ELM Milestone Summary with NIMROD

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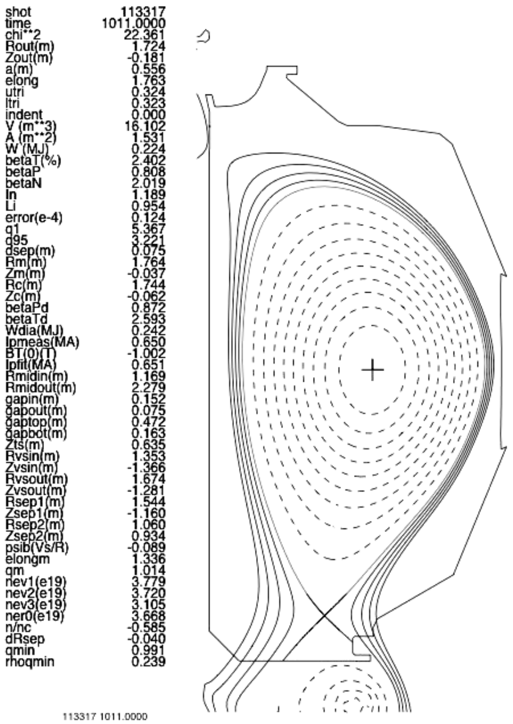
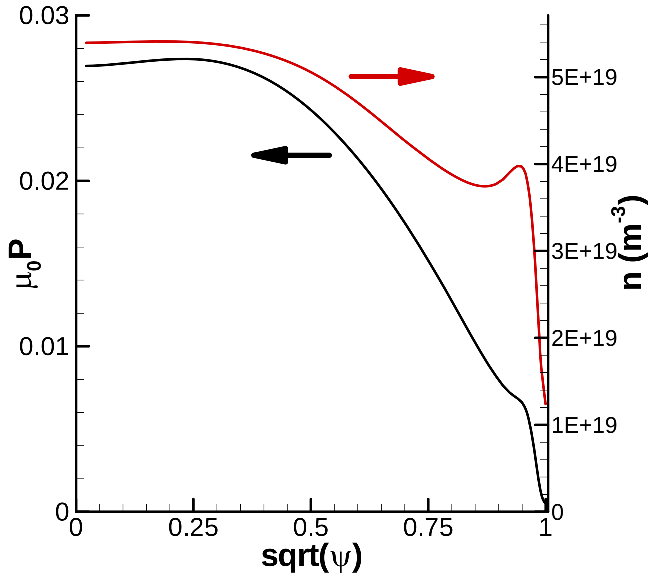
Our ELM computations for the FY06 OFES 'Performance Targets' use MHD equilibria fitted to laboratory measurements (EFIT) to model specific DIII-D discharges.

- The NIMROD code treats the equilibrium as a separated steady state.
- This year, we also use the number density profile and solve particle continuity.

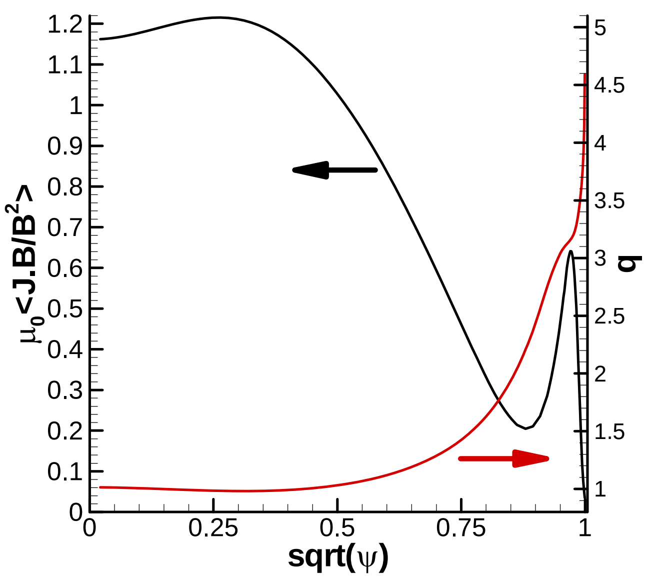


Fitted flux-surfaces for DIII-D discharge 113317.

(courtesy of T. Osborne, GA)



Pressure and number density profiles.



Parallel current density and safety factor--note large edge current.

