A FAST L-H BIFURCATION PHYSICS IN A REALISTIC, DIVERTED, TOKAMAK EDGE GEOMETRY

S. Ku
Princeton Plasma Physics Laboratory
Princeton, NJ, USA
Email: sku@pppl.gov

C.S. Chang
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

R.M. Churchill
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

I. Cziegler1
University of California San Diego
La Jolla, CA, USA

M. Greenwald
MIT Plasma Science and Fusion Center
Cambridge, MA, USA

R. Hager
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

J. Hughes
MIT Plasma Science and Fusion Center
Cambridge, MA, USA

G. Tynan
University of California San Diego
La Jolla, CA, USA

Abstract

A fast edge turbulence suppression event has been simulated in the electrostatic version of the gyrokinetic particle-in-cell code XGC1 in a realistic diverted tokamak edge geometry under neutral particle recycling. The results show that two mechanisms of the poloidal flow shearing from radial electric field contribute to the turbulence suppression in sequence. The former is driven by turbulence Reynolds stress and the later is driven by neoclassical ion orbit-loss. The Reynolds work causes a conservative eddy tilting-stretching-absorption process. The orbit-loss takes over with the dissipative to smaller-scale eddies and finishes up the turbulence quenching process while keeping the turbulence suppressed.

1. INTRODUCTION

The H-mode is often envisioned as the operating mode of choice for fusion reactors, and will be relied on by ITER in achieving its goal of ten-fold energy gain. However, despite over 30 years of routine H-mode operation in all the major tokamaks, there has not been a fundamental understanding at the kinetic level on how the H-mode turbulence bifurcation occurs. There is also a concern over ITER’s achievability of the H-mode operation with available heating power if the neoclassical $E \times B$ shearing is solely responsible for the H-mode transition and its rate is expected to be weak due to smallness of $\rho^* = \rho_i/a$, where $\rho_i$ is ion gyro-radius and $a$ is

1 Present and permanent address: University of York, York, UK
minor radius of tokamak. The answer to this concern relies on a more fundamental physics question: Will a neoclassically-driven mean $E \times B$ shearing ($\nabla p$-driven or X-point orbit-loss driven) be essential for the L-H turbulence bifurcation, or will the turbulent stress-driven $E \times B$ shearing be? Experimental observations appear to diverge on the cause and dynamics of L-H bifurcation. Some detailed experiments with fast L-H transition report that the turbulent stress-driven shear flow first leads to a collapse of the turbulence, which is then followed by the development of the edge pedestal in a rather longer time scale, claiming that the turbulence suppression is not maintained by the simultaneous build-up of the steep pedestal and the associated $E \times B$ shearing [1, 2]. Some experiments (i.e., [3]) report a different evidence that the experimentally observed Reynolds work from turbulent stress is too weak to explain the L-H bifurcation and, thus, the $E \times B$ shearing from the neoclassical orbit loss physics [4, 5] is solely responsible for the bifurcation. Some LCO type transition experiments that showed little Reynolds work suggest that the $E \times B$ shearing from the build-up of the steep pressure pedestal is responsible for the turbulence suppression [6].

This body of evidence commonly suggests that the H-mode transition could indeed be related to the sheared $E \times B$-flow, either turbulence- or neoclassical-driven. However, the existing models are based upon simplified ad-hoc equations and the turbulence simulations assume specific instability mechanisms, ignore possible important kinetic effects, and are not carried out in a realistic geometry. We present an L-H transition study using a first-principles based electrostatic gyrokinetic simulation using the edge gyrokinetic code XGC1.

We find that a neoclassical-driven (X-point orbit-loss driven in this case) $E \times B$ shearing is essential to quench the turbulence irreversibly and works together with the Reynolds-stress driven $E \times B$ shearing [1]. A new XGC1 study also indicates that, in ITER, the weak $\nabla p$-driven $E \times B$ shearing can be compensated by the X-point orbit-loss effect if the edge $T_i$ is high enough. We report here new understandings of the edge turbulence suppression event in an electrostatic gyrokinetic simulation that is much beyond what was described in [7]. For the sake of completeness, we will repeat the basic observations that was already reported in [7].

