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EFFECT OF THE RADIAL ELECTRIC FIELD ON TURBULENCE*

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For many years, the neoclassical transport theory[1–3] for three-dimensional magnetic configurations, such as magnetic mirrors, ELMO Bumpy Tori (EBTs), and stellarators, has recognized the critical role of the radial electric field in the confinement. It was in these confinement devices that the first experimental measurements of the radial electric field were made[4] and correlated with confinement losses.[5] In tokamaks, the axisymmetry implies that the neoclassical fluxes are ambipolar and, as a consequence, independent of the radial electric field. However, axisymmetry is not strict in a tokamak with turbulent fluctuations, and near the limiter ambipolarity clearly breaks down. Therefore, the question of the effect of the radial electric field on tokamak confinement has been raised in recent years.[6–8]. In particular, the radial electric field has been proposed to explain[9,10] the transition from L-mode to H-mode confinement. There is some initial experimental evidence supporting this type of explanation,[11,12] although there is not yet a self-consistent theory explaining the generation of the electric field and its effect on the transport. Here, a brief review of recent results is presented.

A radial electric field in a tokamak causes a sheared poloidal flow that can modify the linear and nonlinear stability properties of the plasma. This modification can change the turbulence level and, as a consequence, the induced transport. From the point of view of linear theory, the main effect occurs for a sheared flow. It is known from hydrodynamic theory that a sheared flow induces the Kelvin-Helmholtz (K-H) instability.[13] The K-H instability arises in a stratified heterogeneous fluid when the different layers of the fluid are

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in relative motion. For a charged fluid in the presence of a magnetic field, it has been shown that magnetic shear has a strong stabilizing effect on the K-H instability. The characteristic parameter is $R^2 = \tau_R V_A{}^2 L_E{}^3/(V_0 L_s{}^2 a^2)$, which gives a measure of the strength of the magnetic shear, with τ_R the resistive time, V_A the Alfvén velocity, L_E the velocity shear length, $2V_0$ the flow velocity jump, and L_s the magnetic shear length. The K-H instability is relevant only for small values of R.[8] In a region of bad curvature, the resistive interchange instability can couple to the K-H drive.[14] In this case, there are two characteristic dimensionless parameters: R and the Richardson number, $\mathrm{Ri} = V_s{}^2 L_E{}^3/(V_0{}^2 L_n r_c)$, the ratio of the buoyancy effects to the shear flow effects. Here, V_s is the sound velocity, r_c is the magnetic field line radius of curvature, and L_n is the density scale length. For low values of the velocity and sheared flow length, that is, for R and $\mathrm{Ri} >> 1$, the resistive interchange mode is unstable and practically independent of the flow. As the sheared flow increases, the growth rate of the mode is reduced (Fig. 1), until the mode is totally stabilized for $\mathrm{Ri} \approx 3/4$. In the regime $\mathrm{Ri} < 3/4$ and $R > 1$, the low-m modes are stable. As the flow continues to increase, the K-H instability can be triggered and the growth rate becomes proportional to the flow rate jump.

Values of the electrostatic potential larger than T_e/e have been measured in tokamak plasmas.[15] However, steep radial electric fields have been measured only at the plasma edge. For instance, in the edge of the Texas Experimental Tokamak (TEXT),[16] $L_E \approx$ 1 cm. This edge region with steep electric field gradient is commonly called the shear layer. Therefore, only at the edge, where the resistivity is high and the radial electric field gradient is large, can R be low enough for the K-H modes to be unstable. Although with presently measured parameters this possibility seems unlikely, the instability is likely in stellarators with zero magnetic shear. Experimental measurements of the edge radial electric field in these devices would be of great interest.

Let us consider the effect of sheared flows on the nonlinear stability of plasmas. The formalism for inclusion of sheared flow effects on turbulence was first developed in Ref. 8, although it was only applied to the turbulence driven by the radial electric field. This formalism has since been applied to the resistivity-gradient-driven turbulence.[9,17,18] In this case, it was shown[17] that the decorrelation time is a hybrid time scale resulting from the rotational shear and the turbulence radial diffusion time. I will reproduced here the physics argument presented in Ref. 17 In the absence of sheared flow, the turbulence may be characterized by the nonlinear diffusivity coefficient D and a radial correlation length Δ. Together they define a diffusive decorrelation time, $(\tau_D)^{-1} \approx D/\Delta^2$, which is the time it takes for the turbulent fluid element to diffuse one radial correlation length (Fig. 2a). On the other hand, in the absence of diffusion, a sheared poloidal flow, $dy/dt = V_\theta(r)$, introduces a differential rotation

$$d(\delta y)/dt = V'_\theta\ \delta r\ . \tag{1}$$

Here, $y = r\theta$ is the length in the poloidal direction. A fluid element with a radial size Δ and a poloidal size $1/k_y$ is strained by this differential rotation (Fig. 2b), and the corresponding decorrelation or shearing rate is

$$1/\tau_s \equiv k_y \Delta V'_\theta\ . \tag{2}$$

When both diffusion and sheared poloidal flow are present, a coupling of the two effects leads to a relation between radial and poloidal correlation lengths,

$$\delta y^2 \approx (V'_\theta)^2 \langle \delta r^2 \rangle t^2 \approx (V'_\theta)^2 D t^3\ . \tag{3}$$

In this case, the decorrelation time is $\tau_c = \{1/[(k_y V'_\theta)^2 D]\}^{1/3}$, a hybrid time scale of the shearing and the diffusive time. The corresponding correlation length when $\tau_S << \tau_D$ is then given by

$$\Delta_c \approx (D/k_y V'_\theta)^{1/3} \approx (\tau_s/\tau_D)^{1/3} \Delta \quad . \tag{4}$$

Therefore, the decorrelation length in the strong sheared flow regime is shorter than the intrinsic decorrelation length of the turbulence. This reduction in correlation length translates to a reduction of the turbulence level. Therefore, when the shear in the flow is large enough—that is, when the shearing time is shorter than the diffusive decorrelation time—the turbulence level is reduced in relation to its level in the absence of flow. Recent results from the TEXT tokamak show direct experimental evidence of this mechanism[19] by showing that the correlation time of the edge turbulence is reduced at the shear layer. At the same time, the TEXT results show a steepening of the density profile at the same radial position. This indicates an improvement in the particle confinement time.

The theoretical result of the reduction of turbulence by the sheared flow is independent of the sign of the electric field. This is not surprising because, as argued in Ref. 20, for the sign of the electric field to play any role a poloidal symmetry-breaking effect, such as plasma diamagnetic rotation, is needed. No such effect was included in the analytical treatments. The numerical results for the resistivity-gradient-driven turbulence[20] show a reduction in turbulence level for negative electric fields and an enhancement for positive electric fields.

The choice of the resistivity-gradient-driven turbulence for the first theoretical analyses of sheared flow effects[9,17,18] was motivated by the suitability of such a model to the analytical treatment. Since the underlying linear instability to the resistivity-gradient-driven turbulence, the rippling mode, is sensitive to an equilibrium sheared flow, it is difficult to separate in the numerical calculations the effect of the sheared flow on the turbulence from the modification of the linear instability.

The resistive pressure-gradient-driven turbulence is another good candidate for these studies for several reasons. First, it has been studied in detail in the absence of electric fields. Second, it may be more relevant to finite-beta transport. Third, we can provide the poloidal symmetry-breaking effect by including the electron diamagnetic effects only and test the importance of the sign of the electric field.

Resistive pressure-gradient-driven turbulence was discussed in the first part of this workshop and has been studied in detail[21–23] for the case with no diamagnetic effects, $\omega^*_e = 0$. The nonlinear evolution of resistive instabilities with diamagnetic effects included generates a DC radial electric field (poloidal velocity) through the convective nonlinearity in the momentum balance equation.[24] In the regime in which $\gamma > \omega^*_e$, this radial electric field has a strong shear and is a major factor in reducing the saturation level of the turbulence. In numerical calculations, the effect of the self-generated electric field can be seen by comparing calculations that include this electric field with calculations that do not allow its generation (Fig. 3). In the latter case, there is practically no reduction in the fluctuation levels due to the diamagnetic effects.

