Reconnection physics and full flux closure during simulations of Coaxial Helicity Injection in NSTX/NSTX-U

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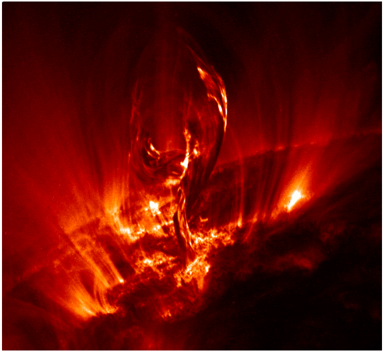
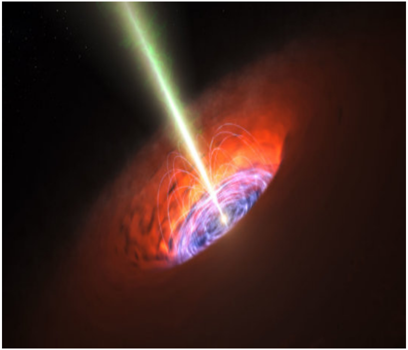
Magnetic reconnection energizes many processes in nature

Solar flares

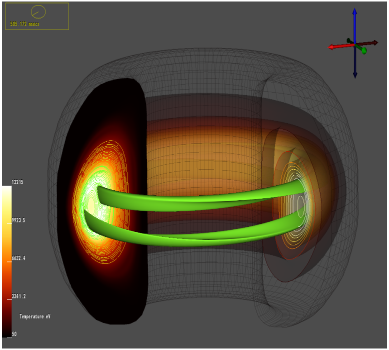


Coronas of accretion disks/jets

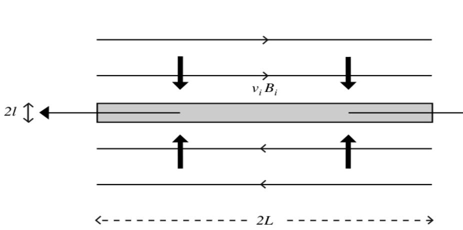


Reconnection is a major interplay for fundamental physical phenomena 1- change in magnetic topology 2- heating 3- relaxation of mean fields 4- particle acceleration 5- magnetic field generation, and 6- momentum transport.

Reconnection physics plays an important role in the nonlinear dynamics of many processes in laboratory plasmas.

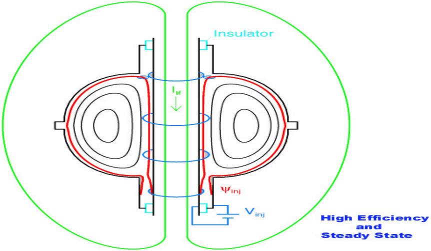


1) global stability of fusion/tokamak plasmas. In toroidal fusion plasmas magnetic reconnection is mainly **spontaneous** as the result of tearing fluctuations.

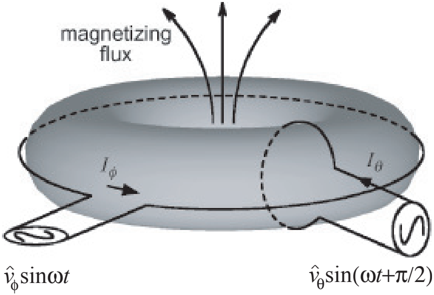


- Sweet-Parker type forced magnetic reconnection in laboratory plasmas has been extensively studied. [H. Ji, Yamada et al. 1998]
- $\boxed{V_{in}/V_{out} = S^{-1/2} = \ell/L}$ $(S = \mu_0 L V_A/\eta)$

2) Reconnection physics (non-axisymmetric tearing) plays an important role on current relaxation during helicity injection



RFPs



- Spheromaks and low aspect ratio tokamaks (CDX, HIT tokamaks, CTX spheromak and NSTX) are formed and sustained through electrostatic helicity injection.

Helicity is injected steadily by oscillating toroidal and poloidal surface voltages

In all these devices, the core current penetration relies on relaxation process through current-driven reconnection.

