THE IMPORTANCE OF RADIAL ELECTRIC FIELDS IN MAGNETIC CONFINEMENT

Guido Van Oost

Department of Applied Physics
Ghent University
Rozier 44
B-9000 Gent, Belgium
guido.vanoost@Ugent.be

I. INTRODUCTION

The importance of radial electric fields was already recognised early in the research on controlled thermonuclear fusion. An initial description of electric field effects in toroidal confinement was given by Budker[1] Such a configuration with combined magnetic and electric confinement („magnetoelectric confinement“, where the electric field provides a toroidal equilibrium configuration without rotational transform) was studied by Stix[2], who suggested that a reactor-grade plasma under magnetoelectric confinement (electric fields of order 1 MV/cm) may reach a quasi-steady-state with ambipolar loss of electrons and some suprathermal ions (e.g. 3.5 MeV α-particles). Experiments such as on the Electric Field Bumpy Torus EFBT[3, 4] provided quite favourable scaling for particle confinement. The possible importance of radial electric fields for transport was in the past repeatedly established [5, 6, 7, 8]. Since the early days the plasma potential has been measured in tokamaks such as ST[9], TM-4[10] and ISX-B[11], but because no significant effects of the radial electric field E_r on plasma transport were observed, no further research was conducted in tokamaks.

However, *a renaissance came* after the transition from a low confinement mode (L-mode) to a high confinement mode (H-mode) was discovered in ASDEX[12]. The interest was suddenly refreshed and a flurry of activity started with the experimental[13, 14] and theoretical recognition[15, 16, 17] of a possible link between E_r and the H-mode phenomenon. Since then research on E_r has flourished and the H-mode has now been seen in a wide variety of magnetic confinement devices. Many theories have pointed to the possible decisive role of E_r in the creation of transport barriers (i.e. zones of finite radial extent where particle and/or heat diffusivity are depressed) and in the L-H bifurcation mechanism.

The H-mode could also be triggered by externally inducing an E_r in the plasma (independently of other plasma parameters) in the tokamaks CCT[13] and TEXTOR[18, 19] and later in many other machines [see reviews[20,48]]. These biasing experiments (induced H-modes) have contributed significantly to the understanding of the H-mode phenomenon and of the effects of E_r on plasma transport[21].

Besides an important theoretical activity, many experiments have since been performed in the plasma edge and the SOL of limiter or divertor devices, (see and review[20]). Imposing electric fields independently of other machine parameters allows to manipulate the edge and SOL profiles and flows, to control impurities and to affect particle and power exhaust[20,24,25].

Radial electric fields have been studied in a variety of devices: tokamaks, stellarators, helical devices, reversed field pinches, mirrors .... In stellarators and helical devices where neoclassical transport dominates, the transport coefficients depend on E_r and a radial electric field can reduce ripple losses and prevent confinement degradation. This is treated in the lectures of D. Hartmann (these proceedings). Therefore, the present paper will concentrate on the effects of radial electric fields on transport and confinement in tokamaks. In tokamaks E_r itself without shear cannot contribute to confinement improvement because the ensuing rigid rotation which reduces orbit losses and improves neoclassical transport has no effect on microturbulence which is regarded as the dominating cause of anomalous transport in auxiliary heated tokamaks. Effects of E_r on transport enter only through derivatives of E_r.

As outlined by Burrell[21], one of the scientific success stories of fusion research over the past decade is the development of the *E×B velocity shear turbulence stabilisation model* to explain the formation of transport barriers in magnetic confinement devices. This model has the universality needed to explain turbulence reduction and confinement improvement under a variety of conditions in limiter- and divertor tokamaks, stellarators, torsatrons, reversed field pinches, mirror machines, etc..

Further details on radial electric fields and their role in plasma confinement and exhaust can be found in review articles[21, 22] and in the proceedings of Topical Workshops[23, 24, 25,47].

