Numerical Simulation of Local and Coaxial Helicity Injection in Pegasus-III

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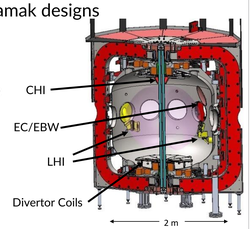
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Pegasus-III Experiment

Helicity Injection on Pegasus-III

- The Pegasus-III Experiment tests new startup and heating techniques relevant for fusion pilot plants
  - Non-solenoidal startup can simplify tokamak designs
    - Central solenoid removed
    - Expand inboard blankets
  - Major research goal is to investigate the physics and scaling of these techniques
    - Local Helicity Injection (LHI)
    - Coaxial Helicity Injection (CHI)



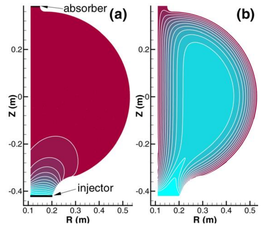
- Magnetic helicity is a topological quantity describing the 'twistiness' of a field configuration
  - $H = \int \boldsymbol{A} \cdot \boldsymbol{B}\, d^3x$
  - Conserved quantity in ideal MHD[1]
  - Approximately conserved in resistive MHD[2]
  - Helicity conservation is central to Taylor relaxation
  - Helicity is required for a rotational transform



Fast camera image of a Pegasus LHI discharge

- Local Helicity Injection
  - Localized injectors drive current along field lines
  - Current streams wind around the device many times
  - Lorentz attraction and reconnection between streams leads to relaxed tokamak-like configuration
  - Current multiplication of 17 previously reported[3]
  - Pegasus-III has been conducting LHI operations since August

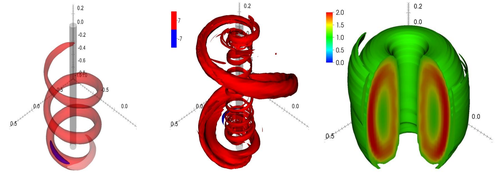
- Coaxial Helicity Injection
  - Nominally axisymmetric electrodes biased relative to each other
  - Drives current along intersecting field lines
  - ***E x B*** drift expands plasma outward
  - Studied on HIT[4-6] and NSTX[7-9]
  - Pegasus-III CHI experiments planned for next year



Poloidal flux contours from NIMROD simulation of CHI on HIT-II[10]

Modeling Startup with NIMROD

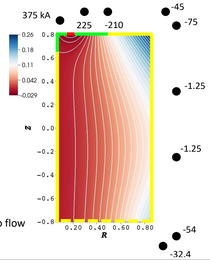
- NIMROD[11] is a 3D code for fluid-based plasma models
  - Spatial representation uses 2D finite elements in the poloidal plane and finite Fourier series in the toroidal angle
  - Particle density, ***B***, flow velocity, and temperature are evolved in a semi-implicit leap-frog time advance
  - Capable of modeling linear and nonlinear physics, visco-resistive dissipation, extended MHD including the Hall term, separate T_e and T_i, and 2-fluid physics
- John O'Bryan previously used NIMROD to investigate relaxation from LHI on Pegasus-II[12-14]
  - LHI injectors are treated as internally localized heat and ***E*** sources
  - $\partial \boldsymbol{B}/\partial t = \nabla \times [\boldsymbol{v} \times \boldsymbol{B} - \eta(\boldsymbol{J} - \boldsymbol{J_s})]$
  - Beam heating small compared to Ohmic, increases local conductivity
  - Provides significant phenomenological understanding of LHI relaxation via magnetic reconnection and current-ring formation



Simulated evolution of LHI parallel current density $\lambda = \mu_0 J_{||}/B$

- O'Bryan's code additions have been ported to the current version of NIMROD for simulations of Pegasus-III
  - Since O'Bryan's work, NIMROD has been modified to better conserve energy for 2-temperature and 2-fluid models
  - Relaxed CFL restrictions, enabling larger time-stepping
  - Initial efforts focus on verification and convergence studies

- New preliminary simulations of CHI have been conducted
  - Goal is to inform discharge scenarios
  - Simple 2D rectangular geometry
  - Electrodes represented as conductors
  - Simplified electrode geometry sized to intercept equivalent flux as design
  - Plasma inflow velocity at injector gap set to ***E x B*** drift speed