Opportunities to use helicity injection experiments (transient Coaxial Helicity Injection) during plasma start-up to study reconnection physics

- **both forced and spontaneous reconnection could occur in tCHI.**
- **the high-S plasma regime**, which may be difficult to access in experiments specifically designed for reconnection, can be accessed during CHI.
- **their large scale** (e. g. NSTX-U with major radius=0.94m, minor radius=0.62m, and height = 3m)
- **there is no pre-existing instability** or current channel.

Global simulations have critical role in understanding the physics and to predict the experimental observations.

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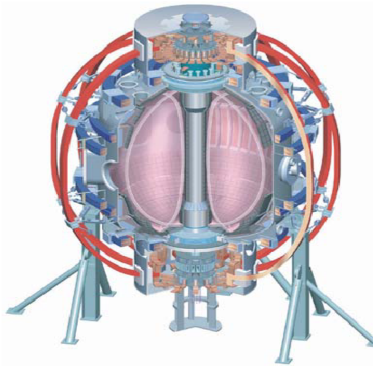
Unique dual nature of helicity-injection experiments for plasma start-up:

1. These experiments are primarily intended to generate plasma current as a fusion application.
2. Transient CHI provides a very rich platform for studying reconnection in the absence of pre-existing instabilities.

- Reconnection process during CHI is of great importance for
  1. formation of closed flux surfaces and to optimize the maximum good flux closure (and CHI plasma current).
  2. the extrapolation to larger devices, ultimately for steady-state current-drive.



Transient CHI plasmas exhibits some fundamental reconnection physics including plasmoid physics.

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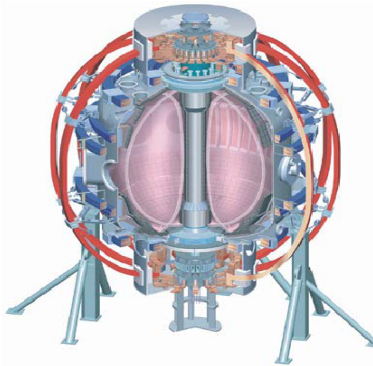

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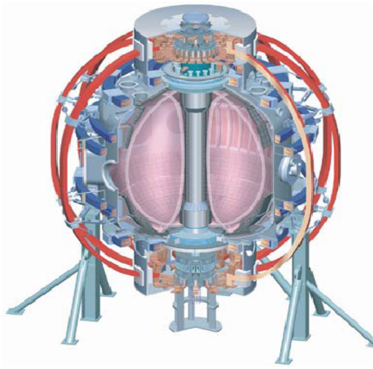

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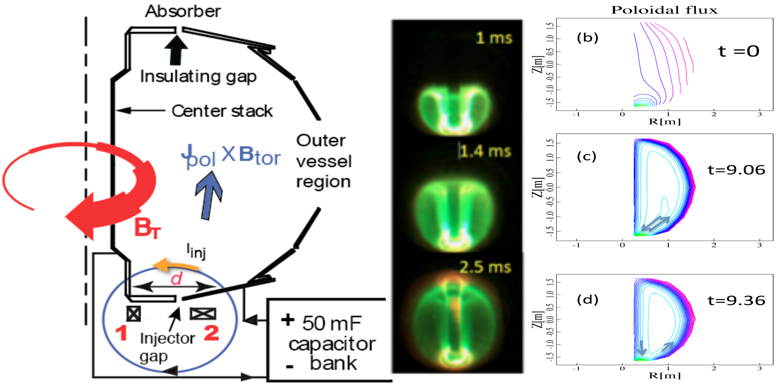
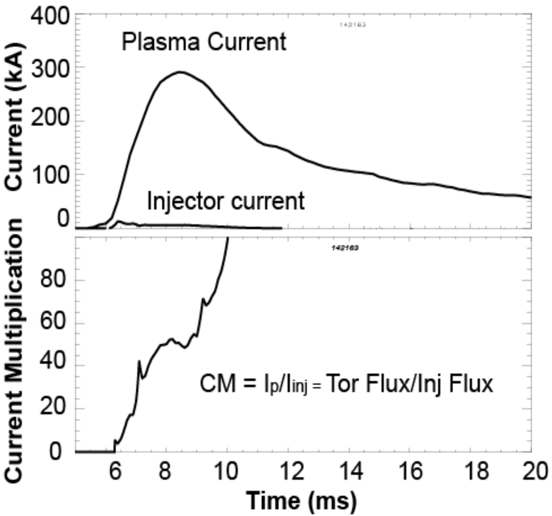
In transient CHI, axisymmetric reconnection generates a high quality closed flux start-up equilibrium in NSTX



(c) The arrows show oppositely directed field lines in the injector region where the S-P current sheet forms. To induce reconnection, the voltage is rapidly reduced to zero at t=9ms.

