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M3D-C^1 simulations of plasma response to external 3D magnetic perturbations & Plans for DK4D

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Meeting of the Center for Extended MHD Modeling

Madison, WI

Sunday, April 3rd, 2016

Introduction

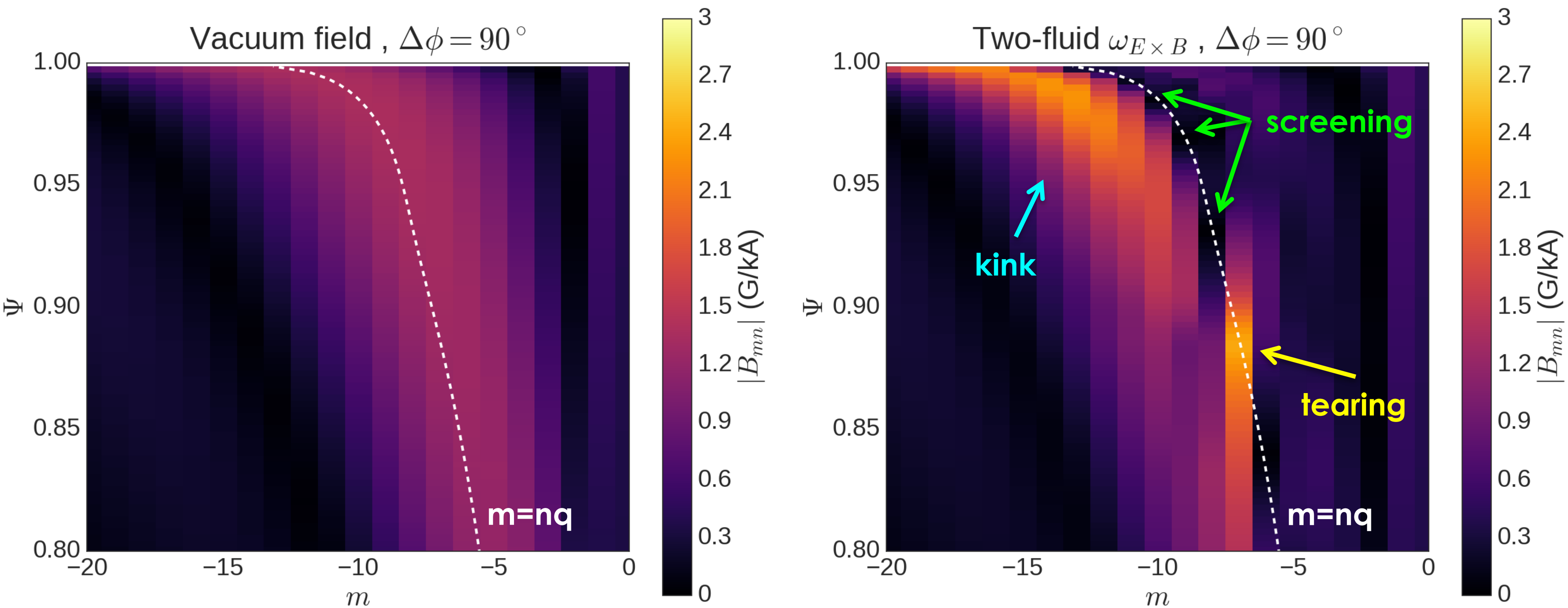
- **External three-dimensional magnetic perturbations have become a principal means of mitigating or suppressing edge-localized modes (ELMs) in tokamaks**
- **Sophisticated magnetohydrodynamics (MHD) modeling is required to understand how the plasma responds to these perturbations**
- **M3D-C^1 is used to model the plasma response in a variety of plasma and magnetic perturbation configurations**
- **Results compared to**
  - Experimental data and observations
  - Numerical results from IPEC and MARS-F

ELMs can be mitigated or suppressed by external 3D magnetic fields

- **DIII-D has demonstrated complete suppression of ELMs using externally-applied 3D magnetic perturbations**
  - Evans, T.E. et al. Nat. Phys. **2**, 419 (2006).
  - Among others
- **Results motivated installation of coils on several machines**
  - ASDEX Upgrade
  - KSTAR
  - MAST
  - NSTX-U
  - ITER (planned)

Plasma response can greatly alter perturbed magnetic spectrum

- **SURFMN-like field decomposition** $\delta B_r(\psi) = \sum_{m,n} B_{mn}(\psi) \exp\left[i\left(m\theta - n\phi\right)\right]$
- **Resonant response at rational surfaces (m=nq)**
  - Tearing enhances
  - Screening suppresses
- **Kink response amplifies non-resonant fields with m>nq**



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M3D-C1 allows for extended MHD simulations of the plasma response to applied 3D fields

- **M3D-C1 [1] is a sophisticated extended MHD code**
  - Fully three-dimensional
  - Two-fluid
  - Linear and nonlinear modes
  - EFIT Grad-Shafranov equilibrium recomputed on adaptive mesh with high-order finite element representation
- **Plasma response calculations**
  - Linear (single toroidal mode number)
  - Mostly time-independent, but some time-dependent
  - Single- and two-fluid
    - Single-fluid presented here
  - Experimental kinetic & rotation profiles
    - Extended beyond separatrix
  - Resistive wall model

[1] S. C. Jardin, et al., Comput. Sci. Discovery 5, 014002 (2012).

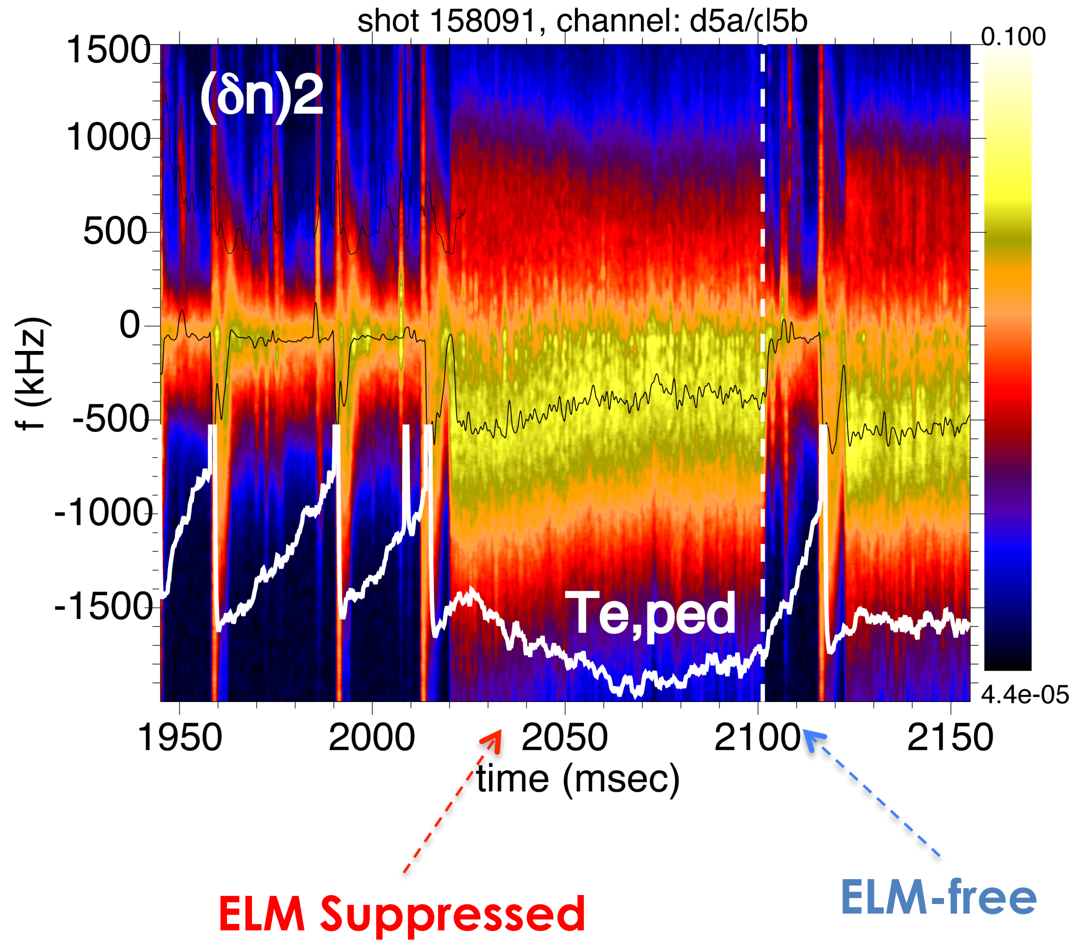
M3D-C1 is being used for many 3D field applications

