Three-dimensional plasmoid-mediated reconnection in tokamaks

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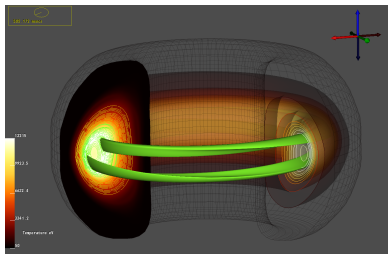
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NSTX-U   PPPL   PRINCETON UNIVERSITY

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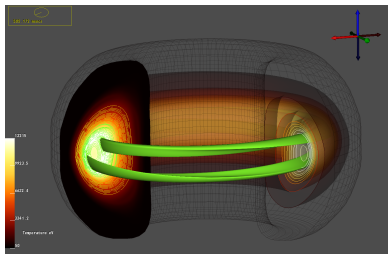

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How about current sheets?

- Are there reconnecting coherent current-carrying structures in fusion plasmas?

- What are the implications of these structures for different nonlinear dynamics?

- Under what conditions could 2-D axisymmetric plasmoids or 3-D filaments be formed?

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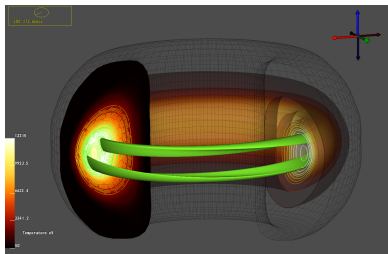

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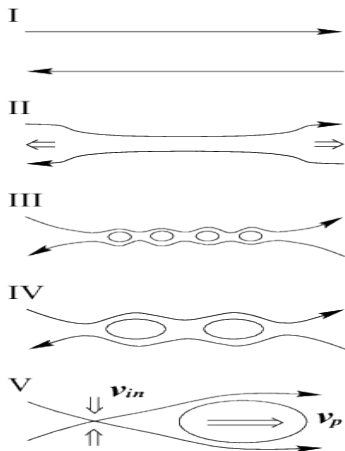
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Plasmoid instability: tearing instability in a current sheet

- Elongated current sheet can become tearing unstable at high S. [Biskamp 1986, Tajima & Shibata 1997]

- The scaling properties of a classical linear tearing changes, as the current-sheet width scales with S ($\gamma \sim S^{1/4}$).

- Numerical development: [Shibata & Tanuma 2001,Loureiro et al. 2007; Lapenta 2008; Daughton et al. 2009,; Bhattacharjee et al. 2009] **shows fast reconnection**.

- Static linear theory does not apply [L. Comisso et al. PoP 2016]
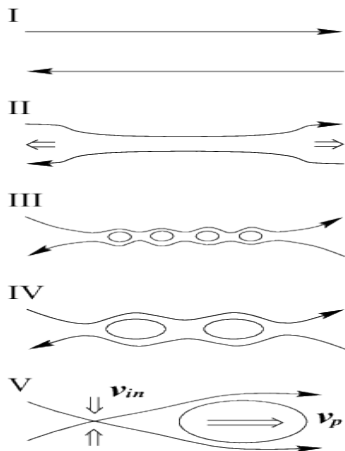

Shibata & Tanuma 2001

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Plasmoid instability in the current sheet of the resistive kink mode

- 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]
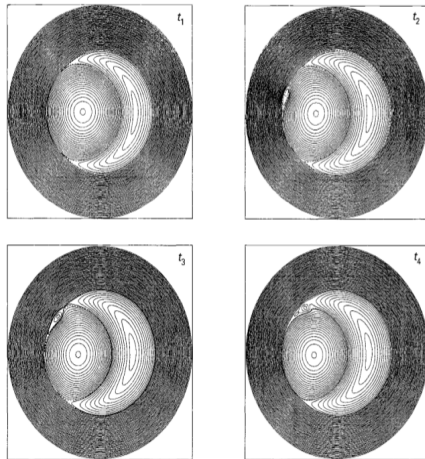
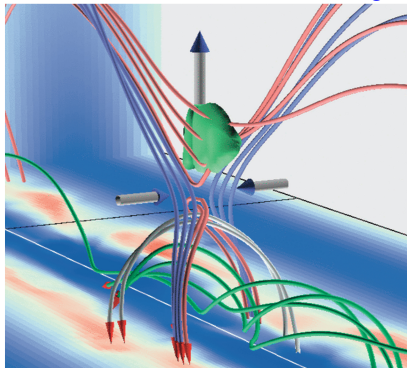Biskamp 1987

