Prospects for Driven Particle Convection Tests in LDX

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Abstract

An attractive consequence of the shear-free magnetic field of levitated dipole confinement devices is the possibility of using advanced fusion fuel cycles [1]. When the pressure and density profiles are isentropic, convective interchange mixing transports particles but does not necessary transport heat. In shear-free magnetic fields, low-frequency convective circulation is interchange-like and the size-scale of the largest circulation motion extends to fill the confinement volume. As a consequence, particles may be convected from the hot central region to the edge in times much less than the energy confinement time. One goal of the Levitated Dipole Experiment (LDX) is to investigate the relative energy and particle time scales and also to explore active means to induce rapid particle circulation that do not alter the dipole's highly peaked pressure isentropic profiles. We discuss a four-part plan involving: (1) optical measurement of localized density and impurity transport, (2) flux-tube charging with insertable bias probes, (3) the impact of localized field errors on convective cell formation, and (4) the application of weak toroidal fields to limit the radial extent of convection and prevent inward particle transport to the dipole magnet.

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[1] Kesner, J., et al., *Nuclear Fusion*, **44** (2004) p. 193.

Outline

- LDX creates high-beta plasmas for basic study of dipole-confinement and for exploration of possible *reduced particle confinement* relative to energy confinement required for fusion with advanced fuels.
- What are isentropic profiles?
- Natural/Driven particle convection and control:
  - Self-generated turbulence
  - Flux tube charging
  - Field error
  - Weak toroidal field

What are Isentropic Processes?

- Isentropic process is one that conserves entropy.
- Isentropic flow is both adiabatic and reversible. No energy is added or removed from the flow.
- Isentropic equation of state:

  $$\delta(P/V^{\gamma}) \sim 0, \text{ with } \gamma = C_p/C_v = 5/3$$

- For a plasma in a strong magnetic field undergoing interchange mixing, the unit of mixing, δV, are tubes of constant magnetic flux. Therefore,

  $$\delta(N) \equiv \delta(\langle n \rangle V) \sim 0.$$

Flux-Tube Averaged MHD with Isentropic Closure Implies a Single Mixing Dynamic

Adiabatic or isentropic closure implies $d(P/\langle n \rangle^\gamma)/dt = 0$, where $\langle A \rangle \equiv \delta V^{-1} \int d\chi A/B^2$, $N/\delta V = \langle n \rangle$.

In low β, when $\mathbf{E} = -\nabla\Phi$, plasma interchange mixing causes particles, N, and "entropy", $G \equiv P\delta V^\gamma$, to be *dynamically similiar*:

$$\begin{aligned} \frac{\partial N}{\partial t} - \frac{\partial}{\partial \varphi}\left(N\frac{\partial \Phi}{\partial \psi}\right) + \frac{\partial}{\partial \psi}\left(N\frac{\partial \Phi}{\partial \varphi}\right) &= 0 \\ \frac{\partial G}{\partial t} - \frac{\partial}{\partial \varphi}\left(G\frac{\partial \Phi}{\partial \psi}\right) + \frac{\partial}{\partial \psi}\left(G\frac{\partial \Phi}{\partial \varphi}\right) &= 0 \end{aligned}$$

When $\partial N/\partial\psi = \partial G/\partial\psi = 0$, plasma profiles are *stationary*, and **convective mixing leaves profiles unchanged**, $\partial N/\partial t = \partial G/\partial t = 0$.

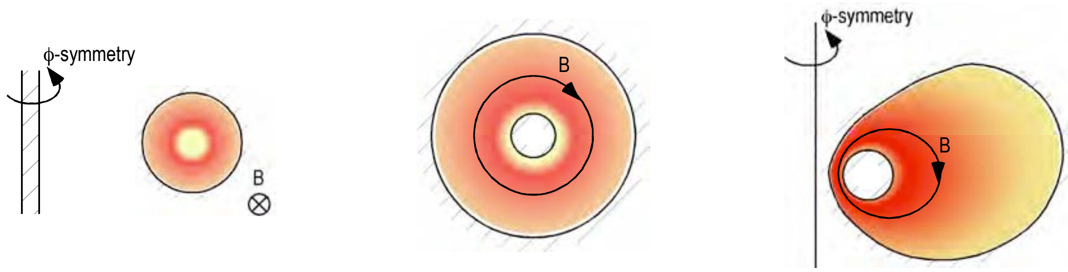
When δG = 0, MHD Interchange Mixing Leaves Energy (and Density) Unchanged

The equations for the change in plasma internal energy, W_p, and for the change in electrostatic energy, W_e (actually, the kinetic energy of the convective mass flow) can be written as

$$\begin{aligned} \frac{dW_p}{dt} &= -\iint d\varphi d\psi \frac{1}{\delta V^{\gamma-1}}\left(\frac{N_m}{N}\right)\tilde{\mathbf{V}}_{\mathbf{E}} \cdot \nabla(P\delta V^\gamma) \\ \frac{dW_e}{dt} + \frac{\partial W_p}{\partial t} &= -\iint d\varphi d\psi\, \gamma P \delta V \left(\frac{N_m}{N}\right)\tilde{\mathbf{V}}_{\mathbf{E}} \cdot \nabla \log \bar{n}\,. \end{aligned}$$