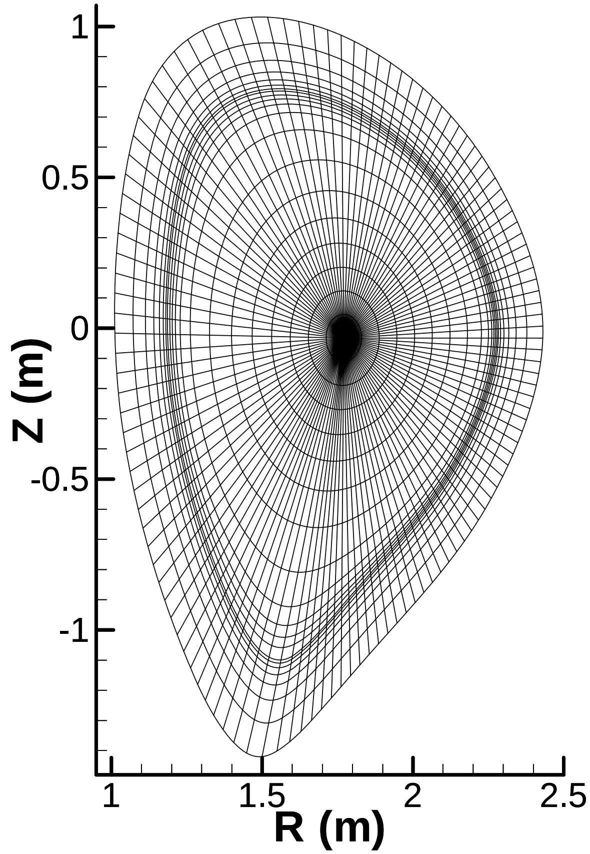
Linear ELM Tests

Before proceeding to nonlinear simulations, we ran linear computations to understand numerical convergence properties with both models and to confirm drift stabilization at high wavenumber.

• Computations with the large density gradient and the spatial representation used for last year's simulations are not converged without large (~1000 m^2/s) values of artificial particle diffusivity.

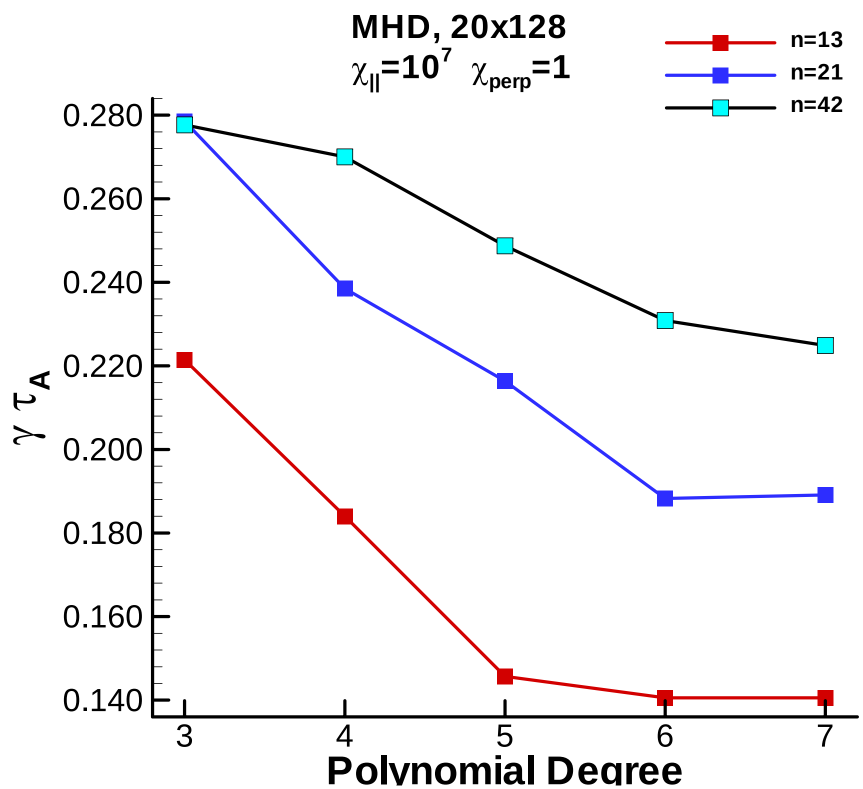
• With the particle diffusivity at 2.5 m^2/s and Spitzer resistivity, the computations ran out of memory before achieving convergence.