II. RADIAL ELECTRIC FIELDS AND ROTATION

Radial electric field and plasma rotation are connected through the radial momentum balance. E_r can be determined from the single ion radial force balance equation (generalised Ohm's law):

$$E_i = \frac{1}{n_i Z_i e} \nabla P_i - v_{\theta i} B_\phi + v_{\phi i} B_\theta \quad (1)$$

where n_i is the ion density, Z_i is the charge of the ion, e is the electronic charge, P_i is the ion pressure, $v_{\theta i}$ and $v_{\phi i}$ are the poloidal and toroidal rotation velocities, respectively, and B_θ and B_ϕ are the poloidal and toroidal magnetic fields, respectively. This equation is valid at each point on any given flux surface, and the quantities involved are local quantities (E_r itself is not a flux function).

It follows from Eq. (1) that E_r is determined by three major driving forces: pressure gradient, poloidal and toroidal rotation. Because E_r can be influenced by particle-, heat- and angular momentum input, and by changing the current profile (changing B_θ), various of these terms can be active in various machines with respect to E × B shear flow reduction of turbulence and transport, which occurs regardless of the plasma rotation direction. This provides the possibility of *active control of transport*; E × B shear as a control mechanism for turbulence and transport has the major advantage of flexibility, in that the shear can be generated or enhanced in several ways. Particle-, heat-, and momentum transport are not independent of each other, but have a complex coupling. Therefore, research on E_r can clarify the complex plasma transport mechanisms.

III. E × B VELOCITY SHEAR REDUCTION OF TURBULENCE

E × B velocity shear suppression of turbulence in a plasma is a mechanism akin to the interaction between sheared velocity fields and turbulence in fluids. However, in a plasma E × B velocity and fluid velocity due to E_r can be quite different. *The fundamental velocity is not the mass velocity, but rather the E × B velocity,* the drift velocity at which all particles move – regardless of their charge or mass – and at which turbulent eddies are convected.

The fundamental physics involved in transport reduction is the effect of E × B shear on the growth, radial extent and phase decorrelation of the turbulent eddies. The identification of individual modes responsible for the observed turbulence may not be as important as the knowledge of turbulence drive suppression mechanisms, which provide a direct route to transport control.

An important point in plasmas are the *synergistic effects between E × B velocity shear and magnetic shear.* In neutral fluid dynamics sheared velocity is a source of free energy which can drive turbulence through Kelvin-Helmholtz instabilities. In a plasma, shear in the magnetic field prevents coupling of the various modes across the velocity gradient so that they are unable to extract energy from the E × B velocity shear and grow[21].

E × B shear is a universal and robust mechanism for regulating and controlling entire classes of turbulent modes at all radii, and thus for controlling transport.

<u>How does E × B shear suppression work?</u> Turbulence is stabilised by the shear rate $\omega_{E\times B}$ in the E × B flow $v_{E\times B}$ induced by E_r[26]

$$\omega = \left|\frac{d\, v_{E\times B}}{dr}\right| = \left|\frac{(RB_\theta)^2}{B} \frac{\partial}{\partial\psi} \frac{E_r}{RB_\theta}\right| \quad (2)$$

where R is the major radius, B_θ is the poloidal magnetic field and ψ is the poloidal flux.

The E × B shear rate enters quadratically into the various theories; accordingly, its sign is irrelevant. Indeed, H-mode edge barriers have been seen with both signs of E_r and its derivative[27]. Equation (2) shows that both E_r and B_θ contribute to the final result; E_r / RB_θ is the toroidal angular speed due to the equilibrium flow driven by E_r in standard neoclassical theory, suggesting that the basic shearing is in the toroidal direction. As illustrated in Fig. 1[21], the differences between the shear in E_r / B and E_r / RB_θ have great practical significance; although the former vanishes locally, the latter is significant throughout this plasma which shows confinement improvement across the whole minor radius.

Equation (2) also shows that the shear rate is not constant on a magnetic flux surface, being significantly larger on the low toroidal field side of a given flux surface. Experimental data on H-modes have indeed demonstrated significant poloidal variation in the effect of E × B shear on turbulence.

