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ABSTRACT. Sheared mass flows are generated in many fluids and are often important for the dynamics of instabilities in these fluids. Similarly, large values of the E×B velocity have been observed in magnetic confinement machines and there is theoretical and experimental evidence that sufficiently large shear in this velocity may stabilize important instabilities. Two examples of this phenomenon have been observed in the DIII–D tokamak. In the first example, sufficient heating power can lead to the L-H transition (transition from low-mode to high-mode confinement), a rapid improvement in confinement in the boundary layer (narrow region just inside the last closed flux surface) of the plasma. For discharges with heating power close to the threshold required to get the transition, changes in the edge radial electric field are observed to occur prior to the transition itself. In the second example, certain classes of discharges with toroidal momentum input from neutral beam injection exhibit a further improvement of confinement in the plasma core leading to a regime called the VH–mode. In both examples, the region of improved confinement is characterized by an increase of shear in the radial electric field E_r, reduced levels of turbulence and increases in gradients of temperatures and densities. These observations are consistent with the hypothesis that the improved confinement is caused by an increase in shear of the E×B velocity which leads to a reduction of turbulence. For the VH–mode, the dominant term controlling E_r is the toroidal rotation v_ϕ, indicating that the E_r profile is controlled by the source and transport of toroidal momentum. At the edge of the plasma, indirect measurements indicate that the change in E_r is initiated by a change in the V×B velocity of the main ions but at later times is dominated by the ion diamagnetic velocity.

I. INTRODUCTION

It has long been recognized in fluid mechanics that the interaction between sheared velocity fields and turbulence can have important consequences for the stability of various modes. Sufficiently large velocity shear can drive the Kelvin-Helmholtz mode unstable [1]. On the other hand, Rayleigh-Taylor modes can be stabilized by velocity shear [2]. Theoretical and experimental work during the last few years has provided strong evidence that similar mechanisms are important in magnetized plasmas. For this case, the fundamental velocity is not the mass velocity but is rather the E×B velocity, the velocity at which turbulent eddies are convected, where E and B are the electric and magnetic fields. Basic scaling arguments of nonlinear theory show that if the shear (spatial gradient) of the E×B velocity varies sufficiently on the scale of a turbulent eddy, the correlation time of the eddy is decreased by the shear [3]; thus, the eddy is effectively ripped apart by the shear leading to a reduction of the rate of transport due to turbulent processes. Numerous linear stability calculations have shown that sufficient shear in the E×B velocity is a robust mechanism to stabilize flute-like modes [4] (modes whose structures are elongated along magnetic field lines). Self-consistent nonlinear simulations have been performed for several modes of interest and they generally support the results of the linear analyses [5]. An important difference is that for some modes, the curvature (second spatial derivative) of the E×B velocity field is predicted to me much more important for stabilizing turbulence than the shear (first spatial derivative) [6].

There is a significant body of experimental evidence that sheared E×B flows do in fact modify and reduce the transport in magnetic confinement devices [7–9]. The evidence comes from machines with a variety of magnetic geometries and indicates that the effect is a basic phenomenon of magnetized plasmas rather than a peculiarity of a given confinement scheme. The clearest example in tokamaks is the L-H transition, which is a spontaneous transition from a base level of confinement called the L–mode to an increased level of confinement called the H–mode [10]. The transition to H–mode is initiated in a narrow layer at the periphery of the plasma. In this narrow layer, it is simultaneously observed that large shear (both first and second spatial derivatives) develops in the radial electric field E_r, that the level of density fluctuations decreases, and that temperature and density gradients increase. This phenomenology is consistent with, and in some cases has been predicted by, the theoretical work on suppression of turbulence due to sheared E×B flows. Thus, the theoretical paradigm that shear in the E×B flow can stabilize turbulence has become the primary hypothesis for guiding studies of the L-H transition. Additional support is given to the hypothesis by experiments in which the transition has been induced with application of a radial electric field from a probe inserted part way into the plasma [11].

In at least two tokamaks, DIII–D [12] and JET [13], the H–mode discharge has been observed to evolve into a further improved regime of confinement called the VH–mode, which exhibits values of τ_E which are 3-4 times those in L–mode discharges. In DIII–D, the phenomenology of the VH–mode is also consistent with the hypothesis of E×B shear suppression of turbulence [14,15]. Whether this phenomenology is peculiar to DIII–D or is a universal aspect of the VH–mode remains to be seen.

