Using large-scale magnetic fusion experiments to explore fundamental reconnection physics during helicity injection

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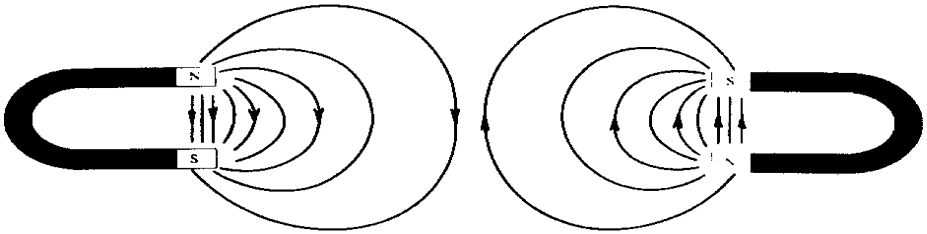
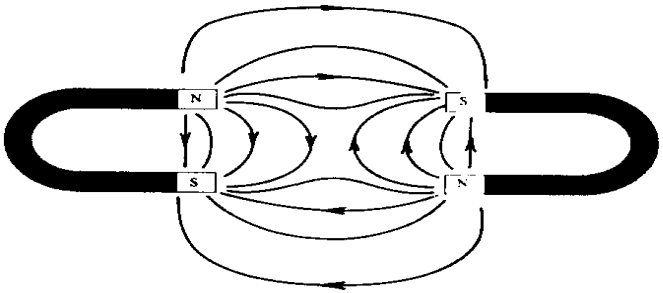
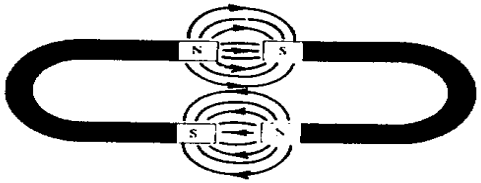
Magnetic reconnection is the rearrangement of magnetic field topology of plasmas.

Magnetic reconnection is a major interplay for fundamentals physical phenomena such as particle acceleration and heating, magnetic field generation, and momentum transport.







<== Forced (driven) reconnection

This process occurs in the solar atmosphere, the solar wind, the Earth's magnetosphere, astrophysical disks, turbulence, and laboratory plasmas.

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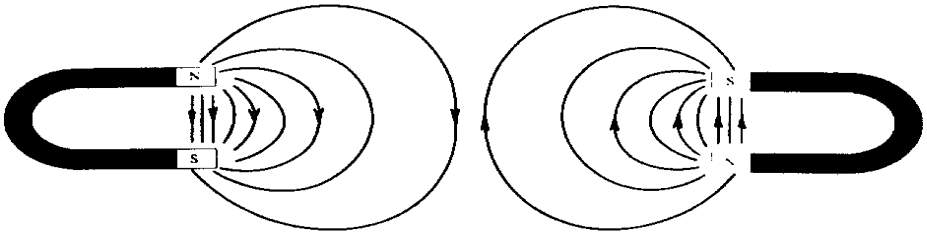

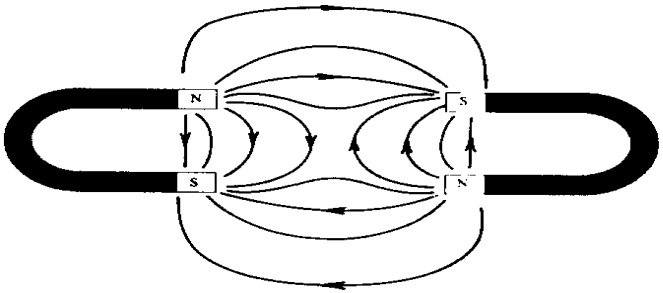

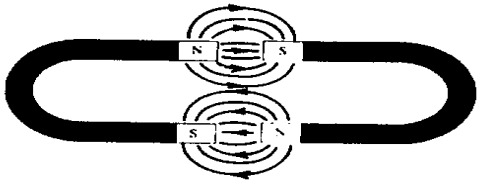

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- Sweet-Parker type forced magnetic reconnection in laboratory plasmas has been extensively studied. [H. Ji, Yamada et al. 1998].

- In toroidal fusion plasmas magnetic reconnection is mainly **spontaneous** as the result of tearing fluctuations (occurs around K.B = 0 surfaces). This also has been extensively but **separately** studied.

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Could fusion plasmas have impact on fundamental reconnection physics?

