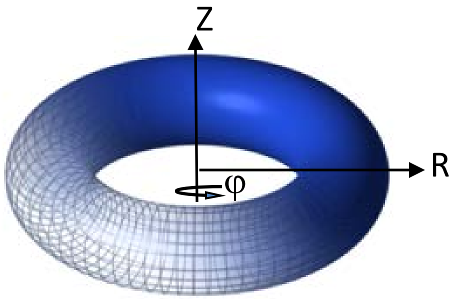
M3D-C1 solves nonlinear three-Dimensional two-Fluid MHD equations in a magnetized torus:



$$\frac{\partial n}{\partial t} + \nabla \bullet (n\mathbf{V}) = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \mathbf{B} = \nabla \times \mathbf{A} \qquad \mathbf{J} = \nabla \times \mathbf{B}$$

$$nM_i\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \bullet \nabla \mathbf{V}\right) + \nabla \bullet \mathbf{P} = \mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{\Pi}_{GV} + \mu \nabla^2 \mathbf{V}$$

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \mathbf{R}_c + \frac{1}{ne}\left(\mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{P}_e\right) - \lambda_H \nabla^2 \mathbf{J}$$

$$\frac{3}{2}\frac{\partial p_e}{\partial t} + \nabla \bullet \left(\frac{3}{2} p_e \mathbf{V}\right) = -p_e \nabla \bullet \mathbf{V} + \eta J^2 + \frac{\mathbf{J}}{ne} \bullet \left[\frac{3}{2}\nabla p_e - \frac{5}{2}\frac{p_e}{n}\nabla n\right] - \nabla \bullet \mathbf{q}_e + Q_\Delta$$

$$\frac{3}{2}\frac{\partial p_i}{\partial t} + \nabla \bullet \left(\frac{3}{2} p_i \mathbf{V}\right) = -p_i \nabla \bullet \mathbf{V} + \mu \left|\nabla V\right|^2 - \nabla \bullet \mathbf{q}_i - Q_\Delta$$

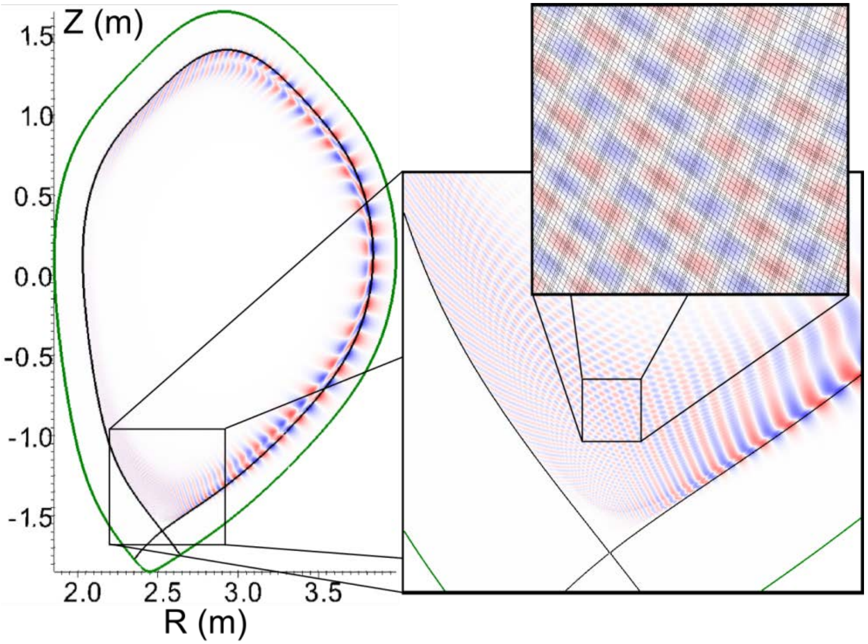
Resistive MHD: $\nabla \bullet \mathbf{P} = \nabla p, \ \ \mathbf{R}_c = \eta \mathbf{J}$

2-fluid terms

Kinetic closures extend these to include neo-classical, energetic particle, and turbulence effects.

