Physics of fast flux closure in coaxial helicity injection experiments in NSTX

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Thanks to: R. Raman, E. B. Hooper,
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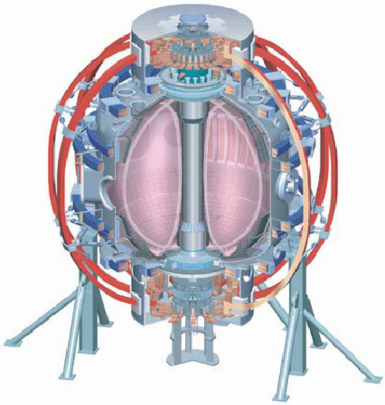
Motivation

- Conventional tokamak designs rely on a central solenoid to generate an inductive initial current.
- Solenoid free non-inductive techniques to form a startup plasma enable lower aspect ratio configurations and simplify tokamak design.
- Coaxial Helicity Injection (CHI) is a promising candidate for plasma start-up current formation in NSTX-U.



Objectives

The physics of magnetic reconnection during transient CHI is examined through MHD simulations

Electrostatic helicity injection has been the most tested solenoid-free plasma start-up method in NSTX

- Magnetic helicity, $K = \int \mathbf{A} \cdot \mathbf{B} dv - \phi_z \phi_p$
- The rate of change of magnetic helicity is

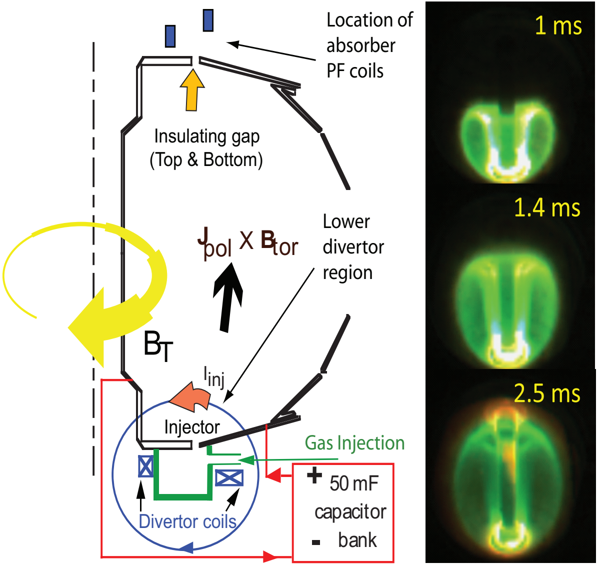
$$\frac{\partial K}{\partial t} = \underbrace{-2 \int \Phi \mathbf{B} \cdot d\mathbf{s}}_{\Downarrow \atop \boxed{\text{dc injection}}} \underbrace{- 2 \int \eta \mathbf{J} \cdot \mathbf{B} dv}_{\Downarrow \atop \boxed{\text{dissipation}}}$$

- Φ is the applied electrostatic potential on the plasma surface, second term represents the intersection of a field line with a surface held at a constant electric potential, when $B_N(a) \neq 0$
- A bias voltage V_{inj}, should be applied to the magnetic flux ψ_{inj} that penetrates two electrodes, $\dot{K} = 2\Psi_{\text{inj}} V_{\text{inj}}$

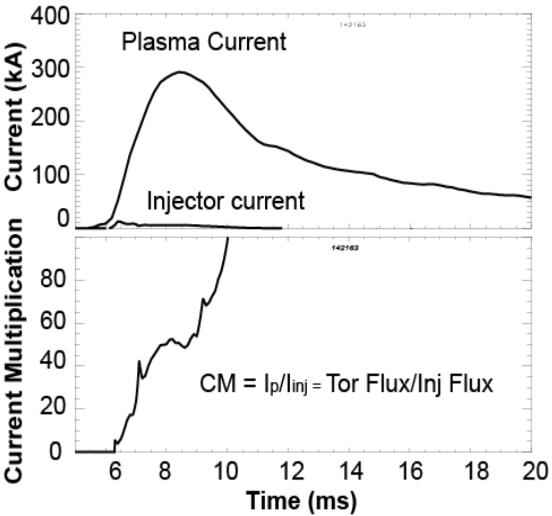
Jensen and Chu 1984

In transient CHI, axisymmetric reconnection generates a high quality closed flux start-up equilibrium in NSTX

