NIMROD Calculations of Linear Plasma Response to RMPs in DIII-D Discharges 142603 and 126006

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CEMM Meeting
Denver, Colorado
November 10, 2013

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Plasma response to RMPs is believed to be key element of 3D effects and MHD control in tokamaks

- RMP induced 3D effects: Nonaxisymmetric magnetic configuration, neoclassical transport, ...
- Profile control and optimization: Rotation, density, and current, ...
- MHD control: ELM, RWM, error field correction ......
- The goal is to calculate and predict plasma response to RMPs in experiments:
  - Calculation is straightforward, but interpretation may be not.
  - Particularly when the equilibrium is not entirely stable (unstable).

Several approaches and codes have calculated plasma response to RMPs with varied results

[Turnbull 2012; Turnbull *et al.* 2013]

- Linear models/codes
  - Linear perturbed equilibrium: NMA [Chu *et al.* 2003], IPEC [Nuhrenberg and Boozer 2003, Park *et al.* 2007]
  - Linear dynamic: MARS-F [Liu *et al.* 2000], linear version of nonlinear dynamic models/codes
- Nonlinear models/codes
  - Nonlinear 3D equilibrium: VMEC [Hirshman and Whitson 1983], PIES [Reiman and Greenside 1986], HINT/HINT2 [Harafuji *et al.* 1989,Suzuki *et al.* 2006], SIESTA [Hirshman *et al.* 2011]
  - Nonlinear dynamic: NIMROD [Sovinec *et al.* 2004], M3D [Park *et al.* 1999], JOREK [Huysmans and Czarny 2007], M3D-C1 [Ferraro *et al.* 2010]
- Different approaches are subjects of comparison in an ongoing “3D equilibrium benchmarking exercise” [Reiman *et al.* 2013].

NIMROD code numerically solves the full set of extended MHD equations in entire 3D domain

[Sovinec *et al.* , 2004]

- Fluid part:

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{u} + D\nabla^2\rho \quad (1)$$

$$\rho\frac{d\mathbf{u}}{dt} = -\nabla p + \mathbf{J}\times\mathbf{B} - \nabla\cdot\boldsymbol{\pi} \quad (2)$$

$$\frac{n}{\gamma-1}\frac{dT}{dt} = -\frac{p}{2}\nabla\cdot\mathbf{u} - \boldsymbol{\pi}:\nabla\mathbf{u} - \nabla\cdot\mathbf{q} + Q \quad (3)$$

$$\frac{\partial\mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} \quad (4)$$

$$\mu_0\mathbf{J} = \nabla\times\mathbf{B} \quad (5)$$

$$\mathbf{E} = -\mathbf{u}\times\mathbf{B} + \eta\mathbf{J} + \frac{\lambda}{ne}(\mathbf{J}\times\mathbf{B} - \nabla p_e) \quad (6)$$

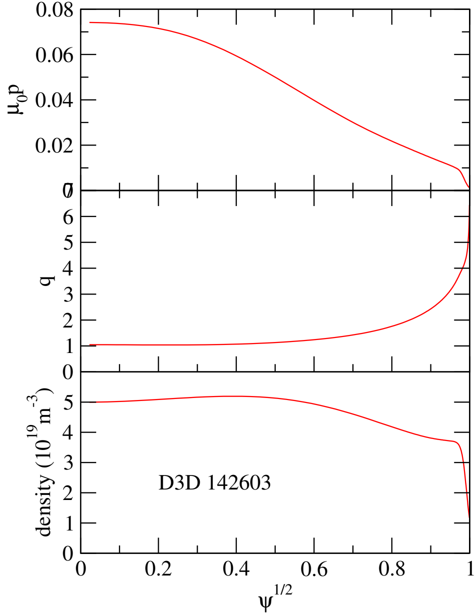
- Kinetic part: can couple to energetic particle dynamics through moment closure.