Interchange motion exchanges energy between the plasma and the convective mass flows at a rate proportional to the volume integral of net release of plasma energy, $\propto \tilde{\mathbf{V}}_{\mathbf{E}} \cdot \nabla G$. The source of the overall release of energy is related to the net transport of plasma down the density gradient. MHD interchange transport flattens the volume-averaged gradient of $G = P\delta V^\gamma$. *A stationary state with a finite fluctuation level can not occur without a source (and sink) of plasma.*

Isentropic, “Constant Entropy Density”, Profiles in Shear Free Configurations



Pure Toroidal Field
(e.g. BLAAMANN, BETA, etc)

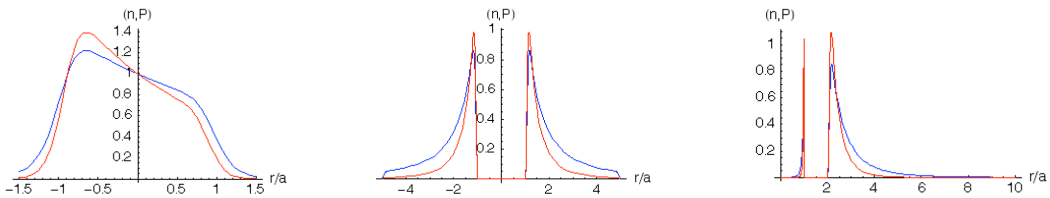
$\delta V \sim R_0^2(2r/R_0)$
$\langle n \rangle \sim 1/r$
$P \sim 1/r^{5/3}$

“Hard Core” Z-Pinch

$\delta V \sim r^2$
$\langle n \rangle \sim 1/r^2$
$P \sim 1/r^{10/3}$

Dipole
(e.g. CTX, LDX, RT-1)

$\delta V \sim L^4$
$\langle n \rangle \sim 1/L^4$
$P \sim 1/L^{20/3}$



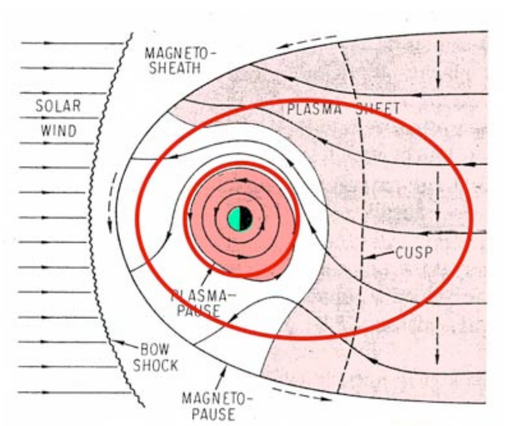
Five Fundamental Questions

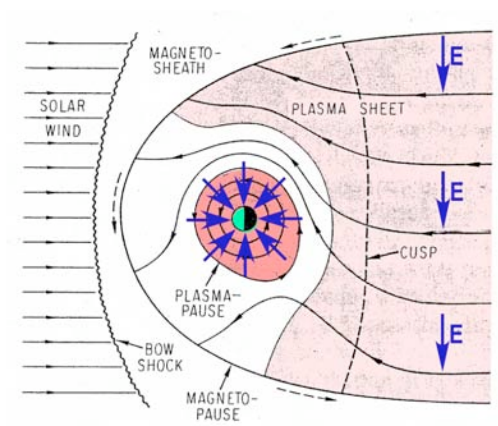
- Does turbulent mixing create isentropic profiles?
- Can particle and energy confinement be decoupled?
- Can interchange mixing be driven and controlled?
- What happens happens at the plasma edge?
- Can (high-field) inward convection be suppressed?

Magnetospheric Convection Drives Isentropic Profiles

- Large-scale fluctuations of geomagnetic cavity (*m* = 1) drive trapped particles to “stationary” profiles: $\partial F(\mu,J)/\partial\psi \rightarrow 0$
- High-beta “ring current” intensifies during geomagnetic storms
- Gold’s “fourth” adiabatic invariant: $\delta G = \delta(PV^\gamma) \sim 0$

Perturbed ψ Caused by Global Fluctuations of Geomagnetic Cavity (Easily Measured!)





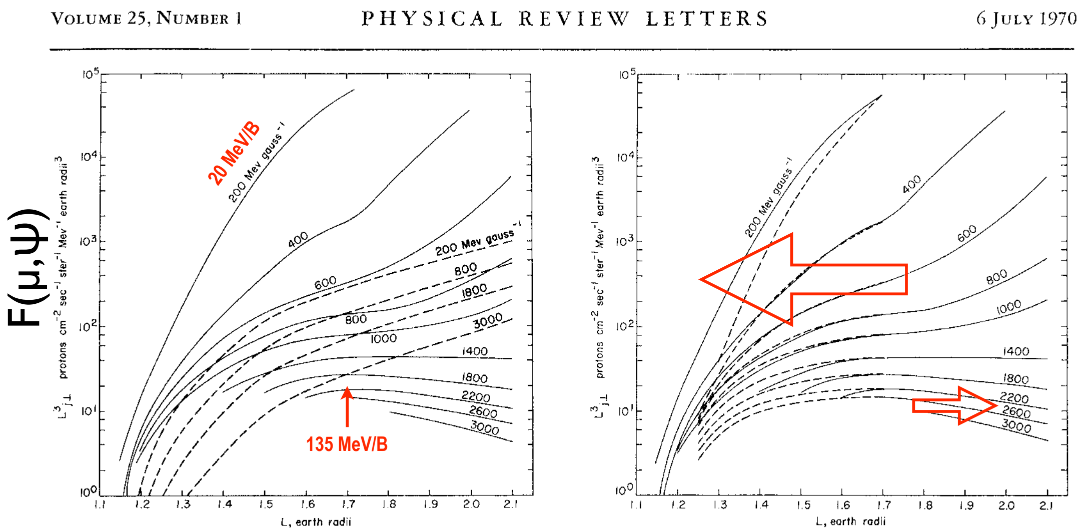
$$\delta A_\phi \sim \overbrace{\frac{L}{4}\left(\frac{R_e}{R_m}\right)^3}^{\text{Axisymmetric}} - \underbrace{\frac{4}{30}\frac{L^2}{R_e}\left(\frac{R_e}{R_m}\right)^4 \cos\phi}_{m=\pm1} + \dots$$

