Full-Plasma Cross Section Landau Fluid Calculations of Ion Temperature Gradient-Driven Turbulence in Tokamaks*

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Ion temperature gradient-driven turbulence (ITGDT) [1] is generally believed to cause the experimentally observed anomalous loss of particles and heat at the core of magnetic fusion devices such as tokamaks. The underlying linear instability is the η_i mode where η_i is the ratio of density to ion temperature gradient scale lengths. Significant progress has been made in the theoretical understanding of ITGDT over the past few years, in large part due to the development of gyrokinetic and gyrofluid computational models [2]. The gyrofluid models in particular have mostly been limited to a local flux-tube description of the plasma and to circular geometry for computational tractability reasons. The remaining challenges, for further comparisons with existing experiments and for predictions of performance for future experiments, are to model the full-plasma cross section and to extend the description to noncircular geometry. We report here on progress towards gyrofluid models covering the full-plasma cross section and applicable to general geometry, as well as on their implementation on parallel computers. These calculations are being carried out as part of the Numerical Tokamak Turbulence Project [3], one of the U. S. Department of Energy's Phase II Grand Challenges.

To keep the full cross section calculations of ITGDT at a computationally manageable level, we only include time evolution equations for the perturbed ion density (vorticity) and perturbed ion parallel velocity, in addition to a perturbed ion temperature equation in which a simple parallel linear Landau closure is imposed [4,5]. Moreover, the electrons are treated as adiabatic and the electrostatic approximation is used throughout. Flux coordinates with straight field lines have been chosen to describe the toroidal magnetic geometry. Straight field lines afford an accurate representation of the parallel derivatives. Both analytic and realistic fixed boundary equilibria from a solution of the Grad-Shafranov equation can be used as input for the stability and turbulence calculations.

Finite differences in radius and Fourier mode expansions in poloidal and toroidal angles allow us to capture the full geometry with a minimal number of relevant Fourier components. The numerical scheme is time implicit for linear terms and time explicit for nonlinear terms. These nonlinear terms are quadratic nonlinearities that become convolutions of the Fourier components. In the numerical calculation, these convolutions are treated analytically. The implicit linear terms give rise to inversion of block tridiagonal matrices. To numerically advance these equations, a two-step, second-order accurate, time-centered advancement scheme is used.

Even in the cylindrical limit, including the full-plasma cross section, requires more memory and CPU time than is available on the National Energy Research Scientific Computing Center's (NERSC's) shared memory parallel vector machines such as the CRAY C90 and J90. Therefore, these calculations are being performed on NERSC's 512-processor distributed memory massively parallel CRAY T3E supercomputer with 256 Mbytes of memory per processor. PVM is used for the multiprocessor implementation of the ITGDT code on the T3E. The serial code is replicated on all processors used. Only matrix operations for the time-implicit linear terms and convolutions for the time-explicit nonlinear part of the calculation are distributed to multiple processors. For matrix operations, parallelization is done over the number of Fourier harmonics in which all physical quantities in the problem are expanded. For the convolutions, parallelization is done over the number of radial grid points. Memory for the matrices is allocated at run time and depends on the number of processors requested for the calculation. Because memory is relocated in going from matrix inversion to the convolutions and vice versa, a global send and receive is done using PVM after all the linear matrix solutions and after all the convolutions each time step. Details on the numerical scheme and its parallel implementation can be found in Ref. [6]. Typical parallel performance results on the T3E are shown in Fig. 1. Optimal performance is assessed in terms the following criterion: CPU time per step is reduced less than 25% by increasing the number of processors by a factor of 2. This in turn sets the optimal number of processors. Figure 1 shows that the optimal number of processors increases with the number of radial grid points and the number of Fourier harmonics. The optimal number of processors for the largest problem size in Fig. 1 is about 128.

