Modeling Edge Plasma with the Continuum Gyrokinetic Code COGENT*

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DOE Workshop in Integrated Simulations; panels B and C; oral presentation is not requested

Objective: As fusion devices operate at higher power, it is increasingly important to achieve an improved theoretical understanding of edge plasma transport in order to control core energy confinement and to provide the necessary limit on plasma heat flux to material components. The problem provides substantial challenges for analytical or numerical analysis due to (a) complex magnetic geometry including both open and closed magnetic field lines **B**, (b) steep radial gradients comparable to ion drift-orbit excursions, and (c) a variation in the collision mean-free path along **B** from long to short compared to the magnetic connection length. A kinetic equation that includes a detailed collision operator must be solved to capture these key features. Furthermore, because both short timescale turbulence and long timescale transport are important to capture, this is also a multiscale temporal problem. Motivated in part by the success of continuum kinetic codes for core physics and in part by their potential for high accuracy, we have been developing such a code called COGENT for the edge. One central feature of such a model that poses a challenge is the presence of the magnetic separatrix within the simulation domain. In more detail, strong anisotropy of plasma transport, which is much faster along the field lines than in the perpendicular direction, motivates the use of the flux-aligned coordinate surfaces for continuum methods that discretize a kinetic equation on a phase-space grid. However, such coordinate surfaces have diverging metric coefficients at the X-point of the magnetic separatrix, thereby introducing a challenge for high-order accurate discretization methods. Therefore, it has been of great practical importance to develop a gyro-kinetic continuum code that could handle the complexity of tokamak divertor geometry with high accuracy. As we move forward, such continuum models should be compared with codes based on particle-in-cell methods [4].

Recent progress: Based on recent advances from the applied math community [1], the Edge Simulation Laboratory collaboration [2] has been developing the first 4^{th}-order finite-volume (continuum) gyrokinetc code COGENT [3] that models plasma transport in a divertor geometry. The underlying numerical algorithms utilize a novel high-order, mapped-multiblock, finite-volume discretization scheme that allows the use of multiple grid blocks (patches) to represent complex geometrical structure of the magnetic field. The coordinate surfaces of each block are flux-aligned everywhere except near the X point, and a high-order interpolation is used to provide data communication in the regions where the grid blocks overlap. The present version of the COGENT code models a nonlinear axisymmetric 4D (**R**, $v_{\|}$, μ) gyrokinetic equation coupled to the long-wavelength limit of the gyro-Poisson equation. Here, **R** is the particle gyrocenter coordinate in the poloidal plane, and $v_{\|}$ and μ are the guiding center velocity parallel to the magnetic field and the magnetic moment, respectively. The code has a number of collision models, ranging from the simple Krook operator to the fully nonlinear Fokker-Plank operator [3]. The COGENT code models and algorithms have been extensively verified with the annular-geometry version of the code in simulations of neoclassical transport and collisionless relaxation of geodesic acoustic modes [3]. The divertor version of the code that includes both the pedestal and the scrape-off-layer regions has recently become available. Cross-separatrix plasma transport can be simulated including the effects of the fully nonlinear Fokker-Plank collisions, self-consistent electric fields, and anomalous radial transport. Results of illustrative simulations performed with the divertor code are shown in Figure 1.