- **Plasma response calculations for a variety of devices**
  - DIII-D
  - ASDEX Upgrade
  - KSTAR
  - NSTX-U
- **At General Atomics**
  - Multimode response (C. Paz-Soldan, S.R. Haskey, N.C. Logan)
    - Cross-code verification with IPEC and MARS-F
    - Experimental validation in various plasma conditions
  - Field line tracing with TRIP3D (W. Wu, T.E. Evans, D.M. Orlov)
  - Divertor footprint analysis with MAFOT (A. Wingen)
  - Impact of multiple toroidal mode numbers and sidebands with PROBE_G fields (D.M. Orlov)
  - Bifurcation dynamics (R. Nazikian, A. Wingen)
    - Island penetration time
    - HFS phase shift

ELM suppression bifurcation dynamics

Bifurcation observed in fluctuations at top of pedestal prior to significant change in pedestal pressure

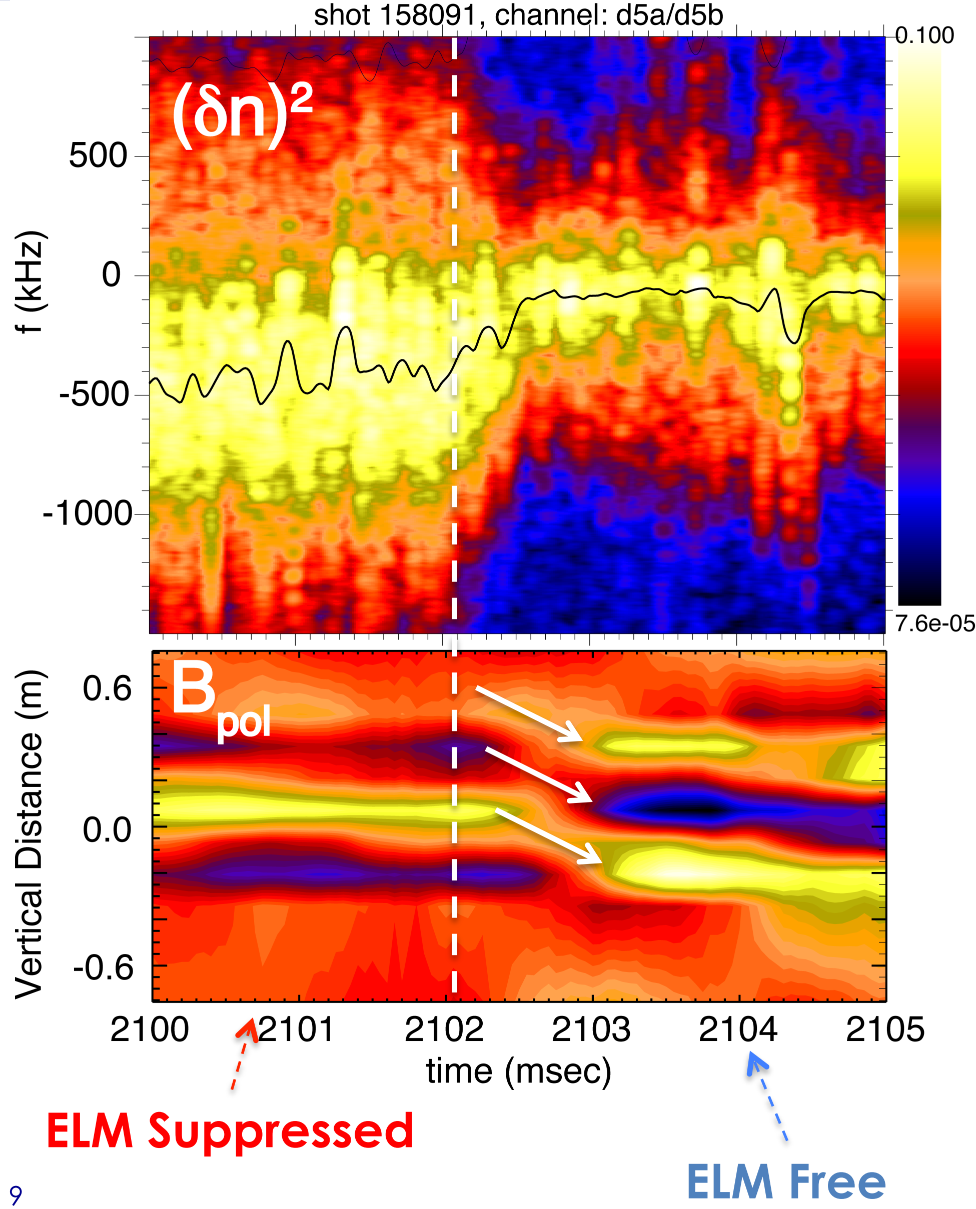
- **Doppler backscatter at top of pedestal reveals**
  - Increased fluctuations during ELM suppression
  - Abrupt rotation shift during transition from suppressed to ELM-free
- **Slow temperature (equilibrium) variation compared to bifurcation timescale**



Based on R. Nazikian, MHD Stability Control Workshop, 11/2015

Detailed analysis reveals HFS magnetic phase shift prior to significant change in pedestal pressure/equilibrium

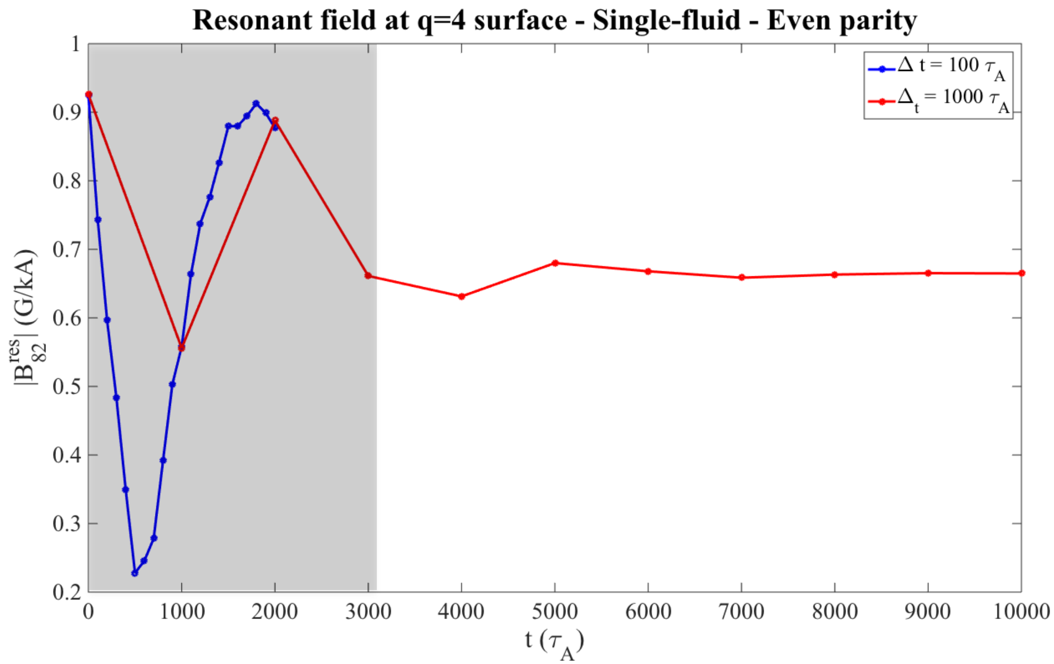
- **Bifurcation and rotation profile evolution occur on millisecond timescale**
- **Phase shift observed on high-field side magnetics on same timescale**
- **Delay on magnetics possibly due to time required for island penetration**



Based on R. Nazikian, MHD Stability Control Workshop, 11/2015

M3D-C1 equilibration time of resonant field consistent with timescale of bifurcation dynamics

- **Linear, time-dependent calculations performed with M3D-C1**
- **Initial condition is fully-penetrated, 3D vacuum field**
- **Resonant field equilibrates after thousands of Alfven times**
  - Island is partially screened over ~2 milliseconds
  - Roughly consistent with experimental observations
  - Nonlinear simulations of resonant penetration are planned