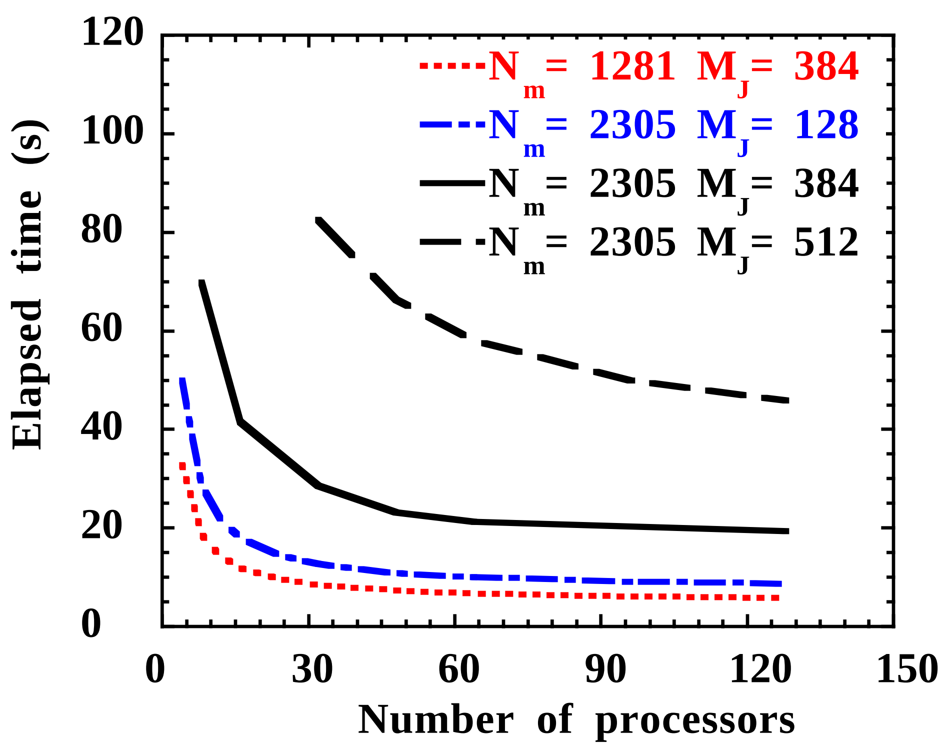


Fig. 1. Elapsed time per step with increasing number of processors and for various calculation sizes.

Large-scale calculations in cylindrical geometry have been performed on the T3E with up to 3073 poloidal (m) and toroidal (n) Fourier components and 512 grid points. These calculations have been completed using up to 128 processors of the T3E. Calculations with and without Landau closure but with identical profiles and parameters demonstrate the reduction in linear growth rates and the spatial localization of the linear eigenfunctions expected with Landau damping. Nonlinear calculations close to marginal stability (with η_i=1.2) further show that spatial localization persists nonlinearly and is not adversely affected by the generation of sheared poloidal flow through Reynolds stress. The radial scales of the turbulence are of the order of the Larmor radius ρ_i. The radial correlation length in the steady-state phase is about 3.0 ρ_i. No large-scale structures are observed as is apparent in Fig. 2. This indicates that the induced transport is local.

