Issues of Perpendicular Conductivity and Electric Fields in Fusion Devices

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Plasma Turbulence

- Turbulence can be regarded as randomly fluctuating rapid motion of the fluid.

- It is a ubiquitous phenomenon in nature and is an effective way of transporting energy quickly as opposed to neoclassical collisional diffusion which is a very slow process in comparison.

- In fusion plasma parameter gradients determine turbulence and various transport modes which is the process through which particles, and energy in the centre of the plasma are lost to surrounding walls.

We need to gain insights into the control of plasma turbulence which is the most important factor working against the efforts towards fusion.

A NEW ERA IN PLASMA CONFINEMENT

- There is accumulating evidence from fusion experiments that regimes with improved confinement can achieve higher values of confinement, beta and bootstrap current than had been thought plausible until recently.
- In spite of the extra free energy available from increased gradients in the improved confinement state, the E x B velocity shear allows the plasma to organize itself into a state of lower turbulence and transport
- This new way to improve confinement is bound to have a major impact on fusion as an energy source for the future.

Transport barrier dynamics is the key scientific concern at present. The interest is enhanced by the fact that a continuously operated fusion reactor will not be operated at a steady-state, since for control purposes, it will necessarily require barriers to be created or lowered from time to time in different portions of a plasma to facilitate a reactor operation. Transport barriers will have to be controlled for operation purposes.

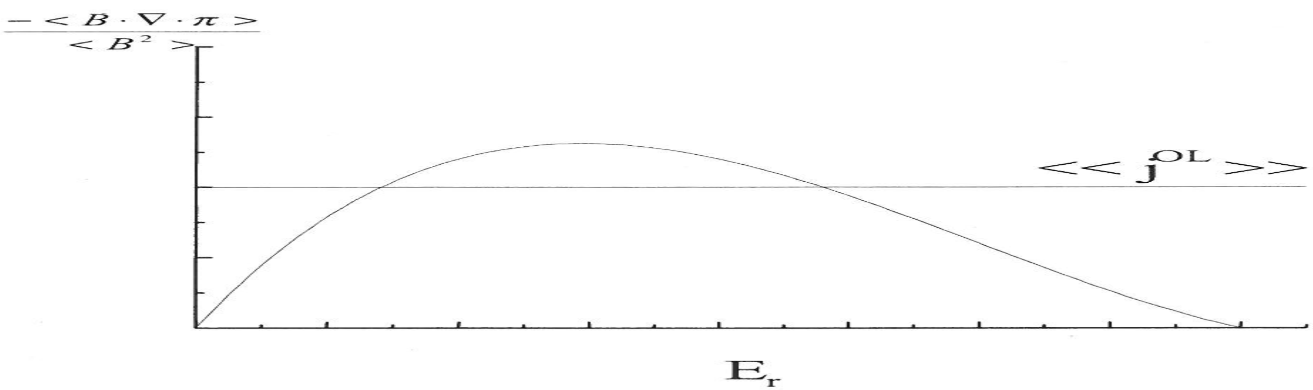
Understanding Transport Barriers

Bifurcation models: Itoh & Itoh (1989), Shaing & Crume (1989)

Current caused by the ion orbit loss is balanced by the current driven by non – linear parallel viscosity

Anomalous (specifically momentum) transport neglected.

Yet, the H – mode was established at high collisionality by Ida et al. (90)



Spin – up due to plasma turbulence: Hassam et al.(1991) Diamond et al (1992) etc.

Anomalous Transport : Zonal flows, Reynolds stress, Effective anomalous viscosity

Yet, no neoclassical effects are included

Electric field profile is governed by neoclassics given by plasma profiles

Electric Fields in Tokamaks

Radial electric field is negative in the core region and positive in the SOL provided no momentum injection.

Tendler 1990, Ida 1998

Radial electric field inside the separatrix is close to the neoclassical electric field for a wide set of plasma profiles provided no momentum injection there.

Rozhansky & Tendler 1992, Heikkinen et al. 2002

In contrast, toroidal rotation is governed by the anomalous viscosity and zonal flows.

Fujisawa 2004, Itoh 2006

Neoclassical Electric Field in Synergy with Anomalous Momentum Transport

Radial electric field is determined by the momentum balance equations including both neoclassical effects and zonal flows.

Rozhansky & Tendler 1992 have demostrated that the radial electric field is close to the neoclassical value for not too steep density and temperature profiles.