• Increasing resistivity by a factor of 100 improves convergence properties but adds to the ballooning character of high-n modes with resistive MHD.

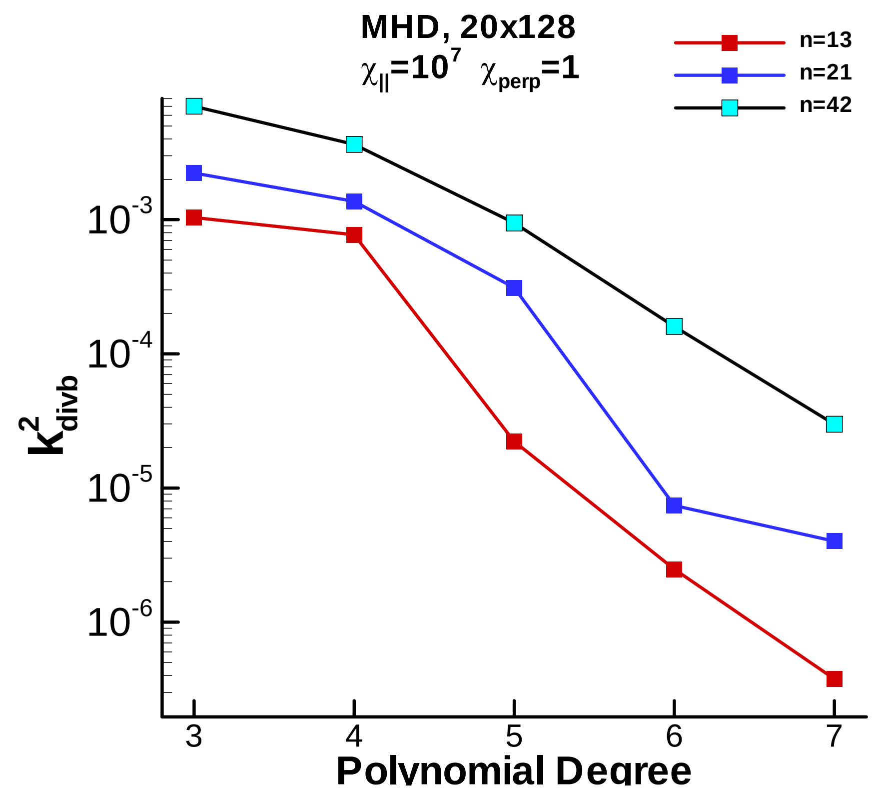


Mesh of curved finite elements packed near the magnetic separatrix.

We converge the MHD modes as in spectral computations, by changing the order of the polynomial basis functions.



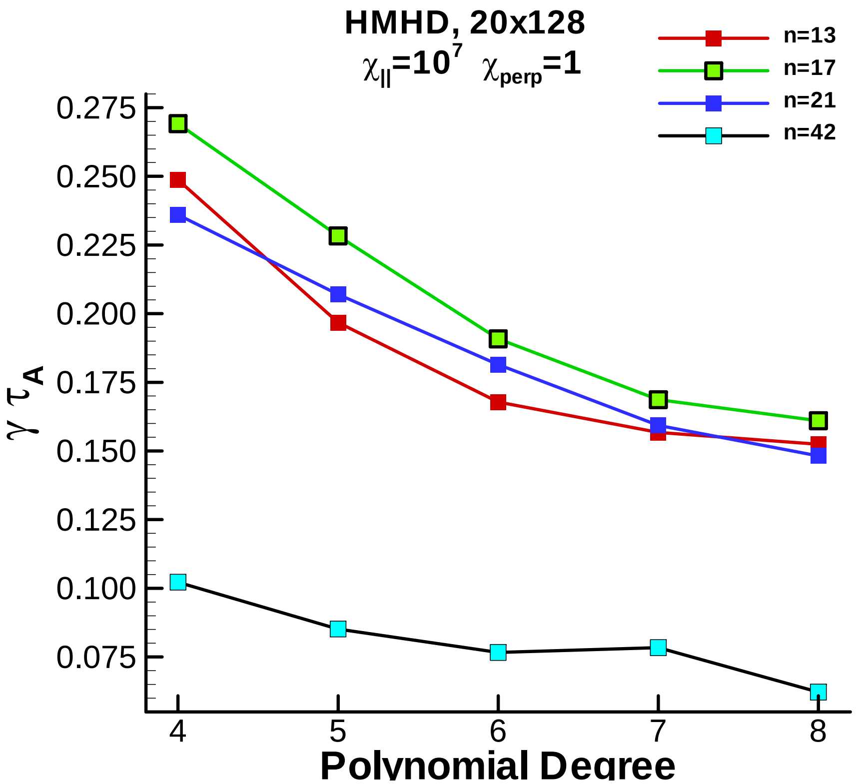
Computed growth-rate for the n=13, 21, and 42 MHD modes with η_{ped}/μ_0=7 m^2/s and anisotropic thermal conduction.



