Self-driven Current Generation in Turbulent Fusion Plasmas

W. X. Wang[1], E. Startsev[1], S. Ethier[1], J. Chen[1], M. G. Yoo[1], C. Ma[1], T. S. Hahm[2]
[1]Princeton Plasma Physics Laboratory, P. O. Box 451, Princeton, New Jersey 08543, USA
[2]Seoul National University, Seoul, Korea

wwang@pppl.gov

Abstract. Plasma self-generated current (e.g., bootstrap current) contributes to the generation of poloidal magnetic field for plasma confinement in tokamaks, and also strongly affects key MHD instabilities. It is found that plasma turbulence may strongly influence self-driven current generation. This could have a radical impact on various aspects of tokamak physics. Our simulation study employs a global gyrokinetic model coupling self-consistent neoclassical and turbulent dynamics with focus on mean electron current. Distinct phases in electron current generation are illustrated in our initial value simulation. In the early phase, before turbulence develops, the electron bootstrap current is established in a time scale of a few electron collision times, which closely agrees with the neoclassical prediction. The second phase follows when turbulence begins to saturate, during which turbulent fluctuations are found to strongly affect electron current. The profile structure, amplitude and phase space structures of electron current density are all significantly modified, relative to the neoclassical bootstrap current, by the presence of turbulence. Both electron parallel acceleration and parallel residual stress drive due to turbulence are shown to play important roles in turbulence-induced current generation. The former can change the total plasma self-generated current through turbulence-induced momentum exchange between electrons and ions, while the latter merely modifies the current density profile while keeping the total current unchanged. In particular, the residual stress may drive a strong current profile corrugation around a low-order rational magnetic surface. The current density profile is modified in a way that correlates with the fluctuation intensity gradient and zonal flow shearing rate through their effects on $k_\parallel$-symmetry breaking in the fluctuation spectrum. Turbulence is shown to reduce (enhance) plasma self-generated current in low (high) collisionality regime, and the reduction of total electron current relative to the neoclassical bootstrap current increases as collisionality decreases. The implication of this result to the fully non-inductive current operation in steady state burning plasma regime could be important and should be investigated. Finally, a significant non-inductive current is observed in flat pressure region, which is a nonlocal effect and results from turbulence-spreading-induced current diffusion.

I. Introduction

Plasma self-generated non-inductive current (e.g., bootstrap current) plays a fundamental role in magnetic fusion. It contributes to the generation of poloidal magnetic field for plasma confinement in tokamaks, and also strongly affects key magnetohydrodynamic (MHD) instabilities, such as neoclassical tearing mode (NTM) and edge localized mode (ELM). A well known non-inductive current is the bootstrap current along the magnetic field, which is driven by pressure and temperature gradients in toroidal geometry, and is associated with the existence of magnetically trapped particles. The bootstrap current was predicted by neoclassical theory [1, 2] and later discovered in tokamak experiments [3] afterward. It is worthwhile noting that the direct measurement of plasma self-generated current is itself very difficult. Usually, total plasma current (sum of all current contributions and volume-integrated) rather than current density is measured in experiments. Experimental data indicates that the plasma self-generated current is roughly within the range of neoclassical bootstrap current, but with significant variations up to a few tens of percent in present-day tokamak devices [4, 5]. There are experimental evidences indicating more significant deviations seeming to appear in the edge pedestal region. For future steady state burning plasma experiments, it is of great interest to explore fully non-inductive current operation with a high bootstrap current fraction. Generally, magnetically confined fusion plasmas are not turbulence-free due to various micro-instabilities driven by free energy in plasma profile gradients. The aforementioned critical research interests provide a strong motivation for us to investigate turbulence effects on plasma current self-generation in fusion devices [6]. Critical questions include: how is neoclassical bootstrap current modified in the presence of turbulence? can turbulence drive a plasma current? More generally, turbulence-driven plasma current generation is a critical, highly interesting issue in the broad field of space plasma and astrophysical phenomena in the context of turbulence-driven dynamo.

