Simulations of Tokamak Boundary Plasma Turbulent Transport

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The BOUT++ code has been used to simulate edge plasma electromagnetic (EM) turbulent transport and to study the role of EM turbulence in setting the scrape-off layer (SOL) widths. More than a dozen tokamak discharges from C-Mod, DIII-D, EAST, ITER, and CFETR have been simulated with encouraging success. The simulation results reproduce the measured pedestal turbulence characteristics and the SOL widths. The principal results are: 1) the blobby turbulence originates in the pedestal peak pressure gradient region inside the magnetic separatrix and nonlinearly spreads across the separatrix. The electromagnetic fluctuations provide anomalous transport, which causes particle and heat to be turbulently transported radially down their gradients across the separatrix into the SOL. The electromagnetic fluctuations show the characteristics of both quasi-coherent modes (QCMs) and broadband turbulence. 2) For simulations of C-Mod EDA H-mode plasmas, the mode spectra are in agreement with the phase contrast imaging data; radial location of the mode is generally consistent with measurements localizing QCMs to the pedestal/separatrix region. For simulations of EAST H-mode plasmas, the mode spectra are in agreement with the probe, interferometer, and POINT diagnostics. A series of simulations also shows that the edge bootstrap current plays a critical role to shift the most unstable mode to lower toroidal mode number, narrow the mode spectrum and enhance radial transport. Therefore, it is suggested to control the peeling modes and associated transport by introducing edge current drive to cancel bootstrap current, for example, by means of lower hybrid waves. This may lead to suppression/mitigation of type-I ELMs and facilitate access to the grassy ELM regime, thus opening a potentially new avenue for steady-state operations in ITER, CFETR and beyond.
SIMULATIONS OF TOKAMAK BOUNDARY PLASMA TURBULENT TRANSPORT
in setting the divertor heat flux width

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Abstract

The BOUT++ code has been used to simulate edge plasma electromagnetic (EM) turbulence and transport, and to study the role of EM turbulence in setting the scrape-off layer (SOL) heat flux width $\lambda_q$ and its scaling with machine parameters. An important goal of this research is to develop a first-principle model that can reproduce the observed inverse current $I_p$ scaling of $\lambda_q$ seen in the international tokamak database and that can project the SOL heat flux width $\lambda_q$ for future machines. More than a dozen tokamak discharges from C-Mod, DIII-D, EAST, ITER and CFETR have been simulated with encouraging success. The plasma profiles inside the separatrix of these discharges used in simulations are taken from fits of a modified tanh function to real experimental data, mapped onto a radial coordinate of normalized poloidal flux for C-Mod, DIII-D, and EAST. The plasma profiles inside the separatrix of ITER and CFETR are taken from feasible burning plasma operation scenarios using CORSICA and OMFIT framework.

For the C-Mod enhanced D$_e$(EDA) H-mode discharges, BOUT++ six-field two-fluid nonlinear simulations show a reasonable agreement of upstream turbulence characteristics and divertor target heat flux: (a) The simulated quasi-coherent modes (QCMs) show consistent characteristics of the frequency vs poloidal wave number spectra of the EM fluctuations when compared with experimental measurements – frequencies are around 60-170 kHz and $k_p$ is around 2.0 cm$^{-1}$ which are comparable to the Phase Contrast Imaging measurements; (b) The location of the QCMs is generally consistent with experiment. The BOUT++ simulations have also been performed for inter-ELM periods of DIII-D and EAST discharges, similar quasi-coherent modes have been found in these discharges. The parallel electron heat fluxes onto the target from the BOUT++ simulations of C-Mod, DIII-D, and EAST follow the experimental heat flux width scaling of the inverse dependence on the poloidal magnetic field. Further turbulence statistics analysis shows that the blobs are generated near the pedestal pressure peak gradient region inside the separatrix and contribute to the transport of the particle and heat in the SOL region. The simulations for ITER and CFETR indicate that divertor heat flux width $\lambda_q$ no longer follows the $1/I_p$ experimental Eich scaling law, possibly due to their large machine sizes and pedestal structures.