Many fundamentals of reconnection physics can be explored during helicity injection

Solar flares field lines modeling

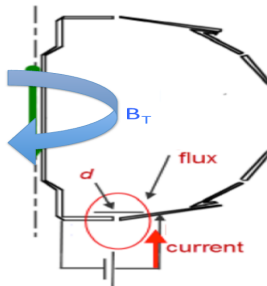$$\frac{\partial K}{\partial t} = -2 \int (\mathbf{A.V})\mathbf{B} \cdot d\mathbf{s}$$

Kusano 2004
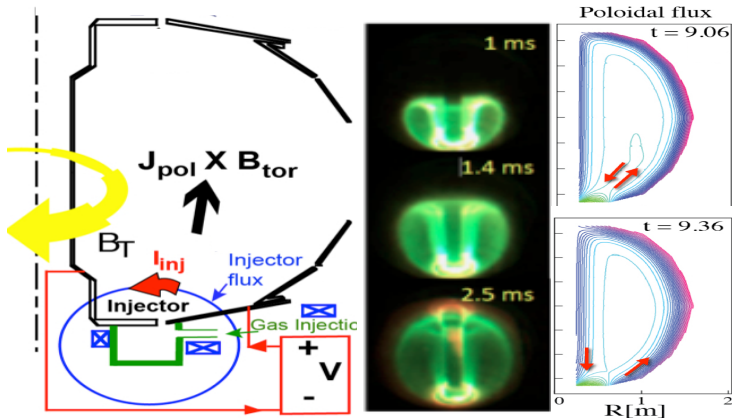Warnecke & Brandenburg 2010

Helicity injection in a lab

$$\frac{\partial K}{\partial t} = -2 \int \Phi \mathbf{B} \cdot d\mathbf{s}$$

Helicity is injected through a surface term.

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

Poloidal flux

t = 9.06

t = 9.36

J_{pol} X B_{tor}

B_T

I_{inj}

Injector

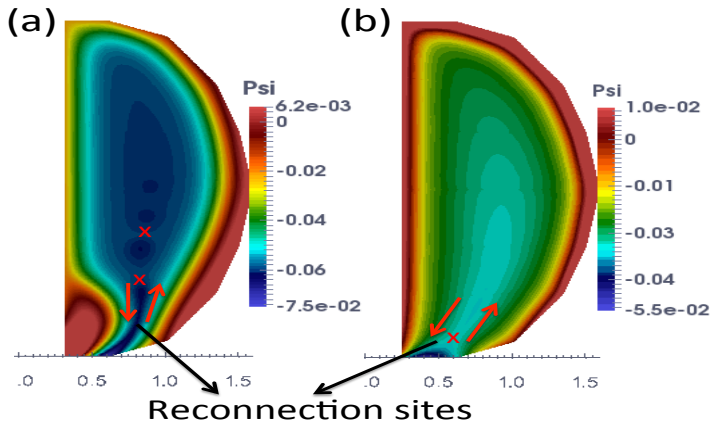Injector flux

Gas Injection

+ V −

R[m]

Transient CHI is used as a solenoid-free plasma start-up method in NSTX & other STs can be used to simplify the tokamak

A rare classical example of 2-D reconnection during helicity injection for tokamak plasma startup

During injection (V_{inj} on)   During decay ($V_{inj} = 0$)

Reconnection sites

Utilize the helicity injection technique to study:

