Plasmoids formation in a laboratory and large-volume flux closure during simulations of Coaxial Helicity Injection in NSTX-U

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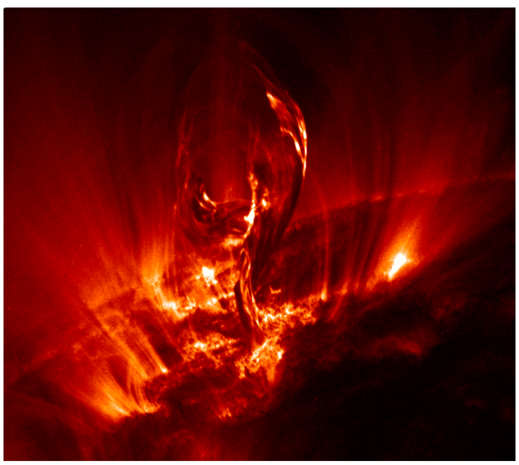
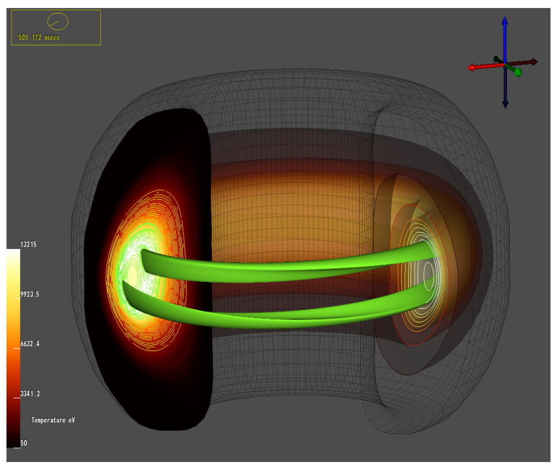
Reconnection plays an important role in the nonlinear dynamics of many processes in laboratory and astrophysical plasmas

Solar flares

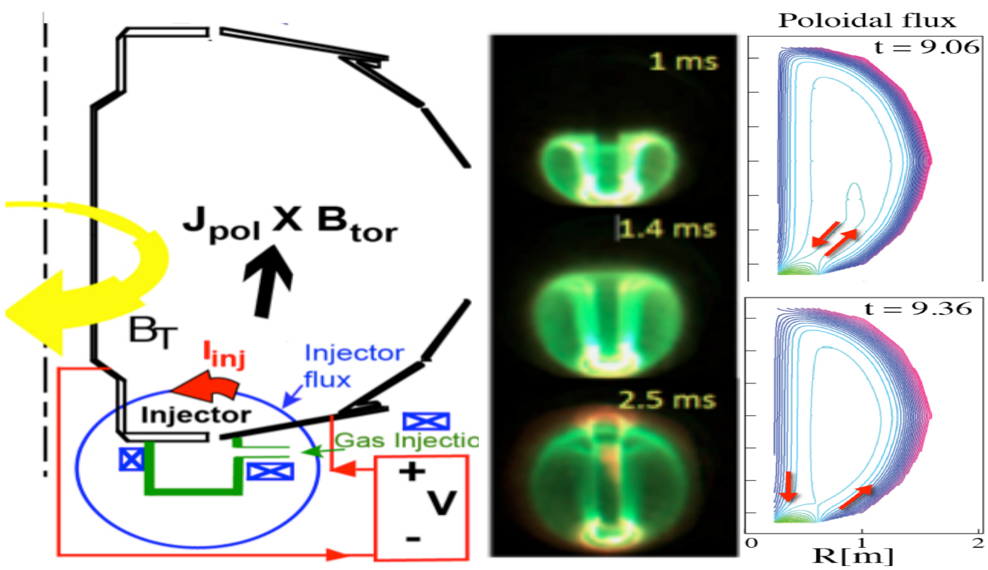


Fusion/lab plasmas



There are two types of trigger mechanism for magnetic reconnection
I- forced (driven) or II- spontaneous reconnection.

Many fundamentals of reconnection physics can be explored during helicity injection



Transient Coaxial Helicity Injection (CHI), the primary candidate for solenoid- free current start-up in the NSTX-U.

