# Experiments with a Supported Dipole

## Reporting Measurements of the Interchange Instability Excited by Electron Pressure and Centrifugal Force

Ben Levitt and Dmitry Maslovsky
Collisionless Terrella Experiment
*Mike Mauel – ICC 2004*

## Outline

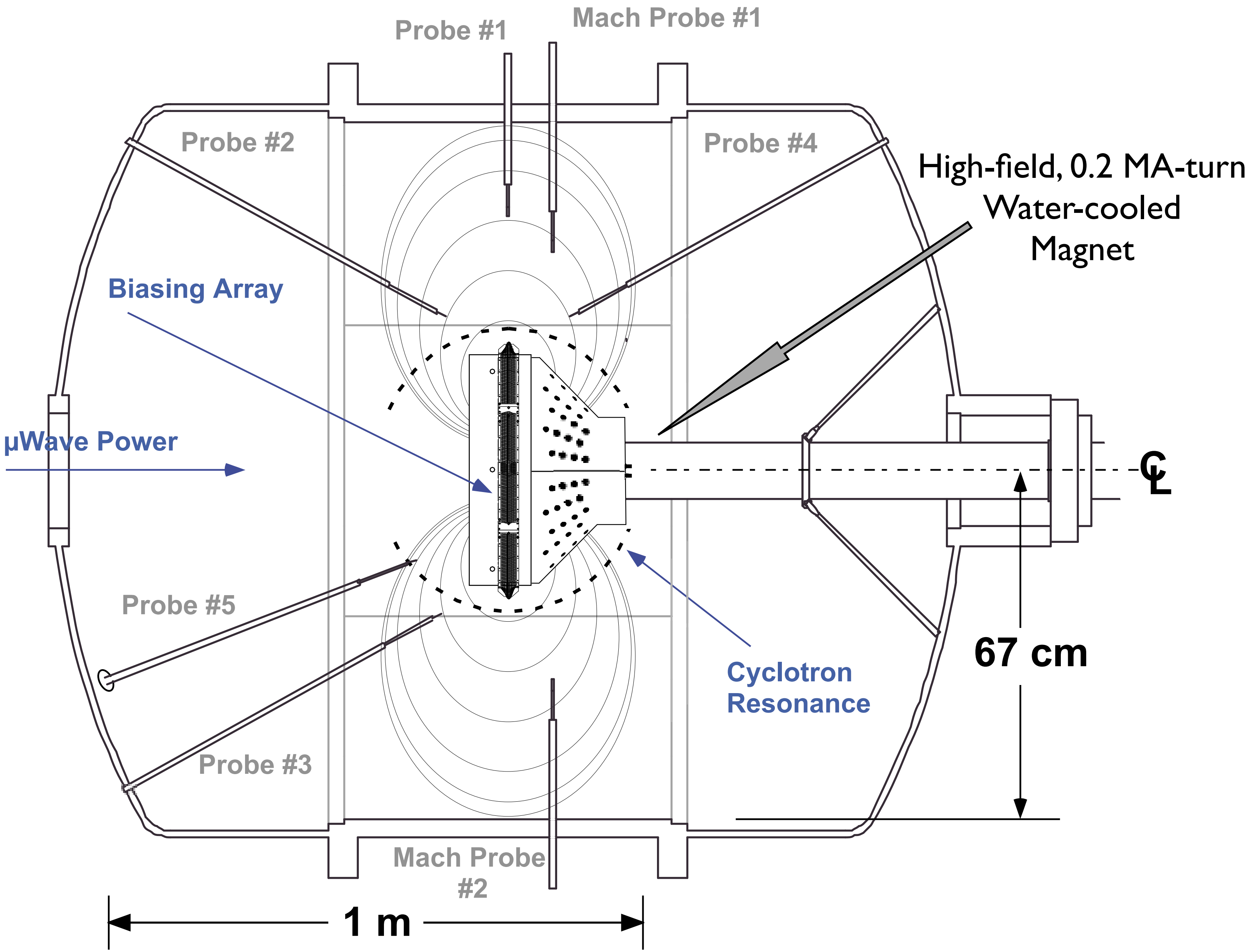
- Introduction
- Description of CTX Experiment
- Hot Electron Interchange Instability
- ☞ Centrifugal Interchange Instability
- Future Experiments and Campaigns

# Introduction

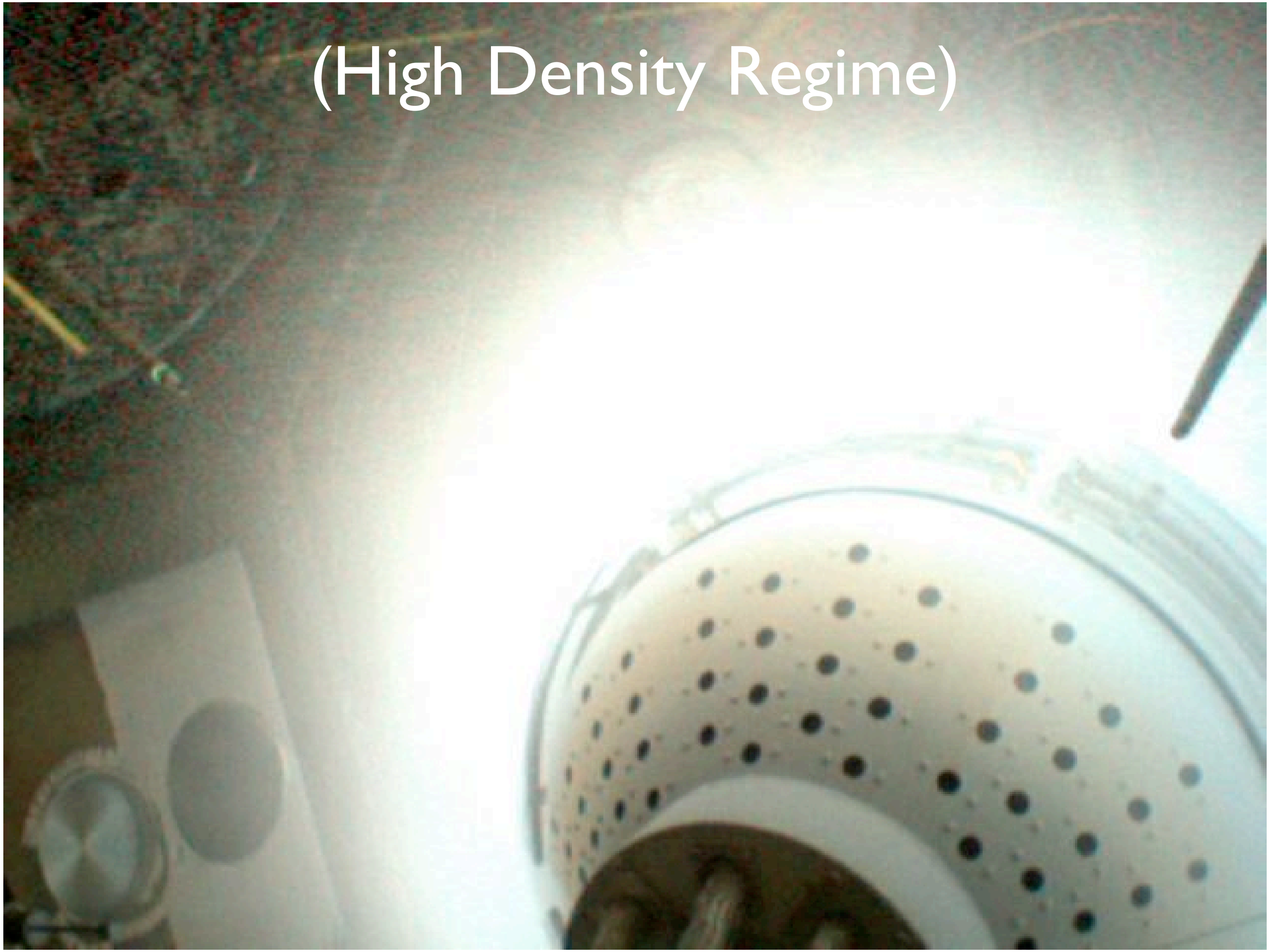
- Interchange ($k \cdot B \approx 0$) mixing is a natural process in planetary magnetospheres that is either externally-driven (e.g. the solar wind) or internally-excited by instability (e.g. Jupiter's Io torus).
- The Collisionless Terrella Experiment (CTX) was built to investigate interchange instability of "collisionless" plasma confined by a strong laboratory dipole magnet.
  - ▷ CTX results have guided physics planning for LDX.
- Since a dipole field has no magnetic shear, exhibits strong compressibility/adiabaticity effects, and with $k \cdot B \approx 0$, interchange dynamics in a dipole is a fascinating ***2D process***.
  - ▷ Beautiful nonlinear "wave-particle" interactions result!
  - ▷ Good agreement between theory and experiment.

