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Resistive MHD Evolution of Shaped RFP Equilibria

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Abstract

Computational modeling of the resistive MHD evolution of reverse-field-pinch (RFP) plasmas with boundary shaping is undertaken. The VMEC code obtains equilibria that are similar to quasi-single helicity (QSH) states in an RFP with a helical axis and a symmetric boundary [J.D. Hanson, et al., *Nuclear Fusion* **53**, 083016 (2013)]. Previous work has shown that axisymmetric boundary shaping affects whether an axisymmetric or QSH equilibrium is obtained in VMEC and it affects the extent of the swing of the helical axis in the QSH state. In this work, these equilibria are used as initial conditions for the NIMROD code [C.R. Sovinec, et al., *Phys. Plasmas* **10**, 1727 (20030]. Resistive MHD behavior will be explored and particular attention will be paid to the evolution of global tearing modes in both axisymmetric and helical equilibria.

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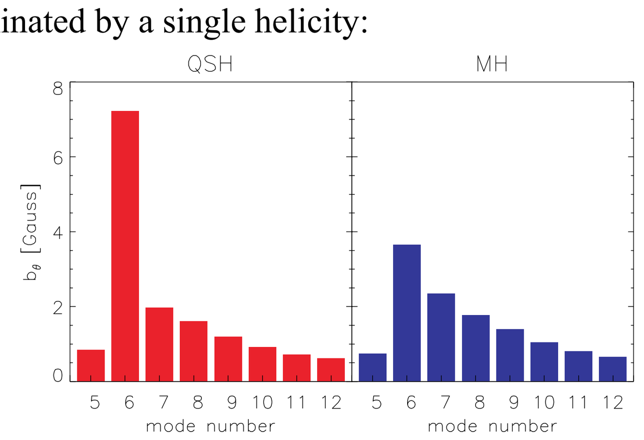
Motivation

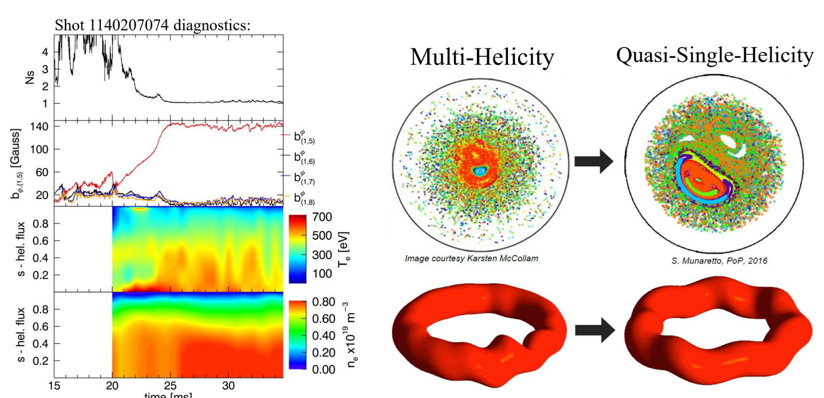
- RFP experiments have observed quasi-single helicity (QSH) or single-helical-axis (SHAx) states that have improved confinement relative to standard multiple helicity (MH) RFP configurations
  - Helical plasma with an axisymmetric boundary!
  - QSH and SHAx states are more likely at higher Lundquist number and higher plasma current
  - Magnetic spectrum dominated by a single helicity:

Toroidal mode number, n, spectrum of magnetic Fluctuations for QSH & an MH configurations



  - Figure 8 from P. Martin, et al., Nucl. Fusion **43** (2003) 1855
  - QSH develops when the inner-most tearing mode grows to large amplitude

Transport barriers develop in the core and secondary modes drop to low amplitude.

