Simulation of current-filament dynamics and relaxation in the Pegasus ST

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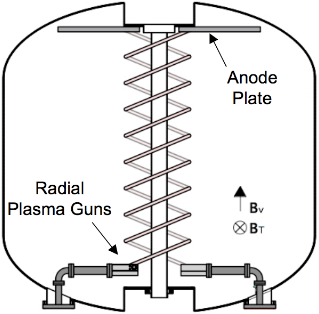
Introduction & Motivation

Non-solenoidal startup is being investigated on the Pegasus Toroidal Experiment (University of WI).

- Spherical tokamaks have limited capacity for ohmic induction due to geometric constraints on the central solenoid.
- Localized washer-gun plasma sources are being used on Pegasus as a means of DC helicity injection. [1] [2] [3]
- The plasma guns can be mounted through diagnostic ports.
- Other startup methods, e.g. CHI, would require dramatic changes to the vacuum vessel or pose additional challenges.



[1] N.W. Eidietis. Ph.D. Disseration. University of Wisconsin–Madison. 2007.

[2] D.J. Battaglia et al. *Phys. Rev. Let.* 2009.

[3] D.J. Battaglia et al. *J. Fus. Energy* 2009.

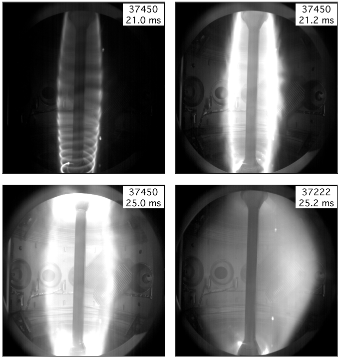
Overview of the experimental startup procedure for DC helicity injection in Pegasus

- The vacuum vessel is filled with neutral gas with a prefill pressure of $1 - 5 \times 10^{-5}$ Torr. [4]
- To the extent that the background gets ionized, the density $n \sim 10^{18}$ m^3 is comparable to that used in the computations.
- Pre-ionization occurs by driving current through the plasma gun arc circuit without applying a voltage bias between the plasma gun(s) and the anode.
- Heating of the background plasma occurs through two mechanisms:
    - Thermal transport from the emitted plasma into the background
    - Ohmic heating along the current filament path
- The plasma guns also provide a significant source of plasma in the experiment.
- Initially, the current channels wind along the vacuum magnetic field lines.

[4] D.J. Battaglia et al. *Nucl. Fus.* 2011.

The gun plasma relaxes into a "tokamak-like" configuration with toroidal current amplification.

- The transition to a "tokamak-like" plasma occurs when the self-induced magnetic field from DC current is large enough to change the sign of poloidal flux at the center column, $I_p \approx 15$ kA.
- In a "tokamak-like" plasma, the $\langle \mathbf{B} \rangle_\phi$ indicates closed, nested poloidal flux surfaces, but the full **B** likely contains significant stochasticity.
- The toroidal current in the relaxed plasma exceeds that computed from the vacuum field geometric winding.
- Poloidal flux compression is then applied on the relaxed plasma resulting in current amplification.
- Solenoidal induction can provide additional current drive.



Soft X-ray emissions.

Motivation for Numerical Simulation (1)

- The helicity injection scheme on pegasus is unique:
  - Spheromak and spherical tokamak plasmas driven by CHI are initially axisymmetric and transition to a non-axisymmetric state when crossing some stability boundary. [5] [6]
  - The gun plasmas in Pegasus are initially non-axisymmetric then relax to an axisymmetric (i.e. "tokamak-like") state.
- While the initial helical plasma state and final relaxed state are well diagnosed in the experiment, the dynamics of the relaxation process have not been directly observed.
  - Diagnostics that provide multidimensional information, such as the soft x-ray camera, are unable to temporally resolve the helical filament interactions.
  - Magnetic diagnostics resolve fluctuations temporally, but are incapable of spatially resolving fine-scale structure.

[5] R. Raman et al. *J. Fus. En.* 2007.

[6] S. Woodruff et al. *Phys. Rev. Lett.* 2003.

Motivation for Numerical Simulation (2)

- During helicity injection while the current filaments remains coupled to the plasma gun(s), magnetic diagnostics indicate the presence of $n = 1$ MHD activity, typically in the $10 - 20$ kHz.
- The presence of MHD activity only during helicity injection and formation of a tokamak-like state suggests it is an important part of the relaxation process.
- Equilibrium reconstructions produce hollow current profiles for the experimental relaxed plasma state, with peak current density at $\psi_N \approx 0.7$.
- The hollow current profile suggests that the plasma guns serve as sources of edge current drive that must diffuse classically or otherwise into the plasma core.

