NIMROD analysis on MHD stability of negative triangularity tokamaks

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on behalf of

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Outline

Negative triangularity tokamak is beneficial for divertor design [M. Kikuchi et al, APPC (2014)]

a) Standard D   b) Negative D SF-divertor   c) Negative D DN
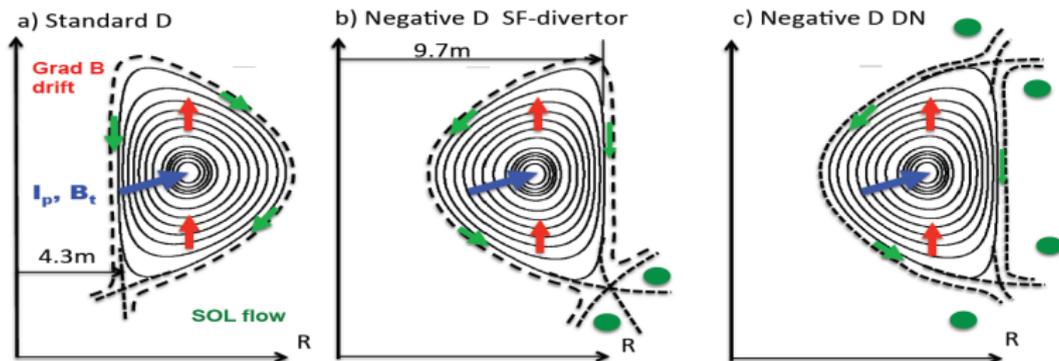
- Larger power handling area for the divertor $S_{div} \sim 2\pi R_{div}(F\Delta)$ ($R_{div}^{\delta<0} > R_{div}^{\delta>0}$). Δ is effective width of heat flux, F is the enhancement factor due to SF flux expansion.
- For example, heat flux can be $4 \sim 7$ times smaller.
- Larger space for engineering design to mitigate the damage to divertor caused by particle and energy loads.

Turbulence and transport can be reduced in negative triangularity discharge compared to positive triangularity one [M. E. Austin et al, APS (2017)]

Summary: Negative Triangularity Discharges Created in DIII-D

- Unconventional **negative** triangularity $(-\delta)$ discharges have been created in DIII-D
- Compared to matching **positive** δ, they have reduced turbulence and transport
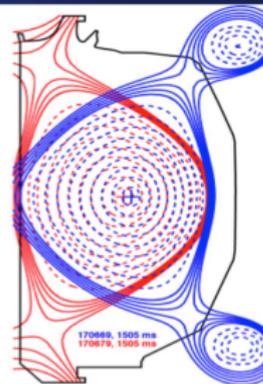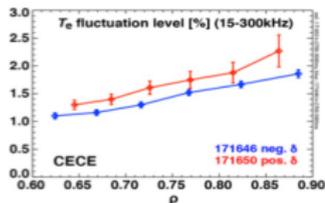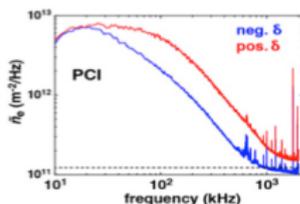
However, the β limit in negative triangularity plasma is often thought relatively low (e.g. $\beta_N \sim 2$) [S. Yu. Medvedev et al, Nucl. Fusion (2015)].

Recent ideal MHD stability study shows that negative triangularity L-mode with high bootstrap current fraction can achieve higher β than H-mode in positive triangularity case [L.-J. Zheng et al, Sherwood (2018)]
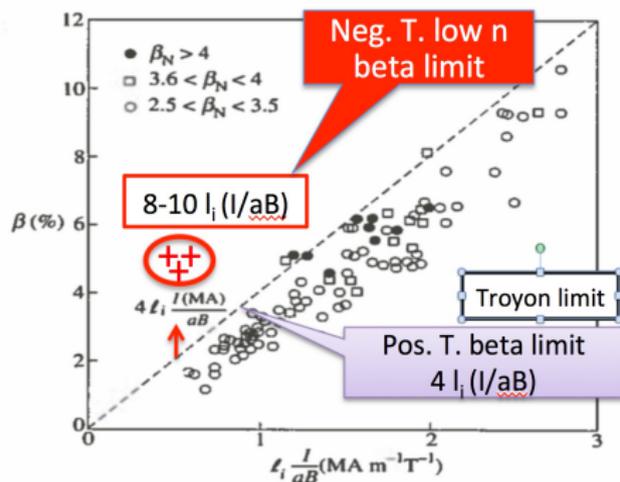
In this work, we use NIMROD to:

- Compare with previous ideal MHD stability study;
- Extend this study to non-ideal, nonlinear scenarios.

Outline

1. Introduction and motivation

2. Simulation on DIII-D negative triangularity experiment

3. Comparison among different triangularity configurations in DIII-D type L-mode scenario

4. Simulation on advanced L-mode scenario with high bootstrap current fraction

5. Summary

DIII-D gfile g171421.03850 is used to generate simulation domain and equilibrium profiles

Finite Element Mesh
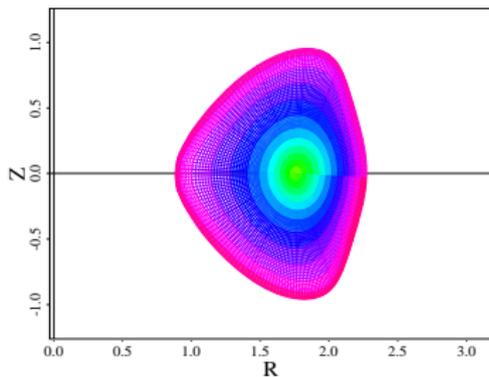
Plasma Pressure
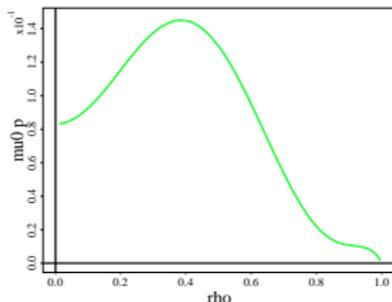
Safety Factor

