MHD and Disruption Studies at USTC

Ping Zhu[1,2]

University of Science and Technology of China[1]
University of Wisconsin-Madison[2]

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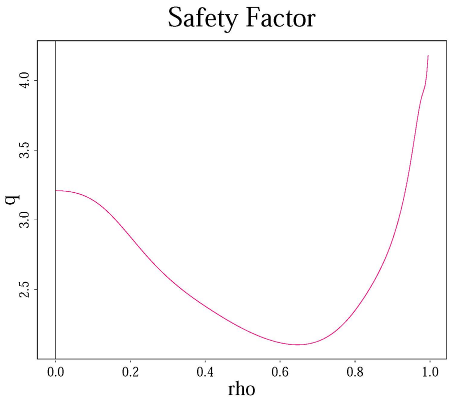
Ongoing and planned MHD and disruption studies

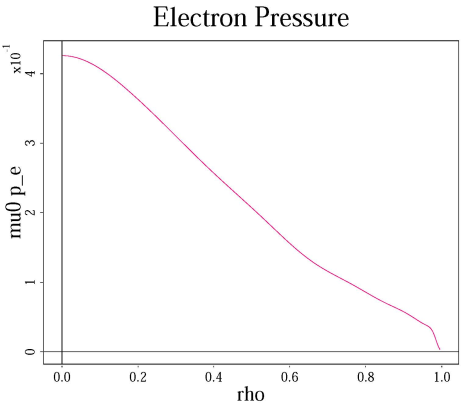
- MHD and EP analyses of CFETR baseline scenarios
  - Ideal (wall) MHD modes (D. Banerjee, S.-K. Cheng, R. Han)
  - RWM (R. Han)
  - TAE/EPM (Y.-W. Hou)
- Disruption-relevant MHD and EP studies
  - NIMEQ-flow and VDE (H.-L. Li)
  - TM/NTM (X.-T. Yan, Z. Chen)
  - LM, plasma response, and NTV (W.-L. Huang, X.-T. Yan, Z.-H. Li)
  - MGI mitigation (D. Banerjee)
  - Fishbone (Z.-H. Zou)

NIMROD is mainly used along with other major codes for linear analysis and nonlinear simulations of MHD and EP physics

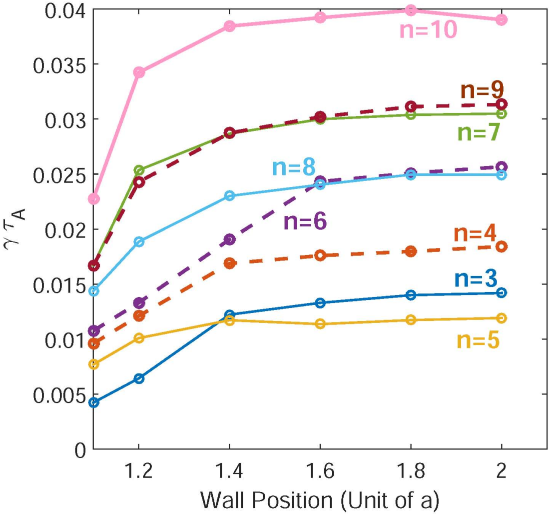
- MHD physics
  - Linear ideal modes: AEGIS, NIMROD, (GATO, MARS, ELITE, BOUT++)
  - Linear resistive modes: NIMROD, (PEST-3, M3D-C1)
  - Nonlinear: NIMROD, (BOUT++, M3D-C1)
  - Control/mitigation (MGI, RMP, ...): NIMROD, (MARS, ...)
  - ......
- EP physics
  - Linear: NIMROD, (NOVA-K, M3D-K)
  - Nonlinear: NIMROD, (M3D-K)
  - ......

CFETR baseline scenario from 1.5D integrated transport simulations features deeply reversed magnetic shear and edge pedestal regions