- Flux surface closure during transient CHI
  - Forced (driven) S-P reconnection

    Ebrahimi et al. PoP 2013, 2014
  - Spontaneous plasmoid-mediated reconnection

    Ebrahimi & Raman PRL 2015

- 3D effects
  - Full flux closure and CHI-generated current in NSTX-U

    Ebrahimi & Raman NF 2016
  - Dynamo-driven reconnection plasmoids formation

    Ebrahimi PoP 2016
  - Reconnecting Edge Localized Modes

    Ebrahimi PoP 2017

  Also CHI modeling **Hooper et al. PoP 2013**, **Hooper & Sovinec PoP 2016**

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

- Solves the linear and nonlinear MHD equations

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} + \kappa_{divb}\nabla\nabla.\mathbf{B}$$

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta\mathbf{J} + \frac{1}{ne}\mathbf{J} \times \mathbf{B}$$
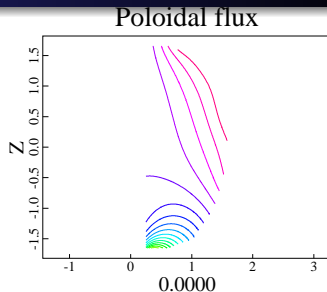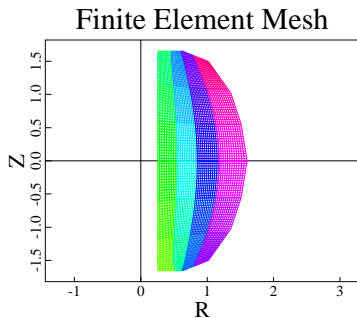
$$\mathbf{J} = \nabla \times \mathbf{B}$$

$$\frac{\partial n}{\partial t} + \nabla.(n\mathbf{V}) = \nabla.D\nabla n$$

$$\rho(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}.\nabla\mathbf{V}) = \mathbf{J} \times \mathbf{B} - \nabla P - \nabla.\Pi$$

$$\frac{n}{(\Gamma - 1)}(\frac{\partial T_\alpha}{\partial t} + \mathbf{V}.\nabla T_\alpha) = -p_\alpha\nabla.\mathbf{V} - \nabla.\mathbf{q}_\alpha + Q$$

- $\mathbf{q} = -n[(\kappa_{||} - \kappa_\perp)\hat{b}\hat{b} + \kappa_\perp\mathbf{I}] \cdot \nabla T$
- Π is the stress tensor (also includes numerical $\rho\nu\nabla V$)
- κ_{divb} and D are magnetic-divergence and density diffusivities for numerical purposes.

Finite Element Mesh

Poloidal flux

- 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 45×90 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
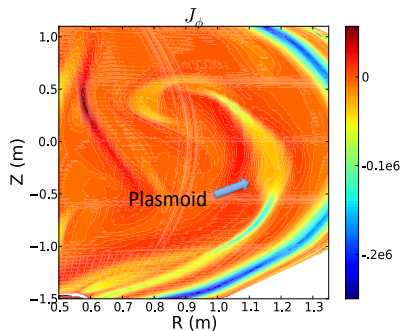
See also poster by E. B. Hooper
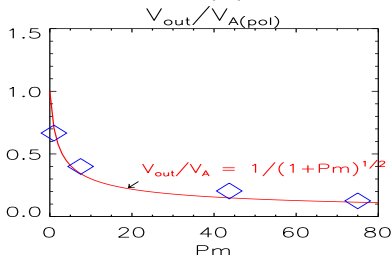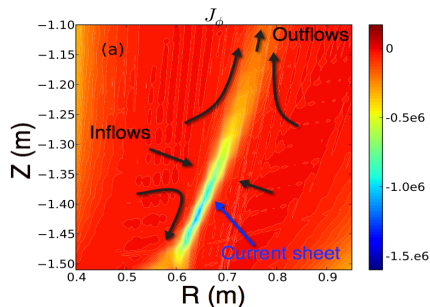
A local 2-D Sweet-Parker type reconnection is triggered in the injection region.
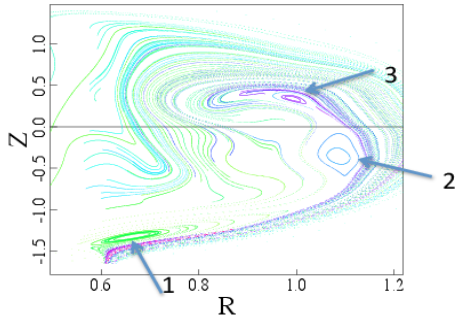Key signatures of S-P reconnection:

