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Radial Electric Fields and Their Importance in Fusion Research

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Abstract

While the importance of radial electric fields was already perceived early in fusion research, a genuine flurry of activity was prompted by the experimental and theoretical recognition of a possible link between E_r and the establishment of edge and internal transport barriers in toroidal plasmas. The effects that the radial electric field and its finer structure is assumed to have on particle orbits, on collisional and turbulent transport and on bifurcation to improved confinement will be reviewed together with the experimental evidence for some of these effects.

Keywords:

radial electric field, particle orbit, collisional transport, turbulence, flow shear stabilization

1. Introduction

The possible importance of radial fields in toroidal plasmas has in the past been repeatedly emphasized [1-6]. The recent flurry of activity was however prompted by the recognition of a possible role of E_r in the establishment of transport barriers either in the edge [7-10] or more internal to the plasma [11-14].

Starting with a short reminder of how electric fields can be set up, the present paper primarily aims at exposing the main arguments on which such a role could be based. The radial electric field or its spatial derivatives modify particle orbits and, as a result of this, affect collisional and turbulent transport. In addition, E_r and especially ∇E_r also directly affect the turbulence level itself, either by providing linear stabilization of the turbulent modes or by achieving nonlinear decorrelation. Bifurcation to improved confinement can be the result of such interactions. The experimental evidence put forward to substantiate some of the claims is also reviewed.

Like in every review paper, the collection of material is restricted by space limitation. As a result, several additional and important aspects linked to E_r are only dealt with in passing or not at all, e.g. its effect on plasma viscosity, on the bootstrap current or on plasma exhaust.

2. Generation of Radial Electric Fields

When describing the plasma by single-fluid MHD equations [15], it can be shown that Ohm's law allows to relate, to a very good approximation, the radial electric field to the toroidal and poloidal rotation velocities of the ions and to the ion pressure gradient according to:

$$E_r = V_{\phi i} B_\theta - V_{\theta i} B_\phi + \frac{1}{e_i n_i} \nabla p_i . \tag{1}$$

In this sense, each of these three terms can be considered as a possible source of E_r. For our subsequent

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discussion, it is important to note that (i) a sudden change (a bifurcation) of E_r can only come about as the result of a sudden change of one of these constituting terms; (ii) since a confinement improvement gives rise to an increase of the pressure gradient, improved confinement leads to increased E_r. The latter correlation will quite often blur the issue of the causality between Er and confinement improvement.

The single-fluid momentum equation, where $\boldsymbol{V}$ is essentially the ion velocity, reads:

$$\rho\partial \boldsymbol{V}/\partial t = -\rho(\boldsymbol{V}\cdot\nabla)\boldsymbol{V} + \boldsymbol{M}_\mathrm{e} + \boldsymbol{M}_\mathrm{i} + \boldsymbol{j}\times\boldsymbol{B} - \nabla(p_\mathrm{e}+p_\mathrm{i}) - \nabla\overline{\overline{\Pi}}_\mathrm{i} - \nabla\overline{\overline{\Pi}}_\mathrm{e} - \rho\nu_\mathrm{io}\boldsymbol{V}\,. \tag{2}$$

$\boldsymbol{M}_\mathrm{a}$ is an external momentum source (like neutral beam injection) for species a, $\overline{\overline{\Pi}}_a$ is the stress tensor and $\rho\nu_\mathrm{io}\boldsymbol{V}$ describes a possible friction force on the ion fluid by the neutrals. Equation (2) allows to identify various ways in which poloidal or toroidal rotation can be set up: (i) poloidally asymmetric diffusion (Stringer spin up through $(\boldsymbol{V}\cdot\nabla)\boldsymbol{V}$) [16], (ii) radial gradient of turbulent Reynolds stress $((\tilde{V}\cdot\nabla)\tilde{V})$ [17], (iii) external momentum input ($\boldsymbol{M}$), (iv) radial return currents ($\boldsymbol{j}$) which counteract loss cone losses of particles [9,18] or collisionless currents of RF or MHD driven ions or electrons [18-21], (v) biasing current [8,22-23].

The presence of the term $\boldsymbol{j}\times\boldsymbol{B}$ in Eq. (2) requires some attention. A continuously non-zero current $\boldsymbol{j}$ would modify the charge distribution in the plasma and a steady state could never prevail. The current $\boldsymbol{j}$ appearing in Eq. (2) is a so-called return current, that opposes - and in magnitude equals - a current $\boldsymbol{j}_\mathrm{ext}$ which, because of its collisionless nature or because of the fact that it enters the plasma for instance through the shaft of a biasing electrode, can itself not exchange momentum with the plasma. Both currents taken together thus maintain the condition of ambipolarity, i.e. zero net radial current flowing through the plasma. The electric field given by Eq. (1), in combination with Eq. (2), is in that sense always the ambipolar electric field $E_{r,\mathrm{amb}}$. Some confusion can arise from the fact that the latter term is sometimes used in a context which relies on simplified versions of Eq. (2).

The development of appropriate means to create and shape the radial electric field must be actively pursued if full profit is to be drawn from the benefits of E_r. Their description is however outside the scope of this paper.

