Exploring Plasma Dynamics with Laboratory Magnetospheres

Mike Mauel and
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Columbia University and PSFC, MIT

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LABORATORY EXPERIMENTS OF MAGNETOSPHERIC INTEREST

Space Science Reviews **15** (1974) 803–825.

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Abstract. Space-related laboratory experiments can play an important role as a complement to observations and active experiments in the magnetosphere. Excluding laboratory experiments for mere developing or testing of techniques for space experiments, we may distinguish between two major types: (1) partial scale model experiments and (2) experiments for clarifying basic plasma physical processes known or expected to be important in the magnetosphere (but without the ambition to simulate actual space configurations). The limitations and potentialities of both types are discussed and examples of experiments are given. It is concluded that there should be an increasing need for the experiments of the second type.

x **Scale models:**

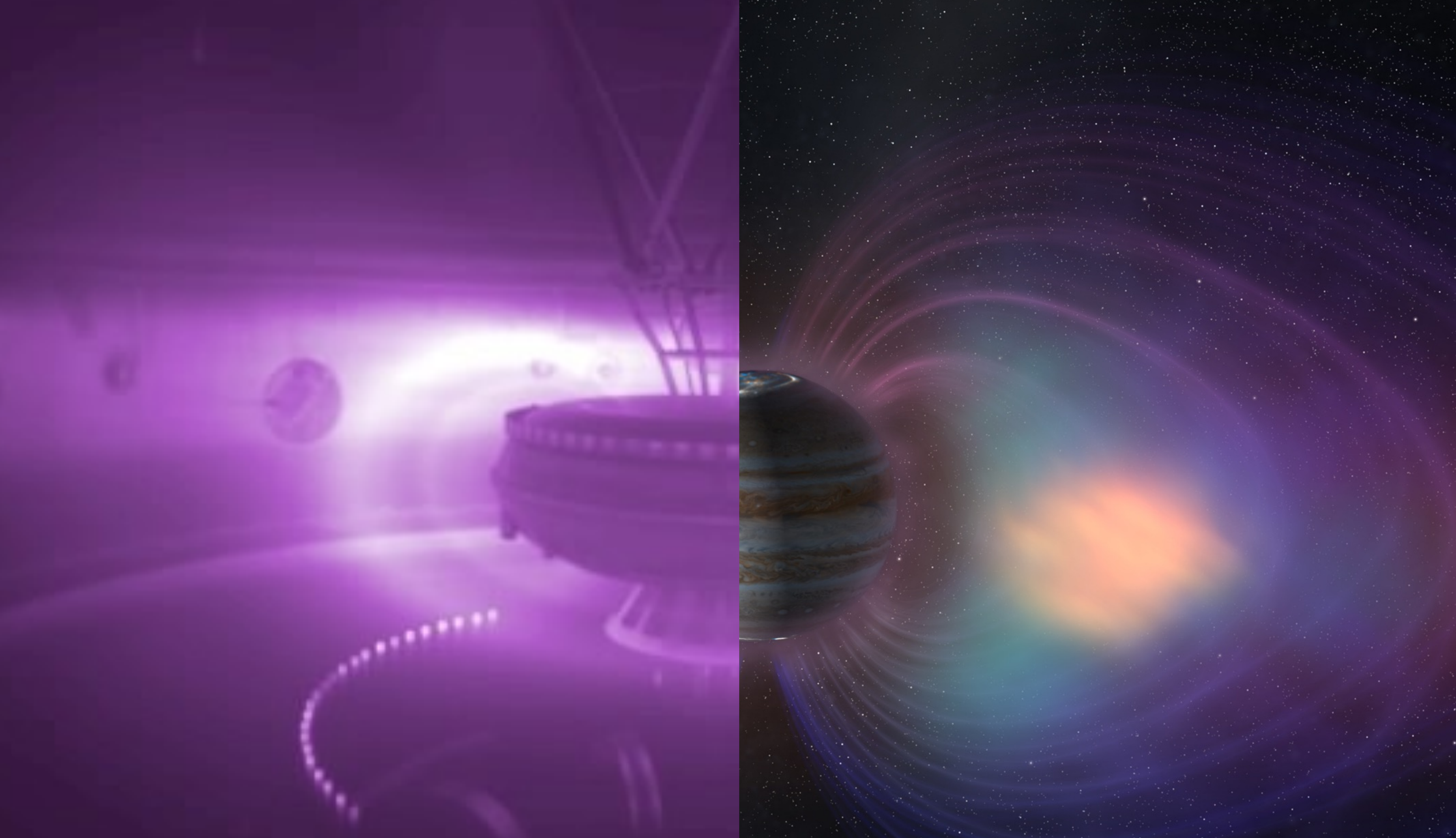
- Understand the magnetospheric configuration?, Terrella, …
- Difficult (*a.k.a.* ***impossible***) to scale magnetospheric parameters

✓ **Clarifying basic plasma processes:**

- Magnetospheric plasma behavior is considerably more complicated than simple models would predict requiring "the actual behavior of real plasmas" to be determined with ***dedicated laboratory and theoretical investigations of basic plasma processes***.

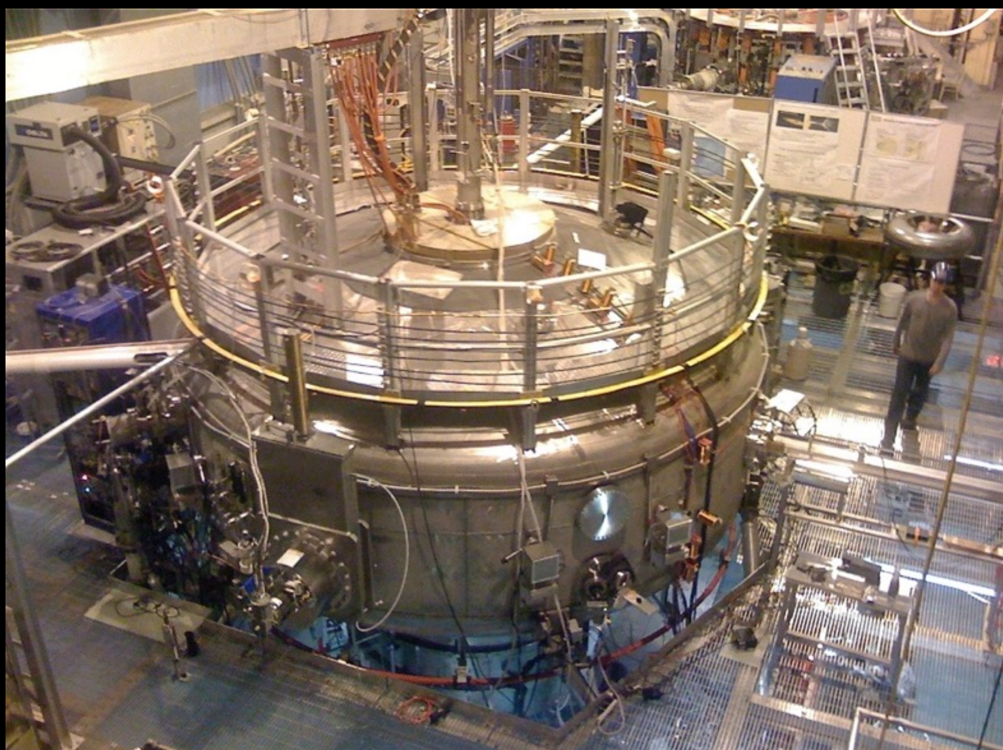
Exploring Basic ***Processes*** with “Comparative” Magnetospheres