II. Effects of turbulence on electron current generation

This simulation study employs a global gyrokinetic model that couples self-consistent neoclassical and turbulent dynamics [7], unlike typical gyrokinetic turbulence simulations which usually exclude neoclassical physics. A number of nonlinear gyrokinetic simulations have been carried out for broad plasma conditions relevant to DIII-D, NSTX and C-MOD experiments and in various turbulence regimes covering collisionless trapped electron mode (CTEM), dissipative trapped electron mode (DTEM) and ion temperature gradient mode (ITG). More specifically, for results presented in this paper, we use the core plasma profiles of an NSTX H-mode [8] (Fig. 1), along with a real DIII-D or NSTX equilibrium. Our study focuses on the mean current of electrons, which forms the majority of plasma self-driven current. Because of strong density gradient in the central core region (Fig. 1), the turbulence effects considered in this study come from CTEM for the DIII-D case and DTEM for the NSTX case [7].

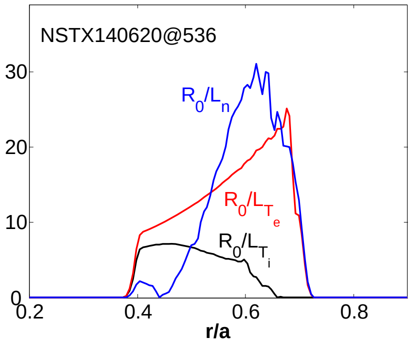

Figure 1: Radial profile of plasma temperature and density gradients from an NSTX H-mode discharge.

It is found that plasma turbulence may strongly influence plasma self-driven current generation, which, consequently, is expected to radically impact various aspects of tokamak physics. Our initial value simulation, including both neoclassical and turbulence physics, follows plasma evolution in a time scale much longer than electron collision time, first to a neoclassical equilibrium state for electrons and then to a quasi-steady state with fully developed turbulence. Following the system evolution, we observe very interesting changes in the electron current generation. The contour plots in Fig. 2 show the spatial distribution of electron parallel current density which is calculated from the simulated non-adiabatic electron distribution δh_e:

$$j_{e,\|}B \equiv e \int v_{\|} B \delta h_e d^3 v.$$

Note that adiabatic electrons do not contribute to the mean electron parallel current. The early neoclassical phase (before turbulence develops) typically lasts for 10 to 100 electron collision time, which is long enough for electrons to reach neoclassical equilibrium. The neoclassical current is non-uniform on magnetic surfaces and locates mostly on the low field side (the left of Fig. 2). This spatial structure of neoclassical current is changed significantly as the instability (i.e., CTEM) starts to grow and saturates (see middle of Fig. 2). In the well developed, quasi-stationary turbulence phase, the simulated electron current shows rich fine scale structures in addition to the large scale (0, 0) component (right of Fig.2).

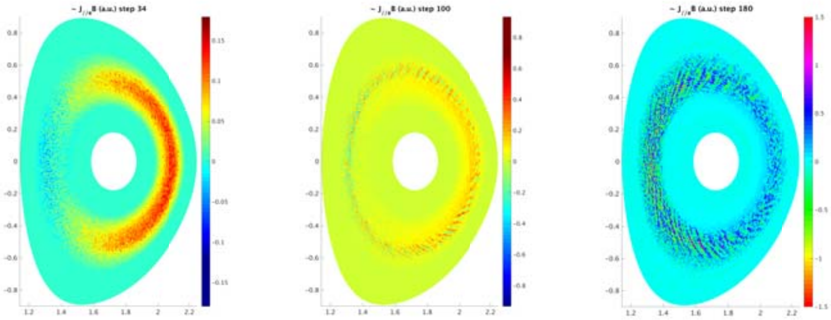

Figure 2: Contour plot of electron parallel current in early neoclassical phase (left), CTEM development phase (middle) and well developed turbulence phase (right).

