Discharges in the JET Tokamak Where the Safety Factor Profile Is Identified as the Critical Factor for Triggering Internal Transport Barriers

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(Received 22 September 2000; revised manuscript received 28 November 2001; published 20 March 2002)

Joint European Torus discharges which demonstrate the critical role the safety factor profile, q, can play in the formation of internal transport barriers (ITB) are examined. In these discharges, the target parameters, including the $\mathbf{E} \times \mathbf{B}$ flows, were kept virtually the same, except for the q profile. In a discharge with a nonmonotonic q, an ITB was triggered whereas a discharge with monotone q made no such transition. Thus, there is strong evidence that the q profile was the critical factor for the triggering of an ITB. Possible interpretations of this finding are discussed.

DOI: 10.1103/PhysRevLett.88.145001 PACS numbers: 52.55.Fa, 52.25.Fi

In order to develop a commercially viable fusion reactor based on the tokamak concept, scenarios in which the tokamak can be operated economically and in a steady state need to be explored. In recent years much attention has focused on scenarios in which internal transport barriers (ITB) can develop [1–6]. In discharges with an ITB, the energy transport is strongly reduced in an internal region of the plasma, resulting in an improved energy confinement and high fusion yields. In addition, the pressure profiles tend to be quite peaked as a result of the ITB. A large fraction of the plasma current could therefore be sustained by the neoclassical bootstrap current, which would facilitate a steady state operation [1].

In present-day tokamaks, the standard method for creating favorable conditions for ITB formation involves two stages. In the first stage, a target plasma is produced by preheating with, e.g., neutral beam injection (NBI) heating and/or ion cyclotron resonance frequency (ICRF) heating during the plasma current ramp-up. This delays the inward diffusion of the plasma current density so that, temporarily, there is a central region of low, possibly reversed, magnetic shear $s = rq^{-1}dq/dr$, where q is the safety factor which measures the magnetic field line pitch. In the second stage, intense auxiliary heating is applied during which an ITB may form.

It is widely believed that a combination of $\mathbf{E} \times \mathbf{B}$ shear flow (where $\mathbf{E}$ is the radial electric field and $\mathbf{B}$ is the equilibrium magnetic field) and magnetic shear stabilization are important factors in explaining the ITB formation [2,7–9]. Of these effects, the $\mathbf{E} \times \mathbf{B}$ shear has received the most attention in the literature (see, e.g., [2,7]), while the influence of the magnetic shear is less well documented. It has even been suggested that the q profile is not necessarily a key factor [7]. Recently, however, results indicating a sensitivity to the presence of $q = 2$ surfaces in the positive shear region have been reported [10]. Moreover, as compared to a previously established scaling [3], the threshold power needed to obtain an ITB has been found to be significantly lower in discharges where the target q profile was modified by application of lower hybrid (LH) waves in the preheat phase [10]. In this Letter we present an analysis of discharges obtained during the 2000 campaign at Joint European Torus (JET), which demonstrate the key role the q profile can play in triggering an ITB. Specifically, we examine discharges where the target q profile has been varied while the other target parameters, including $\mathbf{E} \times \mathbf{B}$ shear flows, are virtually identical. Consequently, the results reported here are complementary to those presented in Ref. [11], where the $\mathbf{E} \times \mathbf{B}$ shear flow was varied at a fixed q profile.

Let us first discuss a few important points concerning the current understanding of ITB formation. In a tokamak plasma with a radial electric field, $\mathbf{E} \times \mathbf{B}$ flows are present. As outlined in Ref. [12], microturbulence can be stabilized by the shear in such flows. In toroidal geometry, the $\mathbf{E} \times \mathbf{B}$ flow velocity is given by E_r/B_p, where E_r is the radial electric field, and B_p is the poloidal magnetic field. Consequently, it is the shear in $E_r/(RB_p)$ that leads to the stabilization of microturbulence in a tokamak [13]. According to Ref. [14], the criterion for turbulence suppression is given by

$$\gamma_{\mathbf{E}\times\mathbf{B}} = [(RB_p)^2 \partial(E_r/RB_p)/\partial\psi]/B = [(RB_p)\partial(E_r/RB_p)/\partial r]/B > k\gamma_{\rm lin}^{\rm max}, \quad (1)$$

where $\gamma_{\mathbf{E}\times\mathbf{B}}$ is the $\mathbf{E} \times \mathbf{B}$ shearing rate, ψ is the poloidal magnetic flux, r is the minor radius in the outer midplane, k is a factor of order unity, and $\gamma_{\rm lin}^{\rm max}$ is the growth rate for the fastest growing mode of the instability causing the microturbulence. This microturbulence is generally believed to be caused by drift wave instabilities, mainly the ion temperature gradient (ITG) driven instability and trapped electron modes (TEM) [15,16].