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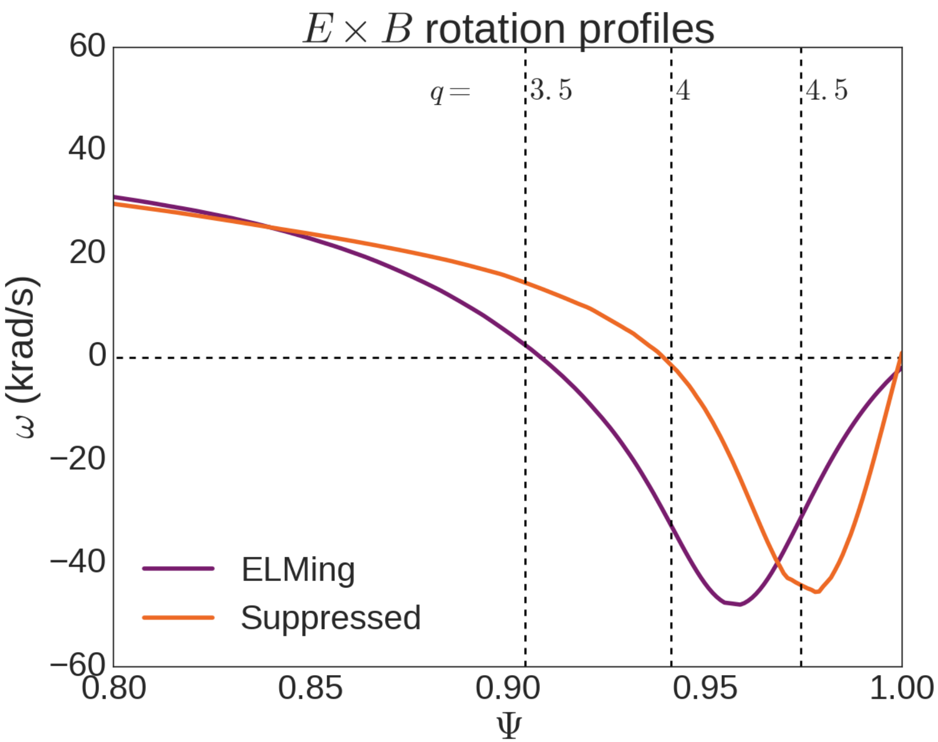
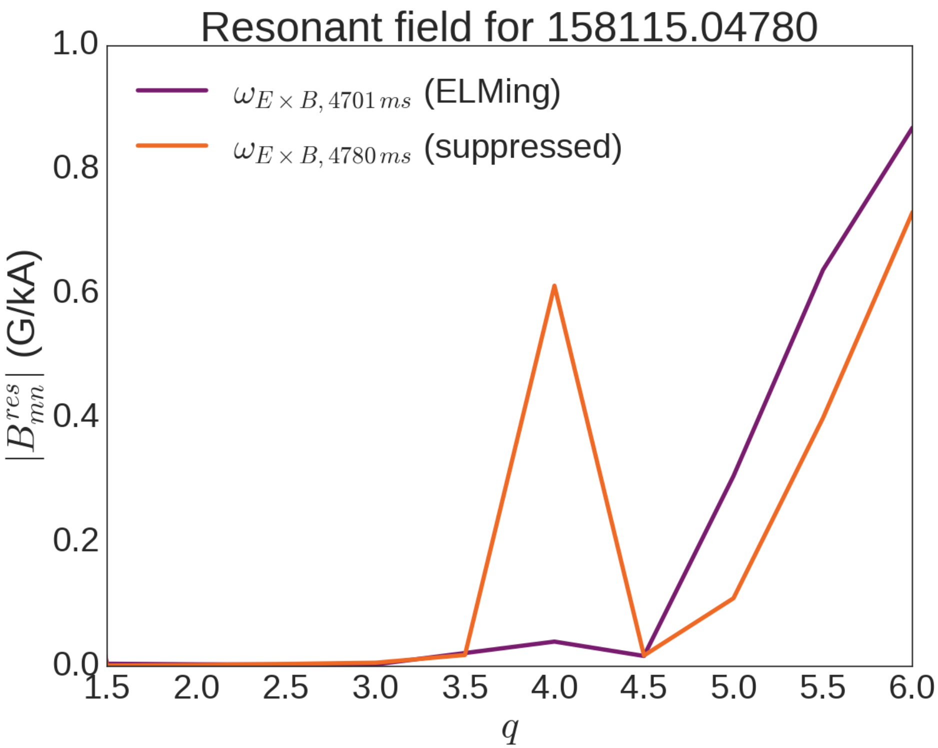
Resonant penetration permitted by zero in ExB rotation profile at q=4 surface

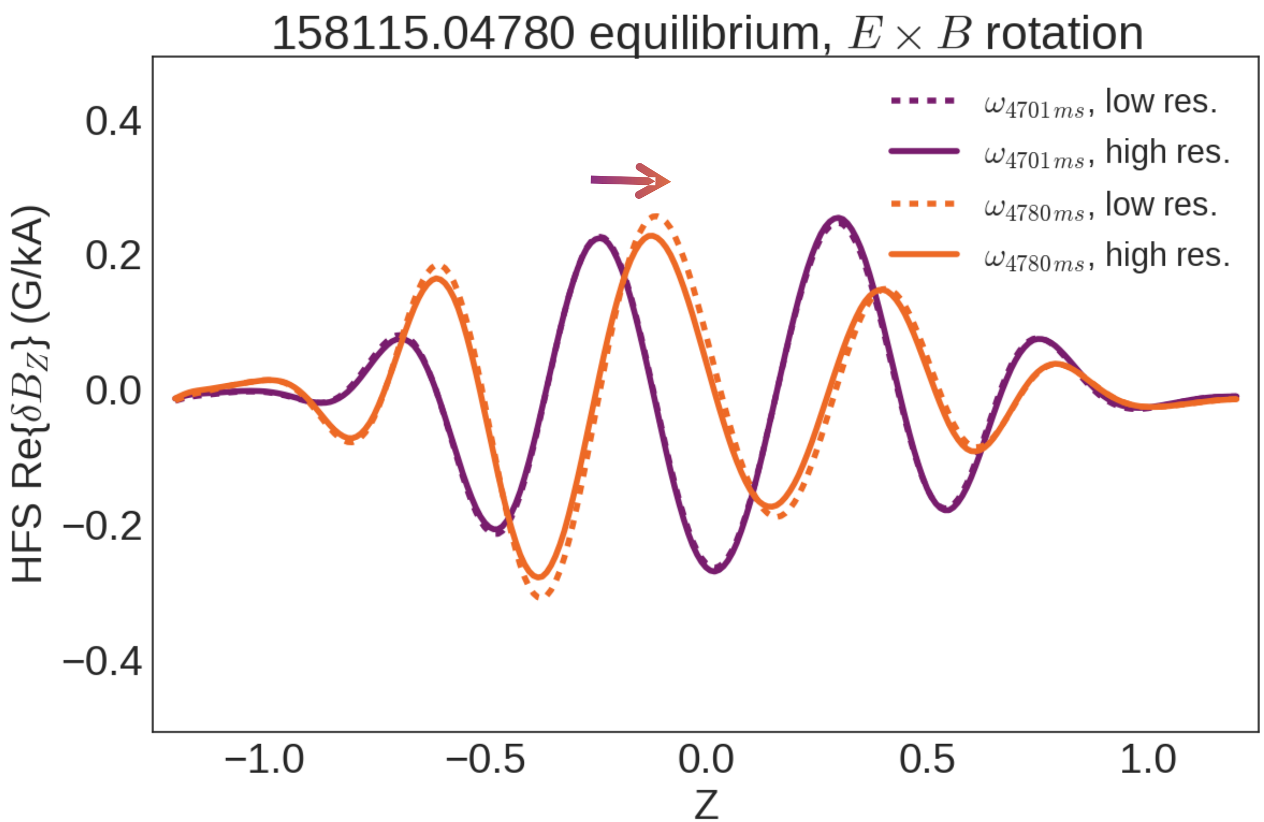
- Fix equilibrium, as largely unchanged across bifurcation
- Rotation profile varied as this changes on bifurcation time scale
- Resonant field at q=4 greatly amplified with ELM-suppressed rotation profile





M3D-C1 simulations of screened versus penetrated states reveal phase shift on HFS wall

- **Phase shift also seen in divertor footprint calculations with MAFOT**
- **Qualitative agreement between M3D-C1, MARS-F, and data**
- **Ongoing verification and validation effort**



