Coherent current-carrying filaments during nonlinear ELMs and VDEs

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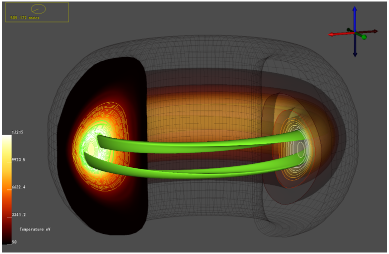
Reconnection physics plays an important role in the nonlinear dynamics of many processes in laboratory plasmas



In toroidal fusion plasmas magnetic reconnection is mainly **spontaneous** as the result of tearing fluctuations (FKR ’63). **Classical tearing only makes a modest modification to the global current density.**

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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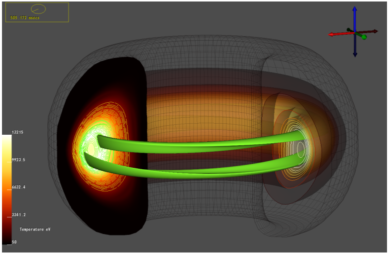

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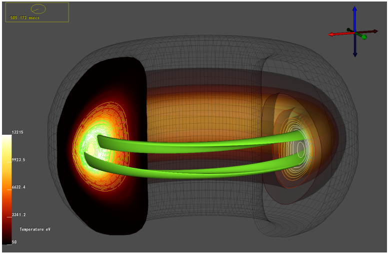

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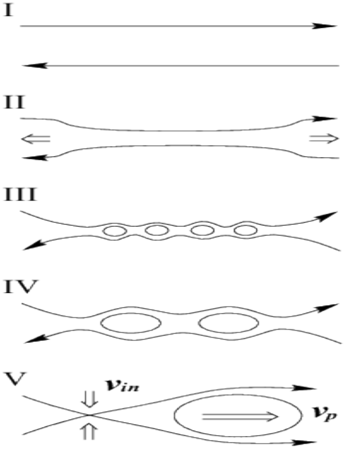
In many fast MHD dynamical processes, plasmoids are essential features (2-D)

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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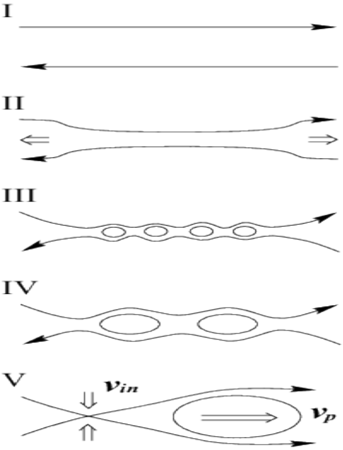
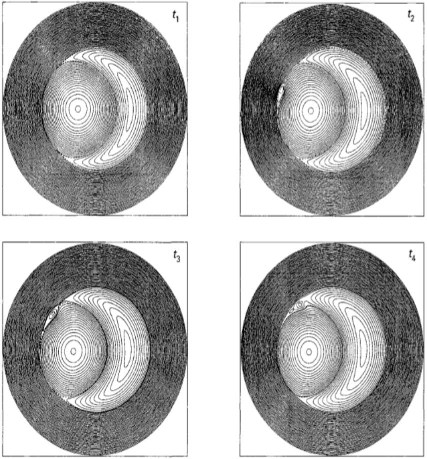


Shibata & Tanuma 2001

Secondary islands (plasmoids) in tokamak-relevant studies

- 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 in the current sheet of the resistive kink mode