3. Theoretical Effects of E_r on Transport

3.1 Effect of the Electric Field on Particle Orbits

In a toroidal plasma, the toroidal magnetic field changes with poloidal angle (θ) and toroidal angle (ϕ) as $B = |B_0|(1-\varepsilon_\mathrm{t}\cos\theta - \varepsilon_\mathrm{h}\cos(l\theta - \mathrm{m}\phi))$. Under conditions of low enough collisionality, the perpendicular transport in tokamaks is dominated by the excursions of banana particles, trapped in the toroidal mirror (ε_t), whereas in stellarators the helically trapped particles (ε_h) prevail.

E_r can change the character of the particle orbits. The projection on a poloidal plane of the orbit of the guiding center (r, θ) is given by the equations [24]

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{V_\mathrm{D}}{r}\cos\theta + \omega$$
$$\frac{\mathrm{d}r}{\mathrm{d}t} = V_\mathrm{D}\sin\theta \tag{3}$$

where V_D is the toroidal drift and ω the angular velocity which can be provided by different mechanisms. Rotational transform, for instance, brings about $\omega = \omega_\mathrm{q} = (B_\theta/B_\phi)(V_\parallel/r)$. In a stellarator, the center of a helical mirror trapped particle experiences the angular speed $\omega = \omega_\mathrm{h} = \frac{\varepsilon_\mathrm{h}}{\varepsilon_\mathrm{t}}\frac{V_\mathrm{D}}{r} f(pitch)$. A radial electric field will create an extra $\boldsymbol{E}\times\boldsymbol{B}$ rotation of magnitude $\omega = \omega_\mathrm{E} = E_r/(rB_\phi)$.

One can now consider various scenarii in which the potential of E_r comes to bearing:

(i) It is in principle possible to exchange the rotational transform rotation ω_q by ω_E and nevertheless sustain a toroidal equilibrium configuration. This is the basis of magnetoelectric confinement, proposed in [1]. Equilibrium was shown [3] to be feasible at radial electric fields reaching about 1 MV/cm in a reactor grade plasma. Experiments, e.g. on the Electric Field Bumpy Torus EFBT [25], provided quite favorable scaling for particle confinement. Whereas the maintenance of the strong bias could be provided by the loss of 3.5 MeV α-particles, the setting-up of the configuration calls for an alternative non-intrusive, non-polluting and powerful biasing scheme.

(ii) In a tokamak, particles become trapped in the toroidal mirror when ω_q becomes zero locally. However, in the presence of $\boldsymbol{E}\times\boldsymbol{B}$ rotation, the point of reflection can be moved by the extra rotation provided by ω_E. When E_r becomes very large, whether positive or negative, all particles can become passing. A substantially fraction of ion banana particles are already made passing [26] when $|E_r| \geq B_\theta V_\mathrm{T}$, where V_T is the ion thermal velocity. At these field levels the radial diffusivity in tokamaks should therefore be reduced.

(iii) Helically trapped particles in stellarators [24,27] strongly enhance perpendicular transport when, in addition, they also get trapped in the toroidal mirror and then become superbanana particles. When $|\omega_E|$ exceeds however $|\omega_h|$, the toroidal mirror trapping can be undone. For the effect to be substantial however, it is necessary to reach $\omega_E > \nu/\varepsilon_h$, as the particles should be rotated significantly before they scatter with the effective collision frequency ν/ε_h.

In a non-uniform E_r, also ∇E_r will affect the particle orbit shape [28]. The width of banana trajectories will be divided by the squeeze factor $S = 1 - \rho_\theta \nabla E_r / B_\theta V_t$. Depending therefore on the sign and magnitude of the ∇E_r, the width can be compressed or enlarged.

Finally, it should be recalled that the various orbit effects described have not only a bearing on transport as here considered but also on e.g. the bootstrap current. Only the first issue is discussed in the present paper.

3.2 Modification of Collisional Neoclassical Transport and Consequences Thereof

3.2.1 Expressions

The authors of [29,30], besides giving similar expressions for the heat flux, show that the neoclassical surface averaged particle flux in an axi-symmetric system, in the absence of a parallel E-field, is given by

$$\Gamma_a = -n_a D_a \left[\frac{n_a'}{n_a} + \gamma_a \frac{T_a'}{T_a} - \frac{e_a}{T_a}(E_r - B_\theta V_{a\parallel}) \right], \qquad (4)$$

where e.g. in the plateau collisionality regime

$$D_a = \frac{\sqrt{\pi}}{2} \varepsilon_t^2 \frac{\rho_{a\theta}}{r} \frac{T_a}{eB} \exp\left[-\left(\frac{E_r}{B_\theta V_{ta}} \right)^2 \right],$$

and $\gamma = 1.5$. The exponential factor expresses the gradual suppression of banana particles by E_r (section **3.1**). Note also that the electric field is moreover felt through the creation of the mobility term in Eq. (4) and that ν_a is the collision frequency of species a with the ions.

