Creating Artificial Radiation Belts in the Lab

or

"Some Observations of Hot Plasma Trapped in a Dipole Magnetic Field"

M. E. Mauel and
Results from the CTX and LDX Experiments

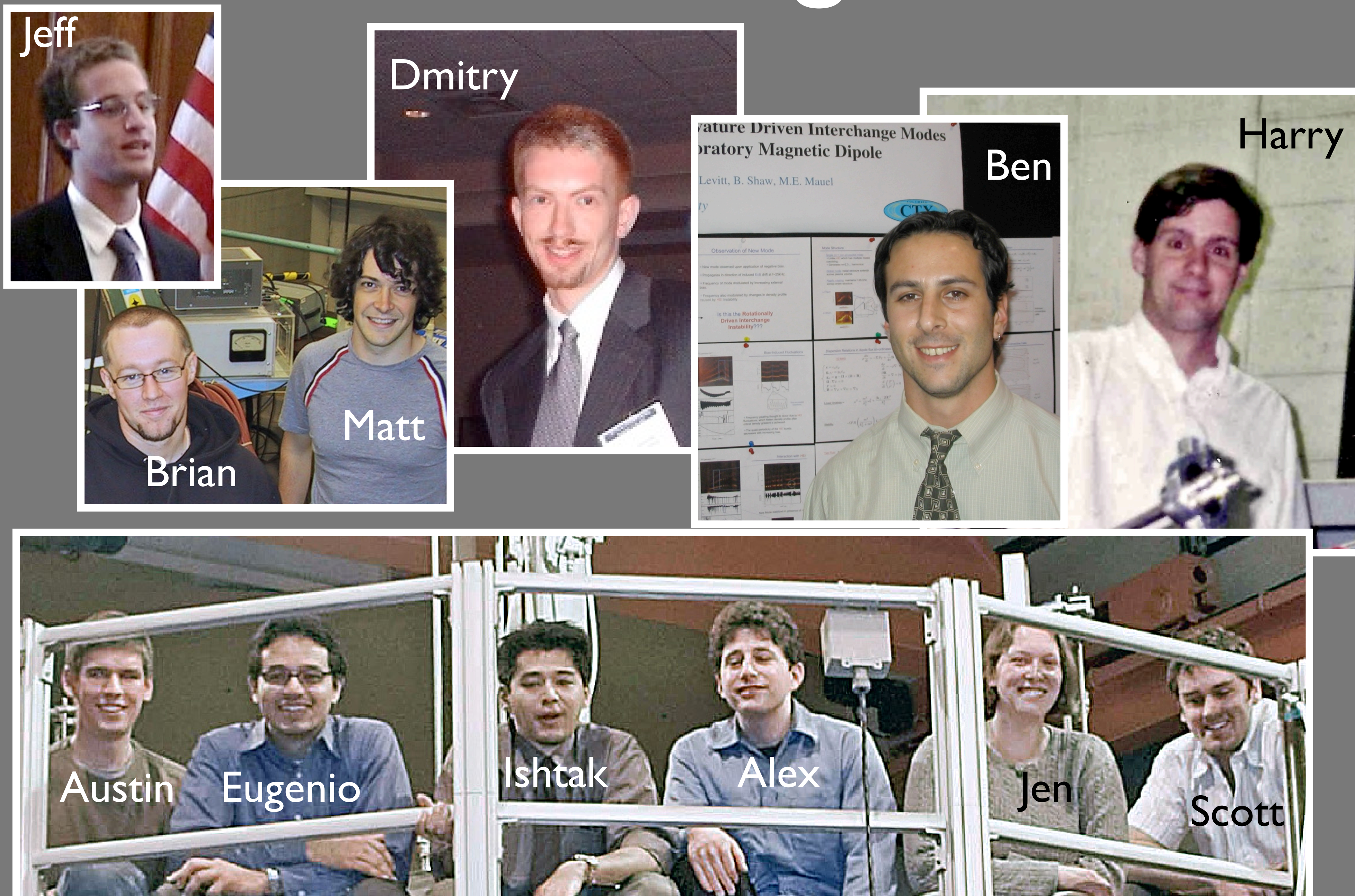
MIT, Sept 16, 2005

New Results

- Fast-electron, gyrokinetic interchange instability creates inward-propagating "**phase-space holes**" (bubbles) and a chorus of rising tones. (Maslovsky, PRL, 2003)
- Slow, MHD-like centrifugal interchange instability creates **broad convection cells** that have the same global structure as the fast-electron mode. (Levitt, PRL, 2005)

★ With a "nearly levitated" dipole, neutral gas programming stabilizes the fast-electron interchange mode and creates the **first high-beta plasma** trapped in a laboratory dipole. (Garnier, DPP, 2005)

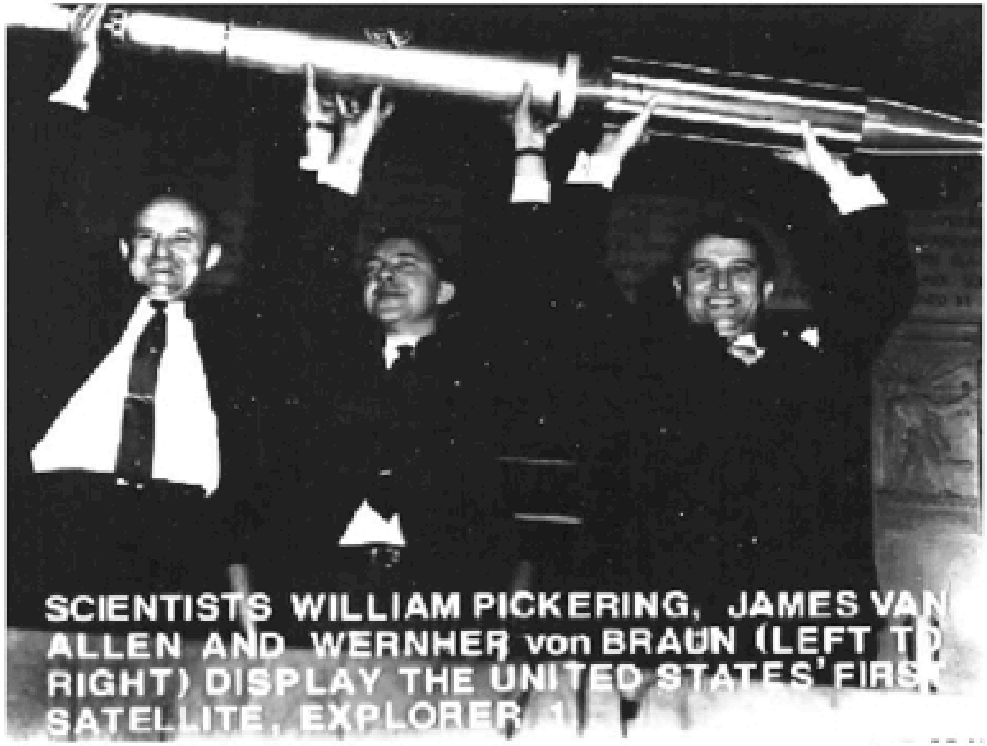
Acknowledgments



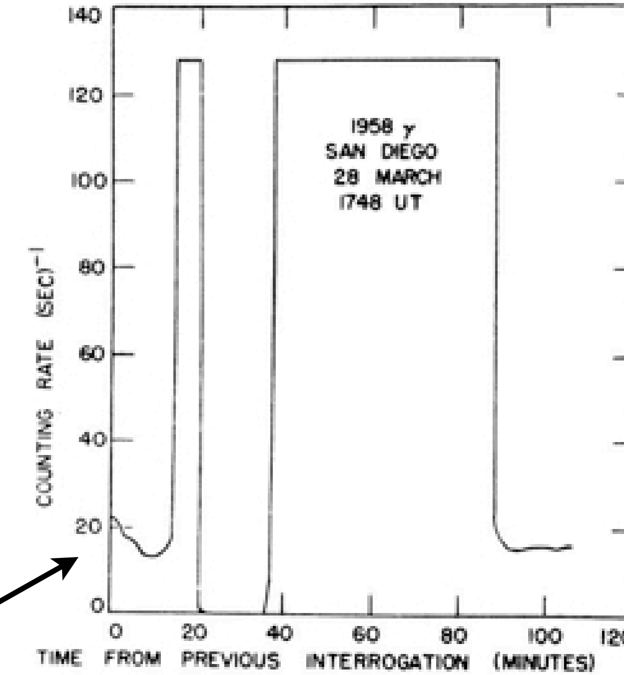
Outline

- The Earth's radiation belts and ring current
- Fast-electron interchange instability in CTX
- Slow, centrifugal interchange instability in CTX
- Creating high-beta plasmas in LDX
- *Not today*: Dipole fusion. Global particle convection and good high-beta confinement may make possible D-D(^{3}He) fusion.

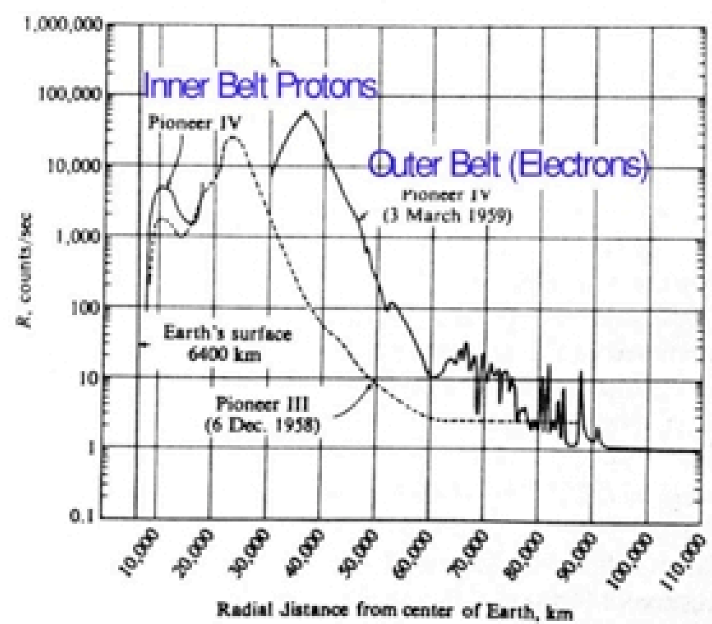
"My God, space is radioactive!"



James Van Allen, Carl McIlwain, Ernest Ray, George Ludwig



Oct 4, 1957	Sputnik 1
Nov 3, 1957	Sputnik 2
Jan 31, 1958	Explorer 1
Mar 26, 1958	Explorer 3
Jul 26, 1958	Explorer 4
Dec 6, 1958	Pioneer 3
Mar 3, 1959	Pioneer 4



“Artificial Radiation Belts”

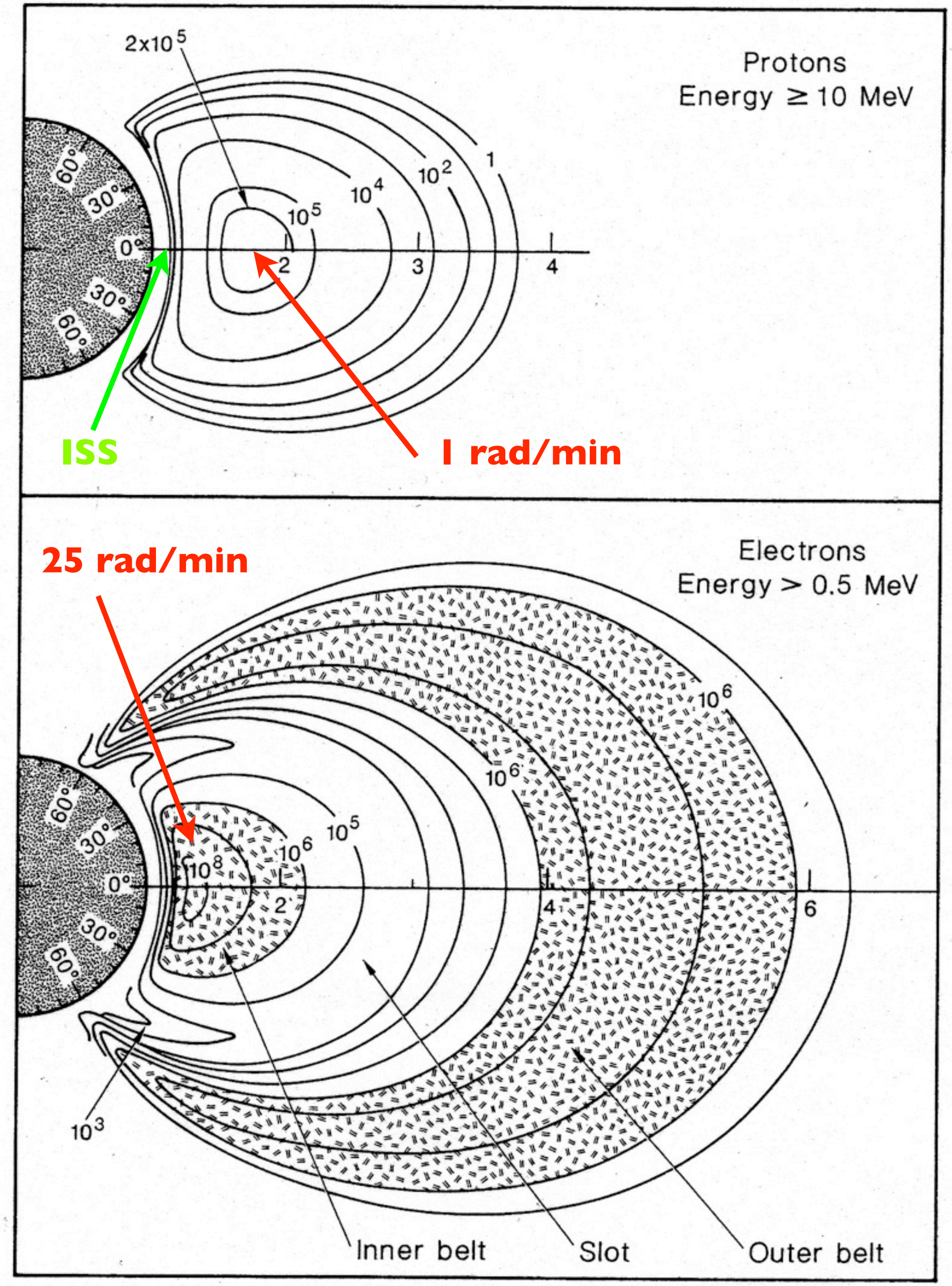
Van Allen kissing Explorer 4 “good bye” before it’s launch to measure the artificial radiation belt produced by the Argus explosions (1958).

(Explosions continued through 1963. By 1968, belts finally returned to “natural” state.)

What are the Radiation Belts?

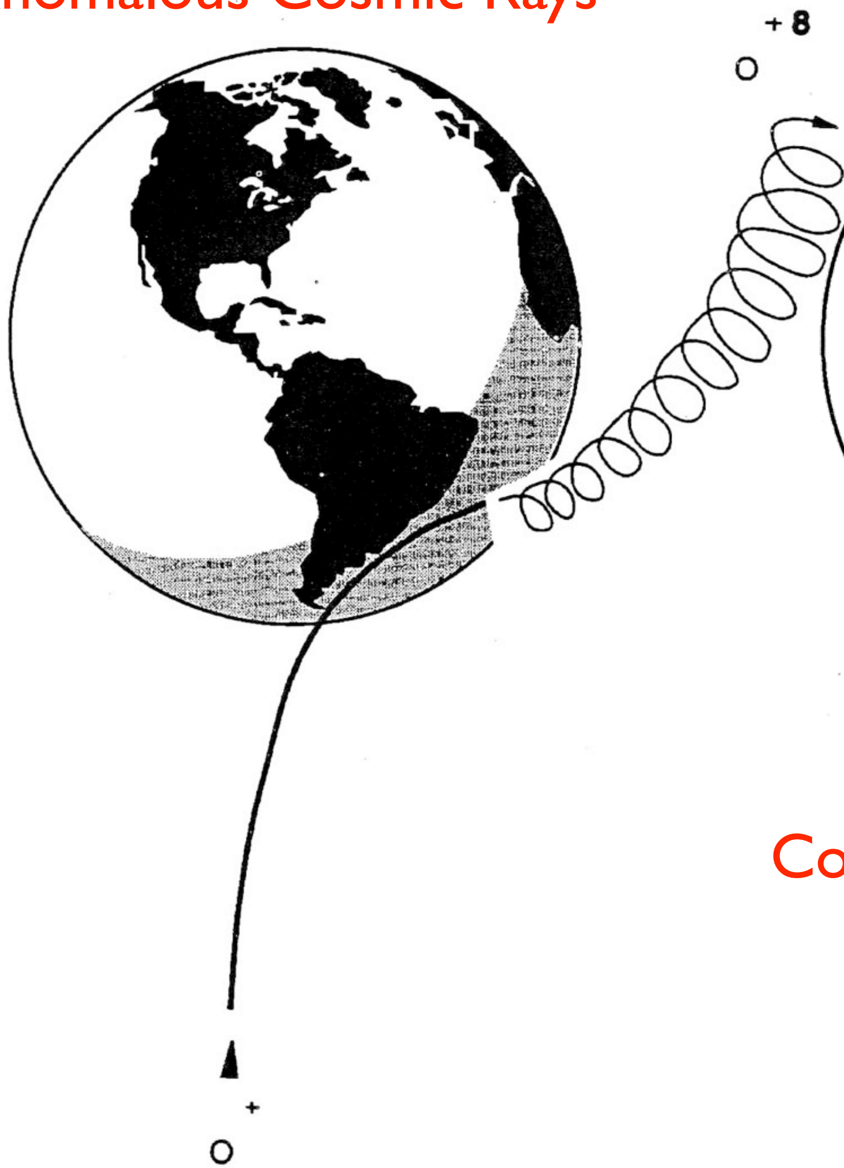
- Two zones:
  - Inner proton and electron belt *L* ~ 1.5
  - Outer zone, *L* > 4, electrons. Highly variable intensity.
- Highly penetrating energetic trapped electrons and protons.
- Radiation belt particles penetrate 0.6 mm of Al!
- **Low beta**, low fractional density, $n_h/n < 10^{-4}$.

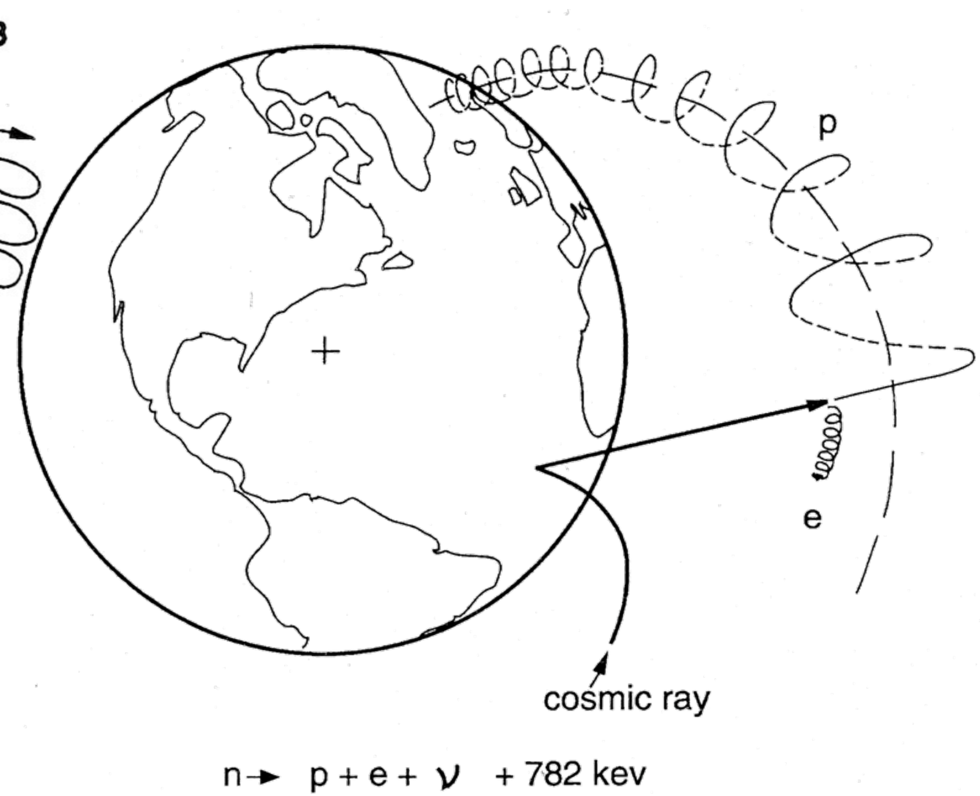
Particles/sec/cm²
Range > 22 mil Al



Where do they come from?

Anomalous Cosmic Rays



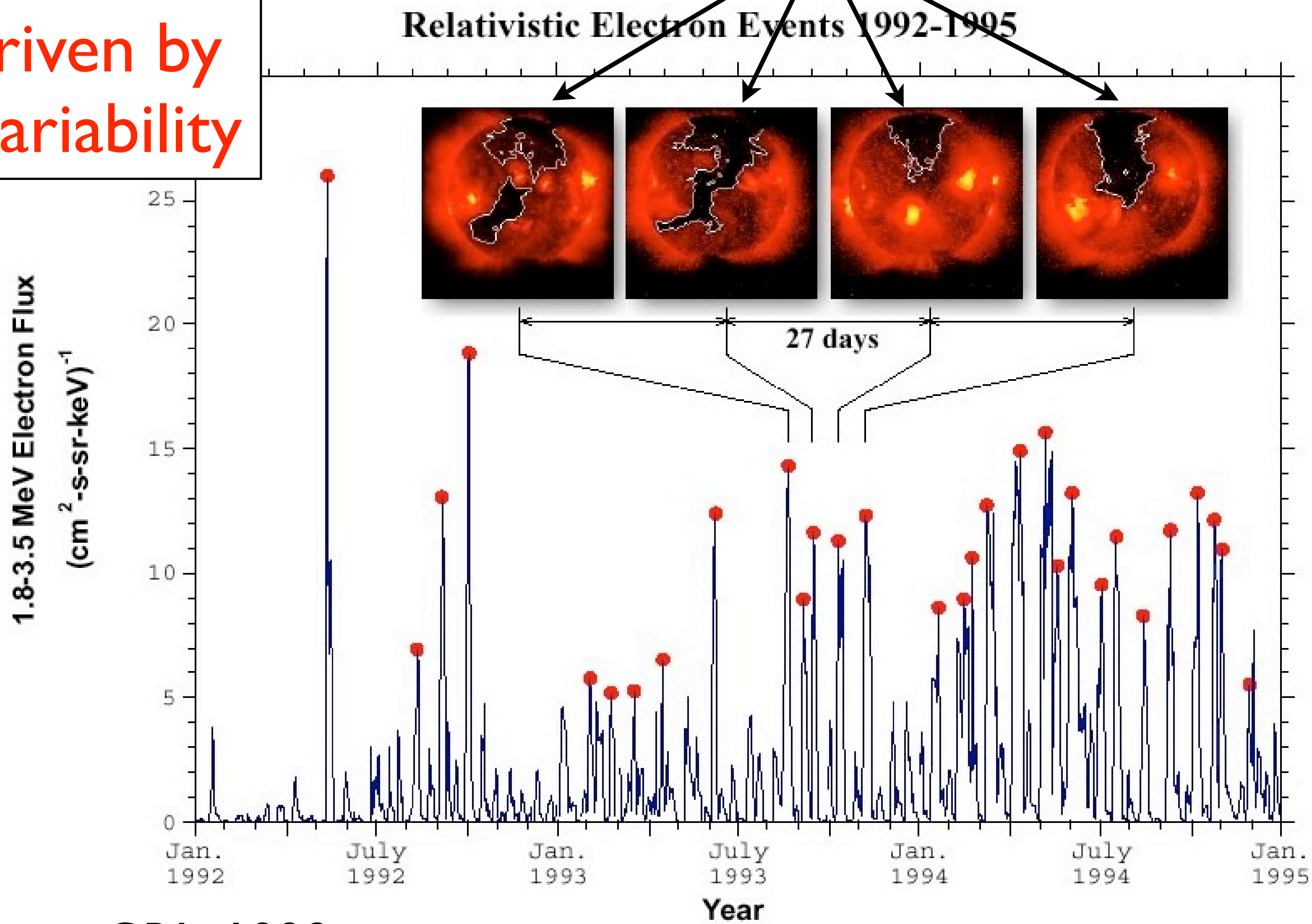


Cosmic Ray Albedo Neutron Decay

Where do they come from?

Outer zone "killer" electrons driven by solar wind variability

Coronal Hole toward Earth



Geoffrey Reeves, GRL, 1998

Where do they come from?

