Multi-scale transport in the DIII-D ITER baseline scenario with direct electron heating and projection to ITER

B. A. Grierson,1 G. M. Staebler,2 W. M. Solomon,2 G. R. McKee,3 C. Holland,4 M. Austin,5 A. Marinoni,6 L. Schmitz,7 R. I. Pinsker,2 and the DIII-D team2

1Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA
2General Atomics, P.O. Box 85608, San Diego, CA 92186-5608
3Department of Engineering Physics University of Wisconsin-Madison, Madison, WI 53796, USA
4University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0417
5University of Texas, Austin, TX
6MIT Plasma Science and Fusion Center, Cambridge, Massachusetts 02139, USA
7University of California, Los Angeles, Los Angeles, California 90095, USA

September 2018

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

This work is supported by U. S. DOE Contract Numbers(s): FG02-08ER54999; FG03-97ER54415; AC02-09CH11466; FC02-04ER54698; FG02-08ER54984; FG02-04ER54235; FG02-07ER54917. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States government is permitted.

Submitted to Physics of Plasmas
Multi-scale Transport in the DIII-D ITER Baseline Scenario with Direct Electron Heating and Projection to ITER

B. A. Grierson,1,∗ G. M. Staebler,2 W. M. Solomon,2 G. R. McKee,3 C. Holland,4 M. Austin,5 A. Marinoni,6 L. Schmitz,7 R. I. Pinsker,2 and the DIII-D team2

1Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA
2General Atomics, P.O. Box 85608, San Diego, CA 92186-5608
3Department of Engineering Physics, University of Wisconsin-Madison, Madison, WI 53796, USA
4University of California San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0417
5University of Texas, Austin, TX
6MIT
7UCLA

(Dated: January 17, 2018)

Multi-scale fluctuations measured by turbulence diagnostics spanning long and short wavelength spatial scales impact energy confinement and the scale-lengths of plasma kinetic profiles in the DIII-D ITER baseline scenario with direct electron heating. Contrasting discharge phases with ECH+NBI and NBI only at similar rotation reveals higher energy confinement and lower fluctuations when only NBI heating is used. Modeling of the core transport with TGYRO using the TGLF turbulent transport model and NEO neoclassical transport reproduces the experimental profile changes upon application of direct electron heating and indicates that multi-scale transport mechanisms are responsible for changes in the temperature and density profiles. Intermediate and high-k fluctuations appear responsible for the enhanced electron thermal flux, and intermediate-k electron modes produce an inward particle pinch that increases the inverse density scale length. Projection to ITER is performed with TGLF and indicates a density profile that has a finite scale length due to intermediate-k electron modes at low collisionality, and increases the fusion gain. For a range of $E \times B$ shear, the dominant mechanism that increases fusion performance is suppression of outward low-k particle flux and increased density peaking.

PACS numbers: AA.bb

I. INTRODUCTION

Understanding transport and confinement in tokamak discharges that match the conditions expected in ITER bolsters confidence in the extrapolations to successful $Q = 10$ DT operation in the high-current baseline scenario. Reactor performance has historically been projected based on zero dimensional scaling of energy confinement time with databases from international tokamak experiments[1, 2]. However, as modern experiments have revealed, more subtle changes in plasma profiles that are not included in these confinement scaling can have dramatic impacts on the plasma performance and stability. Thermal transport modeling has received the most attention in the community, but there is a clear increasing need to understand particle (main plasma and impurity) and momentum transport to validate existing and emerging models in order to increase confidence in performance projections and safe machine operation. In particular, when performing ITER simulations the core electron density profile has often been imposed to be flat, but plasma density profiles are almost ubiquitously observed and predicted[3, 4] to be peaked in existing experiments. Density peaking both increases the fusion power by increasing the density in the high reactivity region, but is also seen in present experiments to cause accumulation of high-Z impurities when peaking occurs very near the magnetic axis[5]. However, recent gyrokinetic results indicate that this impurity accumulation may not occur in future larger reactors[6].

