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JT-60UのType-I ELMy Hモードにおけるプラズマ周辺部の径電場の時空間構造

Spatio-temporal structure of the edge radial electric field in JT-60U Type-I ELMy H-mode plasmas

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Introduction

The radial electric field and its associated shear play a key role for plasma stability and enhanced plasma confinement [1]. The phenomenon of spontaneous generation of the sheared ExB flow is observed in nearly all tokamaks at the plasma peripheral region of just inside the separatrix after the L-H transition, in which there is a strong (or complex) relationship with the plasma turbulence and transport.

Observations from small/medium sized devices suggest that the causality of the L-H transition could be related to the bifurcation of the edge radial electric field as predicted by a theory [2, 3], which was partially supported by experiments with H-modes produced by direct biasing of plasma at just inside the separatrix. In addition, E_r-shear stabilization effects have also been observed in many deices. However the exact causality seems to be still unclear, including the origin of the various parameter dependences of the threshold power for the L-H transition in terms of the E_r bifurcation at the plasma edge region. Furthermore, the effect of E_r-curvature on the turbulence suppression, including its dependence on the sign, is important for considering the nonlinear effects resulting in a radial squeezing or broadening of the turbulent eddies [4]. It needs a more detailed experimental and theoretical verification based on a high-resolution measurement with a better signal-to-noise ratio.

On JT-60U, we measured the radial profiles for the density, temperature, and poloidal/torodal plasma flows for the fully stripped carbon impurity ions using CXRS diagnostic with fast time resolution (up to 400 Hz) at 59 spatial points (23 toroidal and 36 poloidal viewing chords). The radial electric field, pressure gradient and plasma velocity perpendicular to the magnetic field are governed by the following radial force balance equation:

$$E_r = \nabla p_j/(Z_j e n_i) - V_{\theta,j}B_{\phi} + V_{\phi,j}B_{\theta} \quad (1)$$

With regard to determining the edge radial electric field, by means of conditional averaging method as defined by the time of the measurement relative to the ELM event, an improved signal-to-noise ratio (S/N) was achieved (in particular, pre- and post-ELM phases).

Experimental results

We performed the following H-mode experiments having Type-I ELMs (f_{ELM}~30-50 Hz), comparing the external momentum input directions between co- (discharge E049228) and counter- (discharge E049229) cases as shown in Fig. 1.

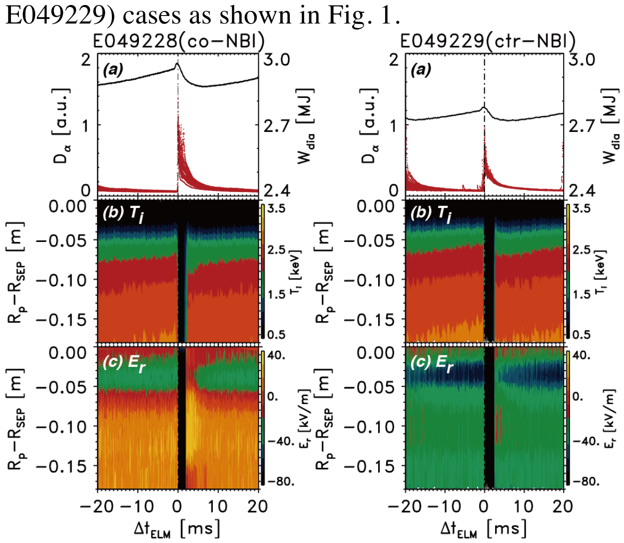

Fig. 1 Temporal evolutions of (a) D_α and W_{dia}, (b) T_i and, (c) E_r, comparing between co- (left column) and counter-NBI discharges (right column) as function of the time relative to the ELM-even, δt_{ELM}. The plasma current, I_P, was 1.6 MA, and the toroidal magnetic field, B_T, was 3.9 T. The corresponding q_{95}, was thus 4.2. The elongation, ϰ, and triangularity, δ, were 1.47 and 0.36, respectively.

As illustrated in Figs 2(a) and (b), the location of the $T_{i,ped}$ at the ELM-onset shifts inwards when $V_{\phi,ped}$ is enhanced in the co-direction. On the other hand, the E_r-well bottom value becomes large when $V_{\phi,ped}$ is enhanced in the counter-direction as shown in Fig. 2(c). The E_r-shear values for both cases are almost zero at which the normalized T_i gradient (as expressed by the inverse scale length of the ion temperature, L_{Ti}^{-1}) has a local maximum value, R_L_{Ti}^{-1}, while R_L_{Ti}^{-1} can be seen near the location at which E_r and/or its curvature (E_r'') have local peak values as shown in figure 1 (c) and (d). It should be noted that this trend described above is confirmed by a various cases, including post-ELM phases.