Modeling

A resistive MHD model is used to study relaxation.

- Anisotropic, temperature-dependent thermal conduction, temperature-dependent resistivity, and ohmic heating reproduce critical transport effects.
- A similar model has been applied to study the interaction between thermal transport and magnetic relaxation in the SSPX spheromak. [7] [8] [9]
- MHD analysis is relevant to Pegasus discharges due to the strongly electromagnetic effects and relatively low temperature (i.e. collision-dominance).
- Nonlinear, numerical computations are performed with the NIMROD code. [10]
- Plasma evolution should not be overly sensitive to boundary conditions for the temperature and magnetic field advances, as long as conditions approximate a cold wall.

[7] C.R. Sovinec et al. *Phys. Rev. Lett.* 2005.

[8] B.I. Cohen et al. *Phys. Plas.* 2005.

[9] E.B. Hooper et al. *Phys. Plas.* 2008.

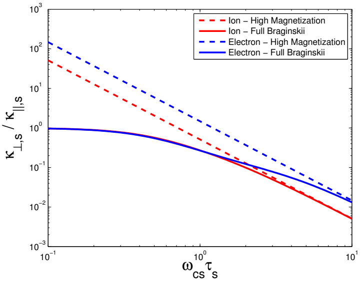
[10] C.R. Sovinec et al. *Phys. Plas.* 2003.

The transition from isotropic to anisotropic thermal conduction is modeled with the Braginskii closure.

$$\boxed{x \equiv x_i = \omega_{ci}\tau_i}$$

$$\kappa_{||} \approx \kappa_{||e} = \frac{n_e T_e \tau_e}{m_e} \frac{\gamma_{0e}}{\delta_{0e}}$$

$$\kappa_{\perp} \approx \kappa_{\perp i} = \frac{n_i T_i \tau_i}{m_i} \frac{\gamma_{1i} x^2 + \gamma_{0i}}{x^4 + \delta_{1i} x^2 + \delta_{0i}}$$

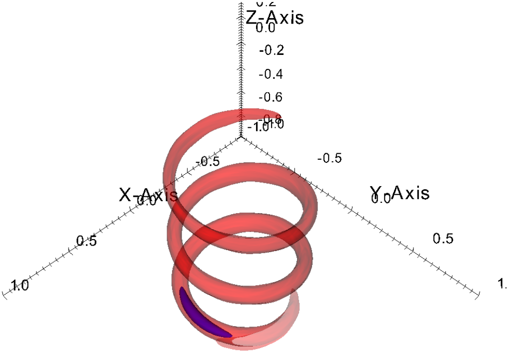


For a $Z = 1$ plasma.

- Simulations are initialized with a cold, uniform plasma $T \approx 0.24\ eV$ ($\omega_{ci}\tau_i \approx 0.025$).
- The Braginskii closure[11] reproduces isotropic thermal conduction in regions of low temperature ($\omega_{ci}\tau_i \ll 1$), e.g. edge regions.
- The closure also captures the transition to anisotropic thermal conduction as the local plasma temperature increases.
- Results show significant 3D variation in the magnetization parameter, with $x \gg 1$ near the channel and $x \ll 1$ near the domain boundary.

[11] S.I. Braginskii. *Rev. Plas. Phys.* 1965.

The plasma guns are simulated with poloidally and toroidally localized current and heat sources.



Spatial distribution of λ_{inj} (half-max shown in blue) and the resulting current channel ($\lambda \simeq 1\text{m}^{-1}$ shown in red)

- An ad-hoc force density on the electrons acts as a source in the combined Faraday / Ohm's Law.

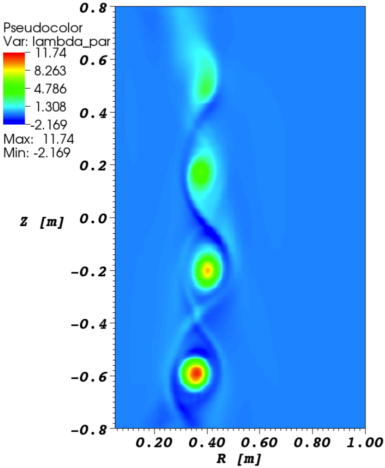
$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} - \mathbf{E}_{inj}$$

- The applied electric field E_{inj} sustains current density in the presence of resistive dissipation.
- The current drive source $\mathbf{E}_{inj} = \lambda_{inj} \mathbf{B}$.
- Source localization is aligned with $\mathbf{B}_{vac}$, i.e. toroidally pitched.