A few examples that current-driven reconnection has a central role in fusion plasmas

1. **plasma disruption/internal mode stability – sawteeth**
2. **non-inductive current sustainment and start-up current formation**
3. **momentum transport**
4. **magnetic field generation - dynamo**

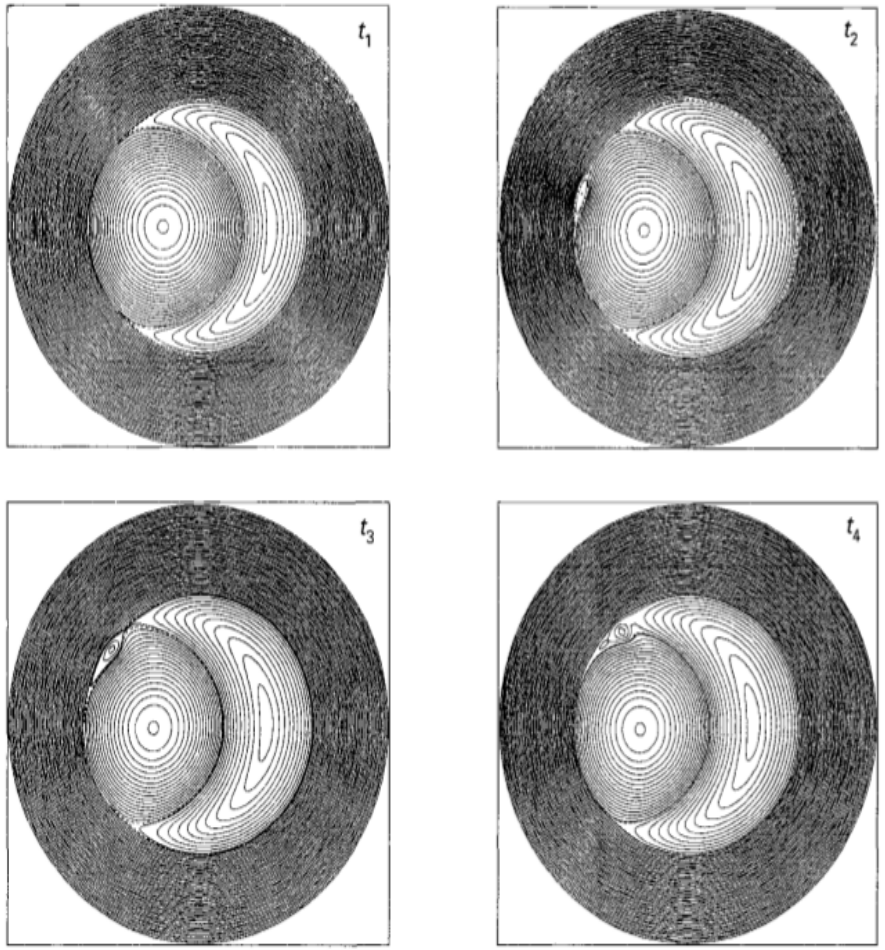
(1) The role of reconnection on the global stability

(1) Reconnection physics plays an important role in the global stability of fusion/tokamak plasmas.

- Secondary islands (plasmoids) seen in reduced MHD simulations during the nonlinear evolution of the tearing instability (at large Δ') in slab geometry [Loureiro et al. 2005], and during the nonlinear growth of an internal kink mode in cylindrical geometry [Gunter et al. 2015]

- Plasmoid instability has not been reported to exist in a laboratory plasma or a fusion device.

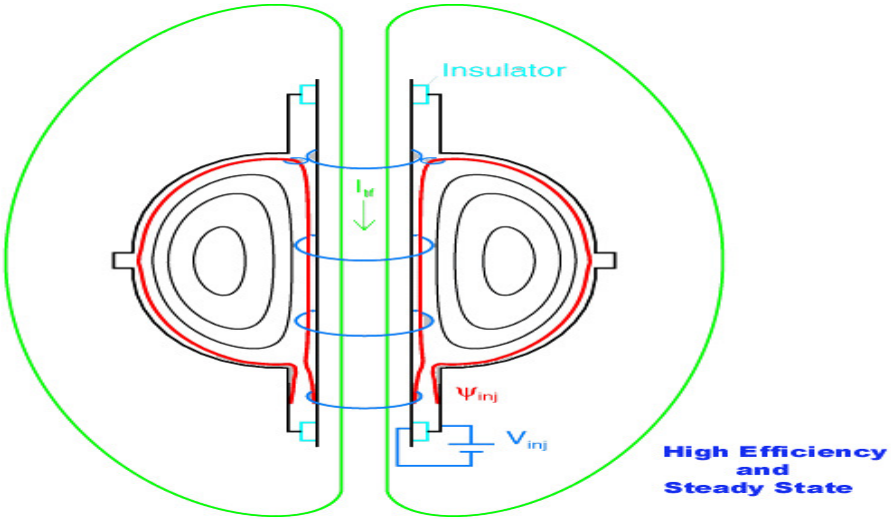
Plasmoid instability in the current sheet of the resistive kink mode