☞ Recently, Ben Levitt succeeded in exciting the **centrifugal interchange instability** in a rotating dipole plasma.

# CTX

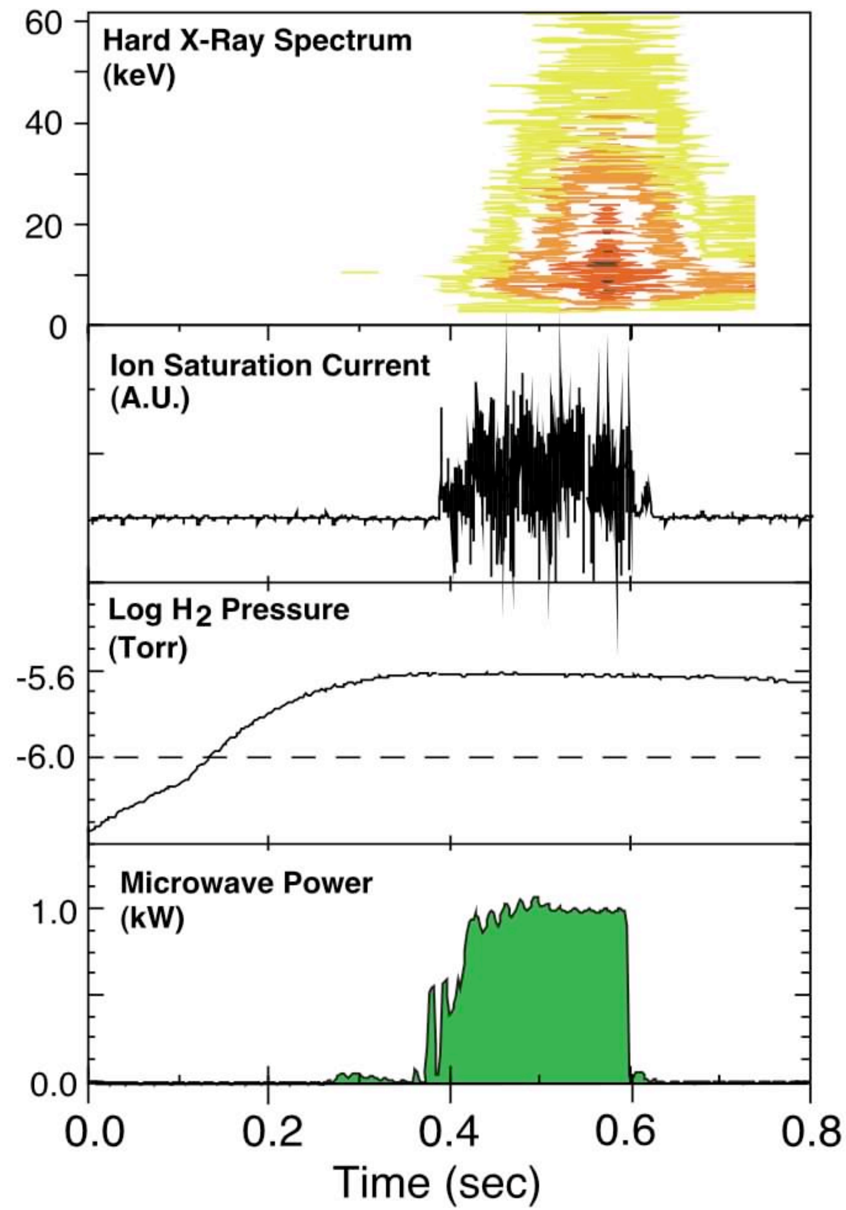

Probe #1
Mach Probe #1
Probe #2
Probe #4
High-field, 0.2 MA-turn
Water-cooled
Magnet
Biasing Array
μWave Power
Probe #5
Probe #3
Cyclotron
Resonance
67 cm
Mach Probe
#2
1 m