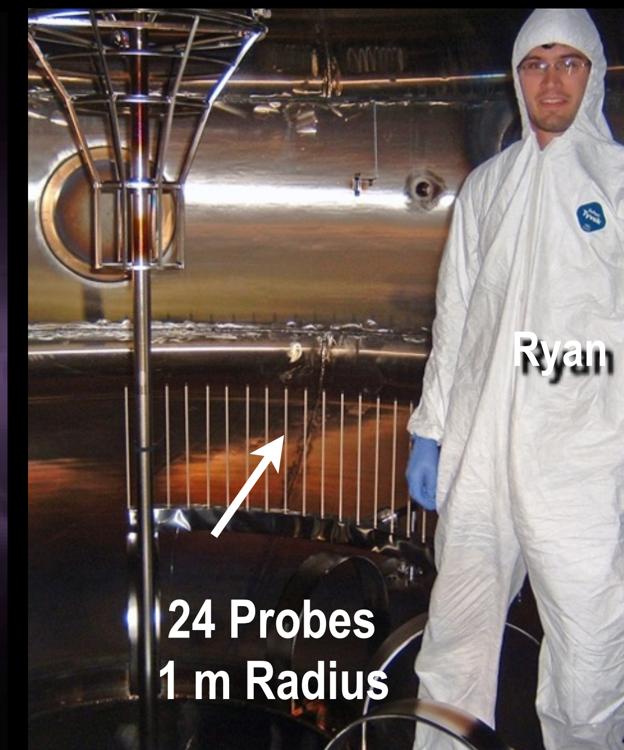
(special acknowledgment to Akira Hasegawa, Henry Radoski, Mike Schulz)

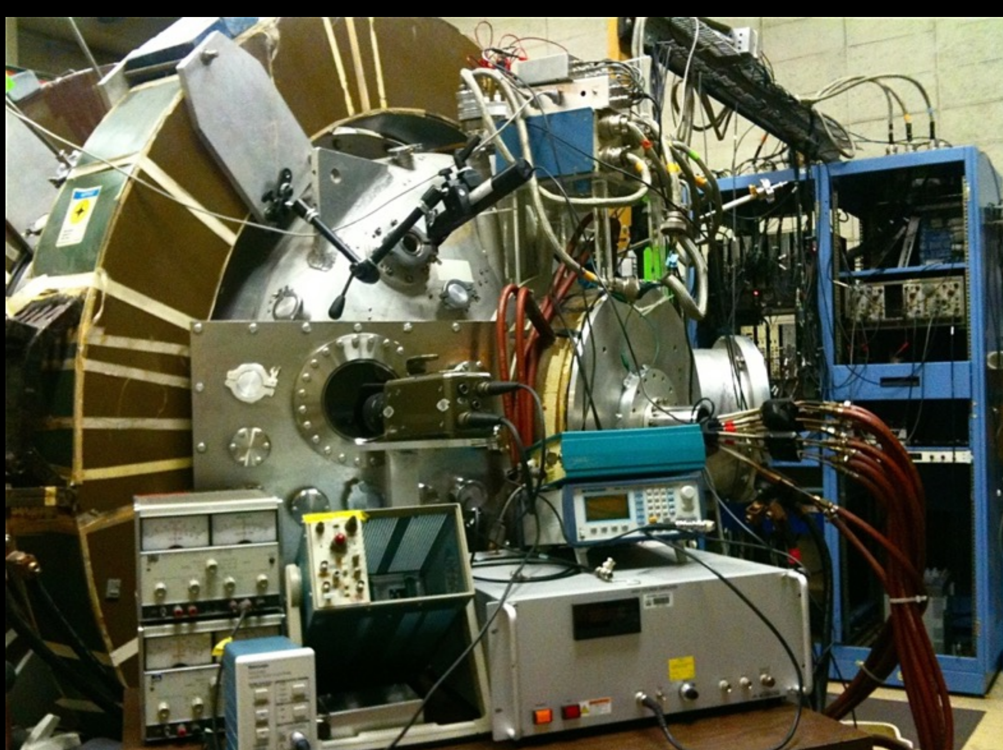


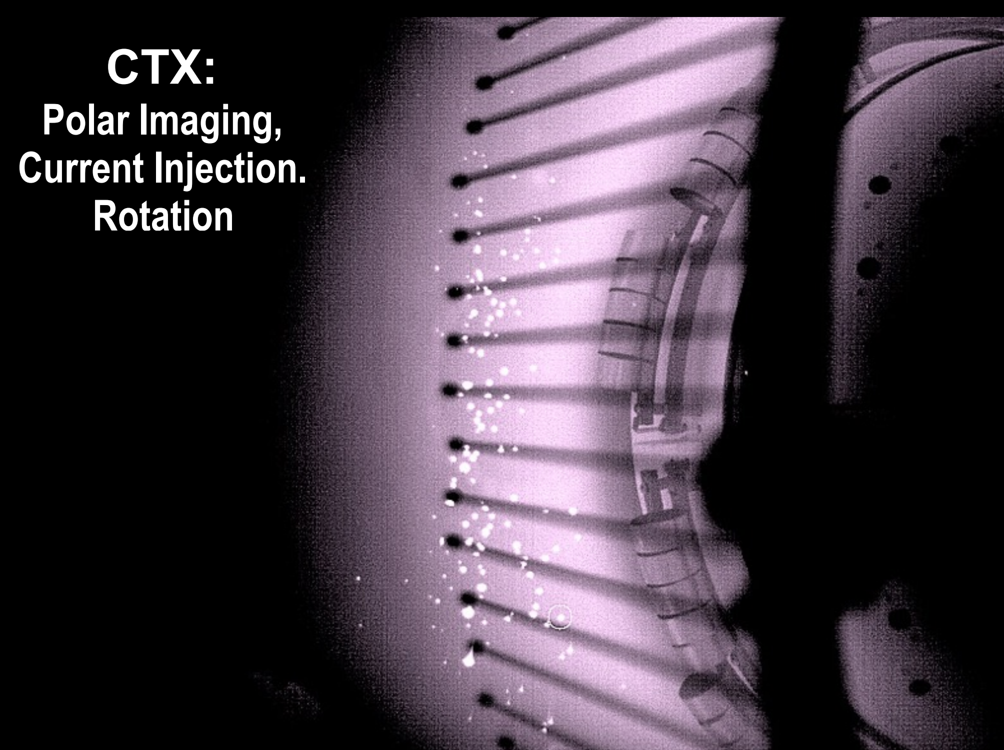
Very large; ***unlike*** any other laboratory plasma; with $\omega_d \sim \omega^*$