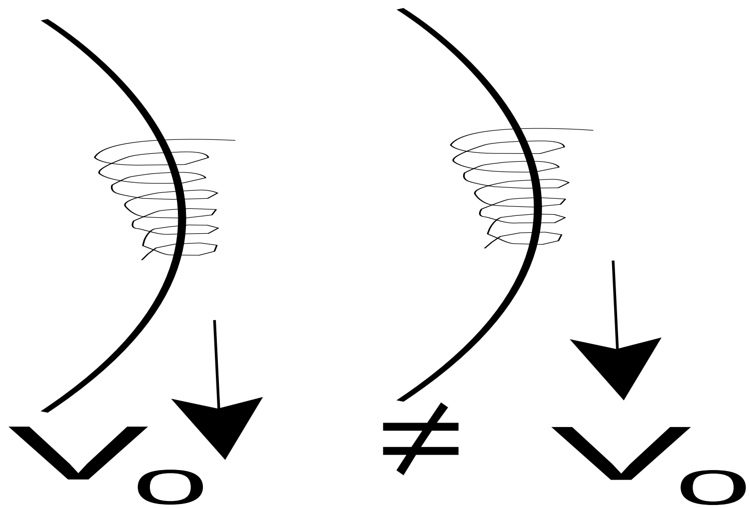
In contrast to standard neoclassical theory the toroidal rotation velocity is mainly determined by anomalous transport of the parallel and toroidal momentum via effective anomalous viscosity.

The radial electric field shows no bifurcation and the origin of the strong electric field shear is governed by the self-consistent evolution of plasma profiles.

Confinement Improvements

Electric Field Shear(d/dr and d^2/dr^2) is the key on the road to fusion reactor

Tokamaks - Gigantic Shredding Machines



Difficult Question :

How to induce strongly varying electric field profiles ?

Neoclassical Electric Fields in Tokamaks

$$E_r = \frac{1}{Z_i e n_i} \frac{\partial P_i}{\partial r} - B_\phi v_\theta + B_\theta v_\phi$$

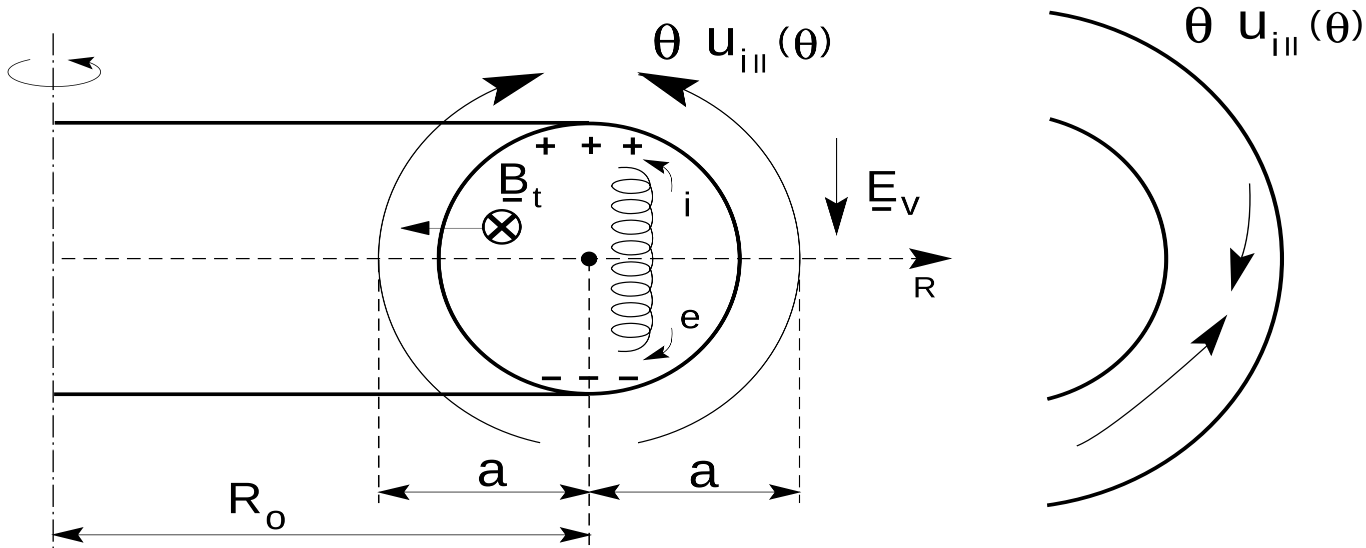
3 knobs to trigger electric fields

$$E_r^{(NEO)} = \frac{T_i}{e} [\frac{d \ln n}{dr} + (1 - k) \frac{d \ln T_i}{dr}] + B_\theta v_\phi$$