For stellarators in the helical trapped regime, the very unfavorable diffusivity scaling $D_a = \frac{\varepsilon_h^{3/2}}{V_a} \frac{\rho_a^2}{R^2} V_{ta}^2$ can be undone by E_r to an extent that depends on the collisionality. For instance, for $\varepsilon_h < \nu/\omega_E < \varepsilon_t^2/\varepsilon_h$, one obtains $D_a = \nu_a^{1/2} (E_r/rB)^{-3/2} \rho_a^2/R^2 V_{ta}^2$. The reader is referred to Refs [31,32] for more details. On account of the non-axisymmetry, ν denotes now the collision frequency of each species [27].

In a non-uniform E_r, the above diffusion coefficients are to be divided by $S^{3/2}$ such that a reduction of transport requires $S > 1$ [33].

3.2.2 Consequences

The ambipolar electric field $E_{r,\text{amb}}$ in the context of neoclassical theory is that field for which $e_i\Gamma_i - e\Gamma_e = 0$ using Eq. (4). Noting that $D_e << D_i$ and assuming that $E_{r,\text{amb}}$ is not much larger than $B_\theta V_{ti}$, it is found that in a tokamak the neoclassical plateau prediction for the ambipolar field is:

$$E_{r,\text{amb}} = B_\theta V_{i\parallel} + \frac{T_i}{e_i}\left(\frac{n_i'}{n_i} + \gamma_i \frac{T_i'}{T_i}\right). \qquad (5)$$

It is important to note that this expression is identical to Eq. (1) provided that the parallel and toroidal directions are assumed to be identical and that $V_{i\theta} = -0.5T_i'/e_i$. Now, the last expression is precisely what is called the neoclassical poloidal rotation [34-36], which is found from Eq. (2) in its neoclassical version, i.e. retaining on the right hand side only the viscosity tensor term (but including the heat flux driven contribution therein). More complete expressions can be found in [37]. Note also that the neoclassical version of Eq. (2) does not allow to evaluate $V_{i\phi} \approx V_{i\parallel}$. Quite often, the latter quantity is taken from experiments by lack of adequate version of Eq. (2). If the experimentally measured field E_r then disagrees with Eq. (5) it must be concluded that the poloidal rotation is not neoclassical. This would for instance be the case if plasma turbulence were capable of creating significant Reynolds stress or if other anomalous processes were active (see section **2**).

Imposing in stellarators the ambipolarity constraint within the neoclassical context leads to a multiroot solution for $E_{r,\text{amb}}$ [31]. The so-called ion root pertains to the condition at $E_{r,\text{amb}} < 0$ when ions are lost preferentially but held back by the electrons. For $E_{r,\text{amb}} > 0$ one talks about the electron root. Which of these roots is experimentally obtained, is of great interest as the heat transport losses that result can be quite different depending on the root achieved. This can be appreciated from Fig. 1 where normalized particle fluxes $\gamma_D^S = a^2/4D$ (a) and energy fluxes $\gamma_\chi^S = a^2/4\chi$ (b) are plotted versus the plasma potential assumed of the form $\phi = a\phi'$ [ϕ in kV, γ in s^{-1}]. ϕ_1 is the ion root, ϕ_2 the electron root. Both the electron and ion heat losses are much lower in the electron root.

Taking the difference of the ion and electron fluxes given by Eq. (4) allows to calculate the neoclassical perpendicular current density in tokamaks in the plateau regime:

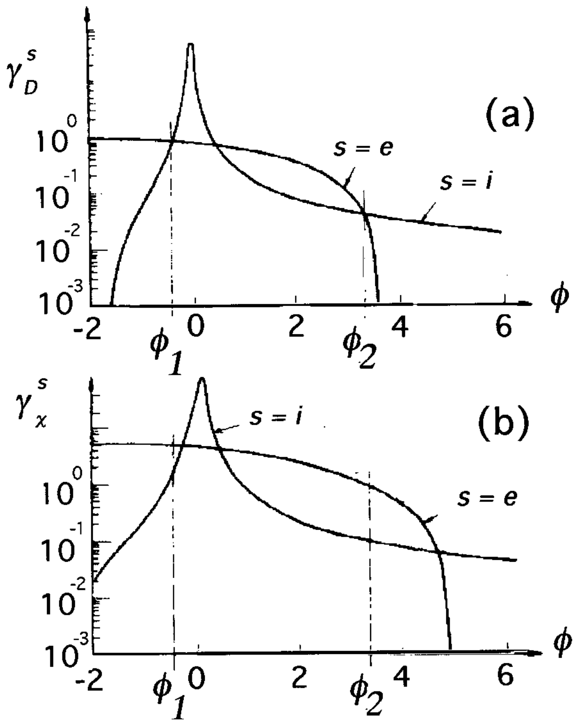

Fig. 1 Normalized electron and ion particle (a) and heat (b) fluxes for a stellarator with parameters $n = 10^{14}$ cm^{-3}, $T_e = T_i = 20.8$ keV, $B = 5$ T, $a = 2.5$ m, $\varepsilon_t = 0.1$, $\varepsilon_h = 0.05$, $r/a = 0.5$ [31].

$$j_r \approx \frac{e^2 n_i D_i \exp[-(E_r / B_\theta V_{ti})^2]}{T_i} (E_r - E_{r,\mathrm{amb}}). \quad (6)$$