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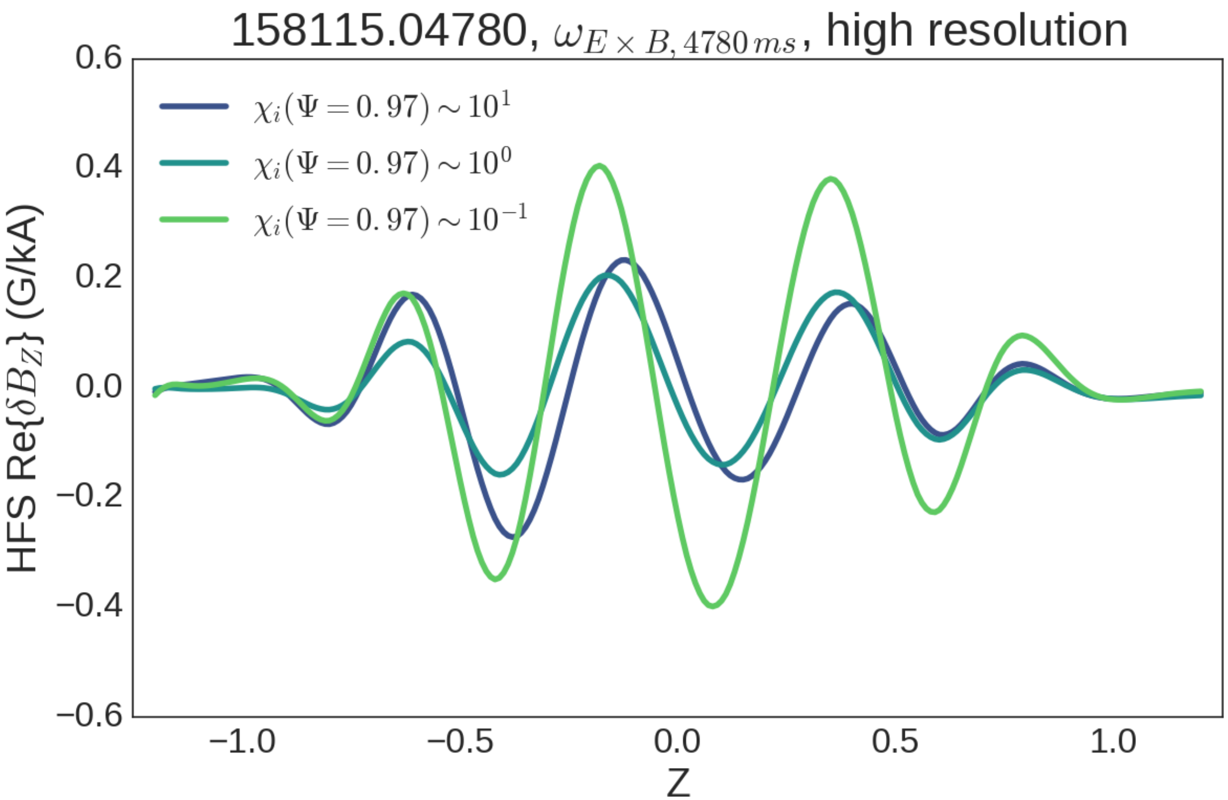
Dissipation levels may be important for plasma response calculations

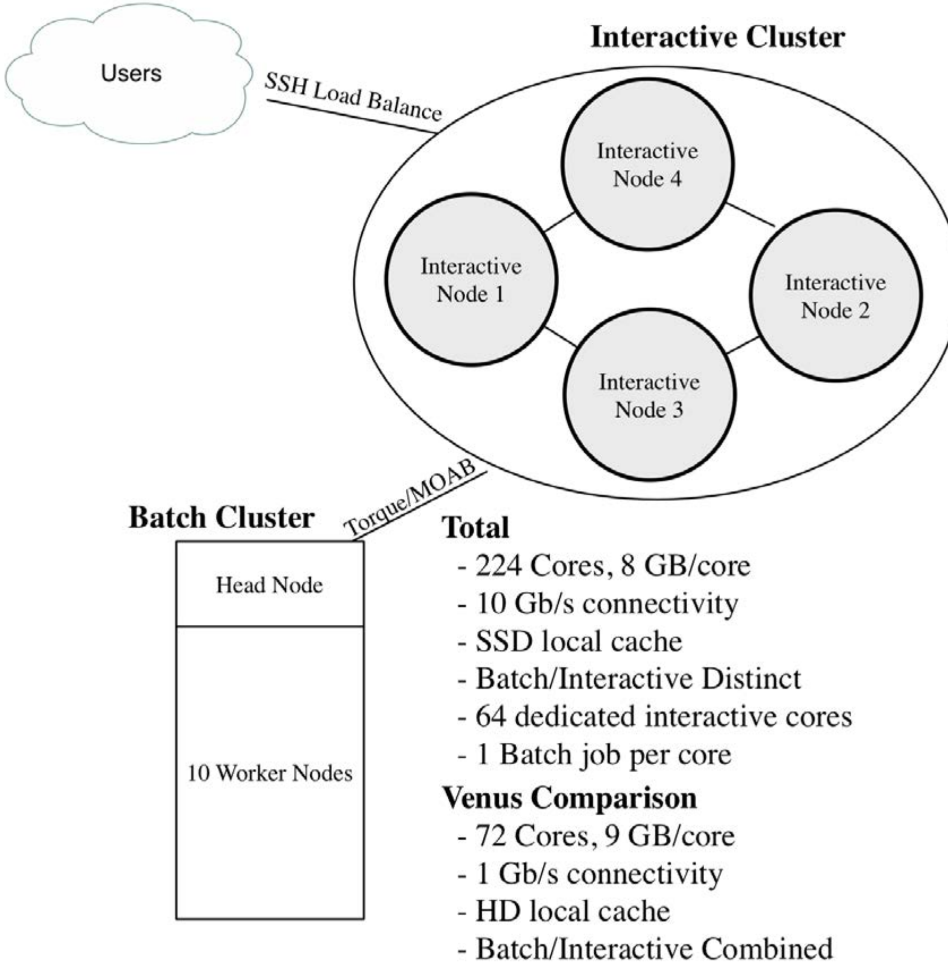
- Varying viscosity (along with density diffusivity and thermal conductivity) can change phase and amplitude of response
- Still verifying numerical convergence
- For validation, may be important to match experimental dissipation



New ways to run M3D-C^1

M3D-C¹ runs on GA cluster and with automated script

- **M3D-C¹ has been installed and tested on Iris, the new cluster that will become the base for computing at GA**
- **A new Python script has been developed to run linear M3D-C¹**
  - Routine parameters and templates
  - Works on GA and PPPL clusters
  - Allows for straightforward analysis of new kinetic EFITs (g-, p-, and a-files)



Iris cluster. D.P. Schissel.
GA Friday Science Meeting. 1/29/16

New script allows for simple running of linear M3D-C^1

- **Tasks that can be run with script**
  - Preprocess kinetic EFIT files into M3D-C^1 readable formats
    - Includes extending density & temperature profiles beyond separatix
  - View EFIT equilibrium within M3D-C^1
  - Recompute equilibrium on uniform finite element mesh
    - Can iterate on this step for better equilibrium matching
  - Adapt finite element mesh to equilibrium
  - Compute equilibrium on adapted mesh
  - Compute linear stability for arbitrary toroidal mode number
  - Compute linear, time-independent response to external 3D magnetic perturbations for arbitrary toroidal mode number
- **Currently used to provide quick turnaround for experimental analysis**
- **Available on GitHub: https://github.com/bclyons12/autoC1**
- **Default parameters, of course, don't always work, so some expertise required**

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Plans for DK4D

DK4D[1] is a time-dependent, axisymmetric drift-kinetic equation (DKE) solver

- **Developed for purpose of extended MHD coupling**
- **Solves ion and electron DKEs for non-Maxwellian part of distribution function**
- **Uses linearized Fokker-Planck-Landau collision operators**
- **Chapman-Enskog-like formulation ensures self-consistency with extended MHD equations**
- **Encouraging initial results**
  - Benchmarked to Sauter model, along with NIMROD, NCLASS, and NEO codes[2]
  - Coupling to reduced MHD code has produced self-consistent simulations of dynamic bootstrap current formation[3]

[1]B.C. Lyons, S.C. Jardin, & J.J. Ramos. Phys. Plasmas 22, 056103 (2015).
[2]E.D. Held et al. Phys. Plasmas 22, 032511 (2015).
[3]B.C. Lyons. Doctoral dissertation. Princeton University 2014.

Coupling M3D-C¹ & DK4D would permit realistic transport-timescale simulations

- **M3D-C¹ can calculate steady-state, axisymmetric equilibria**
  - Sources included in two-fluid MHD equations (e.g., particle source)
  - Transport model assumed (Spitzer resistivity, Braginskii pressure tensor)
  - Evolve to steady-state to predict axisymmetric equilibria (e.g. NSTX[1])
- **DK4D could be used to provide neoclassical transport model**
  - Friction force and pressure anisotropy close momentum equations
  - Parallel heat flux closes temperature equation (if needed)
    - Instability with heat flux term in DKE may complicate this
  - Self-consistent neoclassical resistivity and bootstrap current would develop
- **Would require code development on both ends**
  - DK4D
    - Read M3D-C¹ equilibria (easy; already done for related NIES code)
    - Fix or find workaround for heat flux instability
  - M3D-C¹
    - Add new closure terms based on moments of drift-kinetic solution
    - Possibly generate equilibrium in flux coordinates without post-processing
  - May require more tightly-coupled implementation for efficiency

[1]Ferraro, N.M. and S.C. Jardin. *J. Comput. Phys.* 228 (2009) 7742–7770.