(d) Closed flux surfaces are formed

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



Raman et al. PRL 2006

Injector current

$\Uparrow$

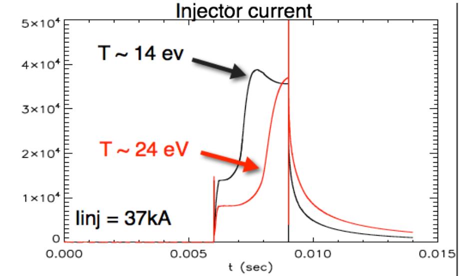
- $I_p = I_{\text{inj}}(\Psi_T/\Psi_{\text{inj}})$

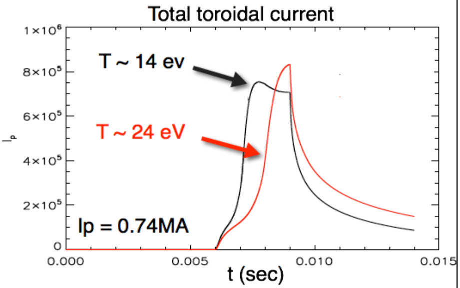
$\Downarrow$

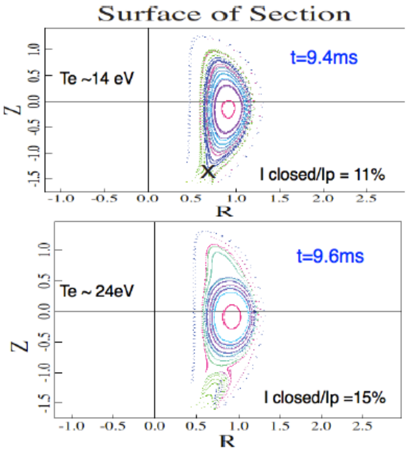
Toroidal flux
[T. R. Jarboe (1989)]

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

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

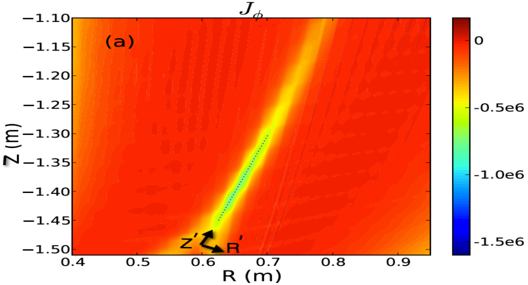


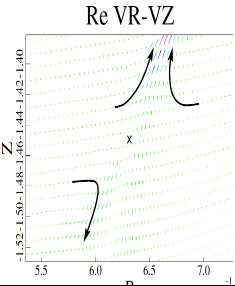


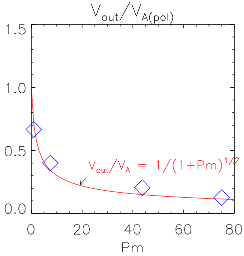


- Closed flux fraction increases as the magnetic diffusivity is reduced

Simulations reveals that a local 2-D Sweet-Parker type reconnection is triggered in the injection region







Key signatures of S-P reconnection

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

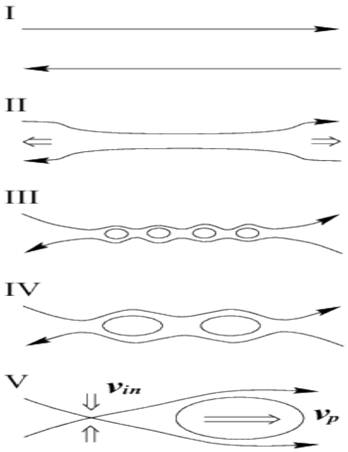
F. Ebrahimi, et al. PoP 2013.

the onset problem – Could the elongated current sheet become unstable?

