White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***6/19/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	s
• Interactions of plasmas and waves	s
• Plasma self-organization	p
• Statistical mechanics of plasmas	

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	"X"
Oral	x
Poster	
Either Oral or Poster	
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Title:	Using large-scale magnetic fusion experiments to explore fundamental reconnection physics during helicity injection
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

Utilizing helicity-injection current-drive techniques to create fusion power and to explore the fundamentals of magnetic reconnection physics in the same fusion device may not seem obviously related. However, in this white paper we aim to call attention to the fact that these two important areas of plasma physics are strongly related and can be treated as a unified new research frontier. In a recently published paper,[1] it was recognized that Coaxial Helicity Injection (CHI) discharges[2.3] in large fusion devices may provide a rich platform for investigating fundamental reconnection physics, in particular reconnecting-plasmoids physics. Magnetic reconnection, which energizes many processes in nature, is a major interplay for fundamentals physical phenomena such as particle acceleration and heating, magnetic-field generation, and momentum transport. Magnetic reconnection also has a critical role in many nonlinear processes in fusion plasmas.

The key goals of laboratory plasma experiments designed specifically for magnetic reconnection are to first achieve reconnection and then to identify the major signatures of reconnection, such as current sheet formations, flows, particle acceleration and ultimately to estimate the reconnection rate. Depending on the operating parameter-regime range of these experiments (such as relevant MHD and kinetic scale lengths and Lundquist number) the measurements can then be compared with physical models and extrapolated to explain the fast reconnection rates in astrophysical systems. However, for magnetic

reconnection in toroidal fusion plasmas, the focus is mainly on the nonlinear process of magnetic self-organization, disruption and sawtooth crashes as the results of non-axisymmetric tearing instabilities.

Here, we want to point out the unique dual nature of helicity-injection experiments for plasma start-up. These experiments are primarily intended to generate plasma current as a fusion application, but can also provide a very rich platform for studying magnetic reconnection in the absence of pre-existing instabilities (kink or tearing). Understanding the physics of magnetic reconnection during CHI, a promising candidate for non-inductive plasma start-up, is of great importance for the success of this technique as a non-inductive plasma start-up and ultimately for steady-state current-drive, a necessity for a viable reactor design. On the other hand, the rich characteristics of magnetic reconnection during CHI, in particular plasmoid-mediated reconnection, which exhibits (a) fast reconnection, and (b) formation of MHD global system-size plasmoid formation, reported in the ref [1], could greatly enhance our understanding of guide-field reconnection with strong implications for astrophysical plasmas.

One of the novel characteristics of the global simulations of CHI in NSTX is that they have been performed in a realistic experimental geometry that includes currents driven in the external toroidal and poloidal field coils. These simulations showed that large-scale system-sized plasmoids are formed and cause fast reconnection in a fusion plasma. Consistent with the theory, fundamental characteristics of the plasmoid instability including 1) the break up the elongated current sheet, 2) the increasing number of plasmoids with Lundquist number, and 3) the reconnection rate, as it becomes nearly independent of S, have been observed in these simulations. Motivated by the simulations, experimental camera images were revisited and suggest the existence of reconnecting plasmoids in NSTX (see figure).

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

Magnetic reconnection physics has been, and can further be, explored during helicity-injection experiments in any large-scale fusion device, such as tokamaks, spherical tokamaks, spheromaks and RFPs. Transient CHI experiments are prime candidates for this research frontier. They are uniquely suited because (a) the high-S plasma regime, which is very difficult to access in experiments specifically designed for reconnection, can be accessed during CHI, and (b) there is no pre-existing instability or current channel in a transient CHI discharge hence the system provides an ideal laboratory for controlling and altering some of the parameters governing S and the current sheet to explore reconnection physics and to better understand conditions under which forced Sweet-Parker type magnetic reconnection[4] transitions to an spontaneous plasmoid instability. 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. These simulations are required to be **performed in realistic 3-D tokamak geometry and boundary conditions**. These global simulations will be performed using global MHD codes used in fusion community [5] and well bechmarcked for helicity injection.[6-8] Through experimental measurements, along with the numerical simulations, we may find out how reconnection, in particular plasmoids, would affect the maximum flux closure and CHI-generated current for optimal start-up.

In short, transient CHI experiments in laboratory fusion plasmas are unique in providing a rich platform to explore fundamental reconnection physics, in particular reconnecting plasmoids physics, because of:

- their large scale (e. g. NSTX with major radius=0.86m, minor radius=0.65m, and height = 3m)

- their accessibility to high-S regime. In NSTX-U transient CHI may have the potential to vary the electron temperature, density and the local reconnecting magnetic field strength over a very wide range, thus providing a well-diagnosed test bed for basic reconnection studies, which may not be possible on any of the smaller device in existence at this time.

