Issues of Electric Fields in Fusion Devices

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At present it is well understood that the key element in the transition physics is the origin of the strong radial electric field and suppression of the turbulence fluctuation level by a strong poloidal rotation in the $\boldsymbol{E} \times \boldsymbol{B}$ fields. As a result, the transport coefficients are strongly reduced at fixed places and transport barriers with steep density and temperature gradients are formed near the separatrix or the last closed flux surface (ETB) or in the core region (ITB). The key element in the transition physics is the origin of the strong radial electric field. The impact of the momentum transport is brought to light.

Keywords: LH transitions, $\boldsymbol{E} \times \boldsymbol{B}$ shear suppression, anomalous momentum transport

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1. Introduction

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 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. 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 $\boldsymbol{E} \times \boldsymbol{B}$ 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.

Recently, strong arguments addressing the validity and the experimental evidence in favour of the crucial role played by the profile of the electric field during LH transitions has been brought to light. Indeed, it was shown that in a tokamak the radial electric field is negative in the core region and positive in the SOL [1, 2]. Radial electric field inside the separatrix is close to the neoclassical electric field profile for a wide set of plasma profiles provided no external momentum injection is employed [3]. In contrast, toroidal rotation is governed by the anomalous viscosity, shear Reynolds stress and zonal flows [4, 5].

In hindsight, the bifurcation models aimed at explaining the LH transitions and invoking current caused by the ion orbit loss [6, 7] were not confirmed experimentally. There, the current caused by the ion orbit loss is balanced by the current driven by non-linear neoclassical parallel viscosity yielding the bifurcation of the poloidal rotation. Yet, it was demonstrated experimentally by Ida *et al.* that the LH transition can be obtained also at a high collisionality regime where the ion orbit loss impact is negligible. Moreover, the poloidal rotation, which should be of the order of the poloidal sound speed also contradicts the experiment, where the radial electric field is determined by the density and temperature gradients. Furthermore, from the theoretical viewpoint the anomalous momentum transport has been neglected. In addition, the orbit loss model contradicts first principles [8].

Along alternative school of thought, the turbulence has been put forward as a major factor causing the transition into regimes with improved confinement. The spin-up of the poloidal rotation has resulted from the poloidal asymmetry of anomalous transport or the shear Reynolds stress [9, 10]. However, the impact of the toroidicity has been either totally or partially neglected and the neoclassical flows and currents were overlooked.

Here, it is iterated that many experimentally observed features may be assessed employing the synergy of the neoclassical theory for the electric field profiles with an anomalous momentum transport mechanism emerging due to zonal flows. The radial electric field profile is determined by the momentum balance equations including

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both neoclassical and anomalous effects [11]. They have demostrated that the radial electric field is close to the neoclassical value for not too steep density and temperature profiles. Indeed, scales of gradients of plasmas profiles (temeperature and density) must not be shorter than poloidal Larmor radius.

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

Furthermore, 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 and electric fields. Their coupling brings to light the strongly nonlinear loop emerging from the modified neoclassical theory. The bottom line is the extreme sensitivity of the solution of transport equations with diffusivities governed by the shear of the electric field to subtle details of plasma density and temperature profiles. Indeed, they are dependent on both gradients and curvatures of evolving profiles. Boundary conditions imposed on the interface of plasmas with discontinuous values of the electric field play also a crucial role yielding unconventional solutions. Hence, it is important to bear in mind that transport is not determined by local densities or temperatures, but globally by subtle details of their profiles thereby making diffusive time scales in principle irrelevant.

Indeed, the high sensitivity of a diffusivity (this may be particle, momentum, energy etc.) to subtle details of equilibrium profiles arising due to the dependence of fluxes on the first and second derivatives of plasma profiles has been put to light within the framework of the $\boldsymbol{E} \times \boldsymbol{B}$ shear suppression paradigm [12].

To this end, the notion of subthreshold transitions (lacking a bifurcation and below the power limit) has been brought about. Scenarios describing this kind of transitions occur primarily due to mentioned above pecularities of anomalous diffusivities. They have been coined "Tunneling Transitions" in analogy with Quantum Mechanics [14, 15].

Finally, an insight is offered addressing both Internal and Edge Transport Barriers (ITB & ETB) from the same angle. These might have their common origin caused by the interface of plasmas with different configurations of confinement thereby providing a large shear of the electric field. The eloquent example of this idea takes place at the separatrix where the electric field within the SOL is governed by a contact with plates. This has to match the self-generated electric field on closed field lines governed by plasma flows and magnetic field geometry. Another example is confronted within the bulk plasma when chains of islands located in the vicinity of rational surfaces interface with the main plasma body yielding the amplification of the shear of the electric field.