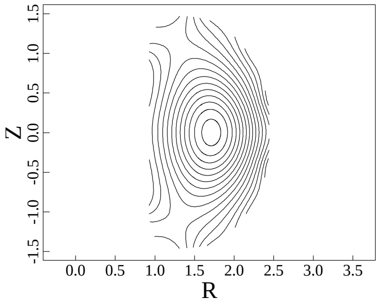
Both resistive and 2-fluid MHD models are used in linear calculations for the two DIII-D discharges

- Previously, NIMROD code was applied to investigating the "RMP enhanced transport and rotational screening in (resistive) simulations of DIII-D (#113317) plasmas" [Izzo and Joseph (2008)].
- Present study starts with resistive MHD model and Spitzer resistivity profile where $S_{\mathrm{core}} \sim 10^8$ and $S_{\mathrm{edge}} \sim 10^6$, and further compares with 2-fluid model with gyroviscosity.
- `48x96` finite elements with polynomials of order 4 in poloidal domain, 22 toroidal Fourier components are included in the calculations.
- Perpendicular toroidal rotation is considered in calculation for the DIII-D 126006 case.

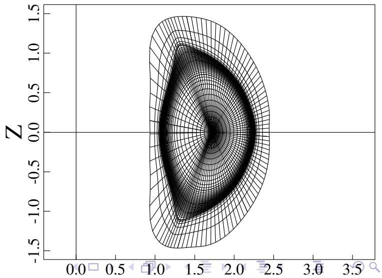
DIII-D discharge 142603 has been subject of a 3D equilibrium benchmarking project

[Courtesy of Turnbull]