- I - Elongated current sheets, $L > \delta$

- II - Scaling of the current sheet width $\delta/L \sim S^{-1/2} \sim V_{in}/V_{out}$

- III - Pinch inflow and Alfvénic outflow

F. Ebrahimi, et al. PoP 2013, 2014

Elongated current sheet becomes unstable - plasmoids form
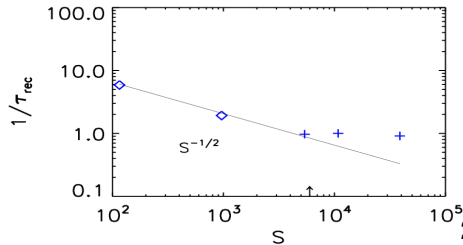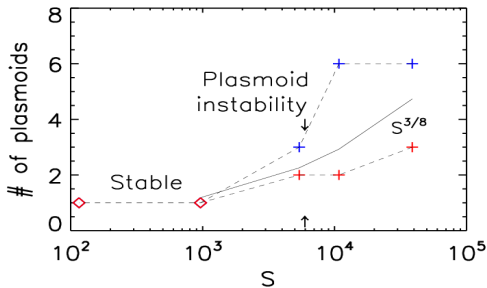

J_ϕ

Plasmoid

Surface of Section

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. Reconnection rate becomes nearly independent of S.

F. Ebrahimi and R.Raman PRL 2015

- 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. **[Here with strong guide field]**

  F. Ebrahimi & R.Raman PRL 2015

First documentation of plasmoid formation in MHD regime in laboratory.

(Loading poloidalflux.mp4)
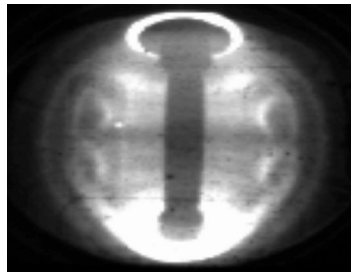
Camera images from NSTX do show the formation plasmoids that then merge into a larger plasma

[Ebrahimi&Raman PRL 2015]

- ▶ 3-D effects

  - ▶ Could 3-D fluctuations (and large-scale dynamo from fluctuations) **trigger** 2-D global reconnection or 2-D reconnecting plasmoids?

  - ▶ **Self-consistent trigger mechanism in 3-D**

  - ▶ Flux closure during CHI plasma start-up in 3-D

Two types of current sheets are formed during flux expansion/evolution
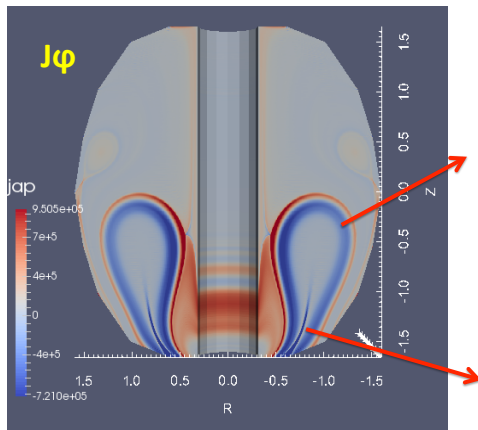
- 1- **Edge current sheet** from the poloidal flux compression near the plasma edge, **leads to 3-D filament structures**

- 2- **Primary reconnecting current sheet** from the oppositely directed field lines in the injector region, **leads to 2-D plasmoids**
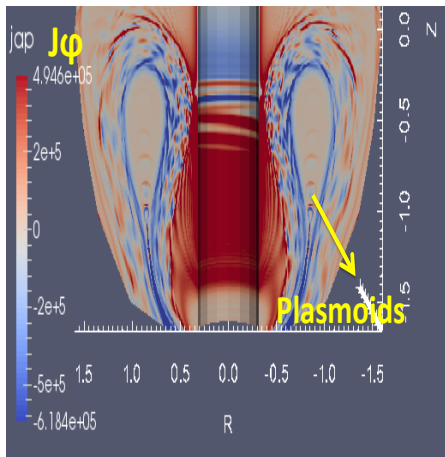
F. Ebrahimi PoP 2016