Modifications to DK4D would allow linear stability analysis of resistive wall modes

- **New coupled drift-kinetic MHD formulation derived by Ramos**
  - Chapman-Enskog-like for self-consistency
  - Fokker-Planck-Landau collisions

  } As in DK4D
  - Rotation of order the sound speed
  - Two-fluid effects
  - Zero-Larmor-radius limit

  } New to model
- **Linearized about an axisymmetric, single-fluid, collisionless equilibrium with Maxwellian distribution function**
- **Linear solution evolves time-dependently**
  - n=0 perturbation which corrects assumed equilibrium
  - Single toroidal harmonic for stability analysis
- **Structure of DKE is very similar to that used in DK4D, which should allow for relatively straight-forward implementation**
- **Can be coupled to M3D-C^1 to study kinetic stabilization of resistive wall modes**

New DKE is very similar to the one already implemented in DK4D

DK4D

$$\frac{\partial \bar{f}_{NMs}}{\partial t} + wy\mathbf{b}\cdot\nabla\bar{f}_{NMs} - \frac{1}{2}w\left(1-y^2\right)\mathbf{b}\cdot\nabla\ln B\frac{\partial \bar{f}_{NMs}}{\partial y} = \left\langle C_{ss} + C_{ss'}\right\rangle_\alpha$$

$$+\left\{\frac{wy}{nT_s}\left[\frac{2}{3}\mathbf{b}\cdot\nabla\left(p_{s\|} - p_{s\perp}\right) - \left(p_{s\|} - p_{s\perp}\right)\mathbf{b}\cdot\nabla\ln B - \mathbf{b}\cdot\mathbf{F}_s^{coll}\right]\right.$$

$$+P_2(y)\frac{w^2}{3v_{ths}^2}\left(\nabla\cdot\mathbf{u}_s - 3\mathbf{b}\cdot\left[\mathbf{b}\cdot\nabla\mathbf{u}_s\right]\right) + \frac{1}{3nT_s}\left(\frac{w^2}{v_{ths}^2} - 3\right)\nabla\cdot\left(q_{s\|}\mathbf{b}\right)$$

$$\left.-\frac{\varsigma\left(e_s\right)I}{3m_s\Omega_s}\left[\frac{1}{2}P_2(y)\frac{w^2}{v_{ths}^2}\left(\frac{w^2}{v_{ths}^2} - 5\right) + \frac{w^4}{v_{ths}^4} - 10\frac{w^2}{v_{ths}^2} + 15\right]\mathbf{b}\cdot\nabla\ln B\frac{dT_s}{d\psi}\right\} f_{Ms}$$

New

$$\frac{\partial \bar{f}_{s1}}{\partial t} + \left(\mathbf{u}_0 + w_\| \, \mathbf{b}_0\right)\cdot\frac{\partial \bar{f}_{s1}}{\partial \mathbf{x}} + \frac{\mathbf{b}_0}{m_s}\cdot\left(T_{s0}\nabla\ln n_0 + e_s\eta_{cl0}\,\mathbf{j}_0\right)\frac{\partial \bar{f}_{s1}}{\partial w_\|} + \frac{w_\perp}{2}\left(\mathbf{b}_0\cdot\nabla\ln B_0\right)\left(w_\|\frac{\partial \bar{f}_{s1}}{\partial w_\perp} - w_\perp\frac{\partial \bar{f}_{s1}}{\partial w_\|}\right) =$$

$$= \left\{-\left[\mathbf{u}_{s1} + \frac{n_1}{n_0}\,w_\|\,\mathbf{b}_0\right]\cdot\nabla\ln n_0 + \left[\left(\frac{3}{2} - \frac{m_s w^2}{2T_{s0}}\right)\mathbf{u}_{s1} + \left(\frac{5}{2} - \frac{m_s w^2}{2T_{s0}}\right)\frac{w_\|}{B_0}\,\mathbf{B}_1\right]\cdot\nabla\ln T_{s0} + \right.$$

$$+\frac{w_\|}{n_0 T_{s0}}\,\mathbf{b}_0\cdot\left[\nabla p_{s\|1} - \left(p_{s\|1} - p_{s\perp1}\right)\nabla\ln B_0 + e_s(n_0 - n_1)\eta_{cl0}\,\mathbf{j}_0 - \mathbf{F}_{s1}^{coll}\right] + \frac{e_s\eta_{cl0}w_\|}{B_0 T_{s0}}\left(\mathbf{B}_1 - B_1\mathbf{b}_0\right)\cdot\mathbf{j}_0 -$$

$$\left.-\frac{m_s}{2T_{s0}}\left[w_\perp^2\nabla\cdot\mathbf{u}_{s1} + \left(2w_\|^2 - w_\perp^2\right)\left(\mathbf{b}_0\mathbf{b}_0\right):\left(\nabla\mathbf{u}_{s1}\right) + \left(\frac{2w_\|^2 - w_\perp^2}{B_0}\right)\left(\mathbf{b}_0\mathbf{B}_1 + \mathbf{B}_1\mathbf{b}_0\right):\left(\nabla\mathbf{u}_{s0}\right)\right]\right\} f_{Ms0} +$$

$$+\sum_{s'}\left(C_{ss'}[f_{Ms0}, f_{Ms'0}] + C_{ss'}[f_{Ms0}, \bar{f}_{s'1}] + C_{ss'}[\bar{f}_{s1}, f_{Ms'0}]\right)$$

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Proposed plan of implementation

- **Expand DKE in DK4D variables/representations (in progress)**
- **Modify DK4D implementation**
  - Change to complex variables for linear stability analysis ($e^{in\phi}$)
  - **Ax**=**B** system
    - **A** will require some modification, but much can be reused
    - **B** will be redone completely for new source terms
- **Couple to M3D-C[1]**
  - Procedure may be similar to transport-timescale simulations
  - Fast evolution of instability could introduce new complications
- **Codes will likely need to be compiled together and run simultaneously**
  - Both codes would be linear
  - Reuse matrices and LU decompositions for maximum efficiency

Summary

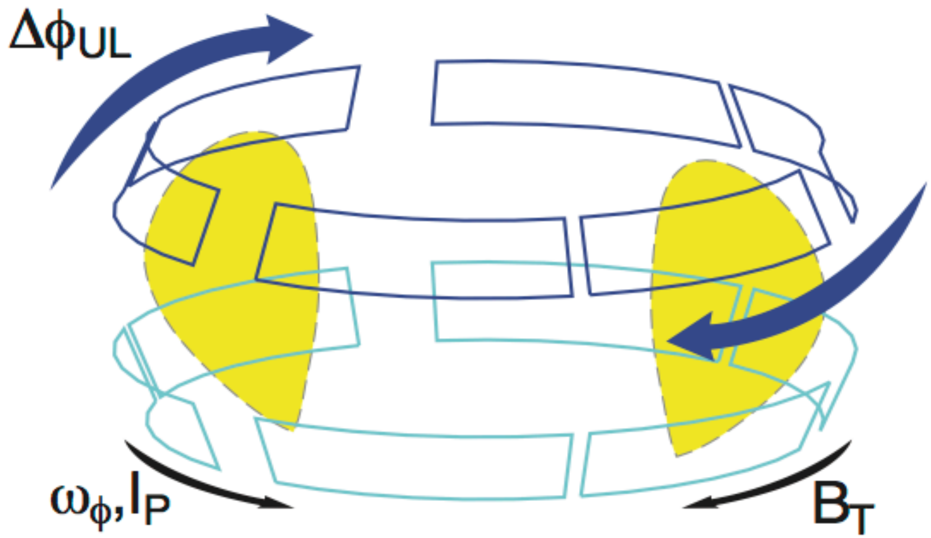
- **M3D-C[1] is used to calculate the linear, plasma response to external 3D magnetic perturbations**
- **ELM suppression bifurcation dynamics**
  - DIII-D experiments reveal bifurcation in and out of ELM suppression with quickly evolving rotation profiles and magnetic signals
  - M3D-C[1] reveals island equilibration timescale and magnetic phase shift roughly consistent observed magnetic signal changes
  - Initial results seem sensitive to dissipation levels
- **M3D-C[1] can now be run on Iris cluster at GA**
- **Automated python script written to facilitate new plasma response calculations**
- **Possible future work on DK4D**
  - Transport-timescale axisymmetric coupling to M3D-C[1]
  - Solve new DKE for kinetic-MHD stability calculations