The E×B shear suppression mechanism is of interest for both basic and applied studies of plasma physics. Non-linear analyses show that a fundamental understanding of saturated turbulence in a magnetized plasma requires self-consistent knowledge of both E×B suppression [16] and transport of momentum by the turbulent fields [17]. From a practical point of view, design studies aimed at producing a tokamak which can obtain an ignited thermonuclear burn generally indicate that some enhancement of confinement over L–mode levels is required to build a practical machine. H–mode and VH–mode discharges are candidates for achieving this increased confinement. Thus, if E×B shear suppression is required to produce the H–mode and VH–mode plasmas, it is a rather important subject from the point of view of applied physics as well as basic physics.

The goal of this paper is to examine the present status of H–mode and VH–mode studies in the DIII–D tokamak. In Section II, the phenomenology of the L-H transition and of the production of VH–mode discharges is briefly examined to show that the observations are consistent with expectations from the E×B shear suppression hypothesis. New results are presented for discharges in which the time scale for the transition has been increased. These discharges exhibit changes in E_r prior to the transition and thus provide evidence that E_r causes the transition. Section III discusses the status of knowledge about the origin of E_r from the point of view of the radial force balance equation for toroidal equilibria. At this level of analysis, it is clear that the observed electric fields are a self-consistent result of various physical processes in the tokamak. Recent evidence is presented which indicates that the V×B term of the main ions controls the rapid change in E_r at the transition. Section IV contains a summary and conclusions. In this paper, the term "shear suppression" will mean suppression of turbulence by an E×B profile with non-zero first or second spatial derivatives. For the cases of interest, it is radial variation of E_r which produces this shear in E×B.

II. STUDIES OF L-H TRANSITION AND VH-MODE

The spontaneous form of the L-H transition is generated in tokamaks by application of heating power above a required minimum called the power threshold. After the heating power is applied, the plasma passes through a phase of L-mode confinement during which temperatures and possibly densities rise monotonically with time. The classic signature marking the time of the transition is an abrupt and marked drop in the intensity of the D_α signal emitted from the plasma boundary. This signature is interpreted as indicating that the outflux of particles from the plasma decreases dramatically due to the formation of a transport barrier at the plasma edge which holds the particles in the plasma. The transport barrier is manifested as a dramatic steepening of the electron density n_e, electron temperature T_e and ion temperature T_i profiles in a region with a width of the order of 1 cm just inside the last closed flux surface and a reduction of n_e on the open field lines [9]. These modified boundary conditions allow an improvement of confinement (thermal diffusivity) in the core of the plasma to occur so that the discharge attains a value of τ_E which is roughly twice its value in the L-mode phase.

The phenomenology of the L-H transition in DIII–D is consistent with the expectations of the shear suppression hypothesis as has been discussed elsewhere [18-23]. Basically, at the L-H transition and in the same region of the plasma, there is a simultaneous formation of a negative "well" in E_r [9,18-21], a reduction in the level of electron density fluctuations $\tilde{n}$ [9,18,19,21-23] and an increase in electron and ion pressure gradients [9,18,19]. Due to the short time scale in which these changes occur, it has not been possible in previous work to unambiguously determine if changes in E_r occur prior to other changes, as might be expected from the shear suppression hypothesis. However, during the last year, experiments have been conducted in which the heating power was adjusted to be near the threshold value required to obtain the transition and this technique has slowed down the rate at which the transition occurs. Notably, significant changes in E_r are observed to occur prior to the transition [19,21], with E_r being determined directly from Langmuir probe measurements and by the standard spectroscopic techniques. These measurements of early changes in E_r are reminiscent of data reported several years ago [24] and are the strongest evidence for the causal role of E_r in the spontaneous L-H transition.

