Impact of Injected Current Streams on Magnetic Field Structure During Local Helicity Injection

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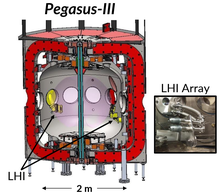
Pegasus-III Experiment

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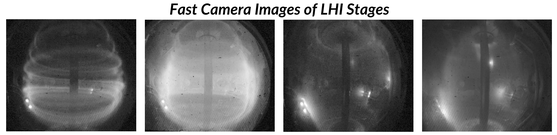
Local Helicity Injection (LHI) Provides Solenoid-Free Startup

- Pegasus-III: a dedicated facility to study solenoid-free tokamak startup
  - Complete removal of Ohmic solenoid
  - Initial operation focused on LHI studies
- LHI uses direct current injection to supply magnetic helicity and drive plasma current
  - Current extracted from small, modular injectors at plasma edge
  - Relaxation to tokamak-like state via helicity-conserving instabilities

Pegasus-III



Fast Camera Images of LHI Stages



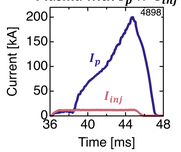
1. Injected current follows helical background field lines
2. Current streams go unstable, reconnect
3. Plasma relaxes to a "tokamak-like" state
4. Tokamak plasma after injector shutoff: stream perturbation goes away

I_{inj} = 3-4 kA per injector, 4 injectors total on Pegasus-III

Majority of magnetic energy is in axisymmetric mode

- LHI initiates a tokamak-like system
  - In relaxed state, magnetic structure looks like a tokamak in a toroidally averaged sense
  - Plasmas have $I_p \gg I_{inj}$
  - Even in relaxed state, there exists ≤16 kA of open field line current that perturbs plasma edge
    - Important to characterize current structure and understand its impact

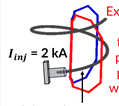
Pegasus-III LHI Plasma with $I_p \gg I_{inj}$



Simple Helix Model of Injected Current

- In unrelaxed discharge, injected current stream follows vacuum $\vec{B}$
  - Intended path: co-I_p, upwards to upper divertor
  - New observation: co-I_p helical field line following current path model insufficient to explain toroidally separated Rogowski coil measurements
- Helical field line following current path model plausibly sufficient if counter-I_p path downwards to lower divertor is accounted for in field line following calculations

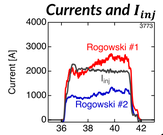
Expected through Rogowski #2: first windup = **2 kA**



Expected through Rogowski #1: first windup + possible full or partial second windup = **2-4 kA**

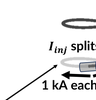
Injected current stream follows vacuum field line traced from injector

Rogowski Coil Currents and I_{inj}



Discrepancy could be explained by downward flowing current

Expected through Rogowski #2: first windup = **1 kA**



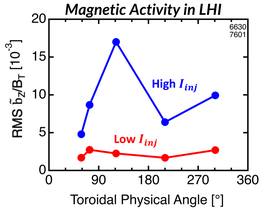
Inefficient line-of-sight break permits parallel paths, divides I_{inj}

Expected through Rogowski #1: first windup + possible full or partial second windup = **1-2 kA**

Injected Current Streams in LHI Create Large 3D Magnetic Perturbation

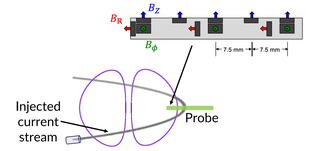
- Injected current streams in LHI create large 3D perturbation: $\frac{\tilde{b}_Z}{B_T} \sim 10^{-3} - 10^{-2}$
- Higher I_{inj} creates larger perturbation with higher toroidal variation
  - Higher I_{inj} plasma has higher peak $\frac{\tilde{b}_Z}{B_T}$ by factor of ~6 for similar I_p and programming

Toroidal Dependence of Magnetic Activity in LHI



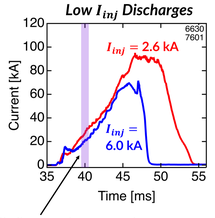
- 3D perturbations as small as $\frac{\delta B}{B_0} \sim 10^{-4}$ shown to drive transport and modify confinement on other tokamaks
- Expected to deform magnetic surfaces and induce stochastic edge region

- Insertable Hall sensor probe measures $\vec{B}(R,t)$ in plasma edge and stream region



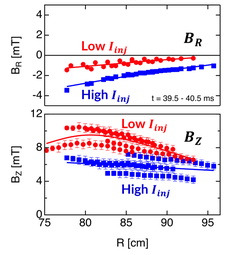
- I_{inj} level impacts local stream field structure, observed in measured $B_R(R)$, $B_Z(R)$

Plasma Current in High and Low I_{inj} Discharges



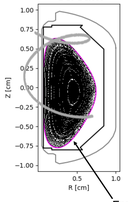
Similar I_p and programming in time window

Measured B_R, B_Z profiles



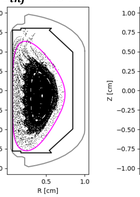
- Perturbation modeling suggests injected current stream impacts magnetic topology
  - FLARE[1] calculates magnetic topology of equilibrium with edge-localized stream
  - Streams ergodize magnetic structure, potentially induce island structures
  - I_{inj} level impacts ergodization

Equilibrium + Stream



From equil. reconstruction (4898)

