Core and Edge full-f ITG turbulence with self-consistent neoclassical and mean flow dynamics using a real geometry particle code XGC1[a)]

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Abstract
Full function (full-f) gyrokinetic particle simulation of ITG turbulence in the XGC1 code, together with the background neoclassical physics, reveals different ITG dynamics from the conventional perturbed function (delta-f) gyrokinetic simulations in a tokamak core plasma. Mutual interaction between ITG and the background free energy, without scale separation, makes the initial radial streamer growth to be restricted by the zonal and mean flows (quasilinear streamers), and the turbulent ion thermal conductivity to be suppressed below the delta-f level. ITG turbulence study in a realistic DIII-D edge geometry shows a nonlocal growth of quasilinear streamers and saturation of turbulence across the linearly unstable (pedestal top) and stable (pedestal slope) regions of an L-mode pedestal. Equilibrium kinetic simulations reveal a strong spontaneous co-current rotation source in the scrape-off plasma of an L-mode type pedestal when the ion Grad-B drift is into a single null divertor. As the pedestal becomes narrower, a spontaneous co-rotation source appears in the pedestal area, while the co-rotation in the scrape-off area becomes weaker. When the ion Grad-B is away from a single null divertor, the overall co-rotation source becomes weaker.

1. Introduction

Kinetic ITG (ion temperature gradient) turbulence is considered to be one of the main causes of anomalous transport in tokamak plasmas. There have been numerous studies reported in the literature on this topic. Owing to the nonlinear nature of a large number of modes in the inhomogeneous toroidal magnetic field geometry, most of the quantitative studies have been performed numerically on high speed computers. Due to the easiness in the computational approach, the background plasma has been fixed and its gradients are analytically described in the conventional simulations. Only the perturbed part of the particle distribution function and electromagnetic field have been simulated (delta-f approach). A few basic turbulence dynamics understood from the delta-f approach [1] are the appearance of the highly elongated radial streamers during the linear growth stage, inverse cascade of the perturbed energy to the longer wave length modes which leads to the formation of the zonal flows and the destruction of the radial streamers through the ExB shearing as the zonal flows grow, and the eventual nonlinear saturation of the turbulence and transport levels.

The main shortcoming of the delta-f approach to plasma turbulence study is the absence of multi-scale interactions between the background mean energy and the turbulently disturbed energy. As a matter of fact, the proven strong interaction of zonal flows with turbulence is an indication that the multi-scale interaction plays an important role. Important multi-scale phenomena, such as the self-organized bifurcation of the plasma into stronger gradient state by turbulence, could not be investigated from a delta-f approach. There have been few efforts to simulate the background and turbulence dynamics together in a full-f gyrokinetic code without scale separation. The semi-Lagrangian approach reported at this meeting [Y. Sarazin, et al] is a rare example of such efforts.

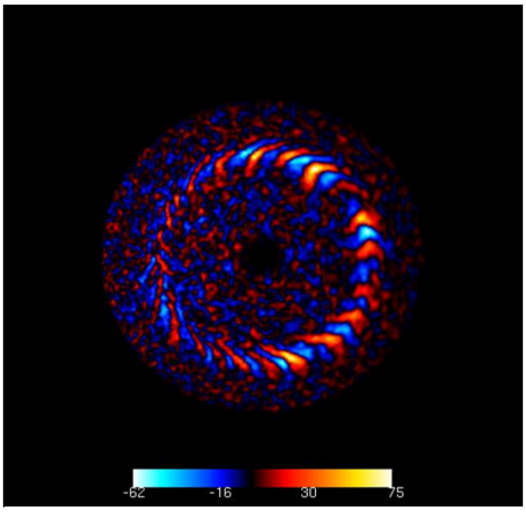

FIG. 1. ITG potential from XGC1 in the growth stage in a full-f cyclone plasma.

