Decay of enhanced density and damping of plasma flows after the electrode biasing termination on the CASTOR tokamak

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Electrode biasing is a standard tool for modification of both edge and global plasma parameters on the CASTOR tokamak ($R = 0.4$ m, $a = 85$ mm, $B_T = 1.3$ T, $I_{pl} \approx 9$ kA, $q_a \approx 10$). During a steady state phase of a discharge, a polarization voltage is applied on an electrode immersed into the edge plasma. This voltage causes radial currents that create radial electric field and, due to the $\mathbf{E} \times \mathbf{B}$ drift, they cause an enhanced rotation. Then, as a consequence, the interaction with walls decreases and particle confinement and density increase. Recently, the decay of plasma density and plasma flows after the termination of the biasing period was investigated on the CASTOR tokamak. These observations are linked to processes and mechanisms that control generation of radial electric fields in plasmas and damping of $\mathbf{E} \times \mathbf{B}$ sheared flows and that therefore represent a key issue for understanding the transition to improved confinements modes. In the contribution, measured time scales of the transition to the ohmic regime after the biasing termination will be shown. Further, possible consequences of these measured scales for the valuation and explanation of important processes in the plasma will be discussed.

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1 Introduction

The mechanisms that control the generation of the radial electric fields ($\mathbf{E}_r$) and damping of the $\mathbf{E}_r \times \mathbf{B}_t$ sheared flows represent a key issue for understanding the transition to improved confinement regimes in magnetically confined plasmas. There has been an intense discussion on the different driving and damping mechanisms of radial electric fields and plasma flows in the plasma boundary region of fusion devices. Both neoclassical (e.g. ion orbit losses [1]) and anomalous mechanisms (i.e. anomalous Stringer spin–up [2, 3], Reynolds stress [4, 5]) have been considered as candidates able to explain the generation of sheared flows. Atomic physics via charge–exchange momentum losses [6, 7], parallel viscosity (magnetic pumping) [8], and turbulent viscosity could explain the flow damping physics. Several biasing schemes have been used to modify the edge plasma parameters and confinement [9]. The evolution of plasma flows after the application of an external biasing has been previously investigated and relations between relaxation rates and viscosity have been obtained [10, 11, 12]. Recent electrode biasing experiments carried out in the

HSX stellarator have shown that it is possible to induce plasma flows in different magnetic configurations. The resulting flow damping rates are higher in the mirror mode than in the quasi–helically symmetric modes, consistently with neoclassical expectations. This paper reports the measurements of the relaxation times of plasma profiles after biasing turn–off in the plasma edge region of the CASTOR tokamak using an electrode.

2 Polarization experiments: Experimental set–up

Poloidal rotation and plasma potential have been modified by means of electrode biasing in the plasma edge region of the Castor tokamak [9]. The electrode, located in vicinity of the last closed flux surface, at $r = 75$ mm, was positively biased ($U_B = 100 \div 230$ V) with respect to the vacuum vessel. Typical radial currents drawn by the electrode were about $(30 \div 40)$ A. Edge density and electron temperature are in the range $n_e \approx 1 \times 10^{12}$ cm^{-3} and T_e $(10 \div 20)$ eV.

Relaxation times of both floating potential and plasma rotation have been investigated after a sudden electrode biasing switch–off. The characteristic relaxation time has been determined using two independent measurements: a) the time evolution of floating probes signals and b) the time evolution of poloidal flows as measured using a Mach probe of the Gundestrup type.

The floating potential profile was measured using a radial rake probe with 16 single Langmuir probe tips. They are radially separated by 2.54 mm and covering both the SOL and edge plasma regions ($r = 65 \div 95$ mm). The probe was placed into the tokamak from the topm of the torus, toroidaly 180° from the limiter.

The Gundestrup probe, placed from the top as well and 45° toroidaly from the rake probe, was used for ion flow measurements in the Castor tokamak [13]. Its ion collecting surface is a nearly continuous cylindrical conductor (a copper tube of diameter 11.7 mm) divided into eight segments separated by 0.2 mm gaps. These segments are biased negatively to measure the angular distribution of the ion saturation current. A single Langmuir probe that is installed at the top of the probe head is used for the measurement of I–V characteristics. From them, the electron temperature is determined and consequently the electron density and plasma potential are calculated. All signals were digitized at 1 MHz sampling rate.

3 Relaxation phenomena

3.1 Floating potential

In figure 1, there are shown the radial profiles of the floating potential and of the radial electric field with and without electrode biasing (i.e. in polarized and ohmic phases of the discharge). The maximum of the floating potential at biasing is of similar amplitude as the applied voltage and it appears in the proximity of the electrode possition ($r \approx 75$ mm). This modification extends radially approximately 10 mm both inward and outward the plasma column.

