Final Progress Report

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"Edge Simulation Laboratory"

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I. Introduction

The goal of the Edge Simulation Laboratory (ESL) multi-institutional project is to advance scientific understanding of the edge plasma region of magnetic fusion devices via a coordinated effort utilizing modern computing resources, advanced algorithms, and ongoing theoretical development. The UCSD team was involved in the development of the COGENT code for kinetic studies across a magnetic separatrix. This work included a kinetic treatment of electrons and multiple ion species (impurities) and accurate collision operators.

II. COGENT code development

Algorithms, physics models, and initial results. The Physics-Math Collaboration COGENT is a joint project of the ESL physics team (including UCSD) and a separately funded collaboration of applied mathematicians from LBNL and LLNL. It is a continuum-based code, based on 4th-order finite-volume discretization of kinetic and field equations, and exploits mapped multiblock grid technology to handle the geometric complexity of the edge/SOL region, with its combination of closed flux surfaces and open field lines, and may also play a key role in handling magnetic shear in the 5D code. It is written in parallel-velocity $v_{||}$ and magnetic-moment μ coordinates, and for now is restricted to electrostatics and axisymmetry (hence, a 4-D phase space), though during the pro-posed funding cycle will progress to three spatial dimensions (5-D phase space).

The division of labor on COGENT has been that the math team provided "bare-bones" codes, initially for closed flux surfaces (mapped single grid block), with advection and an electrostatic field solve; they provided a first release of a single-null-geometry edge-plus-SOL code (mapped multiblock; henceforth we will refer to this as "the divertor version" of COGENT) with advection in fall 2011, and have just completed implementation of a field solve in the multiblock code. The physics team is responsible for defining the physics models, adding physics capability (collisions, sources, model radial transport, neutrals,...) and diagnostics, and performing code verification and physics studies; the physics team was also, prior to October 2012, providing some utility development (restart capability, reading/interpolation of a numerically prescribed grid, code testing system) via part-time support of a programmer (this activity has been terminated because of the FY13 funding decrease). The teams collaboratively developed a grid ex-trapolation strategy, described below, to deal with rapidly changing metrics near the separatrix X-point, and are jointly engaged in validating/debugging the divertor code.

Additional physics models. We have implemented and tested a succession of increasingly detailed collision operators in COGENT [1] during the present funding period. The collision operators include (a) the Krook model with options to conserve density, parallel momentum, and energy; (b) a model with drag and diffusion in parallel velocity; (c) an energy-dependent Lorentz pitch-angle scattering model with an option to conserve parallel momentum; (d) the Lenard-Bernstein model, a simple diffusive model which numerically conserves density, momentum, and energy, and (e) a recently proposed model linearized Fokker-Plank operator by Abel et al. [Phys. Plasmas **15**, 122509 (2008)], which conserves density, parallel momentum, and energy, and obeys Boltzmann's H-theorem (collisions can't decrease entropy). In addition, the implementation of the fully nonlinear Fokker-Plank operator has begun (completion expected by the end of the current funding cycle).

We have also adapted and implemented a model of anomalous radial transport model in COGENT to represent turbulence. The mode has velocity-dependent diffusion and advection coefficients, which provides the flexibility to match an arbitrary set of fluid transport coefficients. As mentioned below under verification, this model has been applied simultaneously with a Coulomb collision model. Ultimately we envision these kinetic coefficients coming from a gyrokinetic turbulence code (e.g. 5-D COGENT), while more immediately we seek to have compatibility with the fluid transport matrix used in plasma transport codes (e.g. 1D ASTRA in the core, or 2D UEDGE). By proper choice of the advection velocity and diffusion coefficient one can fit an arbitrary fluid cross-field transport matrix (e.g., purely diffusive, purely conductive, or a mix).

Turning to collisions, it is important to ensure that the pitch-angle scattering process can be accurately represented using COGENT's $v_{||}$, μ coordinates, which were chosen in part to simplify particle advection, without introducing spurious energy diffusion. The 4th order finite-volume scheme in COGENT provides significant reduction (to a tolerable level) of the spurious diffusion for quite modest grid resolution, as shown in Fig. 1.