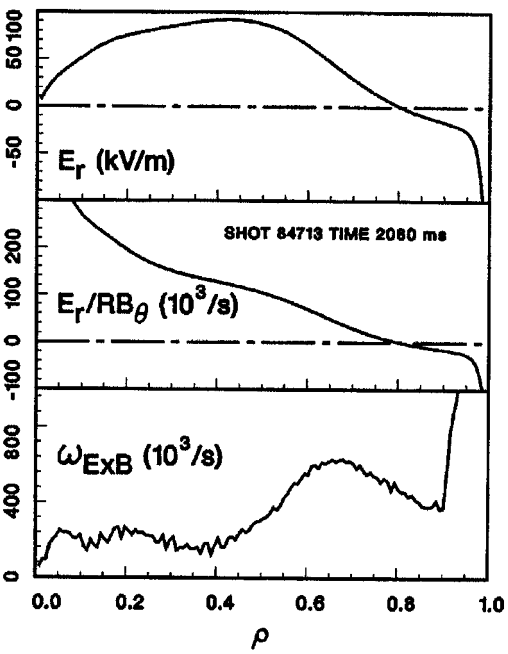

Fig. 1 Plot of radial electric field E_r , toroidal angular speed E_r / RB_θ , and the E × B shearing rate defined in Eq. (2) as a function of flux surface label ρ for a high performance, deuterium VH-mode plasma in DIII-D. Here, ρ is proportional to the square root of the toroidal flux inside a given flux surface. Although the derivative of E_r vanishes near ρ = 0.5, the E × B shearing rate is appreciable across the whole plasma. Plasma conditions are 1.2 MA plasma current, 1.6 T toroidal field, 9.8 MW injected deuterium neutral beam power, and 4.7 × 10^{19} m^{-3} line averaged density. Discharge is a double-null divertor[21].

Theoretically, there are two points of view[21] .The first (non-linear suppression) is that the turbulent eddies are distorted and the radial transport is reduced if the E × B shear rate exceeds the decorrelation rate of the ambient turbulence in the absence of E × B shear; this is valid for entire classes of turbulent modes. The second is linear stabilisation, which is mode specific, and therefore the details depend on the turbulence driving mechanisms. The fluctuation spectra are E×B–Doppler–shifted, and the stabilisation is mainly due to shear in this Doppler shift.

A simple rule of thumb which is also used in comparisons between theory and experiment, is that for turbulence stabilisation $\omega_{E \times B}$ is to be comparable to the linear growth rate of the most unstable mode in the plasma; however, theory and experiment show factors of 2 – 3 deviation from that rule.

IV. TRANSPORT BARRIERS AND CONFINEMENT IMPROVEMENT

As outlined in the review paper of Burrell[21] (see also references therein) the E × B shear stabilisation model was originally developed to explain the transport barrier formation at the plasma edge at the L to H transition. More recently, it has been applied to explain the wider edge transport barrier at the H to VH (very high) mode transition seen in some tokamaks such as DIII-D and JET. Most recently, this model has been applied to the core or internal transport barriers (ITB) formed in plasmas with modified (negative, optimised) central magnetic shear (DIII-D, TFTR, JT-60U, JET, ASDEX Upgrade, Tore Supra, ...), and to plasmas with transport reduction across the whole plasma radius (JT-60U and DIII-D). During electrode biasing experiment in TEXTOR the role of E × B flow shear in the confinement improvement and the temporal causality has been clearly established[28,48,51].

All these experimental results, some of which will be outlined below, show that *the E × B shear stabilisation concept has the universality needed to explain transport barriers at different radii seen in limiter- and divertor tokamaks, stellarators, reversed field pinches, and mirror machines with a variety of discharge- and heating conditions and edge biasing schemes.*