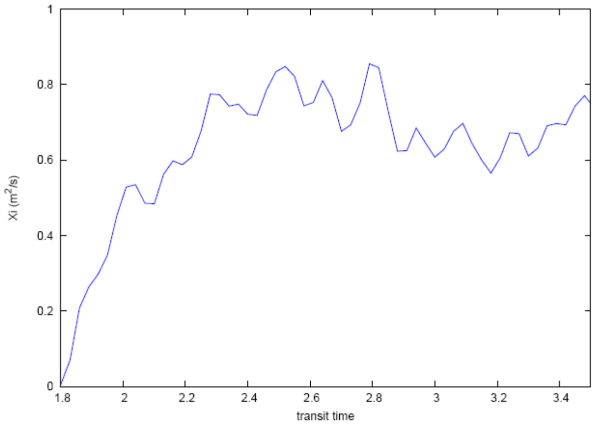

FIG. 2. Full-f ion thermal conductivity from collisionless ITG turbulence in the global cyclone plasma. Interaction of the turbulence with the background plasma is

Moreover, there has been no previous record of ITG turbulence simulation in the edge pedestal in a realistic edge geometry. The reduced transport models simply assumed that ITG-driven transport does not exist in the pedestal since the ion temperature gradient is below the conventional criticality value compared to the density gradient.

We report here a particle approach to the full-f ITG turbulence without the scale separation, in a realistic DIII-D tokamak geometry with magnetic X-point and material wall. It uses a numerical g-eqdsk magnetic and limiter geometry data, as well as an analytic geometry. XGC1 is capable of simulating the whole plasma from the central core to the material wall. However, due to the limited computational resources, we normally study the core and edge regions separately. The results presented here are collisionless. Collisional effects will be presented in a subsequent manuscript. In general, collisions are known to enhance the ion diffusivity by damping the zonal flows. We note here that XGC1 tested in the delta-f mode reproduces the conventional delta-f results.

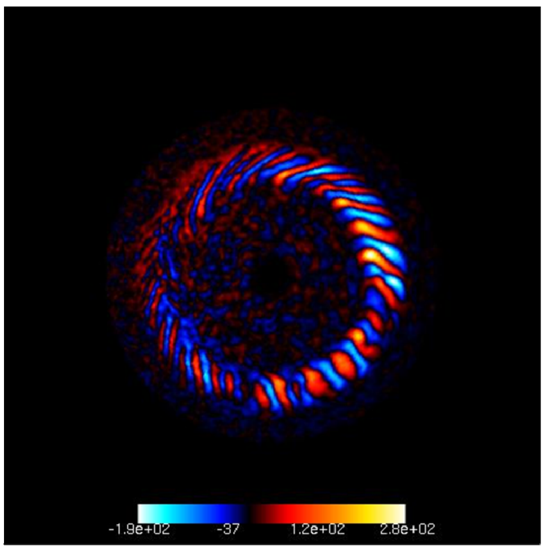

FIG. 3. Streamers become more elongated at higher η_i (=6).

2. Full-f ITG turbulence in the plasma core in a global cyclone plasma

In order to compare our full-f results with the well-known previous ITG results, we first studied the so-called "global cyclone plasma" in the circular concentric flux-surface geometry [1]. The plasma gradients at the inside and outside radial boundaries are kept to be zero to remove the boundary effects. Between the two radial boundaries, the plasma gradients are initialized in the hyperbolic tangent profile shape with ratio of the ion temperature to the plasma density gradients (=η_i) to be 3 at the hyperbolic tangent inversion point. The temperature gradient then evolves according to the turbulent transport. In the results shown here, the ions are full-f, but the electrons respond to the turbulence adiabatically.

Non-adiabatic electron response is under investigation and to be reported in the future. In order to save the computing resources, we have initialized the plasma using the neoclassical relationship between the radial plasma gradient, parallel flow and the radial electric field. However, this relationship is freed up once the full-f simulation begins, and the turbulence and neoclassical physics are allowed to self-organize by interacting with each other.

Figure 1 shows the fluctuating ITG electrostatic potential profile on a poloidal plane in the instability growth stage, from the full-f XGC1 simulation in a cyclone geometry with a moderate system size a/ρ_i=169, where a is the minor radius and ρ_i is the characteristic ion gyroradius. Unlike what a conventional delta-f simulation (including XGC1 in delta-f mode) reported, the full-f zonal flows are found to coexist with the streamers, as can be seen from FIG. 1, from the beginning of the ITG growth stage until the streamers are broken up at the nonlinear stage. As a result, the streamers are not much elongated. The turbulent ion thermal conductivity is (~0.7 m^2/s, see FIG. 2), much smaller than the conventional delta-f cyclone case by an order of magnitude. The mean parallel flow of plasma shows strong interaction with the turbulence (not shown). Again, the main physical difference of the full-f plasma from the conventional delta-f plasma is the self-organizing interaction of the turbulence with the background plasma. As the ITG instability driver (η_i) becomes stronger, the radial streamers become more elongated (Figure 3) and the ion thermal conductivity becomes higher (~2 m^2/s at η_i=6, see FIG. 4).