Extensive neoclassical transport verification tests have been performed in annular geometry, as a prelude to studies in the full edge + SOL system, using the collision models mentioned earlier.

For the Lorentz model with constant collision frequency and no electrostatic potential, we recovered the analytical re-sults of Lin [53]. A new analytic expression for the effects of self-consistent electrostatic potential on the ion poloidal velocity for the Krook model was derived and shown to agree very well with COGENT results in all collisionality regimes. Likewise, COGENT compares well with analytical results for the Lorentz collisional model with or without momentum-conserving terms and energy-dependent collisionality, including self-consistent electrostatic potential variations. Finally, COGENT simulations with the Abel linearized Fokker-Plank collision operator is in generally good agreement with the results of NEO code for the poloidal velocity and ion heat diffusivity.

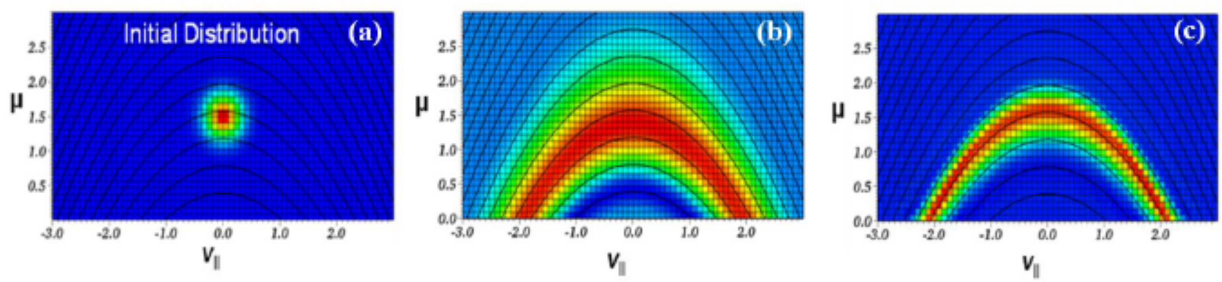

Figure 1: COGENT simulations of the pitch-angle scattering of a highly localized distribution function in velocity space [1]. Here, (a) the initial distribution (t = 0), (b) distribution function at $\nu_c t = 4$ obtained with a second-order implementation of the Lorentz operator, and (c) distribution function at $\nu_c t = 4$ for a fourth-order implementation. Here, ν_c is the collision frequency. The solid black lines are contours of constant energy.

Verification.

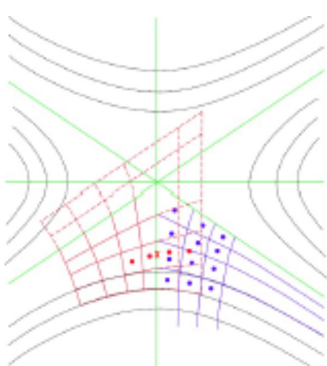

Figure 2: Extrapolation of grid across block boundaries near X-point. Shown are cell boundaries for two grid blocks (red and blue solid lines); the long-dashed lines denote ghost cells for one block, while the short-dashed lines denote flux surfaces.

We have demonstrated fourth order convergence with grid refinement of advection across the X-point of a phase space blob (with a specified advection velocity), a significant benchmark because of the increasing curvature of field lines with distance from the separatrix and changing grid topology across the separatrix, making consistent convergence difficult to achieve and errors are hard to quantify. To the best of our knowledge there has been no previous attempt to characterize the accuracy of solutions in the vicinity of an X-point in a cross-separatrix edge code. Key to achieving this result in COGENT is a grid extrapolation strategy (jointly conceived and implemented by the physics and math teams), whereby the coordinate system in a given cell block is flux-surface-following away from the X-point, but departs from following flux surfaces near the X-point and continues to depart from flux surfaces in the ghost cells bordering a grid block in the X-point region, as shown in Fig. 2. Fourth-order interpolation from data on the adjacent grid block is used to populate the ghost cells; in particular, in Fig. 2, interpolation from the cells denoted by the blue dots is used to determine the cell-averaged distribution function f in the two ghost cells denoted by the right-most two red dots; the values of f in all four cells denoted by red dots is then used to determine the fourth-order flux at the point marked with the red "x".