In many fast MHD dynamical processes, plasmoids are essential features.

- At high S, the elongated Sweet-Parker current sheet can become tearing unstable. [Biskamp 1986, Shibata & Tanuma 2001]

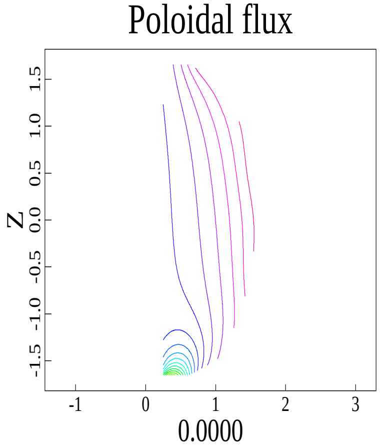
- The scaling properties of a classical linear tearing changes if the current sheet width (a) is replaced by S-P current sheet width $\delta \sim L/\sqrt{s}$, ($\gamma \sim S^{1/4}$). Numerical development: [Loureiro et al. 2007; Lapenta 2008; Daughton et al. 2009,; Bhattacharjee et al. 2009]



Shibata & Tanuma 2001

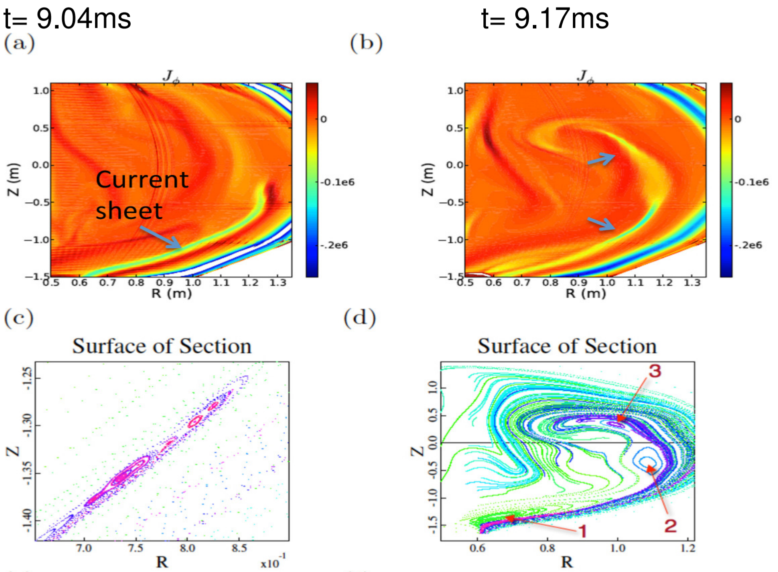
With narrow injector flux footprint and at high inj. current, transition to a plasmoid instability is observed – NSTX simulations

Is there is a possibility that the forced reconnection during TCHI transitions to spontaneous reconnection (instability) – Plasmoid instability in NSTX?

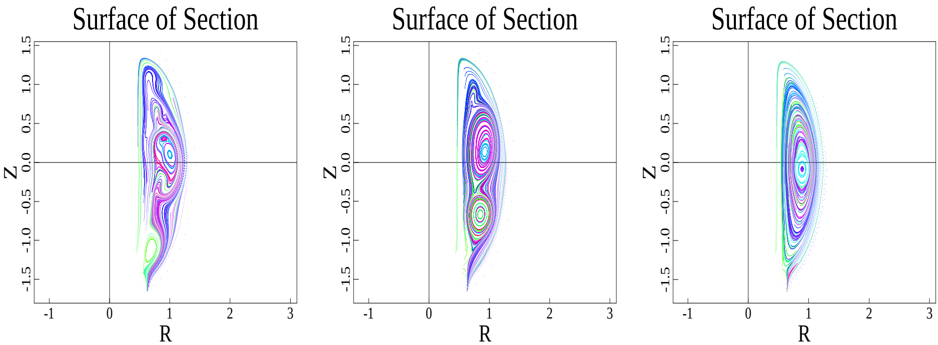


- To access the plasmoid instability regime, S is increased through
  1. decreasing magnetic diffusivity (η) or
  2. increasing injector voltage
  3. using narrow flux footprints.

