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Gyrokinetic Validation Study Using KSTAR Plasma

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1. Introduction

To successfully generate enough energy through a fusion reaction, a high-temperature, high-density plasma must be confined long enough. Therefore, understanding fusion plasma transport related to energy confinement is important.

The fusion plasma transport is recognized to be governed by turbulence. One of the models to analyze the dynamics of turbulence is gyrokinetics [1]. If a current gyrokinetic model is validated, then it is possible to predict the performance of future fusion plasma to design the future fusion reactor. As a result, the gyrokinetic validation study is essential work in the nuclear fusion field to move toward the future fusion reactor for generating fusion energy. Recently, progress in fluctuation diagnostics and analysis tools of KSTAR motivates to initiate the gyrokinetic validation study using KSTAR plasmas. This paper describes the initial gyrokinetic validation study results using KSTAR plasma and identifies requirements for the next round validation study.

2. Preparation for gyrokinetic validation study

In this section, preparation for the gyrokinetic simulation is described. The preparation process includes analysis of experimental data and uncertainty quantification process.

2.1 Experimental Setup

The neutral beam injection (NBI) heated L-mode plasma discharge 21631 was selected for gyrokinetic analysis. In 21631, the required diagnostics for transport analysis, which are Thomson scattering for electron density and temperature, Charge exchange spectroscopy (CES) for ion temperature and toroidal velocity, and Motional stark effect (MSE) for current density and safety factor, is available. In addition, magnetohydrodynamic effects were weak in 21631.

The experimental transport analysis was performed by iterating the profile analysis, power balance analysis, and equilibrium reconstruction for the experimental analysis. At the profile analysis, the experimental profiles are generated from diagnostic data. The power balance analysis was performed using TRANSP [2]. TRANSP was run with NUBEAM [3] that provides fast ion information using the Monte Carlo technique. Equilibrium was reconstructed using EFIT [4] with constraints of current density profile measured by MSE and kinetic pressure from profile analysis and transport analysis.

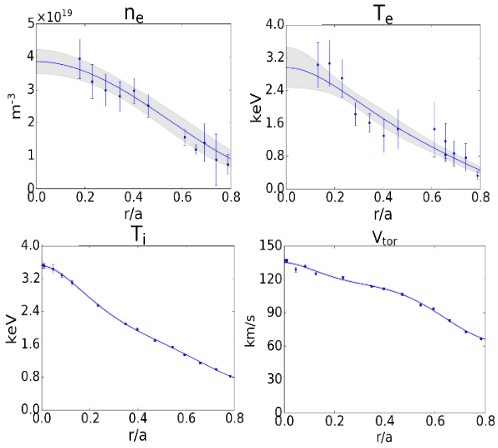


Fig. 1. The uncertainty quantification results of $\mathbf{n_e}, \boldsymbol{T_e}, \boldsymbol{T_i}$, and $\boldsymbol{V_{tor}}$

2.2 Uncertainty Quantification

The uncertainty quantification is required in the validation study to compare results of experiment and simulation. For the gyrokinetic validation study, the uncertainties of input parameters including $n_e, T_e, T_i, \frac{a}{L_{ne}}, \frac{a}{L_{Te}}, \frac{a}{L_{Ti}}, V_{tor}$ and ω_{EXB} should be quantified where $\frac{a}{L_X} = \frac{a\nabla X}{X}$, $\omega_{EXB} = -\frac{r}{q}\frac{d}{dr}\left(\frac{c}{R}\frac{E_r}{B_p}\right)$, and $E_r = \frac{\nabla p_i}{Z_i e n_i} + V_{tor}B_{pol} - V_{pol}B_{tor}$. The uncertainties of n_e, T_e, T_i, and V_{tor} profiles were quantified from randomly generated profile samples. Each profile sample is generated by fitting polynomial function to random data set generated from a normal distribution with the measurement value as its mean and the uncertainty of the measurements as its standard deviation. Uncertainty of the fitted profile is estimated by calculating the standard deviation of profile samples. Fig.1 shows the uncertainty quantification results of n_e, T_e, T_i, and V_{tor}. In addition, uncertainty of gradient could be quantified by applying error propagation to numerical method. The uncertainty of gradient is calculated as the equation (1):

$$\sigma_{\frac{dX}{dr}} = \frac{1}{(a+b)h}\sqrt{\sigma^2_{X(x+ah)} + \sigma^2_{X(x-bh)} - 2\sigma_{X(x+ah),X(x-bh)}} \quad (1)$$

Here, the covariance term is calculated from profile samples. Likewise, the uncertainties of $\frac{a}{L_X}$ and ω_{EXB} were quantified using error propagation. The poloidal velocity V_{pol} was obtained from neoclassical theory using NEO [5] for calculating the uncertainty of ω_{EXB}.