In summary, although the perpendicular transport is grossly anomalous in tokamaks it is also inherently ambipolar because anomalous transport is mainly caused by $\boldsymbol{E} \times \boldsymbol{B}$ fluctuations. In contrast, neoclassical transport imposes the equilibrium electric field profile in order to satisfy conditions of ambipolarity in a tokamak. Hence, the electric field is governed by the extended neoclassical theory incorporating the anomalous momentum transport. The evidence is primarily due to experiments and theories explaining biasing in its capacity to trigger transitions into improved confinement. Therefore, the issue of perpendicular conductivity emerges as the major factor in comparing the theory and experimental data.

2. The Impact of the $\boldsymbol{E} \times \boldsymbol{B}$ Shear on Turbulence

The bottom line of the $\boldsymbol{E} \times \boldsymbol{B}$ shear concept consists of two issues: the impact of the $\boldsymbol{E} \times \boldsymbol{B}$ drifts on a residual turbulence and a more difficult question about a plausible origin of significant temporal and spatial variations of the electric field within the plasma volume [13].

Turbulence often coexists with large mean flows. In plasmas flows are self-generated either due to toroidicity (neoclassical) or due to turbulence (zonal) or externally imposed due to any form of physical or virtual biasing. Turbulence is fed into plasmas via energy cascades due to local or global instabilities. In the L mode turbulent 3D flows prevail characterized by strong turbulent fluctuations causing small mean shear flows. If this is the case particle trajectories are chaotic and turbulent transport is very large. In contrast, in the H mode turbulent fluctuations are strongly reduced. Strong mean shear flows emerge and more regular trajectories lead to the reduced transport of moments.

Energy cascades to larger scales in magnetized plasmas is a well-known phenomenon describing a mean flow at low k numbers due to the spectral condensation. It is the finite-system-size phenomenon requiring low dissipation in a bounded system. Mean flow generation provides the evidence for suppression of turbulence by a mean shear of the flow. Shearing acts more efficiently on large scales. Assuming an appearance of the mean flow due to the drift in the electric field, theory predicts complete stabilisation of various modes with the increment γ_{max} by the $\boldsymbol{E} \times \boldsymbol{B}$ rotational shear rate provided

$$\omega_{\mathrm{s}} > \gamma_{\mathrm{max}}, \qquad \omega_{\mathrm{s}} = \frac{RB_{\theta}\partial(E_r/RB_{\theta})}{\partial r};\ \gamma_{\mathrm{max}}\text{-linear growth rate.} \tag{1}$$

Therefore, the complete stabilisation is the mode specific feature providing for the ample suppression of a dominant turbulence channel (f.e. Ion Temperature Gradient mode driven turbulence in discharges with the ITB's). The main physical effect relies upon an amplified damping due to an interaction between an unstable mode with a nearby, stable mode and the resulting from it the increase of the Landau damping of an unstable mode.

However, a bulk of other modes usually unstable and detrimental to confinement under conventional tokamak operation mode such as Trapped Electron and/or Electron Temperature Gradient modes remain the cause of enhanced losses.

In general, the turbulence consists of short-lived eddies, rather than coherent vortices. Therefore, the break-up of coherent vortices described above has never been observed experimentally.

In reality, the shear leads to the reduction in the eddy lifetimes according to the following formula. Shearing rate can be calculated as the function of the poloidal velocity profile from the neoclassical theory as

$$\varpi_{\mathrm{S}}^{\mathrm{NEO}} = \frac{1}{B}\left[\frac{T_{\mathrm{i}}}{eL_{\mathrm{n}}^2} - \frac{B_{\varphi}}{L_{\mathrm{V}}}V_{\phi}\right].$$

where L_{n} and L_{V} is the scale of the density and the flow velocity, respectively. B, B_{φ} are total and poloidal magnetic field and V_{ϕ} is the average toroidal velocity.

Indeed, the effective growth rate γ_{c} can be shown to decrease dramatically according to

$$\gamma_{\mathrm{c}} = (\Delta\varpi_{\mathrm{D}}\varpi^{\mathrm{NEO}}{}_{\mathrm{S}}{}^2)^{1/3}. \tag{2}$$

where $\Delta\varpi_{\mathrm{D}}$ is the nonlinear decorrelation rate in absence of the $\boldsymbol{E}\times\boldsymbol{B}$ shear [13].

