Relaxation in Magnetic Confinement Experiments

by

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to

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Outline

- Relaxation in general
- What helicity conservation tells us about relaxation
- What we have learned beyond helicity conservation
- Some outstanding issues for using relaxation in controlled fusion
- Summary

Definition of relaxation

•The saturation of instability leading to a new equilibrium or sustainment of the equilibrium.

•Physical constraint(s) limit(s) the action of instability

•In a tokamak: saw tooth activity is relaxation while a disruption is not.

•Sometimes now called “self-organization” which implies relaxation with a beneficial outcome

Helicity constraint yields the required helicity and power injection needed for steady state:

- Local (energy dissipation)/(helicity dissipation) = $\mathbf{E}\cdot\mathbf{j}/2\mathbf{E}\cdot\mathbf{B} = \lambda(\psi)/2\mu_o$ ($\lambda(\psi)$ is local $\mu_o j/B$)
  - $\lambda_{inj} > \lambda_{equ}$ (relaxation takes energy)
  - $\varepsilon = \dfrac{\lambda_{equ}}{\lambda_{inj}}$ [Jarboe 87]
  - Efficiency is orders higher than rf or beams [Boozer 88]

- Helicity constraint during relaxation tells us:

$$\int \mathbf{E}\cdot\mathbf{B}\,dVol = \int \eta\mathbf{j}\cdot\mathbf{B}\,dVol$$

- Does not say that $\mathbf{E}\cdot\mathbf{B}$ is equal to $\eta\mathbf{j}\cdot\mathbf{B}$. (For example, in CHI, relaxation can drive current in a closed flux region where time averaged $\mathbf{E}=0$ but $\mathbf{E}$ must be larger than $\eta\mathbf{j}$ in open flux regions.)

Summary of information from the helicity constraint

- Helicity is the best constant of the motion of a magnetized plasma.
- Plasma with helicity cannot dissipate all of its magnetic energy through instability.
- Instability makes $\lambda(\psi)$ more uniform.
- Driving $\lambda(\psi)$ high in any convenient region leads to current drive throughout the volume.
- Gives the helicity injection requirements for formation and sustainment via helicity injection.
- Gives the efficiency of helicity injection current drive ($\approx$ 50%).
- Helicity injection current drive requires helicity barrier at the boundary.
- Configurations move downhill in λ.

Helicity is only a small part of the relaxation story

The helicity constraint alone does not tell us

- Profile where relaxation ceases
- Impedance of helicity injectors
- Relaxation physics
  - Energy confinement during relaxation
  - Relaxation rate

What we have learned, in addition, about relaxation

- Some dynamics are needed for relaxation, once stability is reached relaxation ceases. Steady state system operates at marginal stability.[Knox 86]
  - –Ideal stability seems to predict margin
  - –Flow effects, two fluid effects, and/or low S may suppress resistive modes
  - –Resistive modes are important in saturation of instabilities (relaxation)
- m = 1 activity is important because it gives relaxation motion across the entire crossection.

Dynamo mechanism may come from fluctuation modes coupling the driven and confinement regions

- Time averaging the generalized Ohm's law including the Hall terms yields [Ji 99]