A. E × B Velocity Shear Effects at the Plasma Edge

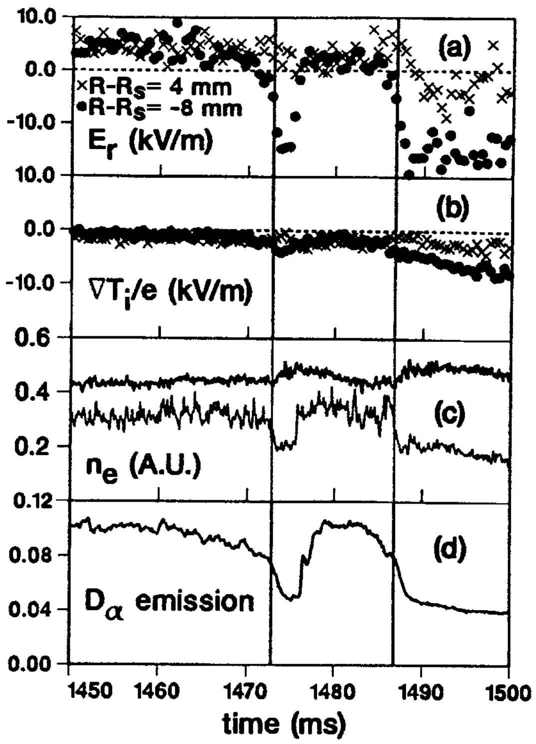

Fig. 2 The temporal evolution of two L to H transitions, where the L to H transition times are indicated by the vertical lines. (a) E_r from CER (Charge Exchange Recombination spectroscopy) of He II spectra 4 mm outside (crosses) and 8 mm inside (filled circles) the separatrix, showing the increase in E_r shear 2 ms before each transition. (b) The main ion temperature gradient $\nabla T_i/e$ contribution to E_r for the same radii as in (a). (c) Two channels of the lithium BES (Beam Emission Spectroscopy) diagnostic showing the earliest rise (upper thick line) and earliest drop (lower thin line) in edge electron density. (d) D_α emission from the channel showing the earliest rapid drop[29].

The largest data base for testing the E × B velocity shear theory is due to the plenitude of edge transport barrier studies in spontaneously occurring H-modes (already discovered in ASDEX[12] in 1982) as well as in edge biasing-induced H-modes[48]. The edge transport barrier has been found in tokamaks, stellarators, mirrors and reversed field pinches. An overview of H-mode physics results can be found in Ref. 23.

A key prediction of the E × B velocity shear theory is that it causes the reduction in turbulence and transport. However, *causality can be difficult to pin down in spontaneous H-modes*. According to Eq. (1), E_r can be sustained by plasma rotation and by the ion pressure gradient.In stationary H-modes, it is quite often found[30,31] that E_r can be upheld by the sole pressure gradient, such that the shear might actually be interpreted as the result of the improved confinement, not as its cause. Therefore, establishing the causal link has to rely on the time sequence in discharges where an electric field growth, not or only partly accountable by the ion pressure gradient, precedes the confinement improvement. The DIII-D team, using high time and space resolved measurements, could firmly reveal such a growth within a few milliseconds prior to an L to H transition. The temporal evolution (see Fig. 2) of a pair of representative L to H transitions in DIII-D[29] shows that the trigger to the L to H transition is the v x B term in Eq (1), and not the main ion pressure gradient. For these same discharges the fluctuation data[29] from far-infrared (FIR) scattering and reflectometry show that the radial electric field shear increases before the fluctuation suppression, consistent with increasing E_r shear as the cause of the turbulence reduction.

Another way to approach the causality question is to look at H-modes produced by plasma biasing[48]. In TEXTOR radial electric fields were externally imposed by means of electrode biasing[19] to study the role of E × B flow shear in improved confinement[28]. Whereas the ion pressure gradient is normally negative in a tokamak plasma, and according to Eq. (1) therefore creates a negative E_r, the external imposition of a positive electric field allows us to avoid the afore mentioned, for causality studies inopportune link between E_r and ion pressure gradient (a steepening of the pressure gradient would tend to counteract the imposed positive E_r). Adequate time and space resolved diagnostics for E_r and edge density profiles allowed to study the role of E × B shear in a controlled way. Under these experimental conditions changes in the local density gradient ∇n can be interpreted as diffusivity changes and a zone of enhanced ∇n is thus a measure for a transport barrier. A particle transport barrier is found to be built up as the electric field gradient increases (prior to the occurrence of bifurcation phenomena). Figure 3 shows E_r profiles measured with a rake probe for two times during the bias voltage ramp together with the corresponding density profiles which are seen to develop a pronounced steepening in the radial region where the electric field is located (the electrical layer). To characterise this steepening, we compare the local ∇n with its pre-biasing value, a measure of which is $\xi(r, t) = \nabla n(r, t) / \nabla n(r, t_0)$. The temporal evolution of the plasma parameters plotted in Fig. 4 shows the two regions of enhanced ξ, where the density gradient steepens (43.9 and 45.0 cm). Generally, the radially innermost