1. INTRODUCTION

Narrow divertor heat flux width is a serious concern to ITER and future reactors. As Goldston showed that the radial drifts balancing with the SOL parallel flow in the separatrix vicinity determines a heat flux width $\lambda_q \approx q\rho_s$, which yields a size independent scaling, so called heuristic drift-based (HD) model [1]. Here q is the edge safety factor and $\rho_s$ is the ion gyro-radius. The HD model, supported by experimental scaling (Eich scaling) [2] in which $\lambda_q \propto 1/I_p$ (or $1/B_{pol}$) with little or no dependence on any other key SOL parameter, predicts $\lambda_q \sim 1.0 \text{mm}$, a factor of ~3 lower than assumed in all plasma boundary modelling used to scope the operational window of the ITER divertor. Here $I_p$ is the plasma current and $B_{pol}$ is the poloidal magnetic field. Such narrow widths would in practice be difficult to handle in terms of divertor target power loads. On the other hand, the electromagnetic fluctuation causes particle and heat to be turbulently transported radially down their gradients across the separatrix into the SOL. In the SOL, parallel transport connects particles and heat to the divertors. Finally, the divertor heat flux width is determined by the competition between cross-field and parallel transport in the SOL [3-6]. The recent gyro-kinetic simulations at the ITER scale give $\lambda_q \sim 5 - 6 \text{mm}$ in 15 MA H-modes [7]. These are still active areas of research throughout the fusion community and consensus has not yet been obtained. Our BOUT++ simulation results show that HD model gives a lower limit of divertor heat flux width.
To simulate pedestal plasma turbulence and understand its role in setting the divertor heat flux width, and validate with the corresponding experimental measurements, the BOUT++ code uses realistic X-point magnetic geometry and plasma profiles. The BOUT++ simulations are based on a set of the C-Mod enhanced D, (EDA) H-mode discharges, DIII-D and EAST quasi-steady inter-ELMs H-mode discharges, including (1) fitted plasma profiles and equilibrium reconstruction utilizing experimental pressure constraints (kinetic equilibrium fitting code (EFIT)). The plasma profiles are obtained from measurements typically averaged over time. The plasma profiles inside the separatrix of ITER and CFETR are taken from feasible burning plasma operation scenarios using CORSICA [8] and OMFIT framework [9]. (2) BOUT++ computation region that spans the magnetic separatrix, including three distinct regions: the outer part of the closed flux region (Edge), the SOL, and the private flux region. The outputs from the BOUT++ simulations are (1) turbulence fluctuation across the separatrix; (2) Power across the separatrix; (3) Divertor heat flux amplitude and width. Since the multi-scale parallel transport along the magnetic field line for electrons and ions, we use both transport and turbulence code.

2. CHARACTERISTICS OF BOUNDARY PLASMA TURBULENCE

2.1. Pedestal turbulence

For BOUT++ turbulence simulations, we use three-dimensional 6-field 2-fluid electromagnetic model [10-13], which evolves perturbed (1) ion density \(n_i\), (2) ion temperature \(T_i\), (3) electron temperature \(T_e\), (4) parallel velocity \(v_{bi}\), (5) vorticity \(\sigma_z\), and (6) magnetic vector potential \(A_t\). Flux-limited parallel thermal transport and sheath boundary conditions are used.

From the given magnetic geometry and plasma profiles corresponding to a specific experimental device and discharge, the simulation is initialized with a set of small random fluctuations. The fastest growing mode dominate the initial phase of the calculations, in which the fluctuations grow at an approximately exponential rate. After this initial linear phase, the density, temperature, electrostatic, and magnetic potential fluctuations evolve to a saturated state. From the saturated steady state, turbulence statistical properties can be extracted from the BOUT++ simulations using Fourier analysis to steady turbulence and validated with the various fluctuation measurements.