For resistive pressure-gradient-driven turbulence, the effect of adding an external electric field has also been considered.[14] For a constant radial electric field, such that $e\phi_E/T_e = \pm 1$ and $\gamma > \omega^*_e$, the effect on the turbulence is very weak, and no change in the saturation levels is observed (Fig. 4). For a sheared electric field, there is evidence of a reduction on the fluctuation level. However, in numerical calculations, it is difficult to distinguish between linear stabilization effects and nonlinear turbulence reduction. The problem is that the condition for turbulence reduction by shearing, $\tau_S \ll \tau_D$, is the same as Ri $\ll \Lambda^3$, where Λ is the nonlinear enhancement factor[21]. As we have already discussed, for low Λ values this condition implies a strong stabilization of low m modes by coupling to K-H effects.

The existence of a sheared flow at the plasma edge has been well documented in tokamaks[16] as well as in stellarators with (magnetic) shear.[25] This sheared flow can result from any of several mechanisms. Neoclassical loss mechanisms were first investigated.[6,7] One possible model, put forward by Shaing et al.,[9] is constructed by balancing the ion orbit loss at the tokamak edge with the poloidal viscosity-driven flux. This leads to a bifurcated solution for the flux-average poloidal velocity. Such a bifurcation is suggestive of a phenomenon such as an L-H transition, as shown by the recent measurements of V_θ at the edge of DIII-D.[11] There are other possible causes for the generation of this poloidal velocity. One of them is the same edge fluctuations which are affected by the electric field. Instabilities with radially propagating wave structure can generate such radial electric fields. One mode of generation occurs near the limiter, where the symmetry of the radial wave propagation is broken, as suggested by Diamond et al.[26] An alternative mode is by means of large low-m fluctuations dominating the turbulence spectrum, as is characteristic of drift-modified MHD turbulence.[14] Finally, at the tokamak edge, large electrostatic potential fluctuations can enhance the ion losses and contribute to the radial electric field generation.[27] Possibly several of these mechanisms are in operation at the same time, making an a priori interpretation of the experimental data rather difficult.

To understand the generation of the electric field by the fluctuations it is important to consider the relevant laws for conservation of toroidal momentum, P_ζ, and toroidal angular momentum, M_ζ. For $\vec{E} \times \vec{B}$ convection, there is no contribution of the convective nonlinearity to the toroidal component of the momentum balance equation; therefore, there is no change in the ambipolarity condition. However, the convection of the toroidal angular momentum density, m_ζ, is nonzero. Unstable modes with nonzero poloidal mode number m grow linearly and because of the ω^* effects generate angular momentum. To conserve M_ζ, an $(m = 0; n = 0)$ component of m_ζ is generated. Since this component integrated over the radius must be zero, m_ζ must change sign at some point in radius. As a consequence, m_ζ is sheared and so is the poloidal velocity.

The instability-generated radial electric field does not appear to lead to bifurcated solutions. However, Hinton[10] has shown that such bifurcation may exist in the transport equations when the transport coefficients include the effect of the shear reduction mechanism.

Although all present theoretical results indicate that turbulence is suppressed by a sheared electric field, the details of how the turbulence is affected depend on the particular dynamics of the turbulence. The same dynamics can play a role in the generation of the electric field; this emphasizes the need for a self-consistent treatment of this problem. It would be interesting to find a turbulence dynamical system for which the undelying linear instability is not affected strongly by the shear flow. In this way, linear and nonlinear effects could be separated. An extension of these studies to other types of turbulence, drift waves, η_i modes, etc., is needed for an overall evaluation of the effect of electric fields on plasma confinement.

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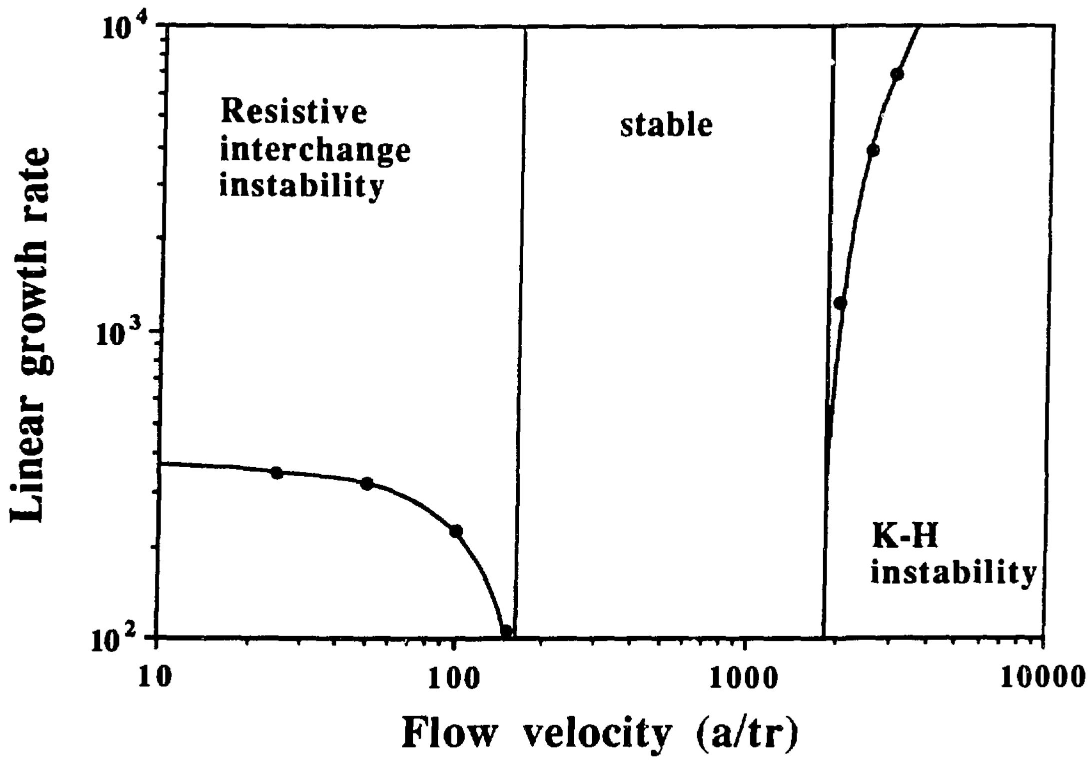

Fig. 1. Linear growth rate of the m = 3 mode as a function of the equilibrium poloidal flow velocity.

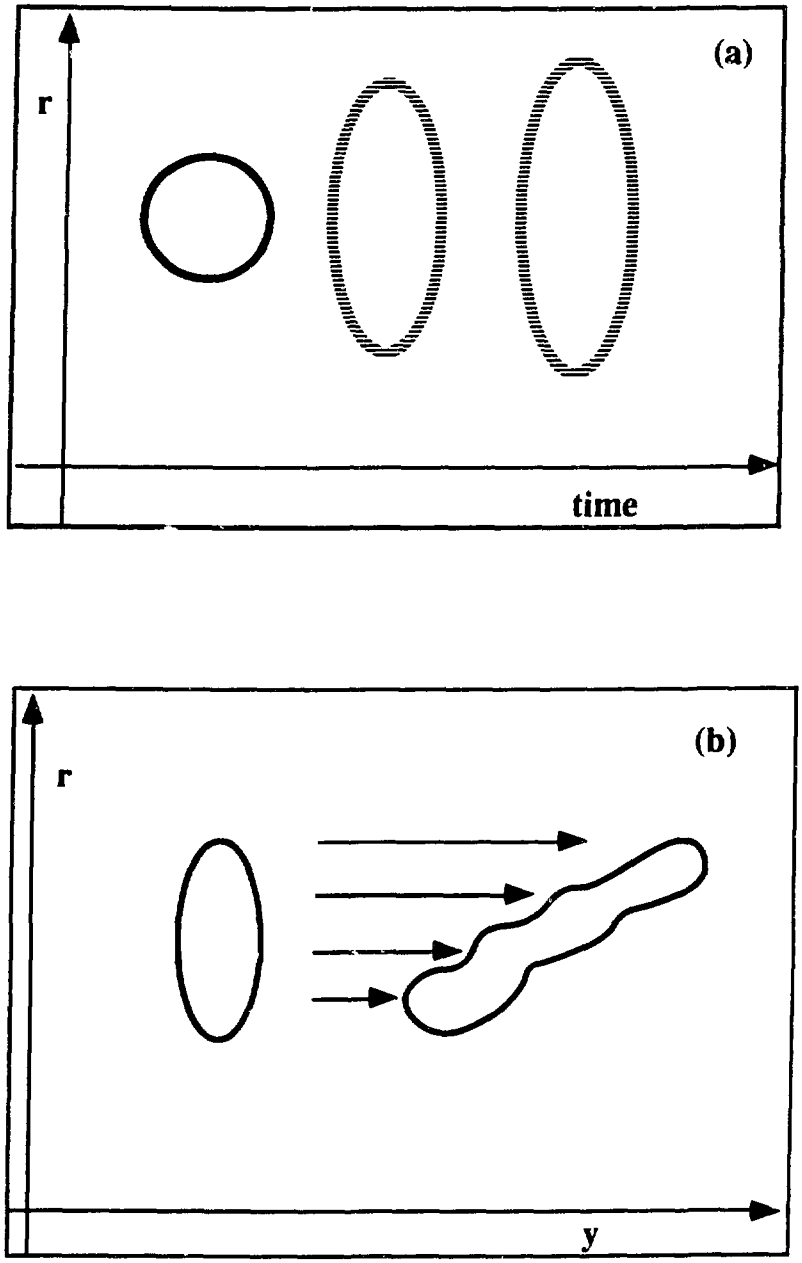

Fig. 2. Schematic representation of (a) diffusion and (b) poloidal shearing of fluid elements.