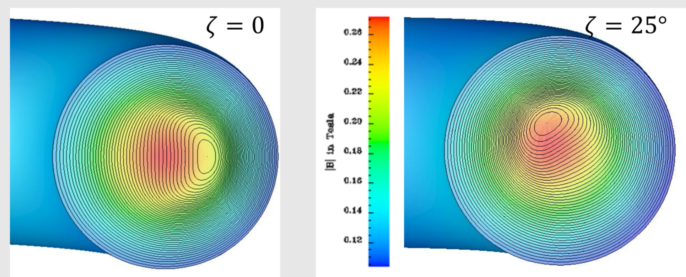


  - Figure from J. Boguski (private communication)
  - See D.F. Escande, et al Phys. Rev. Lett. **85** (2002) 1662 and P. Martin, et al., Nucl. Fusion **43** (2003) 1855–1862 and others
- Shaping the boundary has been hugely beneficial in improving stability for tokamaks – could shaping of the boundary have a beneficial impact for a reverse field pinch?
  - Current RFP experiments have essentially circular boundaries
- Previous work has examined the impact of axisymmetric shaping on RFP equilibria in VMEC
  - Adding ellipticity to the boundary of an RFP equilibrium results in a larger swing of the helical axis
  - We are able to optimize for the helical swing of the axis by changing the axisymmetric shape of the boundary
  - See Poster CP11.00140 Ware, et al., for more details
- What impact does this boundary shaping have on MHD stability in these RFP equilibria?
  - We can examine the effect on resistive MHD stability and dynamics using the NIMROD code

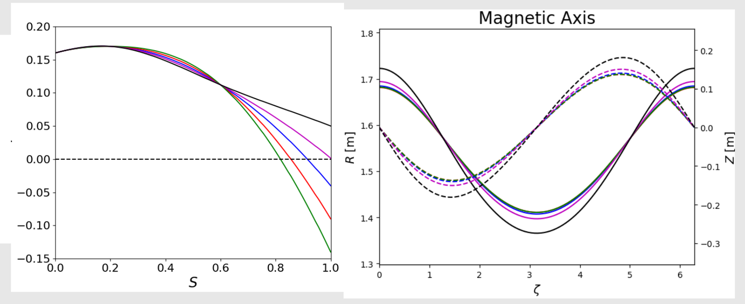
Shaping the boundary affects the equilibrium

- We have previously used the VMEC code to analyze RFP equilibria
  - Under certain conditions the solutions bifurcate to either an axisymmetric solution or a QSH-like state with a large swing of the helical axis, depending on the initial guess of the magnetic axis

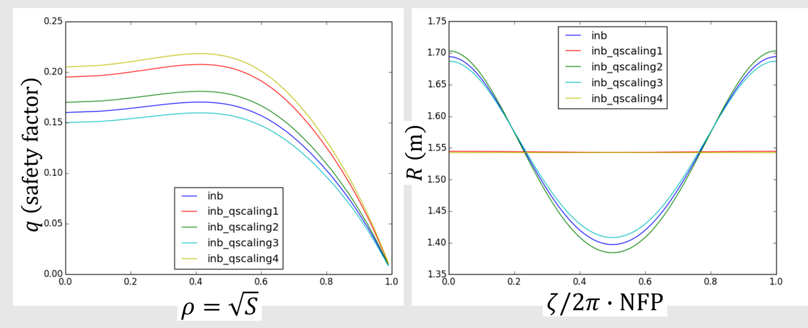
Two cross sections of an MST-like equilibrium with an axisymmetric boundary and a helical axis, i.e., a QSH-like state.



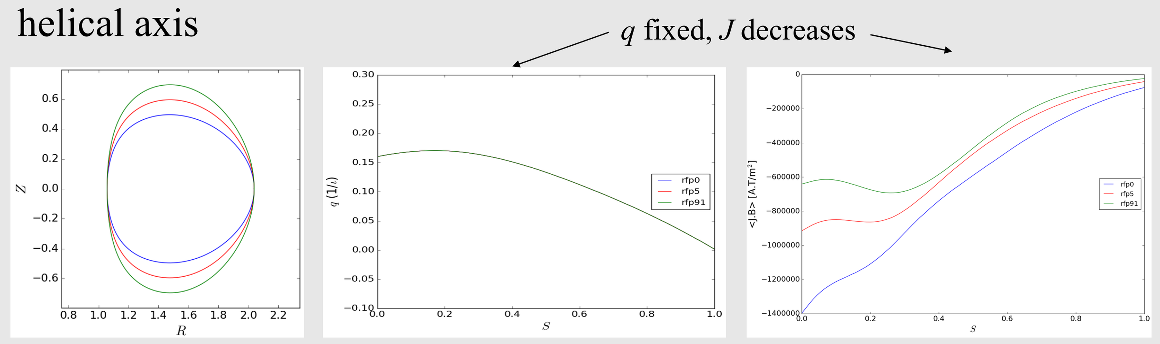
Varying the q-profile to move the reversal surface in and out had modest effect on the QHS solution.