Number Density (m^-3)

<J.B/B^2>
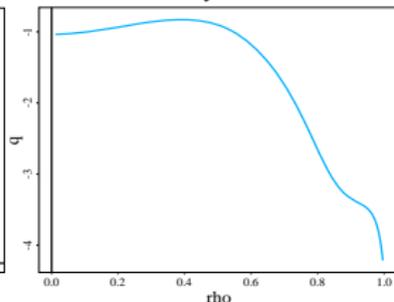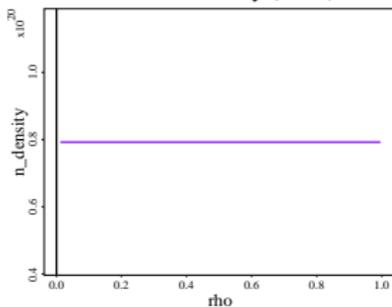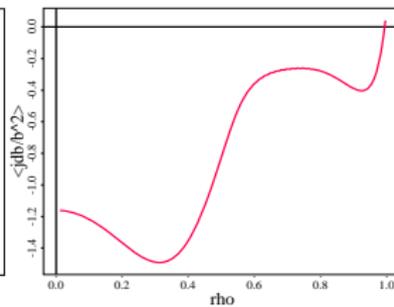
$n = 1$ linear growth rate scales as $\gamma \propto \eta^{0.49}$, contour plot shows $(1,1)$ mode structure (No vacuum region, ohms='mhd', uniform resistivity)
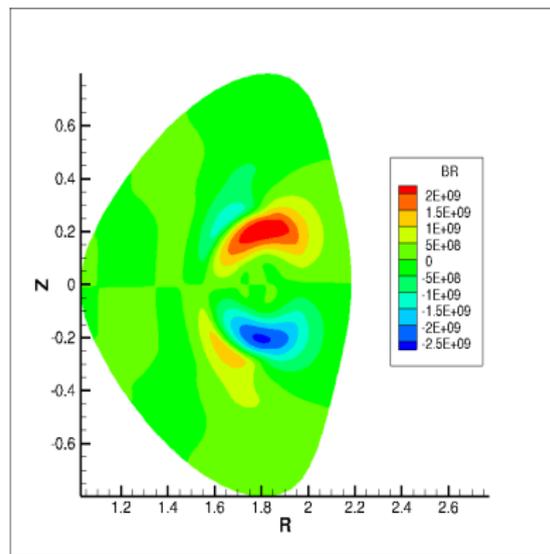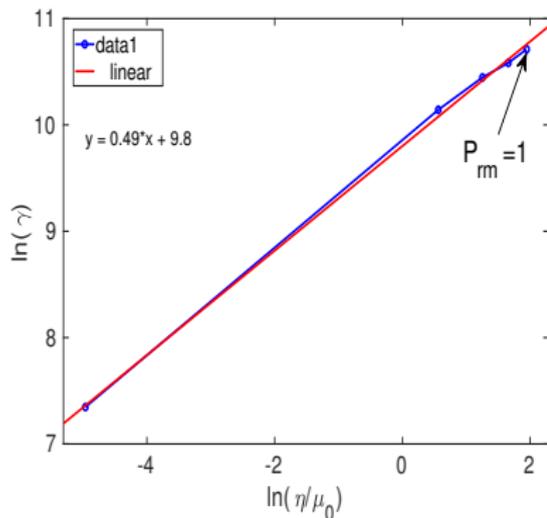
Figure: Viscosity is kept to be a constant so that $P_{rm} = 1$ at the point marked in the left plot.

