Electrostatic Interchange Instabilities of a Rotating, High-Temperature Plasma Confined by a Dipole Magnet: Experiment and Theory

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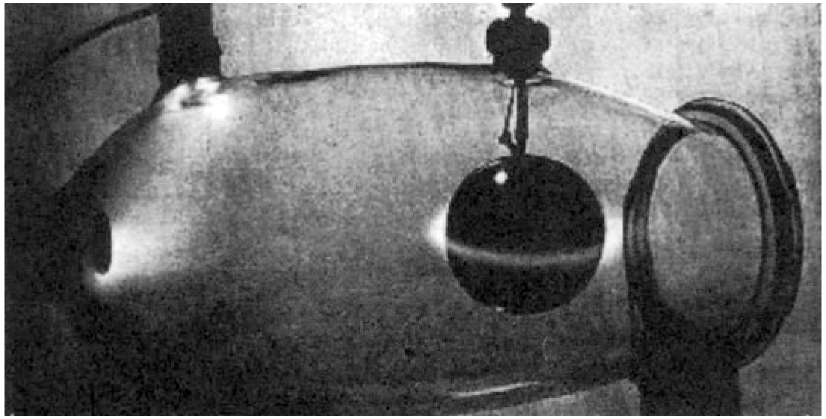
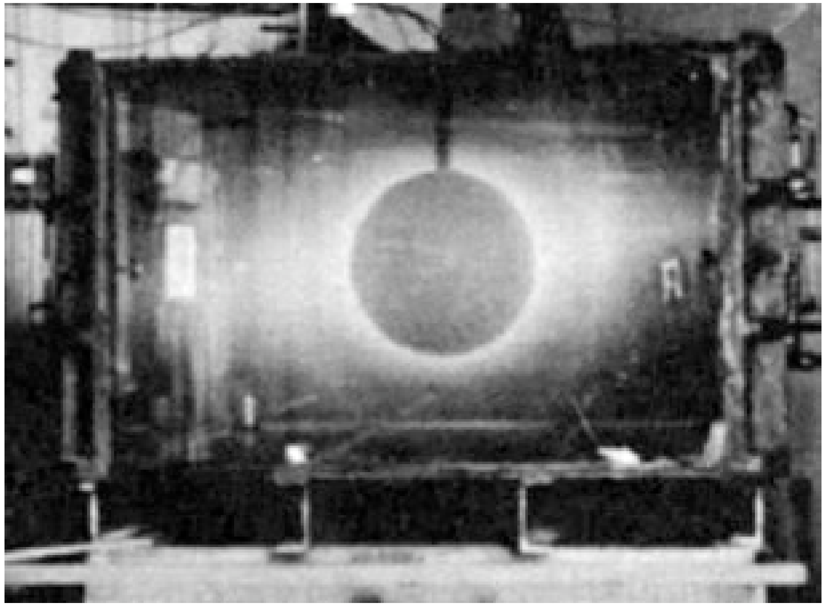
http://www.phys.uit.no/IPELS05/

- Motivation for the study of dipole-confined plasma:
  - Interrelationship between laboratory and space plasma
  - Large ∇B leads to big profile effects from adiabatic mixing of magnetized plasma ("electrostatic self-organization")
  - Large plasma; tiny magnet $\Rightarrow$ easy access and measurement
- (Discovery) Dipole interchange instabilities are large-sized/global…
  - **Fast** hot electron interchange instability: drift-resonant transport; *Gryokinetics*; phase-space holes; …
  - **Slow** centrifugal interchange instability in a rotating plasma: convective mass flow; *MHD*; profile modification (?); …

Acknowledgments

- Kristian Birkeland (1887-1913), the world's first laboratory plasma physicist
- [*Not* related to "mini-magneto-sphere" like L. Danielsson and L. Linberg (1963-65)]
- Bo Lehnert and Torbjörn Hellsten (1959-1980), "spherator", "average maximum B", and plasma rotation





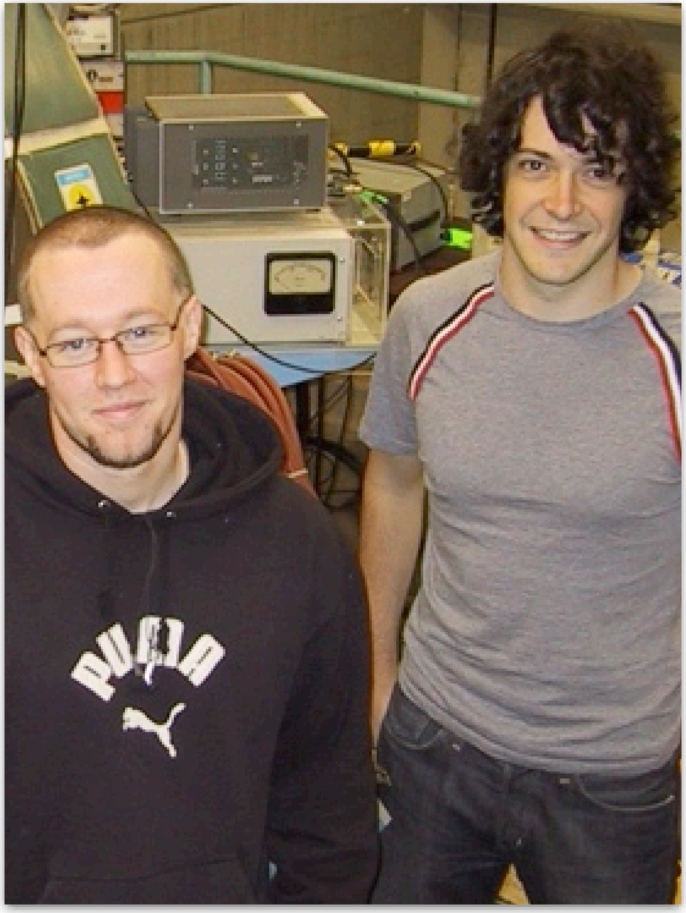
Acknowledgments

- Harry Warren (NRL) for discovery of the HEI in a dipole and understanding chaotic drift-resonant radial transport.

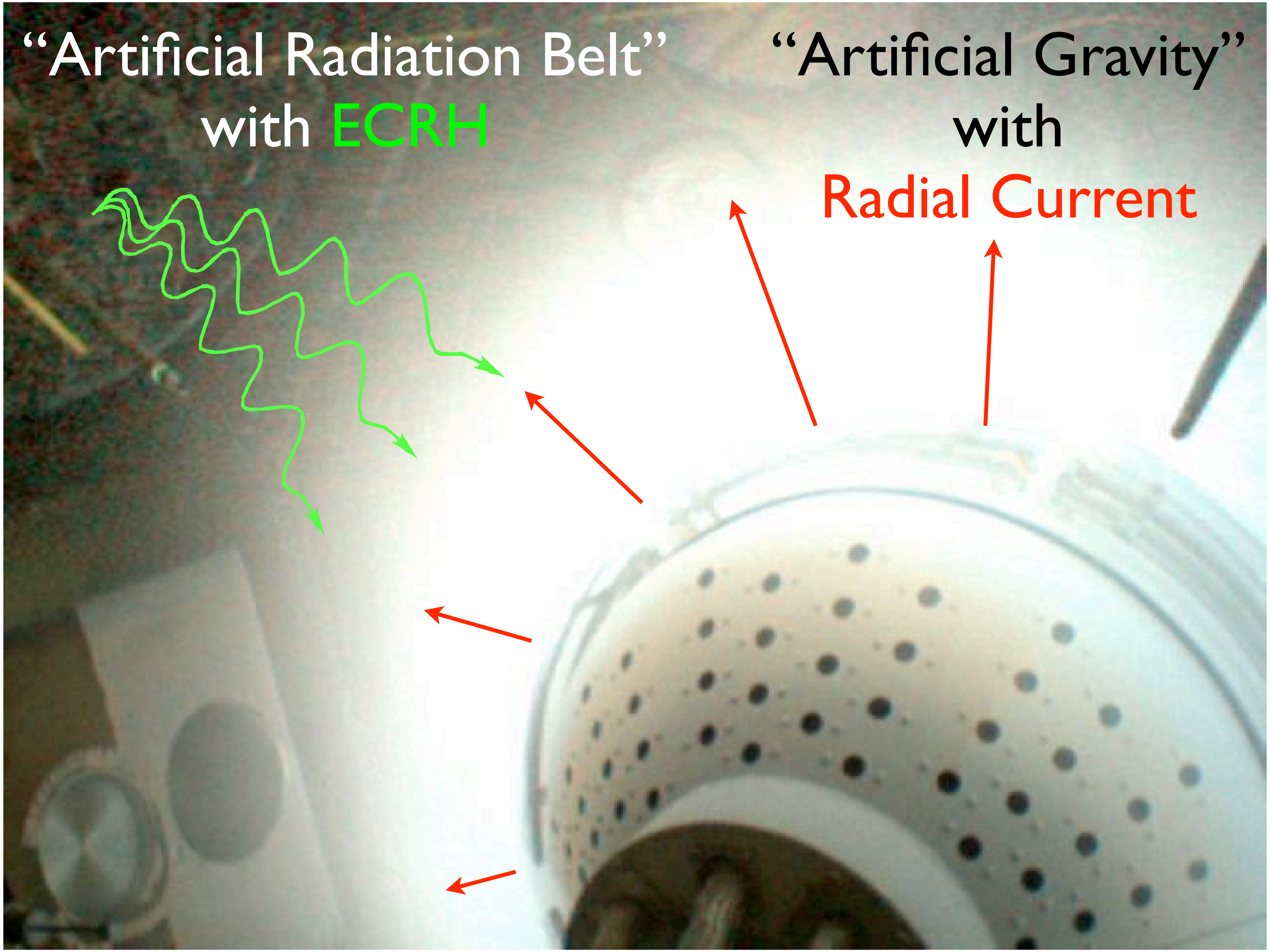
- Dmitry Maslovsky (Columbia) for demonstrating the existence of "phase-space holes" during frequency-sweeping.

- Ben Levitt (Harvard) for observing the global structure of interchange modes and creating the centrifugal interchange mode.

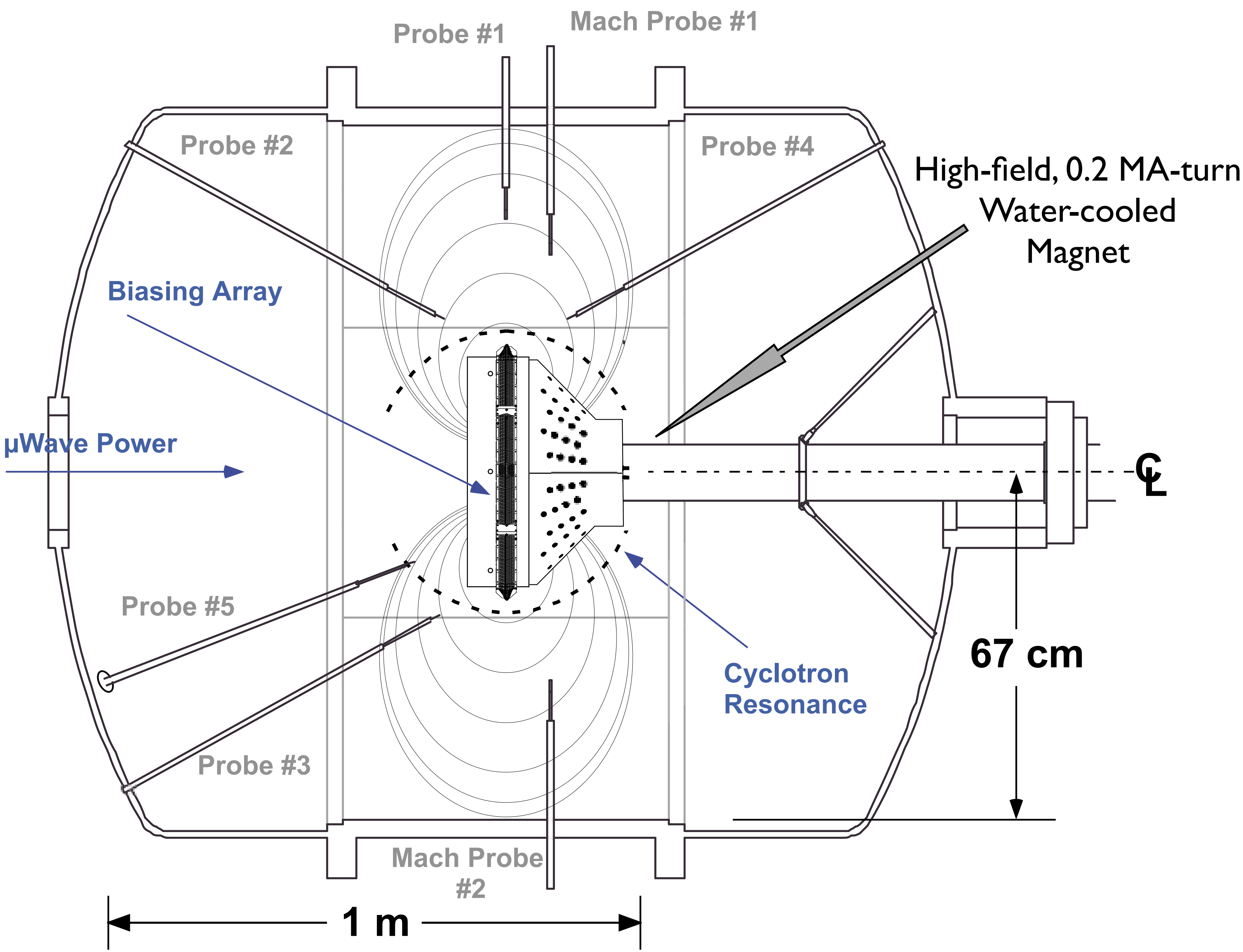
- Newest students: Brian Grierson and Matt Worstell (right) now driving, probing and understanding convective flows/transport.



CTX Plasma Torus



Collisionless Terrella Experiment (CTX)

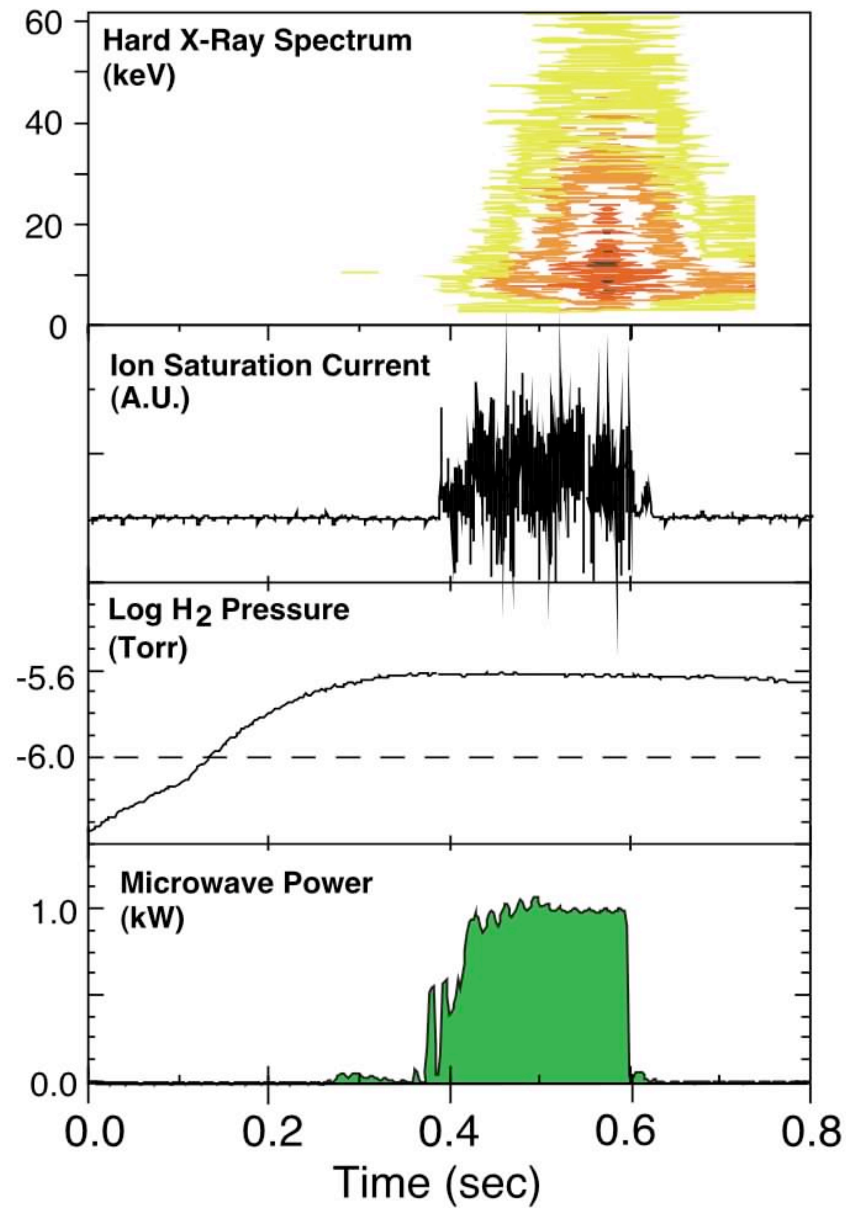


Interchange Modes

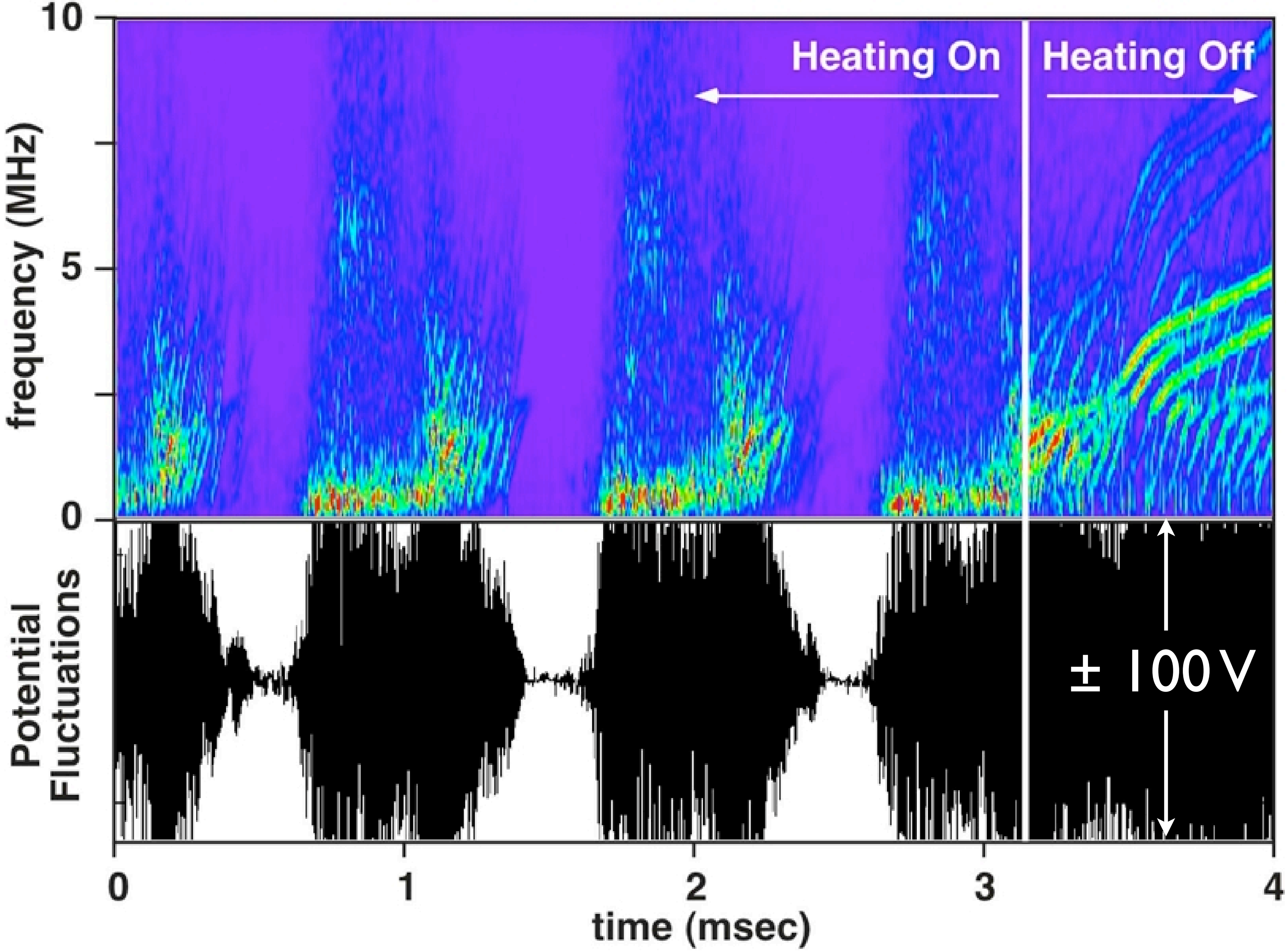
- Artificial Radiation Belt
  - "Fast" gyrokinetic interchange
  - $\gamma_h \sim \sqrt{\omega_{ci}\omega_{dh}\alpha}$, $\omega_{dh}/2\pi$ ~ 0.1 - 1.0 MHz
- Artificial Gravity
  - "Slow" centrifugal interchange
  - $\gamma_g \sim \sqrt{\omega_{ci}\omega_g}$, $\omega_g/2\pi$ ~ 0.2 - 1.0 kHz

Creating an "Artificial Radiation Belt"

- Low-pressure microwave discharge in hydrogen (2.45 GHz, 1 kW)
- Energetic electrons (5 – 40 keV) produced at fundamental cyclotron resonance: an "artificial radiation belt"
- Electrons are strongly magnetized ($\rho/L \ll 1$) and "collisionless". Equatorial drift time ~ 1 μs.
- Intense fluctuations appear when gas pressure is adjusted to maximize electron pressure



Hot Electron (Fast) Interchange Instability



Creating "Artificial Gravity" through Rapid Plasma Rotation

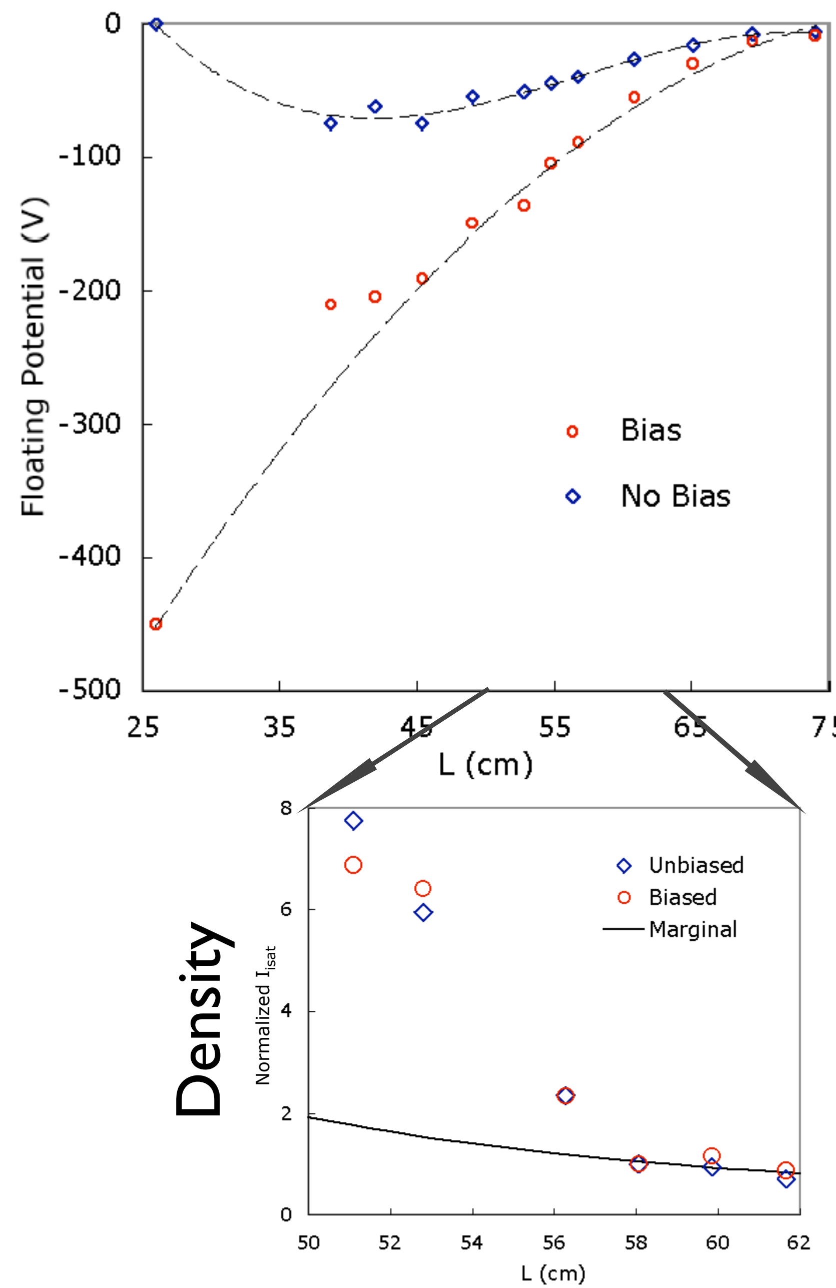
- Floating potential scales with radius as $\Phi \sim R^{-2}$ (negative bias)

- Corresponds to **rigid rotation** in a dipole, $\omega_e/2\pi$ = 18 kHz

- Potential profile consistent with radial current proportional to the field-line integrated Pedersen (ion-neutral) conductivity:

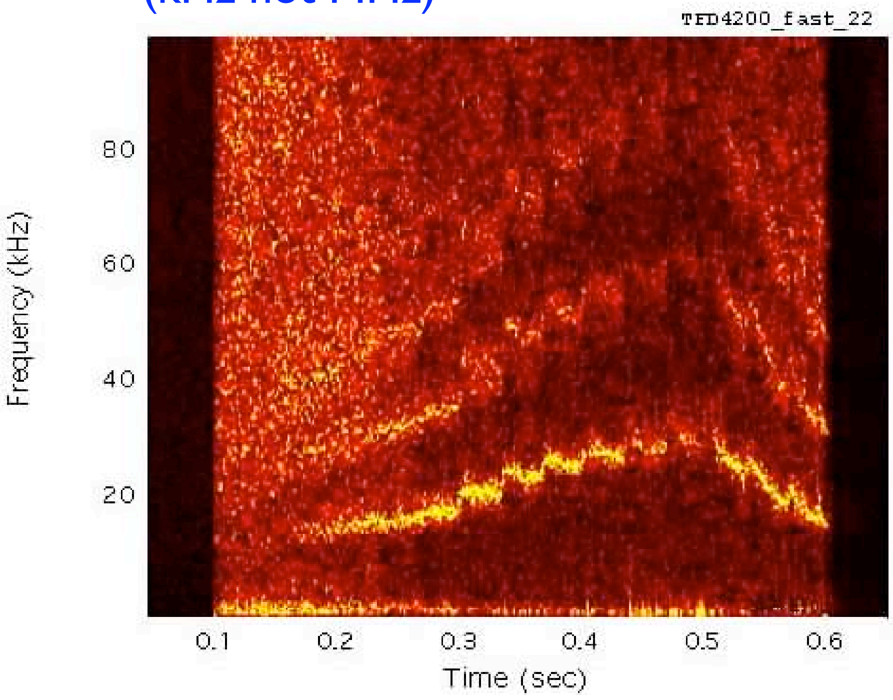
$$I \approx 8\pi\, M\, \omega_e(R)\, \Sigma_p(R)$$

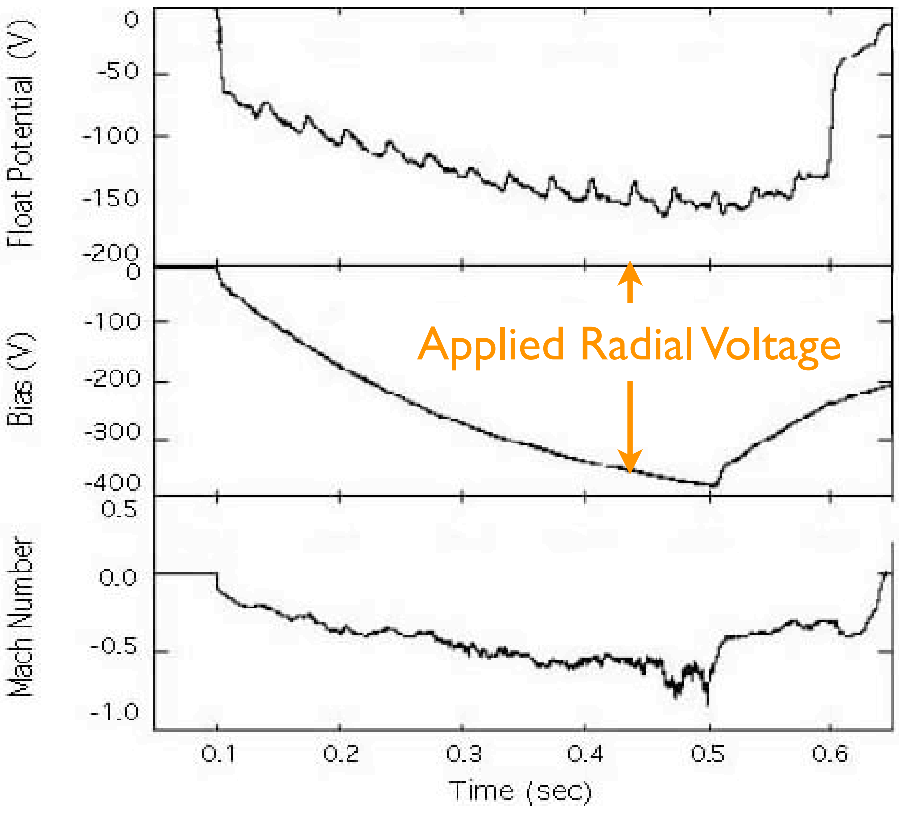
- $\Sigma_p(R)$ is constant if density profile, $n \sim R^{-6}$, **exceeds** centrifugal instability threshold.



Centrifugal (Slow) Interchange Excited by Rapid Plasma Rotation

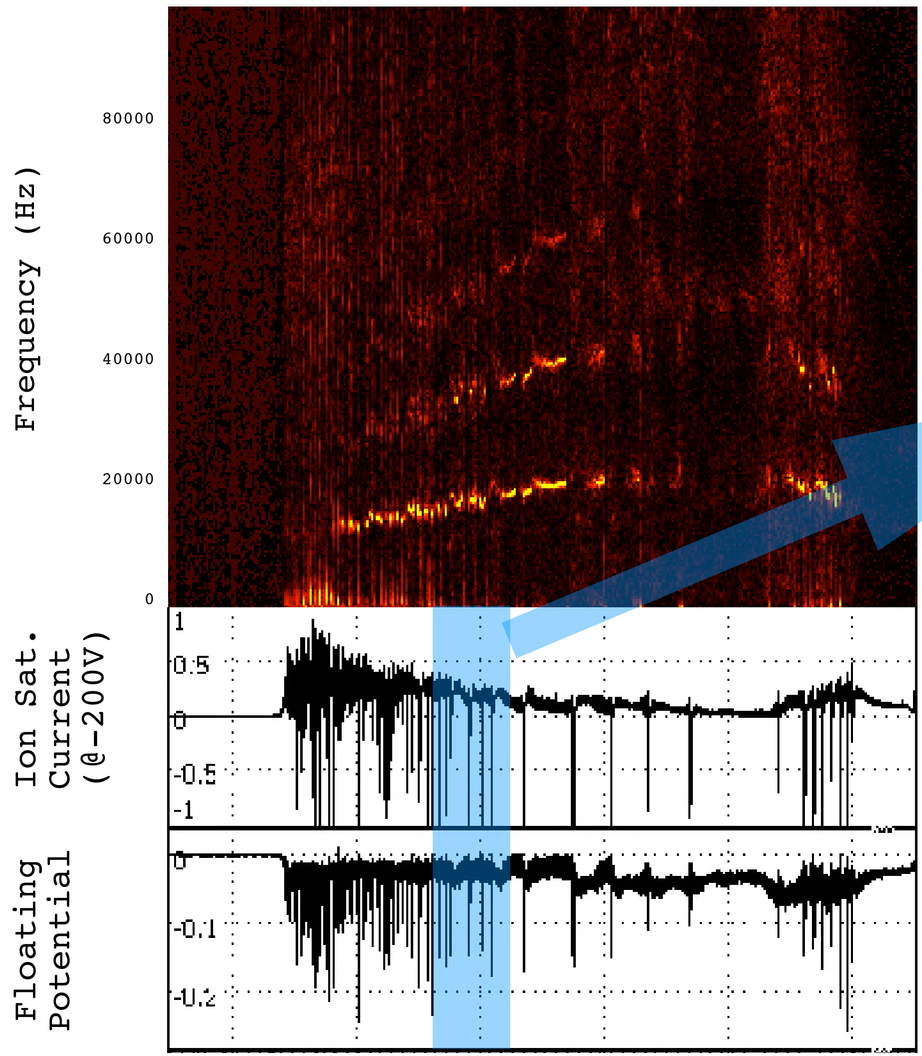
(kHz not MHz)



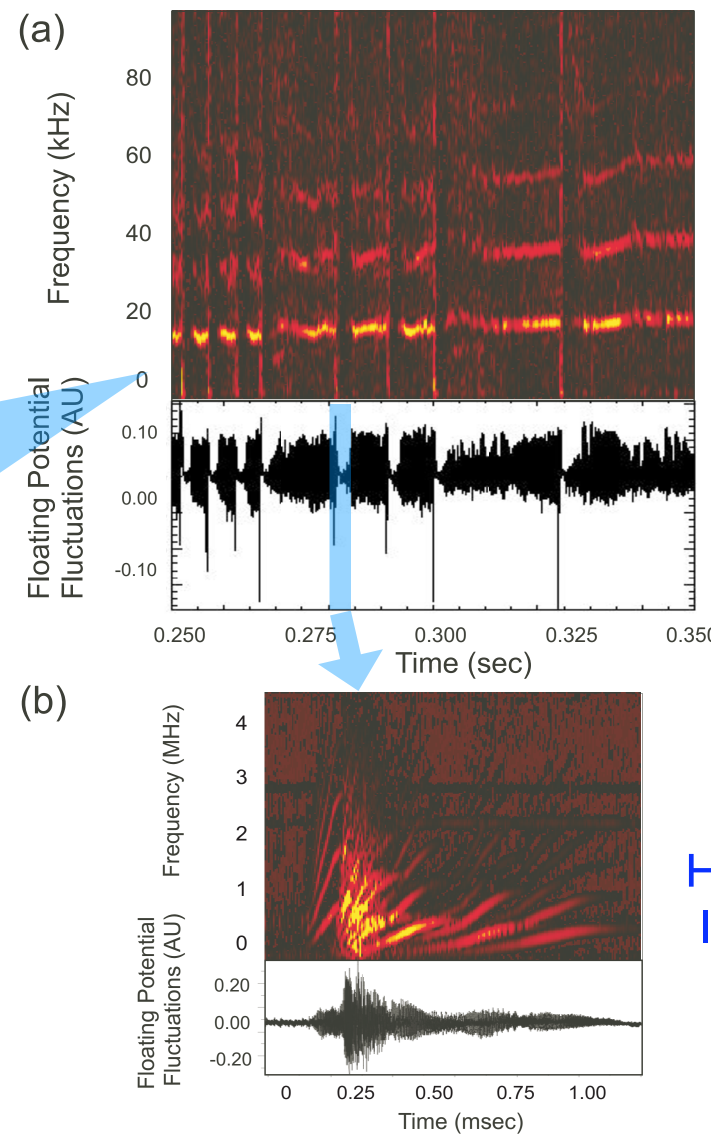


(Seconds not msec)

At Lower Density, Centrifugal Instability Modulated by Hot Electron Interchange Bursts

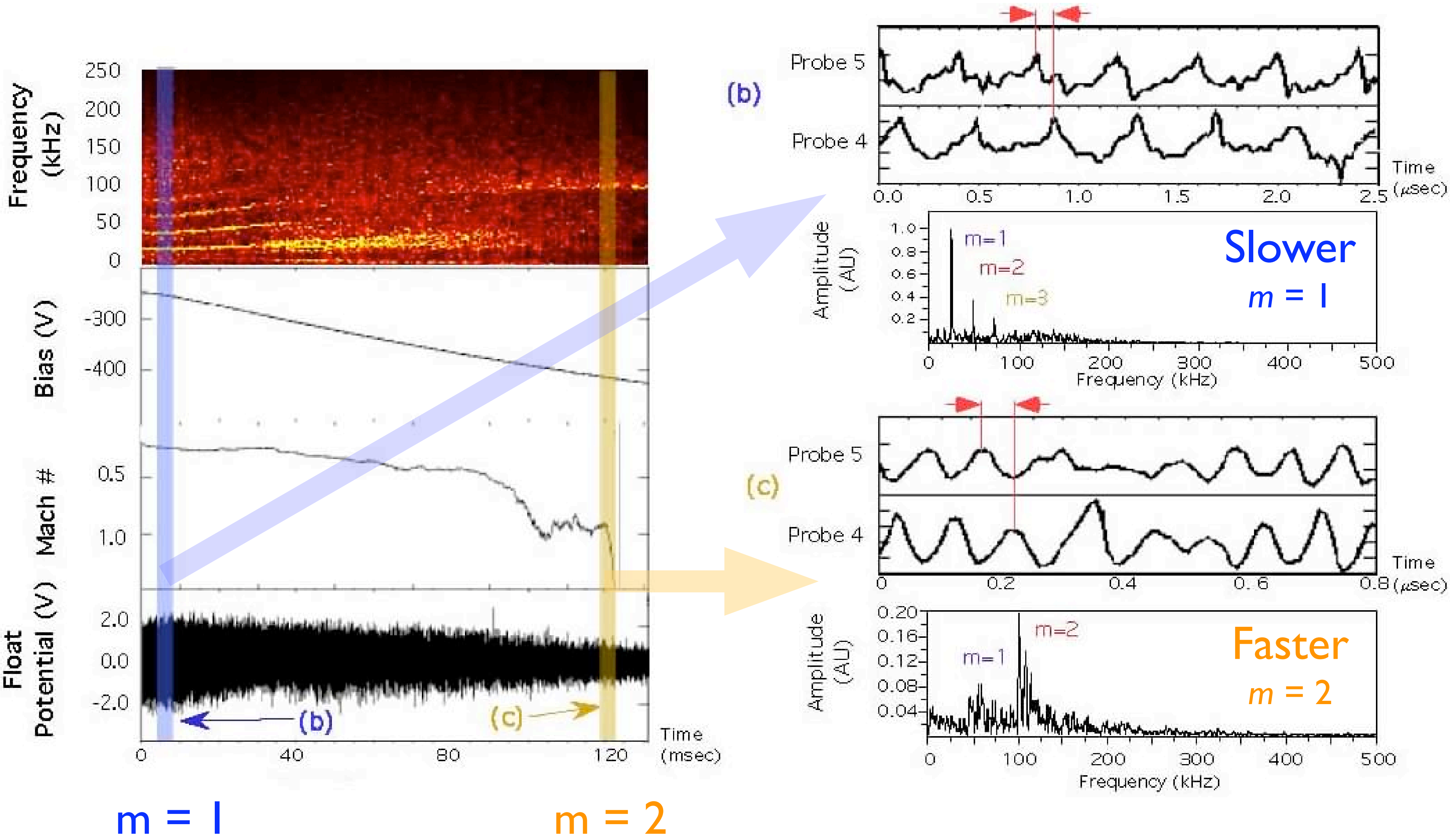


Outward Bursts of Energetic Electrons

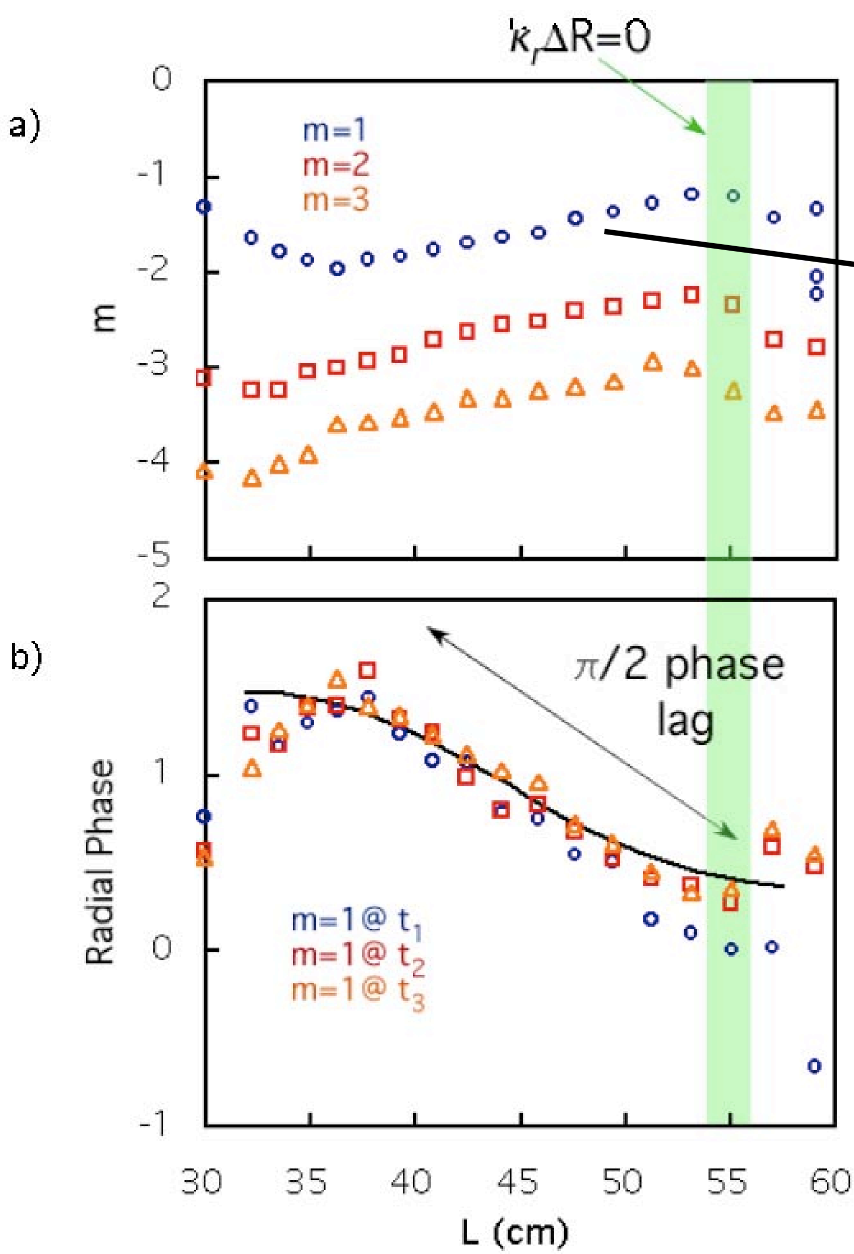


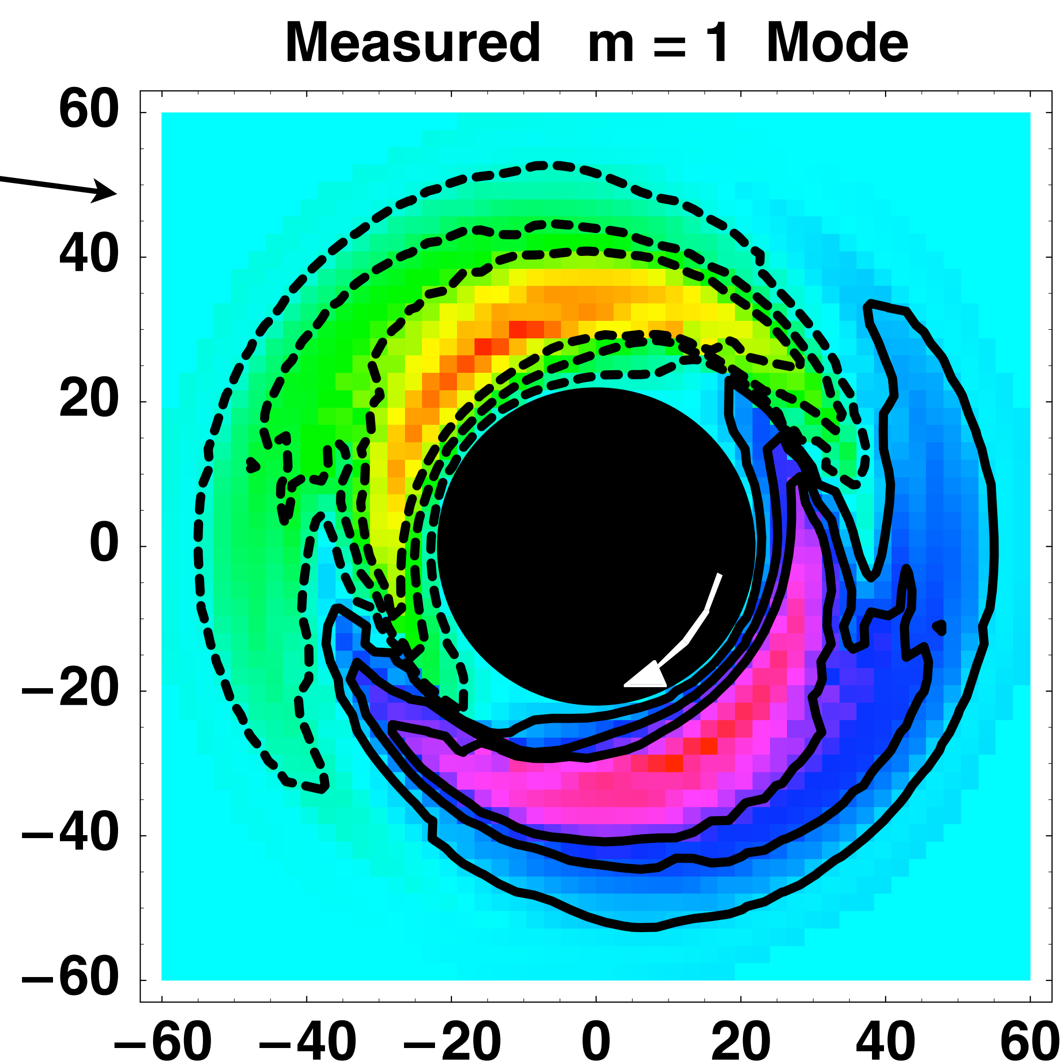
Close-up: Hot Electron Interchange

Reduced B: Faster Rotation & Fewer Hot Electrons Excites *m* = 2 Dominated Mode Structure



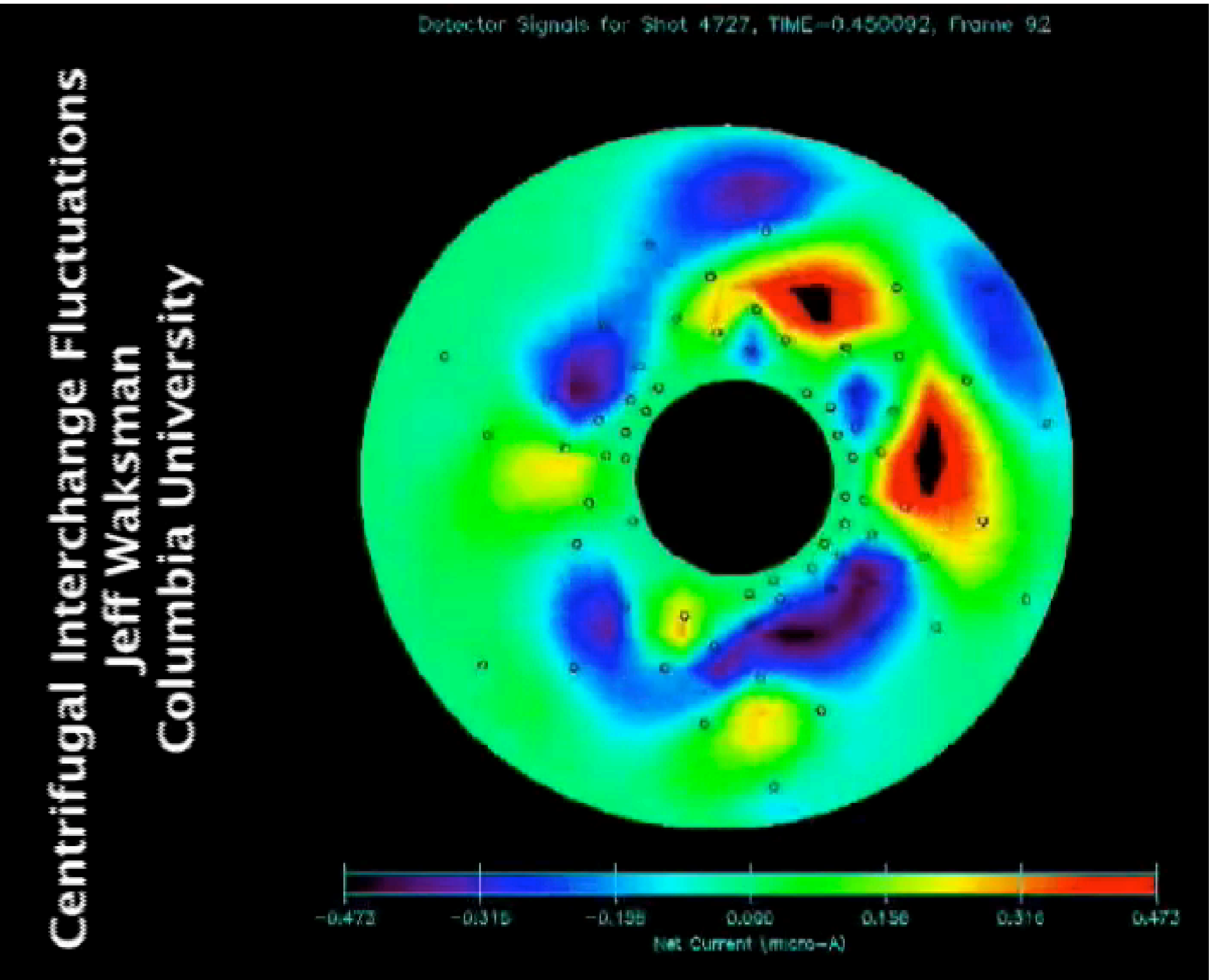
Phase Measurements Show "Spiral" Mode Structure of Centrifugal Mode

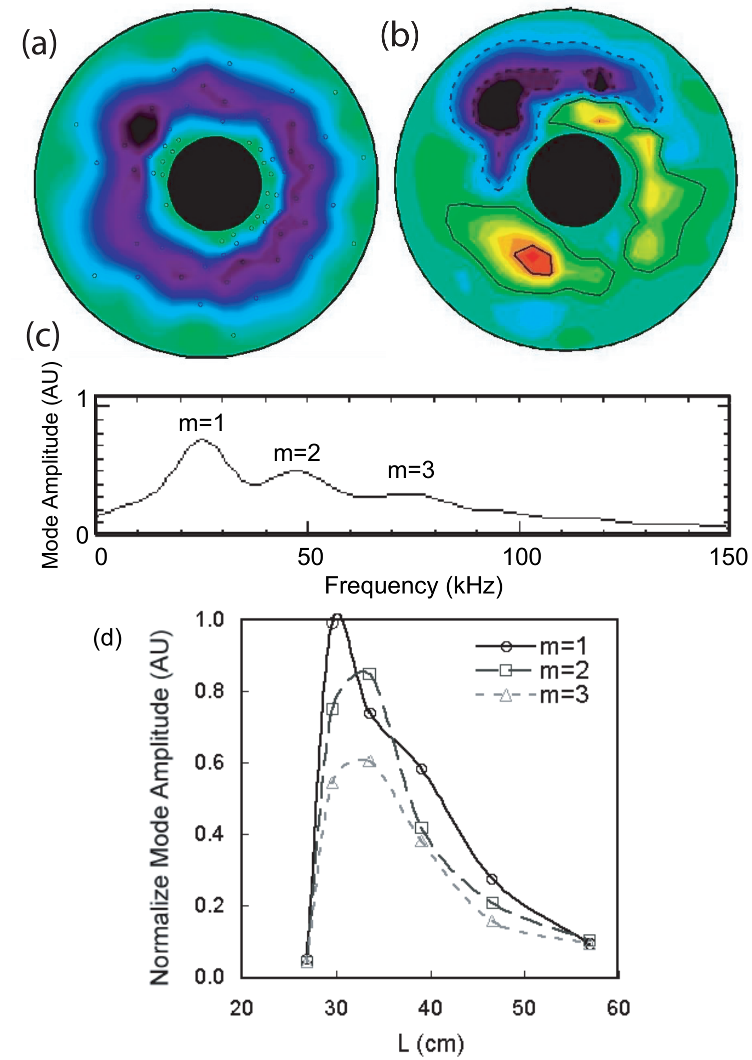




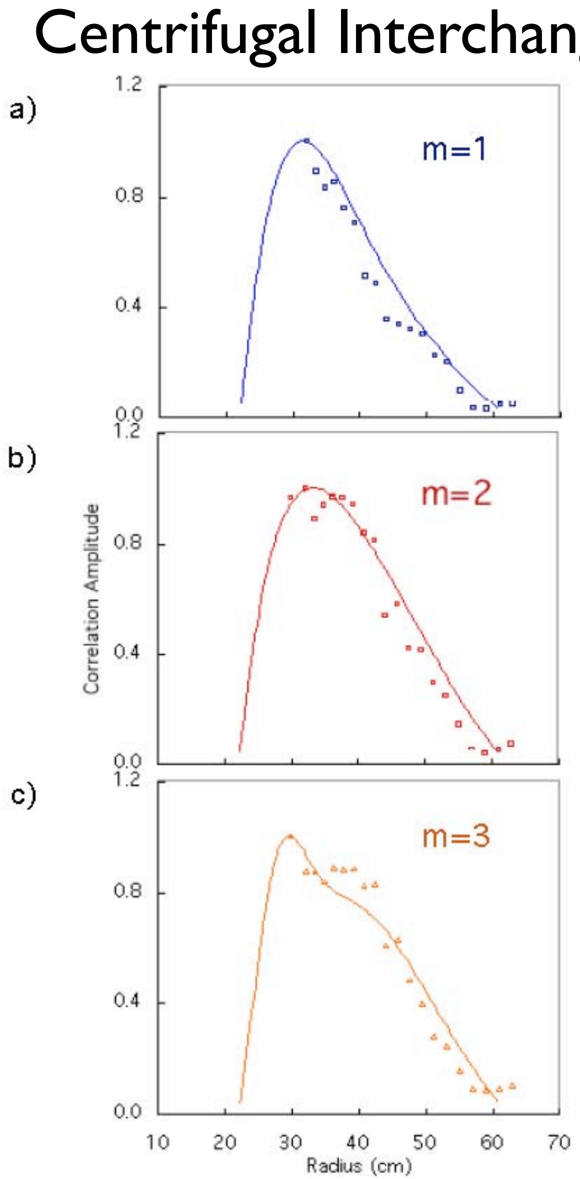
(ϕ ~ Stream function)

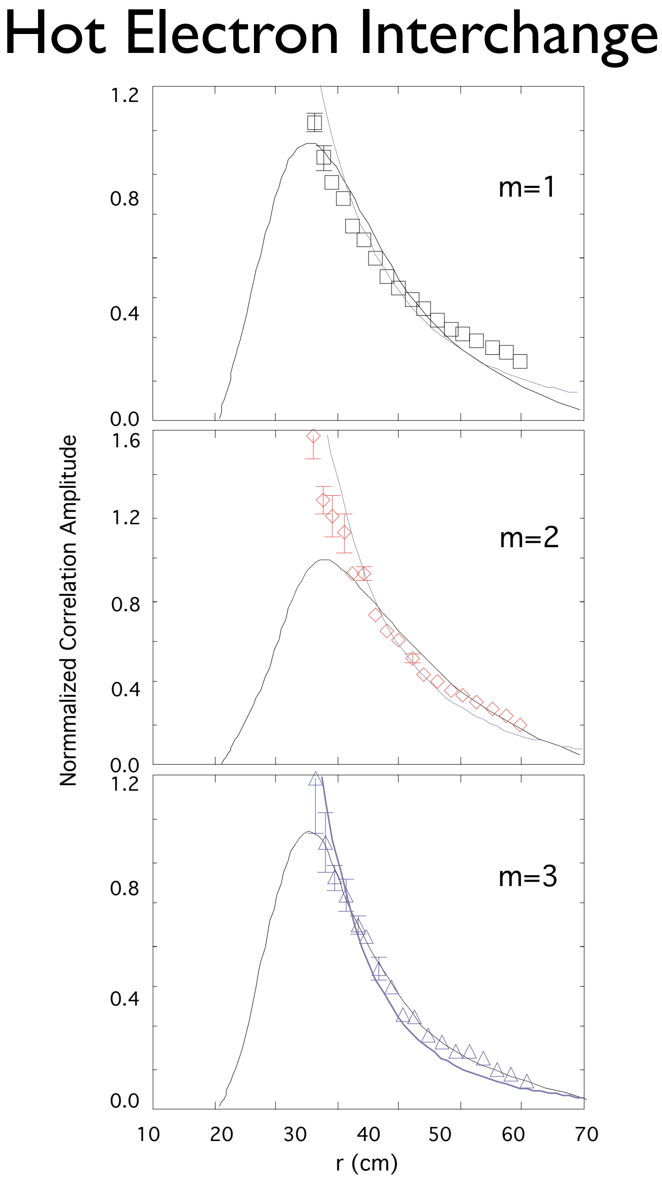
Polar Current Fluctuations also show **Broad** Radial Mode Structure





Dipole Interchange Modes have **Broad** Radial Structures



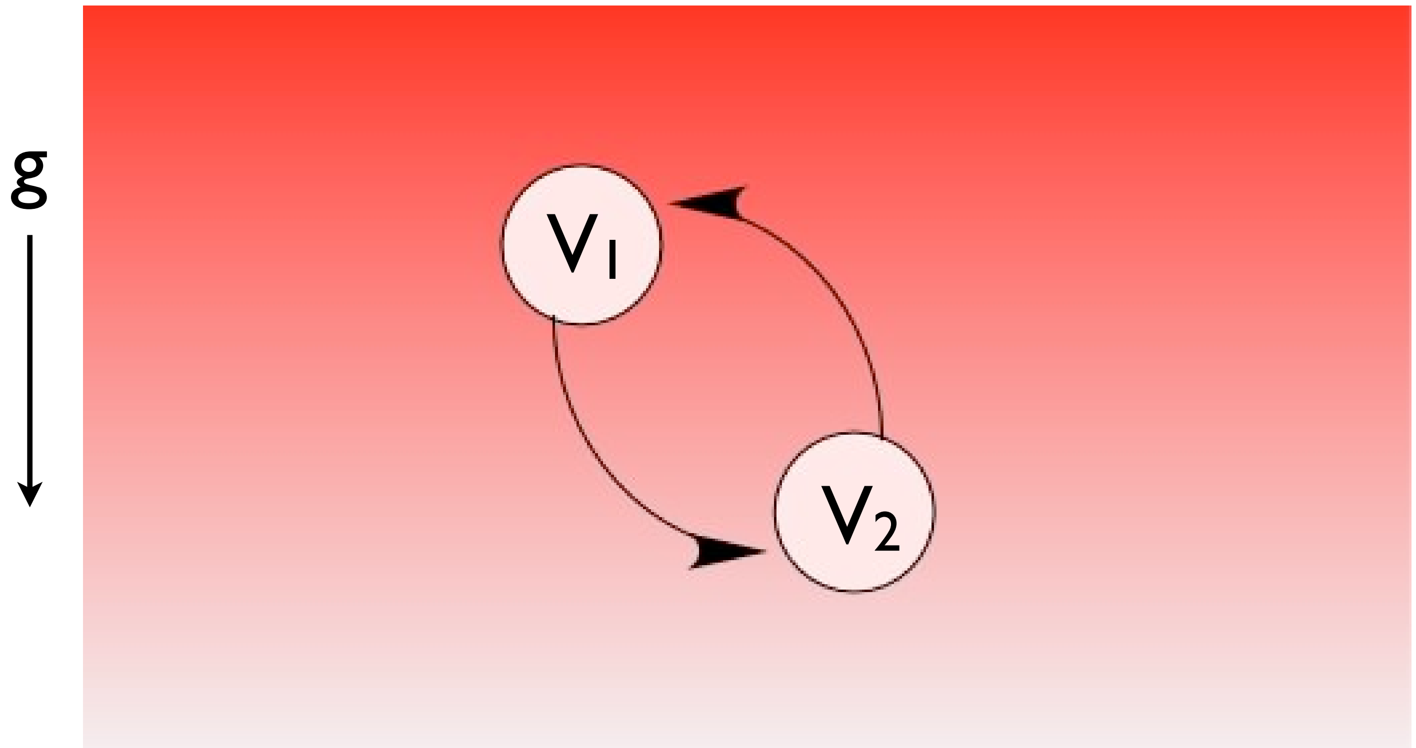


(2D Poisson's Equation: Computed mode structure shown with solid lines.)

Modeling Interchange

- ✓ Interchange mode structure (relatively easy)
- ✓ Adiabatic nonlinear dynamics
- Transport, dissipation, confinement (not easy)

Example 1:
Straight Uniform Magnetic Field
(like the Ionosphere)



B = Constant

$\therefore V_1 = V_2$

Unstable if $\delta(nV) > 0$.
Adiabatic mixing preserves particles and entropy.

Example 1:
Straight Uniform Magnetic Field
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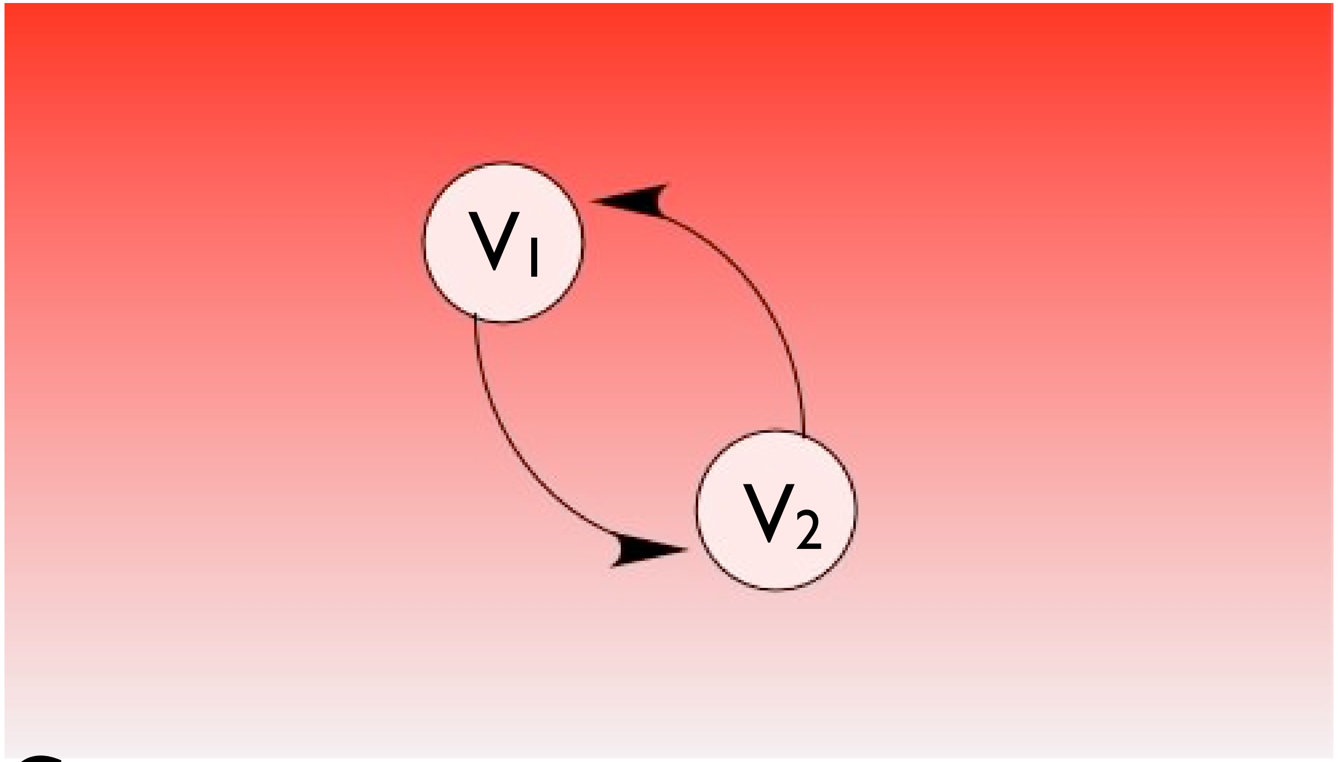
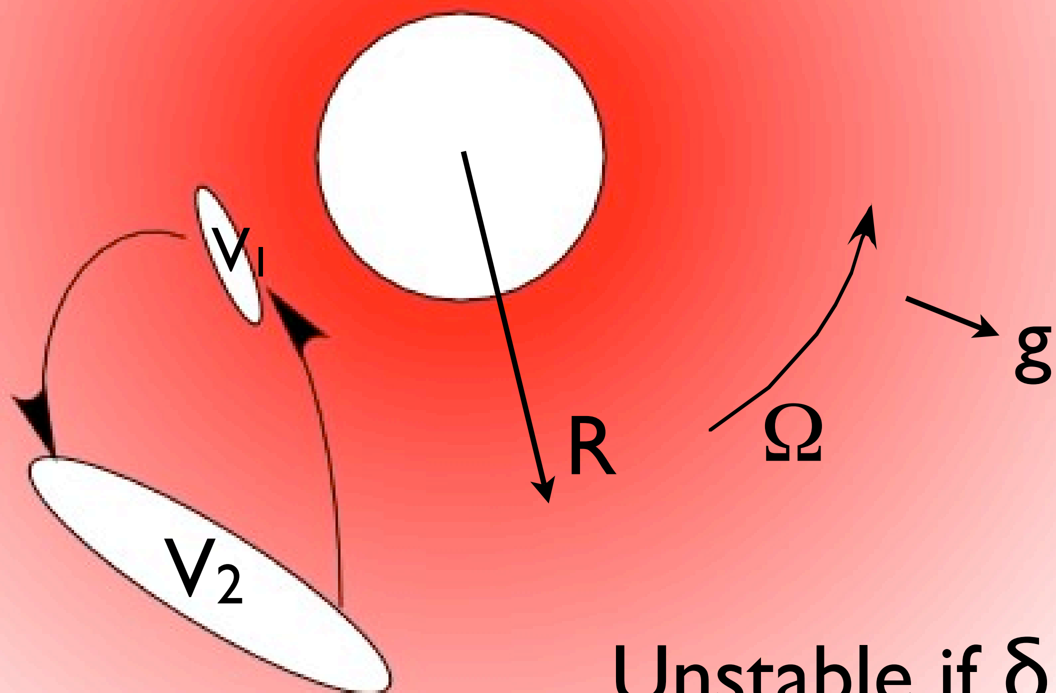


B = Constant
$\therefore V_1 = V_2$

After dissipation/diffusion
$\delta(nV) \sim 0 \Rightarrow \nabla n \sim 0$ (+ heating)

Example 2:
Curved Non-Uniform Magnetic Field

(like the Magnetosphere)



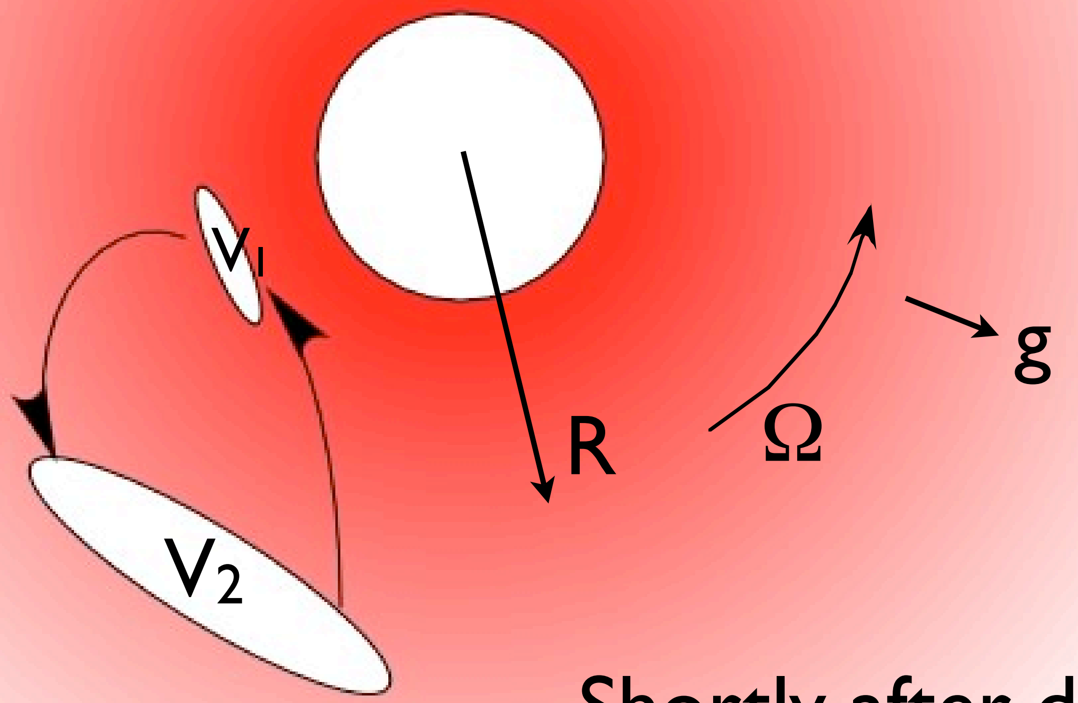
$B \propto R^{-3}$

$\therefore V_1 \neq V_2$

Unstable if $\delta(nV) > 0$ or $\delta(pV^{\gamma}) > 0$.
Adiabatic mixing preserves particles and entropy.

Example 2:
Curved Non-Uniform Magnetic Field

(like the Magnetosphere)



$B \propto R^{-3}$

$\therefore V_1 \neq V_2$

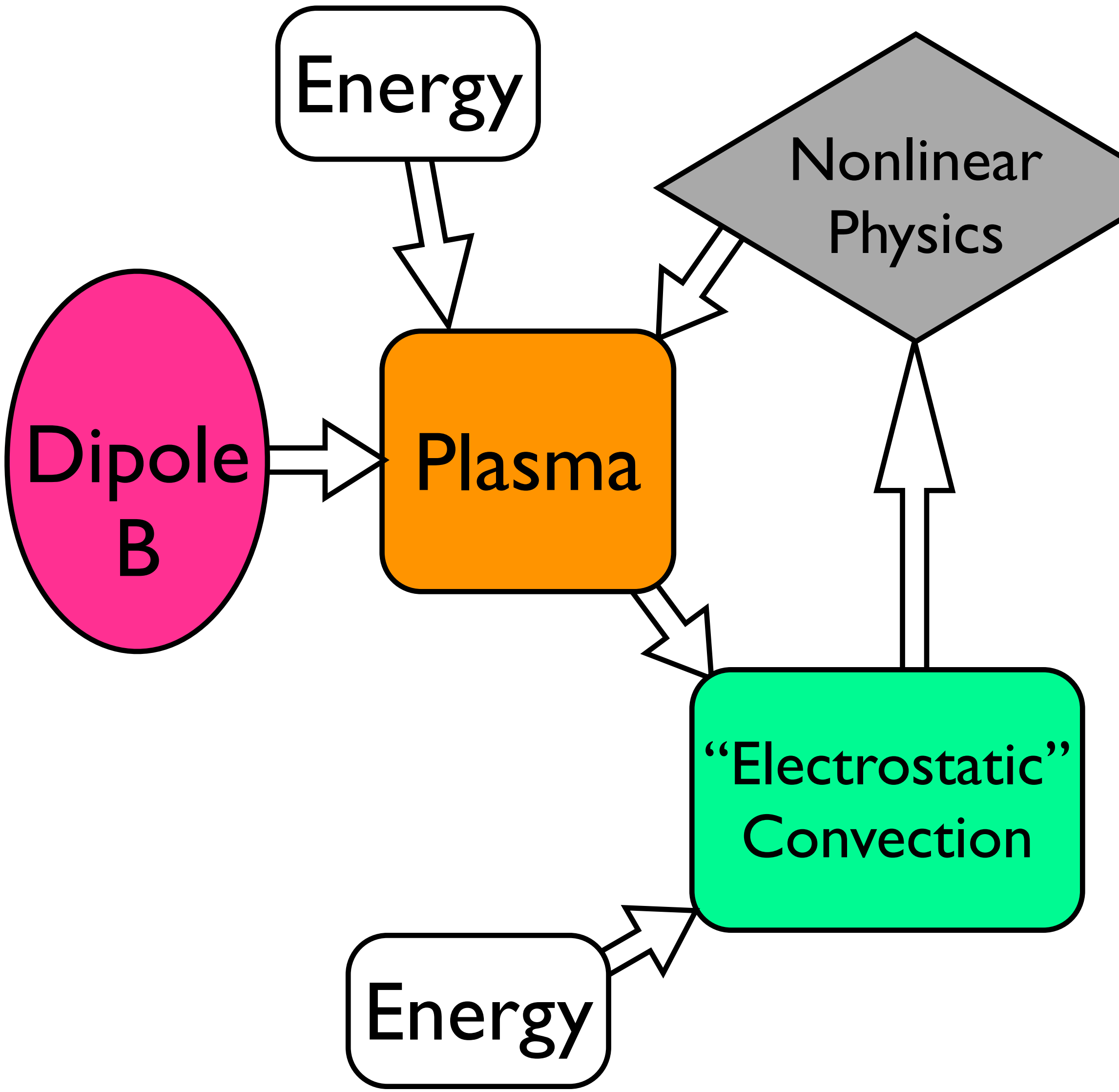
Shortly after dissipation/ diffusion

$\delta(nV) \sim 0 \Rightarrow n \propto R^{-4}$

$\delta(pV^{\gamma}) \sim 0 \Rightarrow p \propto R^{-20/3}$

Interchange Mixing in Dipole: Route to "Electrostatic Self-Organization"

- "Inward" Adiabatic Heating
  - Ring current intensification
  - Storm-time belt formation
- "Outward" Transport/Profile Consistency
  - Planetary winds (Centrifugal)
  - Magnetic confinement
- Phase-Space Structures
  - Drift-echos (injections)
  - Holes (bubbles)
  - Frequency sweeping



Flux-Tube Integrated Dynamics

Gyrokinetic Electrons and Cold Ion Fluid Coupled through 2D Electric Fields

Electrons ($F \propto n_e V$)

$$\dot{\varphi} = \frac{\partial \mathcal{H}}{\partial \psi} = \mu \frac{c}{e} \frac{\partial B}{\partial \psi} - c \frac{\partial \Phi}{\partial \psi}$$

$$\dot{\psi} = -\frac{\partial \mathcal{H}}{\partial \varphi} = c \frac{\partial \Phi}{\partial \varphi}$$

Curvature

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial \varphi}(\dot{\varphi} F) + \frac{\partial}{\partial \psi}(\dot{\psi} F) = 0$$

Ions ($N \propto n_i V$)

$$\frac{\partial N_i}{\partial t} + \frac{\partial}{\partial \varphi}(N_i \| \nabla \varphi \cdot \mathbf{V} \|) + \frac{\partial}{\partial \psi}(N_i \| \nabla \psi \cdot \mathbf{V} \|) = 0$$

Gravity

$$\frac{\partial N_i}{\partial t} + \frac{\partial}{\partial \varphi}\left[c N_i \left(\omega_g(\psi) - \frac{\partial \Phi}{\partial \psi} - \left\| \frac{|\nabla \varphi|^2}{\omega_{ci} B} \right\| \frac{\partial^2 \Phi}{\partial \varphi \partial t} \right) \right] + \frac{\partial}{\partial \psi}\left[c N_i \left(\frac{\partial \Phi}{\partial \varphi} - \left\| \frac{|\nabla \psi|^2}{\omega_{ci} B} \right\| \frac{\partial^2 \Phi}{\partial \psi \partial t} \right) \right] = 0$$

$$\frac{\partial}{\partial \varphi}\left(h_\varphi \frac{\partial \Phi}{\partial \varphi} \right) + \frac{\partial}{\partial \psi}\left(h_\psi \frac{\partial \Phi}{\partial \psi} \right) = -4\pi e (N_i - N_e)$$

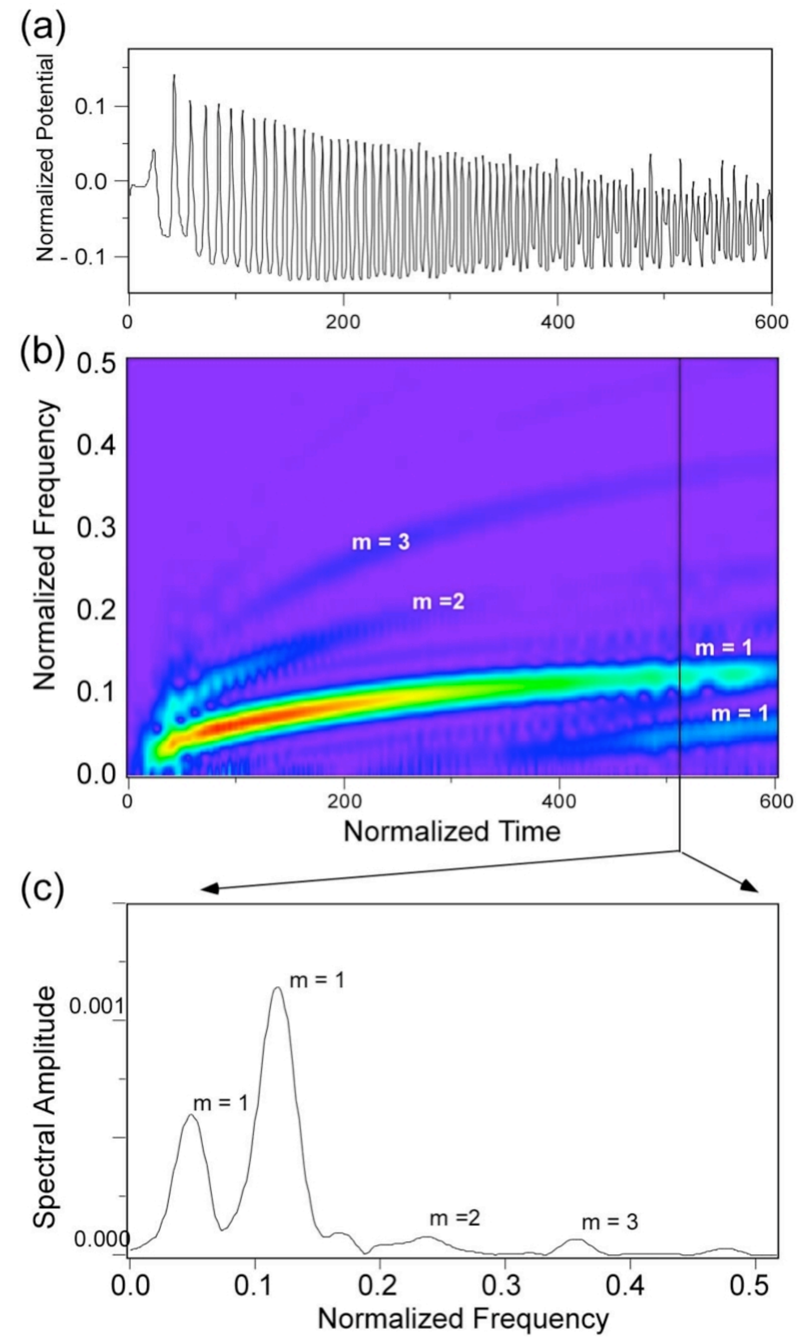
Electric Potential

(Constant along B-line & small dissipation)

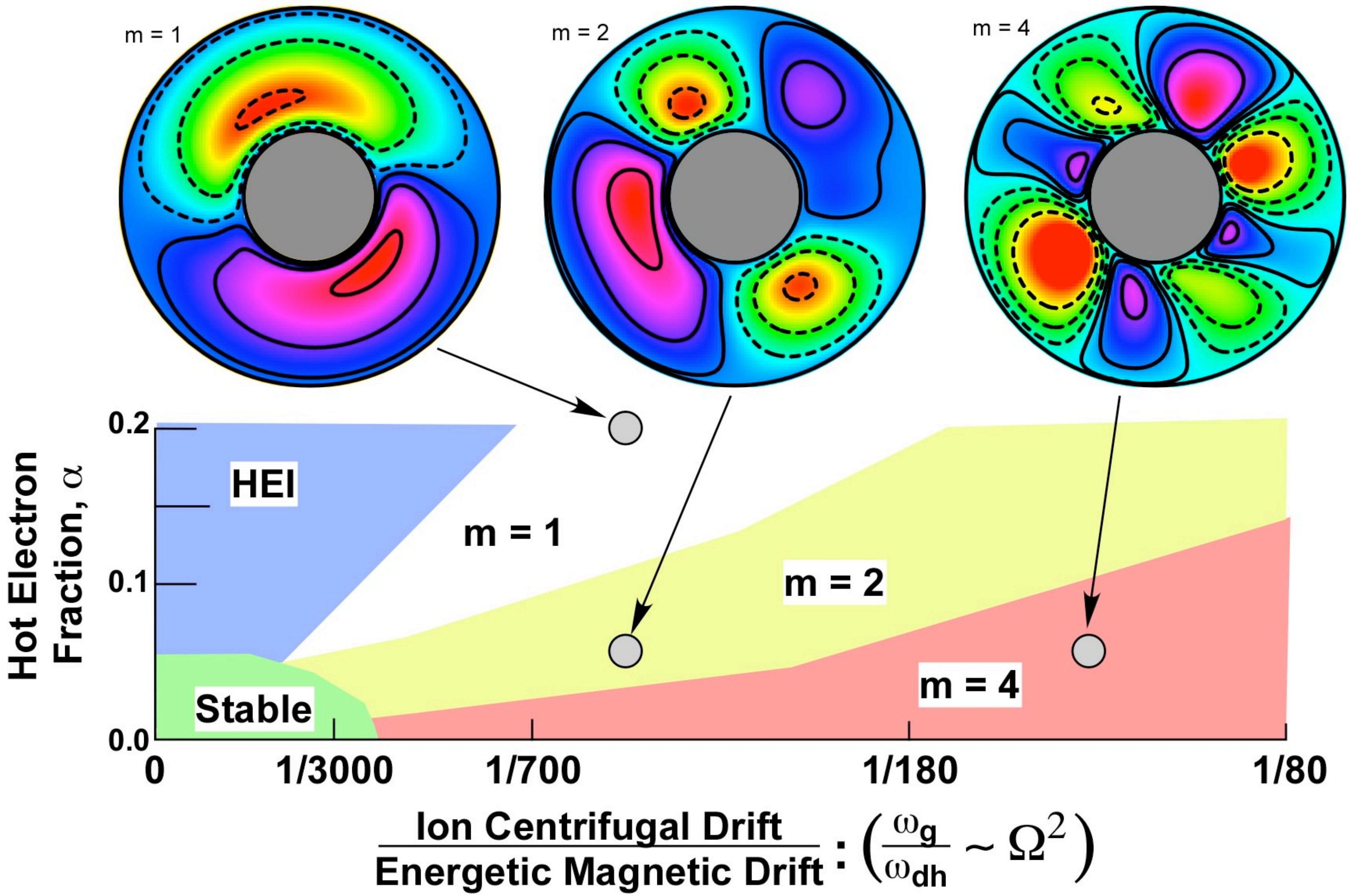
Self-Consistent, Nonlinear, **Flux-Tube Integrated,** Simulation Reproduces Dipole Interchange Dynamics

- ✓ Global mode structure
- ✓ Frequency sweeping
- ✓ Mode amplitude
- ✓ RF scattering effects
- ✓ Combined centrifugal (slow) & gyrokinetic (fast) effects

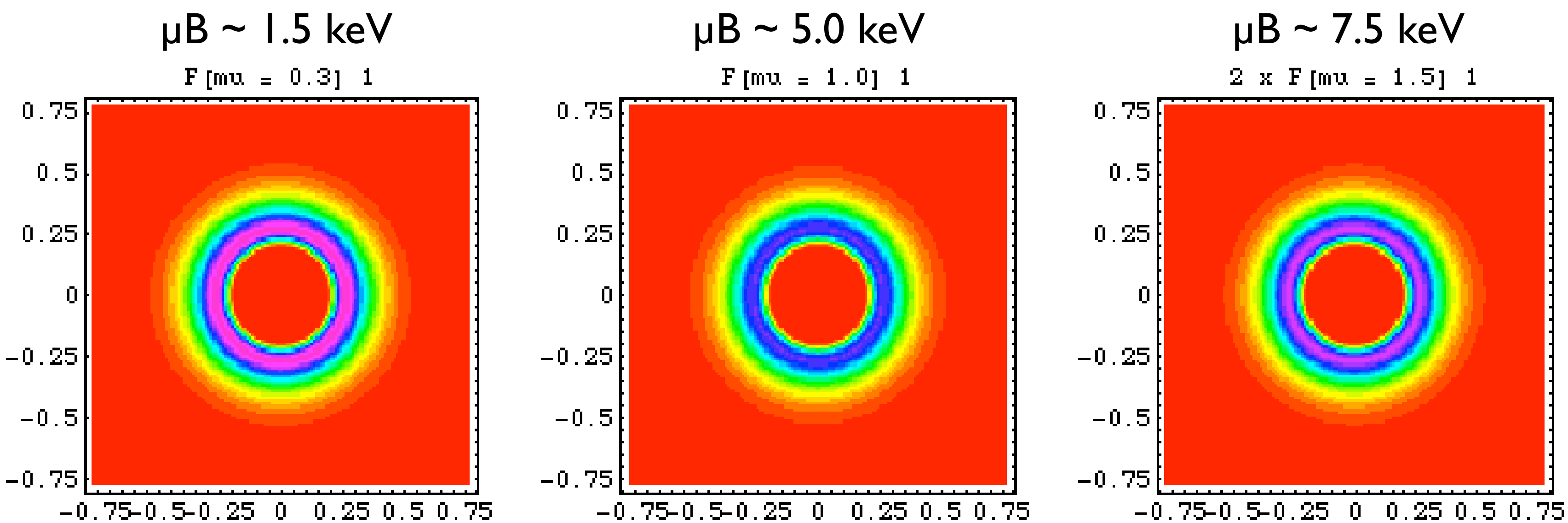
➡ Initial value; no sources



Relative Strength of Centrifugal and Curvature Drives Determine Mode Structure



Gyrokinetic Interchange Creates Persistent Phase-Space Structures

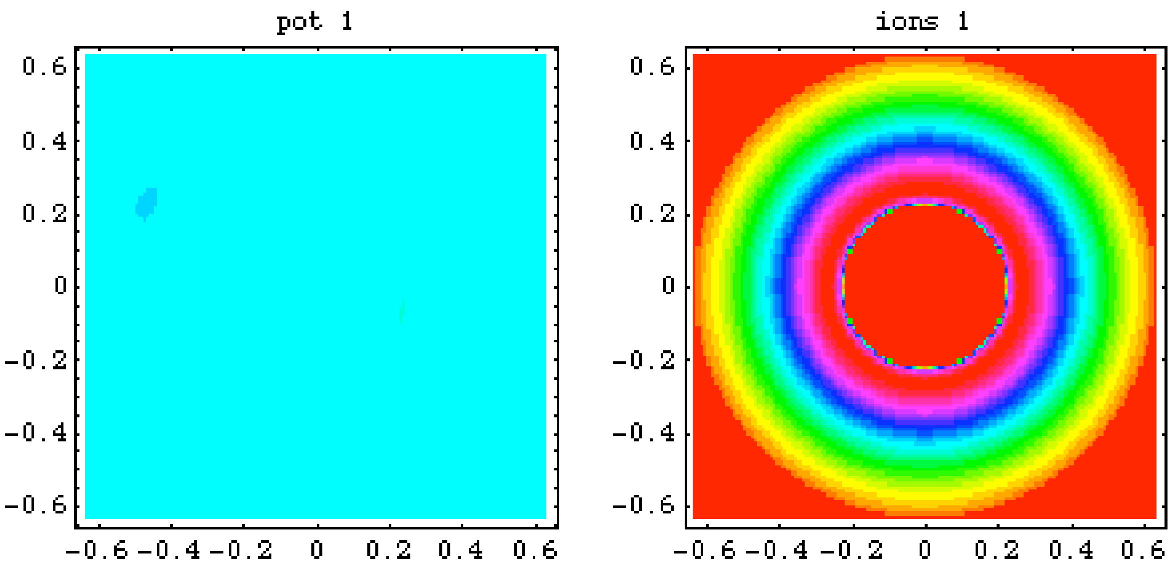


- Low energy (slower) electrons resonantly interact before (faster) high energy electrons.
- Field-line integrated phase-space spatial structures have energy dependence since drift frequency ∝ energy.
- Oscillations persist at drift resonance of high energy electron pressure peak.

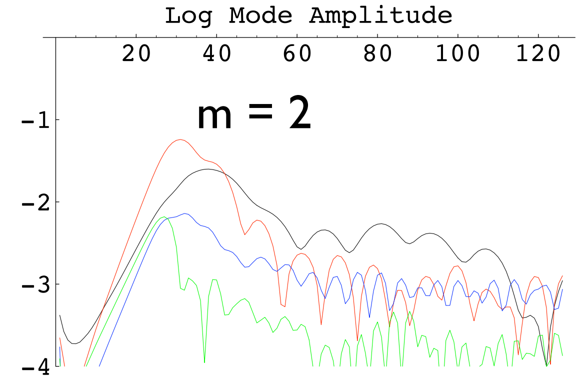
Centrifugal (Slow) Interchange with Rigid Rotation

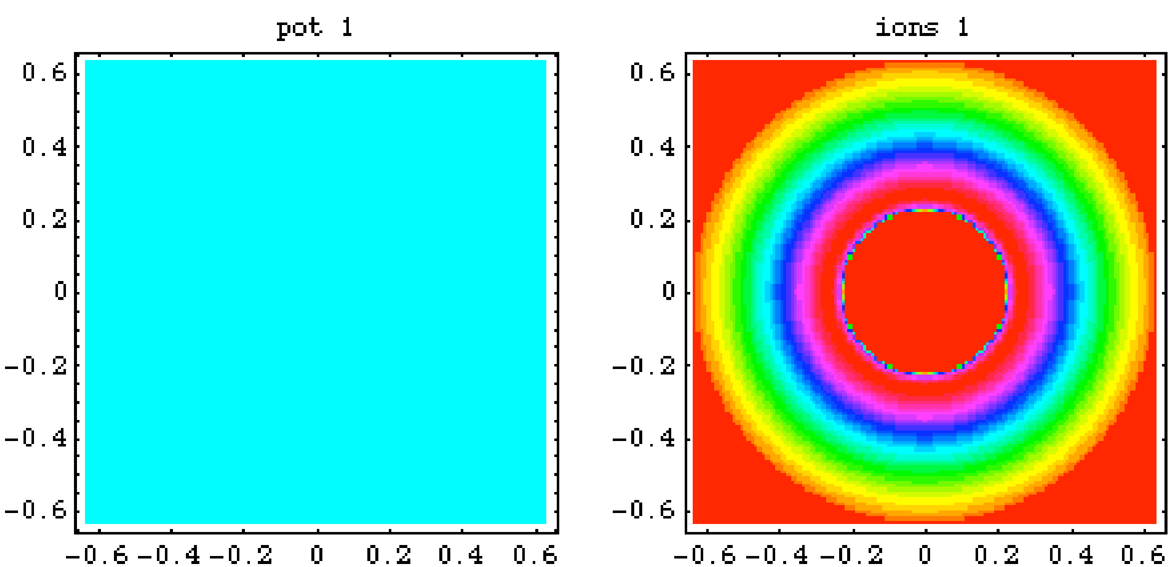
Computed in **Rotating Frame**

Unstable Growth and Saturation from Noise

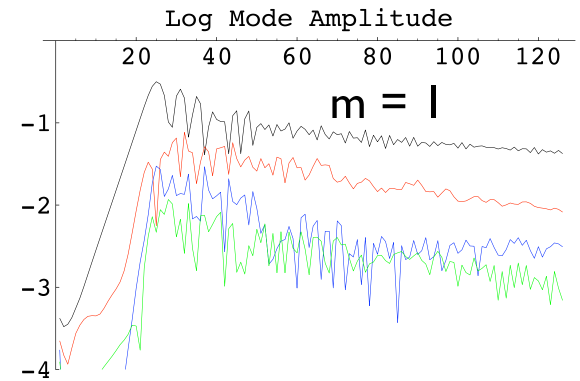


5% Hot Electron Fraction



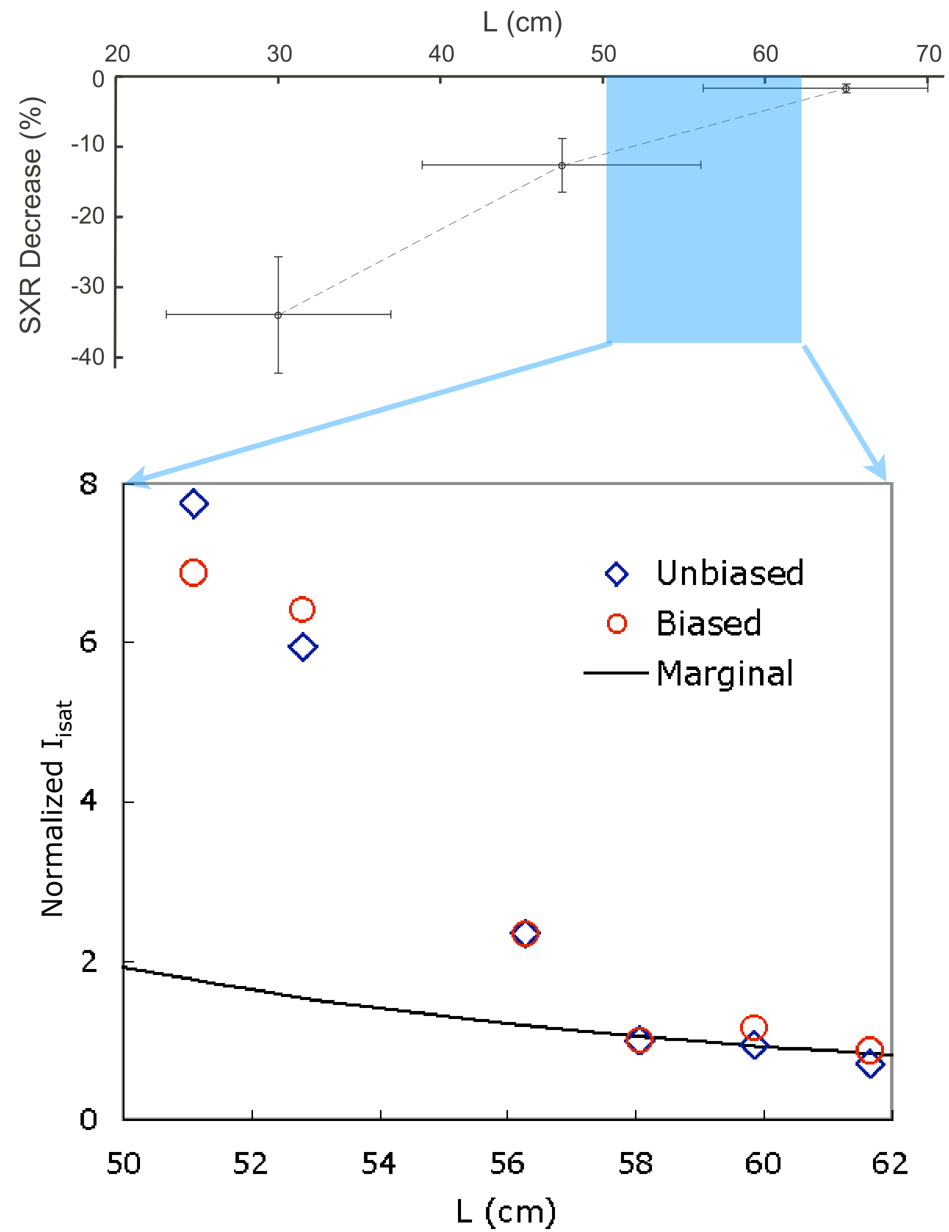


20% Hot Electron Fraction



(Slow) Interchange Mixing Does NOT Strongly Effect Mass Profile Near Edge

- Estimated mass-convection turn-over time ~ 10 msec with $\Phi \sim \pm 2$ V is **slower** than ionization time
- Very little I_{sat} change at plasma edge
- Drift-resonant electron turn-over time is 20 times faster.
- Change in SXR diode array shows electron profile change; but …



Summary

- Magnetic dipole has a unique field structure for study interchange mixing.
- Two types of interchange instabilities excited:
  - Hot electron interchange (fast) modes illustrate collisionless gryokinetic dynamics with "phase-space" mixing and "bubbles".
  - Centrifugal interchange (slow) modes illustrate MHD mass flows and convective mixing.
- Interchange modes have **broad** radial structures.
- 2D nonlinear simulations for interchange dynamics reproduces observed dynamics and mode structures.

➡ To do: intensify convection, measure/tag convective turn-over, drive convection, observe "electrostatic self-organization", …

LDX: A New Confinement Experiment

MIT-Columbia University

- Large 5m Diameter Vessel: Very Large Plasma (x4 CTX)
- Three Superconducting Magnets: Long Pulse Plasmas
- Multiple-Frequency Microwave Heating: High Temperature Electrons & Profile Control
- High beta for Confinement Studies: No aurora!!

“Music” by E. Ortiz