# CTX Plasma

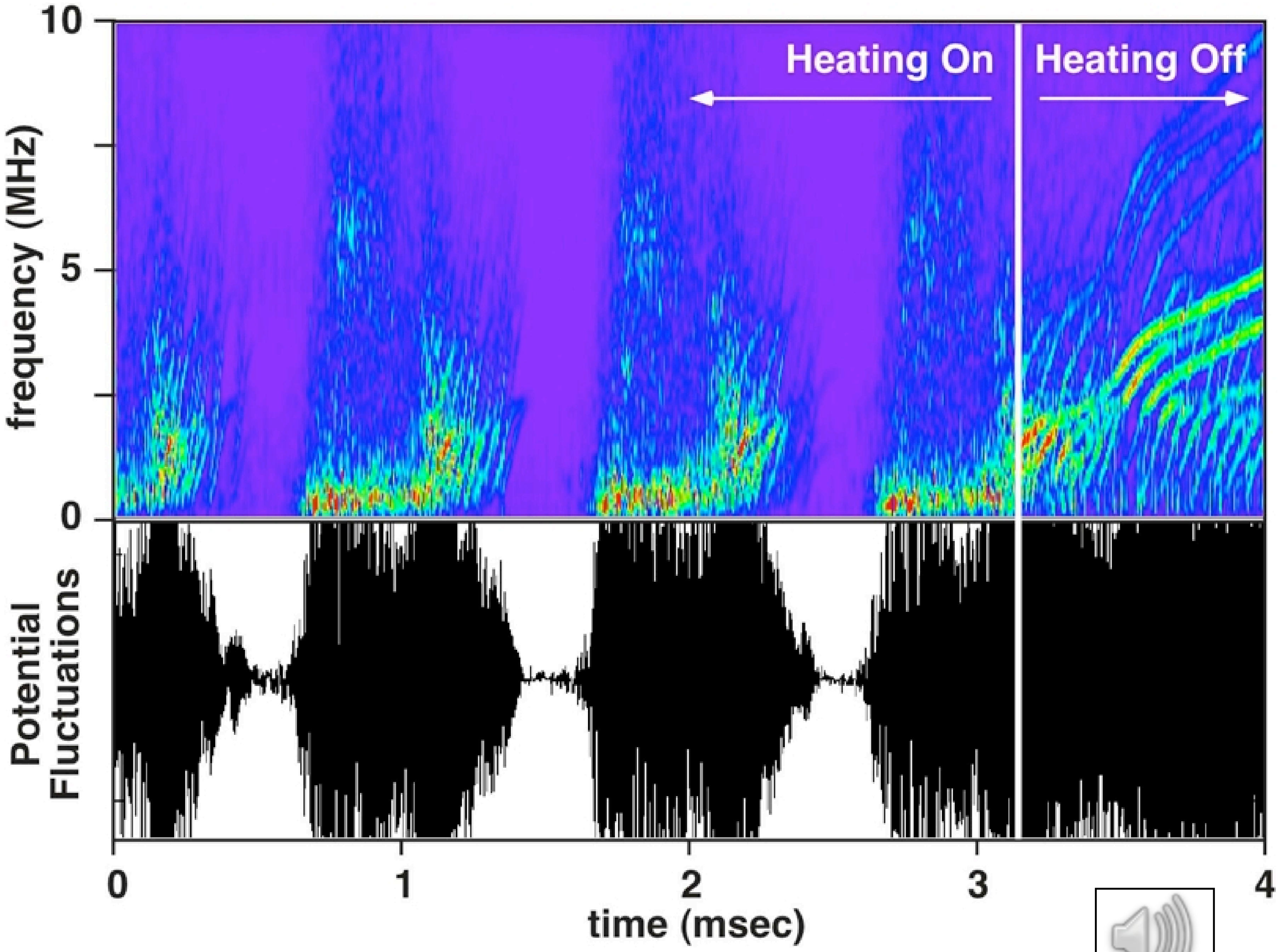


# Creating an “Artificial Radiation Belt”

- 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



# Close-up: Hot Electron Interchange Instability



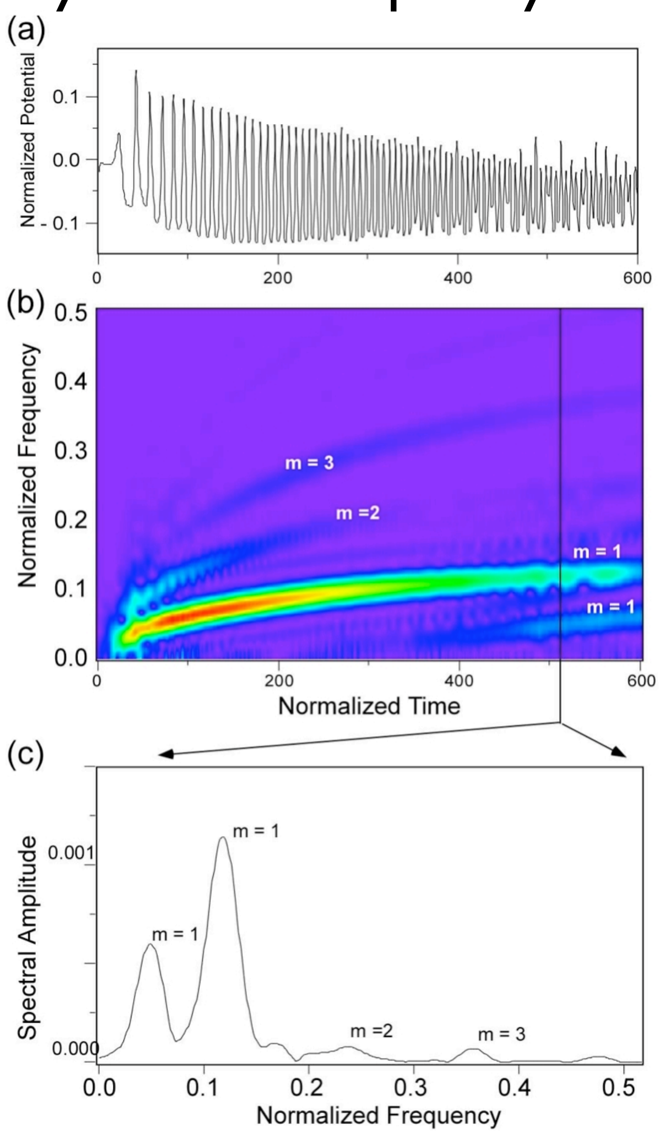
# Properties of Interchange Instability Driven by Energetic Electrons

- Instability acquires a real frequency, $\omega \sim \omega_d$, from the rapid magnetic drift of the electrons.
- Stabilizing ion polarization currents allow pressure gradients to exceed the usual MHD limit, $\delta(pV^\gamma) > 0$, creating a threshold to instability and suppressing short azimuthal wavelength.
- Drift-resonance with electrons create "phase-space holes" (or "vacuum bubbles") that propagate inward. These holes can be "plugged" by applying RF scattering with a secondary source [Maslovsky, PRL03].
- Strong modulations in electron density occur that are radially localized (but azimuthally extended) [Warren, PRL95] and have a shorter length-scale as the fluctuating potential [Levitt, POP03].

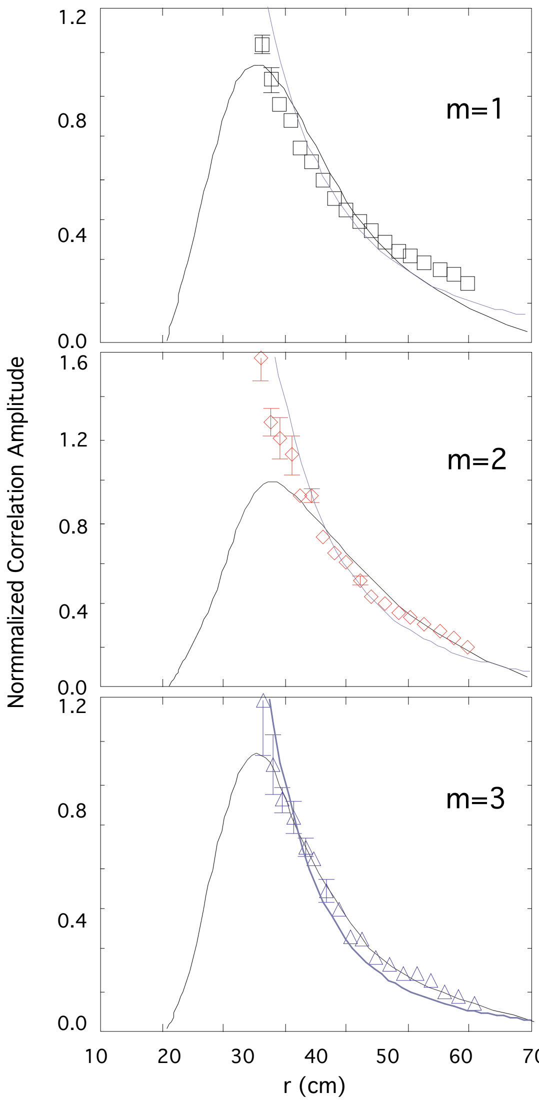
# Self-Consistent, Nonlinear, Multi-Fluid, **Field-Line Integrated,** **2D** Simulation Reproduces Dipole Interchange Dynamics and Mode Structure

[Levitt, POP03]

