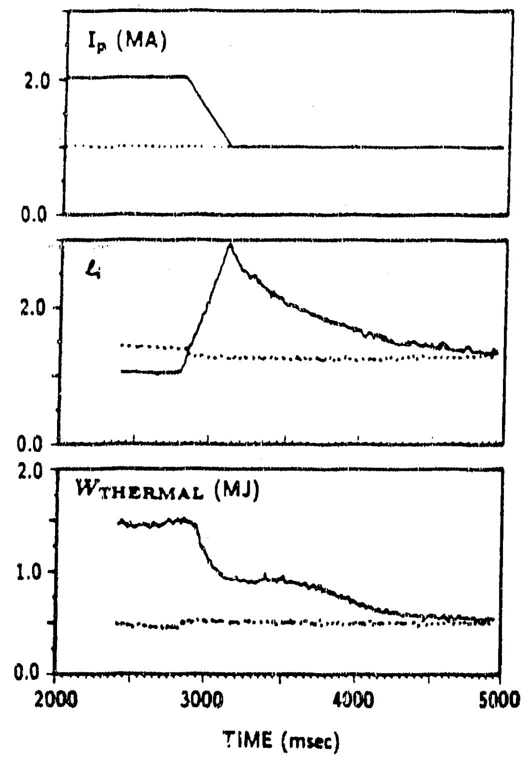

FIG. 3. The time evolution of an H–mode, double-null divertor discharge during and after a rapid current ramp (solid lines). The dashed lines show a comparison discharge for which the plasma current was constant.

elongation discharge and the high elongation discharge, on the short time scale of the current ramp, the current density change is localized to the outer portion of the discharge. Scaling of energy confinement with the total plasma current has been well established for both L–mode and H–mode, so in the case of the negative current ramp in the circular discharge, the local change in the current density profile must offset the change in plasma current because there is no net change in local transport and no net change in confinement. In the double-null case, the effect of the local change in the current profile must be weak because the confinement scales with current during the ramp. These observations are consistent with theories that link pressure gradient driven turbulence and energy confinement.[5] These theories suggest that the level of transport is proportional to the ratio of the local pressure gradient to a function of the local magnetic shear which is approximately the critical pressure gradient for the onset of instability ($P'_{\rm crit}$). An increase in the local magnetic shear which results from the change in the current profile can result in an increase in $P'_{\rm crit}$, offsetting the decrease which would result from a decrease in the total current.

A simple test of this idea has been made using a global parameter, β, rather than the local parameter, P'. The time evolution of the energy confinement is compared to the ratio of the critical beta to the measured value of beta: $\tau \propto f(\beta_{\rm crit}^{\alpha}/\beta)$. Since $\beta \propto \tau P_{\rm aux}$, we expect that the time evolution of energy confinement will be similar to the time evolution of the critical value of beta: $\tau \propto h(\beta_{\rm crit}^{\gamma}/P_{\rm aux})$. Here α and γ represent unknown power laws, $P_{\rm aux}$ is the auxiliary heating power which is constant in these experiments, and $\beta_{\rm crit}$ is obtained from the integral of $P'_{\rm crit}$. The pressure gradient driven mode which might be responsible for the turbulence is not known at this point, so we use the well established stability theory[6] for the infinite-n, ideal ballooning mode to provide a value for $\beta_{\rm crit}$. The modes actually responsible for the turbulence would be expected to be unstable at values of β below $\beta_{\rm crit}$ for the ideal mode, but the assumption is made here that the value of the critical pressure gradient which drives the turbulence scales in the same manner as $P'_{\rm crit}$ for the ideal mode.

In both the near-circular discharge and the strongly shaped discharge the time evolution of $\tau_{\rm thermal}$ is similar to that of the critical beta for the ideal ballooning mode. Figure 4(a) shows the result of calculations for the $\kappa = 1.2$, L–mode discharge shown in Fig. 2. With no change in the form of the current profile, the factor of 2 change in the total current during the ramp would be expected to be responsible for a factor of 2 change in $\beta_{\rm crit}$. However, ideal ballooning stability calculations show that in a circular discharge the value of $\beta_{\rm crit}$ increases nearly linearly with ℓ_i,[6] so that the change in total current is offset by the change in ℓ_i and the values of $\beta_{\rm crit}$ before and after the ramp are nearly equal. $\beta_{\rm crit}$ decays slowly as the current profile relaxes, as does $\tau_{\rm thermal}$. Numerical calculations for a strongly shaped discharge such as the double-null divertor show that the scaling of $\beta_{\rm crit}$ with ℓ_i is much weaker than it is in the case of the circular discharge.[6] Thus an increase in ℓ_i would be expected to have a smaller effect on confinement. Figure 4(b) illustrates the calculated time evolution of $\beta_{\rm crit}$ for the discharge in Fig. 3. There is a comparable, large, difference in both $\tau_{\rm thermal}$ and $\beta_{\rm crit}$ after the current ramp compared to the value before the current ramp. In the period after the current ramp, as ℓ_i decays there is only a small change in both $\beta_{\rm crit}$ and $\tau_{\rm thermal}$.