In section 2, the numerical approach used in this work is briefly summarized. In section 3, the simulation setup is described. In section 4, the dynamics of the edge turbulence suppression is presented. Section 5 is devoted to conclusion and discussions.

2. NUMERICAL APPROACH

XGC1 is a multiscale 5-dimensional (5D) gyrokinetic code that solves the turbulence-neoclassical-neutral transport physics together and specializes tokamak edge plasma based on the particle-in-cell technique combined with a velocity-space grid technique (hybrid-Lagrangian scheme).

The simulation domain normally includes the whole plasma volume -- from the material wall, across the magnetic separatrix surface with X-point, and to the magnetic axis -- in order to avoid artificial Dirichlet or Neumann boundary conditions at the core side. Unstructured triangular mesh that follows approximately the equilibrium magnetic field lines is used to describe the complicated wall geometry and the X-point. The only solver boundary condition is the grounded, zero electrostatic potential at the material wall, which is approximated to be axisymmetric. Once a magnetic field-line intersects a material limiter other than in the divertor chamber, it is assumed that the high parallel electrical conductivity holds the electrostatic potential to be zero along the magnetic field lines. The material wall geometry, the magnetic equilibrium profiles and the initial plasma profiles are imported from experimental data using the EFIT code outputs [8], or from an analytic Grad-Shafranov equilibrium. Wall loss of the plasma particles induces birth of Monte Carlo neutral atoms at the Frank-Condon energy at a specified recycling rate.
XGC1 solves the 5D gyrokinetic Boltzmann equation with gyrokinetic Poisson equation which is from the lowest-order quasi-neutrality equation [9], [10]. The electrons are drift kinetic hence the electron temperature gradient driven modes are ignored in this study. In solving the gyrokinetic Boltzmann equation, XGC1 uses the hybrid-Lagrangian total-δf scheme, which utilizes a 2D structured rectangular grid in the velocity space in addition to the 3D unstructured triangular particle-in-cell grids in the configuration space. In the hybrid-Lagrangian total-δf scheme, the perturbed distribution function δf is decomposed into \( f = f_0 + f_\delta + \delta f_\delta \), with \( f_\delta \) being described by particles, \( f_0 \) being either an analytic or numerical initial distribution function, and \( \delta f_\delta \) residing in the 5D grid-space [11]. Also, in this scheme, the entire distribution function \( f \) is presented on the 5D continuum grid at each time step and the fully nonlinear Coulomb collision operator and source terms (e.g. neutral particle source) are evaluated on the 5D continuum space.

This hybrid-Lagrangian total-δf scheme is especially useful in handling the non-Maxwellian distribution of tokamak edge plasma together with nonlinear Coulomb collisions. The Coulomb collision operator is solved using a fully nonlinear Fokker-Plank-Landau collision operator on the phase-space grid [12, 13]. The neutral ionization and charge exchange part is from the built-in Monte Carlo neutral transport routine that uses the rate coefficients of atomic processes [14]. Heating and radiative cooling are applied in an isotropic way in the 2D velocity space while preserving the particle density and the net parallel momentum on the configuration grid so that the heating and cooling themselves do not inject a net mass or momentum into the plasma. Torque is applied in the 2D velocity space while preserving the particle density and energy.

In XGC1, the tokamak wall (divertor and limiter) gives the boundary condition to the particle dynamics. Plasma particles are absorbed at the wall boundary unless reflected by the sheath potential. All the ions are absorbed, but the electrons whose parallel kinetic energy is lower than the sheath potential are reflected back. The configuration space grid distance is about the ion gyroradius (~1mm). The Debye sheath and the quasi-neutral sheath are not resolved in the configuration space grid. Thus, the sum of the Debye sheath potential and the quasi-neutral sheath potential is determined by the logical sheath model, making the number of lost electrons and ions equal. More detailed numerical algorithms used in this work are described in [10].

3. SIMULATION SETUP

A global transport time-scale gyrokinetic investigation of the L-H transition (starting from a global L-mode transport equilibrium, gradually increasing the heating power to get the transition, and observing a pedestal build-up) has been prohibitively expensive on the present-day leadership class computers. In the present study, we make the simulation possible by reducing the computational resource requirement as much as possible via a model simplification; i.e., by choosing a fast electrostatic bifurcation case under strong forcing by a high rate of heat deposition in the edge bifurcation layer without prolonging it to the slow, follow-on pedestal build up.

