Seeding NTM Simulations via Forced Reconnection

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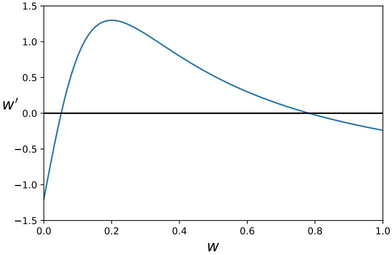
A technique is developed for seeding neoclassical tearing mode (NTM) simulations using forced reconnection

Modified Rutherford equation describes NTM evolution

$$\frac{dW}{dt} = k_0\eta^* \left[\underbrace{\Delta^*}_{\text{Tearing drive}} + \underbrace{\frac{D_{nc}W}{W^2 + W_d^2}}_{\text{Bootstrap drive}} + \underbrace{\frac{D_R}{\alpha_s - H}\frac{1}{\sqrt{W^2 + W_d^2}}}_{\text{"GGJ" Curvature correction}} + \underbrace{\frac{D_{pol}}{W^3}}_{\text{Polarization drive}} \right]$$

- NTMs require a seed island for growth
- NTMs are seeded by MHD transients in experiments
- Simulations require method for generating seed island



Forced reconnection is used to generate seed islands [1]

- Linear response model provides insight into the forced reconnection process

$$B_\psi = \frac{\Delta'_{ext}\rho_s}{-\Delta'\rho_s + i\Delta\omega\tau_{VR}} B_{vac}$$

- Resonant external fields B_{vac} create islands in a vacuum
- Resonant fields are screened by a rotating plasma: $\Delta\omega\tau \gg 1$
- Fields that rotate with the plasma are amplified by marginally stable modes: $|\Delta'\rho_s| \ll 1.0$
- Magnetic island width scales with the radial magnetic field: $W \propto \sqrt{B_\psi}$

[1] Builds on development by Matt Beidler

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Heuristic Closures Model the Neoclassical Stresses[2]

$$\rho\left(\frac{\partial \vec{v}}{\partial t}+\vec{v}\cdot\nabla\vec{v}\right)=\vec{J}\times\vec{B}-\nabla p-\nabla\cdot\vec{\vec{\Pi}}_i$$

$$E=-\vec{v}\times\vec{B}+\eta J-\frac{1}{ne}\nabla\cdot\vec{\vec{\Pi}}_e$$

$$\nabla\cdot\vec{\vec{\Pi}}_i=nm_i\mu_i\left\langle B_{eq}^2\right\rangle\frac{\left(\vec{V}-\vec{V}_{eq}\right)\cdot\vec{e}_\Theta}{\left(\vec{B}_{eq}\cdot\vec{e}_\Theta\right)^2}\vec{e}_\Theta$$

$$\nabla\cdot\vec{\vec{\Pi}}_e=-\frac{nm_e\mu_e}{ne}\left\langle B_{eq}^2\right\rangle\frac{\left(\vec{J}-\vec{J}_{eq}\right)\cdot\vec{e}_\Theta}{\left(\vec{B}_{eq}\cdot\vec{e}_\Theta\right)^2}\vec{e}_\Theta$$

- Closures model dominant neoclassical effects
  - Bootstrap current drive
  - Poloidal ion flow damping
  - Enhancement of polarization current

[2] T. Gianakon, POP 9, 2002

Post-processing diagnostic calculates Fourier transformed $B \cdot \nabla\psi$ [3]

- Magnetic island width scales with the perturbed flux

$$W \propto \sqrt{\tilde{\psi}_{m,n}}$$

- Perturbed flux is related to the radial component of the perturbed magnetic field

$$\frac{\partial \tilde{\psi}}{\partial \Theta} = \mathcal{J} \tilde{B} \cdot \nabla \psi_0$$

- Poloidal field line integration calculates flux surface averaged cos and sin transforms of B_ψ

$$B_\psi \equiv \sqrt{B_{\psi,c}^2 + B_{\psi,s}^2}$$

$$B_{\psi,c} = \frac{\oint \oint \mathcal{J} \tilde{B} \cdot \nabla \psi_0 \cos \alpha d\Theta d\phi}{V'}$$

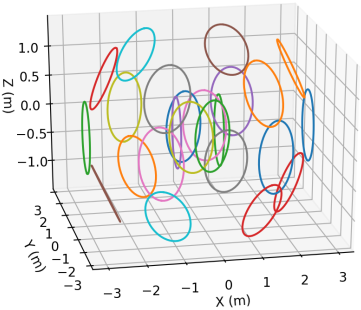
$$V' = \oint \oint \mathcal{J} d\Theta d\phi$$

$$\alpha = n\phi - m\Theta$$

[3] M.J. Shaffer et al, NF 48 (2008) 024004

External fields generated using planar coil array

- Biot-Savart integration calculates magnetic field at nodes along NIMROD's computational boundary
- The number of coils and their orientation can be varied to tune the external field