To simulate tokamak divertor heat flux width, special sources are added to maintain the experimentally measured plasma profiles inside the top of the pedestal, plasma profiles in the bottom of pedestal and in the SOL are free to evolve [3-6]. The equilibrium electric field is either from experimental measurement when available (such as for DIII-D quasi-steady inter-ELMs H-mode discharges) or determined from force balance with no net flow \(V_0 = V_{\text{th}} + V_{\text{tr}} = 0\). Therefore, the equilibrium electric field is \(E_{r0} = \left(1/n_0 Z_e e\right) \nabla_0 \delta P_{\text{th}}\). Similarly in the present model, net turbulent zonal flow has also been set to be zero \(\langle \delta \psi \rangle_x = \langle \delta v_x \rangle_x = \langle \delta v_y \rangle_x = 0\). Therefore, the perturbed electric field is \(\langle \delta E_r \rangle_x = \left(1/n_0 Z_e e\right) \nabla_0 \langle \delta P_{\text{th}} \rangle_x\). The impact of these assumptions is a subject of further investigation using the BOUT++ code. The zonal magnetic field is also set to zero as it is negligibly small compared with the equilibrium magnetic field \(B_0\).
Figure 1 is a contour plot of root-mean-square of density fluctuation across separatrix at outer mid-plane. The plot shows that electromagnetic turbulence originates inside the pedestal near the peak pressure gradient \( \nabla P_{\text{peak}} \) position and non-linearly spreads across the separatrix into the SOL, not local instabilities in the SOL. Simulations have been performed for C-Mod, DIII-D and EAST discharges. The results show the similar characteristics, as shown in Figure 1 (a) for C-Mod and Figure 1(b) for EAST.

### 2.2. Validations

QCMs (quasi-coherent modes) are well characterized on multiple diagnostics in the C-Mod Enhanced D\(_{\alpha}\) (EDA) H-mode operating conditions [14-17] and on multiple other machines. BOUT++ six-field two-fluid nonlinear simulations have been performed for these C-Mod discharges with self-consistent calculation of the electric field across the separatrix into the scrap-off-layer (SOL) [3,4]. Based on the experimentally measured plasma density and temperature profiles inside the separatrix, the radial electric field (E\(_r\)) is calculated across the separatrix using plasma transport equations with the sheath potential in the SOL [18]. The simulation results show a reasonable agreement of pedestal turbulence characteristics and divertor target heat flux width and amplitudes. (1) The electromagnetic turbulence shows the characteristics of QCMs and broadband turbulence. (2) The resistive-ballooning modes and drift-Alfven wave are dominant instabilities, which are generally consistent with the experimental observations as a separatrix-spanning electron drift-wave with significant interchange drive and electromagnetic contributions [3,4]. (3) Radial location of the mode is generally consistent with experimental measurements showing the QCMs amplitude peaked near the pedestal/separatrix [15,16]. Figure 2 shows the relative location of the radial mode structure at different time slices to E\(_r\) profile at outside midplane from the BOUT++ simulation data. (4) The mode spreads across the whole poloidal cross section but still dominant at the low field side with the structure of ballooning mode. (5) The mode spectra are in agreement with the phase contrast imaging data [14]. Typically, the frequencies are around 100 kHz, poloidal wave numbers are around 1-2.0 cm\(^{-1}\). (6) Blobby turbulence originates in the peak pressure gradient position inside the separatrix and non-linearly spreads across the separatrix. The magnetic flutter causes the fluctuations spreading into the SOL. (7) The frequencies of the modes are proportional to E\(_r\) which is consistent with previous BOUT simulations [4].

The BOUT++ simulations have also been performed for inter-ELM periods of DIII-D and EAST discharges, and similar EM turbulence characteristics with QCMs have been found in these discharges [5,6]. The EAST simulations of the QCMs with different plasma currents and geometries show that the perturbation of electron temperature spreads widely in the radial direction with the same frequency and almost covers the entire pedestal region inside the separatrix. The fluctuation is peaked around the largest pressure gradient position. The frequencies of the simulated QCM for different plasma currents are different, but in the range of 20-40kHz, which are in the range of the edge-coherent-mode (ECM)/coherent-mode (CM) observed on EAST by probe and interferometer diagnostics [19-23]. The value of k\(_B\) at outer mid-plane is in the range of 0.5-0.7cm\(^{-1}\), which are consistent with those of ECM/CM on EAST measured by the POINT diagnostics [21].