## Dynamics: Frequency Rise



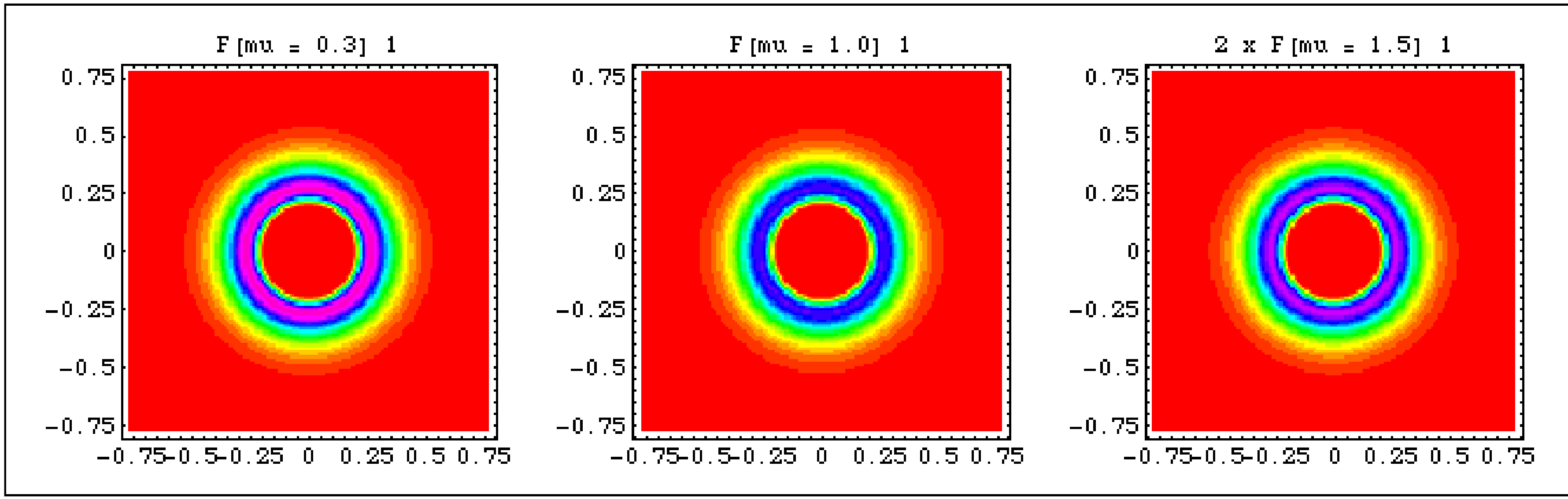

## Structure: Broad, Multi-Mode



# Interchange Burst Causes Strong Localized Electron Modulations

[Warren, PRL95]

μB ~ 1.5 keV μB ~ 5.0 keV μB ~ 7.5 keV




- Low energy electrons resonantly interact before (faster) high energy electrons.
- Field-line integrated phase-space spatial structures have complex energy dependence due to drift frequency differences.
- Oscillations persist due to at high energy drift resonance at hot electron pressure peak.

# Observation of Centrifugal Interchange Instability

[Levitt, 2004]

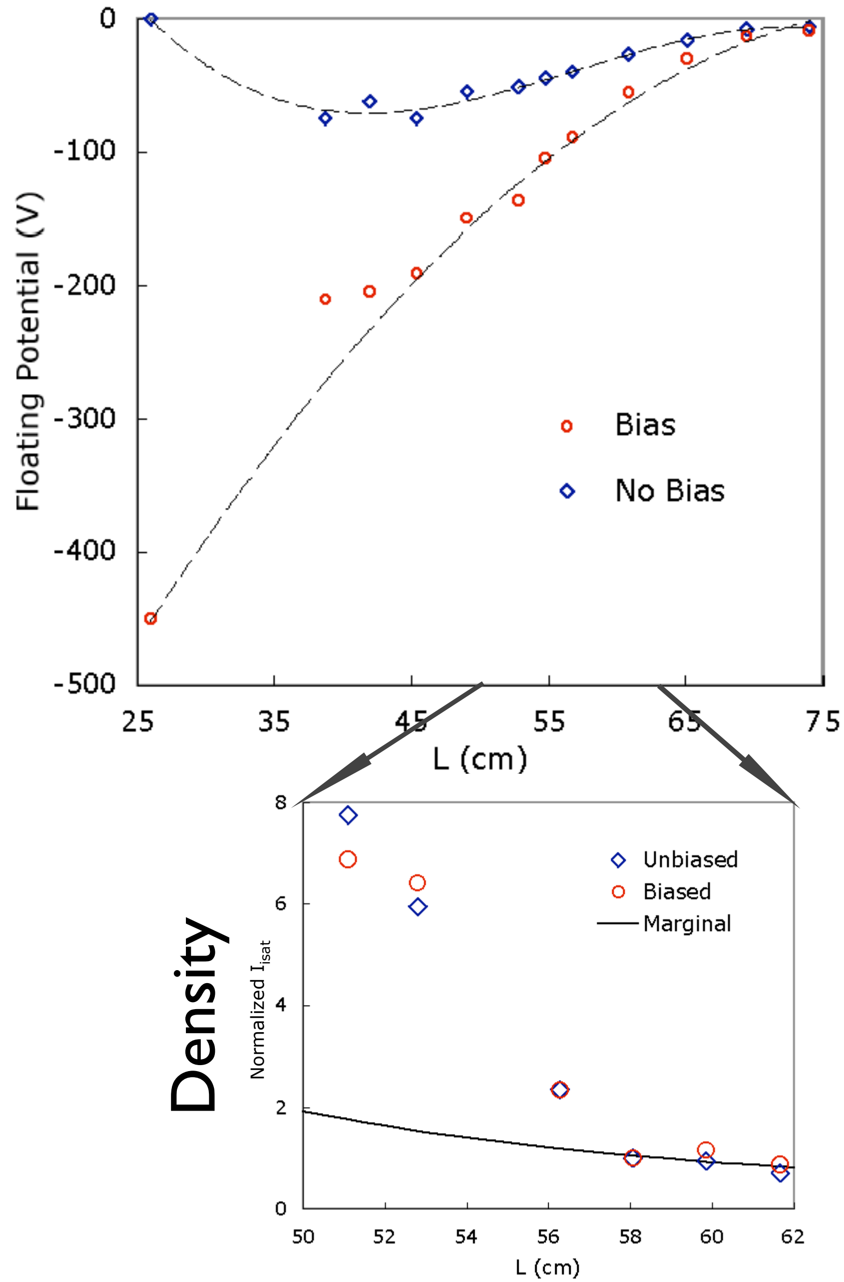
- Axisymmetric bias voltage ($\leq$ 500 V) applied to equatorial mesh placed at plasma's inner boundary.
  - ▷ Axisymmetric radial current drives azimuthal E×B rotation.
  - ▷ Current increases with neutral pressure and fixed $\omega_e$.
  - ▷ "Near sonic" speeds ($\omega_e/2\pi \sim$ 18 kHz) on outer flux tubes.
- Instability appears only with sufficient rotation drive.
- Low instability frequency, $\omega \gtrsim \omega_e \ll \omega_{dh}$.
- Low amplitude, ~ 10% of HEI, Reduces central density peaking.
- Broad global mode structure, dominated by long azimuthal wavelengths (m = 1, 2) but with a weak radial "spiral".
- Good agreement with theory/simulation **when effects of fast electrons are included**.