Yields smooth profiles of E_r unless no V_T or j_r x B_θ is employed

Electric field varies slowly in tokamaks in accordance with neoclassics

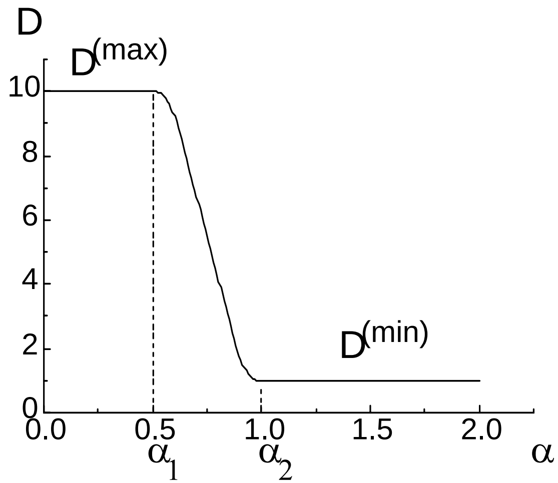
The impact of parallel flows and currents



"Biasing" is the most effective way to induce large variations of E_r

Modelling Transport Barriers

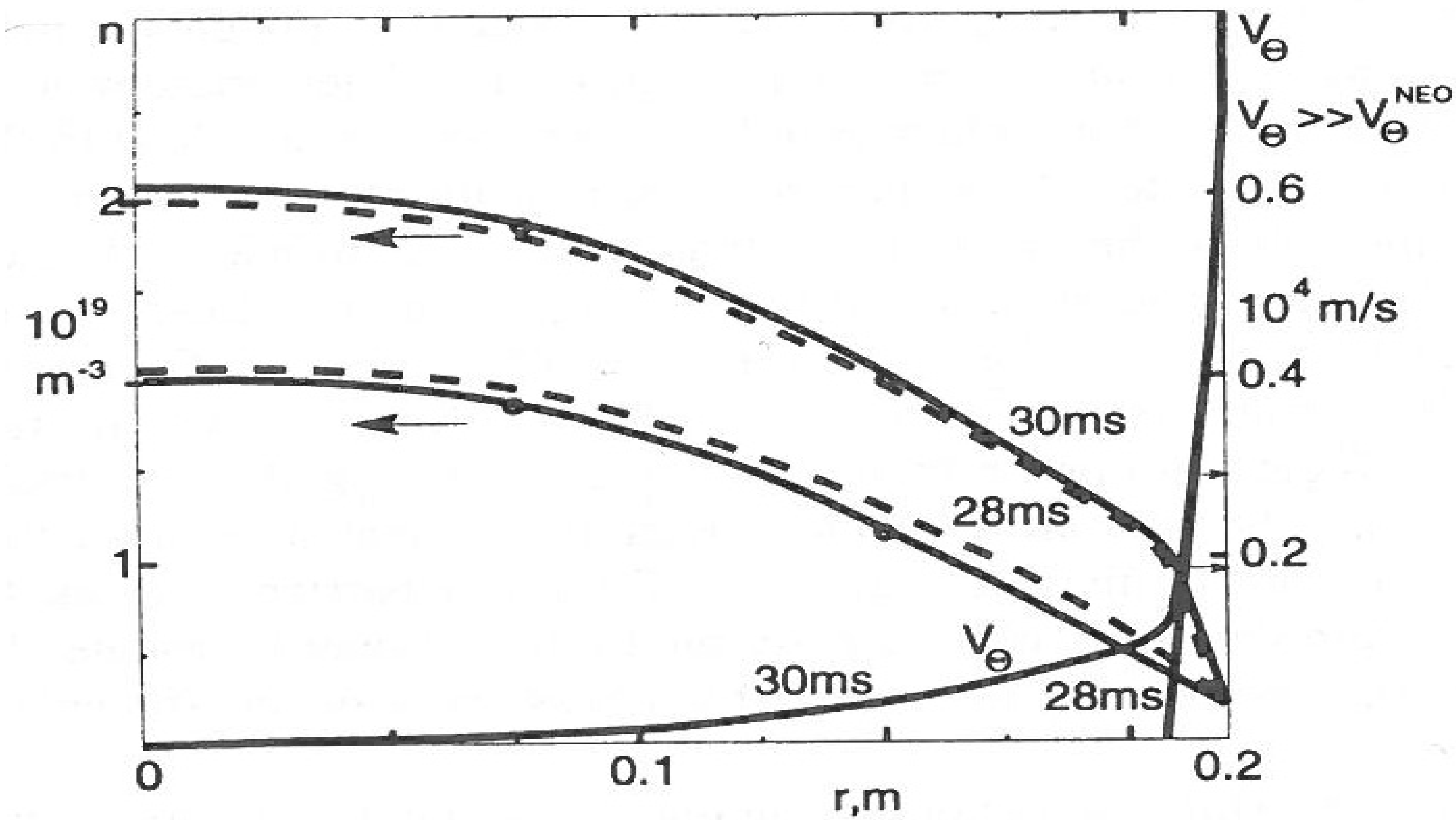
Fluid Equations with Arbitrary Diffusivities dependent on Electric Field Shear dEr/dr



Includes particle, momentum and heat diffusivities in synergy with electric fields

