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PROGRESS ON A FULLY GYROKINETIC TRANSPORT CODE

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*Oak Ridge National Laboratory, Oak Ridge, Tennessee.

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Progress on a fully gyrokinetic transport code

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I Introduction

This paper reports on recent progress in connection with the *Steady-State Gyrokinetic Transport Code (SSGKT) project*, a *Scientific Discovery Through Advanced Computing* (SciDAC) initiative funded by the US Office of Advanced Computing Computing Research (OASCR). The goal is to develop a transport code that integrates micro-scale gyrokinetic simulations into a framework for practical multi-scale simulation of a burning plasma core, the International Thermonuclear Experimental Reactor (ITER) in particular. The resulting transport code will be used to predict the performance (the fusion energy gain, Q) given the H-mode pedestal temperature and density. At present, projections of this type rely on transport models like GLF23 [1], which are based on approximate fits to the results of linear and nonlinear simulations. Our goal is to improve these performance projections by direct use of nonlinear gyrokinetic simulations. The method of approach is to couple a master transport code to multiple independent (each massively parallel) GYRO [2] simulations. The proposed method will allow highly efficient use of very large processor counts (several thousand); the master code must only compute relatively simple feedback information based on transport power balance, and the independent instances of GYRO will scale very well because of the relatively low processor count per instance (32 to 256). Each instance of GYRO will compute local radial fluxes to be periodically communicated to the master. A rough schematic of the design is shown in Fig. 1. The key numerical challenge is to determine the most efficient feedback algorithm. Although the power source and transport balance coding in the master are standard, it is nontrivial to design a feedback loop that can cope with outputs that are both intermittent and extremely expensive to compute.

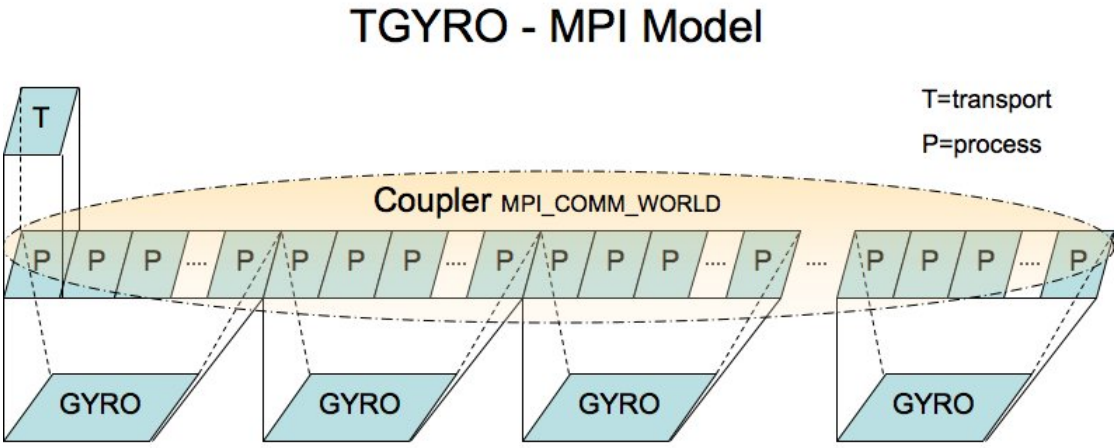

Fig. 1. TGYRO schematic. Multiple instances of GYRO, each with its own `MPI` communicator, are weakly coupled through a transport module (T) which provides feedback based on a integrated power balance.

II Formulation

In principle, we begin with the full-F gyrokinetic equation (electrostatic for simplicity) written in conservative form:

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial \mathbf{R}} \cdot \left(\dot{\mathbf{R}} \, BF \right) + \frac{\partial}{\partial v_\parallel} \left(\dot{v_\parallel} \, BF \right) = C[F,F] + S(x,v,t) \ , \qquad (1)$$

where F is the total distribution function, C is the nonlinear collision operator, S is the source (of particles, momentum, energy) and B is the magnetic field strength. This master equation describes physics at multiple scales: the slow, long-scale balance between sources and quasi-steady turbulence is reflected in the ensemble-averaged distribution $\widehat{F}$, whereas the fast, short-scale turbulence determines the fluctuating part δf. Short-scale GK simulations must ensure that the equilibrium does not evolve (that is, that $\widehat{\delta f} = 0$), such that the long-scale steady-state transport equation balances S with turbulent loss. Also, the ensemble average $\widehat{F}$ should be Maxwellian, so that the collision operator can be linearized in the usual way assuming $\delta f \ll \widehat{F}$. Integrating Eq. (1) over velocity-space, and further taking a flux-surface average