Moving the $q = 1/5$ surface into the plasma results in no helical axis states for NFP = 5.

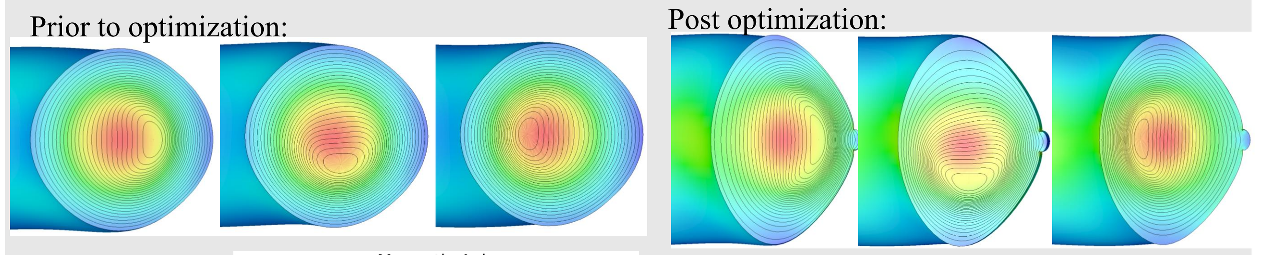


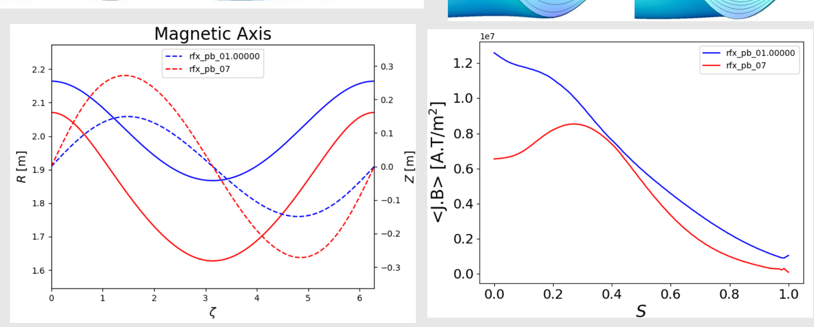
- Adding ellipticity to the outer boundary decreases the current required to achieve the same q-profile and increases the swing of the helical axis



- Optimizing for an increased swing of the helical axis results in increased ellipticity in the outer boundary

Prior to optimization: Post optimization:





  - Again, see Poster CP11.00140 Ware, et al., for more details

NIMROD: A resistive MHD code

- The NIMROD code uses a finite element discretization in the poloidal plane of fusion devices with a semi-implicit time step to capture the time-dependent nature of the MHD equations [See A.H. Glasser, et al., Control. Fusion **41** (1999) A747-A755]
  - The 2D elements allow for arbitrary selection of cross-sections, but the Fourier series require periodic symmetry within the device
  - The elements are either quadrilateral or triangular, and allow for nonlinear spacing according to flux surface, so that particular surfaces of interest may gain higher resolution
  - There is a rich background of research utilizing NIMROD to model non-ideal plasmas

Preliminary NIMROD runs

- NIMROD uses non-ideal MHD equations with 2-fluid effects, but for the purposes of our work we limit NIMROD to the resistive MHD model

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

$$\frac{3n}{2}\left(\frac{\partial T}{\partial t} + \vec{V}\cdot\nabla T\right) = -\frac{p}{4}\nabla\cdot\vec{V} - \nabla\cdot\vec{q} + Q$$

$$\frac{\partial n}{\partial t} + \nabla\cdot(n\vec{V}) = -\nabla\cdot(D\nabla\nabla^2 n)$$

