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Highly resolved measurements of periodic radial electric field and associated relaxations in edge biasing experiments

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Abstract

High time-space resolved measurements of the radial electric field E_r and plasma rotations have been performed during edge biasing experiments in the CASTOR tokamak. During polarization, edge sheared $E_r \times B$ flow is routinely generated, triggering a transition to a global improved confinement and a formation of an edge transport barrier (ETB). Furthermore, on top of the biasing-imposed DC E_r, we observed, for the first time, concurrent fast periodic oscillations (dubbed as relaxations) on E_r, plasma rotations, edge recycling and the ETB as well. Although the global confinement improvements are not much affected by the relaxation event, the local edge plasma parameters and the ETB are substantially modulated during the oscillating phases. Moreover, throughout the relaxation period a possible link between the modulated radial transport and the toroidal plasma flow is found. The results support the paradigm of the nonlinear dynamical coupling and energy transfer between the turbulence eddies and plasma flows.

JNM keywords: Plasma Properties, Plasma-Material Interaction

PSI-17 keywords: Relaxations, Edge transport, Plasma Flow, Radial Electric Fields

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1. Introduction

The importance of the edge radial electric field (E_r) and its shear for plasma transport has already been recognized for a long time. Many theoretical models successfully studied the link between E_r and the formation of edge or internal transport barriers triggering an improved confinement [1, 2, 3]. The transition from low (L-mode) to high confinement (H-mode) can occur spontaneously or can be induced by an externally imposed electric field through edge biasing [4, 5, 6]. A biased electrode can drive a radial current in the plasma edge resulting in a $j_r \times B_\phi$ force and thus a sheared $E_r \times B_\phi$ poloidal flow, which may suppress turbulence and related transport [7]. Therefore, the radial electric field perturbs the plasma edge and acts as a trigger mechanism to modify the plasma confinement. However, hitherto a thorough understanding of the flow shear and its role in inducing confinement improvements is still a challenge for fusion researchers. Consequently, detailed studies on this subject are still needed.

In this paper, we report the experimental results performed during edge biasing experiments in the Czech Academy of Science Torus (CASTOR) tokamak [8]. In addition to the improvement of global confinement, fast relaxation events on E_r and related quantities during the biasing phase are also observed for the first time. The paper is organized as follows. In section 2, we describe the experimental set-up of the biasing experiments. The results and discussions are presented in section 3. Section 4 gives a summary and conclusions.

2. Experimental set-up

Polarization experiments were conducted on the CASTOR tokamak which has a major radius R_0 = 40 cm and a minor plasma radius a = 6.6 cm. An electrode was inserted from the top of the torus well inside the last closed flux surface (LCFS) (r/a = 0.6). To create an edge radial electric field E_r and its shear, a biasing voltage abruptly ramped from 0 to +260V was applied during the flat-top phase of a discharge, which typically has the following parameters: central chord-averaged plasma density $\overline{n}_{e,0}=1.0\times10^{19}m^{-3}$, plasma current $I_p=12$ kA and B_T = 1.3 T in ohmically heated hydrogen plasmas. A conventional rake probe, consisting of 16 radially separated Langmuir probe pins (radial separation between two adjacent pins = 2.54 mm) and located 40° toroidally from the electrode, was used to simultaneously measure the floating potential ϕ_f and ion saturation current I_s at various radial positions. A Gundestrup probe, located 180° toriodally from the electrode, was inserted from the top of the vessel to measure the toroidal and poloidal flow velocities. The Mach probe consists of eight collector plates surrounding a cylindrical boron nitride body [9]. The data were digitized at a sampling rate of 1 MHz for both the rake and Mach probe. The H_α diagnostic is located at the top of the vessel at the same toroidal location as the rake probe to monitor the radiation due to recycling with a sampling frequency of 40 kHz.