This paper details the observation and modeling of thermal, particle and momentum transport in the DIII-D ITER baseline scenario with direct electron heating and reveals a significant amount of electron thermal energy transport in the high wavenumber range, high fluctuation levels, an enhanced electron density gradient and flattening of the ion temperature profile. The TGLF[7, 8] transport model is used to predict the core electron and ion temperature profiles and displays good agreement with the experimental observations, performing equally well during strong electron heating and only neutral beam heating. Neoclassical transport is com-

---

∗Electronic address: bgriers@pppl.gov
†B. A. Grierson acknowledges valuable discussion with R.J. Hawryluk, D.R. Ernst, E.A. Belli and J. Candy
puted with the NEO drift-kinetic code. One key dependency investigated in this study is the relationship between electron heating and density peaking and momentum transport. With direct electron heating the ELM frequency increases and the pedestal and line-averaged electron density is reduced, which is sometimes referred to as a global 'density pump-out'. However, locally at mid-radius we observed an increase in the intermediate-k turbulence and an increase in the electron density inverse scale length. Modeling indicates that the steeper density profile in the region of additional electron heating is due to an increase in the intermediate-k inward particle flux. This inward particle flux can be made stronger by higher $E \times B$ shear that reduces the low-k outward flux contribution. When extrapolating these processes to ITER conditions, we find that similar high-k electron thermal flux is expected and that the particle peaking is increased with reduced collisionality. The dominant effect of varying the $E \times B$ shear in ITER simulations is not to affect the temperature profiles directly, as would be commonly expected, but rather to vary the particle peaking, which can in turn stabilize high-k turbulence. Therefore, the overall impact of varying $E \times B$ shear on fusion $Q_{DT}$ reactivity is by increasing density rather than temperature. In addition, simulations using the quasi-linear TGLF and neoclassical indicate that strong tungsten accumulation will not occur in ITER even with a peaked background density profile, in qualitative agreement with Ref.[6].

II. ITER BASELINE SCENARIO ON DIII-D

On the DIII-D tokamak, the ITER baseline scenario is designed to mimic the ITER high current baseline scenario as accurately as practical with the shape adjusted for pumping, toroidal field selected for ECH, the plasma current chosen to match the normalized current $I/aB$ resulting in $q_{95} \approx 3$ and operated with feedback on the normalized plasma pressure $\beta_N \approx 1.8$. In this paper, we focus on an ITER baseline scenario discharge operated with a transition from ECH+NBI to NBI only heating.

Displayed in Fig. 1 are time histories of the plasma evolution, along with the plasma shape and ECH trajectories showing higher energy confinement with only NBI heating. The L-H transition occurs at 1260 ms and the plasma reaches the $\beta_N$ target at 1900 ms, after which $\beta_N$ is held constant. From 1900-2500 ms is the quasi-steady ECH phase of the discharge, which is sustained for multiple energy confinement times with a total auxiliary heating power of 6.3 MW. At 2500 ms the ECH is turned off, while maintaining $\beta_N$ feedback. Additionally, at 2500 ms the NBI torque is lowered in anticipation of plasma “spin-up” that commonly occurs when application of ECH is removed. The plasma enters a second quasi-stationary ELMing phase in approximately 100 ms, which persists from 2600 ms until the end of the discharge at 4000 ms. In the following sections, two times are chosen for detailed profile analysis and modeling: 2400 ms in the ECH phase and 3000 ms in the NBI only phase because beyond 3090 ms a core $n=4$ tearing mode occurs and causes rotation degradation. Detailed modeling of the sub-confinement time changes in turbulence and transport have been documented recently[13], whereas here we focus on the stationary phases. It is noteworthy that, at constant $\beta_N$ the removal of 3.3 MW of ECH requires an increase of NBI power from 2.6 to 3.5 MW, averaged over an energy confinement time, and demonstrates the reduced energy confinement when applying direct heating to electrons. An implication is that the usage of auxiliary electron heating has a small impact on controlling the total plasma stored energy in this operating regime.

III. PROFILES, TRANSPORT COEFFICIENTS AND FLUCTUATIONS

Investigation into the profile variations during ECH+NBI and NBI only reveals distinct impacts of the two heating schemes on the core and pedestal plasma
conditions. Fig. 2 presents the plasma profiles at the two chosen time slices for transport analysis and modeling in the next sections of this paper, including the location of the narrow ECH deposition at \( \rho = 0.4 \). During ECH heating the ELM frequency is higher, which causes the plasma line-averaged density and impurity content to be lower. The electron temperature profiles appear self-similar, with the boundary temperature higher for the lower density resulting in the same stored energy. Profiles of ion temperature display significant changes in the local profile shape; \( T_i \) is strongly flattened just outside of the ECH deposition location. Plasma rotation and total angular momentum are kept nearly constant, as prescribed by the pre-programmed reduction of injected torque.