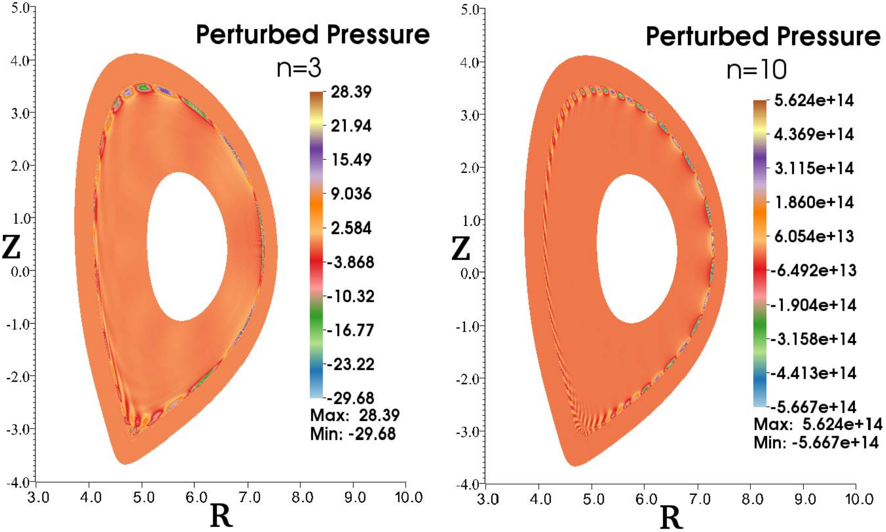




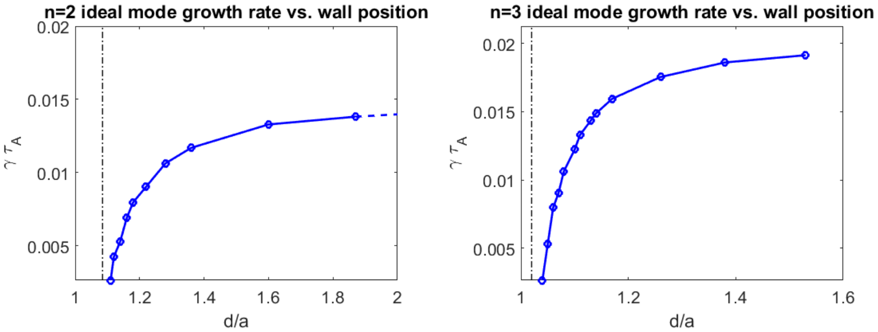
IWM: NIMROD calculations indicate the baseline scenario linearly unstable to ideal (wall) MHD modes for $n = 3 - 10$ [Banerjee *et al.* 2017, Cheng *et al.* 2017]



IWM: NIMROD calculations show linear ideal modes all localized near edge for $n \geq 3$

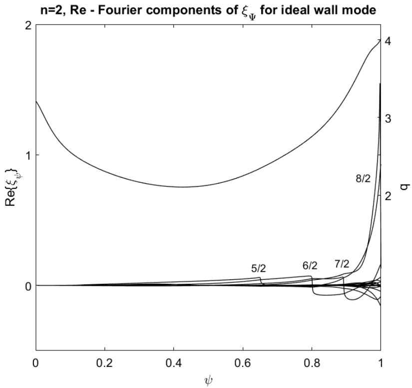


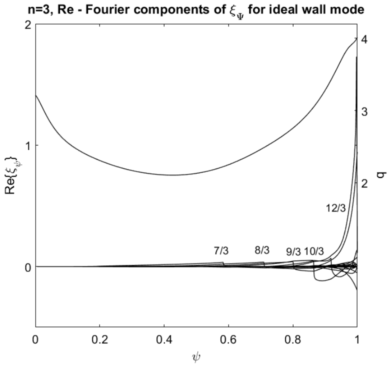
IWM: Linear growth rates of low-n ($n \leq 3$) ideal MHD modes can be obtained from AEGIS calculations [Han *et al.* 2017]



- The $n = 3$ ideal MHD mode critical wall position agrees with NIMROD calculation.

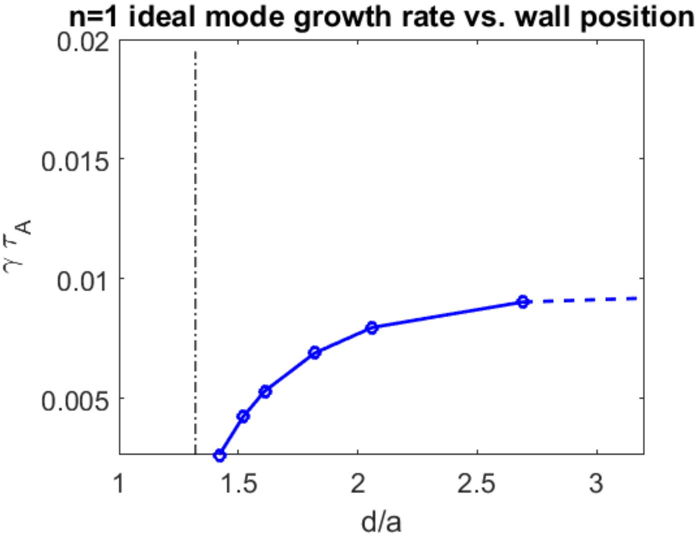
IWM: Mode profiles from AEGIS calculations indicate that unstable low-n ($n = 2, 3$) ideal MHD modes remain localized near edge