Biskamp 1987

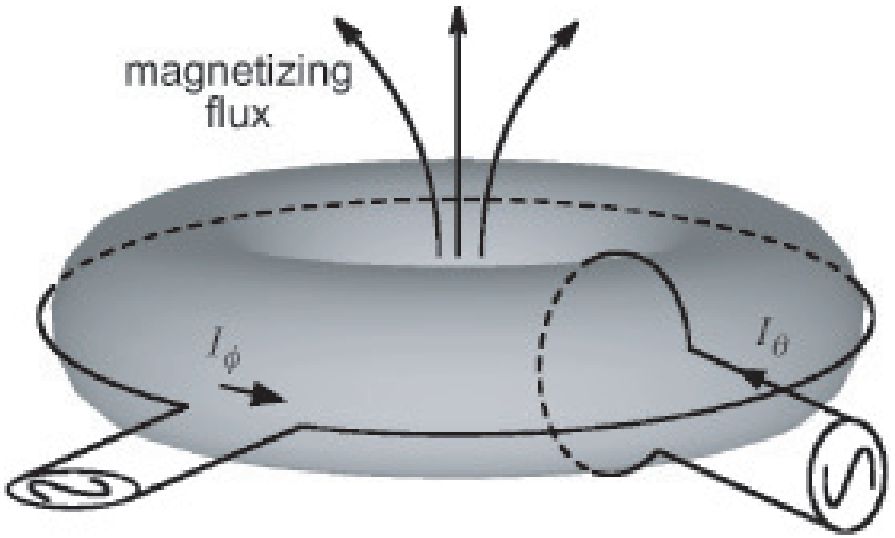
(2) The role of non-axisymmetric tearing on current relaxation during helicity injection

Helicity injection has been used to form various types of fusion plasmas through nonaxisymmetric instabilities.



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

RFPs



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.

What is the research frontier?

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

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

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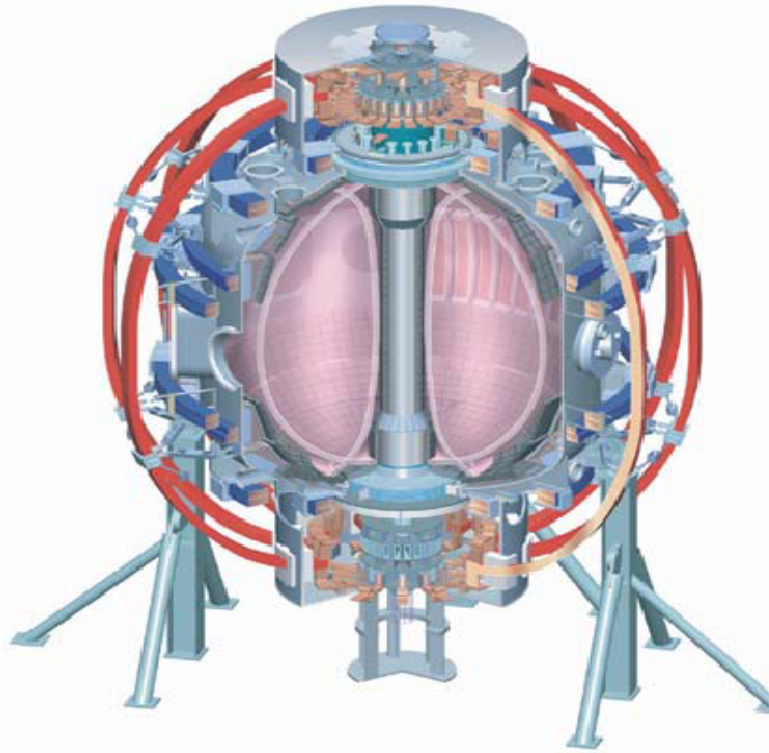
Global simulations have critical role in understanding the physics and to predict the experimental observations.

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



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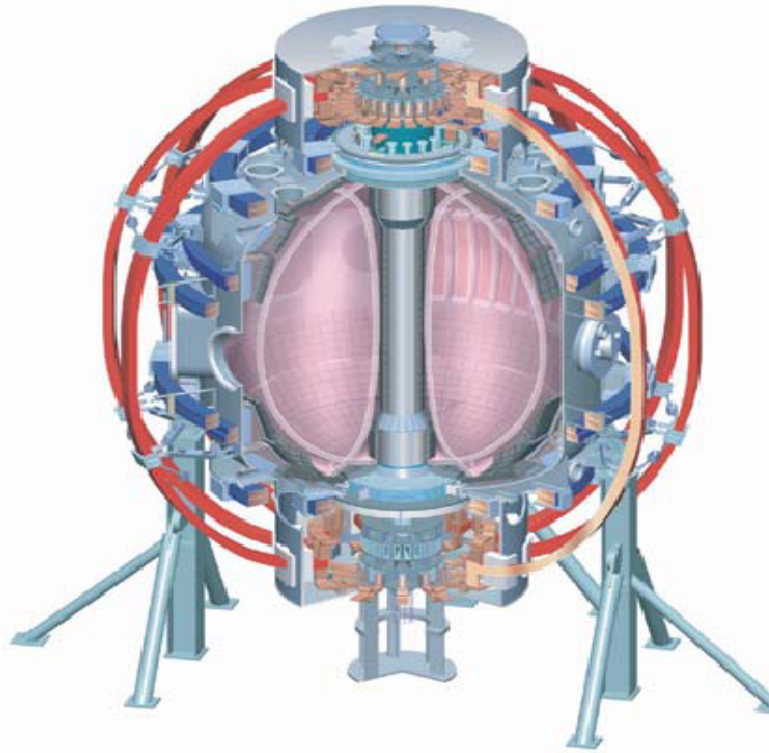