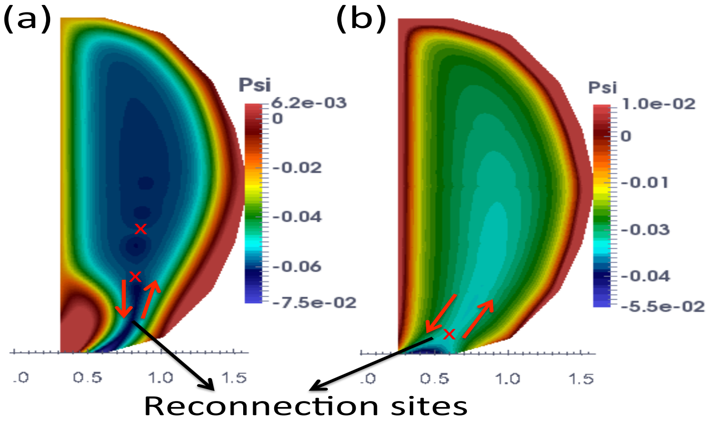


Biskamp 1987

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

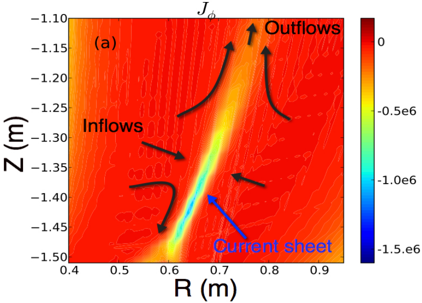
During injection (V_{inj} on)

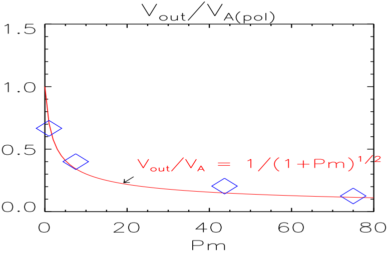
During decay (V_{inj} =0)



Reconnection sites

Current-sheet formation during forced reconnection in a tokamak





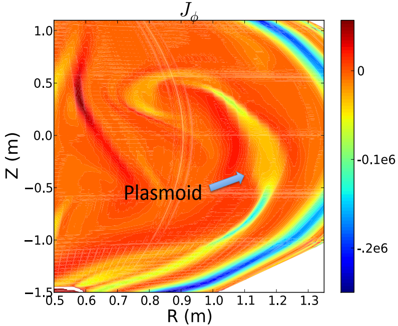
A local 2-D Sweet-Parker type reconnection is triggered in the injection region.

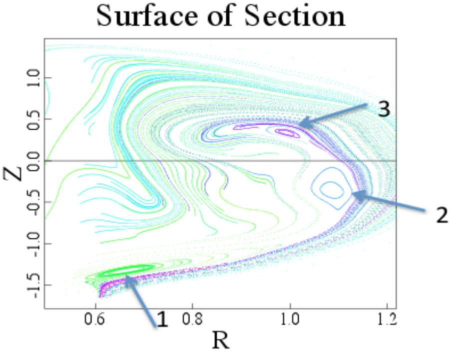
Key signatures of S-P reconnection

- 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





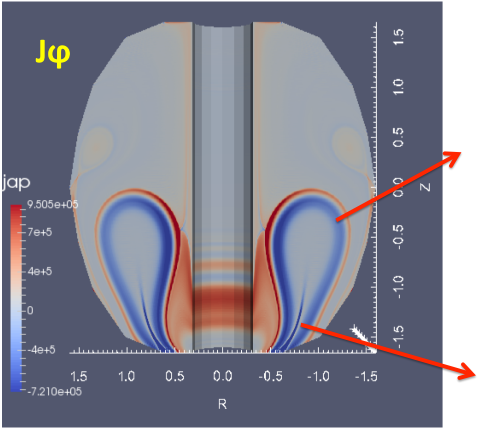
At high S, a transition to a plasmoid instability is demonstrated in the simulations.

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

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

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

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 - low-n ELM peeling-driven filament structures**
- **II - reconnecting edge filaments during VDEs**

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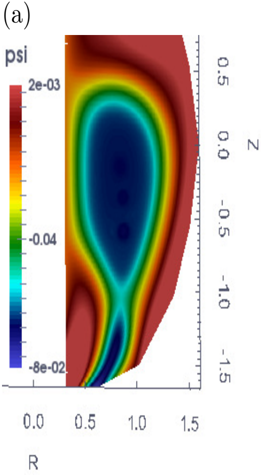
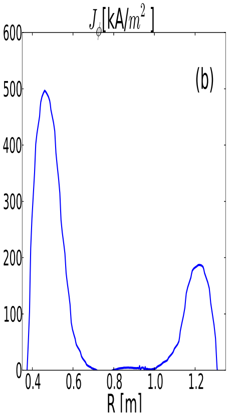
I- Model for current-driven ELMs

- Here edge current formed non-inductively (unlike pressure-driven current in the H-mode)
- Our model has been able to reproduce low-n ELM peeling-driven filament structures, that have been experimentally observed in Pegasus
- Simulations have local edge S = LV_A/η as high as 5×10^5, in the range of collisionality of standard tokamak operation
- Nonlinear resistive MHD simulations using NIMROD code will be used to study reconnection physics.