Hence, the imposed rotation by the $\boldsymbol{E}\times\boldsymbol{B}$ flow leads to turbulence reduction. In more detail, mean flows enforce vortices into the relative motion to the magnetic field thereby reducing energy input into the turbulence drive . The mechanism has a potential to benefit confinement provided an option to affect the electric field profile may be found.

3. Main Features of the Model

The model dwells upon two major assertions. The first is the ubiquitous suppression of diffusivities by the electric field shear described in the previous Section. The second is the dependence of the electric field profile on plasma temperature and density profiles. The difficult issue is how plasma can generate an electric field profile in order to fulfill stringent requirements for turbulence suppression imposed on the shear of the electric field profile. To elucidate the origin of the electric field in plasma the following equation stringently derived from the radial force balance equation provides the first insight

$$E_r = \frac{1}{Z_{\mathrm{i}}en_{\mathrm{i}}}\frac{\partial p_{\mathrm{i}}}{\partial r} - B_{\phi}v_{\theta} + B_{\theta}v_{\phi}. \tag{3}$$

Here, the beneficial impact of the electric field seems to be assured if an electric field E_r and contributing to it poloidal and toroidal rotation velocities provide for the stringent requirement imposed on the shear. Therefore, there are basically three “knobs” (diamagnetic drift, poloidal and toroidal rotations) affecting the radial electric field. In real conditions, all of them evolve simultaneously both in space ant in time thereby contributing to the complexity of the issue.

According to standard neoclassical theory (i.e. ignoring regions with steep gradients of plasma parameters) this is found in toroidal geometry to yield

$$E_r^{(\mathrm{NEO})} = \frac{T_{\mathrm{i}}}{e}\left[\frac{\mathrm{d}\ln n}{\mathrm{d}r} + (1-k)\frac{\mathrm{d}\ln T_{\mathrm{i}}}{\mathrm{d}r}\right] + B_{\theta}v_{\phi}. \tag{4}$$

where k is the constant dependent on collisionality [17].

Although Eq. (4) is the subject to stringent constraints (the absence of unbalanced neutral beam injection and the lack of regions with steep gradients of the order of the poloidal gyroradius) it provides many useful insights, in particular during an initial stage of the transition. Indeed, employing Eq. (4) the shear of the electric field results to depend on both gradients and curvatures of density and temperature profiles.

The transport barrier is modelled by diffusion equations with arbitrary diffusivities taken as functions of the shear of the electric field $\mathrm{d}E/\mathrm{d}r\sim\alpha$.

Hence, the system of governing equations reads

$$\frac{\partial n}{\partial t} - \frac{\partial}{\partial r}\left[D(\alpha)\frac{\partial n}{\partial r} - V(\alpha)n\right] = S. \tag{5}$$

This model equation is assumed to describe any kind of transport such as the particle and heat transport, the toroidal and poloidal momentum transport and the turbulence transport.

The parameter α is proportional to the shear of the radial electric field.

Tentative plot of diffusivities $D(\alpha)$ as the function of shear α is shown on Fig. 1.

At first, in order to gain insights into the physics governing transport under these assumptions few comments following from simple analytical considerations are offered. To this end, we wish to make an important point commenting on the crucial importance of the dependence of transport on the first order versus the second order derivatives of plasma profiles. In more detail, the flux either emerges to be a function of only gradients (see Fig. 2) and/or curvature of density and temperature profiles. If the former situation is the case then the plot of the flux $\Gamma = -D\mathrm{d}n/\mathrm{d}r$ versus the gradient takes the useful form yielding the effect of the flux bifurcation usually invoked in order to explain the L-H transition (the S-curve) (see Fig. 2).

Therefore, ignoring the dependence of the shear of the electric field on the second derivative of a profile the scenario of the transition is significantly simplified and emerges either as dwelling on the left or the right branches of this curve. The straightforward and fast transition occurs then $\Gamma > \Gamma_{\max}$. The case of $\Gamma = \Gamma_{\max}$ describes the situation when prelude profiles prior to the transition represent an equilibrium unstable to an arbitrary perturbation. Therefore, an option of the transition caused entirely due to the diamagnetic drift (without employing a change in