Outer zone "killer" electrons driven by solar wind variability

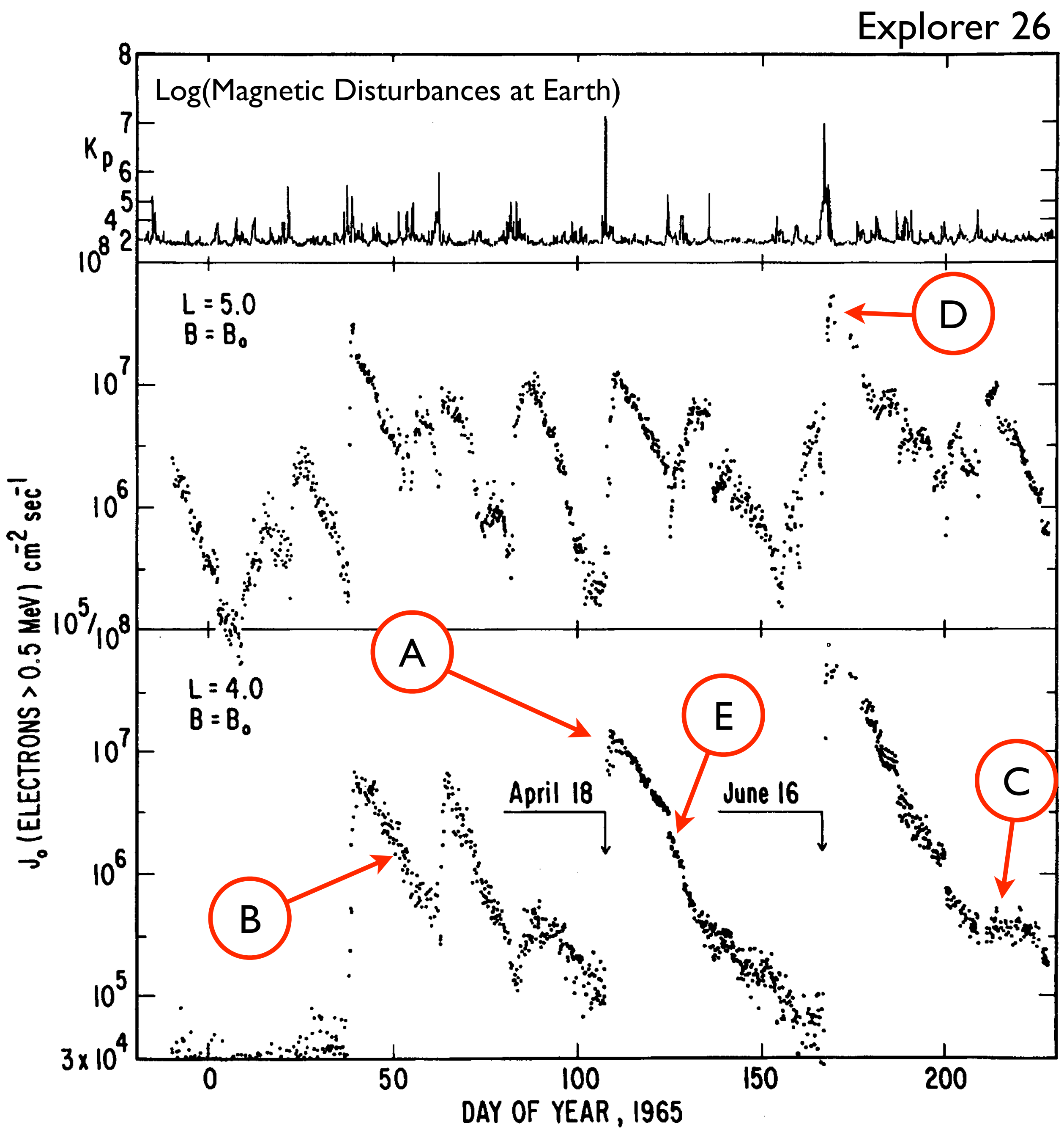
Rapid Injection (A)

~2-Week Decay (B)

Radial Diffusion (C)

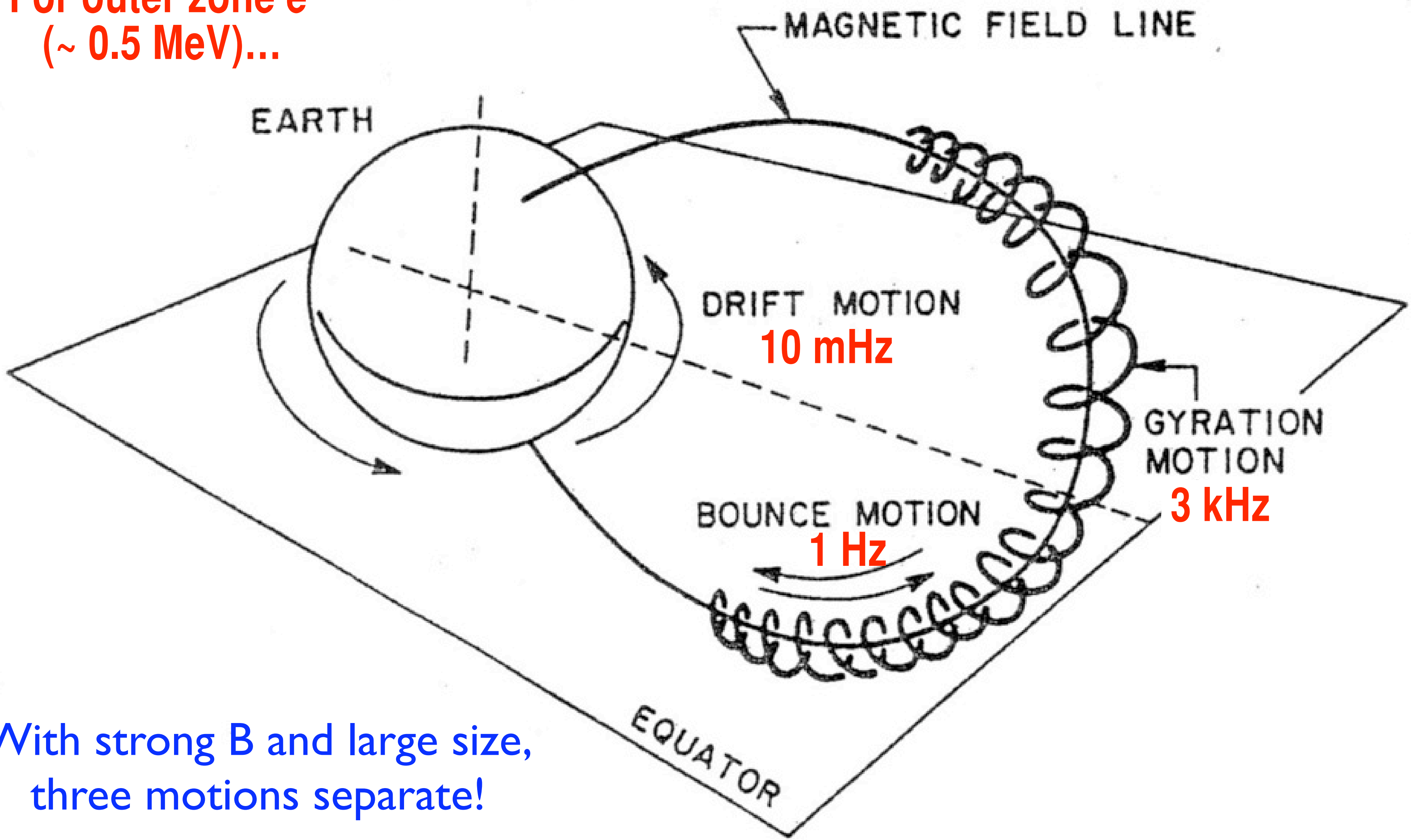
Adiabatic Motion (D)

Rapid Lost (E)



Rad Belt Dynamics Characterized by Adiabatic Invariants: Gyration (μ), Bounce (J), and Drift (ψ)

For outer zone e^- (~ 0.5 MeV)...



With strong B and large size, three motions separate!

Low-Frequency Dynamics is One-Dimensional

(1D, $k_\perp \rho \ll 1$, Gyrokinetics!)

$$\mathcal{H} = \frac{m_e c}{2e}\rho_{||}^2 B_0^2 + \mu\frac{c}{e}(B_0 + \delta B) - c\delta\Phi$$

$$B_0 \gg \delta B\,,\ \delta\mathbf{B} = \nabla\times\delta\mathbf{A}\,,\ \text{and } \delta\mathbf{E} = -\nabla\delta\Phi - \frac{1}{c}\frac{\partial\delta\mathbf{A}}{\partial t}$$

$$\begin{aligned}
\dot{\mu} &= 0\ (\omega \ll \omega_c) \\
\dot{J} &= 0\ (\omega \ll \omega_b)
\end{aligned}$$

2D Phase Space

$$\left\{\begin{aligned}
\dot{\psi} &= -\frac{\partial\mathcal{H}}{\partial\phi} = -c\frac{\partial\delta\Phi}{\partial\phi} + L\frac{\partial\delta A_\phi}{\partial t}\ (\propto \delta\mathbf{E}\times\mathbf{B}) \\
\dot{\phi} &\approx \mu\frac{c}{e}\frac{\partial B}{\partial\psi} - c\frac{\partial\delta\Phi}{\partial\psi} \approx \frac{3\mu}{eM^2}\psi^2 = \omega_d(\mu,\psi)
\end{aligned}\right.$$

A. Chan, L. Chen, R. White, *GRL* (1989)

Adiabatic Radial Dynamics

$$\frac{\partial F}{\partial t} + \dot{\phi}\frac{\partial F}{\partial \phi} + \dot{\psi}\frac{\partial F}{\partial \psi} = 0$$

$$F(\mu,\, J,\, \psi,\, \phi,\, t) = F_0(\mu,\, J,\, \psi) + \delta F_{m,\omega}\, e^{-i(\omega t - m\phi)}$$

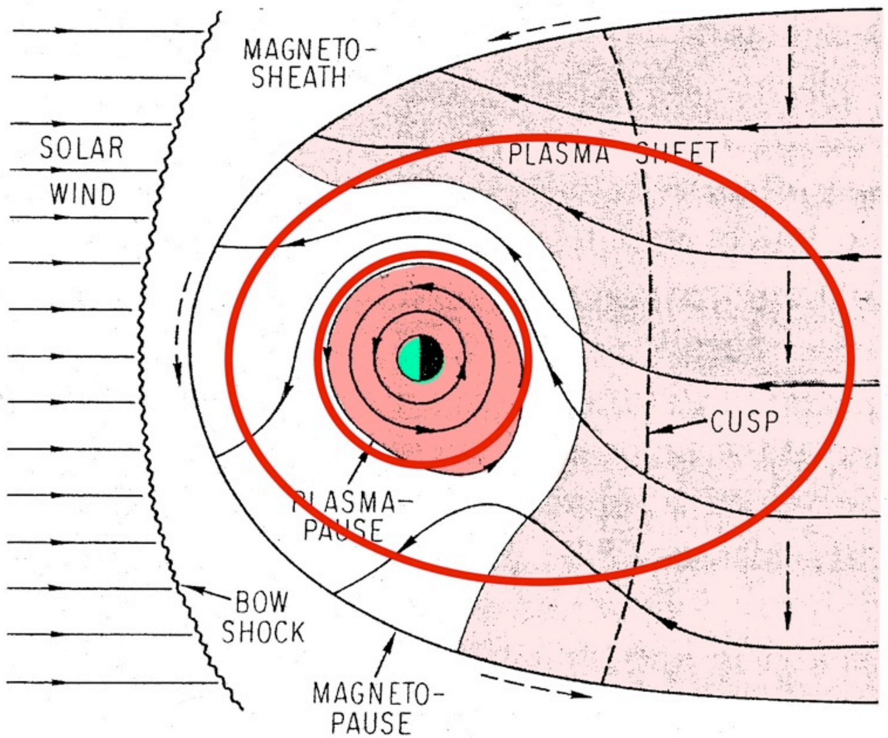
Linear Response...

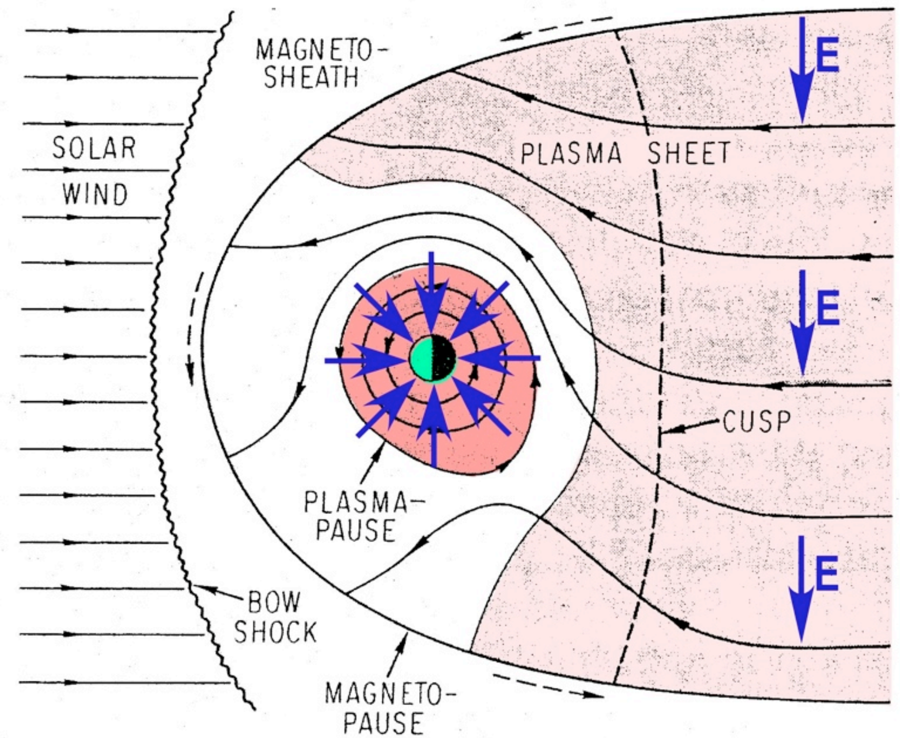
$$\delta F \approx \frac{-i\dot{\psi}_{m,\omega}\, \partial F_0 / \partial \psi}{\omega - m\omega_d}$$

Quasilinear Diffusion...

$$\frac{\partial F_0}{\partial t} = \frac{\partial}{\partial \psi} D_{\psi\psi} \frac{\partial F_0}{\partial \psi} \text{ with } D_{\psi\psi} = \sum_{m,\omega} \frac{\pi}{2} \delta(\omega - m\omega_d) \underbrace{\left|\dot{\psi}_{m,\omega}\right|^2}_{\text{Fluctuating } E \times B}$$

Perturbed $\dot{\psi}$ Caused by Global Fluctuations of Geomagnetic Cavity (Easily Measured!)





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

Nakada and Mead, *JGR* (1965)

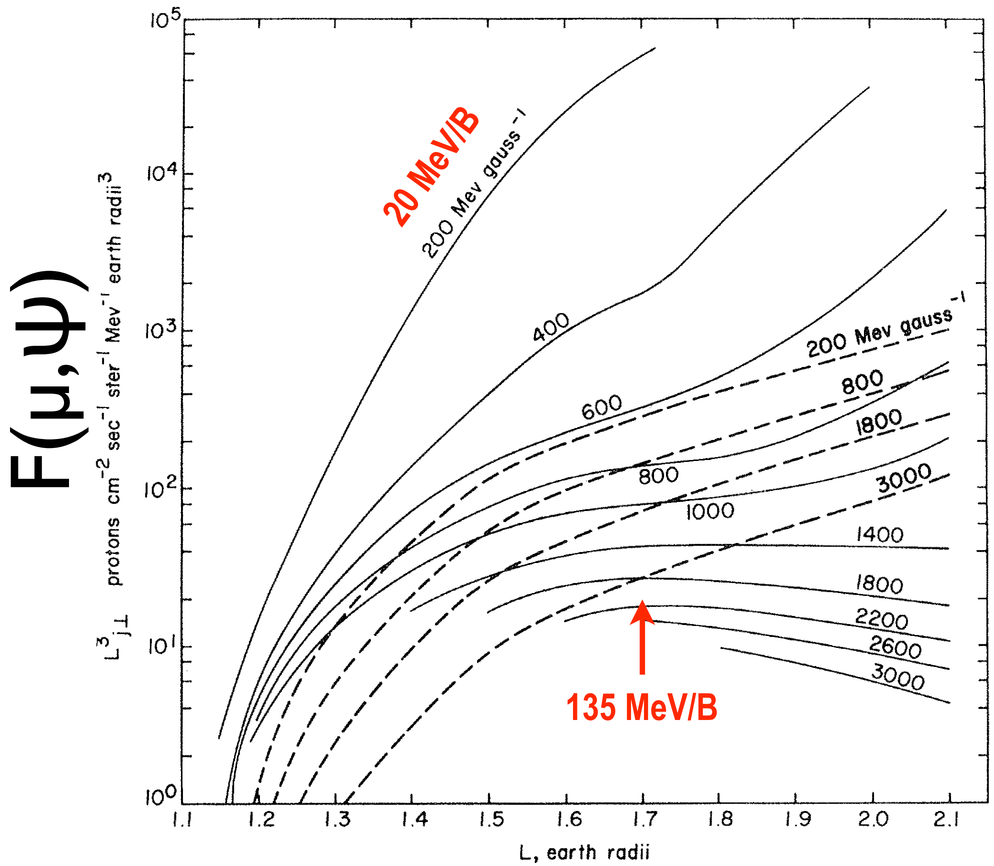
$$\delta\Phi \sim -\overbrace{E_c\left(\frac{R_e^2}{L}\right)}^{\text{Axisymmetric}} + \underbrace{E_c L \sin\phi}_{m=\pm1} + \ldots$$

T. Birmingham, *JGR* (1969)

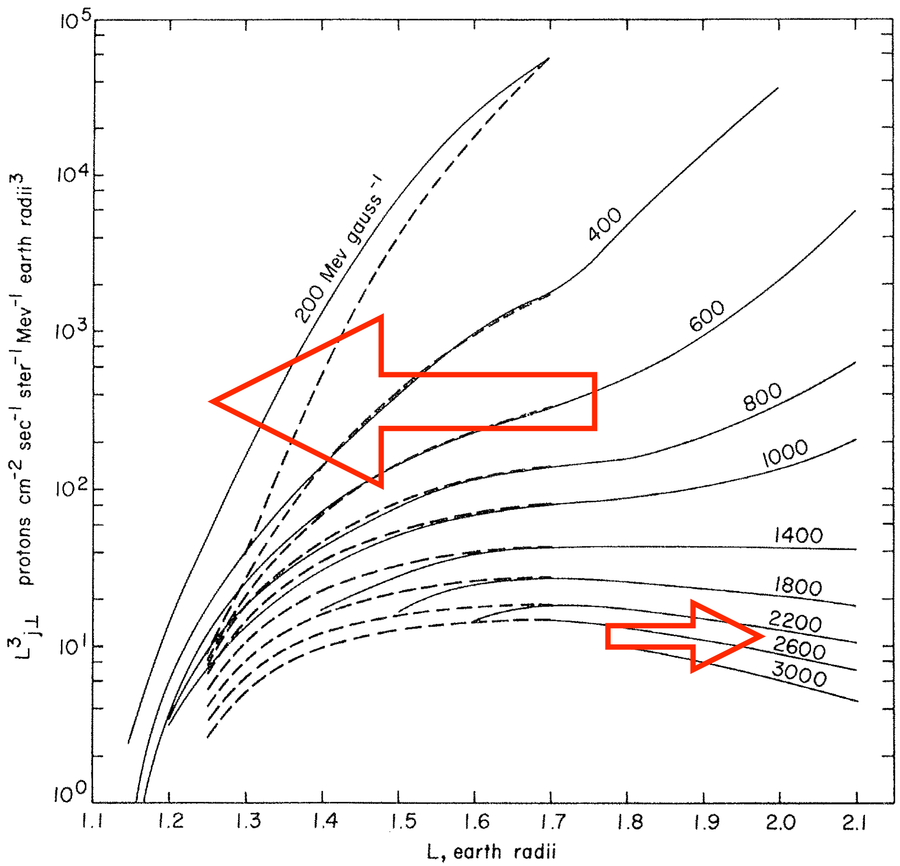
Quasilinear Radial Diffusion

(Farley, Tomassian, Walt)

