Spontaneous magnetic reconnection - Lecture III

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Current-driven magnetic reconnection - Tearing instability
Spontaneous reconnection

Furth, Killeen, and Rosenbluth (1963)

THE

PHYSICS OF FLUIDS

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Finite-Resistivity Instabilities of a Sheet Pinch

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(Received 17 September 1962)

The stability of a plane current layer is analyzed in the hydromagnetic approximation, allowing for finite isotropic resistivity. The effect of a small layer curvature is simulated by a gravitational field. In an incompressible fluid, there can be three basic types of "resistive" instability: a long-wave "tearing" mode, corresponding to breakup of the layer along current-flow lines; a short-wave "rippling" mode, due to the flow of current across the resistivity gradients of the layer; and a low-g gravitational interchange mode that grows in spite of finite magnetic shear. The time scale is set by the resistive diffusion time τ_R and the hydromagnetic transit time τ_H of the layer. For large $S = \tau_R/\tau_H$, the growth rate of the "tearing" and "rippling" modes is of order $\tau_R^{-3/5}\tau_H^{-2/5}$, and that of the gravitational mode is of order $\tau_R^{-1/3}\tau_H^{-2/3}$. As $S \to \infty$, the gravitational effect dominates and may be used to stabilize the two nongravitational modes. If the zero-order configuration is in equilibrium, there are no overstable modes in the incompressible case. Allowance for plasma compressibility somewhat modifies the "rippling" and gravitational modes, and may permit overstable modes to appear. The existence of overstable modes depends also on increasingly large *zero-order* resistivity gradients as $S \to \infty$. The three unstable modes merely require increasingly large gradients of the *first-order* fluid velocity; but even so, the hydromagnetic approximation breaks down as $S \to \infty$. Allowance for isotropic viscosity increases the effective mass density of the fluid, and the growth rates of the "tearing" and "rippling" modes then scale as $\tau_R^{-2/3}\tau_H^{-1/3}$. In plasmas, allowance for thermal conductivity suppresses the "rippling" mode at moderately high values of S. The "tearing" mode can be stabilized by conducting walls. The transition from the low-g "resistive" gravitational mode to the familiar high-g infinite conductivity mode is examined. The extension of the stability analysis to cylindrical geometry is discussed. The relevance of the theory to the results of various plasma experiments is pointed out. A nonhydromagnetic treatment will be needed to achieve rigorous correspondence to the experimental conditions.

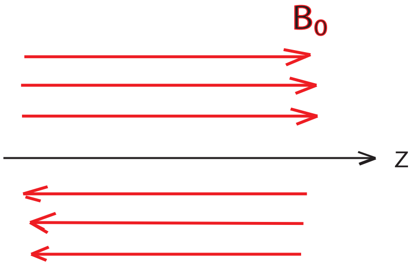
I. INTRODUCTION

A PRINCIPAL result of pinch[1,2] and stellarator[3] research has been the observed instability of configurations that the hydromagnetic theory[4,5] would predict to be stable in the limit of high electrical conductivity. In order to establish the cause of this observed instability, the extension of the hydromagnetic analysis to the case of finite conductivity becomes of considerable interest.

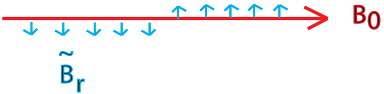
A number of particular "resistive" instability modes have been discussed in previous publications. Dungey[6] has shown that, at an x-type neutral point

[1] S. A. Colgate and H. P. Furth, Phys. Fluids **3**, 982 (1960).
[2] K. Aitken, R. Bickerton, R. Hardcastle, J. Jukes, P.

Spontaneous magnetic reconnection as the result of tearing fluctuations

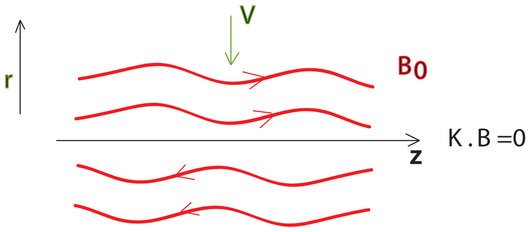


with small perturbation



Magnetic reconnection

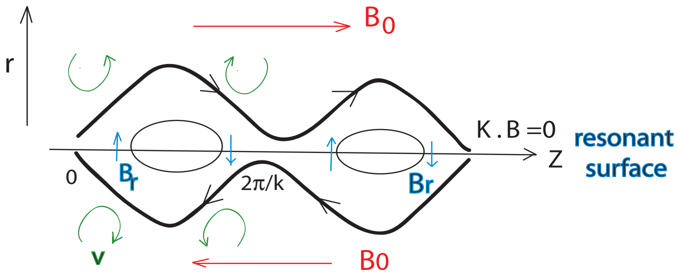
if $\eta = 0$



$$\frac{d\mathbf{B}}{dt} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

$\widetilde{V}_r = \gamma \widetilde{B}_r/(k \cdot B) ===> \boxed{\widetilde{B}_r = 0}$