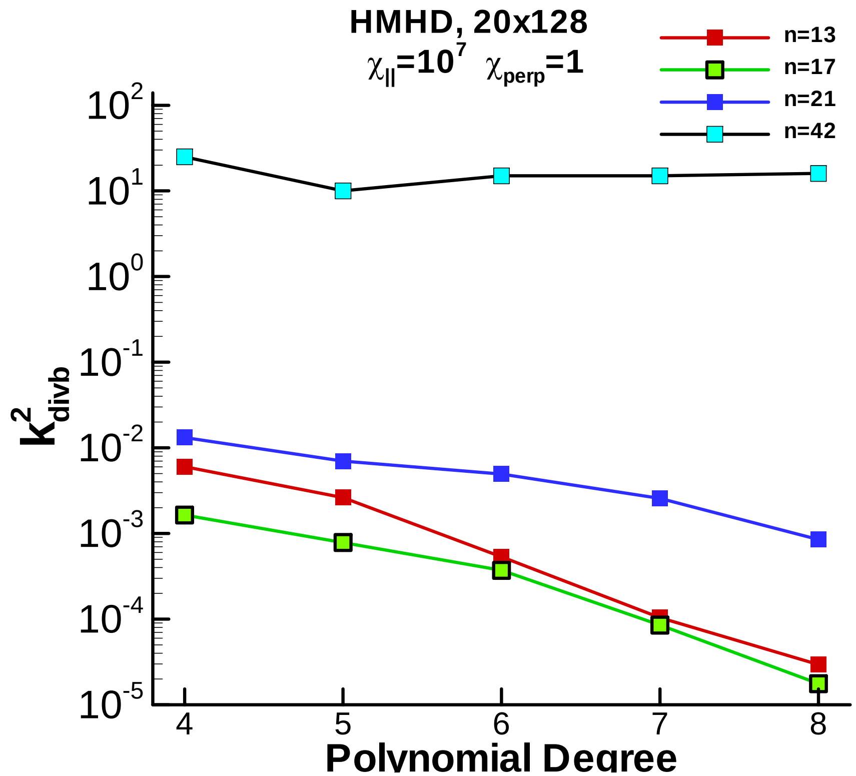
Magnetic divergence error for the n=13, 21, and 42 MHD (k^2_{divb}= $\int\left(\nabla\cdot\tilde{b}\right)^2 dVol \Big/ \int \tilde{b}^2 dVol$) modes with η_{ped}/μ_0=7 m^2/s and anisotropic thermal conduction.

- Growth-rate increasing with n is a ballooning trait.
- This may be an artifact of the resistivity, and further study is warranted.

The same set of parameters also resolves the fastest-growing part of the two-fluid spectrum but not the high-n modes.