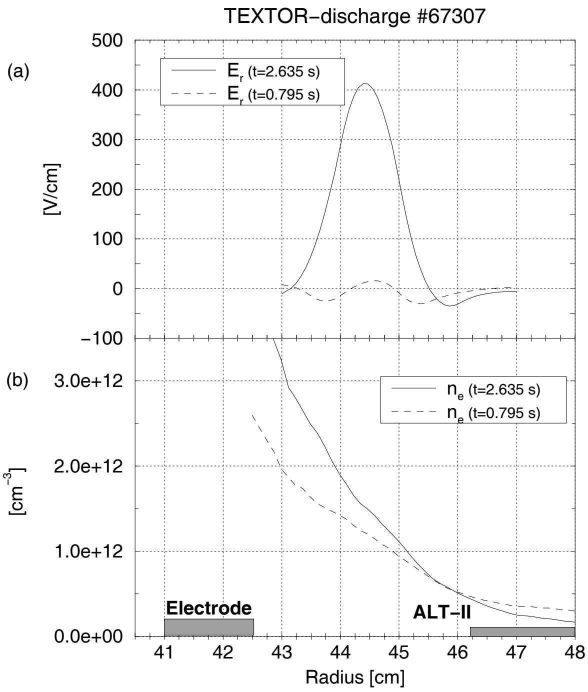

Fig. 3 Radial profiles of (a) electric field and (b) electron density at two times during a voltage ramp (see Fig. 5). The electric field is pointing outward for positive biasing in contrast to an unbiased ohmic discharge[28].

maximum is 2 to 4 times higher than the outer one. The figure also demonstrates the temporal link between ∇n and ∇E (and not E_r or ist curvature). Probe measurements of electrostatic turbulence have clearly demonstrated E × B shear flow turbulence stabilization in the double shear layer[33,48,51]. *In conclusion, the experimental evidence points to E × B shear as the decisive element for the confinement improvement* (see $N_{e,tot}$ in Fig. 4, the main energy gain in these discharges being density related[19]): there is a strong spatial correlation between ∇E and transport barrier formation, the temporal causality is clearly established (∇E leads ∇n), and the magnitude of the shear at which the confinement improvement occurs, agrees rather well with theoretical models, both in the value of the critical shear and in its global shear dependence[32]. This critical ∇E (about 50 V/cm^2) required to create a transport barrier seems to be the same in different machines.