Magnetic reconnection occurs at finite resistivity

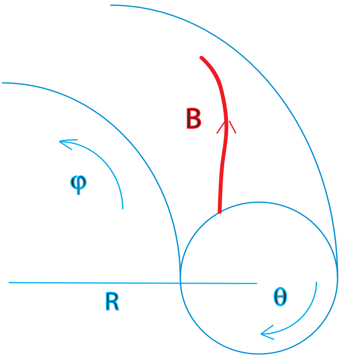


magnetic diffusion equation:

$$\frac{d\mathbf{B}}{dt} = \nabla \times (\mathbf{V} \times \mathbf{B}) - \frac{\eta}{\mu_0}\nabla^2\mathbf{B}$$

- $\widetilde{B}_r(\mathbf{r}, t) \sim \widetilde{B}_r(r)\exp(ik_z z - i\omega t)$

Helical magnetic field in tori



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

- Consider perturbations: $\widetilde{V}, \widetilde{B} \sim e^{ik\cdot\mathbf{r}} \sim e^{i(m\theta - n\phi/R)}$ periodic in ϕ and θ
- Resonant surfaces where $k \cdot B = mB_\theta/r - nB_\phi/R = 0$ $q = rB_\phi/RB_\theta = m/n$

Classical tearing mode growth rate scales with a negative power of S.

Dimensionless equation

$$\frac{d\mathbf{B}}{dt} = S\nabla \times (\mathbf{V} \times \mathbf{B}) - \eta\nabla^2\mathbf{B}$$

measure of plasma resistivity, Lundquist number $S = \tau_R/\tau_A$

$\tau_R = \mu_0 a^2/\eta \quad \tau_A = a/(B^2/(\mu_0\rho)^{1/2})$

Growth rate is a hybrid between resistive and Alfven times:

$\boxed{\tau_{growth} \sim \tau_R^{-3/5}\tau_A^{-2/5}}$, $\boxed{\gamma\tau_A \propto S^{-3/5}\Delta'^{4/5}(ka)^{2/5}}$

a= is a measure of the thickness of the current layer. [FKR]

What is Δ'?

- $\Delta' = (B'_r|^+_{rs} - B'_r|^-_{rs})/B_r|_{rs}$ is the jump in the logarithmic derivative of B_r across the resistive layer.
- **For tearing mode to be unstable, $\Delta' > 0$**
- Δ' is a measure of the magnetic energy to be gained by the perturbed magnetic field at the resonant surface.
- Can be calculated from the unstable eigenfunction (Br) obtained in linear simulations.
- Can be also directly calculated from the **outer solution** (ideal solution in the absence of resistivity).
- Outer solution is given in FKR (eq.16,17 in the limit of $S- > \infty$)

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Stability parameter is calculated from the outer solution

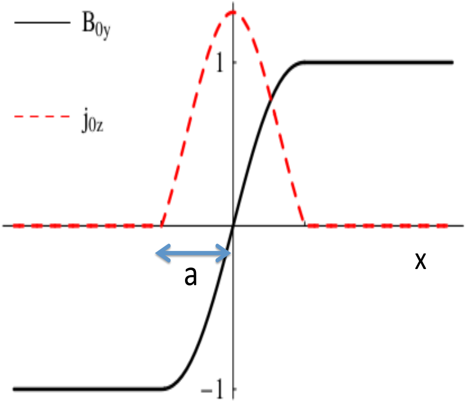
$$\psi'' - [(ka)^2 + F''/F]\psi = 0 \qquad \text{(FKR Eq.20)}$$

where $\psi = \widetilde{B}_r/B$

For a slab Harris sheet equilibrium $\mathbf{B} = B_0 \tanh(x/a)\hat{y}$
$F = \mathbf{k}\cdot\mathbf{B}/kB_0 = \tanh(x/a)$,

Δ' can be calculated from above

$$\boxed{\Delta' = 2[1/(ka) - (ka)]}$$

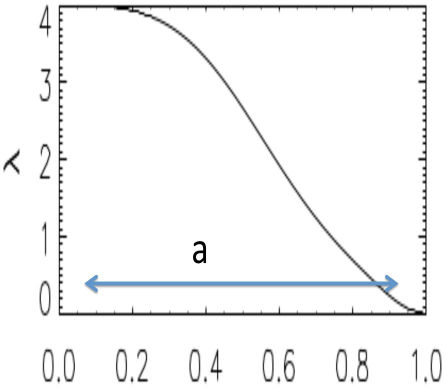


Solutions for a general tearing mode case in cylindrical geometry

For a general case, a force free case,

$$\nabla \times \mathbf{B} = \lambda \mathbf{B}$$

where $\lambda = \mathbf{J} \cdot \mathbf{B} / B^2$



Is this unstable?

