Continuum kinetic modeling of the tokamak plasma edge

Mikhail Dorf (LLNL)

In collaboration with

M. Dorr, J. Hittinger, T. Rognlien, R. Cohen (LLNL)

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

57 APS DPP Meeting
Savannah, Georgia; Nov. 16 - 20, 2015

Prepared by LLNL under Contract DE-AC52-07NA27344 and LBNL under contract DE-AC02-05CH11231. This material is based upon work supported by the U.S. DOE, Office of Science, Fusion Energy Sciences. (LLNL-PRES-678931)

Outline

- ***Overview of the ESL project and the COGENT code***
- ***Edge plasma modeling***

  -- Complex geometry / strong gradients, …
- ***Annular-geometry simulations***

  --Verification studies

  -- Steep gradients: effects of strong E_r
- ***Cross-separatrix simulations***

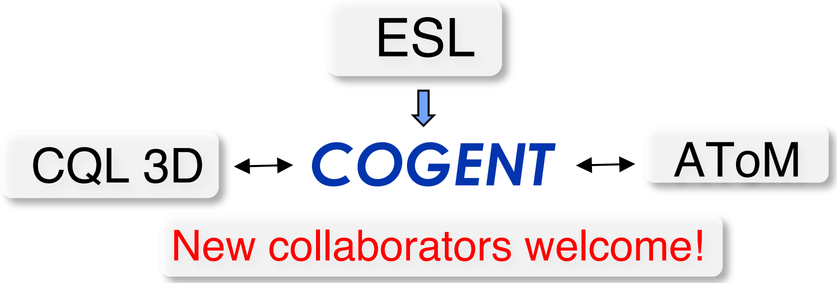
  --Ion orbit loss / intrinsic toroidal rotation

  --Transport solutions / integrated modeling capabilities
- ***Conclusions/Future research***

Edge Simulation Laboratory (ESL)

- ***COGENT is being developed as part of the ESL collaboration***
  - ESL is a project to develop gyrokinetic simulation for MFE edge plasmas based on **continuum** (Eulerian) techniques
- ***Why continuum?***
  - Concerns about PIC noise in the environment where there are large density variations and where the full-F approach is required
  - Exploit advanced numerical methods from the fluids community
  - Build on successes of continuum core codes (GYRO, GENE)
- ***ESL collaboration:***
  - Physics team: GA, LLNL, UCSD
  - Math team: LLNL (CASC), LBNL

COGENT team



Kinetic modeling of edge plasmas

- ***Advanced particle-in-cell (PIC) codes***
  - USA: XGC (PPPL)
  - Internationally: ASCOT (Finland), PARASOL (Japan)

- ***Developing continuum codes***
  - USA
    - ESL pilot code (TEMPEST)
    - ESL second-generation code (COGENT)
    - GKEYLL (PPPL) [X-point geometry is not yet included]

COGENT: First (4D) high-order continuum simulations spanning separatrix (include the effects of electric fields, Fokker-Plank collisions, …)

Continuum gyrokinetic code COGENT

Currently operates in the long-wavelength (i.e., drift-kinetic) limit

4D (axisymmetric) gyrokinetic equation for gyroaveraged $f_\alpha(\mathbf{R}, v_{||}, \mu)$

$$\frac{\partial B^*_{\|\alpha} F_\alpha}{\partial t} + \nabla_{\mathbf{R}}\left(\dot{\mathbf{R}}_\alpha B^*_{\|\alpha} F_\alpha\right) + \frac{\partial}{\partial v_\|}\left(\dot{v}_\| B^*_{\|\alpha} F_\alpha\right) = C_\alpha\left[B^*_{\|\alpha} F_\alpha\right]$$

Long wavelength gyro-Poisson equation

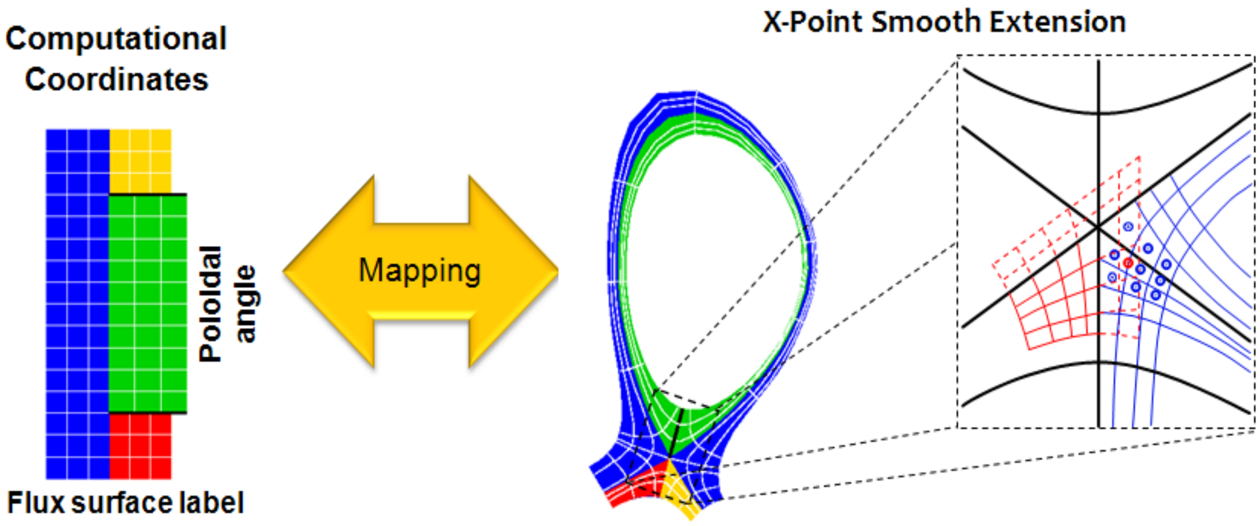
Includes the adiabatic option for electrons $n_e = C^*\exp(e\Phi/T_e)$