B. E × B Velocity Shear Effects in the Plasma Core

<u>1. VH mode.</u> A key feature of the VH mode, an

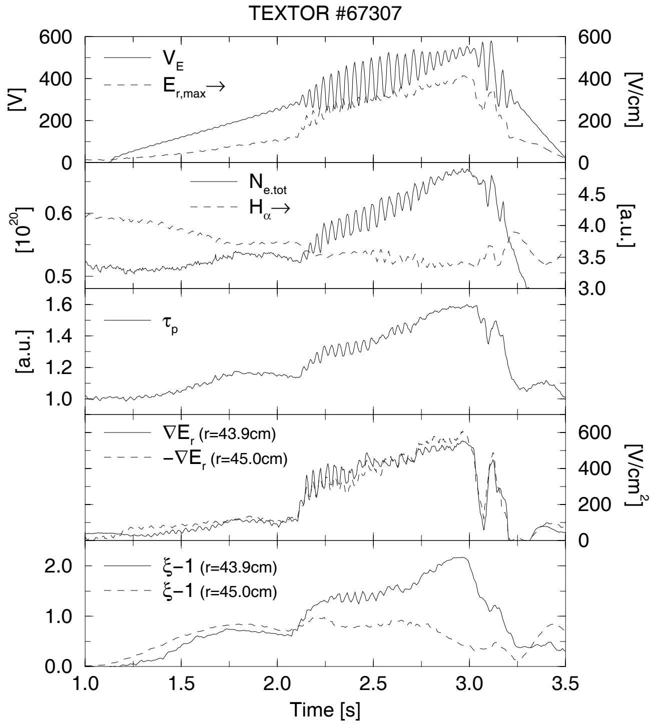

Fig. 4 Time traces of the electrode voltage V_E, electric field maximum $E_{r,max}$, total number of electrons N_{tot}, H_α-light, particle confinement time τ_p, field gradient maxima ∇E and the relative change of the density gradient ξ - 1 at the corresponding radii[32].

improved confinement H-mode, is the penetration of the

H-mode edge transport barrier deeper into the plasma. In DIII-D it was shown that the region in the outer half of the

plasma where the local thermal diffusivity changes the most is the same where the E × B velocity shear and density fluctuations change the most. Furthermore, the change in the E × B velocity begins 20 – 40 ms prior to the first change in thermal transport.

<u>2. High l_i discharges[21,42].</u> Peaked current density profiles (high internal inductance discharges) are transiently obtained by ramping up the vertical elongation in a time short compared to the current diffusion time. A correlation has been seen between the increased E × B shear and the confinement improvement.

As a causality test in VH-mode and high l_i discharges, magnetic breaking was used on DIII-D to directly change the toroidal plasma rotation and hence the E × B velocity shear without changing the other plasma parameters. This test demonstrated that changes in the E × B velocity shear causes changes in turbulence and transport.

<u>3. Internal transport barriers (ITB).</u> Exciting results have been obtained during recent years: reduced transport in the central region of tokamak plasmas and concomitant record fusion performance in DIII-D[34], JT-60U[35] and JET[36]. The example of JT-60U in Fig. 5 demonstrates that impressively steep core gradients can be produced[32]. The formation of an ITB dramatically reduces ion heat and particle flux from the core (sub-neoclassical ion thermal diffusivity obtained). In as much as neoclassical transport is usually considered to be as the minimum transport possible in a tokamak, these results represent a dramatic improvement in confinement and performance .

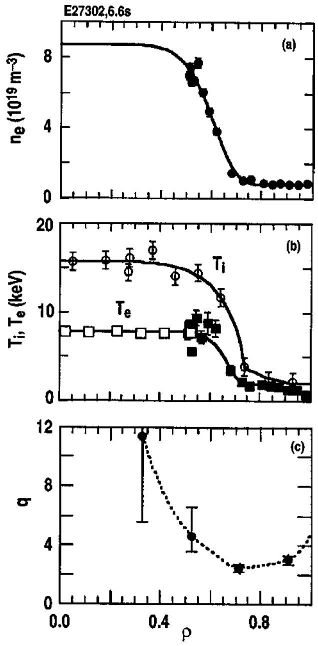

Fig. 5 Radial profiles for a high performance, negative central shear discharge in JT-60U. (a) Electron density n_e measured by Thomson scattering. Solid curve is obtained by fitting interferometer data (one tangential and two vertical chords). (b) T_i from charge exchange recombination spectroscopy and T_e . In the T_e profile, closed points are measured by Thomson scattering and open points are by electron cyclotron emission. (c) q profile from motional Stark effect measurements[21,37].

Although the target plasmas have modified central magnetic shear, it appears that the key physics for the transport reduction is the E × B velocity shear as illustrated in Fig. 6 where RS (reverse shear, unimproved confinement) and ERS (enhanced reverse shear, improved confinement) transition data in TFTR[38] are compared; the difference is the time evolution of the E × B shear rate. Other evidence that negative magnetic shear is not the key factor in core (ion) transport barrier formation is that in most machines with negative magnetic shear no confinement improvement is reached until a power threshold is observed which is also consistent with the idea of E × B shear stabilisation (see also the TEXTOR results outlined in IV A).

