Gyrokinetic simulations of edge pedestal turbulence

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Abstract. First-principle studies of edge pedestal microinstabilities are performed with a coupled global gyrokinetic GEM-XGC0 simulation. The code coupling is implemented under the End-to-End Framework for Fusion Integrated Simulation (EFFIS).The equilibrium density, temperature and radial electric field (E_r) profiles are calculated by the XGC0 code and the anomalous transport coefficients are calculated by the GEM code. The turbulence from simulation results peaks at the position of strongest pressure gradient and hence the minimum E_r. The dominant linear instability is driven by the strong density gradient. As a result, the H-mode pedestal is linearly more unstable than L-mode. However, the nonlinear steady-state flux level of H-mode is indeed lower than L-mode. The linear instability requires kinetic electrons but is not due to trapped electrons, and it is nearly insensitive to ion and electron temperature gradients. Hence, the dominant instability is likely to be electron drift wave. It is also found in the pedestal that E_r nearly balances the diamagnetic pressure term in the radial force balance equation.

1. Introduction

To achieve high fusion power in a tokamak plasma such as the International Thermonuclear Experimental Reactor (ITER) [1], an H-mode (high-confinement mode) edge pedestal plasma is crucial. The physical mechanism of the transition from an L-(low confinement-) mode to H-mode, as well as the transport and turbulent properties of both modes are still not well understood. It is desirable, therefore, to have first-principle simulations that self-consistently evolve these physical processes. However, such simulations are difficult because multiple spatial and time scales are involved. The current state of the art is for different simulation codes to model specific physical scales. The focus of the Center for Plasma Edge Simulation (CPES), a SciDAC (Scientific Discovery through Advanced Computing) project, is to study the edge plasma with the interplay of physics from different scales, including neoclassical transport, microturbulence, and magnetohydrodynamic (MHD) instabilities. One approach is to couple several codes together for long time simulation of edge pedestal evolution. For example, four codes, including XGC0, M3D-IMP, ELITE, and M3D-MPP are coupled to study the MHD instability known as edge localized modes (ELMs) [2,3].

Here we present results of simulations of the edge pedestal plasma with code coupling of GEM and XGC0. GEM [4] is a gyrokinetic δf particle code that is suitable for the short turbulence scale but lacks the capability to self-consistently evolve the plasma profiles and equilibrium radial electric field

(E_r). XGC0 [5], on the other hand, is a full-*f* particle code suitable for the longer transport time scale provided that the transport coefficients are given. With the two codes coupled together, GEM can calculates the electromagnetic turbulent transport coefficients, and XGC0 can evolve the equilibrium profiles.

The long term goal is to use this scheme to study the full process of the L-H transition. Currently, with the coupled simulation we have studied properties of L-mode and H-mode pedestal turbulence. We find that the main instability is driven by the density gradient, a phenomenon very different from the ion-temperature gradient (ITG) driven turbulence usually observed at core plasmas. The H-mode plasma is linearly more unstable than L-mode, and it is a nonlinear effect that the H-mode has lower transport levels. Furthermore, the shape of E_r, which is believed to be a main stabilizing effect, is found to balance the equilibrium pressure profile.

2. GEM-XGC0 Code Coupling

The code coupling scheme is implemented under the EFFIS (End-to-End Framework for Fusion Integrated Simulation) framework [6,7,8], specifically developed by computer scientists to facilitate the integrated plasma edge study as part of CPES. The EFFIS framework consists of three components. One is the ADIOS (ADaptable I/O System), which is a binary data format and it provides portable, fast, scalable and easy-to-use metadata rich output with a simple API. Another main part of EFFIS is the Kepler workflow system that can orchestrate the coupling of several parallel codes running on different platforms simultaneously. Finally, the relevant physical quantities from each code at any time throughout the simulation can be selected and displayed via the Dashboard, a monitoring tool implemented using AJAX and flash. A scientist can directly view the data simply by using a standard web browser.

The work flow scheme of the GEM-XGC0 code coupling is shown in Figure 1. The workflow program runs on the Infiniband cluster *ewok*, the XGC0 code is run on the Cray XT4 supercomputer *jaguar*, and the GEM code is run on another Cray XT4 supercomputer *franklin*. Initially, the workflow starts the XGC0 code, which starts the simulation with a set of DIII-D [9] experimental profiles and typical anomalous transport parameters, and the simulation should stop before the profiles change too much (e.g., less than 1%). The new profiles calculated by XGC0, including electron and ion density, temperatures and E_r, are transfered to the GEM code via the workflow. In order to reduce numerical noise, the density and temperature profiles are fitted into some modified hyperbolic tangent functions defined by five parameters each, similar to Ref. [10]. The GEM code then runs with these profiles until a steady state is reached, and the particle and heat transport coefficients are transferred back to XGC0 for a new cycle. Throughout the process the simulation results of both codes can be viewed in real time from the Dashboard, as shown in Figure 2.