3. Experimental results and discussions

3.1 Global confinement improvement

The effects of the positive edge electrode biasing on the main plasma parameters are shown in Fig. 1 for a time interval of interest (a full discharge duration ≈ 30 ms). The figure shows time traces of the electrode voltage (V_E) and current (I_E), central line-averaged density $\overline{n}_e$, H_α emission and the ratio of $\overline{n}_e/H_\alpha$ along with the radial electric field E_r measured at r = 60 mm by the rake probe (radial derivative of ϕ_f on two adjacent pins). Before biasing, the electrode was grounded so no current flows between the electrode and the vessel. At about 10 ms, a positive biasing voltage $V_E \approx 260$ V is abruptly applied and maintained constant thereafter for ~5 ms, during which a current $I_E = -20$ A is drawn by the electrode, as seen in Fig. 1(a). In Fig. 1(b), it can be seen that during biasing, $\overline{n}_e$ is built-up gradually and reached 1.7×10^{19} m^{-3} at t = 14 ms before falling off to its original pre-bias value of 1×10^{19} m^{-3}. In the initial stage of the biasing, from 10 to 12.5 ms, we can see a clear reduction in recycling indicated by a drop in H_α emission, and thus, a net increase of the ratio $\overline{n}_e/H_\alpha$ (which is roughly proportional to the particle confinement time τ_p) by a factor of 4 with respect to the pre-bias case. All of these results indicate an improvement of the global particle confinement induced by the electrode biasing, as observed earlier [10]. After 12.5 ms, the H_α increases simultaneously with the C_{III} signal (not shown here), suggesting an overheating on the electrode head which contaminates the plasma. In Figs. 1 (c)-(e), the signals display periodic oscillations, which will be discussed in section 3.2. Fig. 2 further illustrates the influence of polarization on the radial dependence of edge plasma equilibrium parameters. In the figures, the radial profiles of the floating potential ϕ_f, E_r and its shear dE_r/dr, and ion saturation current I_s are obtained by averaging over a time window of 4 ms before (open symbols) and during (filled symbols) the biasing phase. Here, E_r is calculated directly from the radial derivative of ϕ_f neglecting the contribution from the T_e gradient, and therefore somewhat underestimated. These approximations are justified due to the very slight changes in edge T_e and ∇T_e before and during the biasing phase observed in similar biasing experiments. In the same context, it is assumed that the I_s profiles reflect mainly the changes in plasma density as $I_s \propto nT_e^{1/2}$. The radial position of the LCFS is around $r_{LCFS} = 66$ mm (indicated by dashed line in figures 2 and 3). During the biasing phase, the radial dependence of ϕ_f is strongly modified (see Fig. 2(a)), leading to a narrow positive and single-peaked E_r structure with a maximum of 11 kV/m at r ≈ 61 mm, just inside the LCFS (see Fig. 2(b)). As a consequence, a strong positive (~1.3MV/m^2) and negative (~ -1MV/m^2) E_r shear is generated inside and across the LCFS, respectively, as shown in Fig. 2(c). The maximum shear decorrelation rate of the E_r×B flow, $\tau_s^{-1} \propto dv_{\bar{E}\times\bar{B}}/dr$, is thus about 1-1.3×10^6 s^{-1}. On the other hand, we have calculated the decorrelation rate of local turbulence scattering, τ_{c0}^{-1}, from the e-folding time of the autocorrelation function of I_s fluctuation data detected before biasing, which gives τ_{c0}^{-1}= 1.6×10^5 s^{-1}. Thus, the flow shear rate significantly exceeds the turbulence decorrelation rate and hence reduces turbulence and turbulent transport [11]. The reduction in I_s and ϕ_f fluctuations during biasing has been observed in the present experiments. The reduced turbulent transport leads to a formation of the edge pedestal and thus steepening of the edge density profile during biasing, as shown in Fig. 2(d). From all the above facts, we conclude that a clear and reproducible transition to an improved confinement is induced by the edge electrode polarization along with a creation of a particle edge transport barrier just inside the LCFS. This barrier is characterized by a (i) substantial increase of the edge density gradient; (ii) reduction in recycling indicated by a drop in H_α signal; (iii) substantial increase of the global particle confinement time; (iv) suppression of the density and potential fluctuation level.