M3D-C1 Successfully Benchmarked Against Ideal-MHD Linear ELM Stability Calculations

- M3D-C1 accurately reproduce peeling-ballooning growth rates calculated with ELITE (ideal-MHD code) in ideal limit



- Non-ideal effects were explored
  - Resistivity of “vacuum” region found to affect growth rates
  - Rotation destabilizes low-*n*; stabilizes high-*n*

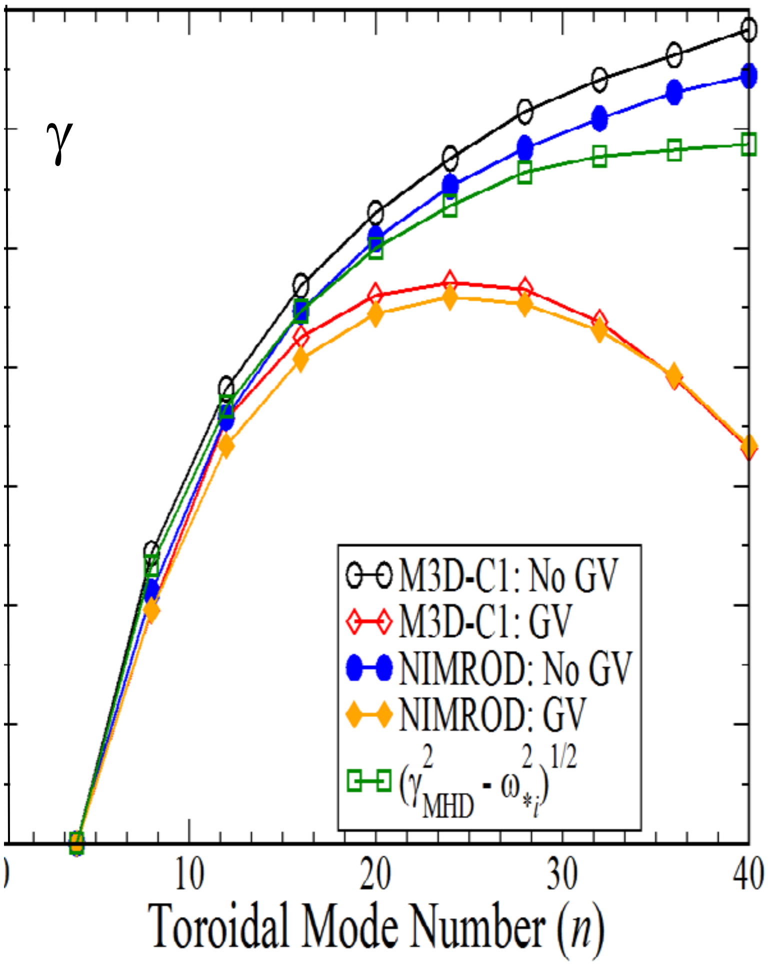
- Benchmarking exercise was challenging due to resolution requirements, especially near separatrix

Diamagnetic Stabilization Observed With M3D-C1 & NIMROD

- "Diamagnetic Stabilization" is an important effect that stabilizes high-*n* ballooning modes

- Ideal-MHD codes cannot calculate this effect

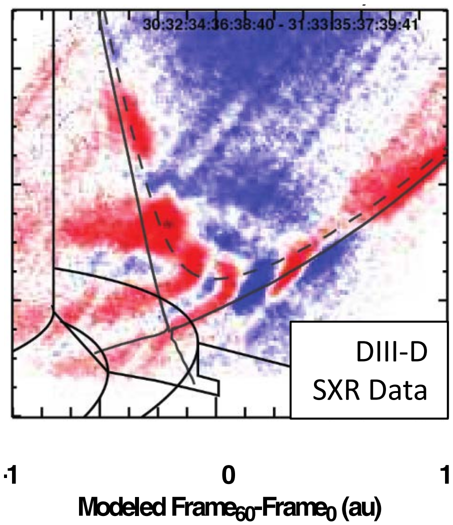
- M3D-C1 & NIMROD are the only codes to calculate the diamagnetic stabilization using the full Braginskii gyroviscosity
  - Stabilization can be significantly different than result from simple theory: $\gamma^2 = \gamma_{MHD}^2 - \omega_{*i}^2$



