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Physics of Flux Closure during Plasmoid-mediated Reconnection in Coaxial Helicity Injection

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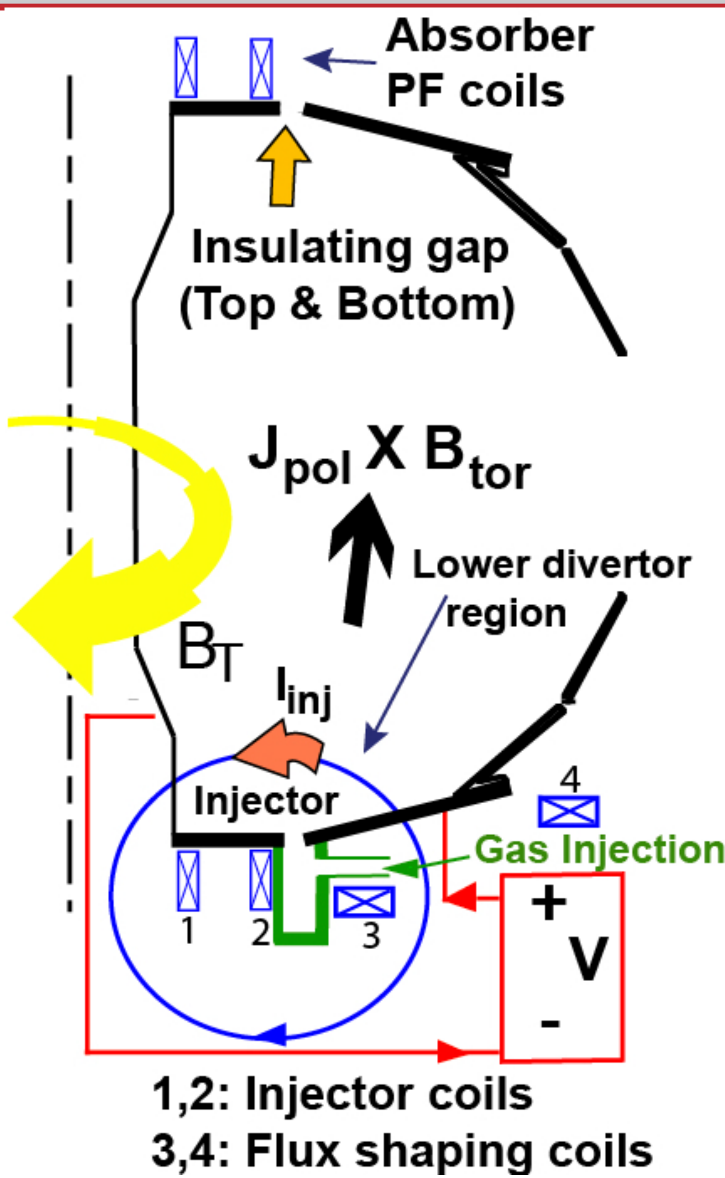
In transient CHI, axisymmetric reconnection generates a high quality closed flux start-up equilibrium in NSTX

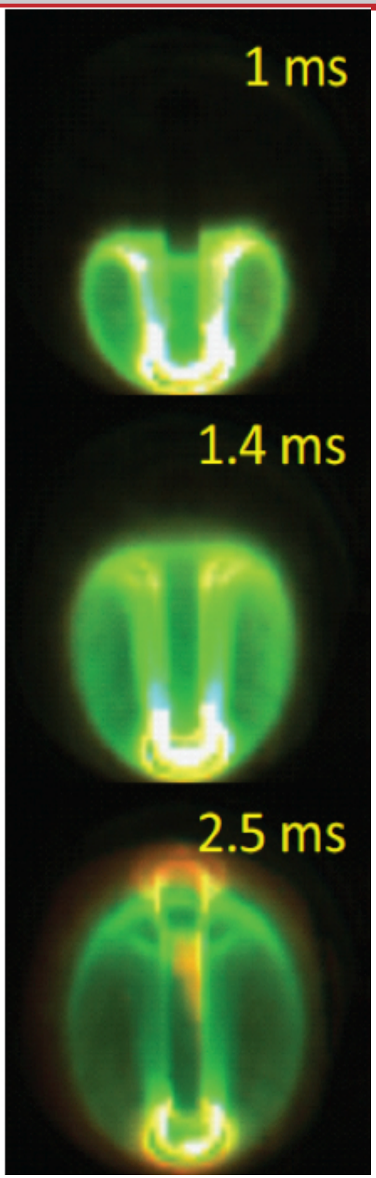
- Solenoid free non-inductive techniques to form a startup plasma enable lower aspect ratio configurations and simplify tokamak Design

- Transient CHI is a promising candidate for plasma start-up current formation in NSTX-U.