- Injected toroidal flux links the poloidal flux $\boxed{\dot{K} = 2\Psi_{\rm inj} V_{\rm inj}}$
- The helicity and plasma expands into the vessel if $I_{\rm inj}$ exceeds a threshold value (when the magnetic compression across the current layer exceeds the field-line tension of the injector flux)



NSTX has demonstrated CHI-generated plasma current up to 300kA



Raman et al. PRL 2006

Injector current

$\Uparrow$

- $I_p = I_{\rm inj}(\Psi_T/\Psi_{\rm inj})$

$\Downarrow$

Toroidal flux
[T. R. Jarboe (1989)]

- Current multiplication increases with toroidal field. Scaling confirmed with TSC & NIMROD simulations [Raman, Jardin, et al. 2011 & Bayliss&Sovinec 2011]

Axisymmetric simulations are performed using the extended-MHD NIMROD code

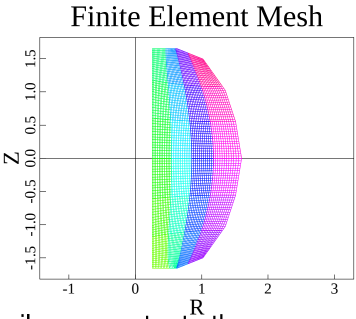
Resistive MHD simulations have been successful in the study of helicity injection in fusion plasmas. Simulations to provide:

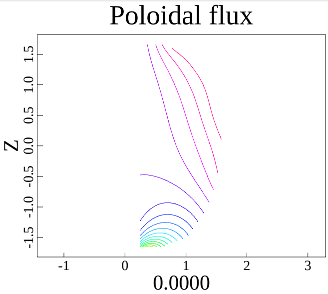
- understanding of the physics of injection, flux-surface closure, and current drive for CHI plasmas
- guidance for existing experiments and extension of these results to NSTX-U
- insight to viability of CHI for steady-state operation of ST reactor
- validation exercises   See also E. B. Hooper NP8.00023

Outline

- Computational model
- Simulations results
- Physics of magnetic reconnection and flux closure

The computational model





- Similar geometry to the experiment with a narrow slot of 4cm
- Initial Ψ_{inj} generated by including NSTX poloidal coil currents (with fixed boundary field)

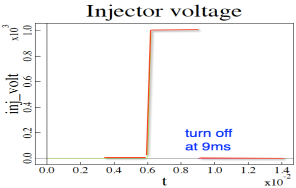
  - Axisymmetric (n=0) with poloidal grid 45 $\times$ 90 fourth or fifth order finite elements
  - Voltage is applied across the injector gap (V_{inj}), and no current is allowed on the absorber gap by setting $\Delta B_{\phi} = 0$ [Bayliss&Sovinec 2010 and Hooper 2011)
  - $E \times B$ normal flows at the injector and absorber gaps

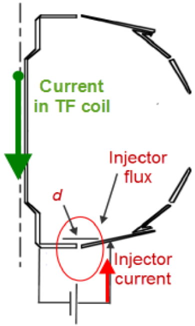
What are the minimum conditions for flux surface to close?

We start with zero pressure model (constant temperature) to allow fuller and more detailed determination of flux closure physics.

These simulations study the role of:

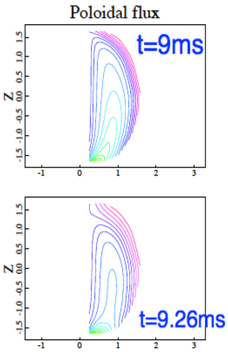
1. Magnetic diffusivity
   F. Ebrahimi, Hooper, Sovinec and Raman, PoP letter October 2013
2. Rate of inj. voltage and current reduction
3. Inj. flux
4. Inj. flux foot print width (d)