A useful relationship for the radial electric field can be derived from the equilibrium force balance equation [7,17]

$$E_r = \frac{\nabla p_j}{Z_j e n_j} + B_p V_{\varphi j} - B_\varphi V_{pj}, \quad (2)$$

where j refers to a species in the plasma, V_φ and V_p are, respectively, the toroidal and poloidal rotation velocities of the species. If condition (1) is fulfilled and a barrier is formed, then $\gamma_{\mathbf{E}\times\mathbf{B}}$ will be affected through the ∇p term in Eq. (2), and also through an improved momentum confinement, expected to be concomitant with improved energy confinement. This nonlinear behavior is often invoked to explain the rather rapid transition into an improved confinement mode experienced in ITB discharges.

If the present paradigm for turbulence suppression by sheared $\mathbf{E} \times \mathbf{B}$ flows is correct, it is not straightforward to disentangle the role played by the q profile, since the poloidal magnetic field appears in several places in expressions (1) and (2). In order to investigate the role played by the q profile, we have examined two JET discharges with similar E_r/B_p profiles and target parameters, but different q profiles, at the time when a barrier is formed. These were produced by keeping the experimental wave forms unchanged in the high power phase between discharges [10]. The only difference occurred in the preheat phase when LH waves were used. These provided off axis current drive and heating, i.e., influenced the q profile.

In Fig. 1 an overview of two discharges is shown; both were carried out in plasmas with a magnetic field of 2.6 T and a plasma current of 2.2 MA. In the first (No. 51611) no LH wave injection was applied whereas in the second (No. 51613) an LH power around 2 MW was applied during almost 3 sec. The current ramp rate, as well as the main heating powers, was the same in the two discharges. In addition, the target parameters, such as the electron temperature, ion temperature, densities (including the carbon density profile), were very similar at 5.7 sec into the discharge. As indicated by the neutron rate and the central electron temperature, an ITB was formed in discharge No. 51613 around 5.7 sec (marked with a vertical dashed line in Fig. 1), whereas discharge No. 51611 made no transition into a state of reduced core transport. This is also confirmed by the ion temperature profiles measured by charge exchange spectroscopy (Fig. 2). These indicate a wide barrier (i.e., wide zone of reduced energy transport) extending out to more than half the plasma radius in the case of discharge No. 51613. Furthermore, at the time of the ITB formation in No. 51613, the ion temperature and the toroidal velocity profiles for the two discharges were very close to each other. However, there was a significant difference in the q profiles from the end of the preheat phase up to around 5.7 sec (Fig. 3). The profiles in Fig. 3 were obtained from two independent equilibrium reconstructions with the EFIT code, constrained either by Faraday rotation or motional Stark effect (MSE) measurements. Interpretation of the latter measurement during the high power heating phase is complicated by several overlapping beams. The q profile obtained from MSE is therefore shown just before the start of the high power phase, whereas the q profile obtained from the Faraday measurements is shown around the time of the formation of the barrier in No. 51613. Both measurements clearly show