- External fields are applied as a slowly varying pulse

$$B_n(t) = B_{ext} \times \underbrace{\Psi(t)}_{\text{Pulse}} \times \underbrace{\exp(i\Omega t)}_{\textit{Rotation}}$$

- External fields are rotated with the plasma to minimize screening

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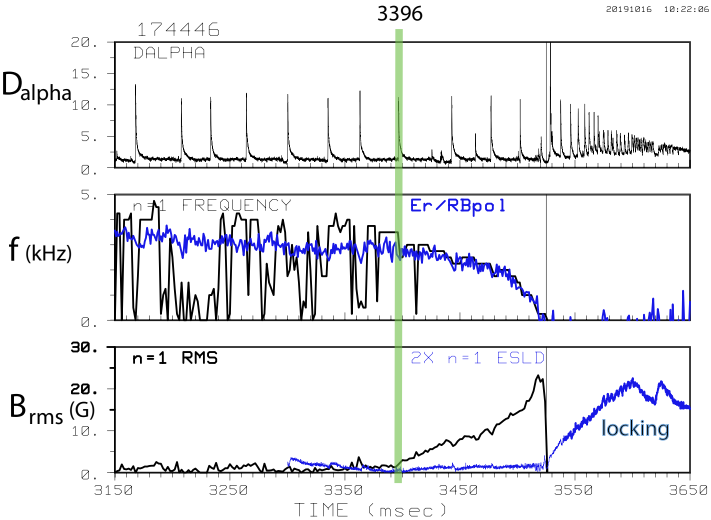
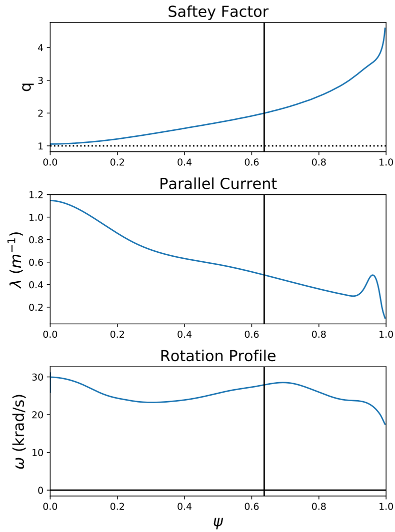
174446 terminates in a well diagnosed NTM disruption



- Synergistic with NTM seeding study[4]

[4]Work preformed with E. Strait, R La Haye, R. Wilcox, C. Chrystal, M. Okabayashi

Simulations use kinetic reconstruction of 174446 at 3390ms.

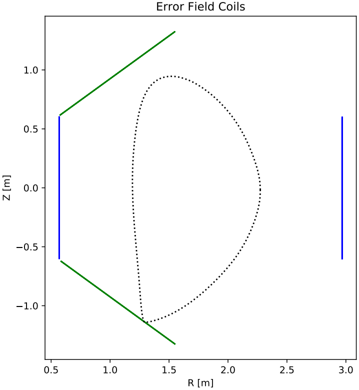


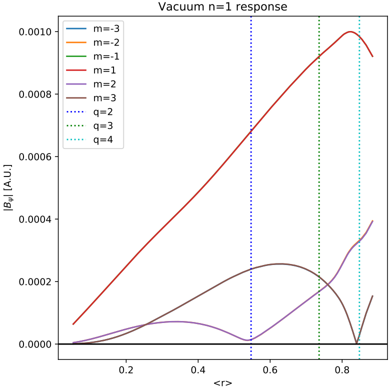
Nominal Numerical Parameters

Lundquist number	10^6
Prandlt number	10
$k_{\|\|}/k_{\perp}$	10^8
μ_e	$10^5 \rightarrow 10^6 \left[s^{-1}\right]$
μ_i	$10^3 \left[s^{-1}\right]$
Toroidal Modes	$n_{max} = 2 \rightarrow 10$
Poly_degree	3
mx, my	80, 64
Ohms Law	MHD

- Modest parameters used to quickly explore parameter space

Coil configuration varied to generate 2/1 vacuum perturbation

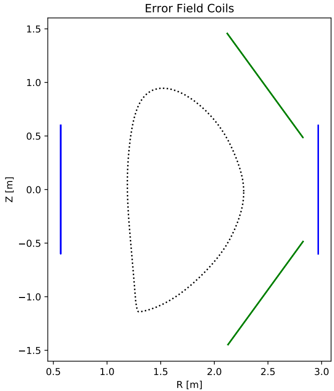


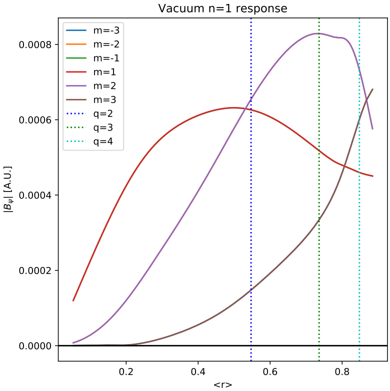


- Reversed D coil configuration has small resonant 2/1 component
- Polarity designed to apply m=2 perturbation
- Configuration designed to mimic flux aligned Θ
- Colors indicate coil polarity