When $S = 10^5$, poincare plots evolution shows the flux surface distortion and magnetic reconnection (nonlinear simulation, $n = 0 - 1$)
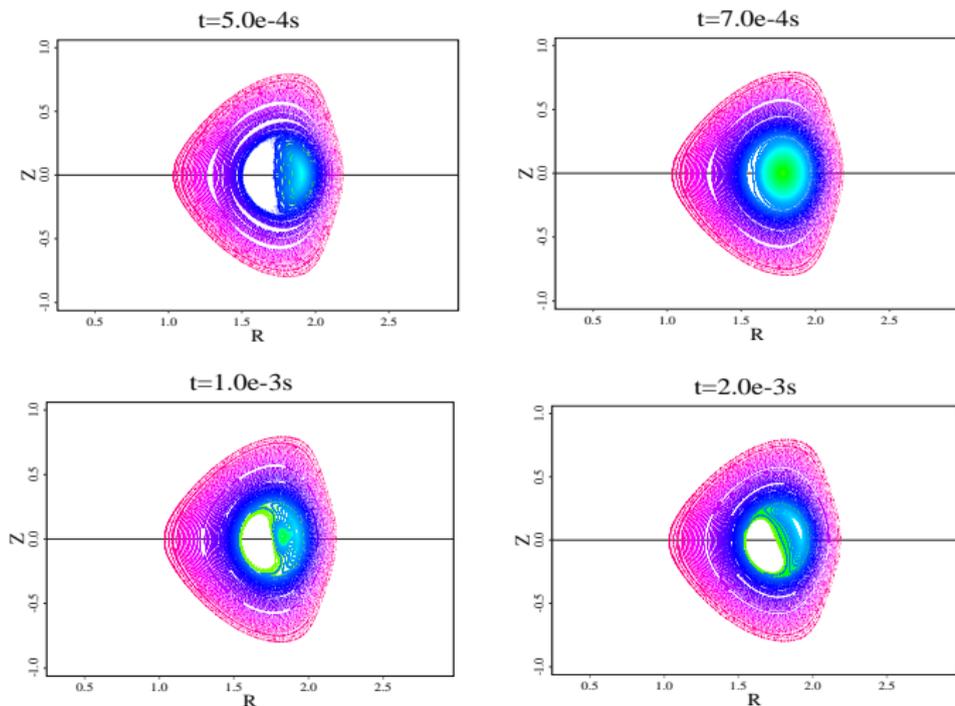
When $S = \infty$, $n = 1$ linear growth rate is nearly zero, no obvious flux surface distortion or reconnection is observed (nonlinear simulation, $n = 0 - 1$)
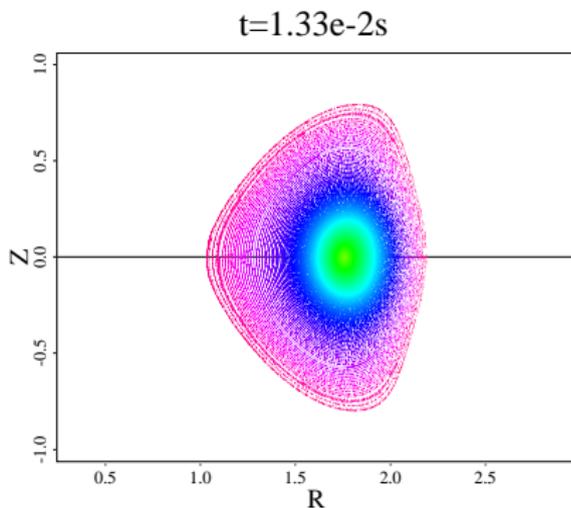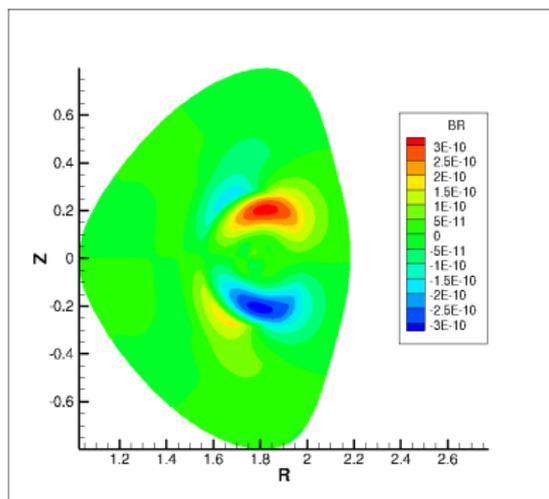
This negative triangularity configuration can be stable in ideal MHD limit.

We further include external mode in calculation (self-similar wall, ohms='2fl', Spitzer resistivity, high viscosity in vacuum region)
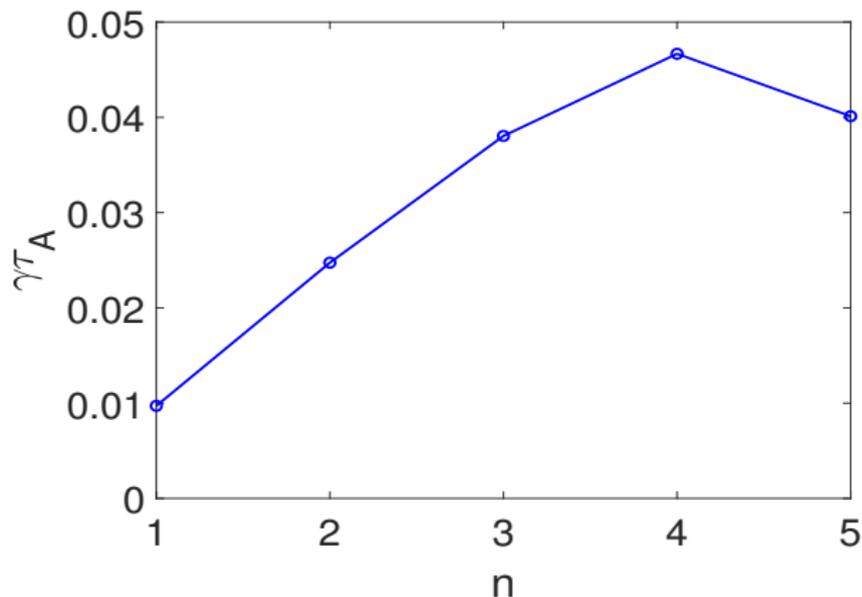
Linear growth rates typical of edge localized modes (ELMs).