Breakup of SOL filamentary structures: adequacy of fluid model. Coherent filamentary structures (blobs and ELMs) play crucial roles in plasma transport toward the main chamber wall [S. Krasheninnikov, D. A. D'Ippolito and J. Myra, J. Plasma Phys. **74**, 679 (2007)]. Previously, the dynamics of individual filaments was studied only with 2D fluid models. However, we realized during the present funding period that the 3D effects, such as onset of drift-wave turbulence and blob spinning due to plasma inhomogeneity along the magnetic field and corresponding Boltzmann electrostatic potential variation, can significantly alter dynamics of the filament. As discussed below, analysis of these results show that fluid approximations begin to break-down, especially for ITER-sized devices, providing a strong motivation to extend the simulations to the kinetic regime with COGENT.
We used the 3D fluid code BOUT++ to model these 3D effects for blobs in the SOL. Our recently published results show that the onset of resistive drift wave turbulence causes a significantly larger effect on blobs in large-size devices like ITER, causing the blobs to dissipate before they reach the chamber wall, thus reducing main chamber damage. For current tokamaks, the effect of resistive drift wave turbulence is marginal because the curvature driving force of blob propagation decreases with increased major radius, R. While the onset of the drift wave turbulence is controlled by the size of the blob δ, the most structurally stable blob size $\delta_* \sim 1$ cm has a weak dependence on both plasma and tokamak parameters. We also found that a strong variation of blob plasma density along the magnetic field caused rapid blob spinning and reduced plasma polarization effects, resulting in blob motion more in the poloidal than radial direction, similar to the impact of a radial electron temperature variation reported previously.
Our examination of these fluid results has shown [2-4] that the most unstable mode has a parallel wavelength is comparable to the electron mean free path, rendering the applicability of the fluid description for 3D blob dynamics questionable, especially for ITER-size devices. Our analysis of the linear dispersion equation [3] derived from electron and ion kinetic equations with a BGK-like collision operators yields a maximum growth rate that is close to that from the fluid model, but the parallel wave number at the maximum growth rate changes. Consequently, an accurate analysis of possible dissipation of blobs before they hit the main chamber will require a more detailed model of collisions and kinetic effects as can be provided by COGENT.

III. Conclusions

Our UCSD Group was quite productive during this stage of the project, publishing 4 papers in refereed journals while heavily participating in the development of COGENT code.

Publications in refereed journals

[1] M. Dorf, R. Cohen, J. Compton, M. Dorr, J. Compton, T. Rognlien, J. Angus, S. Krasheninnikov, P. Colella, D. Martin and P. McCorquodale, *Contrib. Plasma Phys*. **52**, 518 (2012). (DOI: 10.1002/ctpp.201210042)

[2] W. Lee, J. R. Angus, M. V. Umansky, S. I. Krasheninnikov, "Electromagnetic effects on plasma blob-filament transport", *J. Nucl. Materials* **463** (2015) 765-768. (DOI: 10.1016/j.jnucmat.2014.09.083)

[3] W. Lee, J. R. Angus, S. I. Krasheninnikov, "Electromagnetic drift wave dispersion for arbitrary collisional plasmas", *Phys. Plasmas* **22** (2015) 072113. (DOI 10.1063/1.4927135)

[4] W. Lee, J. R. Angus, M. V. Umansky, S. I. Krasheninnikov, "Electromagnetic effects on high-beta filamentary structures", *Phys. Plasmas* **22** (2015) 012505. (DOI 10.1063/1.4905639)