The resulting model is insensitive to initial conditions due to strong nonlinearity

Different Scenarios of Transitions into Improved Confinement Modes



Scenarios triggered by poloidal rotation (solid) or density depletion (dashed) almost coincide

Sensitivity to plasma profiles

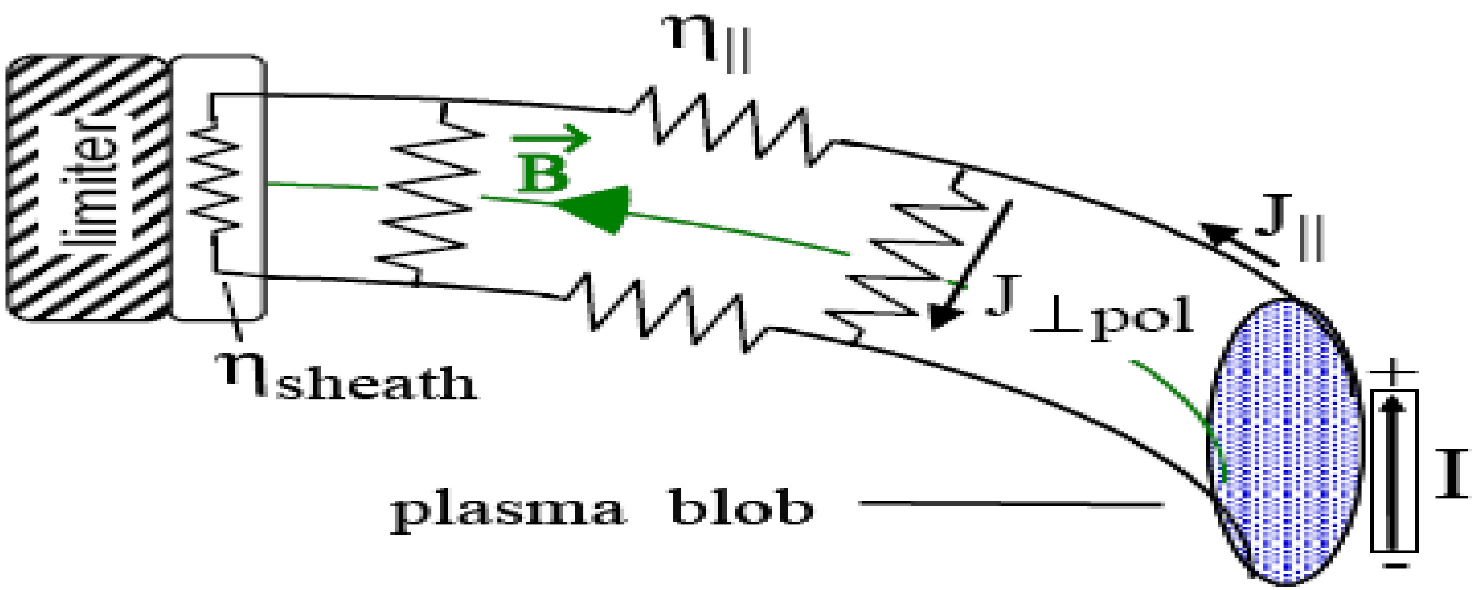
$$\boldsymbol{(dE_r/dr) \sim d^2 \ln n/dr^2 \sim [\, - (n' / n)^2 + n''/n \,]}$$

Depends on both first ***dn(T)/dr*** and second ***$d^2n(T)/dr^2$*** derivatives of plasma profiles

Easier to amplify at the edge where density and temperature is much lower

In contrast, in the core more subtle effects such as ” virtual biasing ” has to be employed

