Integrated code framework for operation scenario development with the global-optimizer-based iterative solver GOTRESS

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Introduction

Due to the sensitivity of turbulent fluxes to profile gradients, robust predictions are still arduous with a stiff turbulent transport model incorporated in a conventional transport code. To overcome this difficulty, we have developed a steady-state transport equation solver, GOTRESS, which benefits from global optimization techniques such as a genetic algorithm [1] and the Nelder-Mead method [2] such that they directly find the solution where a transport flux matches an integrated source [3]. Benchmark tests have been successfully performed with a time-dependent transport code TOPICS [4, 5] and the other code at a steady state. GOTRESS has advantage to rapidly predict steady-state plasma profiles compared to time-dependent transport codes and thus we would like it to be employed for operation scenario development. The integrated transport code TOPICS can calculate equilibria, heating profiles and so on and so forth within its framework, while so far GOTRESS cannot do that by itself and it has required them to perform simulations in advance. This motivated the development of a novel integrated model with GOTRESS as a kernel thereof, GOTRESS+, mainly consisting of the equilibrium and current profile solver ACCOME [6] and the neutral beam (NB) heating code OFMC [7]. In the following, after a brief introduction of GOTRESS, the integrated mode GOTRESS+ is detailed.

Steady-state transport solver GOTRESS

In the light of the aim of the code, GOTRESS is similar to TGYRO [8]. Both codes solve a steady-state transport equation and calculate the kinetic profiles that give rise to the transport flux coinciding with the integral of source and sink profiles. However, they take a completely different approach to get a solution. While TGYRO discretizes the volume-integral form of the equation and solves it with Newton method and fixed point iteration, GOTRESS does not spatially discretize governing equations in a usual fashion. GOTRESS has two volume-integral equations for heat fluxes and temperatures, respectively In the code, a normalized gradient is treated as one of the dependent variables as well as temperature and thus it is not evaluated from a temperature profile by some differentiating scheme. From the edge boundary to the core region, GOTRESS successively tries to find a solution on each grid point that match the conducted heat fluxes to the target fluxes obtained by integrating heat sources and sinks over the volume. Owing to global optimization, GOTRESS can avoid likely wiggles of profiles originating from the discretization of the equation and the differentiating scheme of the variables even when a stiff transport model applies. Details of the numerical method should be consulted in Ref. [3]. The code is parallelized via MPI to accelerate genetic algorithm calculation and at the same time to be able to exchange data between GOTRESS and an external transport model. This Multiple-Program Multiple-Data (MPMD) structure enables us to execute in a straightforward manner GOTRESS together with a parallelized transport model like TGLF [9].

Novel integrated model GOTRESS+

TGYRO is characterized as a profile solver in the OMFIT framework [10], which is a comprehensive integrated modeling framework that has been developed to enable physics codes to interact in complicated workflows. As explained above, GOTRESS can naturally play a same role as TGYRO in an integrated modeling framework. Accordingly, the integrated model GOTRESS+ has been developed, mainly consisting of the equilibrium and current profile solver ACCOME and the neutral beam (NB) heating code OFMC, other than GOTRESS.

A procedure of GOTRESS+ execution is described in the following. Figure 1 demonstrates a workflow of GOTRESS+ in the case of high-beta steady-state scenario in JT-60SA, what is called #5-1: $B_{\mathrm{T}} = 1.72\,\mathrm{T}$, $I_{\mathrm{p}} = 2.3\,\mathrm{MA}$, $P_{\mathrm{NBI}} = 18.85\,\mathrm{MW}$ and $P_{\mathrm{ECH}} = 7\,\mathrm{MW}$ [11]. The settings of