Mode structure characteristic of ELMs
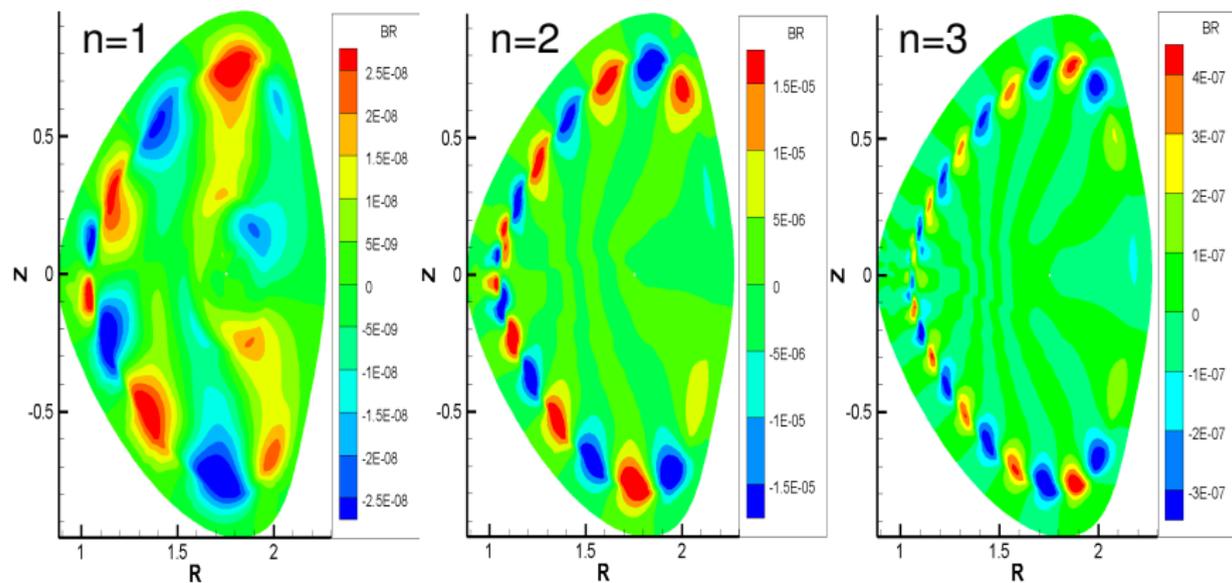
Two types of $n = 1$ mode structures have been found in the calculation
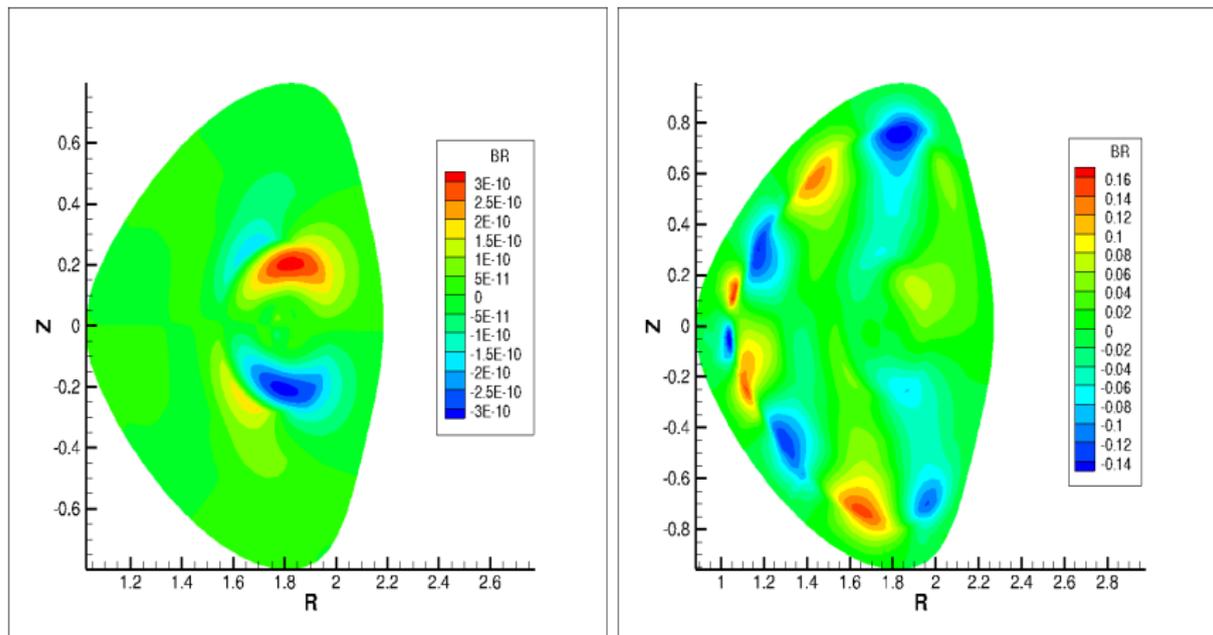
Figure: Left: No vacuum region, uniform resistivity; Right: Self-similar wall located at $b = 1.2$, Spitzer resistivity.

Outline

Three kinds of triangularities based on DIII-D configuration adopted for comparison

Finite Element Mesh
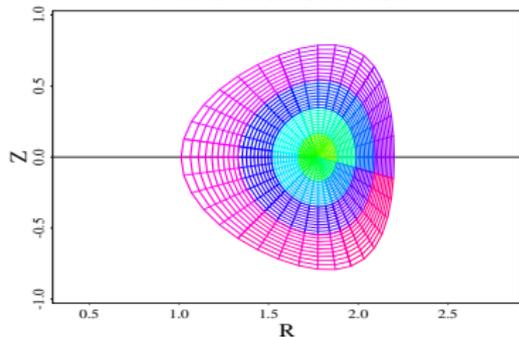
Finite Element Mesh
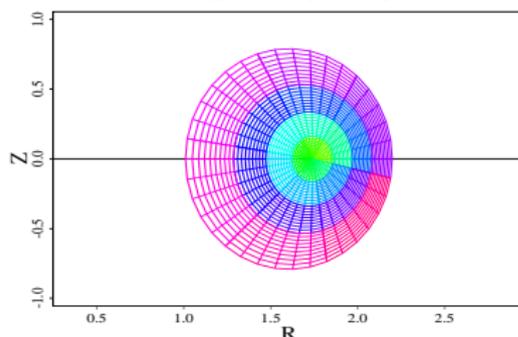
Finite Element Mesh
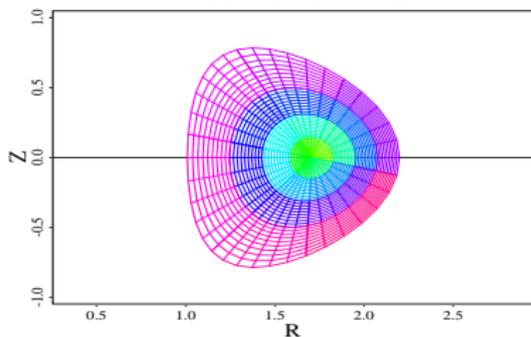
- Top left: $\delta = -0.4$
- Top right: $\delta = 0$
- Bottom left: $\delta = 0.4$