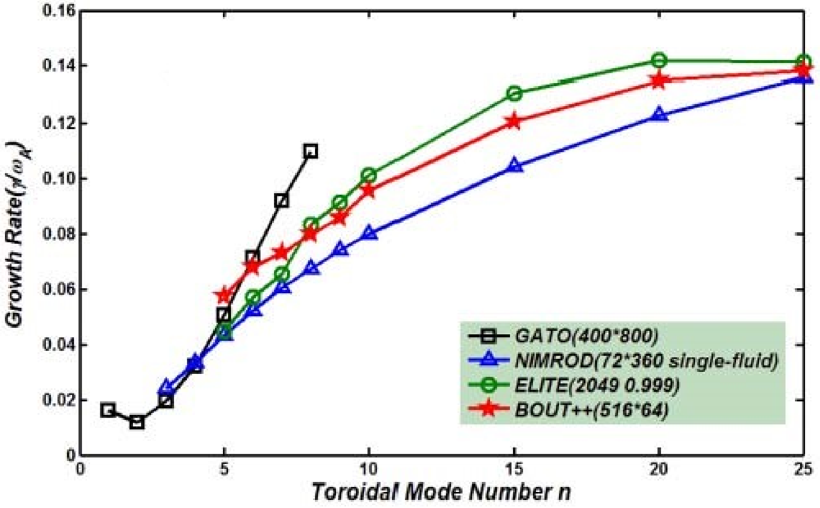


- The $n = 3$ ideal MHD mode profile agrees well with NIMROD calculation.

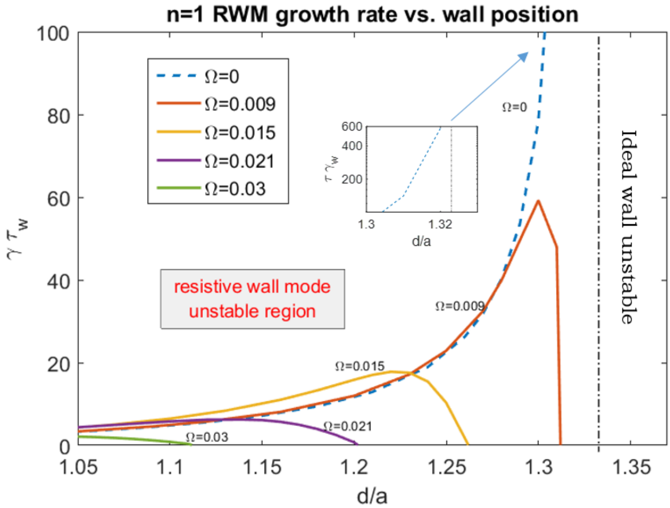
IWM: AEGIS calculations indicate $n = 1$ ideal mode stable for designed wall location $d/a = 1.2$



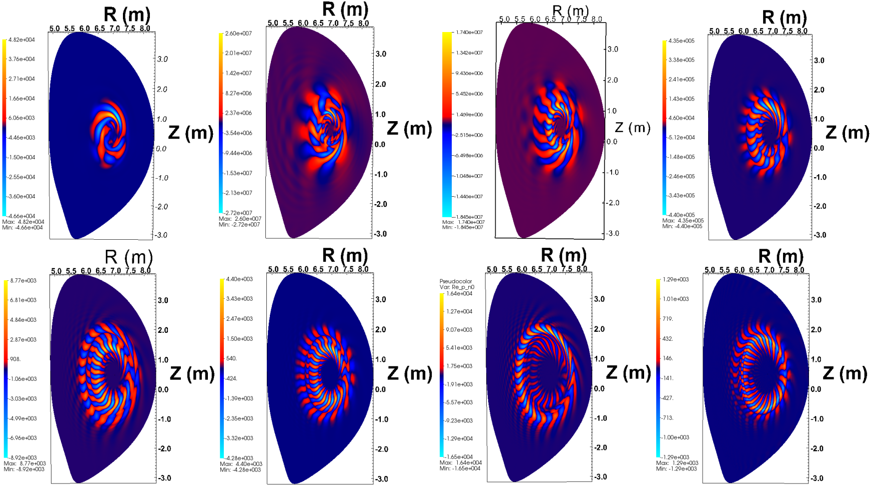
IWM: Linear growth rates of ideal MHD modes have been benchmarked among multiple major MHD codes for CFETR [Li *et al.* 2017, Banerjee *et al.* 2017]