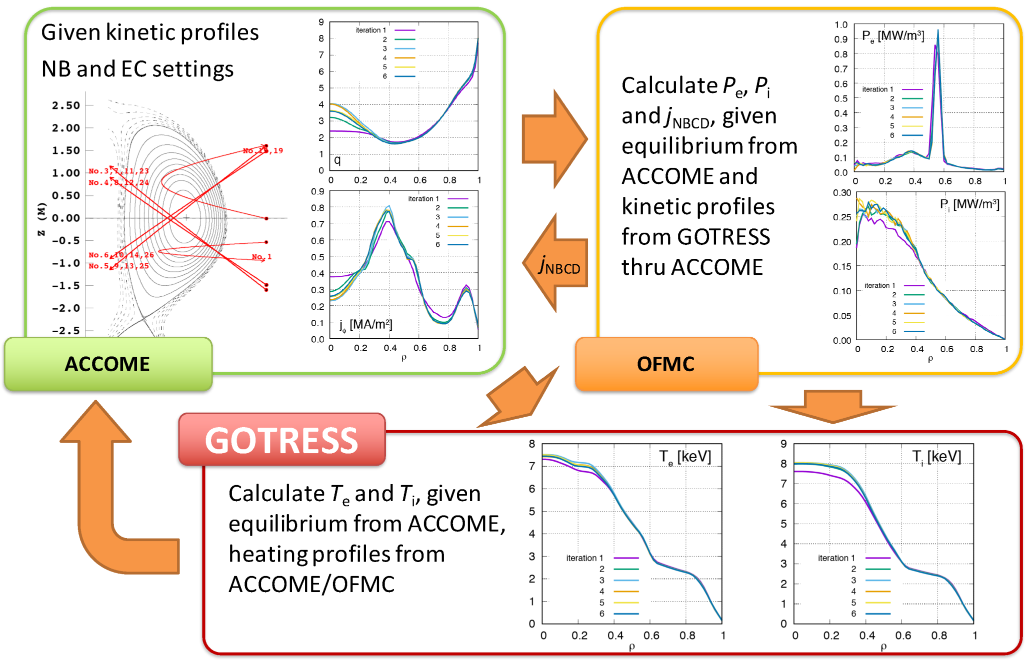

Figure 1: Workflow of operation scenario development in JT-60SA by the integrated code framework GOTRESS+.

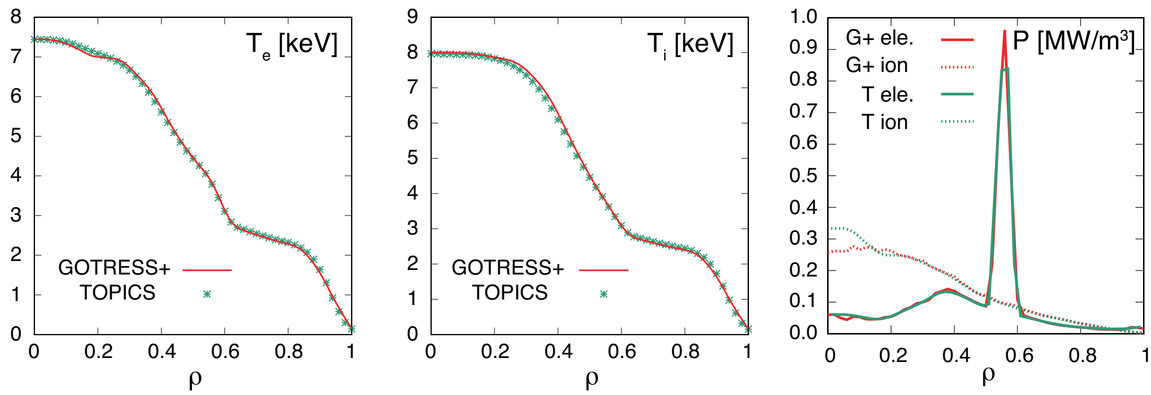

Figure 2: Comparison of steady-state profiles of electron (left) and ion (middle) temperatures and heating power (right). Red colors indicate GOTRESS+ results and blue, TOPICS ones.

auxiliary heating systems such as NB heating and electron cyclotron heating (ECH) and the coils that support an equilibrium are described in an input file of ACCOME. The prescribed density and temperature profiles are also given as initial guess. After iterative calculations in ACCOME, a consistent solution is obtained between an equilibrium and a current profile according to the given kinetic profiles. At the same time, ACCOME also estimates ECH and EC current drive (ECCD), if needed. The profiles required for OFMC as input are sent to OFMC, and then the profiles of NB heating and NB current drive (NBCD) are estimated. Now the current density profiles, the equilibrium and heating profiles have been computed, which are all requisites for GOTRESS. GOTRESS in turn predicts the temperature profiles based on them. At this point, the first iteration of GOTRESS+ is completed, shown as "iteration 1" in fig. 1 The predicted temperature profiles are sent to ACCOME and replaces the prescribed ones used in the first iteration. The second iteration then commences. Note that optionally ACCOME can make use of an NBCD profile calculated by OFMC instead of its own Fokker-Planck solver, but the choice is up to a user. This iterative calculation continues until the profiles are well converged. For this case, all the profiles are converged after 6 iterations. The developed plasma meets the target values: the normalized beta of 4.42 > 4.3, the energy confinement improvement of 1.65 > 1.3 and the loop voltage of 0.003 ~ 0.

We now compare steady-state profiles of the temperature and the heating power predicted by GOTRESS+ and TOPICS with the CDBM turbulent transport model exploited [12]. The boundary conditions were imposed at $\rho = 0.9$ in both simulations, where ρ is the normalized radial coordinate. In fig. 2, shown is the comparison of these profiles between GOTRESS+ and TOPICS. Regardless of completely different numerical schemes used, both codes clearly predicted almost the same temperature profiles. The peaked electron heating power profile is formed by ECH around the middle core of the plasma. A slight discrepancy of the ion heating profiles appears near the magnetic axis. This was caused by the interpolation scheme adopted in TOPICS, but is certainly negligible due to the volumetric effect. The GOTRESS+ simulation took 6,812 seconds, around 10 hours faster than the TOPICS simulation. Thanks to the easy-to-use feature, GOTRESS readily makes it possible to lower the loop voltage much closer to nil by manipulating heating power carefully. We have undertaken the development and the validation of another operation scenario.

Currently GOTRESS predictions are confined to the heat transport channel solely. GOTRESS will be updated to cover multi-transport channels in near future.

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