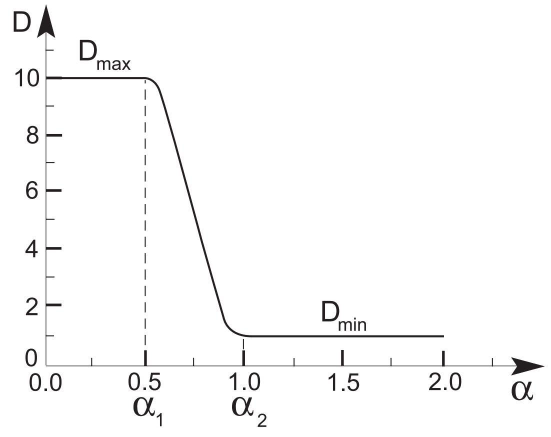

Fig. 1 Tentative dependence of a diffusivity on the shear of the electric field

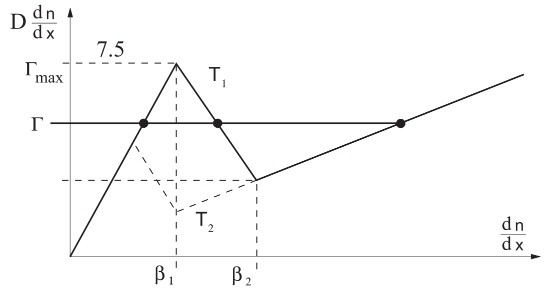

Fig. 2 Simplified picture of transitions ignoring second derivatives of plasma profiles

plasma rotation (Fig. 2) emerges. In reality, the flux is a function of both gradients and/or curvatures of density and temperature profiles. Employing the first term in square parenthesis for the self-consistent electric field as yielded by the neoclassical theory one obtains an important estimate for the shear of the electric field

$$\alpha \sim |\mathrm{d}E_r/\mathrm{d}r| \sim \mathrm{d}^2 \ln n/\mathrm{d}r^2 \sim [-(n'/n)^2 + n''/n]. \tag{6}$$

Focussing on the first term the beneficial effect for a transition of an amplification of the density gradient without changing the local density at the same time is clearly seen from Eq. (6) because it provides more shear of the electric field for given values of other parameters. This may be brought about at the plasma edge by injecting small pellets tangentially as shown also in experiments addressing H-mode and Internal Transport Barriers carried out on the DIII-D tokamak [15] and the LHD stellarator [16], where H & ITB plasmas have been directly produced by injecting frozen deuterium pellets into the L-mode plasma. The pellet triggers the transition at lowered edge temperatures indicating that a critical plasma temperature is not required for the transport barrier. The pellets are also able to lower the threshold power required to produce the H-mode transition indicating an agreement with predictions of the model.

On the other hand, it is obvious that for a given gradient of a density profile, it is easier to trigger a transition scenario at locations with a lower density f.e. at the edge of a confined region born out during the LH transition.

Hence, it becomes obvious why LH transitions with the pedestal located at the edge were the first to be found among plentiful other regimes with improved confinement [18].

Notwithstanding transparency and clarity of arguments based upon Eqs. (5 & 6), it is important to bear in mind that within a spatial range of a plasma body characterised by steep gradients (f.e. plasma parameters within the transport barrier) of the order of poloidal Larmor radius the neoclassical expression Eq. (4) cannot be adopted everywhere because assumptions employed in deriving them are not justified uniformly. Therefore, the electric field has been found self-consistently from the poloidal rotation balance coupled with the concurrent evolution of plasma profiles [3]. There, it has been shown that Eqs. (5 & 6) unfold when neoclassical terms dominate. In other words, the neoclassical parallel viscosity is the governing factor providing for the ambipolarity.

At this point, the issue of causality for transitions into regimes with improved confinement such as the LH transition comes to mind. Indeed, the problem is whether the trigger is due to a change in the rotational $V \times B$ term or the pressure gradient term of main ions. Here, it is important to keep in mind that a steep pressure gradient has a potential to provide for large local values of the electric field by its own virtue according to Eq. (3). However, this effect can be either counteracted or reinforced depending on a quantitative impact rendered by both poloidal and toroidal rotations.

To this end, it has to be kept in mind that due to diagnostic difficulties, it is almost impossible to answer questions related to causality experimentally because the resolution of the majority of diagnostics adopted on many devices is too slow to address the causal dependence in depth. Furthermore, data reported from JET on the magnitude and sign of the poloidal rotation [19] contradicts the same data obtained by the DIII-D team [20]. Yet, a scenario of the transition triggered entirely by the diamagnetic term emerges spontaneously provided the given form of prelude profiles is assumed. In reality, both scenaria merge on a very short timescale.

