Turbulent transport reduction by ExB velocity shear during edge plasma biasing in tokamaks

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ABSTRACT

Experiments in the tokamaks TEXTOR, CASTOR, T-10 and ISTTOK have provided new and complementary evidence on the physics of the universal mechanism of ExB velocity shear stabilization of turbulence, concomitant transport barrier formation and radial conductivity by using various edge biasing techniques.

INTRODUCTION

The understanding and reduction of turbulent transport in magnetic confinement devices is not only an academic task, but also a matter of practical interest, since high confinement is chosen as the regime for ITER and possible future reactors since it reduces size and cost.

An extensive review on the physical mechanisms determining the radial electric field in a toroidal plasma has been published by Ida [1]. He describes amongst others the effect of variations in the radial electric field and shear in the bulk rotation velocity on the improvement of transport properties. Since the pioneering work on the tokamak CCT [2], many papers have been devoted to the effect of electric field biasing in specific machines (see e.g. reviews 3,4,5), which in general leads to a strongly varying radial electric field as a function of radius and a resulting sheared E×B flow, giving rise to improved confinement properties. Due to space limitation, an historical overview of edge biasing work will not be given here, and the collection of material is limited. This paper attempts at bridging the gap between the early and the new, more detailed understanding.

The importance of radial electric fields for plasma transport was in the past repeatedly established. Since the discovery of the transition from a low confinement mode (L-mode) to a high confinement mode (H-mode) in 1982 [6], a flurry of activity started with the experimental and theoretical recognition of a link between E_r and the formation of edge and internal transport barriers in toroidal plasmas. The importance of radial electric field shear in the L-H transition was suggested for the first time in [7,8]. The (spontaneous) H-mode has been obtained in a variety of tokamaks mainly with elongated plasma cross section and divertor, and recently also in the limiter tokamak T-10 with ECRH as the only auxiliary heating. An (induced) H-mode can also be triggered externally by imposing an electric field and the resulting ExB rotation in tokamaks like TEXTOR, CASTOR, T-10 and ISSTOK, as well as in reversed field pinches like RFX. These electrode biasing experiments have contributed significantly to the understanding of the H-mode phenomenon and of the effects of E_r on plasma transport.

The L-H transition is accompanied by a reduction of turbulent transport, confirming the paradigm that microturbulence is responsible for a considerable part of energy and particle losses. The shearing of turbulent eddies by differential ExB flow velocity has been proposed as a universal mechanism to stabilize turbulence in plasmas [9], an hypothesis supported by early work on the tokamak TEXT [10], and has been observed with different magnetic configurations. The ExB velocity shear can suppress turbulence due to linear stabilization of turbulent modes, and in particular nonlinearly by decorrelation of turbulent vortices, thereby reducing transport by acting on both the amplitude of the fluctuations and the phase between them [11]. The shearing rate, $\omega_{ExB,}$ must be comparable to $\Delta\omega_{D,}$ the nonlinear turbulence decorrelation rate in the absence of shear.

This paper reports on recent results of a coordinated study of radial electric fields (E_r) and their role in the establishment of edge transport barriers and improved confinement in the circular limiter tokamaks TEXTOR in Jülich, CASTOR in Prague, and T-10 in Moscow, where E_r is externally applied to the plasma in a controlled way using a biased electrode. Edge biasing is the controlled creation of radial electric fields by driving a current through the edge plasma inside the last closed flux surface (LCFS). In the circular limiter tokamak ISSTOK in Lisbon Er is externally applied by DC or AC electrode or limiter biasing.

TEXTOR: SCALING OF TURBULENCE WITH SHEAR, AND CAUSALITY BETWEEN ExB SHEAR AND TRANSPORT BARRIER FORMATION

Since the early nineties pioneering research has been conducted on TEXTOR in the domain of edge radial electric fields using electrode biasing [13-21]. The biasing experiments on TEXTOR (R=1.75 m, a=0.46 m) with the well diagnosed plasma edge using probes to measure all relevant quantities such as electric field, parallel and perpendicular plasma flow, fluctuation and turbulent particle flux, have given the first proof for transport suppression due to sheared ExB flows. Quantitative analysis has shown that the diffusion coefficient decreases at the shearing rate predicted by theory. These findings are in good agreement with measurements of the fluctuating quantities, which contribute to the turbulent transport. Changes in the cross-phase are essential for substantial quenching of turbulence. A 1D fluid model, in which parallel viscosity and neutral friction were already identified as important components to explain the very important and localised electric fields has been developed. Recent work has focused on the convection and shear viscosity, introduced by anomalous radial flows, and their subsequent reduction by the quenching of the turbulence. It has been shown that without the quenching of the turbulence, it is impossible to explain the magnitude and the shape of the measured electric field. The destruction of parallel viscosity by strong poloidal plasma rotation has been identified to cause a bifurcation in the electric field. Rapid changes in the polarisation driving current have been used as a diagnostic tool to study the causality between rotational shear and confinement improvement. The flow shear is clearly leading the transport changes and as a result, a hysteresis between the imposed shearing rate and the particle diffusion coefficient arises.