Electrotechnical Approach Current Pathways in Fusion Plasmas



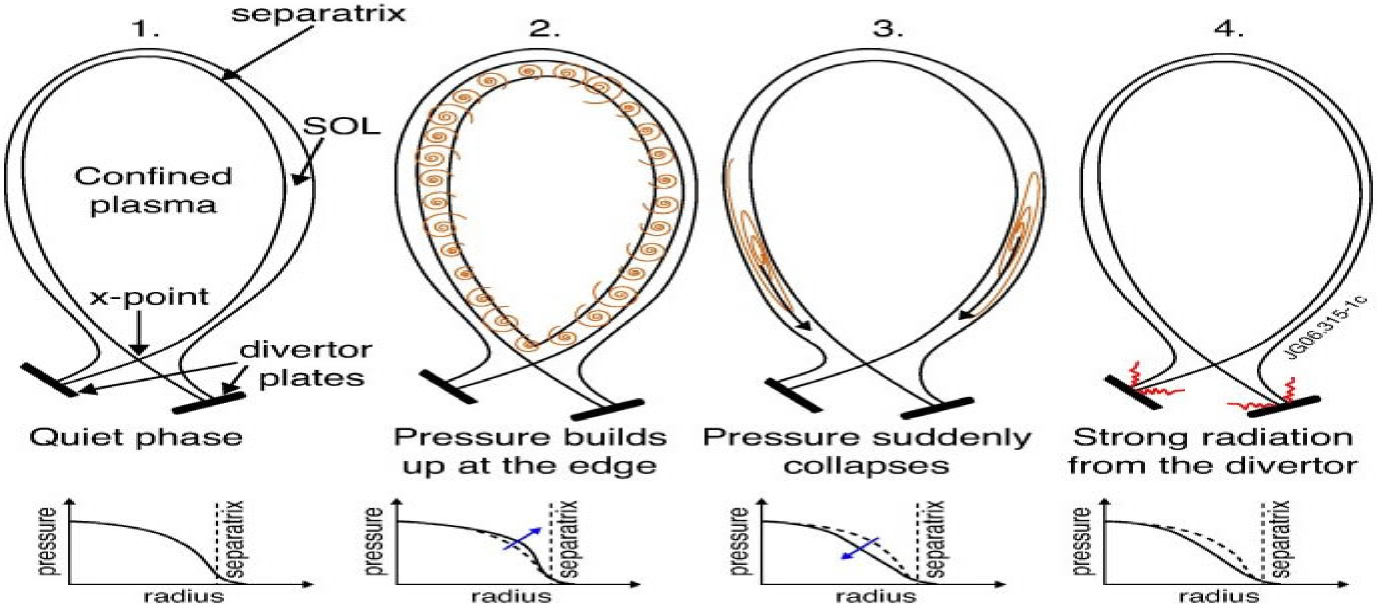
In the core plasma perpendicular conductivity is governed by the magnetic field geometry and determined by the momentum transport

Two specific Examples

Suppression of ELM´s by the Resonant Magnetic Perturbations

Dynamics of Blobs within the Edge Plasmas at the Periphery of Tokamaks

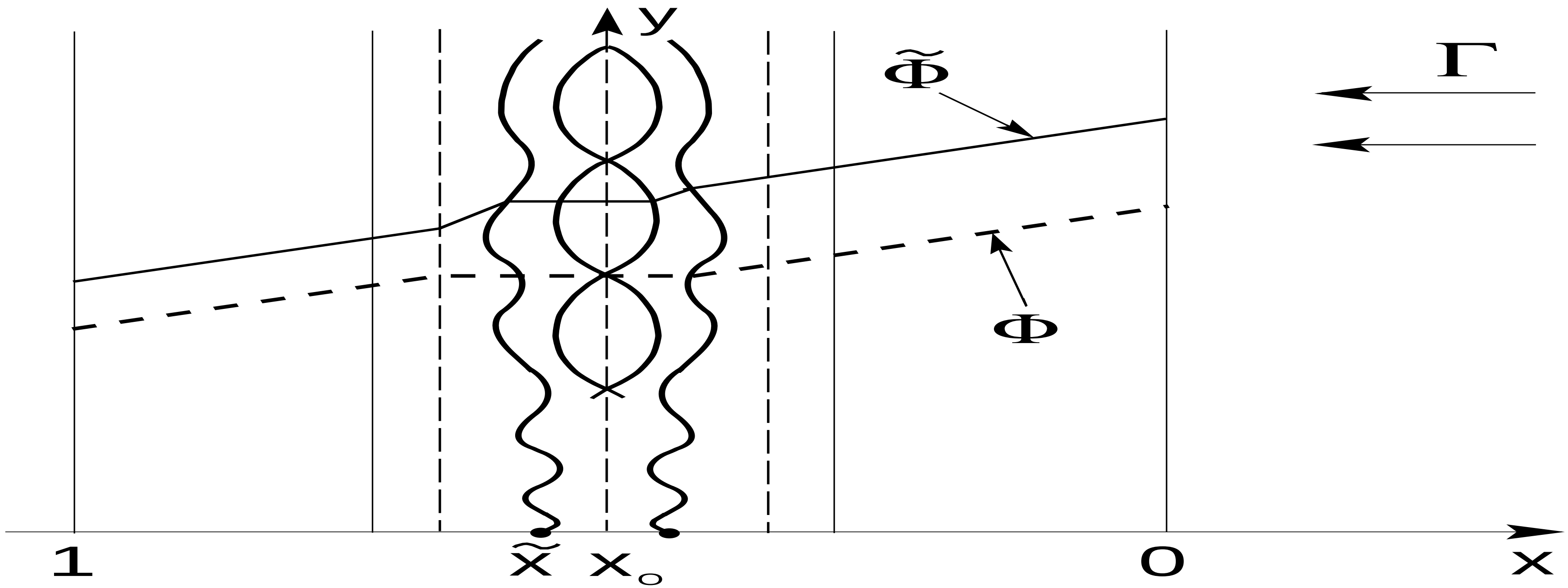
The main danger for ITER benchmark scenario is the existence of Edge Localised Modes (ELMs) – intermittent loss of confinement. Edge Localised Modes are repetitive bursts of the edge plasma.