FIG. 1. Initial radial profiles of Ti, Te and ne in the edge region (solid line). The profiles around \((t=0.174\, \text{ms}, \text{dotted line})\) and after \((t=0.27\, \text{ms}, \text{dashed line})\) the bifurcation event have been plotted together.
process. XGC1 simulations and analytic study show that edge turbulence saturation is usually established within 0.1 ms [15, 16], while in the core plasma the nonlinear turbulence saturation is established in 1 ms or longer.

Since a turbulence-bifurcating plasma is not in a global transport steady state, we study an edge transport barrier formation with a simulation of much less than 1 ms of plasma time by strong forcing, which is before the establishment of a global transport steady-state. This enables the L-H bifurcation simulation on the 27 peta-flop-peak computer Titan at ORNL for a few days.

For the present study, we use the magnetic field geometry and the plasma profile from the Alcator C-Mod L-mode plasma discharge #1140613017 as the simulation inputs, but taking the toroidal magnetic field $B_T$ to yield the magnetic drift $V_{RB}$ toward the magnetic X-point (i.e. the favorable direction for an H-mode transition); the actual discharge had $V_{RB}$ away from the X-point. The plasma current is parallel to $B_T$. FIG. 1 shows the initial profiles of density and temperatures near edge and those of later time. In these plasmas $\beta_e$ (=the electron kinetic energy density/magnetic energy density) is only 0.01% just inside the separatrix and thus the magnetic fluctuation effects could be minimal. How the electromagnetic effect could alter the present L-H bifurcation study is a subject of future study. 99% wall-recycling of neutral particles is used in the built-in Monte-Carlo neutral particle routine.

In order to induce a fast transition within the available computing resources, a strong forcing is imposed via a high rate of heat deposition in the edge layer: $\Delta W_{\text{layer}} \approx 0.8$ MW in $0.947 < \Psi_N < 0.989$, where $\Psi_N$ is normalized poloidal flux. For typical plasmas of this kind, $P_{LiH}$ that flows into the edge layer in the experiments is 1-1.5 MW. It is found from a few different simulations that this strong forcing can routinely induce the turbulence bifurcation as soon as the nonlinear L-mode turbulence establishes.

4. DYNAMICS OF EDGE TURBULENCE SUPPRESSION

An edge turbulence suppression is observed in this gyrokinetic simulation with GAM activities. In FIG. 2(a)-(b), the radial heat transport of ion and electron are suppressed together with the turbulence suppression at $\approx 0.21$ ms as to be explained in detail below. In FIG. 2(c), we observe that GAMs propagate from inner radii towards the edge, with gradually decreasing radial propagation speed as they approach the edge and with some interference pattern as they are reflected from the edge. In the edge layer near the magnetic separatrix, the positive peaks of the sheared $E \times B$ flow oscillations do not penetrate very well into the region $\Psi_N > 0.96$ before $t=0.175$ ms, suggesting that at this time there is some mechanism at play to suppress the positive $E \times B$ shearing in this region. The negative $E \times B$ shearing implies positively charged plasma in the region. This also implies that the electrons lead the particle loss. All of sudden at $t=0.175$ ms, the $E \times B$ shearing becomes

![FIG. 2. Time behavior at $\Psi_N=0.975$ of (a) $\left( \frac{Q_i}{\Psi} \right)^2$, $E \times B$ shearing rate, and $E \times B$ flow; (b) electron heat flux; (c) $E \times B$ shearing rate in radius; (d) Reynolds force at $\Psi_N=0.972$ and 0.984; and (e) orbit-loss force. All the one-dimensional quantities are flux surface averaged values except $\left( \frac{Q_i}{\Psi} \right)^2$ in (a), which is measured at the outboard midplane.](image)
positive and increases further in the positive direction. The $E \times B$ shearing and turbulence density at this position now show an out-of-phase, nonlinear limit-cycle behaviour.