3.2 Periodic relaxation on E_r and related quantities

In these experiments, an important finding is the periodic relaxation behaviour of E_r and related quantities during the biasing period. As shown in Fig. 1(e), the E_r signal in the biasing phase (between 11-14 ms) clearly exhibits periodic oscillations (f ~ 10 kHz, amplitude 7 kVm^{-1}) on top of a DC E_r value (~ 11 kVm^{-1}). The concurrent oscillations in H_α and τ_p can also be seen in Figs. 1(c) and (d), respectively. These oscillations do not affect the global confinement properties, since the averaged values of H_α and τ_p evolve continuously with time. Nevertheless, a modulation on the edge transport barrier (ETB) can still be seen from the edge density profile on top of its average level. Plotted in Fig. 3 are the radial dependence of density ($\propto I_s$) at three different times. The reference one (open squares - pre-bias) is the same as that shown in Fig. 2(d), i.e. the averaged value detected prior to the biasing phase. The other two are measured at time t_1 and t_2, when the oscillating E_r is maximum and minimum, respectively, as indicated in Fig. 4. Fig. 3 clearly shows that (i) during biasing the averaged density gradient, i.e., average of profiles of t_1 and t_2, is much steeper than that of pre-bias profile; (ii) with oscillation of E_r, the density profiles change from a very steep one at t_1 to a less steep one at t_2, indicating a modulation of the ETB during the improved confinement stage. Meanwhile, it is found that the edge poloidal and toroidal plasma rotations also oscillate simultaneously with E_r at the same time period. We dub this phenomenon as a relaxation event (RE). The details of the RE are shown in Fig. 4 for a time window of 0.35 ms. Plotted in Fig. 4 are time traces of E_r, H_α, poloidal (v_θ) and toroidal (v_ϕ) plasma flow velocities measured at r=60 mm and I_s measured at two different radial positions (I_{s1} at r_1=53 mm, I_{s2} at r_2=68 mm) across the ETB region. The absolute value of the density gradient around the transport barrier $\left(\propto |\nabla I_s| = \left|(I_{s2}\text{-}I_{s1})/(r_2\text{-}r_1)\right|\right)$ is shown in Fig. 4(e). In Fig. 4(c), v_θ and v_ϕ are deduced from Gundestrup probe measurements using an improved one dimensional fluid probe model in which a constant $T_e = 35$ eV is assumed [12,13]. From the figures, we can see that E_r, v_θ and $|\nabla I_s|$ are changing in phase while v_ϕ and H_α vary out of the phase with E_r. The lowest order single ion radial force balance equation $E_r = \nabla_r P_i / n_i Z_i e - v_{\theta,i} B_\phi + v_{\phi,i} B_\theta$ has been checked using the measured quantities, where P_i denotes the ion pressure and $Z_i e$ the electric charge. It has been found that the equation is well verified throughout the oscillation phase. Moreover, the in-phase-oscillations between E_r and v_θ and the out-of-phase-oscillations between E_r and ∇I_s ($\propto \nabla P_i$) indicate that the diamagnetic term ∇P_i alone cannot account for the development of the E_r oscillations, but are rather dominated by the poloidal flow oscillations. The overall feature of the E_r relaxation can be further illustrated by a one-period process. First, E_r increases gradually to its threshold value (18kV/m) at t_1. Meanwhile, v_θ and $|\nabla I_s|$ increase, whereas H_α drops indicating an increase of poloidal sheared flows, decrease of the local particle flux and strengthening of a local transport barrier (see profile at t_1 in Fig. 3). From t_1 to t_2, with the relaxation of E_r from its maximum to bottom, the concomitant drop in $|\nabla I_s|$ and increase in H_α reveal a fading of the local barrier, as shown also in Fig. 3 by the profile at t_2. It is interesting to see that, throughout the above process, the behaviour of the toroidal flow, v_ϕ, is completely different from that of E_r and v_θ, but follows the variation of the radial transport. For example, from t_1 to t_2, with the fading of the local transport barrier, the flattening of the edge density profile implies an enhancement of outflux, which may transfer energy to the toroidal flow via dynamical coupling and thus increases v_ϕ substantially. This coupling can occur through the turbulence-driven Reynolds stress. Similar phenomena for the nonlinear dynamical interaction between the turbulent transport and the toroidal flow have been reported on JET [14, 15] in non-biasing experiments, where, in particular, the large scale components (~ 12.5 kHz) show dominant effects. In our case, the periodic link between the turbulent transport and the parallel flow takes place at an almost fixed frequency of $f \approx 10$ kHz, which is probably triggered by E_r and interestingly close to the dominant frequencies in JET. Further investigation on the mechanism of the oscillations is still underway.