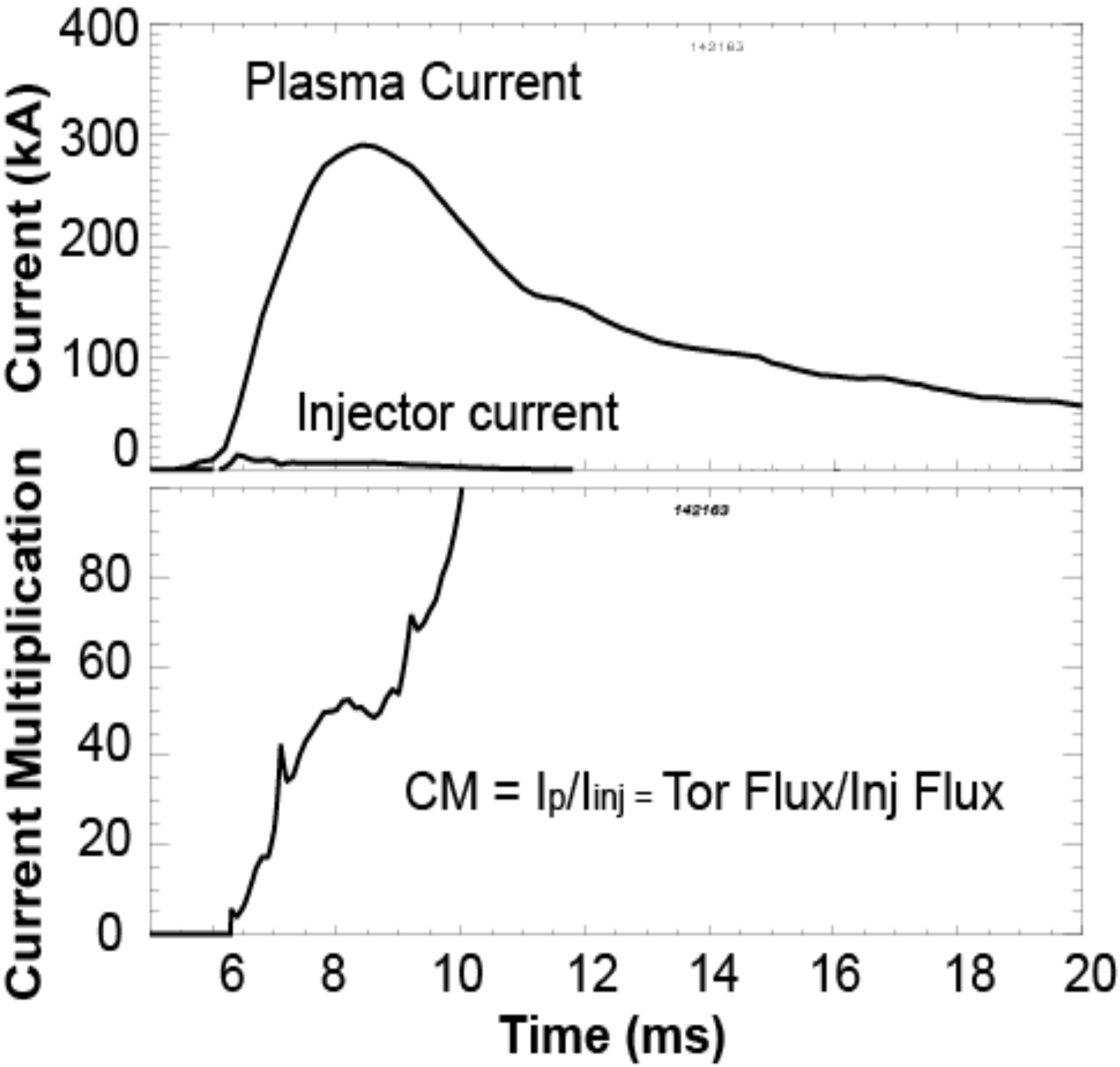
<u>Reconnection process during CHI is of great importance for</u>

- to optimize the maximum good flux closure (and CHI plasma current).
- the extrapolation to larger devices, ultimately for steady-state current-drive





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



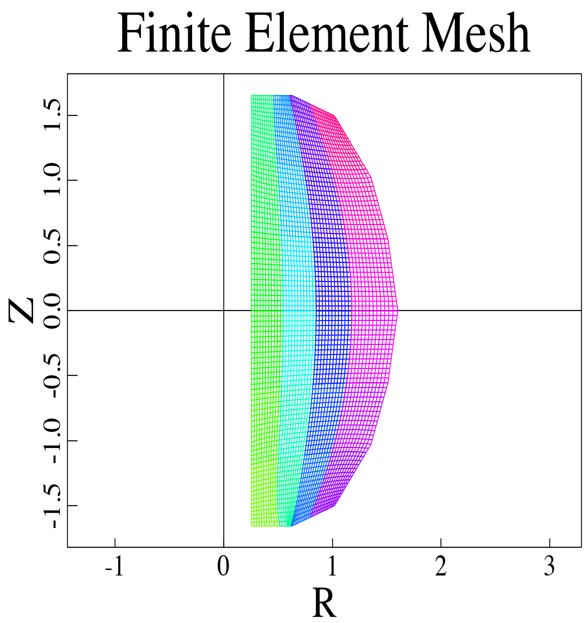
Ip = $\mathbf{I}_{inj}(\psi_T / \psi_{inj})$

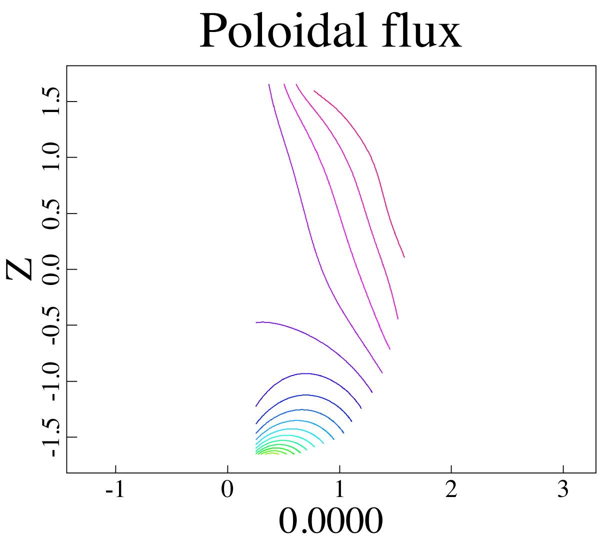
ψ_T = Toroidal flux
$\mathbf{I}_{in}$ = Injector current

[T. R. Jarboe (1989)]

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

Simulations are performed using the extended-MHD NIMROD code





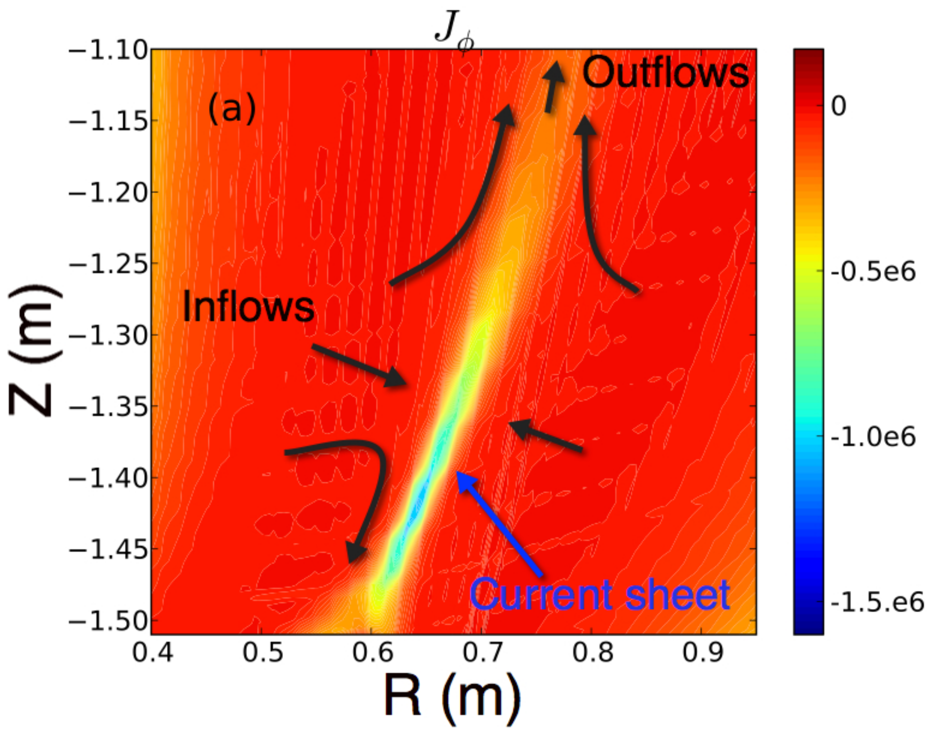
- Similar geometry to the experiment with a narrow electrode gap in the injector region.