Figure 1 illustrates typical waveforms from these discharges with "slow" transitions. The time of the transition is inferred from Fig. 1(d) which displays the D_α emission from the divertor target. The drop in the signal at 1480.4 ms is the classic signature of the transition. This time coincides with a marked reduction of the ion saturation current drawn by Langmuir probes in the divertor target. Figure 1(a) displays the values of E_r as obtained from two radii very near the plasma edge and shows that E_r starts becoming more negative and that the shear in E_r starts to increase several milliseconds before the transition. The level of electron density fluctuations is reduced abruptly at the transition as indicated by an FIR scattering system [Fig. 1(b)] and a microwave reflectometer system [Fig. 1(c)]. The signal from both instruments originates at the plasma edge. As indicated in Fig. 1(e), the electron pressure in the same region increases during the H–mode with a time constant of several milliseconds.

Under appropriate conditions, H–mode discharges evolve into a new regime of enhanced confinement, called the VH–mode, which exhibit τ_E values 50%–100% larger than those obtained in H–mode discharges. The transition to VH–mode confinement occurs gradually over a period which is typically several tens of milliseconds [14,15]. During this time, the energy confinement time is increasing, the transport barrier gradually builds further into the plasma, there is an increase in the toroidal rotation velocity v_ϕ in the core of the plasma, and there is a simultaneous reduction of core microturbulence as determined via FIR scattering [25]. Heat transport coefficients in the plasma decrease during this time. The increasing value of v_ϕ indicates that shear in the E×B velocity is increasing in the region in which transport improves and the turbulence decreases. The changes in the VH–mode occur in the core of the plasma rather than at the plasma boundary as for the L-H transition. The shear suppression hypothesis predicts that if the core E_r shear is destroyed, then the VH–mode should be destroyed. This prediction has been verified with the aid of a magnetic perturbation which decreases the toroidal rotation [18,19,26] with a corresponding decrease in the shear of E_r. Simultaneously, the core turbulence levels rise, the local heat diffusion coefficients increase and the global confinement decreases. Thus, the hypothesis of E×B shear suppression of turbulence is capable of describing the phenomenology of the VH–mode as well as of the L-H transition in DIII–D.

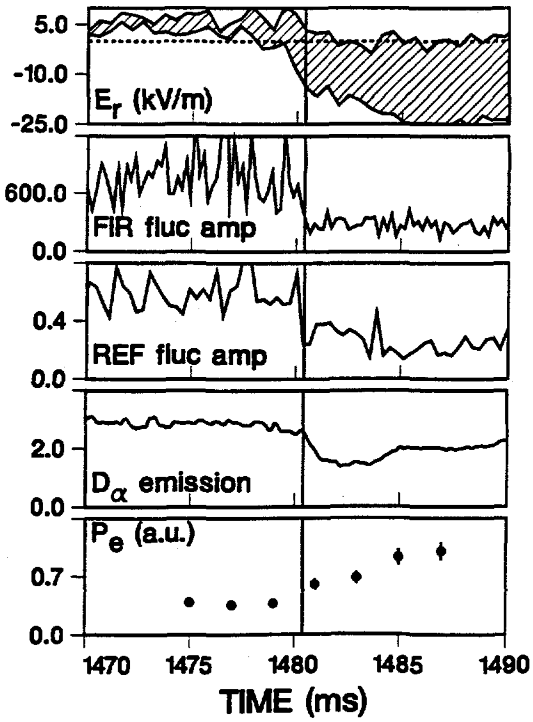

Fig. 1. Waveforms for a "slow" L-H transition, occurring at 1480.4 ms as indicated by vertical line. (a) E_r at R = 2.289 m (lower line) and R = 2.295 (upper line); cross-hatching highlights the shear in E_r; (b) Density fluctuations from FIR scattering; (c) Amplitude of fluctuating signal from 24 GHz microwave reflectometer channel shows reduction in level of density fluctuations at transition; (d) D_α emission from plasma hit spot in divertor; (e) Electron pressure at R = 2.281 m.

III. ORIGIN AND SHAPE OF RADIAL ELECTRIC FIELD

A full understanding of the L-H transition and of the VH–mode requires an understanding of the physics which controls the shape and magnitude of E_r. There has been a large theoretical effort devoted to this issue which has led to the formulation of equations to describe E_r near the plasma boundary in toroidal geometry with neoclassical and anomalous effects included [27–29]. The experimental assessment of theory is very difficult due to the fact that many of the quantities of interest cannot be measured with existing diagnostic capability. The ideas which are being actively pursued can perhaps be divided into four categories:

1. Ion orbit loss [30–32]. Ions are preferentially lost from the plasma edge because ions in the loss cone intersect material surfaces. Thus, the plasma is charged up negatively.