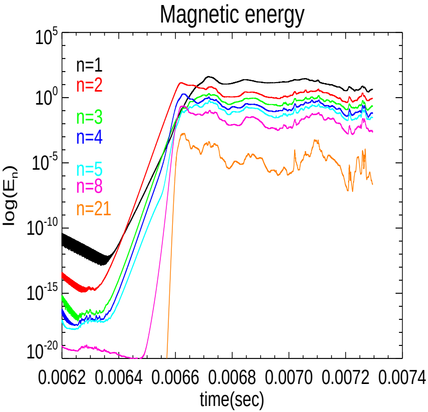
Edge current spikes provide the free energy for nonaxisymmetric edge instabilities





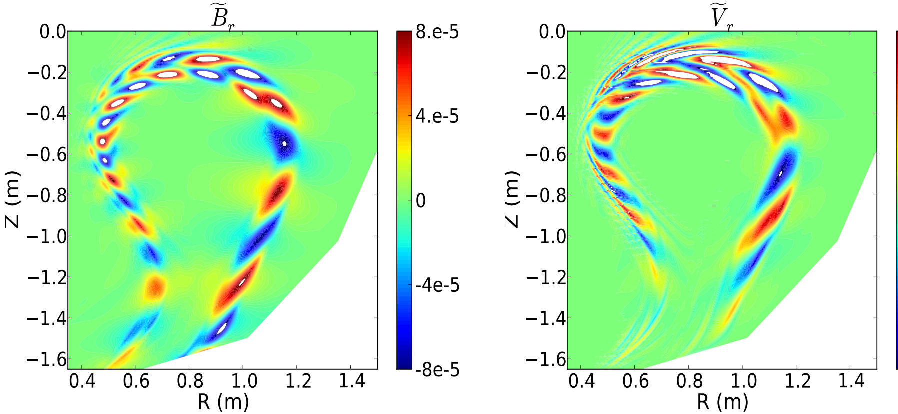
- Typical poloidal flux and axisymmetric toroidal current density during nonlinear simulations
- Unlike classical tearing, for current-sheet instability, edge current sheet width scales with S

3-D, non-axisymmetric magnetic fluctuations arise due to current-sheet instabilities localized near the edge region



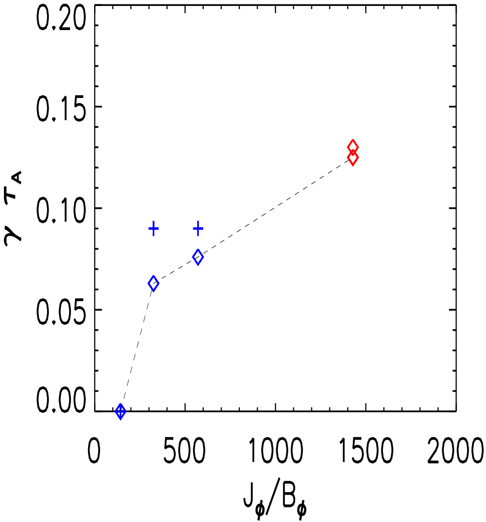
- $J_\phi = 500kA/m^2$, $B_\phi = 0.7T$, $B_z = 0.1T$
- n=1-6 linearly unstable, $\gamma\tau_{A(n=1)} \sim 0.086$
- higher toroidal modes numbers grow only nonlinearly and saturate at much lower amplitudes

Localized mode around the edge current sheet has tearing parity



The radial velocity changes sign in the current layer, similar to peeling mode structures with tearing parity observed near the X point region [Huysmans 2005, also Hooper & Sovinec 2016]