RWM: $n = 1$ **RWM is unstable for the designed wall location but can be stabilized by toroidal rotation above a low threshold** [Han *et al.* 2017]

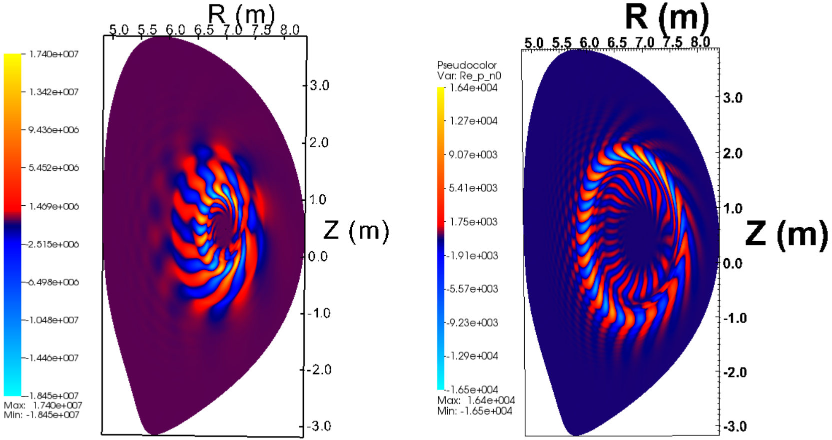


TAE: CFETR baseline scenario found unstable to EP-driven TAEs from NIMROD calculations [Hou *et al.* 2017]



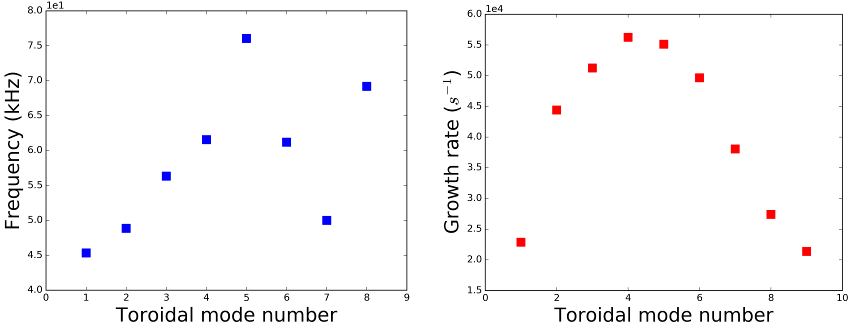
Upper: $n = 1 - 4$; Lower: $n = 5 - 8$

TAE: EP-driven TAE instabilities analyzed in NIMROD simulations



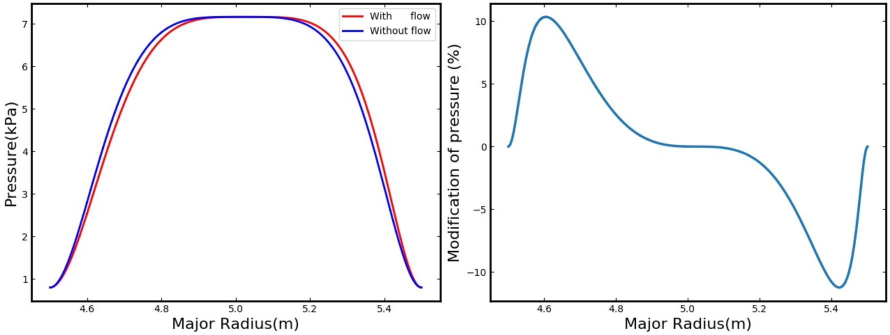
- Slowing-down EP distribution with β_h fraction of 0.2.
- Global twisted mode structure characteristic of TAE and RSAE (left: $n = 3$; right: $n = 7$).

TAE: NIMROD simulations find EP-driven TAE instabilities in low n range



- TAE real frequencies (left) are located in the Alfvénic continuum gap, consistent with analysis from NOVA-K [Zou *et al.* 2017].
- TAE growth rates (right) are peaked at $n = 4$.