Examination of the inverse gradient scale lengths \( a/L_{ne} \), \( a/L_{Te} \), \( a/L_{Ti} \) \((a/L_X = -(a/X)dX/dr_{minor})\) in Fig. 3 exposes changes in the profiles related to gradient driven transport. The plasma density profile has a higher \( a/L_{ne} \) when electron heating is applied, indicating a reduced particle diffusivity or less positive outward particle convection. This different character in the electron density scale length is quite stationary during the ECH+NBI and NBI only heating, shown by the contour in Fig. 4. Although the electron heating has changed dramatically, \( a/L_{Te} \) has not changed outside of the error bars, and from this one can infer that \( \chi_e \) must have strongly increased. There is also impact on the ion energy channel, as reduction of \( a/L_{Ti} \) is seen outside of the ECH deposition location, indicating a local increase in ion thermal diffusivity \( \chi_i \). From the electron heated phase to the NBI only phase, the ion to electron temperature ratio is near unity, and varies between \( T_i/T_e \approx 0.8 \) during ECH to \( T_i/T_e \approx 1.1 \) during NBI only. Power balance analysis with TRANS\(^{14}\) provides the quantitative changes in transport beyond inspection of plasma profiles and gradients. Time-dependent analysis of the entire discharge is executed with profiles averaged over 20 ms using MSE-constrained equilibrium reconstruction. Plasma heating is calculated with

FIG. 2: Plasma profiles during ECH+NBI (red/grey) heating and NBI heating only (black) at \( \beta_N = 1.8 \) and torque adjusted to prohibit rotation spin-up. Noticeable differences are the lower density and high electron temperature with ECH. Ion temperature is flat near ECH deposition. Impurity content is lower with ECH+NBI due to higher ELM frequency.

FIG. 3: Transport-relevant quantities. Inverse scale lengths for profiles in Fig. 2 with Monte-Carlo uncertainty. Outside of the ECH deposition location the electron density displays noticeable steepening. Electron temperature profile scale length is similar within error bars, while ion temperature profile is noticeably flatter. During ECH+NBI heating \( T_i/T_e \approx 0.8 \) near deposition, while \( T_i/T_e \approx 1.1 \) during NBI only.

FIG. 4: Electron density inverse gradient scale length. ECH heating ceases at 2500 ms.

NUBEAM\(^{15}\) for Monte-Carlo neutral beam injection and TORAY\(^{16}\) for ECH heating. During the two times presented in Fig. 5 the thermal transport conductivities \( \chi_e \) and \( \chi_i \) are computed and quantify the change in transport associated with ECH+NBI and NBI only heating. When ECH is applied, \( \chi_e \) increases by more than a factor of two outside the ECH deposition location. Ion thermal conductivity also increases dramatically, with \( \chi \) that increases by a factor of more than 6, but with large uncertainty due to the small profile gradient. It is noteworthy that the reletive energy flux through the electron and ion channels is \( Q_e/Q_i \approx 2.4 \), between the spatial location of the ECH deposition location and the top of the pedestal. This is similar to the conditions expected in recent ITER simulations\(^{17}\), which possess \( Q_e/Q_i \approx 2.1 \).

Increasing the electron heating mix from NBI only and ECH+NBI produces clear changes in turbulent fluctuation intensity and spatial scale of activity shown in Fig. 6. ECH heating increases the fluctuation intensity at
long wavelengths, and excites fluctuations at short spatial scales. Long wavelength $k_0 \rho_e < 1$ electron density fluctuations with beam emission spectroscopy (BES) [18] and intermediate wavelength $k_0 \rho_e \approx 3 - 8$ electron density fluctuations with doppler backscattering (DBS) [19] are much higher when direct electron heating with ECH is present. These increases in the turbulence intensity are consistent with the increased thermal diffusivity shown in Fig. 5 and will be compared to linear turbulence properties in the following sections.

**FIG. 5:** (a)Electron and (b)ion thermal transport coefficients during ECH+NBI and NBI only auxiliary heating. Thermal diffusivity is higher during direct electron heating.

**FIG. 6:** (a)Long wavelength BES and (b)intermediate wavelength DBS fluctuations displaying increased turbulence intensity with ECH heating.