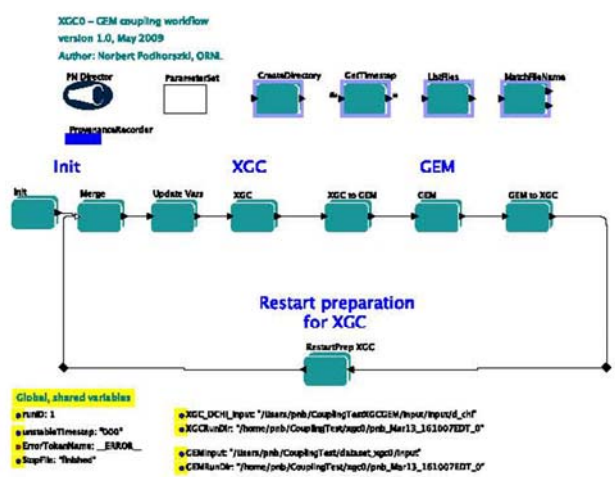

Figure 1. The GEM-XGC0 coupling workflow.

One limitation to the coupling scheme is that XGC0's magnetic geometry includes the separatrix and the X-point, while the GEM simulation region is inside the separatrix. It is then necessary for GEM to smooth the profiles from XGC0 at the radial boundaries [11]. The smoothing causes the transport coefficients calculated by GEM to be artificially small near the boundary. One way to overcome this limitation is only pass the transport coefficients at center of the simulation box back to XGC0, as uniform parameters. This may be reasonable when the simulation region is small. The other

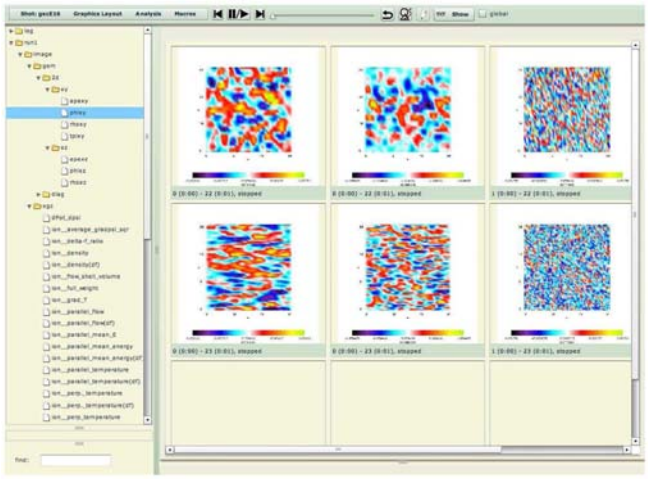

Figure 2. A screen shot of the dashboard.

approach is to extend the profiles in GEM outside of the separatrix. Both methods are implemented and tested, nevertheless in the work reported here only the first approach is used.

3. Physical Results

In this section we report preliminary results from the coupled simulation, specifically the GEM simulation of the profiles provided by XGC0. In studying these profiles we begin to obtain basic properties of L and H-mode edge plasmas. The temperature, density and radial electric field profiles from XGC0 are shown in Figure 3. In generating these profiles, XGC0 has used preset anomalous diffusion coefficients. For the L-mode, the ion particle transport coefficient $D_i = 0.5\ m^2/s$, and the heat diffusivity $\chi_i = 2.0\ m^2 s$. For the H-mode, much lower coefficients of $D_i = 0.05\ m^2/s$ and $\chi_i = 0.1\ m^2 s$ are applied for the steep pedestal, and the same D_i and χ_i as the L-mode are applied on the top. Compared to L-mode, the width of the H-mode pedestal is smaller and the height is bigger. The characteristics of these simulated profiles are consistent with experimental observations [10,12].