### 3. TOWARDS UNDERSTANDING THE ROLE OF TURBULENCE ON SCALING OF TOKAMAK DIVERTOR HEAT FLUX WIDTH

#### 3.1 Divertor heat flux width from turbulence simulations

The electromagnetic fluctuation causes particle and heat to be turbulently transported radially down their gradients across the separatrix into the SOL. In the SOL, parallel transport connects particles and heat turbulently transported across the separatrix near the outer midplane to the divertors. Finally, on the divertor footprint, the radial profiles of parallel heat fluxes are mapped to the outside midplane according to the Eich-fitting formula [2]. The fitting function is a convolution of a Gaussian with an exponential function. Here the
exponential captures transport processes in the SOL, which yields the divertor heat flux width $\lambda_q$. To compare with the experimental results, we used the same formula with the same fitting method as used by the experimentalists.

Figure 3 is a plot of divertor heat flux width $\lambda_q$ vs poloidal magnetic field at outer midplane $B_{pol,MP}$. The solid black curve is the experimental scaling determined by a regression for the ITPA multi-machine database to the Eich fitting formula [2], dashed curves for the error bar. The gray symbols are from DIII-D and C-Mod experiments. Purple squares are for EAST simulations, blue triangles for DIII-D and red bullets for C-Mod. The simulated electron divertor heat flux width for C-Mod, DIII-D and EAST follows “Eich” scaling. Divertor heat flux width is inversely proportional to poloidal magnetic field $B_{pol,MP}$ at outer midplane. The green star is for ITER and the dark purple star is for CFETR from transport simulations. The details will be described in section 3.3. The amplitude of the electron heat fluxes is within a factor of 2 compared to experimental measurements.

3.2 Divertor heat flux width from transport simulations

As we described in the section 2, the electromagnetic fluctuation causes particle and heat to be turbulently transported radially down their gradients across the separatrix into the SOL. Because the electromagnetic fluctuations have a more ballooning character, and the fluctuations are larger in low field side. In the SOL, parallel transport connects particles and heat turbulently transported across the separatrix near the outer midplane to the divertors. Because of the different electron and ion parallel transport time scale, for initial-value turbulence simulations, even electron divertor heat flux is well saturated within 100 $\mu$s, but it will take much longer time for ion divertor heat flux to reach saturation (on order of 10s ms). Therefore, in order to get steady state divertor heat flux solution for both electrons and ions, it is more efficient to use BOUT++ transport model.

To cross-examine the assumptions of Goldston’s HD model [1], BOUT++ transport model has been developed for transport simulations with the electric and magnetic drifts and with the sheath potential in the SOL [18]. The three-dimensional 6-field 2-fluid transport code evolves (1) ion density $n_i$, (2) ion temperature $T_i$, (3) electron temperature $T_e$, (4) parallel velocity $v_{||i}$, (5) vorticity $\vec{\omega}$, and (6) Ohm’s law for current $J_\parallel$. The radial electric field is calculated by solving the electric potential from vorticity. Flux-limited parallel thermal transport is used.

Fig. 4. (a) Divertor heat flux width for different currents or poloidal magnetic fields. Simulation data of total heat flux width overlaid on independent fits of experimental heat flux decay length $\lambda_q$ versus poloidal magnetic field $B_{pol,MP}$ at outside midplane for four selected C-Mod EDA H-mode discharges. The solid black curve is the experimental scaling determined by a regression for the ITPA multi-machine database to the Eich fitting formula [13], dashed curves for the error bar. Red bullets are calculated from the BOUT++ turbulence code [24]; green stars from the BOUT++ transport code; blue squares from Goldston’s HD Model and the gray symbols from the experimental data. For $I_p=1.4M$ and $B_{pol,MP}=1.11T$ case, $T_{e,sep}=74.5eV$ is used. (b) Divertor heat flux width vs SOL thermal diffusivity $\chi$ for C-Mod. The solid black curve is from transport simulations, green star from interpretation of experimental data, red bullet from turbulence simulations and blue star from HD model.
Transport coefficients are calculated from the experimental profiles inside separatrix, then extending to the SOL. For the divertor heat flux width simulations, two-dimensional option of the 6-field 2-fluid transport code is used by assuming toroidal symmetry.