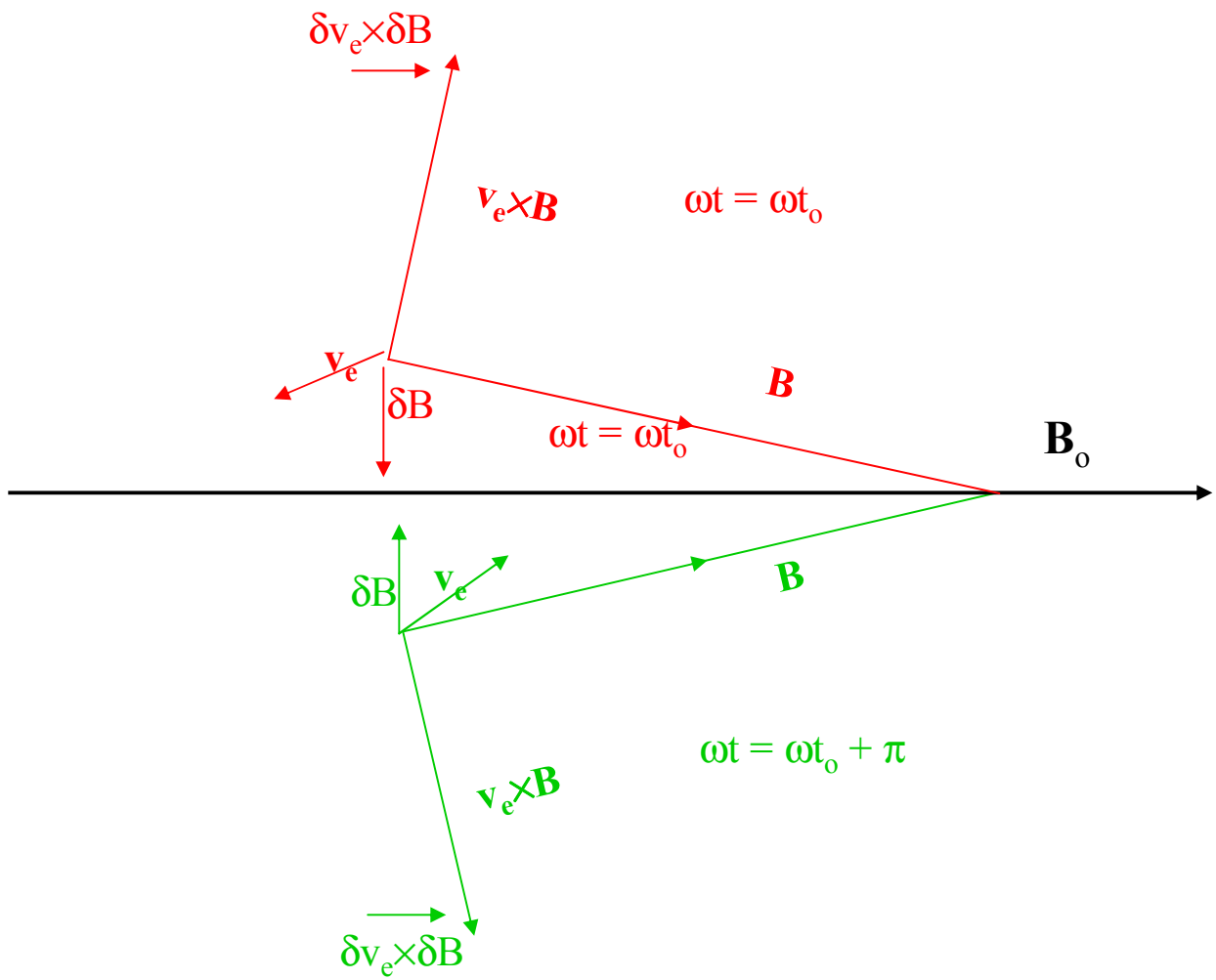
$$E_{\square} = -\langle \delta \mathbf{v_e} \times \delta \mathbf{B} \rangle_{\square} + \eta j_{\square}$$

- For simplicity, assume ion fluctuation currents are small

$$E_{\square} = \frac{\langle \delta \mathbf{j} \times \delta \mathbf{B} \rangle_{\square}}{ne} + \eta j_{\square}$$

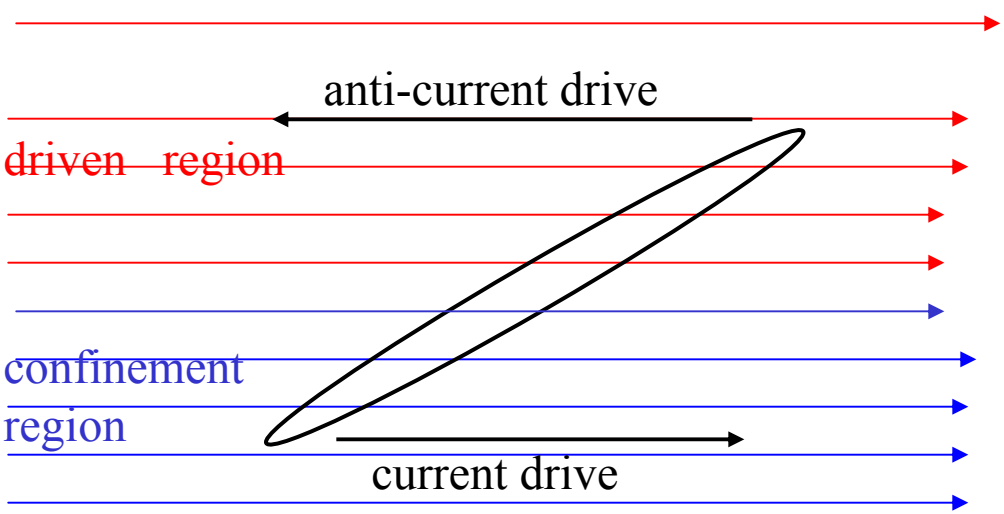
- Fluctuation magnetic structure alone provides the coupling between driven and confinement regions and our intuitive pictures of field line tension and pressure are valid for that.