$$\Delta^2\Phi = 4\pi e\underbrace{\left(n_e - \sum_\alpha n_{\alpha,gc}\right)}_{\text{gyroaveraged density}} - 4\pi\underbrace{\sum_\alpha \nabla_\perp \cdot \left(\frac{c^2 m_\alpha n_{\alpha,gc}}{B^2}\nabla_\perp\Phi\right)}_{\text{polarization density}}$$

Advanced numerical methods

- 4th order finite-volume (conservative) discretization
- Arbitrarily mapped multiblock grid technology to handle
  - strong anisotropy of plasma transport
  - X-point divertor geometry

Tokamak edge is distinguished by complex geometry



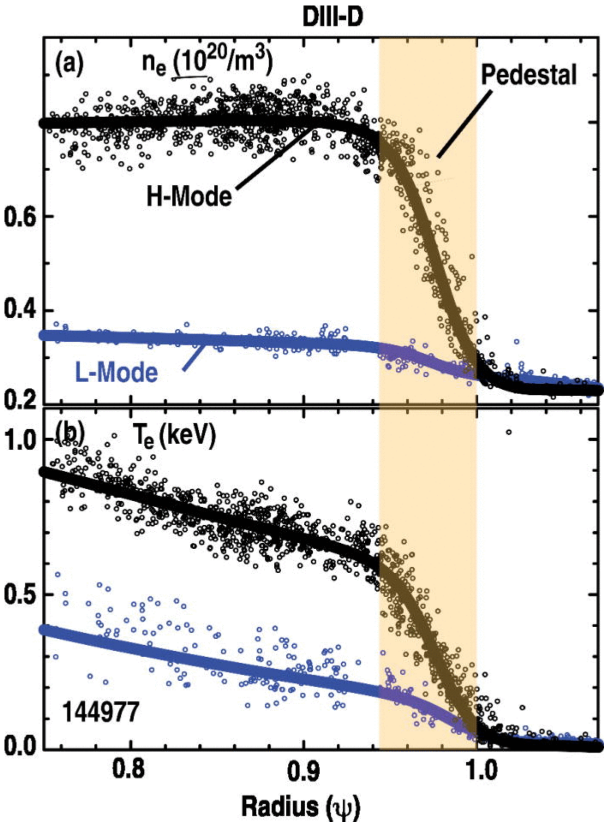
Strong anisotropy of plasma transport motivates the use of flux-aligned grids

Problem: *the metric coefficients diverge at the x-point*

COGENT approach: *the use of multiblock grid technology*

4-th order convergence has been demonstrated
(McCorquodale, JCP 2015)

Tokamak edge is distinguished by steep plasma gradients



[A. W. Leonard, Phys. Plasmas 21, 090501 (2014)]

Radial length scales are comparable to particle drift orbit excursions

- Strong deviations from a Maxwellian distribution
  - *COGENT: full -F*
- Pronounced poloidal variations in electrostatic potential
  - *COGENT: 2D gyro-Poisson equation*
- Detailed collision operator is required
  - *COGENT: full Fokker-Planck operator**

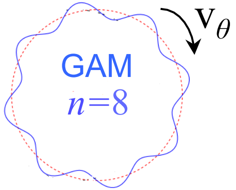
*M. Dorf et al., CPP (2014)

Annular-geometry simulations

- Verification studies
  - Collisionless relaxation of geodesic acoustic modes (GAMs)
  - Neoclassical transport
- Effects of a strong (H-mode) radial electric field

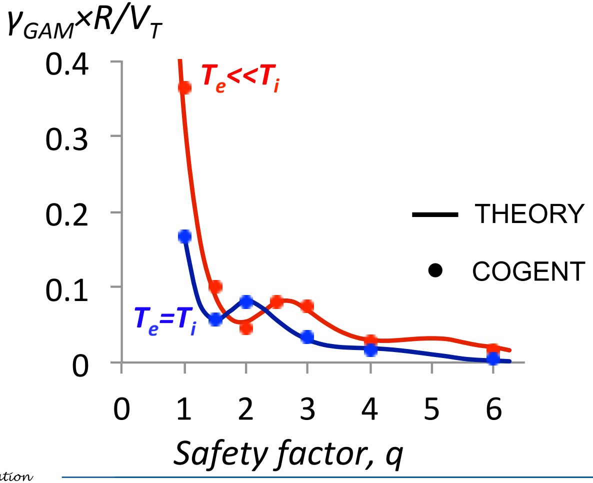
Extensive verification studies have been performed