For C-Mod EDA H-mode discharges, steady state solutions of divertor heat flux calculated from transport simulations show: (1) a similar scaling to the Goldston's HD model; (2) The amplitude of the simulated heat fluxes is within a factor of 2 compared to the experiment data; (3) The ExB drift reduces the heat flux width by 30% [24]. Figure 4 shows the comparison of the results from the BOUT++ transport simulations and those from turbulence simulations, experimental measurements and HD model. Here BOUT++ transport simulation results of the Eich heat flux width \( \lambda_q \) is around 1-2 times larger than the experimental results, especially for high current case. The electron heat flux widths are larger than that of the ions; the same trend is found for both ion and electron heat flux width. The trend of transport simulation results is consistent with turbulence simulations and follows the experimental data at low current cases, though not exactly following the \( I_p \) experimental scaling law [24]. The error bars on the HD model are from the separatrix temperature error considering the uncertainty of the separatrix position. The uncertainty in the actual location of the last closed flux surface (LCFS) leads to the uncertainty in the value of \( T_{e,sep} \) from the measurements. Here we evaluate the uncertainties in the Goldston’s HD model by assuming a range of the separatrix position \( d\psi \sim 0.01 \) inside the separatrix.

In order to determine the relative role of drifts vs turbulent transport in setting the divertor heat flux width, we do a scan of SOL transport coefficients, the radial thermal diffusivity \( \chi_r \) (assuming \( \chi_e = \chi_i = \chi_L \)). We fix the thermal diffusivities \( \chi_L \) inside the separatrix which yield temperature profiles to match those as experimentally measured, while the SOL thermal diffusivities \( \chi_L \) vary by 500 times, from 0.01 m²/s to 5 m²/s. The particle transport coefficient is interpreted from experimental density profile and is fixed for the scan: \( D_L^{C-Mod} = 0.13 \text{ m}^2/\text{s} \) near separatrix. Figure 4(b) is a plot of divertor heat flux width \( \lambda_q \) vs the SOL transport coefficient \( \chi_L \) for C-Mod high current discharge with \( I_p = 1.4 \text{MA} \), \( B_{pol,min} = 1.11 \text{T} \) and the separatrix temperature \( T_{e,sep} = 74.5 \text{eV} \). The results show that divertor heat flux width is first constant and then increases with the SOL thermal diffusivity \( \chi_L \). The constant is roughly consistent with that of Goldston’s HD Model (blue star) with \( \lambda_q = 1.01 \text{mm} \). The critical value of thermal diffusivity is \( \chi_L^c \approx 0.3 \text{m}^2/\text{s} \). When \( \chi_L > \chi_L^c \), divertor heat flux width is not sensitive to the SOL thermal diffusivity, therefore drifts dominate cross-field transport; When \( \chi_L < \chi_L^c \), the divertor heat flux width increases with the SOL thermal diffusivity \( \chi_L \). Turbulence dominates cross-field transport. The interpreted diffusivity from experiment data is \( \chi_L = 0.23 \text{ m}^2/\text{s} \) corresponding to the green star with \( \lambda_q = 1.09 \text{mm} \). The turbulence simulation yields the red bullet with \( \chi_L = 0.16 \text{ m}^2/\text{s} \) and \( \lambda_q = 0.85 \text{mm} \). The simulation results show that the drifts and turbulent transport are locked in a tight competition in setting the divertor heat flux width for C-Mod.