Plasma edge ergodisation by resonant perturbations of the magnetic field. Studies at the DIII-D tokamak demonstrated an unexpectedly strong ELM suppression via resonant magnetic field perturbations. This is considered to be a very promising result for a reactor-relevant operation.

The remedy is to create the strongly varying electric fields by means of the Resonant Magnetic Perturbations

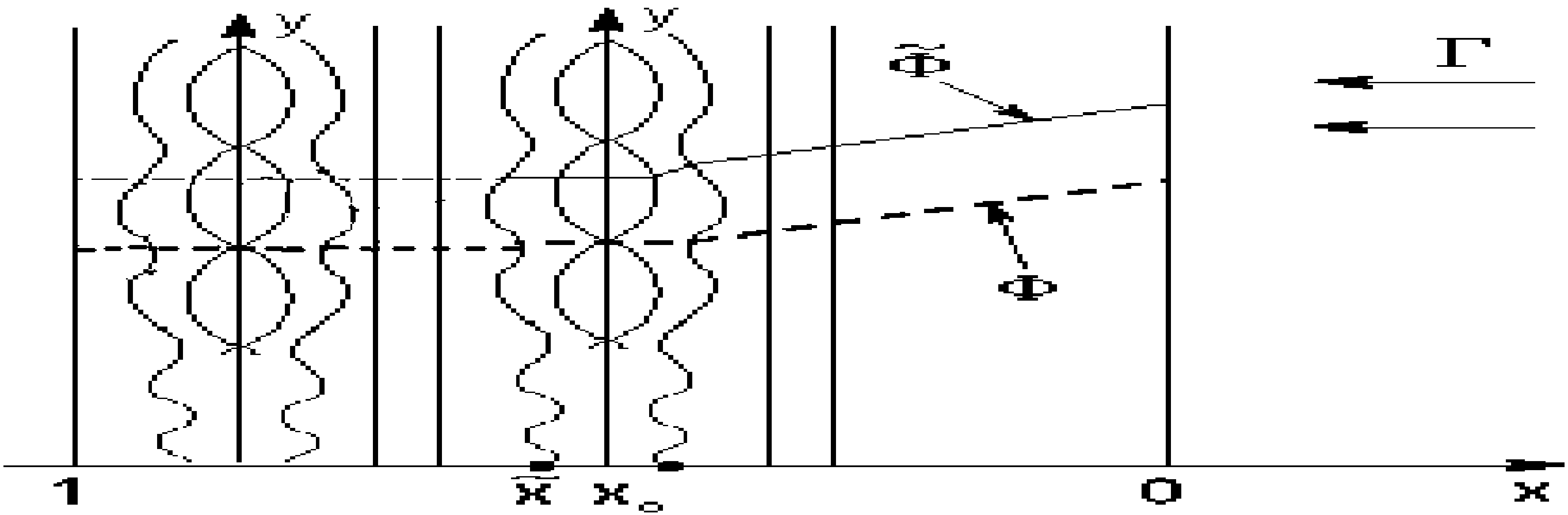
Magnetic Islands Yield Strongly Varying Electric Field Profiles in the Vicinity of Rational Surfaces



Conjecture: Matching may result in the emergence the steep Er profiles yielding Internal Transport Barriers

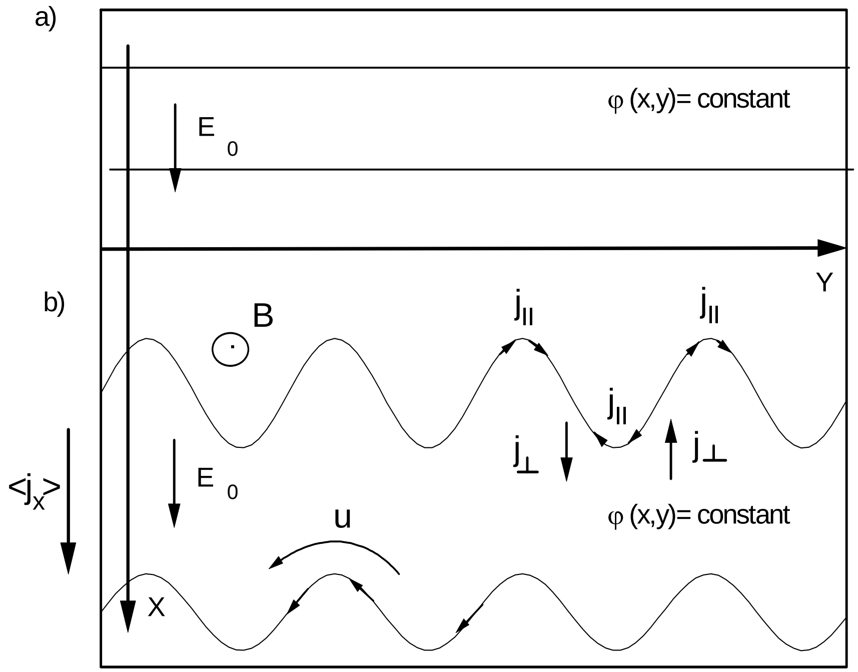
Link of MHD Activity & Turbulent Transport