Collisionless damping of GAMs



$$\frac{v_\theta^{res}}{r} = \frac{\omega_{GAM}}{n} \sim \frac{V_{i,th}}{nR}$$

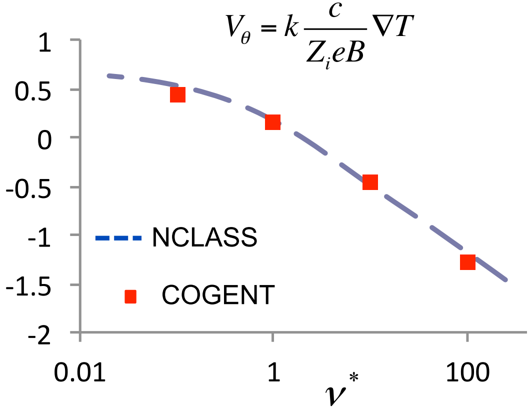
Relaxation rates are recovered



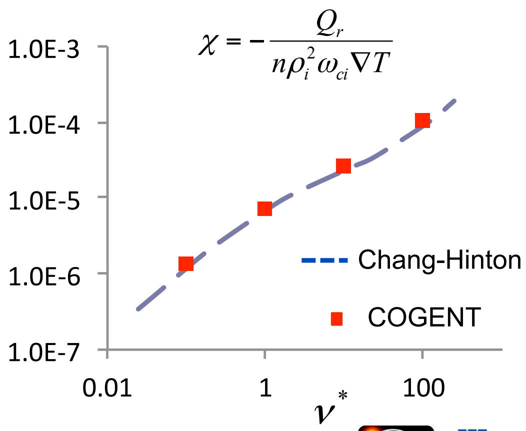
Neoclassical transport simulations

Neoclassical flows and transport coefficients are recovered

Poloidal velocity coefficient, k



Normalized ion heat diffusivity, χ



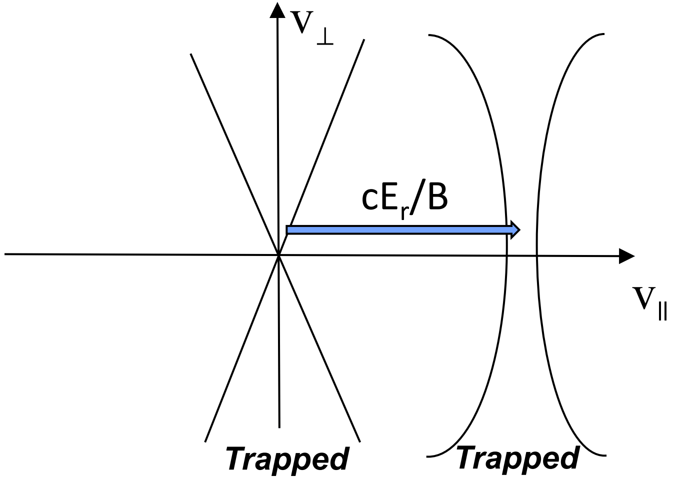
Effects of strong E_r: poloidal flow reversal/heat flux mitigation

THEORY

Banana regime

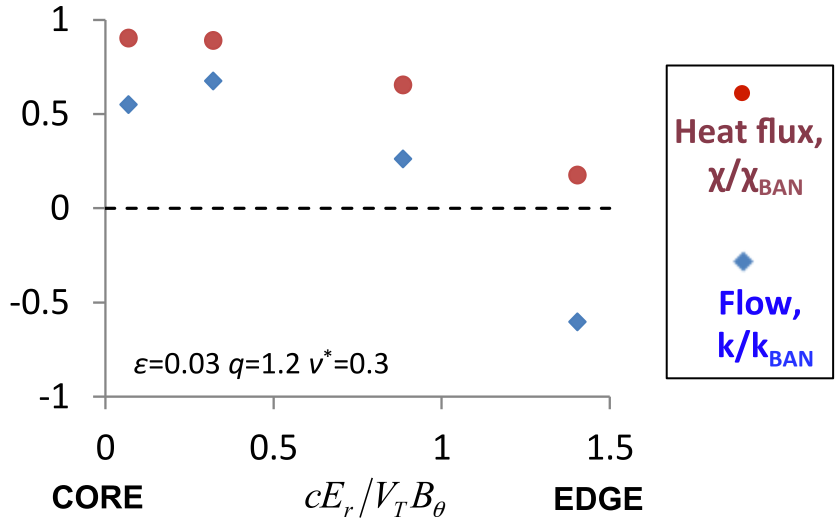
CORE ⇨ EDGE (H-mode)

$$v_\theta = v_\parallel \frac{B_\theta}{B} \qquad v_\theta = v_\parallel \frac{B_\theta}{B} - c\frac{E_r}{B}$$



Kagan and Cato, PPCF (2010)