4. Conclusion

In conclusion, the results of highly resolved spatio-temporal measurements of the edge radial electric field E_r and plasma rotations during the edge polarization experiments in the CASTOR tokamak have been presented. With biasing, a clear and reproducible transition to an improved confinement is routinely observed along with the formation of an edge transport barrier. Furthermore, we observed for the first time the concurrent fast periodic relaxations on E_r, plasma rotations, edge recycling and the edge transport barrier during the globally improved confinement phase on top of the biasing-imposed DC E_r. The oscillation event does not much affect the global confinement properties, but does modulate the local edge plasma parameters and the transport barrier as well. During the oscillating phase, E_r and associated quantities well obey the radial force balance E_r-equation, suggesting a radial equilibrium of the local parameters unaffected in the process. In addition, a possible link between the relaxation of the radial transport and the parallel flow is evidenced during the relaxation process of E_r, which supports the paradigm of the nonlinear dynamical coupling and energy transfer between the turbulence eddies and zonal (or mean) flows.

Acknowledgments

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Figure Captions

Fig. 1 Time evolution of plasma parameters during a typical edge electrode biasing experiment on CASTOR (shot No. 24076). (a) the electrode voltage V_E (thick line) and current I_E (thin line), (b) the central line-averaged electron density $\overline{n}_e$, (c) H_α radiation, and (d) the ratio of $\overline{n}_e / H_\alpha$. Shown in (e) is the time trace of the radial electric field measured at r = 60 mm.

Fig. 2 Radial profiles of (a) the floating potential ϕ_f, (b) the radial electric field E_r, (c) the E_r shear, and (d) the ion saturation current I_s averaged over 4 ms before (open symbols) and during (filled symbols) the polarization, where ϕ_f and I_s are measured by a rake probe. The vertical dashed line marks the position of the LCFS.

Fig. 3 Radial ion saturation current profiles measured by a rake probe at three different times. The curve of "pre-bias" is the averaged value detected before the biasing phase (the same as in Fig. 2(d)). The other two are the I_s-profiles measured at times t_1 and t_2 indicated in Fig. 4. The vertical dashed line marks the position of the LCFS.

Fig. 4 Time evolution of (a) E_r, (b) H_α, (c) poloidal v_θ (thin line) and toroidal v_ϕ (thick line) velocities measured at $r = 60$ mm, (d) I_{s1} (thin line) and I_{s2} (thick line) measured by a rake probe at $r_1 = 53$ mm and $r_2 = 68$ mm, respectively, and (e) $|\nabla I_s| = |(I_{s2}\text{-}I_{s1})/(r_2\text{-}r_1)|$ showing oscillations of the signals. The two dashed vertical lines mark the times when a relaxation of E_r starts (t_1) and ends (t_2).