- Codes are in good agreement with each other

Perturbed 3D Equilibria Calculated with M3D-C1 and Validated With DIII-D Data

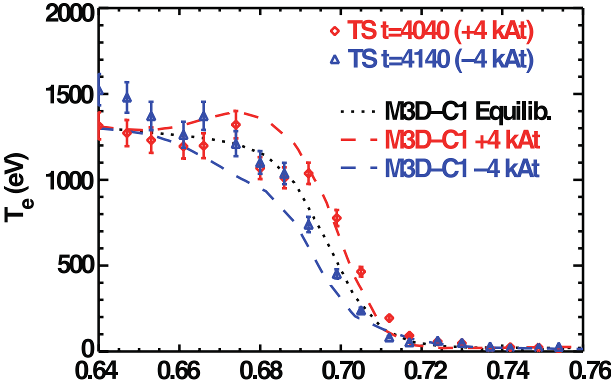
- Applying non-axisymmetric (3D) fields in tokamaks has major effects on tokamak performance
  - ELM suppression, density pump-out, rotation drive



DIII-D SXR Data

- M3D-C1 can now calculate time-independent linear response to applied 3D fields
  - M3D-C1 is the only code capable of calculating perturbed two-fluid 3D response
  - Uses realistic (experimental) values of dissipation

- Calculations of perturbed edge temperature agree well with experiment



M3D-C1 Modeling

Future Work: Nonlinear ELMs and EHO

- Nonlinear calculations will address several questions of fundamentally nonlinear physics:
  - Can we predict the heat/particle fluxes due to an ELM?
  - How does the equilibrium become unstable as the pedestal evolves?
  - Can we predict when ELM saturates to form EHO (QH-Mode)?

- We plan a direct comparison of nonlinear ELM evolution between M3D-C1 and NIMROD. This is made possible by accomplishments in past few years:
  - Nonlinear capability in M3D-C1
  - Improved meshing, parallel scaling, and resolution capabilities

- Comparison presents challenges
  - In most cases, high-n modes (n>30) are unstable but unresolved; how these are dealt with may affect comparison
  - Two-fluid terms, anisotropic heat flux impose restriction on time step

Future Response Calculations Will Address Locking, and Response in ITER

- Rotational braking due to applied fields can reduce stability and limit applicability in ITER
  - We will demonstrate quantitative calculations of both resonant (J×B) and nonresonant (NTV) torque
  - NTV calculation will make use of ion parallel viscosity closures from analytic models and drift-kinetic codes
  - We will attempt to self-consistently model mode-locking event

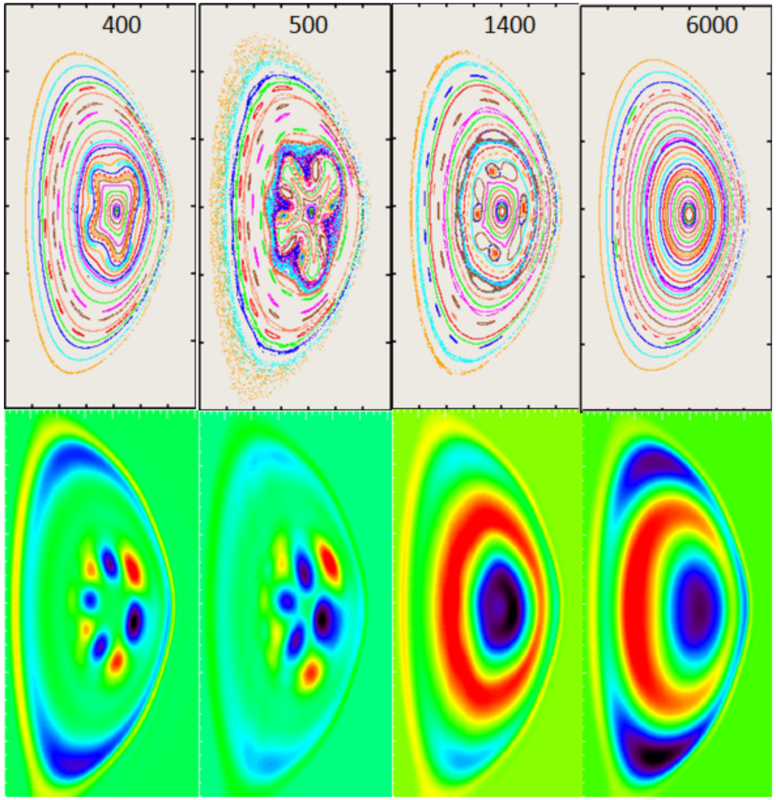
- M3D-C1 is being used to assess plasma response to proposed ITER ELM control coils. These calculations will be extended by
  - Improving preconditioner for nonlinear two-fluid response calculations with anisotropic heat flux, to achieve more realistic parameters
  - Improving meshing and resolution capabilities

Mechanism for a soft beta limit in NSTX

- When the beta limit is exceeded, will the plasma disrupt (hard limit) or just exhibit increased transport (soft limit)

- We have used M3D-C1 to mode a soft-limit in NSTX where the central surfaces distort as beta is increased, enhanced transport follows, and then the surfaces reform as the beta decreases.