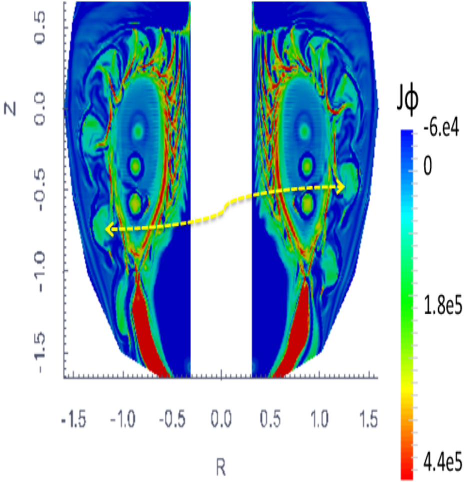
The growth of current-driven reconnecting edge localized modes (with tearing parity) scales with $J_{||}/B$



- 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 diamond]
- Scaling consistent with the instability drive for the traditional ideal peeling modes, $qRJ_{||}/B$
- Our limited scaling study for three S values in the range of $(1-4\times10^5)$ shows a weak dependency on S

Formation of 3-D coherent structures

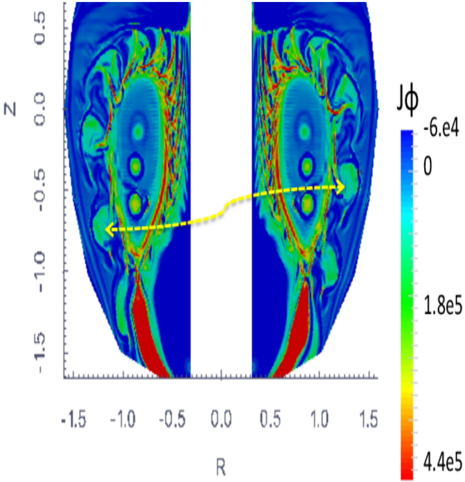
Nonlinear w/ 22 toroidal modes



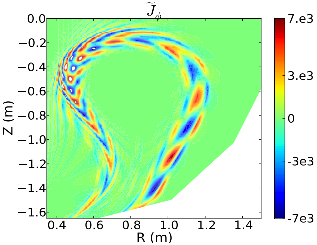
- Nonaxisymmetric structures break the initial axisymmetric current density
- Because of the very localized nature of the magnetic fluctuations, the amplitude of the associated perturbed toroidal current density can be as high as 50% of the n=0 component

The radially propagating filament n=1 structures can only become coherent as the number of toroidal modes increased

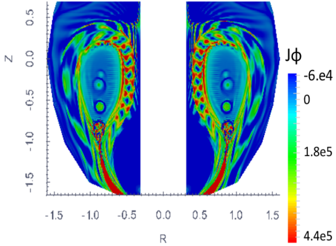
Nonlinear w/ 22 modes



Linear

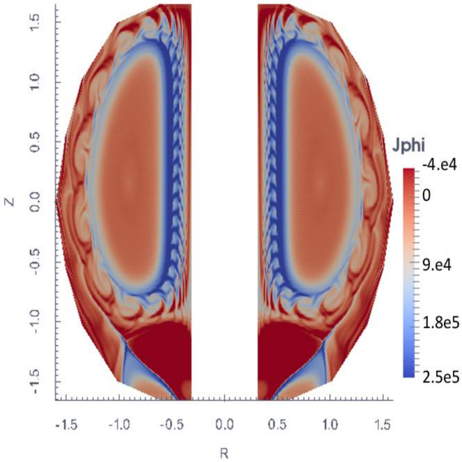


Nonlinear w/ 2 modes



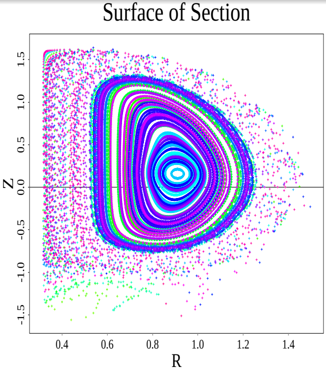
Coherent filaments also form in single X point configuration

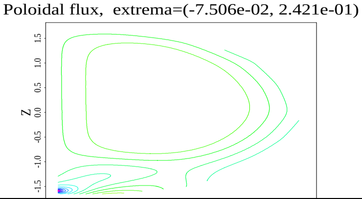
Nonlinear saturated toroidal current density



- 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.