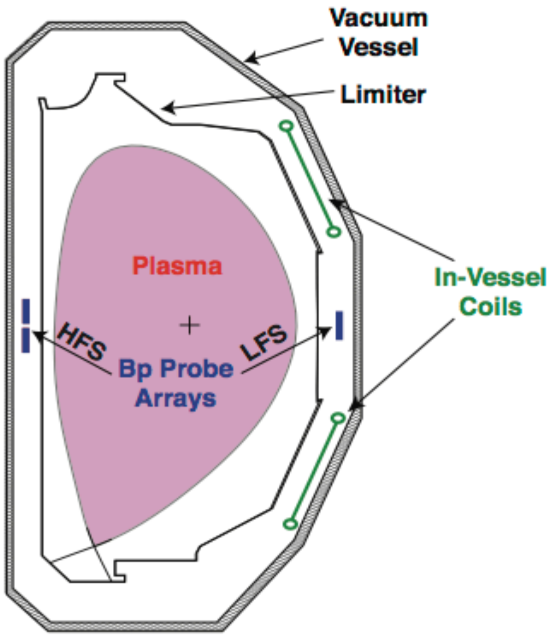
Additional Slides

DIII-D Reference Equilibrium

158103.03796

External field coils on DIII-D

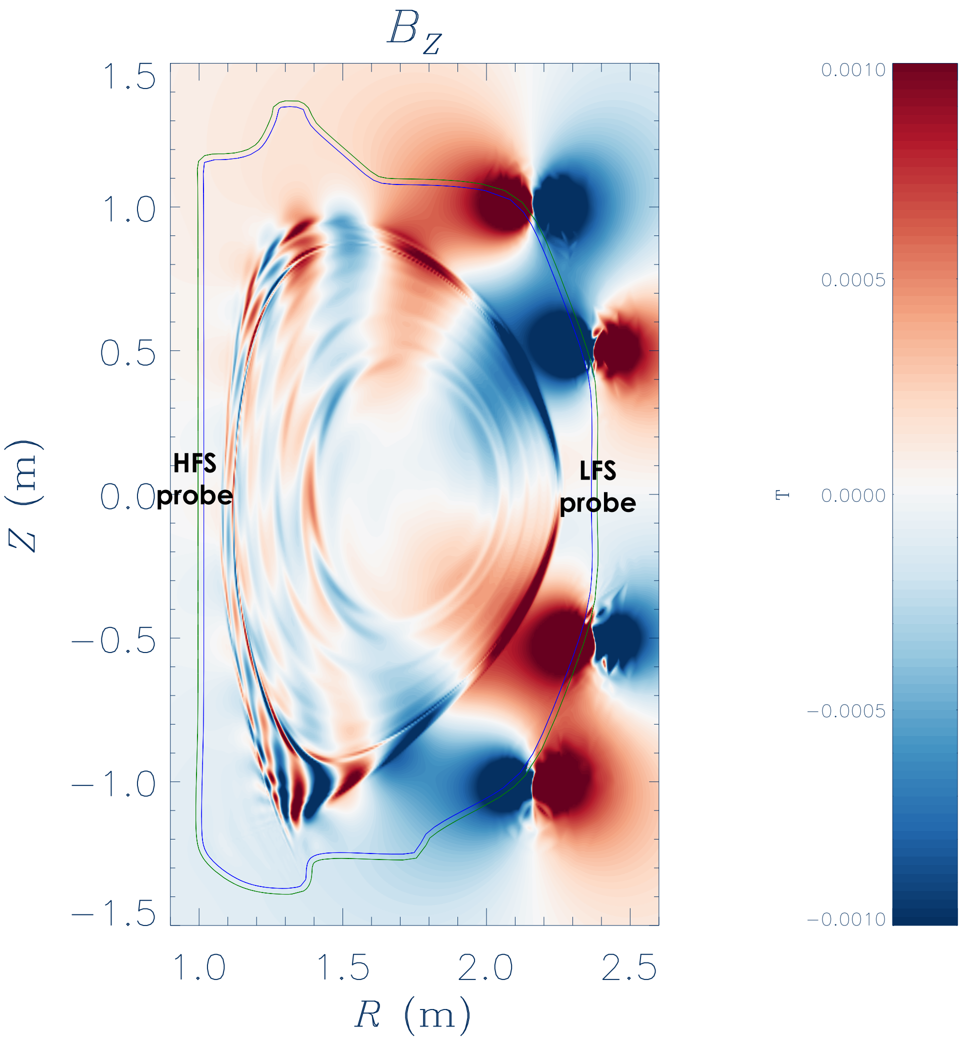




- **Three rows of six saddle coils**
  - Two in-vessel rows (I-coils)
  - One external row (C-coils, not pictured)
  - Toroidal mode number of perturbations up to n=3
- **For n=2 fields, phasing $\Delta\phi_{UL} = \phi_{up} - \phi_{low}$ can be varied between upper and lower coils sets**

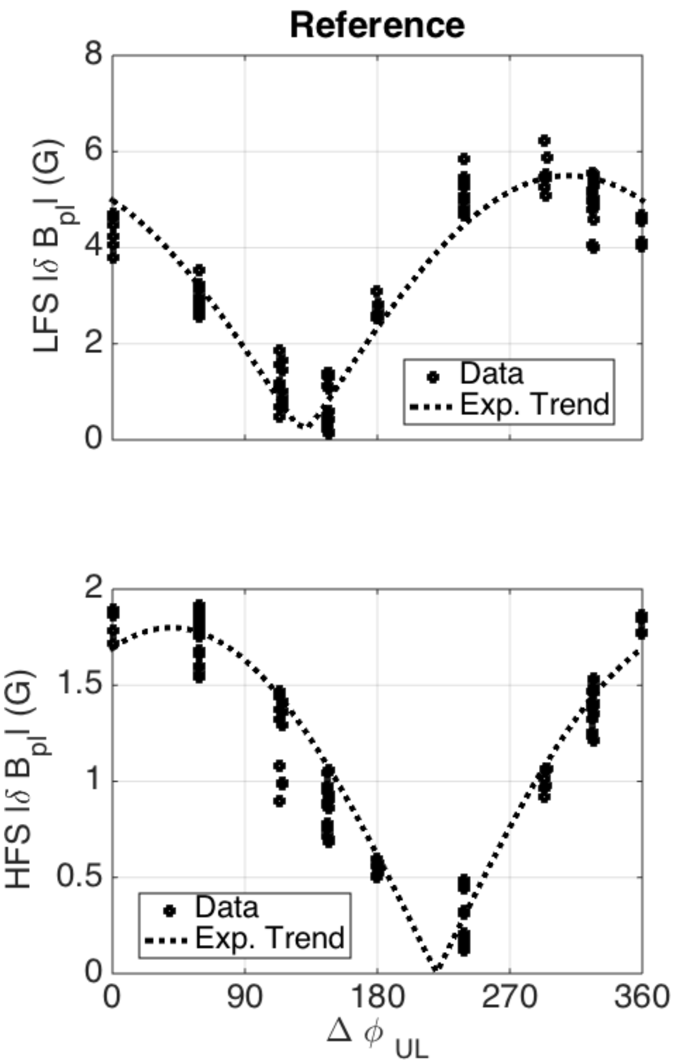
Reference is ITER-similar shape, lower single null plasma

- **Reference equilibrium (shot 158103 at 3796 ms) has**
  - $B_T = 1.93$ T and $I_P = 1.36$ MA
  - $\beta_N = 2.2$
  - $\nu_{e*} = 0.3$
  - $q_{95} = 4.15$
- **n=2 external 3D field applied with I-coils**
  - Phasing between upper and lower coil changed in piecewise fashion
  - Phase of both coils flipped throughout shot for nonaxisymmetric diagnostic purposes