A key causality test has been performed on TFTR[39]. The angular momentum input to the plasma was changed by varying the fraction of the beam power which came from neutral beams injecting parallel to (co) and antiparallel to (counter) the plasma current. Clean temporal correlation between the decrease in E × B shear rate, the increase in the fluctuations, and the increase in transport was observed.

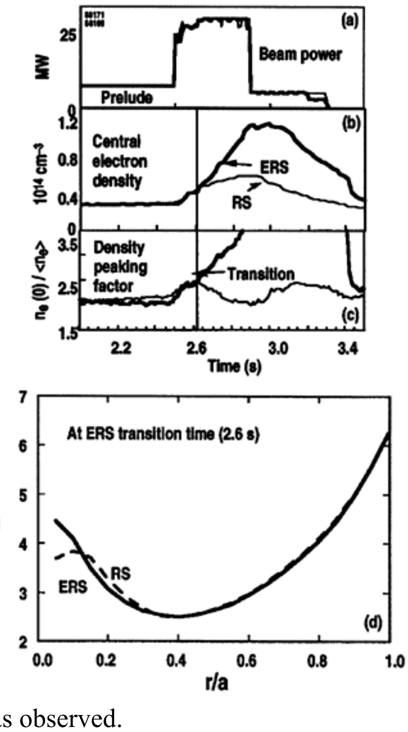

Fig. 6 Plots from two discharges in TFTR showing that the q profile is identical at the time of the RS-ERS transition. (a) Deuterium neutral beam input power, (b) central electron density, (c) density peaking factor all plotted as a function of time, (d) q profile at the time of the transition. The RS plasma trace is the dashed line[38].

4. Transport reduction across the whole plasma. In JT-60U[40] and DIII-D[34] the combination of H-mode edge confinement improvement and core confinement improvement has been achieved. In these discharges, the transport is reduced throughout the plasma and the radial profiles show *no sign of a local transport barrier.*

The importance of radial electric fields is now widely recognised. It has been demonstrated in limiter- and divertor tokamaks, stellarators and mirror machines with a variety of discharge- and heating conditions as well as edge biasing schemes that E × B velocity shear turbulence stabilisation is a robust and universal