The profile of the radial electric field ($\mathbf{E}_r$) has been computed using the expression:

$$\mathbf{E}_r = -(\nabla U_{fl} + \alpha \nabla T_e) , \quad (1)$$

where U_{fl} is the floating potential, T_e is the electron temperature and α depends on the probe material, the ion species and its temperature, and the secondary emission coefficient [16]. In the present experiments we have used $\alpha \approx 2$ as determined for our plasma in [17].

Further, we will concern on the characteristic time of the floating potential decay, see figure 2. The time evolution of the floating potential decay can be fitted to a function with the following shape:

$$U_{fl}(t) = U_{fl}^{B} \exp(-\mathrm{time}/\tau) + U_{fl}^{OH} , \quad (2)$$

where U_{fl}^{B} and U_{fl}^{OH} represent respectively the mean floating potential values in the biasing phase and in the unbiased ohmic regime, and τ is the exponential relaxation time. This fitting procedure has been done for floating potential signals measured at several radial positions in the proximity of the polarization electrode. The floating potentials relax in a characteristic time of about $(10 \div 20)\,\mu$s.

3.2 Flow measurements

The ion mass flow was measured by the standard arrangement of the Mach probe of the Gundestrup type [17]. The perpendicular Mach number ($M_\perp$), i.e. the perpendicular flow, is related to the ratio of ion saturation currents measured by poloidally oriented segments of the probe. The parallel Mach number ($M_\|$) is related to the ratio of the upstream and downstream segments (with respect to the magnetic field lines).

The experiments have shown that the behaviour of flows at the end of the polarization period is reversed for the probe located inside the separatrix and in the edge plasma respectively. The poloidal flow decreases in the SOL ($r = 84$ mm), while it shows an increase in the edge plasma ($r = 71$ mm). As the poloidal flow is dominated by the $\mathbf{E}_r \times \mathbf{B}_t$ drift in the CASTOR device, the change of the flow direction (the change of ion current ratio with respect to unity) is consistent with the change in $\mathbf{E}_r$ at the two radial positions. The measured relaxation times of the poloidal flows are in the range of $(10 \div 30)\,\mu$s.

4 Discussion and conclusions

It is interesting to compare the measured relaxation times of the floating potential and the plasma flows with the theoretical characteristic times of the parallel viscosity, the plasma turbulence, and charge exchange mechanisms. The characteristic time scale of the viscosity would depend on the plasma conditions (e.g. collision time and safety factor) in case of the magnetic pumping [14] whereas the eddy viscosity is expected to be related with the time scale of the energy transfer between different turbulent scales (i.e. a few turbulence correlation times) [15] and the atomic physics damping rate is directly related with the density of neutrals [8].

In the following, we will discuss all the three mechanisms. The correlation time of plasma turbulence, defined as the full width of the autocorrelation function at its half maximum, is in the range of 5 μs in the plasma edge region (Fig. 3), as calculated using the floating potential measurements. The momentum loss rate due to charge exchange can be expressed as $\tau_{cx} = (<\sigma_{cx} v_i> n_n)^{-1}$, where n_n is the neutral density. Assuming $T_e \approx T_i$ and $n_n \approx 10^{11}\,\mathrm{cm}^{-3}$, it follows $\tau_{cx} = 500 \div 1000\,\mu s$. Poloidal flows can be damped by parallel viscosity (magnetic pumping) and several of the neoclassical viscous forces can be found in the literature [14, 7, 18]. In the collisional regime, the poloidal momentum damping time can be estimated as

$$\tau_\theta = \left(2 + \frac{1}{q^2}\right) \frac{1}{\omega_{T_i}^2 \tau_{ii}} \tag{3}$$

where ω_{T_i} is the ion transit time, τ_{ii} is the ion collision time [14], and q the safety factor. For CASTOR edge plasma parameters, τ_θ is in the order of 100 μs.

The present investigation shows that the experimentally measured damping times of the floating potential and of the poloidal flows (10 ÷ 30 μs) are smaller than the expected damping time based on magnetic pumping mechanism (in the range of 100 μs) and atomic physics via charge exchange (in the range of 500 μs) and slightly larger (or rather nearly comparable) with the correlation time of plasma turbulence (5 μs). This finding suggests the existence of anomalous (turbulent) mechanisms in the damping rate of radial electric fields and poloidal flows in the plasma boundary of the tokamak plasmas.

These results have a direct impact on the understanding of the L–H transition in tokamaks and stellarators. Parametric studies of the influence of different plasma regimes (e.g. collisionality, turbulence correlation times, magnetic configuration) on the damping time of poloidal flows and radial electric fields are clearly needed. This investigations would help to quantify the importance of anomalous versus neoclassical mechanisms on the damping physics of radial electric fields and poloidal flows in fusion plasmas.

