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

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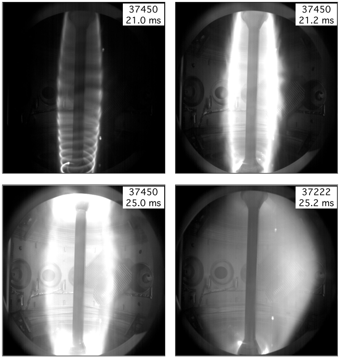
Non-solenoidal startup is being investigated on the Pegasus Toroidal Experiment (University of WI).

- 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 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.
- The toroidal current in the relaxed plasma exceeds that computed from the vacuum field geometric winding.



[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.

Motivation for Numerical Simulation

- 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. [4] [5]
  - 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.
- 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.
- A 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.

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

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

Relaxation in Pegasus is studied with nonlinear resistive MHD computations with the NIMROD code.

- Anisotropic, temperature-dependent thermal conduction using the Braginskii closure[6], 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]
- Computations with separate ion and electron temperature evolution have temperature-dependent thermal equilibration between the species.
- A decay rate equations is used in the boundary conditions for temperature (entire boundary) and toroidal magnetic field (inboard and outboard surfaces) of the form:

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

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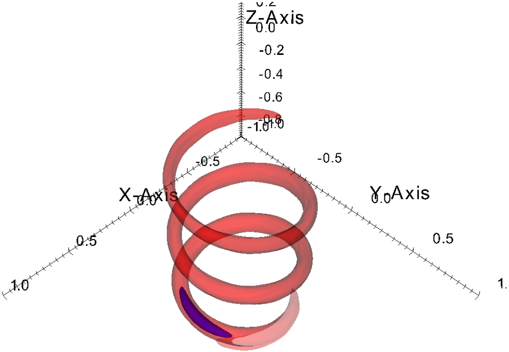
[6] S.I. Braginskii. *Rev. Plas. Phys.* 1965.

[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.

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



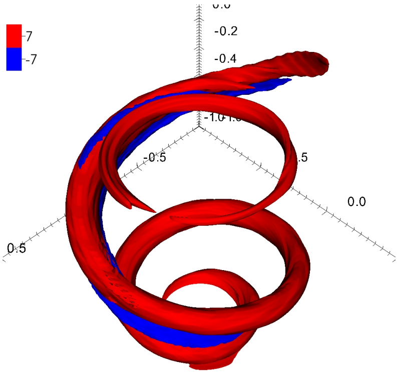
Spatial distribution of λ_{inj} (half-max shown in blue) and the resulting current channel ($\lambda \simeq 1\text{m}^{-1}$ shown in red)

- 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.

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

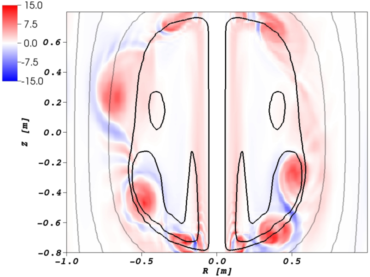


- When the self-induced magnetic field of the current channel significantly exceeds the vacuum field, adjacent passes of the channel fully reconnect.
- Unlike parallel co-helicity flux tubes,[10] the current channel passes do not remain merged.
- The passes separate with changed connectivity that releases an axisymmetric current loop from the shortened driven current channel. [11]
- The current ring forms slightly inboard of the current channel near the midplane and slowly propagate vertically away from the gun.

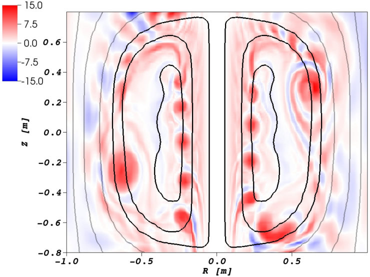
[10] M.G. Linton et al. *Astrophys. J.* 2001.
[11] J.B. O'Bryan, C.R. Sovinec, and T.M. Bird. *Phys. Plas.* 2012.

