Effects of Injected Current Streams on MHD Equilibrium Reconstruction of Local Helicity Injection Plasmas on Pegasus-III

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Pegasus-III Experiment

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Newly Commissioned Pegasus-III Studies Solenoid-Free Startup

- Mission: Compare, contrast, and synergistically combine power-plant relevant solenoid-free startup techniques to solve the tokamak startup challenge
- Pegasus-III startup systems:
  - Local Helicity Injection (LHI)[1,2]
  - Coaxial Helicity Injection (CHI)[1]
  - Radio-frequency (RF) assist and sustainment[1]
- **Goal:** develop validated physics and technology basis for MA-class startup

New Pegasus-III facility

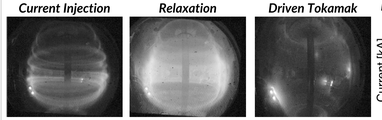


[1]J.A. Reusch *et al.*, YP11.00029 [2]A.C. Sontag *et al.*, YP11.00032

LHI makes Tokamak-like Plasmas via Edge Current Injection

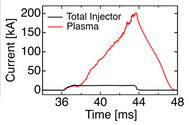
- Injected current streams reconnect and relax to tokamak-like state
  - Tokamak-like = toroidally averaged nested flux surfaces
- Experimental observations suggest injected current streams persist near outboard plasma edge throughout tokamak-like phase [1-5]
- Persistence of injected current stream presents challenges for MHD equilibrium analysis of LHI discharges
  - Important analysis tool for developing LHI physics basis

Current Injection | ***Relaxation*** | ***Driven Tokamak***



$I_p \sim N_{turns}\, I_{inj}$ $I_p \gtrsim N_{turns}\, I_{inj}$ $I_p \gg N_{turns}\, I_{inj}$

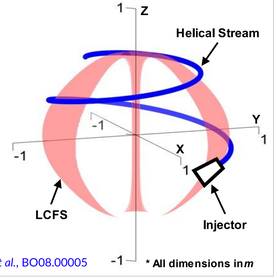
Pegasus-III LHI plasma with $I_p \gg I_{inj}$



Experimental Observations Motivate Current Stream Model

- Streams reasonably described by line-tied kink geometry, tied at the injector, and localized to the outboard plasma edge [1,3]
- **Model:** superposition of axisymmetric core plasma surrounded by helical injected current stream
- Simple stream geometry:
  - Originate at injector aperture
  - Follows helical magnetic field lines
  - Truncated at top of core plasma
  - Single filament of negligible cross-section
  - Uniform current density
- Model can be readily extended as understanding of stream structure continues to develop[1]

Schematic of simplified LHI plasma-stream model

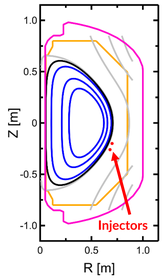


[1]C.E. Schaefer *et al.*, BO08.00005

Streams are a Measurable Perturbation to Pegasus-III Diagnostics

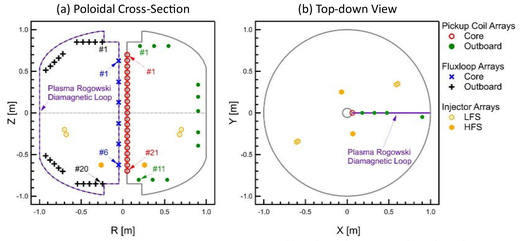
- Forward modeling used to quantify stream perturbation on Pegasus magnetic diagnostics
- Generated model equilibria spanning Pegasus and Pegasus-III operational space using KFIT [6,7] equilibrium code:
  - $100\ kA \leq I_p \leq 300\ kA$
  - $0.15\ T \leq B_T \leq 0.30\ T$
  - $2\ kA \leq I_{inj} \leq 4\ kA$ per injector
  - Low-ℓ_i, highly-shaped equilibria
  - Injectors positioned just outside LCFS