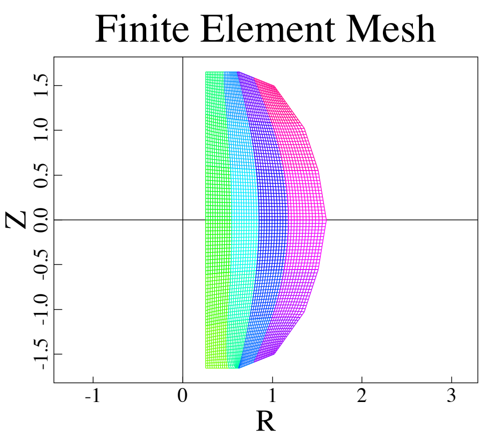
Outline

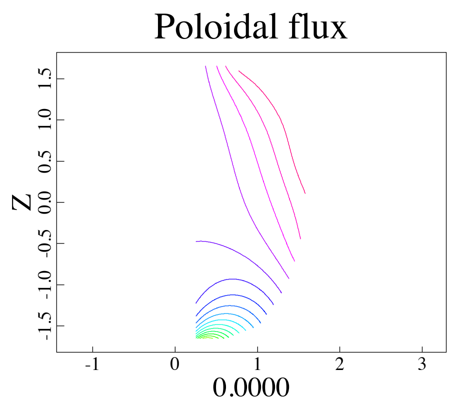
- Flux surface closure during helicity injection
  - Forced (driven) S-P reconnection
  - Spontaneous reconnection

- 3D effects
  - dynamo-driven reconnection plasmoids formation
  - Flux closure and CHI-generated current in NSTX-U

Nonlinear resistive MHD simulations using NIMROD code will be used to study reconnection physics.

The computational model (Nonlinear NIMROD simulations)





- Similar geometry to the experiment with a narrow slot.
- Initial Ψ_{inj} generated by including NSTX poloidal coil currents (with fixed boundary field)
    - Poloidal grid 45 $\times$ 90 fifth order finite elements, 2-D (n=0) and 3-D (up to n= 22 toroidal modes) simulations
    - Voltage is applied across the injector gap (V_{inj})
    - $E \times B$ normal flows at the gaps

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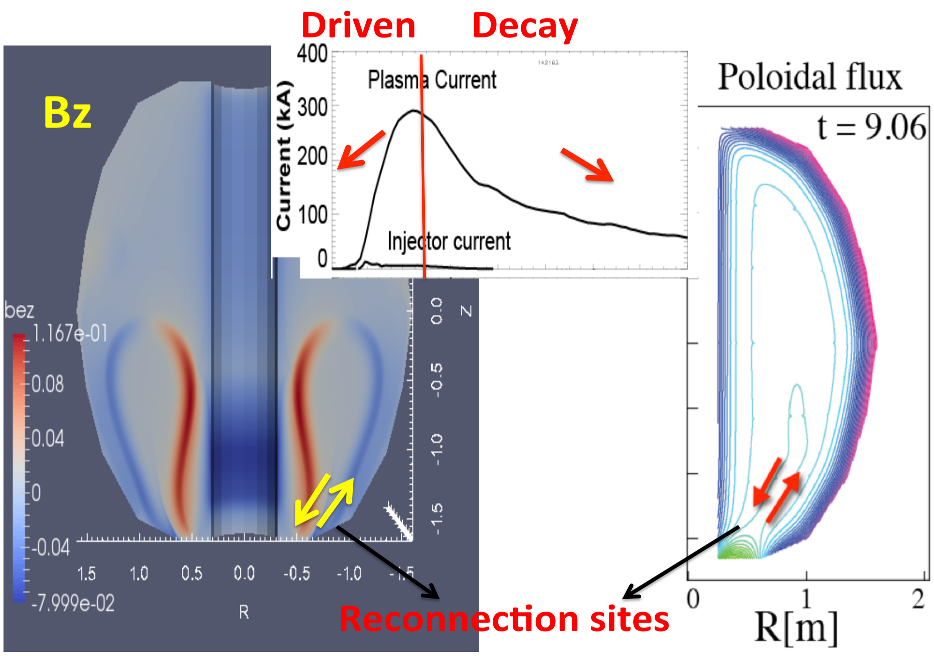
Reconnection could occur during both stages of helicity injection

During injection (V_{inj} on)

During decay (V_{inj} =0)



Outline

- How are the closed flux surfaces formed?
  - $\Longrightarrow$ **Forced (driven) S-P reconnection**

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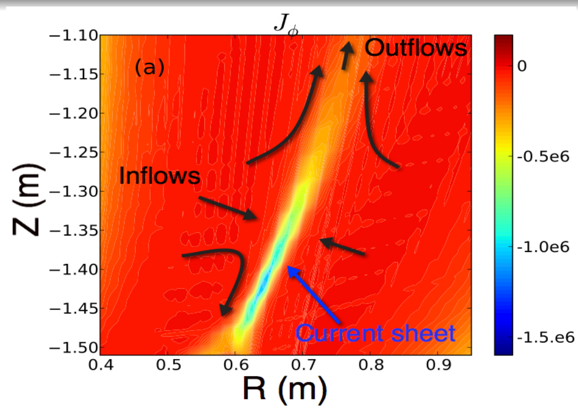
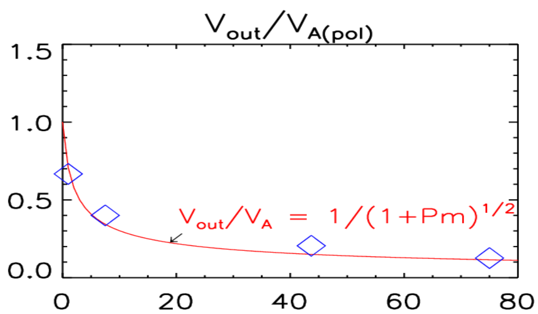
I - Forced S-P reconnection