The scaling of plasma turbulence suppression with velocity shear has been established, revealing the cross-phase as a key element. To important results should be noted: Firstly, that the scaling of the cross-phase term is as strong as that of the turbulence amplitudes, revealing the cross-phase as a key element in the suppression of turbulent transport. Secondly that there is a difference in the scaling of the cross-phase between the positive and negative shear regions, an effect not included in the theories [22-24], which are phase-sign blind and therefore these results [25,26] should be considered closely by theoreticians. First measurements of the suppression of electron temperature fluctuations in a strongly sheared velocity field have been made [27]. Reduction in poloidal electric field, temperature, and density fluctuations across the shear layer lead to a reduction of the anomalous conducted and convected heat fluxes resulting in an energy transport barrier that is measured directly.

CASTOR: ExB FLOW MEASUREMENTS AND STRUCTURE OF EDGE TURBULENCE

CASTOR (R=0.4 m, a=60 or 85 mm) . The impact of sheared electric fields on the structure of edge fluctuations and plasma flows is investigated on the CASTOR tokamak with a non-intrusive biasing scheme, whereby a mushroom-like electrode (made of carbon) is located in the scrape-off layer (SOL), but its top is just touching the separatrix (see Fig. 1). In such scheme, called “separatrix biasing”, the potential is affected only in a relatively narrow region near the separatrix and the radial electric field is amplified at both sides of the electrode, because, in contrast to the standard biasing arrangement, the bulk plasma remains unbiased [28].

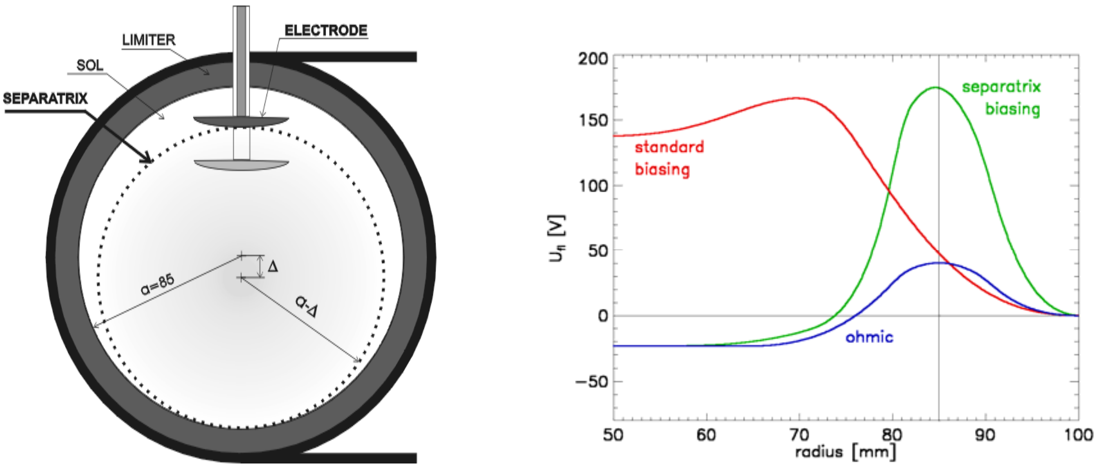

Fig. 1 Left: Poloidal cross section of the CASTOR tokamak, schematically showing the respective position of plasma column and biasing electrode at the "standard" and at the "separatrix biasing" arrangements. Right: Comparison of radial profiles of floating potential inohmic and biasing cases (schematically). Here, the separatrix is at 85 mm. Position of the electrode at standard biasing scheme is 70 mm.

This experiment has been predicted theoretically [12]; in order to trigger an L-H transition, the model requires a value of the electric field larger than that given by neoclassical theory. At the separatrix 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. Therefore, the peripheral plasma plays the crucial role in controlling the global confinement and affecting plasma profiles and local transport diffusivities [29].

