Exploring the Regime of Validity of Global Gyrokinetic Simulations with Spherical Tokamak Plasmas

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Gradient-driven gyrokinetic simulations have often been used to explain turbulence-driven transport in present fusion devices. Furthermore, many present predictive codes are based on the assumption that turbulence is gradient-driven. However, using the electrostatic global PIC Gyrokinetic Tokamak Simulation (GTS) code [1], we found that global gradient-driven gyrokinetic simulations are not able to explain observed electron thermal transport variation in a set of NSTX L-mode plasmas. On the other hand, these global gradient-driven gyrokinetic simulations provide decent agreement in the ion thermal transport for a set of NSTX H-mode plasmas. Thus, identifying the regime of validity of the gradient-driven assumption is essential for first-principle gyrokinetic simulations. This understanding will help us more confidently predict the confinement performance of ITER and other future magnetic confinement devices.

A fast response of electron-scale turbulence to auxiliary heating cessation was observed in a set of RF-heated L-mode plasmas [2,3], where, following the cessation of RF heating occurring in less than 200 μs, a reduction in electron-scale turbulence spectral power was observed to occur on a time scale of 0.5-1 ms, much smaller than the energy confinement time of about 10 ms. Ion-scale gradient-driven global nonlinear gyrokinetic simulations were found not to be able to explain the factor of 2 decrease in electron heat flux after the cessation of RF heating. The simulations were carried out with the GTS code at t=465 ms (with 1 MW injected RF power) and at t=482 (after the RF heating cessation) using experimental equilibrium profiles to assess global effects on electron thermal transport. These global simulations cover a radial domain from Ψ_N=0.25 to 0.8 (R ~ 120 cm to 147 cm), where Ψ_N is the square root of the normalized toroidal flux. The size of grids on poloidal planes is about local ρ_i, and 80 particles per cell·species were used. The experimental equilibrium E×B shear is turned on from the beginning of the simulations. Figure 1 compares electron energy flux, $Q_{e,GTS}$, radial profiles at t=465 and 482 ms from GTS simulations with those of the inferred electron heat flux, $Q_{e,exp}$. It can be clearly seen that while $Q_{e,GTS}$ is essentially the same for both t=465 ms (with RF heating) and for t=482 ms (after the RF cessation) at R≳136 cm, $Q_{e,GTS}$ at R≲134 cm is larger at t=482 ms than at t=465 ms. The observed change in $Q_{e,GTS}$ before and after the RF cessation is opposite to the change in experimental

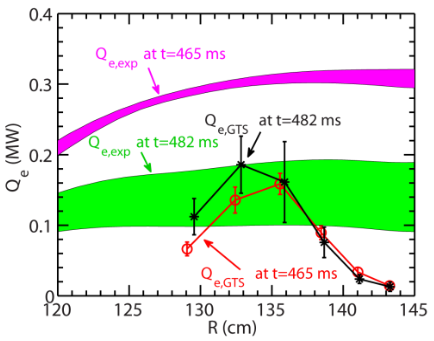

Figure 1 Red circles: electron energy flux, $Q_{e,GTS}$, at t=465 ms (before the RF cessation) as a function of major radius from nonlinear GTS simulation; black asterisks: $Q_{e,GTS}$ at t=482 ms (after the RF cessation) from nonlinear GTS simulation; magenta band: radial profile of experimental electron heat flux, $Q_{e,exp}$, at t=465 ms from power balance analysis; green band: radial profile of $Q_{e,exp}$ at t=482 ms. Note that the vertical widths of the magenta and green bands denote the experimental uncertainties. $Q_{e,GTS}$ is averaged over a quasi-steady saturation period, and the errorbars of $Q_{e,GTS}$ are the standard deviation of $Q_{e,GTS}$ in the averaging time period.

electron heat flux, $Q_{e,exp}$, from power balance analysis, in which $Q_{e,exp}$ at t=465 ms is about a factor of 2 higher than $Q_{e,exp}$ t=482 ms. The GTS simulation result is consistent with linear and nonlinear local electromagnetic gyrokinetic simulations (not shown), which show that the observed equilibrium profile changes cannot explain the reduction in Q_e. Thus we conclude that global effects from profile variation, e.g. turbulence spreading, are not likely able to explain the observed reduction in electron thermal transport. It is interesting that $Q_{e,GTS}$ at t=465 and 482 ms are both in good agreement with $Q_{e,exp}$ at t=482 ms (after the RF cessation) but not with $Q_{e,exp}$ at t=482 ms (with RF heating). These results imply that a nonlocal flux-driven mechanism may be important for the observed electron thermal transport [4].

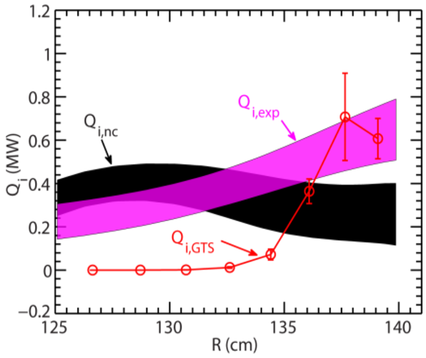

Figure 2 Red circles: ion energy flux, $Q_{i,GTS}$, at t=332 ms as a function of major radius from a nonlinear GTS simulation of an NSTX H-mode plasma, shot 141767; magenta band: radial profile of experimental ion heat flux, $Q_{i,exp}$, at t=332 ms from power balance analysis; black band: radial profile of neoclassical ion heat flux, $Q_{i,nc}$. The same definition of uncertainties and errorbars applies as in Fig. 1.

Good agreement in the ion thermal transport between ion-scale GTS simulations and experiment has been found in an NSTX NBI-heated H-mode plasma (shot 141767), where electron-scale turbulence was observed to be reduced/stabilized by large electron density gradient [5]. Figure 2 compares the ion energy flux, $Q_{i,GTS}$, radial profiles at t=332 ms from the GTS simulation with those inferred from the experiment along with neoclassical ion heat flux, $Q_{i,nc}$, from NCLASS [6]. It can be seen that $Q_{i,exp}$ is comparable to $Q_{i,nc}$ at R$\lesssim$132 cm, which is consistent with the very small $Q_{i,GTS}$. At larger radius, i.e. R$\gtrsim$136 cm, $Q_{i,GTS}$ is significantly larger than at smaller radius, consistent with $Q_{i,exp}$ being significantly larger than $Q_{i,nc}$. In fact, considering the errorbars and uncertainties in $Q_{i,GTS}$, $Q_{i,exp}$ and $Q_{i,nc}$, $Q_{i,GTS}+Q_{i,nc}$ is approximately equal to $Q_{i,exp}$, indicating that the ion-scale turbulence is responsible for observed anomalous ion thermal transport. We note that $Q_{e,GTS}$ is significantly smaller than $Q_{e,exp}$ (not shown), which may be due to the possible contribution from some residual ETG turbulence that is not captured by this ion-scale GTS simulation or by electromagnetic effects, which are not yet taken into account by the GTS code.

In summary, global GTS simulations have been used to study NSTX L and H-mode plasmas. Agreement and disagreement in thermal transport between simulation and experiment have been observed, which shows that global gradient-driven gyrokinetic simulations are insufficient in a set of NSTX RF-heated L-mode plasmas. Future experiments on NSTX-U will help quantify the regime of validity of gradient-driven GTS simulations. This work was supported by the U.S. Department of Energy under Contracts No. DE-AC02-76CH03073, No. DE-FG03-95ER54295, and No. DE-FG03-99ER54518. The computational resource is provided by NERSC.

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