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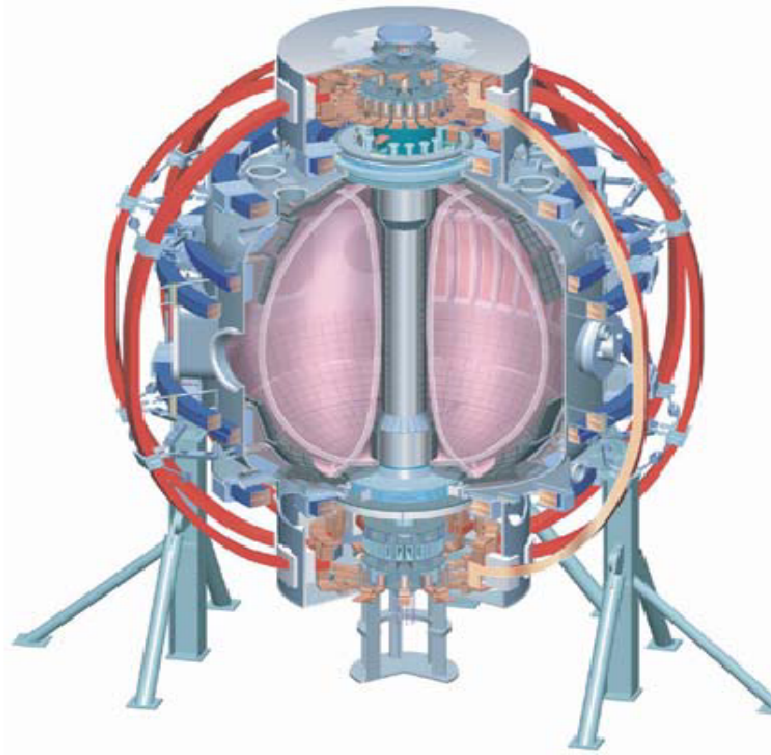
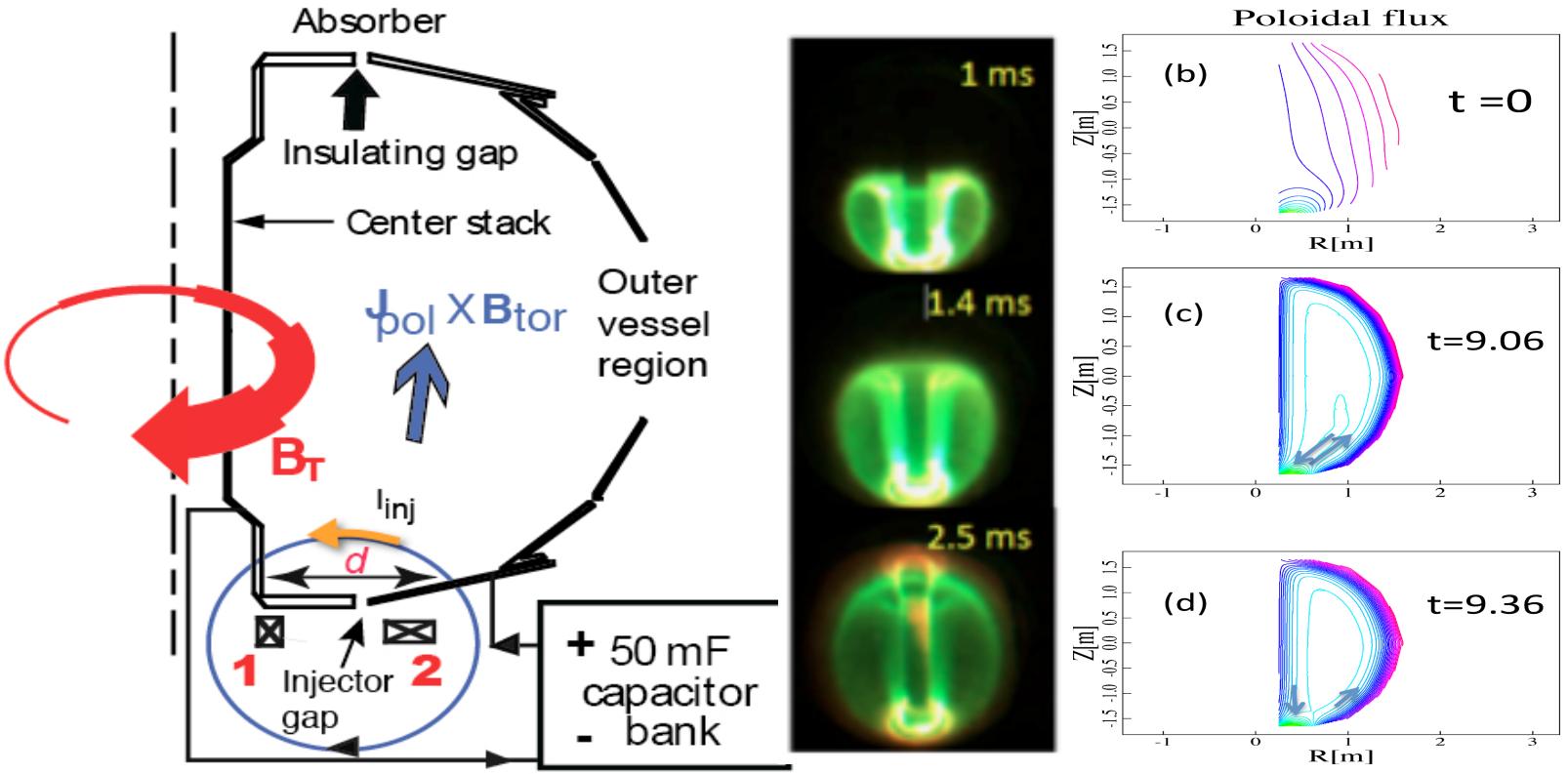