Without a thermal flux at the inside boundary (the highertemperature side), we find that the ion thermal conductivity is not sustained indefinitely. Figure 4 also shows a decay of the saturated ion thermal conductivity at the ion toroidal transit time τ about 6. However, with a heat flux drive, the ion thermal conductivity is sustained in the entire simulation duration at an elevated level. We have tried to increase the amount of heat flux and steepen the temperature gradient, in an effort to find a possible bifurcation into an internal transport barrier. However, we have not so far found an internal transport barrier formation in a monotonically increasing q profile of the cyclone plasma. At the present time, we are continuuing this investigation in a reversed q profile.

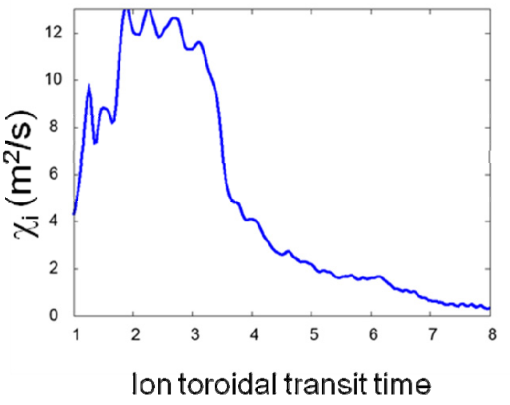

FIG. 4. Ion thermal conductivity for η_i=6 without a heat-flux drive. Notice the decay starting at τ~6.

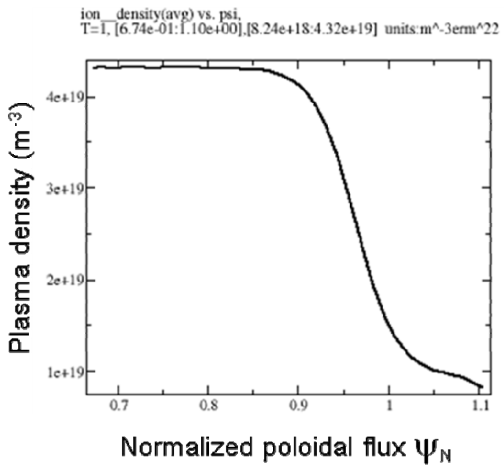

FIG. 5. Edge density profile used in the simulation. ψ_N=1 corresponds to the magnetic separatrix location.

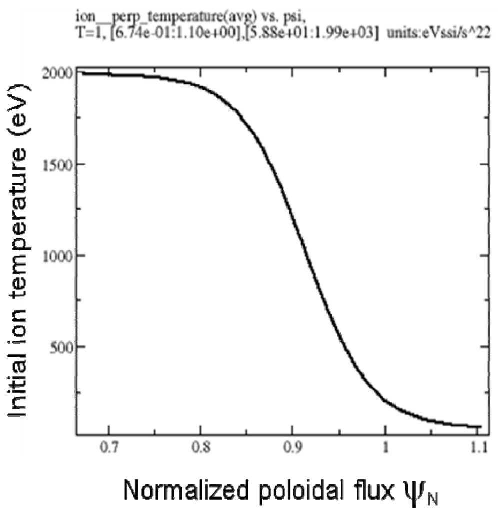

FIG. 6. Initial ion temperature pedestal used in the edge simulation.

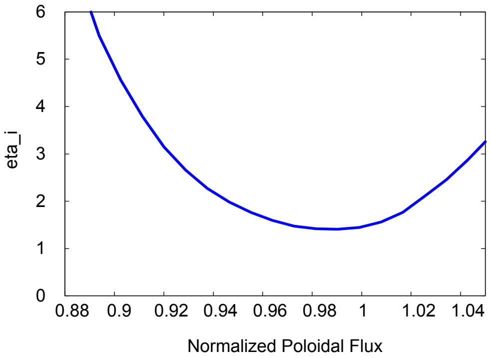

FIG. 7. Initial η_i profile in the edge. Turbulence relaxes this profile moderately.