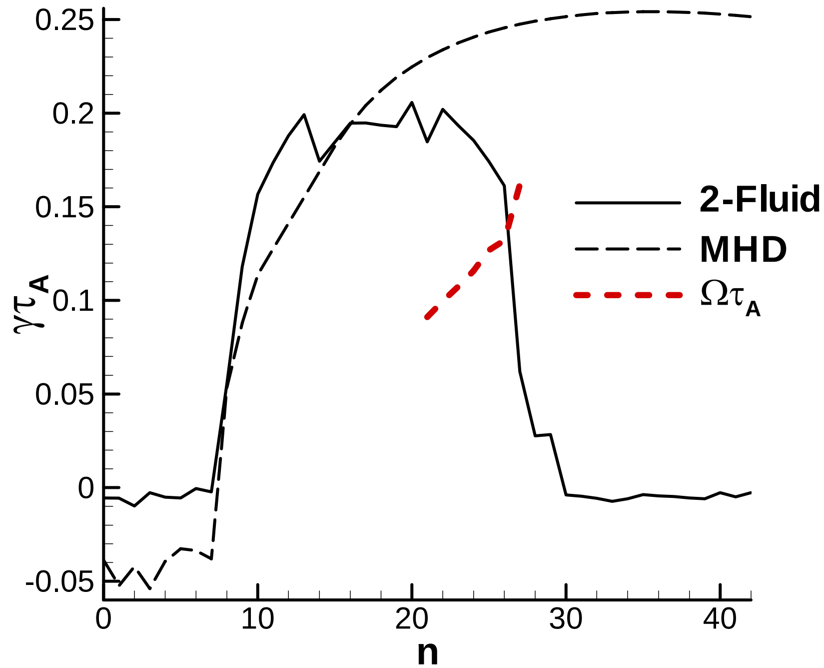
Computed growth-rate for the n=13, 17, 21, and 42 two-fluid modes with η_{ped}/μ_0=7 m^2/s, anisotropic thermal conduction, and D=2.5 m^2/s.



Magnetic divergence error for the n=13, 17, 21, and 42 two-fluid modes.

- Two-fluid effects tend to stabilize the computed high-n modes.
- The divergence error shows that n=42 is not resolved at these parameters.

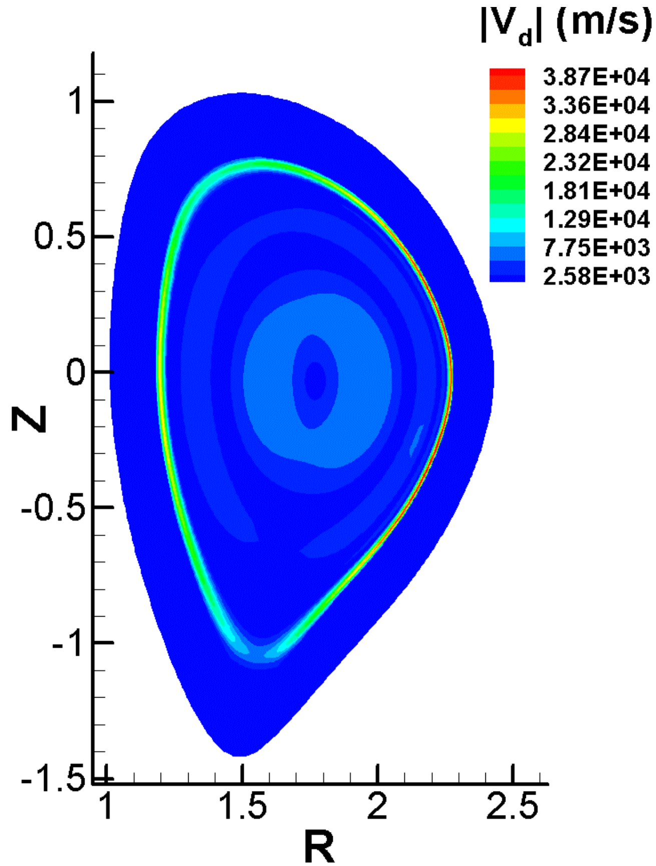
With D increased by a factor of 2 and smaller time-step, the two-fluid computations find that modes with n≥30 are stable.