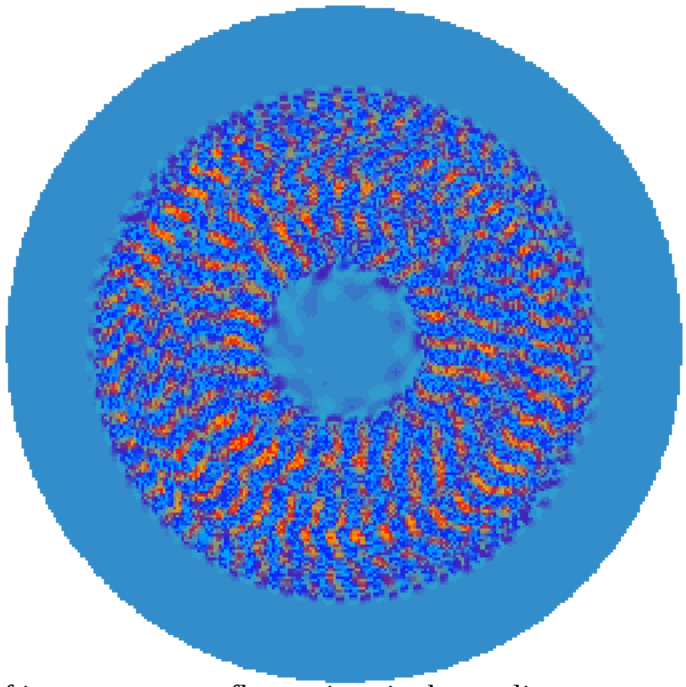


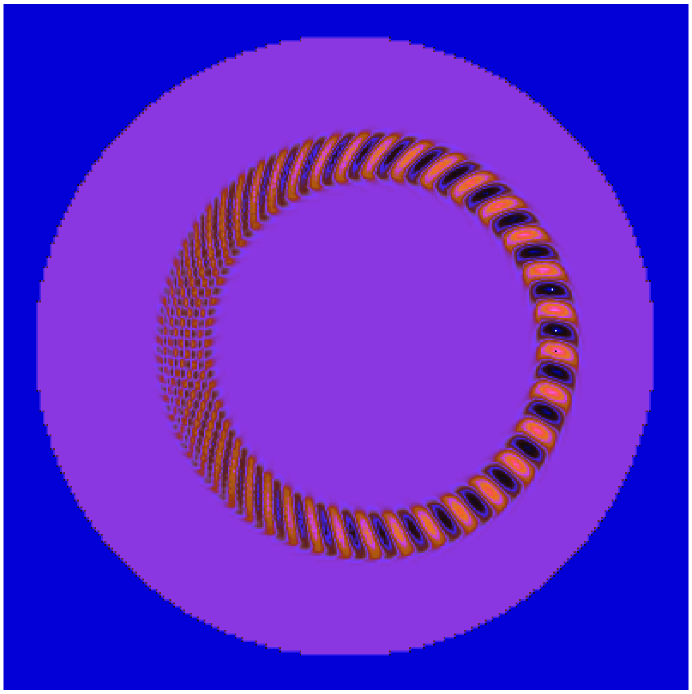
Fig. 2. Contours of ion temperature fluctuations in the nonlinear saturated turbulent steady state.

Full-torus Landau fluid calculations of ITGDT with Landau closure have also been initiated for eventual comparison with flux tube models of ITGDT. The linear results for the Cyclone benchmark equilibrium [7] shown in Fig. 3 demonstrate the flexibility of our representation of the magnetic geometry given that we are able to handle circular as well as noncircular plasma cross sections.

Calculations with toroidal coupling are more computationally intensive than their cylindrical equivalent. When the geometry is cylindrical, the block tridiagonal matrices, which arise from the implicit treatment of the linear terms, do not couple terms that have different (m,n) values. The block size is given by the number of fields, here the three-time evolved equations plus the electrostatic potential determined from the inverse Laplacian of the vorticity, and the number of blocks is given by the number of radial grid points. When toroidal coupling is introduced, the situation changes, and components with different m but the same n are coupled. In this case, the block size is multiplied by the number of m's included for a given n. The toroidal mode number n being the only good quantum number points to a decomposition in n for parallel implementation of the full-torus model. Efficient parallelization then rests on keeping as many n's as the number of processors used, all the while keeping within the memory limit per processor. These issues are currently under study.

Circular Plasma

D-Shaped Plasma



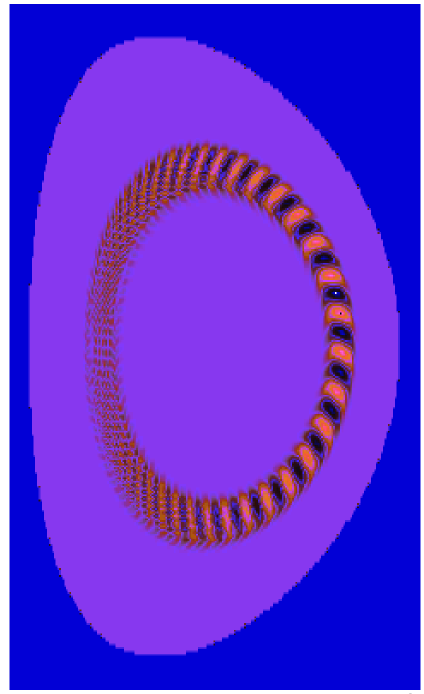


Fig. 3. Linearly unstable eigenmode for toroidal mode number $n = 30$ in the case of circular and D-shaped plasmas.

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