### 3.3 Divertor heat flux width prediction for ITER and CFETR

The similar geometry and transport simulations have been performed for ITER and CFETR. The magnetic geometry and plasma profiles inside the separatrix of ITER and CFETR are taken from feasible burning plasma operation scenarios using CORSICA [8] and OMFIT framework [9]. The simulated ITER plasma is generated from 15MA baseline operation scenarios using CORSICA with a high ratio of fusion power gain Q=10 by operating D-T plasmas in the type-I ELMy H-mode regime. The major ITER parameters are \( R=6.2 \text{m}, a=2.0 \text{m}, B=4.5 \text{T}, q_0=3.3, \beta_p=0.67, \delta_u=0.4, \delta_l=0.46, \kappa=1.8, \) and the separatrix temperature \( T_{e,sep}=200 \text{eV} \). The simulated CFETR plasma is generated from 1GW steady state operation scenarios in the ELMy H-mode regime using OMFIT with \( Q=11.9 \). The major CFETR parameters are \( R=7.2 \text{m}, a=2.2 \text{m}, B=7.3 \text{T}, I_p=13.8 \text{MA}, q_0=5.93, \beta_p=2.34, \delta_u=0.39, \delta_l=0.49, \kappa=2.37, \) and \( T_{e,sep}=91.7 \text{eV} \).

The results show that ITER and CFETR will possibly be in a turbulence dominant regime. Figure 5 is a plot of divertor heat flux width vs perpendicular thermal diffusivities \( \chi_L \) for CFETR and ITER. In these simulations, we fix the thermal diffusivities \( \chi_L \) inside the separatrix which yield temperature profiles to match those from scenario studies, while the SOL thermal diffusivities \( \chi_L \) vary by \( \sim 1000 \) times, from 0.01m²/s up to 5m²/s for CFETR and up to 10m²/s for ITER. The particle transport coefficient is interpreted from scenario density profiles and is fixed for the scan: \( D_{CFETR}^{ITER} = 0.1 \text{ m}^2/\text{s} \) and \( D_{ITER}^{ITER} = 0.48 \text{ m}^2/\text{s} \) near separatrix. The transport simulation results in Fig. 5 (a) for CFETR (solid blue curve) show that divertor heat flux width is first constant and then increases with the SOL thermal diffusivity \( \chi_L \). Similar to that of C-Mod as shown in Fig.4(b). The Goldston’s HD model gives a lower limit of divertor heat flux width (blue star) with \( \lambda_q = 0.96 \text{mm} \). The critical value of thermal diffusivity is \( \chi_L^c \approx 0.1 \text{m}^2/\text{s} \). When \( \chi_L < \chi_L^c \), divertor heat flux width is not sensitive to the SOL thermal diffusivity, therefore drifts dominate cross-field transport; When \( \chi_L > \chi_L^c \), the divertor heat flux width increases with the SOL thermal diffusivity \( \chi_L \). Turbulence dominates cross-field transport. The interpreted
diffusivity from scenario temperature profile (green star) is $\chi_L = 0.85 \text{ m}^2/\text{s}$. This CFETR data point is also added to Fig.3 of divertor heat flux width vs poloidal magnetic field at outer midplane as a dark purple star symbol. The turbulence simulation yields the red bullet with $\chi_L = 1.0 \text{ m}^2/\text{s}$ with $\lambda_q = 4.17 \text{ mm}$. The simulation results show that the turbulent transport dominates drifts for CFETR.