Laboratory Magnetospheres:
Process Investigations of Space-Relevant Heating/Transport









Comparing Laboratory and Planetary Magnetospheres

Low-frequency ($\omega \sim m\omega_d$)

Internally-driven interchange instabilities

←

Externally-driven by solar wind

→

High-frequency ($\omega \sim n\omega_c$)

Externally-driven by applied µwave power

←

Internally-driven by plasma chorus

→

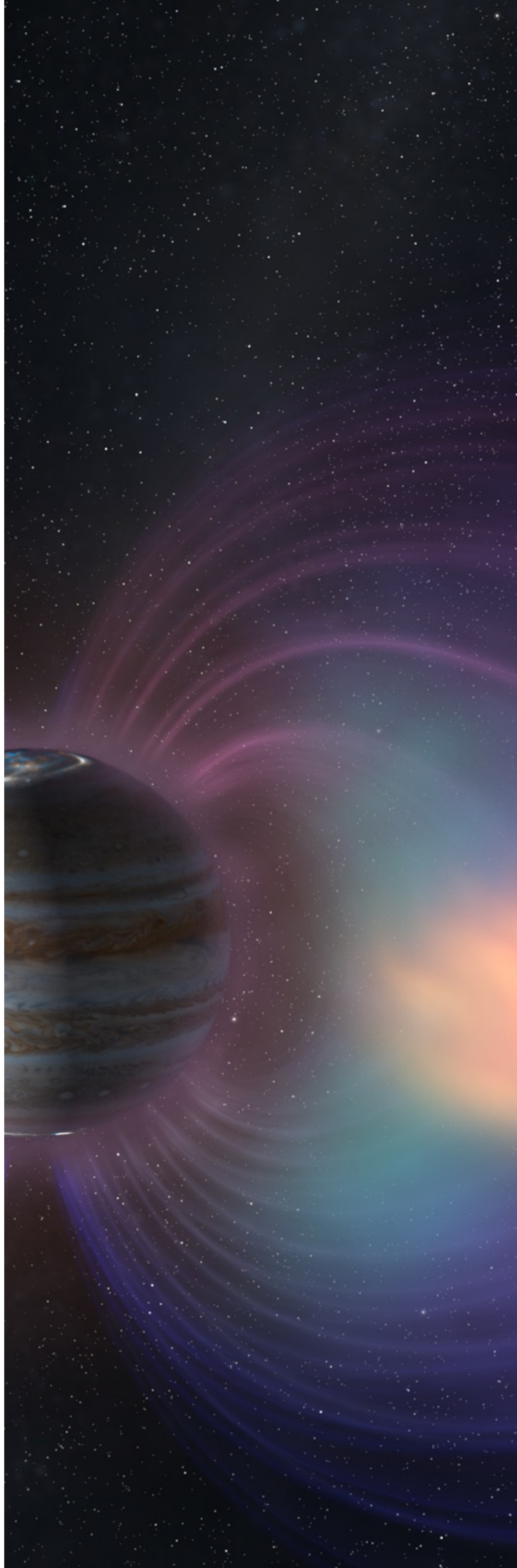
Ionosphere?

*No**

←

Yes

→



Some Basic Processes Explored

- ➡ ***Drift-resonant transport*** of energetic electrons (a.k.a ***artificial "radiation belt"***)
- Low-frequency MHD turbulence and ***2D turbulent cascades***
- ***Centrifugal instability*** at sonic rotation
- ***"Whole plasma" transport*** and the "inward" turbulent particle pinch
- Controlling convection w localized current injection (a.k.a. "***artificial ionosphere***")
- "Swarm" ***multi-point measurements*** of plasma dynamics
- ➡ Dynamics with ***internal*** (***transient) injection of particles*** (a.k.a.***"artificial moon"***)
- **Opportunities:**
  - Alfvén wave spectroscopy and turbulence @ large size / small ion inertial length

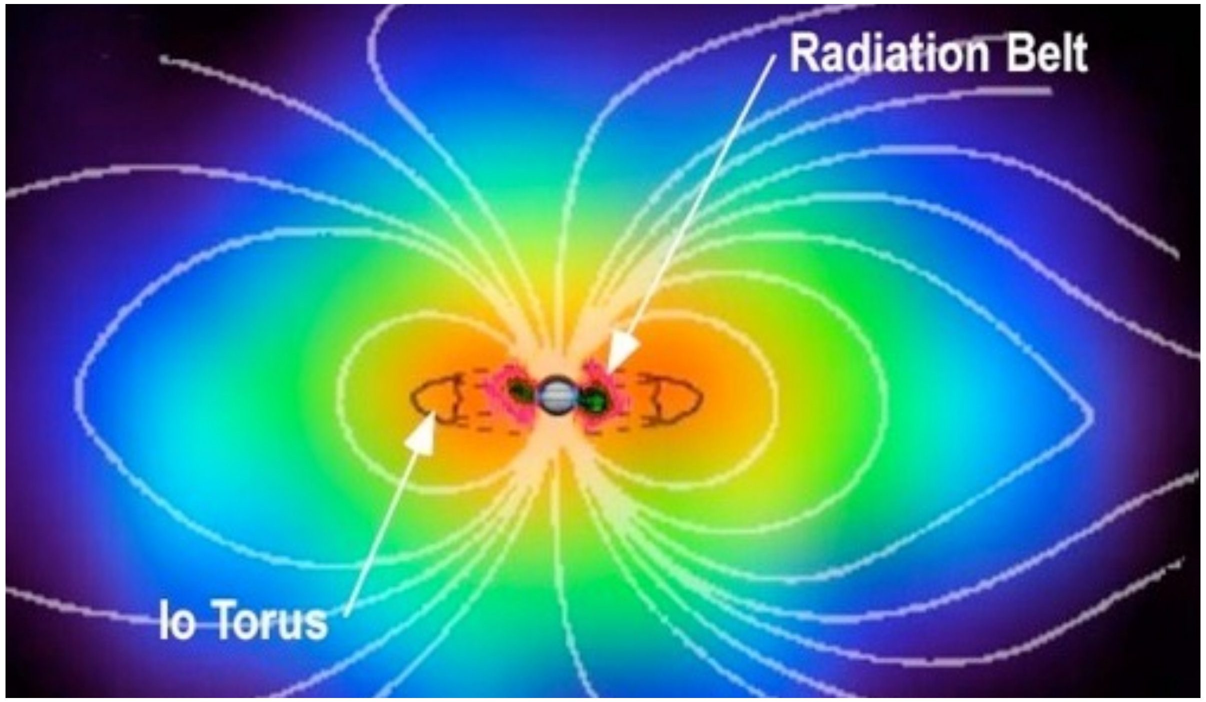
Trapped energetic particles very well confined
(about 1/2 pressure of high-β discharges from energetic electrons)