In summary of the experimental observations, the salient features that emerge are 1) the stark reduction of energy confinement and increase in turbulent electron density fluctuations with direct electron heating, 2) Enhanced electron and ion thermal diffusivity in the radial region outside of the ECH deposition location, and 3) increased $a/L_{ne}$ in the radial region with increased $\chi$ indicating reduced effective particle flux by either lower diffusion coefficient or more negative convective velocity. In the next sections we will review the theoretical expectations from transport theory, and use the TGLF transport model to compare trends and assess quantitative accuracy.

**IV. QUASI-LINEAR TRANSPORT MODELING**

In this section we present quasi-linear transport modeling with TGLF that indicates direct electron heating excites electron fluctuation in the intermediate-$k$ and into the high-$k$ approaching $k_0 \rho_e = 0.7$. In this study, we use TGLF including electrostatic ($\delta \phi$) and electromagnetic ($\delta A_i$) fluctuations. According to TGLF, intermediate-$k$ TEM fluctuations produce an inward electron particle pinch predicted to cause steepening observed in Fig. 2 while high-$k$ modes produce stiff electron thermal transport and increase the electron thermal diffusivity. High ion thermal diffusivity observed during ECH heating is due to both increased $T_e/T_i$ and lower $Z_{eff}$ that causes a down-shift in the ITG critical gradient, as well as the increased $a/L_{ne}$ that leads to a rise in ion energy flux. The section is organized as follows; first the TGYRO [20] transport solver is used to produce flux-matching inverse scale lengths for the core profiles inside $\rho = 0.8$, and the linear growth rates and quasi-linear flux spectrum producing the flux-matching gradients is presented to display the underlying linear modes and the spatial scales and quasi-linear characteristics of the fluctuations. Second, sensitivities of the fluxes to the driving gradients are explored to expose the thermal transport stiffness and response of the particle and momentum fluxes to key performance parameters such as $\mathbf{E} \times \mathbf{B}$ shear. Finally, expectations approaching reactor relevant conditions will be presented.

**A. TGYRO Modeling**

Prior to presenting linear growth rates or turbulent flux spectra, the experimental profile gradients and values are adjusted to match the power balance flux using TGYRO in an experimental “snapshot” at a single time. This is done because the turbulent fluxes are extremely sensitive to the normalized inverse scale length $(a/L_{Te}, a/L_{Ti}, a/L_{ne})$, and propagating the experimental uncertainty in the profile scale length through the transport model will produce an extremely large range of possible fluxes. Instead we solve the inverse problem by numerical optimization, solving for normalized inverse scale lengths and profiles that produce the flux that matches power balance. This analysis is performed during relatively stationary times in the discharge because TGYRO solves the time-independent transport equations with fixed equilibrium and auxiliary power sources. Snapshot analysis permits Monte-Carlo uncertainty propagation of the experimental profiles through the power balance fluxes and TGYRO solution, forming an ensemble of solutions and normalized inverse scale lengths. The procedure that produces the TGYRO ensemble is to produce a nominal set of fits to the plasma profiles ($n_e, T_e, T_i, \Omega, n_C, E_c, P_{rad}$), execute a transport code to provide the fast ion density $n_{fast}$ and bootstrap current $j_{BS}$, and reconstruct the equilibrium with EFIT based on constraints to magnetics, MSE pitch-angles, pressure of thermal and NBI fast ions and total current $j$, and then re-fitting the profiles on the new equilibrium. Then, a set of Monte-carlo plasma profiles is produced within experimental uncertainty. For randomly
selected sets of profiles, the transport code is re-run and the equilibrium is reconstructed again. This forms a self-consistent set of all quantities required to run TGYRO (EFIT, power balance, profile of \( \mathbf{E} \times \mathbf{B} \) shear). The \( \mathbf{E} \times \mathbf{B} \) shearing rate was also produced by forming Monte-Carlo \( E_r \) profiles from measurements of the carbon density, toroidal rotation and poloidal rotation[21]. An envelope of the resulting TGYRO solutions are displayed in Fig. [7] for the ECH+NBI and NBI-only phases of the discharge.