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

- **I - Elongated current sheets, $L > \delta$.**
- **II - Scaling of the current sheet width** $\delta/L \sim (1 + P_m)^{1/4} S^{-1/2} \sim V_{in}/V_{out}$
- **III -Pinch inflow and Alfvénic outflow**

S = LV_A/η (Alfven velocity based on the reconnecting B, L is the current sheet length) F. Ebrahimi, et al. PoP 2013, 2014

Outline

- How are the closed flux surfaces formed?
  - **Forced (driven) S-P reconnection**
  - $\Longrightarrow$ **Spontaneous reconnection**

    Could the elongated current sheet become unstable?

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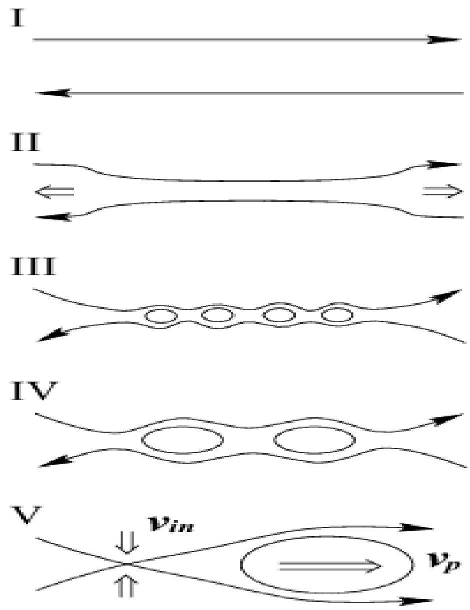
In many fast MHD dynamical processes, plasmoids are essential features

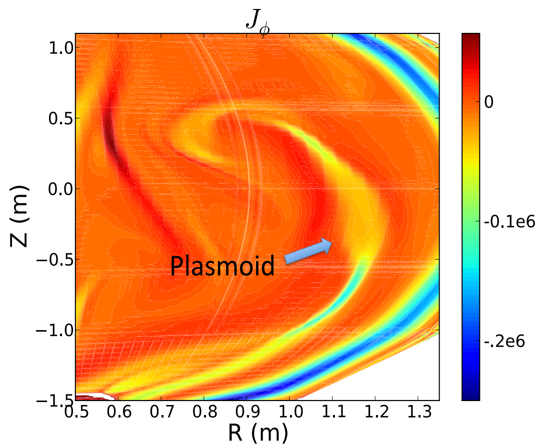
- Elongated current sheet can become tearing unstable at high S. [Biskamp 1986, Shibata & Tanuma 2001]

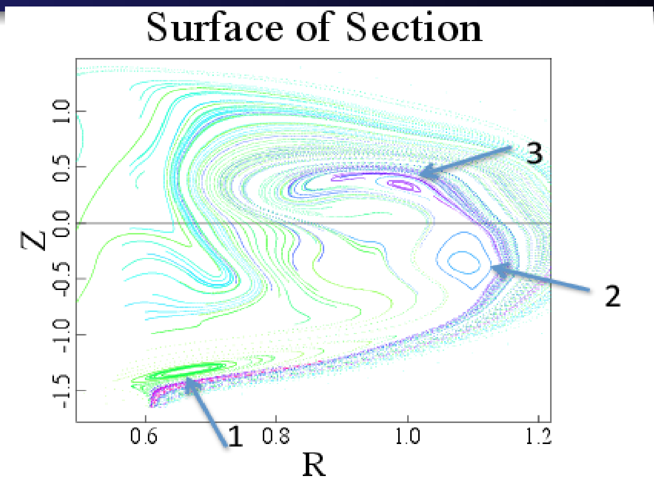
- The scaling properties of a classical linear tearing changes, ($\gamma \sim S^{1/4}$).
  Numerical development: [Shibata & Tanuma 2001,Loureiro et al. 2007; Lapenta 2008; Daughton et al. 2009,; Bhattacharjee et al. 2009]
  show fast reconnection.