2. Stringer spin-up [33,34]. A large poloidally asymmetric sink or source of particles overcomes the natural damping of poloidal rotation and allows a large

poloidal rotation to develop. The relationship between poloidal rotation and E_r has not been specified in this model.

3. Pressure-gradient drive [35,36]. A toroidal equilibrium naturally develops a negative radial electric field to balance the pressure gradient of the ions. The large and negative E_r generated by the pressure gradient reduces transport through E×B shear. This feedback can cause a transport bifurcation.

4. Anomalous viscosity [27,37,38,39] or turbulent Reynold's stress [17,40]. Transport of momentum can modify the average flow profile of the plasma. The relation between plasma velocity and E_r has been specified for these models.

On the experimental side, a convenient framework which is being used to examine the origin and shape of the E_r profile is the lowest order radial force balance equation

$$E_r = (Z_i e n_i)^{-1} \nabla p_i - v_{\theta i} B_\phi + v_{\phi i} B_\theta \quad , \tag{1}$$

where i labels the ion species, Z_i is the charge of the ion, n_i is the ion density, e is the electronic charge, p_i is the ion pressure, $v_{\theta i}$ and $v_{\phi i}$ are, respectively, the poloidal and toroidal rotation velocities and B_θ and B_ϕ are, respectively, the poloidal and toroidal magnetic fields. Although this equation hides a great deal of physics, it shows clearly that the plasma's E_r is a self-consistent solution which satisfies several physical processes. These include the sources and transport of toroidal momentum, poloidal momentum, heat and particles as well as the generation of the magnetic equilibrium. Although the sources of several of these quantities are fairly well understood, the transport mechanisms in tokamaks are not understood. Thus, radial transport of heat, particles and momentum is generally considered to be "anomalous". There are theoretical suggestions that neoclassical effects may be important for rotation at the edge of the plasma, particularly in H–mode [30,31,38,41-43]. An underlying assumption of present research is that, for a given experimental situation, one term on the right hand side of the force balance equation dominates and is considered to be responsible for E_r and the present goal of experimental research is to determine which is the dominant term.

For the VH–mode in DIII–D, the dominant term controlling E_r is $v_{\phi i} B_\theta$. At this level of understanding, the E_r profile and its shape are controlled by the input of toroidal momentum from neutral beam injection, which is understood to be a classical process, and the transport of toroidal momentum, which is not understood and is considered to be an anomalous process.

Studies of L-H transition have generally been based on the premise that the main ions control the physics of the edge E_r, and one research goal has been to determine whether it is a change of the pressure gradient or of the V×B term of the main ions which initiates the rapid change in E_r observed at the L-H transition. Although direct measurements of the behavior of pressure gradient and V×B terms for the main ions are not available at the transition, the slow transitions discussed above provide strong evidence that the main ion pressure gradient does not control the change in E_r at the transition [19]. These conclusions are based on measurements which show that the gradient of T_i does not change sufficiently at the transition to account for the E_r change and measurements which show that there are no significant changes in the electron density prior to the transition [19].

More quantitative analysis of the discharge discussed in Fig. 1 supports this conclusion. For this discharge, E_r and T_i profiles are available at the plasma edge every 0.5 ms before and after the L-H transition. These data are obtained from He II, which is present in the plasma as an impurity and these measurements are a diagnostic used to determine the E_r and T_i values for the main ion force balance equation. In addition, a sequence of profiles of n_e and T_e from Thomson scattering are available every 2 ms from 1475 ms to 1487 ms, a range which brackets the L-H transition. Under the assumption that the ratio of n_e to the main ion density n_i is constant through the region of interest, the measurements of T_i and n_e can be combined to make an indirect estimate of the main ion pressure gradient contribution to E_r. This is so because the constant of proportionality between n_i and n_e cancels out in the pressure gradient term of the force balance equation for the main ions.