(denoted by angular brackets) gives

$$\frac{\partial\langle n_\sigma\rangle}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial r}\left(V'\langle\Gamma_\sigma\rangle\right) = \langle\int d^3v\ S_\sigma\rangle \sim 0\ , \tag{2}$$

$$\frac{\partial\langle p_i + p_e\rangle)}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial r}\left(V'\langle Q_i + Q_e\rangle\right) = \langle\int d^3v\ E\ \ (S_i + S_e)\rangle\ . \tag{3}$$

For simplicity, we assume $T_i = T_e$ and sum the electron and ion energy equations to avoid dealing with energy exchange terms. Quasi-steady solution to Eqs. (2) and (3) thus take the form:

$$\Gamma_e(x,y) = \Gamma_i(x,y) \sim 0 \quad \text{and} \quad Q_e(x,y) + Q_i(x,y) = Q_{\text{target}}(n,T)\ , \tag{4}$$

where

$$x = -\frac{a}{n}\frac{\partial n}{\partial r}\,, \quad y = -\frac{a}{T}\frac{\partial T}{\partial r}\,, \tag{5}$$

and

$$Q_{\text{target}}(n,T) = \frac{1}{V'}\int_0^r dr\ V'(r)\int d^3v\ E\ (S_\alpha + S_{\text{aux}})\ . \tag{6}$$

We ignore radiation loss and other effects, prefering simply to describe approach in its most basic form. We want to *find the roots* of the algebraic equations, Eq. (4), at radial points r_p for $p = 1,\ldots,N_p$. Each instance of GYRO functions independently, with an exchange of information only through the transport balance. Further, each instance of GYRO can operate on its own intrinsic time-scale, a/c_s, length scale, ρ_s, and therefore its own local (gyroBohm) diffusion scale $\chi_{\text{GB}} \doteq \rho_s^2 c_s/a$. We remark that at the small values of $\rho_* = \rho_s/a$ in ITER, gyroBohm scaling and the locality of turbulence is largely assured. With larger ρ_* machines like DIII-D, there may be some nonlocal transport – in which the temperature gradient at one distant location may effect the power flow at another [3].

III Method of Solution

Methods of solution are preliminary and under development. For the restricted case of $T_e = T_i$ considered here, one strategy is to construct analytic fits of the fluxes in the (x,y) plane, including the critical gradient locations (see Fig. 2 for crude intensity plots). Then, the problem is reduced to simple root finding. Alternatively, we could proceed iteratively. Define the gradient vector $g = (x,y)^{\text{T}}$, the profile vector $p = (n,T)^{\text{T}}$ and the flux vector