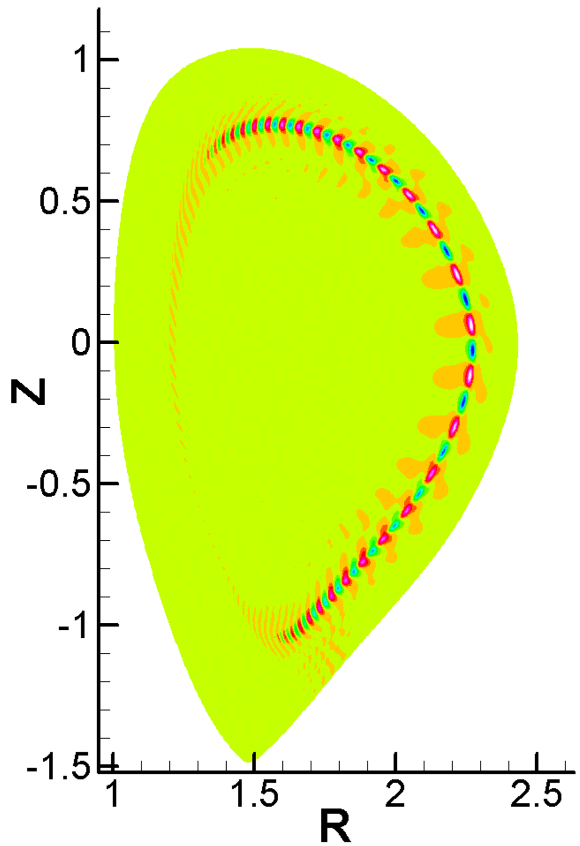
Comparison of resistive MHD and two-fluid growth-rate spectra computed with *D*=5 m^2/s. Mode frequency is not a simple Doppler shift.

- Ion flow has not been included in the steady-state component of our calculations. This implies an electrostatic potential profile such that $\mathbf{v}_\mathbf{E}$ and $\mathbf{v}_{\mathrm{di}}$ cancel.
- Nonetheless, the gyroviscous force contains similar terms ~ $\mathbf{v}_{di} \cdot \nabla \mathbf{V}$

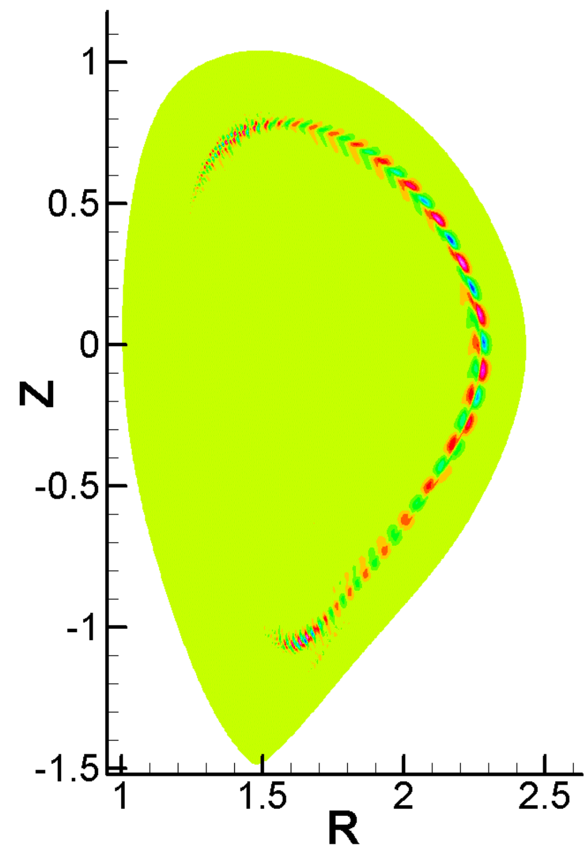
The diamagnetic drift profile is narrower than the low-n ELM eigenfunctions.



Poloidal component of diamagnetic drift.



Toroidal flow velocity from the n=21 MHD eigenmode.



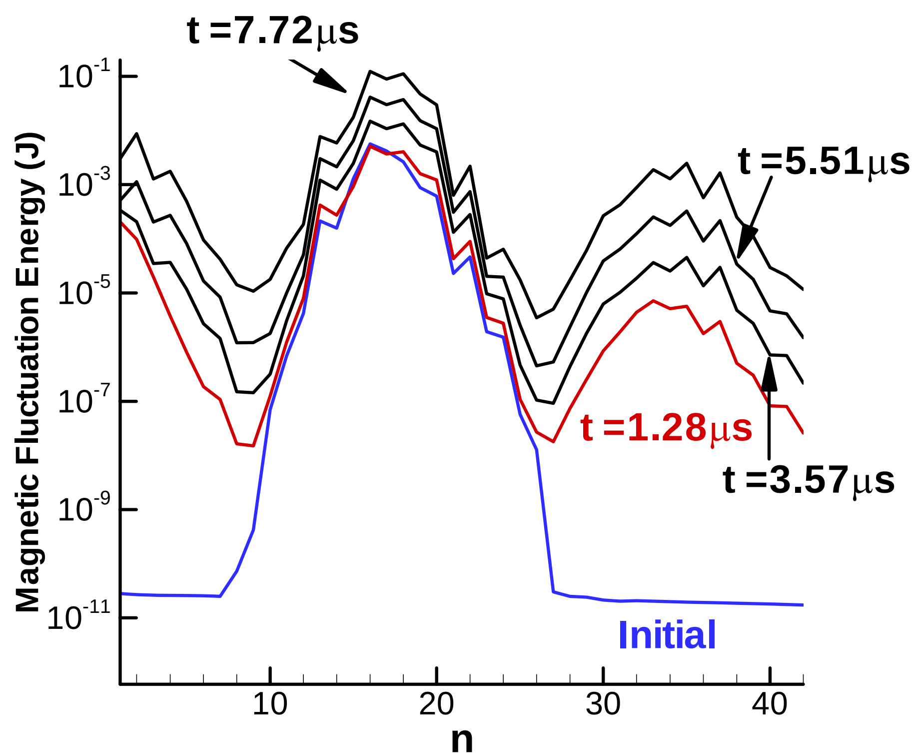
Toroidal flow velocity from the n=21 two-fluid eigenmode.