Equilibrium profiles used in analysis are DIII-D L-mode type
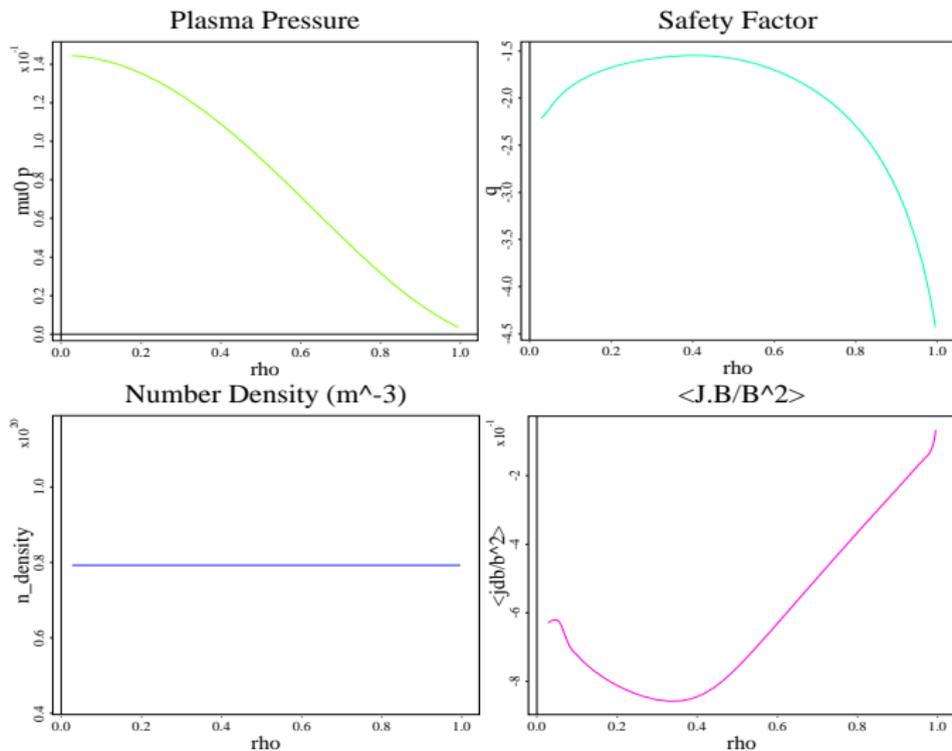
Critical wall positions for $n = 1$ mode from NIMROD consistent with AEGIS results
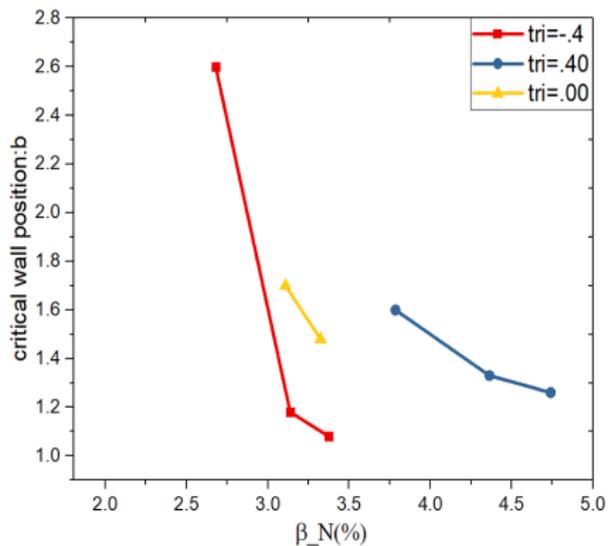
NIMROD simulation
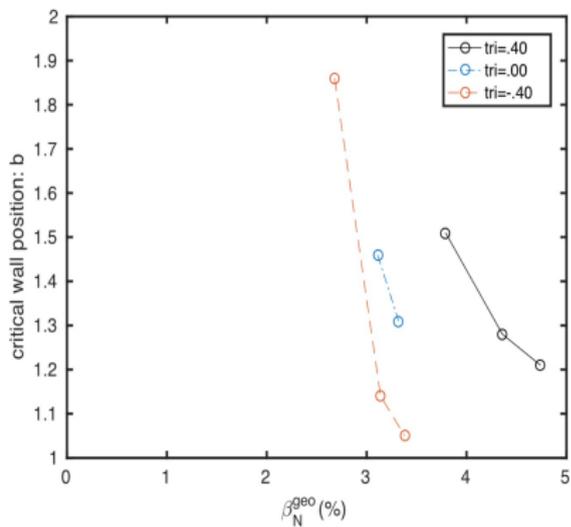
AEGIS simulation [L.-J. Zheng et al, Sherwood (2018)]

For a fixed wall position, β limit in negative triangularity configuration is lowest, but acceptable