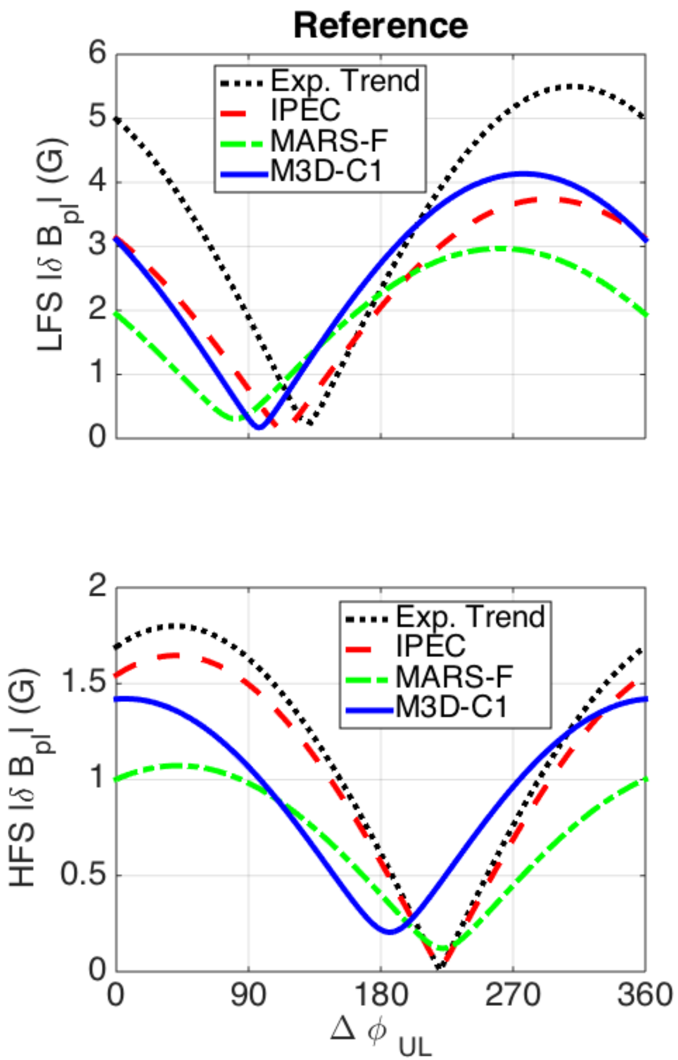
LFS and HFS magnetic response measurements show multimode response on DIII-D

- **These plots show**
  - Magnitude of perturbed magnetic field as the phasing is varied
  - Signal at low-field side (LFS) and high-field side (HFS) probes
  - Field from plasma response only
  - Null occurring where response from upper and lower coils cancels
- **Signals at LFS and HFS have different phasing dependences**
- **Indicates multiple modes are being driven simultaneously in DIII-D with n=2 fields**
- **For more detail, see C. Paz-Soldan et al., PRL 114, 105001 (2015)**



Modeling of reference shows excellent agreement between experimental data and various codes

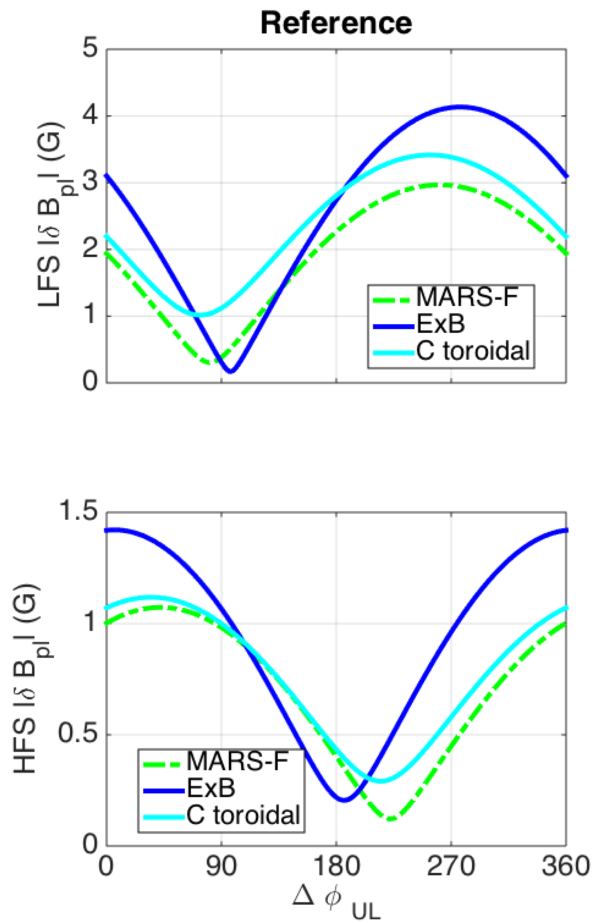
- **IPEC[1] uses an ideal MHD model**
  - No rotation
  - Perfect screening at rational surfaces
- **MARS-F[2] uses a single-fluid, resistive MHD model**
  - Simulations performed with carbon toroidal rotation profile
  - Resistivity allows for tearing or imperfect screening
- **Here, M3D-C[1] use single-fluid model with ExB rotation profile**



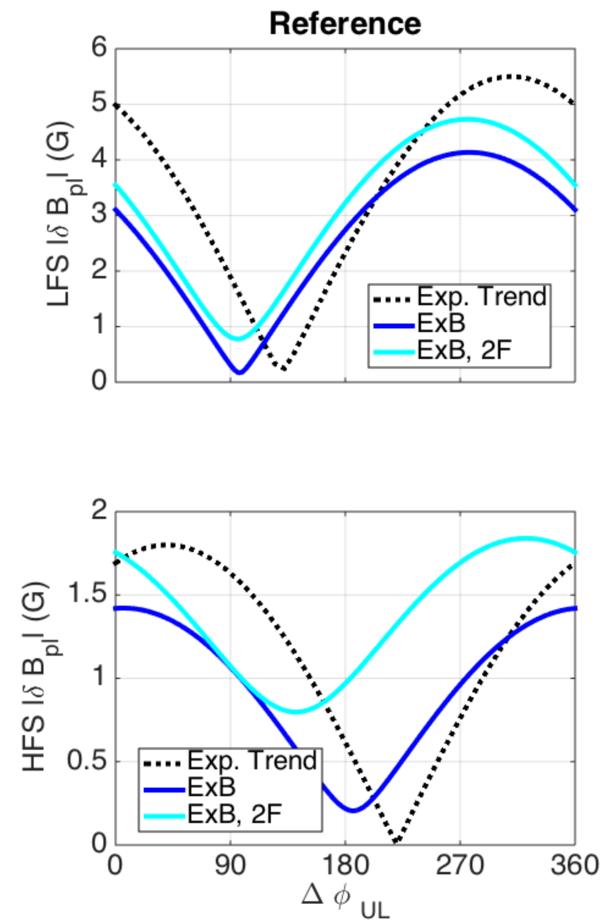
[1] J.-K. Park, A.H. Boozer, and A.H. Glasser, Phys. Plasmas 14, 052110 (2007).
[2] Y. Q. Liu, et al., Phys. Plasmas 7, 3681 (2000).

M3D-C[1] results sensitive to changes in non-ideal effects

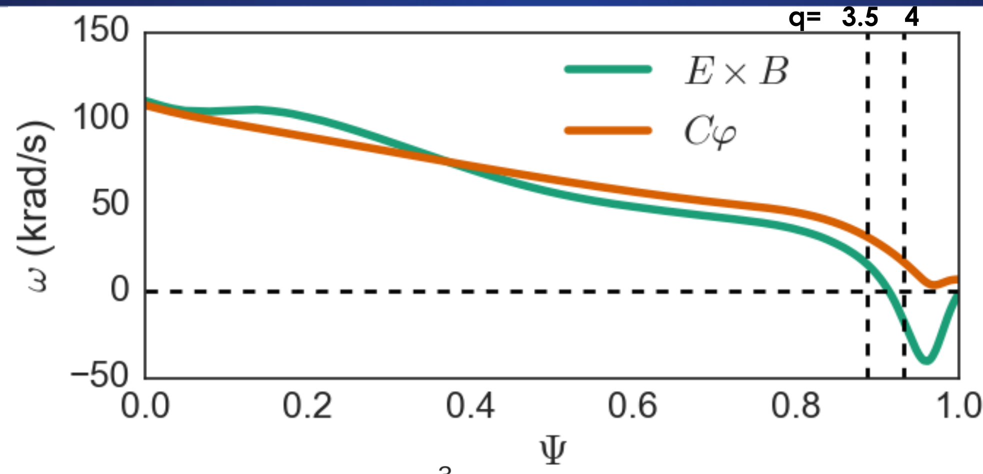
Difference from MARS-F largely due to rotation profile choice