Now we focus on the large scale (0, 0) component, namely the flux-surface averaged mean electron current density. The spatio-temporal evolution of the parallel current density shows the evolution of the current from early neoclassical phase ($t < 14\tau_{ei}$), followed by a transition phase during which CTEM starts to grow and saturates, and to a fully developed turbulent phase (left of Fig. 3). In the early neoclassical phase, a stationary electron bootstrap current is established in a time scale of a few electron collision times to a level which closely agrees with the neoclassical prediction (see middle of Fig.3). During CTEM growth and saturation, the electron current is largely modified. As the system evolves into a fully developed, quasi-stationary turbulence state, the current also settles down to a new steady state, with its amplitude, however, significantly different from that of the early neoclassical bootstrap current (see middle of Fig.3). The radial profiles of the current density are obtained by taking time averages over the neoclassical phase and the stationary turbulent phase. It shows that the simulated current profile, which closely reproduces the neoclassical bootstrap current profile in early turbulence-free phase, is substantially modified by the presence of CTEM turbulence (see right of Fig.3). The influence of CTEM on plasma self-driven current generation can be considered to drive an additional current, which, in this case, is positive (negative) in the outer (inner) side of the turbulence region. In addition, CTEM fluctuations are also found to modify the current profile by introducing fine scale corrugations near rational surfaces [6].

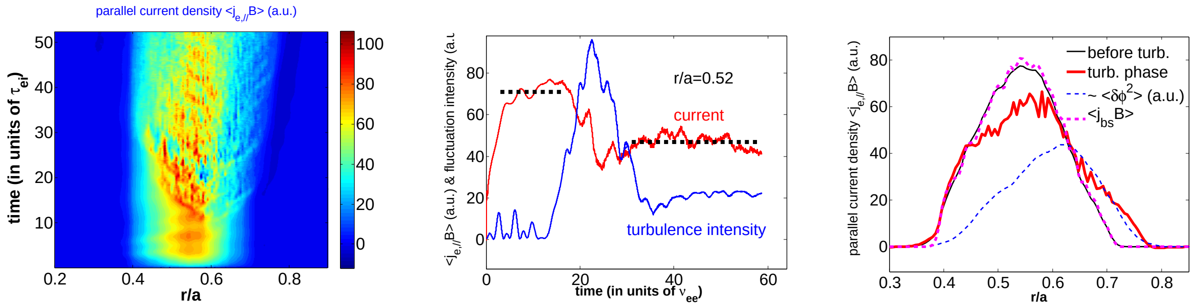

Figure 3: Spatio-temporal evolution of mean electron current density (left), time evolution of current density and turbulence intensity at a mid-radius (middle), and simulated stationary current density profile in neoclassical phase and fully developed turbulent phase (in comparison with neoclassical prediction of bootstrap current) and potential fluctuation intensity profile in turbulent phase (right). Simulation was carried out with GTS code for a DIII-D geometry and ∇n-driven CTEM turbulence.

The velocity space structure of electron current density is also significantly changed by turbulence, as illustrated in Fig.4. It is well known that the neoclassical bootstrap current originates from the diamagnetic effect associated with drift orbits, along with collisions. The neoclassical diamagnetic effect of trapped particles produces an asymmetry in the trapped particle distribution function $f_t(v_\parallel)$, and collisional momentum exchange between trapped and passing particles further introduces an asymmetry into passing particles, leading to an overall asymmetry in the distribution function (see the upper left of Fig.4). The simulated equilibrium electron distribution function in the early neoclassical phase produces the consistent velocity space structure (the upper middle of Fig.4), and associated bootstrap current distribution in velocity space is shown in the upper right of Fig.4. In the turbulent phase, CTEM fluctuations can drive the electron distribution function largely away from neoclassical equilibrium, and the perturbed non-adiabatic electron distribution function is found to be dominated by deeply trapped electrons (lower left of Fig.4). Correspondingly, the perturbed electrons of $\pm v_\parallel$ contribute to the parallel current in opposite directions, which, however, does not cancel with each other, resulting in a net parallel current (lower right of Fig.4).