Transient CHI plasmas exhibits some fundamental reconnection physics including plasmoid physics.

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.

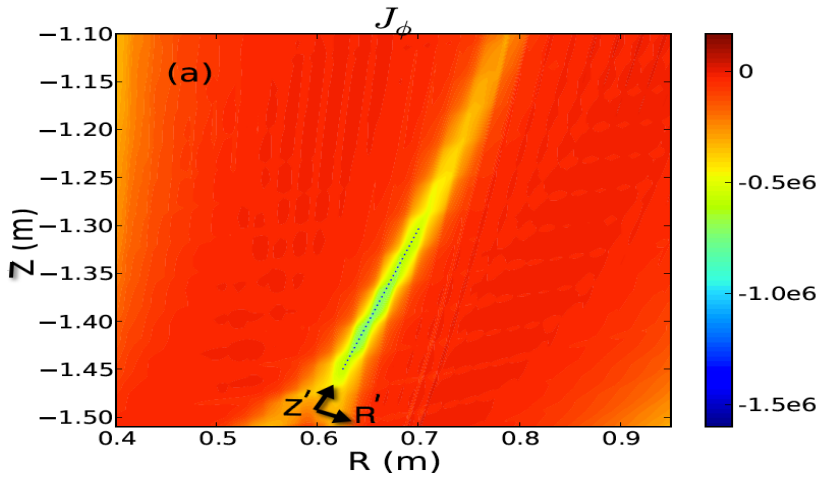
(d) Closed flux surfaces are formed

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

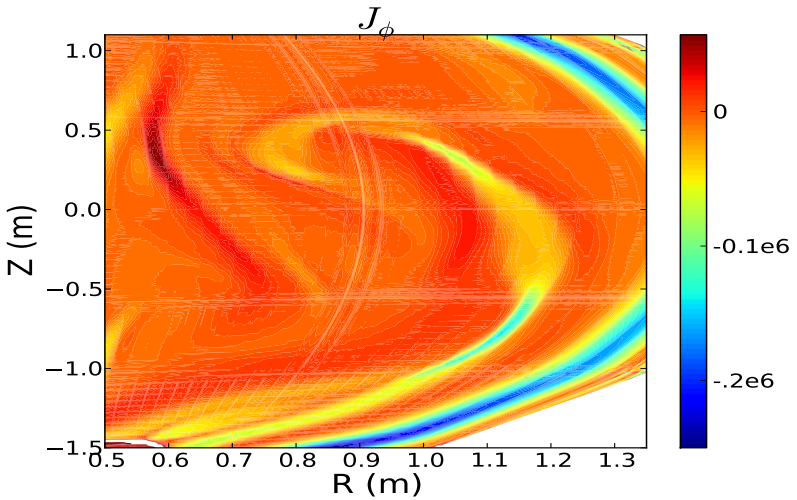
- A local Sweet-Parker type reconnection in a global domain may occur as the electromagnetic forces bring oppositely directed field lines closer together to reconnect.

- At high S, the elongated S-P current sheet can become unstable, a transition to a plasmoid instability is demonstrated in the simulations.