(1) Magnetic fluxes are only reconnected at low magnetic diffusivity

High η

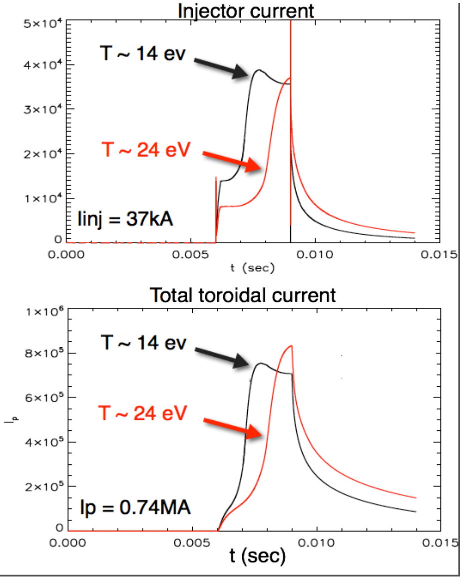


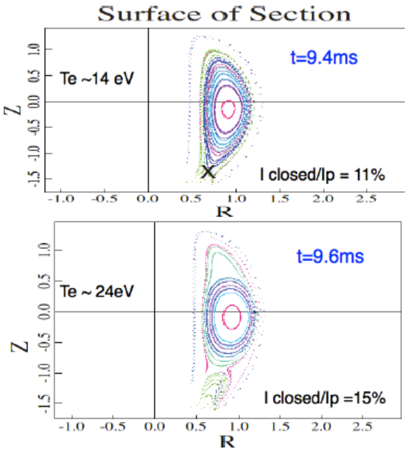
Low η

(Loading poloidalflux.mp4)

- No closed flux surfaces are obtained diffusion time is too fast for relevant helicity drive.

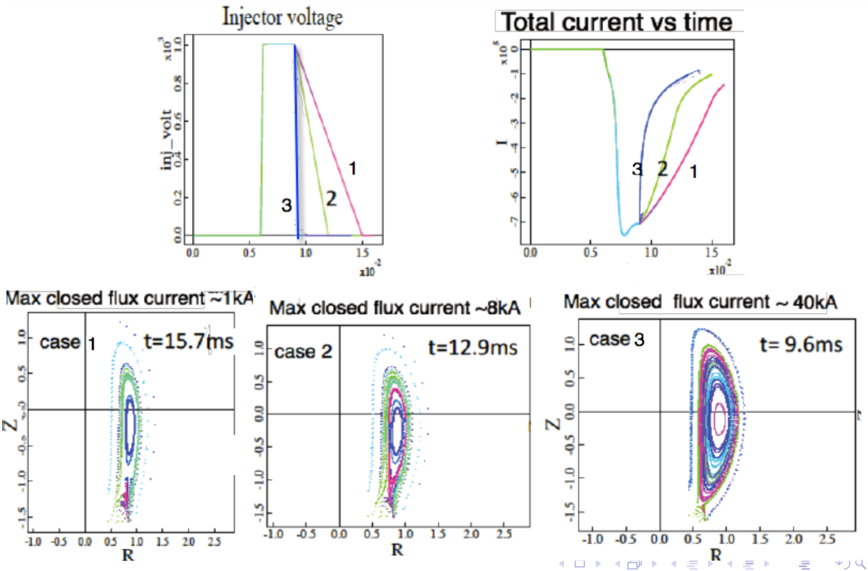
Simulations with magnetic diffusivities similar to those in the experiment produce flux closure



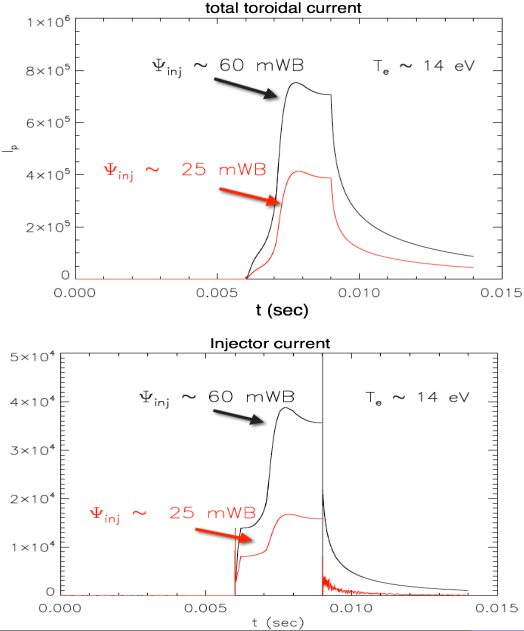


- Closed flux fraction increases as the magnetic diffusivity is reduced

(2) Rapidly reducing the injector current (and voltage) increases closed flux current

