Numerical Simulations of Current Channel Relaxation For Non-Inductive Startup

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Outline

- Methods of Non-Inductive Startup
- Washer-Gun Injection in Pegasus
- Modeling Current Injection in NIMROD
- Progress with Anisotropic Thermal Conduction
The Need For Non-Inductive Startup and DC Helicity Injection in Spherical Tokamaks.

- The low aspect ratio of Spherical Tokamaks has important implications for current drive.
- ST's can access a larger stable operating space, especially at high normalized currents.
- Geometric constraints severely limit available Ohmic current drive.

[A. Sontag, APS-DPP 2007]
Utilizing Washer-Gun Sources for Non-Inductive Startup in Pegasus.

- Gun sources are placed in the lower divertor region.
- A helical background magnetic field guides the injected current to an anode plate (or the vacuum vessel itself) in the upper divertor region.

Illustration of gun-driven helical current filaments in Pegasus. [Eideitis et. al., JFE 2007].
Demonstration of Relaxation into a “Tokamak-like” Plasma.

Under certain conditions, helical or sheet-like current filaments are observed to relax into a configuration resembling a normal ST plasma.
Current Multiplication and Poloidal Flux Reversal Signal The Onset of Relaxation.

● The poloidal flux at the center column reverses due to large induced poloidal fields overtaking the background vertical field.

● Changes in magnetic topology result in plasma currents much larger than the injector current.

Data from a relaxing discharge in Pegasus. [Eideitis et. al., JFE 2007].
A Volumetric Source Term Has Been Added to the NIMROD Time Advance.

\[
\rho \left( \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right) = \vec{J} \times \vec{B} - \nabla \cdot \left( \rho \nu \nabla \vec{v} \right)
\]

\[
\frac{\partial \vec{B}}{\partial t} = -\nabla \times (-\vec{v} \times \vec{B} + \eta (\vec{J} - \frac{\lambda_{in,j} \vec{B}}{\mu_0}))
\]

- For 0-beta simulations, NIMROD solves this system of equations.
- This term produces an artificial electric field along the magnetic field which drives parallel current.
- The spatial structure of the \( \lambda_{in,j} \) parameter (and the magnetic field) determines the strength and location of this artificial source term.
Localization of the Volumetric Source Term.

- In the poloidal plane, the $\lambda_{in,j}$ parameter has the following structure:

$$\lambda_{in,j}(R, Z) = \frac{\lambda_{rf}}{\mu_0} \exp\left(\frac{(\vec{r} - \vec{r}_{rf})^2}{w_{rf}^2}\right)$$

- Implementing toroidal localization has been complicated, but for initial work we have used a simple half-cosine waveform:

$$\lambda_{in,j}(\phi) = \begin{cases} 
\cos\left(\frac{\pi - \phi}{n_{\lambda}}\right) & \text{if } |\phi| \leq \frac{\pi}{2}, \\
0 & \text{if } |\phi| > \frac{\pi}{2}.
\end{cases}$$
The Artificial Source Term Drives Current Indirectly By “Twisting” The B Field.

1. Apply localized $F_{AF}$
   
   $\vec{F} = \frac{F_{AF}}{n_0}$
   
   $\vec{B}_0$

2. $\vec{E}$
   
   $\vec{B}_0 + \vec{B}$
   
   [$\vec{B}$ adds a little twist like a candy wrapper.]

3. \[ \vec{B} \rightarrow \vec{F} = \vec{J} \times \vec{B}_0 \]

4. $\vec{J} \times \vec{B}_0$ launches a torsional Alfvén wave that tends to unwrap and spread localized twist.
   
   Side View
   
   $\vec{B}_0 \times \vec{B}$
   
   With Damping
General Simulation Parameters.

- Rectangular, Toroidal Domain.
- $30+ \times 30+$ FE Grid
- $5^{\text{th}} - 6^{\text{th}}$ Degree Polynomials.
- $20+ \text{ Fourier Components}$
- Radial mesh packing at the injection location.

Current injection is centered at $R=.35\text{m}, Z = -.7\text{m}$
After Initial Transients, Net Current Is Driven Along The Helical B Field.
One 0-Beta Simulation Has Been Driven Into Relaxation Conditions.

\(B_{\text{tor}} = 0.14 \, \text{T} \)  
(at center stack)

\(B_z = 3.7 \, \text{mT}\)

\( \text{elecd} = 10 \)

\( \text{kin_visc} = 1 \)

\(S = 3 \times 10^4\)

Time scale is thrown off due to a NIMROD reset to increase resolution.
The Initial Filamentary Structure Is Distorted As Field Reversal Occurs.

\[ I_{\text{tot}} = 4.6 \text{ kA} \]

\[ I_{\text{tot}} = 2 \text{ kA} \]

\[ I_{\text{tot}} = 0.5 \text{ kA} \]
Regions of Closed Poloidal Flux Have Formed on the Inboard Side.

The vertical magnetic field has reversed over a small portion of the inboard side.
Recent Simulations Have Utilized Anisotropic Thermal Conduction.

\[
\frac{n}{\gamma - 1} \left( \frac{\partial T_\alpha}{\partial t} + \mathbf{V}_\alpha \cdot \nabla T_\alpha \right) = -p_\alpha \nabla \cdot \mathbf{V}_\alpha - \nabla \cdot \mathbf{q}_\alpha + Q_\alpha
\]

- Anisotropic thermal conduction is expected to keep this heating localized along the current channel to maintain a cold, diffuse background plasma.
- p_model “aniso1” is used: user specified thermal diffusivity coefficients (both parallel and perpendicular) are used for Temperature evolution.
- Electrical resistivity has a \( T^{-3/2} \) dependence with respect to a user-specified value at 1 eV.
- With a hot current channel and a cold, diffuse background plasma we expect to see faster dissipation of reverse currents.
Finite Temperature Simulations Have Well Structured Reverse Current Sheets.

- With a fixed value of the injection parameter there is no observed saturation at a fixed total current as in the zero beta simulations.
- Finite temperature simulations require significantly less computational resources.
Viscous and Ohmic Heating Remain Localized to the Current Channel.

- Background temperature: 0.1 eV
As the Net Current Approaches 10 kA We Observe Two Distinct Types of Oscillations.

Large negative growth rates correspond to an instability in the current channels.

Sinusoidal oscillations in the growth rate are due to the nonlinear coalescence of the current channels.
Periodic Sloshing and Merging of the Filaments Leads to Instability as the Net Current Increases.

- As the net current is increased, instabilities are driven when the filaments directly interact.
- We also see strong reconnection being driven during these events.
Instabilities Temporarily Break Up the Structure of the Current Channels.

- As the filaments directly interact, large reverse current sheets form between them as reconnection is driven.
Instability in the Filament Develops on an Alfvenic Timescale.

$Dt = 4e^{-5}$ s
The Instability Quickly Saturates and the Filament Splits in Two.
Significant Field Reversal Has occurred with 20 kA of Net Current.

- Field reversal and poloidal flux amplification are beginning to occur on the inboard side of the filaments.
- This has begun to affect the filament dynamics – small regions of current have separated and moved inboard.
- The region of PF amplification is expanding vertically to fill out the domain.
Conclusions and Future Work

- Our simulations see significant movement and interaction of the current channels during ramp-up, which is consistent with fast camera imaging from Pegasus.

- As the vertical magnetic field is reversed on the inboard side we see a significant change in filament dynamics. This is encouraging because in experiment the relaxation process occurs after the center column poloidal flux reverses sign.

- Anisotropic thermal conduction simulations will continue to be run though relaxation conditions.