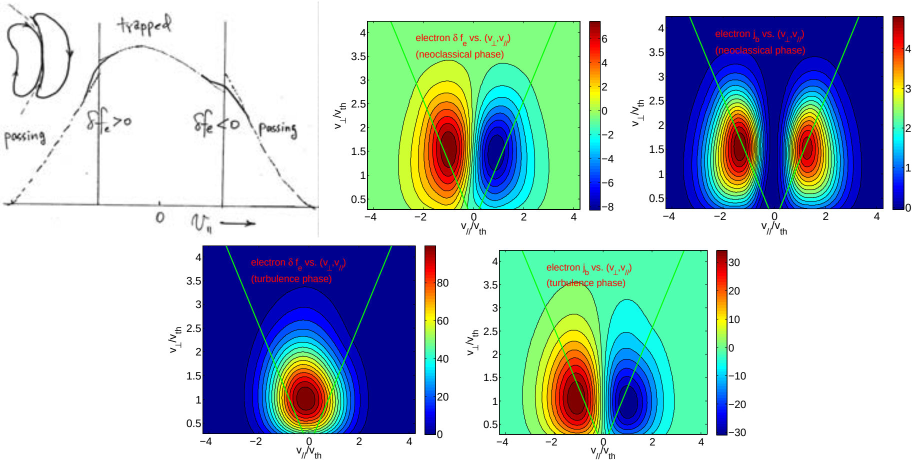

Figure 4: Schematic diagram of distribution function due to neoclassical diamagnetic effect and collisions (upper left); velocity space structure of perturbed electron distribution function in the neoclassical phase (upper middle) and turbulent phase (lower left); the corresponding electron parallel current density in the the neoclassical phase (upper right) and turbulent phase (lower right). The straight lines denote boundaries of trapped and passing electrons.

One interesting result obtained from the simulations is that a significant mean current can be generated in the flat pressure region, as seen in the right of Fig.3 ($r/a > 0.7$). In this outer core region, all plasma profiles ($T_e(r)$, $T_i(r)$ and $n_e(r)$) are flat, and therefore, the bootstrap current is close to zero and all drift waves are linearly stable. Turbulent fluctuations due to ∇n-driven CTEM in the inner core region, however, can penetrate into the outer core region through turbulence spreading [9]. Following turbulence spreading, the current can gradually diffuse toward the linearly stable zone, as illustrated in Fig.5. This current is fully driven by fluctuations and not associated with local profile gradients. This nonlocal, anomalous current generation mechanism found in the simulations may have important implications. Firstly, it may provide a possible source for seed current near the magnetic axis. Secondly, this nonlocal mechanism may allow ambient turbulence to drive an anomalous current inside a magnetic island, and consequently impact NTM dynamic. These two interesting issues need to be further investigated.

III. Turbulent mechanisms for anomalous current

The underlying dynamics for turbulence-driven current generation may be linked to electron parallel momentum transport and flow generation [6]. The current generation in toroidal plasmas can be described through a generalized neoclassical Ohm's law [10, 11]:

$$\langle (j_\parallel - j_{bs}) B \rangle = \sigma_{neo} \langle E_\parallel^{\text{ind}} B \rangle + \langle j_{dyn} B \rangle. \tag{1}$$

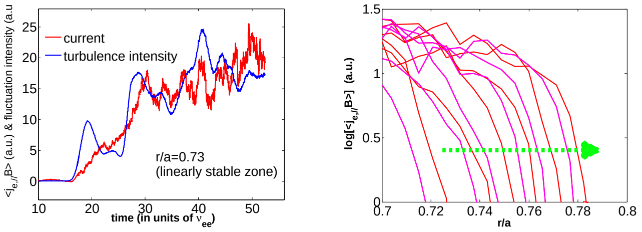

Figure 5: Time history of fluctuation intensity and current density at a radial location of linearly stable zone (left), and time evolution of fluctuation intensity profile in the linearly stable zone (right).