COGENT

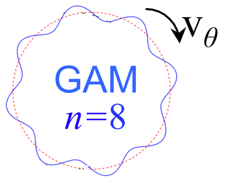


Dorf at et, PoP (2013)

Effects of strong E_r have been recovered in COGENT

Effects of strong E_r: enhanced GAM relaxation

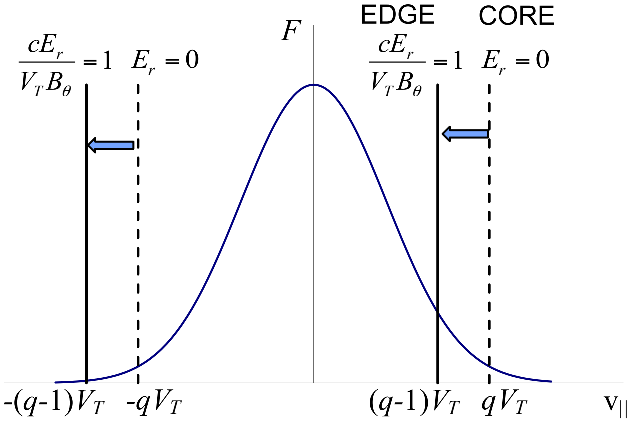
E_rxB contribution needs to be retained in the poloidal motion of passing particles



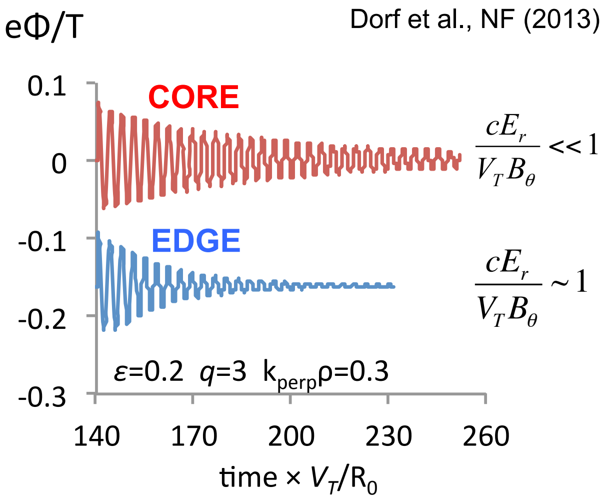
$$\frac{v_\theta^{res}}{r} = \frac{\omega_{GAM}}{n} \sim \frac{V_{i,th}}{nR}$$

$$v_\theta = v_\parallel \frac{B_\theta}{B} - c\frac{E_r}{B}$$

Wave-particle resonance moves toward the bulk of ion distribution



Enhanced relaxation occurs (observed in COGENT)

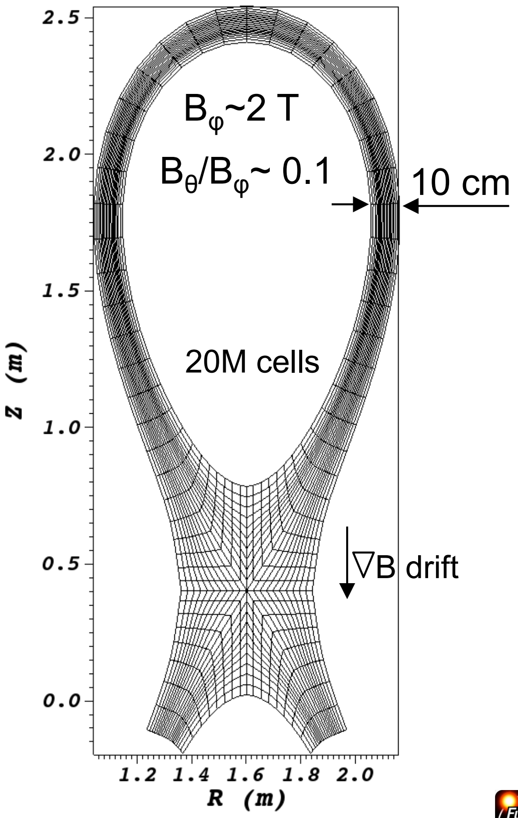


Enhanced GAM relaxation in the presence of strong E_r has been predicted and observed in COGENT

Divertor-geometry simulations

- Ion orbit loss/intrinsic toroidal rotation
- Illustrative transport solutions
- Integrating modeling capabilities