- Estimates based on Roberts-Taylor $\omega_{*i} = 2\gamma_{MHD}$ suggests stability to n ~$O(1)$.
- Hastie, Catto, and Ramos have shown that radial localization reduces the 2fl effect.

Nonlinear ELM Computation

Though poloidal resolution is marginal (growth rates only accurate to ~35%) with a 20×120 mesh of elements biquintic elements, memory and CPU limitations do not allow for larger computations at this time.

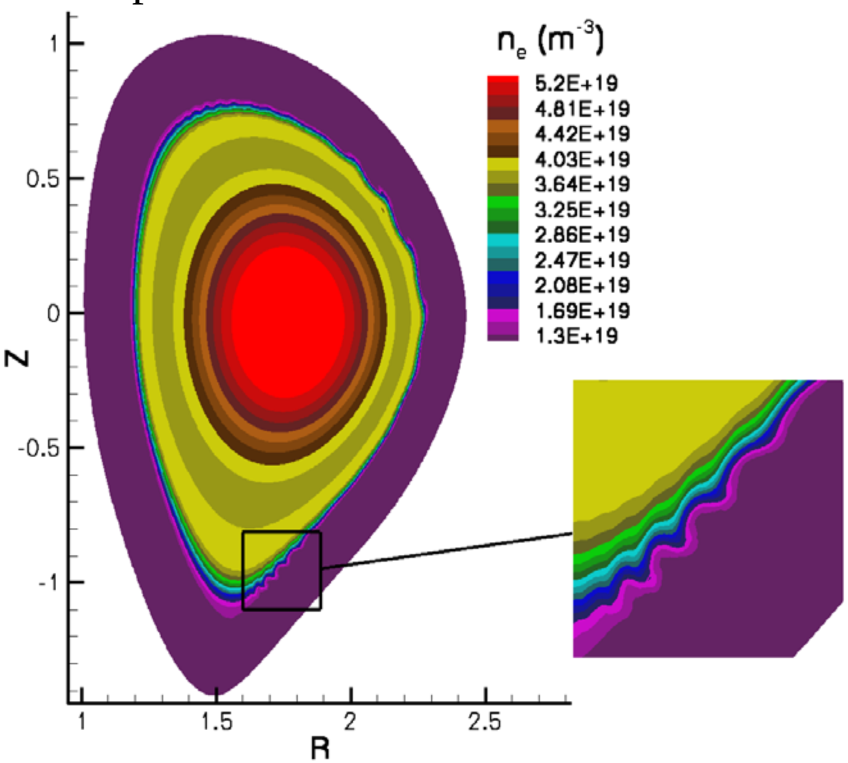
- Though increased by a factor of 100, the resistivity evolves with the local temperature ($\eta \sim T^{-3/2}$).
- The 3D evolving number density is used in all coefficients.
- Toroidal resolution of 0≤n≤42 satisfies the milestone requirement.
- The nonlinear computation is initiated with eigenmodes from the two-fluid spectrum calculation.
- High-n harmonics of the unstable band and an n=1 distortion are generated nonlinearly.