Importantly, the explicit dependence of the shear on the curvature merits a special emphasis because this enables a transition below the threshold $\Gamma < \Gamma_{\max}$. This result is supported both by analytical and numerical calculations [12]. In Fig. 3 it is shown that both transition scenaria triggered either by poloidal rotation (solid line) or diamagnetic drift (dashed line) merge on a very short time scale (of a few microseconds) beyond resolution of any available diagnostics. In more detail, the scenario of the transition resulting from solutions of the model yields a very fast propagation of the front of improved confinement

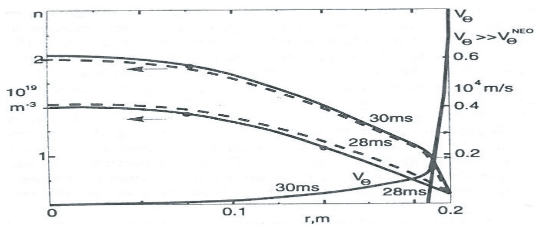

Fig. 3 Scenarios of two LH transitions. Full curves are transitions triggered by poloidal rotations, broken curves are transitions triggered by density depletions with poloidal rotation imposed to zero.

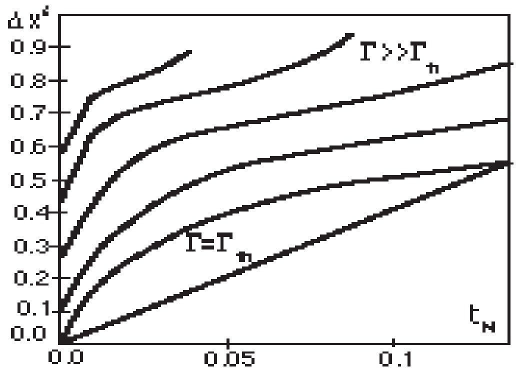

Fig. 4 Propagation of the front of Improved Confinement. Random walk width normalized to the width of the Barrier versus time in ms.

(see Fig. 4) in comparison with the random walk estimate (straight line in Fig. 4) based upon the conventional diffusive model. The main reason for this is the decorrelation of fluctuations carried up and down between the moving front of improved confinement and a separatrix. Therefore, the solution of the model obtains convective features significantly reducing the effective time scale required by the transition. Hence, experimental studies showing the quench of turbulence on a very rapid time scale during the transition find its theoretical explanation [12].

In general, the transport is scale-free and any effective time scale does not exist at all under these circumstances because of the peculiarity of this kind of diffusivity. Hence, the important signature of self organised systems relying upon intermittence and yielding avalanches is recovered.

Another interesting application of this model emerges addressing the so called dithering regime of confinement characterized by oscillations between L and H modes of confinement. It has been shown that the direct LH transition emerges provided the particle influx at the interface between the core and the thermal barrier was kept constant during the transition above the threshold value. In contrast when a possibility of the feedback has been taken into account the dithering arises due to an interaction between inlet and outlet boundary conditions resulting from the feedback of the flux in the core on the flux into the SOL. The second constraint required to obtain either a monotonic or a time dependent solution is due to the dependence of the core flux on the varying density at the interface.

In the first scenario, the steepening of the density evolves gradually from the separatrix up the interface due to the reduced diffusion, thereby bringing about the bifurcation evolving into the thermal barrier. In the second scenario, the outflow at the separatrix ($\approx D_\alpha$ signal) dithers, being linked to the flux at the interface whereas absolute values of density vary insignificantly [21].

In general, if the dependence on the second derivative is taken into account the picture of the transition gets modified. Thence, there is a more global relation strongly dependent on the distribution of sources of moments within the plasma. Furthermore, even for a given distribution of sources, the relation between fluxes and gradients is not unique anymore [22]. Hence, additional boundary conditions are required because the governing system of transport equations obtains the form of the higher order.

In summary, the peripheral plasma plays the crucial role in controlling the global confinement and affecting plasma profiles and local transport diffusivities. Moreover, properties of the plasma within the SOL must be within the restricted range if a stationary solution of transport equations is to be found at all. Indeed, it has been shown before that a steady state solution does not emerge outside the narrow range of boundary conditions imposed on the density gradient at the separatrix. The only solution found for mixed Dirichlet boundary conditions describes autonomous oscillations implying dithering between the Low and the High Confinement. This regime has been also demonstrated on many devices. Time dependent solutions appear to be a subtle phenomenon arising due to peculiar features of the model and the specific choice of boundary conditions.