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

$I_p \approx 26$ kA



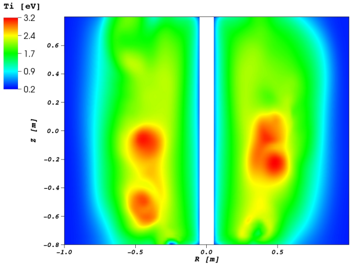
$I_p \approx 42$ kA

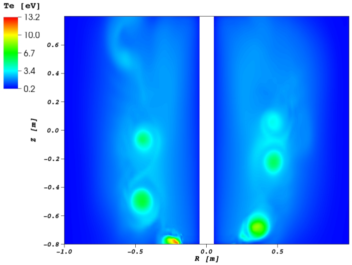


- The overlaid contours show the poloidal flux function, where darker contours correspond to the amplified-flux region.
- Shortly after large-scale magnetic field reversal, current flows diffusely along the inboard side of the amplified-flux region.
- At larger I_p, current on the inboard side flows in a distinct channel that connects to the outboard driven current channel.

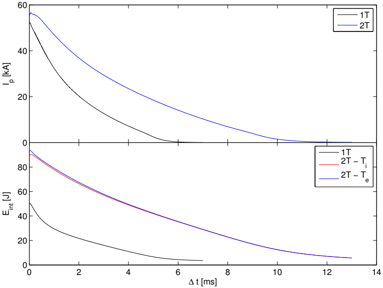
Computations are in progress with separate ion and electron temperatures and the 2-fluid Ohm's Law.

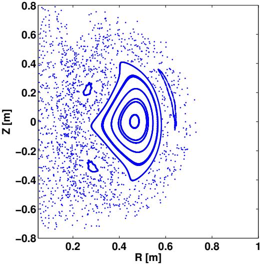
- Contour of T_i and T_e from a 2-temperature simulation shown at right indicate better electron heat confinement to the drive channel.
- This is consistent with expectations from species magnetization, as $\omega_{ce}\tau_e >> \omega_{ci}\tau_i$ for a given T.
- As the Hall parameter $(\delta_i/w \approx 3.6)$ is large compared to the current channel width w, non-MHD effects may significantly influence current channel evolution.
- The same basic phenomenology of current ring formation is observed in computations with 2 temperatures and the 2-fluid Ohm's law.





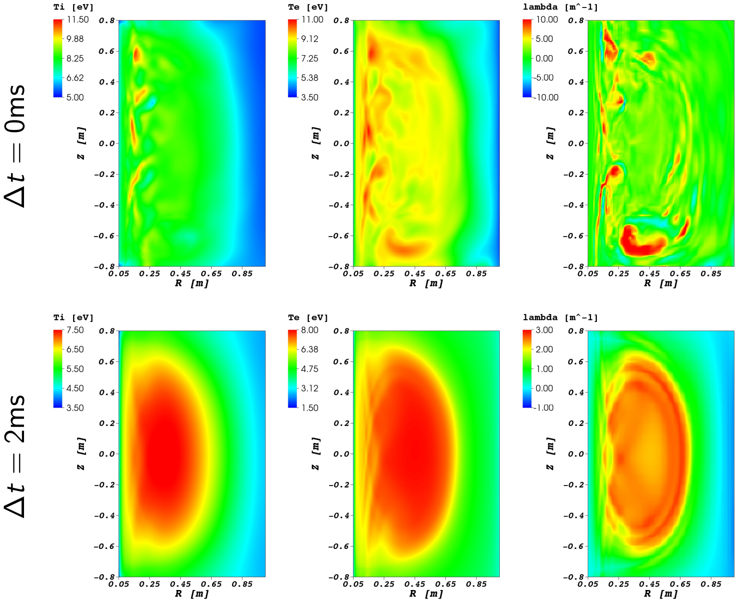
After the plasma gun sources are turned off, the plasma decays toward a tokamak equilibrium state.



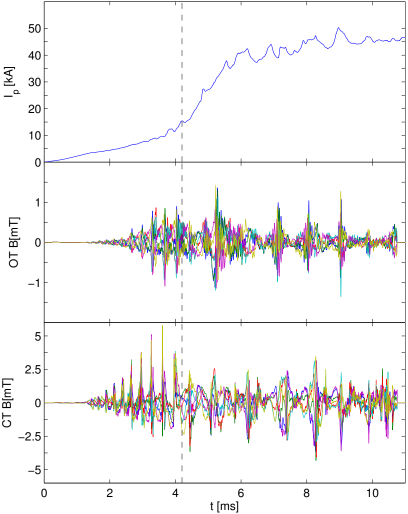


- Closed flux surfaces form almost immediately near the magnetic axis and slowly expand to encompass a larger volume over several ms.
- The plasma in the single fluid temperature computation undergoes a very high rate of resistive decay relative to the plasma in the two-temperature computation.
- Despite having similar peak temperatures, the internal energy of the plasma in the two-temperature computation plasma is nearly double that for the single fluid temperature computation.