VOLUME 25, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JULY 1970



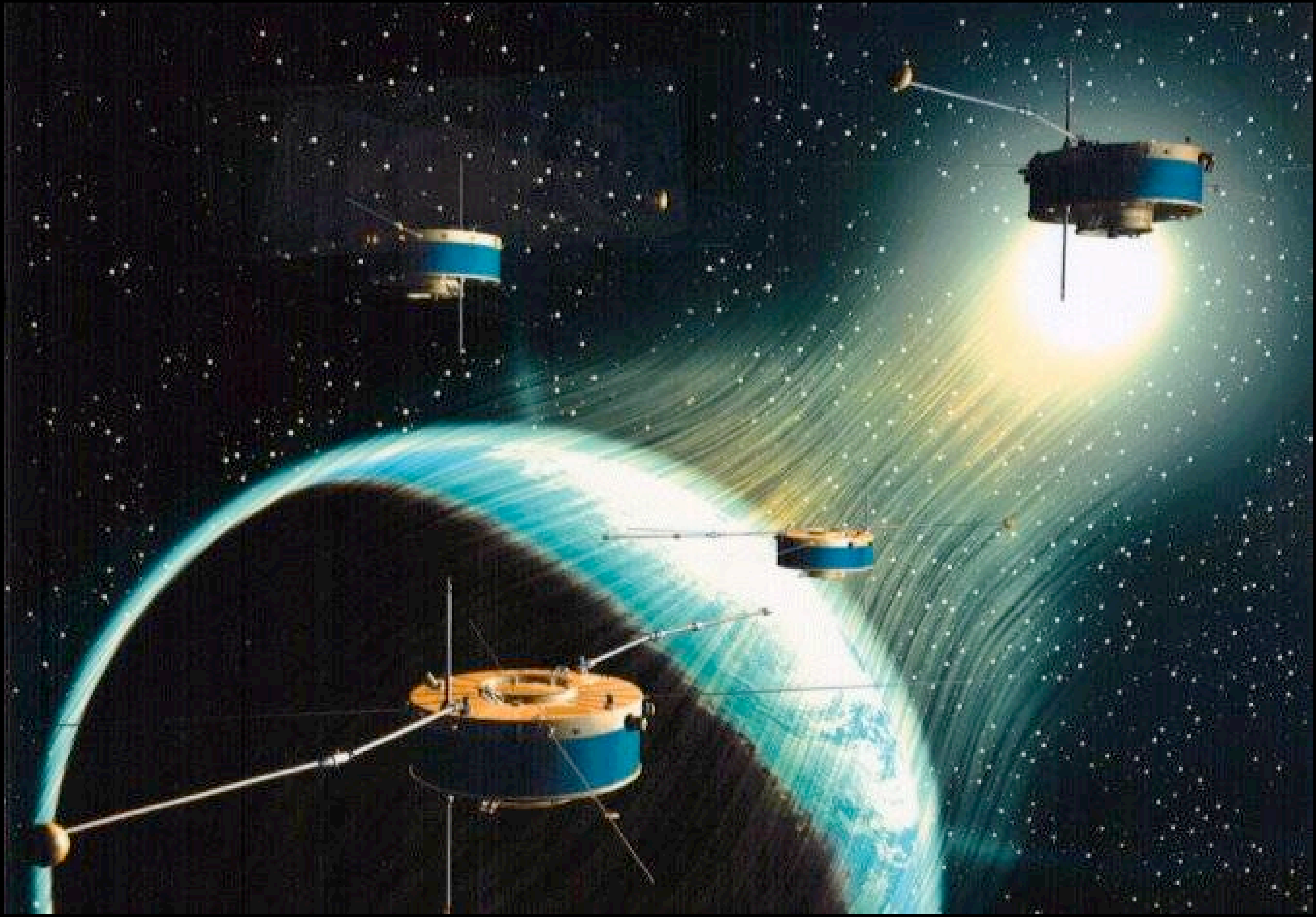
No Diffusion



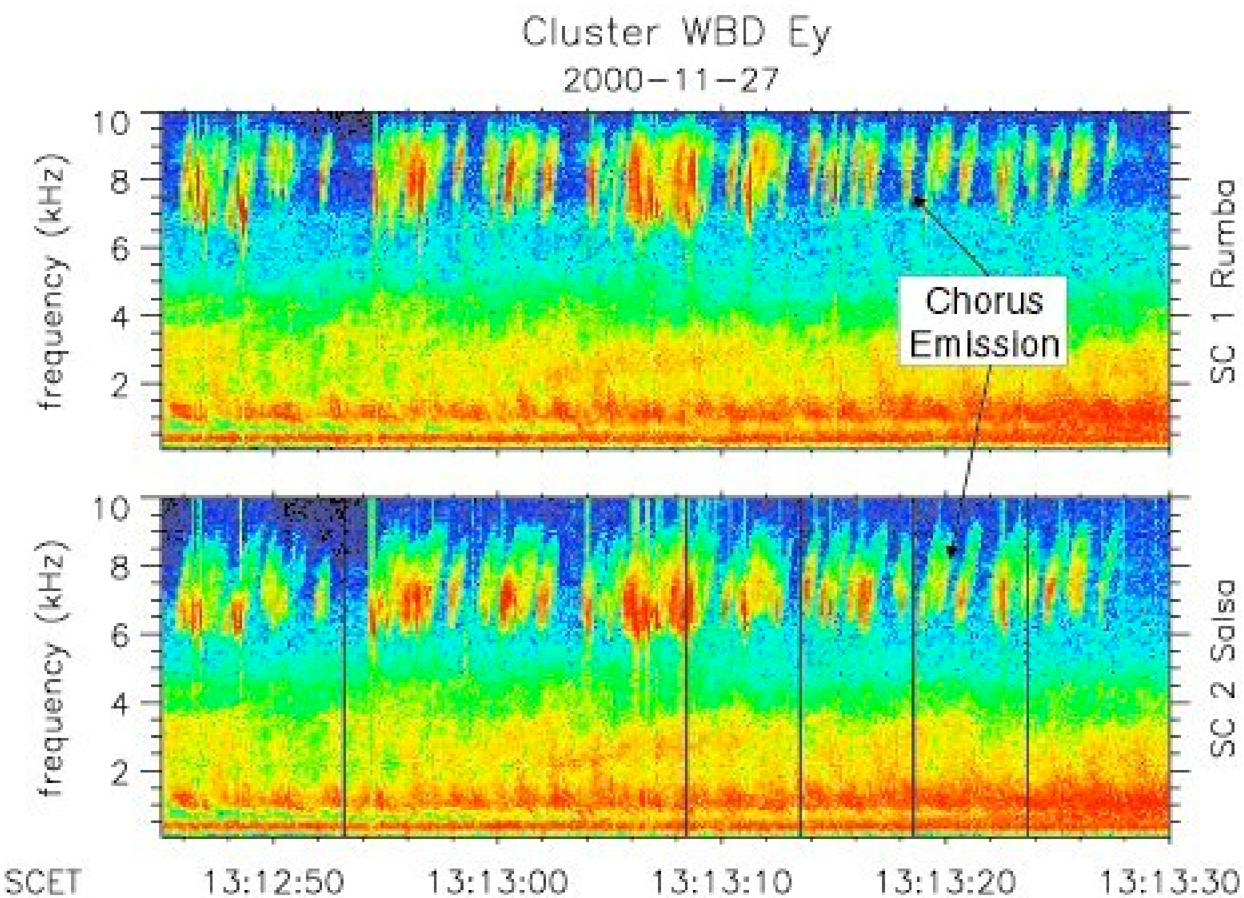
With (Inward!) Diffusion

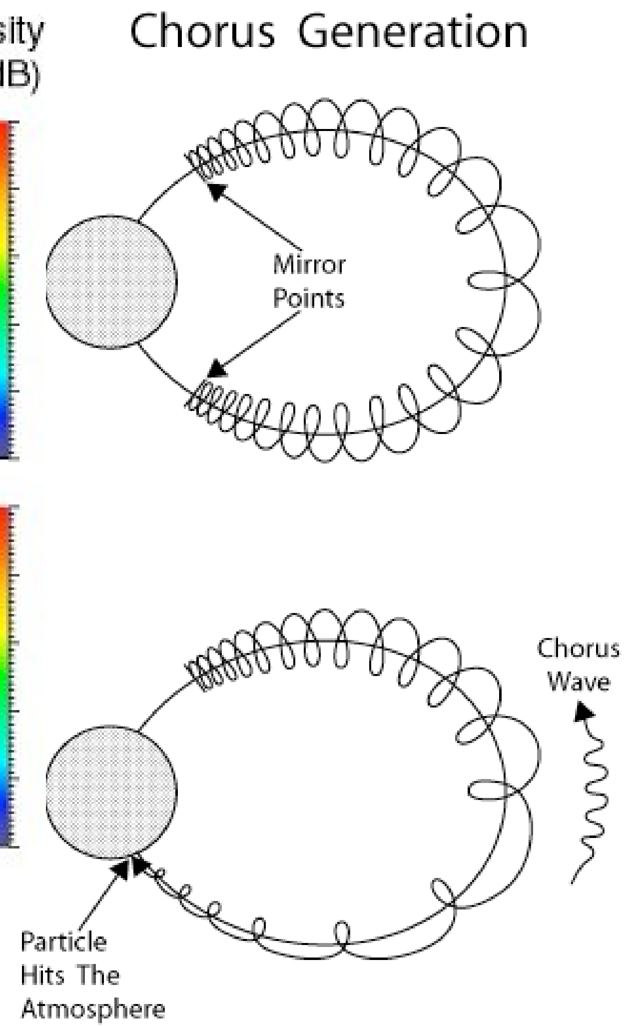
Cluster II

(Launched 16 July 2000)



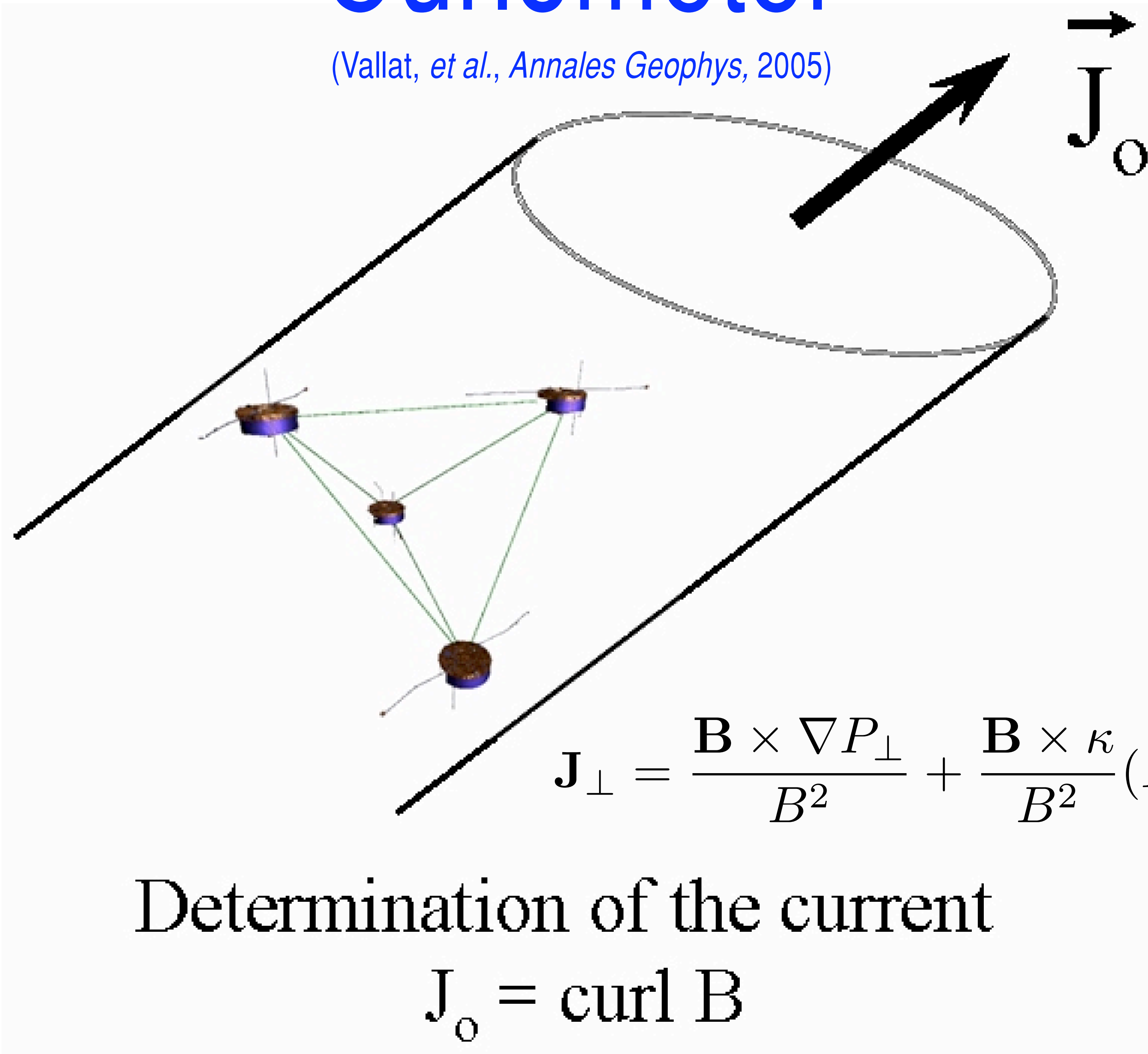
Cluster II Wideband Plasma Wave Investigation (Don Gurnett, ...)





Curlometer

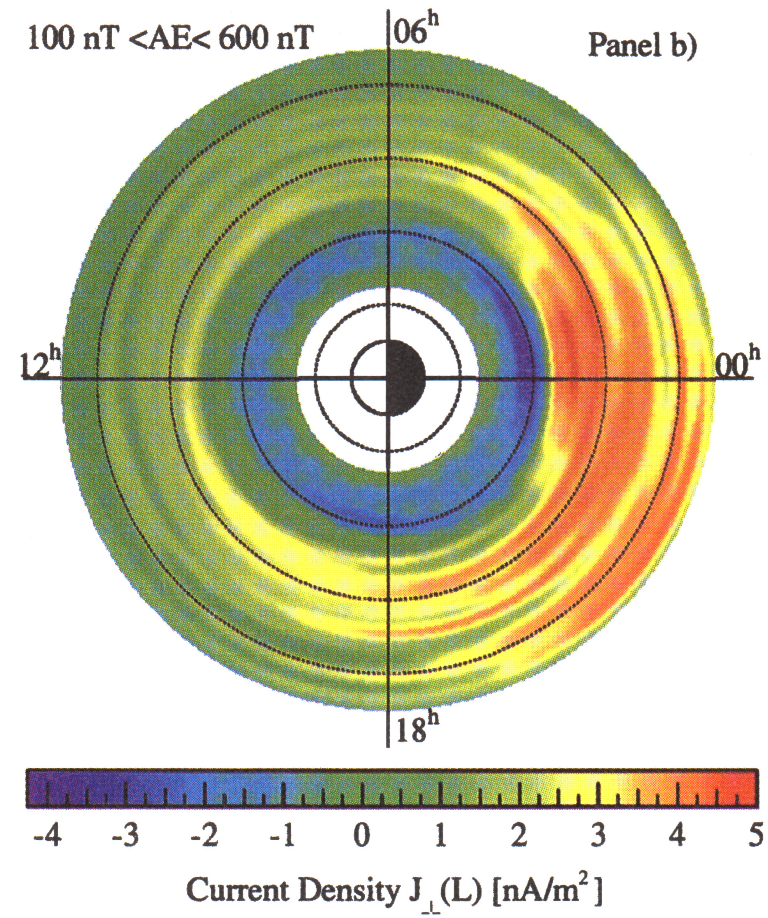
(Vallat, *et al.*, *Annales Geophys,* 2005)



$$\mathbf{J}_\perp = \frac{\mathbf{B} \times \nabla P_\perp}{B^2} + \frac{\mathbf{B} \times \kappa}{B^2}(P_{||} - P_\perp)$$

Ring Current:
Trapped, High-β Protons (15-250 keV)

- Greatly intensified during geomagnetic storms
- $T_i \sim 7T_e$ and $P_\perp \sim 1.5\ P_{||}$
- Monthly storms: ~5 MA. (LDX: 3-4 kA)
  10 MA storms few times a year.
- Current centered near $L \sim$ 4-5R_e;
  $\Delta L \sim 2.6R_e$ wide and $\Delta z \sim 1.6R_e$;
  Not axisymmetric.
- Curlometer during storms:
  $J_{RC} \sim 25$ nA/m² (Cluster II, 2005)



AMPTE/CCE-CHEM Measurements
Averaged over 2 years
(De Michelis, Daglis, Consolini, *JGR*, 1999)

D_{st} and the Dessler-Parker-Sckopke Relation

(Burton, McPherron, Russell, *JGR*, 1975)

- Disturbed Storm Time Index (D_{st}):

  $\Delta B_H = (\mu_0/2) \times I_{RC}/R_{rc}$ measured near equator

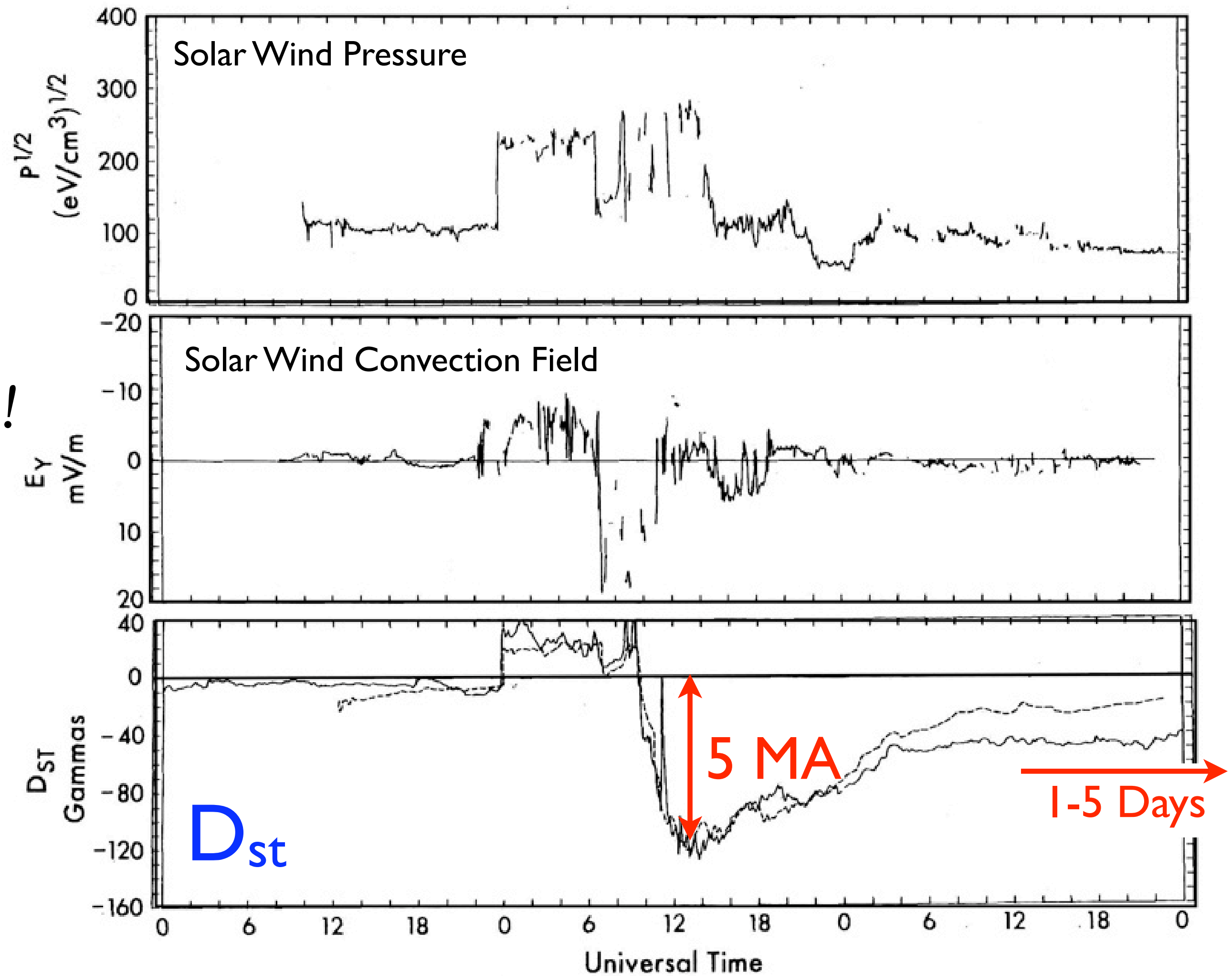
  plus Earth's induction fields!

  (LDX: $\Delta I_F \approx -0.25\ I_{rc}$)

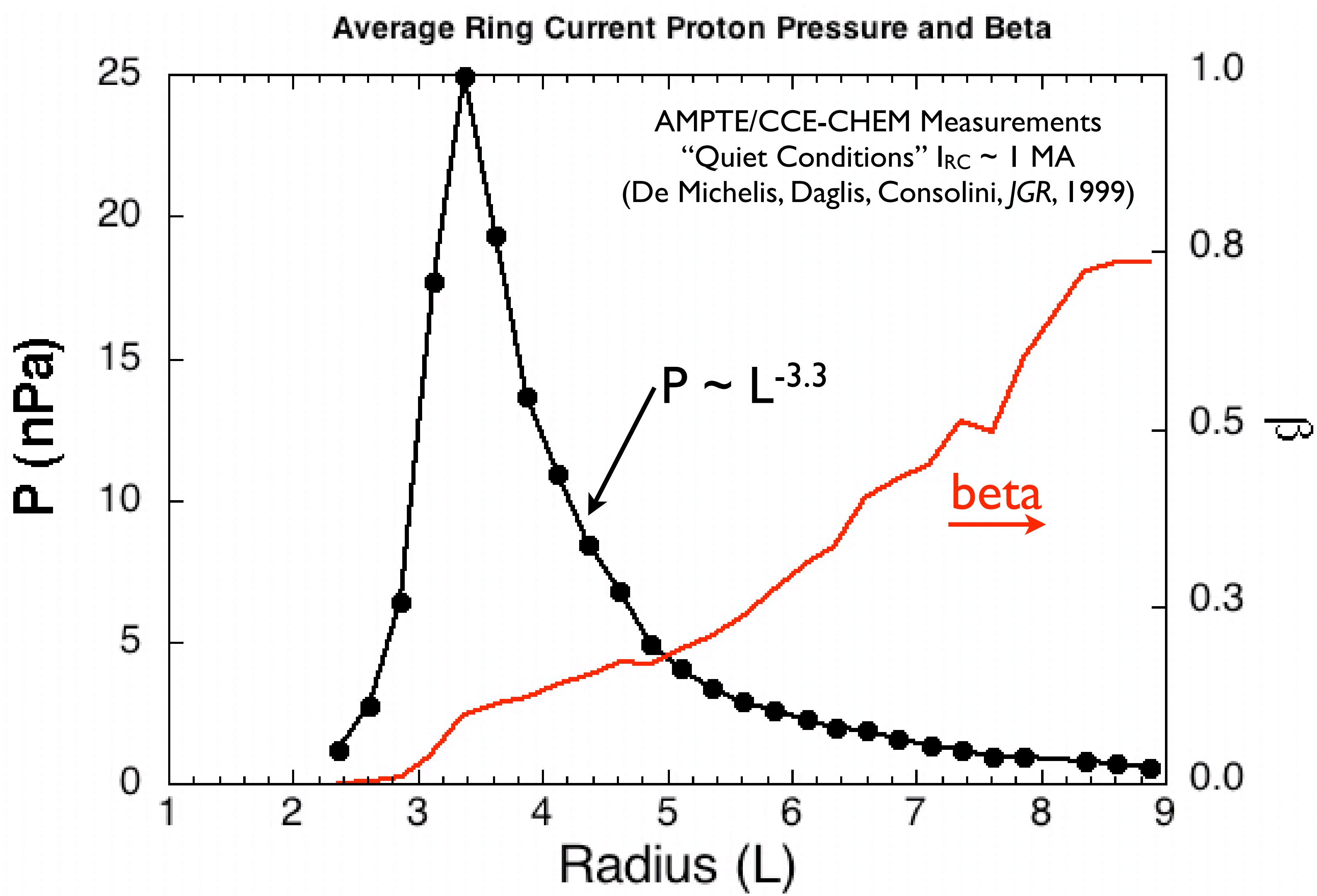
- Dessler-Parker-Sckopke:

  Energy = 0.54 GJ/A × I_{RC}

  (LDX: 0.12 J/A)

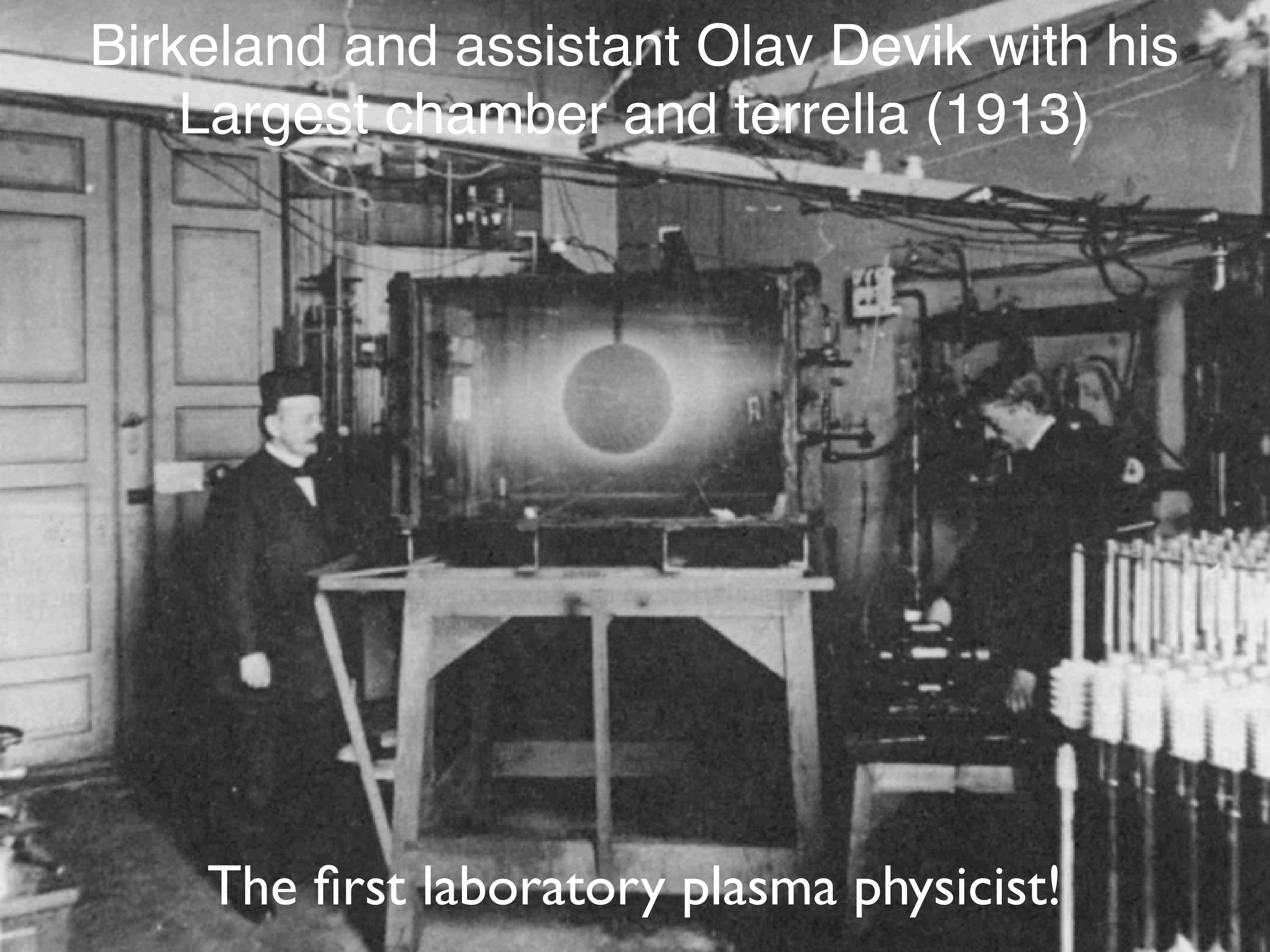


Centrally-Peaked Proton Pressure
(Even with Plasma Sheet, Outer-Edge, Source!)