- These studies are continuing in order to better understand:
  - the transport mechanism
  - under what conditions this occurs rather than the "hard limit"



Poincare plots (top) and change in temperature (bottom) from the start of the calculation at 4 different times.

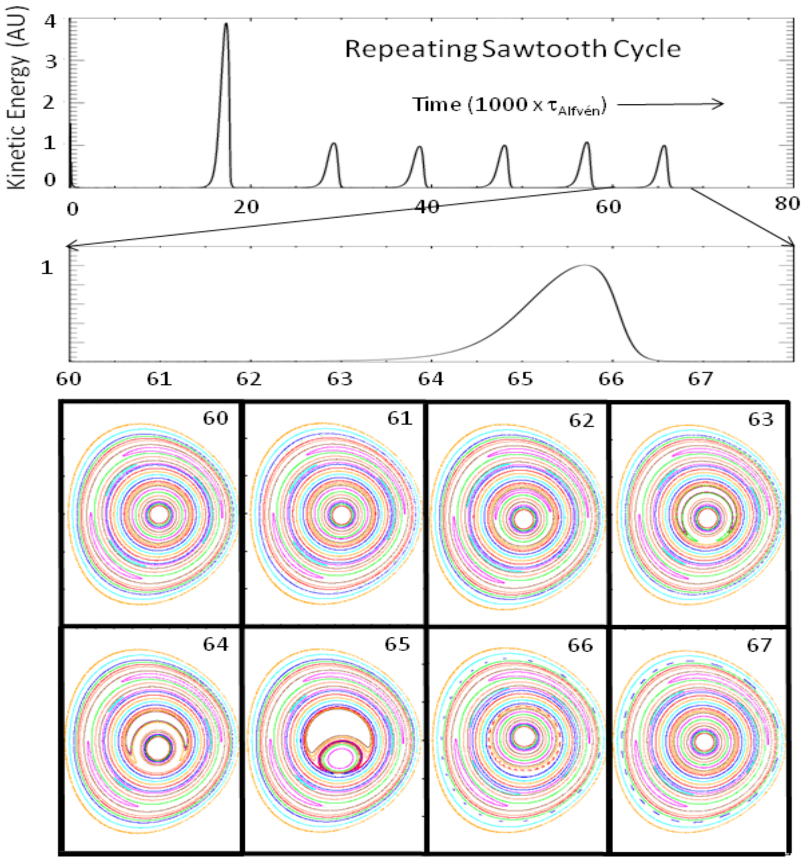
Long-time modeling of periodic sawteeth in CMOD, DIII-D, and ASDEX-U

- Highly implicit algorithms of M3D-C1 allow large time steps and hence long time simulations.

- We have started using M3D-C1 to study to better understand the physics of sawteeth: when they repeat and when they saturate to a region with q=1 in the center.

- Present emphasis is on:
  - physics of the temperature crash
  - role of sheared rotation
  - effect of shaped cross section
  - dependence on transport coefficients

- This study will continue. (A German PhD student, Isabel Krebs, is now involved).



Repeating sawtooth cycle. Top is kinetic energy vs time. Bottom are Poincaré plots for a single cycle.