- Initial ψ_{inj} generated by including NSTX poloidal coil currents (with fixed boundary field)

- Voltage is applied across the injector gap (**V_{inj}**).
- **E x B** normal flows at the injector and absorber gaps

How are the closed flux surfaces formed?
(a) S-P reconnection

I- S-P reconnection



Forced reconnection:

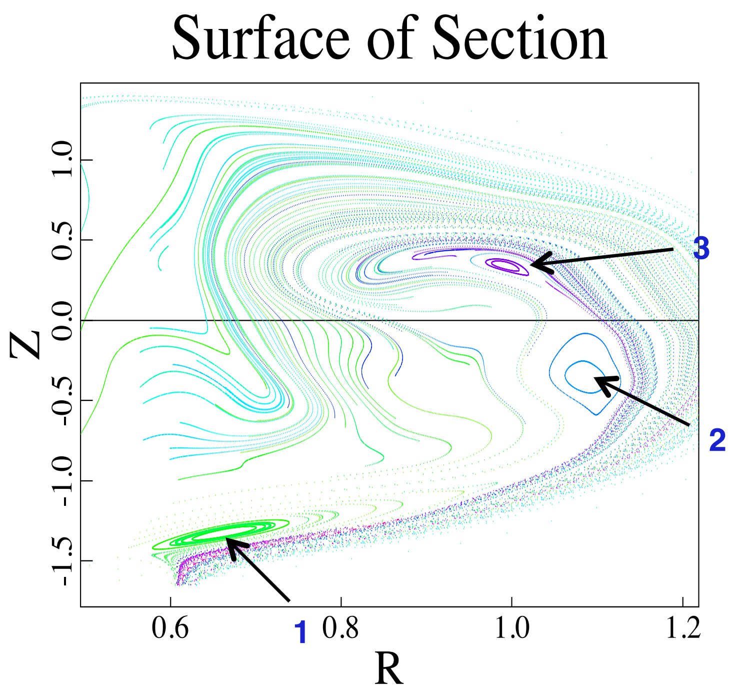
- A local 2-D Sweet-Parker type reconnection is triggered in the injection region. Key signatures:

1. Elongated current sheets, L > δ .
2. Scaling of the current sheet width $L/\delta \sim S^{-1/2} \sim V_{in}/V_{out}$
3. Pinch inflow and Alfv ´enic outflow

[F. Ebrahimi et al. PoP 2013, 2014]

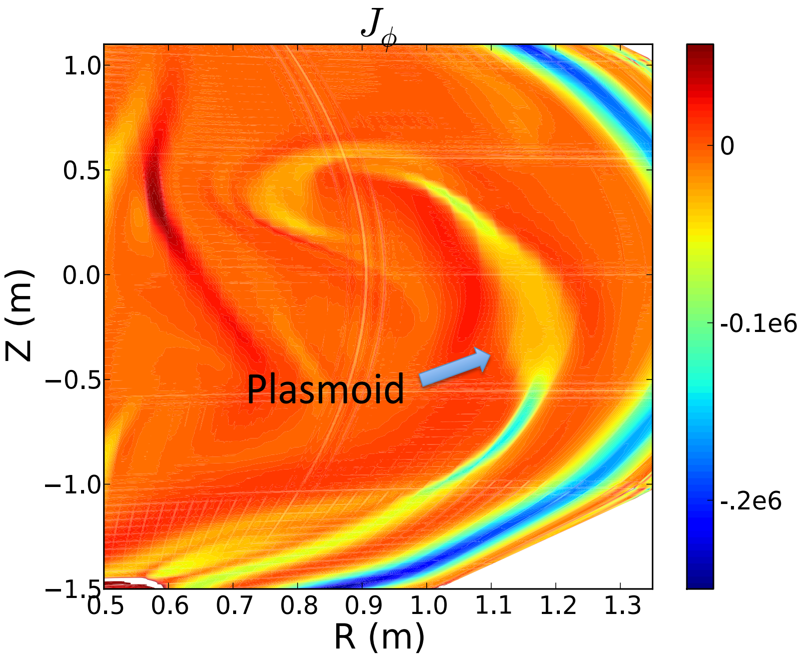
Simulations with magnetic diffusivities (temperatures) similar to those in the experiment produce flux closure.

How are the closed flux surfaces formed?
(b) Plasmoid-mediated reconnection



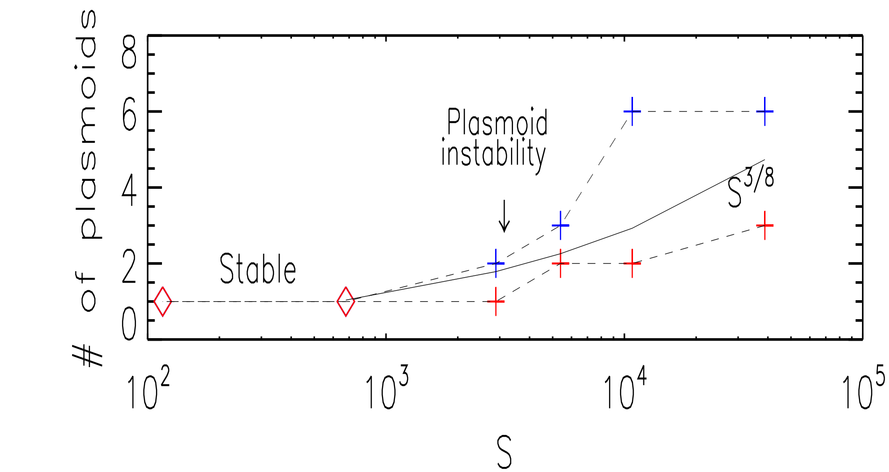
- Both small sized transient plasmoids and large scale plasmoids are formed.