The peak shearing rate at $\Psi_N = 0.975$ exceeds 300 kHz at $t=0.205$ ms, which coincides with the maximum linear growth rate of the most unstable dissipative modes (i.e., dissipative trapped electron modes in the modelled plasma). Also, the second kick into the positive $E \times B$ shearing direction that peaks at $t=0.205$ms penetrates deeper toward the separatrix. After $t=0.205$ ms, the $E \times B$ shear oscillations at $\Psi_N = 0.975$ cease but the $E \times B$ shear grows continuously in the positive direction, and the turbulence continuously decays after $t \approx 0.22$ ms.

FIG. 2(d) shows that the Reynolds stress force becomes small after $t \approx 0.19$ms and cannot be effective. Figure 2(e) shows that by $t=0.205$ms the X-point orbit-loss force has grown above the level of the preceding Reynolds force. This suggests change of mechanism for the $E \times B$ shear and turbulence suppression from Reynolds force to X-loss.

Theories exist [18] saying that a sheared mean $E \times B$ flow can 1) shear the turbulence eddies to smaller structures and higher frequency, leading to dissipation at high wave numbers, or 2) quench the turbulence via an eddy tilting-stretching-absorption process. The latter process is different from the former in that it happens via Reynolds work through a conservative absorption process from the turbulence kinetic energy into the plasma $E \times B$ flow energy.

FIG. 3 depicts a contour plot of the turbulence amplitude behaviour in the frequency-time space at $\Psi_N = 0.94$, at a small distance (~5mm) away from the main transition layer ($\Psi_N = 0.96-0.98$) in order to avoid some fine-grained activities right in the transition layer. It can be seen that the lower frequency turbulence begins to decay and the higher frequency turbulence begins to appear at $t=0.175$ms (vertical dash-dot line). This time coincides with the appearance of strong positive Reynolds stress forces in the edge layer [Fig. 2(d)]. From about 0.205ms, however, turbulence is sheared away at all frequencies with the high-frequency part disappearing (dissipation).

In FIG. 4, the rate of Reynolds work becomes momentarily large enough to consume a significant portion of the turbulence kinetic energy, as indicated by $P>1$ around $t=0.18$ ms and the cut-off of the top in the GAM-oscillating turbulence energy at the corresponding time in FIG. 2(a). We emphasise here that the significant part of the Reynolds work exists only momentarily between the time $t \sim 0.175$ ms and $t \sim 0.19$ ms.

The first shearing event corresponds to the case 2) above and the second event to the case 1). Between the start of the first shearing event and the second shearing event, a short limit-cycle oscillation period ($t$-phase) is seen. Multiple simulations with different conditions (including reversed BT) show that the turbulence bifurcation
irreversibly occurs when the combined $E \times B$ shearing rate from the Reynolds and X-point orbit-loss forces exceeds the maximal growth rate of the dissipative trapped electron modes ($\approx$300kHz) in this plasma. If the edge heating-rate were weaker, so that the edge $T_e$ would grow more slowly, then the limit-cycle oscillation period (I-phase) could continue longer. If the limit-cycle oscillation period becomes long enough for the edge $\nabla p$ to grow substantially [19], then the $\nabla p$-driven $E \times B$ shearing could also add to the X-point orbit-loss driven $E \times B$ shearing. Without the neoclassical $E \times B$ shearing, the bifurcation may not be completed irreversibly.

FIG. 5 shows the time-averaged wavenumber spectrum of the turbulence at $\Psi_N=0.975$ before the first $E \times B$ shearing event starts ($t=0.12-0.17$ ms) and well into the second-phase shearing activities ($t=0.22-0.26$ ms). The white-red dotted line represents the $E \times B$ Doppler-shift, $\nu_p$, and the white-black dashed line represents the maximum amplitude for each wavenumber. Electron (ion) modes are characterized by $(\nu-\nu_i)k_\theta > 0$. Thus, most of the electron (ion) modes reside in the positive (negative) $k_\theta$ space. During $t=0.12-0.17$ ms, there are both ion and electron modes. It is interesting to find that the electron modes have already disappeared by $t=0.22-0.26$ ms while the ion modes are being actively sheared away to higher frequency. The dual modes as in FIG. 5(a) have been experimentally observed prior to the L-H bifurcation in a low density, deuterium discharge in DIII-D [20].

