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

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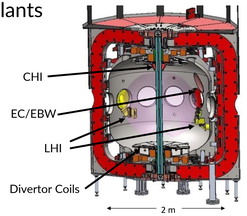
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Pegasus-III Experiment

Helicity Injection on Pegasus-III

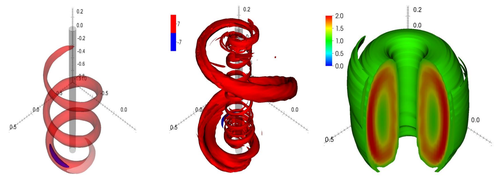
- The Pegasus-III Experiment tests new startup and heating techniques relevant for fusion pilot plants
  - Particularly important for low aspect-ratio tokamaks
  - Non-solenoidal startup methods:
    - Local Helicity Injection (LHI)
    - Coaxial Helicity Injection (CHI)
  - Supported by numerical work



- NIMROD[1] 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

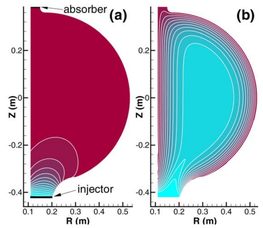
- Local Helicity Injection
  - Localized injectors drive current along intersecting field lines
  - Previous modeled with NIMROD by John O'Bryan for Pegasus-II [2-4]
  - Injectors are treated as internally localized heat and ***E*** sources

$$\partial \boldsymbol{B}/\partial t = \nabla \times [\boldsymbol{v} \times \boldsymbol{B} - \eta(\boldsymbol{J} - \boldsymbol{J}_s)]$$



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

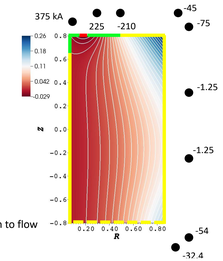
- Coaxial Helicity Injection
  - Nominally axisymmetric electrodes biased relative to each other
  - ***E*** x ***B*** drift expands plasma outward
  - Studied on HIT [5-7,11] and NSTX [8-14]



Poloidal flux contours from NIMROD simulation of CHI on HIT-II [15]

CHI Simulations

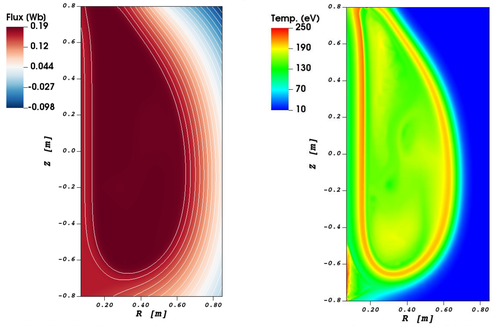
- New simulations of CHI have been conducted
  - Goal is to inform discharge scenarios
  - Simple 2D rectangular geometry
  - Electrodes represented as conductors
  - Simplified electrode geometry sized to intercept equivalent flux as design
  - Plasma inflow velocity at injector gap set to ***E*** x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



Boundary conditions for CHI simulations

conductor
injector gap
insulator
insulator open to flow

- Thermal effects have been incorporated, and have contributed to more realistic magnetic flux expansion
  - Density and temperature evolution, Ohmic heating, temperature-dependent resistivity, and Braginskii transport coefficients

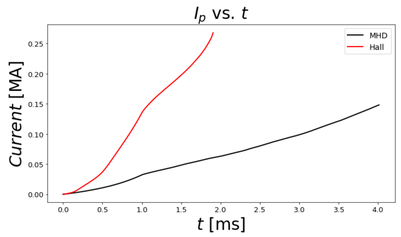


Poloidal flux and temperature contours of expanded CHI plasma

- Initial Hall-MHD results suggest relevance of the Hall term

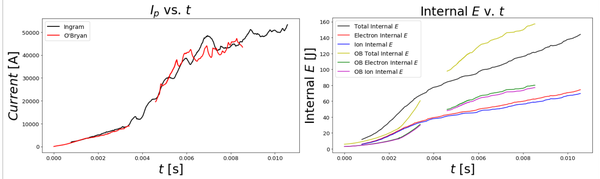
$$\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B} = \eta \boldsymbol{J} + \boldsymbol{J} \times \boldsymbol{B}/n_e e$$