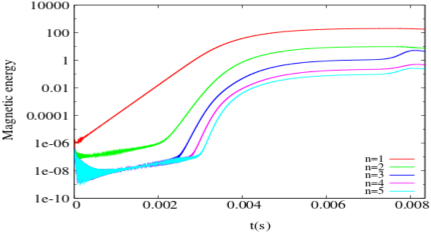
NIMEQ: Modification of pressure is up to 10% when toroidal rotation Mach number ~ 0.1 (frequency $8.0 \times 10^4 rad/s$) [Li and Zhu 2017]

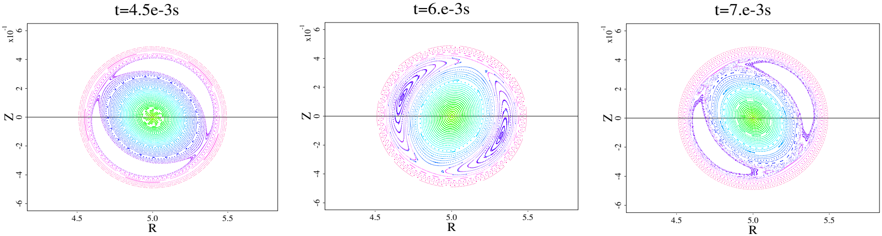


- Left: Pressure with and without toroidal flow.
- Right: Relative change of pressure $(P_{with\ flow} - P_{without\ flow})/P_{without\ flow}$ induced by toroidal flow.

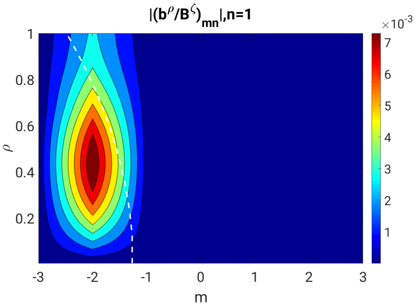
TM: NIMROD nonlinear benchmark on double helicity tearing in presence of poloidal flow (ITPA-MHD JA2) [Yan and Zhu 2017]

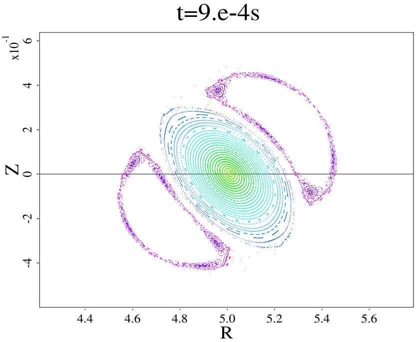
- $q(r) = 1.4(1 + (r/0.74a)^4)^{1/2}$
- $S = 10^5$, $P_{\rm rm} = 1$
- $u_\theta = 6480\frac{r}{a}[1-(\frac{r}{a})^3](m/s)$





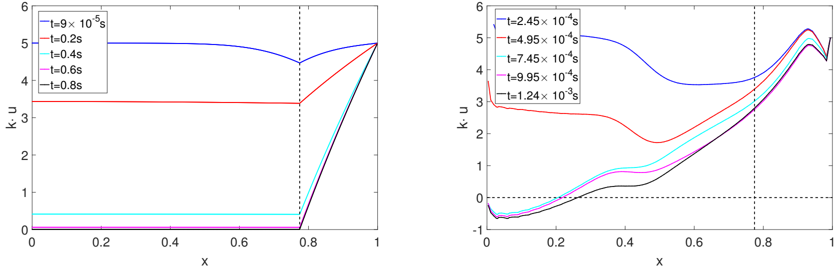
LM: Nonlinear plasma response to RMP of tokamak in Rutherford regime from NIMROD simulations [Zhu *et al.* 2017]





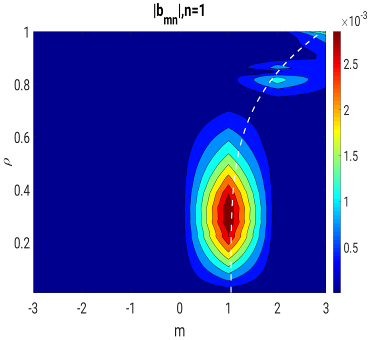
- RMP helicity $(2, 1)$, amplitude range $10^{-4} \sim 10^{-3}$.
- Nonlinear response simultion includes 6 toroidal Fourier modes.

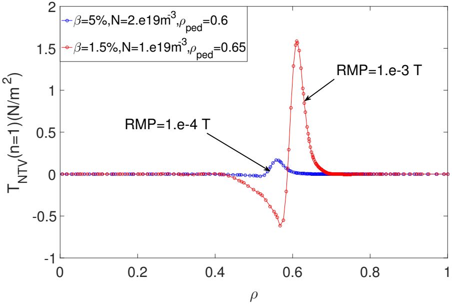
LM: Locked mode state of nonlinear plasma response qualitatively agrees with theory [Zhu *et al.* 2017]



- $\mathbf{k} \cdot \mathbf{u}$ profile evolution from theory (left, cylinder) and NIMROD simulations (right, torus) similar.
- Mode locking location ($\mathbf{k} \cdot \mathbf{u} = 0$) inward of resonant surface in simulation.