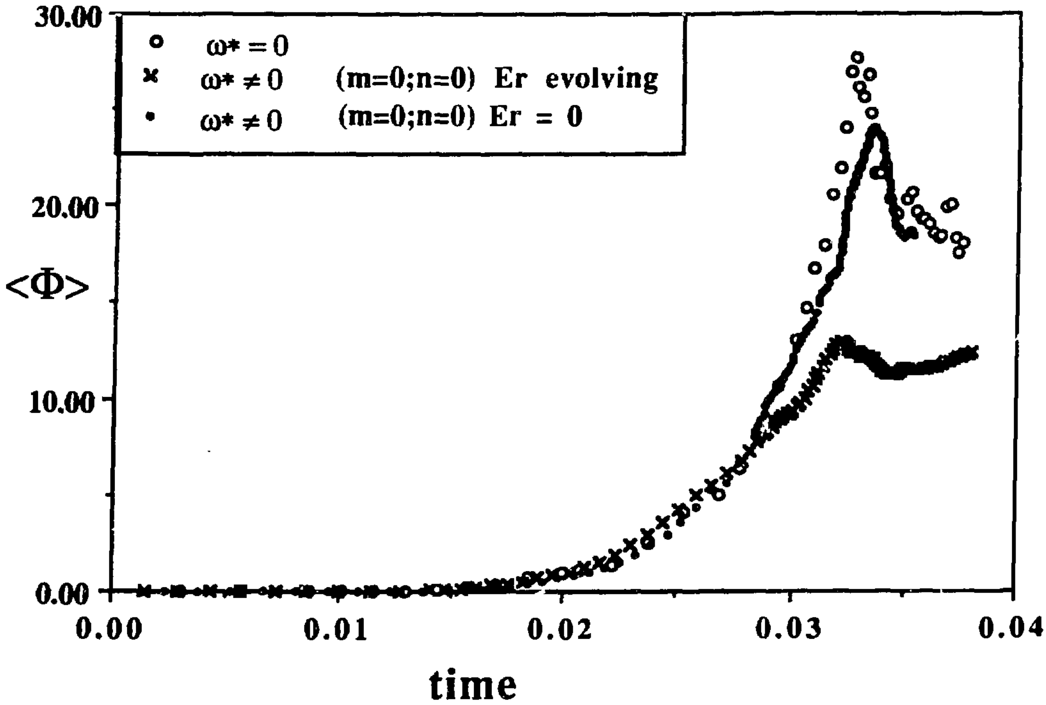

Fig. 3. Evolution of the electrostatic potential fluctuations with and without diamagnetic effects. In the later case, the stabilizing effects of the self-generated electric field are made evident by comparing with a case where the electric field is forced to be zero.

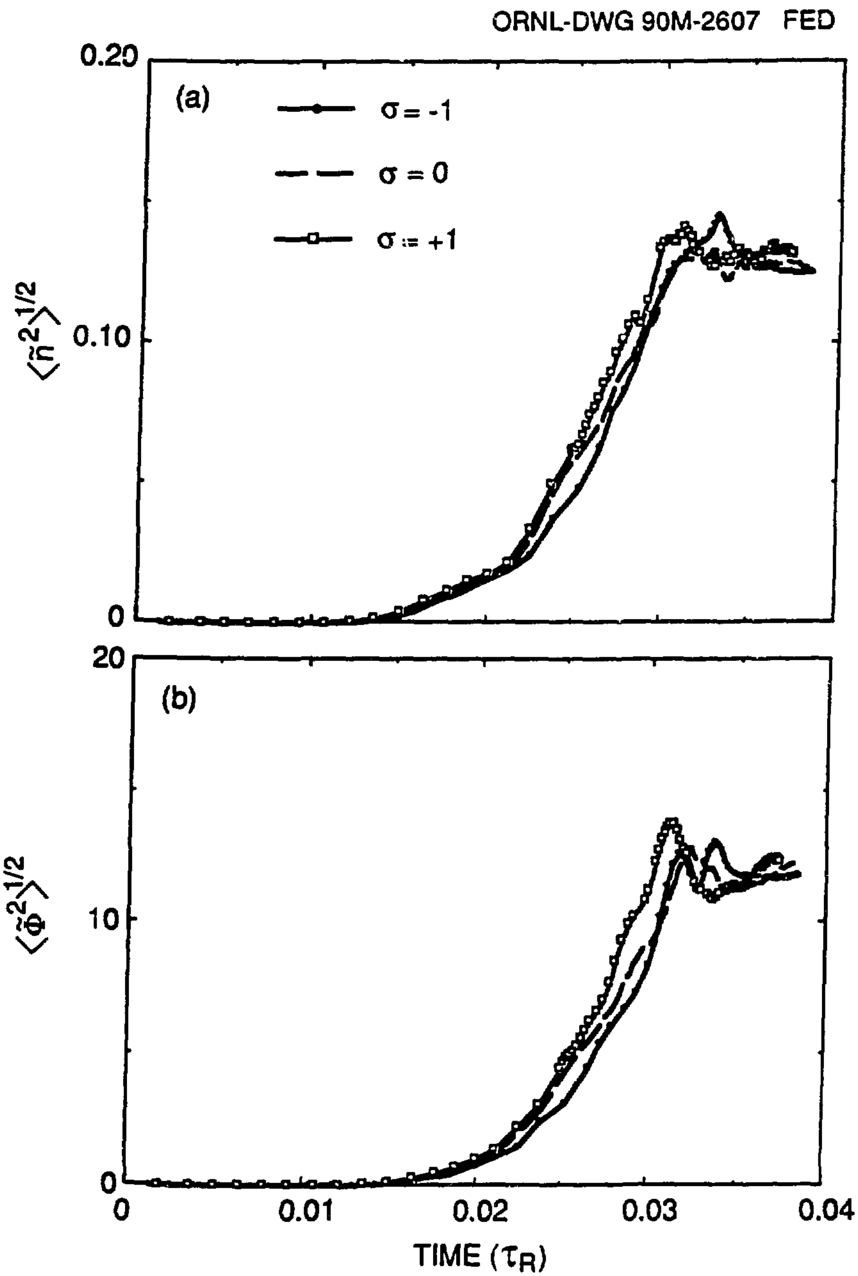

Fig. 4. For a constant radial electric field, such that $e\phi_E/T_e = \pm\sigma$ and $\gamma > \omega^*_e$, there is no change in the saturation level.

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RADIAL ELECTRIC FIELD AND CONFINEMENT

- Conventional wisdom was: Tokamak is axisymmetric ⇒ particle flows are ambipolar (independent of electric field) ⇒ **radial electric field does not play a role in tokamak confinement.**
- Other magnetic confinement concepts are intrinsically three-dimensional:
  - Tandem mirror
  - EBT → First experimental measurements of E fields
  - Stellarator

  Neoclassical transport theory, including radial electric field effects, was developed for these concepts (late 70's and early 80's)
- In the mid 80's, these theoretical ideas started to migrate to tokamaks because
  - Near the limiter (a few ρ_i), where ambipolarity does not hold, large electric fields are generated
  - Tokamaks are not axisymmetric (plasma turbulence), sheared electric fields can modify the level of turbulence and hence the induced transport.
- Recent theoretical work shows that the **radial electric field can play a critical role in explaining the improved confinement regimes in tokamaks.**

RADIAL ELECTRIC FIELD AND CONFINEMENT

- The question of the effect of the radial electric field on tokamak confinement has been raised in recent years. In particular, it has been put forward as an explanation of the transition from L to H confinement regime.

