LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-CONF-669640

# Modeling Edge Plasma with the Continuum Gyrokinetic Code COGENT

M. Dorf, M. Dorr, J, Hittinger, T. Rognlien, P. Colella, P. Schwartz , R. Cohen, E. Lee

April 14, 2015

DOE Workshop on Integrated Simulations for Magnetic Fusion Energy Sciences
Rockville, MD, United States
June 2, 2015 through June 4, 2015

# Modeling Edge Plasma with the Continuum Gyrokinetic Code COGENT*

**M. Dorf, M. Dorr, J. Hittinger, T. Rognlien (LLNL)**

**P. Colella, P. Schwartz (LBNL)**

**R. Cohen (CompX), W. Lee (UCSD)**

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

**Objective:** It is increasingly important to achieve an improved theoretical understanding of edge plasma transport in order to optimize the performance of divertor tokamaks. The problem, however, offers a significant challenge for analytical or numerical studies due to (a) a complex magnetic geometry, which includes both open and closed field lines, and (b) the importance of kinetic effects as the short radial length-scales for edge plasma density and temperature variations become comparable to particles drift-orbit excursion. Contrary to core plasmas, which have been extensively simulated with both particle-in-cell (PIC) and continuum gyro-kinetic codes, edge plasmas have been previously kinetically modeled only by making use of the PIC approach (e.g., the XGC code [1] developed through the CPES SciDAC project). Such preference was made, in part, due to the presence of the magnetic separatrix within the simulation domain that poses significant challenges for a continuum code. 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. In contrast, the PIC approach uses macroparticles to integrate along the characteristic of the kinetic equation, and therefore is not sensitive to the presence of the X-point as it does not introduce any challenges for evaluating the magnetic drift-velocity of plasma particles. On the other hand, PIC codes may require a very large number of macro particles to suppress numerical noise in the edge-plasma simulations, where deviations from the background distribution are large and the full-F approach is required. 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. Moreover, having multiple kinetic codes that address edge plasm transport is of particular importance to code verification.

**Recent progress:** Based on recent advances from the applied math community [2], the Edge Simulation Laboratory collaboration [3] has been developing the first $4^{th}$-order finite-volume (continuum) gyrokinetc code COGENT [4] 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 ($\mathbf{R}$, $v_{\|}$, $\mu$) gyrokinetic equation coupled to the long-wavelength limit of the gyro-Poisson equation. Here, $\mathbf{R}$ is the particle gyrocenter coordinate in the poloidal plane, and $v_{\|}$ and $\mu$ 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 [4]. 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 [4]. 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.

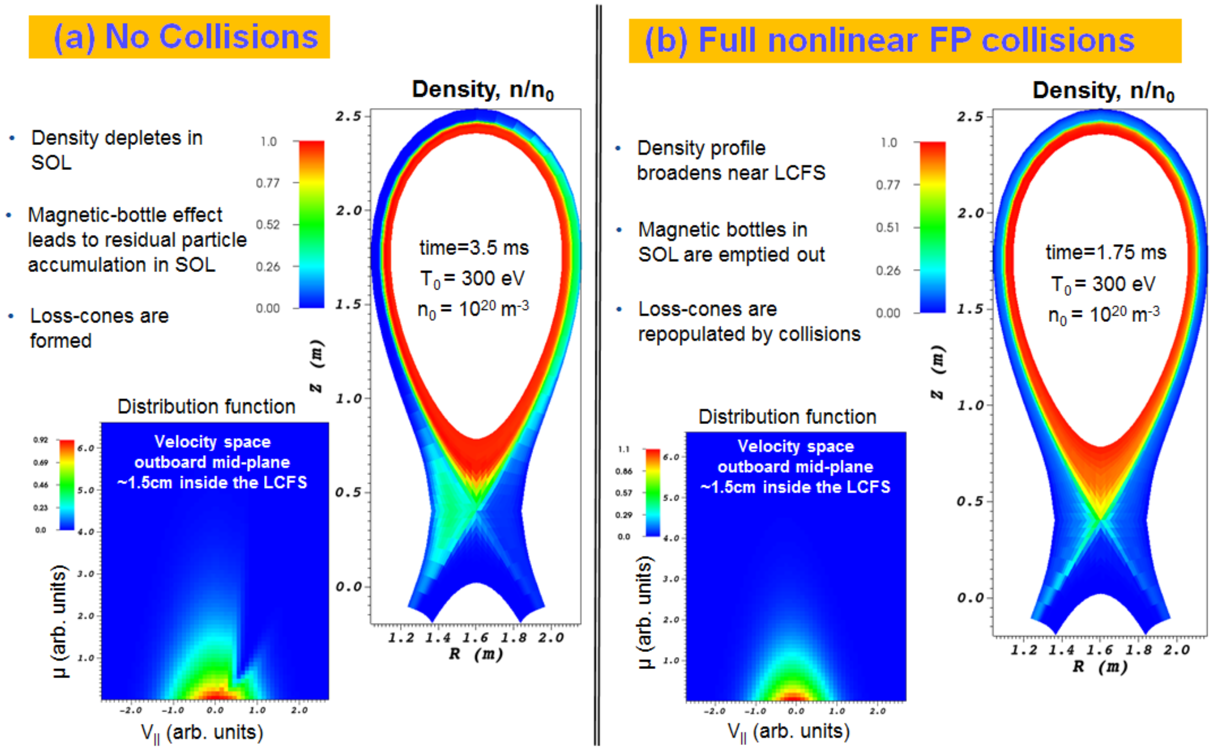


Figure 1. Ion dynamics in the absence of electric fields. Frames (a) and (b) show the ion density and velocity phase-space obtained in the absence of collisions and with the fully nonlinear Fokker-Plank collision model, respectively. The initial (uniform) ion temperature and density are $T_0$=300 eV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

**Future work:** The near-term future work will include development of additions capabilities for the 4D divertor code. In particular, a succession of increasingly detailed neutral models will be added. Furthermore, 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] D. J. Battaglia et al., Phys. Plasmas **21**, 072508 (2014); also see http://w3.physics.lehigh.edu/xgc/ for more details about the XGC code.
[2] P. Colella et al., J. Comput. Phys. **230**, 2952 (2011); P. McCorquodale et al., J. Comput. Phys., **288**, 181 (2015).
[3] Edge Simulation Laboratory (https://esl.lbl.gov)
[4] 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).

*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.