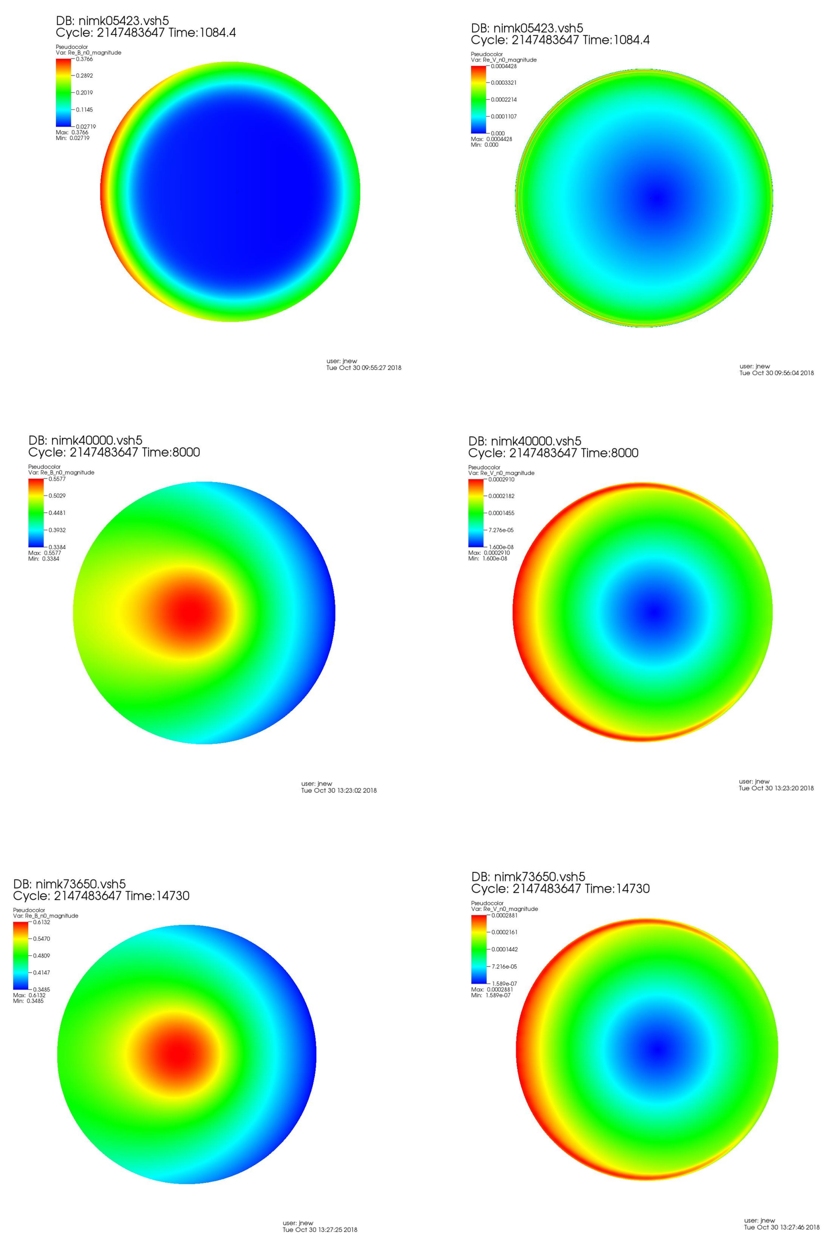
$$\frac{\partial\vec{B}}{\partial t} = \vec{\nabla}\times(\vec{V}\times\vec{B} - \eta\vec{J}) + \kappa_{divB}\nabla\nabla\cdot\vec{B}$$

$$p = nk_B(T + T_e)$$

$$\vec{J} = \frac{\nabla\times\vec{B}}{\mu_0}$$

$$\vec{E} = -\vec{V}\times\vec{B} + \eta\vec{J}$$

- We have installed and compiled the main version of NIMROD on Edison at NERSC
- We have begun preliminary NIMROD runs to establish that our implementation of the code is working as expected
  - We have run several linear trials examining the n = 0 toroidal mode in an RFP device from files given to us by Urvashi Gupta at the University of Wisconsin Madison



To the left are 3 instances of the time evolution of the n = 0 toroidal mode. The left column shows the time evolution of the magnetic field strength, and the right column shows the progression of the ion velocity

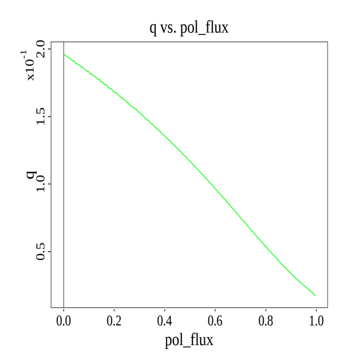
As time increases the ion flow on the outer flux surfaces generates a magnetic field which increases the magnitude of the magnetic field in the core of the device