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  Chiueh, T., Terry, P. W., Diamond, P. H., and Sedlak, Phys. Fluids 29 (1986) 231.

  Hinton, F. L., "An L-H Mode Bifurcation Theory Involving Poloidal Rotation"

- The formalism for inclusion of the sheared flow effects in turbulence was first developed by Chiueh et al., but has most recently been applied to the understanding of its effect on the resistivity-gradient-driven turbulence

  Shaing, K. C., Crume, E. C., Houlberg, W. A., "Bifurcation theory of poloidal rotation and suppression of turbulent fluctuations: A model for the L-H transition in tokamaks," to be published in Phys. Fluids B.

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RADIAL ELECTRIC FIELD EFFECT ON TURBULENCE

OUTLINE

I. Radial electric field and poloidal flow.

II. Modification of the stability properties by a poloidal flow

1) Linear stability: Kelvin-Helmholtz

2) Nonlinear effects:
Shearing

III. Experimental results

IV. Impact on anomalous transport

V. Conclusions.

ELECTRIC FIELD AND FLOW VELOCITY

- **Radial electric field:** A non-zero electrostatic potential in the plasma, $\Phi(\rho)$, causes a radial electric field and a poloidal flow velocity

$$E_\rho = -\frac{d\Phi(\rho)}{d\rho} \longrightarrow \vec{V} = \frac{\vec{E}\times\vec{B}}{B^2} \approx \frac{1}{B_o}\frac{d\Phi(\rho)}{d\rho}\vec{\theta}$$

- **Convection of a scalar:**

$$\frac{\partial T}{\partial t} + \langle V_\theta \rangle \frac{1}{r}\frac{\partial T}{\partial \theta} + \vec{V}\cdot\vec{\nabla}T = S$$

Expanding the poloidal flow term

$$\frac{\partial T}{\partial t} + \left[\langle V_\theta \rangle \Big|_{r=r_0} + (r - r_0)\langle V'_\theta \rangle \Big|_{r=r_0} \right] \frac{1}{r}\frac{\partial T}{\partial \theta} + \vec{V}\cdot\vec{\nabla}T = S$$

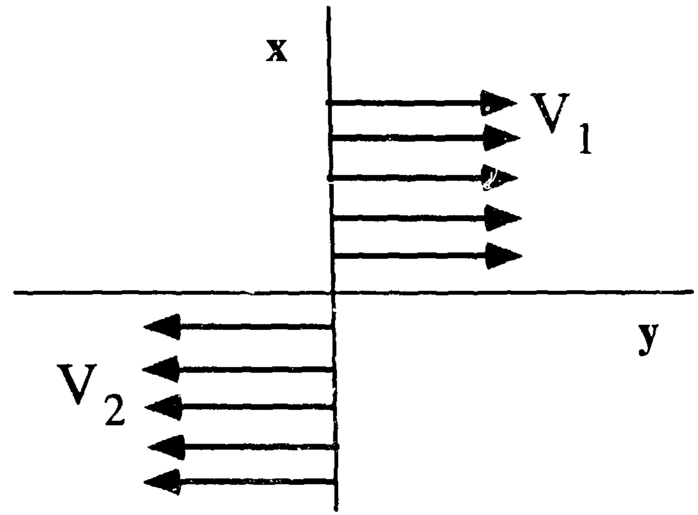
Constant flow effect
$\Rightarrow$ Doppler shift

Sheared flow effect

FLOW VELOCITY EFFECT ON LINEAR STABILITY

KELVIN-HELMHOLTZ INSTABILITY IN HYDRODYNAMICS

- K-H instability arises in a stratified heterogeneous fluid when the different layers are in relative motion.



- Equilibrium

$$\vec{V}_0 = (0, V_{0y}, 0)$$

$$\vec{U}_0 = \left(0, 0, \frac{dV_{0y}}{dx}\right)$$

- Stability:

$$\rho_m\left(\frac{\partial \tilde{U}_z}{\partial t} + V_{0y}\frac{\partial \tilde{U}_z}{\partial y} + \tilde{V}_x \frac{d^2 V_{0y}}{dx^2}\right) = 0$$

driving term

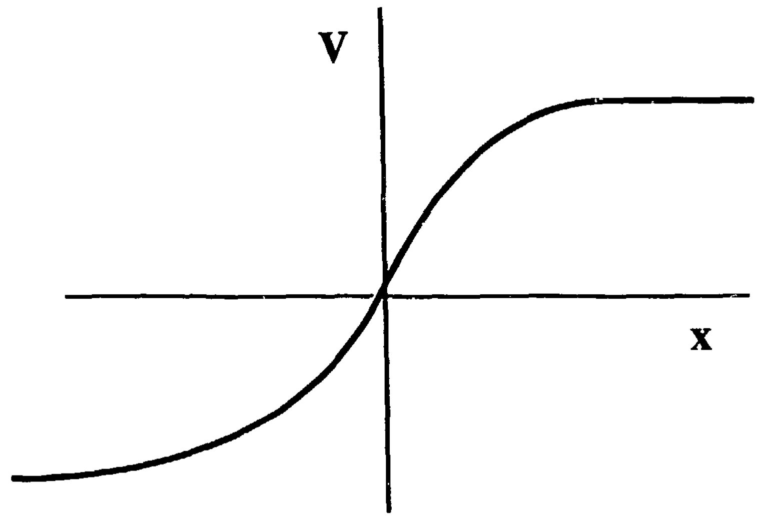
stabilizing term
(Rayleigh criterion)

the linear growth rate in the case of uniform density is $\gamma = k_y |V_1 - V_2|$

FLOW VELOCITY EFFECT ON LINEAR STABILITY

KELVIN-HELMHOLTZ INSTABILITY IN MAGNETOHYDRODYNAMICS

- The shear in the flow is the source of free energy
- Magnetic shear has a strong stabilizing effect
- An example: resistive interchange with sheared flow:



$$\frac{d}{dx}\left[(\omega + k_y V)\frac{d\Phi}{dx} - k_y V' \Phi\right] =$$

$$\left[k_y^2(\omega + k_y V) + \frac{V_s^2 k_y^2}{r_c L_p}\frac{1}{\omega + k_y V} + i\frac{S}{a^2 \tau_{hp}}\frac{m^2}{q^2}\frac{x^2}{L_q^2}\right]\Phi$$

K-H drive

Flow stabilization (Rayleigh criterion)