$(2, 1)$ mode structures are shown in three triangularity cases
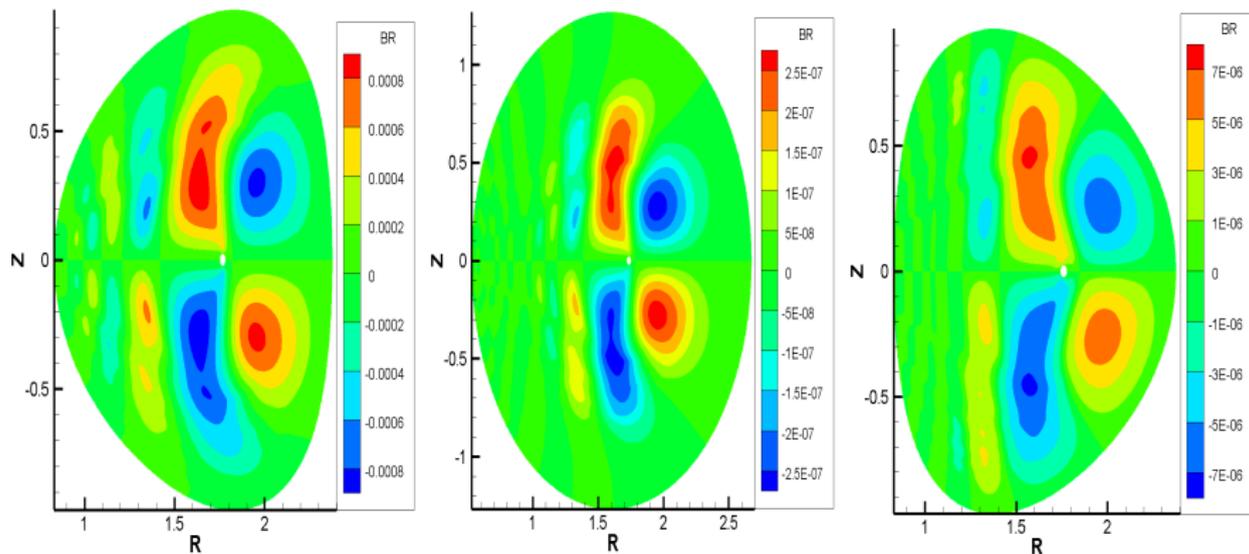
From left to right: $\delta = -0.4$, $\delta = 0$, $\delta = 0.4$

With similar equilibrium profiles, $n = 1$ internal mode stability is evaluated for three triangularities ($S = 10^5$, no vacuum region)
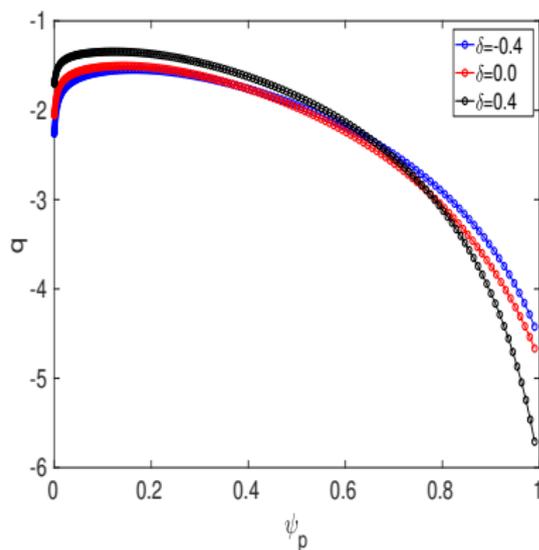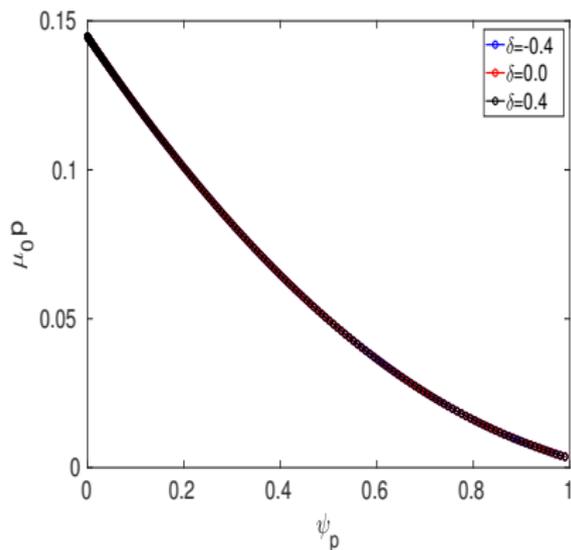
Left: pressure profiles; Right: safety factor profiles

$(2, 1)$ **unstable mode and magnetic island are found only in negative triangularity case. Positive and zero triangularity cases are stable**
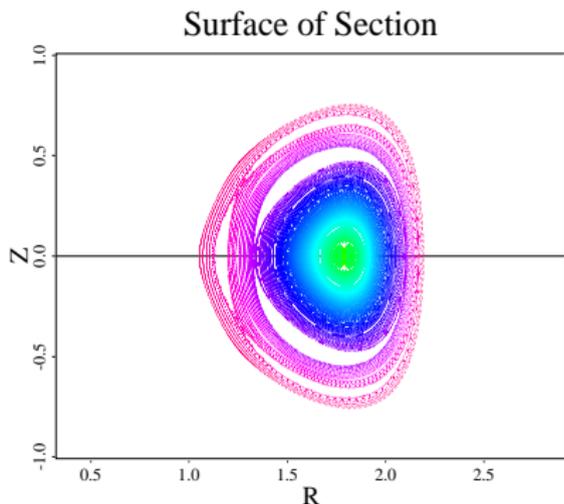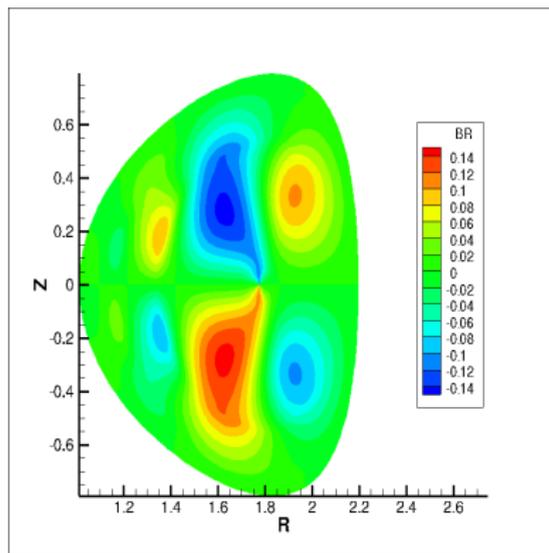
Negative triangularity more unstable for resistive internal mode as well.