Figure 1(a) demonstrates that there is a large change in the edge E_r between 1475 ms, the time of the first Thomson laser pulse during the time of interest, and 1481 ms, the time of the first Thomson laser pulse after the transition. Figure 2 is a comparison at these two times of the full E_r profiles and of the estimate for the pressure gradient term in the main ion force balance equation. These data show that although there is a profound change in E_r from 1475 to 1481 ms, there is only a very modest change in the estimate for the main ion pressure gradient term. Thus, it must be concluded that either changes in the main ion pressure gradient do not cause the change in E_r across this transition or that the gradient of n_i changes drastically between these two times with little change occurring in the gradient of n_e. The second possibility appears unlikely, particularly because simple estimates suggest that n_i may have to go negative to provide the required pressure gradient.

The lowest order force balance equation is expected to be valid for timescales much shorter than 1 ms. Thus, the estimate of the main ion pressure gradient term developed above can be used to make an estimate of the temporal behavior of the V×B component of the main ion force balance equation at the L-H transition. Figure 3(a) shows the time history for the total radial electric field E_r, obtained at the location where the most negative value of E_r is observed in the H-mode. At the same location, Fig. 3(b) shows the temporal history of $(en_e)^{-1}$ $\nabla(T_i n_e)$. There is very little change in this term across the transition (1480.4 ms) with the pressure gradient term subsequently becoming significantly more negative. Figure 3(c)shows the difference of E_r and the pressure gradient term and is an estimate of the temporal behavior of the V×B term of the main ions at the L-H transition. With the

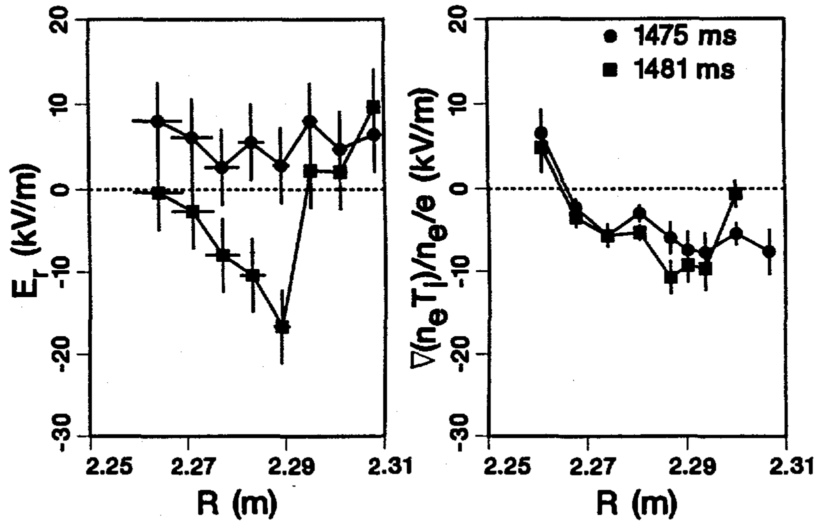

Fig. 2. Profiles at midplane of terms in force balance equation. Data for 1475 ms obtained in L-mode and data for 1481 ms obtained within one ms after transition. (a) E_r (obtained from He II force balance equation) shows significant changes between 1475 and 1481 ms; (b) Estimate of main ion pressure gradient term, based on assumption that n_e and n_i profiles have similar shapes, shows little change between 1475 and 1481 ms.

caveats already discussed, these data indicate that the primary reason that E_r becomes more negative at the transition is that the V×B term of the main ions rapidly becomes less positive. The data suggest that the V×B term changes sign at the transition, but such a conclusion is perhaps premature until more data are examined. Figure 3(c) also suggests that as the H–mode develops the main ion V×B term tends to go more positive again. For the claims made here, it is crucial that the relative timing accuracy of the Thomson Scattering and charge exchange recombination spectroscopy (CER) systems be better than about one millisecond. The absolute timing system accuracy of the CER system is good to within 0.1–0.2 milliseconds and the accuracy of the Thomson system is even better.