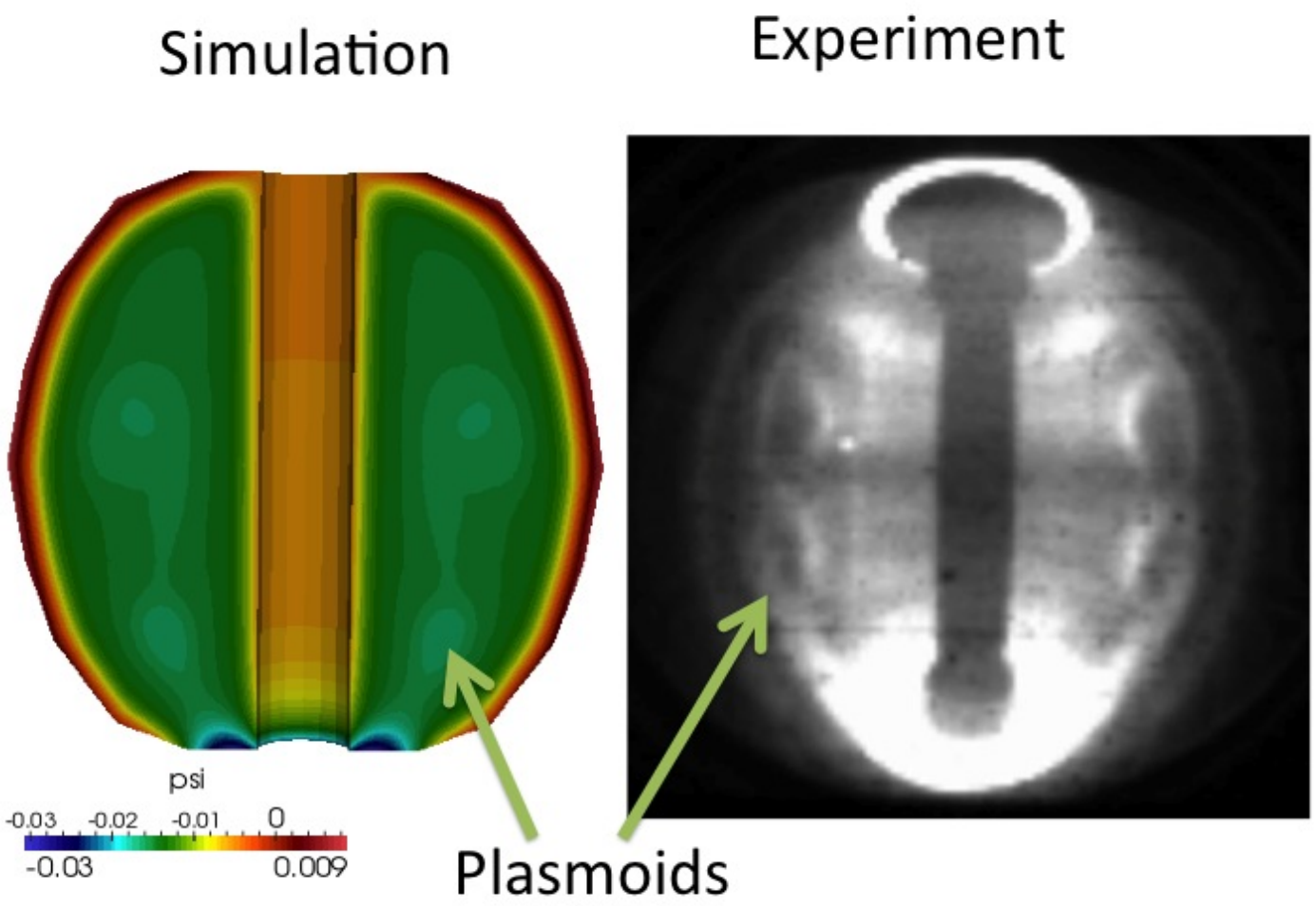
S-P reconnection



Plasmoid instability



Simulations showed that large-scale system-sized plasmoids are formed and cause fast reconnection in a fusion plasma.

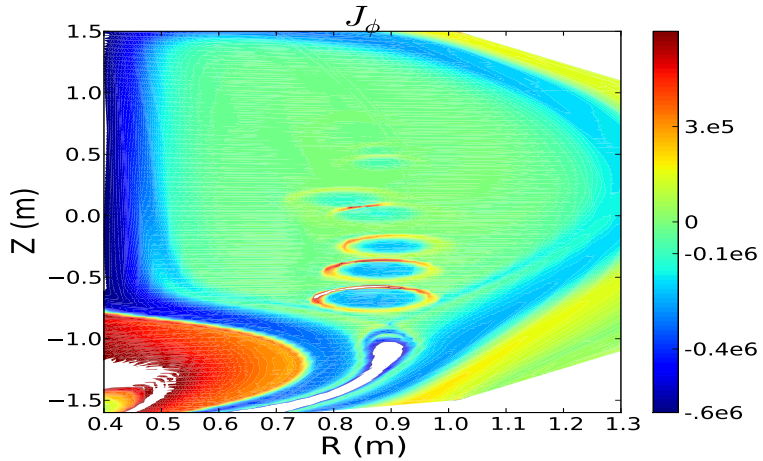


F. Ebrahimi & R. Raman **PRL** 2015.

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

(Loading poloidalflux.mp4)

(a)