Due to their flexibility in changing parameter regimes (see Fig2), these experiments could exhibit many aspects of fundamental reconnection physics:

- occurrence of forced magnetic reconnection. 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 in a global domain.
- a transition from a forced reconnection to spontaneous reconnection. At high Lundquist number, the elongated current sheet formed through a Sweet-Parker forced reconnection process breaks up, and transitions to spontaneous reconnection (plasmoid instability) **- the onset problem** in H. Ji white paper.
- **the multiple scale, the rate and partial ionization problems** as described in H. Ji white paper. Transition from MHD scale to two-fluid/kinetic scales as S is increased and the rate problem as the reconnection rates becomes nearly independent of S in the presence of plasmoids can be investigated.
- **the 3D problem**, as these experiments are toroidal with a large toroidal guide field.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

This research frontier will significantly contribute to understanding the process of fast reconnection that is believed to be causing solar flares. There is ample observational evidence of plasmoid-like structures in the Earth's magnetosphere and the solar atmosphere. 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. This would allow us to directly analyze and understand the plasmoid structures in a controlled laboratory large-scale fusion plasma. In addition, 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.

References

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Figures

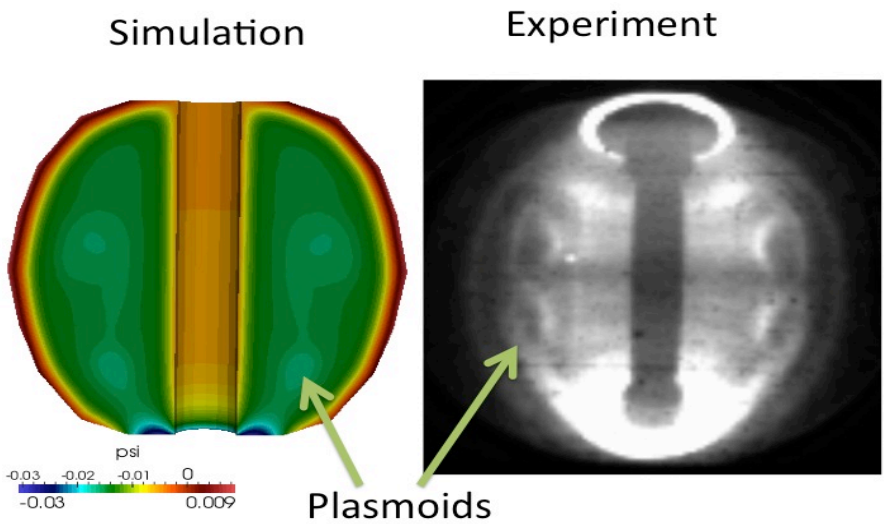

Fig. 1: Left: Plasmoid formation in MHD simulations of NSTX during CHI Right: Camera image in NSTX shows two discrete bubble plasmoid-like structures [1]

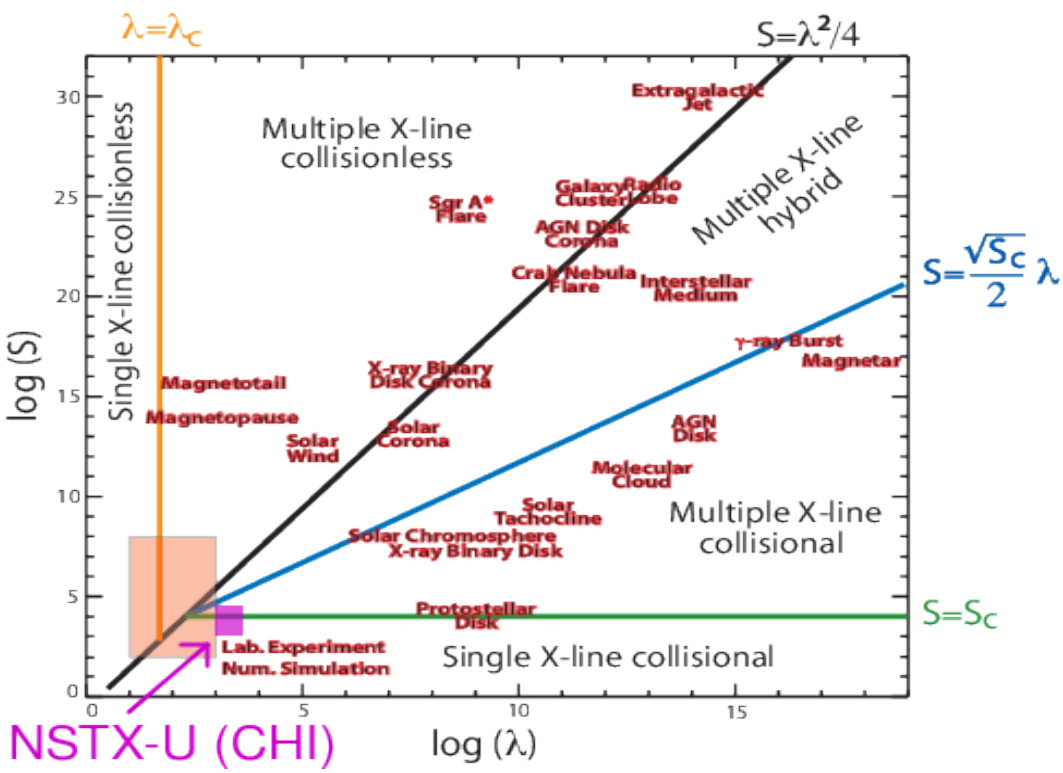

Fig. 2: The access regime for fundamental reconnection studies in NSTX-U during transient CHI shown in the phase diagram taken from ref [9].