The first term on the right hand side represents the inductive current driven by an inductive electromotive force. Turbulent waves may also contribute a dynamo electromotive force which can drive a dynamo current (the second term). External current drive due to, for example, NBI, LHCD, etc. can contribute a non-inductive current. The turbulence driven dynamo current may essentially relate to two effects. The first one is turbulent parallel acceleration, which can drive an electron current against resistive decay [10, 12 - 15] , as expressed as follows:

$$j_{\|,turb} \sim \tilde{E}_{\|}\tilde{n}^{*}e^{2}/m_{e}\nu_{ei} \sim \langle k_{\|}\delta n_{k}^{2}\rangle. \tag{2}$$

This effect involves nonlinear beating between parallel electric field and density fluctuations, which is shown to be proportional to $\langle k_{\|}\delta n_{k}^{2}\rangle$. It is important to notice that a finite value of $\langle k_{\|}\rangle$ (averaged) is needed for turbulence acceleration. This effect originates from the turbulence-induced momentum exchange between electrons and ions. While this effect does not change the total momentum of electrons and ions, the momentum transfer from ions to electrons may effectively induce a current in the electrons because of the large ion-to-electron mass ratio, which results in a change in total plasma self-driven current. The second effect is due to divergence of parallel electron momentum radial flux $\Pi_{r,\|}$ [10, 13 - 15], which can drive a current as

$$j_{\|,turb} \sim \nabla \cdot \Pi_{r,\|}/m_{e}\nu_{ei}. \tag{3}$$

Since it appears in the transport equation of parallel electron momentum as a divergence form, apparently, this effect does not change the total electron current, but causes a current redistribution (namely, change of electron current density profile). Particularly, there is a significant, non-diffusive contribution to the parallel electron momentum flux due to residual Reynolds stress, as observed in the previous simulations of turbulence-driven current [6]. The residual parallel Reynolds stress is determined by $\Pi_{r,\|}^{\mathrm{RS}} \sim \langle k_{\theta}k_{\|}\delta\phi_{k}^{2}\rangle$ which invokes $\langle k_{\theta}k_{\|}\rangle$, a correlator of two wave number components k_{θ} and $k_{\|}$. As k_{θ} is always finite, a non-vanishing residual parallel stress is sensitive to a finite value of $k_{\|}$ (on average). Interestingly, an averaged finite $k_{\|}$ is critical for both effects to be efficient. Therefore, the physics of $k_{\|}$-symmetry breaking of the fluctuation spectrum, which has been extensively studied in the problem of turbulence-driven intrinsic rotation generation [16- 18], enters and also plays a central role in the current generation by turbulence.

Further analysis shows that both turbulence-induced parallel acceleration and residual stress drive can play important roles for driving electron current under different situations. The results discussed so far are obtained for an L-mode DIII-D equilibrium with normal magnetic shear in the entire radii. As shown in the right of Fig.3, the CTEM-induced current in this case appears to be essentially in a large scale, and switches direction at $r/a \sim 0.63$ (namely, negative in inner core region and positive in the outer core region). Fig.6 shows the radial profile of $\langle k_{\|}\delta n_{k}^{2}\rangle$ estimated in the same time period of the turbulent phase as that for the corresponding current in Fig.3. This quantity is a measure of the electron parallel acceleration effect, which is found to change sign at roughly the same radial location as that for the turbulence-induced current. The change of sign is linked to the sign change in the spectrum-averaged $\langle k_{\|}\rangle$. In this case, the

$k_\parallel$-symmetry breaking is mainly caused by turbulence intensity gradient, which is positive in the inner side of $r/a \sim 0.63$ and negative in the outer side (see turbulence intensity profile plotted on the right of Fig.3), leading to $\langle k_\parallel \rangle$ and the associated turbulence acceleration to change direction.

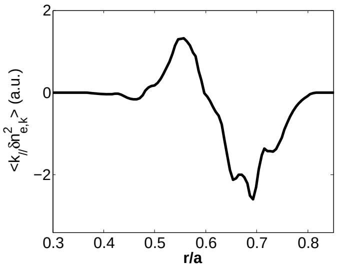

Figure 6: Radial profile of of turbulence-induced electron parallel acceleration $\sim \langle k_\parallel \delta n_k^2 \rangle$. This result is from the same simulation as that of Fig.3.