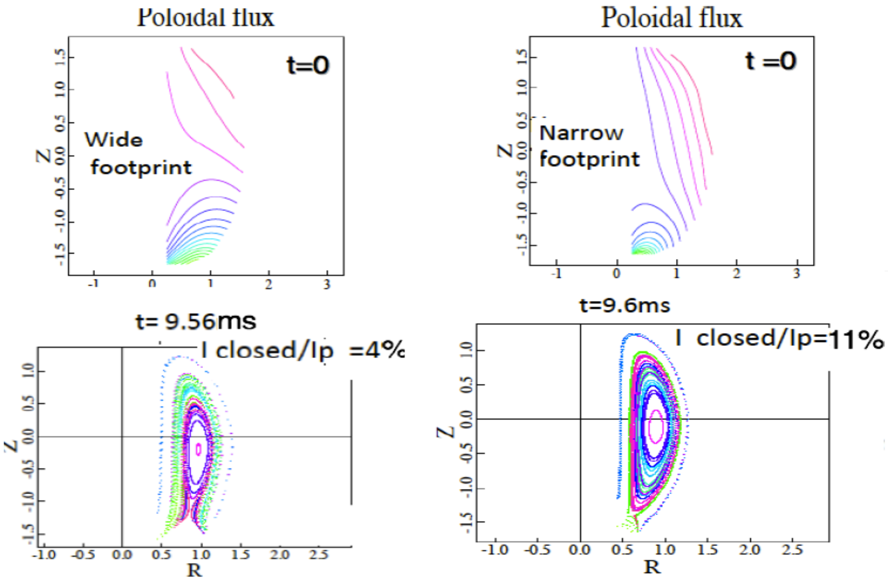


(3) Generated toroidal current scales with injector flux



- Coil currents are reduced to give $\Psi_{inj} \approx 25mWb$
- Fraction of closed flux current is the same

(4) The closed flux fraction increases as the injector flux footprint width is reduced



Physics of X point formation and magnetic reconnection

What triggers magnetic reconnection?

The system is almost in equilibrium before reconnection, and when voltage is turned off and B_ϕ drops around the injector region, magnetic compression exerts a radial force and system is imbalanced

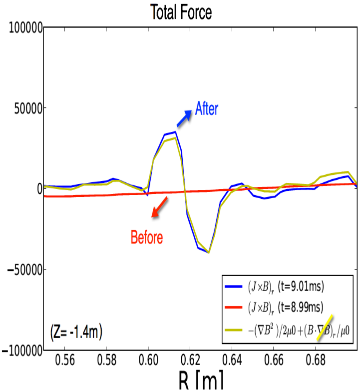
- Total field consists of a fixed background field and evolving axisymmetric fields ($\mathbf{B} = \mathbf{B}_0 + \widetilde{\mathbf{B}}$).

$$(\mathbf{J} \times \mathbf{B})_r$$

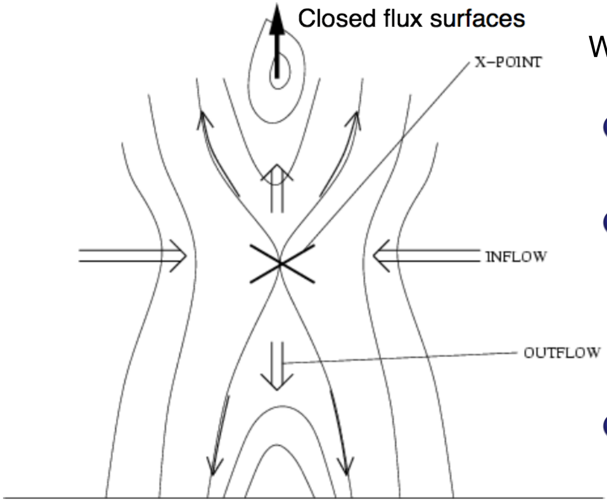
$$= \underbrace{-\nabla(B_z^2 + B_\phi^2)/2\mu_0}_{\text{magnetic compression}} \underbrace{- B_\phi^2/r\mu_0 + B_z dB_r/dz\mu_0}_{\text{curvature}}$$