Dynamo picture of phased fluctuations of B and v_e giving a time averaged Lorentz force on electrons in the equilibrium $-B_o$ direction. ($v = \delta v$, $v_o = 0$)



Intuitive shape of relaxation dynamo mode emerges

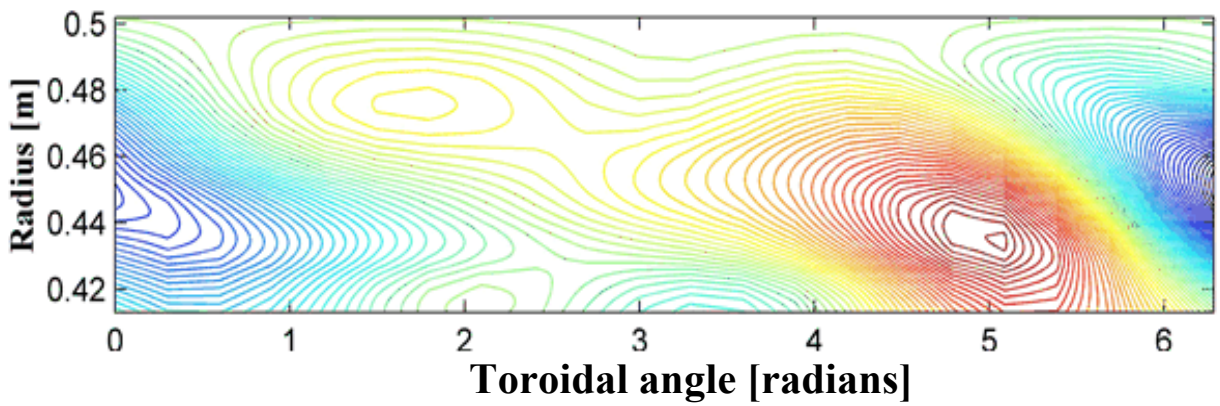
- Shape of a crossection of the mode depends critically on the angle of the crossection with respect to the equilibrium field.
- Mode crossection (black) in plane of equilibrium field (red, blue)



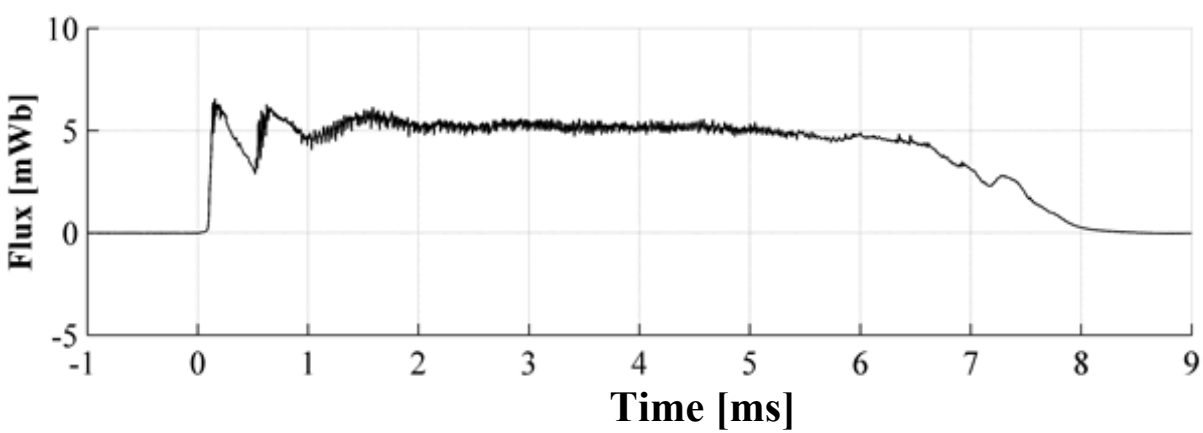
- Assumes electron flow is in the direction of field
- External drive must overcome anti-current drive
- Current drive can maintain closed flux current

Experimental data also shows a current driving n=1 mode structure in an ST.

Fluctuation flux at 3ms, (10μWb spacing)



Poloidal flux at innermost probe (10cm)



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- A magnetic probe array was inserted into a rotating CHI driven discharge on HIT-II.
- Discharge has a well repeating n=1 mode so that a rigid rotation analysis reveals the toroidal mode structure.
- Current drive and anti-current driving fluctuations have also been measured on MST [Den Hartog 99, Fontana 00] and SPHEX [al-Karkhy 93]

Simple picture of dynamo relaxation current drive gives an acceptable scaling of required fluctuation amplitude

•If $\delta B/B$ is small enough then confinement will be acceptable.

•Assuming constant n, j, β, and mode shape and $\eta \propto T^{-3/2}$ yields a favorable scaling.

$$\frac{\delta B}{B} \propto S^{-2/5}$$

•This is an acceptable scaling but parasitic fluctuations need to be controlled.

•Less favorable scaling was found in MST [Stoneking 1998] but the fluctuations were driving the edge current and S was that of the central region.

- •One does not expect a correlation between fluctuation amplitude and S in anti-current-drive regions.
- •Scaling may be very different in edge driven systems.

Summary

- Relaxation plays a central role in low toroidal fields ICC concepts.
- Helicity conservation is a useful constraint.
- We have learned much but have a great deal more to learn about relaxation.
- With adequate understanding relaxation might be harnessed for the ST concept.
- NSTX is a great machine to acquire this new understanding

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