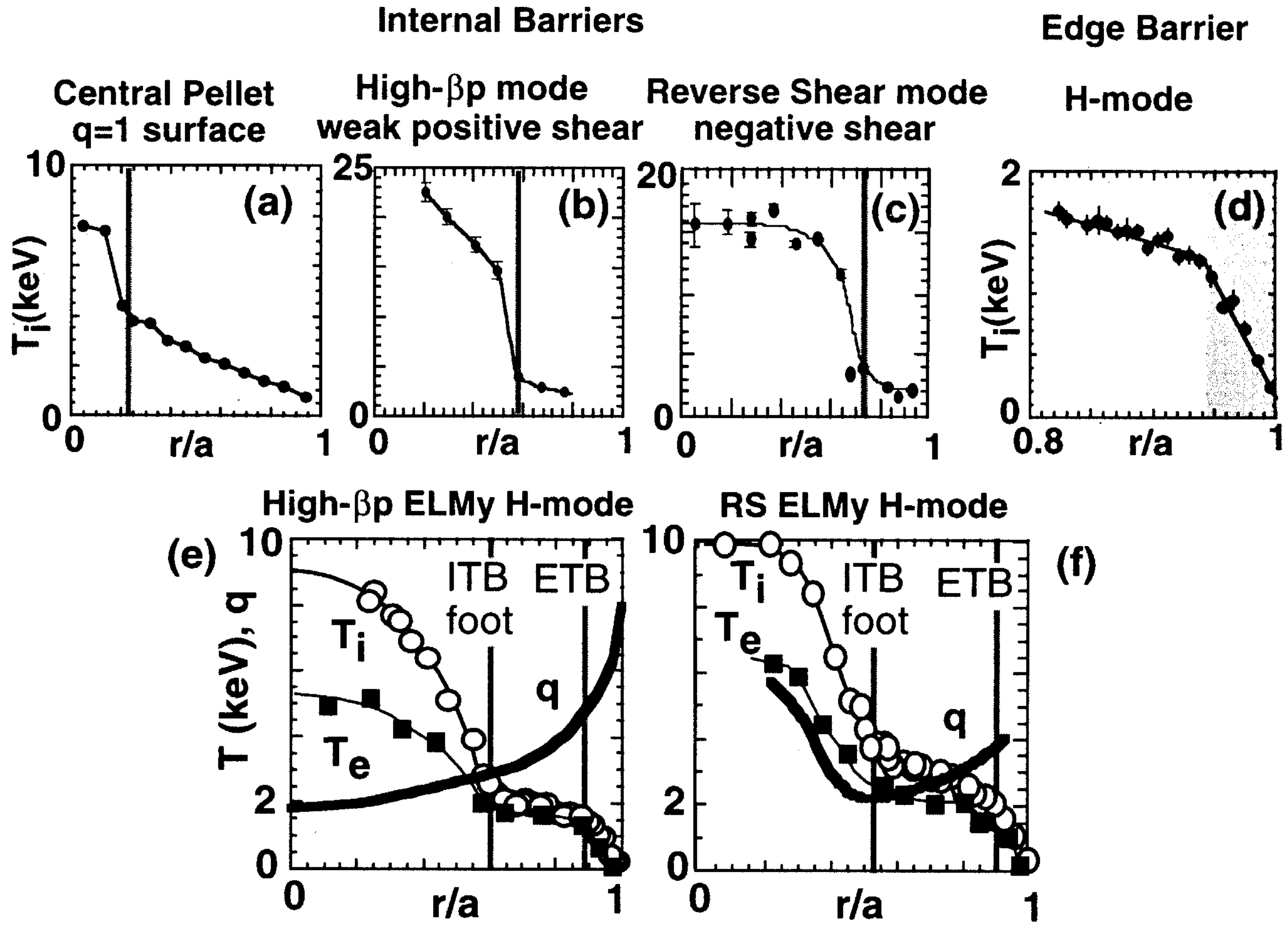

Fig. 7 Transport barriers observed in JT-60U: Internal transport barriers (ITB) in (a) the central pellet injection mode with the ITB foot at the q=1 surface, (b) the high β_p mode with the ITB foot (ρ_{foot}) in weak positive magnetic shear, (c) the reversed shear (RS) mode with ρ_{foot} in negative or zero magnetic shear. Edge transport barrier (ETB) in ELM-free H-mode (d). (e) and (f) show profiles of T_i, T_e and q in the high β_p ELMy H-mode and the RS ELMy H-mode with ITB and ETB.

In JT-60U four types of transport barriers have been observed[41] as shown in Fig. 7. The high confinement modes are characterized by the combination of an ITB with an H-mode. Most of these high performance results were obtained transiently. Recently, substantial progress has been made to extend these discharges towards steady state[36, 41, 42].

V. CONCLUSIONS AND OUTLOOK

mechanism which can explain the formation of transport barriers in magnetic confinement devices. The experimental results show good qualitative agreement with theory which however still needs considerable improvement. Furthermore, an improved comparison between experiment and theory requires improvement of plasma diagnostics such as E_r measurements(see review[49] using the motional Stark effect[43] and the heavy ion beam probe[44], emissive probes[50], as well as the direct measurements of fluctuation-driven fluxes in the core plasma.

Electrode biasing experiments on TEXTOR and more recently on the tokamak CASTOR[46,48], where so-called separatrix biasing has been performed, demonstrated the decisive role of E x B velocity shear in confinement improvement.

There also exist synergistic effects between E × B velocity shear and magnetic shear, although *the key physics for the (ion) transport reduction is the E × B velocity shear mechanism*[45,48], which can be operational in various regions of the plasma because there are a number of ways to change the radial electric field. These synergistic effects and the extension of high performance discharges towards steady state are presently investigated on large tokamaks like JET.

Ion thermal and particle diffusivities at or below the standard neoclassical values have been observed. Experiments[52,53] are going on to study the formation of electron transport barriers.

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