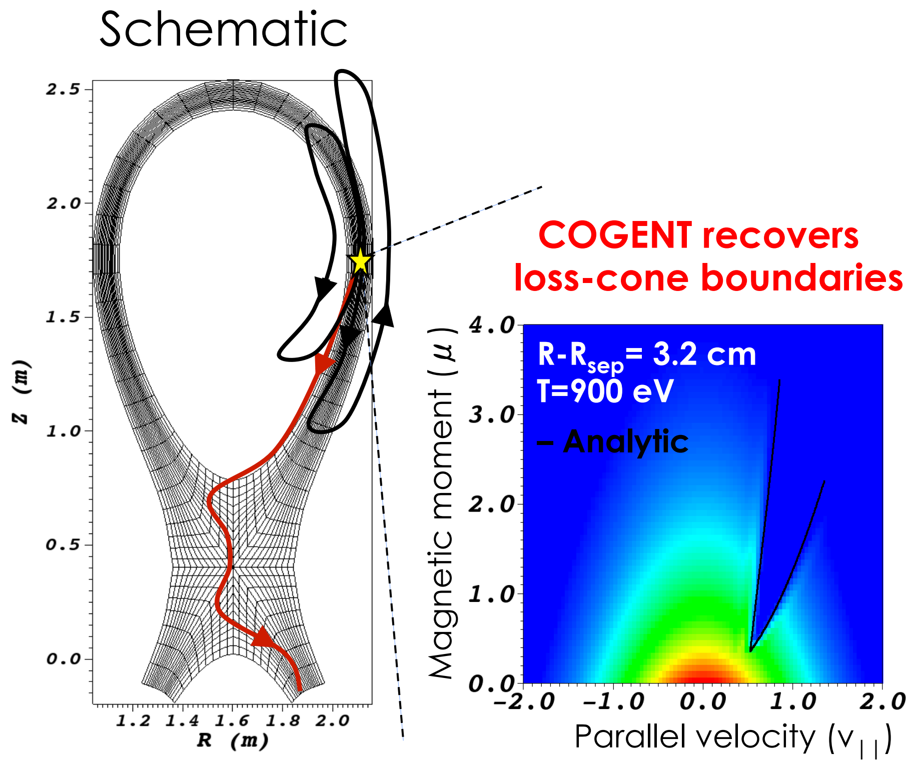
Model geometry



Ion orbit loss can provide intrinsic toroidal rotation

- Co-I_p intrinsic toroidal rotation is routinely observed in the H-mode pedestal
- Important for tokamak performance
  - Can stabilize the resistive wall mode
  - It's shear may regulate turbulence
- One of the possible mechanisms* can be related to ion orbit loss

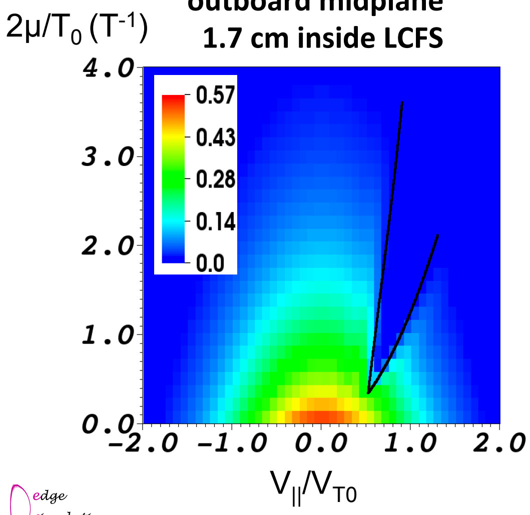
* e.g., Chang et al PoP (2008), deGrassie et al., NF (2009)

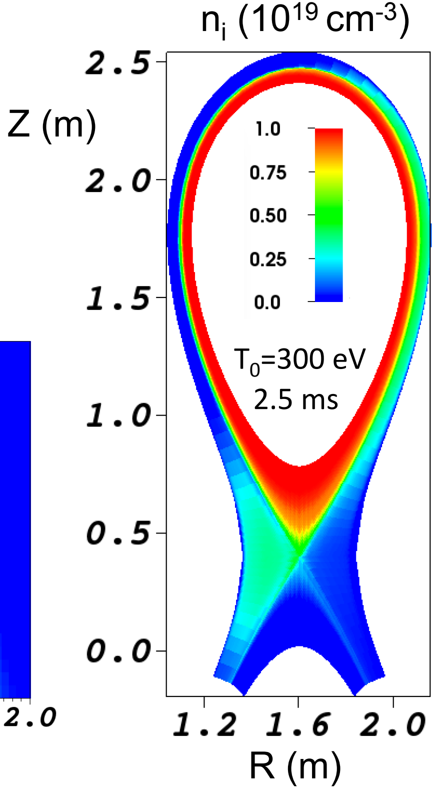


Effects of collisions: loss cone repopulation

No collisions (E=0)

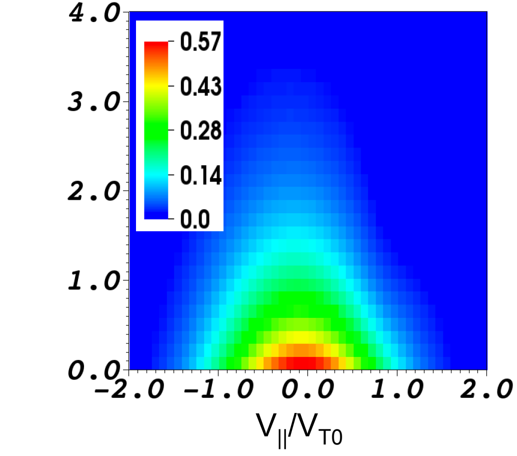
- Magnetic-bottle effect confines particle in SOL
- Loss cones are formed

