Prediction of kinetic profiles using a new transport solver based on global optimization techniques

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Introduction

It is of quite importance to validate transport models with experimental data in order to gain predictive capability of plasma kinetic profiles in future devices. In tokamaks, turbulence-driven transport typically predominates and thus validating transport models is equivalent to validating turbulent transport models. Local flux-tube gyrokinetic codes, which can be regarded as a comprehensive transport model, have been widely applied to analyze experiments, but they often fail to reproduce the experimentally-observed transport level in case that nominal gradients are used as inputs as it is, because their results are very sensitive to values of kinetic profile gradients, which have large uncertainty bands due to arbitrariness of profile fitting. Within error bars, the input gradients are usually modified so as to fit calculated fluxes to the experimental ones by trial and error [1]. This procedure demands painstaking work. One solution is to couple a transport solver and transport models and they are time-dependently solved until a steady state. Many turbulent transport models show strongly nonlinear dependence on the gradient of kinetic profiles, however, and such stiff behavior makes it difficult to robustly obtain smooth transport coefficients and kinetic profiles without spikes in less computation time.

In [2], we have proposed the basic concept of an intrinsically oscillation-free transport solver based on global optimization techniques, even though stiff transport models are employed. The code, dubbed GOTRESS, benefiting from both a genetic algorithm [3] and Nelder-Mead method [4], solves the steady-state transport equations. GOTRESS is now able to incorporate almost all the components which conventional transport codes usually possess in heat transport channel: Multi-species, collisional equipartition, off-diagonal particle flux contributions, and actual shaped equilibria are all taken into account. The aim of GOTRESS, which is to find a steady-state temperature profile and its radial derivative consistent with a sum of neoclassical and turbulent heat fluxes predicted by the respective models used in the code, is the same as that of TGYRO [5], but the way of finding the solution differs.

The major differences are briefly listed as follows. GOTRESS does not require any derivatives in the course of calculation. This is because GOTRESS solves the governing equations that are obtained by integrating the steady-state transport equations over the volume and in addition the normalized gradient is treated as one of the dependent variables. Therefore, the governing equations are not spatially discretized and hence the information at a certain grid point is independent of that at an adjacent grid point. From the edge boundary to the core region, GOTRESS successively tries to find the solutions at each grid point that match the conducted heat fluxes to the target fluxes that are obtained by integrating heat source and sink over the volume. Details of the method of solving should be consulted in [2]. The code is parallelized with MPI to accelerate genetic algorithm calculation and at the same time to exchange data between GOTRESS and an external transport model, if any. This Multiple-Program Multiple-Data (MPMD) structure enables us to execute in a straightforward manner GOTRESS together with a parallelized transport model like TGLF [6] and also get along with a neural-network-based transport model even if it is written in Python.

Benchmark tests

For the so-called current hole plasma with negative magnetic shear in the core region, GOTRESS results are compared with those by TRESS code [7] using IFS/PPPL model, which is famous as a stiff transport model. TRESS is a one-dimensional transport code that solves a set of the time-dependent transport equations, and is discretized using the finite element method with Hermite interpolation function, which realizes the third-order accuracy in space. Thanks to the choice of the basis function, a variable and its derivative can be both dependent variables of TRESS. Its feature is advantageous when a stiff transport model is adopted. As a result, we have obtained very good agreement between them in all aspects except for computation time: 72 secs with 26 cores for GOTRESS while 7.5 hours with a 1single core for TRESS. TRESS had to choose $\Delta t = 10^{-6}$sec to avoid advent of spikes of the diffusivity profiles, a fact which requires much computation time until a steady state is reached.

Benchmark tests by different transport codes with different transport models have been performed for multiple scenarios in JT-60SA. Here, scenario 5.1 'high power' version is focused on as an example. The 0D data of the scenario are tabulated in Table 3 of [8] and predicted profiles are displayed in Figure 11 thereof. Using CDBM05 model [9], predicted temperature profiles are compared between TOPICS and GOTRESS. The equilibrium and the profiles of the density, heating and quantities associated with fast ions are taken from TOPICS and are used as inputs to GOTRESS. As shown in Figure 1, both results agree very well. GOTRESS requires 28 secs to get the results, while TOPICS does 10,006 secs, even though TOPICS calculates many profiles that are used in and are not calculated by GOTRESS. This is the scenario with reversed magnetic shear. The internal transport barriers (ITBs) will be likely to appear and the