Can calculate Δ' from the outer solutions

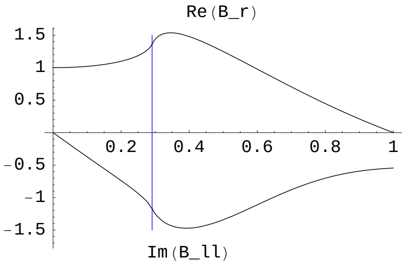
The linearized outer solutions are obtained from Newcomb equation (force free)

From the linearized, ideal-MHD force balance equation,

$$\boxed{(r\widetilde{B}_r)'' + f/r(r\widetilde{B}_r)' - g(r\widetilde{B}_r) = 0}$$

$$f = (m^2 - k_z^2 r^2)/(m^2 + k_z^2 r^2)$$

$$g = m^2/r^2 + k_z^2 - \lambda^2 + 2mk_z\lambda/(m^2 + k_z^2 r^2) + \lambda' G/F$$

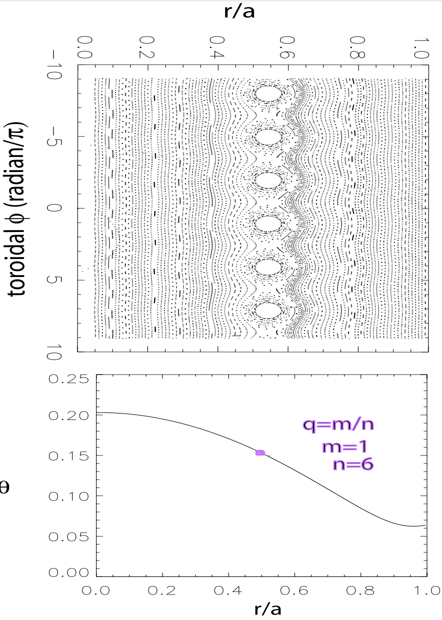


$$\widetilde{B}_{||} = i\left[\frac{Fr(r\widetilde{B}_r)' - rG\lambda(r\widetilde{B}_r)}{B(m^2 + k_z^2 r^2)}\right]$$

$$F = mB_\theta/r - k_z B_z$$
$$G = mB_z/r + k_z B_\theta$$

- $\widetilde{B}_r$ solved numerically for a given $\lambda = \mathbf{J} \cdot \mathbf{B}/B^2$

Single tearing mode becomes unstable.

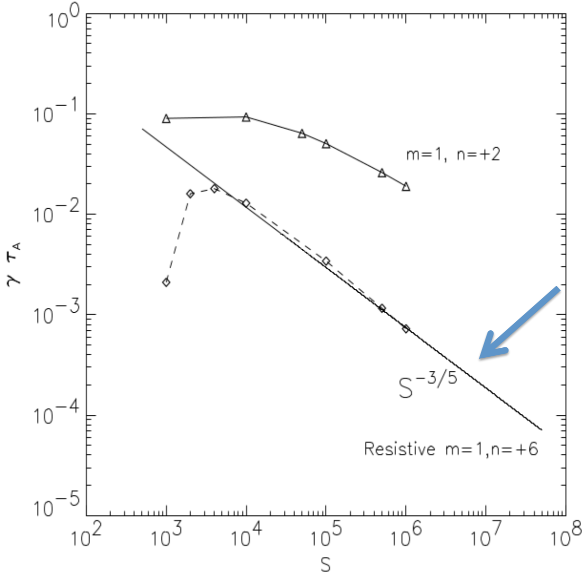


$$q=\frac{r\,B_z}{R\,B_\theta}$$

- Puncture plot shows islands formation for a **single tearing mode with particular m,n resonant at r/a=0.5**

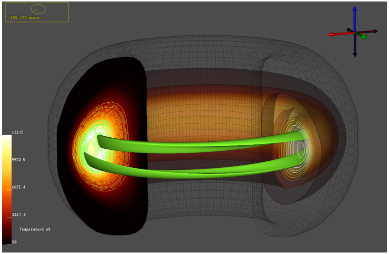
How do we know it is a classical tearing mode?

Has to follow the FKR S scaling.



Most of the reconnection physics in fusion plasmas have been so far based on the classical tearing modes or neoclassical NTM.

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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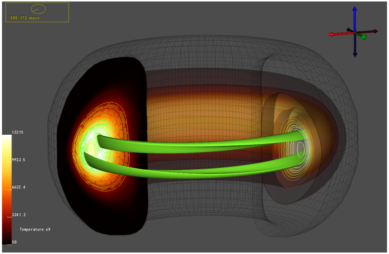

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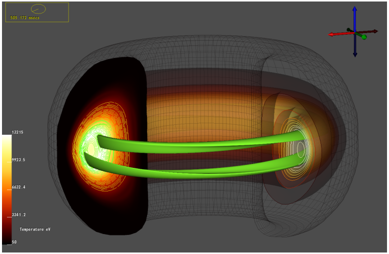