Shibata & Tanuma 2001

How are the closed flux surfaces formed?
II - Spontaneous reconnection



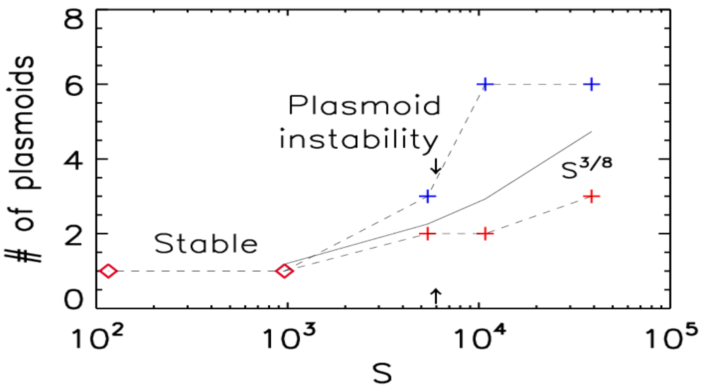


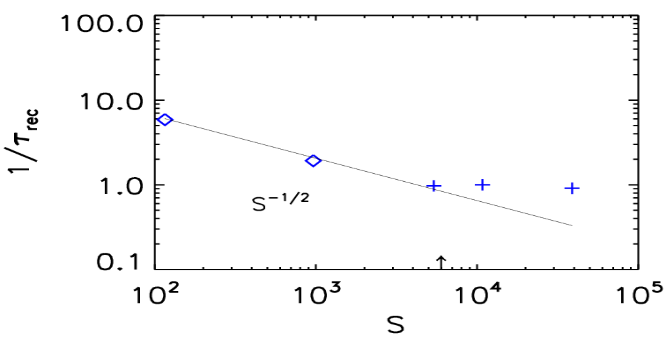
At high S, a transition to a plasmoid instability is demonstrated in the simulations.

Both small sized transient plasmoids and large system-size plasmoids are formed and co-exist. (S=39000)

Plasmoids merge to form closed flux surfaces.

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 current sheet evolves in time, static linear theory doesn't apply [L. Comisso et al. PoP 2016]
- Reconnection rate becomes nearly independent of S.

F. Ebrahimi and R.Raman PRL 2015

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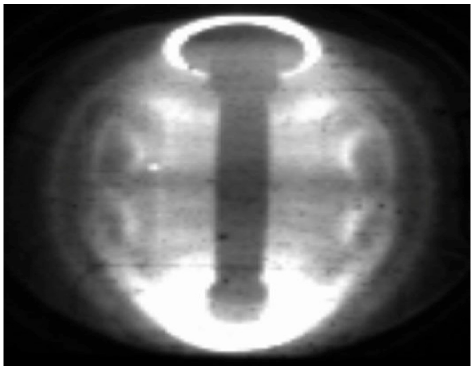
First documentation of plasmoid formation in MHD regime in laboratory.

(Loading poloidalflux.mp4)



Camera images from NSTX do show the formation plasmoids that then merge into a larger plasma

[Ebrahimi&Raman PRL 2015]

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- 3D effects
  - **dynamo-driven reconnection plasmoids formation**
  - Could large-scale dynamo from 3-D fluctuations trigger reconnecting plasmoids?

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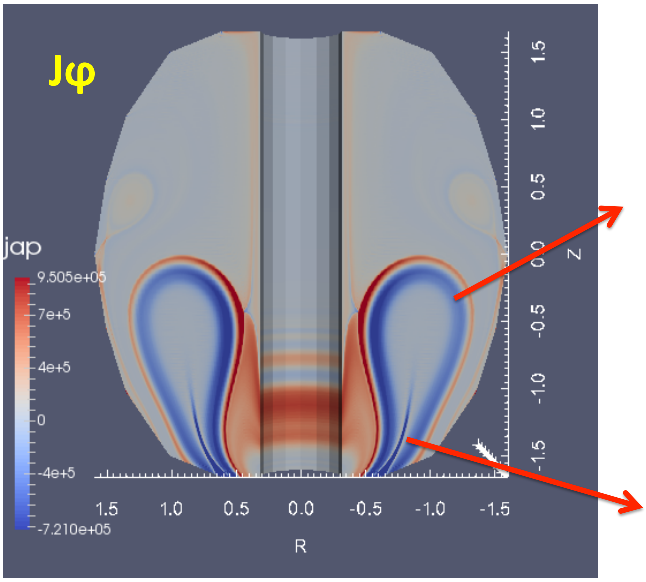
As helicity is injected, two types of current sheets are formed



Consider an idealized case at increased helicity injection (increased poloidal flux)

- 1- **Edge current sheet** from the poloidal flux compression near the plasma edge.
- 2- **Primary reconnecting current sheet** from the oppositely directed field lines in the injector region.