$$\delta\Phi \sim -\overbrace{E_c\left(\frac{R_e^2}{L}\right)}^{\text{Axisymmetric}} + \underbrace{E_c L \sin\phi}_{m=\pm1} + \dots$$

Nakada and Mead, *JGR* (1965) T. Birmingham, *JGR* (1969)

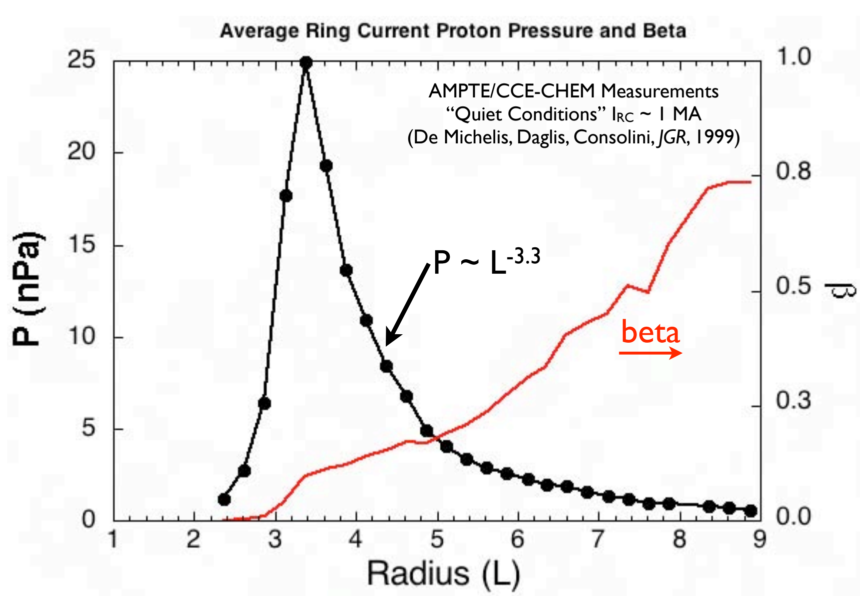
Quasilinear Radial Diffusion

(Farley, Tomassian, Walt)



No Diffusion With (Inward!) Diffusion

Centrally-Peaked Proton Pressure (Even with Plasma Sheet, Outer-Edge, Source!)



Fusion Energy Applications

- Better understanding of turbulent transport, interchange mixing, SOL dynamics, …

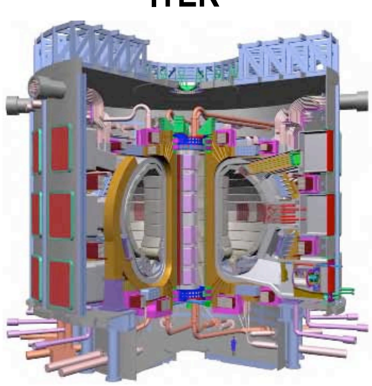
  The dipole configuration provides an easy-to-diagnose plasma to study: core turbulence, profile consistency, edge turbulence, fluctuation control, …

- If the dipole can successfully de-couple particle and energy confinement (a result of global-scale isentropic convection), then fusion using advanced fuels may be possible!
  [Kesner, J., et al., *Nuclear Fusion*, **44** (2004) p. 193.]

  Advanced fuels do not require tritium breeding nor advanced fusion materials development.

Dipole Fusion Concept

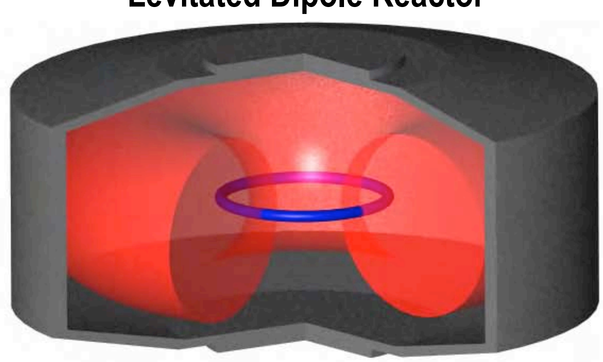
ITER



30 m

400-600 MW
DT Fusion

Levitated Dipole Reactor



60 m

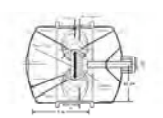
500 MW
DD(He3) Fusion

Kesner, et. al. Nucl. Fus. 2004

Natural and Driven Plasma Convection and Control in Dipole Plasmas

- Self-generated turbulence: Are turbulent processes and natural profiles isentropic?
- Flux-tube charging: Can global convection be driven from a biased edge?
- Magnetic field error: Do ambipolar losses due to field errors cause static convection cells?
- Weak toroidal magnetic field: Can a weak toroidal field suppress convection to floating coil?