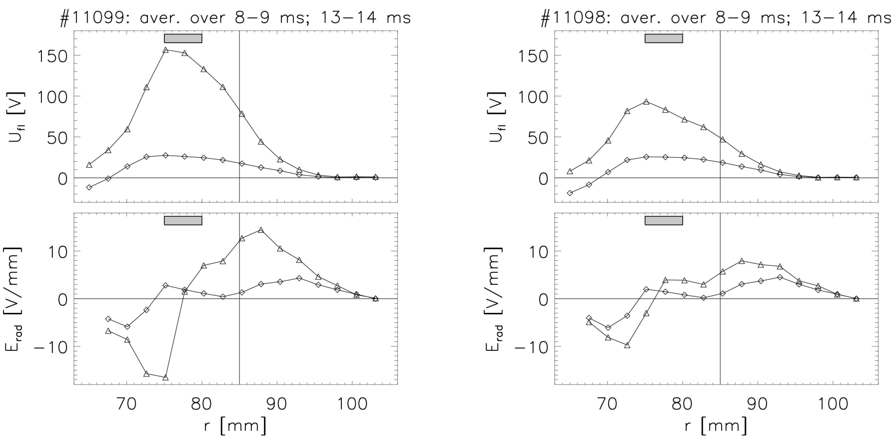

Fig. 1. Radial profiles of floating potential and radial electric field in the ohmic (before biasing; diamonds) and polarized (triangles) phases of two discharges with different biasing voltage (left: +200 V, right: +100 V). The vertical line denotes the radial position of the circular limiter, separatrix is at $r = 75$ mm. The solid rectangle denotes the electrode position.

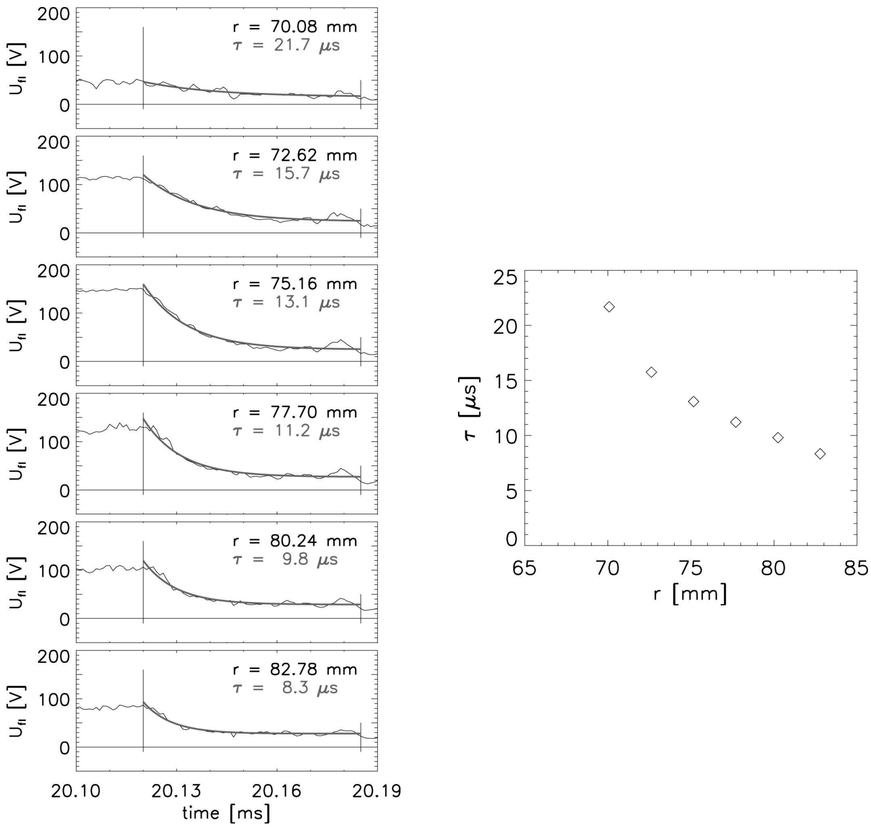

Fig. 2. Relaxation of the floating potential (from the level of $U_{\mathrm{fl}}^{\mathrm{B}}$ to $U_{\mathrm{fl}}^{\mathrm{OH}}$) measured by the rake probe tips at different radii after the electrode biasing is turned off (left panel). The radial profile of the characteristic exponential decay time τ (right pannel).

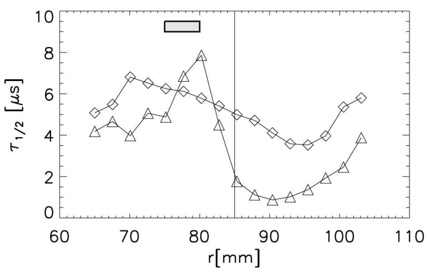

Fig. 3. Correlation time of floating potential fluctuations in the ohmic (diamonds) and polarized (triangles) phases of a discharge as determined from the rake probe data in # 11099 ($U_{\mathrm{B}} \approx +200\,\mathrm{V}$). The rectangular denotes the radial position of the polarization electrode.

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