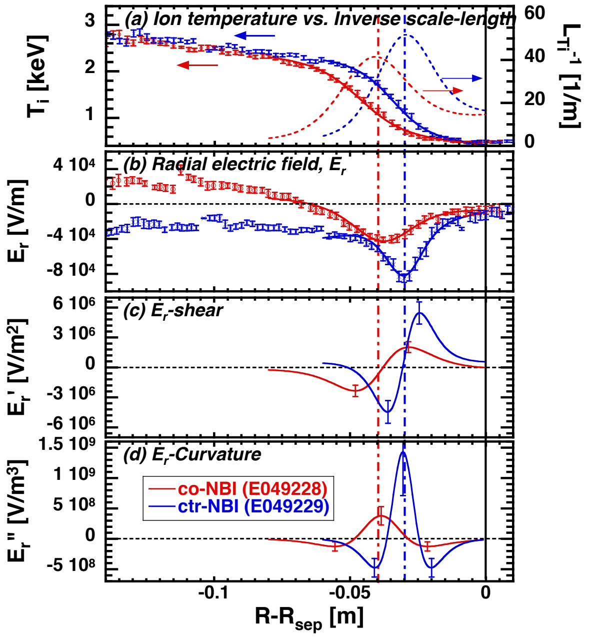

Fig. 2 Radial profiles of (a) T_i *and* $L_{Ti}^{-1} \equiv -\nabla T_i/T_i$*, (b)* E_r*, (b)* E_r'*, and (d)* E_r''*, comparing between co- (red line) and counter-NBI discharges (blue line) as function of the distance from separatrix* $R-R_{SEP}$*. The data are measured just before a set of reproducible ELMs (80-90% intervals of the ELM cycle). Vertical dash dot lines correspond to the locations at which* L_{Ti}^{-1} *has a local maximum value.*

Comparison with theory

An important caveat to this discussion is that the E_r-shear (E_r') stabilization effects (∝ E_r'E_r') have a double hump structure, since the sign in the E_r' can change when E_r structure has a local peak value (regardless of E_r-well or –hill structures) but we have never observed a double hump structure in the gradient of the temperature and density (and hence, pressure) profiles in the pedestal region.

Because of the importance of the localized radial electric field for the transport barrier formation at the pedestal, we have made a comparison between these experimental results [5, 6] and theoretical model [7].

In the previous publication [8], it was shown that the radial electric field jumps to a larger value during an ELM-free H-mode phase, while the ion temperature gradient does not change much simultaneously. This phenomenon happens in the parameter regime of the absolute value of the radial electric field, $|E_r| \approx T_i/(e\rho_{\theta i})$ as shown in Fig. 3, at which E_r-bifurcation is associated with n=0 fluctuation [9]. Here, the $\rho_{\theta i}$ is ion poloidal Larmor radius. It has been pointed out theoretically that the strongly localized radial electric field structure could be self-organized owing to the nonlinear dependence of the radial current on the radial electric field, $J_r(E_r)$, [7]. According to the model, the radial scale length of the isolated peak of radial electric field, ℓ, is given (for the plateau regime) as

$$\ell^2 \approx \chi_i^{NC}/\omega_{T_i} \qquad (2)$$

where the χ_i^{NC} is the ion thermal conductivity and ω_{T_i} is the ion transit frequency, $\omega_{T_i} \equiv C_S/qR$, C_S is ion sound speed, q is safety factor, and R is major radius. In deriving the result from Ref. 10, an approximation that the neoclassical perpendicular viscosity is close to the neoclassical ion thermal conductivity, and a neoclassical model of $J_r(E_r)$ is employed according to Ref. 7. This relation provides an order of magnitude estimate as

$$E_r E_r'' \approx -[T_i/(e\rho_{\theta i})]^2/(\epsilon \rho_b^2) \qquad (3)$$

where the ϵ is inverse aspect ratio, and ρ_b is ion banana width. If experimental plasma parameters are substituted into this relation, the RHS gives an order of $\approx 10^{13\sim14}$ $[V^2/m^4]$. This value is not far from experimental observation as illustrated in Fig. 1(c) and (d). This comparison encourages future experimental test of the bifurcation model, by comparing the time scale of transition, to the observation in the relevant tokamak experiments.

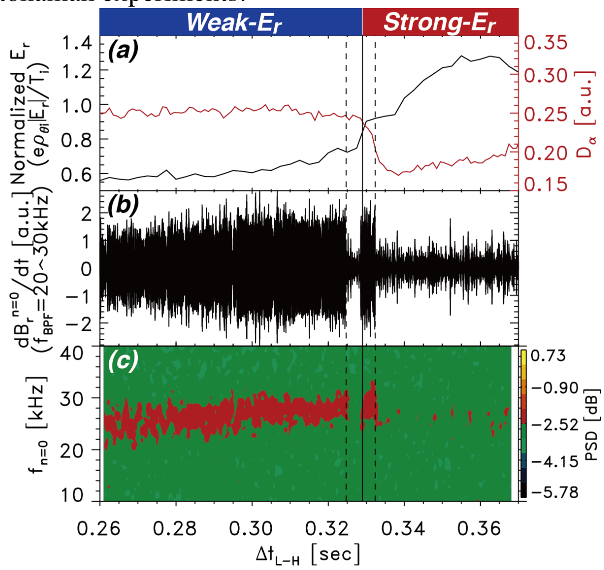

Fig. 3 Time history for (a) normalized E_r *and Dα intensity, (b) amplitude for n = 0 component in the magnetic fluctuation, and (c) frequency and time resolved spectrogram for n = 0 component in the magnetic fluctuation detected by the sum of eight channel saddle loop arrays (toroidal).*

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