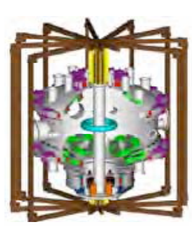
Significant Experience Achieved by World's Dipole Program

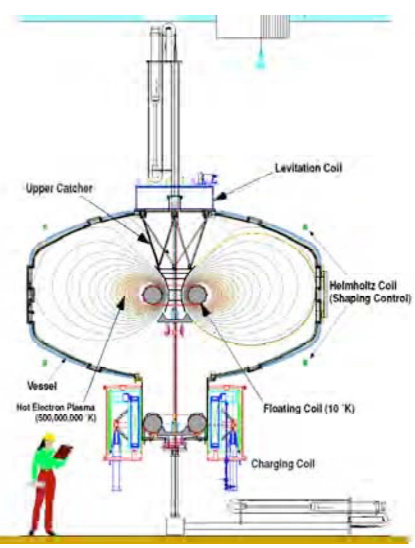


Investigate Instability- or Electrostatically-Driven Interchange Mixing

CTX (Columbia)

150 kA turns
(Not Levitated)
0.15 m



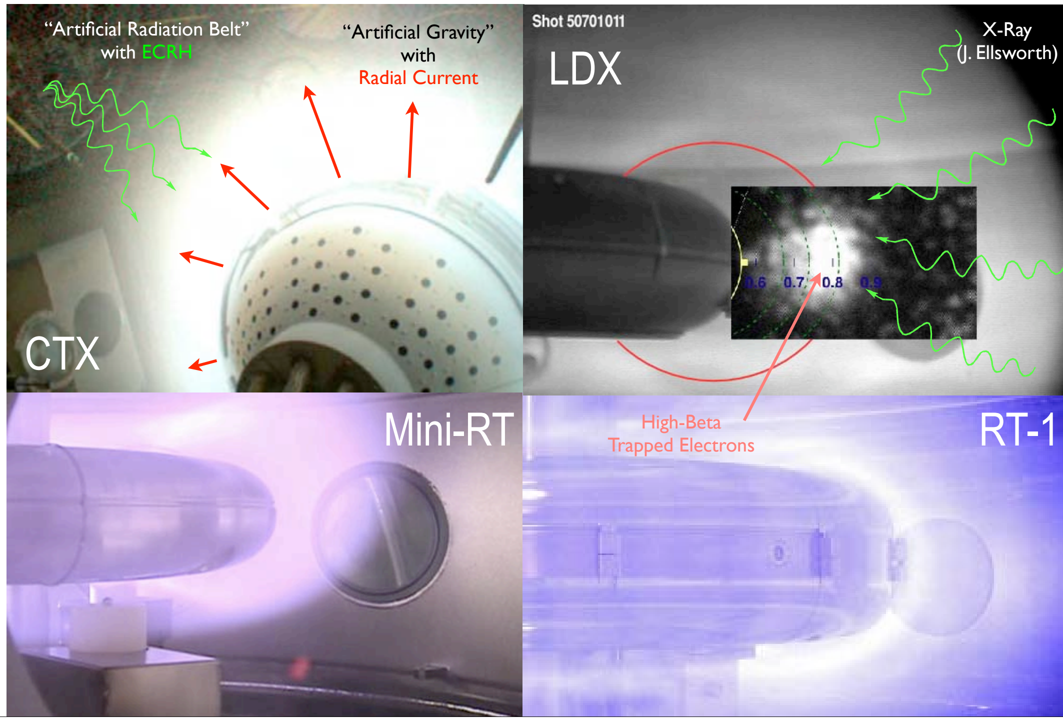


Mini-RT (Univ. Tokyo)	RT-1 (Univ. Tokyo)	LDX (Columbia-MIT)
50 kA turns	250 kA turns	1200 kA turns
17 kg	110 kg	565 kg
0.15 m	0.25 m	0.34 m

Test Beltrami Physics (Mini-RT, RT-1)

Test Fusion-Dipole Physics (LDX)