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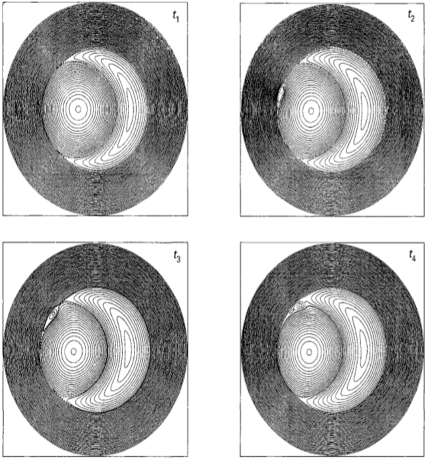
Secondary islands (plasmoids) in tokamak-relevant studies

- 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]

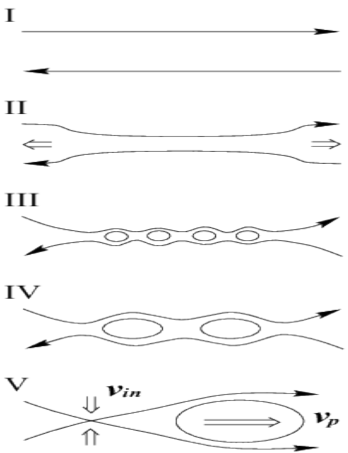
Plasmoid instability in the current sheet of the resistive kink mode



Biskamp 1987

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, Cassak et al. (2009), Huang et al. 2011,2013, Ebrahimi & Raman 2015, Uzdensky & Loureiro (2016)] **shows fast reconnection.**
- Static linear theory does not apply [Pucci & Velli (2014)] with a general theory [Comisso et al. PoP 2016]



Shibata & Tanuma 2001

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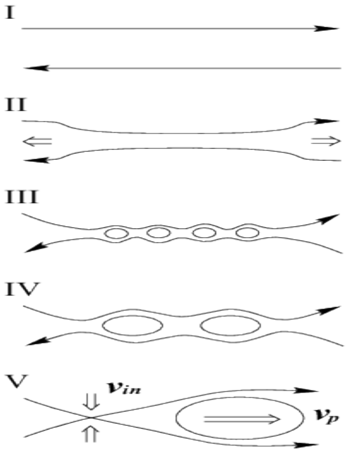
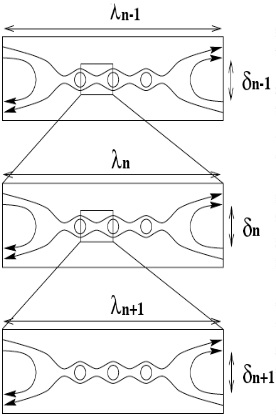
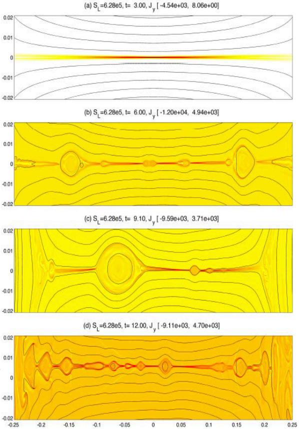
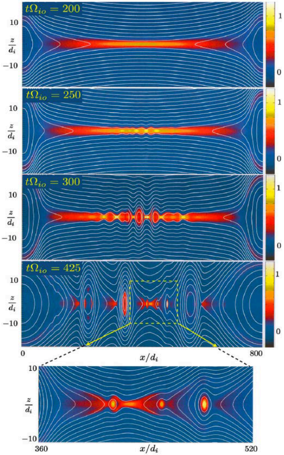


Shibata & Tanuma 2001

Plasmoid instability gives rise to a hierarchy of interacting current sheets and islands







[Shibata & Tanuma 2001]

[Ji & Daughton (2011)]

MHD

[Bhattacharjee et al. 2009]

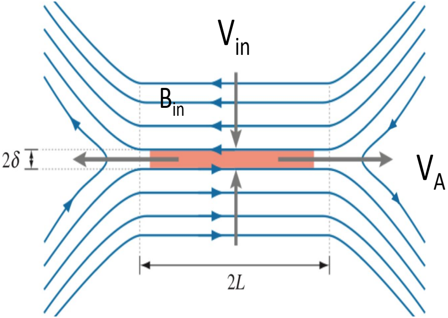
Kinetic-MHD

[Daughton et al. (2011)]

How could tearing mode in MHD model give rise to super Alfvenic growth rates and fast reconnection ?

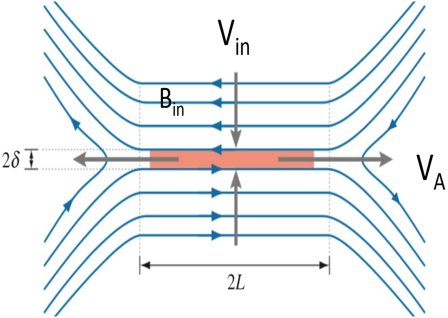
Both Sweet-Parker and FKR give slow reconnection and negative scaling with S!