# Driven Plasma Rotation Appears Rigid

- Floating potential scales with radius as $\Phi \sim R^{-2}$
- Corresponds to rigid rotation in a dipole, $\omega_e/2\pi$ = 18 kHz
- Potential profile consistent with constant radial current proportional to the field-line integrated Pedersen conductivity:

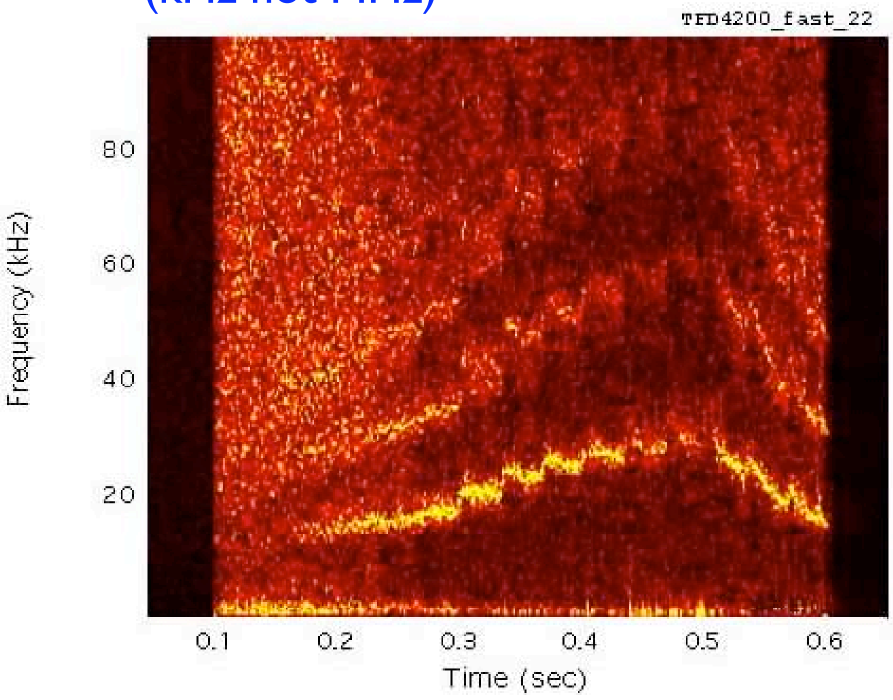
$$I \approx 8\pi\, M\, \omega_e(R)\, \Sigma_p(R)$$

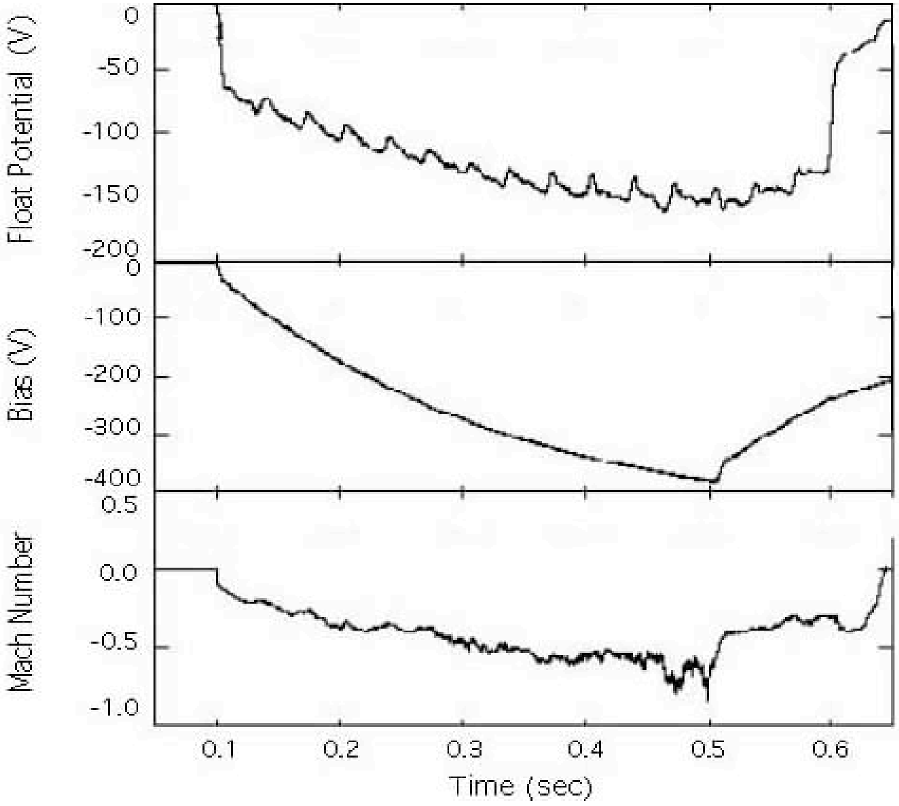
- $\Sigma_p(R)$ is constant if density profile, $n \sim R^{-6}$, exceeds instability threshold.



# Centrifugal Interchange

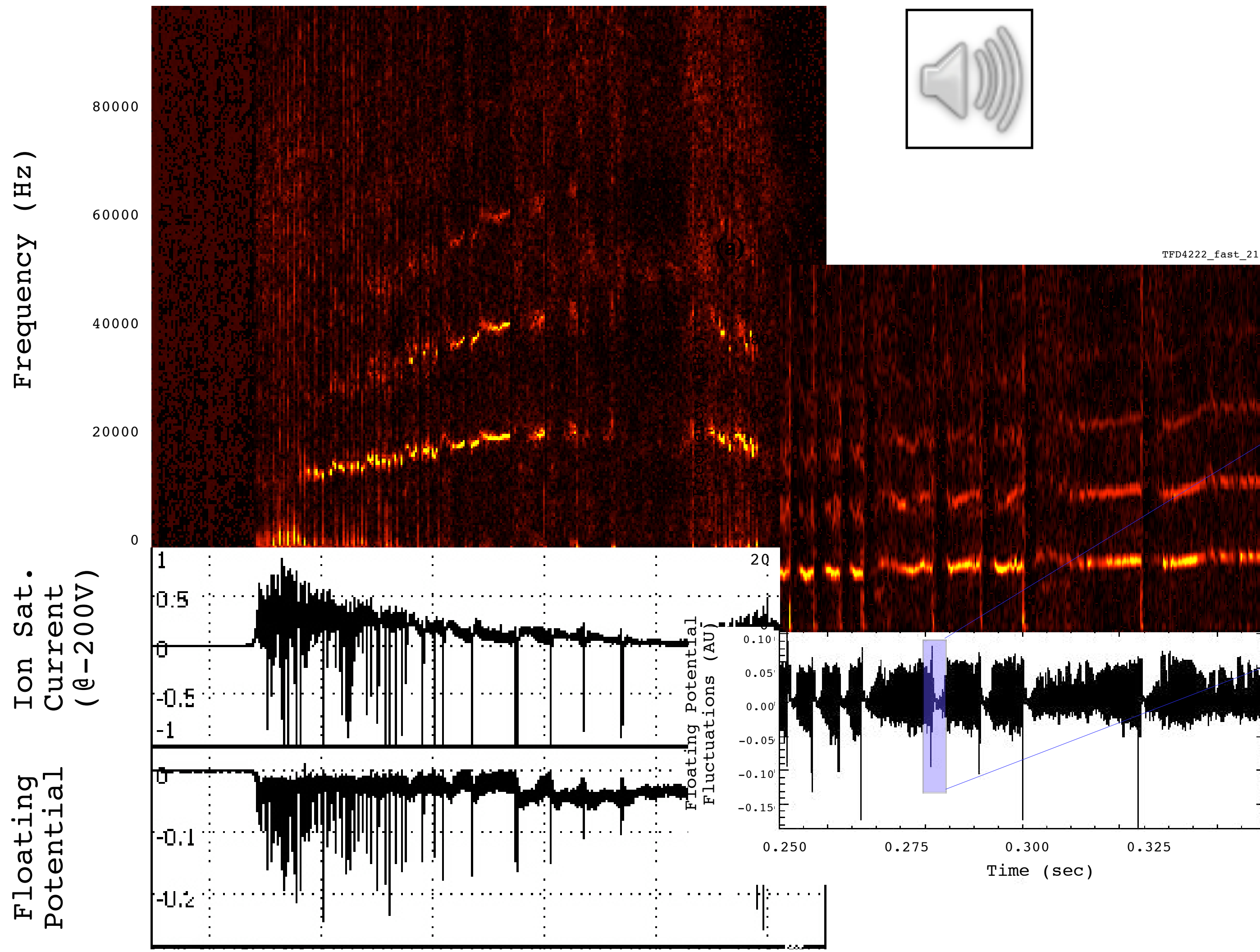
(kHz not MHz)