Variation in the electron density profile is the largest term affecting power balance due to the electron-ion energy exchange. However, TGYRO solves for the power flows using a self-consistent exchange based on the solution profiles, and discards the experimental exchange. Due to the low \( q_{95} \) and sawtoothing of the ITER baseline scenario, there is little variation in the resulting safety factor and magnetic shear inside of the top of the pedestal, and is a minor source of uncertainty. In general, the TGF transport model has a strong sensitivity to the \( \mathbf{E} \times \mathbf{B} \) shearing rate, which depends on gradients of the profiles from charge-exchange. Therefore it is important to assess both the inclusion and neglect of \( \mathbf{E} \times \mathbf{B} \) shear, as well as uncertainty in the experimental shearing rate. Additionally, the solution depends on whether or not the density profile gradients have been adjusted or taken directly from the experiment because the total energy flux will increase for higher \( a/L_n \) via convection, which reduces \( a/L_T \) required to match power balance. Sensitivity to these factors on the ion temperature prediction during NBI+ECH are displayed in Fig. [8]. When predicting \( T_e, T_i \) without \( \mathbf{E} \times \mathbf{B} \) shear, the peak in \( a/L_{T_i} \) near \( \rho = 0.4 \) in Fig. [8](b) is under-predicted resulting in a lower \( T_i \) inside of this radius in the prediction shown in Fig. [8](a). When including \( \mathbf{E} \times \mathbf{B} \) shear the ion energy flux produced by TGF is reduced, and a higher \( a/L_{T_i} \) is required to match power balance, resulting in a higher predicted ion temperature that is closer to the experiment. It is well known that plasma dilution can also produce a stabilizing effect on ITG and increase \( a/L_{T_i} \) and fixed energy flux. However in order to produce a similar increase in \( a/L_{T_i} \) that is achieved by including \( \mathbf{E} \times \mathbf{B} \) shear, the carbon impurity content would need to be more than doubled in this case. Finally, adding the electron density prediction modifies the prediction by reducing \( a/L_{T_i} \) at \( \rho = 0.2, 0.5 \) (because \( a/L_{ne} \) increases), and displays the largest variability. In general, the prediction is reasonable and the structure in \( a/L_{T_i} \) with a peak near \( \rho = 0.4 \) and strong well near \( \rho = 0.6 \) is reproduced.

In the remainder of this investigation, TGYRO solution profiles that incorporate \( \mathbf{E} \times \mathbf{B} \) shear and density prediction are used in the next sub-section for detailed inspection of the TGF growth rates, frequencies and flux-spectra as a function of wavenumber at a chosen radius.

**B. Linear Stability and Quasi-linear Flux Spectrum**

During NBI heating linear growth rates from TGLF are dominantly in the low wavenumber range, near or below the \( \mathbf{E} \times \mathbf{B} \) shearing rate, and propagate in the ion diamagnetic direction. However, during NBI+ECH heating the growth rates span spatial scales with levels increased above the \( \mathbf{E} \times \mathbf{B} \) shearing rate, and propagate dominantly in the electron diamagnetic direction. These results are distinct from observations on ASDEX-Upgrade[22], which reports ITG dominance during electron heating. Seen in Fig. [9](a) is the comparison of the TGLF linear growth rate and frequency spectra at \( \rho = 0.6 \) for the two selected times in Fig. [2] Fig. [9](b) displays the linear growth rates. Sensitivity analysis indicates that during the NBI-only phase, the dominant instability is ITG for \( k_B \rho_i S < 1 \), while during the ECH+NBI phase, the dominant instability is temperature gradient driven TEM near \( 0.3 < k_B \rho_i S < 2 \). These linear eigenvalues produce fluxes with differing qualitative features and quantitative magnitudes, particularly for particles. Seen in Fig. [10](a) is the comparison of the TGLF quasi-linear fluxes at \( \rho = 0.6 \) for the two selected times in Fig. [2] Electron energy flux produced by TGF in Fig. [10](a) is increased across all spatial scales during the ECH+NBI phase compared to NBI only. The particle flux spectrum in Fig. [10](b) changes character between the two heating schemes, where the NBI only displays low-k outward flux, while the ECH+NBI phase produces a mix of fluxes; low-k outward and intermediate-k inward. It is noteworthy that the version of TGF used here is local in wavenumber, and the version of the model does not contain multi-scale coupling between low-k and high-k modes, which is included in a recent version of the model[23] and subject to future validation studies. Multi-scale simulations[24] indicate that in a range of strong turbulence the electron and ion energy fluxes are equivalent to combining individual low-k and high-k simulations, with weak multi-scale interaction. Large nonlinear gyrokinetic simulations would be required to verify that these ITER baseline conditions with direct electron heating are in such a regime, and this is left as a possible future work.