Inclusion of neoclassical effects

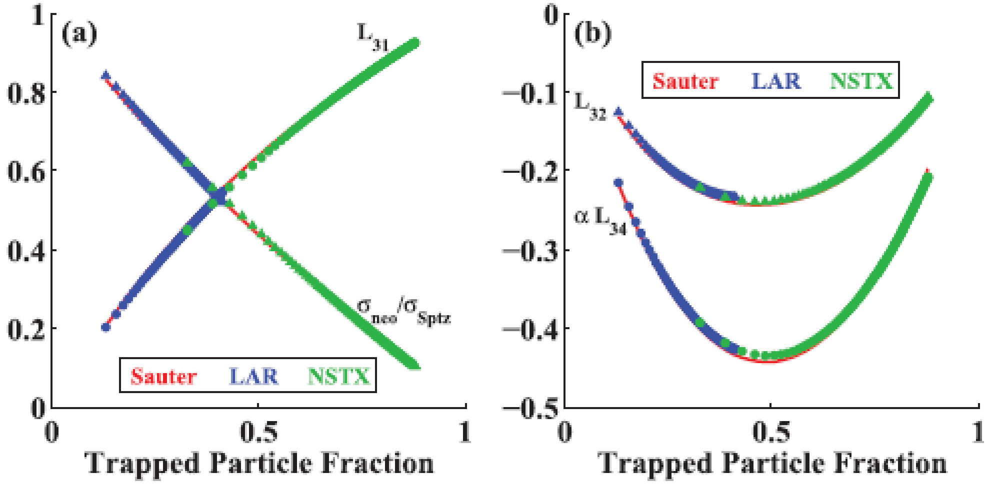
- M3D-C1 has effort underway to include neoclassical effects in the 3D calculations

- A subsidiary calculation is done to calculate non-Maxwellian part of distribution function (including full collision operator) and then velocity moments are taken (Ramos formulation)

- Has now been verified against established codes in axisymmetric limit.

- Brendan Lyons PhD Thesis

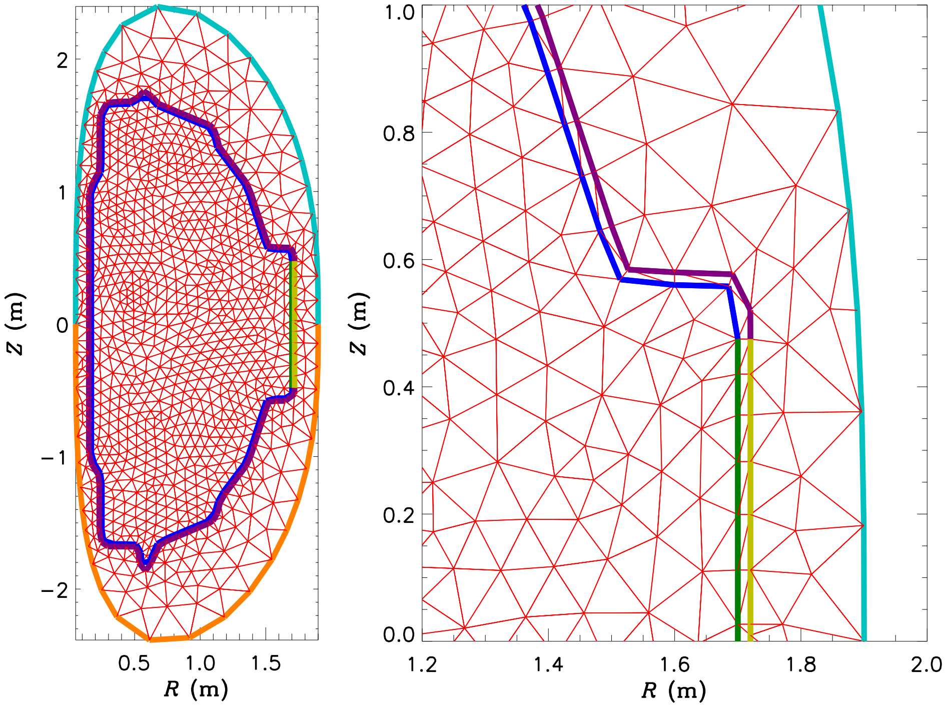
$$\langle \mathbf{J}\bullet\mathbf{B}\rangle = \sigma_{neo}\langle \mathbf{E}\bullet\mathbf{B}\rangle - cI\left[L_{31}\frac{dP}{d\psi} + L_{32}n_e\frac{dT_e}{d\psi} + \alpha L_{34}n_i\frac{dT_i}{d\psi}\right]$$



Comparison of neoclassical terms in Ohm's law between M3D-C1 and Sauter model for both large aspect ratio model and an NSTX equilibrium using JSOLVER.

Numerical representations of external regions allow greater flexibility.

- Nonlinear M3D-C1 computations use Hermite cubics in ϕ for the plasma region, and the external-region implementation is being developed with the same representation.
- Walls are are also meshed and magnetic diffusion through them is computed numerically.
- The poloidal plane is meshed with MeshSim from Simmetrix and the PUMI/FMDB infrastructure.



M3D-C1 meshing for NSTX showing plasma, wall and vacuum regions with large elements for clarity.

Sample calculation of current decay in NSTX