Edge current sheet/spikes can develop

- during flux expansion (during CHI)
- from pressure-driven edge bootstrap current
- due to strong current ramp up
- during vertical displacement of plasma [Ebrahimi PoP 2017]

Edge nonaxisymmetric current-sheet instabilities grow on the poloidal Alfven time scales and could cause

- I - poloidal flux amplification to trigger axisymmetric (2-D) reconnecting plasmoids formation [Ebrahimi PoP Letter 2016]
- II - low-n ELM peeling-driven filament structures[Ebrahimi PoP 2017]

In 3-D, edge current sheets are a common characteristic for several dynamical processes

Edge current sheet/spikes can develop

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Edge nonaxisymmetric current-sheet instabilities grow on the poloidal Alfven time scales and could cause

- **I - poloidal flux amplification to trigger axisymmetric (2-D) reconnecting plasmoids formation** [Ebrahimi PoP Letter 2016]

- **II - low-n ELM peeling-driven filament structures**[Ebrahimi PoP 2017]

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

1. I- **Edge-localized modes arising from the asymmetric current-sheet instabilities**

2. II- With 3-D fluctuations, axisymmetric plasmoids are formed, **local S increased to S $\sim$ 15000.** [Ebrahimi PoP Letters 2016]

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
   $\gamma\tau_{A(n=1)} = 0.16$,
   $\gamma\tau_{A(n=2)} = 0.18$,
   $\gamma\tau_{A(n=3)} = 0.2$,
   $\gamma\tau_{A(n=4)} = 0.23$,
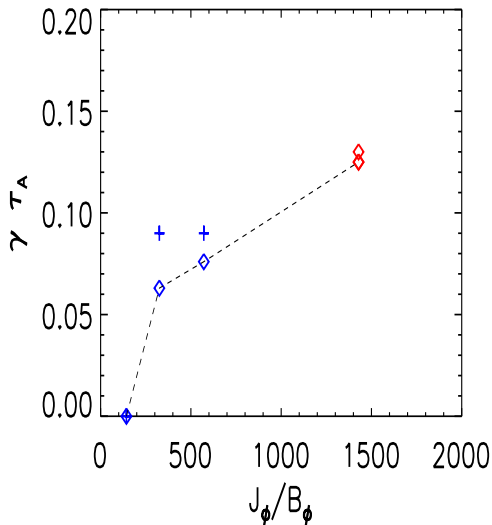 $\gamma\tau_{A(n=5)} = 0.26$.
   $S = 2 \times 10^5$
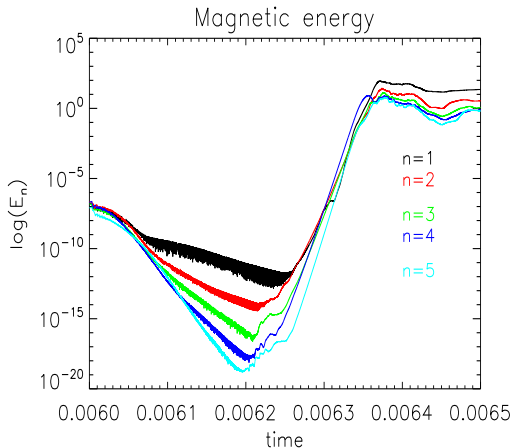
Magnetic energy

n=1
n=2
n=3
n=4
n=5

$B_z[T]$
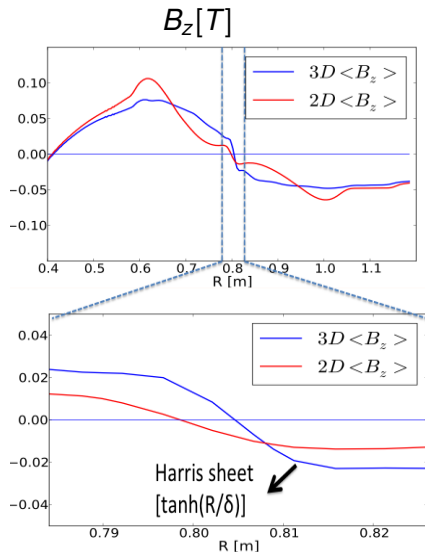
- For the first time a dynamo poloidal flux amplification is observed