Vicinity and Overlapping of Chains of Magnetic Islands result in Strongly Varying Electric Field Profiles due to Enhanced Perpendicular Conductivity



The effect results from the toroidal spin-up due to j_rxB forces and the consequent enhancement of the electric field shear suppression of ELM´s

Cross – field ”biasing” current is driven due to the braided magnetic field

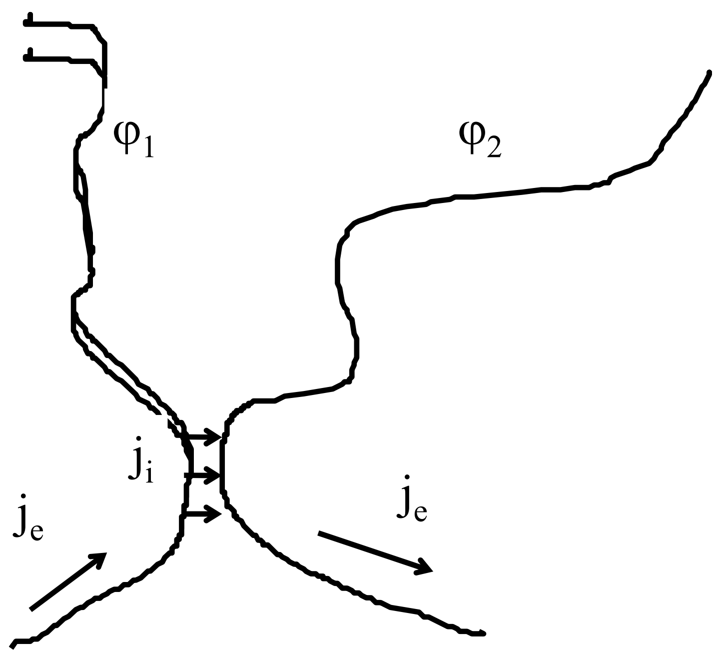


Toroidal rotation and the shear of the electric field is strongly enhanced. Electric field might even become positive on closed magnetic surfaces Ida 2002.

Fig.1 Scheme of equipotentials: a) without account of local ambipolarity constraint b) with account of potential perturbations.

Cross-field and parallel currents are shown.

Formation of the stochastic layer may occur during the MHD activity according to Chirikov criterion

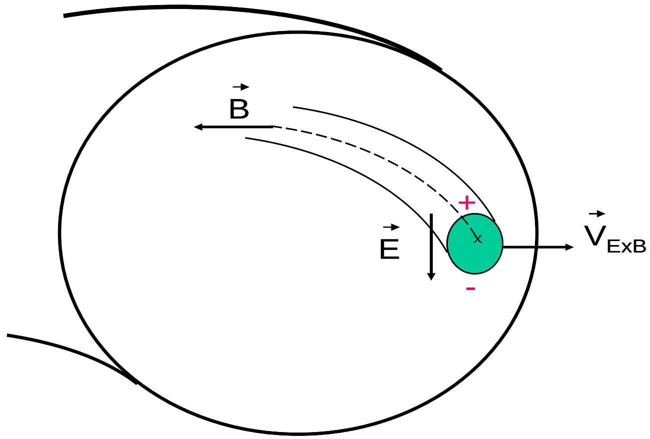


The strongly enhanced cross – field conductivity between equipotentials for stochastic magnetic lines causes the toroidal spin-up due to $j_r x B_p$ forces and the consequent enhancement of the electric field shear suppression of ELM´s.

The injected momentum due to stochastic nature is balanced by the neoclassical parallel viscosity