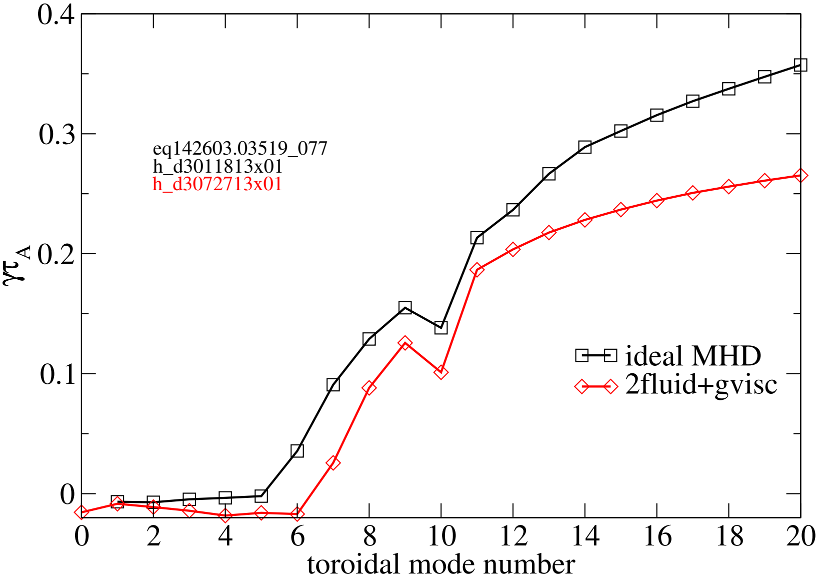




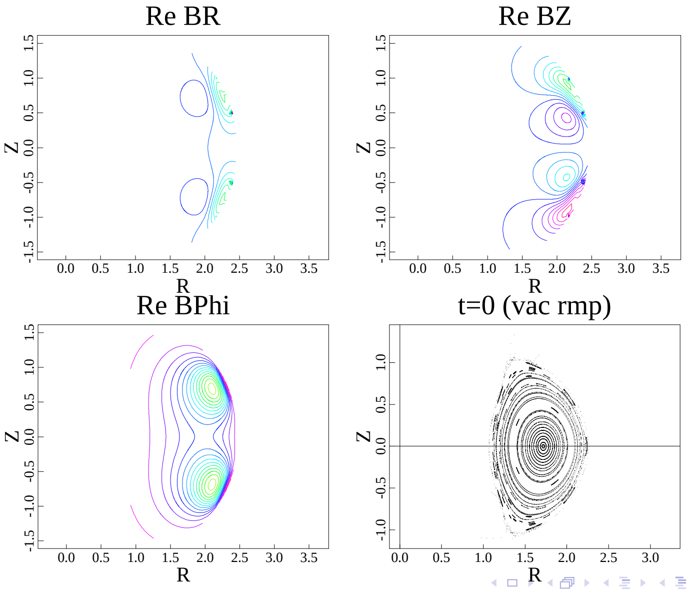
Finite Element Mesh



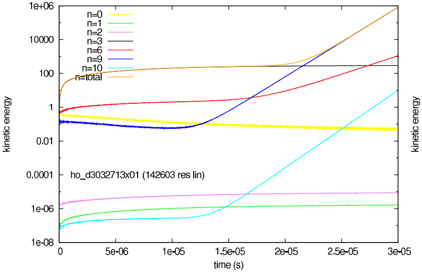
Equilibrium is unstable to middle to high-*n* edge localized modes in both ideal and 2-fluid models

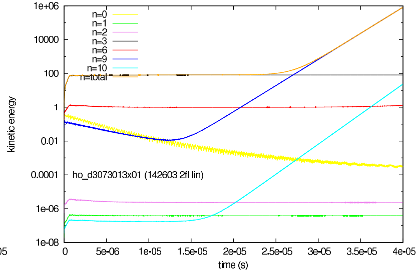


I-coil vacuum field is imposed as initial and boundary conditions ($n_{\rm rmp} = 3$, even parity) [Courtesy of Izzo]



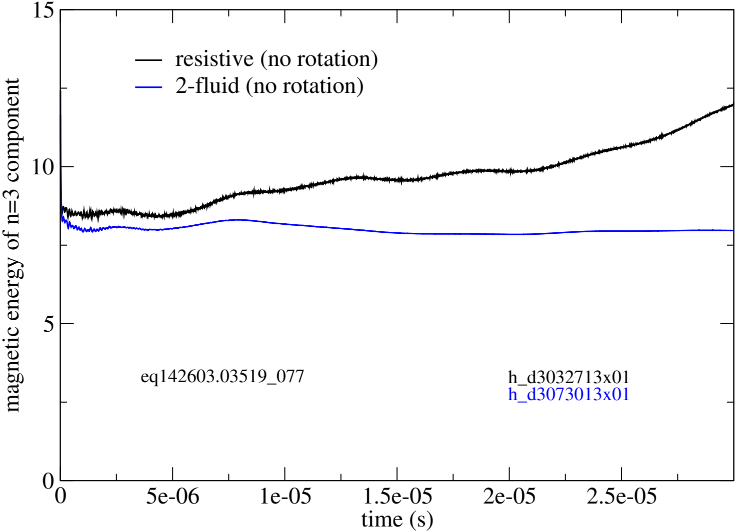
Linear response (both stable and unstable) of static plasma mainly in the RMP toroidal harmonics ($n = 3, 6, 9$)