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

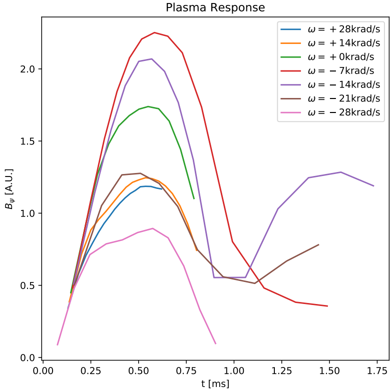
Coil configuration varied to generate 2/1 vacuum perturbation

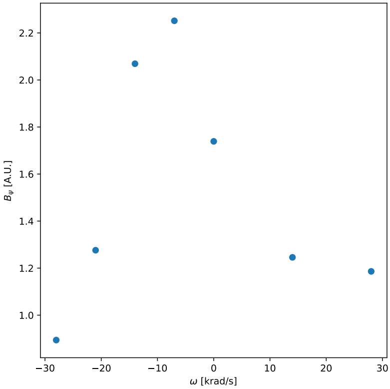




- Forward D coil configuration has large resonant 2/1 response
- Coil geometry is similar to DIII-D's C-coils

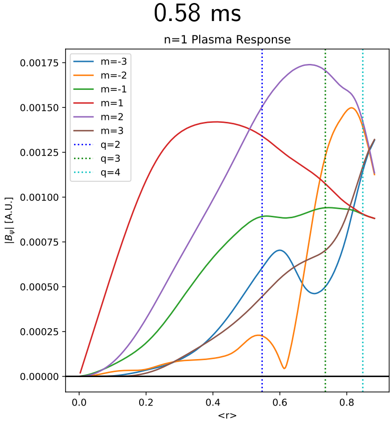
External field rotation frequency varied to minimize screening

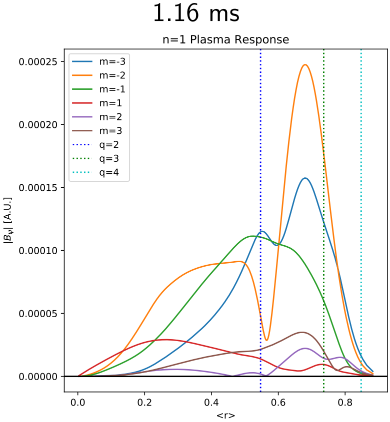




- Largest response observed around $\Omega \sim -7$ krad/s
- Resonant plasma rotation frequency is $\omega \sim -9 krad/s$
- External fields applied as a 1ms pulse

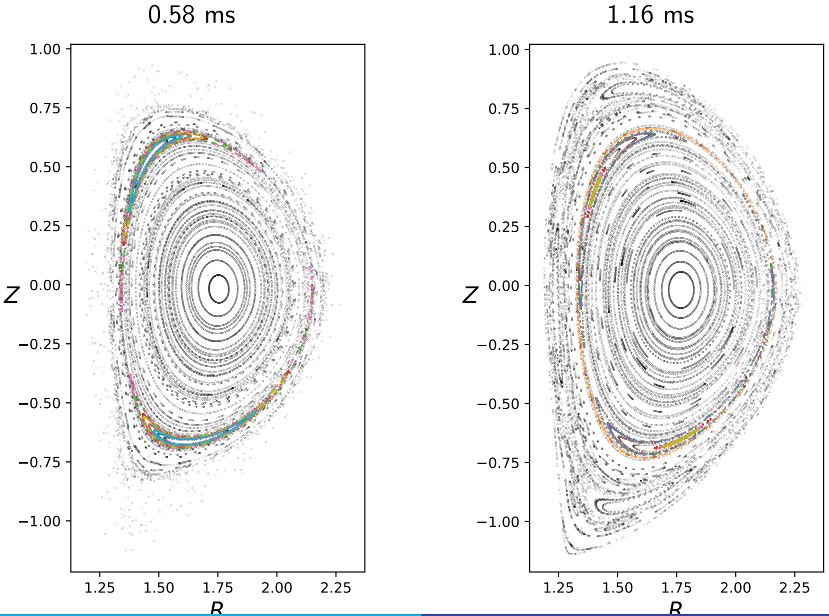
-2/1 perturbation strongly screened at $\omega = -7krad/s$





- Resonant 2/1 and 3/1 perturbations slowly decay following the pulse

Application of external fields generates rotating 2/1 island



Conclusions/Future Work

- Forced reconnection shows promise as a method for seeding NTM simulations
- Perturbations seed 2/1 island that slowly decays following the application of the external fields
- Screening is minimized when the magnetic perturbation is rotated with the plasma
- Increasing external field amplitude increases resonant 2/1 amplitude but completely stochasticises the edge
- Future work: Optimize coil configuration to maximize external resonant 2/1 component and minimize 3/1 and 4/1 components
- Study NTM locking using 174446 equilibrium