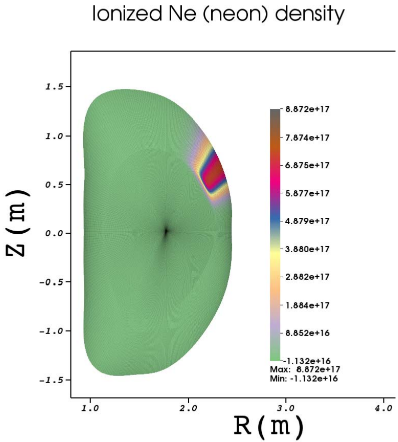
NTV: RMP can induce NTV torque in edge pedestal to the order of NBI torque ($\sim 1 N/m^2$) [Yan *et al.* 2017]

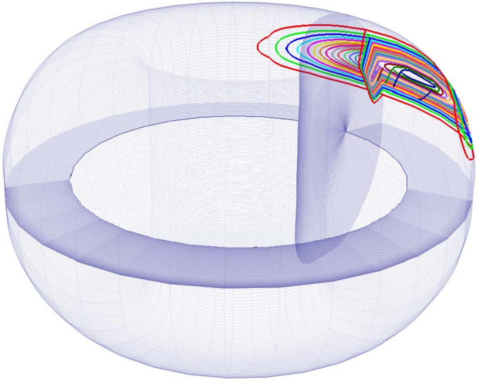




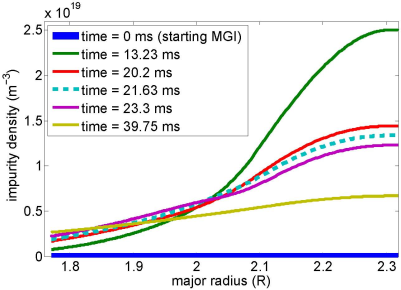
- RMP helicity $(2, 1)$, amplitude range $10^{-4} \sim 10^{-3}$.
- Fourier spectrums of perturbed magnetic field strength localized and peaked around resonant surfaces $(1, 1)$ and $(2, 1)$.
- NTV torque density profile peaked in edge pedestal region.

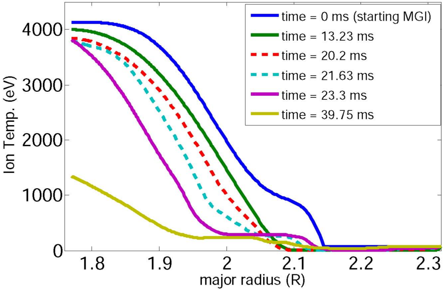
MGI: Initial distribution Neon gas injection localized near edge (DIII-D) [Banerjee *et al.* 2017]



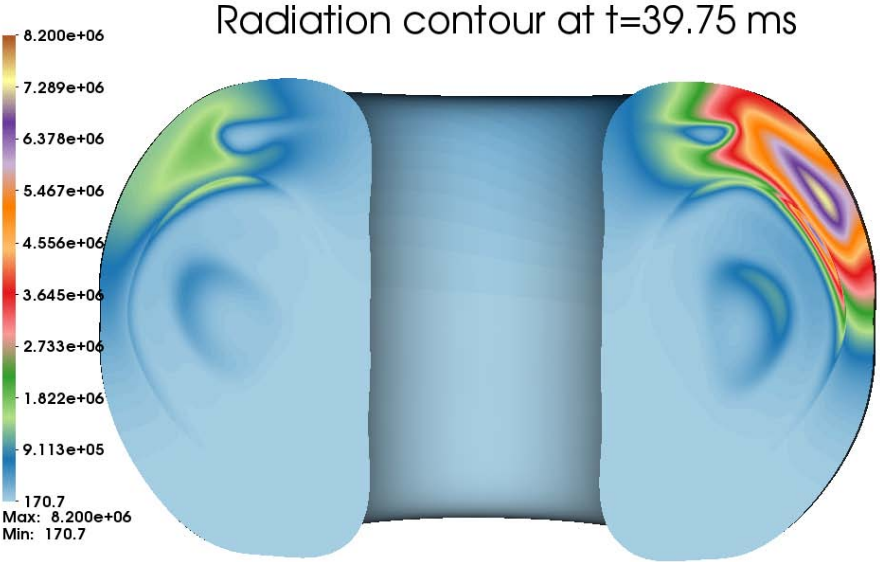


MGI: NIMROD simulation demonstrates Neon gas injection leads to thermal quench (DIII-D)