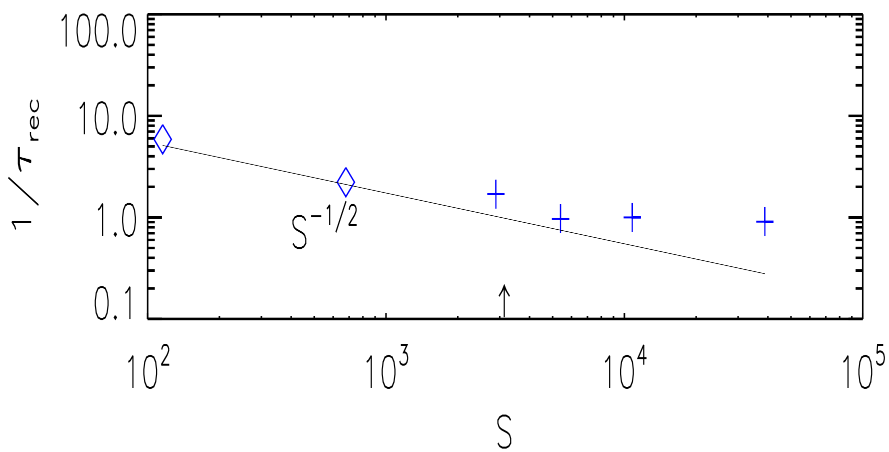
II - Plasmoid instability



Spontaneous reconnection: At high S, a transition to a plasmoid instability is demonstrated in the simulations.
[Ebrahimi&Raman PRL 2015]

At high S, a transition to a plasmoid instability occurs.



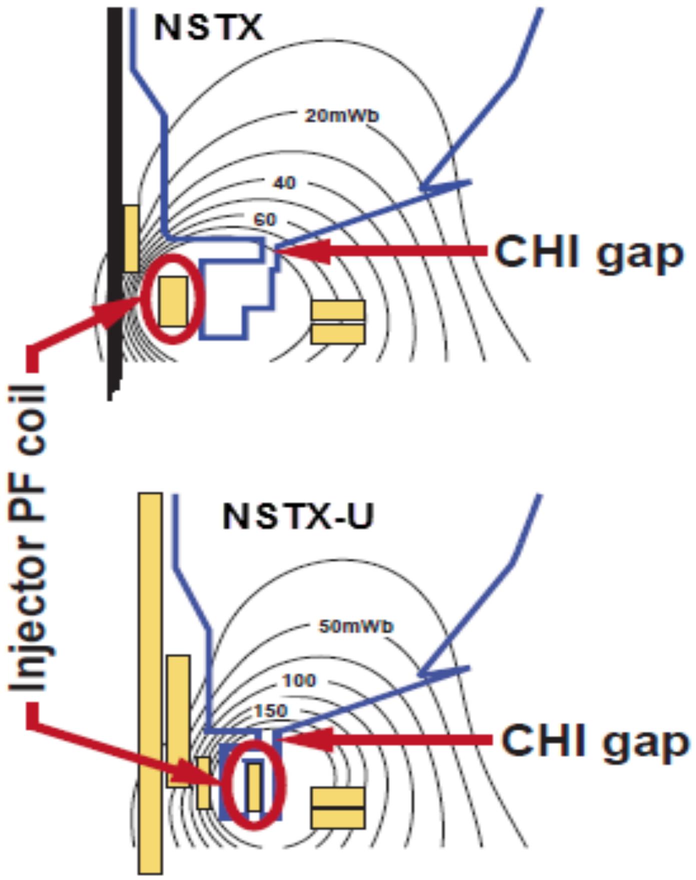


- Number of plasmoids is an increasing function of S. Blue: small sized transient plasmoids Red: large scale and persistent Plasmoids

- As the transition to plasmoid instability occurs, the reconnection rate becomes nearly independent of $S = L\mathbf{V_A}/\eta$ ($\mathbf{V_A}$ is the Alfven velocity based on the reconnecting magnetic field, L is the current sheet length).

In NSTX-U, the natural injector flux footprint is narrower than in NSTX.

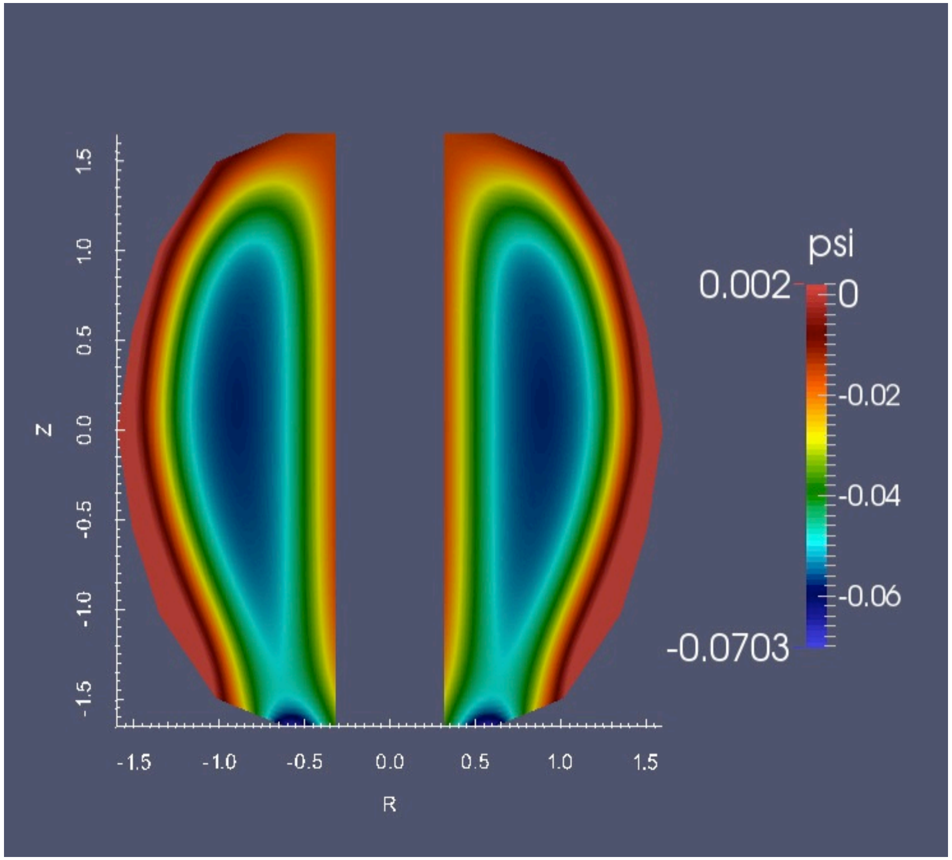
Important upgrades for transient CHI in NSTX–U