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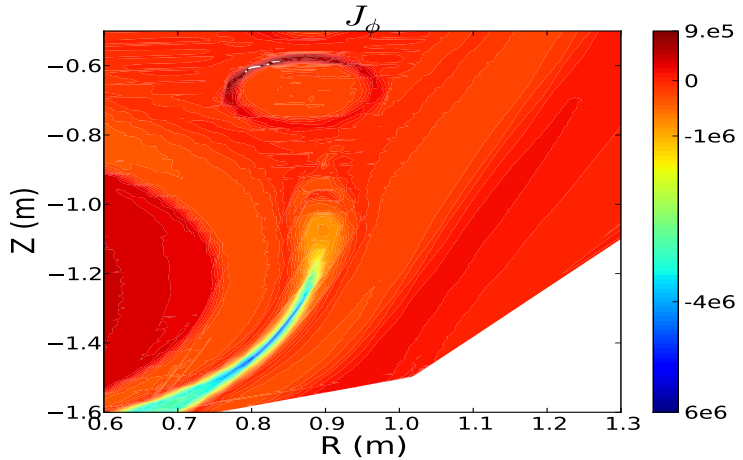


Transient CHI experiments are prime candidates for this research frontier.

They are uniquely suited because:

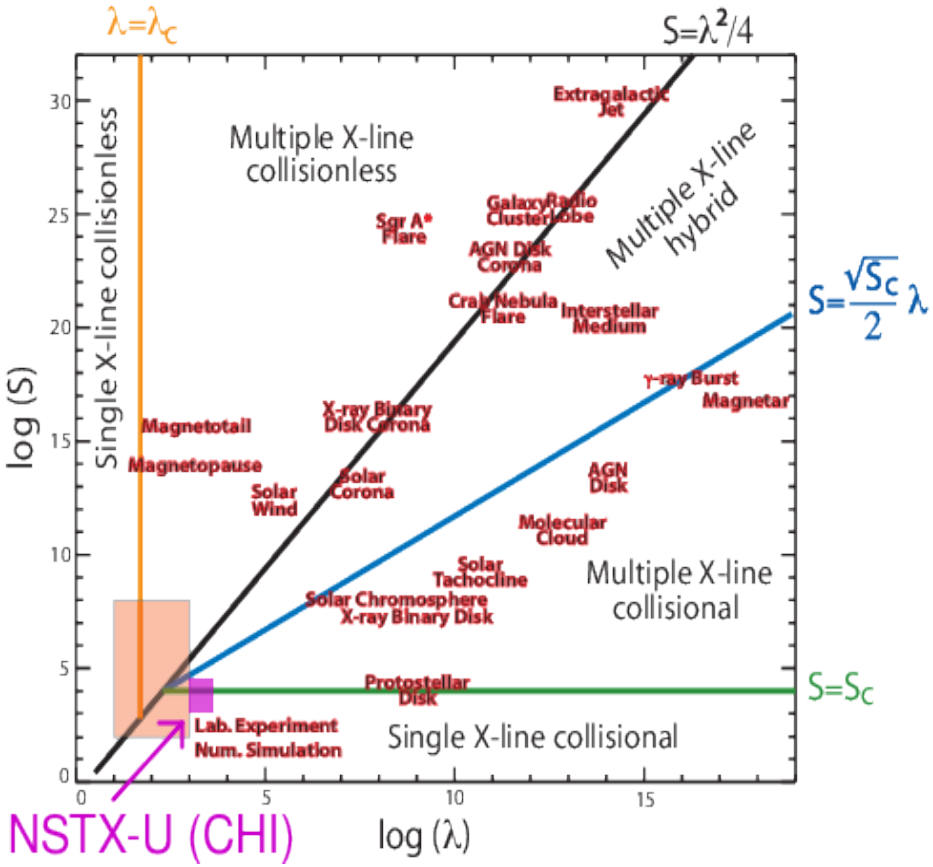
- **the high-S plasma regime**, which may be difficult to access in experiments specifically designed for reconnection, can be accessed during CHI.
  - may have the potential to vary the electron temperature, density (T_e and n_e) and the local reconnecting magnetic field (B_{rec}) strength over a very wide range.
- **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.

Transient CHI in NSTX-U may be able to access a much wider range in plasma parameters because:

1. Less radiative losses should produce a higher Te plasma
2. ECH will further heat the plasma
3. More control of the local magnetic field

What aspects of fundamental reconnection physics could be explored?