A measurement of this current (as a biasing return current e.g., see section **2**) would provide a direct test of neoclassical theory. As the turbulent fluxes in the plasma edge surpass the neoclassical ones by far, success is only then possible when the turbulently induced fluxes are intrinsically ambipolar, as is expected for electrostatic turbulence [38]. It is furthermore important to point out that Eq. (6) can be derived from the poloidal component of that version of Eq. (2) in which only the $\boldsymbol{j}\times\boldsymbol{B}$ term and the ion stress tensor term are retained [39]. This is not surprising as it is a manifestation of the fact that also here the damping of flows in the magnetic surface leads to the particle diffusion across the magnetic field. In this instance, this damping is due to parallel viscosity and the confrontation of Eq. (6) with experiments then provides insight in this fundamental damping mechanism. Please remember that the latter sets the amplitude of poloidal rotation, the critical ingredient in a score of theories on L-H transition and $\boldsymbol{E}\times\boldsymbol{B}$ shear flow stabilization of turbulence.

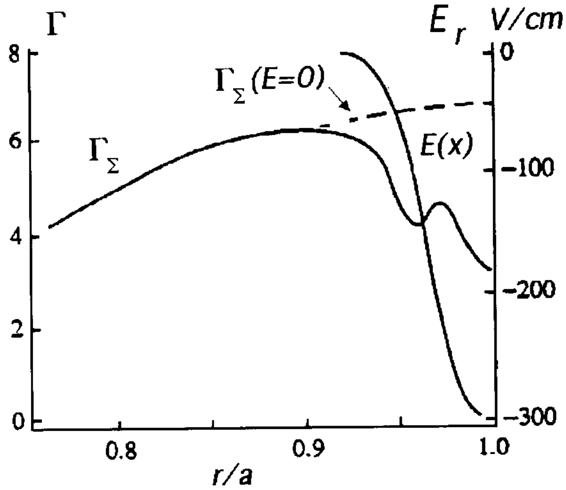

Fig. 2 Radial profile of ion heat flux Γ with (solid line) and without E_r (dashed line) for an electric field well typical for H-mode [43].

3.3 Effect of the Electric Field or Its Gradient on Turbulence-induced Transport

Quasi-linear theory allows to express the transport induced by turbulence as a function of the turbulence amplitude and spectral distribution [40-42]. The determination of the fluctuation spectrum and its amplitude constitutes a formidable task as it is mode dependent and requires the knowledge of the saturation mechanism of the turbulence. In the case of electrostatic turbulence, this difficulty is quite often circumvented by assuming that, when the density scale length is L_n, the amplitude $\tilde{n}$ of the density fluctuations of wave number $k_\perp$ is set by the so-called mixing length estimate $\tilde{n}/n = 1/(k_\perp L_n)$. The resulting diffusivity is then of order of magnitude $D \approx \gamma/k_\perp^2$, where γ is usually taken as the maximum growth rate of all the unstable modes in the plasma.

Even for a given and constant spectrum, the level of transport is however strongly dependent on the particle orbits, and it should therefore not be surprising that changes in the orbits brought about by E_r or ∇E_r can have profound effects. An example, at constant fluctuation spectrum, is given in Fig. 2 showing the radial profiles of the ion heat flux without $E_r(\Gamma_\Sigma(E = 0))$ and as shaped by an H-mode electric well ($E_0 = -300$ V/cm, $\Delta E/a = 0.03$) (Γ_Σ).

E_r and especially ∇E_r can however directly affect the turbulence level itself [see e.g. 43] either by providing linear stabilization [44] of the turbulent mode or by achieving nonlinear decorrelation [45-47]. The basic mechanism for the latter can be understood by a simple model [34] of an (surface conserving) eddy stretched over a time period $\tau_{corr} \approx \gamma^{-1}$ by a sheared flow with shear rate $\omega_{E\times B} = dV_{E\times B}/dr = B^{-1}dE_r/dr$ and equating its perpendicular dimension to an effective $k_{\perp,eff}^{-1}$, where $k_{\perp,eff}^2 = k_{\perp,0}^2(1 + S_v^2\tau_{corr}^2)$. The diffusivity now becomes

$$D \approx \frac{\gamma}{k_{\perp,eff}^2} = \frac{D_0}{(1+\omega_{E\times B}^2\tau_{corr}^2)} = \frac{D_0}{(1+\nabla E_r^2/\nabla E_{r,crit}^2)}\ . \quad (7)$$

where a critical shear gradient has been defined as that gradient for which the shear rate equals the diffusive decorrelation rate in the absence of shear $\nabla E_{r,crit} = B\tau_{corr}^{-1}$. This relation is completely equivalent to the expression $\omega_{E\times B,crit} = \gamma$ that has become known as Waltz's rule. It should be added that the interaction of flow shear and turbulence is an intrinsic one, as the turbulence itself (see section **2**) can set up flow and flow shear. In this way the turbulence can regulate its own amplitude to a low but non-zero level while at the same time forming radially and temporally localized poloidal flow, known as zonal flows [48,49].