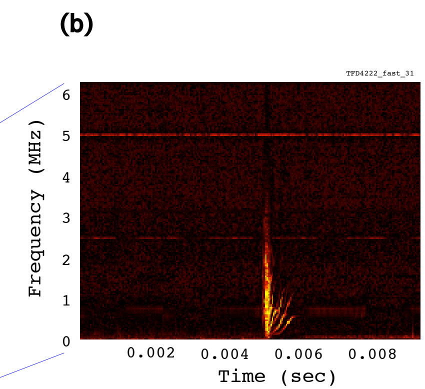




(Seconds not msec)

# At Lower Density, Centrifugal Instability Mixes with Hot Electron Interchange Bursts

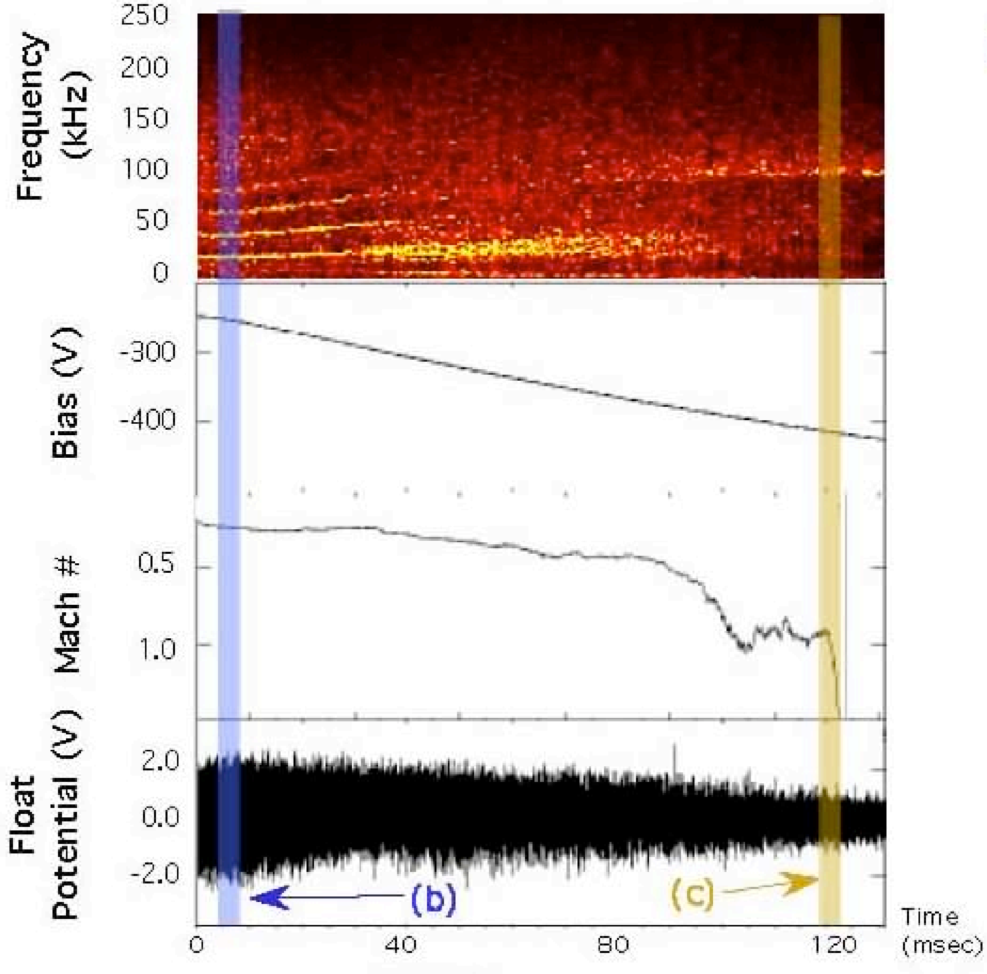



Outward Bursts of Energetic Electrons

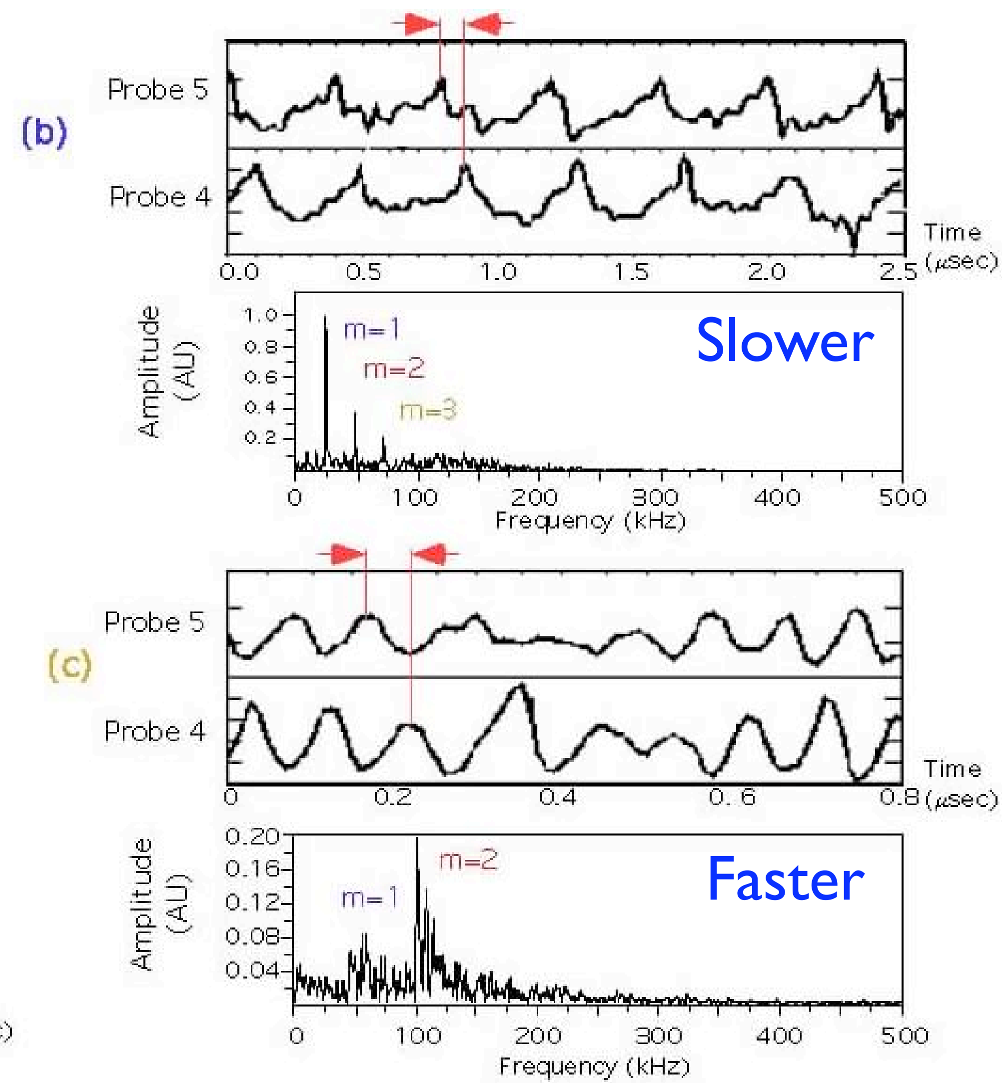



Close-up:
Hot Electron Interchange

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



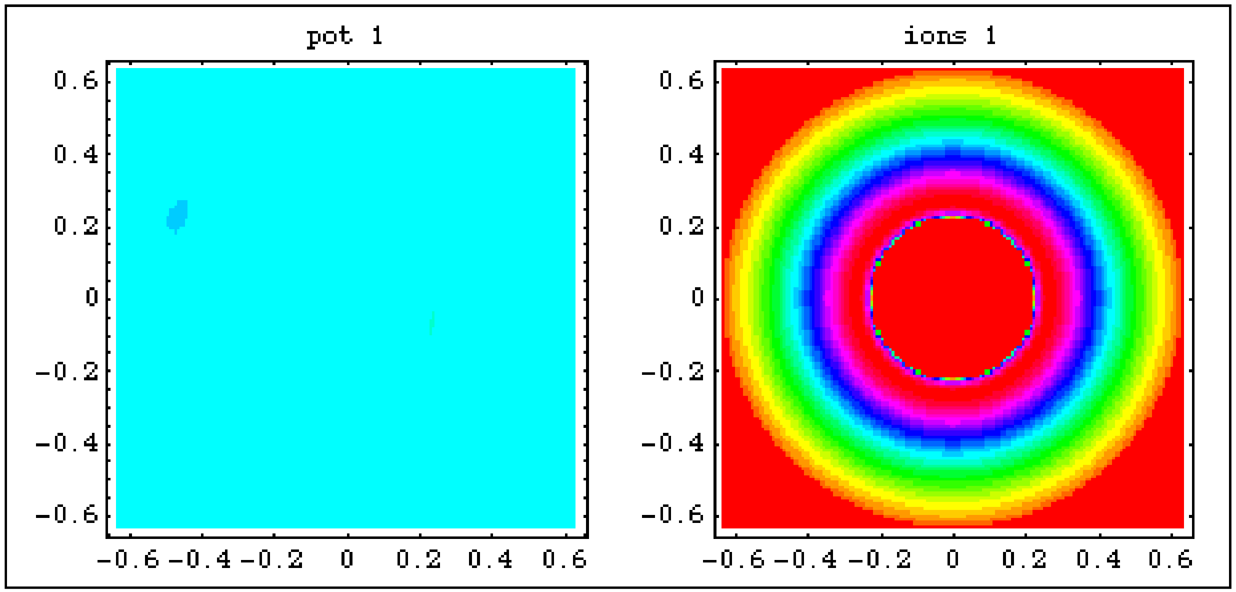

m = 1
m = 2



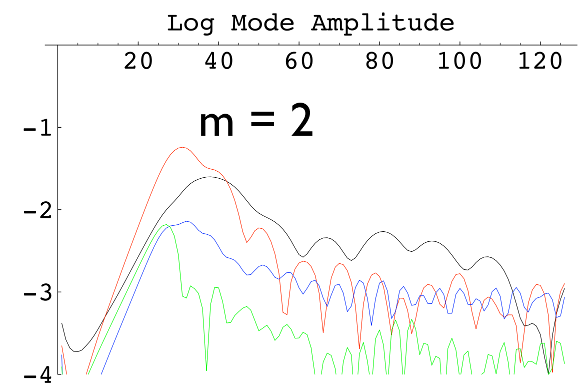
# Nonlinear Simulation with Rigid Rotation