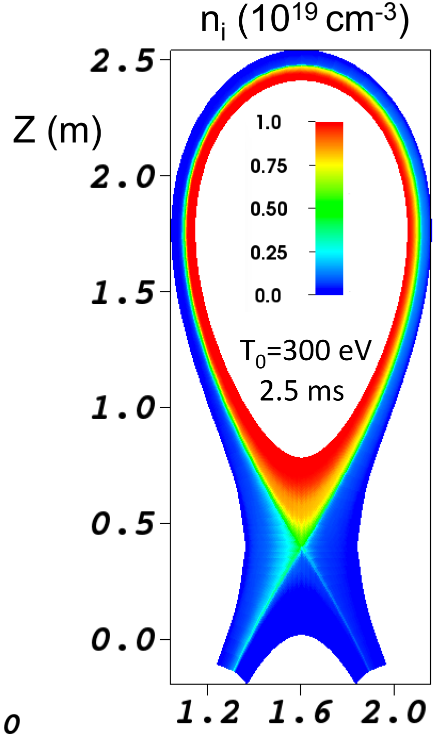




Fully nonlinear Fokker-Planck model (E=0)

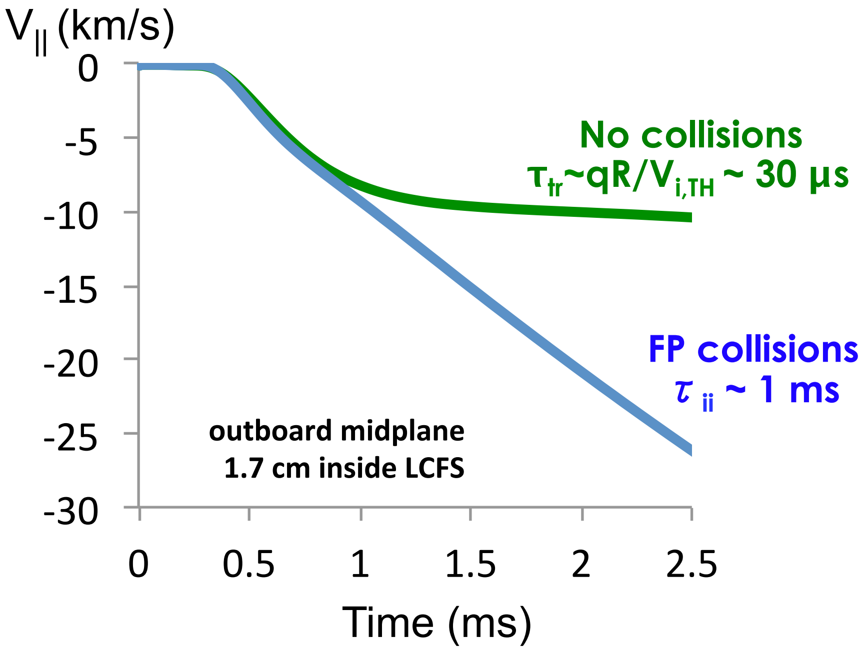
- Magnetic bottles in SOL are emptied out
- Loss-cones are repopulated