Thermal boundary conditions with a decay rate equation prevent unphysical shielding of the current channel.

- A decay rate equation permits spatial and temporal variation of the temperature, unlike a fixed-value Dirichlet boundary condition.
- With the decay rate equation, temperature and resistivity gradients at the ends of the channel are relaxed, allowing the conducting path to extend to the electrode surfaces.
- With fixed-value boundary conditions, return current surrounds the channel, shielding the attractive Lorentz force between adjacent passes.
- A constant thermal energy decay rate α_T is applied uniformly across the entire boundary ∂V.

$$\left.\frac{\partial T}{\partial t}\right|_{\partial V} = -\alpha_T T\Big|_{\partial V}$$



$$\lambda = \mu_0 J_{\|} / B$$

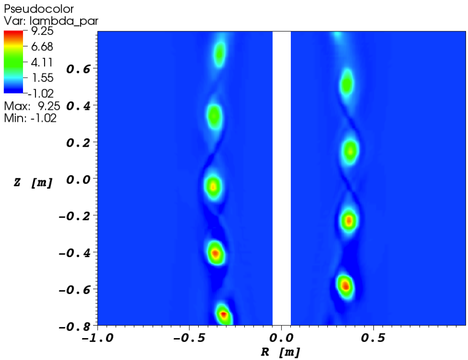
An effective surface resistance prevents the unphysical accumulation of toroidal flux.

- Accumulation of toroidal flux with conducting boundary conditions causes radial compression of the plasma, preventing expansion into the domain.
- The effective surface resistance α_η is applied uniformly to the inboard and outboard surfaces $\partial V'$ ($R = 0.05$ & 1.00 m, respectively).
- For the inboard surface, the nearly constant toroidal flux corresponds to constant toroidal field current flowing through the central solenoid.
- For the outboard surface, the surface resistance corresponds to either a toroidal cut in the vacuum vessel or a small resistive wall time relative to the oscillation period.

$$\left.\frac{\partial B_\phi}{\partial t}\right|_{\partial V'} = -\alpha_\eta B_\phi \Big|_{\partial V'}$$

Numerical Results

The current channel initially winds along the vacuum magnetic field lines.

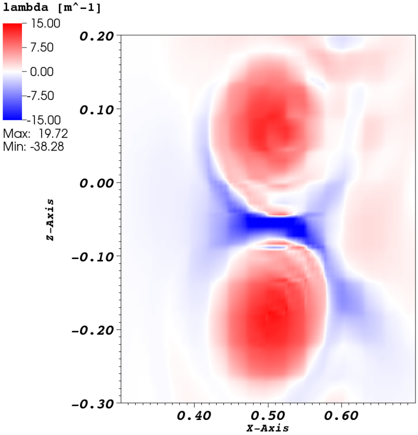


Initial winding of the current channel along $\mathbf{B}_{vac}$

- During the initial phase, the current channel is essentially static.
- With sufficient channel current, the channel begins to elliptically oscillate in the poloidal plane from the attractive Lorentz force between adjacent passes.
- Eventually, adjacent passes of the current channel come into contact.
- Fluctuations of plasma current and internal energy coincide with the oscillations.

Reversed current sheets between adjacent passes of the current channel suggest magnetic reconnection.

- With sufficient displacement of adjacent passes, good electrical conductivity exists between the two passes.
- 2D cross-sections are similar to Sweet-Parker reconnection of parallel merging co-helicity flux tubes. [12] [13]
- However, magnetic reconnection between adjacent passes of current filaments in Pegasus is fundamentally 3D.



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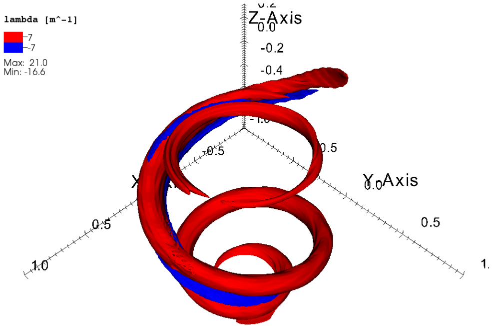
[12] J.A. Breslau. Ph.D. Disseration. Princeton University. 2001.