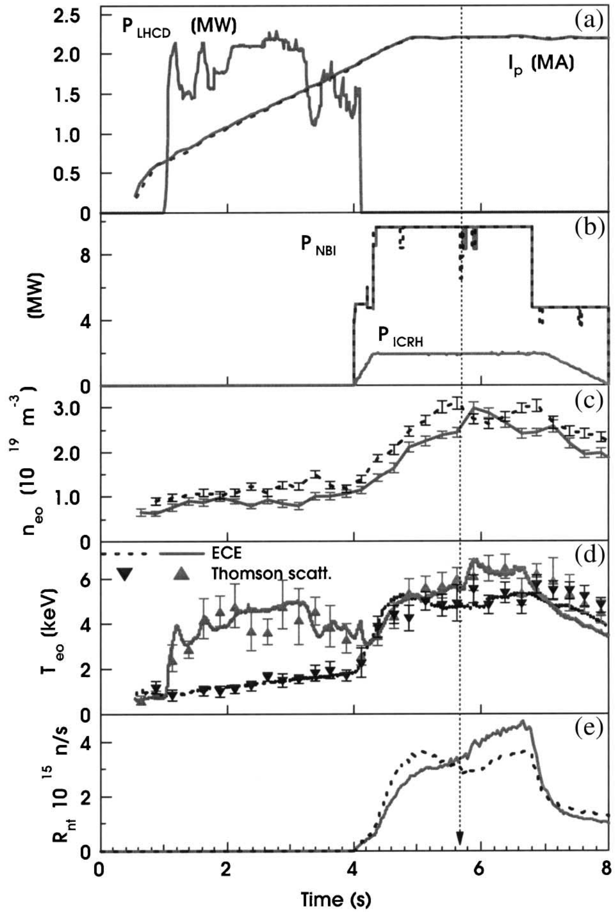

FIG. 1. Overview of two JET discharges: No. 51611 without LH (–––), and No. 51613 with LH (—). Plasma current and LH power (a); NBI and ICRF power (b); electron density (c); electron temperature (d); neutron rate (e).

that there was a significant difference between the q profiles in the two discharges.

Turning to the radial electric field, all the quantities in Eq. (2), except the poloidal rotation velocity are measured in JET. One can therefore reconstruct the radial electric field from the measurements provided the poloidal rotation velocity can be reasonably estimated. The standard procedure usually applied is to assume the poloidal rotation velocity to be given by the neoclassical expression [17]. The rotation velocity and the density profile of the carbon (C^{6+}) impurity in the plasma are measured with charge exchange spectroscopy. These quantities together with the ion temperature profile and the neoclassical expression for the poloidal rotation [17] have been used to reconstruct the radial electric field, E_r, profile in Fig. 4a. It is displayed together with the contributions from the different terms in Eq. (2) as a function of $r/r_{\max}$ at around the time of the barrier formation in No. 51613. The dominating contribution to E_r comes from the toroidal rotation velocity V_φ; cf. [18]. The corresponding $\gamma_{\mathbf{E}\times\mathbf{B}}$ are shown in Figs. 4b and 4c. In order to estimate the error bars on the calculated E_r and $\gamma_{\mathbf{E}\times\mathbf{B}}$, we have varied all the parameters

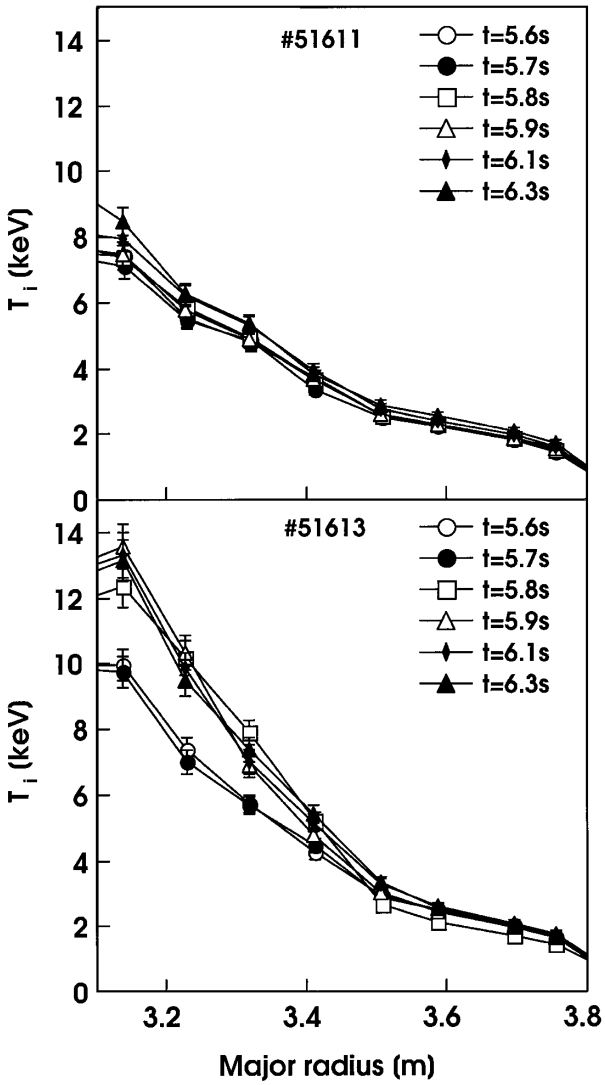

FIG. 2. Ion temperature versus major radius at various times.