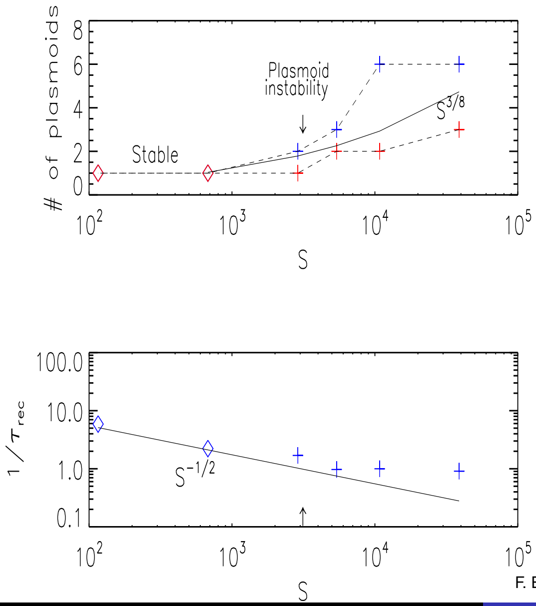
Both small sized transient plasmoids and large scale plasmoids are formed (S=39000)



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



At S $\sim$ 3000, a transition to a plasmoid instability occurs.



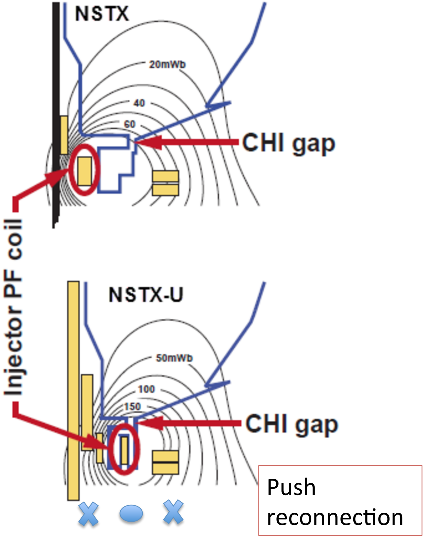
- Number of plasmoids is an increasing function of S. Blue: small sized transient plasmoids Red: large scale and persistent plasmoids
- As the transition to plasmoid instability occurs, the reconnection rate becomes nearly independent of S = L V_A/η (V_A is the Alfven velocity based on the reconnecting magnetic field, L is the current sheet length)

F. Ebrahimi and R.Raman PRL 2015

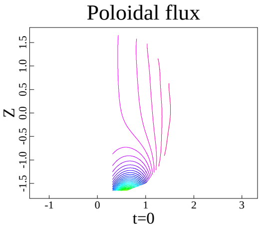
Simulations in NSTX–U

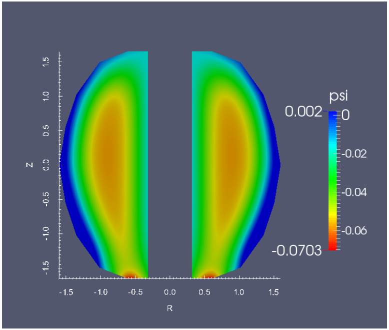
Important upgrades for transient CHI in NSTX–U

- Better shaping due to the location of CHI injector coil in NSTX-U
- Double injector flux ($\Psi_{inj} \approx 0.25 Wb$), CHI-generated current will be 2.5 to 3.5 times of that in NSTX
- Double toroidal field (1T) causes the current multiplication factor to increase.