[13] J.A. Breslau and S.C. Jardin. *Phys. Plas.* 2003.

Magnetic reconnection releases a current ring from the driven channel plasma.

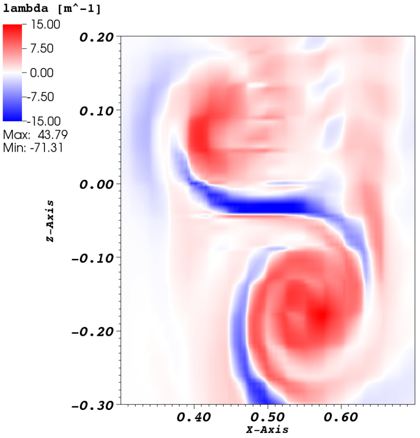


- When the self-induced magnetic field of the current channel significantly exceeds the vacuum field, adjacent passes of the channel fully reconnect.
- Unlike parallel co-helicity flux tubes[14], the current channel passes do not remain merged.
- The passes separate with changed connectivity that releases an axisymmetric current loop from the shortened driven current channel.
- The current ring forms slightly inboard of the current channel near the midplane and slowly propagate vertically away from the gun.

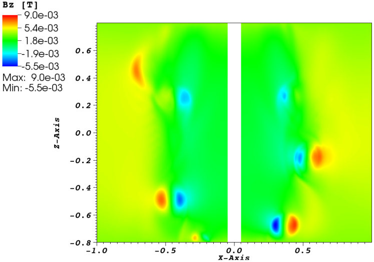
[14] M.G. Linton et al. *Astrophys. J.* 2001.

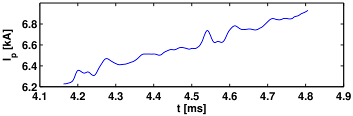
The current channel passes slide past one another in the outflow direction during current ring formation.

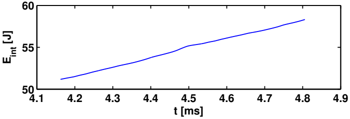
- Relatively higher pressure in the inflow region than in the compressed outflow region creates an elongated x-type structure.
- An elongated current sheet is observed after passes have stagnated in the inflow direction and begun to slide past one another in the outflow direction.
- The loss of drive causes the upper pass to move radially inward as it separates from the current channel.
- Magnetic pressure from the self-induced field causes the driven low pass to move radially outward.



Even prior to the onset of large-scale magnetic field reversal, parallel current profiles suggest significant magnetic reconnection activity.