The experimental heat flux levels were estimated from power balance analysis using TRANSP, and their uncertainties were also quantified from the randomly generated input profile samples. The pairs of n_e, T_e, T_i, and V_{tor} were selected randomly from profile samples. The selected pairs of profile samples were used as inputs of TRANSP. By calculating the standard deviation of experimental heat flux obtained from TRANSP results, uncertainty of the experimental heat flux was quantified.

3. Gyrokinetic simulation result

This section describes the linear and nonlinear gyrokinetic simulation results. The gyrokinetic simulation was performed using CGYRO [6], which is an Eulerian gyrokinetic solver with δf approximation. In this study, simulation is electromagnetic and focuses on ion scale $k_\theta \rho_s \leq 1$ where k_θ is poloidal wave number and ρ_s is ion gyro radius. Since impurity profile measurements were not available in this discharge, impurity profile should be assumed. Here, carbon was used as a single impurity and effective charge Z_{eff}, which is defined as $\sum_j \frac{Z_j^2 n_j}{Z_j n_j}$ where j is ion species, was assumed as 2 with flat profile.

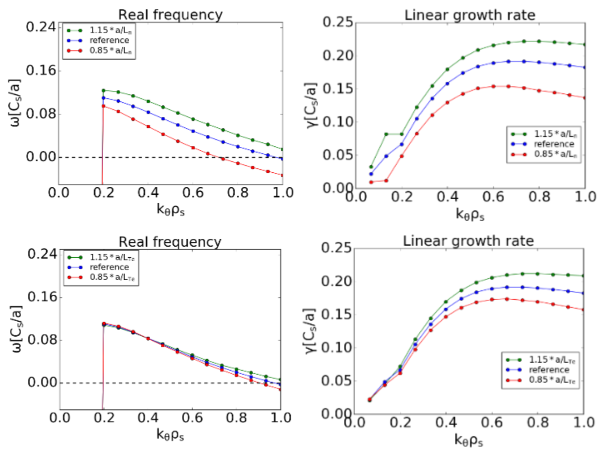


Fig. 2. The results of linear stability analysis. Top show the $\mathbf{a/L_n}$ scan and bottom is $\mathbf{a/L_{Te}}$ scan. The sign of real frequency denotes the diamagnetic direction (+): electron, (-): ion

3.1 Linear gyrokinetic simulation

The linear gyrokinetic simulation was performed to understand the characteristic of ion scale turbulence. The results of linear stability analysis are shown in Fig. 2. The real frequency of the most dominant mode is in the electron diamagnetic direction. The linear growth rate is sensitive on a/L_n and a/L_{Te}. These parameters destabilize the dominant mode. Therefore, it is possible to conclude that trapped electron mode is the most unstable mode at r/a=0.5 in this plasma.

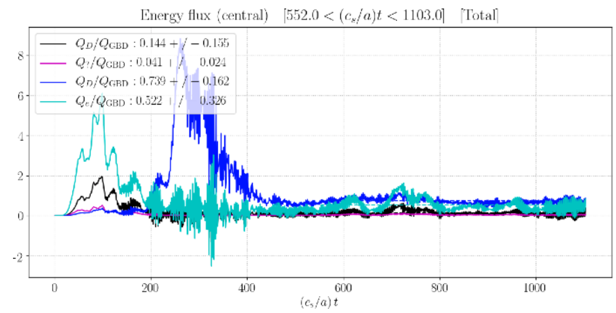


Fig. 3. The nonlinear gyrokinetic simulation results. The simulated heat fluxes are calculated by time-averaging