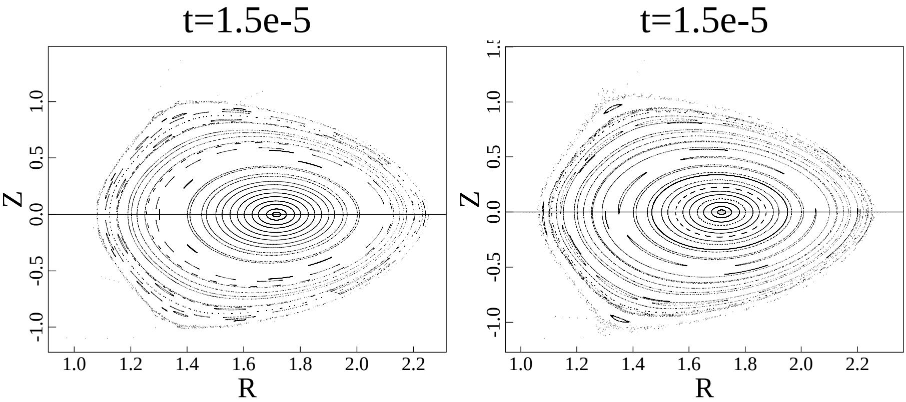


- Left: resistive MHD; Right: 2-fluid model.
- Saturation level of $n = 3$ response is about $\sqrt{10}$ times lower in 2-fluid model.
- Unstable high-n ($n = 9$) response eventually dominates growth in both MHD and 2-fluid models.

Magnetic response to $n = 3$ component of RMP shows shielding effects likely due to 2-fluid diamagnetic flows

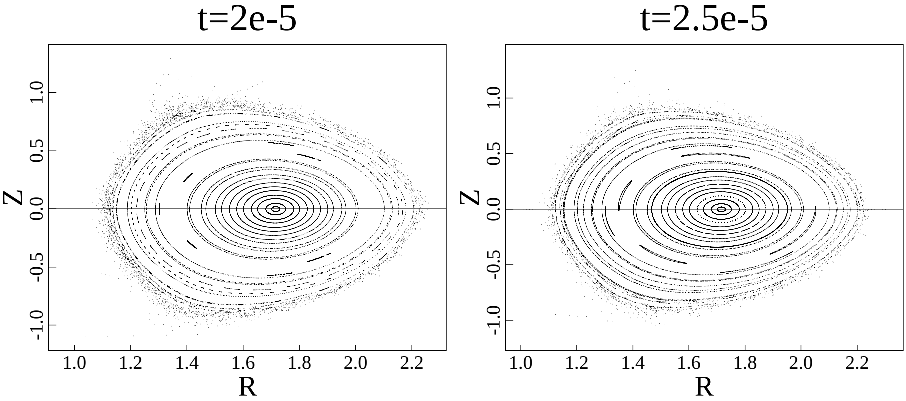


Two-fluid effects introduce visible changes in island size and location in magnetic response



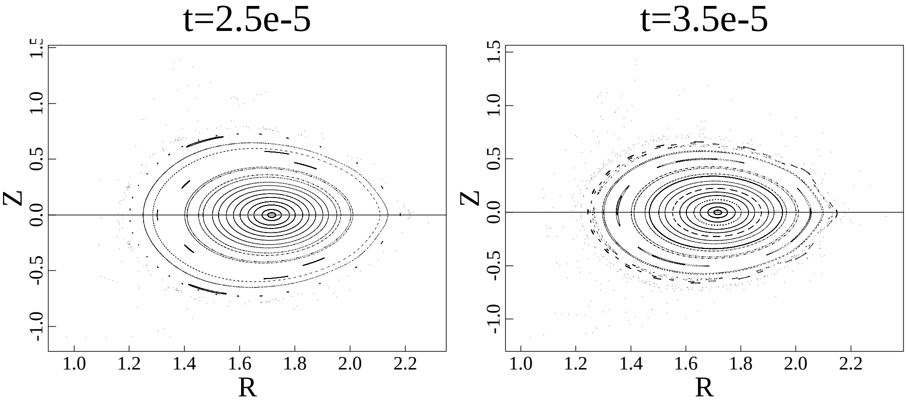
- Left: MHD model; right: 2-fluid model.
- Islands and perturbed flux surfaces are mostly localized at the edge pedestal region inside separatrix.