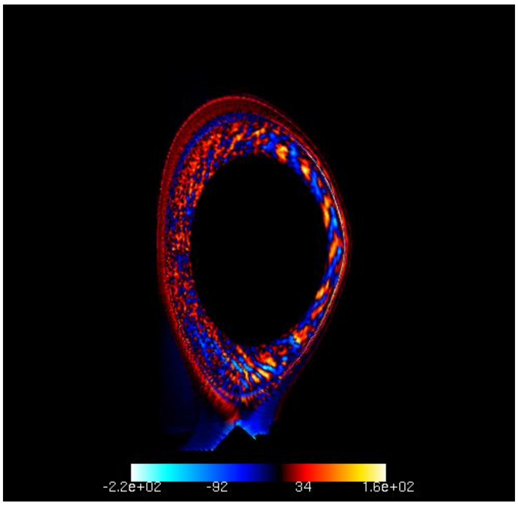

FIG. 8. ITG growth in the DIII-D pre-transition L-mode edge with the m=n=0 mode suppressed.

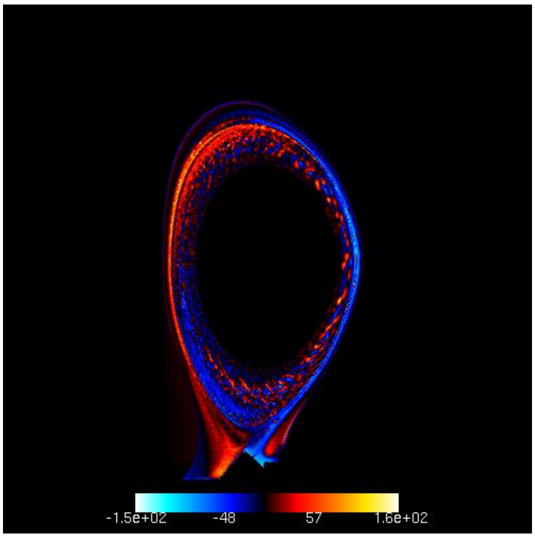

FIG. 9. ITG growth in the DIII-D pre-transition L-mode edge with the m=n=0 mode turned on.

3. Full-f ITG turbulence in a realistic DIII-D edge geometry

We now turn our attention to the edge pedestal region in a realistic DIII-D separatrix geometry. The egde pedestal model we use here for this report is an L-mode type before the H-mode transition. The density pedestal width is relatively wide (~4 cm), with the temperature slope width even wider (~8 cm). Thus, η_i>3 in the top and shoulder of the density pedestal, but <2 in most of the density slope region (see FIG. 5, 6 and 7). The known value of critical ion temperature for core ITG growth is η_{ic} =2.2. However, η_{ic} in the edge geometry is unknown. The η_i profile shown in FIG. 7 relaxes somewhat by turbulent thermal transport. But, the basic features of η_i remains unchanged (η_i>3 in the top and shoulder, and <2 in the sloped region).

We first present the full-f ITG result without any toroidally axisymmetric electric potential. To a surprise, we find that the ITG streamers grow simultaneously (FIG. 8) in the linearly unstable region (pedestal top and shoulder) and the linearly stable region. The saturated turbulence also exists in both regions. In other words, the ITG turbulence is highly nonlocal. If we were to characterize this nonlocality of ITG as a turbulence spreading, the spreading should occur within the ω_* time scale with the radial spread speed higher than 100 m/s.

As we turn on the axisymmetric potential dynamics, self-consistently with the turbulence dynamics, the radial streamers are noticeably reduced (FIG. 9) due to the presence of the zonal flows, mean flows and the background neoclassical ExB shearing. This feature is similar to the observations made in the core plasma (see the text associated with FIG. 1). The nonlocal nature of ITG is still strong, as can be seen in FIG. 10 which shows the time behavior of the ion thermal conductivity at the pedestal top (η_i>3) and in the density slope (η_i<2). A noticeable feature in the edge ITG turbulence is that the initial χ_i grows stronger in the pedestal top where η_i>3, but the final χ_i is stronger in the pedestal slope where η_i<2. We find that the magnetic separatrix acts as a partial wall to the turbulence spread, resulting in the compressed turbulence energy just inside the separatrix. This feature is to be investigated further in XGC1, in connection with the "blob" formation and transport across the magnetic separatrix.