Figures

Fig. 1

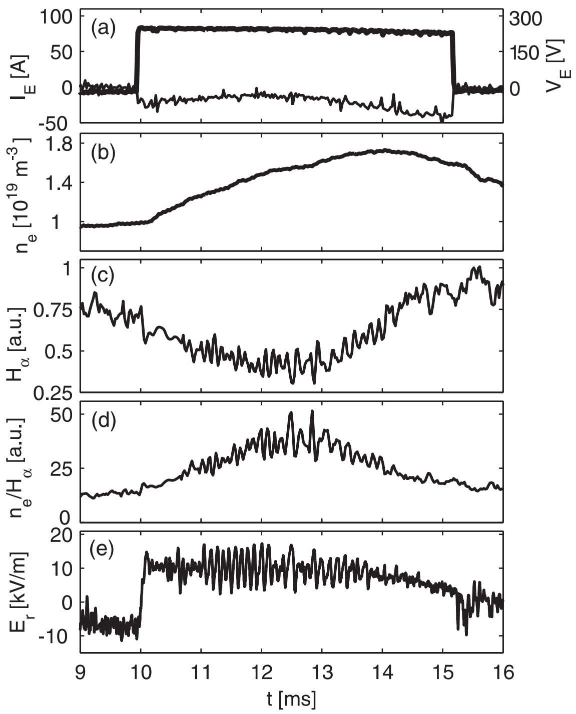


Fig. 2

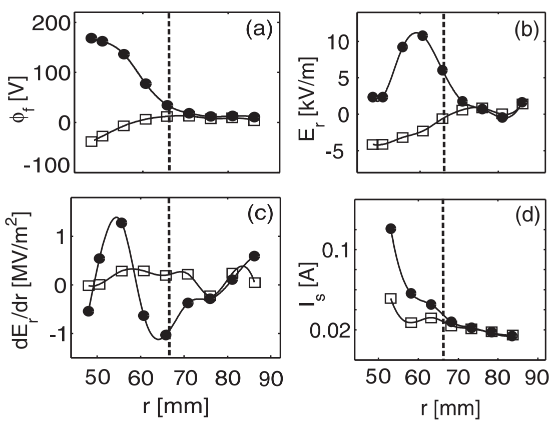


Fig. 3

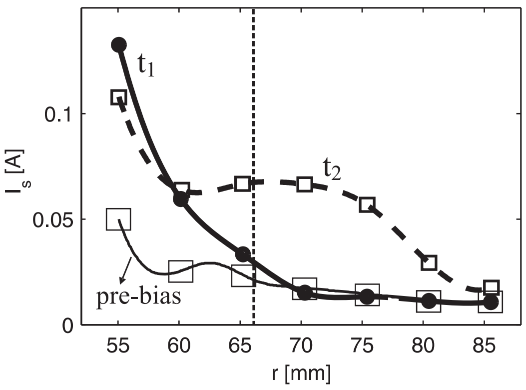
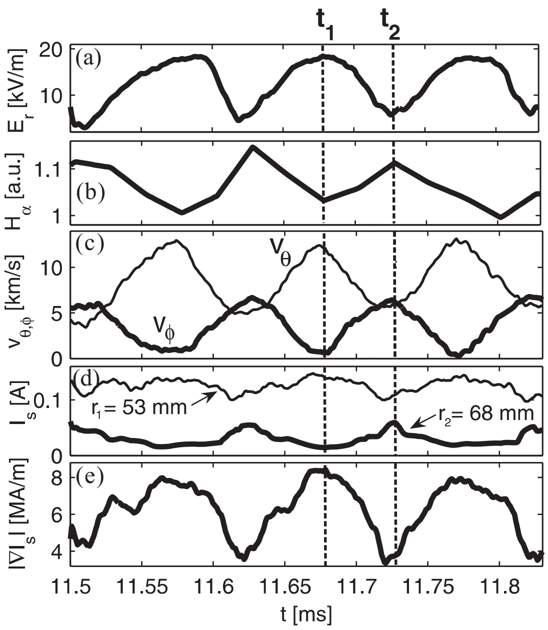

t1
t2
pre-bias
Is [A]
0.1
0.05
0
55
60
65
70
75
80
85
r [mm]

Fig. 4


t1
t2
(a)
(b)
(c)
(d)
(e)
Er [kV/m]
Hα [a.u.]
vθ,φ [km/s]
vθ
vφ
Is [A]
r1 = 53 mm
r2 = 68 mm
|∇Is| [MA/m]
11.5
11.55
11.6
11.65
11.7
11.75
11.8
t [ms]