Here in 2-D no plasmoid formation (stable $S < 10^4$)

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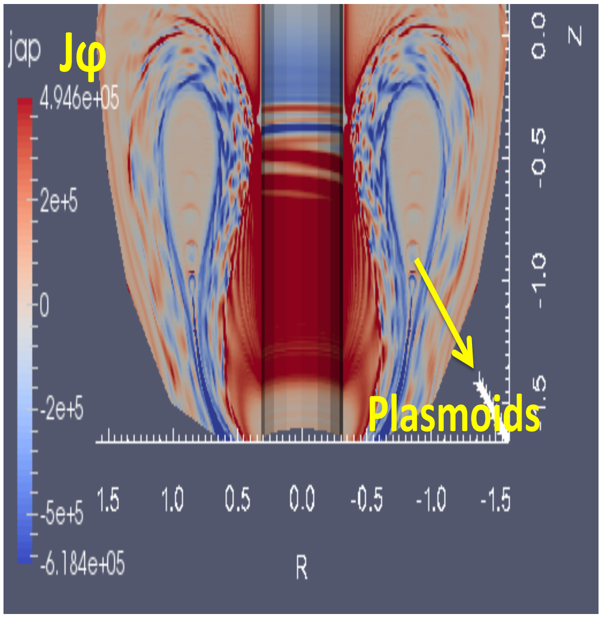
Edge current-sheet instabilities are triggered in 3-D, and break the current-sheet

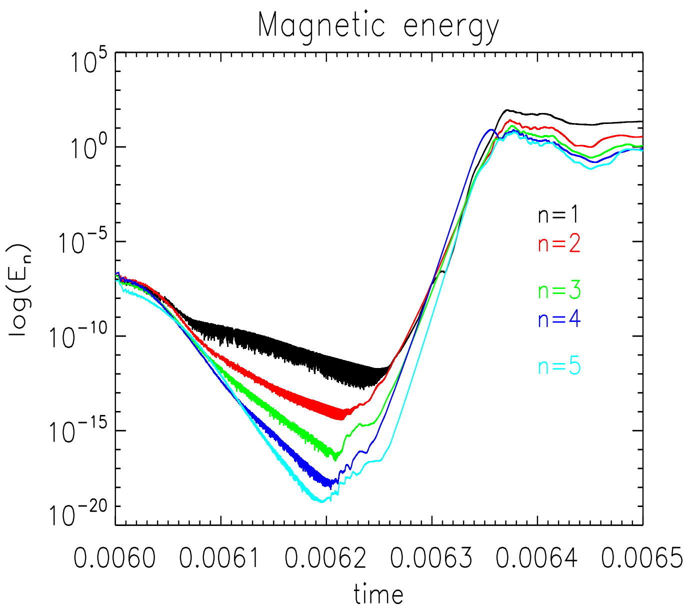


1. I- **Edge-localized modes arising from the current-sheet instabilities**
2. II- With 3-D fluctuations, axisymmetric plasmoids are formed, **local S increased to S $\sim$ 15000.** [Ebrahimi submitted, arXiv:1610.09050]

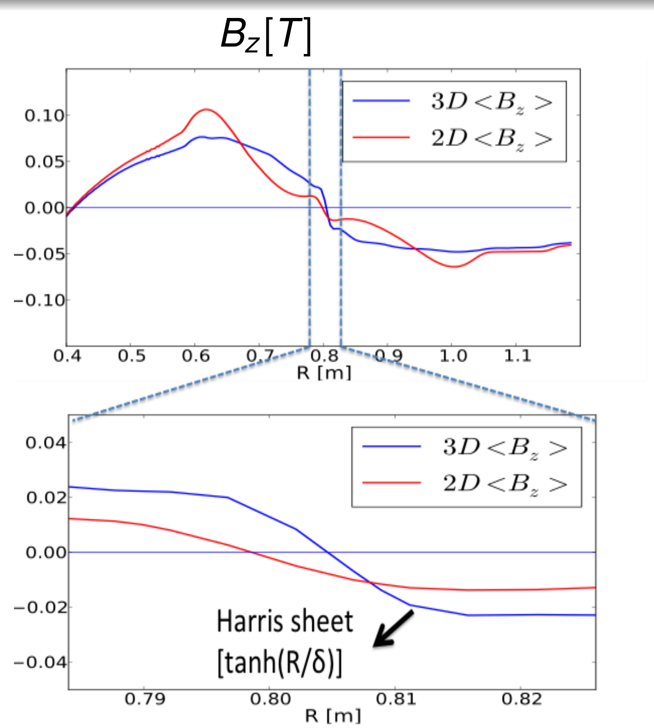
I- Edge modes grow on the poloidal Alfven time scales