- This **fluctuation-induced flux amplification increases the local S** $==>$ **triggers a plasmoid instability** $==>$ breaks the primary current sheet.

The growth of current-driven reconnecting edge localized modes (with tearing parity) scales with $J_\parallel/B$


- Simulations with varying B_ϕ = [2.8, 1.23, and 0.7T], but keeping the current-density profile fixed, $J_\phi = 400kA/m^2$ (S=11000) [blue diamonds]
- Scaling consistent with the instability drive for the traditional ideal peeling modes, $qRJ_\parallel/B$
- Our limited scaling study for three S values in the range of $(1 - 4 \times 10^5)$ show a weak dependency on S.

Magnetic energy

Surface of Section

For NSTX-U relevant parameters, the nonaxisymmetric fluctuations saturate at low amplitudes (3-D). **These are peeling-type modes with tearing parity**
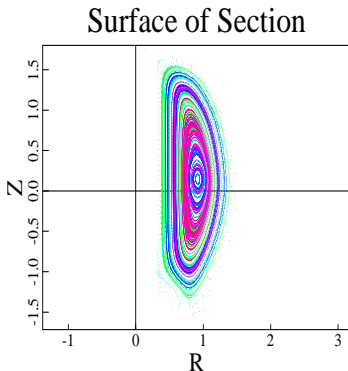
Similar to 2-D ([F. Ebrahimi & Raman NF Letter 2016]), **nearly 70% of the injected open flux converts to closed flux in NSTX-U (3-D simulations)**

Model for current-driven ELMs

To capture the essential reconnection physics in the edge region of tokamak and to understand the quasiperiodic dynamics of low-n ELMs

- consider large edge current formed non-inductively (unlike pressure-driven current in the H-mode),

- isolate nonlinear evolution of edge current from the core

- simulations have local edge S = LV_A/η as high as 5×10^5, in the range of collisionality of standard tokamak operation

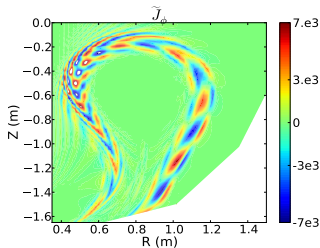Nonlinear w/ 22 toroidal modes
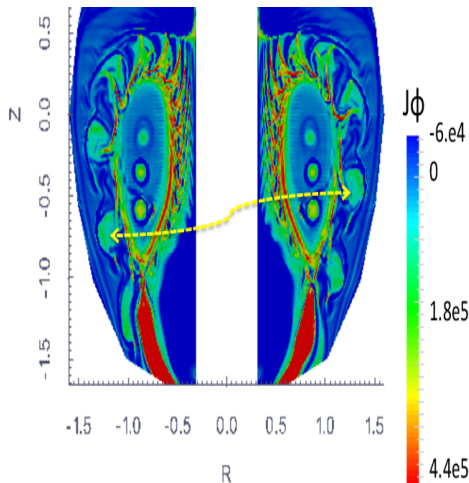
- Nonaxisymmetric structures break the initial axisymmetric current density
- Because of the very localized nature of the magnetic fluctuations, the amplitude of the associated perturbed toroidal current density can be as high as 50% of the $n=0$ component
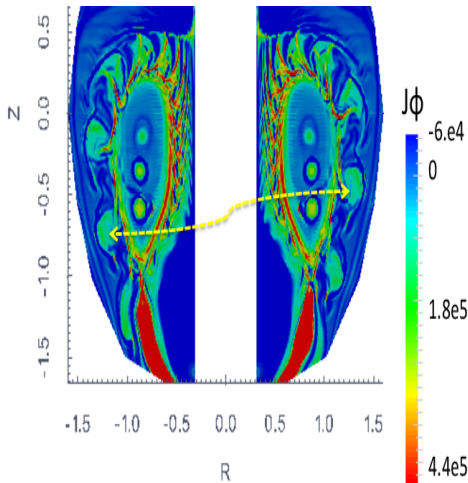
Linear