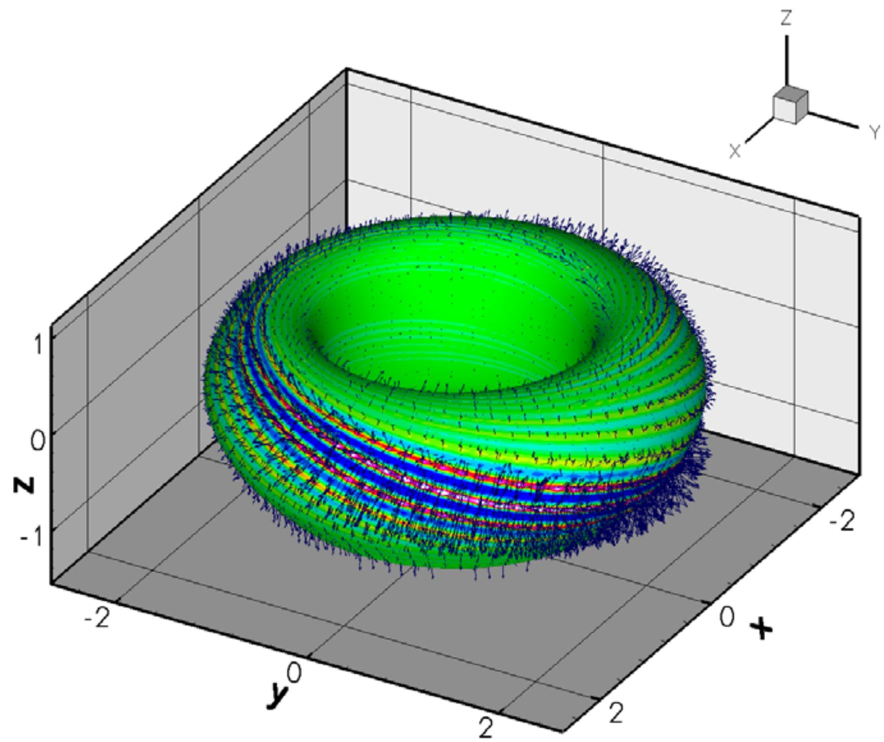
Evolution of the magnetic fluctuation energy spectrum.

Unlike our previous MHD results, the nonlinear two-fluid computation forms a helically localized structure.

- The broad range of unstable modes shows nearest-neighbor (in n-space) coupling of modes resonant at about the same *q*-value, which is 3 in this case.
- The low-n distortion and high-n harmonics appear to lock the unstable ELMs together--this point needs further verification.
- The results are similar to those reported by P. Snyder for reduced-Braginskii flux-tube computations.



Number density in the ϕ=0 plane at *t*=7.92 μs shows three groups of ripples.



Temperature perturbations reach 100 eV at *t*=7.72 μs (T_{ped}=400 eV). Perturbed plasma flow vectors are superposed.

Computation-Oriented Discussion

- There are successes in this application of NIMROD:
  - Code's first large, three-dimensional two-fluid computation
  - Use of new gyroviscous capabilities
  - Completion within the milestone deadline
- There is room for improvement:
  - Poloidal and toroidal resolution are marginal.
    - The next harmonic bands may lead to further shaping.
  - Toroidal coupling must be added to the preconditioning operation.
    - Solves have algebraic vectors as large as 7.5×10^{6} complex elements
    - GMRES orthogonalizes iterates--large iteration counts are costly
    - Time-step was severely limited just to improve condition numbers
  - The distributed-memory interface to the SuperLU library will reduce memory requirements.
  - Modifying some aspects of the basis functions may improve resolution of high-wavenumber modes, as noted earlier.
- This exercise motivates 'peta-scale' computing and provides an indication of what is needed. (Besides above, parallel i/o and high-performance graphics.)

Conclusions

- Physics:
  - Global computations have obtained two-fluid stabilization at high-n via gyroviscous stress.
  - Radial localization of the drift flow profile in DIII-D equilibria has a large influence on two-fluid stabilization.
  - Nonlinear interaction of ELMs generates high- and low-n perturbations of the same helicity.
  - A helically localized structure emerges as the perturbations approach $O(1)$ amplitude.
- Computation:
  - NIMROD needs further work on preconditioning and spatial representation.
  - We need to prepare for peta-scale computing.
- Programmatic:
  - The NIMROD Team has met the theoretical performance targets for OFES for the past two years.