Edge pedestal region becomes more stochastic when unstable higher-n response becomes comparable to $n = 3$ component



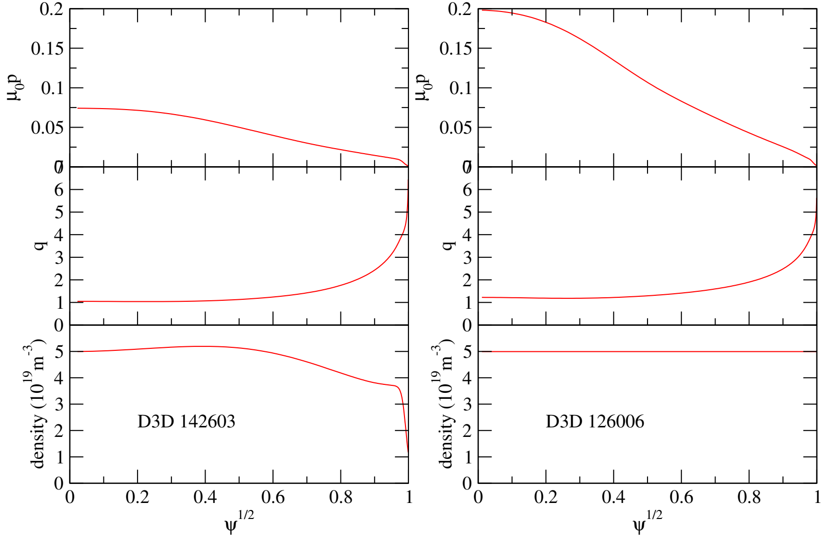
- Left: MHD model; right: 2-fluid model.
- Islands disappeared in stochastic edge pedestal region.

Eventually field lines in edge pedestal region become open as growing higher-*n* components start to dominate

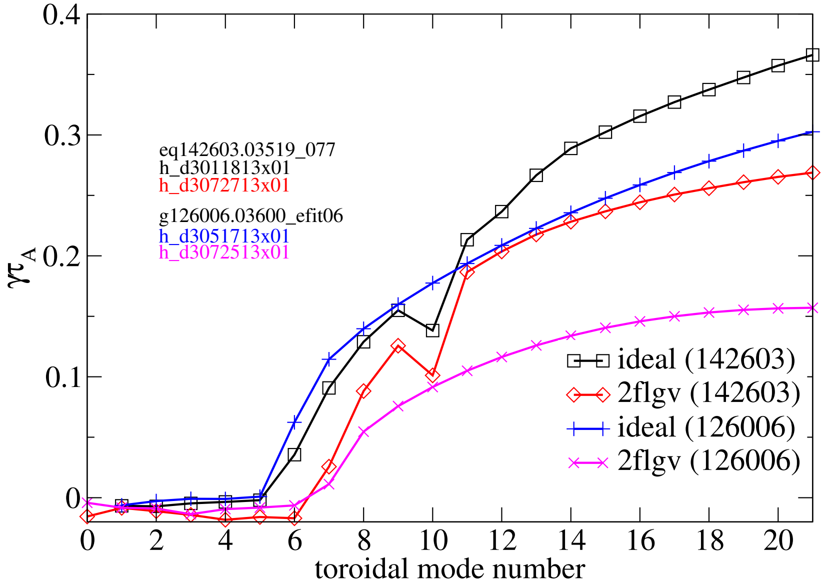


- Left: MHD model; right: 2-fluid model.
- Magnetic structures inside edge pedestal remain similar to vacuum field.