**V. Predictions for ITER**

Previous sections of this paper have shown that the TGLF transport model captures the core confinement changes associated with direct electron heating, which will be the dominant heating source from fusion alphas in ITER, as well as auxiliary radiofrequency and high energy neutral beams. Although the DIII-D ITER baseline displayed in Sec. is designed to match the conditions expected in ITER as best as practical, certain dimensionless parameters are not (or can not be) well matched, such as \( \nu^* \) and \( \rho^* \), and we therefore need to either extrapolate the physics of these scalings or rely on physics-based predictive models. One particular scaling that is of interest in
light of the observations in this paper is the collisionality scaling of particle transport. Variations in the shape and peakedness of the plasma density profile has previously been investigated from both experimental\cite{25} and theoretical considerations\cite{26} and highlighted the key role of the collision frequency, temperature scale length and turbulent mode. Shown in Fig. 11 is the particle flux spectrum and total flux beginning with the flux in Fig. 10(b) with ECH heating, and scanning the normalized collision frequency with fixed $a/L_{ne}$. Variation of the low-k and intermediate to high-k particle flux indicates that when collisionality is decreased, a larger inward particle flux develops between the range of $0.4 \leq k_\theta \rho_S \leq 10$, and overwhelms the outward low-k contribution, seen in Fig. 11(a). The net effect produced by summing over wavenumber is presented in Fig. 11(b), which shows that as collisionality decreases a stronger inward pinch develops. When performing a density profile prediction, this pinch will require an increased $a/L_{ne}$ to match the particle balance flux associated with ITER’s low NBI fueling and weak neutral penetration ($\Gamma \approx 0$). However, it is noteworthy that at the lowest collisionality shown in Fig. 11, the eigenvalues are all in the electron direction, and the plasma is in a pure TEM regime, which is not expected in ITER. Additionally, we find that these results are relatively insensitive to the electron beta $\beta_e$, which is known to decrease the magnitude of the inward particle flux\cite{27}. For ITER conditions that will be investigated, a doubling of the electron beta at mid-radius to approximately 1% results in a 15% decrease in the electron particle flux. In the next section we will use TGYRO to simulate the temperature and density profiles, and show that similar to the DIII-D case the elec-

FIG. 7: TGYRO solutions for (a) electron temperature, (b) ion temperature and (c) electron density for ECH+NBI and (d-f) NBI only. Measurements and spline fits (black) show with overlay of ensemble TGYRO solutions (grey).

FIG. 8: Experimental ion temperature profile and TGYRO solutions for a range of settings showing (a) ion temperature and (b) temperature scale length.

FIG. 9: TGLF eigenvalue (a) frequency spectra showing low and intermediate-k electron directed modes for ECH+NBI heating and low-k ion modes for NBI only heating. TGLF eigenvalue (b) growth rates are above the $E \times B$ shearing rate for ECH+NBI, but at or below the shearing rate for NBI only heating.
tron flux is a mix of outward-directed low-k and inward directed intermediate-k modes. Electromagnetic effects are included self-consistently in the TGYRO simulations.

FIG. 10: TGLF (a) particle flux spectra showing multi-scale outward and inward directed particle flux for ECH+NBI heating and low-k only outward particle flux during NBI only heating. TGLF (b) energy flux spectra showing multi-scale energy flux for ECH+NBI heating and low-k only energy flux during NBI only heating.

In order to simulate the core transport in ITER we begin with time-dependent predictive TRANSP simulations previously performed in [28] but with pedestal parameters taken from the EPED model[17, 29]. Auxiliary heating sources are taken from the TRANSP simulation, and profiles are predicted using TGYRO with TGLF and NEO transport models. Fusion power is computed self-consistently inside TGYRO.