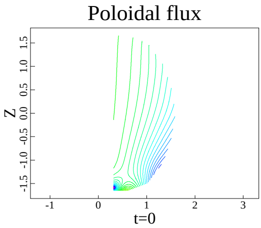


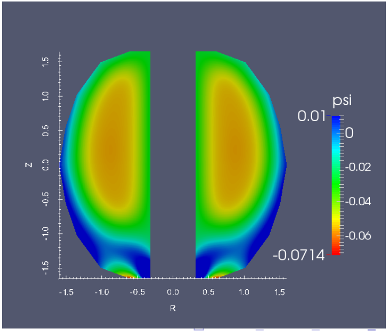
Without SF coils





Strong SF coil currents





Plasmoid instability with continued injection of plasmoids is observed during the injection phase (S $\sim$ 29000)

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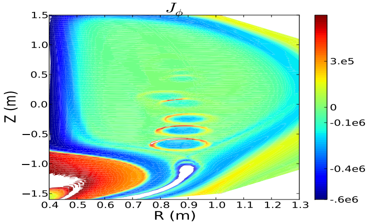
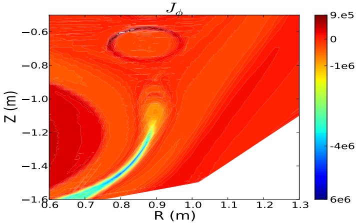
(a)



(b)



Full flux closure is obtained in MHD simulations of NSTX-U

with plasmoids during injection

without plasmoids $t > 9ms$

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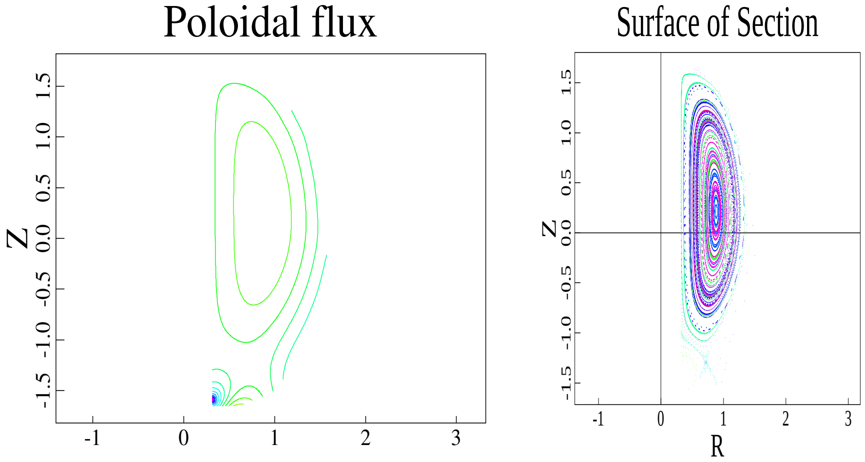
Maximum closed flux current is obtained. Configuration is at equilibrium state after the voltage is turned off.



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

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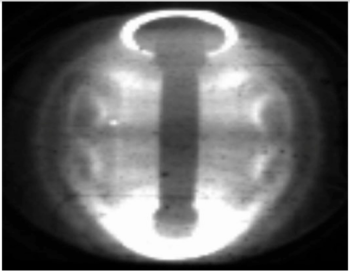

- $T_e \sim 5eV$, $n \sim 4 - 5 \times 10^{18} m^{-3}$
- $B_{rec} \sim 100\text{G}$, $L \sim 1m$
- estimated local S =2000-4000.
- $V_p \sim 25$ km/s

Summary I

Forced magnetic reconnection in NSTX/NSTX-U

- It was found that closed flux surfaces expand 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]
- Consistent with the theory, simulations showed
  1. the break up the elongated current sheet
  2. the increasing number of plasmoids with S
  3. the reconnection rate becomes nearly independent of S
- Motivated by the simulations, experimental camera images have been revisited and suggest the existence of reconnecting plasmoids in NSTX.
- Full flux closure is obtained in the NSTX-U simulations [Ebrahimi&Raman under preparation]

Summary II

1. The direct detection of plasmoids in large fusion devices during magnetic reconnection would have a significant impact as these large-scale plasmoids are similar to the plasmoids on the surface of sun.
2. Understanding the fundamentals of the reconnection process during helicity injection would help us to initiate plasma efficiently and ultimately to produce plasmas that undergo fusion reactions indefinitely.

There is ample observational evidence of plasmoid-like structures in the Earth's magnetosphere and the solar atmosphere.