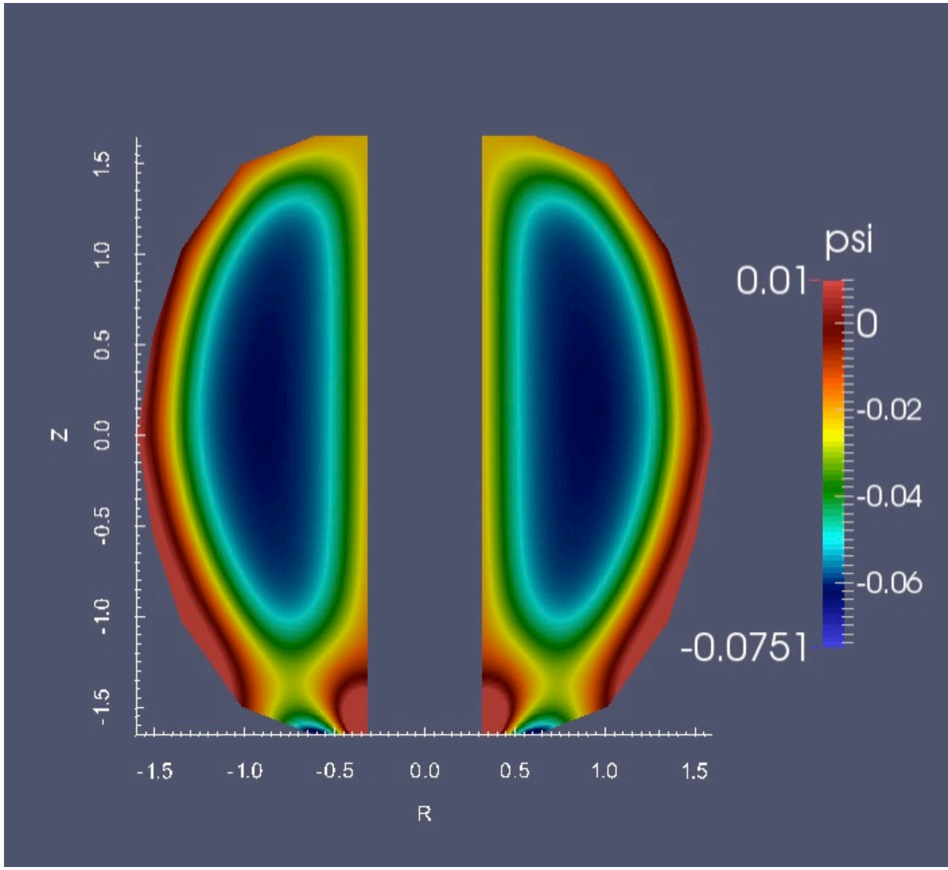
- Better shaping due to the location of CHI injector coil in NSTX-U
- Because of improved positioning of injector flux and shaping coils in NSTX-U, the volume of flux closure is large.
- Double injector flux (ψ_{inj} ~ 0.25Wb), CHI-generated current will be more than 2 times of that in NSTX

Flux closure increases with narrow flux footprints in MHD simulations of NSTX-U.

Wide flux footprint - W/O Flux Shaping coils



Narrow flux footprint - W/ Flux Shaping coils

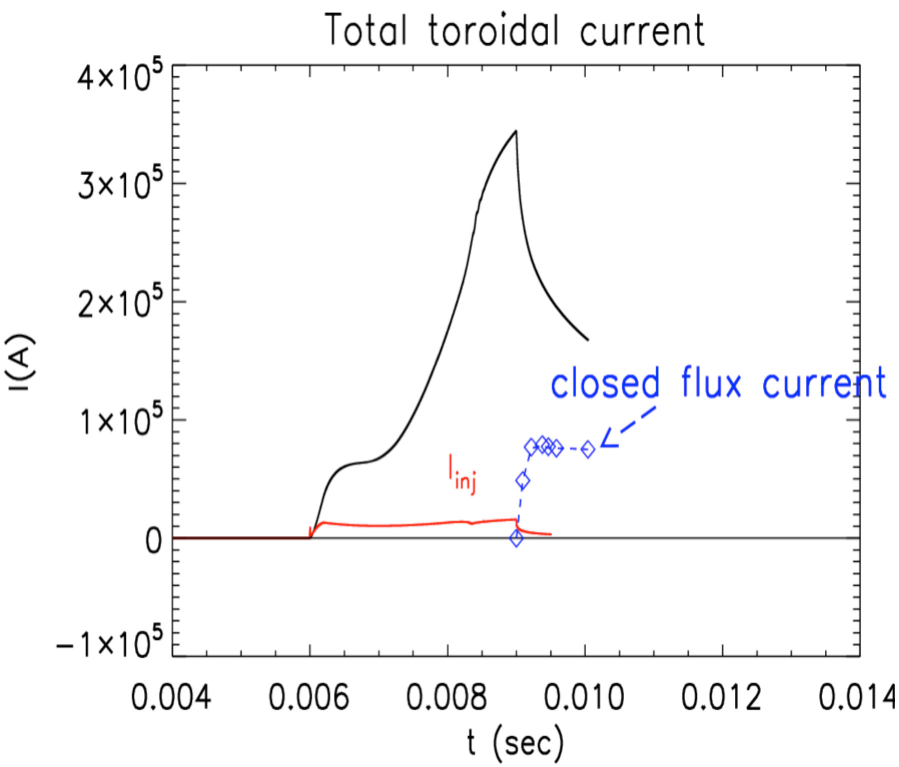


Only a small fraction, about 10 – 30% of the current is on closed field lines.

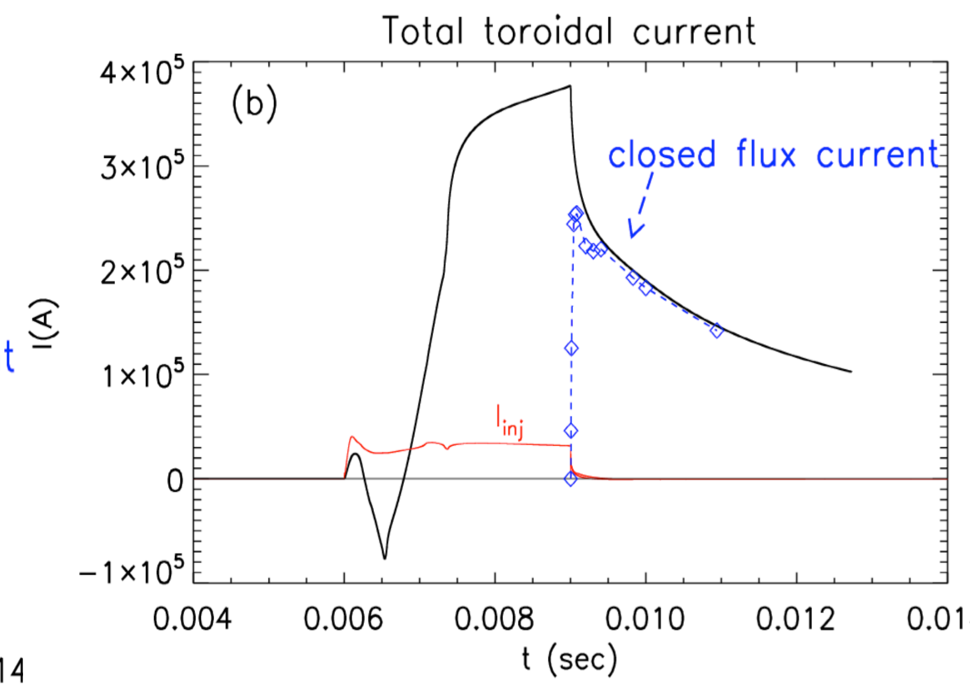
Poloidal flux within the last closed flux surface is 40 mWb and, is about 60 – 70% of the injector flux.