This model is obviously quite approximate, as basic properties of the fluctuations have been assumed to be unchanged by E_r or ∇E_r. Different exponents in the parametric dependence of D upon $\omega_{E\times B}/\gamma$ are possible [50], meaning that the rate of change of the confinement improvement with gradient can change according to modes or models. $\nabla E_{r,crit}$ is moreover thought to be mode dependent and is expected to increase [51] going from Ion Temperature Gradient turbulence (ITG) to Trapped Electron Mode (TEM) and to Electron Temperature Gradient (ETG) turbulence. More precise evaluation [52] furthermore shows that the expression for the shear rate should be

$$\omega_{E\times B} = \frac{RB_\theta}{B}\frac{\partial}{\partial r}\left(\frac{E_r}{RB_\theta}\right),$$

such that also magnetic shear contributes to turbulence suppression. Finally, it should be reminded that according to some theories [53] also the curvature of the electric field ∇E_r^2 can be important. It can therefore be concluded that numerical modeling, preferably of gyrokinetic nature [54, 55], is required for accurate appraisal of nonlinear decorrelation and that Waltz's rule should only be taken as a rule of thumb.

4. Experiments

4.1 Effects of the Electric Field on Neoclassical Collisional Transport

Detailed measurements of the ambipolar potential in tokamaks were performed on the few devices on which Heavy Ion Beam Probing (HIBP) is available [56,57]. These generally confirm Eq. (5) in the inner half of the plasma, as illustrated in Fig. 3. In the outer half, the experimental potential is quite often higher than the prediction from theory and it can even become positive. This has been attributed to the creation of stochastic magnetic field regions [56,57], giving rise to anomalous electron losses that change the toroidal and poloidal flows (see section **2**).

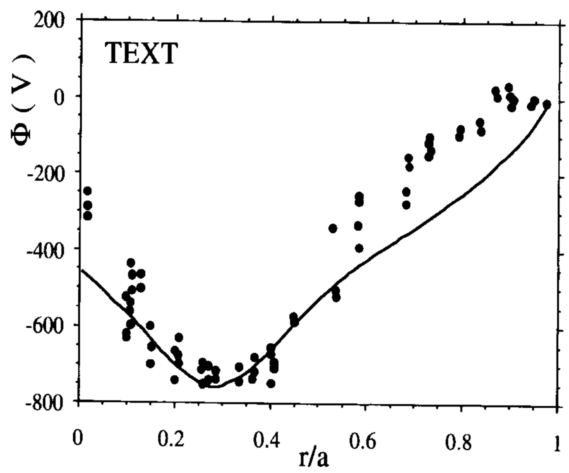

Fig. 3 Comparison between experimental plasma potential and neoclassical prediction in TEXT [57].

In stellarators, the existence of the two roots has been confirmed. Figure 4a shows an example [58] in which both roots exist in the same plasma: the electron root in the inner part, the ion root in the outer part. Whereas in Fig. 4 good agreement is obtained with the neoclassical predictions, in other cases the need to invoke anomalous toroidal momentum input has been stressed [59]. Figure 4b compares the measured electron heat diffusivity under the experimental conditions of Fig. 4a with neoclassical theory. It can be concluded that E_r is indeed capable of substantially reducing the heat losses in stellarators [58,60].

Measurements of the perpendicular conductivity have also substantiated the significance of E_r for neoclassical transport in tokamaks. The destruction of the banana orbits and consequently of parallel viscosity was confirmed in biasing experiments [22,23] and was found to take place at the field level [23] expected from Eq. (6). The parallel viscosity thus constitutes the essential non-linearity that brings about the sudden bifurcation of E_r that is observed in these experiments (see Fig. 8). Figure 5 shows the variation, at the location of the maximum of E_r, of the radial current density j_r when E_r is changed by electrode biasing in TEXTOR. More detailed studies have been made on the radial

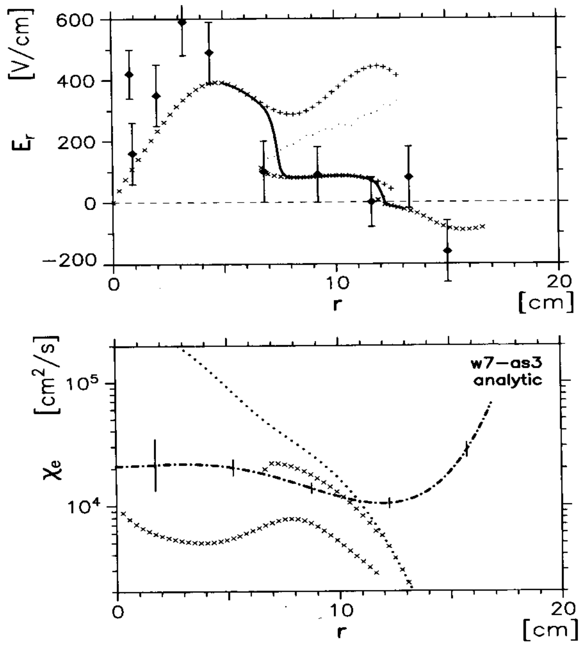

Fig. 4 (a) E_r on W7-AS [58] (x: neoclassical prediction; solid line: match by field diffusion equation; dots with bars: experiment).
(b) electron heat diffusivity χ_e (x : neo-classical prediction for each root; dotted line: idem for E_r = 0; dot-dashed line: experiment).