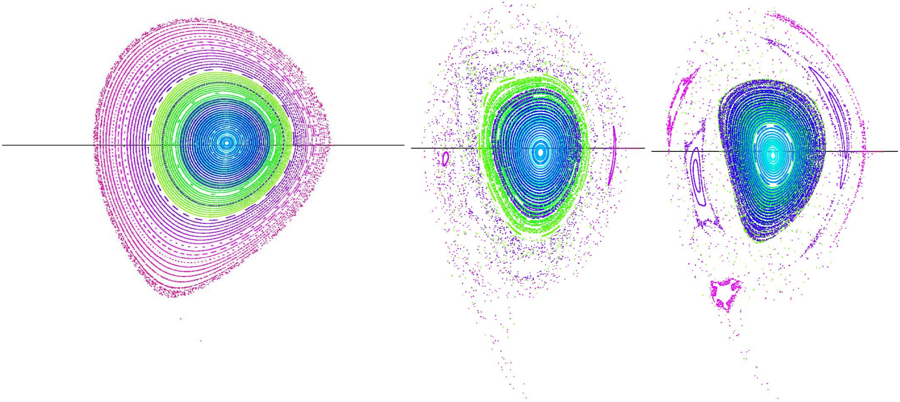




MGI: Radiation power density distribution during TQ phase (DIII-D)

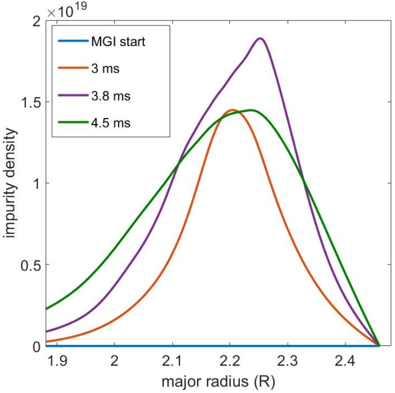


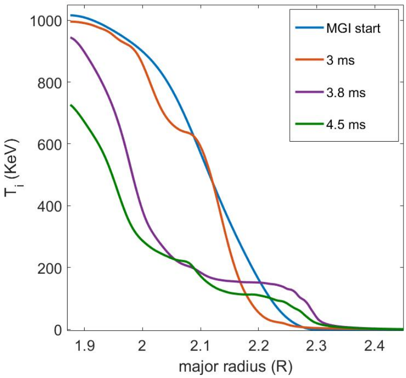
MGI: During TQ phase magnetic flux surface lost outside core region (DIII-D)



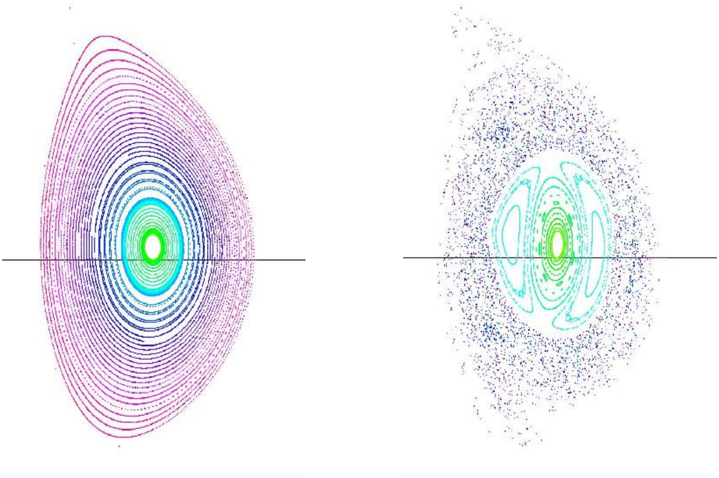
MGI: Simulation demonstrates thermal quench phase induced by lithium gas injection on EAST

[Banerjee *et al.* 2017]