Tromsø, Norway
July 2005

Birkeland and assistant Olav Devik with his Largest chamber and terrella (1913)

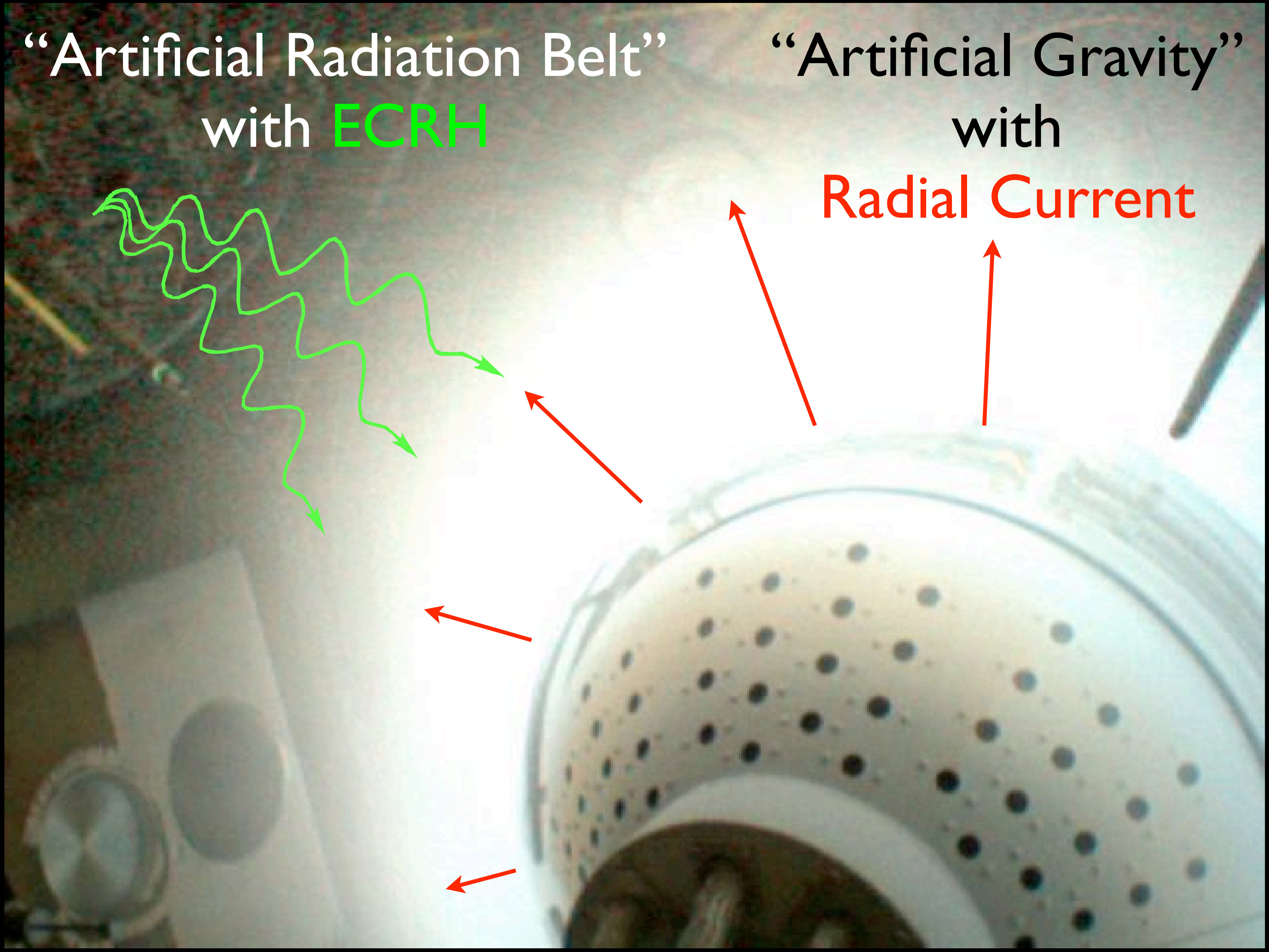


The first laboratory plasma physicist!

200 Kroner (~ $30) Issued by Norway in 1994

Back side shows a map of the north polar regions, where Birkeland established a network of auroral observatories, and the location of the "Birkeland currents" as depicted in 1908.

CTX Plasma Torus



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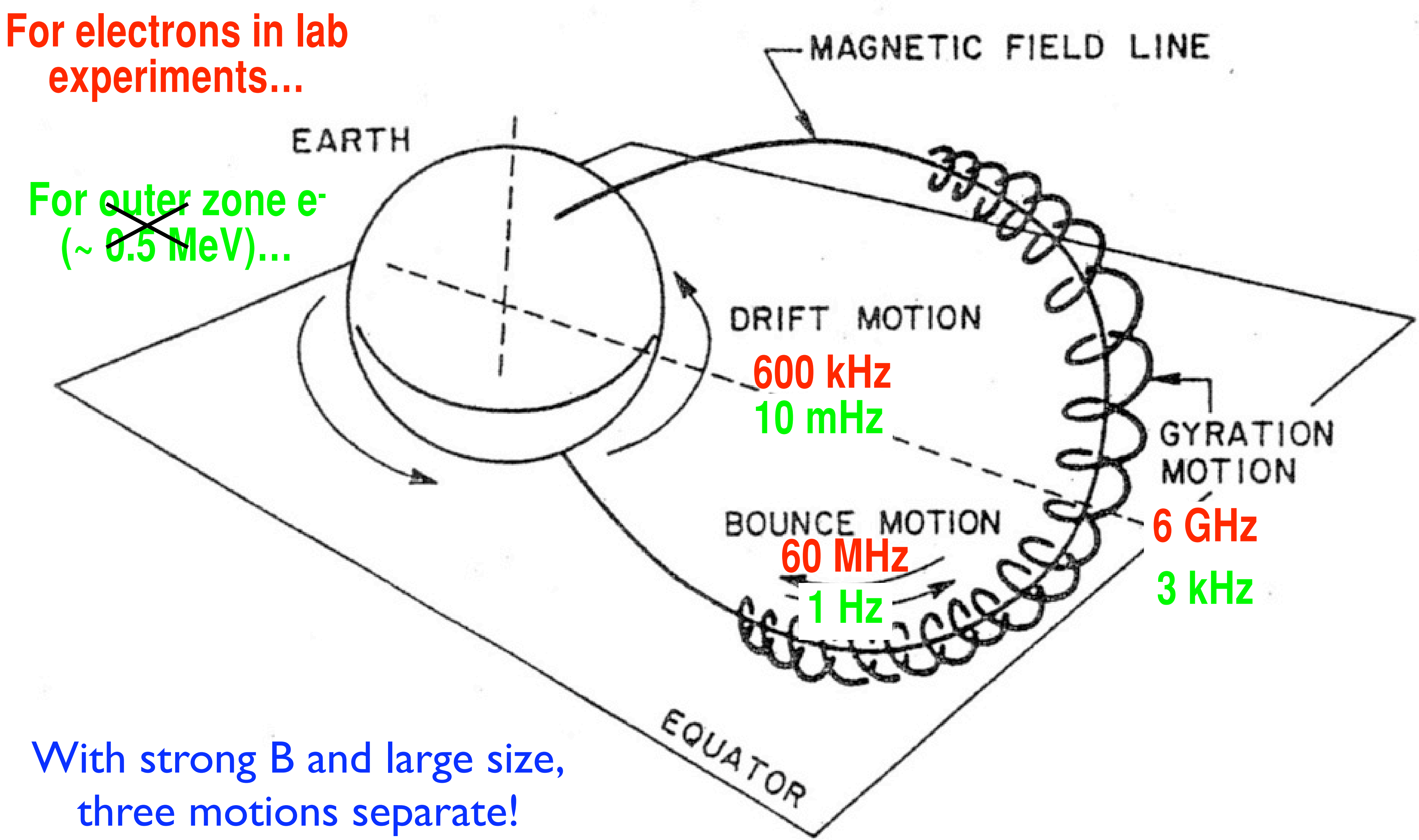
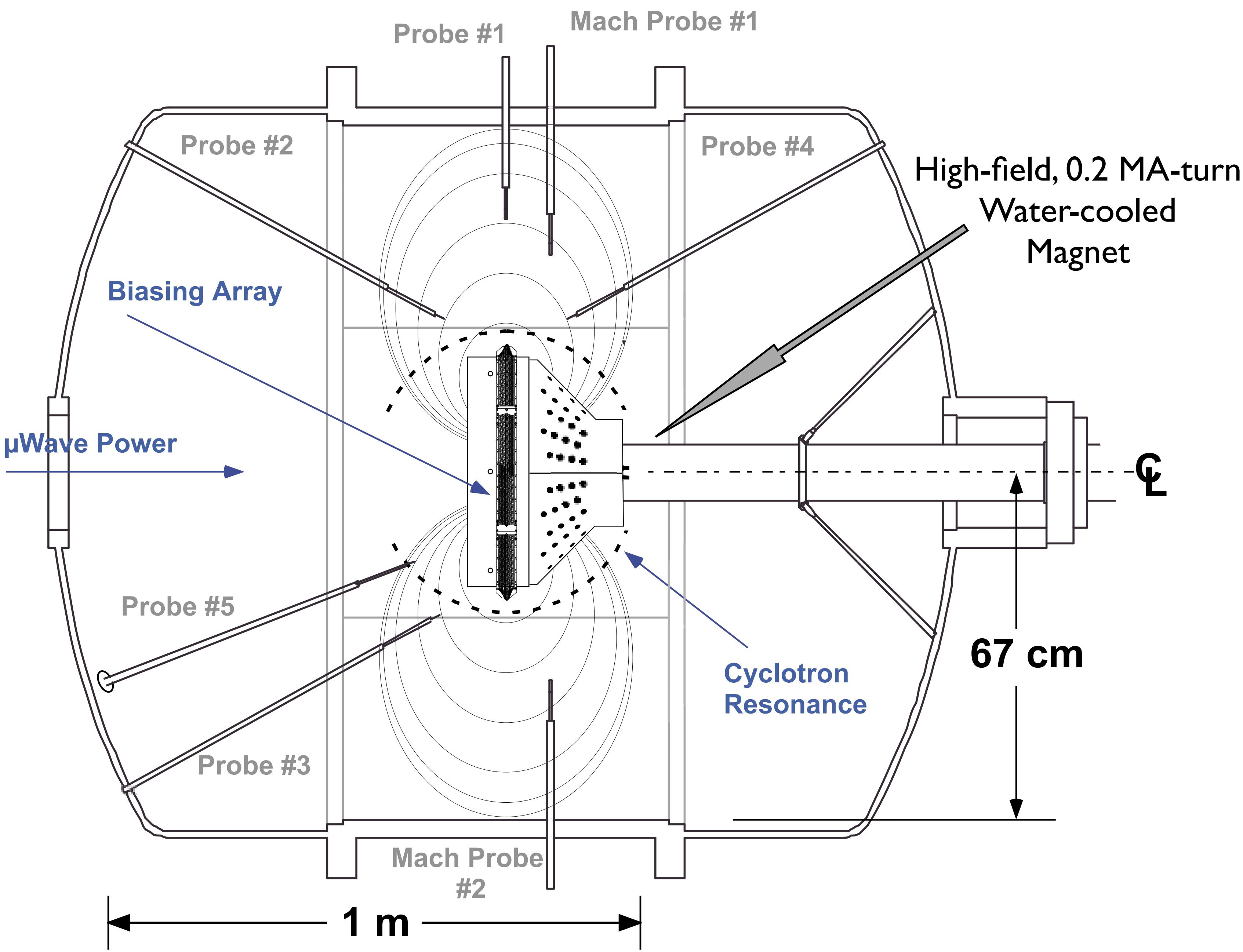


With strong B and large size, three motions separate!

Observing Interchange Modes

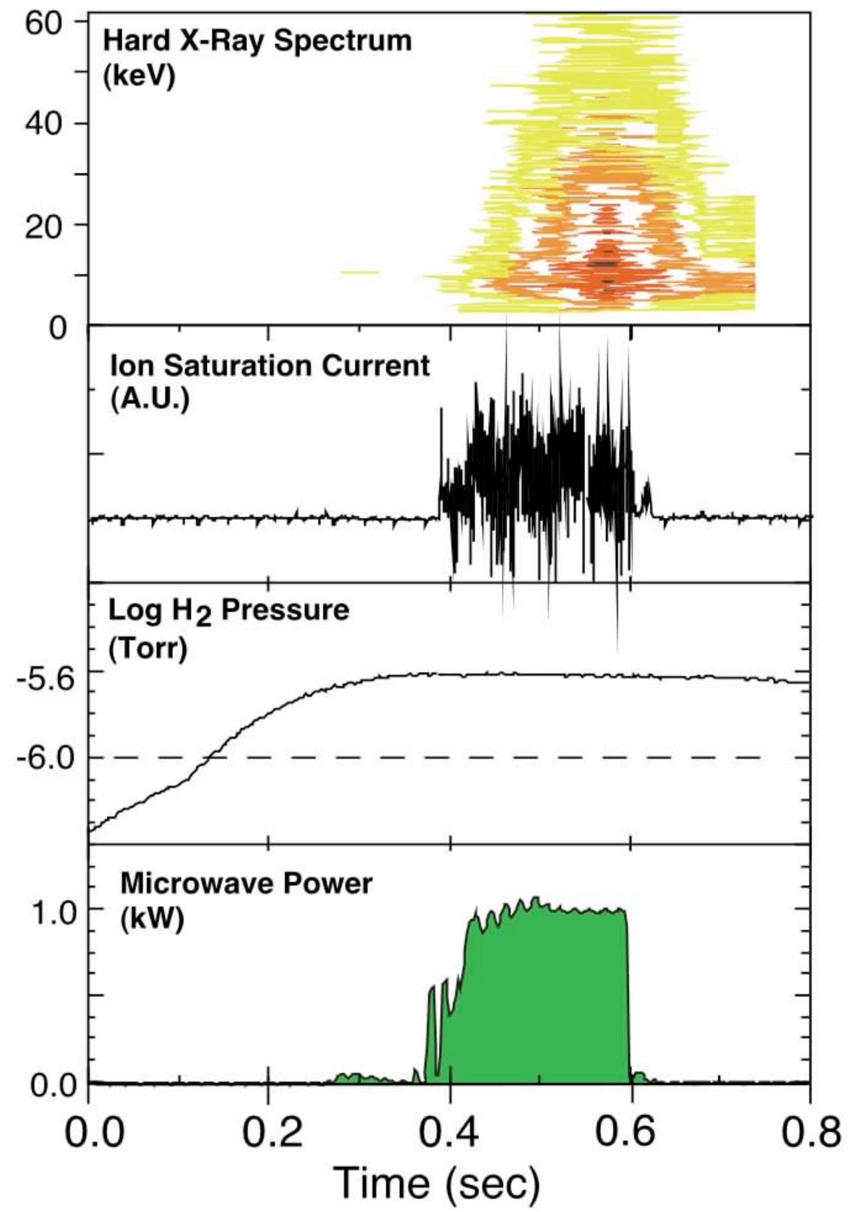
- Artificial Radiation Belt
  - "Fast" gyrokinetic interchange
  - $\gamma_h \sim \sqrt{\omega_{ci}\omega_{dh}\alpha}$, $\omega_{dh}/2\pi \sim 0.1 - 1.0$ MHz
- Artificial Gravity
  - "Slow" centrifugal interchange
  - $\gamma_g \sim \sqrt{\omega_{ci}\omega_g}$, $\omega_g/2\pi \sim 0.2 - 1.0$ kHz

Collisionless Terrella Experiment (CTX)

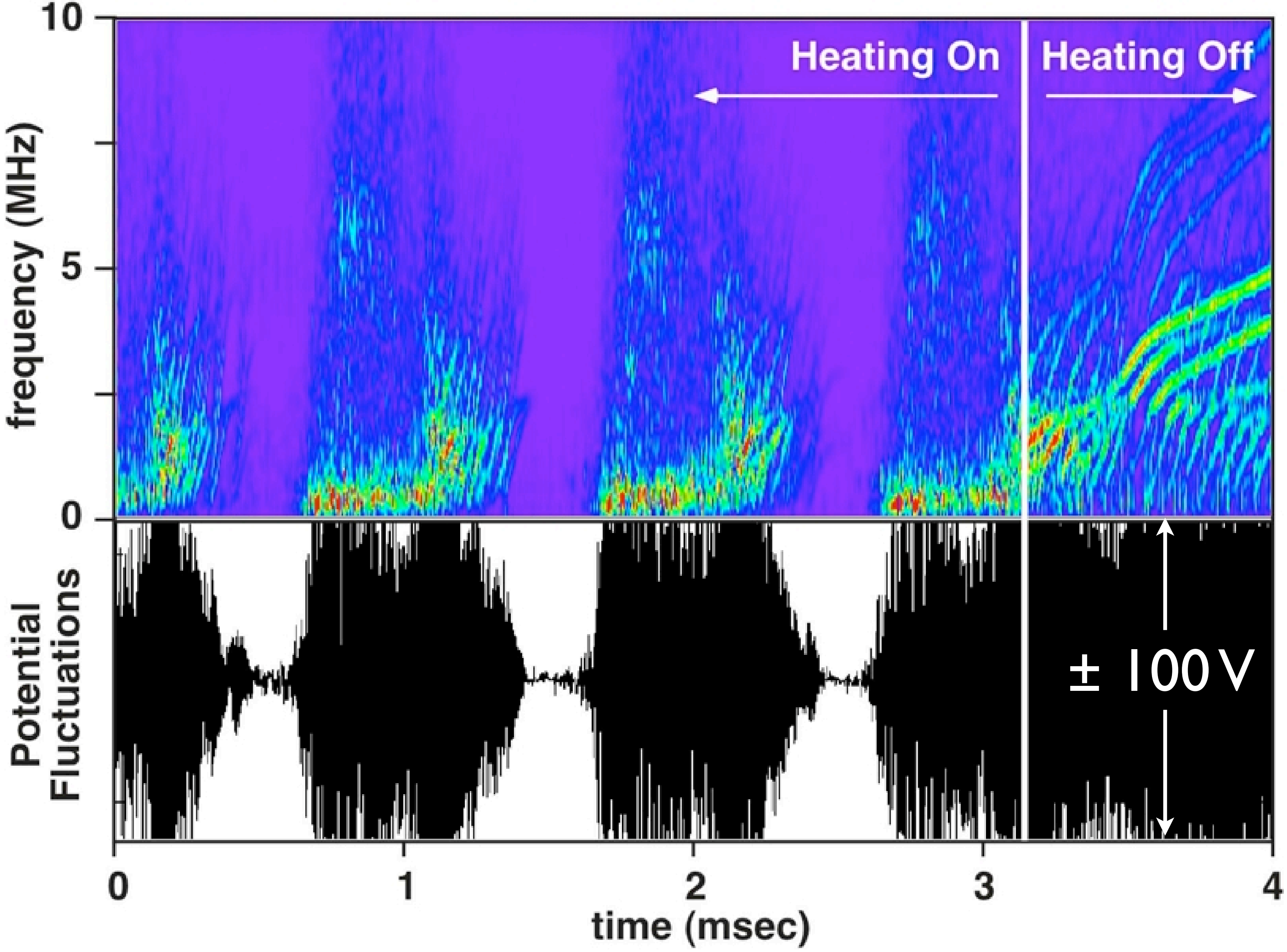


Creating an "Artificial Radiation Belt"

- 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

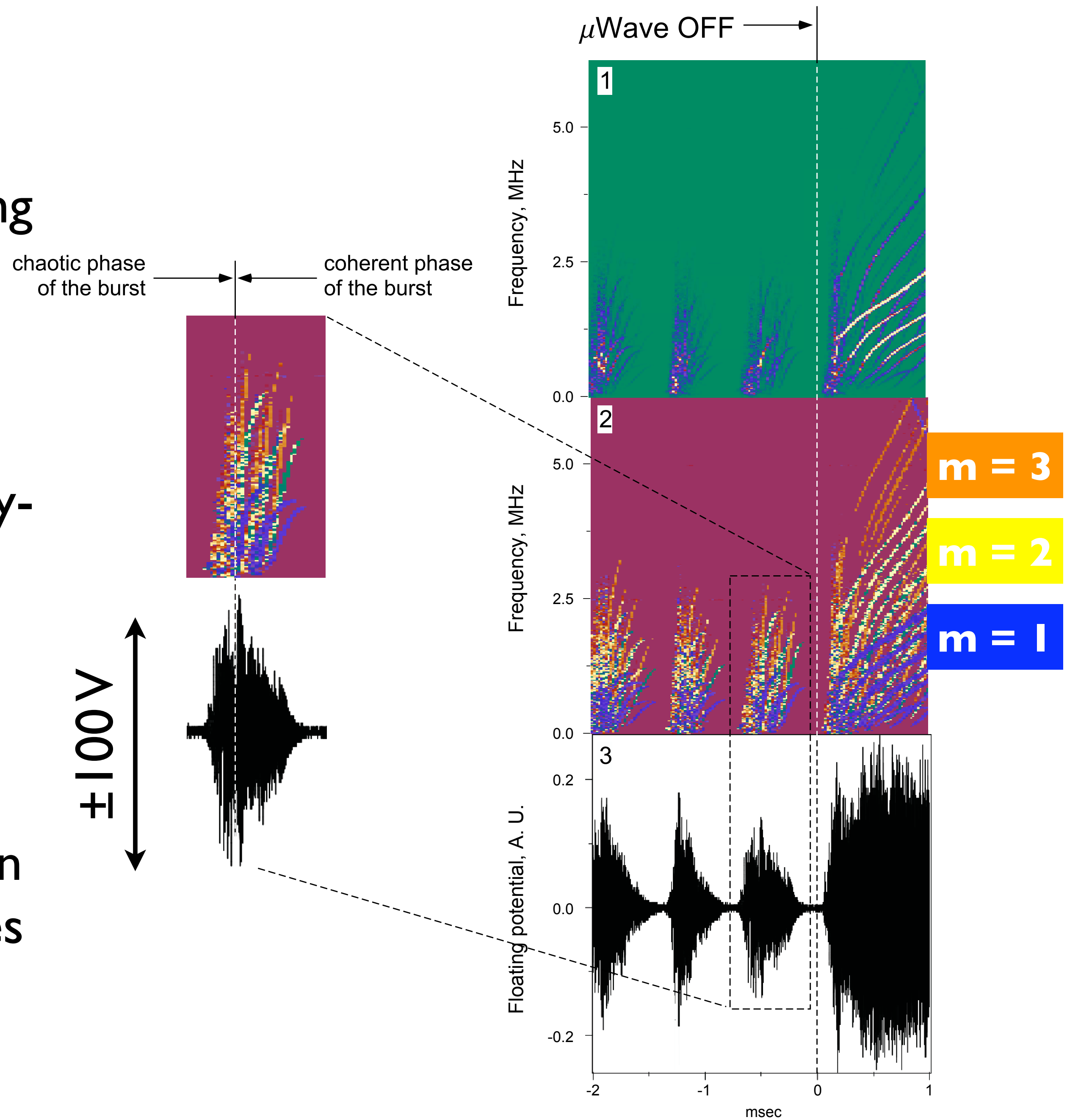


Hot Electron (Fast) Interchange Instability



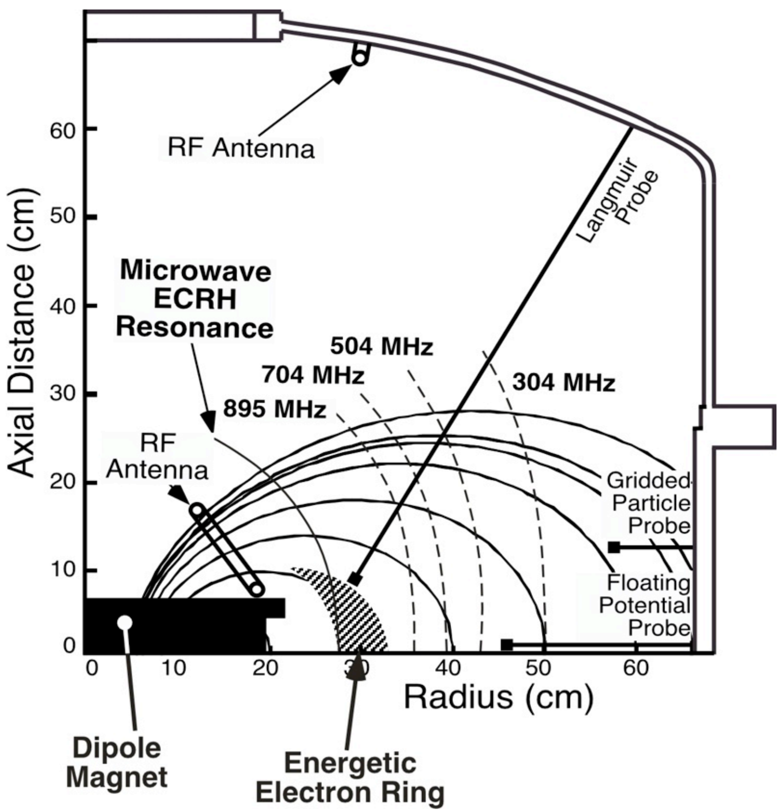
Multiple Low-*m* Modes & Frequency Sweeping

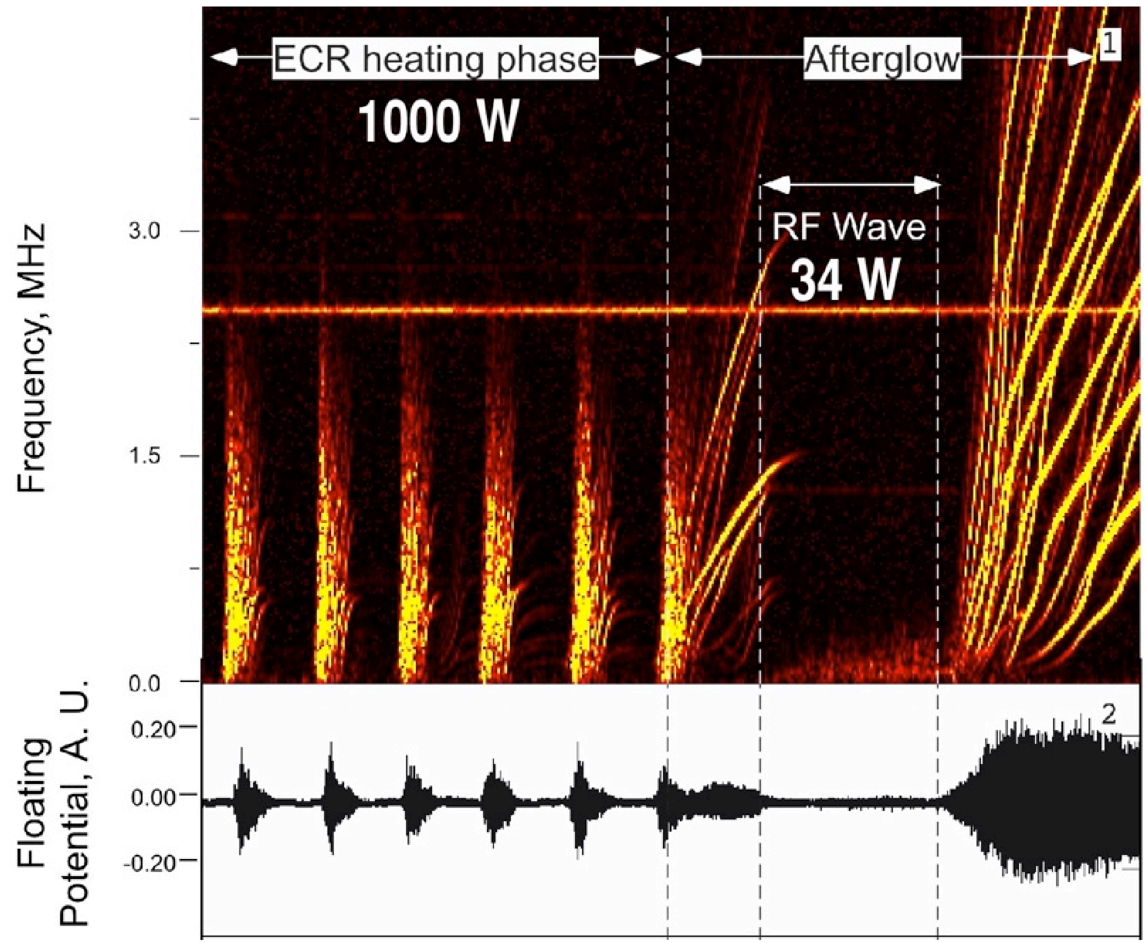
- Chaotic drift-resonant transport measured during dense spectral content. (Warren, PRL, 1995)
- Quasi-coherent frequency-sweeping indicates **collisionless** wave-particle dynamics.
- Multiple probe correlation measurements determines global mode structure.



Bursting "Phase-Space" with Low-Power RF

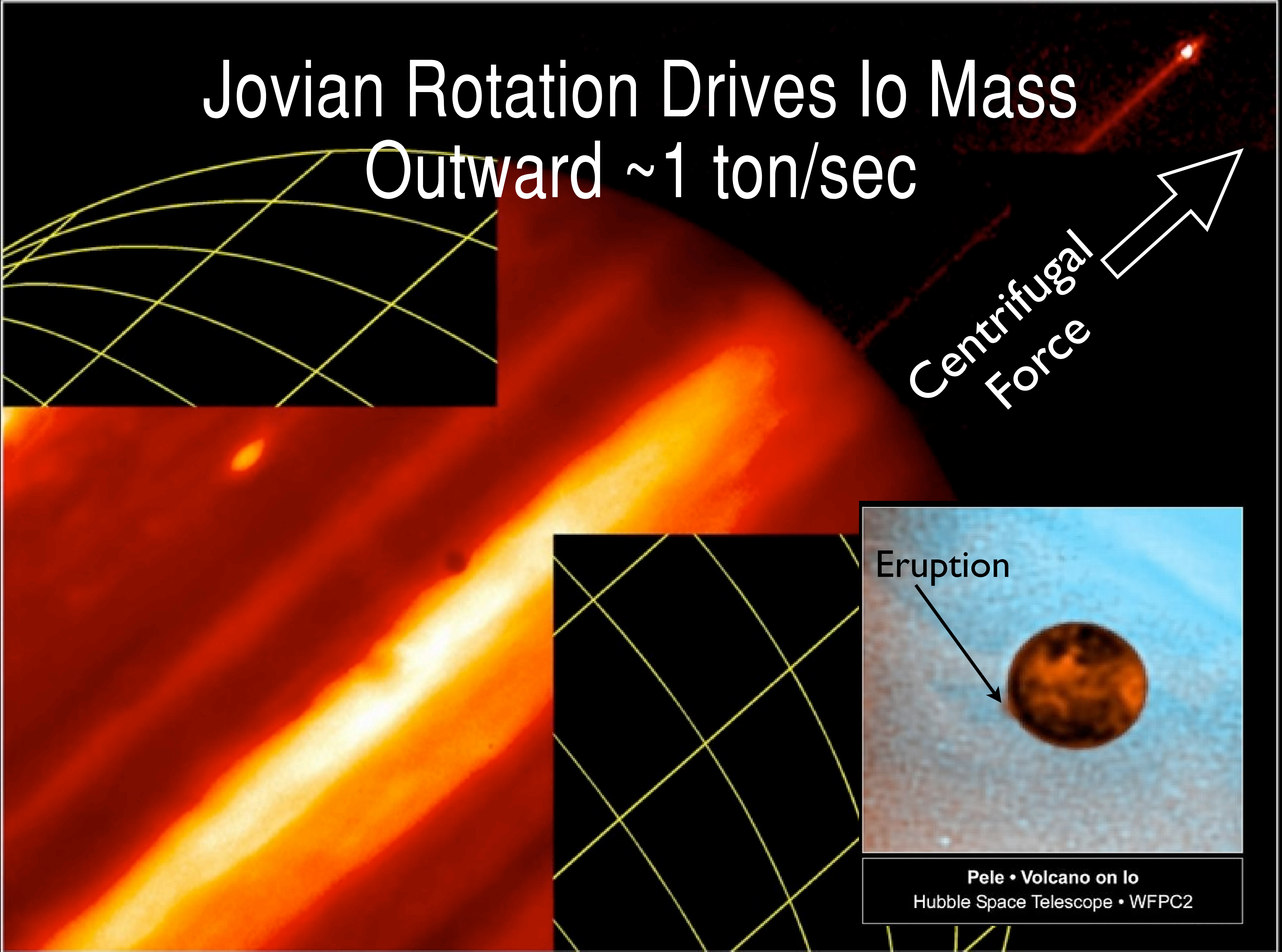
(Maslovsky, *PRL*, 2003)





Related work: Heeter, Fasoli, Sharapov, *PRL* (2000)

Jovian Rotation Drives Io Mass Outward ~1 ton/sec

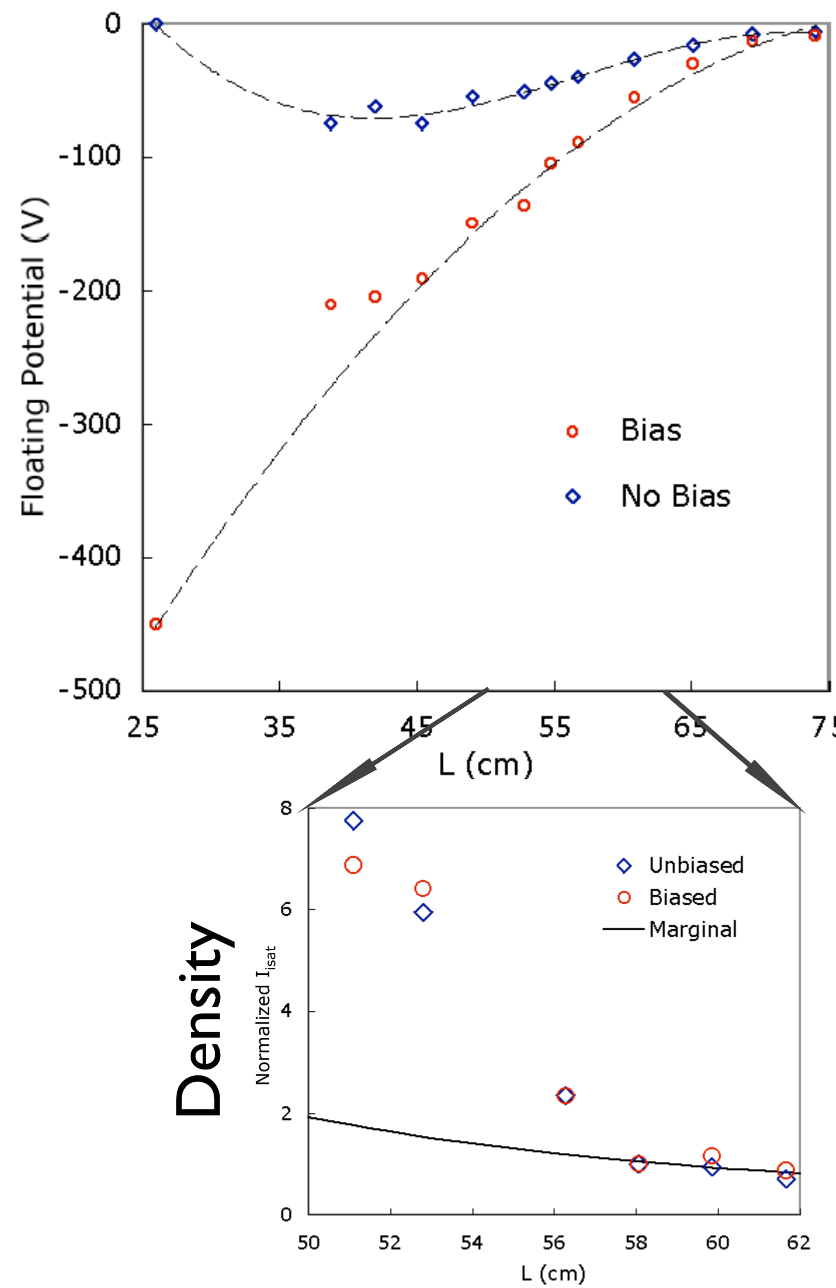


Creating "Artificial Gravity" through Rapid Plasma "Co-Rotation"

- Floating potential scales with radius as $\Phi \sim R^{-1}$ (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:

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

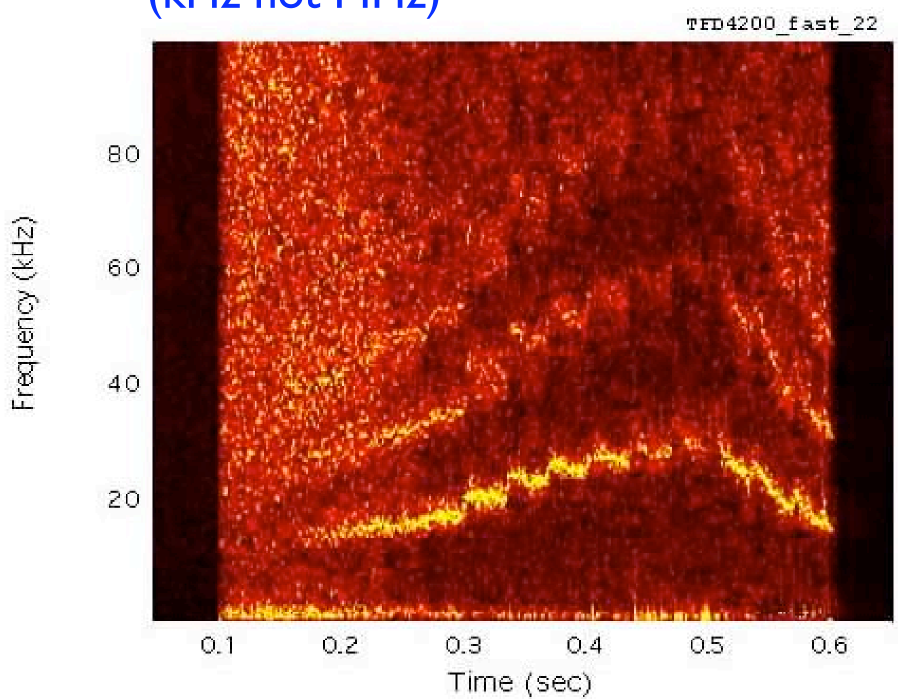
- $\Sigma_p(R)$ is constant if density profile, $n \sim R^{-6}$, **exceeds** centrifugal instability threshold.

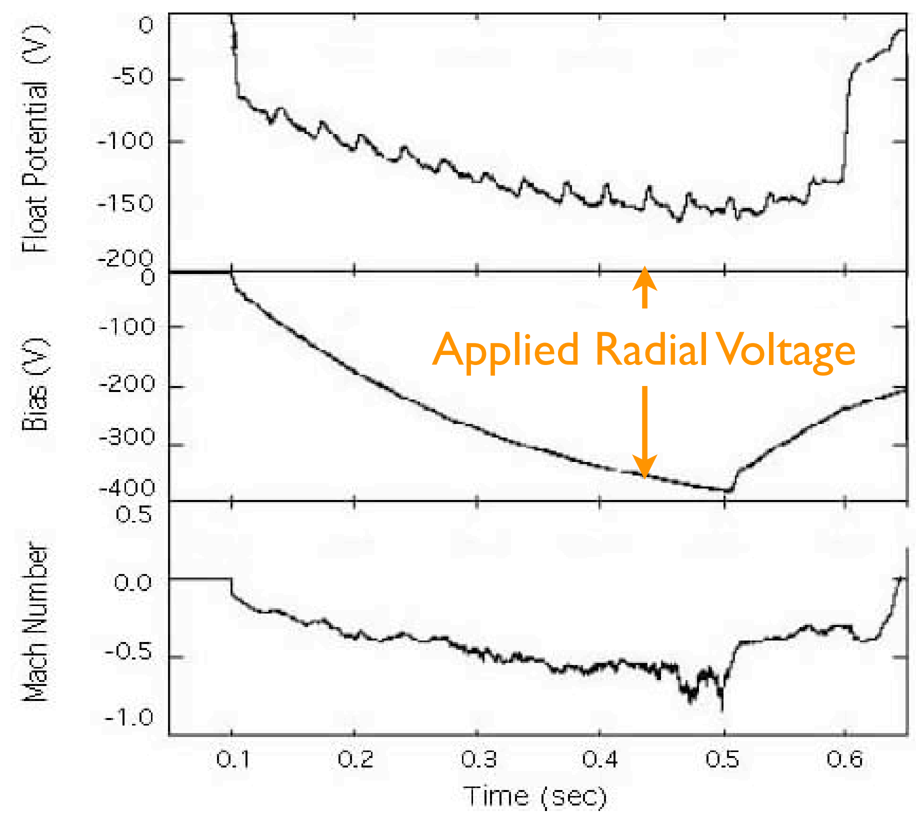


Centrifugal (Slow) Interchange Excited by Rapid Plasma Rotation

(Levitt, *PRL*, 2005)

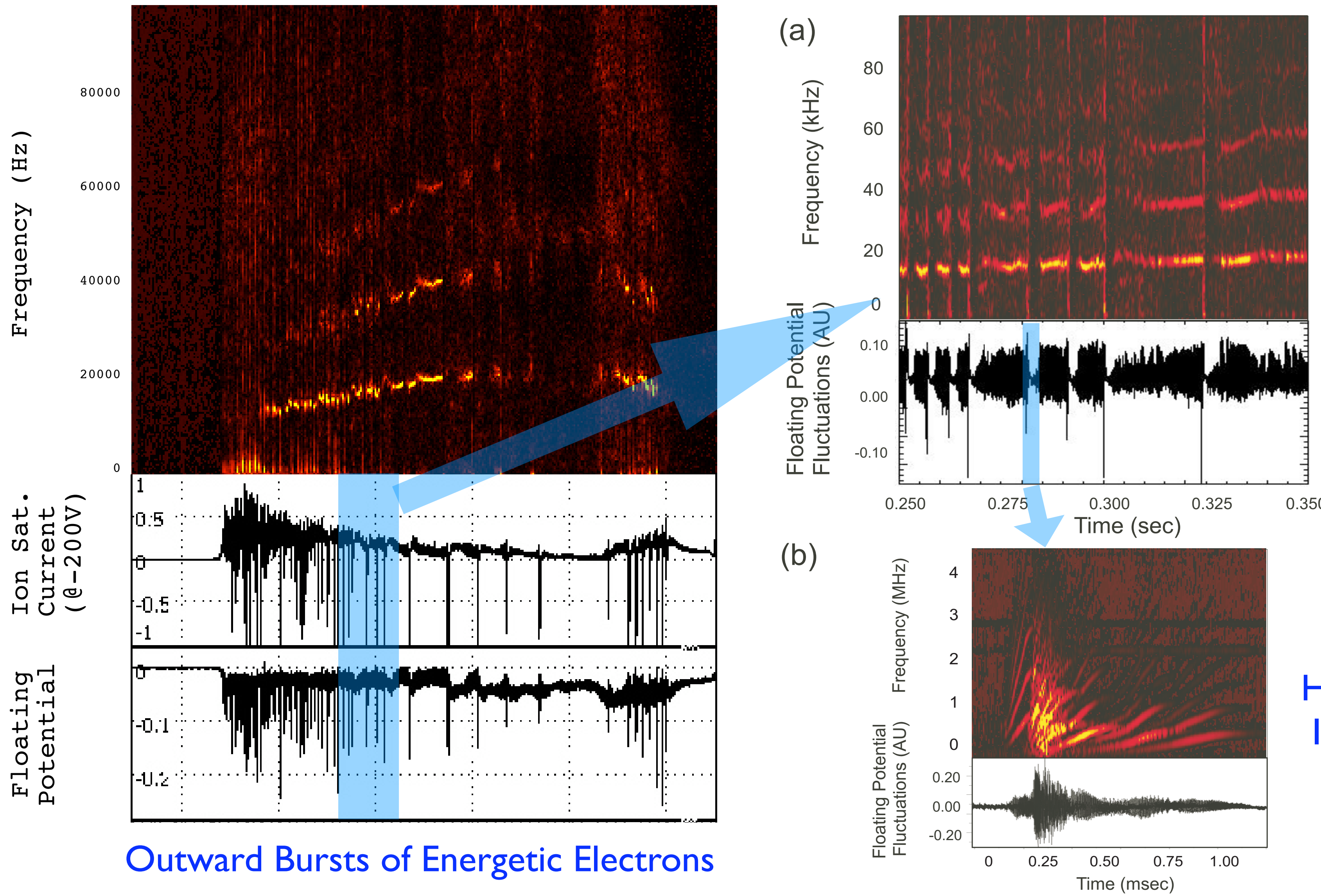
(kHz not MHz)





(Seconds not msec)

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



Outward Bursts of Energetic Electrons

Close-up:
Hot Electron
Interchange

Modeling Interchange

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

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

① "Inward" Adiabatic Heating

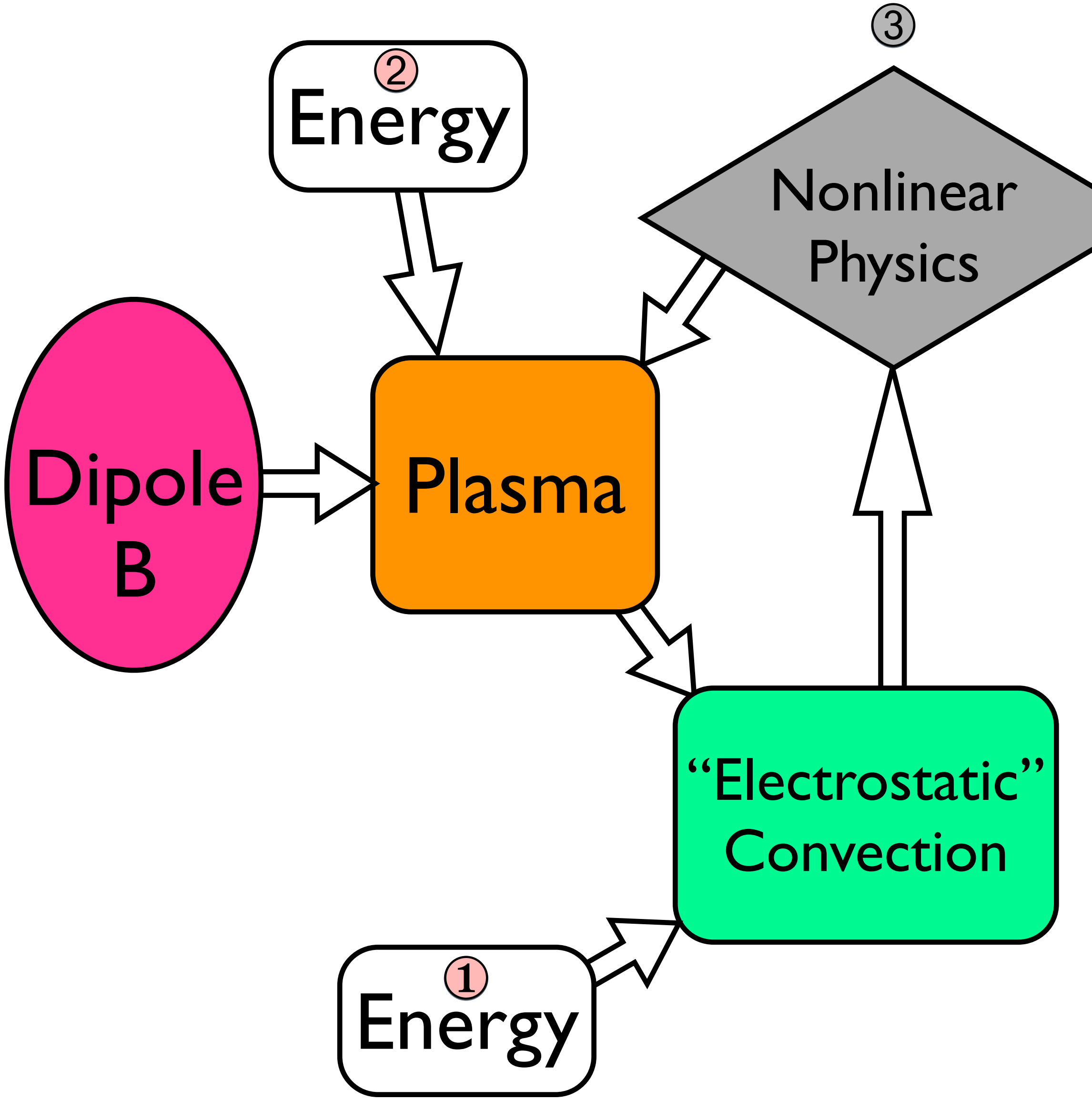
- Ring current intensification
- Storm-time belt formation

② "Outward" Transport/Profile Consistency

- Planetary winds (Centrifugal)
- Magnetic confinement

③ "Phase-Space" Structure

- Drift-echos (injections)
- Holes (bubbles)
- Frequency sweeping
- Centrally-peaked profiles



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

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

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

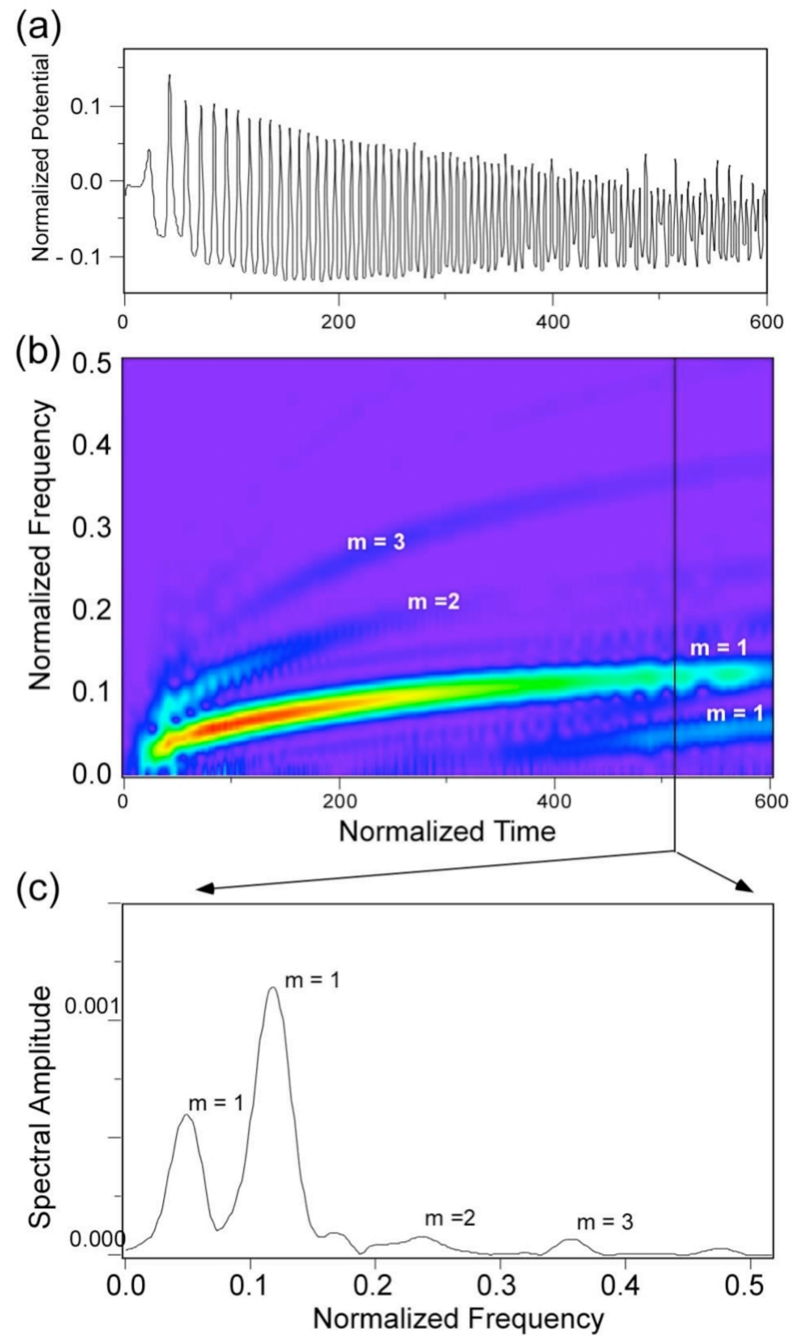
Electric Potential

(Constant along B-line & small dissipation)

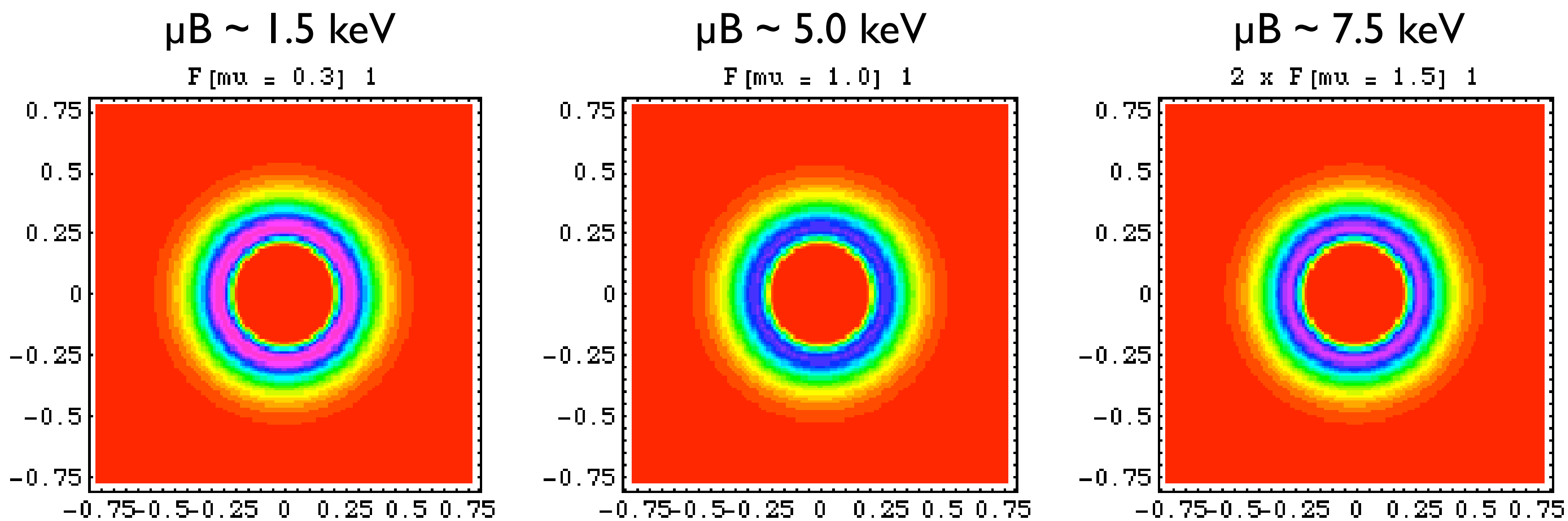
Self-Consistent, Nonlinear, **Flux-Tube Integrated,** Simulation Reproduces Dipole Interchange Dynamics

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

➡ Initial value; no sources

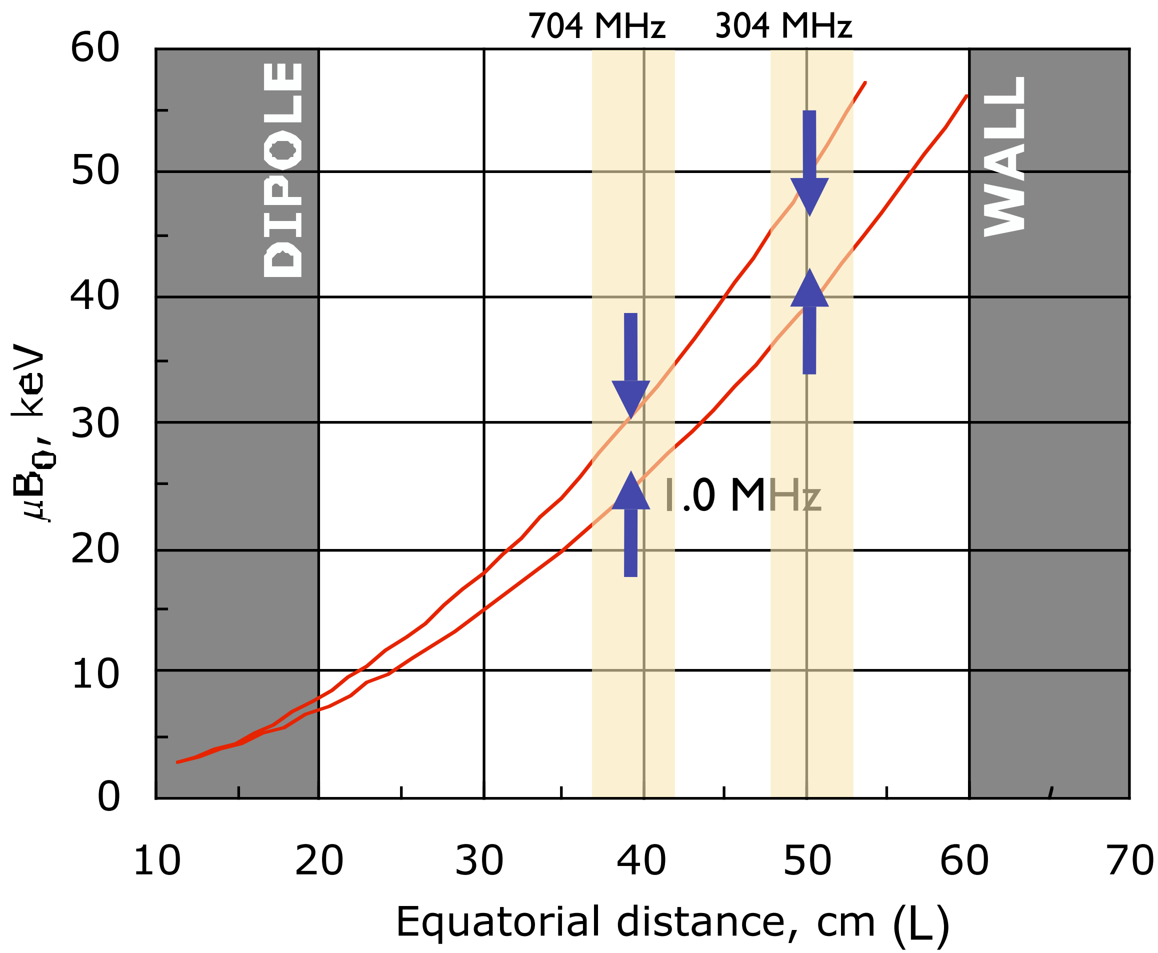


Gyrokinetic Interchange Creates Persistent Phase-Space Structures



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

Physical Picture of Frequency Sweeping Suppression

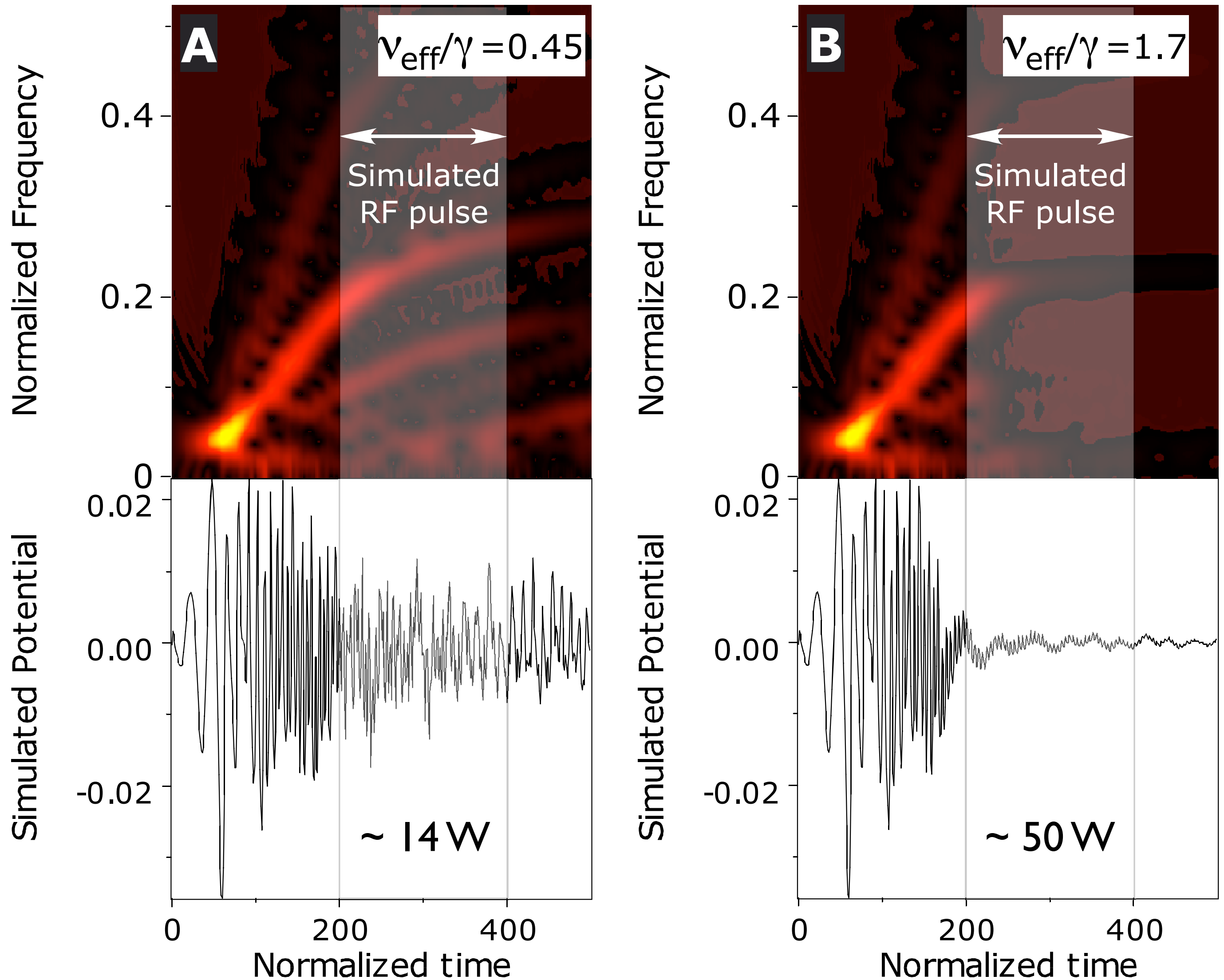


Location of a ~100 V phase-space "hole" at 1.0 MHz. $\omega = m\, \omega_d(\mu,L)$

RF cyclotron resonant fields applied are localized at the outer flux surfaces - locations where phase-space "holes" are initiated

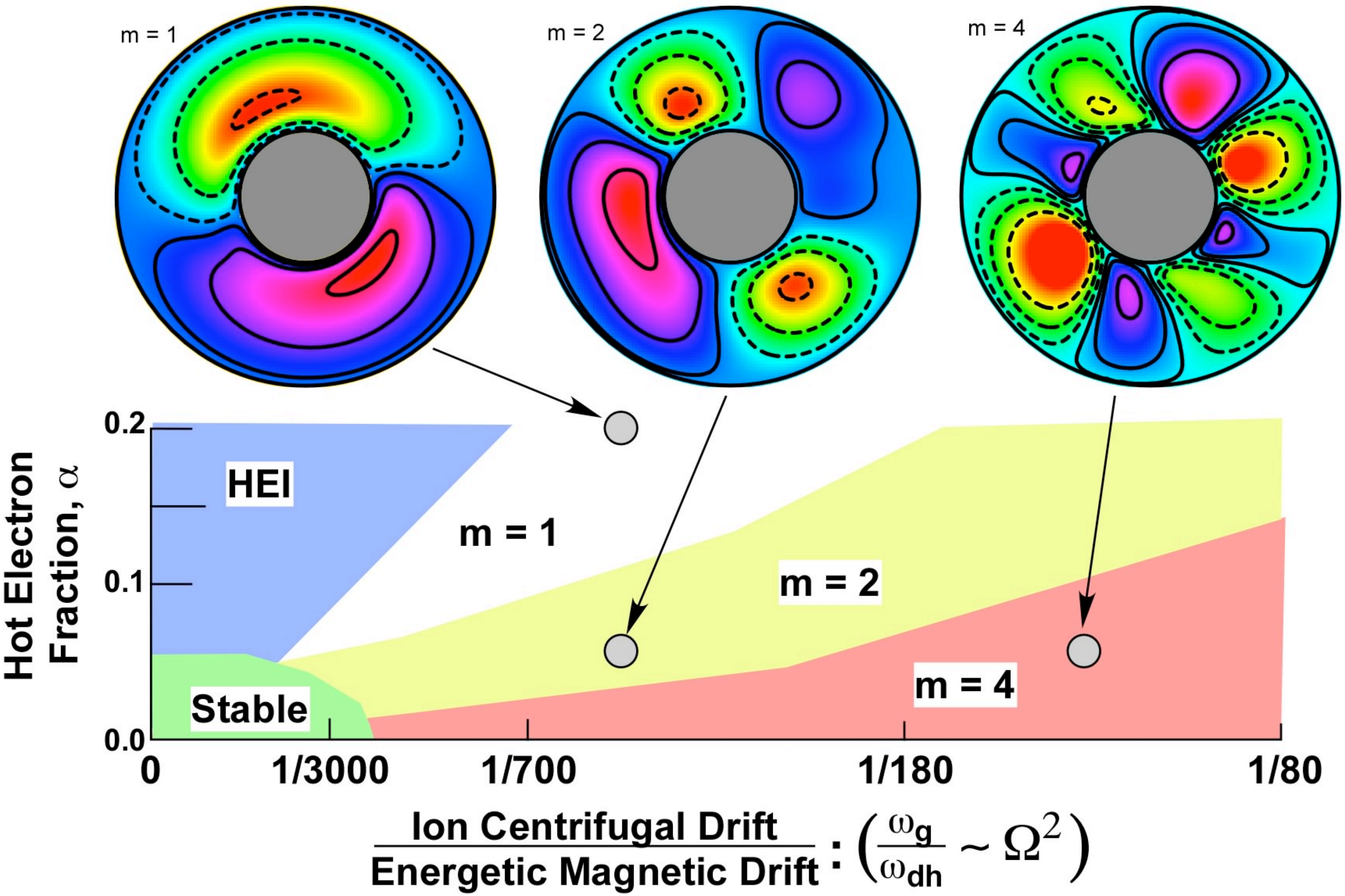
RF mixing along μ causes the phase-space "holes" to fill/ untrap and suppress frequency sweeping

Nonlinear Simulation Reproduces Measured Frequency Sweeping Suppression



$$\frac{\partial}{\partial t} F(\mu, \psi, \varphi, t) = D(\psi, t) \frac{\partial^2}{\partial \mu^2}(F - F^*)$$

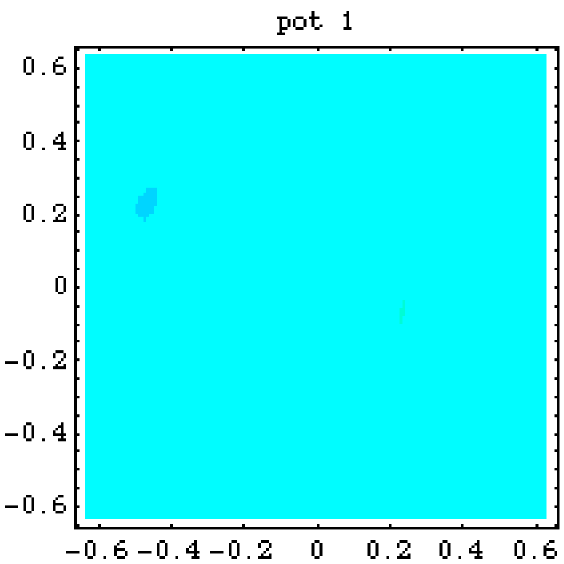
Relative Strength of Centrifugal and Curvature Drives Determine Mode Structure

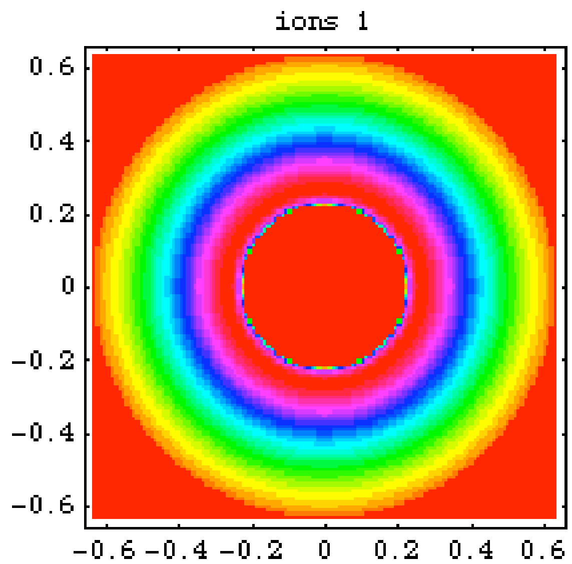


Centrifugal (Slow) Interchange with Rigid Rotation

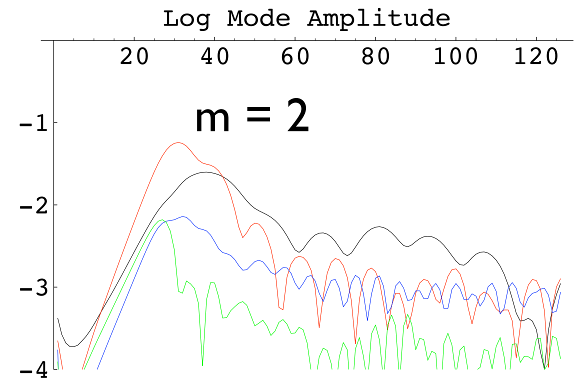
Computed in **Rotating Frame**

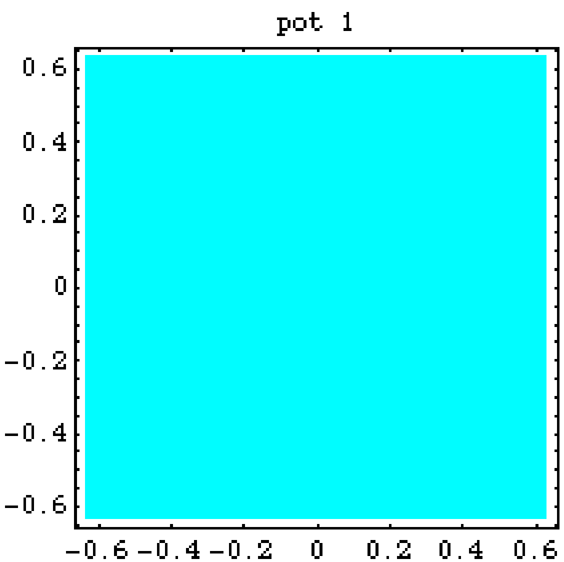
Unstable Growth and Saturation from Noise

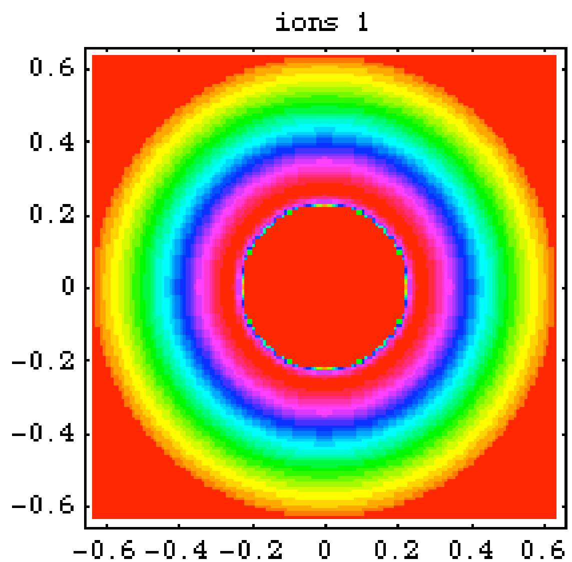




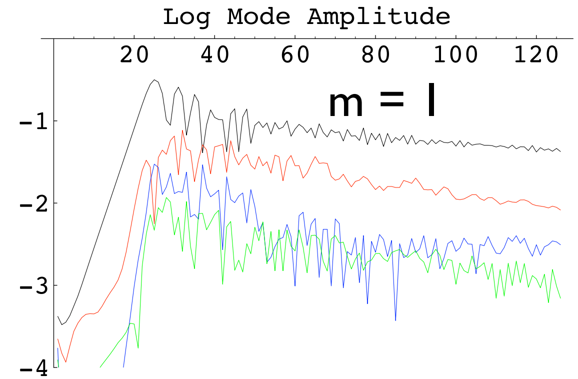
5% Hot Electron Fraction



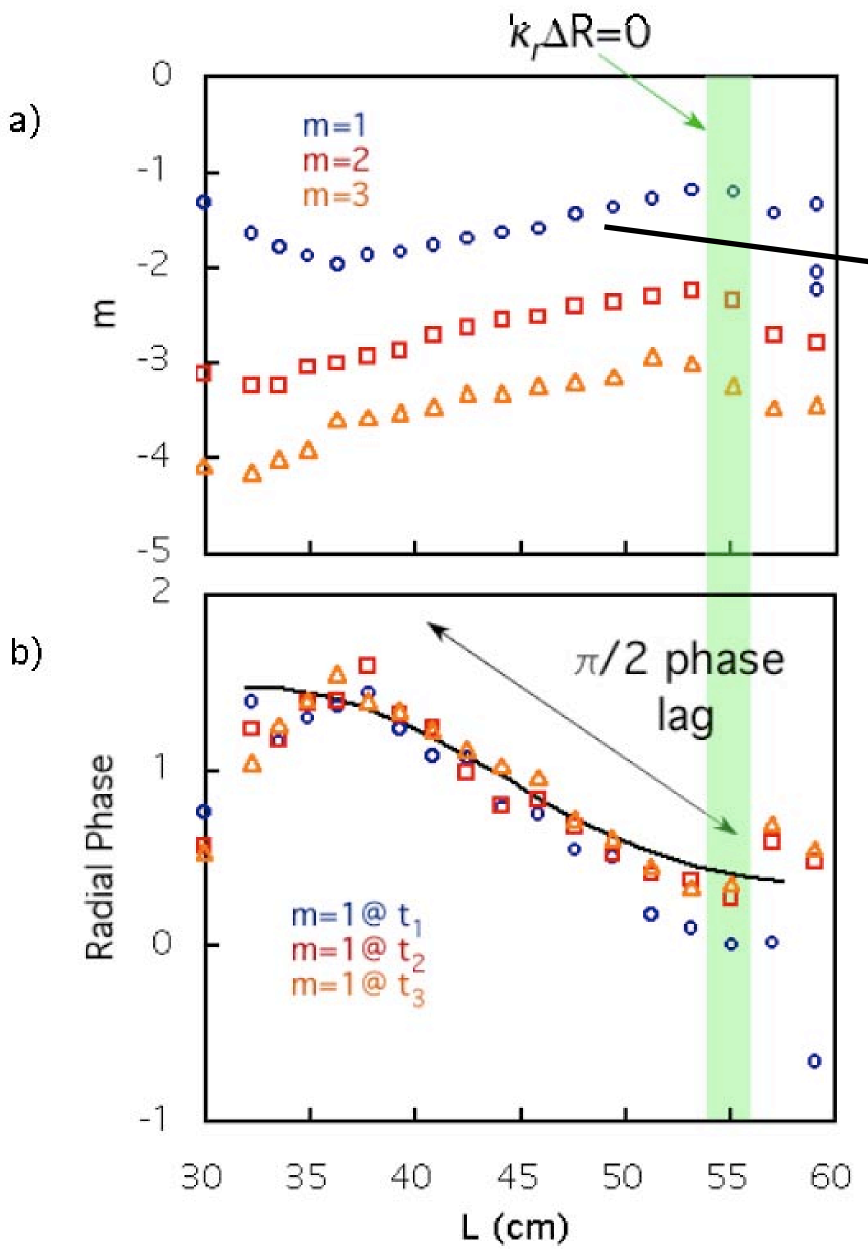


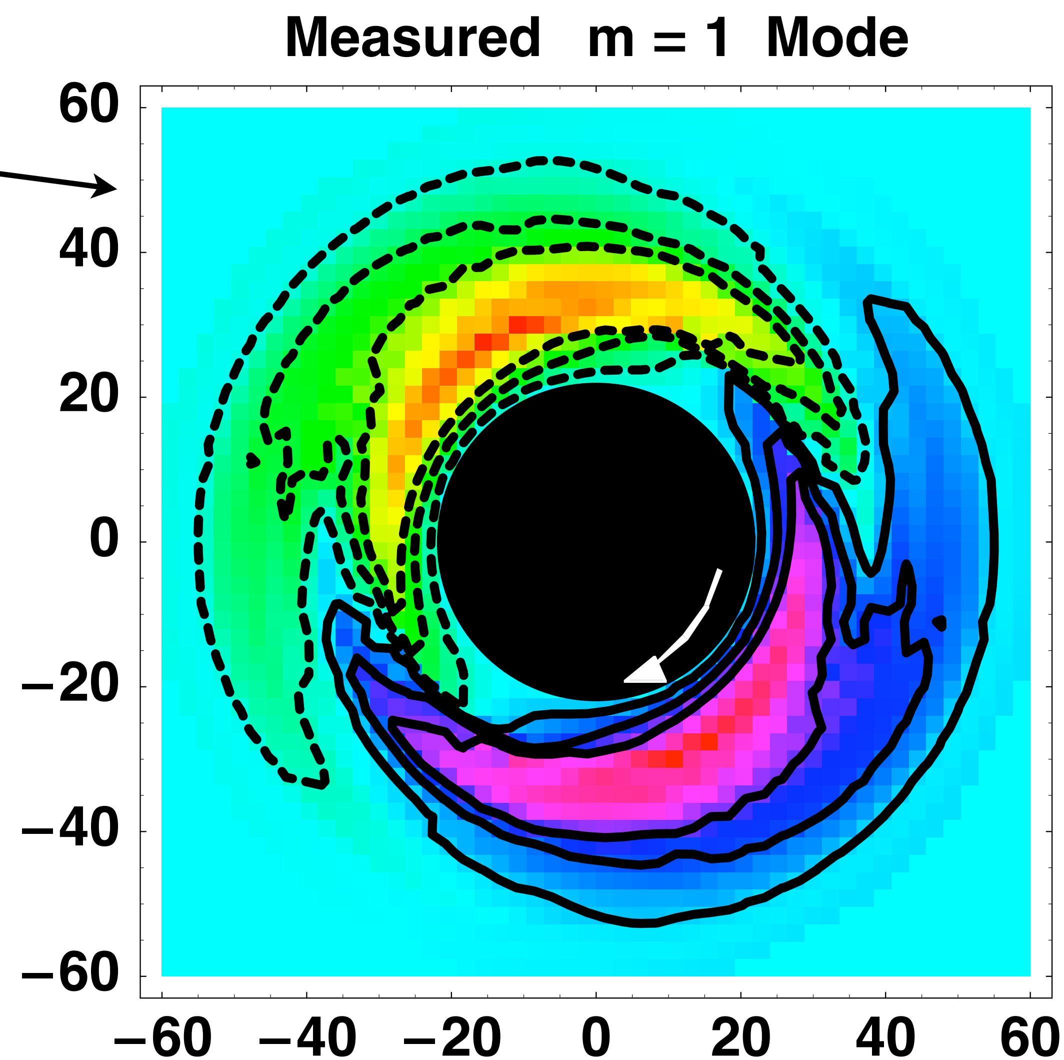


20% Hot Electron Fraction



Phase Measurements Show "Spiral" Mode Structure of Centrifugal Mode

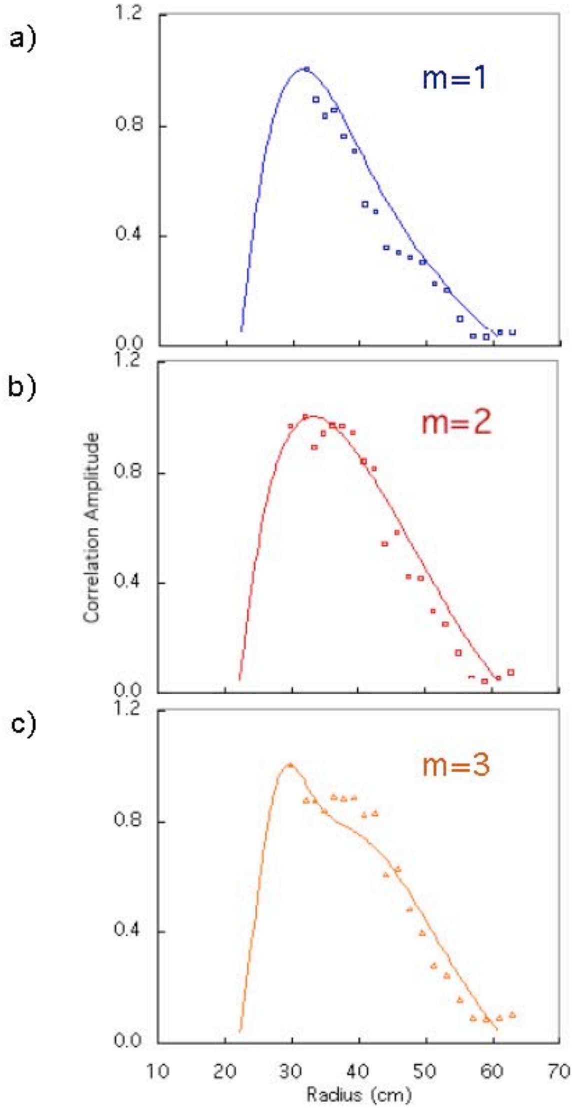




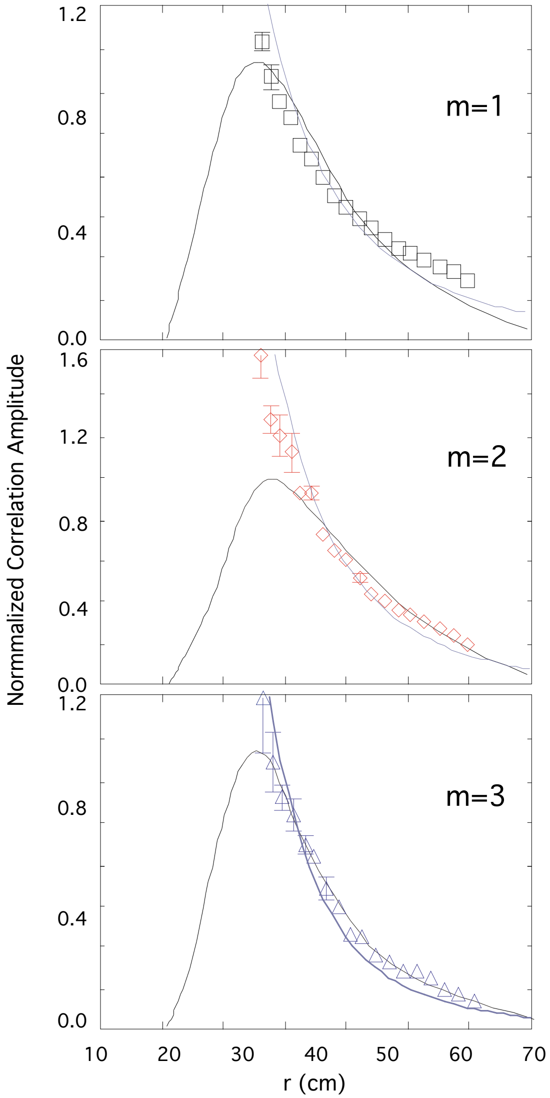
(ϕ ~ Stream function)

Dipole Interchange Modes have **Broad** Radial Structures

Centrifugal Interchange



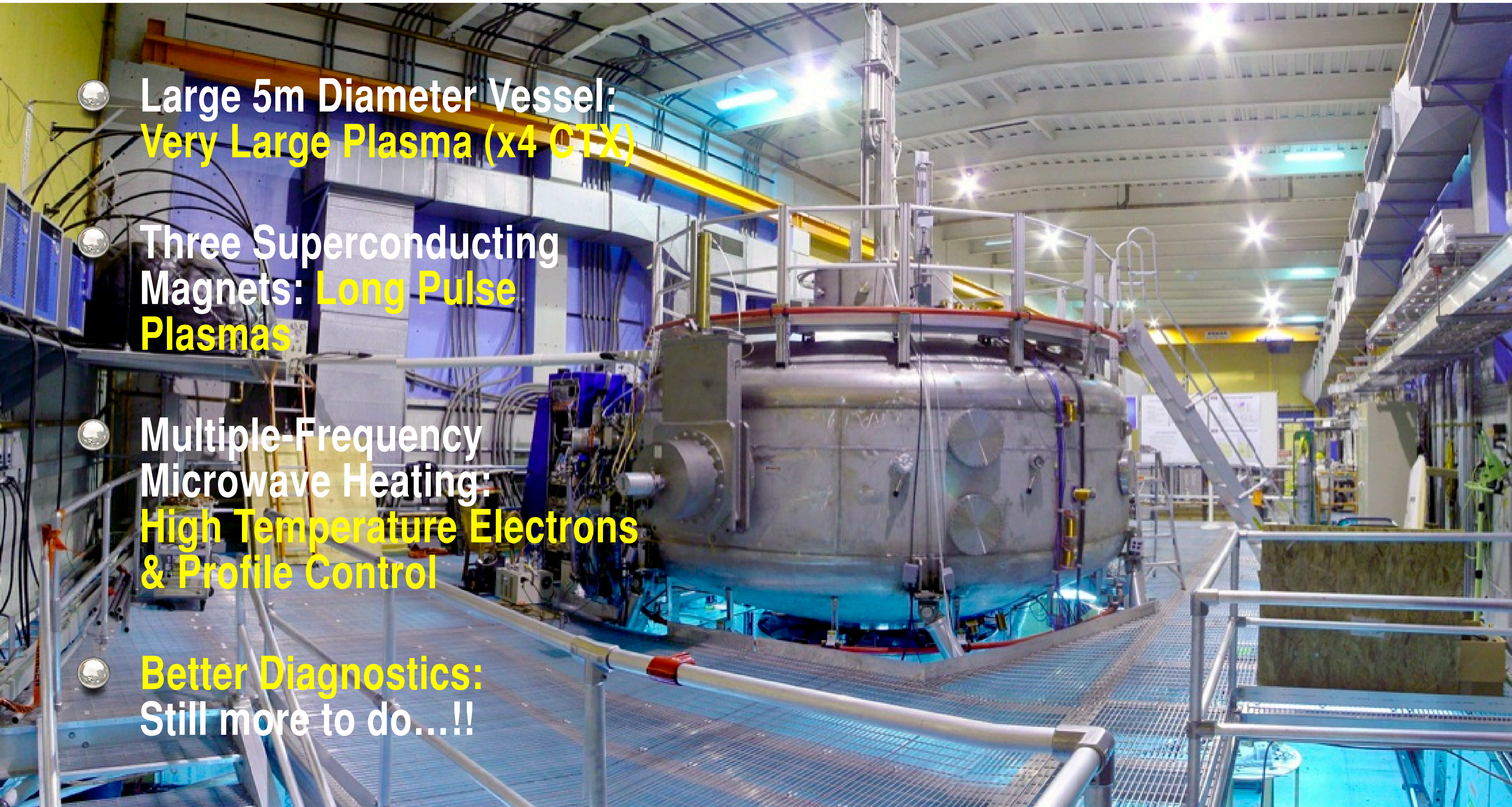
Hot Electron Interchange



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

LDX: A New Confinement Experiment

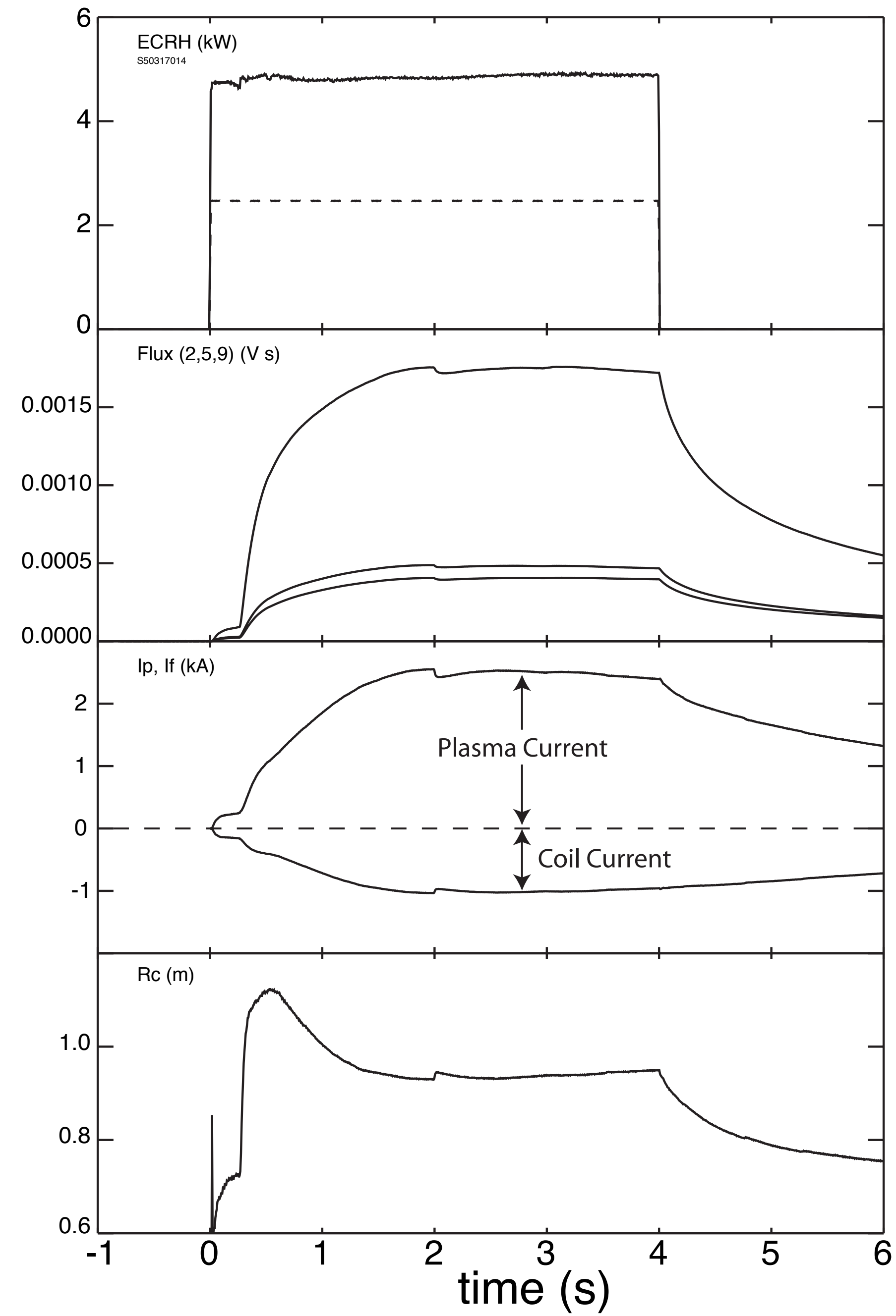
MIT-Columbia University



- Large 5m Diameter Vessel: Very Large Plasma (x4 CTX)
- Three Superconducting Magnets: Long Pulse Plasmas
- Multiple-Frequency Microwave Heating: High Temperature Electrons & Profile Control
- Better Diagnostics: Still more to do...!!

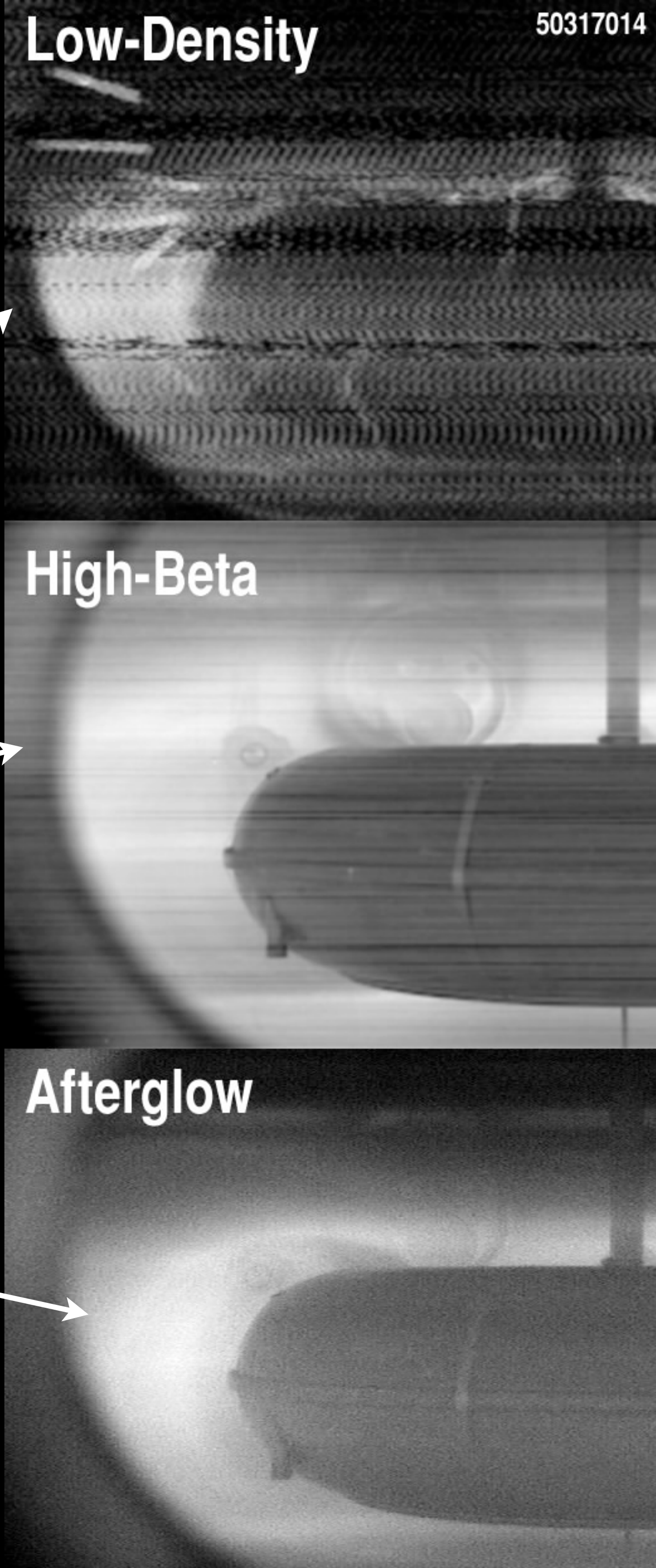
Big Plasma "Ring Current" Observed!

- Plasma currents reconstructed from **least-squares best fit** to magnetic diagnostics (*and inductive coupling to superconducting coil*.)
- For a given pressure profile shape, diagmagnetic **current is proportional to stored energy**. (Dessler-Parker-Sckopke)
- **Plasma current up to 4 kA ~ 300 J!** (Global energy confinement τ_E ~ 50 ms)
- Motion of ring current radius indicates profile evolution



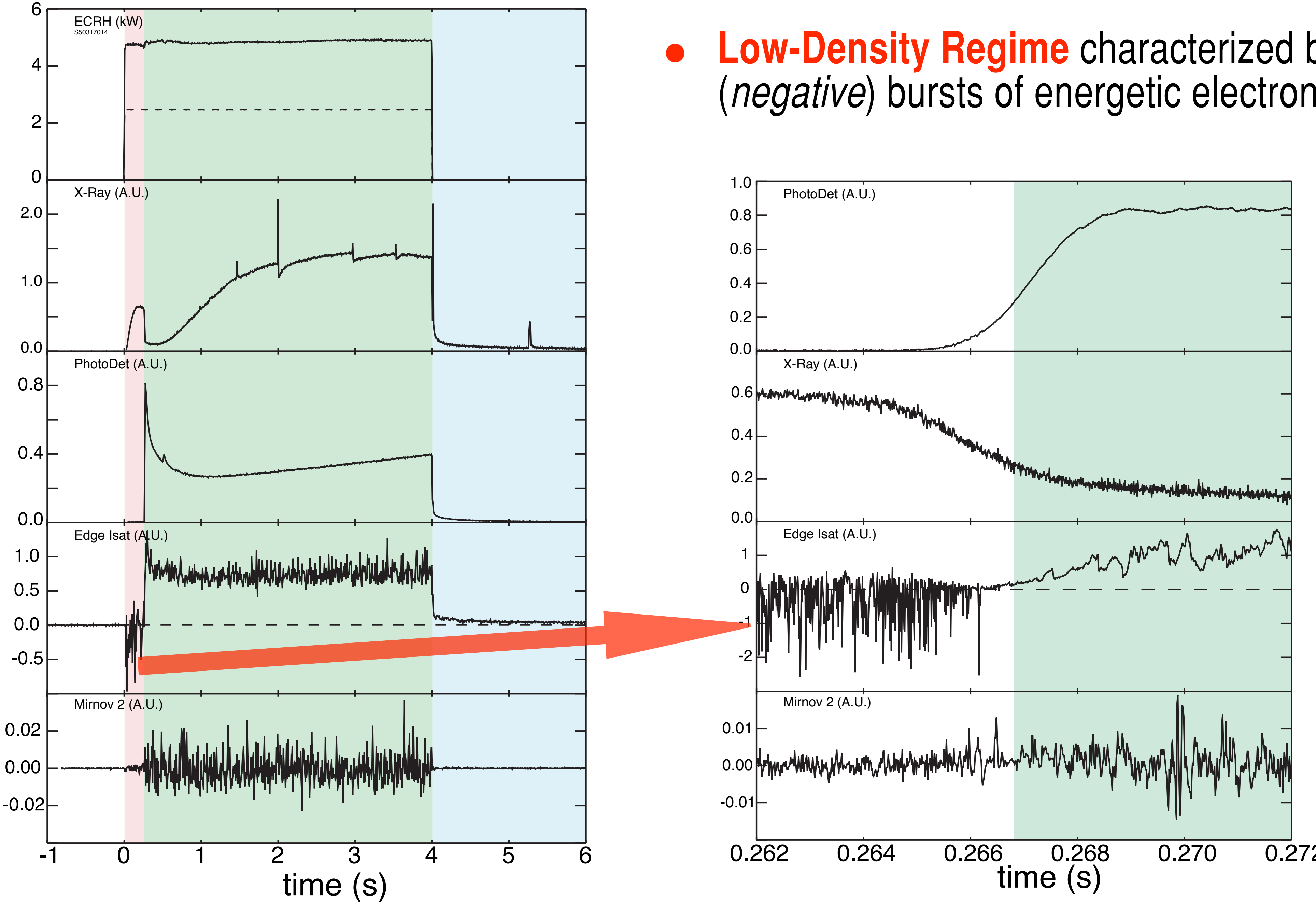
Three Regimes in LDX…

- Intense, quasi-continuous hot-electron interchange pulsations. Visible image shows inward fast-electron transport.
- High-beta (~10%), higher-density. Quasi-steady state. Bright “halo” surrounds fast-electrons.
- “Afterglow” lasting several seconds. No heating; lower density. Fast-electrons visible as neutrals penetrate.



Continuous “Bursty” Fluctuations During Low-Density

- **Low-Density Regime** characterized by (*negative*) bursts of energetic electrons.



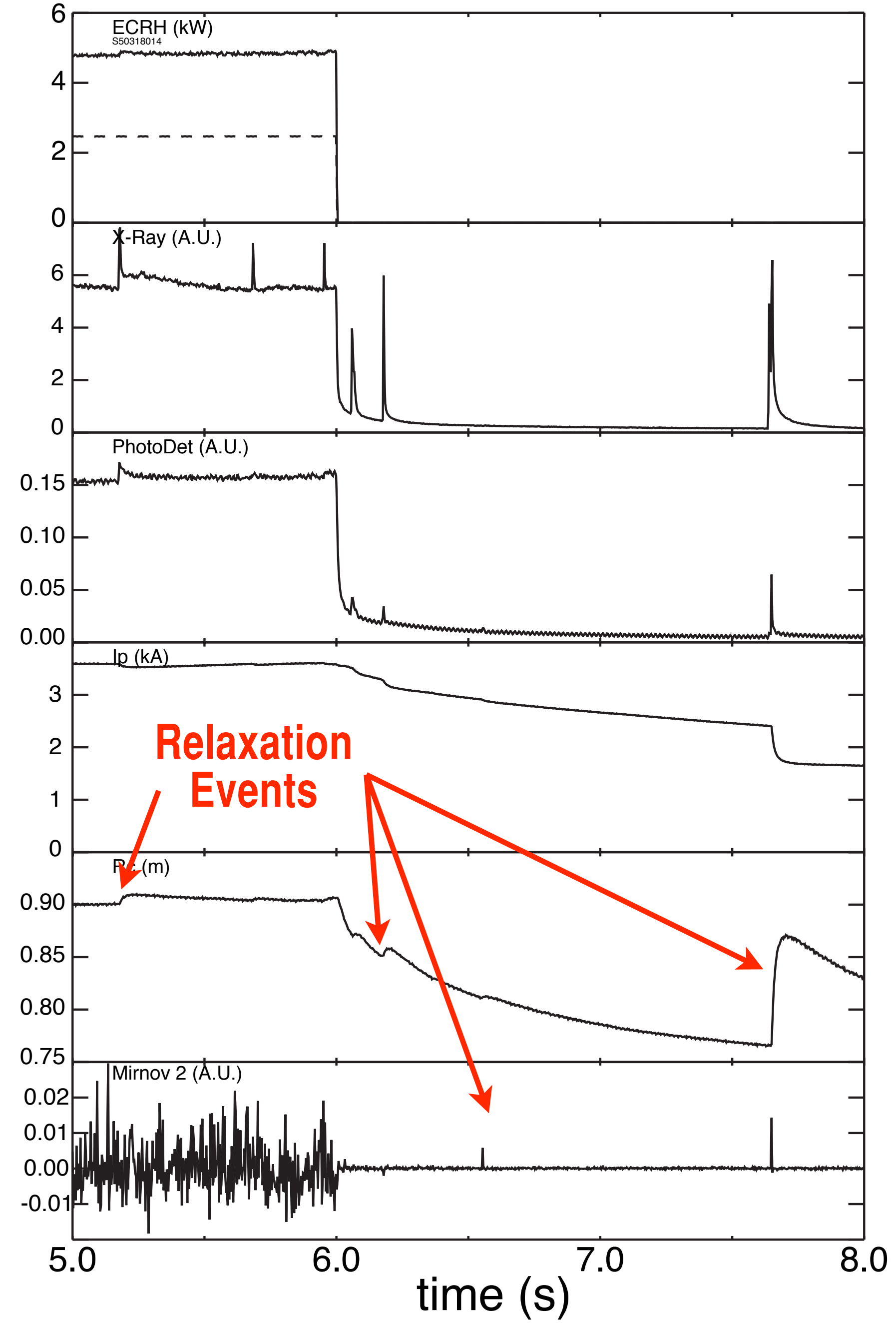
Isolated Relaxation Events
During High Beta Regime and During Afterglow

- At high β, periodic "relaxation" events occur a few times per second. **Outward motion of ring currrent.** (Also, x-ray and µwave bursts !)

- Depending upon neutral fueling and heating power, relaxation events can be ***small*** or ***fully disrupt*** high-beta regime.

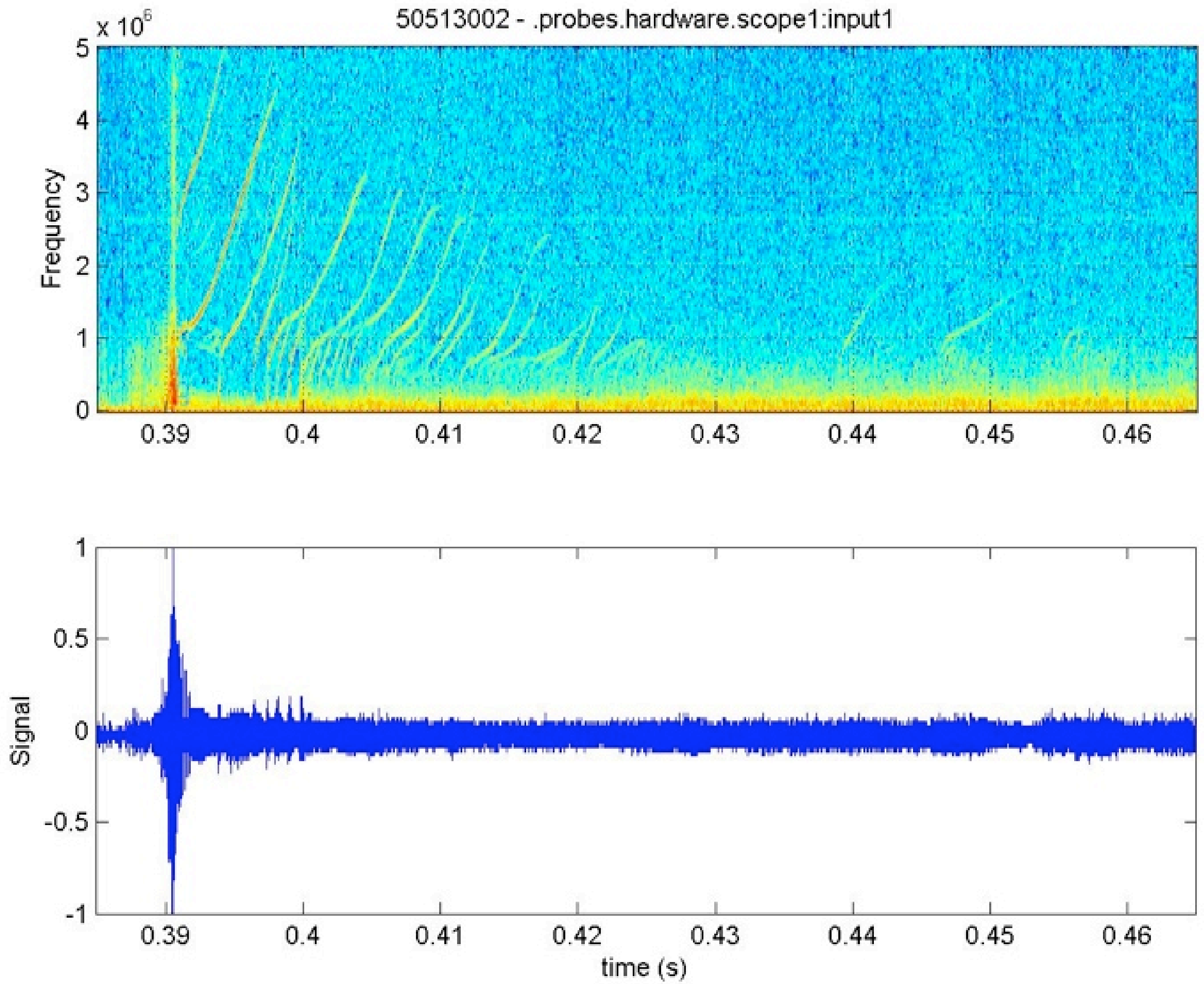
- HEI can appear in (nearly?) all cases

- LDX is the first to observe the HEI in a ***high-beta*** dipole plasma!

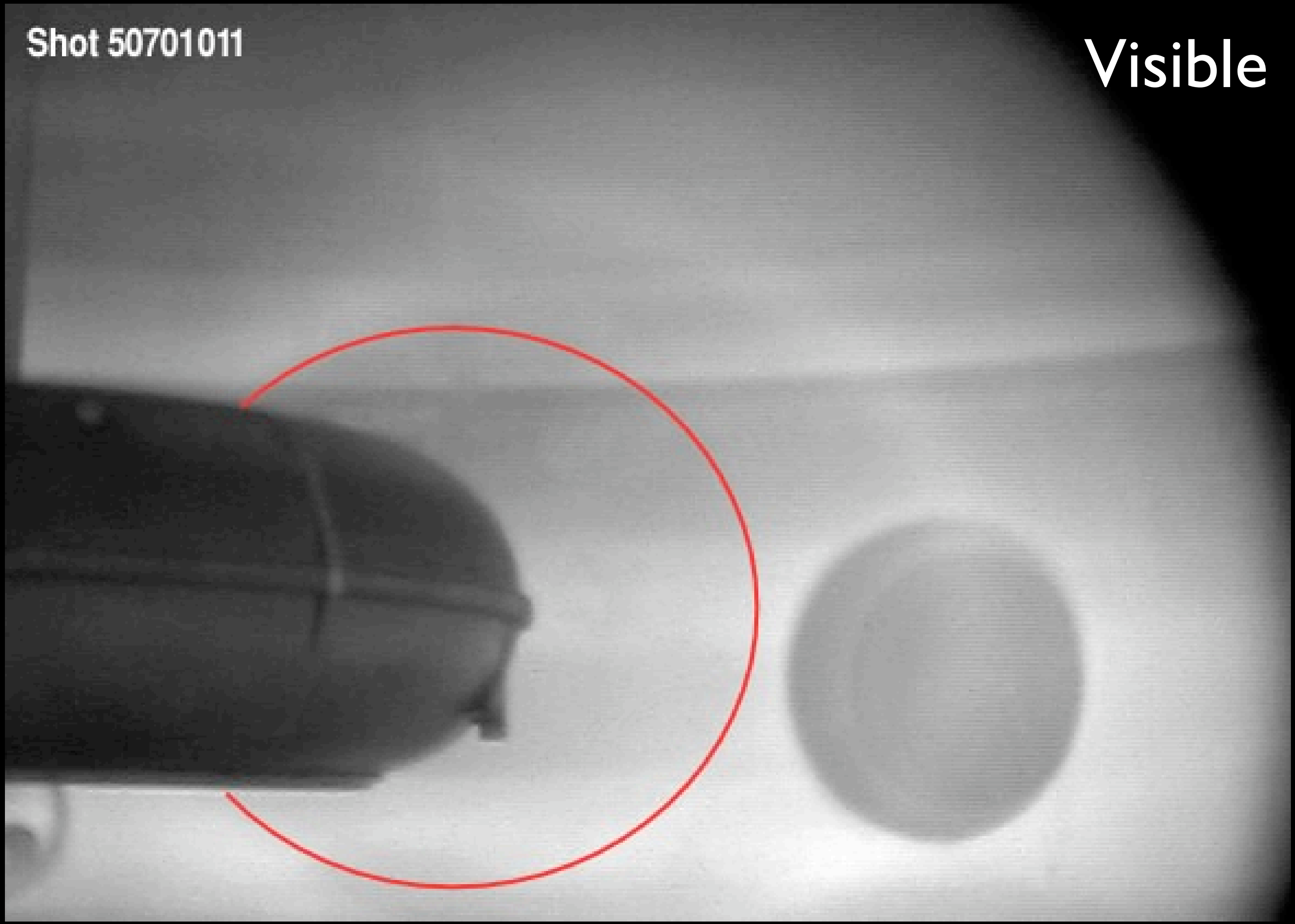


All Events Characterized by Frequency Sweeping

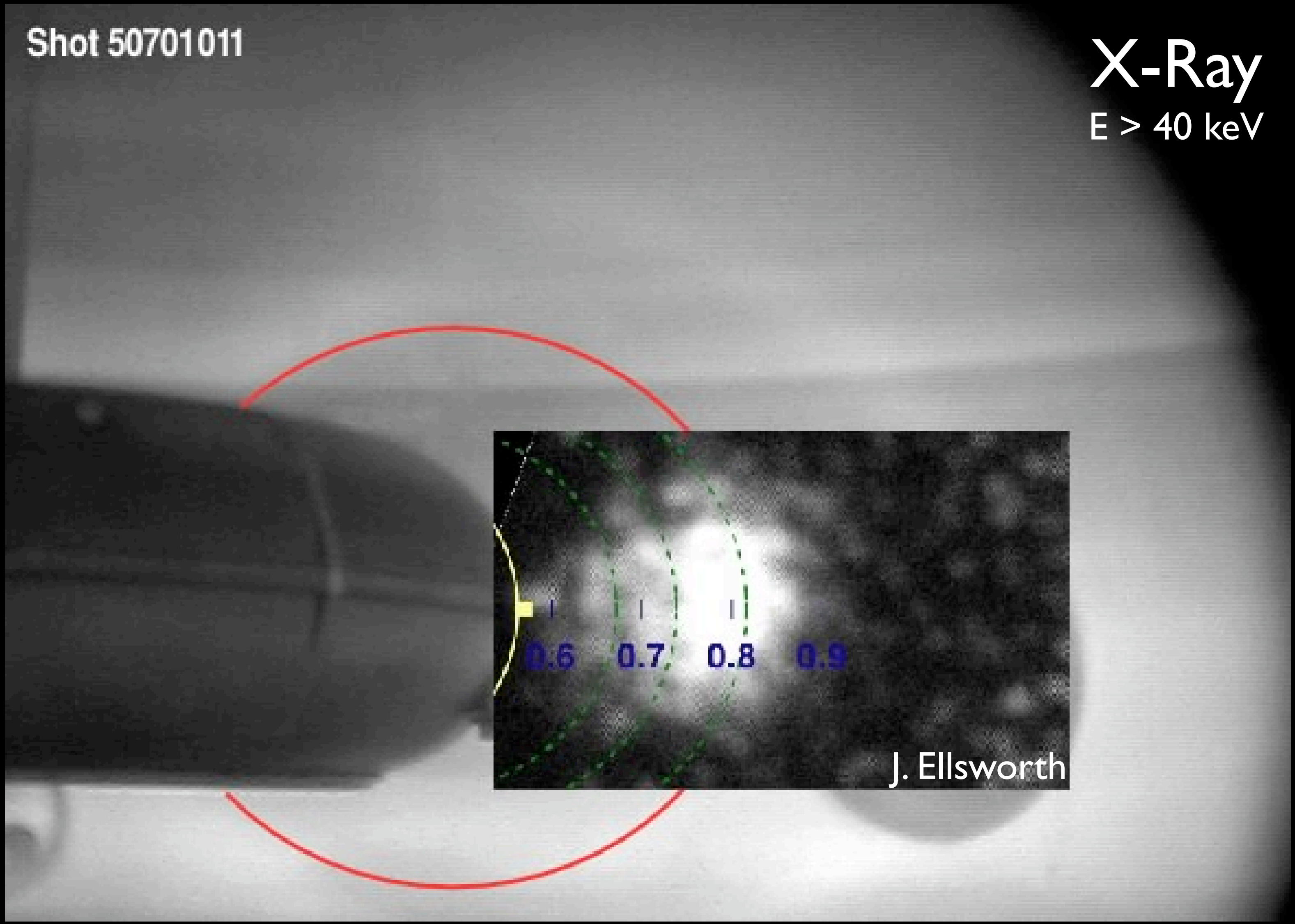
(E. Ortiz)



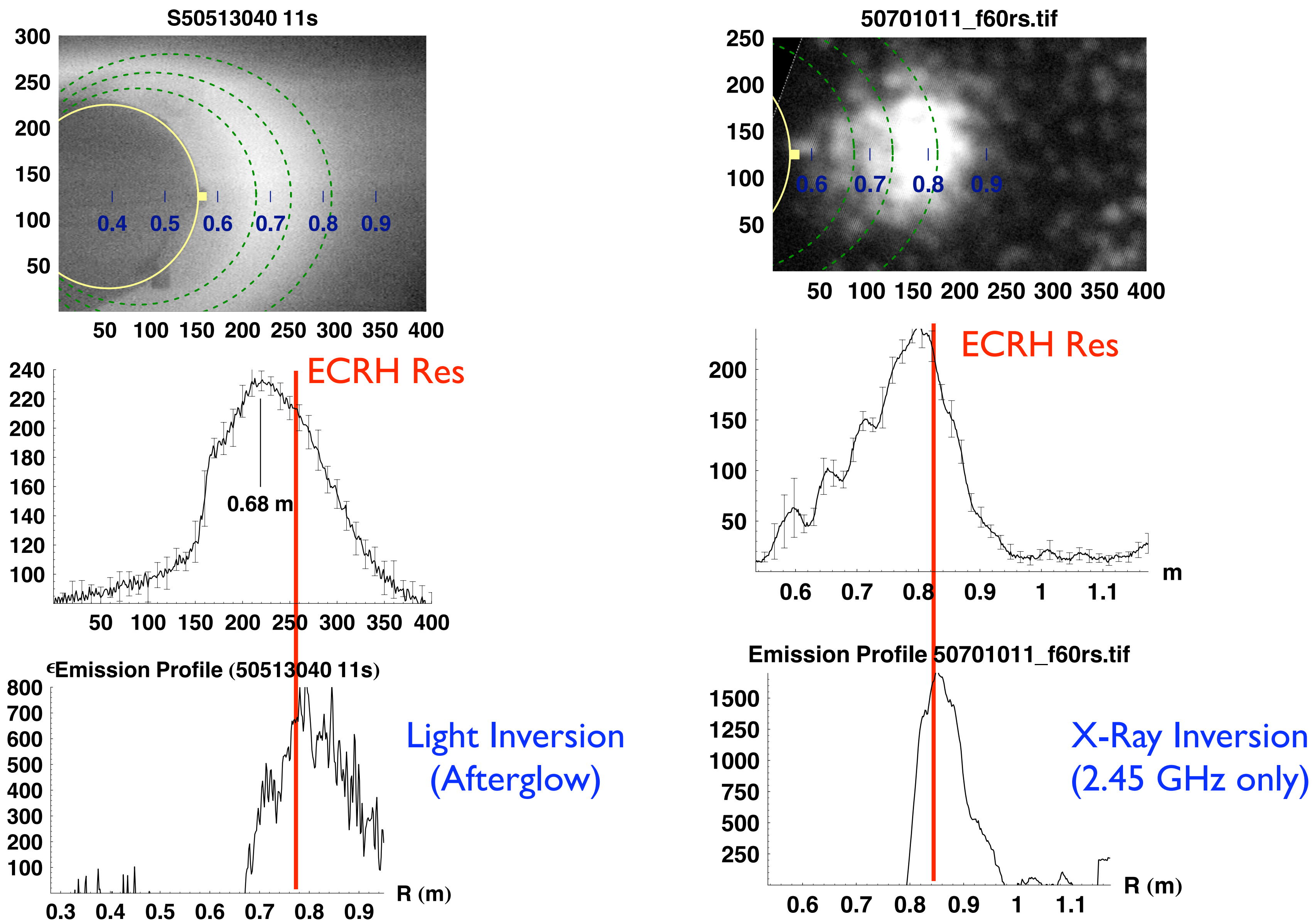
Where is the High-β Plasma?



Where is the High-β Plasma?



Abel Inversion (Equatorial) Show Profiles Highly Peaked Near 2.45 GHz Resonance

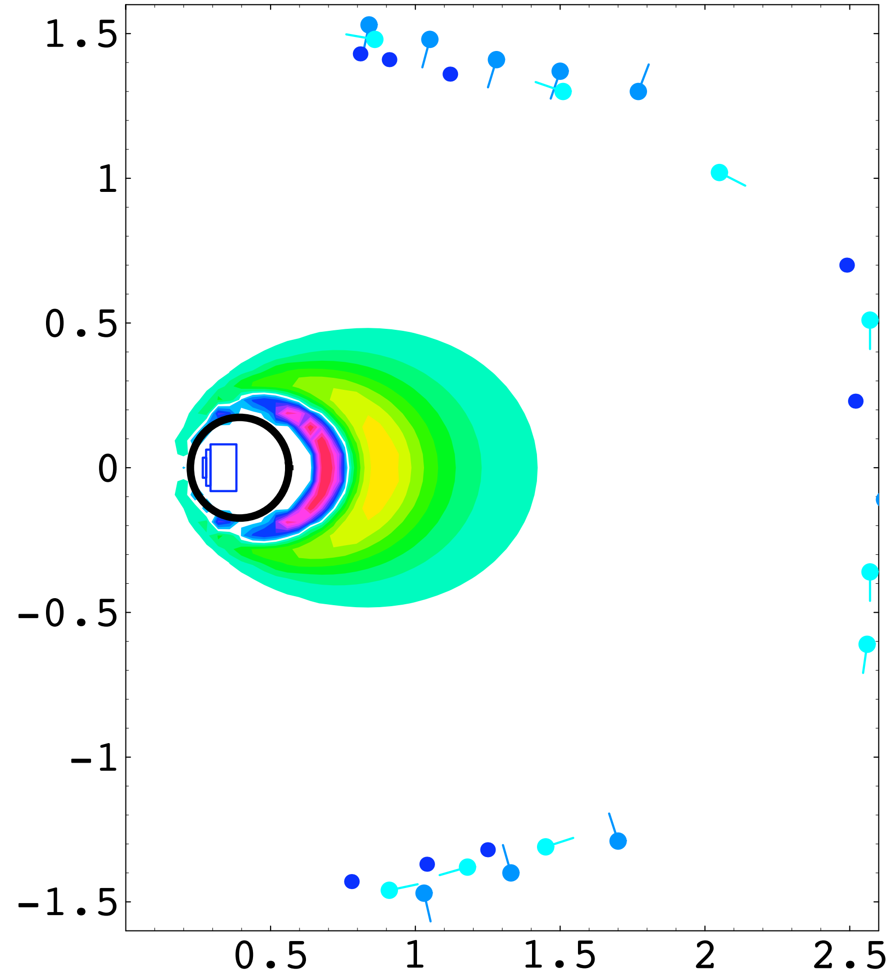


Where is the Ring Current?

(I. Karim)

$$\mathbf{J}_\perp = \frac{\mathbf{B} \times \nabla P_\perp}{B^2} + \frac{\mathbf{B} \times \kappa}{B^2}(P_{||} - P_\perp)$$

- 8 flux loops
- 9 normal-B sensors
- 9 tangential-B sensors
- Constant flux constraint on superconducting dipole
- Isotropic now ($P_\perp > P_{||}$ in future)
- 26 measurements;
  3 unknowns: (p_0, ψ_0, g) …



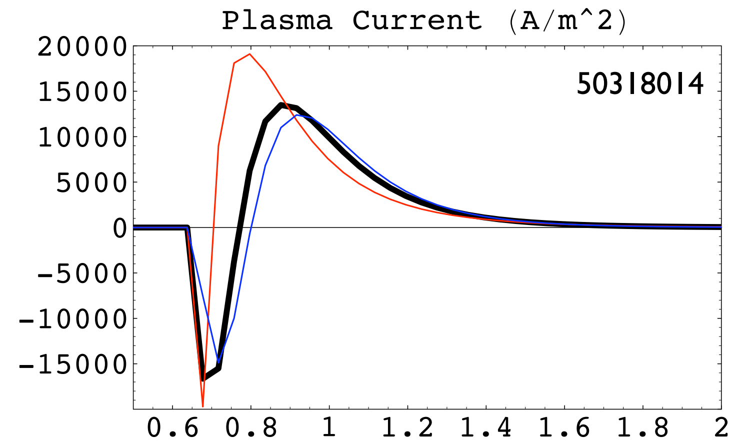
$$p(\psi) = p_0 \left(\frac{\psi - \psi_{fcoil}}{\psi_0 - \psi_{fcoil}} \right)^{\alpha} \left(\frac{\psi}{\psi_0} \right)^{4g}$$

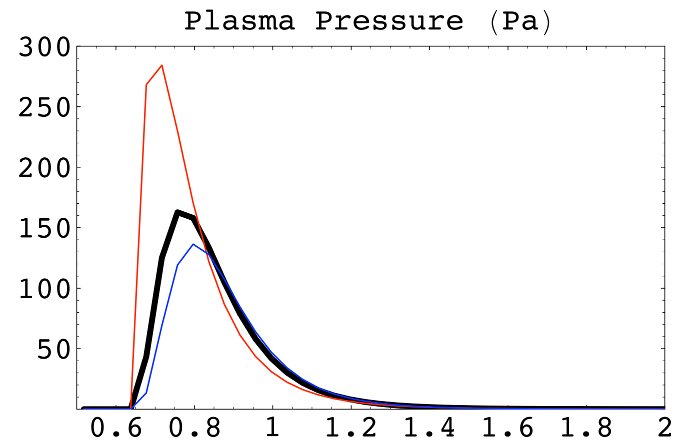
Family of Profiles with Same χ^2

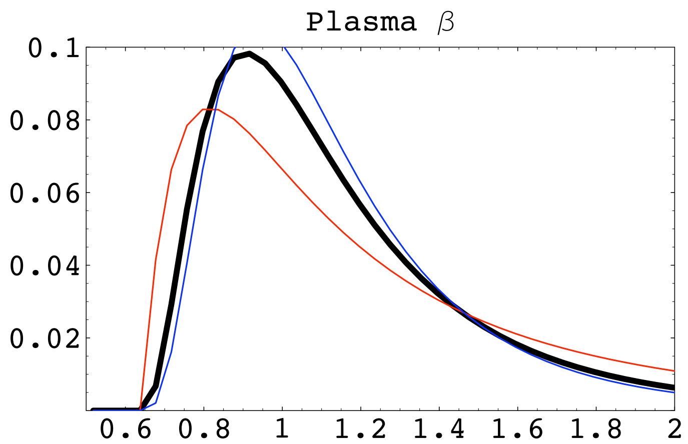
- More than 1 m separation between plasma current and magnetic detectors.
- Profiles with same plasma dipole moments, fit magnetics equally well.
- New, nearby magnetic sensors to be installed.

➡ Where is the pressure peak?
Answer: at ECRH Resonance

χ^2	Peak P	I_P (kA)
10.4	0.70	3.2
➡ 10.6	0.77	3.1
10.7	0.80	2.9







Summary

- Dipoles provide magnetic confinement for hot plasma in nature and in the laboratory.
- The dipole has a unique field structure for study of confined plasma: unmatched diagnostic access, well-characterized magnetic geometry, and fascinating (and musical) wave-particle interactions.
- Two types of global interchange instabilities excited/modeled:
  - 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.
- The world's first **high-beta** dipole-confined plasma has been created in LDX. LDX offers a new facility to study high-beta instability, "electrostatic self-organization", controlled convection, energy and particle confinement, …