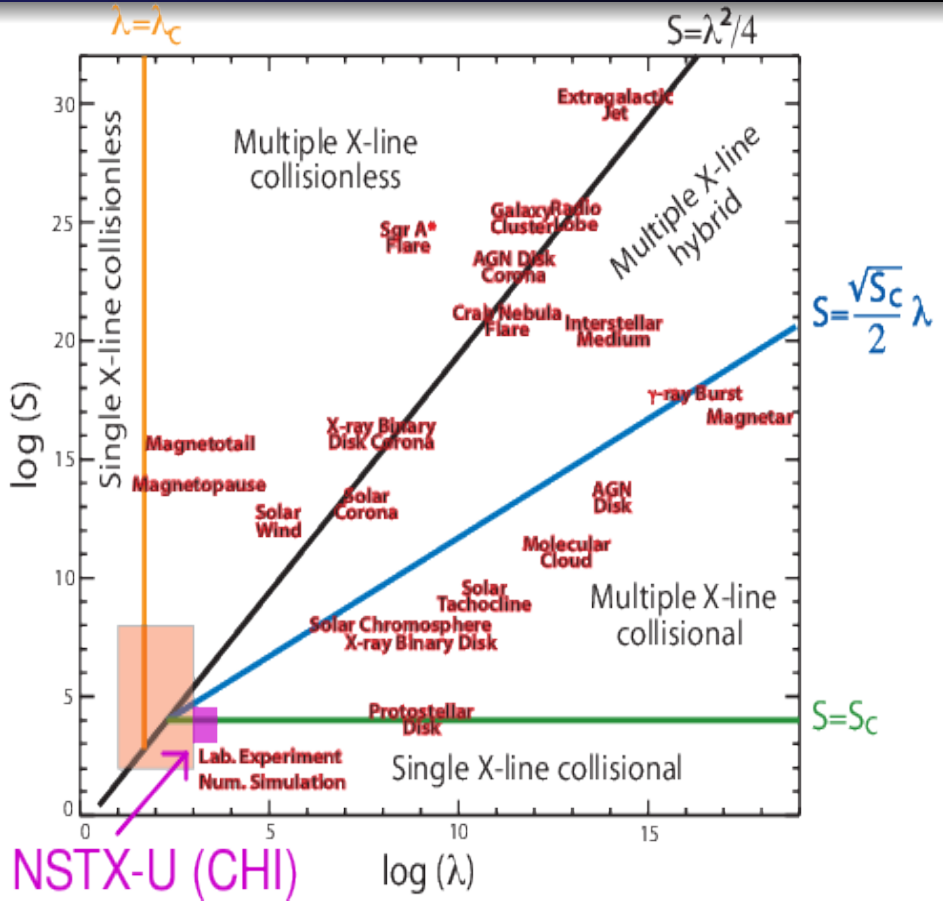
- Each phase means a different mechanism to couple global scale to local dissipation scales, which can be collisional or collisionless.
- Two key dimensionless parameters are S and the macroscopic system size in units of the ion sound gyroradius λ.
- Critical Lundquist number, S_c, is for the onset of the plasmoid instability
- Transient CHI in NSTX-U could provide access to some of these regimes.



The access regime for fundamental reconnection studies shown in the phase diagram [See H. Ji white paper on reconnection]

What aspects of fundamental reconnection physics could be explored?

- **the onset problem** – a transition from a forced to spontaneous reconnection (plasmoids)
- **the multiple scale, and the partial ionization problems** – Transition from MHD scale to two-fluid/kinetic scales as S is increased
- **the rate problem** – as the reconnection rates becomes nearly independent of S in the presence of plasmoids
- **the 3D problem** – as these experiments are toroidal with a large toroidal guide field.



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Required research tools

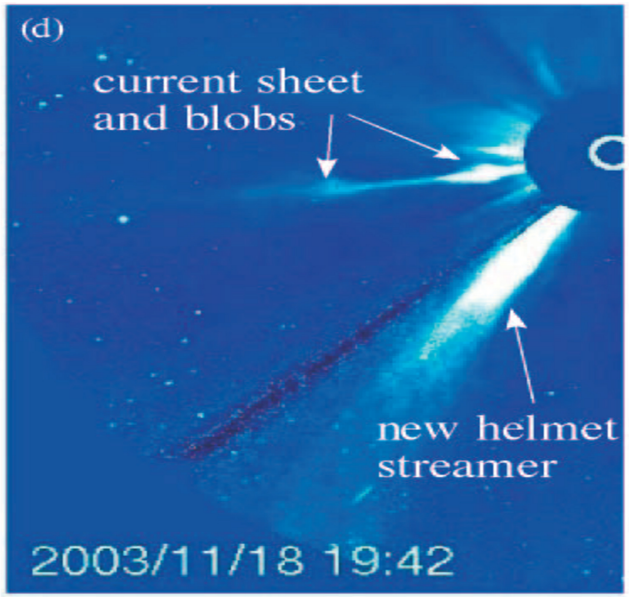
- To detect and measure all the signatures of reconnection (such as plasma flows and current sheets) high resolution cameras (full spatial and temporal diagnostics) are required.

- At every stage advanced **nonlinear 3-D single and two-fluid global MHD simulations** are required to provide support for understanding the physics and to predict the experimental observation.

Summary

- 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.
- 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.



- Plasmas are formed via magnetic reconnection in fusion experiments. These experiments can thus be used as a rich platform to explore reconnection physics. Global realistic simulations are critical.

Diagnostics for reconnection studies using CHI

Existing diagnostics:

- External surface magnetic probes inside vessel to measure B_{pol} on wall surface
- Spectroscopic diagnostics with filters to obtain an idea of relative changes to Te and ne
- High resolution fast cameras with filters to look at entire plasma and the divertor region for plasmoid motion

Desired diagnostics for quantitative measurements

- Internal probes for magnetic field measurements
- Divertor Thomson for electron temperature and density
- CCD based coherent imaging and spectrometers for flow measurements