4. The Link between the MHD activity and the Improved Confinement

Another important application along these lines arises considering the interface of chain of islands located at rational q surfaces with the rest of the plasma core. Therefore, the ITB may stem from the necessity to force a uniform electric field generated within a chain of magnetic islands (dwelling on rational q-surfaces) to match the neoclassical electric field primarily governed by temperature and density profiles. The electric field within the chain of magnetic islands is a constant due to fast mixing, while the neoclassical values are employed within the main plasma body. Therefore, steep gradients of the electric fields result from the matching because of the helical structure of neighboring magnetic surfaces. Indeed, the close proximity occurs at the location of 0 points poloidally whereas the maximum of the shear of the electric field is at X points.

Thus, the shear of the electric field is significantly amplified locally thereby triggering the front of the improved confinement to propagate inwards.

Thus, the shear of the electric field emerges at these locations naturally and self-consistently. This conclusion appears to be generally valid and is not pertinent to any specific magnetic configuration.

It is specially interesting to apply this idea at the edge of the plasma, where rational surfaces are crowded and occasionally overlapping due to the MHD activity. Indeed, during rise of the MHD activity the change of the edge radial electric field from negative (directed inward) to positive (directed outward) values has been observed in the Ohmic discharges on TUMAN-3M tokamak [25]. Measurements were performed by means of Doppler reflectometry method and by using probe technique. According to the heavy ion beam probe (HIBP) diagnostics the potential in the central region of TUMAN-3M also changed sign and became positive during MHD events while normally it is negative. There are experimental evidences that MHD activity is associated with the rise of magnetic island at $q = 3$ flux surface in the core few centimeters inside from the last close flux surface (LCFS). Also the rise of smaller islands at $q = 4$ and $q = 2$ surfaces is reported. Indeed, the overlapping of neighboring magnetic surfaces results in formation of a stochastic layer in the LCFS vicinity provided the width of the island is of the same order as the minimum distance between rational q-surfaces.

Along these lines, the model for the origin of the positive radial electric field during the rise of the MHD activity has been developed [26]. It is based on the emergence of a strong electron radial flux resulting from the formation of an ergodic layer [24]. The radial electron flux requires the same radial flux of ions to provide quasineutrality. Hence, the emerging positive radial ion current provides the torque in the toroidal direction forcing the radial electric field to become more positive (see Eq. 3). This situation is similar to the biasing experiments and corresponding theory has been already developed [11]. In the extreme case, when the electron conductivity associated with the stochastic layer dominates over the neoclassical ion cross-field conductivity [23]. The ion and electron behaviors with emphasis on the cross-field conductivity in the ergodic field were calculated in detail there. Therefore, the radial electric field becomes positive inside the stochastic layer. In more detail, the radial ion current generates toroidal rotation in the co-current direction by the toroidal $\vec{j}_r \times \vec{B}_\varphi$ torque, so the ergodic layer becomes the source of the toroidal momentum at the periphery. The co-current toroidal rotation has to be transported outside the ergodic layer to the core by the anomalous cross-field viscosity thus creating the co-current toroidal rotation in the center of a tokamak even without external sources of momentum injection. The co-current toroidal rotation makes the radial electric field more positive also outside the ergodic layer and for sufficiently fast toroidal rotation the radial electric field becomes positive also in the central regions in accordance with the neoclassical theory.

In the tokamak physics there are several other areas, where the return ion current and associated plasma toroidal acceleration plays a crucial role. The external current of fast ions generated during NBI should be compensated by return radial current of the main ions. The external ion current can be also associated with the ICRH heating causing the loss of fast ions. Externally imposed toroidal magnetic field ripples or islands used for the divertor operation may be the source of the externally generated radial currents. Resonant Magnetic Perturbations normally not resulting in the stochastization of the magnetic field and corresponding loss of electrons can be successfully used for the mitigation of ELM's crucial for the ITER performance.

5. Conclusions

The model invoking the paradigm of shear suppression addresses many effects observed experimentally. Indeed, it yields novel insights and conclusions consistent with measurements. For example, it points us toward the insight that both zonal and neoclassical flows are crucial for improvements in confinement.

In general, it has to be kept in mind that the phenomena of transport barriers are very robust and sensitive only to prelude profiles. The most important practical conclusion from ideas and insights offered above that issues of perpendicular conductivity and electric fields are crucial for progress of the fusion research.

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