Sweet-Parker model (1958)



- Mass conservation
  $V_{in}L \approx V_{out}\delta$
- Energy conservation (acceleration along sheet)
  $V_{out} \approx V_A = B_{in}/\sqrt{(\mu_0\rho)}$
- matching ideal E outside the layer with the resistive E in the layer
  $V_{in}B_{in} \approx \eta J \rightarrow V_{in} \approx \eta/\mu_0\ell$
  (using $J \approx B_{in}/\mu_0\delta$)
- $\boxed{V_{in}/V_{out} = S^{-1/2} = \delta/L}$
  $(S = \mu_0 L V_A/\eta)$

Recon. Rate $\sim$ flux * $V_{in}/\delta \sim B_{in}\delta V_A S^{-1/2}$
For solar flares, $S \sim 10^{14}$ theory predicts
==> $\tau_{s-p} \sim$ 2 months
Flares only last min to an hour
==> Rate is too slow
Also see Zweibel & Yamada (2009)



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Sweet-Parker current-sheet scaling needs to be incorporated in the classical tearing model

Let's revisit FKR constant-ψ scaling
here we insert Δ' for Harris sheet equilibrium

$$\Delta' = 2\left[\frac{1}{(ka)} - (ka)\right]$$

into the FKR growth rate $\gamma\tau_A \propto S^{-3/5}\Delta'^{4/5}(ka)^{2/5}$
we obtain:
1- $\gamma\tau_A \propto S^{-3/5}(ka)^{-2/5}[1-(k^2a^2)]^{4/5}$ for $ka >> S^{-1/4}$
also Coppi et al. (1976) obtained growth rate with weaker dependency to S for the non-constant-ψ regime
2- $\gamma\tau_A \propto S^{-1/3}(ka)^{2/3}$ for $(ka << S^{-1/4})$
The maximum growth rate from these branches (1) and (2) is

$\gamma_{\max}\tau_A \sim S^{-1/2}$ at $(k_{max}a \sim S^{-1/4})$

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Now **a** (current sheet width) must be replaced with the S-P scaling **a** $\sim L/\sqrt(S_L)$

$\tau_A = a/V_A ==> L/(\sqrt(S_L)V_A ==> 1/\sqrt{S_L}\tau_A$
$S = aV_A/\eta ==> L/(\sqrt(S_L)V_A/\eta ==> S_L^{1/2}$
Replacing above into the maximum growth rate eq. gives:

$$\boxed{\gamma_{max}\tau_A \sim S_L^{1/4} \quad \text{at} \quad (k_{max}L \sim S_L^{3/8})}$$

(Tajima & Shibata 1997 Plasma Astrophysics, Loureiro et al. 2007)

Here : $\tau_A = L/V_A$ and $S_L = LV_A/\eta$
(L is the length of the current sheet)

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Fast reconnection due to plasmoid instability

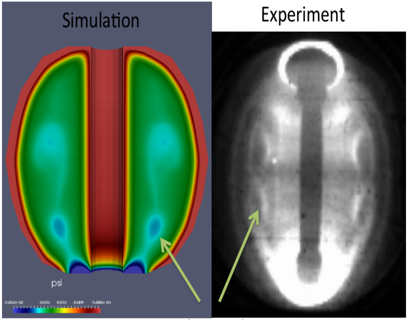
In the past several years nonlinear simulations have shown that plasmoid-mediated reconnection is fast (independent of S)

- For a Harris sheet equilibrium, within resistive MHD fast reconnection has been shown to occur [Lapenta 2008],also in resistive MHD, a reconnection rate $\sim 0.01\, V_A B$, nearly independent of S has been obtained numerically [Bhattacharjee et al. 2009; Huang & Bhattacharjee 2010;Loureiro et al. 2011]
- Plasmoid can trigger even faster collisionless/Hall reconnection if width of the secondary current sheets become smaller than ion skin depth d_i or Larmor radius ρ_i [Daughton et al. 2009; Shepherd & Cassak 2010; Huang et al. 2011]

Also in a tokamak: Fast reconnection rate (weakly dependent on S) in resistive MHD in the presence of strong guide field has been demonstrated. [Ebrahimi&Raman 2015]

What is the practical implication of plasmoid-mediated magnetic reconnection and generation of coherent magnetic structures?

2-D plasmoids

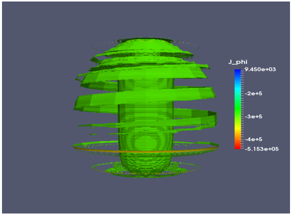


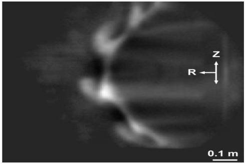
Plasmoids

Camera images from NSTX do show the formation of plasmoids – cause plasma startup formation

[Ebrahimi&Raman PRL 2015]
[Ebrahimi PoP 2016,2017]

3-D filaments

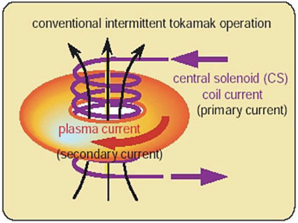


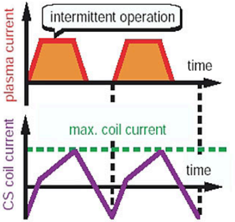


Coherent current-carrying filament formation near the plasma edge (ELMs) - could damage PFC

Magnetic reconnection in laboratory for current-drive?