Vacuum Field Superposition: I_{inj} ~ 1.5 kA



Vacuum Field Superposition: I_{inj} ~ 3 kA



$$\boldsymbol{B}_{total} = \boldsymbol{B}_{equil} + \boldsymbol{B}_{pert,vacuum} + \boldsymbol{B}_{response}$$

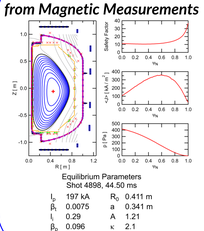
- Plasma response not included yet, motivates M3D-C1 calculations

Plasma Response Calculations in Progress

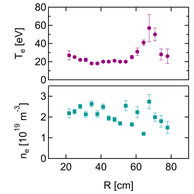
- Studies on other tokamaks suggest importance of including MHD plasma response to applied 3D fields[4,5]
  - Plasma can generate currents that screen out applied field
- Perturbation modeling of LHI plasmas on Pegasus-III is being extended to include plasma response
  - Injected current stream perturbation generates 3D plasma response
  - Calculations with M3D-C1[6] underway
  - Code inputs generated from Pegasus-III measurements and simple helix model of inject current
  - Initial studies will include sensitivity analyses to assess impact of injected current stream geometry, kinetic profiles, etc. on plasma response

Initial Inputs to M3D-C1

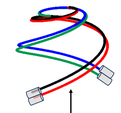
Equilibrium Reconstructed from Magnetic Measurements



T_e and n_e Profiles via Thomson Scattering Measurements



3D Field Generated from Simple Helix Model for Injected Current

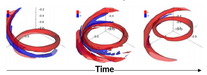


Injected current streams follow equilibrium magnetic field lines

Simulation and Measurements Suggest Complex, Dynamic Stream Structure

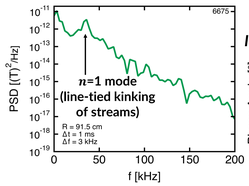
- NIMROD simulations of LHI show current drive from macroscopic reconnection of adjacent stream passes[2]

Passes attract, merge, reconnect to form current rings

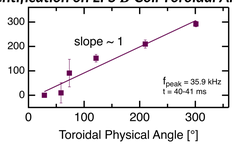


Rings diffuse inward, building poloidal flux

- Mechanism consistent with experimentally observed n=1 bursts that correlate with I_p increases on Pegasus[3]
- n=1 mode associated with singly line-tied kink of injected current streams
  - $f \sim$ 20—50 kHz
  - Identified in LHI magnetic spectrum

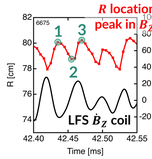


n=1 Confirmed with Phase-Slope Mode Identification on LFS $\dot{B}$ Coil Toroidal Array

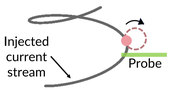


- Dynamics of Hall probe profile features correlated with n=1 stream motion
  - Probe $B_Z(R,t)$ shows in-out radial motion
  - Radial motion correlated with n=1 activity on LFS $\dot{B}_Z$ coil

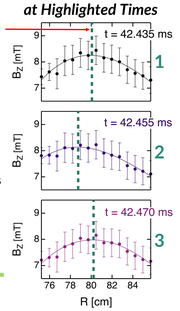
n=1 Oscillation Cycle



Consistent with stream pass undergoing transverse oscillations near probe

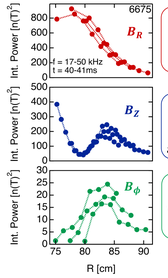


Hall Probe B_Z Profiles at Highlighted Times



- Variation in spatial localization of n=1 magnetic activity observed between field directions and with respect to time

Integrated Magnetic Fluctuation Power in n=1 Mode from 3D Hall Probe



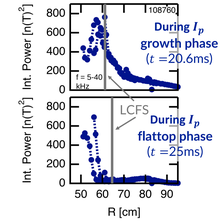
B_R power strong, peaked at R~78 cm

B_Z power peaked farther radially inward and at R~84 cm

B_ϕ power weaker, peaked at R~84 cm

- Possible coupling of stream motion in different directions to different internal modes

Time-Evolving Power in n=1 Mode from $\dot{B}_Z(R)$ Probe Relative to LCFS



- n=1 power peaks at LCFS initially, ~10 cm inward of LCFS later in time
- Possible low-f internal MHD activity rather than stream motion later in time

Summary

- Injected current streams in LHI plasmas create large 3D magnetic perturbation
  - Expected to ergodize plasma edge
  - Increasing I_{inj} level → larger perturbation, impacts local field structure
- Simple helix model of injected current stream structure plausible in unrelaxed discharges, serves as initial stream geometry for perturbation modeling input
- Simulation and measurements of LHI show a complex, time-evolving stream structure
  - n=1 mode associated with line-tied kinking motion of streams observed on LFS magnetics
  - Spatial localization of n=1 mode varies in time and between different directions
- Perturbation modeling is being extended to include plasma response to stream perturbation via M3D-C1 calculations

References: [1] H. Frerichs, Nucl. Fusion **64**, 106034 (2024); [2] J. B. O'Bryan and C. R. Sovinec, Plasma Phys. Control. Fusion **56**, 064005 (2014); [3] Reusch *et al.*, Phys. Plasmas **25**, 056101 (2018); [4] Frerichs *et al.*, Nucl. Mater. Energy Fusion **34**, 101380 (2023); [5] G.P. Canal *et al.*, Nucl. Fusion **57**, 076007 (2017); [6] N.M. Ferraro *et al.*, Phys. Plasmas **23**, 056114 (2016)

For more information: