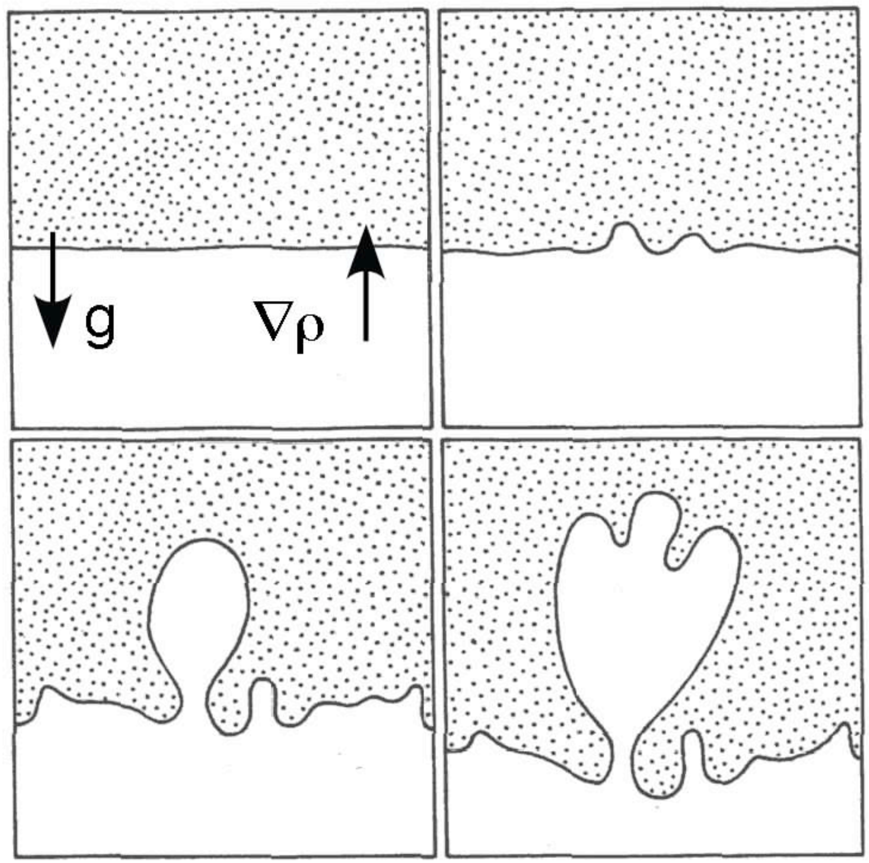
Interchange Instability and “Bubbles”

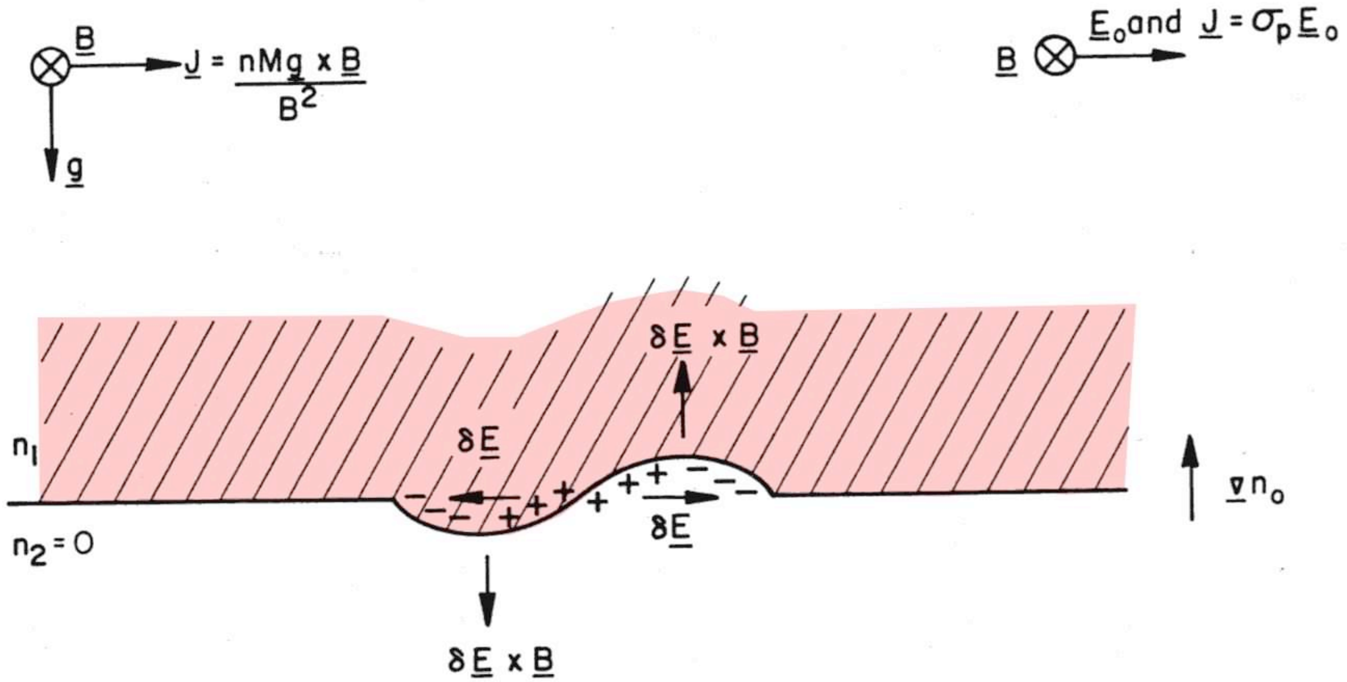
Gravitational Rayleigh-Taylor



Linear

Nonlinear:
Bubbles,
fingers,
vortices,
…

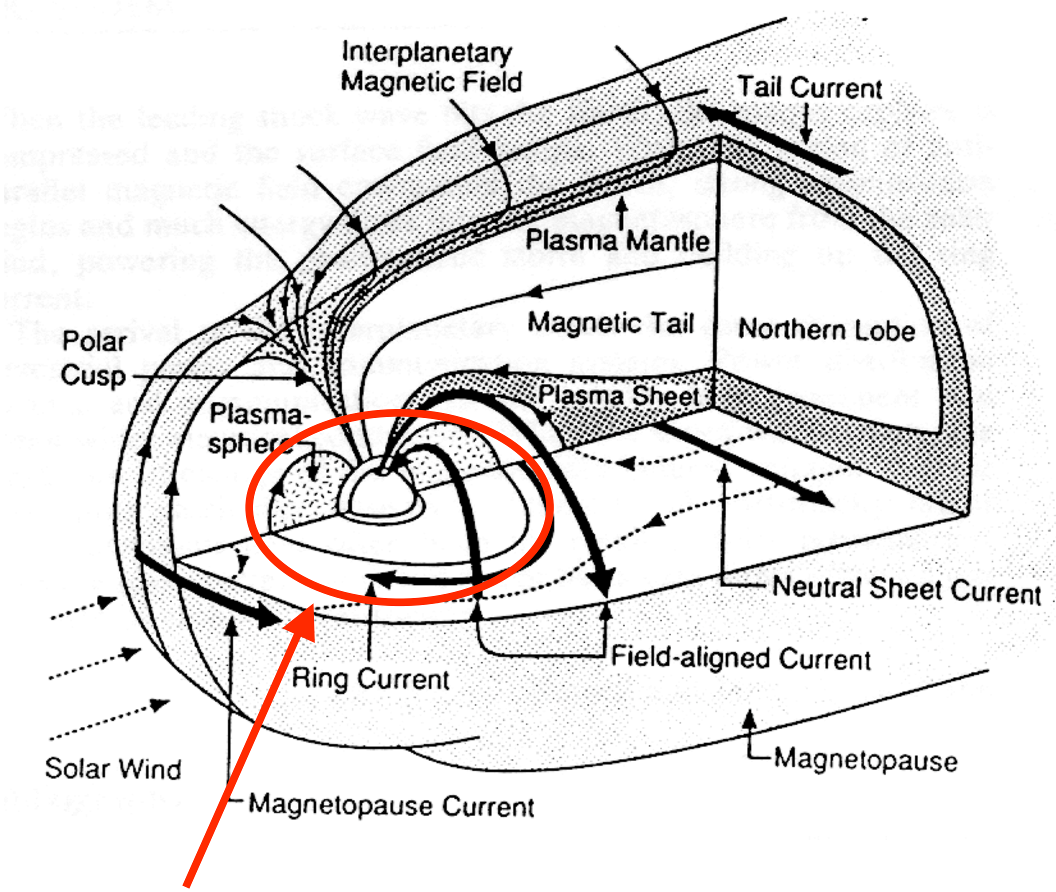
Rayleigh-Taylor Instability in Magnetized Plasma



- **Anisotropic! (constant along B)**
- **These instabilities occur every evening as the sun sets.**
- **Also driven by magnetic curvature and pressure.**

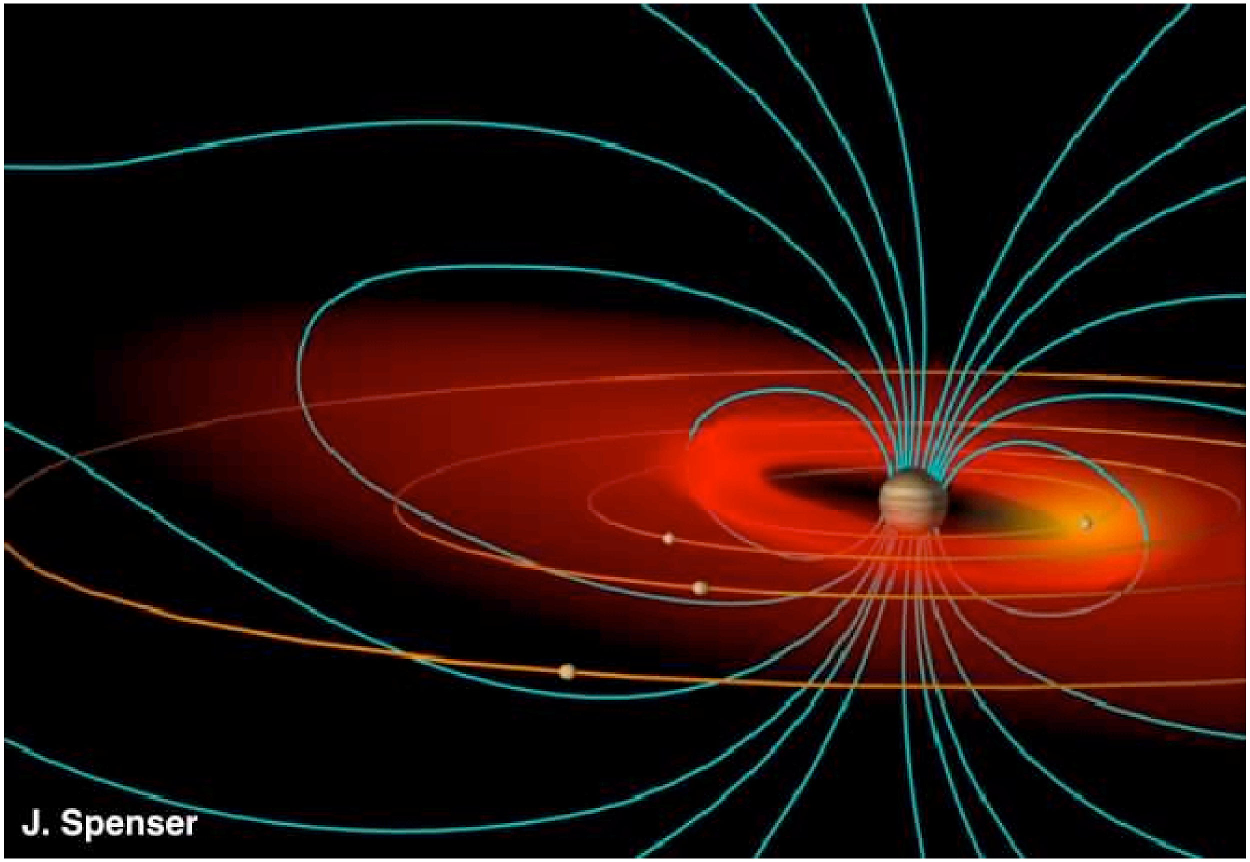
Avoiding these instabilities by shaping the magnetic bottle is a guiding principle of fusion research.

Earth's Magnetosphere

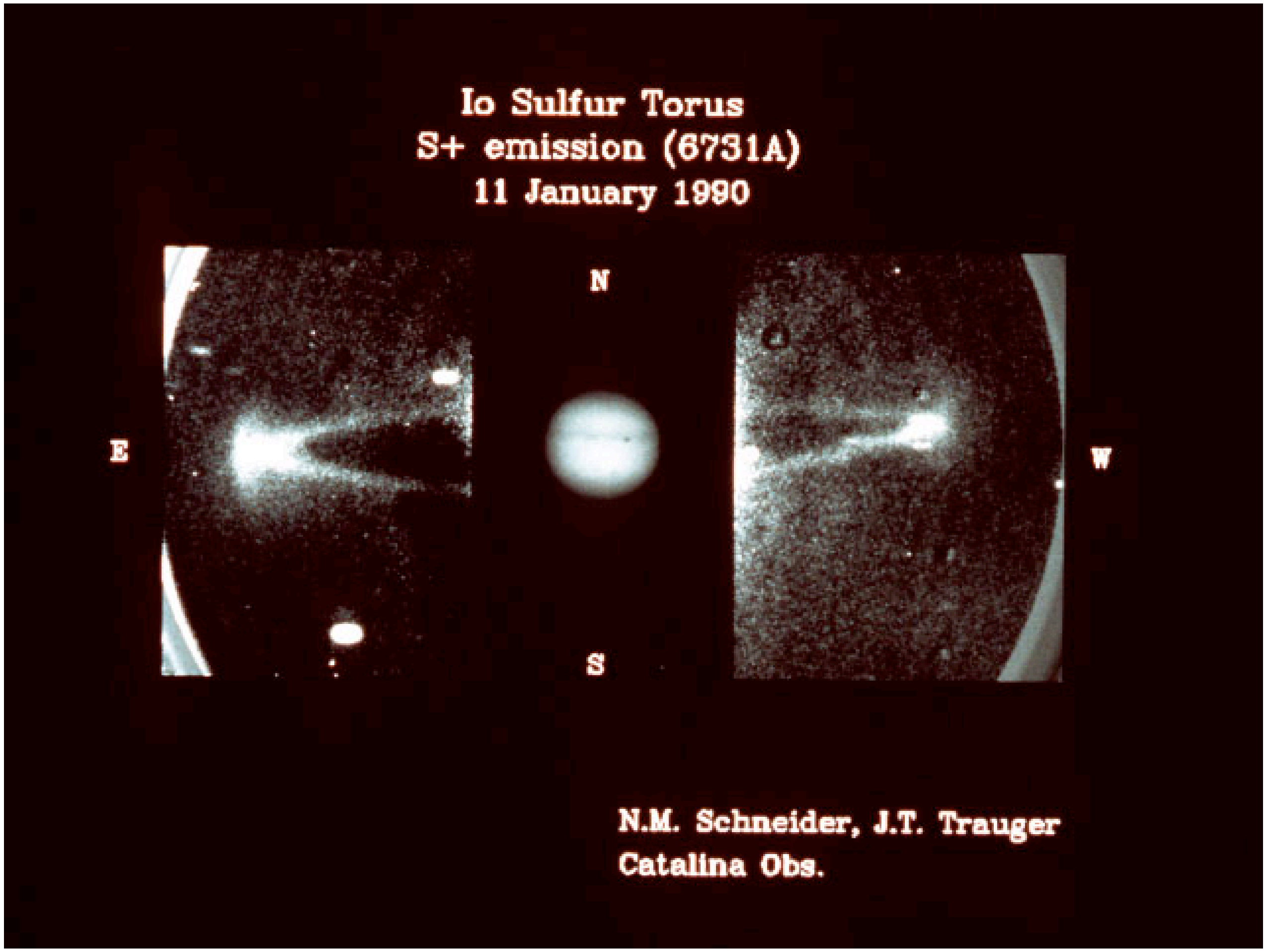


Sharp edge of plasma sphere is **stable** to interchange modes.

Jovian Magnetosphere

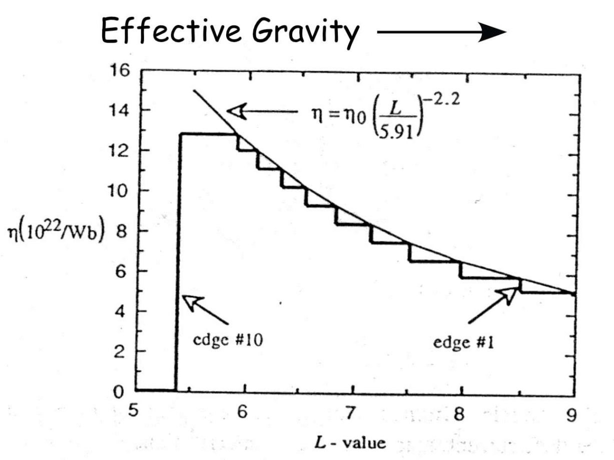


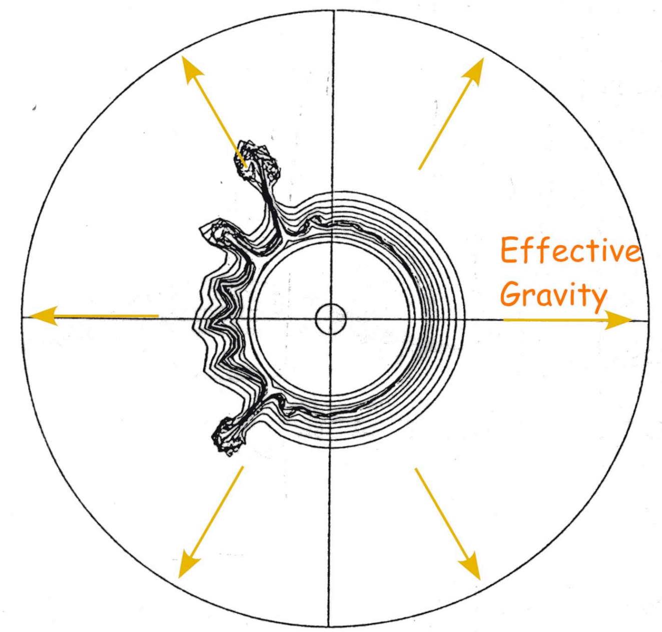
Jovian Magnetosphere



Interchange Bubbles should Propagate ***Inward*** through the Io Plasma Torus

Jovian day is 11 hours!





Numerical simulation of torus-driven plasma transport in the Jovian magnetosphere
Yang, Y. S. *et al.*, *JGR* (1994)

Interchange Bubble seen in Jovian Magnetosphere?

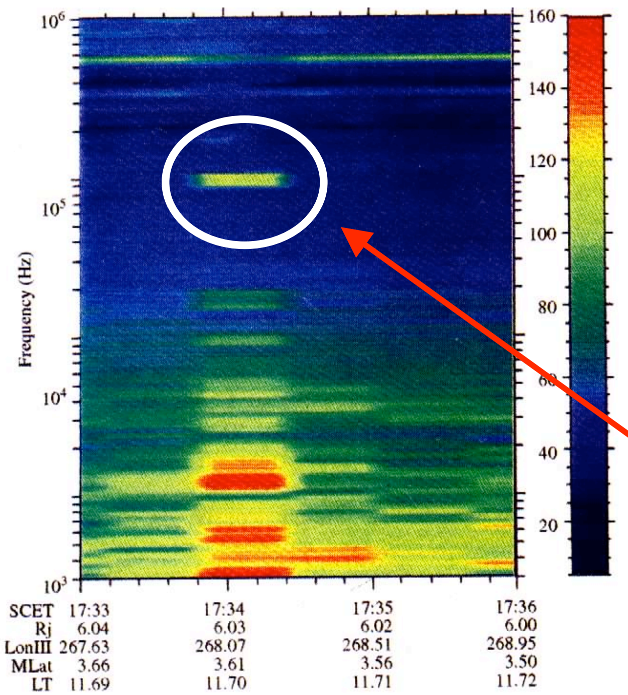


Figure 1. Plasma signatures in MAG (top panels), EPD (middle), and PWS (lower) during the 17.34 UT event.

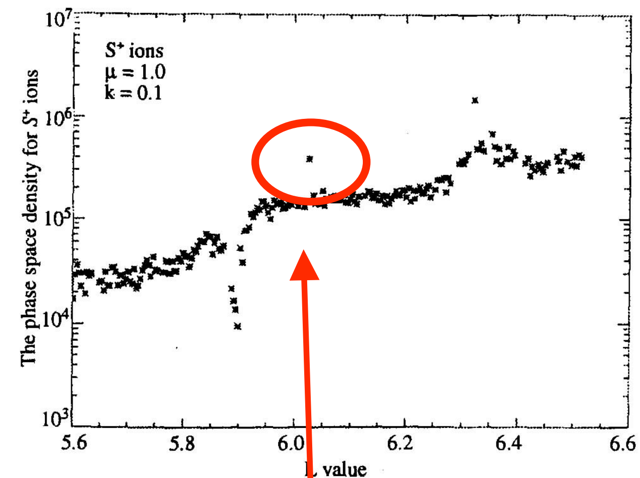


Figure 3. The radial profile of phase space density for energetic (1.0 MeV/nuc. G) S⁺ in the torus. For the anomalous enhancement at L=6.03, the phase space density is comparable to that measured in the outer torus near L= 6.3.

Bubble (?)

B. H. Mauk, et al., *GRL* (1999): Gallieo encounter

Motivating Questions

- **What is the nature of interchange instability for plasma trapped by a dipole magnetic field?**
  - Geometric structure of the electric fields?
  - Size and shape of plasma dynamical motion?
- **Nonlinear evolution…**
  - Do “bubbles” form?
  - How do the bubbles evolve in time?
  - How do the plasma profiles evolve?
- **Can we develop a physical model describing the dynamics of interchange instability in a dipole?**

Observing Interchange Instabilities in a Laboratory Magnetic Dipole:

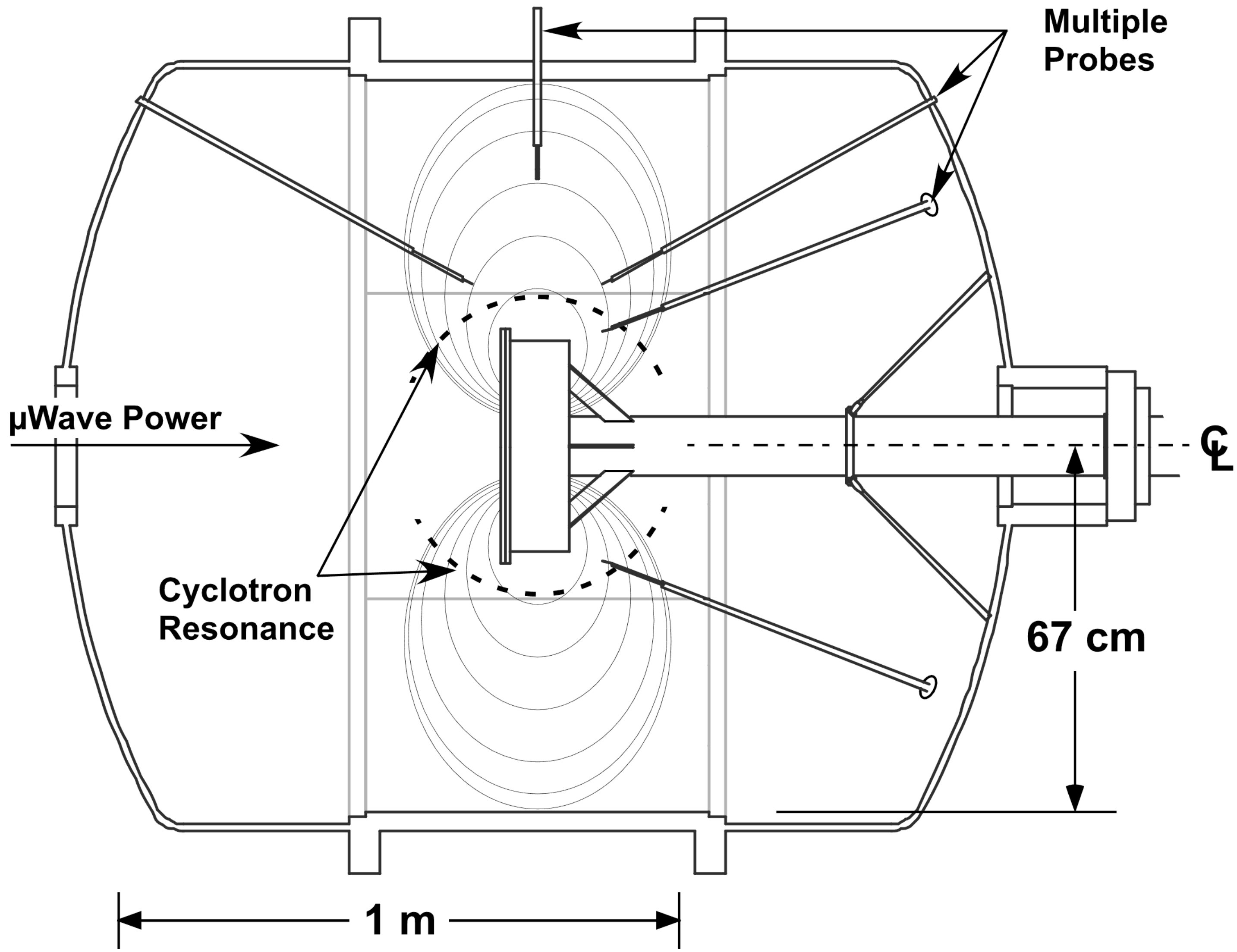
Rising Bubbles and Rising Tones

Mike Mauel, representing work by
Ben Levitt, Dmitry Maslovsky, and Harry Warren
Columbia University

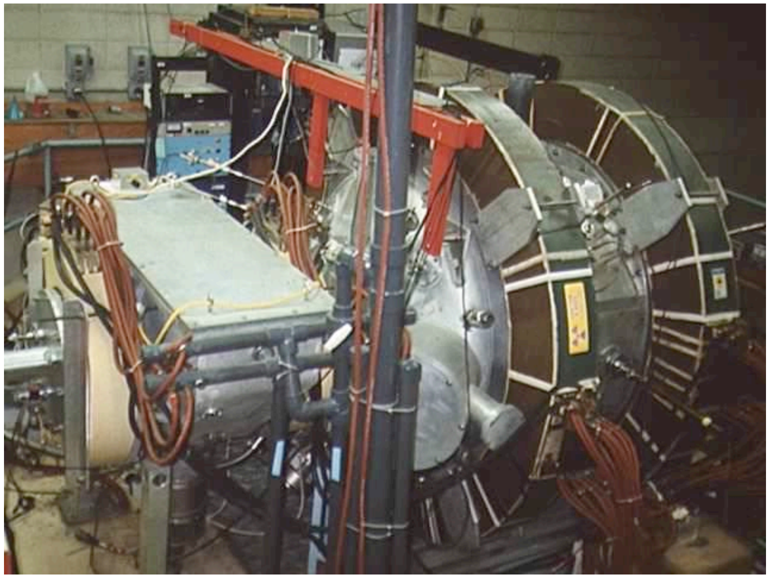
Outline

- Collisionless Terrella Experiment (CTX)
- Hot Electron Interchange (HEI) Instability
  - Global mode structure and frequency sweeping
  - Inward motion of phase-space holes (or vacuum “bubbles”)
- Self-consistent Numerical Simulation
- (*Application to Fusion Energy: High pressure, confinement by a levitated dipole magnet*)

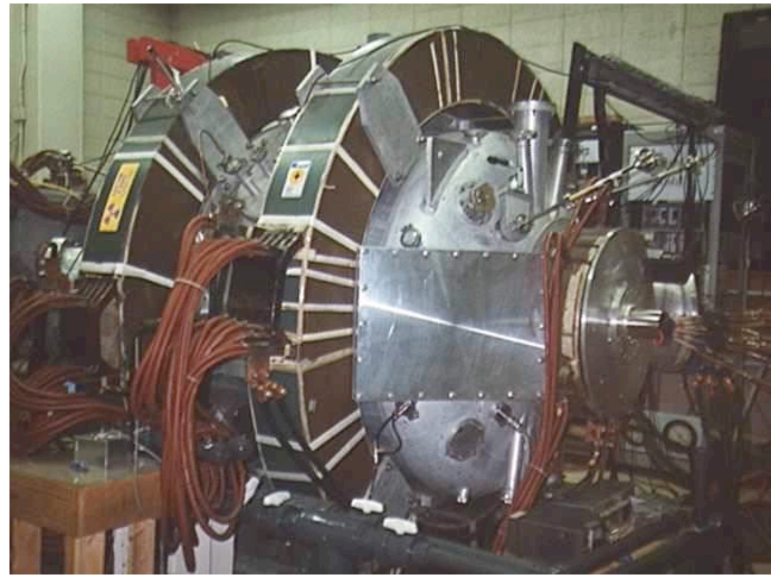
CTX



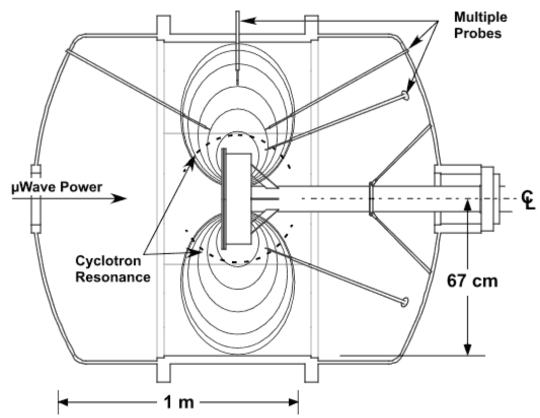
CTX



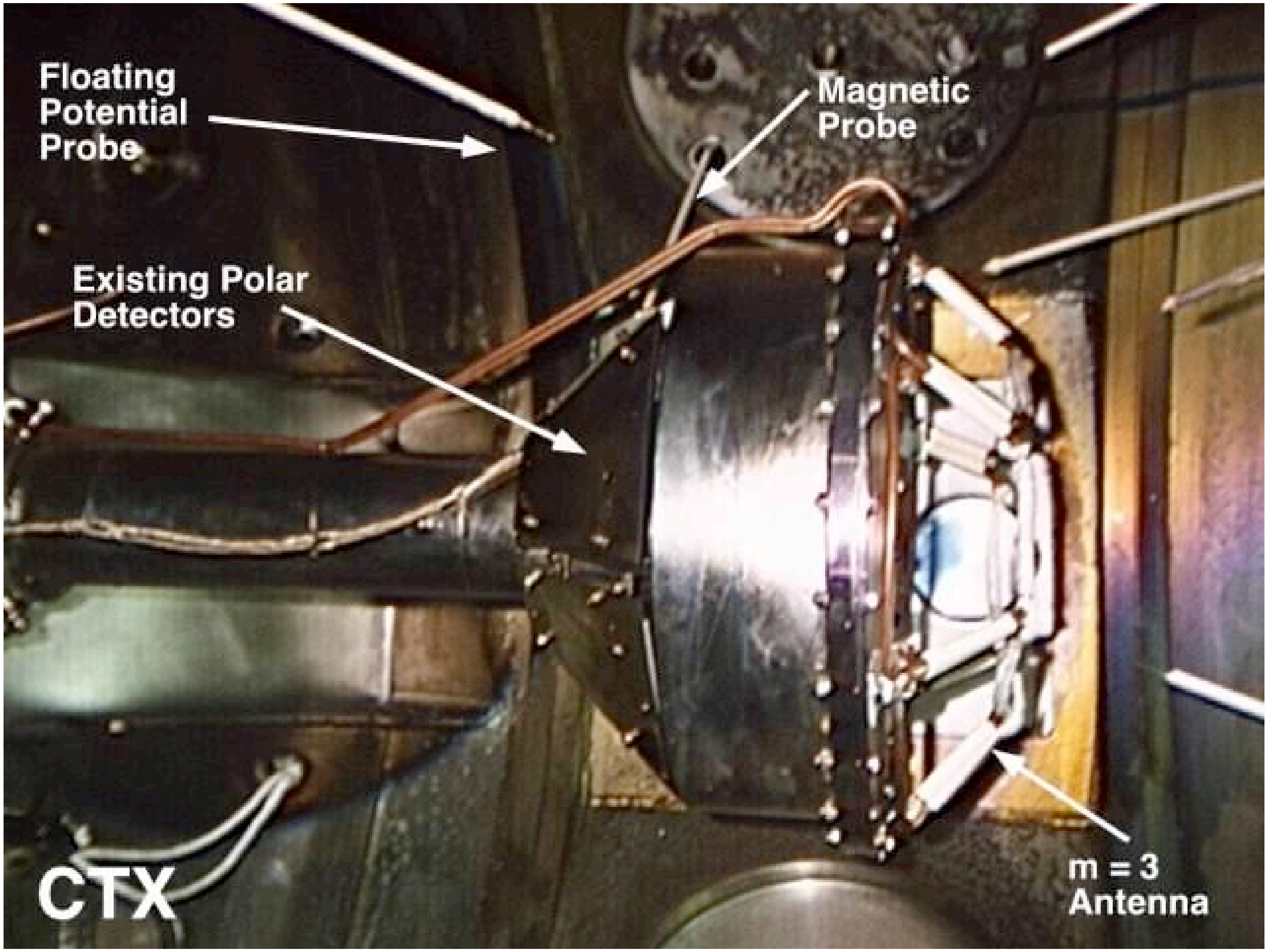
1 kW 2.45 GHz μWave Discharge



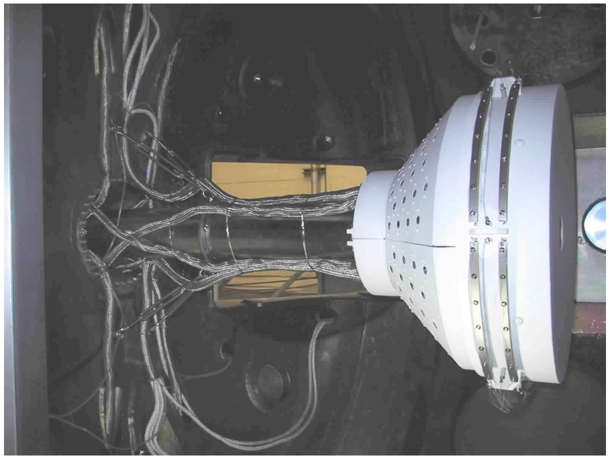
144 x 1kA Supported Electromagnet

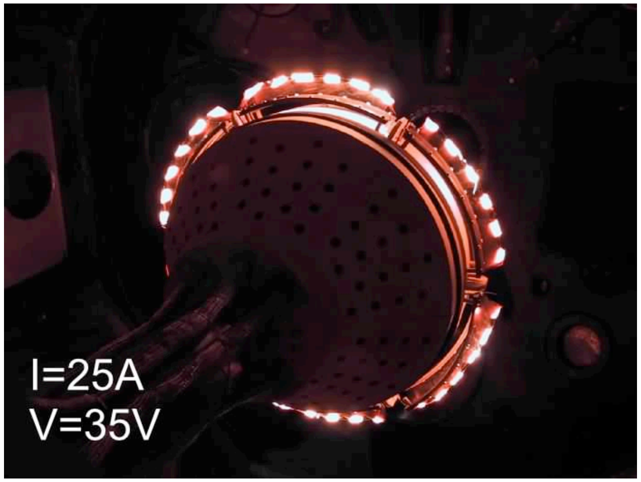


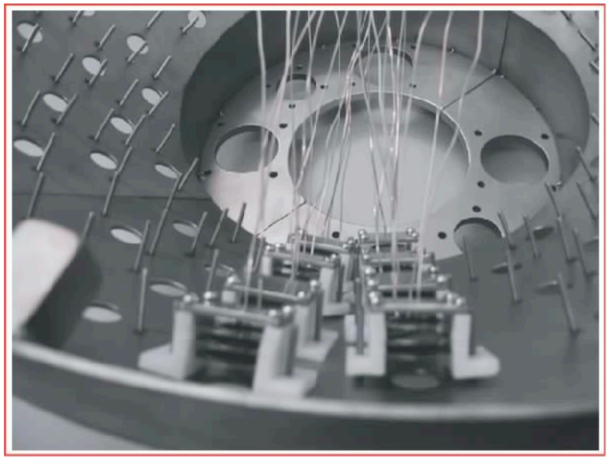
CTX


Floating Potential Probe
Magnetic Probe
Existing Polar Detectors
m = 3 Antenna
CTX

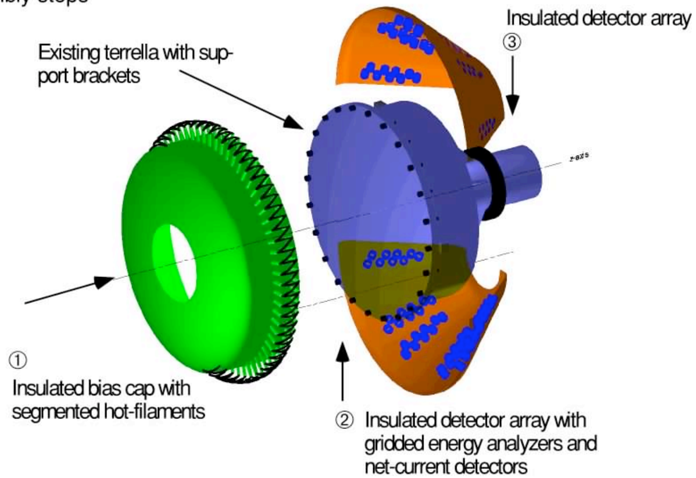
CTX (something newly installed)



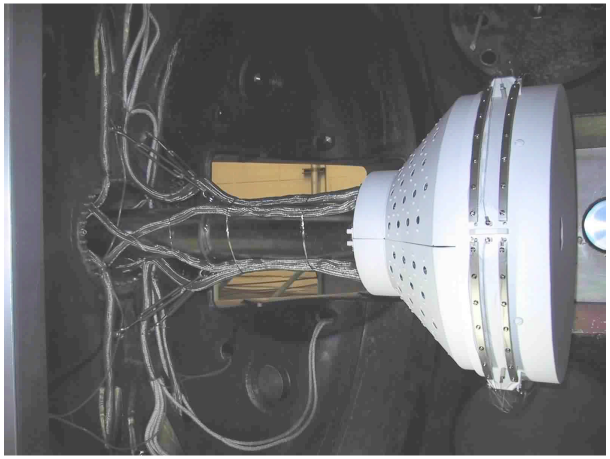


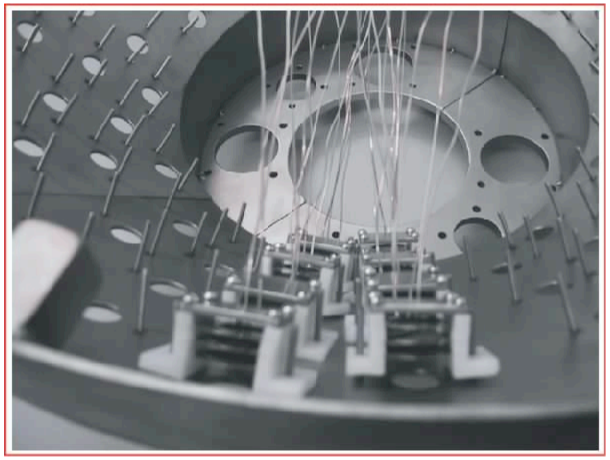


(b) Exploded-view of insulated bias and detector and illustration of assembly steps



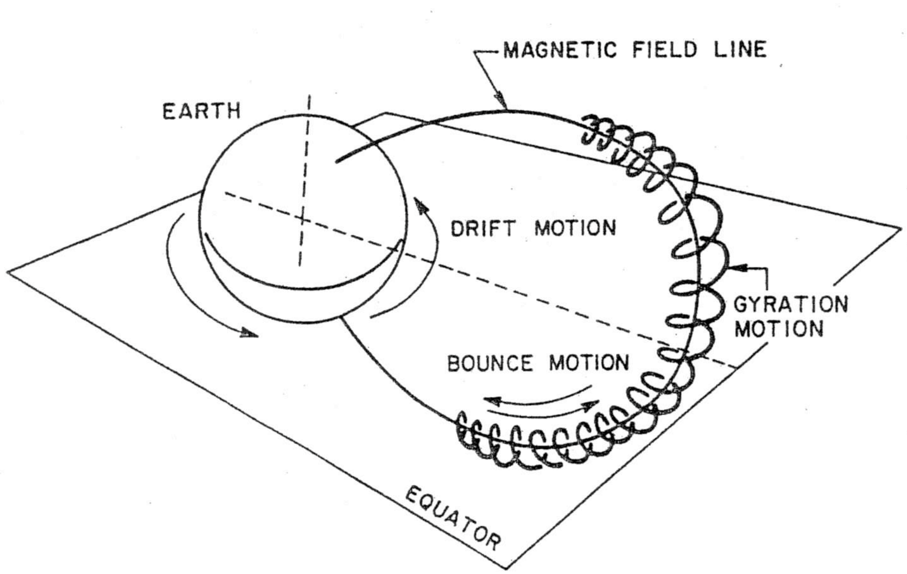
CTX (something newly installed)





Low Frequency Convective/Drift Motion

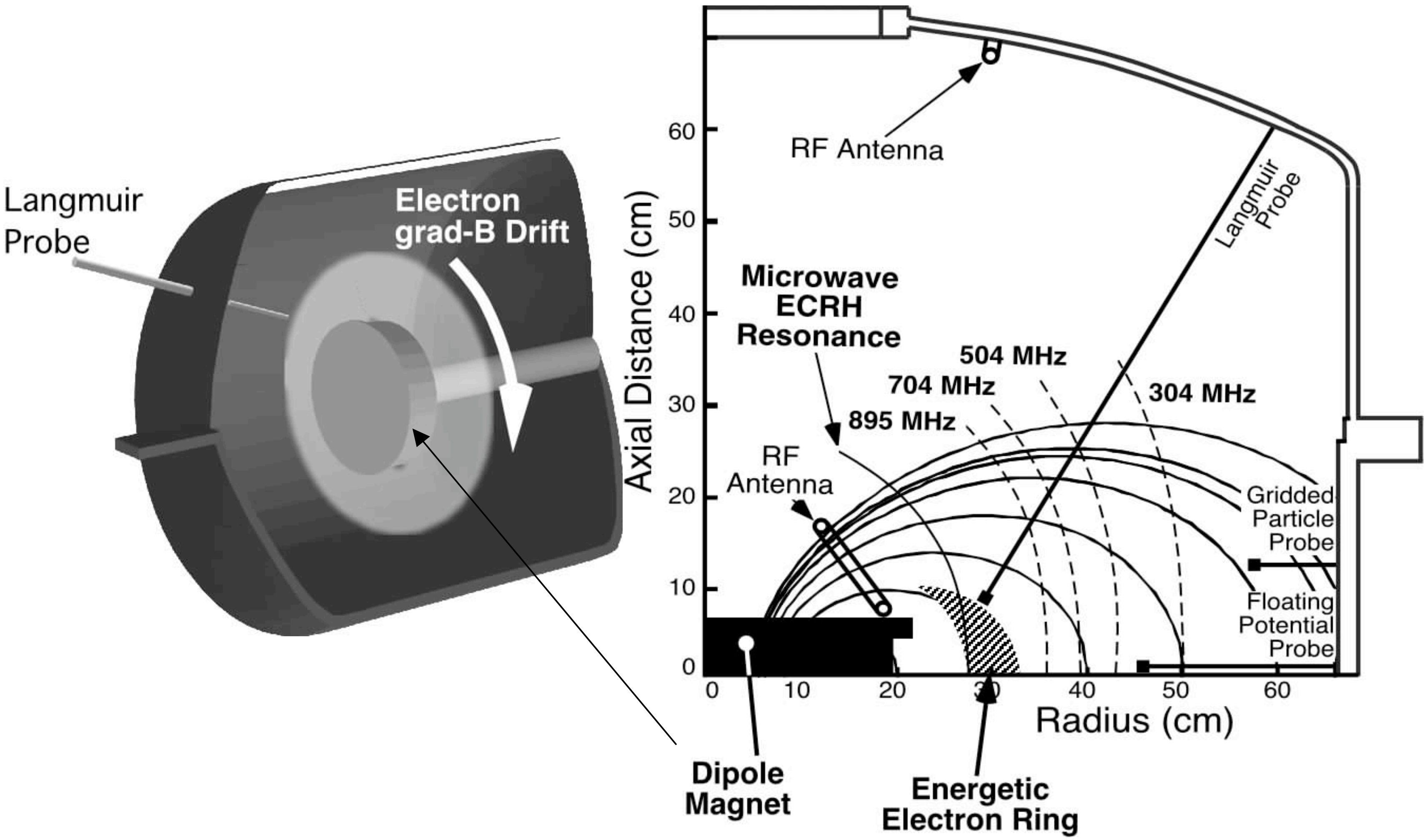
Trapped Electron Orbits



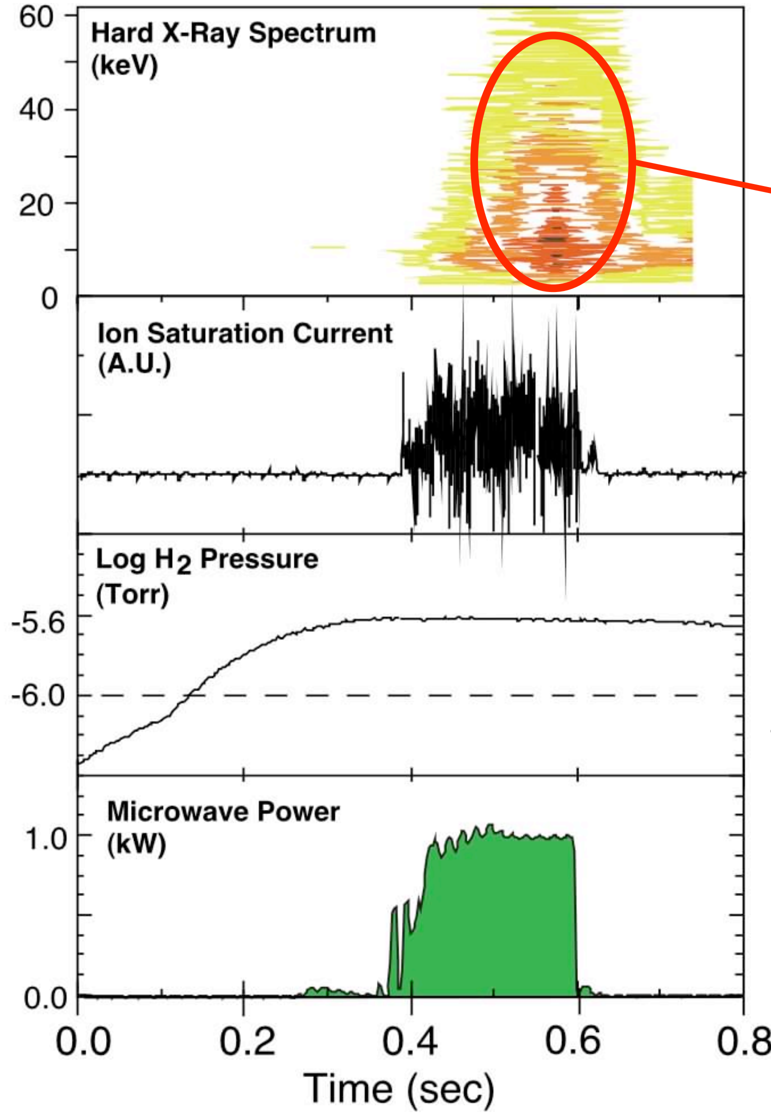
- Motion described by three well-separated frequencies
- Adiabatic invariants: (μ, J, □) □> ($\square_c$, $\square_b$, $\square_d$)
- (**Normally**, for these experiments, μ and J are constant. **Electron dynamics is 1D**!)

Important: $\square_d$ ~ energy/R^2 $\square_c$ ~ $1/R^3$

Magnetic Geometry



Typical Microwave Discharge



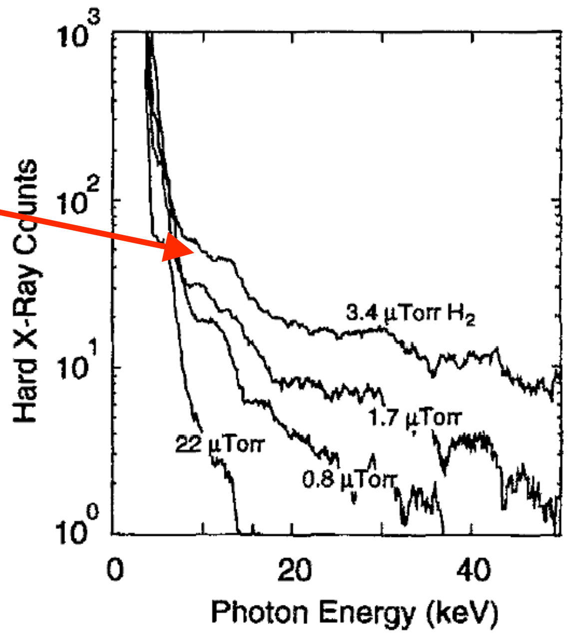
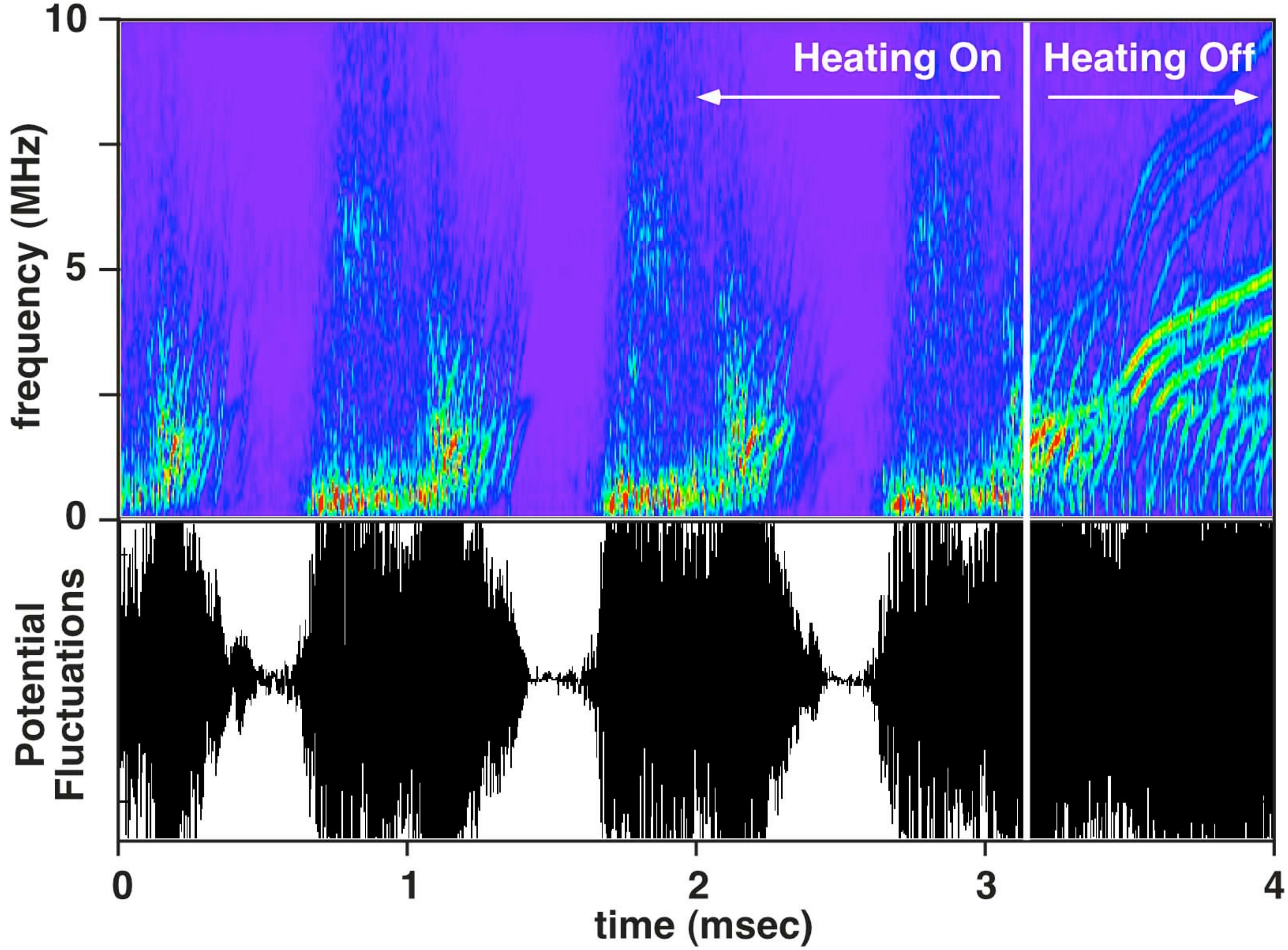


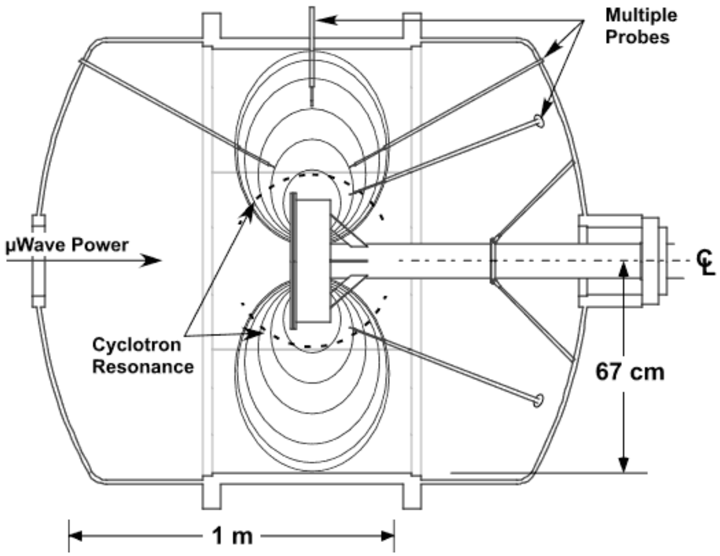
FIG. 3. Hard x-ray emission as a function of hydrogen fill pressure. If the peak pressure falls above or below the optimal value, the hot electron energy will be reduced.

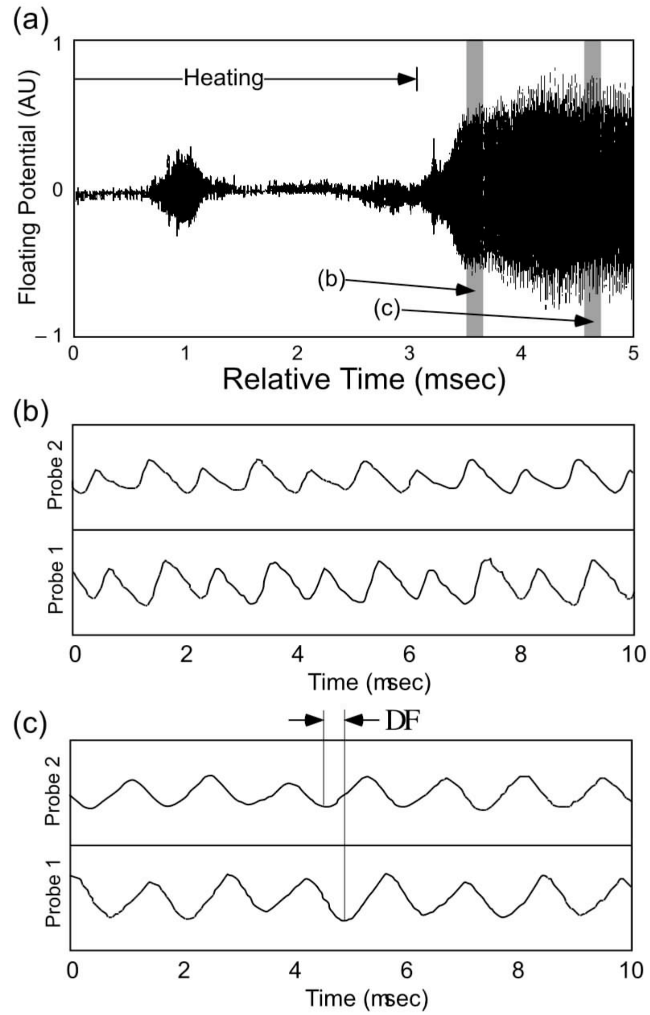
Cyclotron frequency, $\omega_c/2\pi$	2 GHz
Bounce frequency, $\omega_b/2\pi$	150 MHz
Drift frequency, $\omega_d/2\pi$	0.4 MHz
Normalized energy, $(\rho/L)^2$	5×10^{-5}

Quasiperiodic Instability Bursts



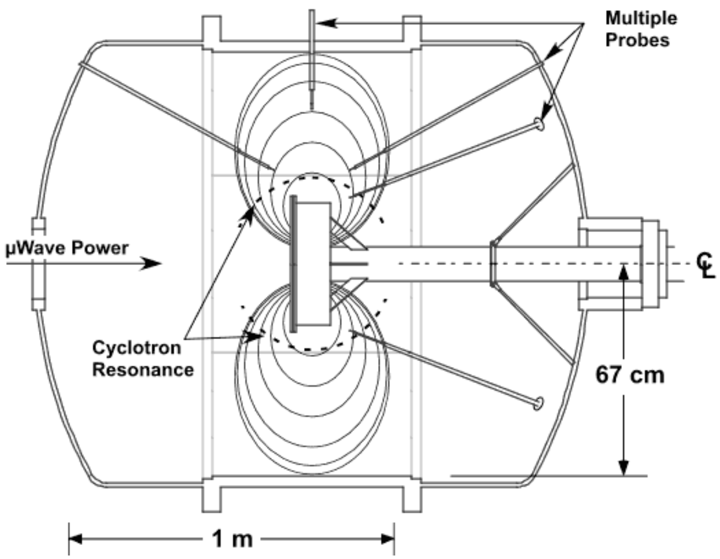
Multi-Probe Cross Correlations



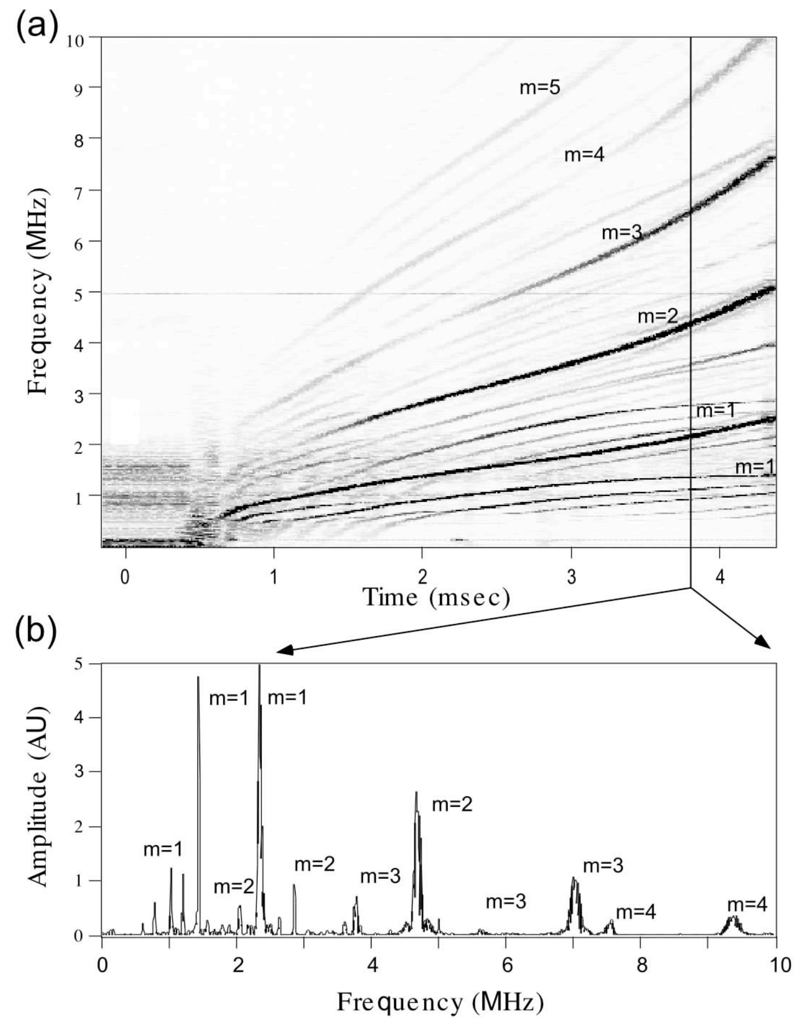


- Phase correlations, direction

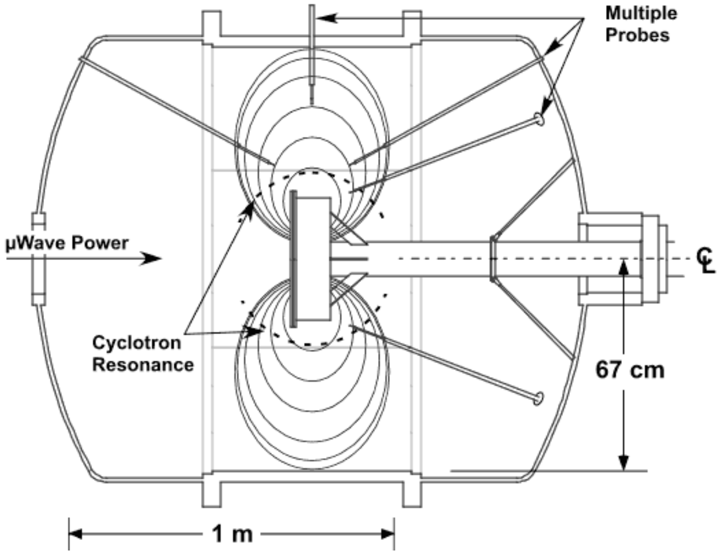
Multi-Probe Cross Correlations

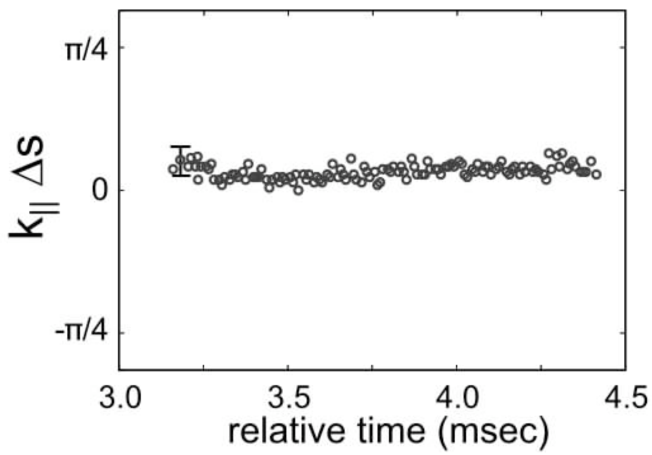


- Phase correlations, direction
- Azimuthal mode, *m*



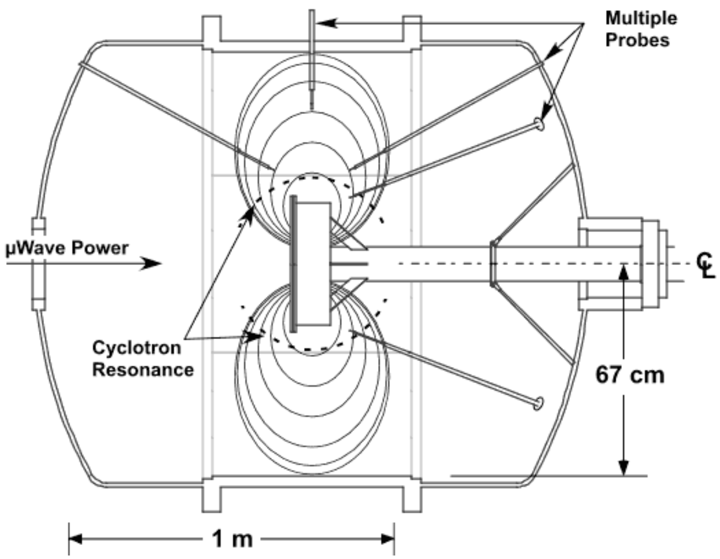
Multi-Probe Cross Correlations

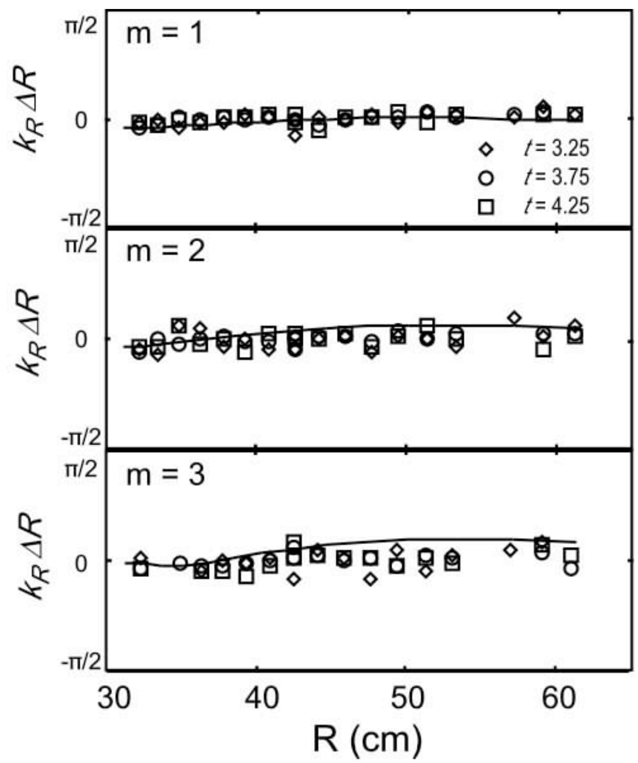




- Phase correlations, direction
- Azimuthal mode, *m*
- Uniform structure along B

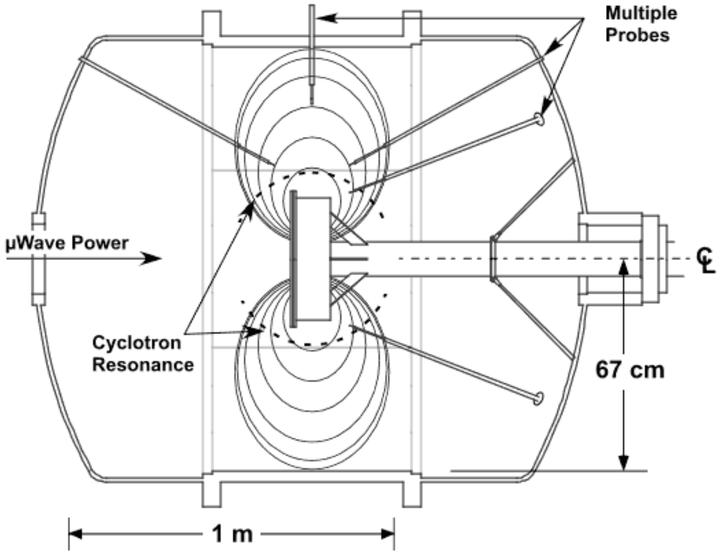
Multi-Probe Cross Correlations

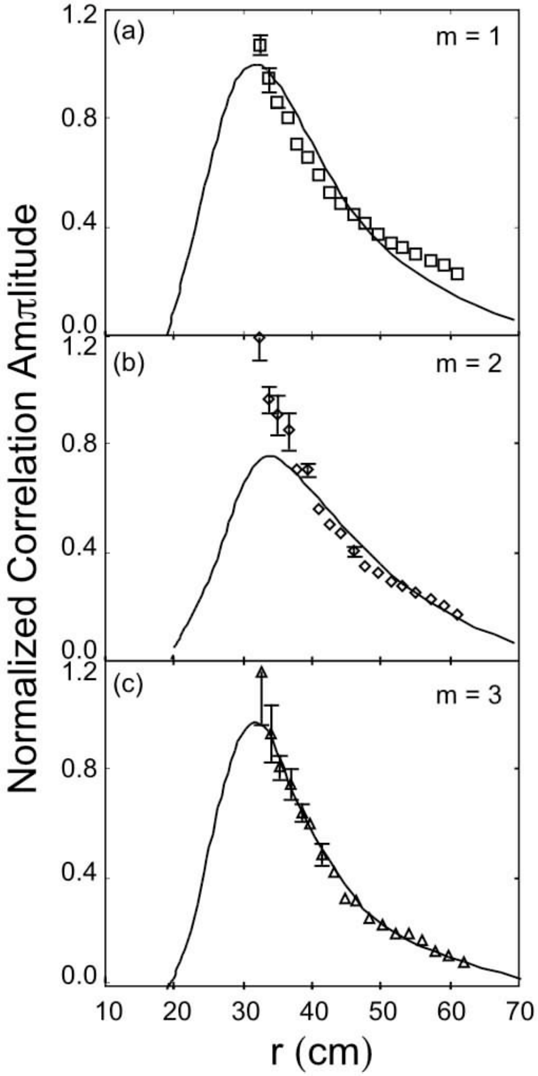




- Phase correlations, direction
- Azimuthal mode, *m*
- Uniform structure along B
- Rigid rotation

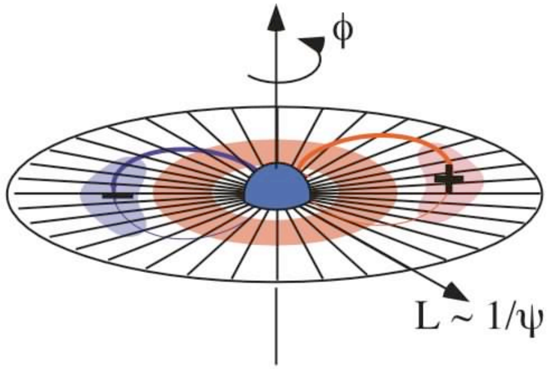
Multi-Probe Cross Correlations





- Phase correlations, direction
- Azimuthal mode, *m*
- Uniform structure along B
- Rigid rotation
- Broad radial structure

Physical Picture of HEI

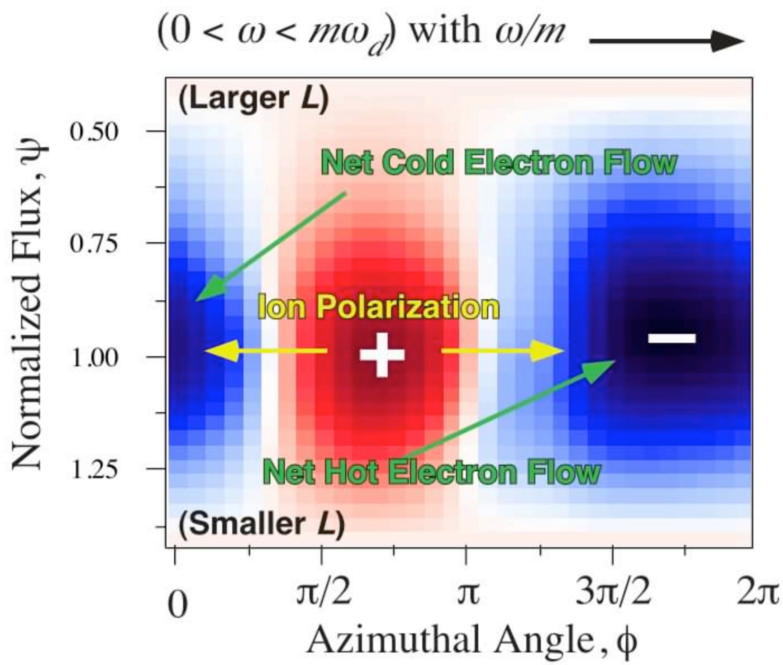


Hot electron disk, $J \approx 0$, described by bounce-averaged distribution, $F(\mu, \psi)$.

Cold electrons force $k_{\|} \rightarrow 0$ and create a 2D problem in time, (ψ, ϕ, t).

Cold neutralizing ions.

Define N_i, N_e, N_h as the total charge on a flux tube. For adiabatic profiles, $\partial N_i / \partial \psi \approx 0$.

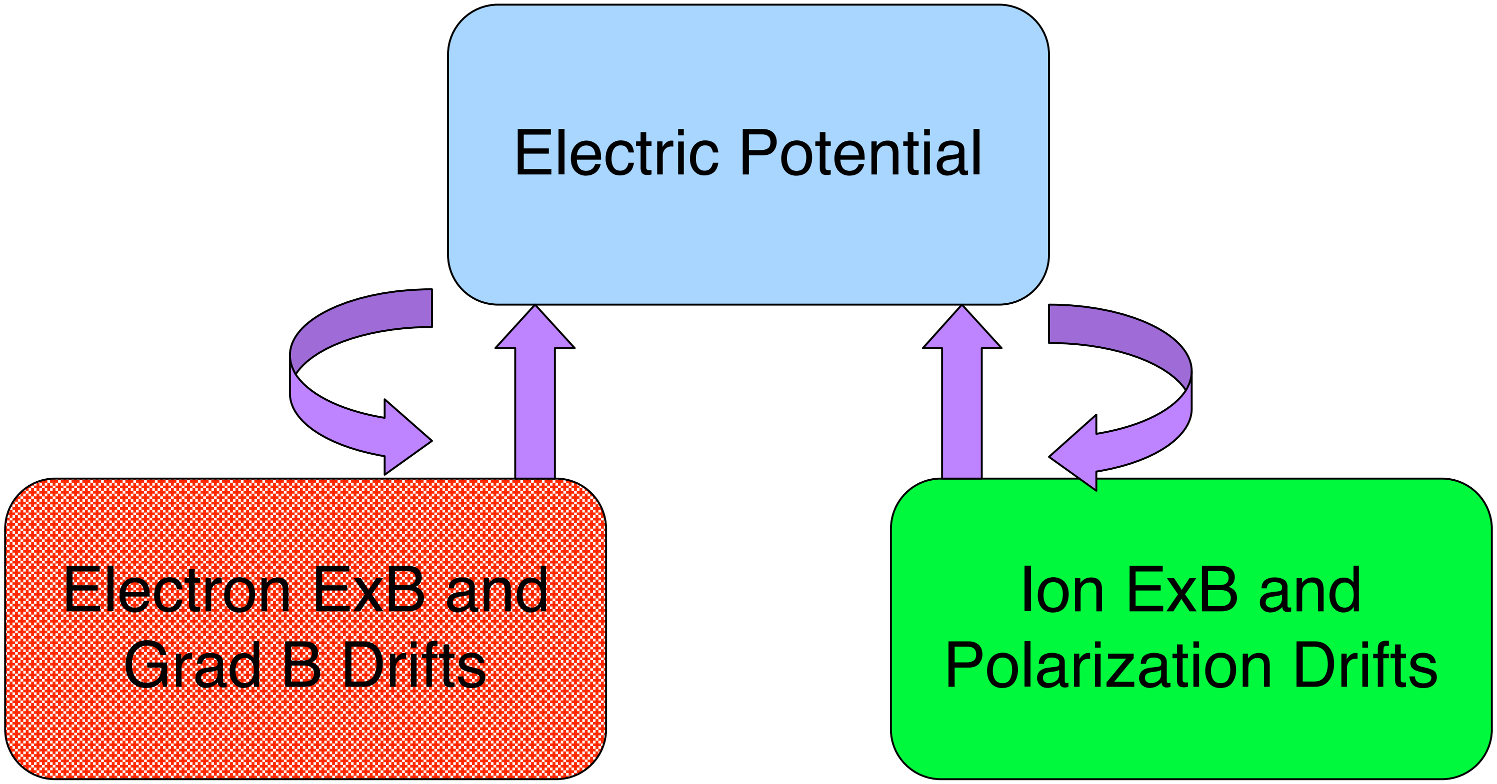


The electron $\mathbf{E} \times \mathbf{B}$ flows are proportional to the hot electron gradient, $\partial N_h / \partial \psi$, and they lag or lead the circulating wave.

The ion polarization current is always stabilizing, and this leads to an instability threshold.

(Ref: Krall, *Phys. Fluids*, 1966)

Simulating Resonant Interchanges



An example of plasma's fundamental nonlinear coupling!

Simulating Resonant Interchanges

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

$$\begin{aligned}\dot\varphi &= \frac{\partial\mathcal{H}}{\partial\psi}=\mu\frac{c}{e}\frac{\partial B}{\partial\psi}-c\frac{\partial\Phi}{\partial\psi},\\ \dot\psi &= -\frac{\partial\mathcal{H}}{\partial\varphi}=c\frac{\partial\Phi}{\partial\varphi}.\end{aligned}$$

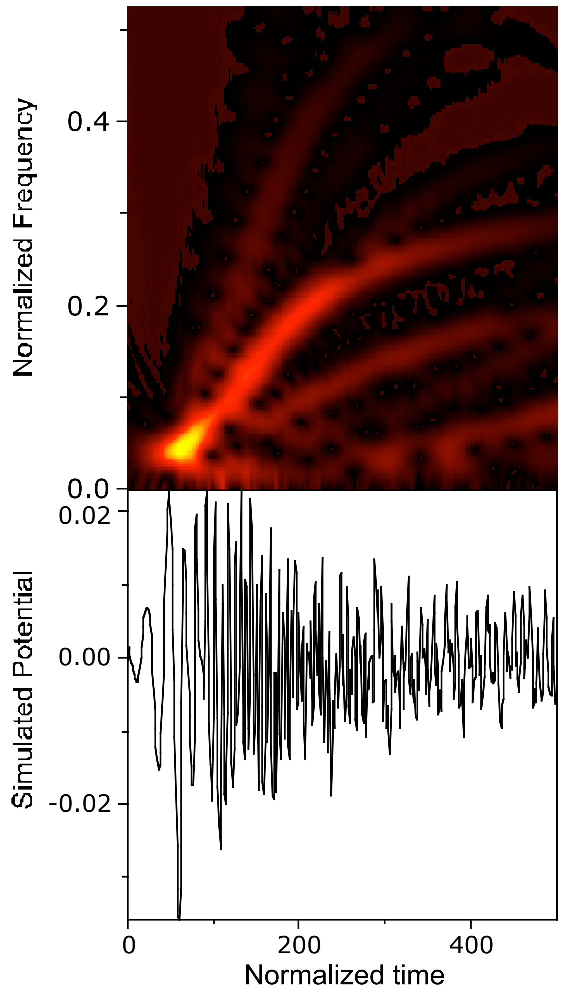
$$\frac{\partial F}{\partial t}+\frac{\partial}{\partial\varphi}(\dot\varphi F)+\frac{\partial}{\partial\psi}(\dot\psi F)=0.$$

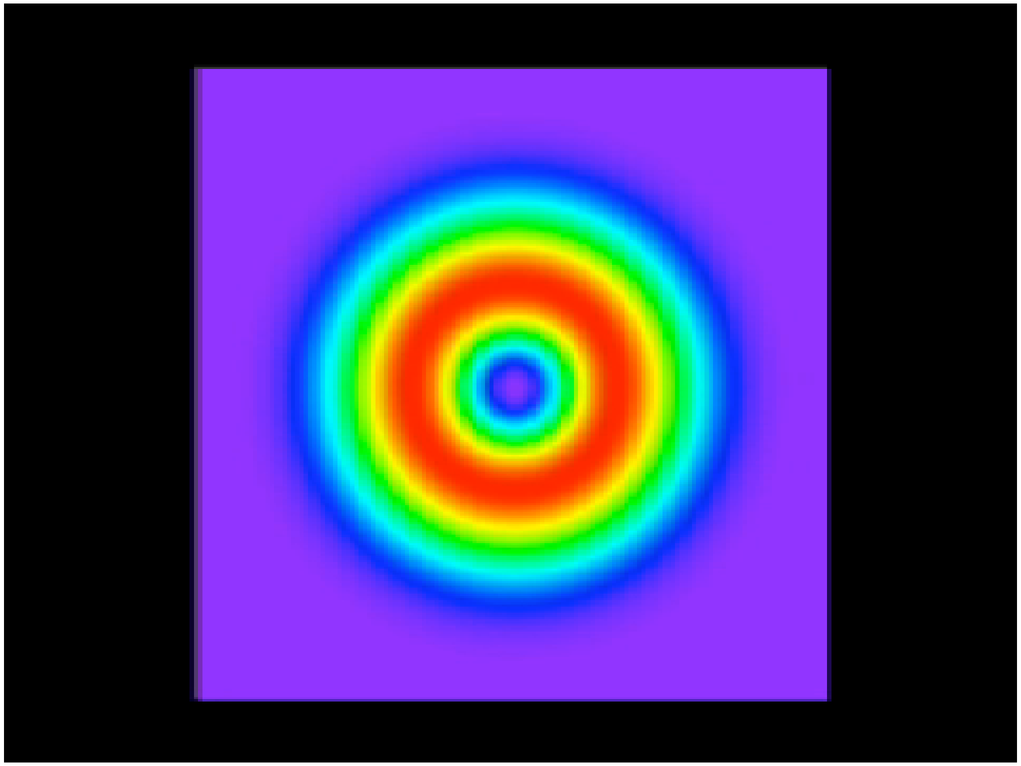
$$\frac{\partial N_i}{\partial t}+\frac{\partial}{\partial\varphi}\left(N_i\|\nabla\varphi\cdot\mathbf{V}\|\right)+\frac{\partial}{\partial\psi}\left(N_i\|\nabla\psi\cdot\mathbf{V}\|\right)=0.$$

$$\begin{aligned}&\frac{\partial N_i}{\partial t}+\frac{\partial}{\partial\varphi}\left[cN_i\left(-\frac{\partial\Phi}{\partial\psi}-\left\|\frac{|\nabla\varphi|^2}{\omega_{ci}B}\right\|\frac{\partial^2\Phi}{\partial\varphi\partial t}\right)\right]\\ &\qquad+\frac{\partial}{\partial\psi}\left[cN_i\left(\frac{\partial\Phi}{\partial\varphi}-\left\|\frac{|\nabla\psi|^2}{\omega_{ci}B}\right\|\frac{\partial^2\Phi}{\partial\psi\partial t}\right)\right]=0\end{aligned}$$

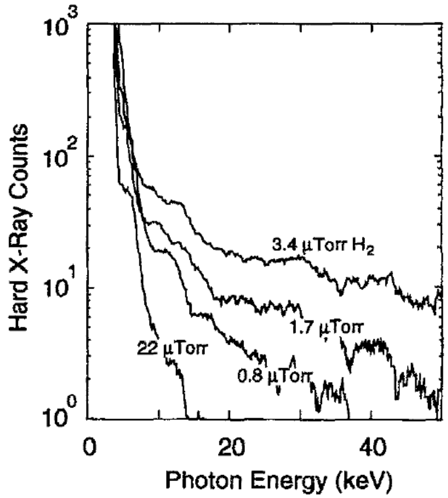
Solved on a 64 x 64 grid: 8 hours on one 2.0 GHz PIV.

Simulation Results





Frequency Sweeping Corresponds to "Holes" in Multiple Hot Electron Phase-Spaces

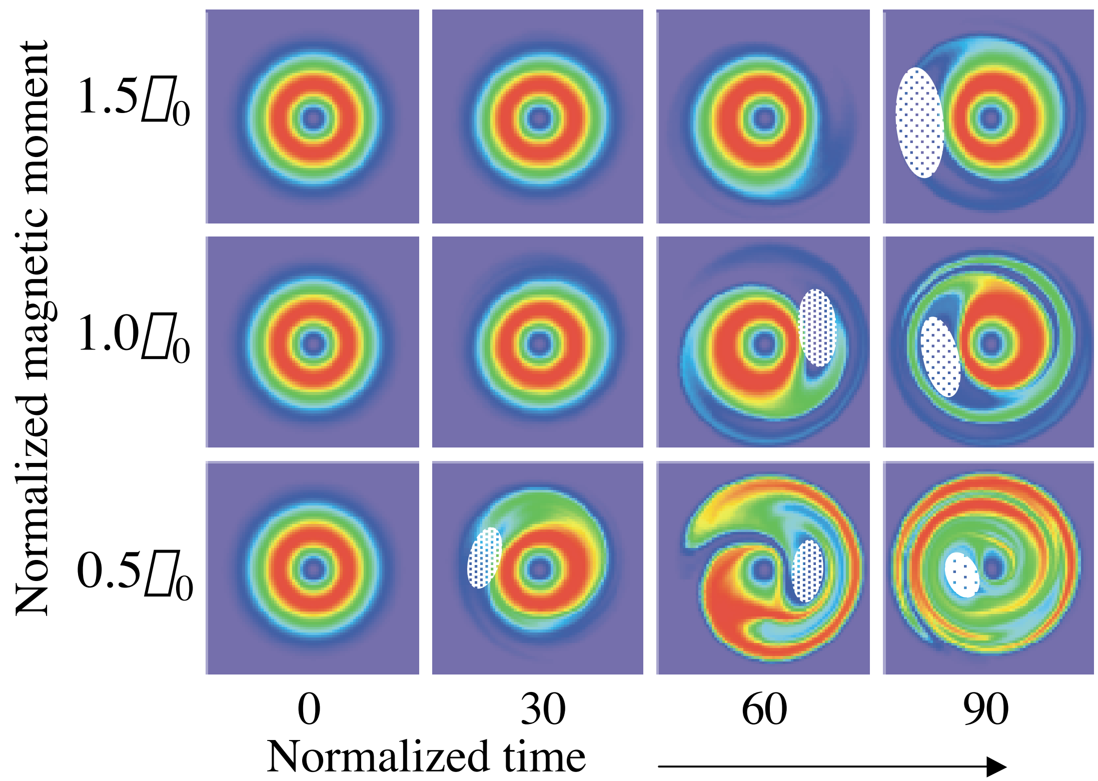


The linear frequency of the mode

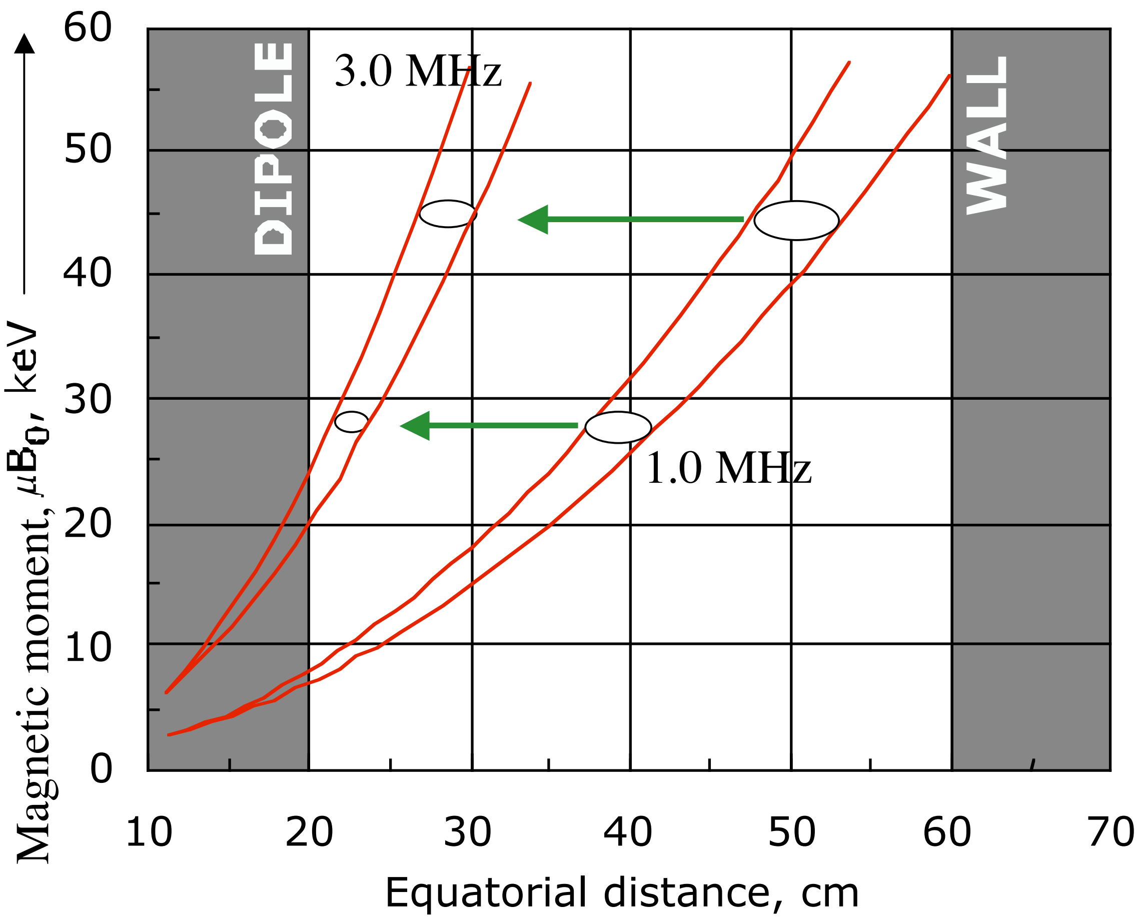
$$\omega < \omega_d / 2$$

Phase-space "holes" begin at low energy and outer flux surfaces.

As frequency increases, "holes" propagate inward.



Motion of Phase-Space Holes



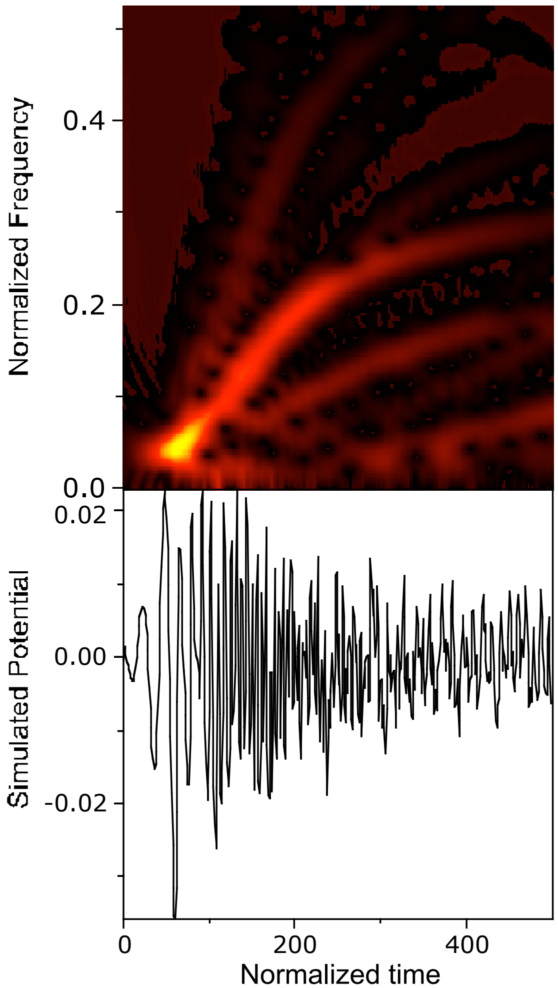
- Magnetic drift proportional to μ (energy)
- Location of a (~100 V) phase-space "hole" is set by resonance condition

$$\omega = \omega_d(\mu) \sim \mu/R^2$$

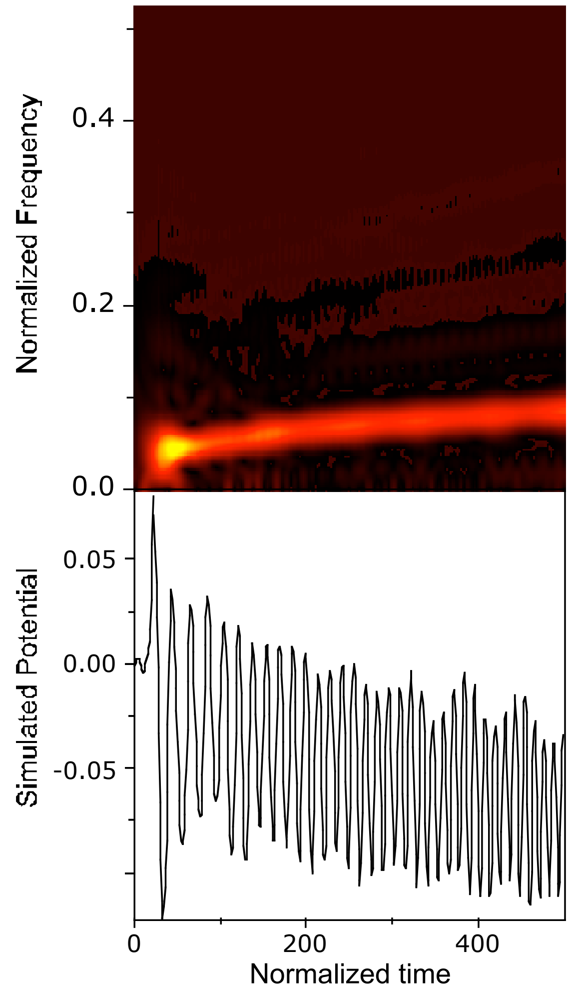
- As frequency rises, phase-space hole moves **adiabatically** inward!

Why does the frequency rise?

(Where does the electron energy go?)



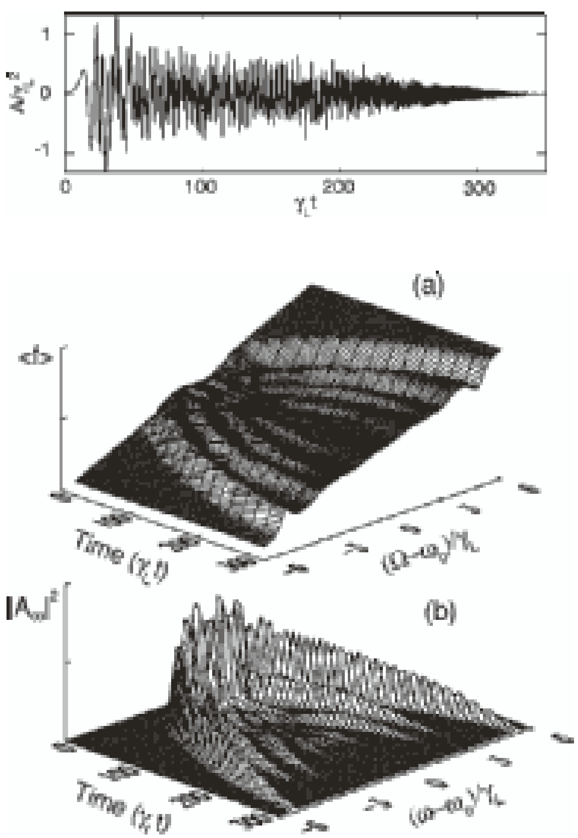
$\Box_L / \Box_d = 1.6$



$\Box_L / \Box_d > 6$

A General Nonlinear Description for Instability near Threshold

H. L. Berk, B. N. Breizman, *et al.*, Phys. Plasmas, 6, (1999)



Berk and co-workers have described spontaneous frequency sweeping.

- Inverted particle distribution profile
- Near threshold: linear growth, balanced by non-resonant dissipation

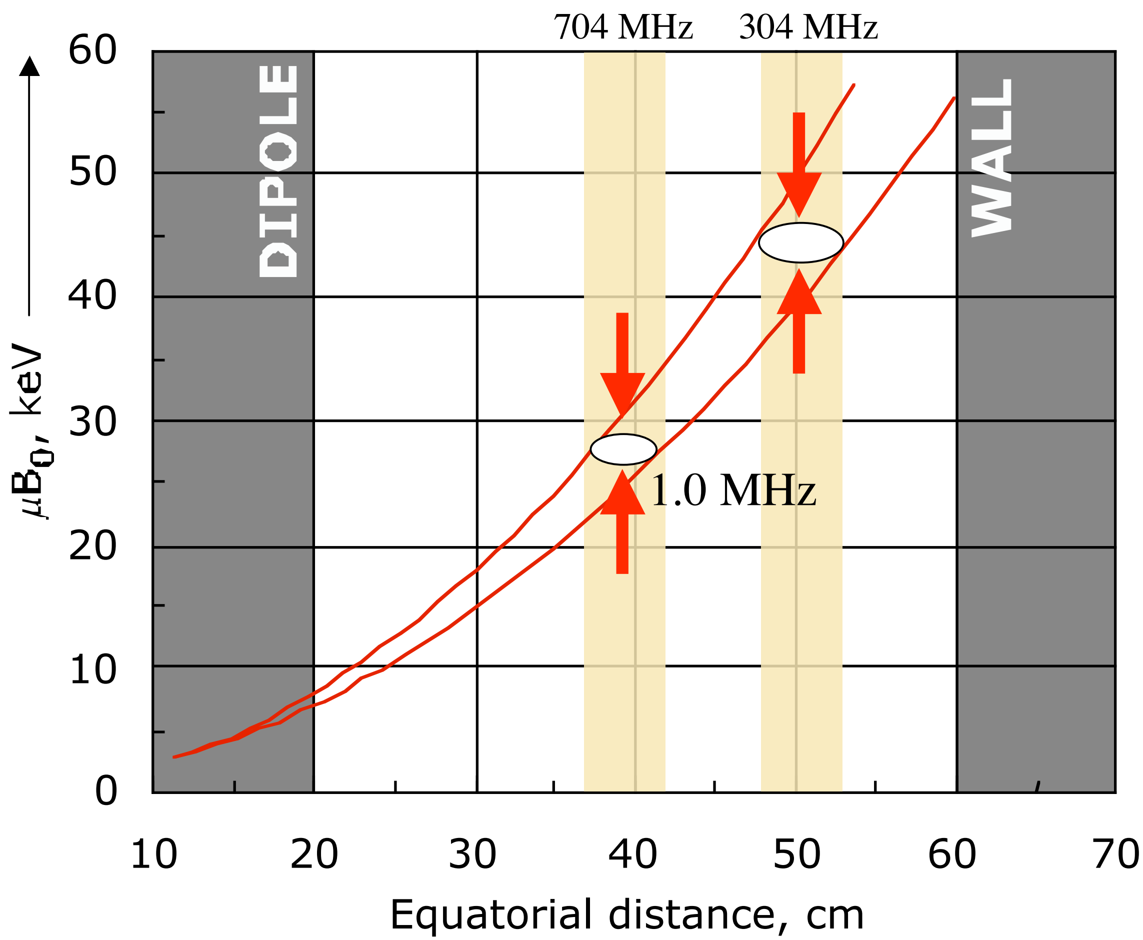
➲Slowed linear growth is followed by an explosive phase and frequency sweeping

➲Requires *collisionless* resonant particles

Two criteria for frequency sweeping:

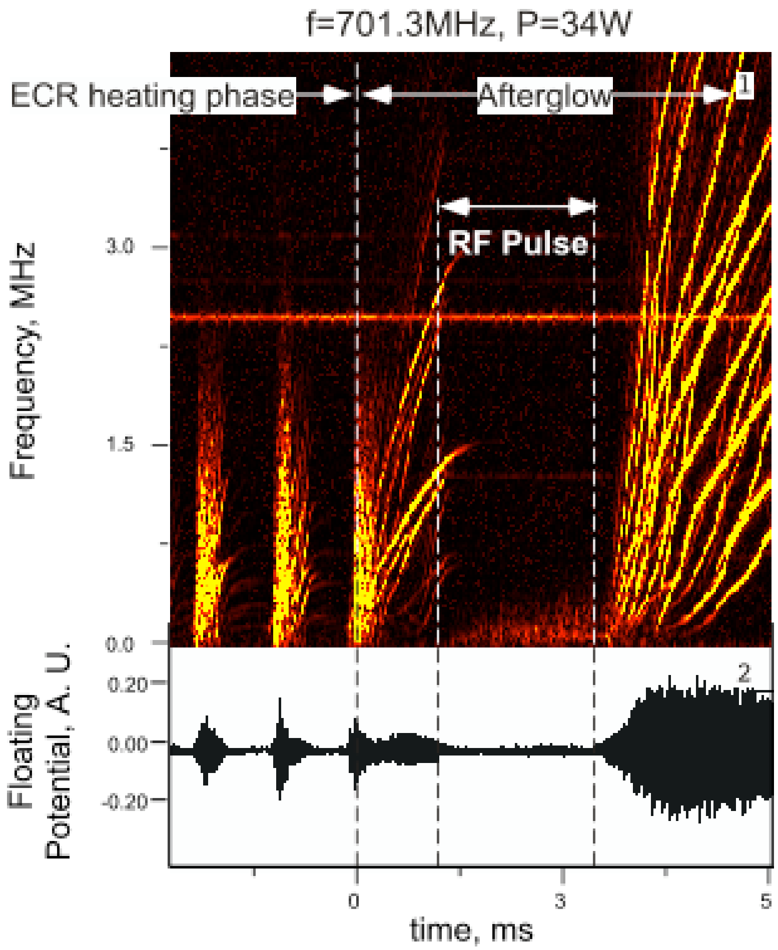
$\gamma_L < 2.5\gamma_d$ $\nu_{eff} < \gamma_L - \gamma_d \equiv \gamma$

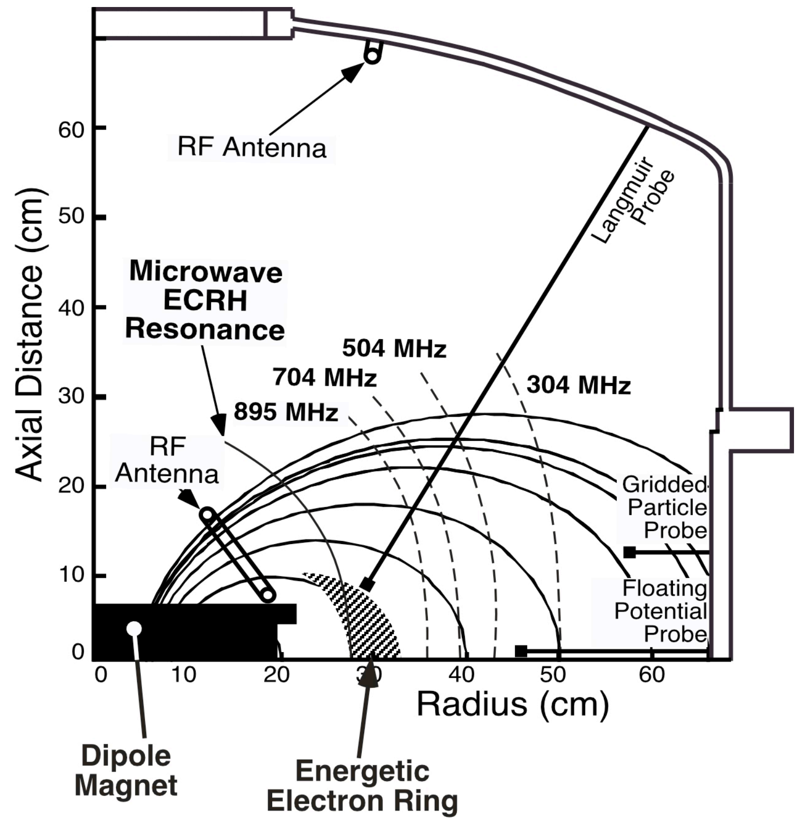
A test for phase-space holes…



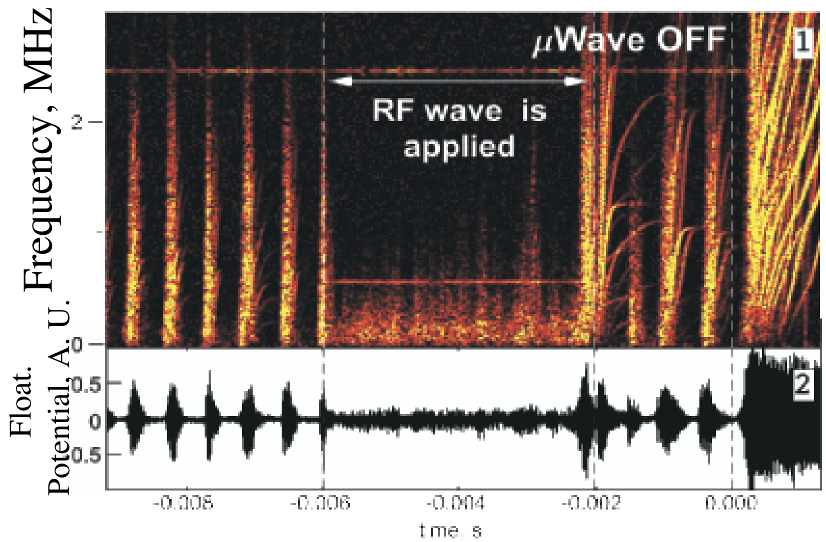
- Apply cyclotron resonant fields to the outer flux surfaces: locations where phase-space “holes” are initiated
- Stochastic energy diffusion (within a flux tube) fills the phase-space “holes” and arrests frequency sweeping

Low-Power RF Fields Suppress Frequency Sweeping

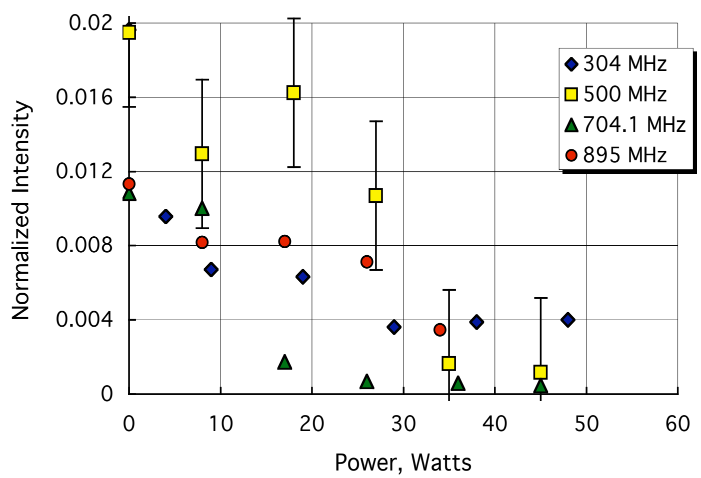


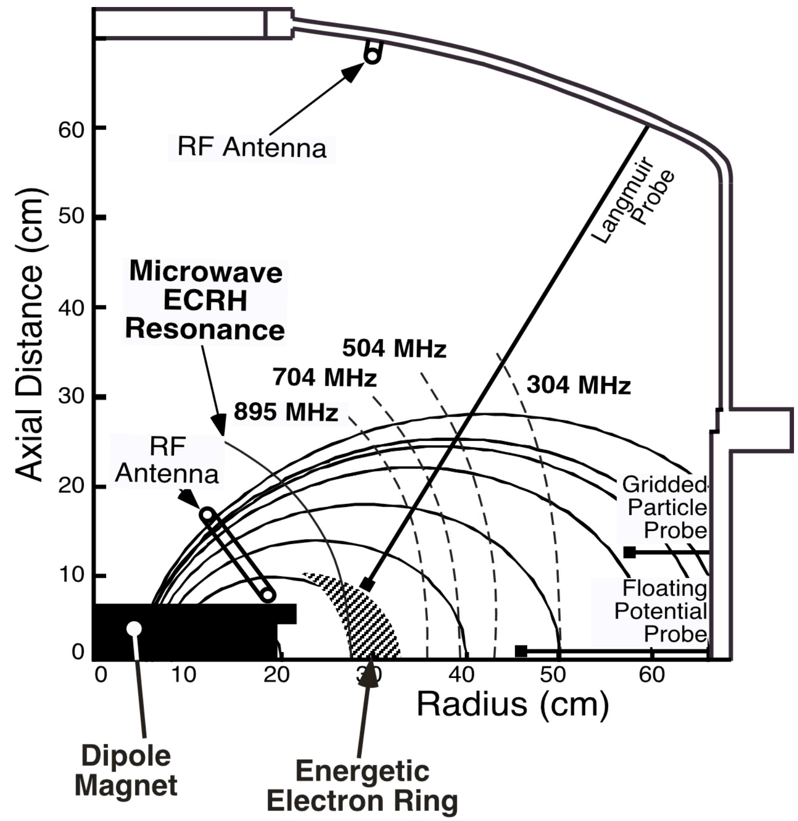


Low-Power RF Fields Suppress Frequency Sweeping



1.9MHz<f<2.1MHz





Modeling ECRH Diffusion

The applied cyclotron resonant RF fields are modeled as causing diffusion of energetic electrons in $\square$-space, according to:

$$\frac{\partial}{\partial t} F(\square,\square,\square,t) + \square = D(\square,t)\frac{\partial^2}{\partial \square^2}\left(F \square F^*\right)$$

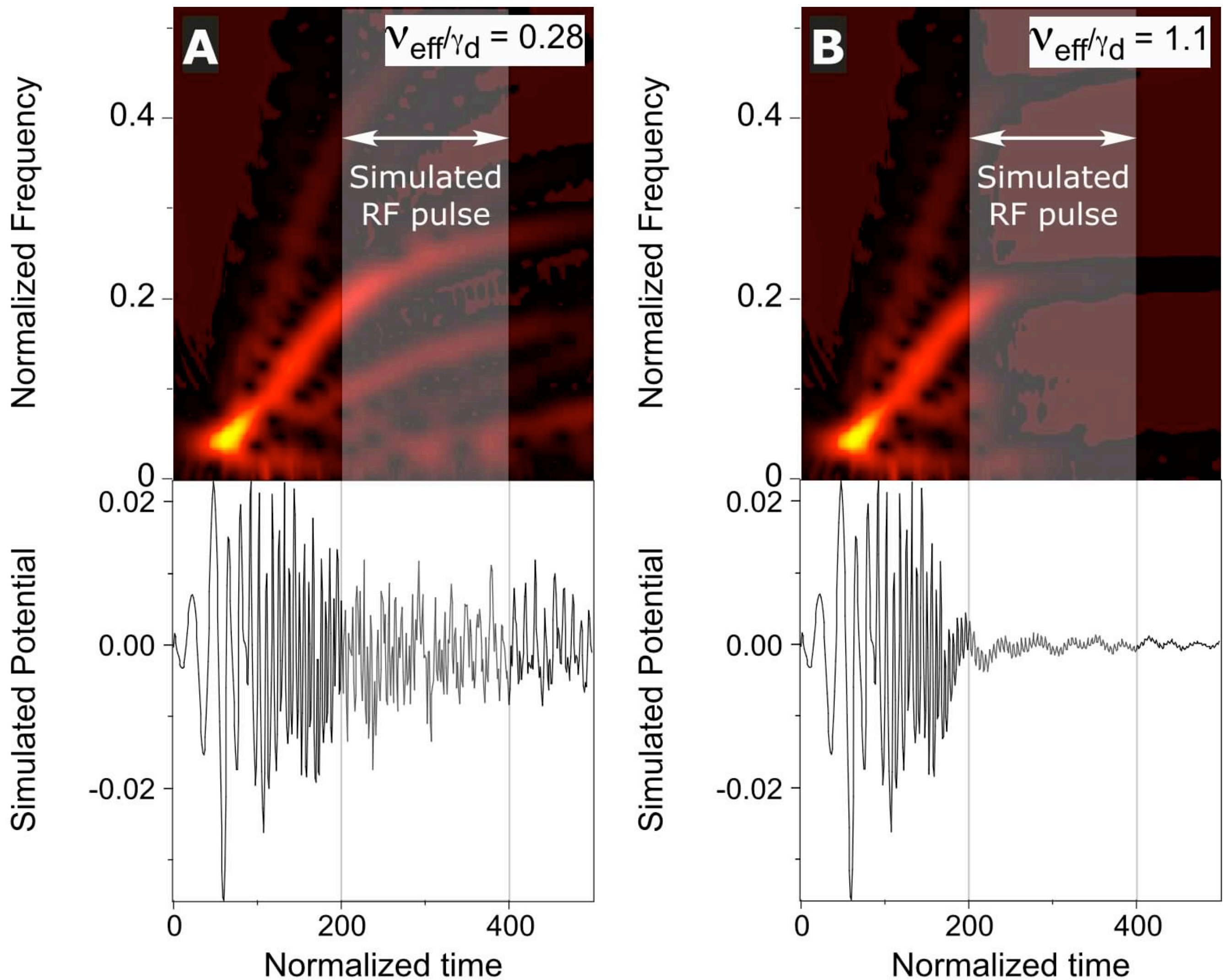
This is similar to velocity-space diffusion described by Berk:

$$\frac{\partial f}{\partial t} + \square = \square_{eff}^3 \frac{\partial^2}{\partial \square^2}\left(f \square f^*\right)$$

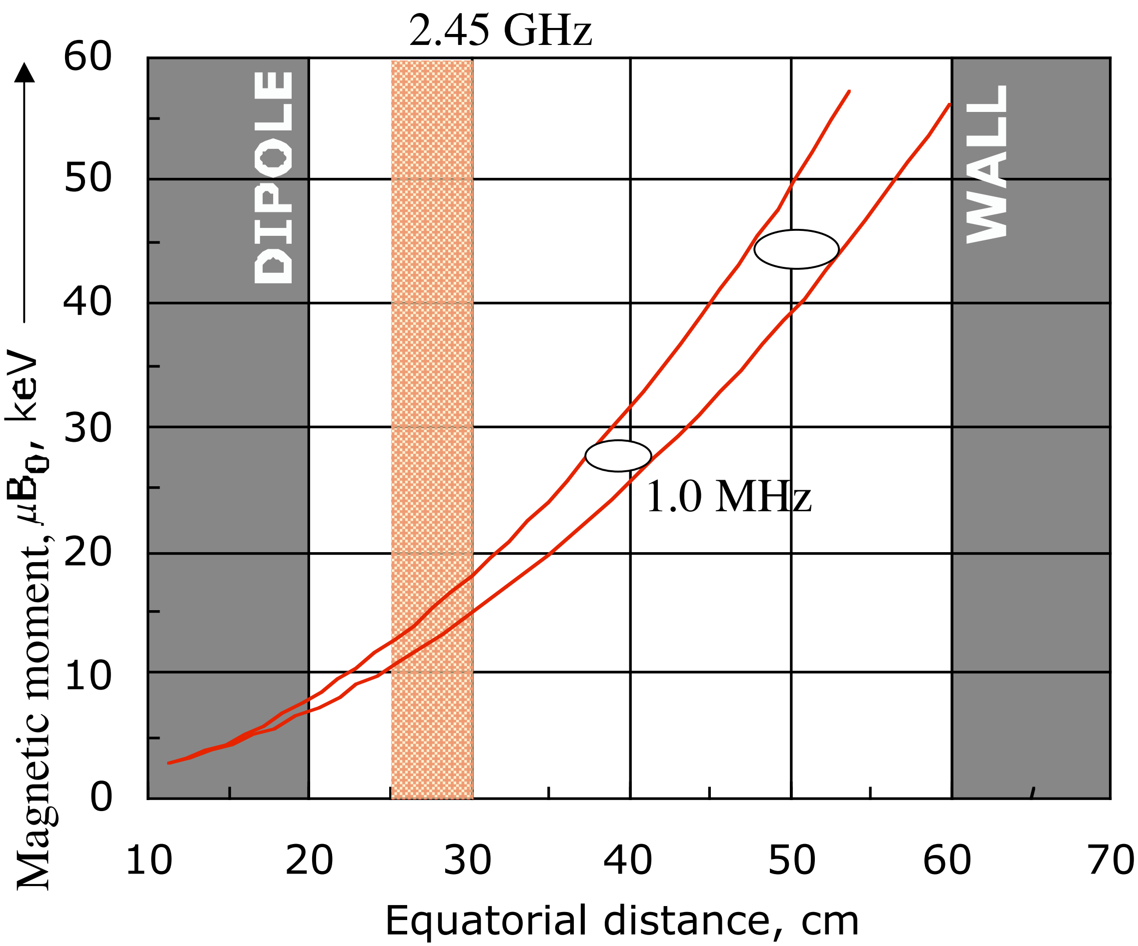
Note, ECRH diffusion is <u>NOT</u> constant across the phase-space:

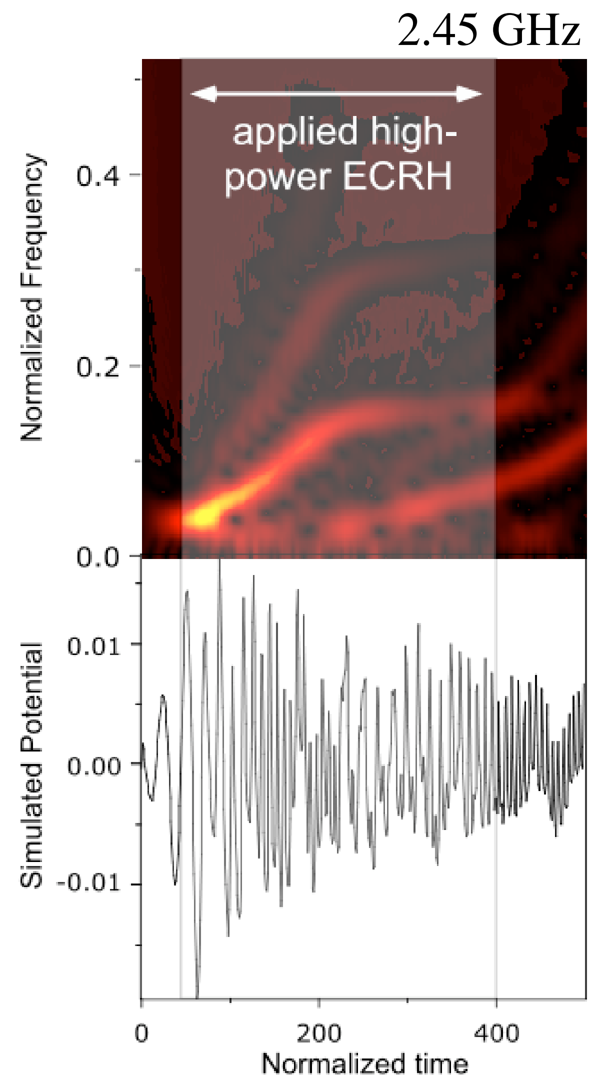
$$\square_{eff}^3 = 9D(\square)\left(cB/e\square\right)^2$$

Simulation Confirms Berk Model…



Mystery (?) of High-Power 2.45 GHz

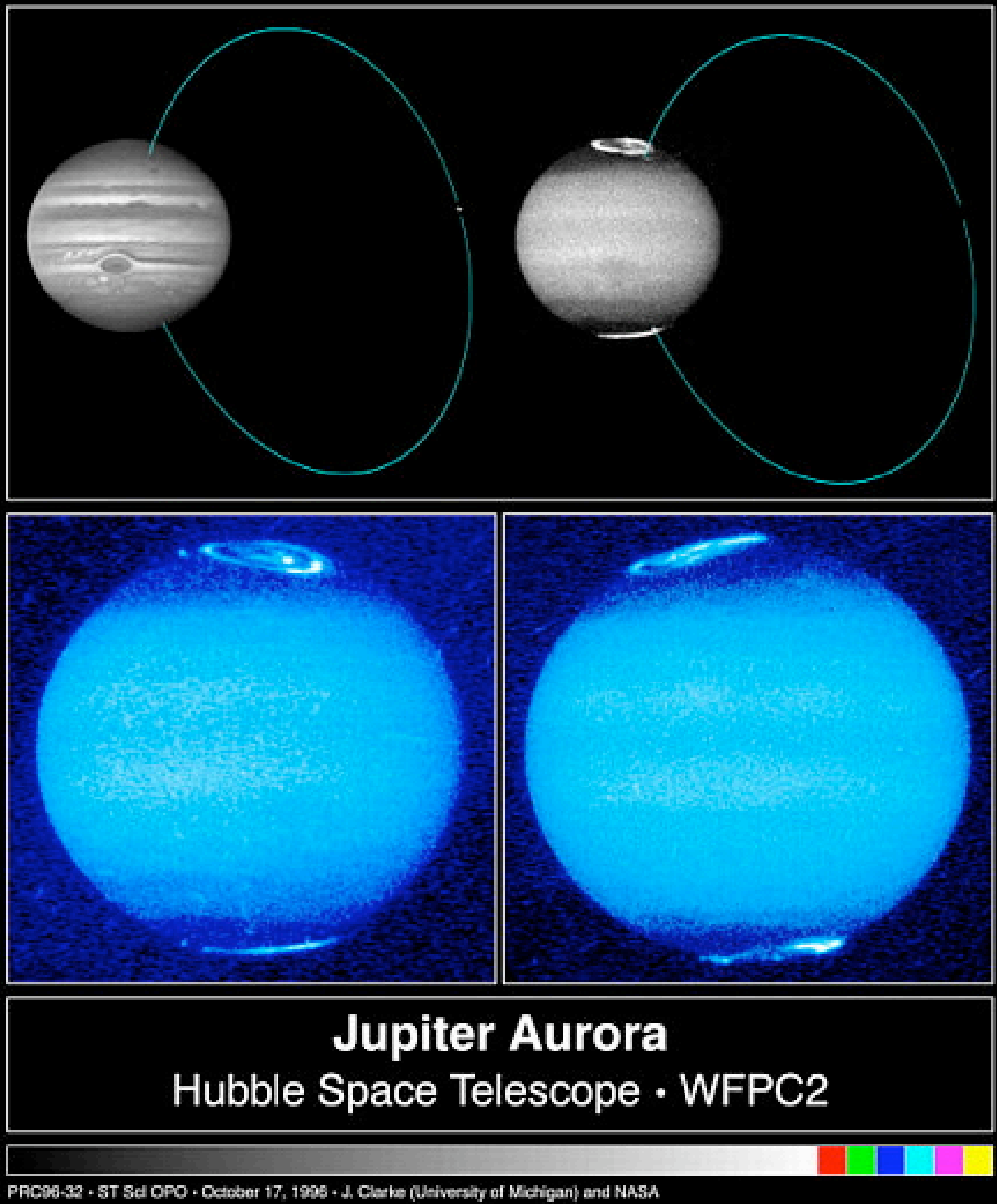




Summary

- Interchange instabilities driven by energetic electrons trapped by a magnetic dipole have broad radial structures and rotate rigidly with the electron drift. The electrostatic fields **create wave-particle resonances** in the 1D phase-space of the electrons.
- "**Bubbles**" form! They appear in phase-space and have a non-uniform structure in energy and radius.
- Nonlinear frequency sweeping results in the **inward propagation of the phase-space holes**.
- Frequency sweeping is suppressed with low-power RF fields.
- A self-consistent nonlinear simulation reproduces frequency sweeping and identifies phase-space holes as predicted by Berk, *et al*. (1999).

Dipole Fusion ?



- Studies and observations of the planetary magnetospheres give good understanding
- High > 1
- Rapid plasma circulation with low energy loss
- **Need to remove the magnetic poles!**

Levitated Dipole Experiment (LDX)

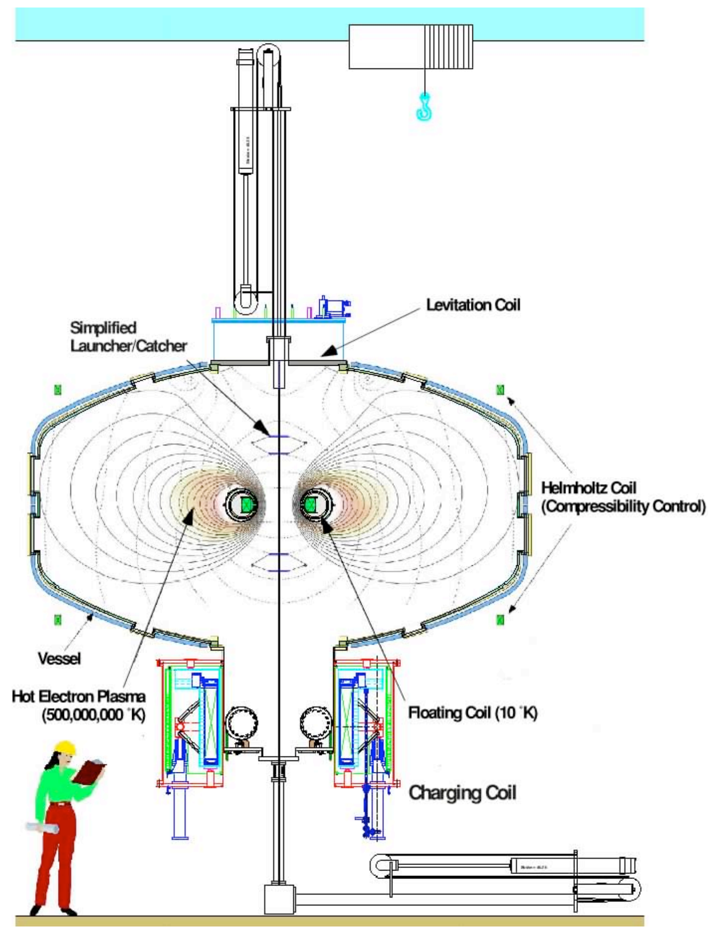
A fusion concept inspired by nature:

Can fusion benefit from unique features found in the planetary magnetospheres?

Simplest magnetic field geometry
Energetic plasma confined with □ > 1
Rapid plasma circulation combined with strong adiabatic compression

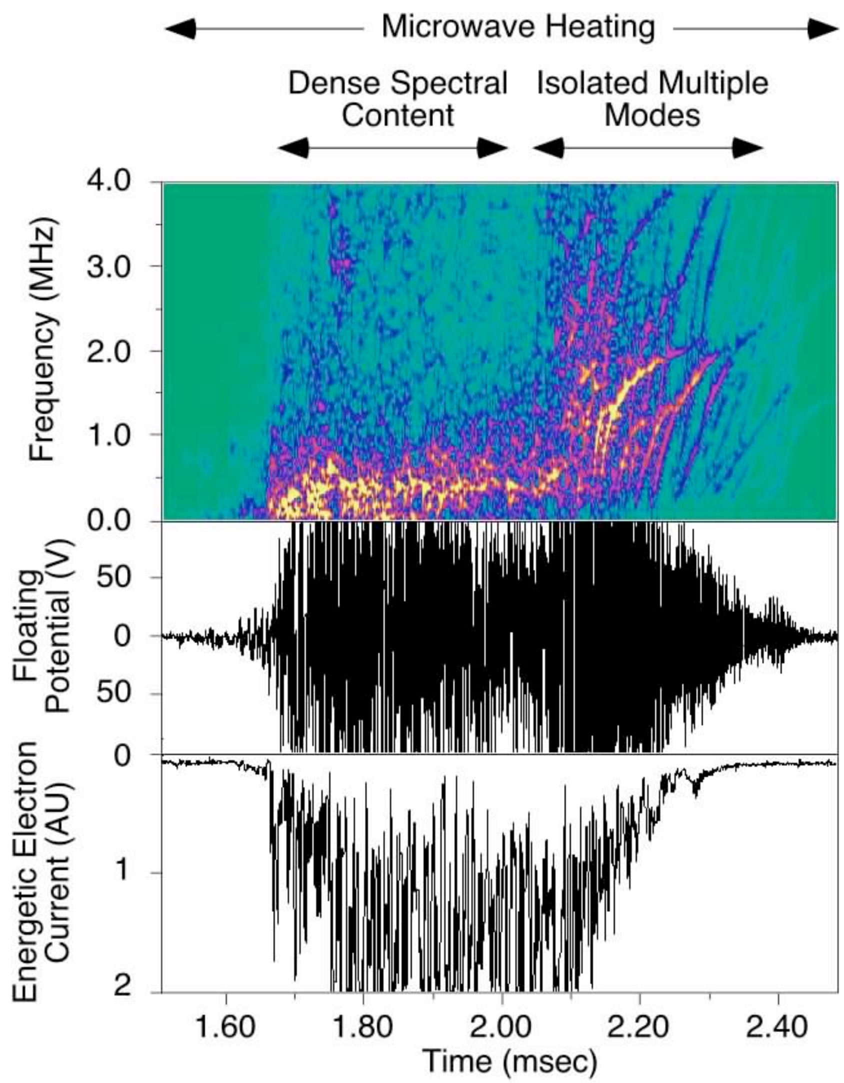
A partnership between plasma physics and magnet technology:

Floating Coil (Nb_3Sn / 1.5 MA)
Charging Coil (NbTi / 4.2 MA)
Levitation Coil (Bi-2223 / 300 kA)



First operation expected within months!

Strong Modulations in e^- Flux



(Ref: Warren and Mauel, *Phys. Plasmas*, 1995)

Hot electron interchange instability Bursts in CTX

Two distinct phases: ECR heating phase and afterglow

In the afterglow: the average drift frequency of the hot electrons is higher, no microwave heating