Presented in Fig. 12 are two TGYRO simulations that were executed with a fixed, flat electron density profile, as well as self-consistent particle balance by matching the particle source flux, with an increase in the fusion $Q_{DT}$ by approximately 1.3. It can be seen that for both simulations, the temperature profiles are nearly identical, but the self-consistent density profile prediction is not flat. This occurs because the increased density increases the alpha heating power, and therefore the temperatures do not decrease when the density rises as would occur in auxiliary-heating dominated discharges in present experiments. Particle transport in ITER will be the balance between turbulent diffusion and pinch without strong central fueling, and the particle density profile will be very near the zero-flux state where $1/L_n = -V/D$, which for the case presented in Fig. 12 is between 15 – 30%. Flux spectra associated with the physics of energy and particle transport in the ITER simulation with flux-matched density profile are shown in Fig. 13 and display the same qualitative features as the DIII-D ITER baseline scenario with direct electron heating. In particular, there is an intermediate-k inward particle flux balanced by an outward low-k flux, and the energy flux spans the wavenumber range with two regions of flux occurring at low-k and intermediate to high-k. Sensitivity analysis for this case indicates that the density peaking is driven by $a/L_{Te}$, particularly in the low and intermediate wavenumber ranges. Regulation of the transport in these two wavenumber ranges is impacted by different processes, with the low-k flux able to be suppressed by $\mathbf{E} \times \mathbf{B}$ shear, and the high-k fluxes reduced by decreasing the density scale length. For example, increased shearing has two clear direct effects, and two secondary effects on confinement and fusion gain. First, increased shearing directly reduces the low-k energy fluxes increasing the temperature profiles, and increased shear directly reduces the low-k outward particle flux, increasing the density peaking, with both increasing the fusion power. The density peaking associated with complete $\mathbf{E} \times \mathbf{B}$ suppression may steepen the profile until the the density gradient driven TEM is excited[30], but no further. Indirectly, increased $a/L_{Te}$ increases density peaking, and increased density peaking through the pinch stabilizes high-k energy flux, both also increasing the fusion power. The stationary state reached by this cycle depends critically on the stiffness of the electron particle and energy flux, because at high stiffness the increased fusion alpha power will have little impact on the temperature profile.

A comparison of the electron thermal stiffness produced by TGLF is shown in Fig. 14 where we compare the electron energy flux $Q_e/Q_{GB}$ response to variation in $a/L_{Te}$. In this display of transport flux, $a/L_{Te}$ is varied independently of all other quantities. For the DIII-D case the transport increases rapidly above the electron critical gradient $a/L_{Te} \approx 1.5$, and near the experimental operating point, the transport stiffness defined as $\partial(Q_e/Q_{GB})/\partial(a/L_{Te}) \approx 2.7$. For ITER, the stiffness is lower with a value of approximately 2.2. Both the DIII-D electron heated plasma and ITER simulation exist in a very similar electron thermal transport regime according to TGLF.

In order to separate the physics of energy and particle transport as the shearing rate is varied, two separate sequences of TGYRO simulations have been performed with fixed or self-consistent density profile. The rotation profile is used as the source of $\mathbf{E} \times \mathbf{B}$ shear, which was obtained by a GLF23 Prandtl number of 0.5. We use this rotation profile for illustrative purposes due to a lack of validated models of momentum transport, and employ the high rotation ordering where the toroidal rotation profile is the source of the $\mathbf{E} \times \mathbf{B}$ shearing rate.
neglecting the diamagnetic and poloidal [31] rotation contributions, which may be important, especially when the toroidal velocity contribution to $E_r$ is on the same order as the other terms in radial force balance. For this case, the toroidal rotation is the dominant contribution to the $E \times B$ shearing rate. Recent work combining empirical scalings of the edge intrinsic torque and core transport models to predict the angular momentum and toroidal rotation profile are given in Ref. [32].

Fig. 15 displays temperature profile predictions for a range of multipliers on the nominal rotation. There is a systematic increase of the temperature profiles for the increased shearing rate, and over the range of multiplier from 0-4 the fusion $Q_{DT}$ increases by a factor of 1.3. It is noteworthy that the option of flat vs. natural density has the same impact on $Q_{DT}$ as a factor of 4 in shearing rate. The same scan in shear was also performed with a self-consistent particle transport solution, and the results shown in Fig. 16. As expected from the characteristics seen in the flux spectrum, both density and temperature profiles peak with increased shearing rate. This cycle produces an increased $Q_{DT}$ by a factor of 1.7 and exceeds $Q_{DT} = 11$. These scans illustrate the effect of $E \times B$ shear in ITER, where the impact on $Q_{DT}$ may not come from the conventional shear suppression of ion thermal transport, but may instead affect density peaking, and
improved thermal confinement may be an indirect effect.