In conventional tokamak plasma current is generated inductively.





Utilize reconnection for non-inductive current-drive?

- Could plasma current be produced by the process of magnetic reconnection through detachment of magnetic loops during helicity injection?

System-size plasmoid formation to produce large plasma current in a toroidal fusion device. [Ebrahimi & Raman Nuclear Fusion 2016]

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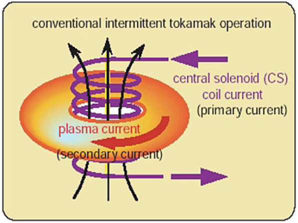

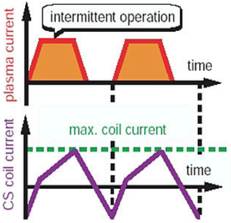

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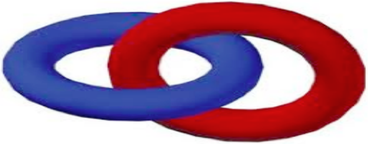
Magnetic helicity, a topological property, measures the knottedness and the twistedness of magnetic fields

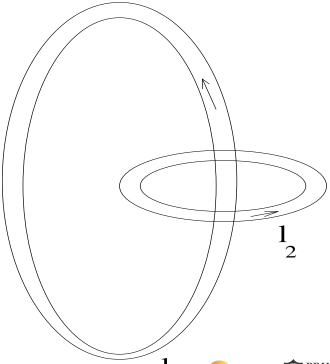


$$K = \int A \cdot B dV = 2\,\phi\ \phi$$

$$B d\mathbf{v}_1 = B \cdot \hat{n} ds_1 dl_1 = \Phi_1 dl_1$$

$$K_1 = \int \mathbf{A} \cdot \mathbf{B} d\mathbf{v}_l$$
$$= \Phi_1 \int \mathbf{A} \cdot dl_1 = \Phi_1 \Phi_2$$

Two interlinked flux tubes $\longrightarrow$



Conservation of helicity for each flux tube in an ideal plasma

The time-derivative of the vector potential A and magnetic field B, given by Maxwell's equations

$$\partial\mathbf{A}/\partial t = -\mathbf{E} - \nabla\phi$$

$$\partial\mathbf{B}/\partial t = -\nabla\times\mathbf{E},$$

using $\mathbf{E} = -\mathbf{V}\times\mathbf{B}$

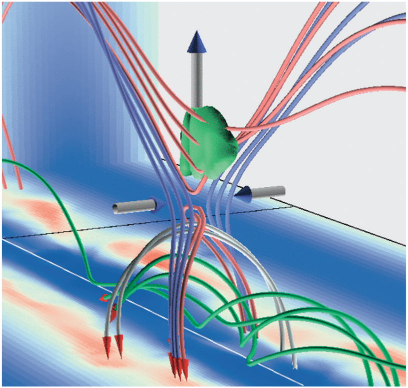
$$\frac{dK}{dt} = \int(\mathbf{A}\cdot\mathbf{V} - \phi)\mathbf{B}.d\mathbf{S}$$

On surface of flux tube $\mathbf{B}\cdot d\mathbf{S} = 0 ==> \frac{dK}{dt} = 0$

First obtained by Woltjer (1958)

Many fundamentals of reconnection physics can be explored during helicity injection

Solar flares field lines modeling

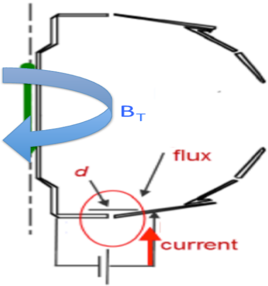


$$\frac{\partial K}{\partial t} = -2\int (\mathbf{A.V})\mathbf{B}\cdot d\mathbf{s}$$