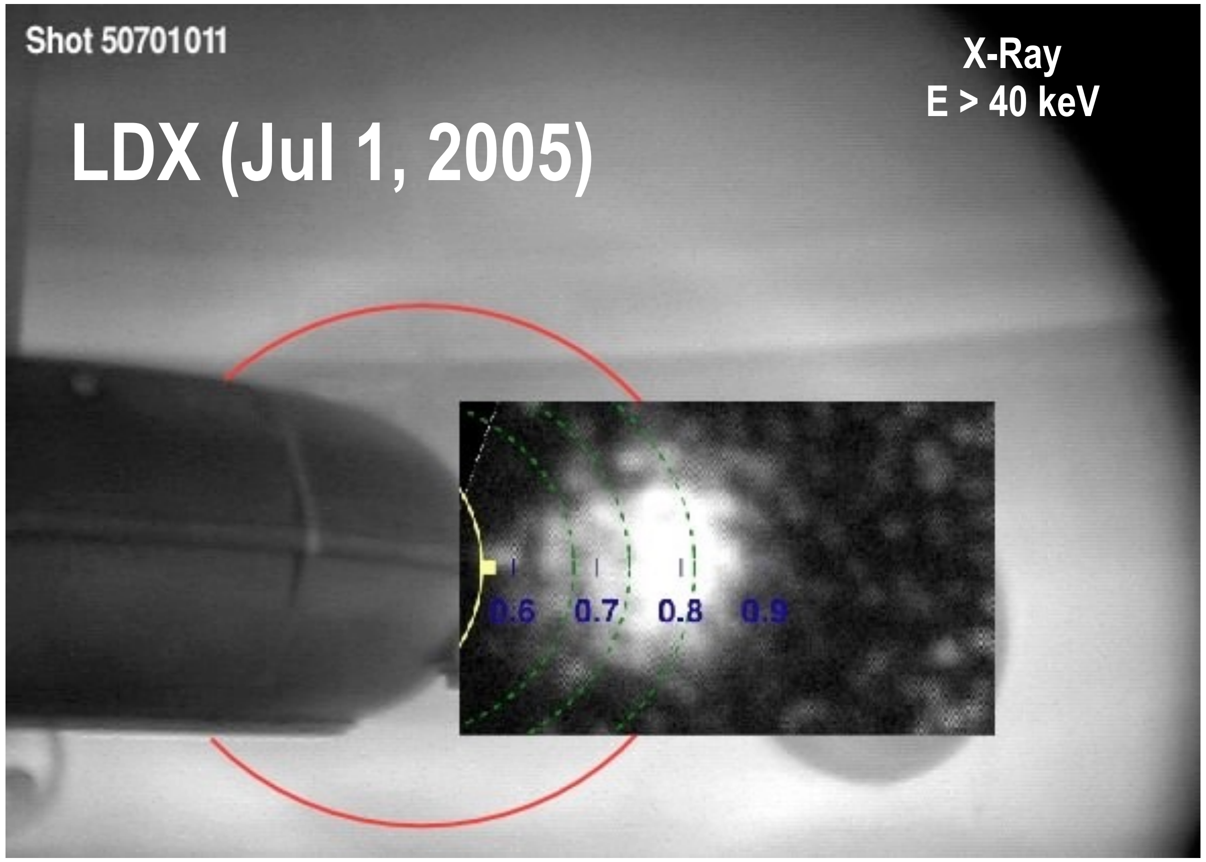
The natural high beta in planetary magnetospheres can be achieved in the laboratory. Steady-state.

- Garnier, POP (1999) shows equilibria with β > 100% possible
- Garnier, POP (2006) reports peak beta 20% achieved
- Garnier, NF (2009) reports peak beta doubles (>40%) with levitation

➡ Nishiura, NF (2015) reports peak beta >100% achieved in RT-1

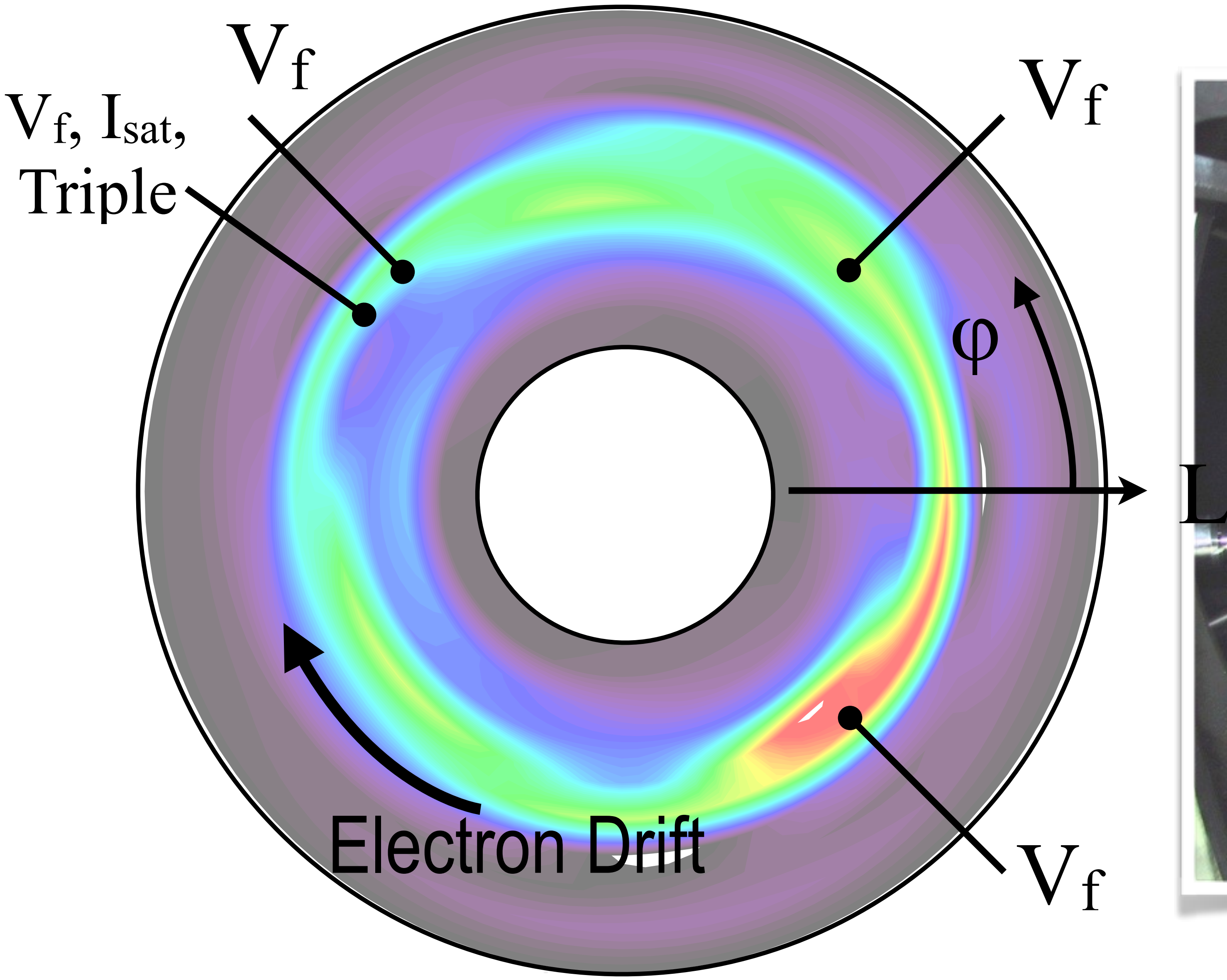
Cassini at Jupiter (Dec 30, 2000)