magnetic compression curvature

$$B_\phi^2 \approx B_{0\phi}\widetilde{B_\phi}$$



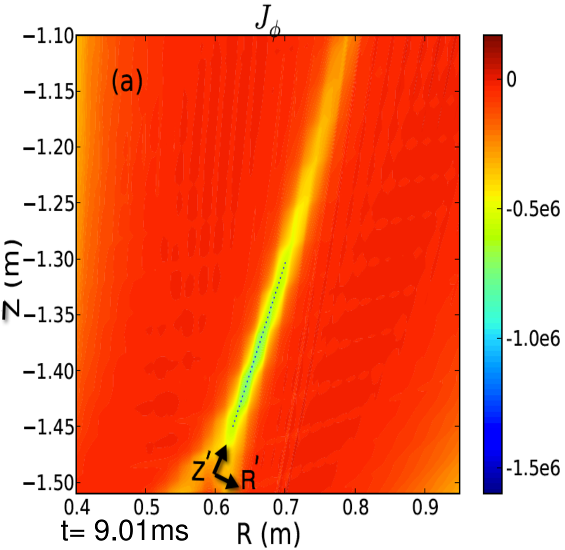
Characteristics of simulation results indicate Sweet-Parker reconnection



What are the signatures?

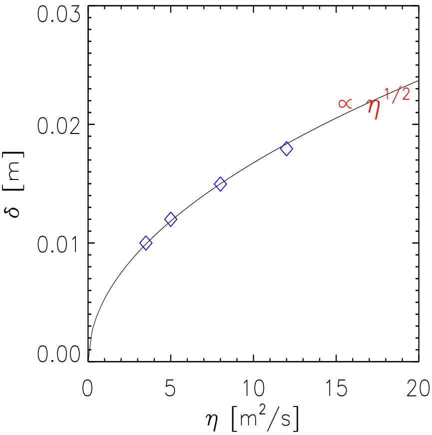
1. Elongated current sheets, $L > \delta$.
2. Scaling of the current sheet width $\delta/L \sim S^{-1/2} \sim V_{in}/V_{out}$ $(S = \mu_0 L V_A/\eta)$
3. Pinch inflow and Alfvénic outflow

(1) An elongated current sheet is formed during the X point formation



- A coordinate transformation to coordinates aligned with the current sheet (shown with dotted black line) is done.

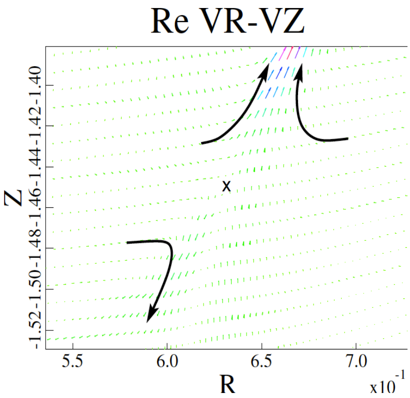
(2) The width of current sheet scales with magnetic diffusivity close to $\eta^{1/2}$, consistent with Sweet-Parker reconnection



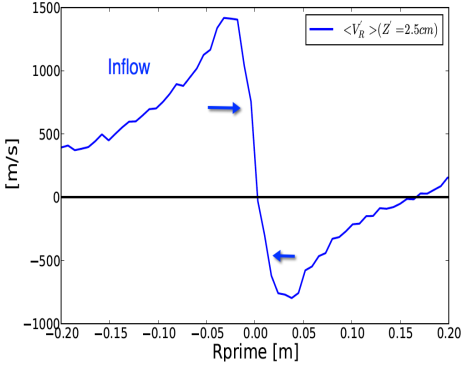
- Simulations for several η
- In these simulations the width calculated using a fit to a Harris type profile.
- τ_{rec} time from X point formation to flux closure
- For reconnection $\tau_V < \tau_{rec} \approx \sqrt{\tau_{RS}\tau_A}(1 + Pm)^{1/4} < \tau_R$