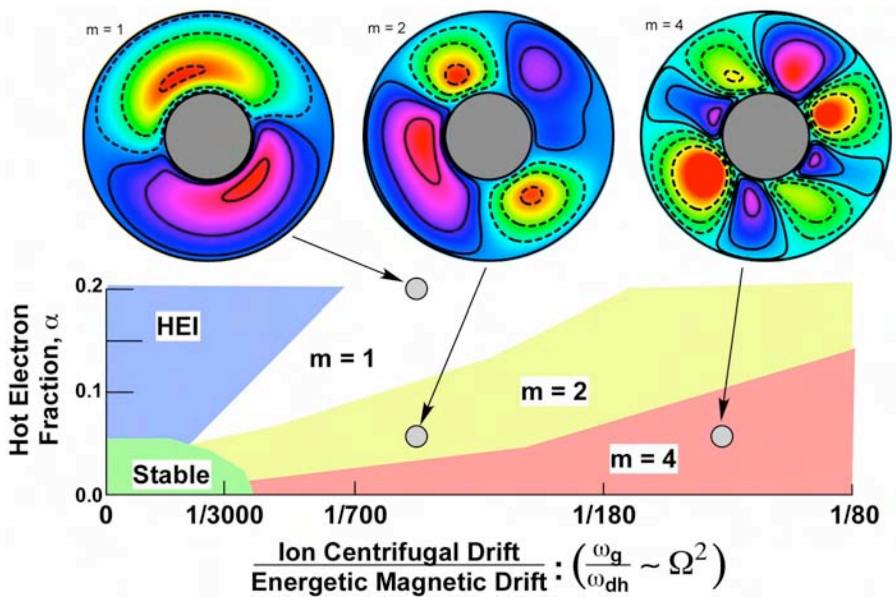
Dipole Plasmas Sustained by ECRH



CTX Observations Show Predominance of Global Interchange Mixing

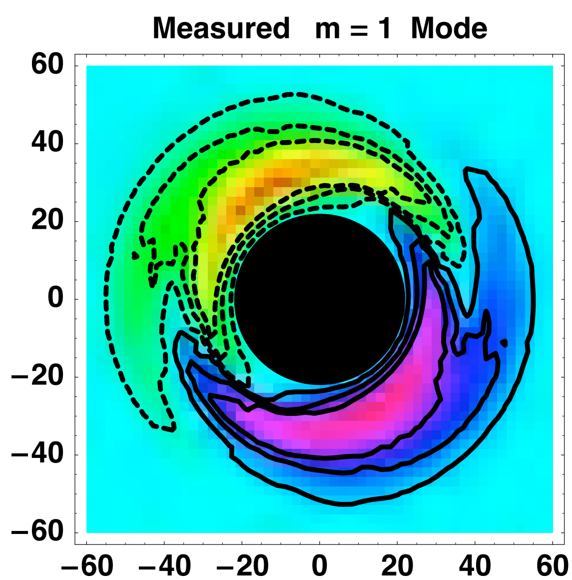
- Hot Electron Interchange (HEI) mode dominated by m = 1 global mode because gryokinetic effects impart a real frequency, proportional to hot electron ∇B drift.
- Centrifugal interchange (MHD) mode dominated by m = 1, except with near sonic flows and reduced energetic electron populations.

Relative Strength of Centrifugal and Curvature Drives Determine Nonlinear Mode Structure



Measured Centrifugal Mode Structure

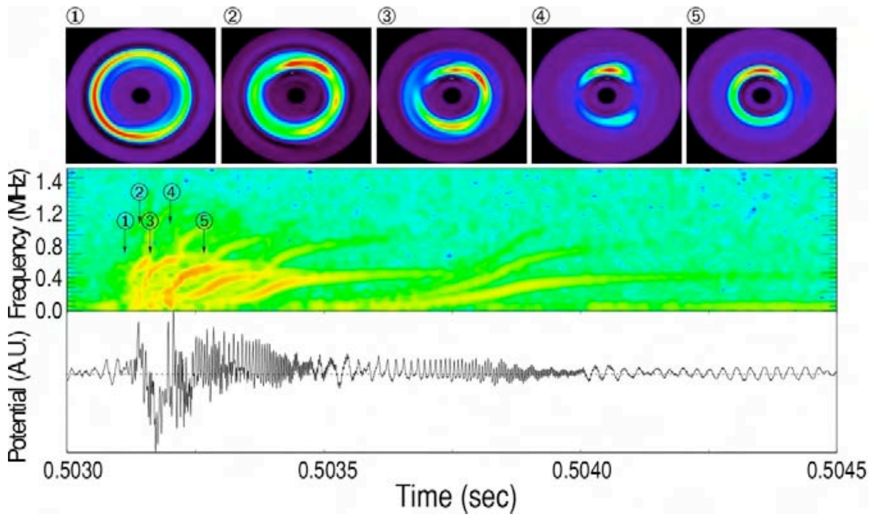
(A "Fixed Boundary" MHD Mode)



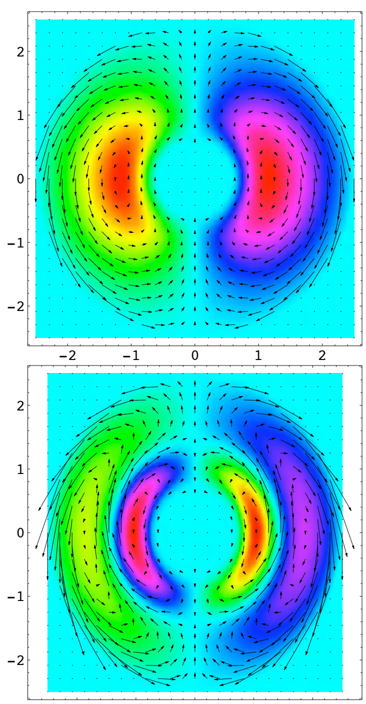
(ϕ ~ Stream function)

Measured Kinetic Interchange Mode: Structure of Driven Polar Losses

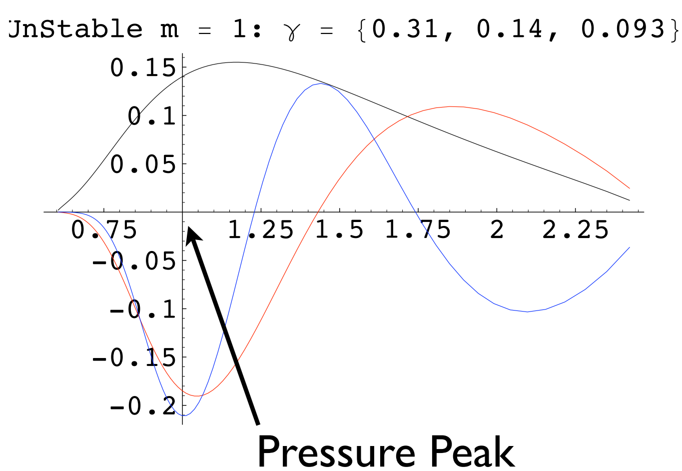
(A Kinetic MHD Mode)