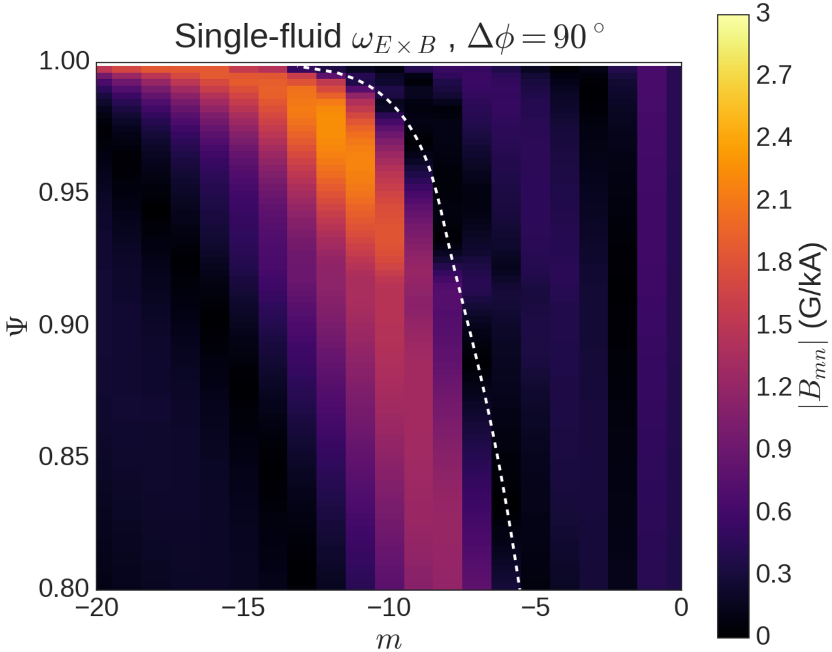


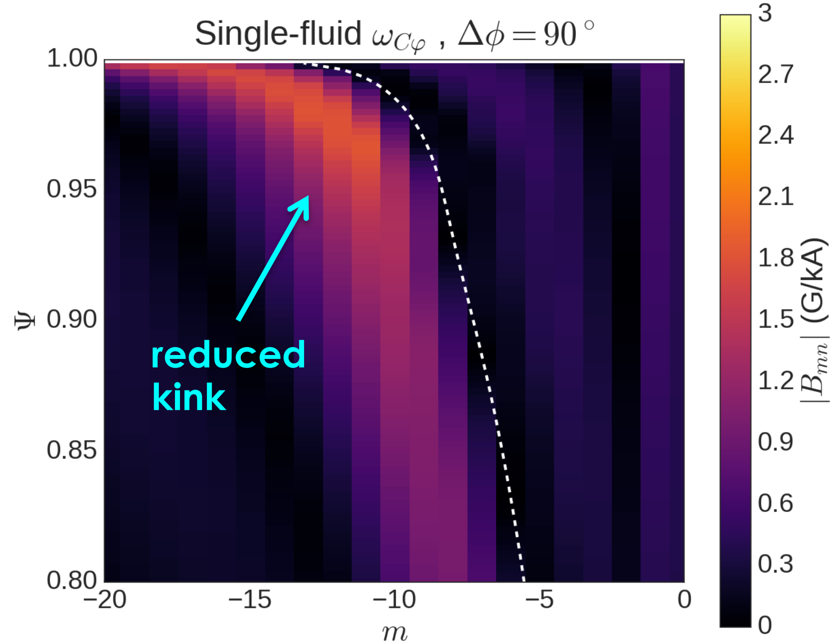
Including two-fluid terms gives poorer agreement with data



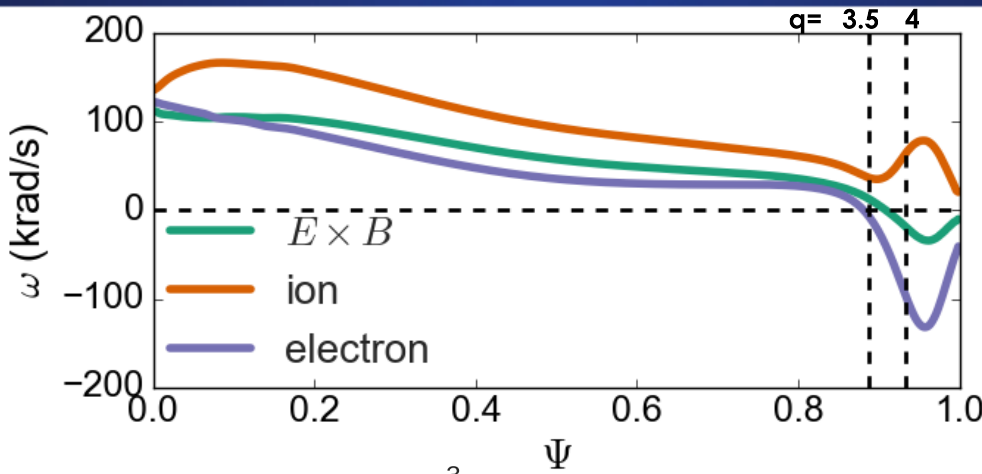
Carbon toroidal rotation results in reduced kink response

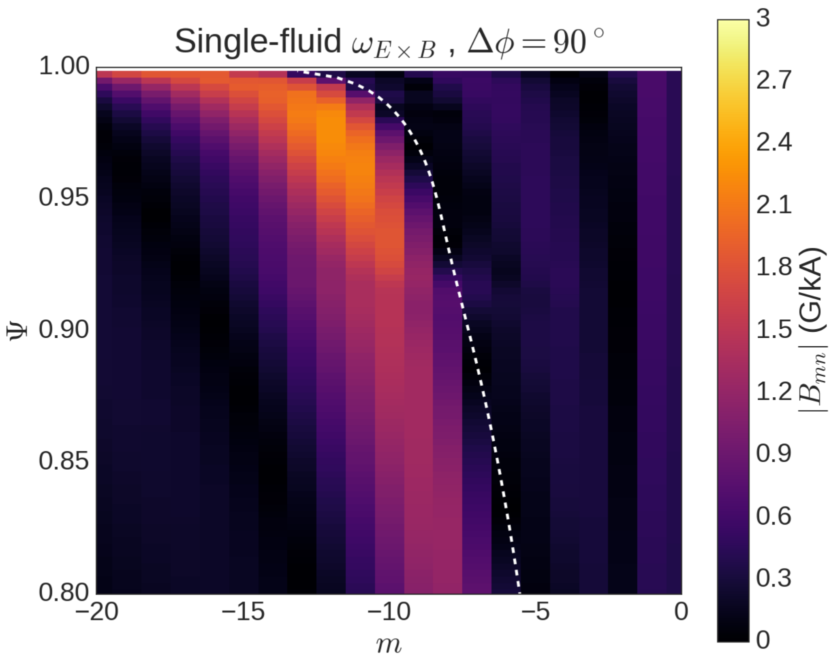


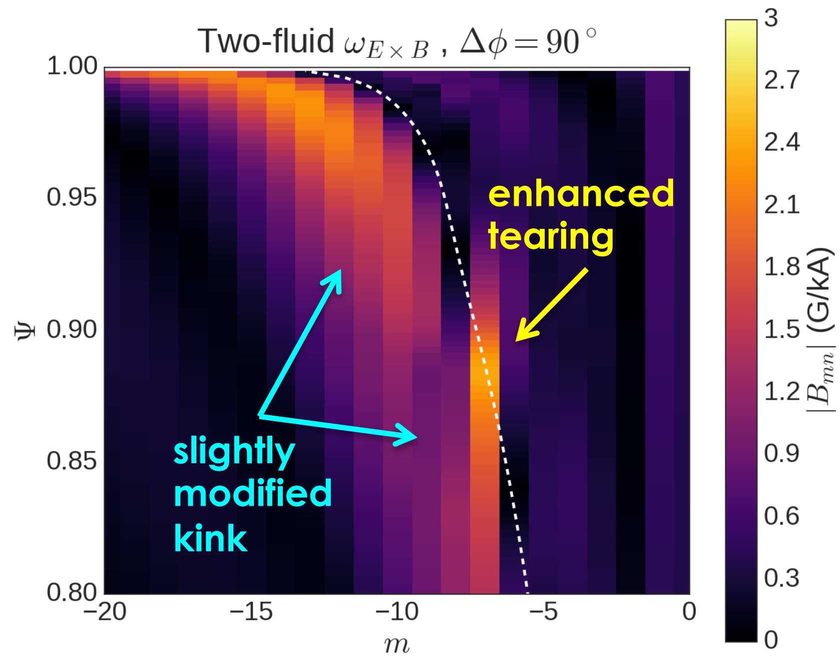




Enhanced tearing in two-fluid simulation due to electron rotation zero crossing near q=7/2







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Implicit heat flux causes instability in DK4D

- **Parallel temperature gradient should develop if parallel heat flux does not have the Pfrisch-Schulter-like return component**
- **Should require tight coupling to temperature equation**
  - Without: exponential growth
  - With: oscillatory, but exponential
- **Unclear if the coupled system is still missing physics or, more likely, there's a numerical instability**