One important discovery from these profiles is that the radialelectric field and the equilibrium diamagnetic pressure are balanced. Theoretically, the radial electric field

$$E_r = \frac{1}{en_i}\frac{\partial}{\partial r}P_i + (\boldsymbol{u} \times \boldsymbol{B})_r. \tag{1}$$

We compare the XGC0 simulated E_r with the pressure gradient term of Eq. (1) in Figure 4, and they almost match. This means the flow contribution is nearly negligible. Since E_r is usually difficult to measure in experiments, this may enable researchers to calculate E_r directly from the pressure profile. The peak of E_r appears at the maximum of the pressure gradient, and because the shear of $\boldsymbol{E} \times \boldsymbol{B}$ flow has a stabilizing effect (see, e.g., Ref. [11]), this implies that turbulent instability should also peak there with a zero E_r shear, and the phenomenon has been confirmed by the mode structures in GEM simulations.

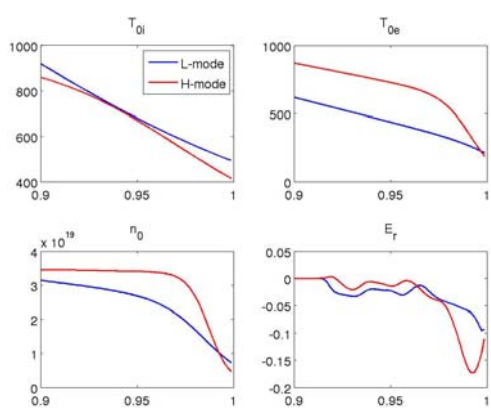

Figure 3. The profiles from XGC0.

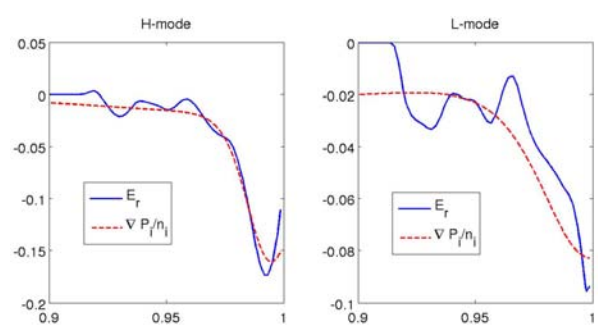

Figure 4. E_r compared to ∇P.

The nonlinear evolution of the ion particle and heat fluxes in GEM simulation are shown in Figure 5. During the initial linear growth stage, it appears that the H-mode is more unstable than the L-mode. In fact, the linear growth rate of the L-mode pedestal is $\gamma = 7.2 \times 10^{-4}\ \Omega_i$, where Ω_i is the ion cyclone frequency, while for H-mode $\gamma = 8.1 \times 10^{-4}\ \Omega_i$. It is only at the nonlinear steady state that the H-mode case has lower transport level. More investigation is needed to understand the stabilizing mechanisms in H-mode. It may be bigger E_r or zonal flows that have a stronger steering effect on fully developed turbulent eddies.

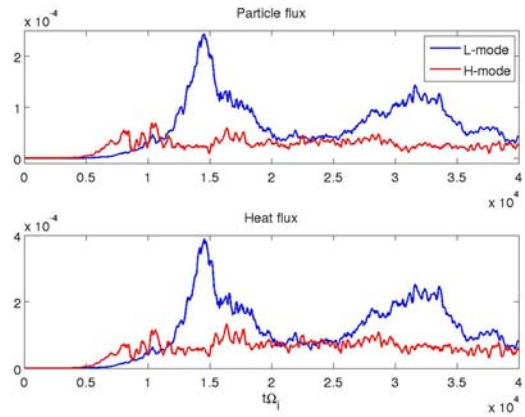

Figure 5. The volume-averaged ion particle and heat fluxes.

A detailed GEM simulation study of the linear instability shows that the most unstable mode moves in the opposite direction of ITG, meaning it is an electron mode. Indeed, the dominant instability is stabilized without kinetic electrons, and it seems to be caused by passing electrons since when the growth rate increases slightly without trapped electrons. The instability is insensitive to ion temperature gradient and is only weakly dependent on electron temperature gradient. In general, the instability is mostly dependent on density gradient, with a bigger growth rate for bigger ∇n, and this explains why H-mode is linearly more unstable. These properties lead to the conclusion that the dominant instability is electron drift wave.

It has been proposed recently [13] that the pedestal width is limited by the onset of kinetic ballooning mode (KBM) near the maximum of pressure gradient at the edge. In a set of simulations with fixed pedestal height but varying pedestal width, we find that the linear growth rate is first lowered then increased as the pedestal width get thinner and thinner, a phenomenon consistent with KBM. The authors are working on further studies for the evidence of KBM at the pedestal.

Acknowledgments

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