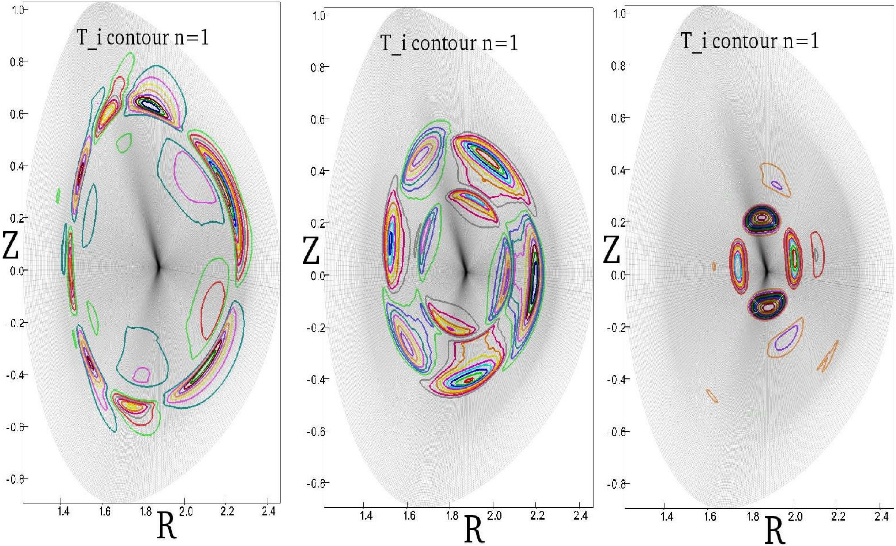




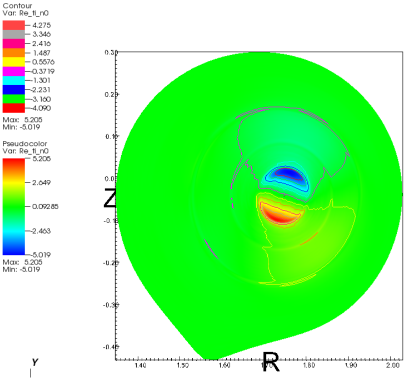
MGI: During TQ phase magnetic flux surface lost outside core region (EAST)



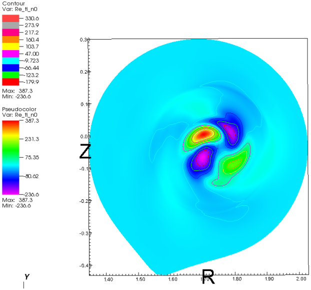
MGI: Unstable 2/1 mode leads to disruption onset (EAST)

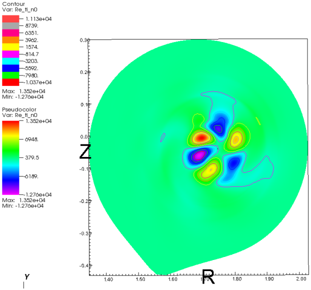


Fishbone: EP-driven 1/1, 2/2, and 3/3 modes on HL-2A reproduced in NIMROD calculations [Zou *et al.* 2017]

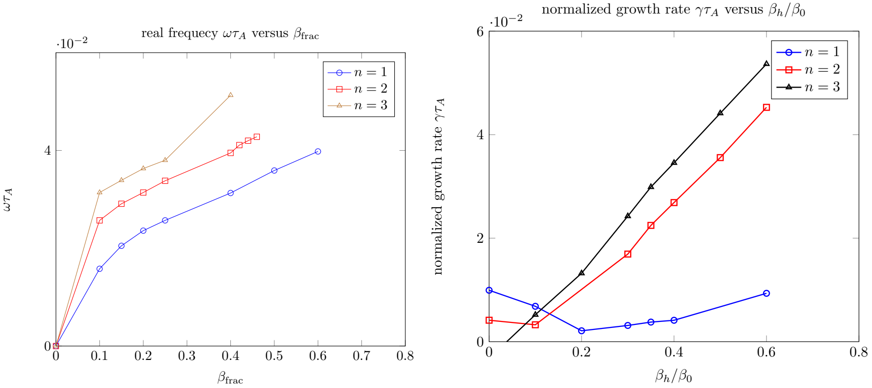


- Mode structures twist poloidally and extend radially.
- $\beta_{frac} = 0.25(1,1), 0.3(2,2), 0.3(3,3).$





Fishbone: 1/1, 2/2, and 3/3 modes can be driven unstable by increasing EP β_h (HL-2A)



- Real frequency (left) and linear growth rates (right).
- (1,1) and (2,2) kink mode first suppressed by β_h, then become fishbone instabilities at higher β_h.
- (3,3) mode are purely driven by EPs.

Summary and plan

- The IWM (ELM), RWM, and TAE stabilities of CFETR baseline scenario have been evaluated.
  - IWM are mostly edge-localized (i.e. ELMs) instead of global (D. Banerjee, S.-K. Cheng, R. Han).
  - RWMs could be stabilized with low toroidal rotation, even in absence of other disspative stabilization mechanisms or feed-back control schemes (R. Han).
  - Both TAE and RSAE can be driven unstable with EPs (Y.-W. Hou)
- Disruption-relevant MHD and EP studies are ongoing and planned
  - NIMEQ-flow and VDE (H.-L. Li)
  - TM/NTM (X.-T. Yan, Z. Chen)
  - LM, plasma response, and NTV (W.-L. Huang, X.-T. Yan, Z.-H. Li)
  - MGI mitigation (D. Banerjee)
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