A. Core Tungsten Transport

Experimental observations in Sec. and flux spectra indicate intermediate-k particle fluxes that peak the density profile. Profiles predicted for ITER in Sec. displayed peaking of the background density profiles from electron modes that are enhanced by shear suppression. Density peaking is only beneficial to ITER performance if it does not lead to neoclassical impurity accumulation in the deep core that causes radiative collapse. Recent results from ASTRA\cite{1} modeling with GLF23+NCLASS indicate that in ITER there will be main-ion density peaking \( n_i(0)/n_i^{ped} \approx 1.6 \), and a region near the axis of low anomalous transport and W peaking\cite{2}. It was noted that GLF23 indicates no diffusion in the deep core \((\tau/a < 0.25)\) and negligible turbulent pinch across the entire minor radius. We find that, contrary to previously reported modeling with GLF23, but in agreement with very recent studies\cite{3}, that the near axis turbulent transport with TGLF is not negligible and the turbulent diffusion remains above the neoclassical diffusion by nearly and order of magnitude. Over much of the inner half-radius the dominant terms are turbulent diffusion and an inward turbulent pinch due to low-k ion modes. However very near the magnetic axis \( a/L_T \) remains high due to the alpha electron heating and \( a/L_T \) is reduced due to lack of ion heating, creating an electron drift direction mode and outward turbulent convection that is stronger than the neoclassical inward pinch. These findings are in agreement with previous studies showing unstable modes rotating in the electron drift direction and outward turbulent convection that is stronger than the neoclassical inward pinch. The TGLF diffusion is reduced when the electron density profile is peaked, producing a stronger tungsten peaking for the self-consistent electron and ion density profile. Assessment of the impact these tungsten profiles will have on ITER performance requires further calculations relying on assumptions of the source rate and impact of centrifugal effects, as discussed in Ref. [4].

VI. DISCUSSION AND CONCLUSIONS

The DIII-D ITER baseline scenario with direct electron heating exhibits fluctuations existing on multiple spatial scales from low-k to high-k measured by beam emission spectroscopy and doppler backscattering. During electron heating, the fluctuations across all spatial scales increase above the levels measured during NBI heating only. Associated changes in confinement and transport are consistent with the increased fluctuations, whereby energy confinement is lower and thermal diffusivities are higher with ECH. Plasma profiles of electron temperature have similar scale lengths, but strong flattening of the ion temperature is observed when applying electron heating. A secondary effect of the ECH is higher ELM frequency and lower line-averaged density, as well as enhanced momentum transport. With direct electron heating, the density scale length is shorter in the region of the plasma outside the ECH deposition location. The TGLF transport model captures the observed profile and confinement changes when used in TGYRO simulations, and this is due to transport processes in multiple spatial scales and multiple channels. TGLF indicates high electron stiffness due to high-k electron thermal flux, and enhanced low-k ion thermal flux with lower \( Z_{eff} \). TGLF shows that intermediate-k electron fluctuations are expected to produce an inward particle pinch and steepen the density gradient, as seen in the experiment, and this inward pinch is expected to increase in magnitude as collisionality is decreased towards ITER conditions. Simulations of ITER high current scenario with EPED pedestal were performed for either imposed flat density or self-consistent density profile. We find the same turbulent modes observed in DIII-D are expected in ITER and cause stiff electron thermal transport and inward particle pinch, i.e. the density profile is not flat. We test the impact of \( E \times B \) shearing rate and find a larger impact on \( Q_{DT} \) in ITER comes about with self-consistent particle transport through increased density peaking. Finally, we find that the density peaking does not promote strong central tungsten accumulation because turbulent transport predicted by TGLF does not vanish near the magnetic axis.

Remaining open questions surround the multi-scale interactions that modify the turbulence stability and transport fluxes. Emerging studies using massively parallel gyrokinetic simulations with realistic electron-to-ion mass ratios have focused on thermal transport\cite{5}, but need to be expanded to particle and momentum transport as well as high-Z impurities. Recent progress on the projection of intrinsic rotation and predictions of momentum transport for ITER\cite{6} indicate that even with low relative NBI torque that the \( E \times B \) shear will be significant enough to affect confinement and fusion performance, but future work on intrinsic torques and residual stress that can produce rotation reversals and transport improvements will be required.

VII. ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Awards DE-AC02-09CH11466, DE-FC02-04ER54698, DE-FG02-08ER54999, DE-FG02-07ER54917, DE-FG03-97ER54415, DE-FG02-04ER54235 and DE-FG02-08ER54984. DIII-D data shown in this paper can be obtained in digital format by following the links at https://fusion.gat.com/global/D3D_DMP.
FIG. 16: TGYRO prediction of temperatures and density for range of $E \times B$ shear

FIG. 17: Predicted tungsten +63 transport coefficients and profile