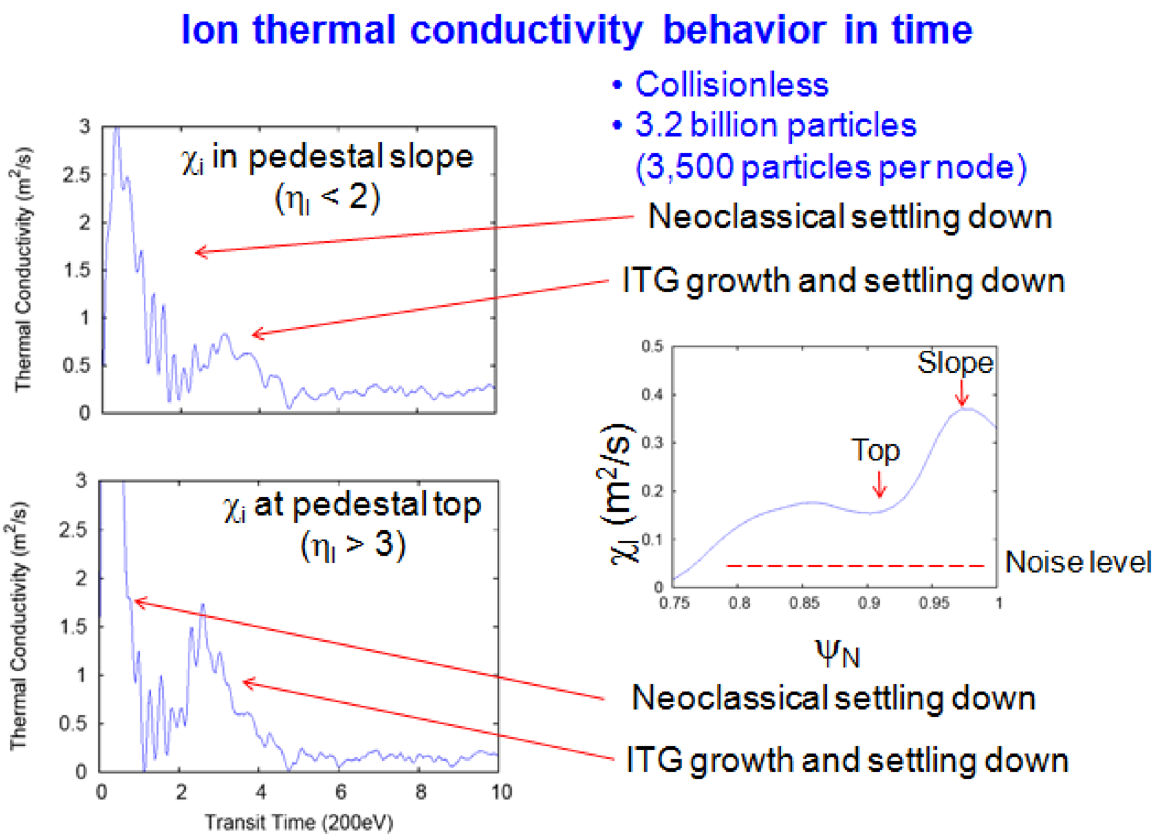

FIG. 10. Time behavior of the ion thermal conductivity χ_i in the pre-transition edge region of DIII-D tokamak.

4. Spontaneous rotation source in the edge

We have also examined the equilibrium toroidal rotation generation in a realistic DIII-D edge geometry using XGC1 [2] (FIG. 11). Due to the high magnetic q values in a tokamak