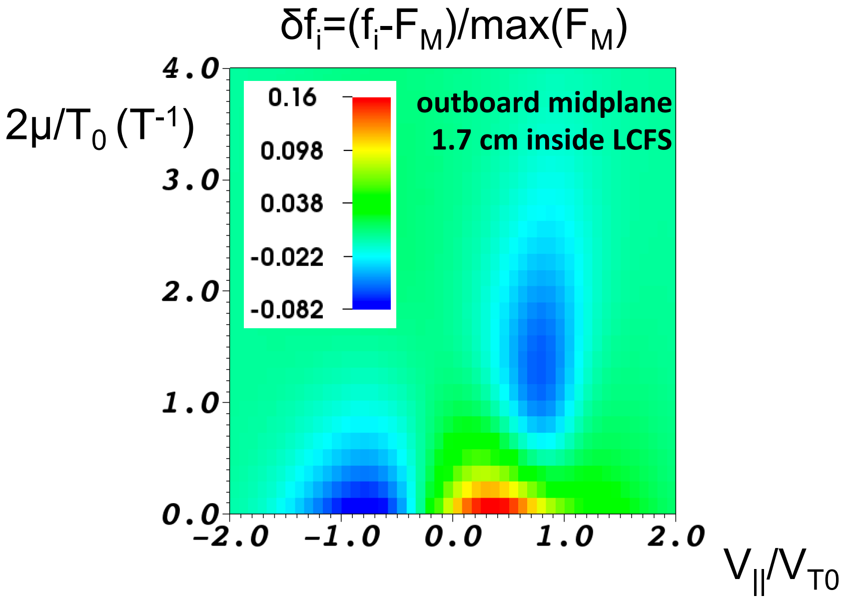


Effects of collisions cont'd

Collisions provide a mechanism for continuous momentum source



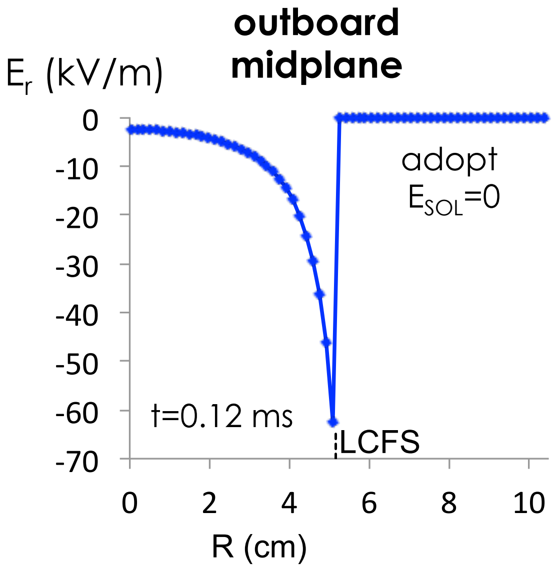
Deviations from a local Maxwellian can be pronounced

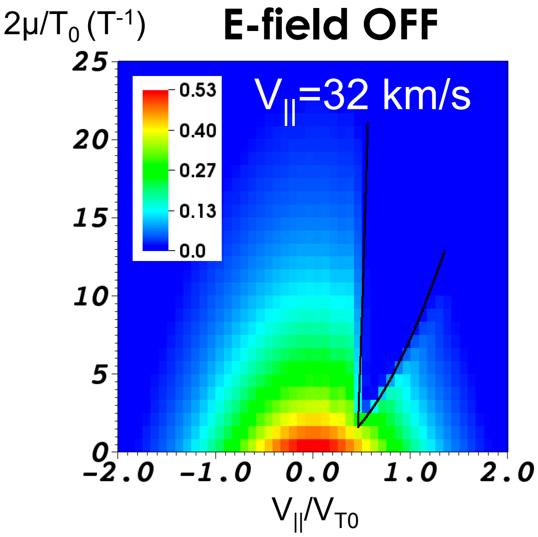


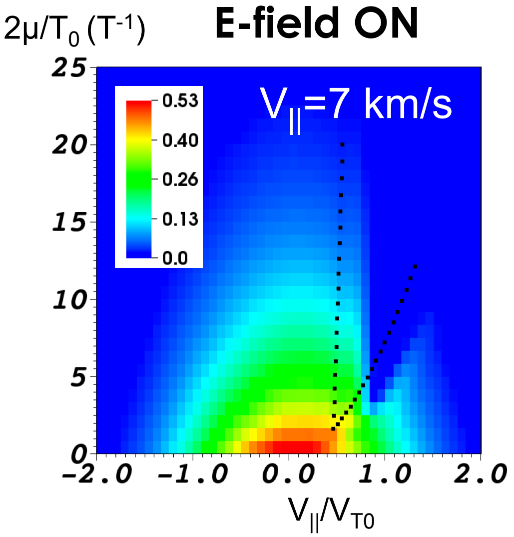
- **Fully nonlinear FP model may be required**

Effects of E_r: mitigation of orbit loss and rotation

$$\underbrace{4\pi n_i m_i c^2 \left\langle \frac{|\nabla\psi|^2}{B^2} \right\rangle \frac{\partial^2 \langle \Phi \rangle}{\partial t \partial \psi}}_{\textit{Polarization current}} = \underbrace{4\pi Ze \left\langle \int d^3\mathrm{v} \left(\mathbf{v}_d \cdot \nabla\psi \right) f_i \right\rangle}_{\textit{Ion neoclassical current}}$$







Here, consider illustrative parameters to relax grid-resolution requirement:

T_0=1000 eV, $B_\varphi \sim B_\theta \sim$ 0.3 T, m_i=2m_p, $\rho_i \sim \Lambda_B$ ~2 cm, collisions – OFF, phase plots – 2.7 cm inside LCFS

Illustrative transport solution for DIII-D parameters

- **Adopt anomalous transport model**

$$\frac{D}{Dt} FB_{\parallel}^{*} = C[FB_{\parallel}^{*}] + \frac{1}{J}\frac{\partial}{\partial\psi}\left[\frac{J}{h_{\psi}^{2}} D(\psi) \frac{\partial FB_{\parallel}^{*}}{\partial\psi}\right]$$

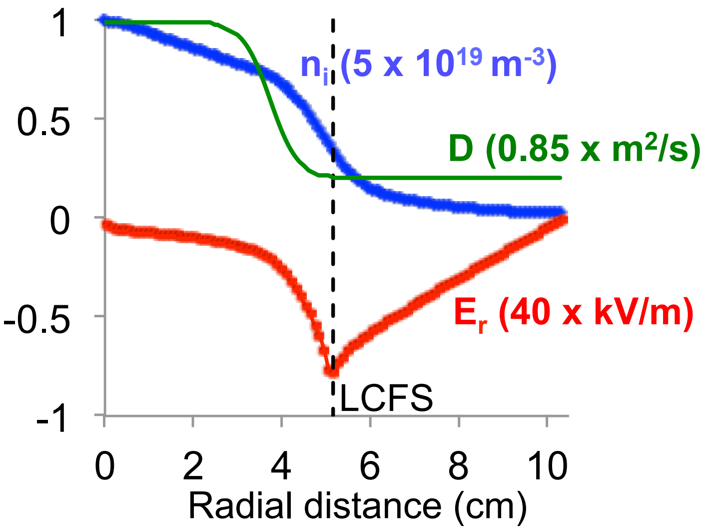
Advection *Collisions* *Anomalous radial transport*