Kusano 2004

Warnecke & Brandenburg 2010

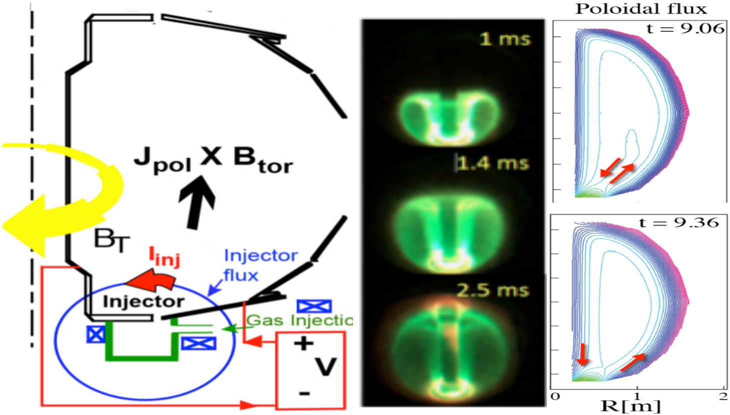
Helicity injection in a lab



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

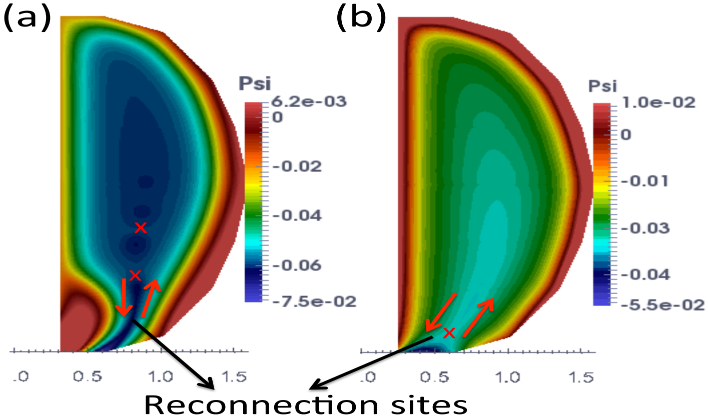
Helicity is injected through a surface term.

Transient Coaxial Helicity Injection (CHI), the primary candidate for solenoid- free current start-up in spherical tokamaks

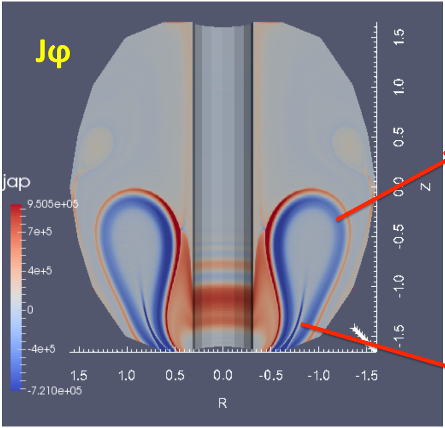


A rare classical example of 2-D plasmoid formation in a large-scale fusion plasma

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

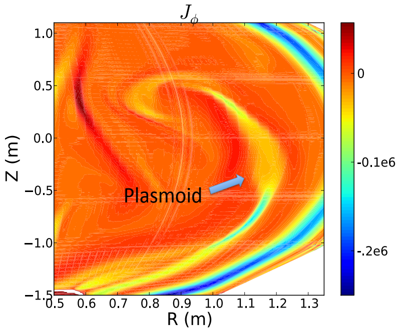


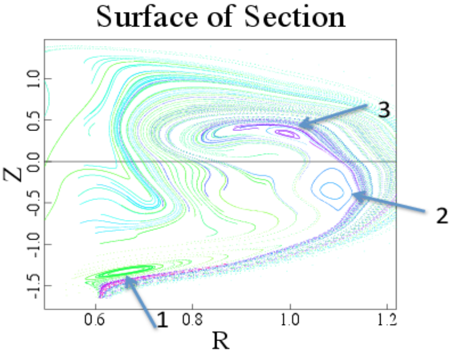
Two types of current sheets are formed during flux expansion/evolution



- 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

Spontaneous plasmoid reconnection



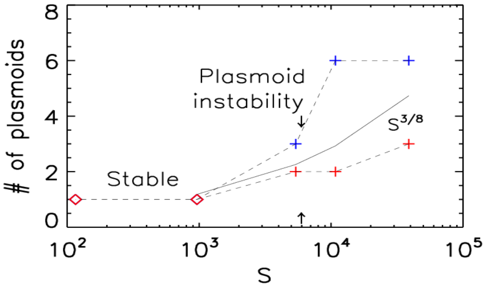


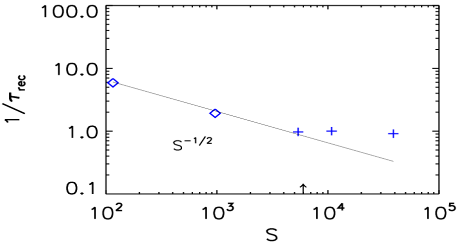
At high S, a transition to a plasmoid instability is demonstrated in the simulations.

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.