Outline

Advanced scenarios of DIII-D L-mode profile can be obtained from reduced Ohmic and enhanced bootstrap current fractions [L.-J. Zheng et al, Sherwood (2018)]
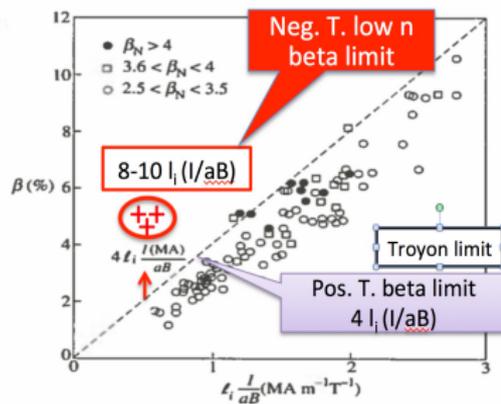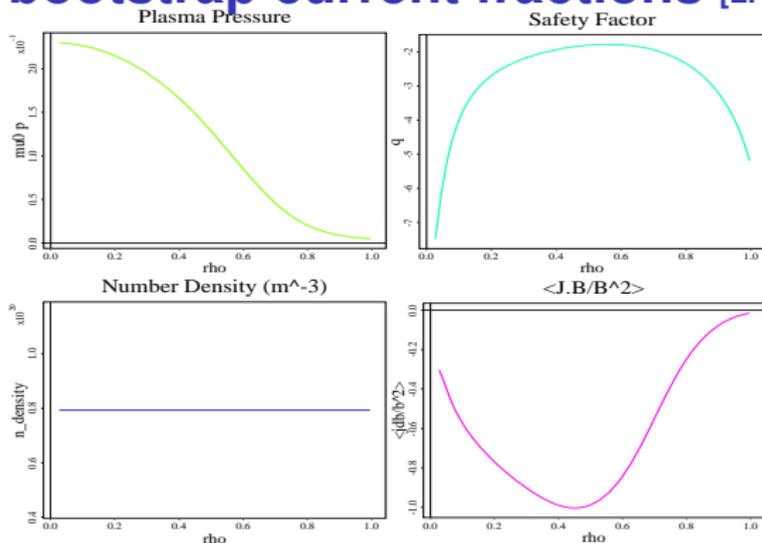
- Both AEGIS and DCON show that positive triangularity becomes unstable above Troyon limit.
- However low n kink modes remain stable in negative triangularity case when β is above Troyon limit.

NIMROD calculation on advanced scenario with positive triangularity is consistent with AEGIS results
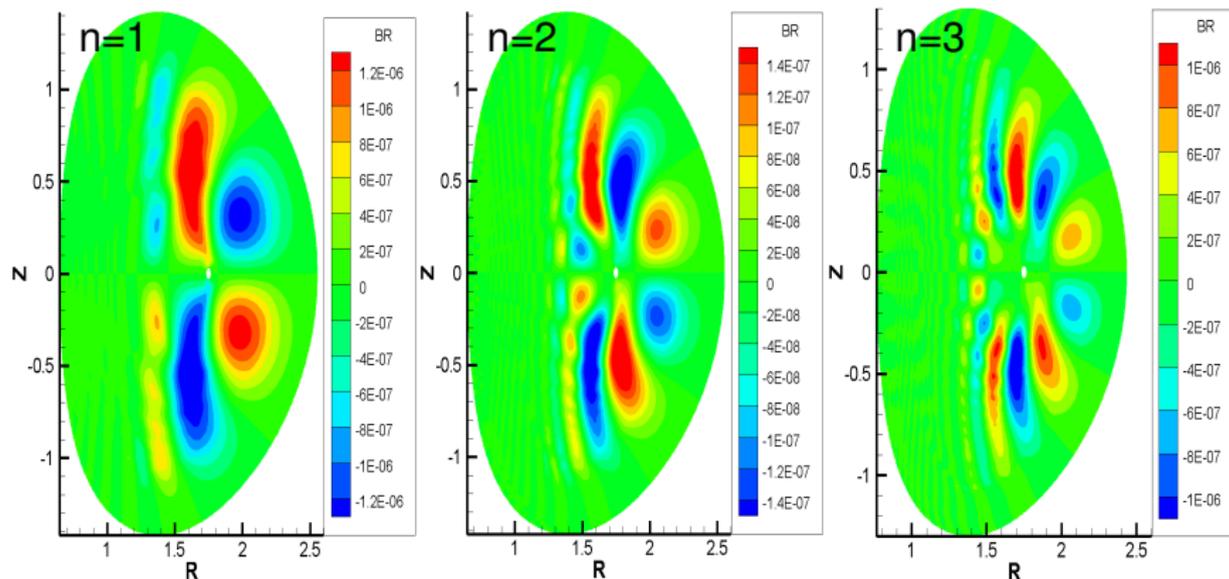
Comparison of critical wall positions (NIMROD/AEGIS):
$1.43/1.4(n = 1)$, $1.52/1.47(n = 2)$, $1.28/1.4(n = 3)$