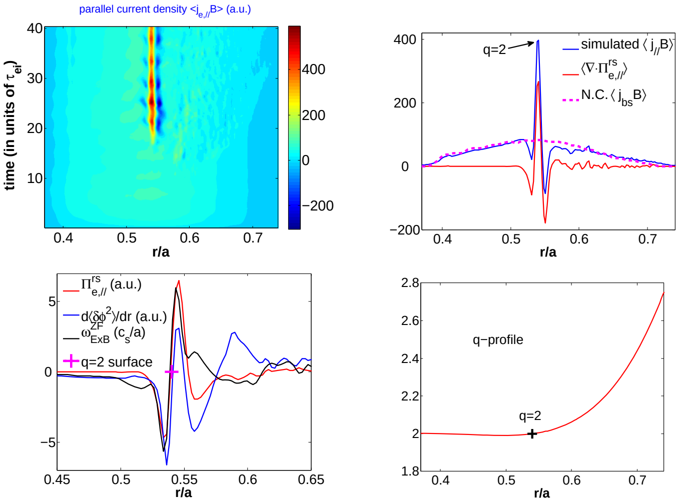

Figure 7: Spatio-temporal evolution of simulated electron current density (upper left); turbulence-modified electron current density profile in comparison with neoclassical bootstrap current, and radial profile of divergence of simulated electron residual parallel Reynolds stress (upper right); radial profile of electron residual stress, turbulence intensity gradient and zonal flow shearing rate (lower left); and q-profile of MHD equilibrium for this simulation (lower right).

Next, we present an interesting case and simulation results which highlight the effect of turbulence-induced parallel Reynolds stress on driving anomalous current. As a key feature, this case has a flat q-profile with $q = 2$ in the inner core region, as shown in the lower right of Fig.7. As shown in the spatio-temporal evolution of electron parallel current density (upper left of Fig.7), the development of the self-driven current in the simulation undergoes a neoclassical phase, which is about $20\tau_{ei}$ long, to the stationary turbulent phase. Again, in the neoclassical phase, the simulated electron current closely agree with the neoclassical bootstrap current. Turbulence, which develops late in the central core region, is found to modify the bootstrap current by generating a strong, localized corrugation in the current profile, with a spike at the $q = 2$ surface. This is seen more clearly in the radial profile of the time averaged current density (blue curve of upper right panel of Fig.7). The scale length of the radial corrugation is about $(5 - 10)\rho_i$. Also plotted on the upper right of Fig.7 is the divergence of electron residual parallel Reynolds stress $\Pi^{rs}_{e,\parallel}$ (red curve). There exists a close correlation between the red and blue curves, clearly indicating that the fine scale anomalous current around the $q = 2$ surface is driven by the electron residual parallel stress. As for the cause of $k_\parallel$-asymmetry needed for the generation of this nontrivial residual stress profile by turbulence, it is found that both the fluctuation intensity gradient and turbulence self-generated zonal flow shear make dominant contributions. This is evident from the lower left of Fig.7, which shows that the electron residual stress (red curve) closely correlates with both the intensity gradient (blue curve) and the zonal flow shearing rate (black curve) in the region of corrugated current profile.

