NIMROD simulations of flux injection in a coplanar gun

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Motivation

• inspired by successful SSPX simulations of coaxial flux injection and sustainment
  
• coplanar flux injection is used in several ICC experiments (e.g. P. Bellan’s experiment, Woodruff Scientific)
  
• study physics and numerics of helicity injection and flux amplification
  
• simulations will help improve operation and efficiency by elucidating physical processes of injection, columnation, reconnection, and flux amplification

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\(^b\) Hsu and Bellan, “On Jets, Kinks, and spheromaks formed by a planar magnetized coaxial gun”, PoP \textbf{12}, 2005
Summary

• axisymmetric NIMROD simulations of coplanar flux injection
  – challenging spatial scales of coplanar injector

• effects of Hall physics in flux injection

• modest success is encouraging, however still challenging spatial and temporal requirements, particularly as we progress to include more physics
  – more toroidal resolution
  – smaller dissipation parameters
  – self consistent dissipation/collision models
  – kinetics
NIMROD\textsuperscript{a} (NonIdeal MHD with Rotation - Open Discussion)

- massively parallel 3-D MHD simulation
- finite elements in poloidal plane and Fourier modes in toroidal direction → axisymmetric geometry
- utilizes Lagrange type quadrilateral structured finite elements in 2-D
- can handle extreme anisotropies, $\frac{X_{\|}}{X_{\perp}} \gg 1$
- flexibility to model general geometry → real experiments
- model experiment relevant parameters, $S > 10^7$
- semi-implicit advance, not restricted by magnetosonic CFL condition
- assumes a steady state background and evolves perturbed quantities $\rightarrow A(x, t) = A_s(x) + \delta A(x, t)$
- allows linear and nonlinear simulations

\textsuperscript{a} APS-DPP08 Dallas, TX
NIMROD equations

- NIMROD evolves the extended MHD equations

\[
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \\
\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \\
\mathbf{E} = -\mathbf{U} \times \mathbf{B} + \eta \mathbf{J} + \frac{1}{ne} \mathbf{J} \times \mathbf{B} \\
\hspace{3cm} + \frac{m_e}{ne^2} \left[ \frac{\partial \mathbf{J}}{\partial t} + \nabla \cdot (\mathbf{JU} + \mathbf{UJ}) \right] \\
\hspace{3cm} + \sum_\alpha \frac{q_\alpha}{m_\alpha} \left( \nabla p_\alpha + \nabla \cdot \Pi_\alpha \right) \\
\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{U}) = \nabla \cdot D \nabla n \\
mn \left( \frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi - \nabla \cdot p_h \\
\frac{n_\alpha}{\gamma - 1} \left( \frac{\partial T_\alpha}{\partial t} + \mathbf{U}_\alpha \cdot \nabla T_\alpha \right) = -\nabla \cdot q_\alpha + Q_\alpha \\
- p_\alpha \nabla \cdot \mathbf{U}_\alpha - \Pi_\alpha : \nabla \mathbf{U}_\alpha
\]
Inductive Flux Injection Model

- NIMROD has two available flux injection models\(^a\)
  - direct flux injection via Faraday’s law (specifying tangential \(E\) field at the boundary)
  - inductive flux injection via Ampere’s law (specifying a tangential \(B\) field at the boundary)
- inductive flux injection (i.e. specifying input current) is closer to (coaxial gun source) experiment
- exploit integral Ampere’s law \(\oint B \cdot dl = \mu_0 I\)
- specify \(B_\phi\) at the boundary corresponding to coaxial gap to induce poloidal current in simulation domain

\(^a\)C. Sovinec, “Ohmic Current Drive in NIMROD Simulation”, NIMROD internal note, 2005
Inductive Flux Injection Model cont.

- along the boundary corresponding to flux gap specify $B_\phi R$
  - otherwise boundary condition is no-slip perfect conductor

- prescribed $B_\phi R$ induces a poloidal current in the simulation domain

- amplitude of $B_\phi R$ may vary with time (e.g. constant slope or programmed from experiment)

- thin highly resistive layer along bottom to rapidly diffuse flux across bottom

- the resulting $\mathbf{J} \times \mathbf{B}$ force pulls in the flux, drives columnation
Coplanar Flux Injection Simulation

- cylindrical vessel with small flux gap of a few centimeters

- vacuum field is dipole-like $\sim 0.1 mWb$
  - flux gap located at top of the arc

- peak current is $40 - 100 kA$ ramped over $4 - 15 \mu s$

- thin highly resistive layer across bottom $10^5$ larger than background resistivity
Coplanar Flux Injection is more challenging than coaxial injection

- SSPX simulations use $\sim 400kA$ ramped over $\sim 100\mu s$
  - coplanar injection simulations use $10 - 100$ kA ramped over $5 - 10 \mu s$
  - initial magnetic flux is $\sim 10 \times$ smaller
  - larger inductive $E$ field

- coplanar geometry is more challenging than coaxial gun
  - coaxial gun is well resolved
  - no discontinuous jump in $\frac{\partial B_\phi}{\partial R}$

- $\lambda_g^{SSPX} \sim 10 - 15 m^{-1}$ - we attempt $\lambda_g \sim 10 - 100 m^{-1}$

- both spatially and temporally more challenging simulation
Coplanar Flux Injection is more challenging than coaxial injection cont.
$B_\phi$ along $Z=0$ shows discontinuity

- 4 curves are at $t = [0.53, 0.69, 0.82, 0.93] \mu s$
- note discontinuity at $R = 0.07$ and $0.095$ where boundary condition is specified
Zoomed in view of Coplanar Injection grid

discontinuous jump in $\frac{\partial B_{\phi}}{\partial R}$ requires high resolution

note the scale
Poloidal Flux Compression after $\sim 4.5\mu s$

- 10 contour lines $[-.13, .9] mWb$
- contour lines same value in both plots
Evolution of Poloidal Current

- left plot at $2.9\mu s$, contour range $[1.2, 11.7]kA$
- right plot at $4.2\mu s$, contour range $[1.8, 16.9]kA$
- current ramp time $10\mu s$, peak current $40kA$
Ongoing Work and Issues

- for resistive MHD fast injection results in strong Alfvénic flows
- Hall physics helps relieve strong flow issues
- but could drive smaller scale fluctuations
- still constrained by strong flows
- flux gap model is incomplete
  - no-slip perfect conductor b.c. no longer applies
  - consistent b.c. remains to be resolved