However, negative triangularity case is found $n = 1$ linearly unstable in NIMROD analysis (inconsistent with AEGIS/DCON)
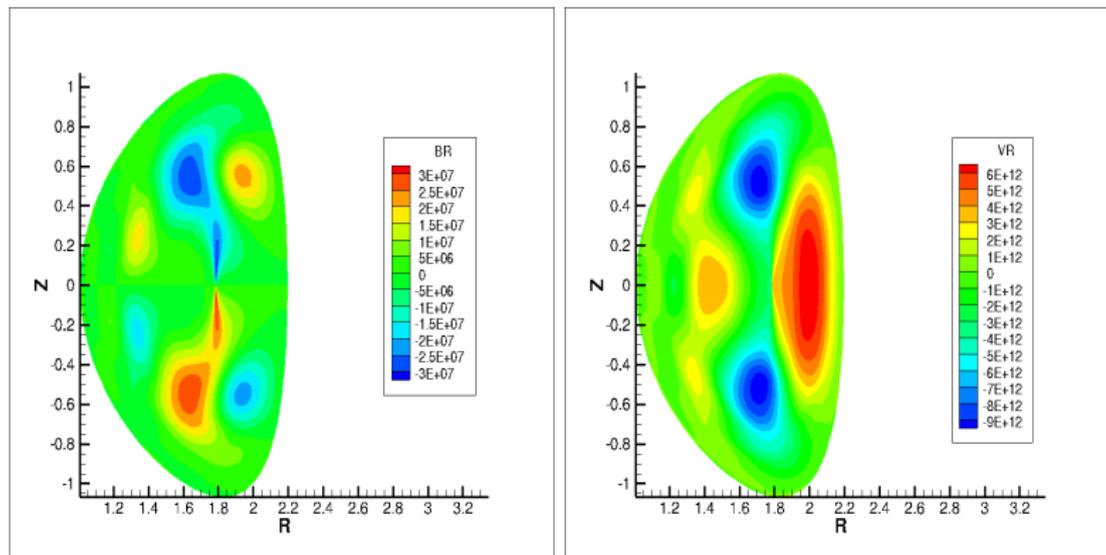
$n = 1$ linear growth rate seems independent on: η/μ_0 ($0 - 7m^2/s$); viscous coefficient ($0 - 0.7m^2/s$); mx/my ($36/36 - 144/144$).

Linear growth rate of $n = 1$ internal modes changes with β non-monotonically

One case looks special: $\beta = 3.51\%$.

Characteristics of this case: edge pedestal, strong reversed shear, bootstrap current near edge
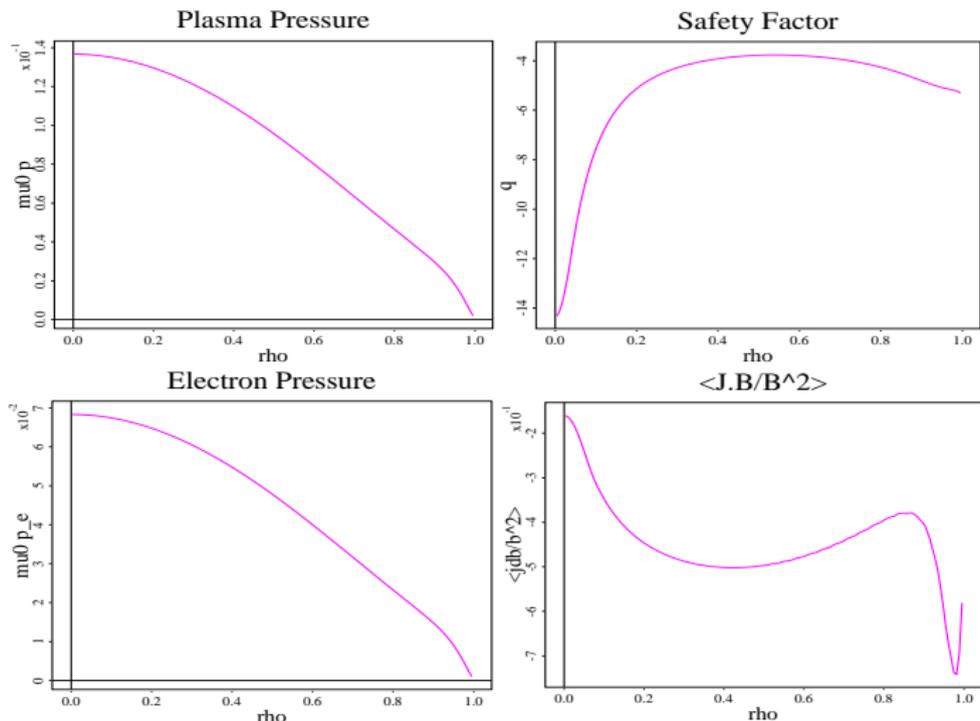
This case may provide a possibility for profile optimization.

Outline

Summary

- NIMROD analysis on DIII-D type L-mode profiles for different triangularities:
  - Consistent $n = 1$ critical wall positions with AEGIS calculation;
  - For a fixed wall location, β limit in negative triangularity configuration is the lowest, but acceptable;
  - Comparison among different triangularities with similar equilibrium profiles shows negative triangularity the most unstable.
- NIMROD analysis on advanced L-mode scenario (with high bootstrap current fraction) profiles:
  - Consistent with AEGIS results in positive triangularity configuration;
  - But not in negative triangularity case (still under investigation);
  - There is a possibility for profile optimization.