$\eta[m^2/s]$	τ_{rec}	$\tau_{RS} = L^2/\eta$	τ_A	$\tau_R = a^2/\eta$	$S = LV_{Az}/\eta$
$8 \approx 14$eV	0.34ms	5ms	0.007ms	45ms	~ 7000

(3) The Sweet-Parker type structure of inflow and outflow are clearly seen in the coordinate along the elongated current sheet

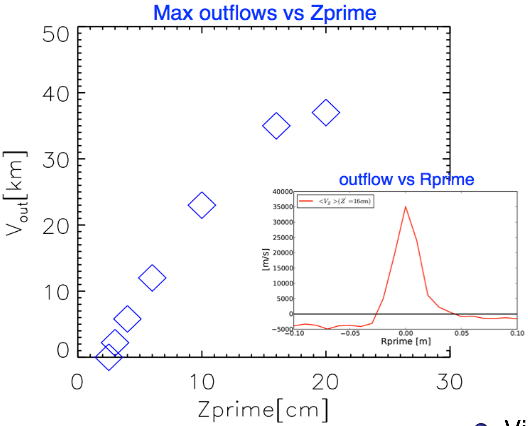


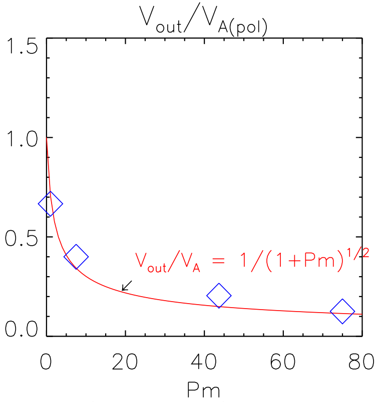
Poloidal flow is zero around X point at (R = 0.63m, Z=-1.445m)



Consistent with the bidirectional pinch force, a radial pinch ExB flow is generated.

The outflows approach poloidal Alfvén velocities and scale with magnetic Prandtl numbers consistent with S-P



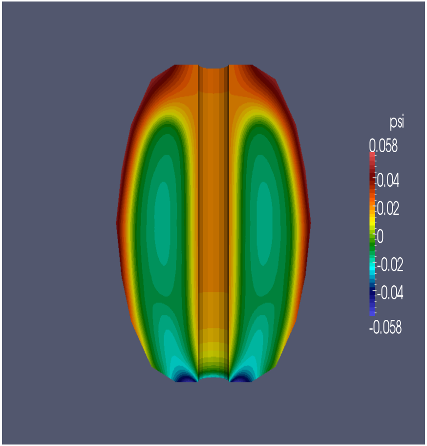


Maximum outflow along the current sheet at Pm=7

- Viscosity modifies the outflows $V_{out}/V_A = 1/\sqrt{(1+Pm)}$

The outflows can reach 60km/s (Pm=1) ($V_{Az} \approx 90km/s$)

Additional physics being considered



1. Simulations with temperature evolution and constant flux also show formation of a fairly large volume of closed flux surfaces on the experimental time scales (Poster PI2.00002)
2. Simulations with temperature evolution and time dependent boundary poloidal fields, see also E. B. Hooper NP8.00023 & [Hooper et al. PoP 2013]
3. Could non MHD effects (2-fluid, Hall terms) affect the volume of the closed flux surfaces?

Summary

- NIMROD simulations show X point & closed flux formation 0.5 ms after the injector voltage and current turned off
- A radial bi-directional pinch flow causes the field lines to reconnect
- Closed flux surface formation during transient CHI is consistent with 2-D Sweet-Parker type reconnection [F. Ebrahimi et al. PoP 2013]
- **Our simulations show that these experiments may be the first to demonstrate a forced magnetic reconnection process in a large scale fusion device during transient CHI in the absence of nonaxisymmetric purturbations**