As would be expected for RFP devices, the velocity of the ions has generated a strong magnetic field in the core

For further information regarding QSH states in RFPs see Urvashi Gupta's poster [UP11.00003]

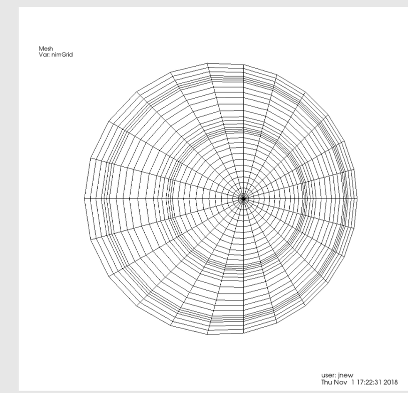
- From these preliminary runs we also want to know how to classify the behavior we would observe, which is conventionally done by observing the safety-factor profile

The safety factor profile of the device above plotted against the poloidal flux

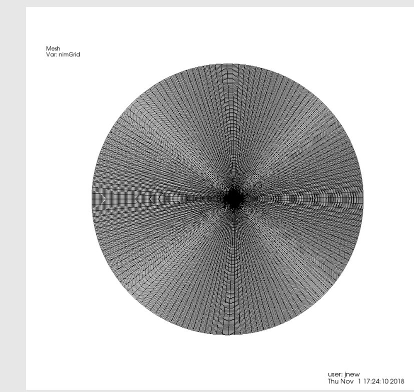


- The next steps involve testing the implementation of NIMROD at higher toroidal numbers, especially the n = 5 and n = 6 mode numbers, where QSH states are most commonly observed
  - We will focus on fitting appropriate mesh configurations to these cases, in preparation for tests involving shaped boundaries

- The mesh used in NIMROD allows for nonlinear packing which yields increased resolution at given flux surfaces, and a wide variety of cross-sectional geometries
  - The mesh is composed of triangular and quadrilateral elements, which give a great range of potential resolutions for the interpolating Lagrange elements
  - We have run several linear and nonlinear tests with different mesh configurations



A flux grid with gaussian packing from a linear test (left) and a circular grid from a nonlinear test (right). Both grids have offset axes from the geometric center of the cross-section, which will be important to packing the mesh around the QSH magnetic axis



- Appropriate choice of packing will be crucial to high quality tests of shaped boundary cases and observations of tearing modes
  - Shaping has been shown to increase the helical excursion for states with QSH, so high degrees of resolution in those regions will allow detailed examination of the evolution of those states in resistive plasmas

Modifying NIMROD to read in an RFP equilibrium from VMEC

- N. Roberds had previously modified NIMROD to read in a VMEC equilibrium to model sawtoothing in the CTH device
  - N. Roberds, et al. Phys. Plasmas **23**, 092513 (2016)
  - Assumed a free-boundary equilibrium
  - This requires a filamentary description of the plasma coils and is incompatible with RFP solutions in VMEC (which are fixed-boundary)
  - This trunk of NIMROD did not become part of the main branch
- We have begun modifying the NIMROD code to accept either a fixed or free boundary VMEC equilibrium
  - Since a fixed-boundary VMEC equilibrium does not have a representation of the coils, we must assume a conducting wall at the plasma boundary
  - No normal component of the magnetic field at the boundary and a no-slip boundary condition

and $\vec{V} = 0$ on the boundary

  - Our goal is to test the effects of axisymmetric shaping of the boundary on the nonlinear MHD evolution of RFP configurations

Discussion

- Shaping of the boundary affects the equilibrium of RFP configurations but we don't know yet the impact of shaping on MHD evolution
- Once the nimvmec branch of NIMROD is rebuilt we can begin testing the effects of axisymmetric shaping of the boundary
  - Need to read wout files from VMEC equilibria of shaped boundaries into NIMROD
  - After the branch is working, we can observe the effects of boundary shaping, with particular attention paid to QSH states in a non-ideal RFP plasma
  - One of the primary challenges is to model a conducting wall at the boundary, with no vacuum region

Copies of this poster can be downloaded at:
hs.umt.edu/physics/research/Plasma_Group/downloads/aps2018_poster_newman.pdf