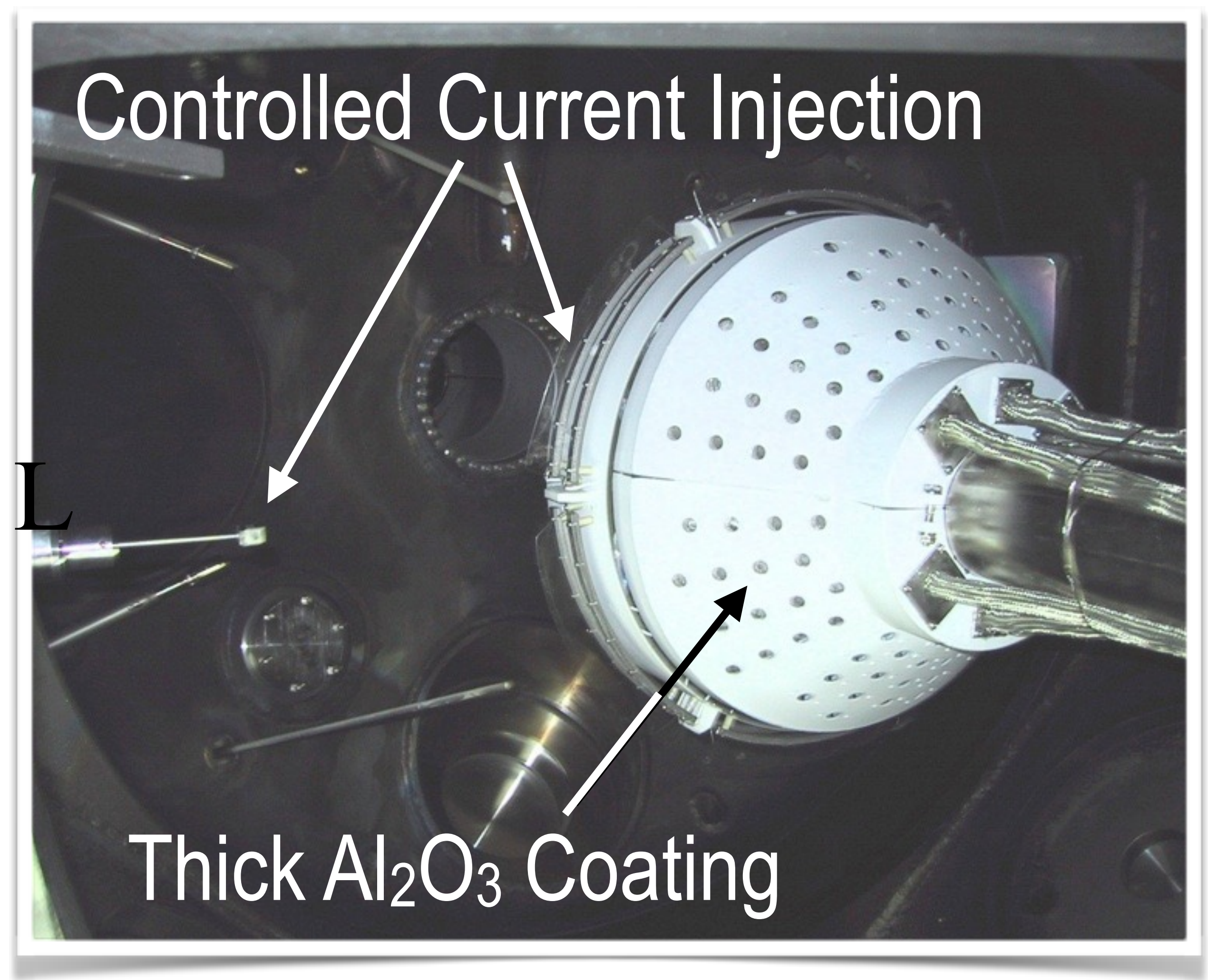




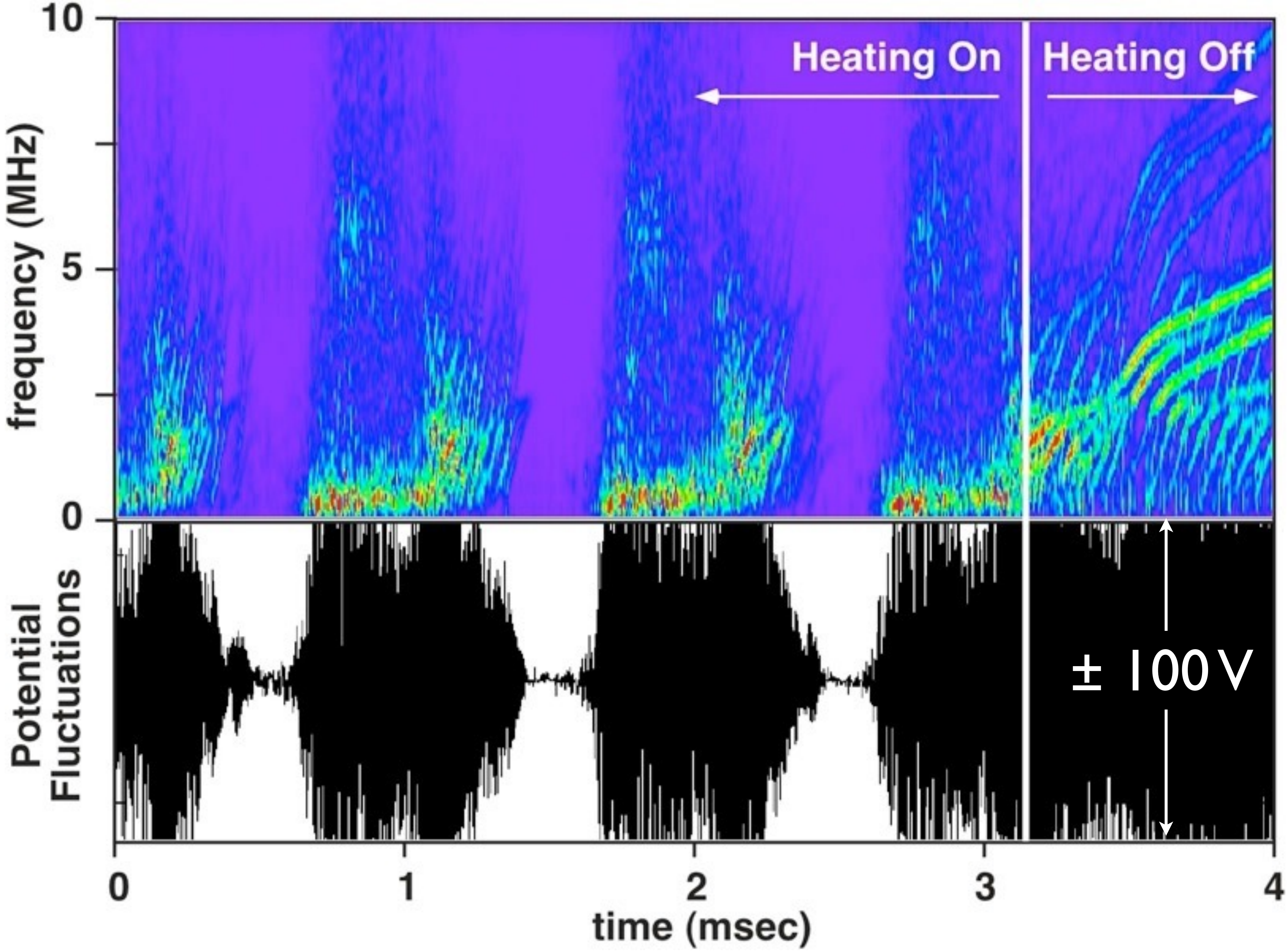
Polar Imaging of Plasma Dynamics

Investigations of Interchange/Entropy