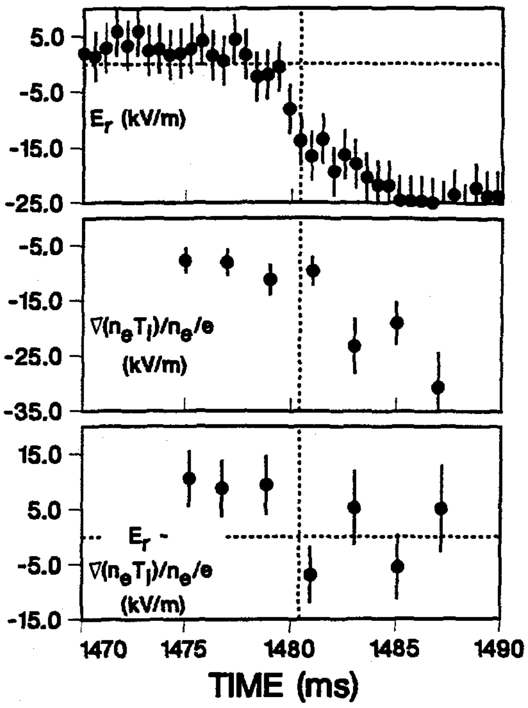

Fig. 3. Temporal study of force balance at location of most negative E_r (R = 2.289 m). (a) E_r starts to become more negative prior to L-H transition; (b) Estimate of main ion pressure gradient term, based on T_i and n_e measurements; (c) Difference of data in (a) and (b). This is estimate of V×B term of main ion force balance equation.

These inferences about the V×B term of the main ions are consistent with direct measurements of the main ions in other discharges. The positive value for the V×B term of the main ions has been confirmed with direct measurements of the main ions in discharges with fast L-H transitions [43]. For those discharges, it is known that the V×B term of the main ions is always positive except for a window of ±3.5 ms around the time of the transition itself. Unfortunately, due to technical limitations associated with the measurements, data for the main ions across the transition are not available. Thus, there are no direct measurements of changes in the main ion V×B term. The direct measurements do show that 3.5 ms after the L-H transition, the pressure gradient of the main ions is the dominant term in the force balance and causes the negative E_r.

At various times in the H–mode, all of the terms of the main ion force balance equation are important in controlling the negative E_r observed in the transport barrier in DIII–D. At the time of the transition itself, the V×B term appears to be important, indicating that the sources and transport of poloidal and, perhaps, toroidal momentum are important processes. Of these quantities, only the source of toroidal momentum in neutral-beam heated discharges can be considered well understood at this time. Shortly after the transition the pressure gradient becomes dominant and thus the edge E_r profile is controlled by the sources of heat and particles, which are understood as classical processes, and the transport mechanisms of heat and particles which are considered to be anomalous.

IV. SUMMARY AND CONCLUSIONS

Sheared mass flows are of general interest in fluid mechanics because of their role in driving or subduing instabilities. For magnetized plasmas, there is a large body of theoretical and experimental evidence which indicates that sheared E×B flows, due primarily to sheared E_r fields, can stabilize a large class of instabilities found in laboratory plasmas. In the DIII–D tokamak, the phenomenology of two modes of improved confinement are consistent with the hypothesis that increased shear in E_r leads to a suppression of turbulence and improved confinement. In both the transition from L–mode to H–mode confinement and the transition from H–mode to VH–mode confinement, there is a strong spatial and temporal correlation between the increase of shear in E_r, a reduction of $\tilde{n}/n$ which is evidence of a reduced level of turbulence and increased gradients in temperature and density profiles.

The mechanisms which control the magnitude and shape of E_r in a tokamak are poorly understood. The core E_r in the VH–mode in DIII–D is controlled by the plasma's toroidal rotation which is in turn controlled by the momentum input from neutral beam injection. Although, this source of momentum input is understood, the transport of toroidal momentum is also important in forming the E_r profile and is not well understood. The situation for the L-H transition is even more difficult, due to the rapidity with which the edge plasma evolves at the transition. However, the time scale for the transition has been increased by operating near the H-mode power threshold. Evidence acquired from such transitions shows that the edge E_r starts to become more negative before changes are observed in turbulent quantities and before the transition occurs. In addition, the available data provides indirect but very strong evidence that it is the V×B rather than the pressure gradient term for the main ions which changes rapidly at the transition. Further studies are required to determine whether it is v_ϕ or v_θ of the main ions which changes at the transition.

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