Typical Ideal Interchange Eigenmodes



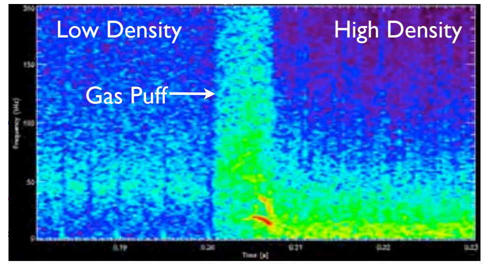
Unstable "LDX"

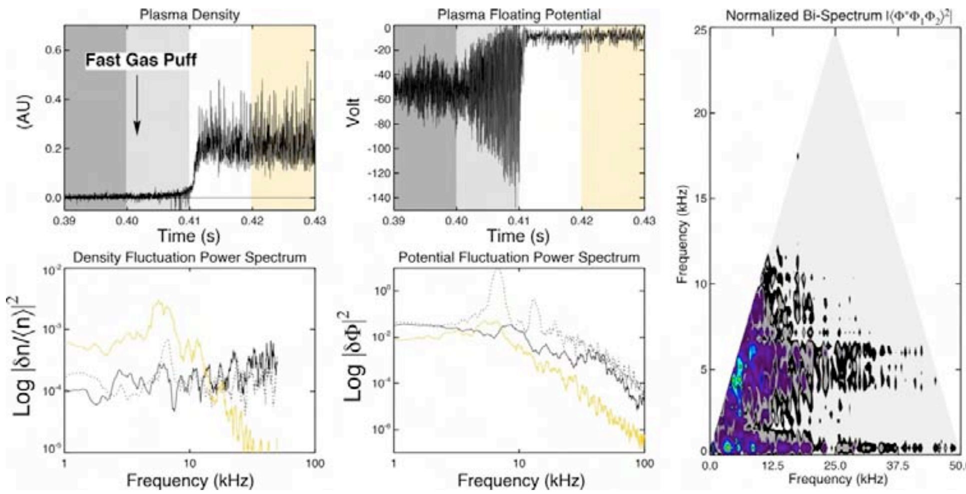


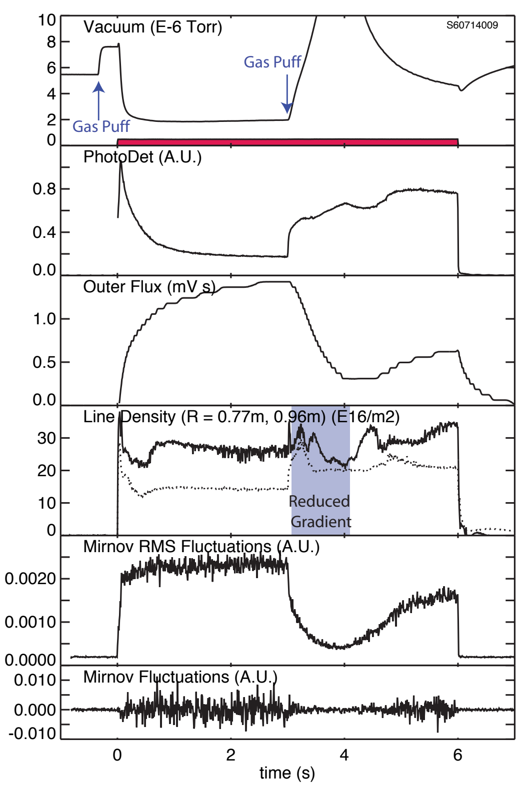
(Radial structure variation always slows mode.)

Evolution of Spectrum with Gas Fueling Rate Change

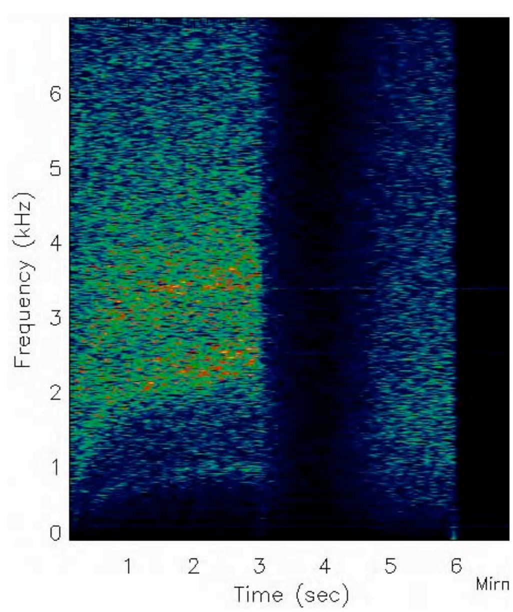
Brian Grierson
Matt Worstell







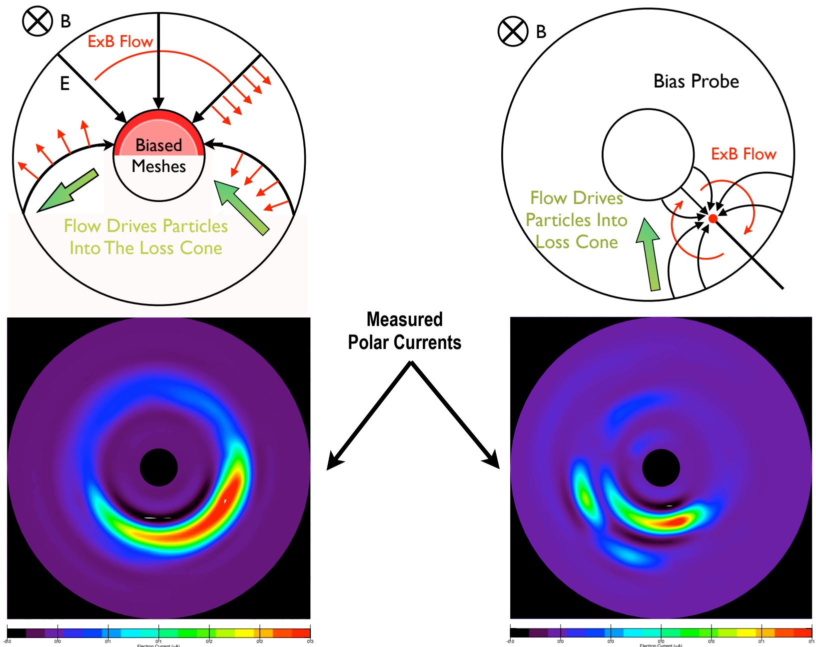
Coherent Fluctuations Suppressed with Flatter Gradient



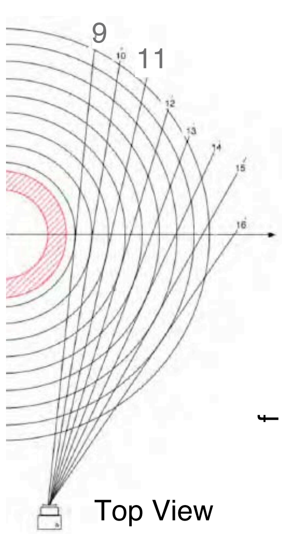
Driving Convection with Biased Electrodes (CTX)

(See Worstell PP8.00148 this session)

Inner Hemispherical Bias | **Movable Probe Bias**

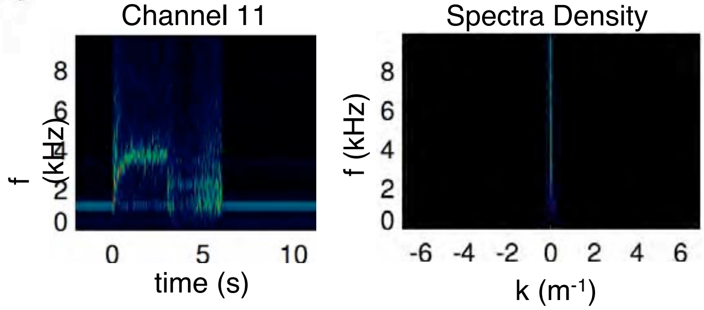


Detecting Convection and Density Fluctuations



- 16 Radial Chords
- All channels see LF mode
- $k_r = 0$ observed

Photodiode TFD Channel 11 | Two-point Estimated Spectra Density

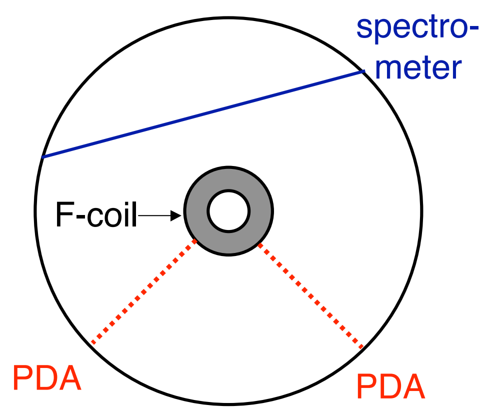


J. Ellsworth

Additional PhotoDiode Arrays

(Density Fluctuations and Impurity Convection rates)

- Two 16-channel arrays will be located 90° apart.
- Will give radial and toroidal mode #s for LF modes
- Can also be filtered to obtain density or temperature profile measurements.



Top View

J. Ellsworth

Field Errors

- Field errors can influence the charge balance on a flux tube.
- Field errors can create stationary potential structures.
- They might, *or might not*, be advantageous as a control tool for isentropic convective mixing.

Field Errors Can Create Significant Wander at Low-Field Edge

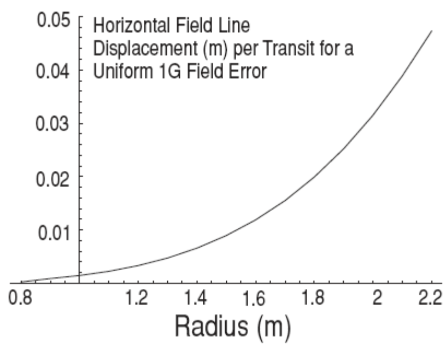


Figure 1: The magnitude of the field line step size estimated for a uniform field error of 1 G.

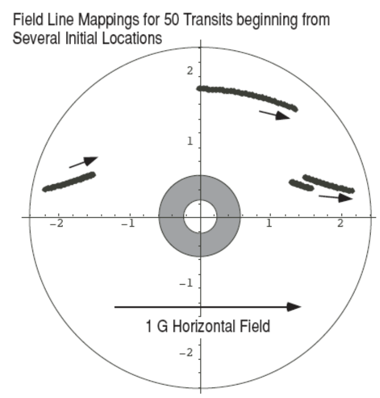


Figure 2: Field line trajectories for a uniform field error of 1 G. 50 transits through the floating coil are shown for each trajectory.

A horizontal field error may create a stationary *m* = 1 ambipolar potential structure.

Weak Toroidal Field May Suppress/Control Convection to Floating Coil

Three types of dipole-confined plasma with a toroidal field:

- Fully relaxed equilibria with a toroidal field produced by a central conductor (passing through the floating coil.) In this case, the structure of the poloidal field is independent of the current flowing in the axial conductor.
- Inductive equilibrium where poloidal currents are generated within the plasma due to time-changing current in the axial conductor. (This creates “ohmic heating”!)
- Equilibria sustained by localized current drive within the plasma. For example, if poloidal currents were driven on field lines near the floating coil, then a toroidal field would exist only within the region containing the floating coil. (*Isentropic mixing in outer region is unaffected!*)

Example LDX Equilibrium with B_t

Table 1: Plasma equilibria parameters.

F-Coil Current (MA-turns)	1.18
H-Coil Currents; $I_{h,up}$, $I_{up,dn}$ (kA)	0,0
C-Coil Current (A)	10
L-Coil Current (A)	104
Axial Current (kA)	50
B_0R_0 (T·m)	0.01
Plasma Poloidal Current (kA)	14.7
Plasma Toroidal Current (kA)	14.3
Plasma Volume (m^3)	14.3
Max Pressure (Pa)	2300
Stored Energy (J)	1270
$\langle\beta\rangle$	1.6
R(P_{max}) (m)	0.78
B(P_{max}) (T)	0.082
$\beta(P_{max})$	3.5

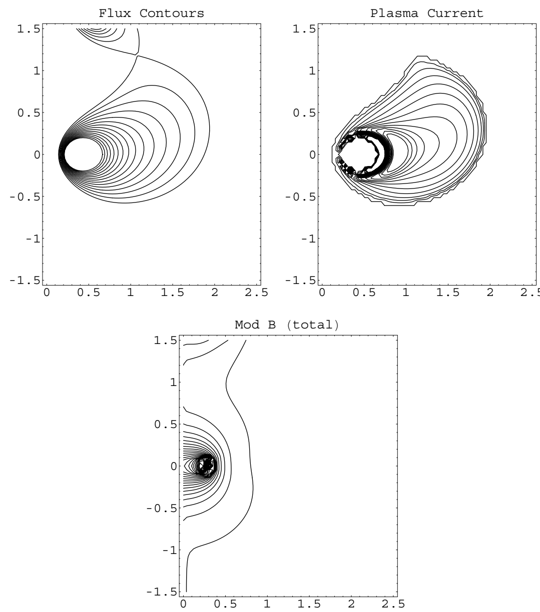


Figure 1: Contour plots of the poloidal flux, toroidal plasma current density, and total $|B|$ for a representative high $\langle\beta\rangle$ LDX equilibrium with 50 kA in a central conductor. (Other equilibrium calculated with the same plasma pressure but with different (weak) toroidal field strengths have essentially the same poloidal field structure.)

Equilibrium Profile Parameters with 50 kA of Axial Current

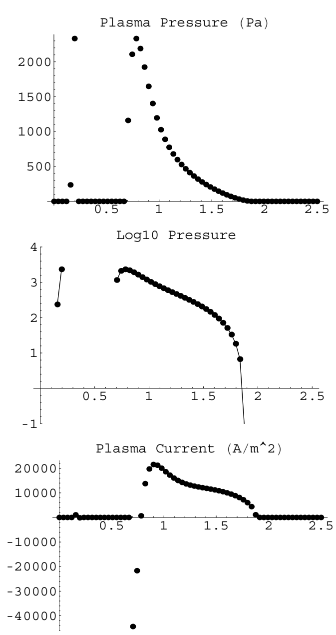
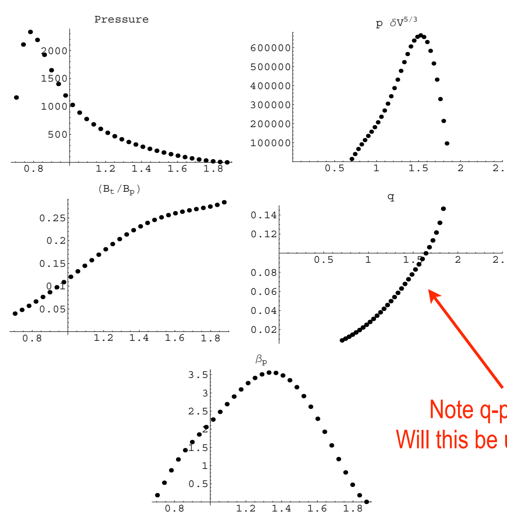


Figure 2: Radial profiles of the plasma pressure and plasma current density.



Note q-profile.
Will this be unstable?

Figure 3: Profiles of plasma parameters along the outer equatorial plane. Notice that the outer edge of the plasma is MHD unstable and that q increases rapidly at the edge even though the local ratio of the toroidal to poloidal fields, B_t/B_p, also increases.

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