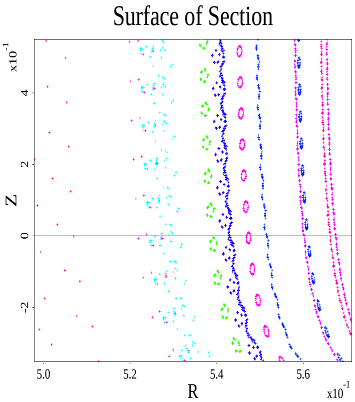
An equilibrium state with closed flux surfaces is fully formed non-inductively



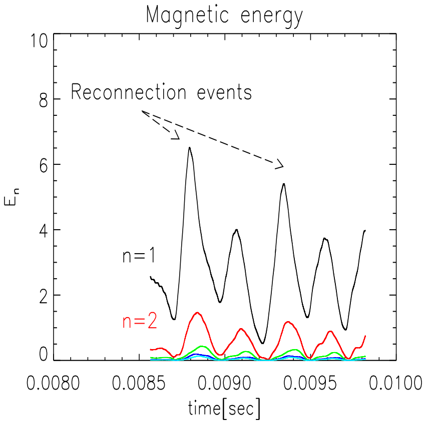


- Puncture plot obtained from the 3-D simulations shows the last closed flux surface (LCFS) extending radially from r= 0.52m-1.26m
- Stochastic region outside of separatrix

Overlapping islands near the edge



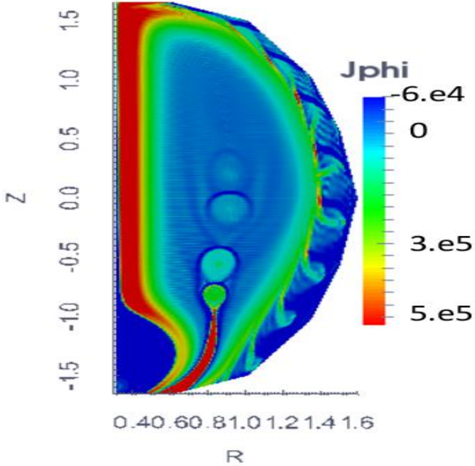
Observed edge localized coherent structures exhibit repetitive cycles during nonlinear stage



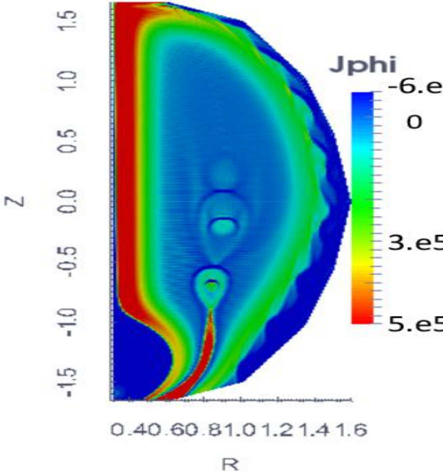
- Energy vs. time during full nonlinear 3-D simulations with 43 toroidal modes and with high toroidal field (B_ϕ =1.23T).
- Nonlinear dynamics during the flat top part of the total current (320kA)