The impact of sheared ExB flow on edge turbulent structures has been measured directly using an optimized Gundestrup probe, a comprehensive set of electrostatic probe arrays as well as emissive probes which provide direct plasma potential fluctuation measurements [30-34]. The Gundestrup probe provides the simultaneous measurement of toroidal and poloidal flows, and of electrostatic turbulence, and has demonstrated the correlation between sheared ExB flow and reduction of turbulence [35-39]. Very recently, a novel concept has been suggested to measure the electron temperature fluctuations and a prototype of the so-called tunnel probe has been successfully tested on CASTOR. Measurements with a full poloidal array [40] with 32 electrodes plus Langmuir probes have revealed quasi-coherent electrostatic waves in the SOL with a dominant poloidal mode number (6) equal to the edge safety factor. At DC biasing with an electrode located near the separatrix, the edge turbulence is modified by a sheared radial electric field, which is imposed to this region. The poloidal velocity of turbulent structures strongly increases and the poloidal mode number is reduced significantly down to 1-2.

The plasma potential and its fluctuations were measured by electron emissive probes in the edge plasma region of two fusion experiments: the ISTTOK (see below) and the CASTOR tokamaks [41,42] . Into ISTTOK, three emissive probes were inserted outside the LCFS on different minor radii. In CASTOR, two poloidally separated emissive probes and two cold cylindrical probes, mounted on the same shaft, were used, which could be radially shifted outside and inside the LCFS. The advantage of a sufficiently emissive probe is that in principle the plasma potential and its fluctuations can be measured directly, without being affected by electron temperature fluctuations or drifting electrons.

T-10: ELECTRODE BIASING IN REGIMES WITH ECR PLASMA HEATING

The H-mode was achieved by inserting the positively biased electrode into the plasma edge inside the limiter in the T-10 tokamak (R=1.5 m, a=0.3 m) in regimes with electron-cyclotron resonant heating [43,44]. The H-mode is characterised by a decrease of D_α emission intensity, a rise of line-average plasma density and an increase of energy confinement time. The increase of core electron and ion temperatures during the electrode biasing implies the formation of the thermal barrier in addition to the barrier for particles.

The Heavy Ion Beam Probe (HIBP) diagnostic was used to directly measure the local values of the plasma potential in the core and edge plasmas [45,46]. It is located at a toroidal angle of $\varphi=180^0$ from the electrode.To obtain the radial potential profile the HIBP was used in the scanning mode. Scanning along the detector line allows to get a set of profiles in a single shot. The scanning was realized by periodical variation of the injection angle. The sampling frequency and bandwidth of the acquisition system allow the observation of slow oscillations.

The first biasing experiments performed on the T-10 tokamak have shown that positive voltage applied to an electrode results in an increase of core electron and ion temperatures and in of energy confinement time in regimes with ECR auxiliary heating, in contrast to the ohmic regime. Hence, edge biasing is clearly improving the global performance of ECR heated discharges. Reflectometry shows the existence of a narrow plasma layer where strong changes of turbulence levels occur. A heavy ion beam probe diagnostic has been used to directly measure the local values of the plasma potential in the vicinity of the electrode radius, outside as well as inside, showing two regions with strong radial electric field and a strong reduction of plasma potential and density fluctuations in the vicinity of the electrode radius, outside as well as inside. To explain the different plasma behaviour in OH and ECRH regimes it is planned to carry out the measurements of profiles of radial electric field, toroidal and poloidal plasma rotation velocity in the plasma periphery between the electrode and limiter.

ISTTOK: COMPARISON OF ALTERNATING ELECTRODE AND LIMITER BIASING

In the ISTTOK tokamak (R=0.46m, a=85 mm) electrode (EB) and limiter biasing (LB) [47,48,50] have been performed. LB has the advantage of using existing plasma facing components in the device contrary to electrode bias where an object must be inserted into the plasma, which is not compatible with plasma operation in large devices. However, the modifications in E_r for limiter biasing are, in general, limited to the SOL[49].

Electrode biasing is found to be more efficient in modifying Er and confinement. The best confinement improvement is obtained with positive electrode biasing, showing a good correlation between confinement changes and ExB shear. Negative (positive) limiter biasing leads to improved (deteriorated) confinement and better (worse) stability of the plasma column. Coordinated emissive probe direct measurements of the plasma potential and its fluctuations are planned on ISTTOK and CASTOR.

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