Representative model equilibria used in this work



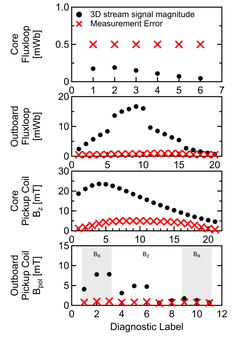
- Green's functions used to simulate Pegasus diagnostic suite
  - PF coils and core plasma: rectangular, axisymmetric current sources
  - Injected streams: Biot-Savart treatment of discretized helical path determined from equilibrium $\vec{B}$

Overview of representative Pegasus magnetic diagnostic suite



- Streams contribute a measurable perturbation to most of Pegasus diagnostic suite
- Stream perturbation increases with:
  - Diagnostic proximity to streams
  - Windup fraction (I_{windup}/I_p)

Simulated stream signal and measurement error for Pegasus diagnostic suite in representative $I_p = 100\ kA$ LHI scenario



Comparison of core and stream component of plasma Rogowski and diamagnetic loop

	Signal Component	
Signal	**Core**	**Stream**
Plasma Rogowski	$100\ kA$	$24\ kA$
Diamagnetic loop	$0.8\ mWb$	$-0.4\ mWb$

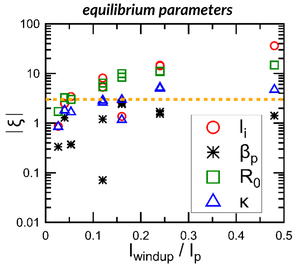
Stream Perturbation Leads to Systematic Errors in Reconstructed Equilibria

- Comparison of two model reconstructed equilibria
  - "Baseline": diagnostic constraints contain only signal from axisymmetric core plasma
  - "Stream perturbed": diagnostic constraints contain core and stream signals
- Differences in reconstructed equilibria are systematic errors introduced by the streams
  - Relative significance quantify by standardized residual: $\xi \equiv (\bar{M} - M)/\sigma$
    - Parameter uncertainty, σ, derived from Monte Carlo analysis
- Comparison shows statistically significant ($|\xi| > 3$) systematic deviations from baseline
  - Relative size of deviation scaled with relative size of the stream perturbation (I_{windup}/I_p)

Model equilibria comparison illustrates stream perturbation impact on reconstructed plasma parameters

	Equilibrium Reconstruction Scenario				
	Exact	**baseline**		**Stream perturbed**	
Parameter	value	value	ξ	value	ξ
$I_p\ [kA]$	100	100 ± 1	0	122 ± 1	22
β_p	0.37	0.38 ± 0.03	0.3	0.43 ± 0.03	2
$\langle\beta_T\rangle$	0.007	0.007 ± 0.001	0	0.012 ± 0.001	5
ℓ_i	0.24	0.24 ± 0.01	0	0.41 ± 0.01	17
$R_0\ [m]$	0.381	0.381 ± 0.002	0	0.421 ± 0.001	40
$a\ [m]$	0.326	0.326 ± 0.002	0	0.366 ± 0.001	40
κ	1.86	1.86 ± 0.01	0	1.73 ± 0.01	−13
δ	0.58	0.58 ± 0.01	0	0.52 ± 0.01	−6

Scatterplot of $|\xi|$ as a function of I_{windup}/I_p for several reconstructed equilibrium parameters



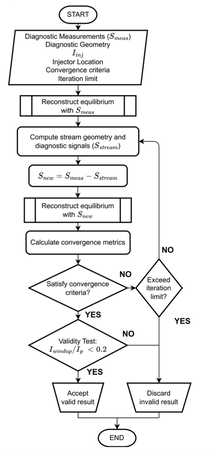
Proposed Iterative Methodology to Reduce Systematic Stream Error