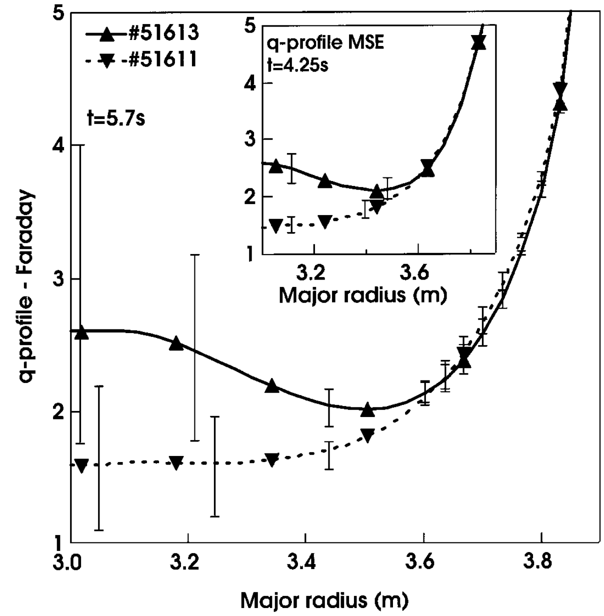

FIG. 3. Safety factor profile obtained from equilibrium reconstruction constrained by either Faraday or MSE (inset) measurements.

that go into the calculations randomly within their error bars. Two hundred different profiles have been realized, and the error bars have been estimated as being the standard deviation of the difference between the profiles. The error bars on the measurements of the toroidal rotation velocity of the carbon impurities and the ion temperature are fairly small, of the order of 5%–10%. We have used the q profile and the associated error bars from the equilibrium reconstruction constrained by the Faraday rotation measurements. A standard error bar of 10% has been assumed for all other quantities. There is very little difference between the E_r/RB_p profiles for the two discharges. The resulting $\gamma_{\mathbf{E}\times\mathbf{B}}$ shown in Figs. 4b and 4c are therefore very similar, except nearer the center where the shearing rate is lower in the discharge that did develop an ITB (due to the lower B_p). Thus, in view of the wideness of the barrier region, there is no indication that the q profiles influenced $\gamma_{\mathbf{E}\times\mathbf{B}}$ significantly in a direction favorable for ITB formation in No. 51613; in fact, the opposite seems to be the case. The influence of the q profile on $\gamma_{\mathbf{E}\times\mathbf{B}}$ has elsewhere been suggested as being part of the explanation for its importance in ITB discharges [2]. Given the error bars, one cannot completely rule out the possibility that there were local differences in $\gamma_{\mathbf{E}\times\mathbf{B}}$ that could account for our results. However, to explain the wide barrier in No. 51613 with such differences, the instability causing the transport must probably be fairly global, of the order of half the plasma radius, which does not seem to be consistent with ITG or TEM turbulence. Thus, our main conclusion is that the difference in q profiles between the two discharges had a very marginal effect on $\gamma_{\mathbf{E}\times\mathbf{B}}$. The most likely factor that led to an ITB in one discharge but not the other is therefore an influence of the q profile on some other quantity than $\gamma_{\mathbf{E}\times\mathbf{B}}$.

The most direct explanation for the results presented here would be a strong dependence of $\gamma_{\mathrm{lin}}^{\mathrm{max}}$ on the q profile. The relation between the q profile and $\gamma_{\mathrm{lin}}^{\mathrm{max}}$ is discussed in, e.g., [8,16,19,20]. We have evaluated this possibility by calculating $\gamma_{\mathrm{lin}}^{\mathrm{max}}$ with the KINEZERO code [21]; $\gamma_{\mathrm{lin}}^{\mathrm{max}}$ for low wave number modes ($k_\theta \rho_i < 1$), for which ITG and TEM modes dominate, are displayed in Figs. 4b and 4c. Measured density, temperature, and q profiles were used in the simulations. In comparing $\gamma_{\mathbf{E}\times\mathbf{B}}$ with $\gamma_{\mathrm{lin}}^{\mathrm{max}}$ it should be kept in mind that there are significant uncertainties in the value of the factor k in Eq. (1), see, e.g., [22], it could easily be up to 2. The calculations indicate a wide stabilized region for No. 51613, whereas No. 51611 is not stabilized in the center. This is consistent with the experimental results. The KINEZERO calculations show that ITG modes dominate in the center, up to $r/a < 0.45$, while TEM modes take over in the outer region. Here it should