At high S, a transition to a plasmoid instability occurs





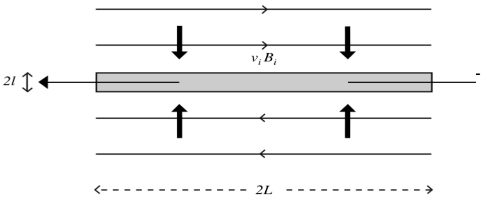
- Number of plasmoids is an increasing function of S. Blue: small sized transient plasmoids Red: large scale and persistent plasmoids
- As the current sheet evolves in time, static linear theory doesn't apply [L. Comisso et al. PoP 2016]
- Reconnection rate becomes nearly independent of S. **[Here with strong guide field]**

F. Ebrahimi & R.Raman PRL 2015

Dynamo-driven plasmoids formation

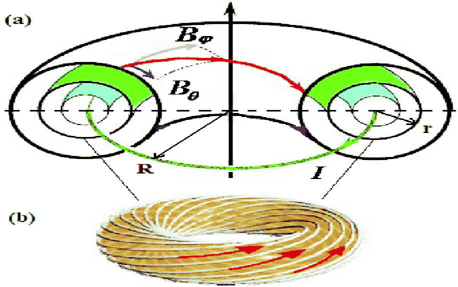
- 3D effects
  - Could large-scale dynamo from 3-D fluctuations trigger reconnecting plasmoids?
  - Self-consistent trigger mechanism in 3-D?

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)

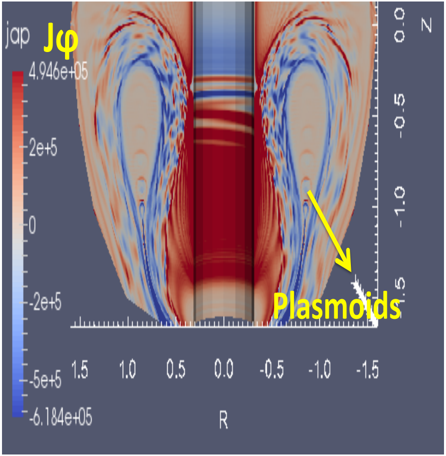


$\mathbf{B} = B_\theta \hat{\theta} + B_\phi \hat{\phi}$

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

Edge current sheets/layers are dynamical not static

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.**

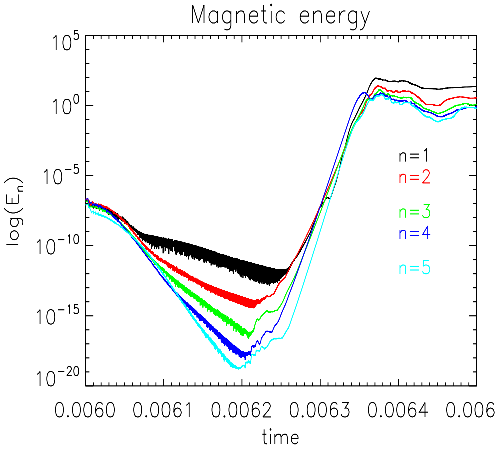
[Ebrahimi PoP Letters 2016]

Edge modes grow on the poloidal Alfven time scales

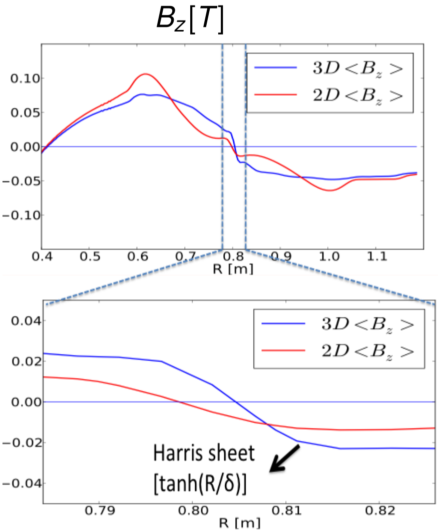
1. These modes grow fast, on the poloidal Alfven time scales, and are **peeling modes with tearing-parity structures.**

2. These modes saturate by modifying and relaxing the edge current sheet

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



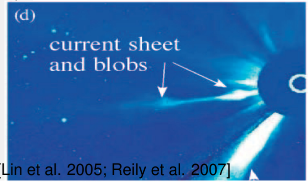
Poloidal flux amplification is observed to trigger axisymmetric reconnecting plasmoids formation



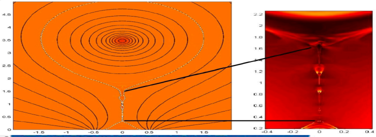
- A dynamo poloidal flux amplification is observed
- This **fluctuation-induced flux amplification increases the local S**
  $==>$
  triggers a plasmoid instability
  $==>$ breaks the primary current sheet.

In order to understand the phenomena in a certain plasma region, it is necessary to map not only the magnetic but also the electric field and the electric currents. Space is filled with a network of currents which transfer energy and momentum over large or very large distances. The currents often pinch to filamentary or surface currents. The latter are likely to give space, as also interstellar and intergalactic space, a cellular structure.

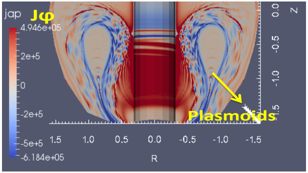
Hannes Alfven



[Lin et al. 2005; Reily et al. 2007]



Guo et al. APJL (2013)



Ebrahimi&Raman PRL 2015, PoP 2016
Other lab observation Jara-Almonte et al. 2016