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

maximum fluctuations

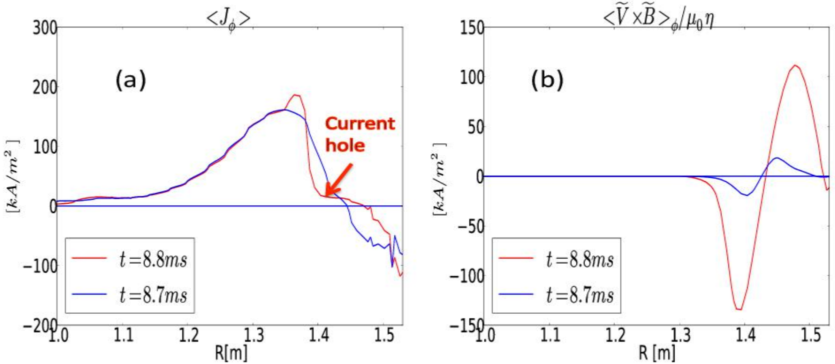


minimum fluctuations



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

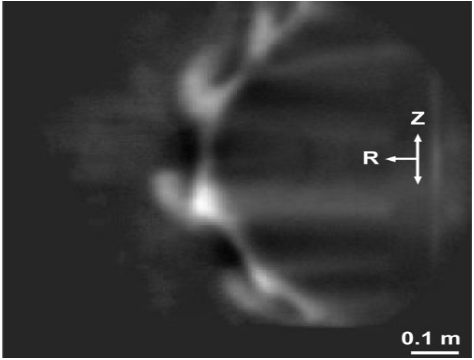
The emf contributes to the formation of current holes and the radially outward expulsion of the current density



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

Coherent filament structures found here are very similar to the camera images of peeling modes from Pegasus



Current-driven peeling modes with $n \leq 3$ were observed. Also low-n ELMs in NSTX [Maingi, et al. PRL 2009].

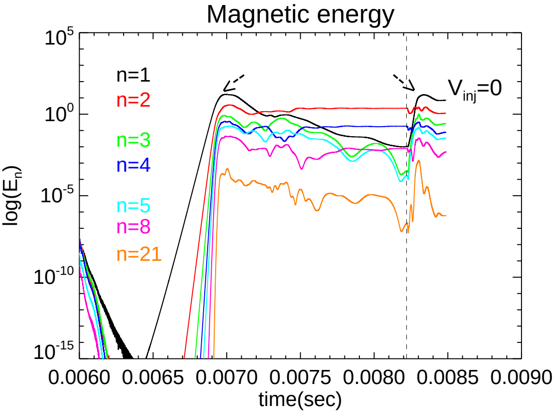
- J_{edge} generated by large skin currents during standard confinement
- $J_{||}/B$ peeling drive found during strong rampup of Ohmic discharges
- High poloidal coherence, with the intensity of the filament structures rising and falling in about $50\mu s$ [Bongard, et al. PRL 2011, Thome et al. PRL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

II- The observation of non-axisymmetric edge current density during plasma vertical displacement (VDEs)

The creation of non-axisymmetric edge current density in the simulations occurs both

1. during the flat top phase of current while a quasi-steady equilibrium state is formed (to study low-n ELMs)
2. while the magnetic flux bubble is expanding in the volume, i.e. the plasma being vertically displaced upward or downward
3. by driving large current in the open field region (using a CHI target), the stability of scrape-off layer currents (halo currents) can be studied

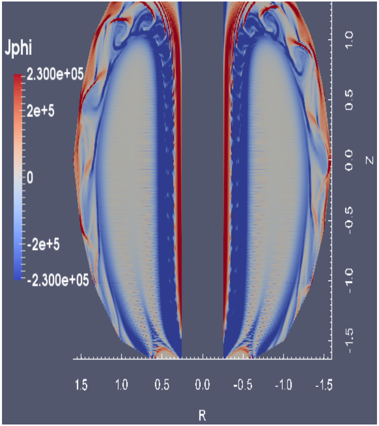
Strong 3-D dynamics as the plasma is being vertically displaced

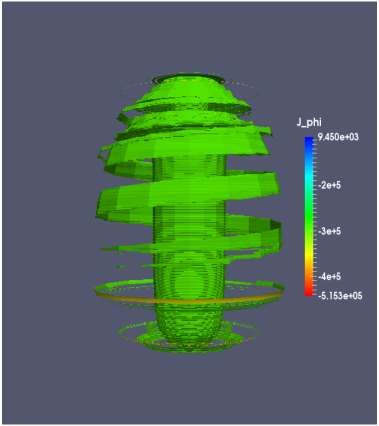


Low-n current-sheet instability triggered when the plasma is vertically expanding upward and when decaying downward