  - 40 kA of injected current, electrode separation of 4 cm

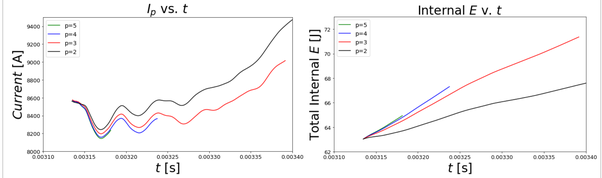


LHI Simulations

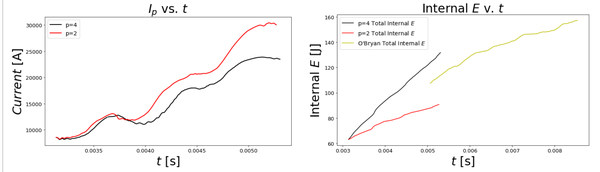
- LHI simulation runtimes have been extended to experimentally-relevant discharge durations (≥10 ms)
  - Reproduces current evolution of O'Bryan's work, not internal energy



- Convergence studies indicate these results are under-resolved
  - Vary spatial resolution through polynomial degree of finite elements

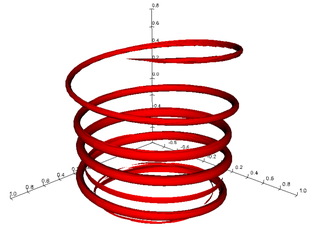


  - Increasing resolution results in significantly increased thermal content, moderately reduced current. These trends hold over time



  - O'Bryan's internal energy can be exceeded with sufficient resolution
  - Increased resolution will enable scaling studies of injector width w_{inj}

- New simulations of outboard LHI have been conducted
  - Outboard injection has engineering advantages
  - Relevant to Pegasus-III experiments



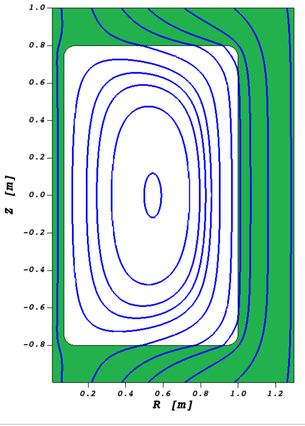
Parallel current density $\lambda = \mu_0 J_{||}/B = 2$ contour for outboard LHI (t=1.53 ms)

Resistive Wall Testing

- Pegasus-III uses programmable poloidal field coils for control
  - Particularly important for outboard LHI, to push current inward
  - Induction also contributes to non-solenoidal startup

- The resistive wall time of Pegasus-III is comparable to the duration of experimental discharges [16]
  - Significant impact on discharge dynamics

- NIMROD has a branch featuring resistive wall modeling
  - Has previously been utilized to investigate VDEs [17-18]
  - Computational domain is divided into two regions: plasma and vacuum
  - Plasma region evolves all the usual variables
  - Vacuum region only evolves the magnetic field
  - The resistive wall forms the interface between regions
  - Wall currents and flux penetration computed self-consistently



Simulated poloidal flux contours (blue) from a 2D flux compression computation of a tokamak equilibrium

The plasma region is shown in white, with the surrounding vacuum region shaded in green

Summary & Future Work

- Helicity injection startup techniques are being studied experimentally and computationally on Pegasus-III
- The physical fidelity of CHI simulations is being improved
- LHI simulations have reproduced prior results and have been studied for convergence. Work on outboard LHI has started
- NIMROD's resistive wall capability is being leveraged for future application to helicity injection studies

References: [1] C. R. Sovinec, *et al*, J. Comp. Phys. 195 (2004); [2] J. B. O'Bryan, *et al*, Phys. Plasmas, **19**, 080701 (2012); [3] J B O'Bryan, *et al*, Plasma Physics and Controlled Fusion, **56**, 064005 (2014); [4] J. B. O'Bryan, PhD. Dissertation, University of Wisconsin-Madison (2014); [5] T. R. Jarboe, *et al*, Phys. Plasmas **5**, 1807 (1998); [6] T.R. Jarboe, *et al*, Nucl. Fusion **41** 679 (2001); [7] R. Raman, *et al*, Phys. Plasmas **4**, 022504 (2007); [8] R. Raman, *et al*, Nucl. Fusion **41** 1081 (2001); [9] R. Raman, *et al*, Nucl. Fusion **49** 065006 (2009); [10] B.A. Nelson, *et al*, Nucl. Fusion **51** 063008 (2011); [11] F. Ebrahimi, *et al*, Phys. Plasmas **20**, 092702 (2013); [12] E. B. Hooper, *et al*, Phys. Plasmas **20**, 090702 (2013); [13] F. Ebrahimi, *et al*, Phys. Plasmas **21**, 056109 (2014); [14] E. B. Hooper, *et al*, Phys. Plasmas 23, 102502 (2016); [15] R. A. Bayliss, *et al*, Phys. Plasmas **18**, 094502 (2011); [16] M.W. Bongard, *et al*, Nucl. Fusion **59** 076003 (2019); [17] C.R. Sovinec, *et al*, Plasma Phys. Control. Fusion **61** 024003 (2019); [18] K. J. Bunkers, *et al*, Phys. Plasmas **27**, 112505 (2020);

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