Centrally peaked temperature and hollow current profiles are observed during the decay phase.



Magnetic fluctuations observed by a new synthetic Mirnov diagnostic correlate with the reconnection events.



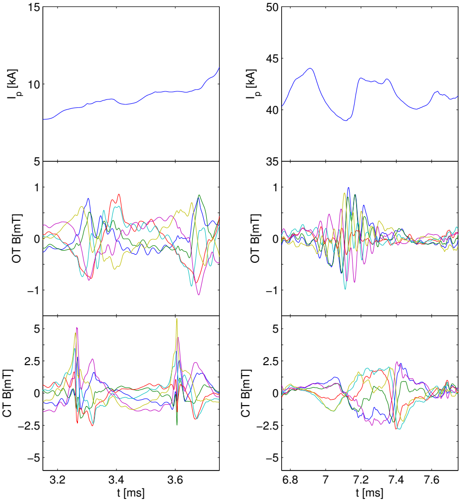
- The synthetic Mirnov locations correspond to the Mirnov coil array positions in Pegasus. [12]
- A drop and subsequent rise in the plasma current occurs with the reconnection events.

Outboard and Inboard Toroidal Mirnov Arrays

name	R (cm)	Z (cm)	Φ (degrees)
OT1	88.2	-17.00	301.7
OT2	90.5	-16.25	329.8
OT3	89.2	-34.75	344.9
OT4	88.2	-17.25	31.5
OT5	91.2	-16.70	122.3
OT6	90.2	-16.9	210.7
CT1	5.445	0	293.1
CT2	5.445	0	344.5
CT3	5.445	0	36.0
CT4	5.445	0	87.4
CT5	5.445	0	241.7
HR11	5.445	0	138.82

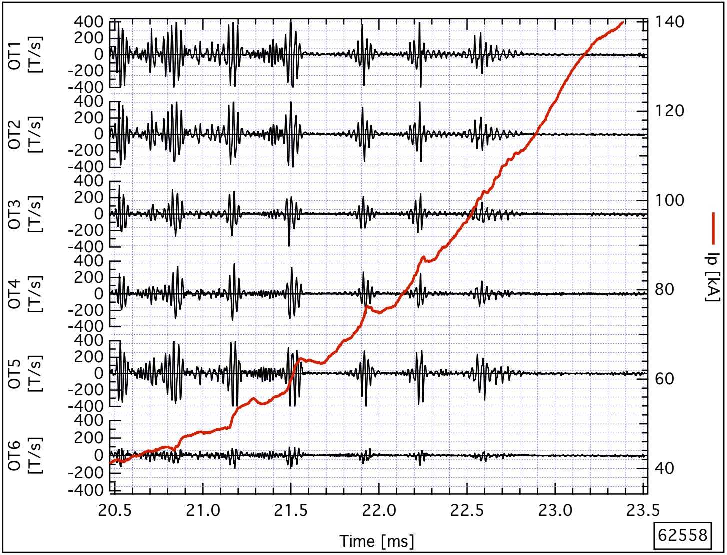
[12] M.W. Bongard. Ph.D. Disseration. University of Wisconsin–Madison. 2011.

The diagnostic signature of the reconnection events is different before and after large-scale field reversal.



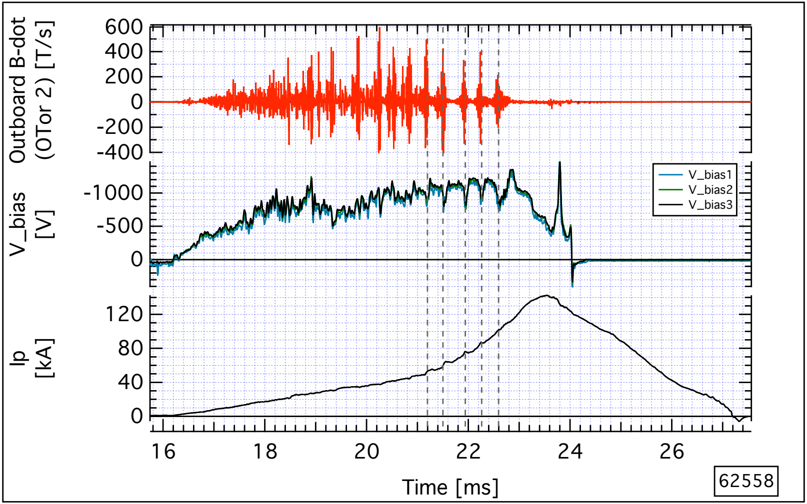
- A rotating mode is observed for the outboard toroidal (OT) Mirnov array.
  - High frequency activity ($\sim$ 20 kHz) = reconnection event + sudden change in driven current channel winding
  - Low frequency activity ($\sim$ 3 kHz) = slow recovery of driven channel winding after reconnection event
- Prior to large-scale field reversal, the inboard toroidal (CT) Mirnov array observes a significant axisymmetric component to each reconnection event.
- After field reversal, a rotating mode is observed on the inboard side as well and significant reconnection activity is occurring between adjacent passes of the inboard channel.