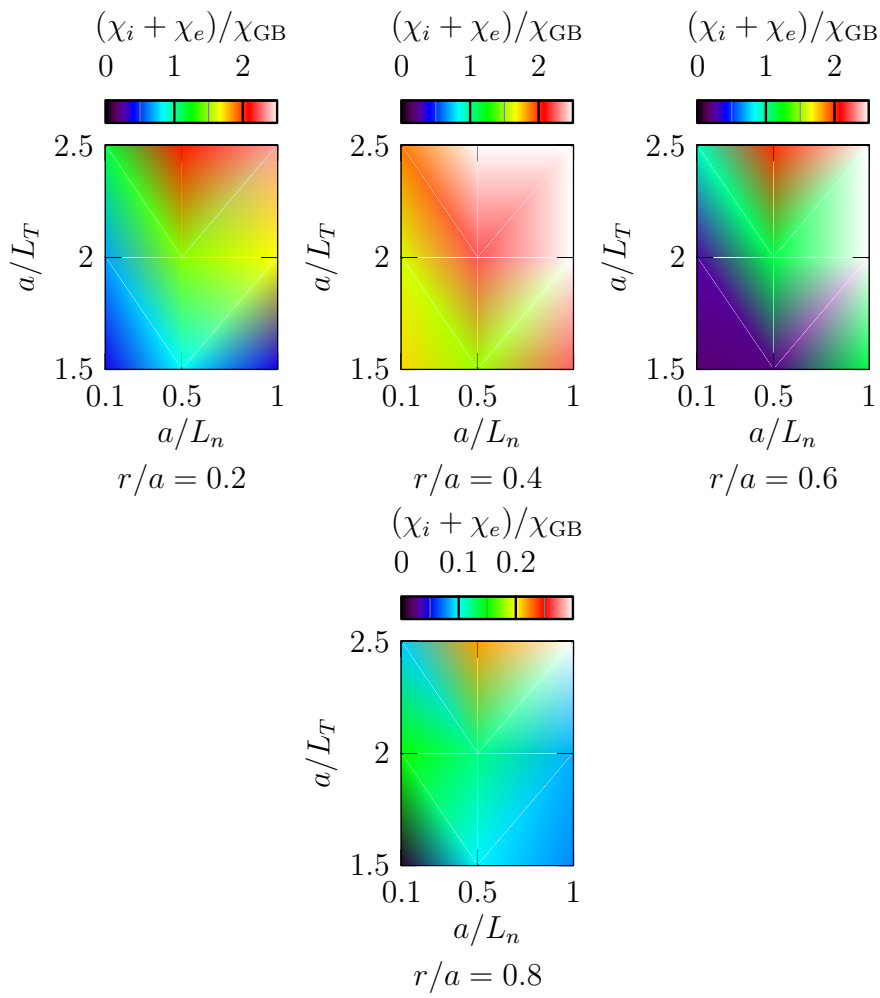

Fig. 2. Contour plots of $(\chi_i + \chi_e)/\chi_{\mathrm{GB}}$ as a function of $x = a/L_n$ and $y = a/L_T$.

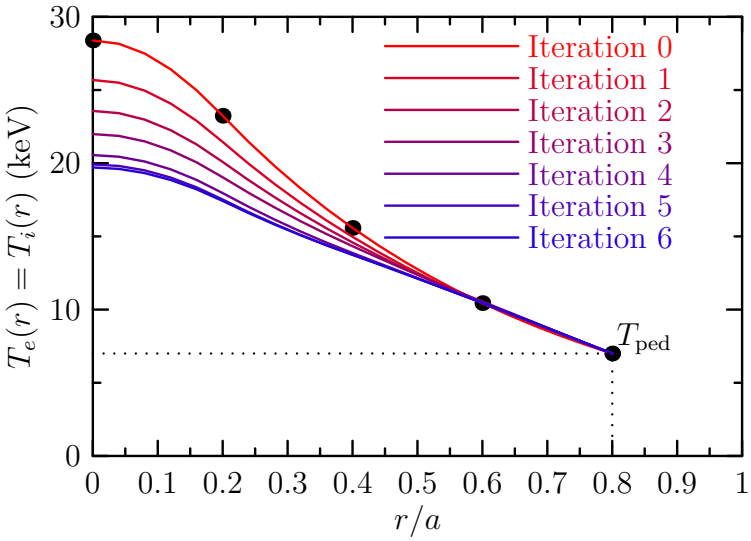

Fig. 3. Illustration of convergent iterations in the solution of Eq. (4). Density profile was fixed in this simulation, and $T_{\rm ped} = 7\,$kev.

$f = (\Gamma, Q)^{\rm T}$, where T denotes a transpose. **Procedure:** Begin with pedestal boundary condition $p = p_*$, and arbitrary initial choice of g. Then:

1. Integrate g to find $p(r) = p_* \exp\left[\int_r^{r_*} g(r')\,dr'\right]$.
2. Compute $f_{\rm target} = f(p)$ from Eq. (6).
3. Run GYRO with input g to obtain $f_{\rm GYRO} = f_i(g) + f_e(g)$.
4. Update g based on difference $f_{\rm GYRO} - f_{\rm target}$ (secant method, etc).
5. Goto Step 1.

An sample result is plotted in Fig. 3, showing a relaxation of the initial temperature to a final temperature which is essentially consistent with the critical gradient. This test treated an ITER-like circular plasma with GYRO simulations at 4 radial points $r/a = [0.2, 0.4, 0.6, 0.8]$, including alpha heating plus 40 MW of auxiliary power, but ignoring radiation losses. A pedestal temperature of $T_{\rm ped} = 7\,$keV was used. The density profile was fixed for this test. The reader should take the result as merely a proof-of-principle of the method, not as a meaningful prediction of ITER performance.

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