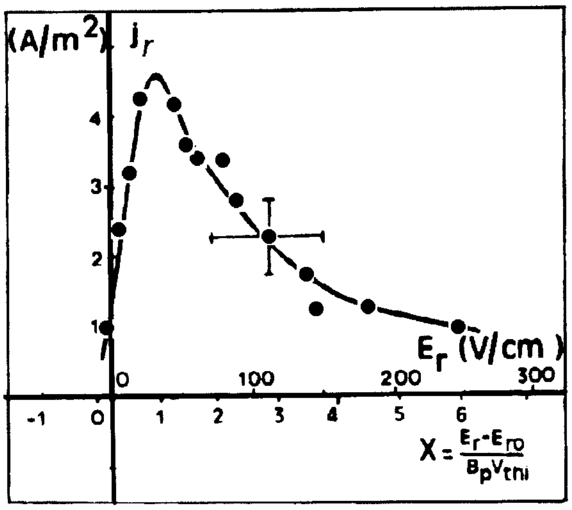

Fig. 5 Radial conductivity as a function of E_r in a tokamak. The abscissa is also calibrated in units of $(E_r - E_{r,\mathrm{amb}})/B_\theta V_{Ti}$. [23]

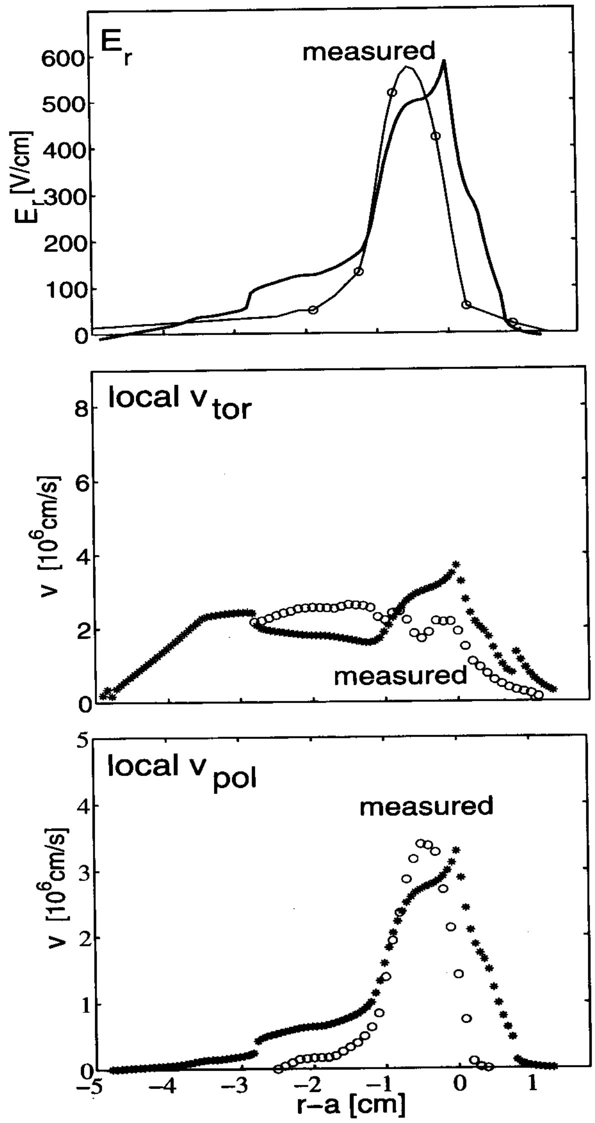

Fig. 6 Comparison for TEXTOR biasing between the measured electric field (E_r), toroidal (v_{tor}) and poloidal (v_{pol}) velocity with theory [65].

localization of E_r [61-64] and on the consistency of the field and the underlying flows [65]. Figure 6 shows an example of a comparison between measurement and theory. In addition to confirming the role of parallel viscosity, this modeling points to the role of neutral collisions as an important sink of rotation at the separatrix and identifies plasma compressibility to be important [35] at the high poloidal rotation speeds imposed in these experiments.

4.2 Effect of the Electric Field or Its Gradient on Turbulence-induced Transport

As this topic has been dealt with in several comprehensive recent reviews [66-69], only global trends will be described in this section.

Ion confinement is quite generally found to improve when Waltz's rule is "satisfied" for ITG turbulence both for edge barriers [10,70] and internal barriers (ITB) [11-14,71]. An example pertaining to the latter case is shown in Fig. 7. In this experiment in TFTR a transition from good to poor confinement is brought about by tailoring the radial electric fields by means of adjusting the ratio of co-injected neutral beam power to the total (co + counter) power [71]. Confinement is high (top panel, showing the central density, which changes in synchronism with the plasma energy, for three conditions) over a time period roughly corresponding to that in which the ***E***×***B*** flow shear is high (middle panel). Turbulence (lower panel) grows exponentially around the time when the shear rate no longer surpasses the calculated growth rate of ITG turbulence. While global consistence with Waltz's rule is obtained, it should be observed that during the improved confinement phase also γ (symbols) increases quite strongly. In the case of balanced injection $\omega_{E\times B}$ and γ remain practically equal during the major part of the improved confinement phase.

When ***E***×***B*** flow shear is thus quenching ITG turbulence (for stellarators, see e.g. [72]), ion transport can be reduced to neoclassical levels, as demonstrated e.g. on DIII-D [73]. Electron transport is found to be much less affected by flow shear. It is believed that electron transport is mainly due to TEM and ETG turbulence, which, because of larger growth rates and smaller spatial scales, are much more resilient to sheared flow [51,74]. Negative magnetic shear or other mechanisms appear then to be needed.

The difficulty to accurately evaluate and experimentally verify the Waltz's condition poses the problem of proof of causality [71]. Recent local measurements at the ITB location using Beam Enhanced Spectroscopy on DIII-D during ion transport barrier formation [75] show, within the experimental time resolution of 100 ms, an increase of poloidal rotation and of ion temperature and a turbulence suppression all taking place simultaneously. Is it feasible that confinement, possibly improved by another mechanism, steepens first the pressure gradient which then assures large values of E_r and E_r shear? Experiments using externally applied changes to the electric field have the potential of more clearly establishing the causality. Experiments in this category are the magnetic breaking experiment on DIII-D [76] or the already mentioned experiments with changing neutral beam torque in TFTR [71]. In the former, a toroidally localized vertical field is imposed on the rotating plasma, which, as a

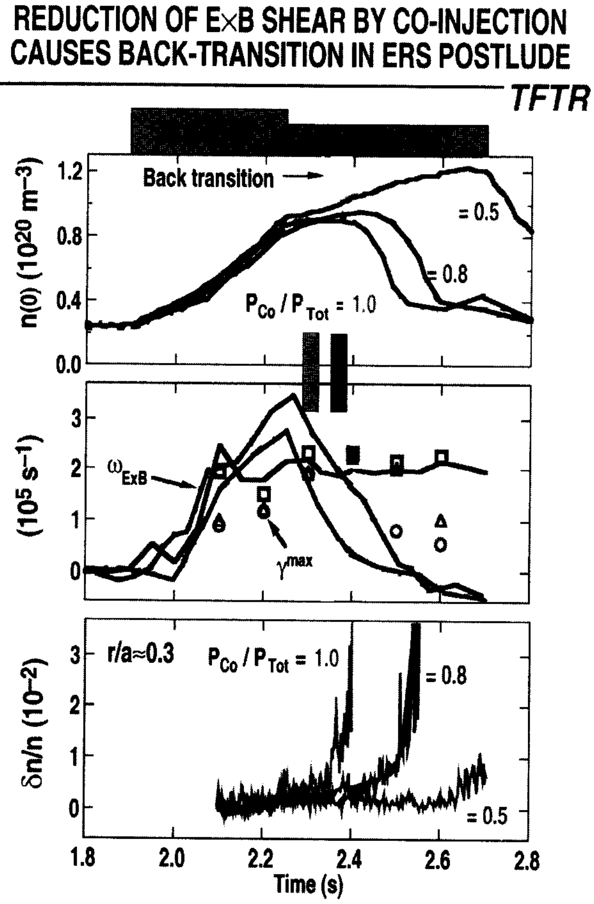

Fig. 7 Temporal evolution of ITB-discharges in TFTR with back transitions triggered by changes in the beam mix. Shown are (top) the central density; (middle) shear rate $\omega_{E\times B}$ (lines) and ITG growth rate γ (symbols); (bottom) density fluctuation ratio [71].

result, slows down, resulting in a lowering of the flow shear rate and a concomitant enhancement of heat diffusivity. In the latter experiments (fig. 7), E_r is always negative because of the dominance of the strong ion pressure gradient. Co-injection lowers $|E_r|$; the more co-injection present, the weaker also the ***E***×***B*** flow shear. In both of these cases the plasma reacts therefore in agreement with the causality prescribed by the flow shear paradigm.

Of particular relevance are the TEXTOR experiments in which cause and effect can clearly be separated by imposing, by means of biasing, positive fields that oppose the E_r normally established by the density gradient. While ramping up the electrode voltage, changes in ∇E_r are induced that are correlated spatially and temporally with changes in the density

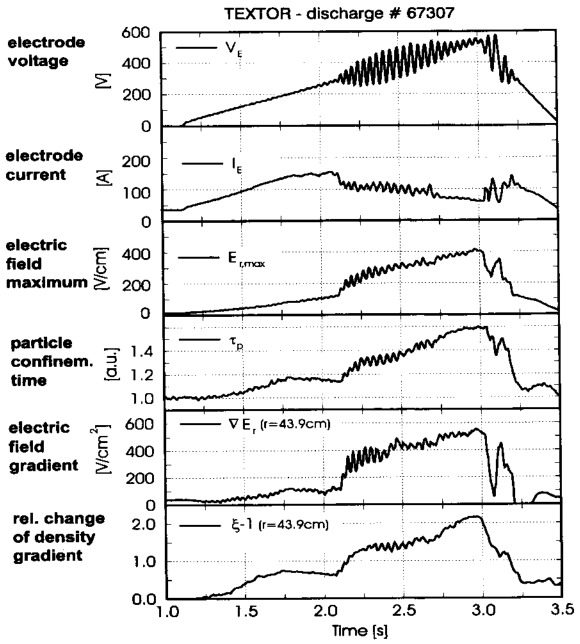

Fig. 8 Temporal evolution of key plasma parameters in TEXTOR during biasing [78].