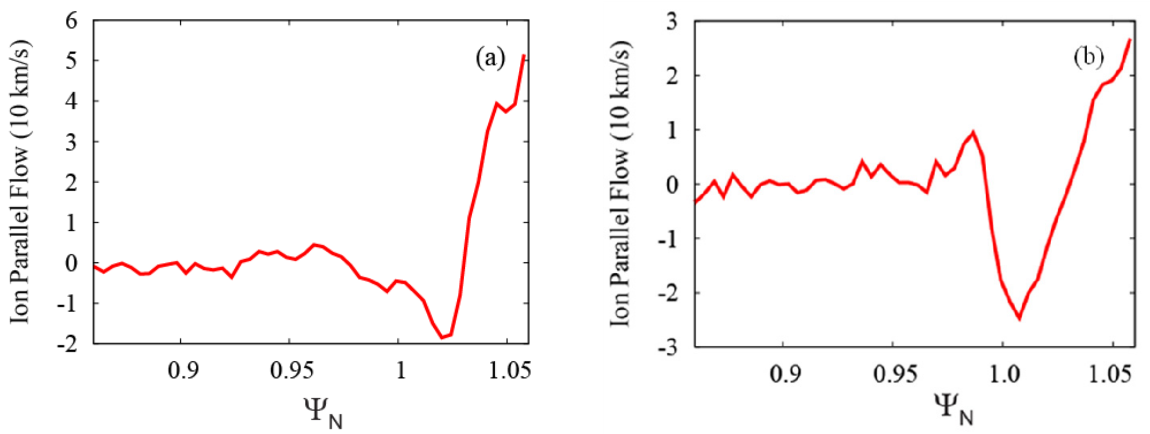

FIG. 11. Plasma parallel flow from XGC1 after suppressing turbulence fluctuations. (a) Wide pedestal case (3 cm width) shows a strong co-current flow in the scrape-off plasma. (b) Narrow pedestal (1 cm width) makes the co-current flow move into the pedestal area, with a deeper valley around the separatrix. Neutral recycling is turned off in these simulations.

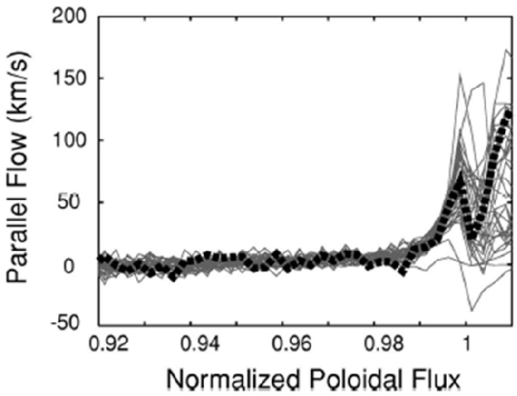

FIG. 12. Parallel flow in a realistic DIII-D edge geometry with the collisions and the neutrals turned on.

edge, we do not distinguish the toroidal rotation from the parallel (to magnetic field) rotation in the present discussion. The conserving Coulomb collisions are turned on for rotation studies, but the neutrals are left off. We have found that, when the Grad-B ion drift is toward the single null divertor, there is a strong spontaneous co-current rotation in the L-mode scrape-off plasma. As the pedestal width narrows, the co-current rotation moves into the pedestal region, while the rotation valley deepens. Using the XGC0 code (which specializes in the equilibrium kinetic solution without turbulence), we ran a case with the neutral recycling turned on. It has been found [3] that the neutrals weaken the rotation valley around the separatrix, but increases the co-rotation in the pedestal (see FIG. 12). The increase of the co-rotation in the pedestal with the narrower pedestal width will be equivalent to the increase of the spontaneous edge co-rotation source for the core plasma. Interestingly, as we reverse the ion Grad-B direction, the co-current rotation is decreased [2].

5. Conclusion and discussion

It has been shown that the full function (full-f) gyrokinetic particle simulation of ITG turbulence in the XGC1 code reveals different ITG dynamics from the conventional perturbed function (delta-f) gyrokinetic simulations in a tokamak core plasma. Mutual interaction between ITG and the background free energy, without scale separation, makes the initial radial streamer growth to be restricted by the zonal and mean flows (resulting in quasilinear streamers), and the turbulent ion thermal conductivity to be suppressed below the delta-f simulation level.

ITG turbulence study in a realistic DIII-D edge geometry shows a nonlocal growth of quasilinear streamers and the nonlocal turbulence saturation simultaneously across the supposedly linearly unstable (pedestal top) and stable (pedestal slope) regions of an L-mode pedestal.

Equilibrium kinetic simulations reveal a strong spontaneous co-current rotation source in the scrape-off plasma of an L-mode type pedestal when the ion Grad-B drift is into a single null divertor. As the pedestal becomes narrower, a spontaneous co-rotation source appears in the pedestal area, while the co-rotation in the scrape-off area becomes weaker. With the neutral recycling, the spontaneous co-current rotation in the pedestal region becomes stronger. When the ion Grad-B is reversed, the overall co-rotation source becomes weaker.

The present work is currently being extended to the study of internal transport barrier formation and the edge L-H transition physics. Kinetic electron effect is being implemented into XGC1 for the electromagnetic turbulence studies.

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