Nonlinear current-carrying filaments are formed during vertical displacement of plasma

t=6.98 ms

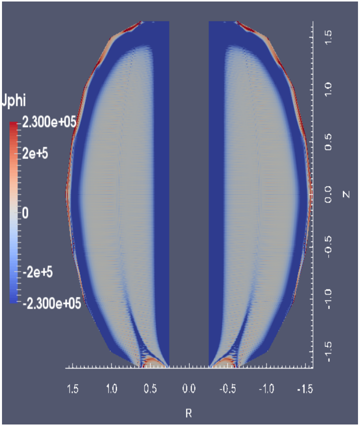


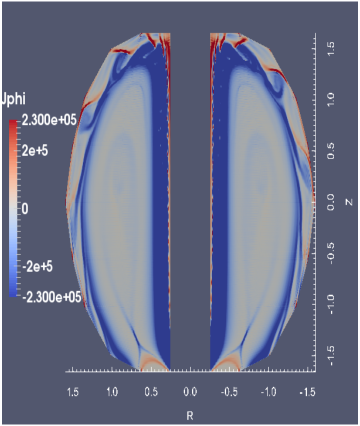


Nonlinear current-carrying filaments are formed during vertical displacement of plasma

t=8.22ms ($V_{inj} = 0$)

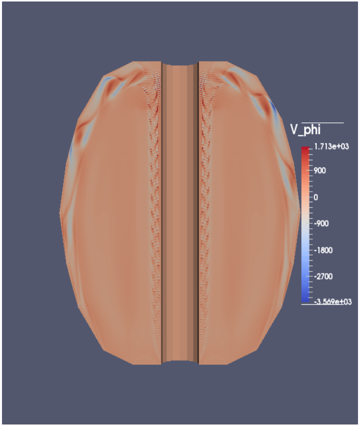
t=8.35ms

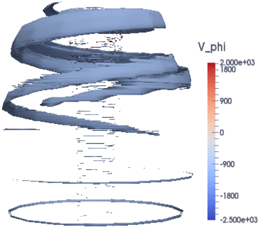




Nonlinear current-carrying filaments do rotate toroidally

Toroidal velocity





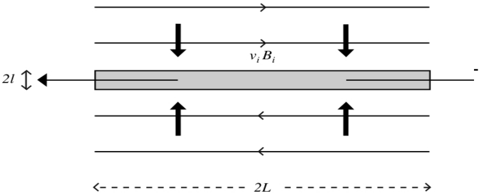
Summary

Reconnection does have a role in the edge region

1. **These simulations are the first to identify the time-evolving edge current sheets in NSTX and NSTX-U configurations**
2. Edge modes arising from 3-D current-sheet instability grow on the poloidal Alfven time scale
3. The quasiperiodic dynamics of low-n ELMs are explained as reconnection events
4. Nonlinear coherent rotating current-carrying filaments during plasma vertical displacement are shown to be driven via 3-D current-sheet instability

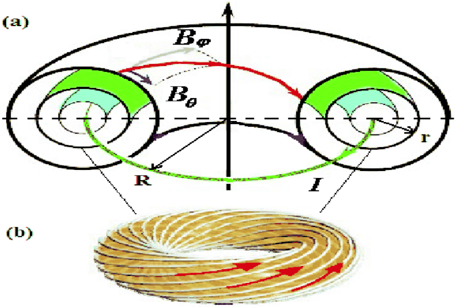
2-D vs 3-D reconnection in tokamaks

2-D (n=0) modes



- A rare, classical example of 2-D plasmoid formation during CHI near the injection region (with the resonant surface $\mathbf{k} \cdot \mathbf{B} = 0$ at the null surface of the poloidal equilibrium field)

3-D (n≠0)



$$\mathbf{B} = B_\theta \hat{\theta} + B_\phi \hat{\phi}$$

- Resonant surfaces where $k \cdot B = mB_\theta/r - nB_\phi/R = 0$
  $q = rB_\phi/RB_\theta = m/n$
  Finite (high) q in the edge

Edge current sheets/layers are dynamical not static