With shaping flux coils, nearly all of the CHI-generated current is closed-flux current (MHD simulations of NSTX-U)

Wide flux footprint



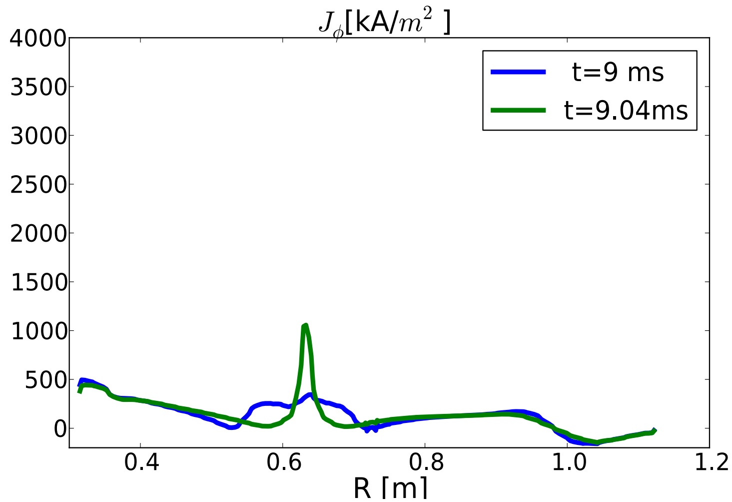
Narrow flux footprint



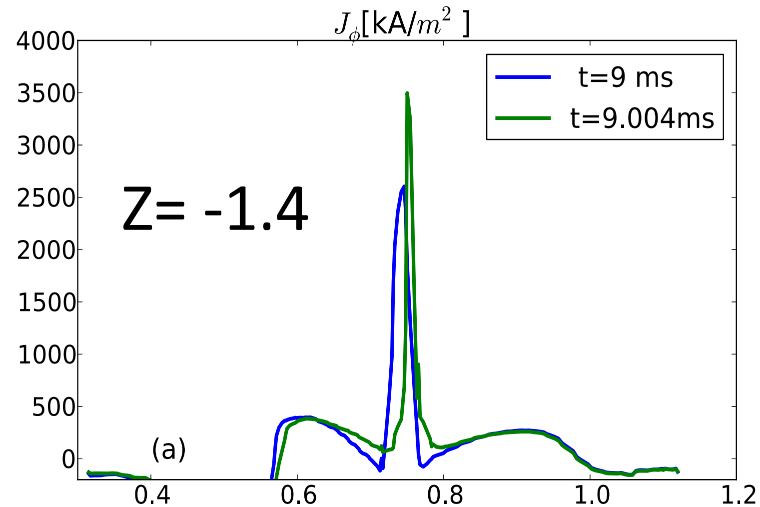
With narrow flux footprint almost all of the total current is in the closed flux region (with a large closed-flux current of about 240kA).
[Ebrahimi&Raman NF Letter 2016]

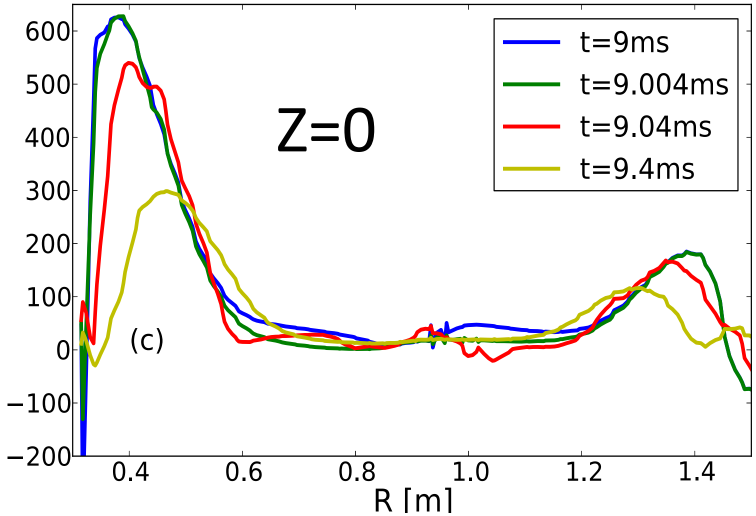
The evolution of current density profiles