3.2 Nonlinear Gyrokinetic Simulation

The nonlinear gyrokinetic simulation was run with the resolution parameters and domain box size determined by the convergence test. The simulated heat flux levels were calculated by time-averaging in the time interval where these levels are saturated. As shown in Fig. 3, nonlinear gyrokinetic simulation using experimental input parameters under-predicts the electron and ion heat fluxes at r/a=0.5. We also observed that simulation results still under-estimated both electron and ion heat fluxes although input parameters were changed within their uncertainties. However, there are free parameters such as a/L_{ni} and a/L_{nc} because impurity density information is missing in this simulation from the assumption of the flat Z_{eff} profiles with Z_{eff}=2. Here, a/L_{ni} and a/L_{nc} are varied together to keep quasi-neutrality constraint, $\sum_j Z_j \frac{\partial n_j}{\partial x} = 0$ where j is ion species and electron. In this scan, we found that simulated heat fluxes were sensitive on these input parameters. CGYRO can even reproduce both experimental electron and ion heat flux levels by varying these two parameters. The a/L_{ni} and a/L_{nc} scan results of the nonlinear gyrokinetic simulation are depicted in Fig.4. Therefore, measurements of the impurity profile which can give the information of Z_{eff}, a/L_{ni}, and a/L_{nc} are necessary for the next round of validation.

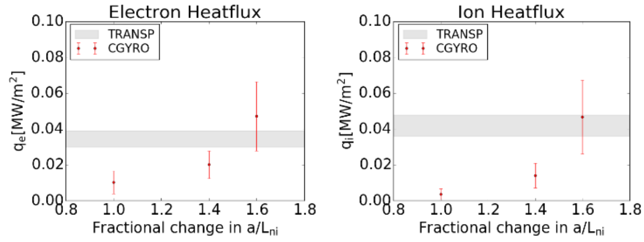
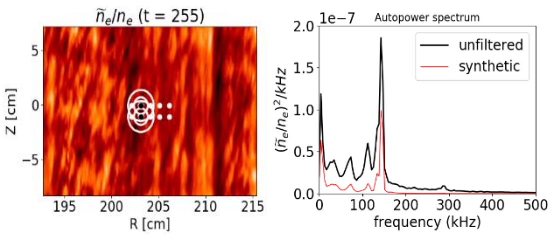


Fig.4. The simulated heat flux with varied $\mathbf{a/L_{ni}}$ and $\mathbf{a/L_{nc}}$. $\mathbf{a/L_{ni}}$ and $\mathbf{a/L_{nc}}$ varies with constraint of quasi-neutrality

3.3 Synthetic Diagnostic

It is necessary to compare not only the heat flux induced by turbulence but also various quantities such as fluctuations for the reliable validation study. Many diagnostics have limitations to their spatial and temporal resolution while simulation results do not. Therefore, we need a synthetic diagnostic that can apply measurement conditions to the simulation results for direct comparison between simulation results and experimental measurements. Here, the synthetic diagnostic [7] is prepared for the next round of gyrokinetic validation study using KSTAR plasmas. The synthetic diagnostic with a gaussian shaped point spread function and 2.2MHz sampling rate was applied to 1.6 $\mathbf{a/L_{ni}}$ and -0.716 $\mathbf{a/L_{nc}}$ case, which predicts heat flux levels most closely matched to the experimental heat flux. The synthetic diagnostic results are shown in Fig.5. The fluctuation level could be calculated by integrating the auto power spectrum over the frequency domain. We will use this synthetic diagnostic tool for direct comparison with fluctuation measurements in future validation study. The synthetic fluctuation levels in the simulation can also provide the fluctuation measurement conditions of future fluctuation diagnostic.



	Unfiltered	Synthetic
Fluctuation level	0.3%	0.15%

Fig. 5. The synthetic diagnostic result of 1.6 $\mathbf{a/L_{ni}}$ & -0.716 $\mathbf{a/L_{nc}}$ case shows the relative density fluctuation.

4. Conclusions

The first gyrokinetic validation study using KSTAR plasmas is presented in this paper. The linear stability analysis states that trapped electron mode is the most unstable mode at r/a=0.5. The nonlinear gyrokinetic simulation underestimated the heat flux. However, because Z_{eff} =2 flat profile was used in simulation, information of impurity density profile is missing. By changing the gradient of impurity density, both electron and ion heat fluxes could be matched to the experimental heat flux. It follows that Z_{eff} profile and constraints in the gradient of impurity density are required for the future gyrokinetic validation study. In addition, a routine for synthetic diagnostic is developed for future validation study and fluctuation diagnostic in KSTAR.

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