Nonlinear w/ 22 modes
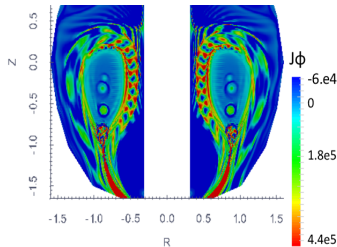
Nonlinear w/ 2 modes

Nonlinear saturated toroidal current density
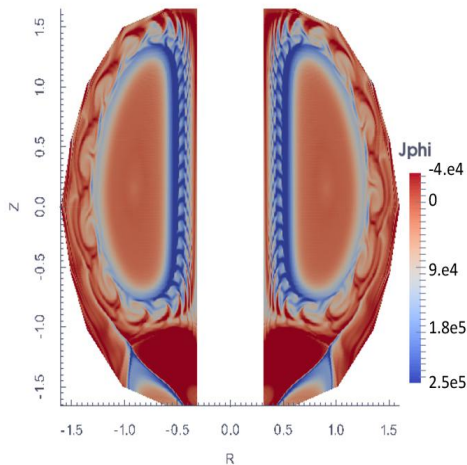
- Nonaxisymmetric nonlinear mode structure radially extends from the closed flux region to the region of open field lines (outside of separatrix).

- The axisymmetic current density layer is strongly affected by the mode and is broken near the edge region of closed flux surface and is radially expanded in form of coherent filaments.

Surface of Section
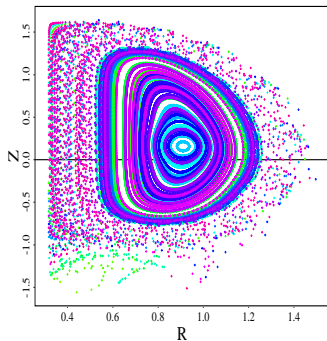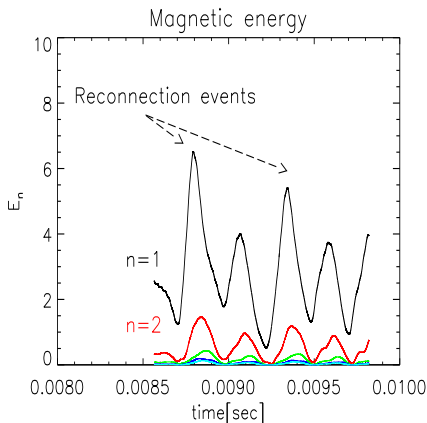

Poloidal flux, extrema=(-7.506e-02, 2.421e-01)

- Puncture plot obtained from the 3-D simulations shows the last closed flux surface (LCFS) extending radially from r= 0.52m-1.26m

- Stochastic region outside of separatrix

# Observed edge localized coherent structures exhibit repetitive cycles during nonlinear stage

Magnetic energy

- Energy vs. time during full nonlinear 3-D simulations with 43 toroidal modes and with high toroidal field (B_ϕ =1.23T).

- Nonlinear dynamics during the flat top part of the total current (320kA)