- Iterative process developed to reduce systematic errors introduced by the streams during equilibrium reconstruction analysis
- Convergence metric: relative change in stream geometry between each iteration

$$CM = \frac{1}{N}\sum_{i}^{N}\left(\frac{|\vec{x}_{cur} - \vec{x}_{prev}|}{|\vec{x}_{prev}|}\right)_i$$

- For this work, $CM = 0.05$ chosen empirically
- Validity test based on inferred I_{windup}/I_p
  - Systematic errors found to be successfully mitigated in model equilibria when $I_{windup}/I_p \leq 0.2$
  - This is satisfied over much of LHI operation space which is typically characterized by $I_{windup}/I_p \leq 0.1$
- Method agnostic to assumed stream geometry
  - Readily incorporates updated models for stream geometry as understanding develops

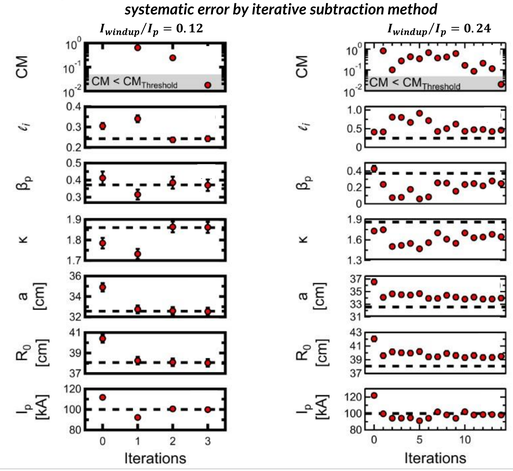
Iterative process workflow for reducing stream systematic errors



Iterative Method Mitigates Systematic Stream Errors

- Applied iterative stream subtraction method to 11 model equilibrium scenarios spanning Pegasus and Pegasus-III operating space
- Algorithm successfully mitigated systematic errors in 9/11 scenarios
  - Convergence typically achieved within ~5 iterations
  - Success = recovery of all prescribed baseline parameters within uncertainty
- The unsuccessful scenarios still converged but did not recover prescribed baseline equilibrium
  - Convergence took significantly longer (~15 iterations)
  - Characterized by $I_{windup}/I_p \gtrsim 0.2$ → sufficiently large stream perturbation
    - Not a major issue: typical LHI plasmas of interest are characterized by $I_{windup}/I_p < 0.1$ [8]

Representative examples of successful (left) and failed (right) reduction of systematic error by iterative subtraction method



Summary

- Newly commissioned Pegasus-III facility will develop several solenoid-free startup techniques, including LHI
- Injected current streams present challenges for MHD equilibrium analysis of LHI discharges
- Forward modeling with simple plasma model used to quantify stream impact on equilibrium reconstruction
  - Streams are a measurable perturbation to Pegasus magnetic diagnostics
  - Perturbation leads to systematic errors in reconstructed equilibrium
- Proposed iterative method can reduce systematic errors with a suitable model for the stream geometry
  - Readily extended as models for stream continue to develop

Reprints available at https://pegasus.ep.wisc.edu/technical-reports.

References: [1] J.A. Reusch *et al.*, Phys. Plasmas **25**, 056101 (2018); [2] J. Y. Park *et al.*, Phys. Plasmas **29**, 052112 (2022) ; [3] N. J. Richner *et al.*, Phys. Rev. Lett. **128**, 105001 (2022) ; [4] ; J. L. Barr, Inductive Evolution and MHD in Local Helicity Injection Discharges on Pegasus, The University of Wisconsin – Madison (2016).
[5] J. L. Pachicano, Characterization of High Field Side MHD Activity During Local Helicity Injection, University of Wisconsin-Madison (2018); [6] A.C. Sontag *et al.*, Nucl. Fusion **28**, 095006 (2018); [7] M.W. Bongard *et al.*, Nucl. Fusion **54**, 114008 (2014); [8] M.W. Bongard *et al.*, Nucl. Fusion **59**, 076003 (2019).