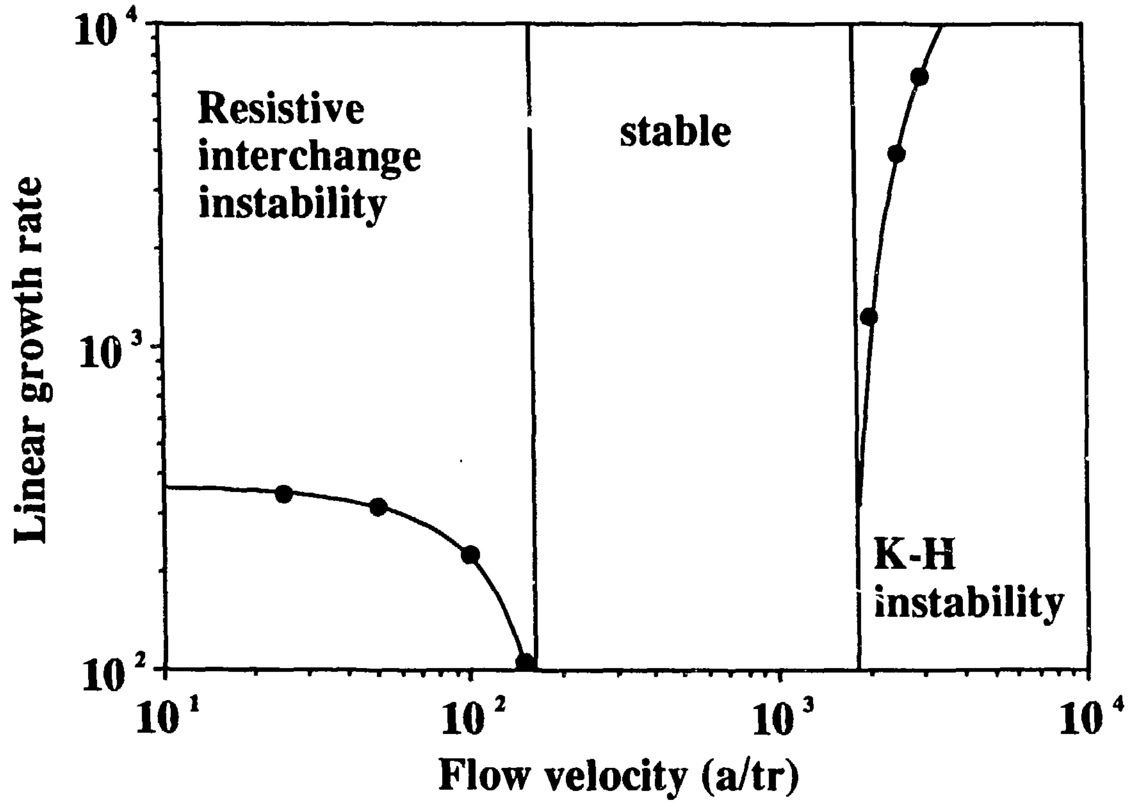
Resistive interchange driving term

magnetic shear stabilizing term

FLOW VELOCITY EFFECT ON LINEAR STABILITY

KELVIN-HELMHOLTZ INSTABILITY IN MAGNETOHYDRODYNAMICS

- Linear growth rate of resistive interchange with sheared flow

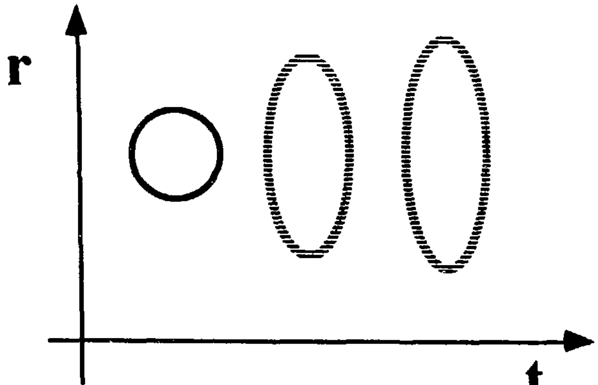


RADIAL DIFFUSION

- The effect of short wavelength modes on long wave lengths is often described by a nonlinear diffusivity term

$$\frac{\partial T}{\partial t} + \left[(r - r_0)\langle V'_\theta\rangle\right]\frac{1}{r}\frac{\partial T}{\partial \theta} + D\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = S$$

- **Radial diffusion**: In the absence of sheared flow, the turbulence may be characterized by the diffusivity, D, and a radial correlation length, Δ. Together they define a correlation time:



$$\langle \delta r^2 \rangle \approx D\, t$$

$$\frac{1}{\tau_D} \cong \frac{D}{\Delta^2}$$

The decorrelation time is the time it takes for the turbulent fluid element to diffuse one radial correlation length

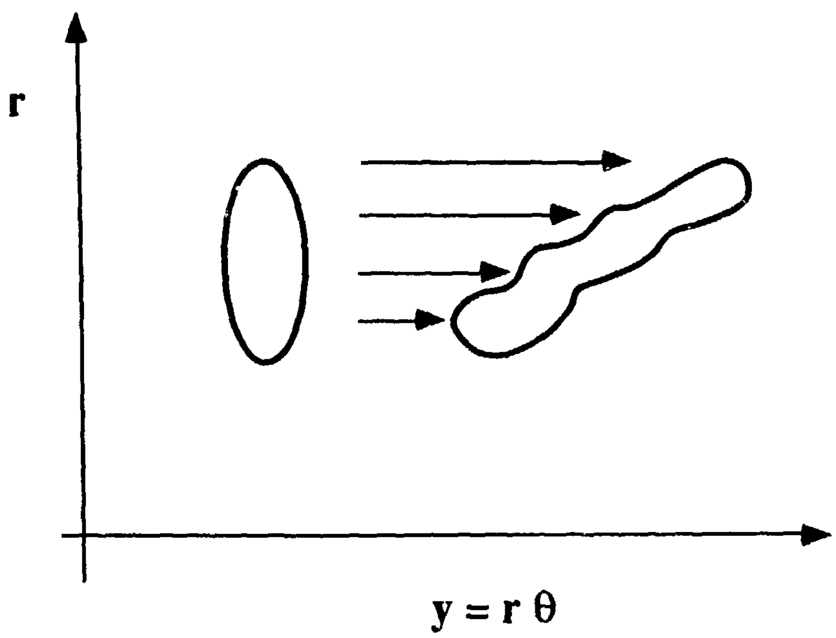
SHEARED POLOIDAL FLOW

- **Sheared flow decorrelation**: In the absence of diffusion, a sheared poloidal flow introduces a differential rotation

$$\frac{dy}{dt} = V_\theta(r) \quad \Rightarrow \frac{d(\delta y)}{dt} = V'_\theta \, \delta r$$

For a blob which radial size is Δ and the poloidal size is $1 / k_y$, the shearing rate is

$$\frac{1}{\tau_S} \cong k_y \, \Delta \, V'_\theta$$



SHEARED POLOIDAL FLOW AND RADIAL DIFFUSION

- When diffusion and sheared poloidal flow are present, there is a coupling of both effects

$$\begin{cases} \langle \delta r^2 \rangle \approx D\, t \\ \delta y \approx V'_\theta \delta r\; t \end{cases} \quad \Rightarrow \quad \delta y^2 \approx (V'_\theta)^2 \langle \delta r^2 \rangle\, t^2 \approx (V'_\theta)^2 D\, t^3$$

- The decorrelation time is a hybrid of the shearing and the diffusive time scales

$$\frac{1}{\tau_c} \cong \left(k_y^2 V_\theta'^2 D\right)^{1/3} = \frac{1}{\tau_D^{1/3}\tau_S^{2/3}}$$

The turbulence scale length is also changed $\Delta_c = \left(\dfrac{D}{k_y V'_\theta}\right)^{1/3}$

- The presence of a sheared flow changes the properties of turbulence. There are some general results applicable to this problem, but as the dynamics change, the nonlinear diffusivity D has to be calculated in each case including the shear flow effects.

SHEARED POLOIDAL FLOW AND RADIAL DIFFUSION

- **Threshold for sheared flow effects on turbulence**. The sheared flow effects are important when the shearing time is shorter than the turbulence diffusion time, that is

$$k_y \, \Delta \, V'_\theta \geq \frac{D}{\Delta^2}$$

Since D and Δ are functions of k, depending on the nature of the turbulence either low-k or high-k modes will be affected first.

- **Saturation level of turbulence.** The sheared flow reduces the turbulence correlation length

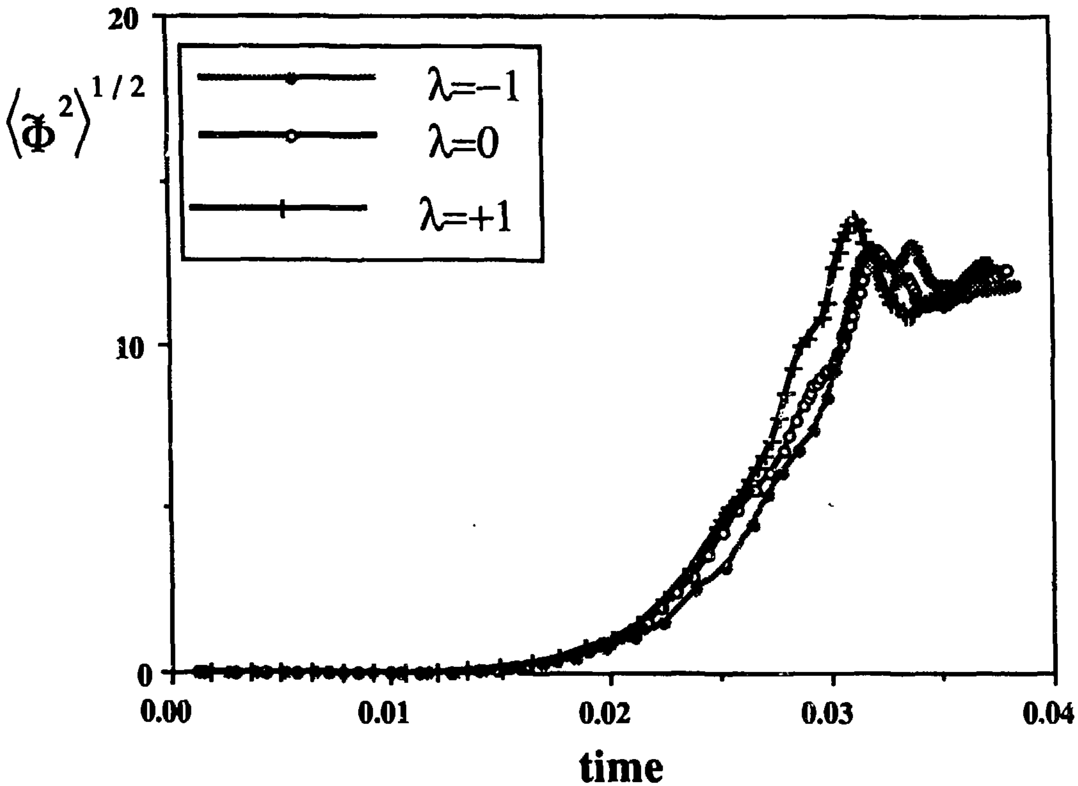
$$\Delta_c^2 \cong D\,\tau_c = D\,\tau_D\left(\frac{\tau_S}{\tau_D}\right)^{2/3} = \Delta^2\left(\frac{\tau_S}{\tau_D}\right)^{2/3}$$

Therefore, we expect a reduction of the turbulence saturation level

$$\left\langle\left(\frac{\tilde{T}}{T_0}\right)^2\right\rangle^{1/2} \approx \left|\frac{dT_0}{dr}\right|\Delta_c = \left|\frac{dT_0}{dr}\right|\Delta\left(\frac{\tau_S}{\tau_D}\right)^{1/3}$$

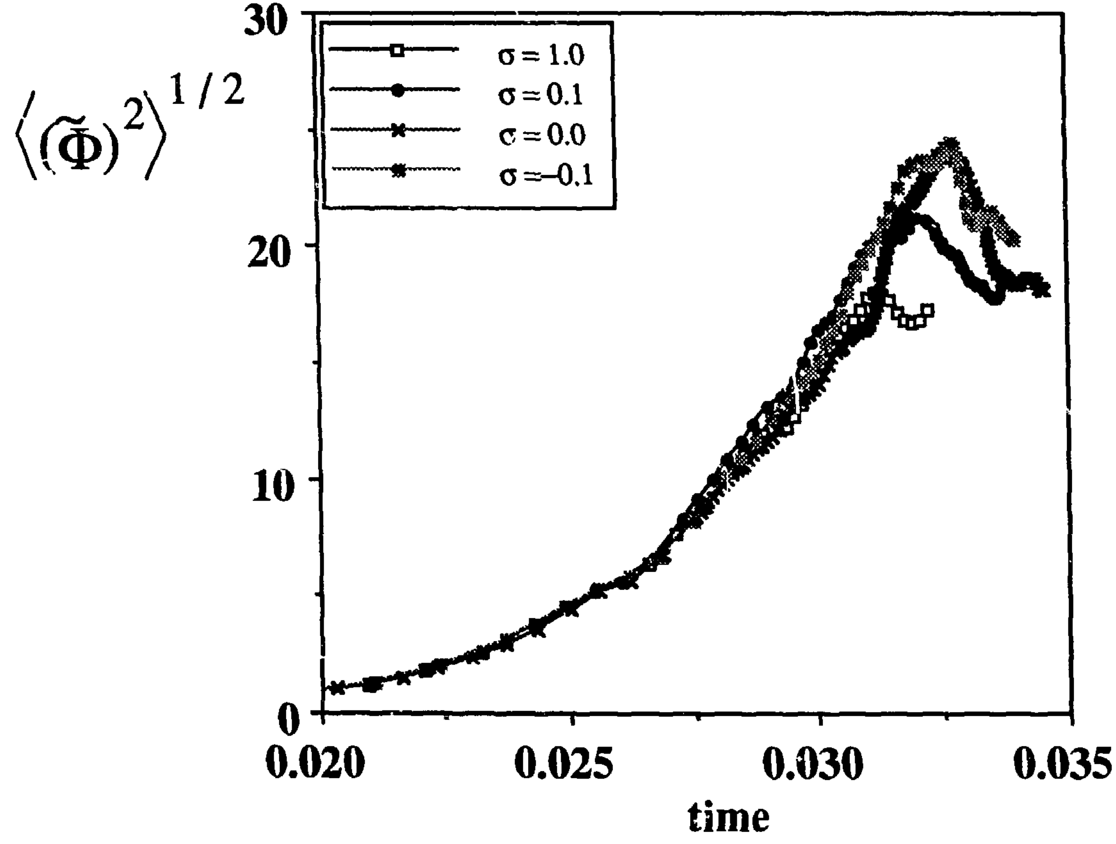
RESISTIVE PRESSURE-GRADIENT-DRIVEN TURBULENCE

- The addition of an external constant electric field of the order $\pm Te/er$ does not affect the electrostatic potential fluctuation level.



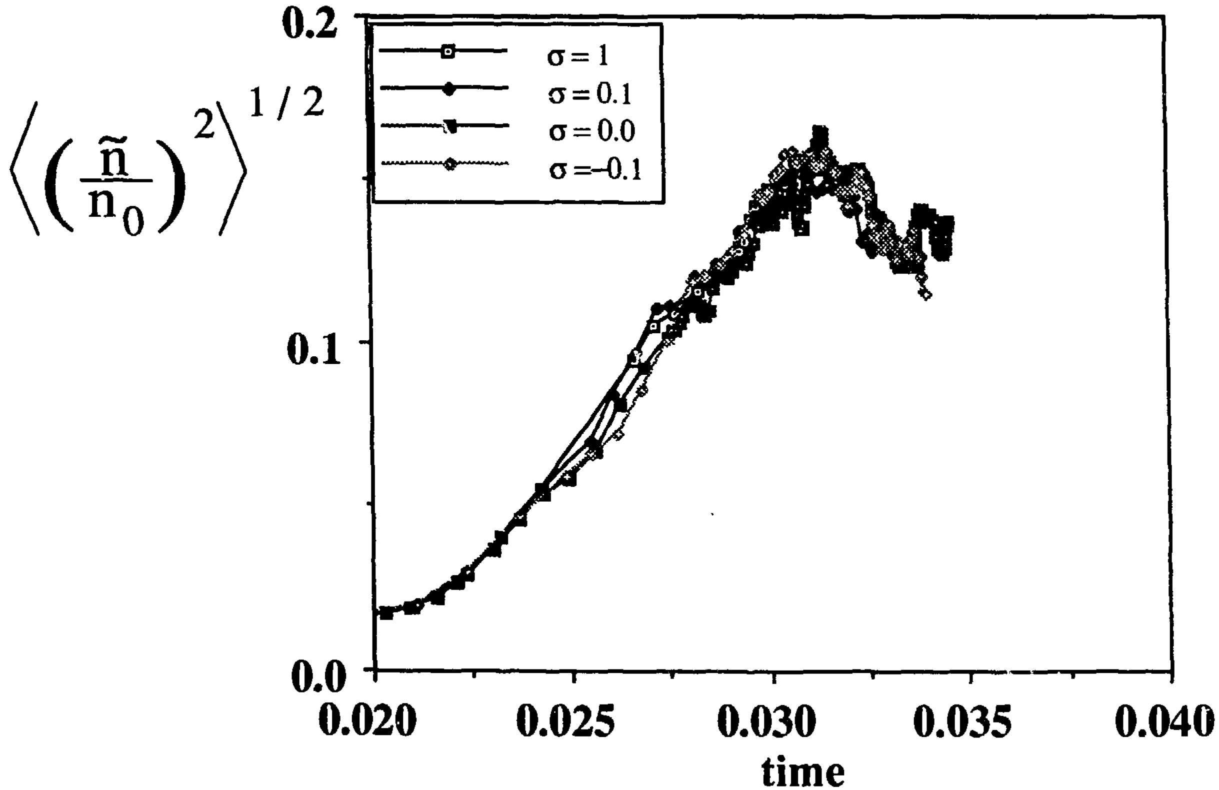
PRESSURE-GRADIENT-DRIVEN TURBULENCE

- The addition of an external sheared electric field of the order $\pm\sigma Te/er\ L_E = 0.1$ a weakly changes the electrostatic potential fluctuation level.