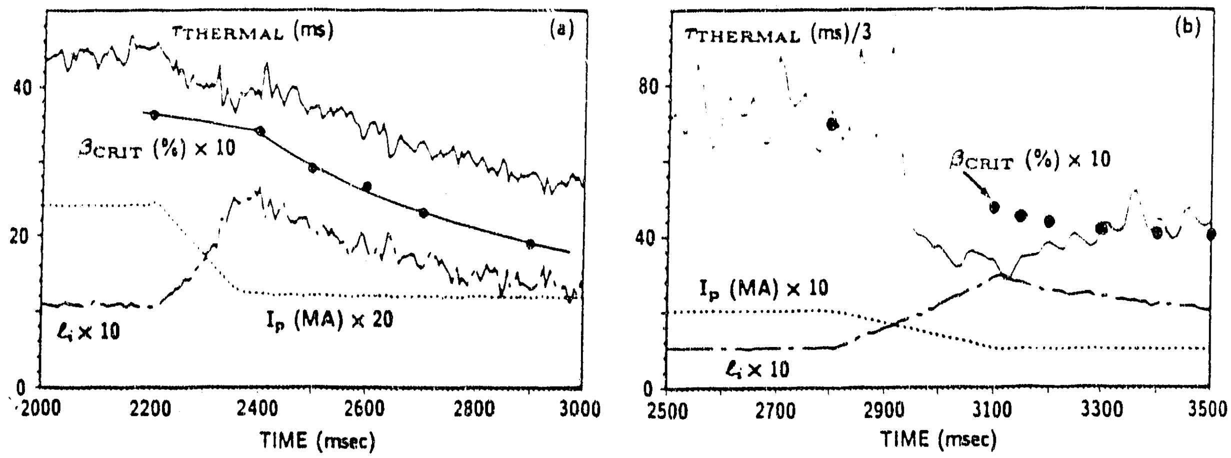

FIG. 4. The time evolution of τ_{thermal} and β_{crit} for the infinite-n, ideal ballooning mode during and after a current ramp. Also shown are total current and ℓ_i. (a) L–mode, nearly-circular discharge, (b) H–mode, double-null divertor discharge.

This difference between the circular and the strongly shaped discharges in the comparison of the time evolution of β_{crit} and τ_{thermal} provides the evidence for a connection between the local magnetic shear and the effect of the current ramp on confinement. In the near circular discharge the confinement remains constant during the negative current ramp because the increase in local shear can offset the decrease in the total current. In contrast, in the strongly shaped discharge the change in magnetic shear has a weaker effect and as a result the effect of the total current dominates the changes in confinement during the current ramp.

A rapid increase in the discharge elongation, at constant total current, has also been used to make the current profile more peaked. Changing κ from 1.2 to 1.8 in 200 ms in an L–mode, inside wall limiter discharge increased ℓ_i from 1.1 to 1.7. When the peak value of κ is below 1.8, the discharge remains in L–mode. In this case, a comparison with a discharge with κ constant at 1.8 shows that there is a small increase in confinement that results from the increase in ℓ_i but that most of the increase in confinement probably results from the increase in κ. This is consistent with the idea that in more strongly shaped discharges, changes in ℓ_i have a weaker effect on confinement, as in the double-null experiments.

In summary, for low elongation discharges there is a linear dependence of energy confinement on the internal inductance and for strongly shaped discharges, such as a double-null divertor or an elongated limiter, the dependence of energy confinement on ℓ_i is much weaker. This behavior is consistent with a model that proposes that a local change in the magnetic shear can reduce the level of transport which results from pressure gradient driven turbulence. This model has been tested using global parameters and been shown to be consistent with the time evolution of the data.

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