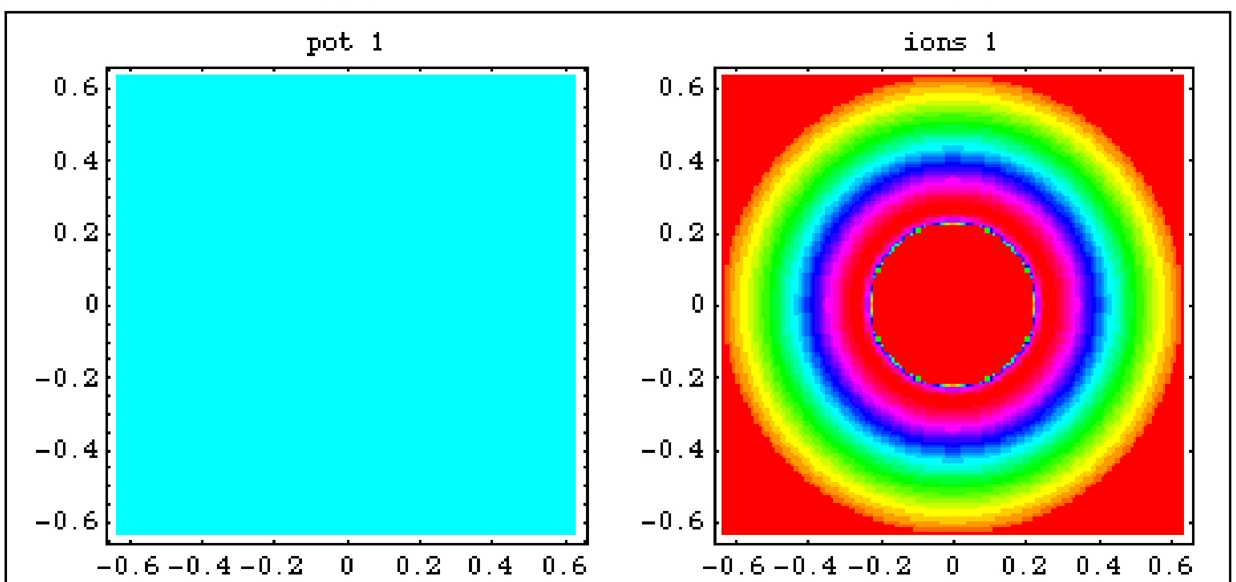
## Computed in Rotating Frame

## Unstable Growth and Saturation from Noise

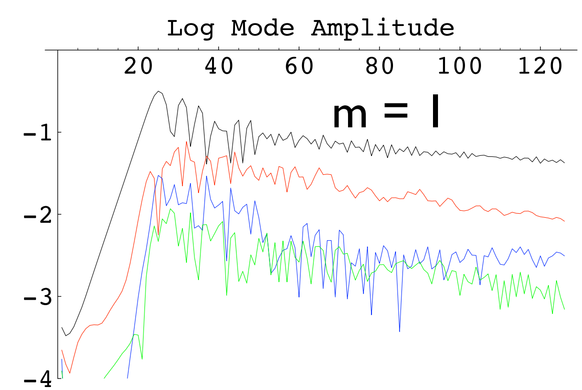



## 5% Hot Electron Fraction

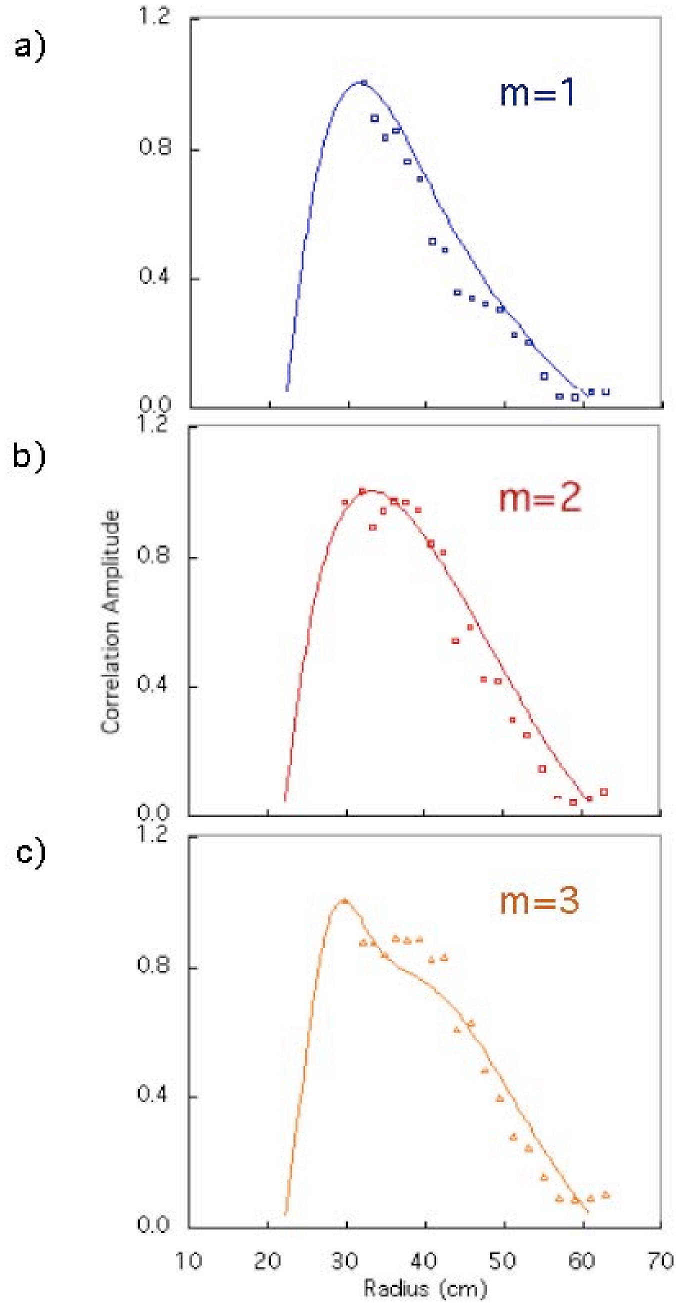


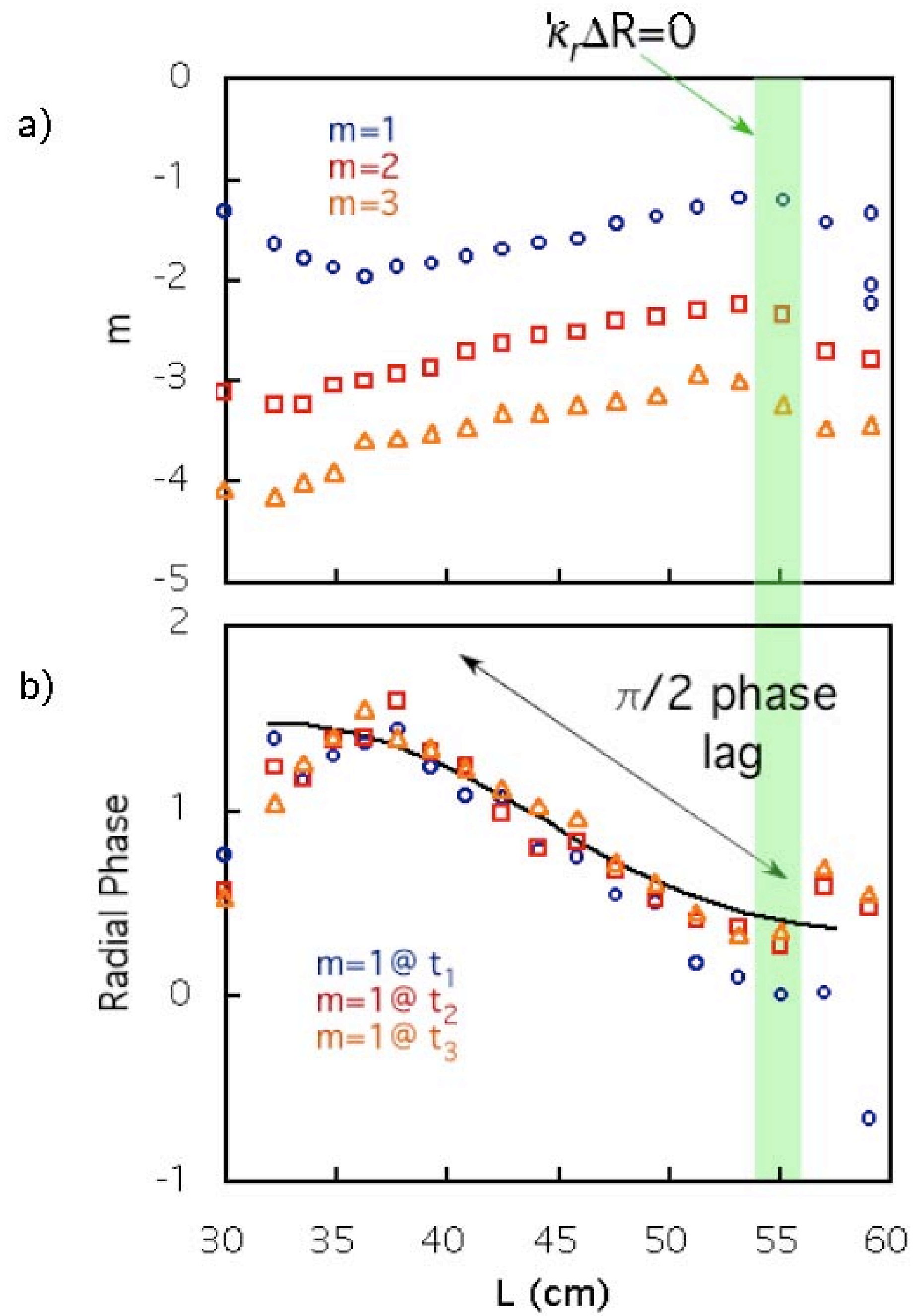




## 20% Hot Electron Fraction



# Broad "Spiral" Mode Structure



# Summary

- Supported dipole experiments have been used to study basic, low-frequency interchange mixing in a dipole plasma. Interchange instabilities are excited by
  - Steep energetic electron pressure gradients ($P(R) > R^{-7}$)
  - Steep density gradients ($n(R) > R^{-4}$) and rigid rotation
- Fast magnetic drift of energetic electrons imparts a real frequency to the interchange mode and creates stabilizing ion polarization effects. The hot electron interchange has a threshold *above* the MHD limit, and the growth of centrifugal interchange modes with short azimuthal wavelengths are suppressed.
- The radial structure of the fluctuating potential is broad.
- 2D nonlinear models for interchange ($k \cdot B \approx 0$) dynamics reproduces both the dynamics and structure of observations.

# This Summer

## Cassini-Huygens Encounters Saturn

June 14: Phoebe

July 1: Orbit Insertion


## LDX Creates First Plasma

See Poster Session #3 (Thurs)

Garnier, Hansen, Kesner