PRESSURE-GRADIENT-DRIVEN TURBULENCE

- The addition of an external sheared electric field of the order $\pm\sigma\, Te/er$ with $L_E = 0.1$ a does not affect the density fluctuation level.



PRESSURE-GRADIENT-DRIVEN TURBULENCE

- What is the cause for the turbulence reduction?

  1) Kelvin-Helmholtz stabilization

$$\mathrm{Ri} \equiv \frac{V_S^2}{r_c L_n} \frac{L_E^2}{V_0^2} \approx 1 \quad \Rightarrow \quad \frac{\gamma_0^2}{W_0^2} \frac{L_E^2}{k_y^2 V_0^2} \approx 1$$

  2) Turbulence reduction by shearing

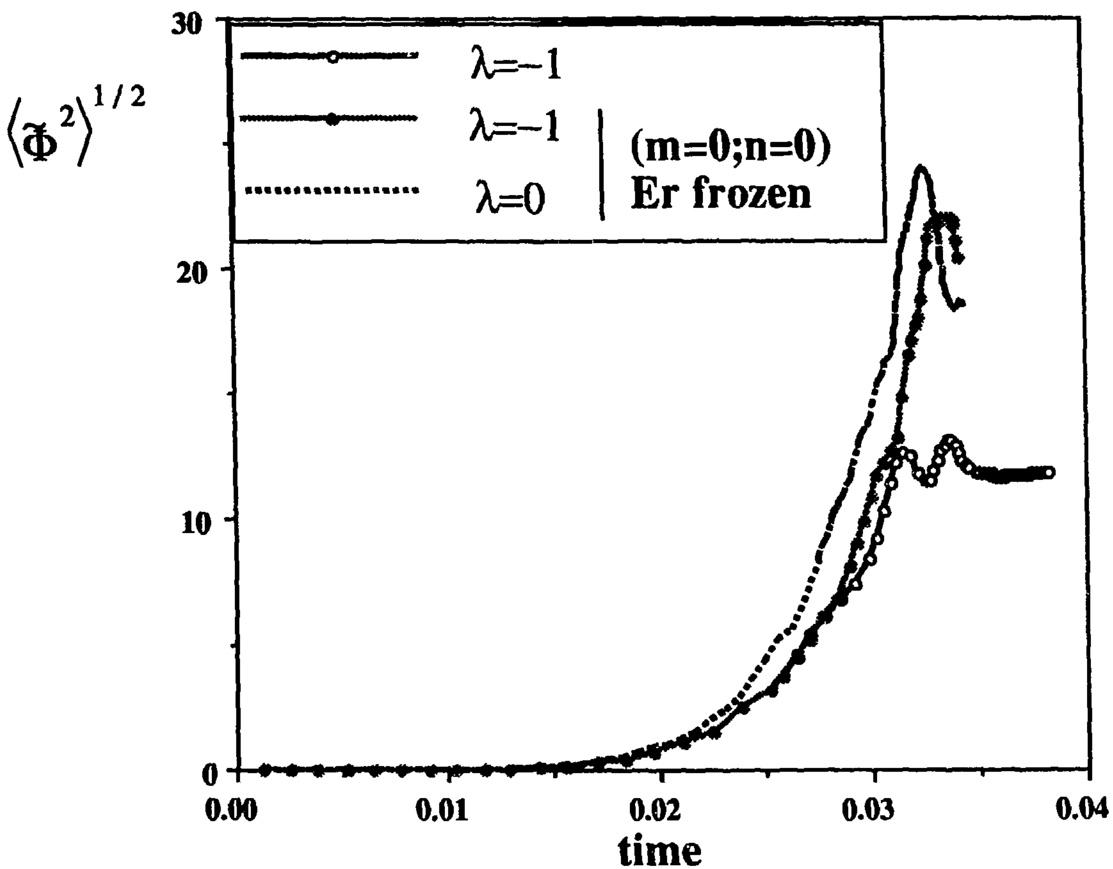
$$\frac{1}{\tau_S} >> \frac{1}{\tau_S} \quad \Rightarrow k_y \left(W_0 \Lambda^{7/6}\right) \frac{L_E}{V_0} >> \frac{\gamma_0}{\Lambda^{1/3}}$$

$$\Rightarrow \quad \frac{\gamma_0^2}{W_0^2} \frac{L_E^2}{k_y^2 V_0^2} << \Lambda^3$$

- It is difficult to separate linear from nonlinear flow effects

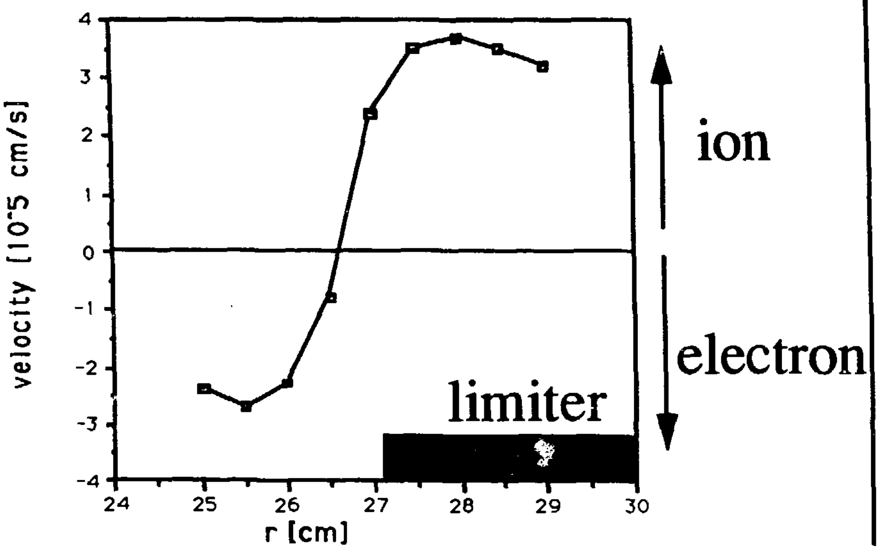
RESISTIVE PRESSURE-GRADIENT-DRIVEN TURBULENCE

- The turbulence level is controlled by the self-generated sheared field, not by the externally added constant electric field.



EDGE ELECTRIC FIELD

- At the edge of TEXT there is a region of strong shear velocity. The shear layer width is $W_s \approx 1$ cm



- Edge turbulence parameters:

$$D \approx 3\ \mathrm{m}^2/\mathrm{s}$$
$$\Delta \approx \sigma_r \approx 0.5\ \mathrm{cm}$$
$$\langle k_\theta^{-1} \rangle \approx \sigma_\theta \approx 1\ \mathrm{cm}$$

For the flow to have an effect on the edge plasma turbulence, the shear has to be

$$V'_\theta \geq \frac{D}{\Delta^3 \langle k_\theta \rangle} = 2.5 \times 10^5\ \mathrm{s}^{-1}$$

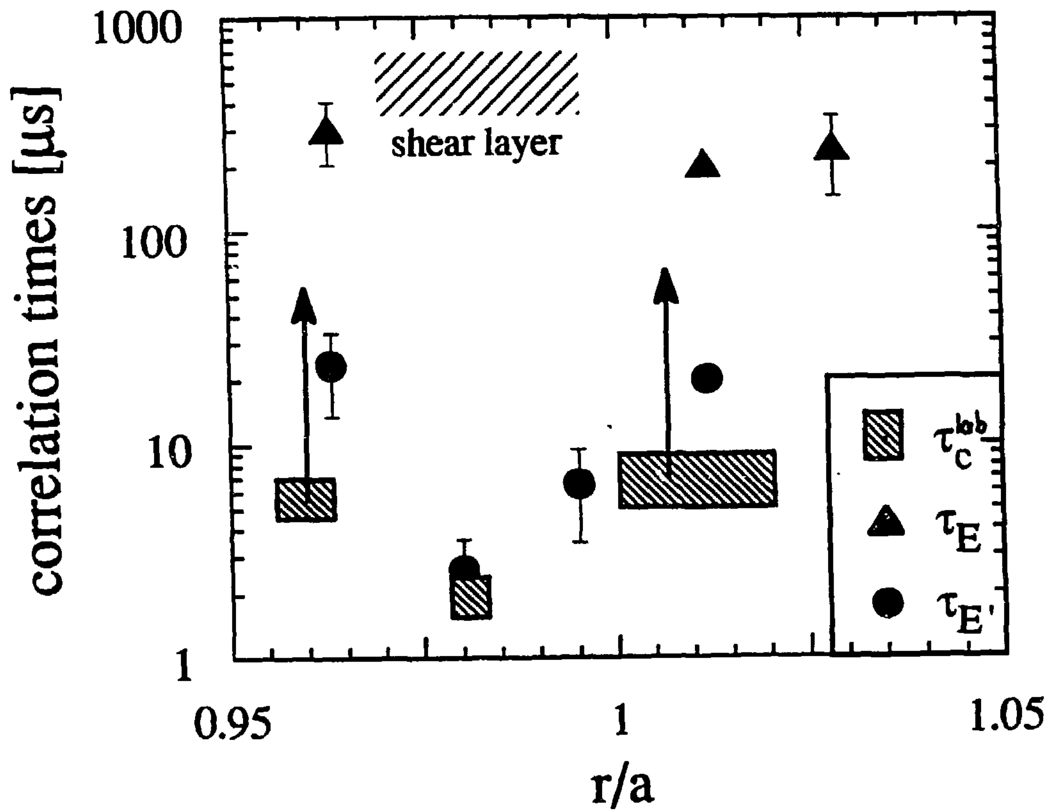
- This value is compatible with the measured shear flow