Mode Turbulence



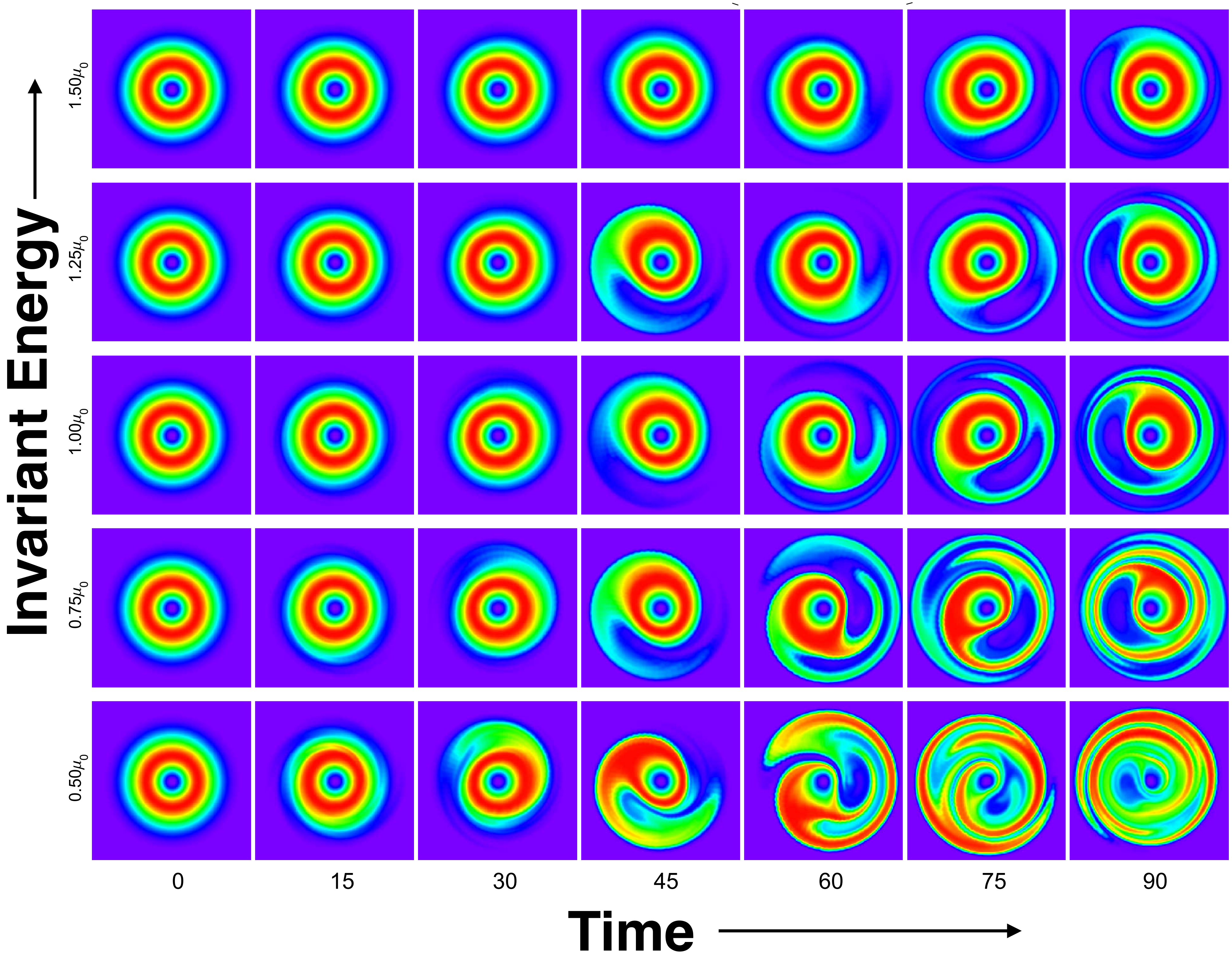


Drift-Resonant (Hot Electron) Interchange Instability

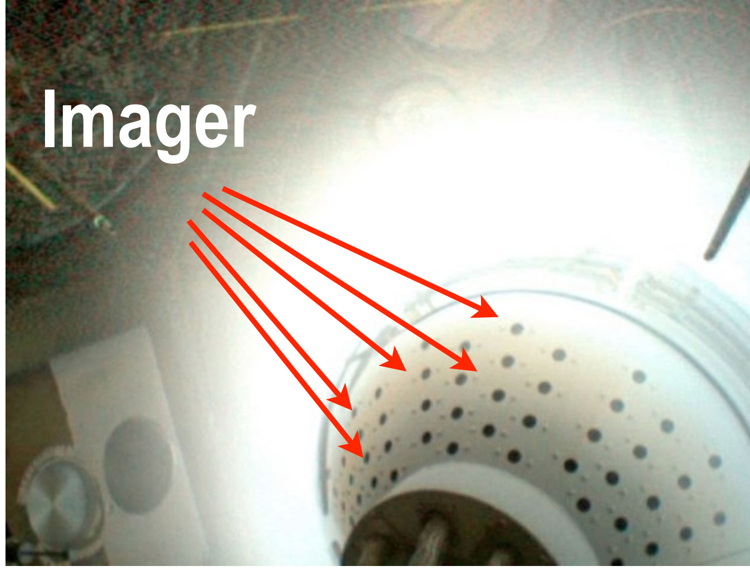