1. These modes grow fast, on the poloidal Alfven time scales, but they have tearing-parity structures.

2. These modes saturate by modifying and relaxing the edge current sheet $\gamma\tau_{A(n=1)} = 0.16$,
$\gamma\tau_{A(n=2)} = 0.18$,
$\gamma\tau_{A(n=3)} = 0.2$,
$\gamma\tau_{A(n=4)} = 0.23$,
$\gamma\tau_{A(n=5)} = 0.26$.
$S = 2 \times 10^5$



II- A 3-D dynamo poloidal flux amplification is observed to trigger axisymmetric reconnecting plasmoids formation



- For the first time a dynamo poloidal flux amplification is observed
- This **fluctuation-induced flux amplification increases the local S** ==> **triggers a plasmoid instability** ==> breaks the primary current sheet.

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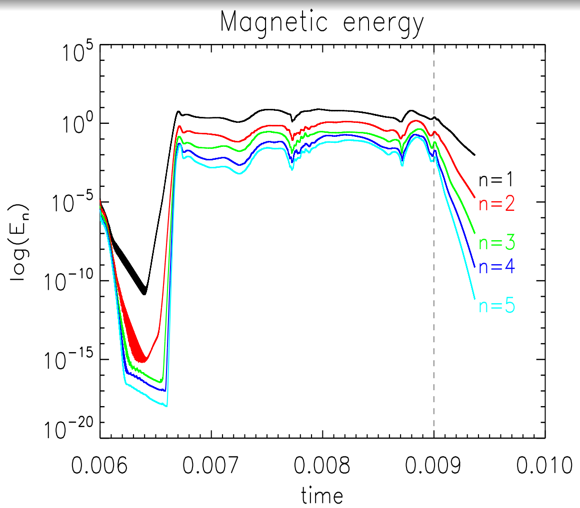
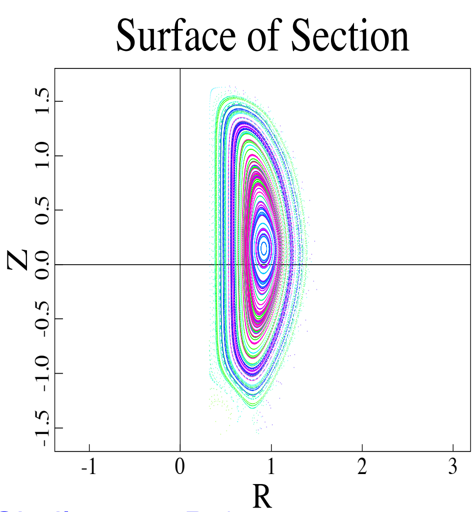
For NSTX-U relevant parameters, large volume flux closure is formed in the presence of 3-D fluctuations



For NSTX-U relevant parameters, the nonaxisymmetric fluctuations saturate at low amplitudes (3-D). **These are peeling-type modes with tearing parity**



Similar to 2-D (**[F. Ebrahimi & Raman NF Letter 2016]**), **nearly 70% of the injected open flux converts to closed flux in NSTX-U (3-D simulations)**

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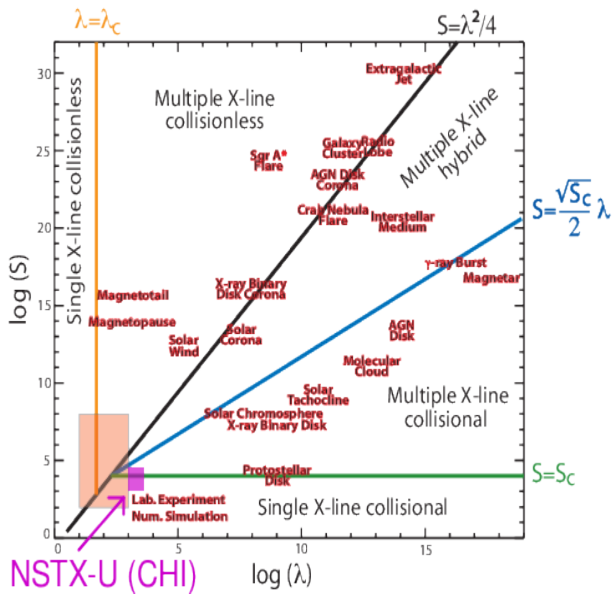
Future directions: In addition to fusion applications, NSTX-U is a rich platform for fundamental reconnection studies

- How transient CHI scales as it is extrapolated to future (larger) devices, such as the ST-FNSF
- The implications of these new results of global plasmoids for 3-D fast reconnection and global tokamak MHD activity including disruption (VDEs and ELMs).