$$V'_\theta = \frac{V_\theta}{W_s} \approx 5 \times 10^5\ \mathrm{s}^{-1}$$

EDGE ELECTRIC FIELD

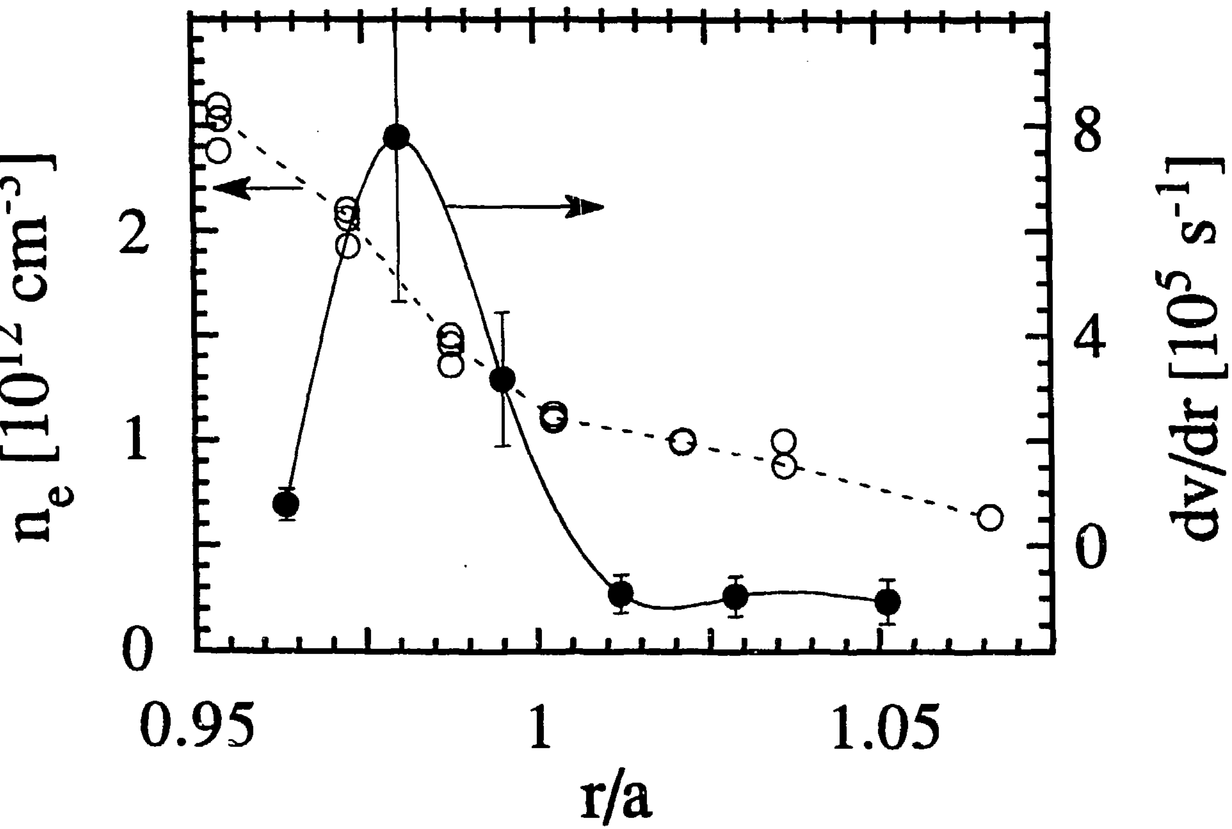
- There is recent experimental evidence from the TEXT tokamak of suppression of edge turbulence by velocity shear (Ch. P. Ritz et al.).

- Measurements of the correlation time of the fluctuations have been done in the region of the shear layer. The results agree with the theoretical predictions using the measured velocity profile



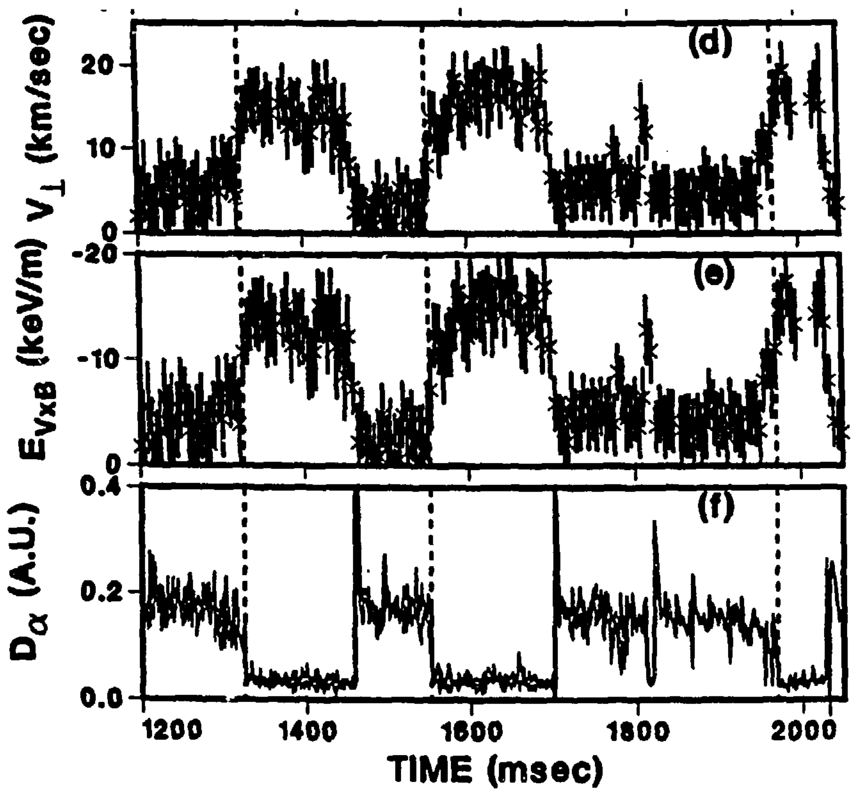
EDGE ELECTRIC FIELD

- The steepening of the density profile at the shear layer indicates that the local confinement improves (Ch. P. Ritz et al.).



ELECTRIC FIELD AND L-H TRANSITION

- DIII-D edge electric field measurements show dramatic changes at all L-H transitions



CONCLUSIONS

- Sheared flows can modify the basic linear and nonlinear properties on plasma instabilities.
- Although it seems unlikely, in tokamaks edge plasmas, where the resistivity is high and the radial electric field gradient is large, the Kelvin-Helmholtz modes can be unstable.

  This instability is likely in stellarators with zero magnetic shear. Experimental measurements of the edge radial electric field in these devices would be of great interest.
- Theoretical results indicate that there is a suppression of turbulence by a sheared electric field. The details of how the turbulence is affected by the electric field depend on the dynamics of the turbulence.
- The same turbulence dynamics can play a role in the generation of the electric field, making the self-consistent treatment of this problem more important.
- Mechanisms based on radial electric field changes at the plasma edge can be the explanation for the L to H mode transition.