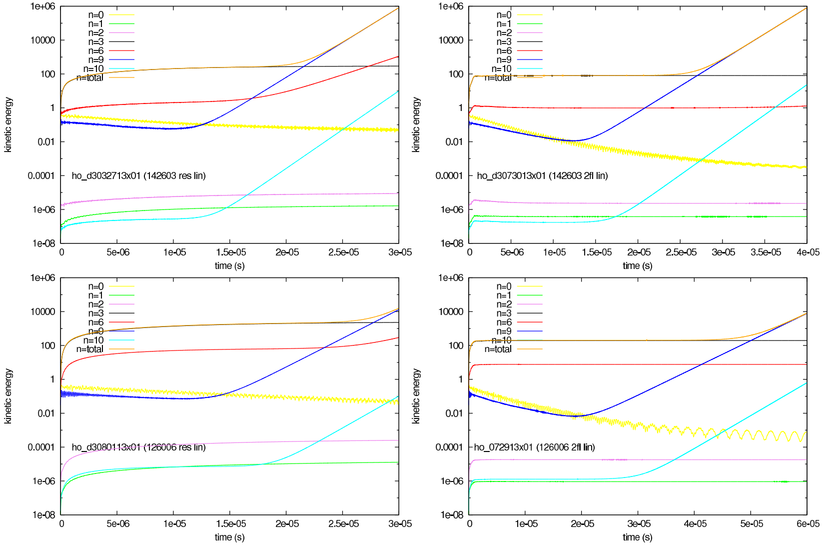
DIII-D discharge 126006 has been also subject of several RMP studies [Courtesy of Ferraro]



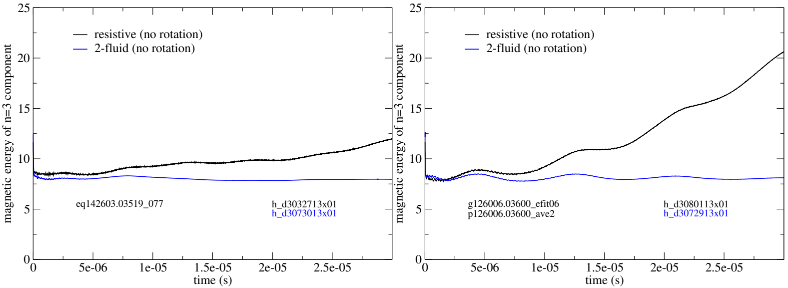
Edge pedestal in DIII-D 126006 is less unstable than in discharge 142603



Linear response in less unstable 126006 case is time delayed but otherwise similar in pattern to 142603 case in both MHD and 2-fluid models



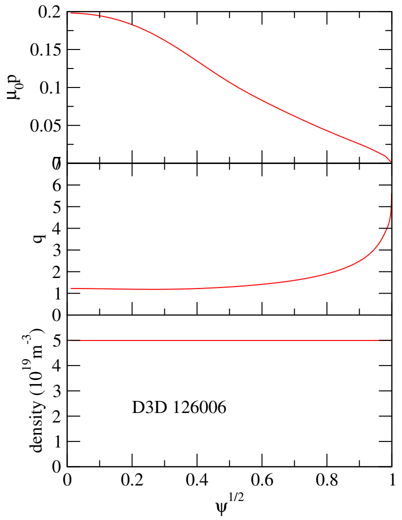
Magnetic responses to $n = 3$ component of RMP in both discharges show shielding effects likely due to 2-fluid diamagnetic flows

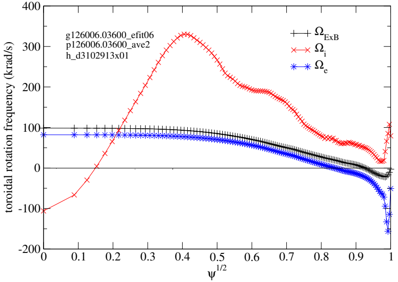


- Left: #142603 ; Right: #126006.
- $n = 3$ magnetic response levels in 2-fluid model are similar in both discharges.