A similar drop in I_p is observed in recent experimental results[13] with outboard midplane plasma guns.



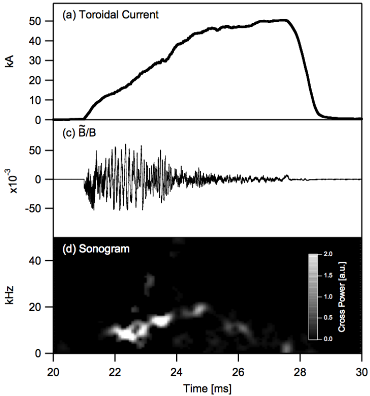
[13] Data courtesy of J.L. Barr.

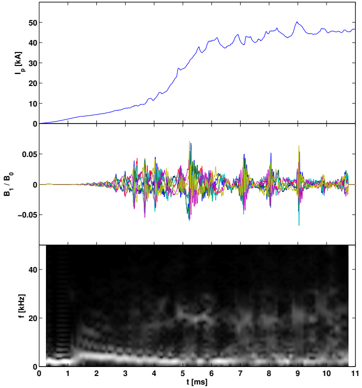
Fluctuations of the measured bias voltage[14] are also suggestive of current ring formation, as the release of a ring would decrease the inductance of the driven channel.



[14] Data courtesy of J.L. Barr.

The frequency spectrum from the synthetic Mirnov diagnostic has similarities with experimental results.[15]



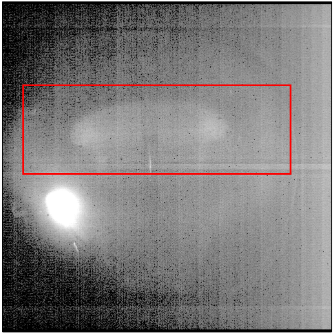


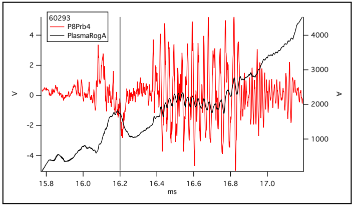
- The outboard toroidal Mirnov arrays for both experimental and computational results had magnetic fluctuations on the order of 5%.
- After large-scale field reversal, both sonograms have significant activity in the $f \simeq 10 - 20$ kHz range.
- The experimental sonogram filters out frequencies of a few kHz.

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

Ringlets observed during Pegasus discharges possess qualitative similarities to the current loops from the simulations.

- The ringlets were observed when operating near the relaxation threshold (large B_z), which slows the typically fast relaxation rate.
- The Phantom camera image was taken very early in the discharge using a fisheye lens and red filter (showing D_α, H_α emission).[16]
- The ringlets are accompanied by a burst of MHD activity and a corresponding drop in plasma current.
- A qualitatively similar drop in plasma current is observed in the simulations during the reconnection events.





[16] Laboratory image and accompanying data courtesy of M.W. Bongard.

Conclusions & Future Work

- The release of current rings from the filaments has not been previously observed for helicity injection in STs, and provides a new phenomenological understanding for filament relaxation in Pegasus. [17]
- The current rings provide the mechanism for poloidal flux amplification over multiple reconnection events.
- The hollow current profile is consistent with the off-axis peaked current profile observed in equilibrium reconstructions of experimental discharges.
- The MHD activity observed with the synthetic Mirnov diagnostic is also consistent with experimental Mirnov observations in both past (divertor guns) and present (outboard midplane guns) discharges.
- Future Work:
    - Model the outboard midplane gun configuration
    - Apply poloidal flux compression and/or solenoidal induction to the decaying plasma

[17] J.B. O'Bryan, C.R. Sovinec, and T.M. Bird. *Phys. Plas.* 2012.