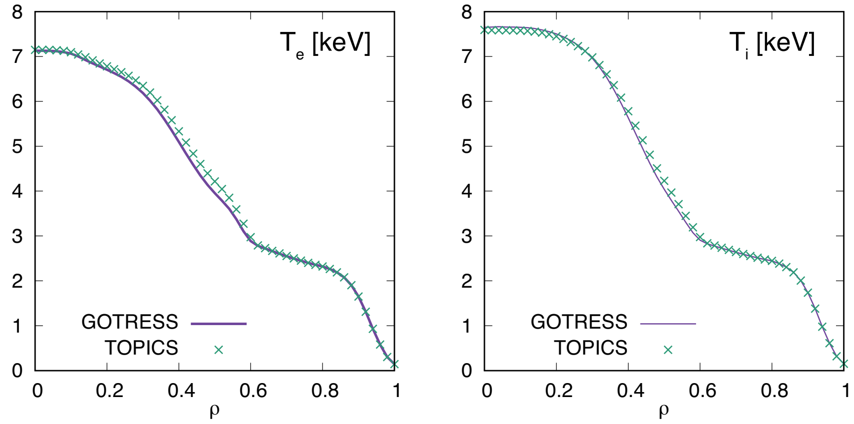

Figure 1: Profiles of electron (left) and ion (right) temperature profiles predicted by TOPICS and GOTRESS for JT-60SA scenario 5.1 with reversed magnetic shear.

simulations predicted so. The positions of the ITB foot exactly agree.

Validation study of transport models in JT-60U plasmas

For the ELMy-H mode plasma in JT-60U, validation studies of several transport models have been performed: CDBM, the neural-network based heat transport model (NN), IFS/PPPL, and Bohm-gyroBohm (BgB) model. The NN model is a model that mimics the semi-empirical gyrokinetic model, which has originally been developed for particle transport [10] and then whose capability has been extended to covering heat transport. The range of application of this model is, however, limited over $0.2 \lesssim \rho \leq 0.6$ as of now, where ρ is the normalized radial coordinate.

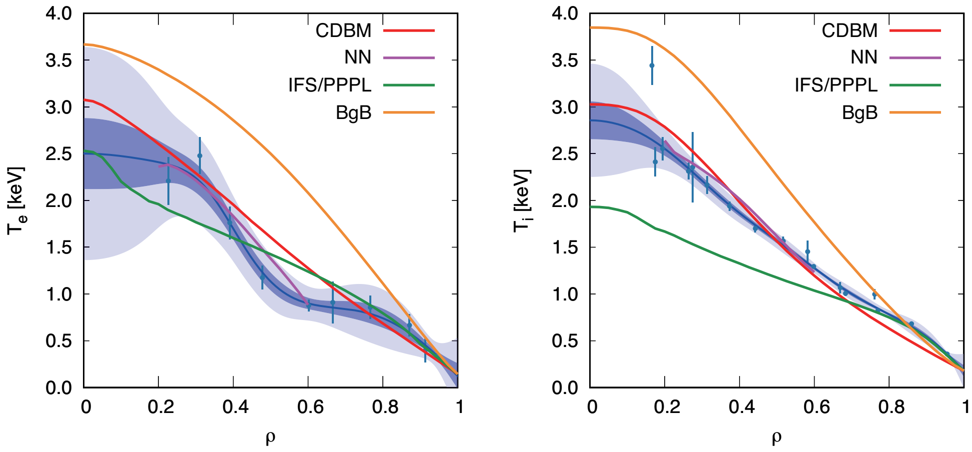

Figure 2: Profiles of electron (left) and ion (right) temperature profiles predicted by GOTRESS with various transport models for JT-60U #39117. The dark shaded are indicates $\pm 1\sigma$ and the light one, $\pm 3\sigma$, where σ denotes the standard deviation.

In Figure 2, comparison of the predictions and the experimental observation is shown. The boundary is set at $\rho = 1$ for CDBM and BgB, while the NN model, at $\rho = 0.6$ and IFS/PPPL, at $\rho = 0.9$. The fitted line and the uncertainty bands were estimated by Gaussian Process Regression [11]. CDBM reproduces both profiles overall, while it fails to capture the barrier-like structure in the middle core of T_e. Despite the limited range, profiles predicted by the NN model are well reproduced. Neither IFS/PPPL nor BgB reproduces the observed profiles. It takes 16 secs for the NN model, 21 secs for CDBM and BgB and 246 secs for IFS/PPPL to obtain the well-converged solutions and the calculations can be executed in a very straightforward manner, a fact which means that GOTRESS is suitable for validation study and experimental analysis. We note that the NN model used here is coded by Fortran and at initial reads the weight data that has been computed by Python code in advance.

GOTRESS and beyond

Coupling of GOTRESS and a flux-tube gyrokinetic code will realize the automation of flux-matching procedure. After finishing flux-matching, we can evaluate the deviation of the predicted temperatures from the experimental observation and thus quantify the accuracy of gyrokinetic predictions. We hope that this procedure can be executed routinely without tough efforts.

GOTRESS can be exploited as a kernel of an integrated transport modeling, which makes it possible to robustly predict steady state profiles in future devices such as JT-60SA and also to check the validity of prescribed profiles that have been used, as one of the examples has been exhibited here. GOTRESS will be extended to deal with other transport channels such as particle and momentum transport.

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