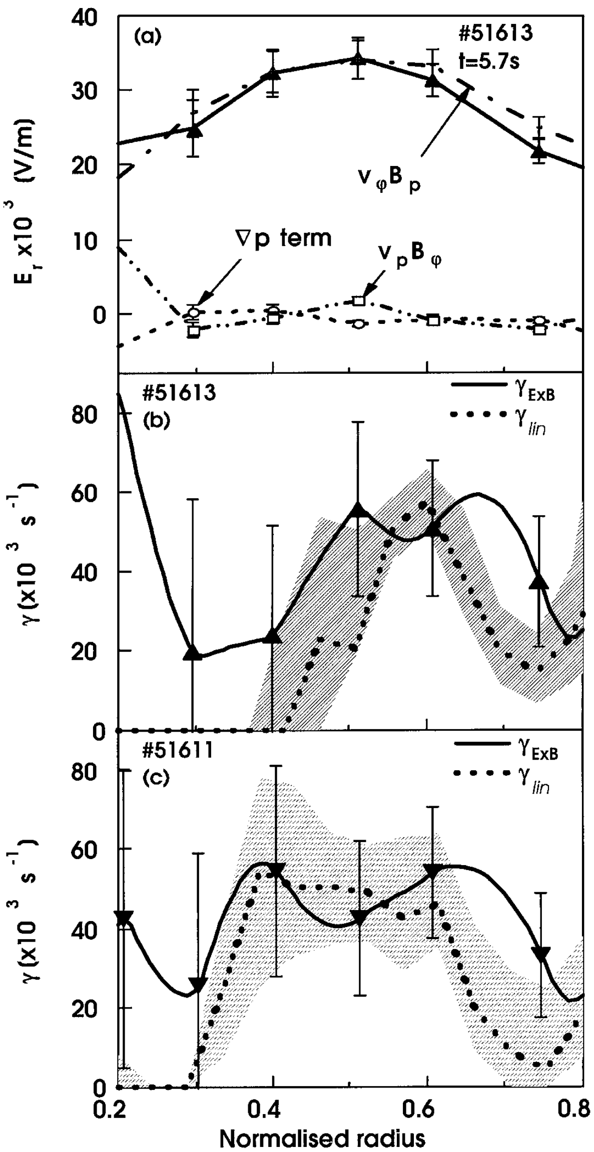

FIG. 4. Reconstructed E_r profile and its components for No. 51613 (a), $\gamma_{\mathbf{E}\times\mathbf{B}}$ and simulated $\gamma_{\text{lin}}^{\text{max}}$ for No. 51613 (b), and No. 51611 (c). The shaded error regions on $\gamma_{\text{lin}}^{\text{max}}$ have been obtained by locally varying the temperature and density gradients within their error bars.

be noted that there is some uncertainty on how efficiently $\mathbf{E}\times\mathbf{B}$ shear reduce TEM mode turbulence [22]. Thus, one should be somewhat cautious in drawing conclusions from a comparison between $\gamma_{\mathbf{E}\times\mathbf{B}}$ and $\gamma_{\text{lin}}^{\text{max}}$ in the outer region.

A strong influence of the magnetic shear on the growth rate might not be the only factor in explaining the experimental results. In the case of low magnetic shear the density of resonant surfaces is very low, leading to a reduced diffusion coefficient [19,23]. This effect, which is enhanced near low order rational q surfaces, could be part of the explanation of the experimental results.

In conclusion, we have presented evidence for the critical role the q profile can play in the formation of an ITB in a tokamak plasma. Indeed, we have shown that by controlling the q profile it was possible to trigger an ITB without increasing the $\mathbf{E}\times\mathbf{B}$ flow shear. A recent theoretical analysis has reached a similar conclusion [24].

We acknowledge the contributors to the EFDA JET Workprogramme.

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