Phase diagram [H. Ji on fundamental reconnection studies]

Summary

I- Forced magnetic reconnection in NSTX/NSTX-U

- A local 2-D S-P reconnection is triggered. [F. Ebrahimi et al 2013, 2014]

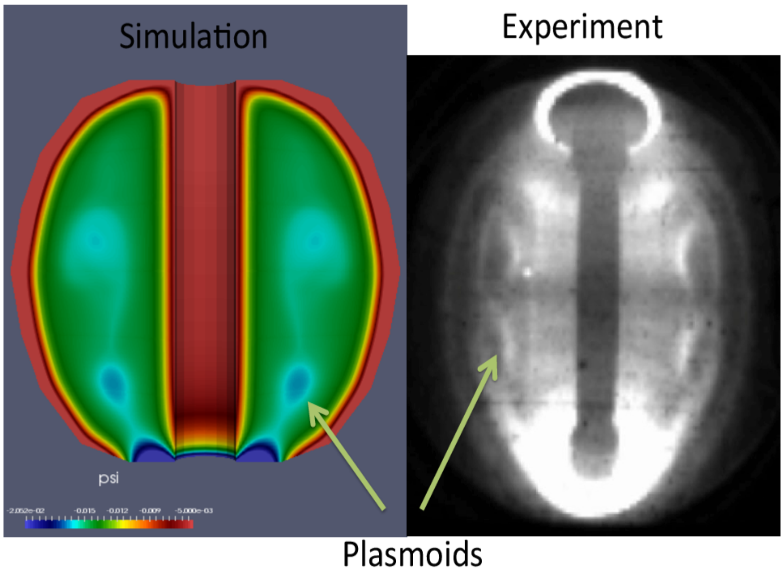
II- Possibility of spontaneous reconnection

- 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 exhibit the existence of reconnecting plasmoids in NSTX.

III- For the first time, a 3-D dynamo poloidal flux amplification is observed to trigger axisymmetric reconnecting plasmoids.) [Ebrahimi submitted, arXiv:1610.09050]

IV- Large-volume flux closure is obtained in the NSTX-U simulations in 2-D [Ebrahimi&Raman NF 2016] **and in 3-D**[to be submitted] extra slides

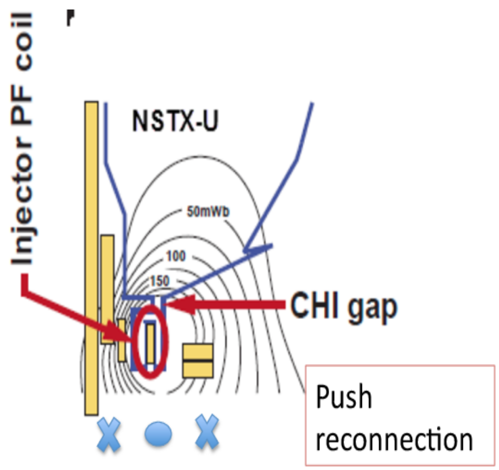
Camera images from NSTX do show the formation, and subsequent separation, of smaller plasmoids that then merge into a larger pre-existing plasma



- $T_e \sim 5eV$, $n \sim 4 - 5 \times 10^{18} m^{-3}$
- $B_{rec} \sim 100$G, $L \sim 1m$
- estimated local S =2000-4000.
- $V_p \sim 25$ km/s

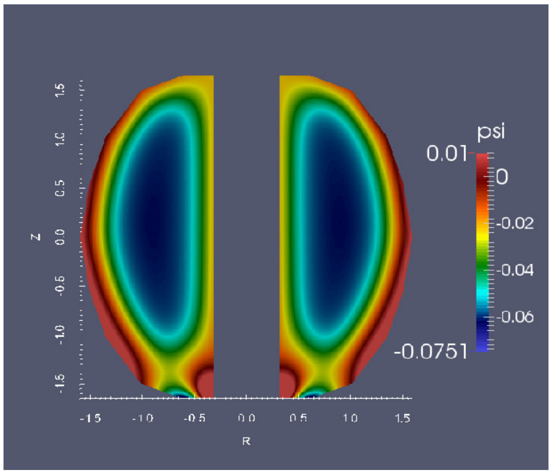
[Ebrahimi&Raman PRL 2015]

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



Because of improved positioning of injector flux and shaping coils in NSTX-U, the volume of flux closure is large.