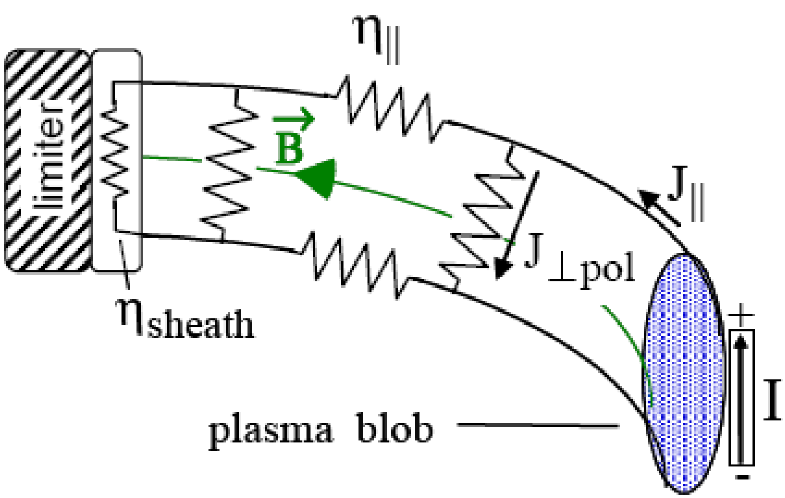
Blobs are a transversal phenomena appearing in different toroidal magnetic devices, both tokamaks and stellarators,

The ubiquitous nature of transport phenomena there.



$$V_b = 2c_S\left(\frac{\rho_S}{\delta_b}\right)^2 \frac{L_\parallel}{R} \quad \text{(C)}$$

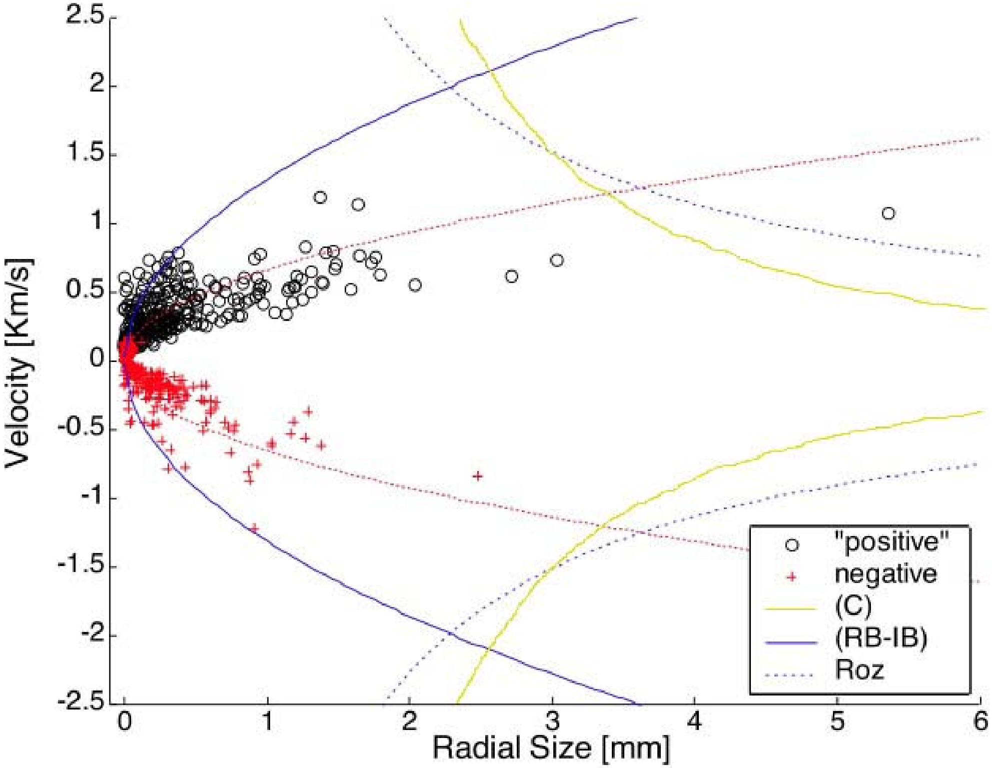
$$V_b = c_S\sqrt{\delta_b}/\sqrt{R} \quad \text{(B)}$$



$$V_b = \frac{T_e^{plasma}}{eB\delta_b} \quad \text{(D).}$$

$$\delta_* = \rho_S\left(\frac{L_\parallel^2}{\rho_S R}\right)^{1/5}, V_* = c_S\left(\frac{\rho_S{}^2 L_\parallel}{R^3}\right)^{1/5}$$

Experimental blob velocity for H-mode on FT -2 compared to theoretical estimates



dashed blue line - current closure through ambient plasma for long filaments

blue line - current closure through mid-plane region due to ballooning mode

yellow line - current closure through electrode sheath

dashed red - experimental data coefficient for fitting to the blue line

The best fit is the blue line, yet it is not quite satisfactory

Advantages of Stellarators :
Long Pulse Operation
Absence of Current Driven Instabilities & Disruptions
Lack of Density Limit. Hence, much higher densities than in tokamaks

Difficulties of Stellarators
Impurity Control
Confinement of Fast Particles
Energetic Particle Modes

First Priorities for LHD:
More Ion Auxiliary Heating, Positive Beam
Fast Particle Studies, D – operation, ITB

4 times upgrade of LHD may be the candidate for DEMO provided the current momentum will be maintained