The structures relax back radially to merge back into an axisymmetric toroidal current density
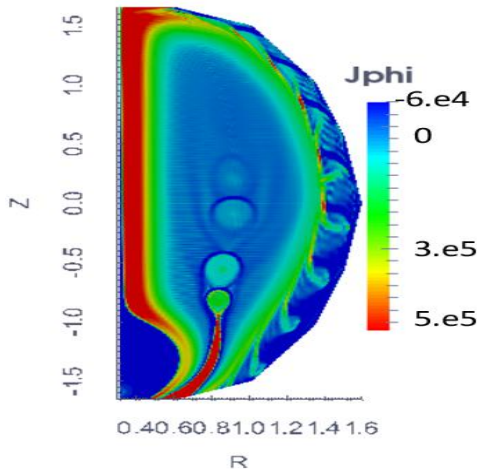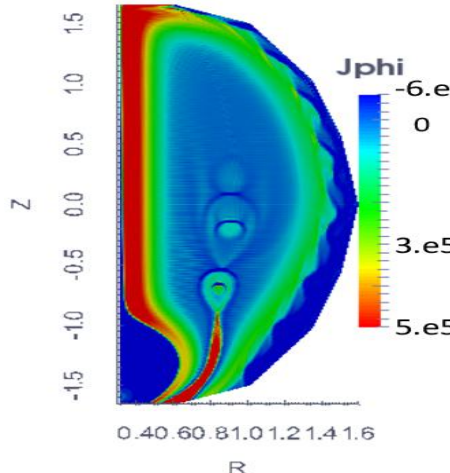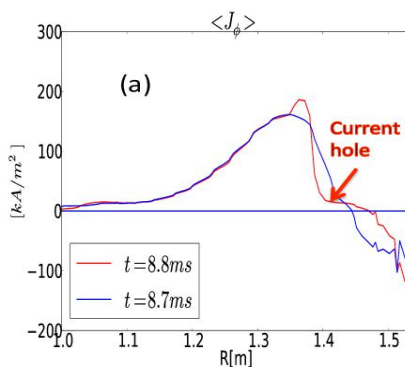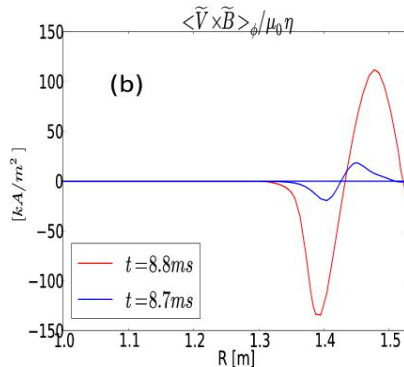

Due to higher toroidal field, only the outer edge (on the low field side) remains strongly perturbed

The emf contributes to the formation of current holes and the radially outward expulsion of the current density

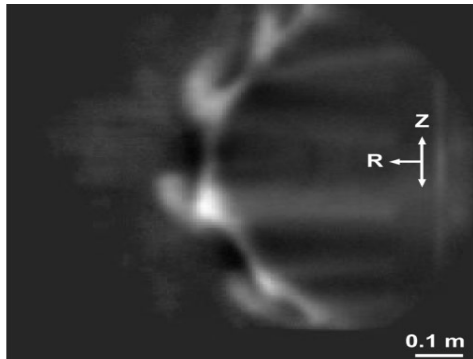The vertically-averaged current density is drastically different because of the nonaxisymmetric fluctuations at t= 8.8ms

The localized dynamo term changes sign around the same radius where the flattening and annihilation of current density occurs

Current-driven peeling modes with $n \leq 3$ were observed. Also low-n ELMs in NSTX [Maingi, et al. PRL 2009]. High m rotating feature during disruption in HBT-EP [Levesque]

- J_{edge} generated by large skin currents during standard confinement
- $J_{\parallel}/B$ peeling drive found during strong rampup of Ohmic discharges
- High poloidal coherence, with the intensity of the filament structures rising and falling in about $50\mu s$ [Bongard, et al. PRL 2011, Thome et al. PRL 2016]

Summary

- 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]

- Large-volume flux closure is obtained in the NSTX-U simulations in 2-D and 3-D

- For the first time, a 3-D dynamo poloidal flux amplification is observed to trigger axisymmetric reconnecting plasmoids [Ebrahimi PoP Letter 2016]

- Edge modes arising from 3-D current-sheet instability grow on the poloidal Alfven time scale

- Observation of nonlinearly formed nonaxisymmetric edge current

- The quasiperiodic dynamics of low-n ELMs are explained as reconnection events [Ebrahimi PoP 2017]