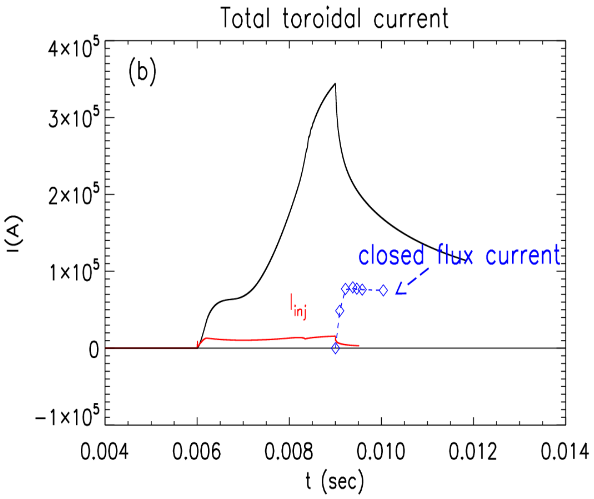
Narrow flux footprint
W/ Flux Shaping coils



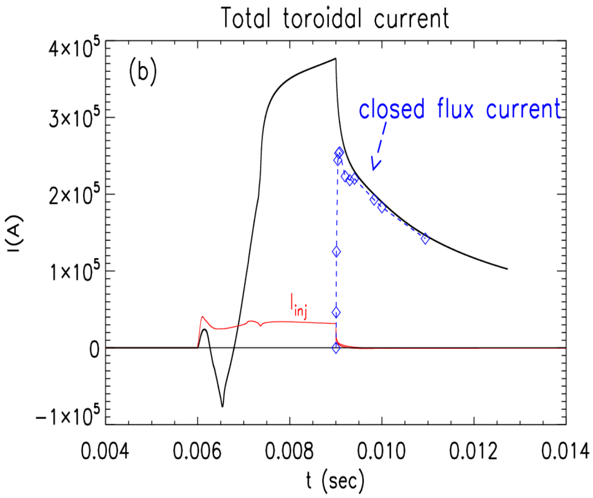
Poloidal flux within the last closed flux surface is 40 mWb and, is about 60 − 70% of the injector flux

Nearly all of the CHI-generated current is closed-flux current.

Wide flux footprint



Narrow flux footprint

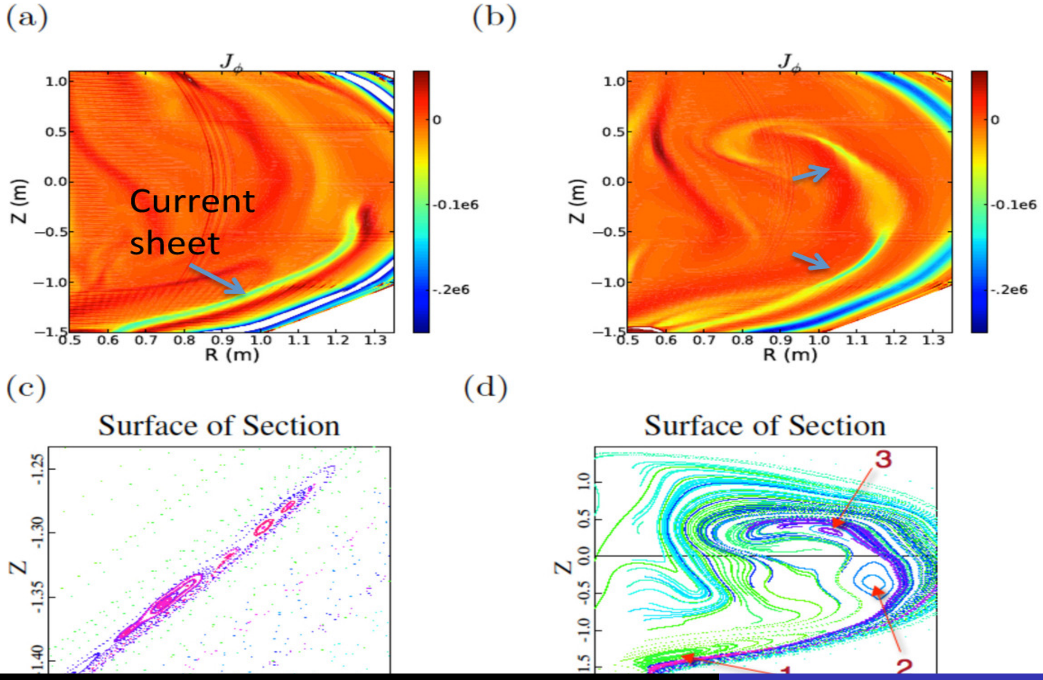


With narrow flux footprint almost all of the total current is in the closed flux region (with a large closed-flux current of about 240kA).

Both small sized transient plasmoids and large scale plasmoids are formed (S=39000)

t= 9.04ms

t= 9.17ms



Large scale islands go through a dynamical process and merge to form closed flux surfaces