Wide flux footprint



Narrow flux footprint



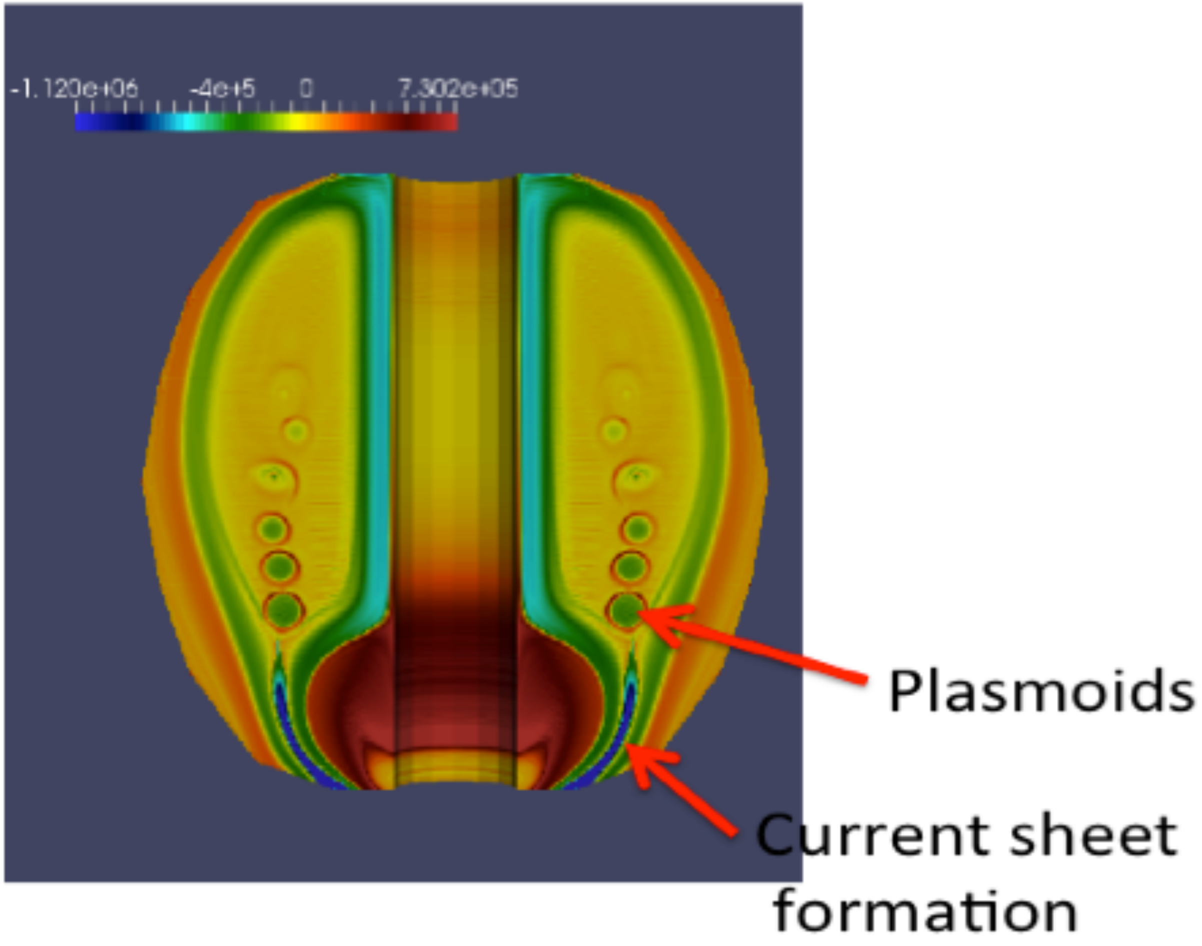


Current density during the injection Phase.

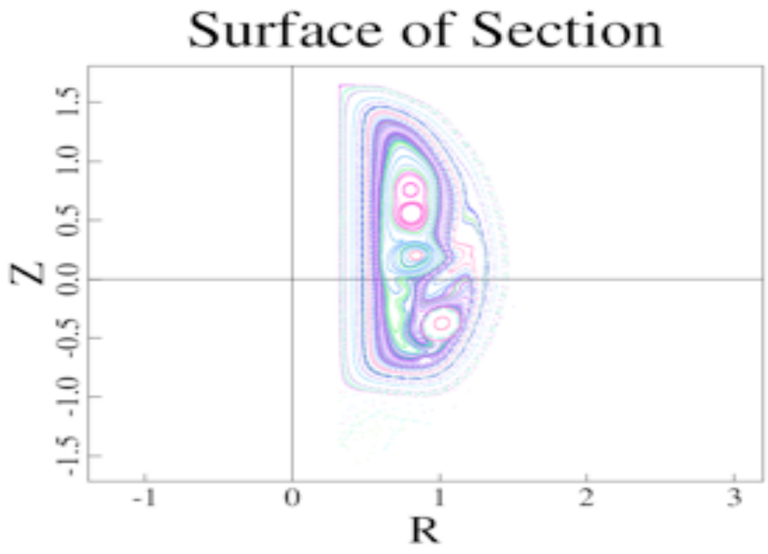
- with wide flux footprint, is radially wide around the injection region.
- is relatively localized with flux shaping coils.

Plasmoid instability with continued injection of plasmoids is observed during the injection phase

- Because of larger reconnecting magnetic field in the injection region, plasmoid instability could occur during the injection phase even at moderate temperatures.

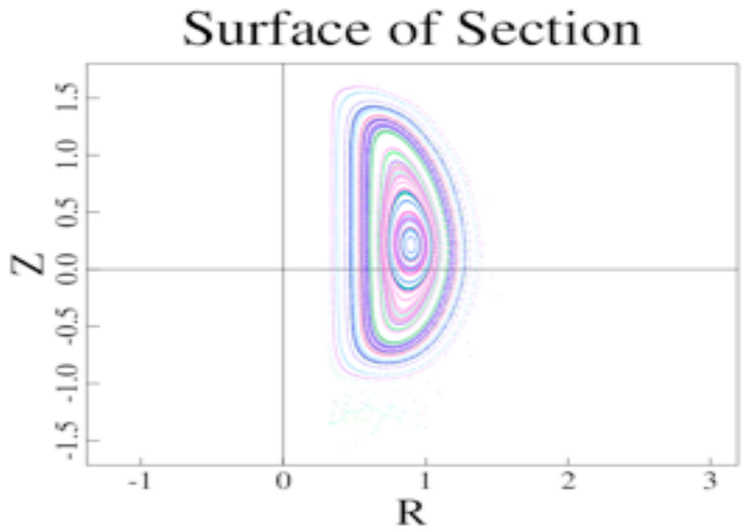


Ragardles of plasmoid formations during injection phase, full flux closure occurs in transient CHI.