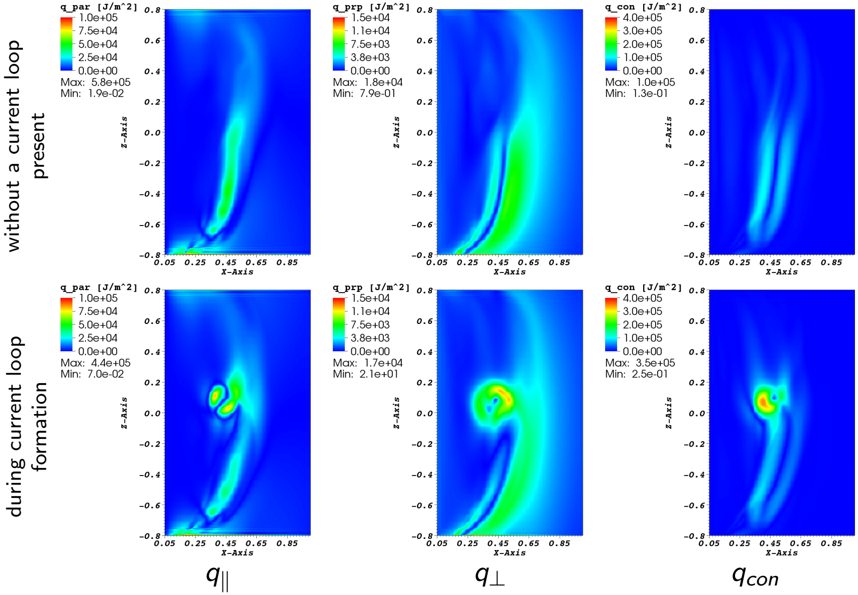




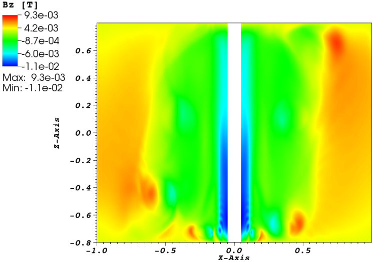


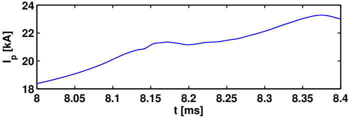
- The oscillations in current and internal energy correspond to reconnection events.
- The movies correspond to the plasma current and internal energy traces shown.
- The 3D and 2D parallel current movies show reconnection and formation of detached current ring.
- The temperature movie shows enhanced thermal transport during reconnection events.

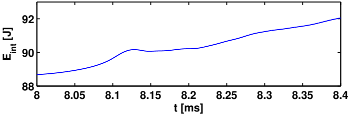
Prior to large-scale magnetic field reversal, most of the heat is transported to the electrodes.



After large-scale magnetic field reversal, parallel current profiles show the formation of a hollow current shell around the plasma.

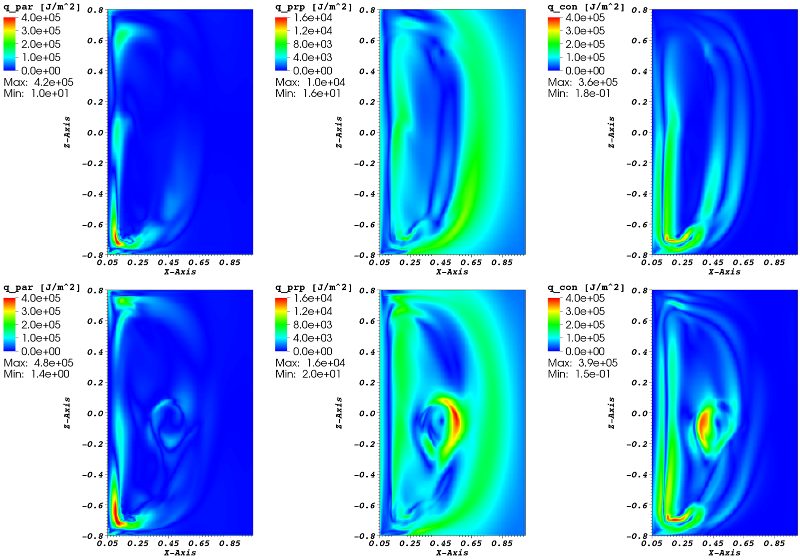






- The oscillations in current and internal energy correspond to reconnection events.
- The movies correspond to the plasma current and internal energy traces shown.
- The 3D and 2D parallel current movies show reconnection and formation of detached current ring.
- The 2D parallel current profile also shows a hollow shell of parallel current around the plasma.
- The temperature movie shows the accumulation of heat near the lower inboard side of the plasma.

After large-scale reversal, a significant fraction of thermal energy recirculates in the amplified flux region.



without a current loop present

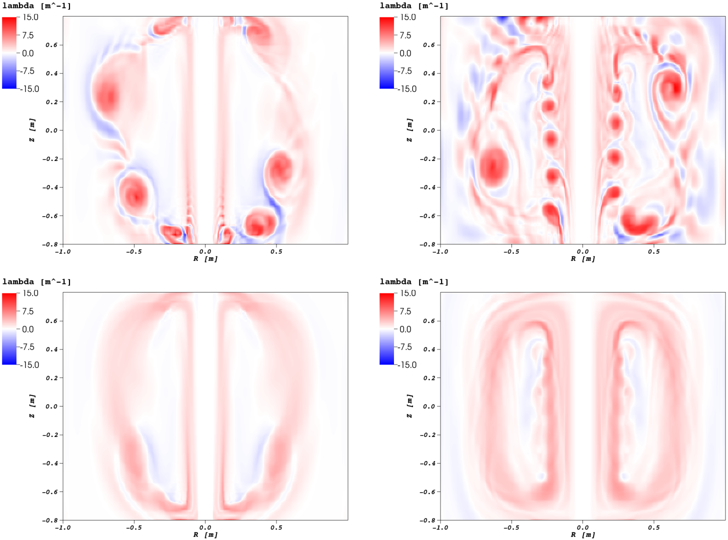
during current loop formation

$q_{||}$ $q_{\perp}$ q_{con}

Hollow current profiles after large-scale field reversal show the spreading of current due to magnetic relaxation.