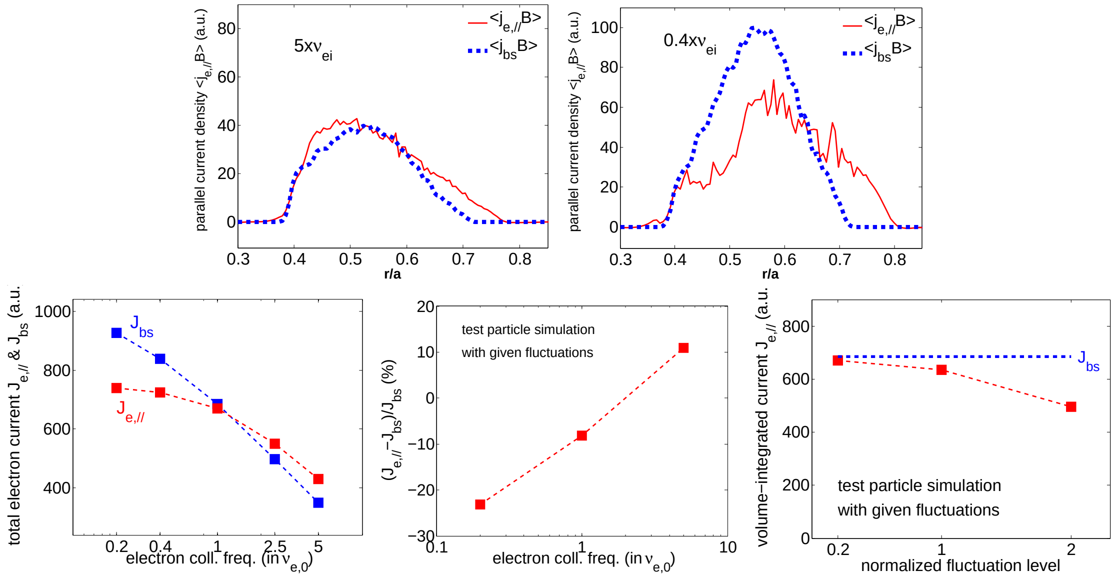

Figure 8: Electron current density profile simulated with with increased (upper left) and reduced (upper right) electron collision frequency, in comparison with the corresponding neoclassical bootstrap current; simulated total electron parallel current and the total neoclassical bootstrap current as a function of electron collision frequency (lower left); relative difference between the total electron current computed by test particle simulations with prescribed fluctuations and the total neoclassical bootstrap current as a function of electron collision frequency (lower middle); and total electron current computed by test particle simulation as a function of fluctuation level (lower right).

IV. Collisionality dependence of self-driven current in turbulent plasmas

The characteristic dependence of the turbulence effect on plasma self-driven current generation has been studied. Since future steady state tokamak experiments will rely on fully non-inductive current with a major contribution from plasma self-driven current for generating poloidal magnetic field for plasma confinement, we are particularly interested in plasma self-driven current generation in low collisionality regime and large-size machines relevant to burning plasmas experiments, such as ITER. To this end, we have carried out a series of nonlinear simulations by artificially changing the electron collision frequency, but with all other parameters identical to those for the simulation presented in Fig.3. The results of simulated electron current density profiles at higher and lower collisionality in comparison with the corresponding neoclassical bootstrap current are presented in the top of Fig.8. It is shown that turbulence not only modifies the current density profile, but also changes the total current. Notice that the neoclassical bootstrap current itself is sensitive to the collisionality, specifically, increasing with decreasing collisionality. It is found that the influence of turbulence on bootstrap current also depends on collisionality. As shown in the lower left of Fig.8, turbulence may enhance plasma self-generated current in high collisionality regime, and reduce it in low collisionality regime. Furthermore, the reduction of total electron current relative to the bootstrap current in the low collisionality regime increases as the electron collisionality decreases. The collisionality dependence of the turbulence effect on the current generation is further examined using test particle simulations. The test particle simulation is performed with prescribed turbulent fluctuations, which are extracted from the corresponding fully nonlinear simulation, as background. A test particle simulation can be useful and meaningful for various reasons. First, situations and assumptions under which a test particle simulation is performed are usually close to what are generally used for deriving a theory. Therefore, a test particle simulation is helpful for developing and testing a theory. Moreover, test particle simulations can provide great convenience for parametric scan of physics effect over multi-dimensional parametric space. The lower middle of Fig.8 shows the relative difference of total (volume-integrated) electron current computed by test particle simulations and the neoclassical bootstrap current as a function of collisionality, which gives the same collisionality dependence as obtained from the fully nonlinear simulations with turbulent and neoclassical physics coupled together. The implication of this result to the fully non-inductive current operation in steady state burning plasma regime should draw our attention, and what level of self-driven current we may expect in burning plasma regimes should be a critical issue to be investigated. Finally, the test particle simulations show that the plasma self-driven current is reduced as the turbulence fluctuation level increases (lower right of Fig.8). This is obtained in the relatively low collisionality regime, and it is possible to have a different trend in high collisionality regime.

This work was supported by U.S. DOE Contract DE-AC02-09CH11466 and DE-FC02-04ER54698.

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