"Perpendicular" toroidal rotation is further included in DIII-D discharge 126006 calculation

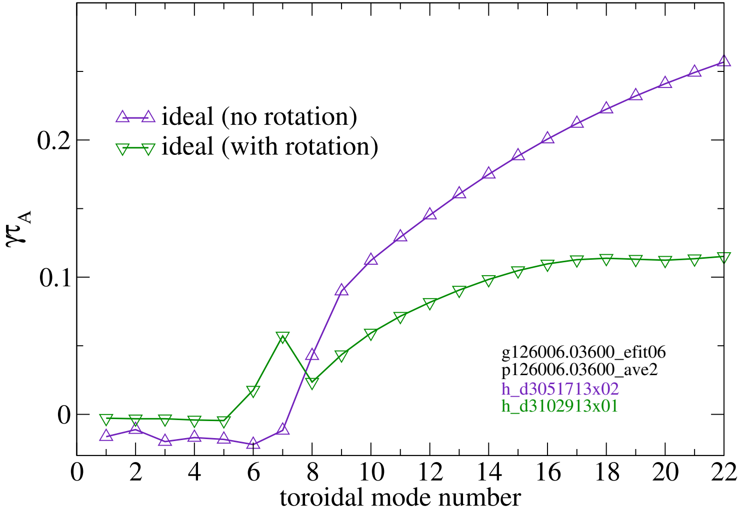
[Courtesy of Ferraro and Callen]



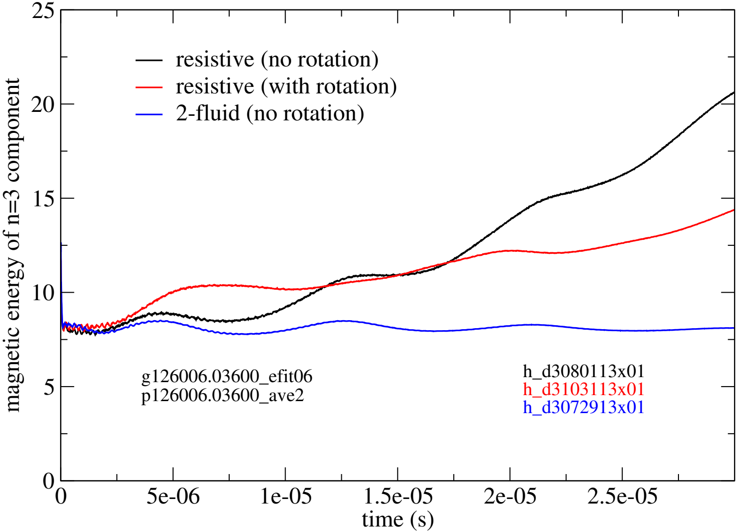


- $\mathbf{u}_a = \Omega_a R^2 \nabla\zeta + K_a \mathbf{B}$
- $\Omega_{a\zeta} = \Omega_a + \frac{K_a I}{R^2}$
- $\Omega_a = \Omega_E + \Omega_{*a}$
- $\Omega_E = -\frac{d\Phi}{d\psi}$
- $\Omega_{*a} = -\frac{1}{n_a e_a}\frac{dp_a}{d\psi}$

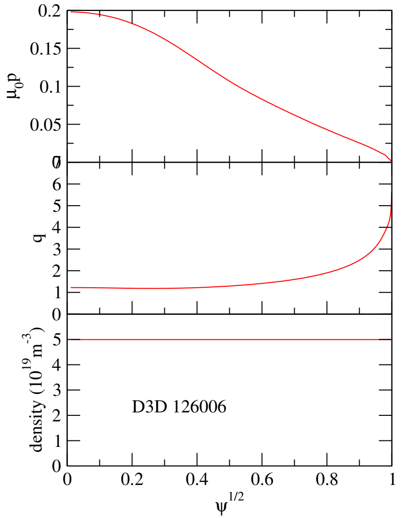
Toroidal rotation is stabilizing to middle to high-*n* edge localized modes and slightly destabilizing to low-*n* modes

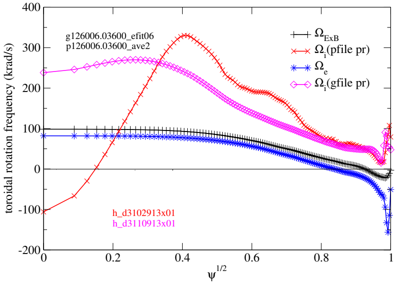


Toroidal rotation introduces less shielding of $n = 3$ component of RMP than 2-fluid effects alone