Local λ

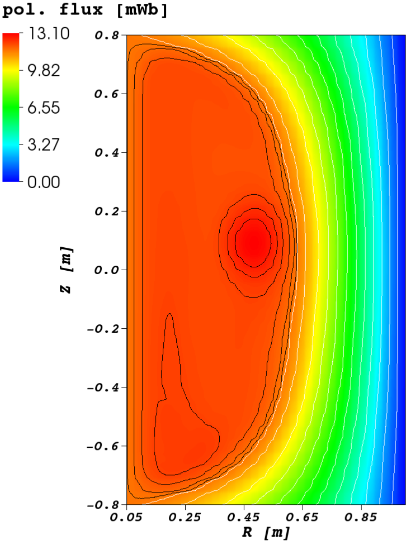
$\langle \lambda \rangle_\phi$



$I_p \approx 26$ kA

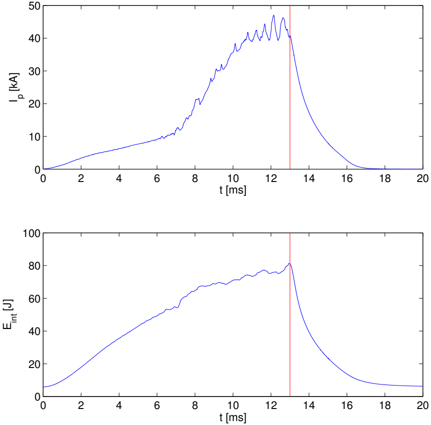
$I_p \approx 42$ kA

Significant poloidal flux amplification has been observed since the onset of large-scale magnetic field reversal.



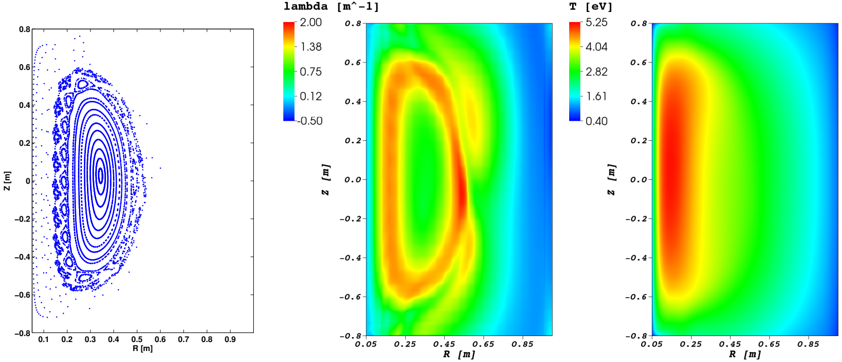
- Poloidal flux accumulates over many reconnection events.
- Poloidal flux amplification of 1.5 mWb is observed at $I_p \approx 36$ kA.
- The black contours enclose the amplified flux region ($\psi \geq 11.6$ mWb).

After the plasma gun sources are turned off, the plasma decays toward a tokamak equilibrium state.



- Both heat and current sources are turned off at $t = 13$ ms.
- Closed flux surfaces are observed almost immediately after the sources are turned off.
- Very high rate of resistive decay.
- Separate species temperatures will likely result in better confinement as $\kappa_{\perp,e} \ll \kappa_{\perp,i}$.

Hollow current profiles in the decaying plasma qualitatively agree with equilibrium reconstructions of relaxed plasmas in the experiment.



$t = 13.7$ ms, $I_p \approx 22$ kA

Summary & Future Work

Summary & Future Work

- The current rings released from the filaments have not been previously observed for helicity injection in STs, providing a new phenomenological understanding for filament relaxation in Pegasus.
- The current rings provide the mechanism for poloidal flux amplification over multiple reconnection events.
- The current rings individually produce large thermal transport, and collectively, may contribute to the centrally peaked pressure profile observed in equilibrium reconstructions of relaxed plasmas in the experiment.
- The hollow current profile is also consistent with the off-axis peaked current profile observed in the equilibrium reconstructions.
- As the Hall parameter ($\delta_i/a \approx 3.6$) is large compared to current channel width a, non-MHD effects may significantly influence current channel evolution.
- Therefore, non-MHD contributions will be investigated through two-fluid computations.