The results in Fig. 5 (b) for ITER simulations (solid blue curve) show that divertor heat flux width almost always increases with the SOL thermal diffusivity $\chi_L$, indicating that the critical value of thermal diffusivity $\chi_L^c$ is very small and the contribution of radial transport from drifts is negligible. To further confirm this statement by turning off the drifts in the code, the transport simulation results show that the divertor heat flux width is almost unchanged (red dashed curve). The Goldston’s HD model gives a lower limit of divertor heat flux width (blue star) with $\lambda_p=1.43 \text{ mm}$. The diffusivity from CORSICA transport study is $\chi_L = 0.34 \text{ m}^2/\text{s}$, which yields $\lambda_q = 5.6 \text{ mm}$. This ITER data point is also added to Fig.3 of divertor heat flux width vs poloidal magnetic field at outer midplane as a green star symbol. The turbulence simulation yields the red bullet with $\chi_L = 10.33 \text{ m}^2/\text{s}$ and $\lambda_q = 19.32 \text{ mm}$. The large width is possibly because of ELM events. By scaling down the pedestal height to 95%, the turbulent thermal diffusivity is reduced to $\chi_L = 8.65 \text{ m}^2/\text{s}$ and $\lambda_q = 13.08 \text{ mm}$. To further scaling down the pedestal height to 90%, the turbulent thermal diffusivity is reduced to $\chi_L = 3.45 \text{ m}^2/\text{s}$ and $\lambda_q = 9.24 \text{ mm}$. Therefore, the SOL turbulent transport coefficients and divertor heat flux width depend on pedestal structures inside the magnetic separatrix [25].

3.4 Transition from drift dominant regime to turbulence dominant regime

Consistent with physics picture presented here that in the turbulence dominant regime, larger turbulence transport in L-mode should yield the wider divertor heat flux width than that found in H-mode, which have been confirmed in recent ASDEX-Upgrade experiments [26]. Further experimental observations on C-MOD and ASDEX-Upgrades have shown a similar parametric dependence for $\lambda_q$ in I-mode and L-mode discharges to that previously found in H-mode, with consistently larger width and weaker current $I_p^{\alpha}$ scaling as turbulence transport increases [27-28]. In C-Mod discharges, the current index is $\alpha = 0.96$ for H-mode, $\alpha = 0.57$ for I-mode and $\alpha = 0.74$ for L-mode [28]. Turbulence transport does increase from H-mode to L-mode, so the divertor heat width increases accordingly, but turbulence seems not strong enough to dominate the radial transport by drifts in I-mode and L-mode discharges, and hence to break the experimental scaling (Eich scaling), in which $\lambda_q \propto 1/I_p$ (or $1/\text{B}_\text{pol}$). The real interesting question is at which point in operating space (namely $I_p$), there would be a transition from drift dominant regime to turbulence dominant regime, which breaks the experimental scaling (Eich scaling).

Figure 6 shows the critical value of thermal diffusivity $\chi_L^c$ vs poloidal magnetic field at outer midplane $B_{\text{pol,MP}}$. When $\chi_L < \chi_L^c$, drifts dominate the cross-field transport; When $\chi_L > \chi_L^c$, turbulence dominates the cross-field transport. The two lower $B_{\text{pol,MP}}$ points (blue squares) are from C-Mod transport simulations; the red star from CFETR and the green star from ITER transport simulations. As plasma current $I_p$ increases, the critical value of thermal diffusivity $\chi_L^c$ decreases. For the first two C-MOD points (blue squares), the critical value of thermal diffusivity $\chi_L^c$ decreases when the current $I_p$ increases because magnetic drifts reduce. From C-Mod to CFETR and ITER, the critical value of thermal diffusivity $\chi_L^c$ is significantly reduced, possibly because of the
large machine sizes, which reduces the contributions of the cross-field transport from magnetic drifts. Once the critical value of thermal diffusivity $\chi_{\perp}$ falls below the lower limit of the nominal range of the SOL turbulent thermal diffusivity \((0.01 \text{ m}^2/\text{s} < \chi_{\perp} < 10 \text{ m}^2/\text{s})\), it enters turbulence dominant regime. Therefore, the critical value of thermal diffusivity $\chi_{\perp}$ for a transition from drift dominant regime to turbulence dominant regime, does depend on two factors: machine size and plasma operating regime.