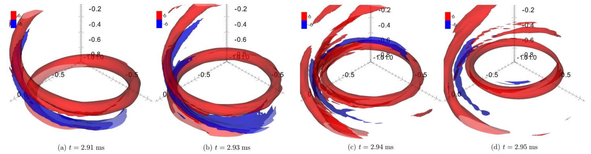


Boundary conditions for CHI simulations



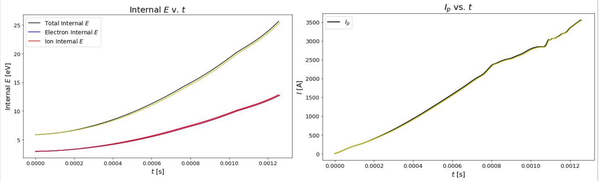
LHI Results

- O'Bryan found significant computational evidence of current-ring formation during the LHI relaxation process



λ contours showing ring formation through reconnection of helical stream

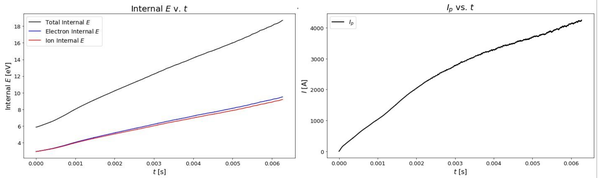
- MHD simulations show good agreement between O'Bryan's results and those from the updated version



Temperature and plasma current evolution for MHD simulations. Results from original code are shown in black, updated code in yellow.

- Simulations with separate T_e and T_i show differences
  - This is likely due to energy conservation changes
  - Remains a subject of investigation

- 2-fluid simulations show behavior qualitatively similar to MHD,

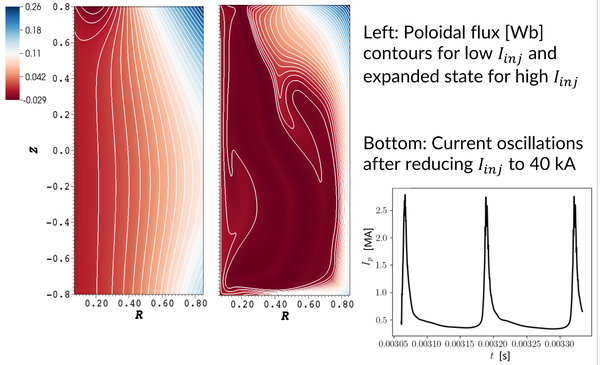


Temperature and plasma current evolution for 2-fluid simulations

- Future work
  - Further verification and convergence studies
  - Model vertical magnetic field ramping
  - Investigate scaling
  - Comparison with experimental results

Preliminary CHI Results

- Initial CHI modeling uses simple conditions
  - No plasma pressure or density evolution
- Simulations show bifurcation of results
  - No significant flux expansion for $I_{inj} \lesssim 40$ kA
  - For $I_{inj} = 45$ kA, flux quickly reaches the bottom boundary
- Large injector current leads to relaxation oscillations
  - Reducing I_{inj} back to 40 kA maintains oscillations
  - Further reduction to 37.5 kA ends expansion – hysteresis?
- No steady expanded flux configuration has yet been found
- Model improvements will make the simulations more realistic
  - Allow temperature and density evolution, variable resistivity
  - Revise simulated electrode configuration, including asymmetries
  - Resistive wall effects



Left: Poloidal flux [Wb] contours for low I_{inj} and expanded state for high I_{inj}

Bottom: Current oscillations after reducing I_{inj} to 40 kA

Summary & Future Work

- Helicity injection offers an alternative to solenoidal start-up
- Local and Coaxial Helicity Injection on Pegasus-III are being investigated experimentally and computationally
- NIMROD simulations provide insight into the dynamics and scaling of these techniques, and inform experimental scenarios
- Increased model fidelity will be aimed at predictive capability for Pegasus-III experiments

References: [1] Woltjer L., Proc. Natl. Acad. Sci. (1958); [2] J. B. Taylor, Phys. Rev. Lett. (1974); [3] D. J. Battaglia, *et al*, Nucl. Fusion **51**, 073029 (2011); [4] T. R. Jarboe, *et al*, Phys. Plasmas **5**, 1807 (1998); [5] T.R. Jarboe, *et al*, Nucl. Fusion **41** 679 (2001); [6] R. Raman, *et al*, Phys. Plasmas **4**, 022504 (2007); [7] R. Raman, *et al*, Nucl. Fusion **41** 1081 (2001); [8] R. Raman, *et al*, Nucl. Fusion **49** 065006 (2009); [9] B.A. Nelson, *et al*, Nucl. Fusion **51** 063008 (2011); [10] R. A. Bayliss, *et al*, Phys. Plasmas **18**, 094502 (2011); [11] C. R. Sovinec, *et al*, J. Comp. Phys. 195 (2004); [12] J. B. O'Bryan, *et al*, Phys. Plasmas, **19**, 080701 (2012); [13] J B O'Bryan, *et al*, Plasma Physics and Controlled Fusion, **56**, 064005 (2014); [14] J. B. O'Bryan, PhD. Dissertation, University of Wisconsin-Madison (2014);

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