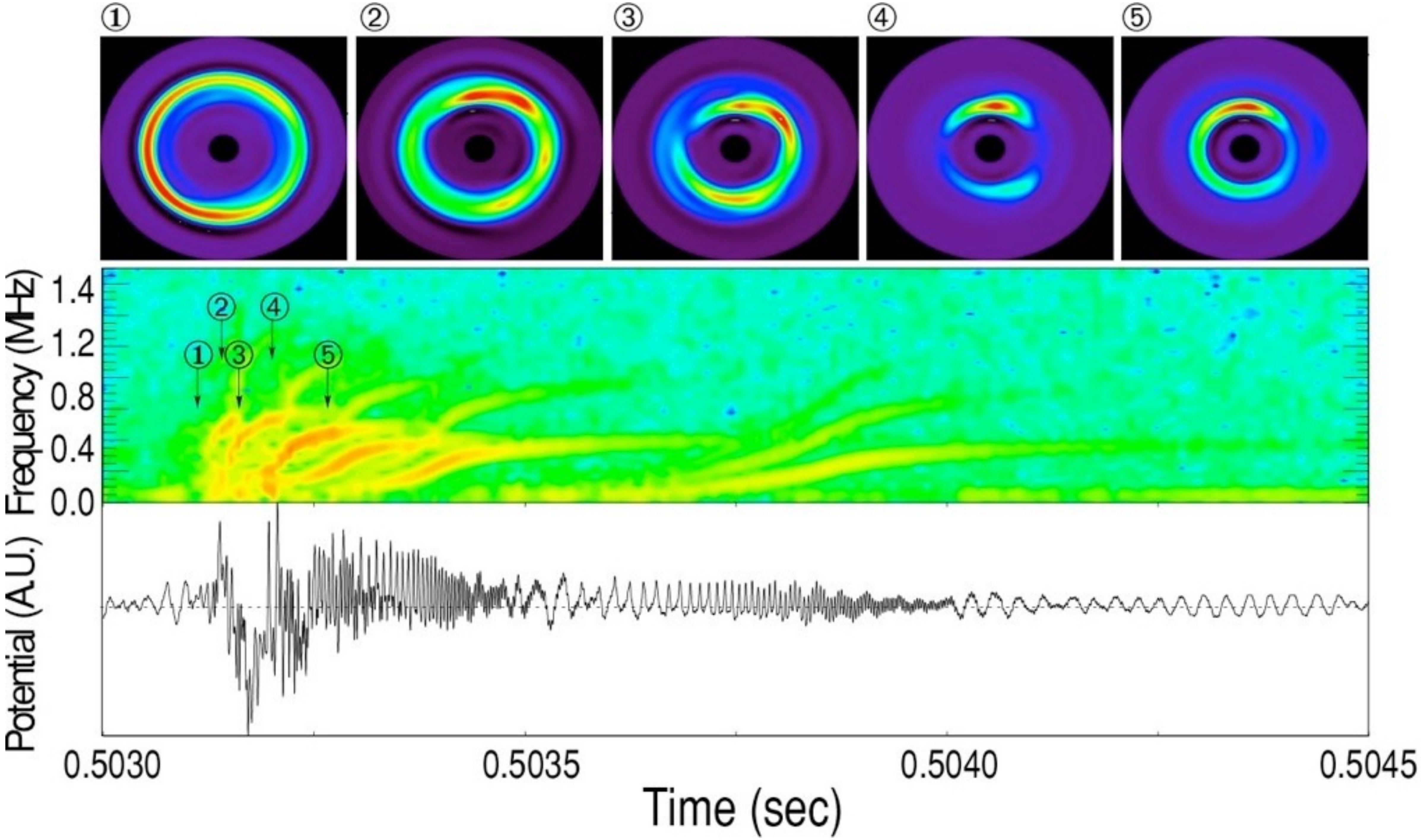
Interchange Drift Resonance $\omega \sim m\omega_d$

Creates inward moving "phase-space holes"