Questions that arise: (1) what triggers the sudden penetration of the strong $V_{ge} > 0$ part of the GAM oscillations into the edge layer at $t=0.15$ and 0.175 and thus triggering the $E \times B$ shearing of the edge turbulence, (2) why does $V_{ge}$ and its oscillations stay positive and keep on increasing after 0.175ms, and (3) what maintains the positive $E \times B$ flow shear as the turbulence is suppressed? The Reynolds force in FIG. 2(d) offers an answer to the first question. There are spatially localized oscillations of Reynolds force into the positive poloidal direction (electron diamagnetic flow direction) in the edge layer at $t=0.155$ms and 0.175 ms, with a radial gradient that promotes positive sheared flow in the edge layer. Furthermore, there is another strong peak in the Reynolds force at $t=0.195$ms at the radial position $\Psi_N=0.984$, that coincides with another push of $E \times B$ shearing into the positive direction above 300 kHz in FIG. 2(a). The second and third question imply that there is a background force pushing the edge layer to a negative charge state or $V_{ge} > 0$. The third question also suggests that this background force is strong enough to keep the turbulence suppressed in the edge layer. The X-point ion orbit loss mechanism fits for the background force. It drives the edge layer to a negative charge state. As the edge $T_i$ increases, the enlarged X-point ion orbit-loss hole provides a stronger background force leading to a negative local charge.

The physics found in the XGC1 simulations reconciles a few different L-H bifurcation dynamics observed in experiments: They are not mutually exclusive but could work together, depending upon plasma conditions. The anticipated weak $\nabla p$-driven $E \times B$ shearing in ITER edge from the small $\rho^*$ effect can be compensated by the X-point orbit-loss effect if the edge $T_i$ can be high enough.

5. CONCLUSION AND DISCUSSION

A fast, forced bifurcation of turbulence and transport has been observed in the simulation of electrostatic version of the gyrokinetic particle-in-cell code XGC1 in a realistic diverted tokamak edge geometry under neutral
particle recycling. The magnetic field geometry and the plasma profile for the simulation are from the Alcator C-Mod L-mode plasma discharge #1140613017. To induce a fast transition within the available computing resources, a strong forcing is imposed via a high rate of heat deposition in the edge layer.

The simulation shows the validity of most of the underlying assumptions used by the popular predator-prey model in this fast transition event, with one important addition that the neoclassical orbit loss physics also plays a critical role in the bifurcation process. We observe that the bifurcation of turbulence and transport occurs with the synergetic dynamics of the turbulence-driven Reynolds force and the neoclassical orbit-loss force when the combined $E \times B$ shearing rate in the edge layer reaches a critical level.

In the simulation, the Reynolds force disappears during the period of turbulence suppression. This implies the necessity of some other mechanism for the generation of the $E \times B$ shearing to keep the turbulence suppressed while a high enough pressure pedestal is formed to provide the needed steady sheared $E \times B$ flow. The orbit loss force can provide the sheared $E \times B$ flow as ion temperature increases in the edge layer. Also, this synergistic orbit-loss mechanism explains the preferred direction of $E \times B$ shearing in the L-H bifurcation. Without a strong neoclassical force (either through the orbit loss or $\nabla p$ force balance), the transition may stay in the deterging state, in the so called “I-phase.”

The present study is electrostatic. How much of an impact the electromagnetic effect will have on the L-H transition dynamics is left for a future study. A turbulence bifurcation event with the backward magnetic drift case has also been studied, and will be reported in the near future. Isotope effect on the L-H transition is under investigation at the present time.

ACKNOWLEDGEMENTS

Authors thank L. Delgado-Aparicio for estimating the radiative power loss estimate. Authors also thank A. Hubbard for helpful discussions on the L-I transition. This work is supported mostly by DOE FES and ASCR through the SciDAC project via the U.S. Department of Energy under contract No. DE-AC02-09CH11466. It used resources of OLCF, ALCF and NERSC through the ALCC and the INCITE programs.

REFERENCES


[17] “No Title.”