"Perpendicular" toroidal ion rotation profiles are different in 126006 g-file and p-file [Courtesy of Ferraro and Callen]





- $\mathbf{u}_a = \Omega_a R^2 \nabla\zeta + K_a \mathbf{B}$
- $\Omega_{a\zeta} = \Omega_a + \frac{K_a I}{R^2}$
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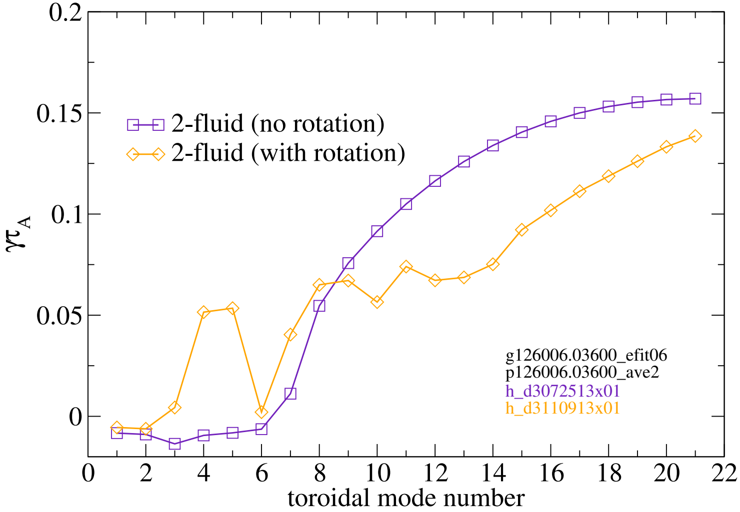
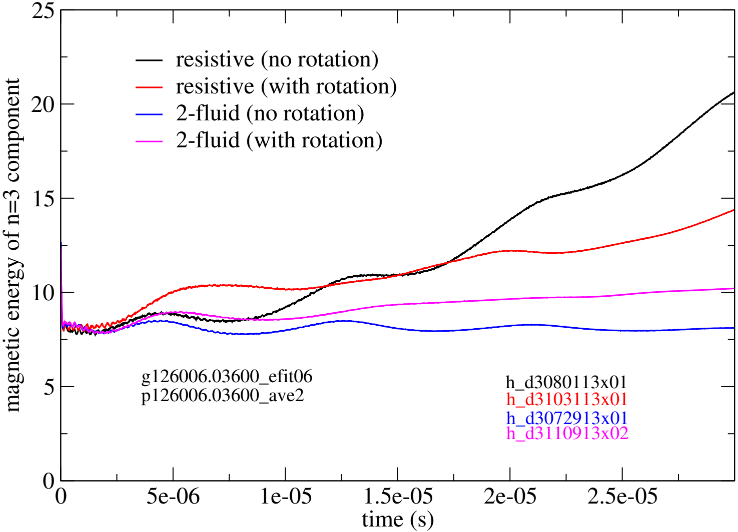
Toroidal rotation effects are similar but may change nature of modes in combination with 2-fluid effects



Toroidal rotation in addition to 2-fluid effects leads to less shielding of $n = 3$ component of RMP



Summary and discussion

- Both DIII-D equilibriums (# 142603 and #126006) are linearly unstable to edge localized modes for $n > 6$ in both MHD and 2-fluid models.
- For static equilibriums, NIMROD calculations of linear plasma response to $n = 3$ component of RMP indicate sheilding effects likely due to 2-fluid diamagnetic flows.
- Perpendicular toroidal rotation introduces moderate but less shielding of RMP than 2-fluid effects alone.
- Benchmark studies with other 3D codes are in progress.