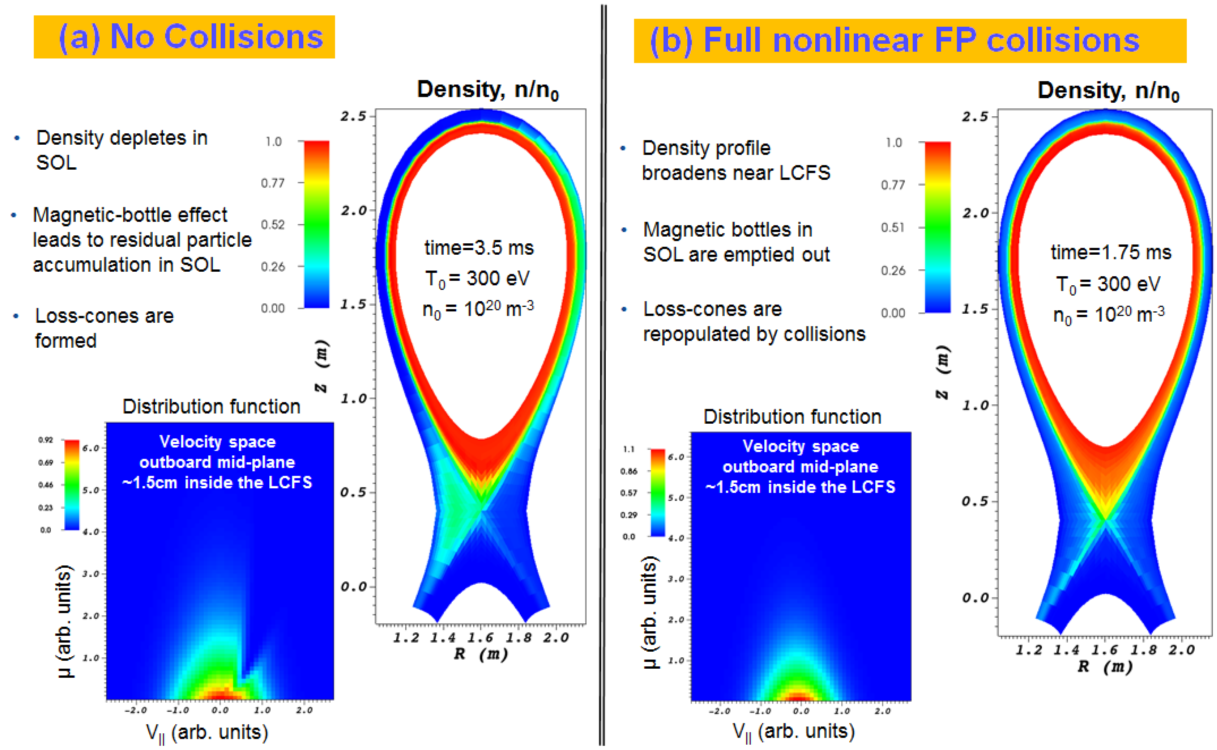

Figure 1. Ion dynamics in the absence of electric fields. Frames (a) and (b) show the ion density and velocity phase-space obtained in the absence of collisions and with the fully nonlinear Fokker-Plank collision model, respectively. The initial (uniform) ion temperature and density are T_0=300 eV and $n_0=10^{20}m^{-3}$, the toroidal magnetic field corresponds to $B_\varphi R$=3.5Tm, B_θ/B_φ~0.1.

Future work: The near-term future work will include development of additional capabilities for the 4D divertor code. In particular, a succession of increasingly detailed neutral and anomalous transport models will be added. Also, development of integrated modeling capabilities will be carried out under the new SciDac project AToM, which is aimed at developing tools and workflows for whole device modeling. The project includes integrating COGENT into a general workflow manager system (OMFIT) and coupling it to other AToM components. In particular, loose coupling with a turbulence fluid code (e.g., BOUT) will be performed in order to improve the COGENT anomalous transport model by providing relevant transport coefficients (e.g., anomalous particle diffusion). On the math side, an advanced IMEX (implicit-explicit) scheme will be implemented to address the vast range of timescales and enabling long-time transport simulation. Such schemes will allow for implicit treatment of selected fast processes (e.g., parallel electron streaming, strong collisions) while explicitly integrating physical processes on the time scale of interest (e.g., ion advection) Work has also begun on an initial 5D version to study edge turbulence, with initial focus on kinetic effects on blob dynamics and drift-wave instability. Over the next several years, a full electromagnetic 5D code is planned, targeting kinetic simulations of edge microinstabilities.

[1] P. Colella et al., J. Comput. Phys. **230**, 2952 (2011); P. McCorquodale et al., J. Comput. Phys., **288**, 181 (2015).
[2] Edge Simulation Laboratory (https://esl.lbl.gov)
[3] Dorf et al., Contrib. Plasma Phys. **54**, 517 (2014); Dorf et al. Nucl. Fusion **53**, 063015 (2013); Dorf et al. Phys. Plasmas **20**, 012513 (2013).
[4] D. J. Battaglia et al., Phys. Plasmas **21**, 072508 (2014)

*Prepared by LLNL under Contract DE-AC52-07NA27344. This material is based upon work supported by the U.S. DOE, Office of Science, Fusion Energy Sciences.