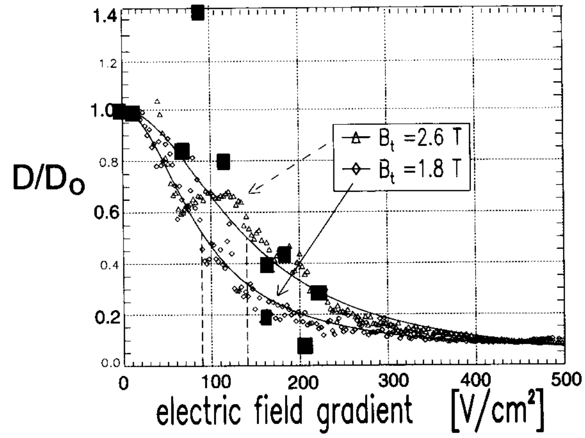

Fig. 9 Small symbols: Variation of the local D/D_0 with ∇E_r at the location of maximum ∇E_r for two values of B_t (1.8 and 2.6 T) [79]. The solid curves are fits through the two data sets with the form of Eq. (7). The large rectangles are the results from fluctuation driven flux measurements at B_t = 2.25 T [81].

gradient and improvements in particle confinement [77,78]. Figure 8 shows the temporal evolution of the electrode voltage and current, the maximum field strength, the global particle confinement time, the maximum electric field gradient and the relative change of the density gradient at the same radial position (r = 43.9 cm). It should be recalled that the electrode extends radially from r = 40 to 42 cm and that the ALT-II limiter is at r = 47 cm. The spatial alignment between ∇E_r and ∇n indicates that ∇E_r (and not E_r) is responsible for the enhanced particle confinement.

The variation of particle transport with ∇E_r has been studied in these experiments in two independent ways (Fig. 9). First, the relations $\Gamma = D\nabla n \propto H_\alpha$ have been used [79,80] to obtain a first approximation of local D, normalized to zero-shear D_0, which was then be compared with Eq. (7) in the form $D/D_0 = [D_{\rm res} + D_{\rm an,0}(1 + \nabla E_r^2/\nabla E_{r,\rm crit}^2)^{-1}]/D_0$, where D_0 was separated in an anomalous part and a residual part: $D_0 = D_{\rm res} + D_{\rm an,0}$. Second, an independent evaluation of the diffusivity was obtained from the measurement of the turbulent particle flux $\tilde{\Gamma}$, found from the amplitudes and phases of the fluctuating density and poloidal electric field by means of a reciprocating probe ($D = \tilde{\Gamma}\nabla n^{-1}$) [81]. The result is also shown in Fig. 9 using the same normalization as before. Both methods are seen to be remarkably consistent in demonstrating the role of shear and in the critical shear value that is needed to affect transport. Furthermore, it is interesting to note that a fit through the data points of Fig. 9 reproduces the exponent two in the dependence of Eq. (7) on $\nabla E_r/\nabla E_{r,\rm crit}$ quite closely and that recent gyro-kinetic simulations confirm this parametric dependence for a resistive ballooning type of turbulence in a tokamak edge [82]. Not withstanding this, indications are that in some circumstances exponents as high as six might be needed [83].

One notes in Fig. 8 that at about 2.1 s a bifurcation in occurs, due to the gradual destruction of parallel viscosity (see [22] and section 3.1). From the point of view of confinement, this bifurcation has no other effect but to allow a prompt passing from one shear (and confinement) value to a higher one. This is an illustration of the fact that in general the physical mechanisms for E_r-bifurcation can be very different from those for confinement improvement.

5. Concluding Remarks

E_r, ∇E_r and/or $\nabla^2 E_r$, in different ways and to different extents, affect neoclassical and/or turbulent transport and are therefore important for advancing fusion research.

Let us first summarize the neoclassical situation. In stellarators, electric fields appear to be essential to counter the very large neoclassical losses in the long mean free path regime and the prospects of achieving and exploiting the electron root look promising. In tokamaks, the neoclassical effects are quite often swamped by anomalous ones, but not all of them. Neoclassical features are found to be, at least partly, capable of controlling the electric field itself which often approaches the value imposed by neoclassical ambipolarity. Neoclassical parallel viscosity is the dominant damping of poloidal rotation and is predicted to be destroyed by large E_r. It is very rewarding that this could be verified by measuring plasma conductivity under non-ambipolar conditions.

E*×*B velocity shear effects have been shown to be able to reduce turbulence and their causal role has been established. Through their action, ion transport barriers have been established both in the plasma edge and the interior resulting in discharges with ion neoclassical transport over the full plasma radius. The electrons however appear quite resilient to flow shear. More theoretical and experimental work is however still needed to establish and in particular control barriers under a wider variety of scenarii or conditions. This asks for the development or improvement of tools for active control of E_r and/or its shear. It should also be stressed that the rate of progress will dependent on the continued success in the development of E_r-specific diagnostics.

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