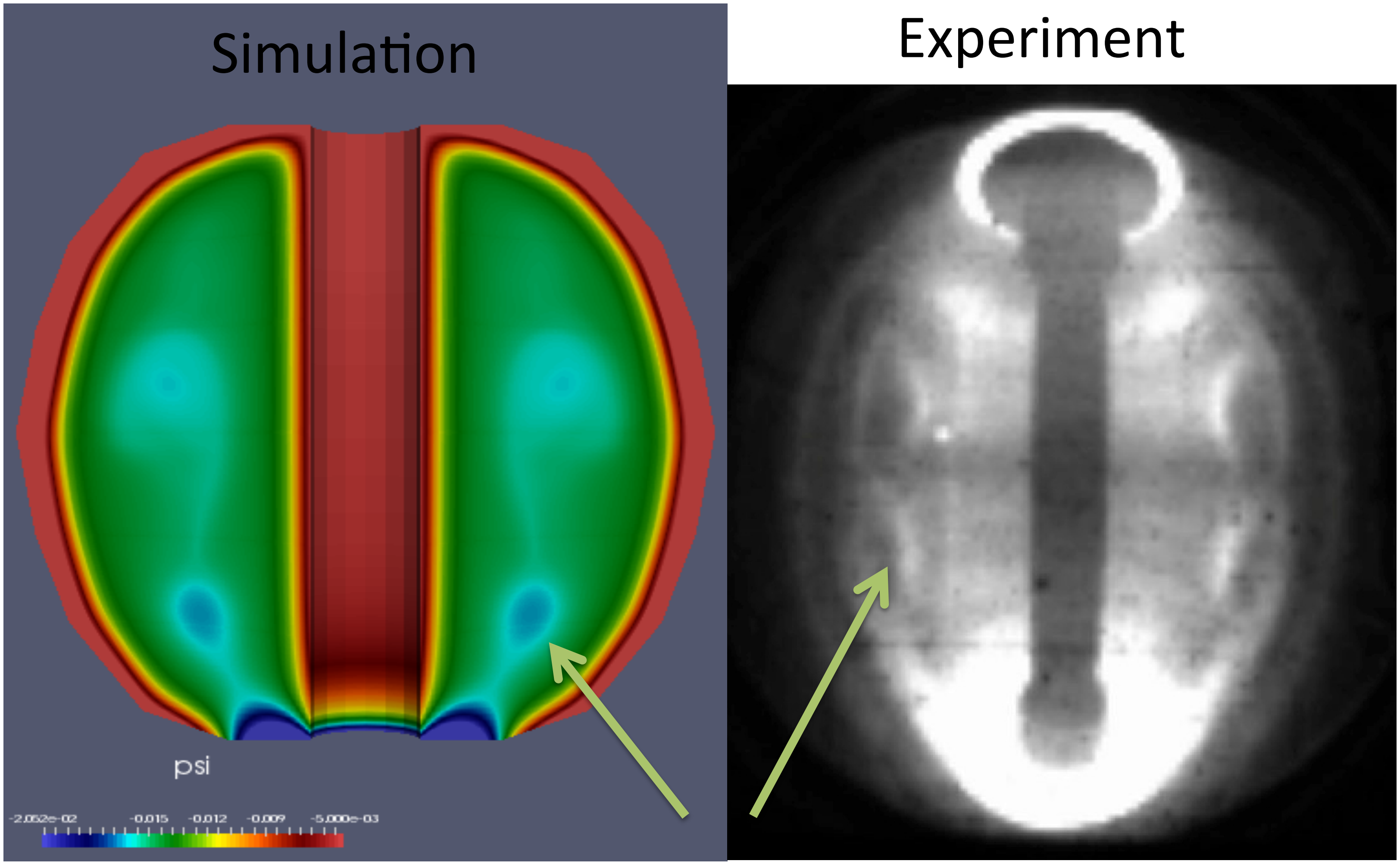
Poincare plots show large volume poloidal flux closure during NSTXU simulations, about 70% of the initial injected flux (Ψinj ~ 75 mWb) is closed.

Top: at t=9.02ms right after the injection is turned off.



Bottom: at t=9.5ms a large volume flux closure is formed.

Camera images from NSTX do show the formation of smaller plasmoids that then merge into a larger pre-existing plasma.



Plasmoids

Summary

Forced magnetic reconnection in NSTX/NSTX-U

- It was found that closed flux surfaces form in the NSTX through a Sweet-Parker type reconnection with an elongated current sheet in the injector region. [F. Ebrahimi et al 2013, 2014]

Possibility of spontaneous reconnection

- a transition to plasmoid instability has for the first time been predicted by simulations in a large-scale toroidal fusion plasma. [Ebrahimi&Raman PRL 2015]

- Motivated by the simulations, experimental camera images have been revisited and suggest the existence of reconnecting plasmoids in NSTX.

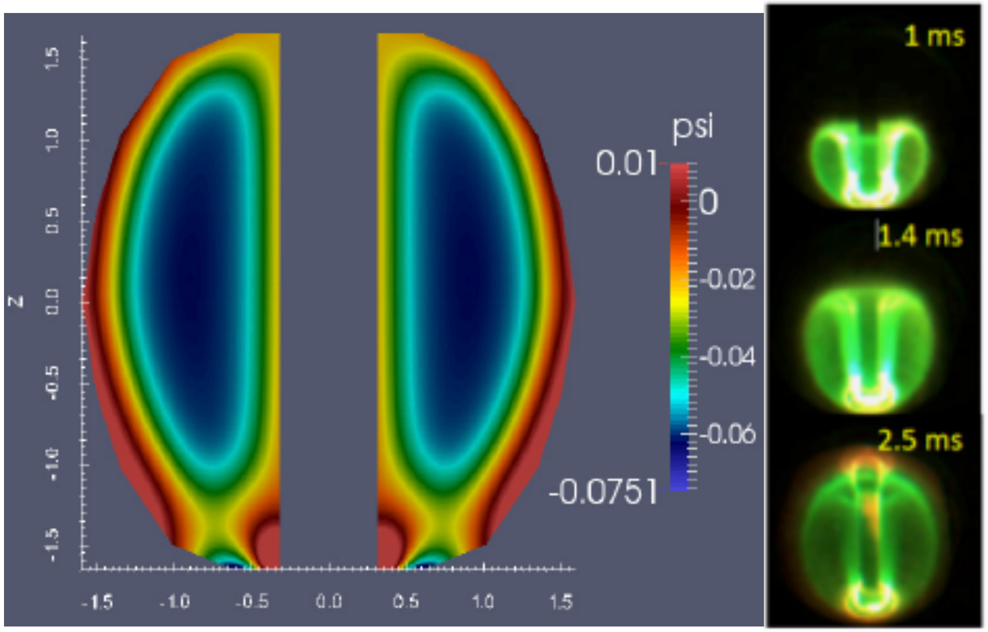
Large-volume flux closure is obtained in the NSTX-U simulations

- Nearly 70% of the injected open flux converts to closed flux. [Ebrahimi&Raman NF 2016]

Physics of Flux Closure during Plasmoid-mediated Reconnection in Coaxial Helicity Injection – TH/P1-2 TH-S

Transient CHI is used as a *solenoid-free* plasma start-up method in NSTX and NSTX-U & can be used to simplify the Tokamak

- Two mechanism for flux closure seen in Resistive MHD simulations
- Sweet-Parker type reconnection (electromagnetic forces cause oppositely directed field lines to come closer in injector region and reconnect)
- New Plasmoid mediated reconnection also observed (the S-P current channel becomes unstable at high Lundquist number and breaks up into plasmoids that merge)
- High flux closure observed during the presence of both mechanisms



Poloidal flux in simulations and fast camera images during NSTX experiments

Transient CHI is applicable to STs and Tokamaks that use superconducting poloidal field coils

- High flux closure (>70%) observed in simulations in which the coil currents are held constant in time