- **Assume ambipolar anomalous transport**

$$4\pi n_i m_i c^2 \left\langle \frac{|\nabla\psi|^2}{B^2} \right\rangle \frac{\partial^2 \langle\Phi\rangle}{\partial t \partial\psi} = 4\pi Ze \left\langle \int d^3 v (\mathbf{v}_d \cdot \nabla\psi) f_i \right\rangle$$

Polarization current *Neoclassical ion current*

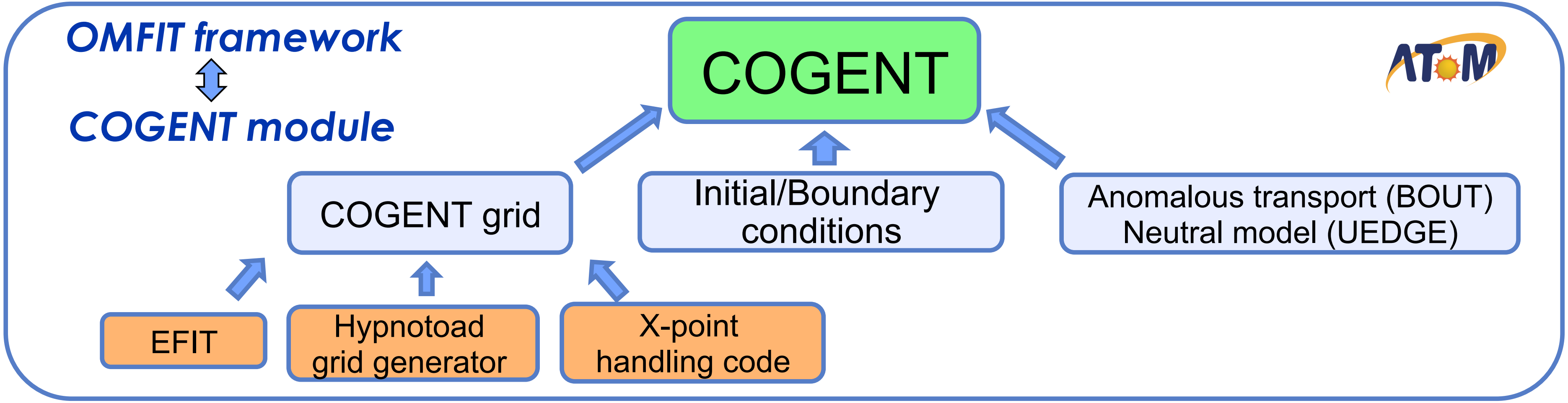
Radial profiles (outboard midplane) @ 2.6 ms

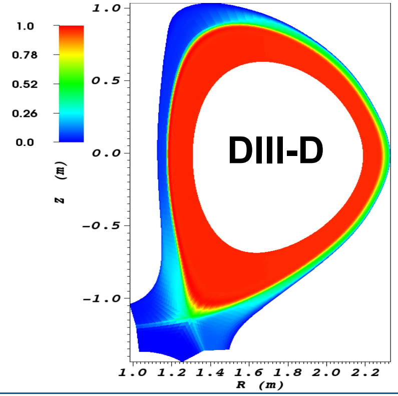


Simulation parameters:

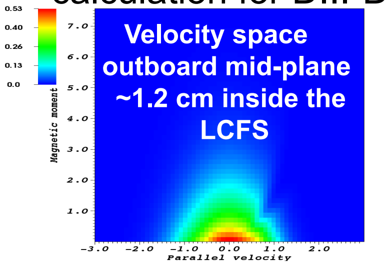
- $B_\varphi R$=3.5 Tm
- B_θ/B_φ~0.1
- m_i=2m_p
- T_0=300 eV (initially uniform)
- Ad-hoc extrapolation of Er into the SOL region
- 12M cells / 6000 steps
- 576 cores X 40 h (Edison)

Developing integrated modeling capabilities





Loss-cone calculation for DIII-D



time=1.4 ms
T_0 = 500 eV
n_0 = 3x10^{19} m^{-3}

Goals:

- Model realistic geometries
- Improve transport models

Conclusions

- The **continuum** gyrokinetic code COGENT is being developed for edge plasma modeling

- COGENT is distinguished by
  - *4^{th}-order finite-volume discretization*
  - *Mapped multiblock grid technology to handle the X-point geometry*

- Strong plasma gradients are addressed by
  - *Full-F/ 2D gyro-Poisson equation/ nonlinear Fokker-Plank operator*

- The closed-flux-surface version of the 4D code is extensively verified
  - *Neoclassical transport / GAM-relaxation simulations*
  - *Effects of strong E_r (characteristic of an H-mode pedestal) are investigated*

- Cross-separatrix modeling capabilities are being developed
  - *Effects of ion orbit loss and initial transport solutions are discussed*

- 5D COGENT development has begun