In these BOUT++ simulations for ITER and CFETR plasmas in the ELMy H-mode regime, the pedestal plasma profiles are flattening during ELM crashes. These ITER and CFETR simulations clearly indicate that divertor heat flux width $\lambda_q$ no longer follows the $1/B_{\text{pol,MP}}$ experimental Eich scaling law as shown in Fig.3, possibly due to their machine sizes and pedestal structures. The large machine size (major radius $R$) reduces the contributions of the cross-field transport from magnetic drifts. Here, the broader ITER pedestal divertor heat flux width from simulations is possibly due to larger ITER pedestal height in the type-I ELMy H-mode regime, while the simulated CFETR plasmas are generated possibly in a grassy ELMy H-mode regime with high $q_{95}=5.93$ and high poloidal beta $\beta_p = 2.34$. Therefore, optimizing the H-mode pedestal in grassy ELM regime seems the best compromise between acceptable divertor solutions and high-performance steady-state operations.

4. SUMMERARIES AND DISCUSSIONS

A fundamental issue of peak divertor target power flux density is to understand the relative role of the cross-field transport: (neo)classical magnetic drifts vs turbulence transport. Because of the different electron and ion parallel transport time scale, for initial-value turbulence simulations, even electron divertor heat flux is well saturated, but it takes much longer time for ion divertor heat flux to reach saturation. We therefore use both BOUT++ turbulence and transport codes to efficiently simulate divertor heat flux and to cross-examine the assumptions of Goldston’s heuristic drift-based (HD) model [1].

The divertor electron heat flux width $\lambda_q$ from BOUT++ turbulence simulations is consistent with ITPA multi-machine database scaling (Eich scaling) for current tokamaks. BOUT++ turbulence simulations show that the SOL turbulence originates from the peak gradient region inside the pedestal, not local instabilities in the SOL. The characteristics of simulated turbulence are compared well with data from C-Mod enhanced $D_a$ (EDA) H-mode discharges. Transport simulations show two distinct regimes: drift dominant regime and turbulence dominant regime. Goldston’s HD model gives a lower limit of divertor heat flux width in the drift dominant regime. For the C-MOD high current discharge with $I_p=1.4$MA and $B_{\text{pol,MP}}=1.1$T, the critical value of thermal diffusivity for a transition between the two regimes is found at $\chi_{\perp} = 0.3 \text{ m}^2/\text{s}$, which is higher than that calculated from turbulence simulation with $\chi_{\perp} = 0.16 \text{ m}^2/\text{s}$, and that interpreted from experiment profile with $\chi_{\perp} = 0.23 \text{ m}^2/\text{s}$. Therefore, for C-MOD EDA H-mode discharges, drifts and turbulence are locked in a tight competition, possibly due to its compact machine size and good pedestal confinement.

From C-Mod to CFETR and ITER, the critical value of thermal diffusivity $\chi_{\perp}$ is significantly reduced, possibly due to their large machine sizes and pedestal structures. BOUT++ simulations for ITER and CFETR plasmas in the ELMy H-mode regime indicate that both ITER and CFETR will possibly be in a turbulence dominant regime. Their divertor heat flux width $\lambda_q$ will no longer follow the $1/B_{\text{pol,MP}}$ experimental Eich scaling law. Although BOUT++ transport simulations of CFETR plasmas show both drift dominant regime and turbulence dominant regime in the scan of the SOL thermal diffusivity and the HD model sets the lower limit of divertor heat flux width $\lambda_q$, the critical value of thermal diffusivity $\chi_{\perp}$ is significantly reduced to $0.1 \text{ m}^2/\text{s}$ in comparison with that of C-Mod. For nominal range of the SOL thermal diffusivity \((0.01 \text{ m}^2/\text{s} < \chi_{\perp} < 10 \text{ m}^2/\text{s})\), the drifts
make almost no contributions to the ITER divertor heat flux width $\lambda_q$. Given ITER and CFETR with similar machine sizes, the broader ITER pedestal divertor heat flux width from simulations is possibly due to larger ITER pedestal height in the type-I ELM regime, which also yield much large intolerable ELM bursting heat load. By contrast, the simulated CFETR plasmas are generated possibly in a grassy ELMy H-mode regime with high $q_{95}=5.93$ and high poloidal beta $\beta_p=2.34$. Therefore, optimizing the H-mode pedestal in grassy ELM regime seems the best compromise between acceptable divertor solutions and high-performance steady-state operations.

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