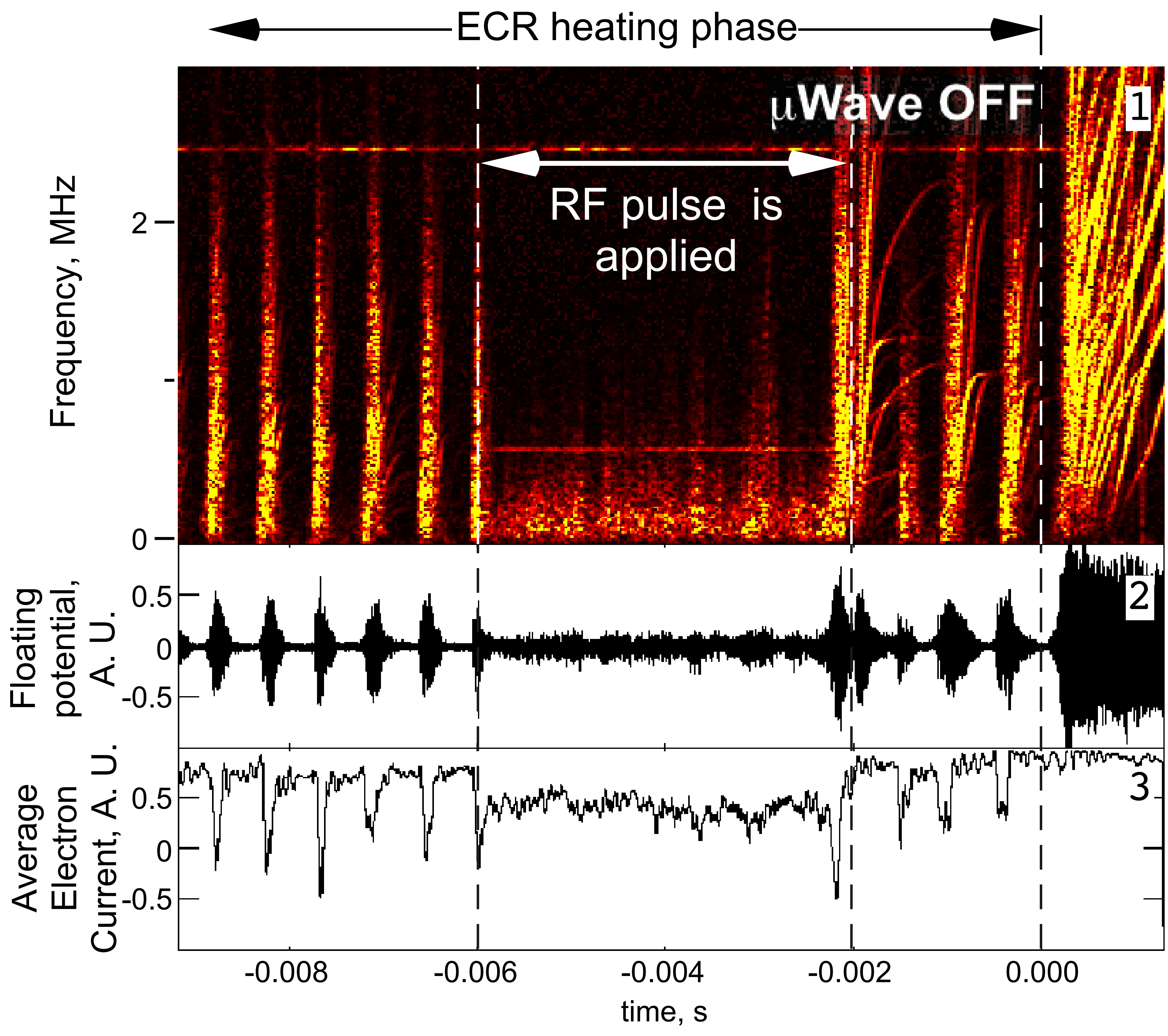
Polar Imager: Measuring Inward Drift-Resonant Transport due Gyrokinetic Interchange Instability



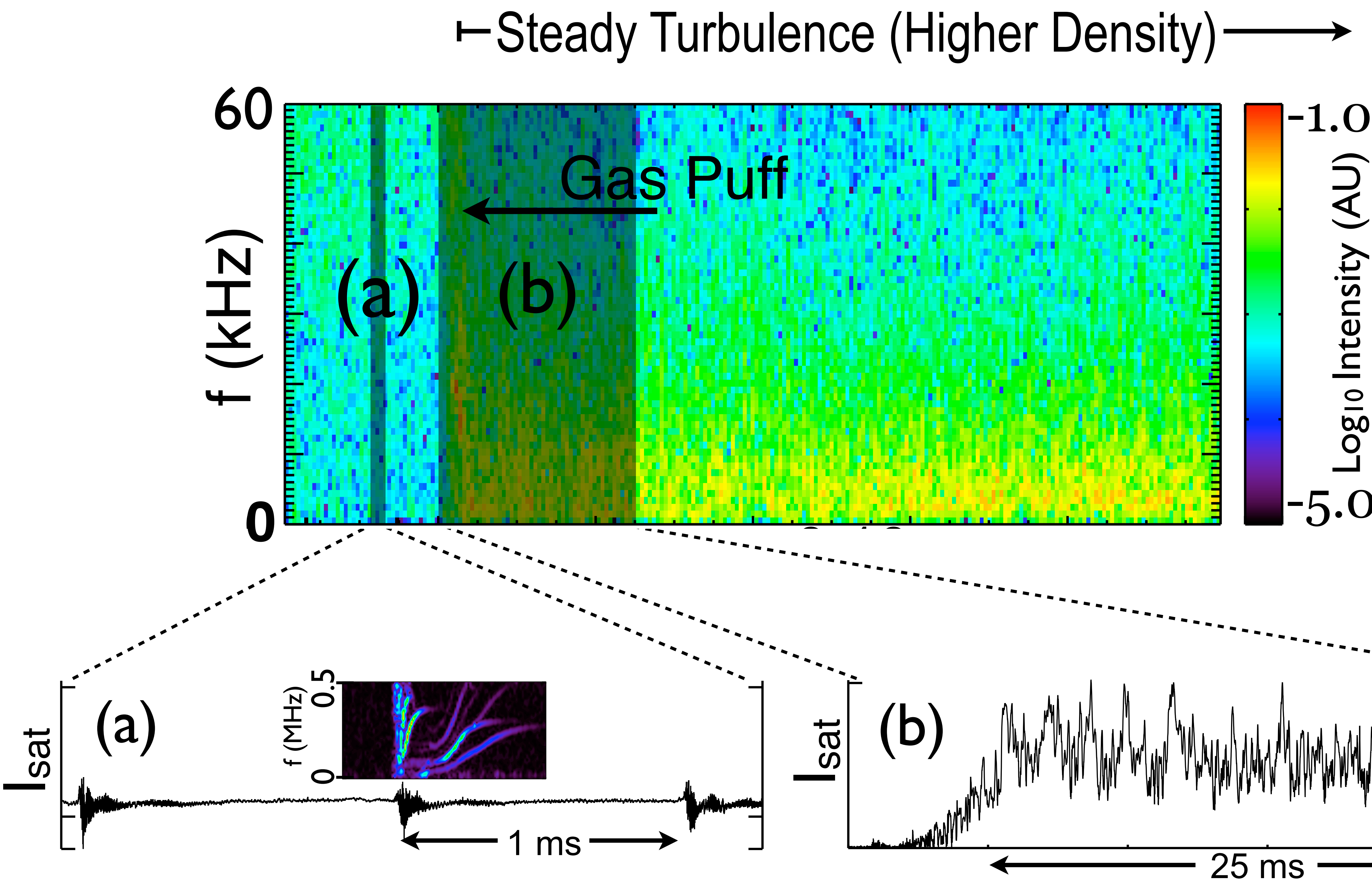


"Chorus" Injection Fills-in Phase-Space Holes

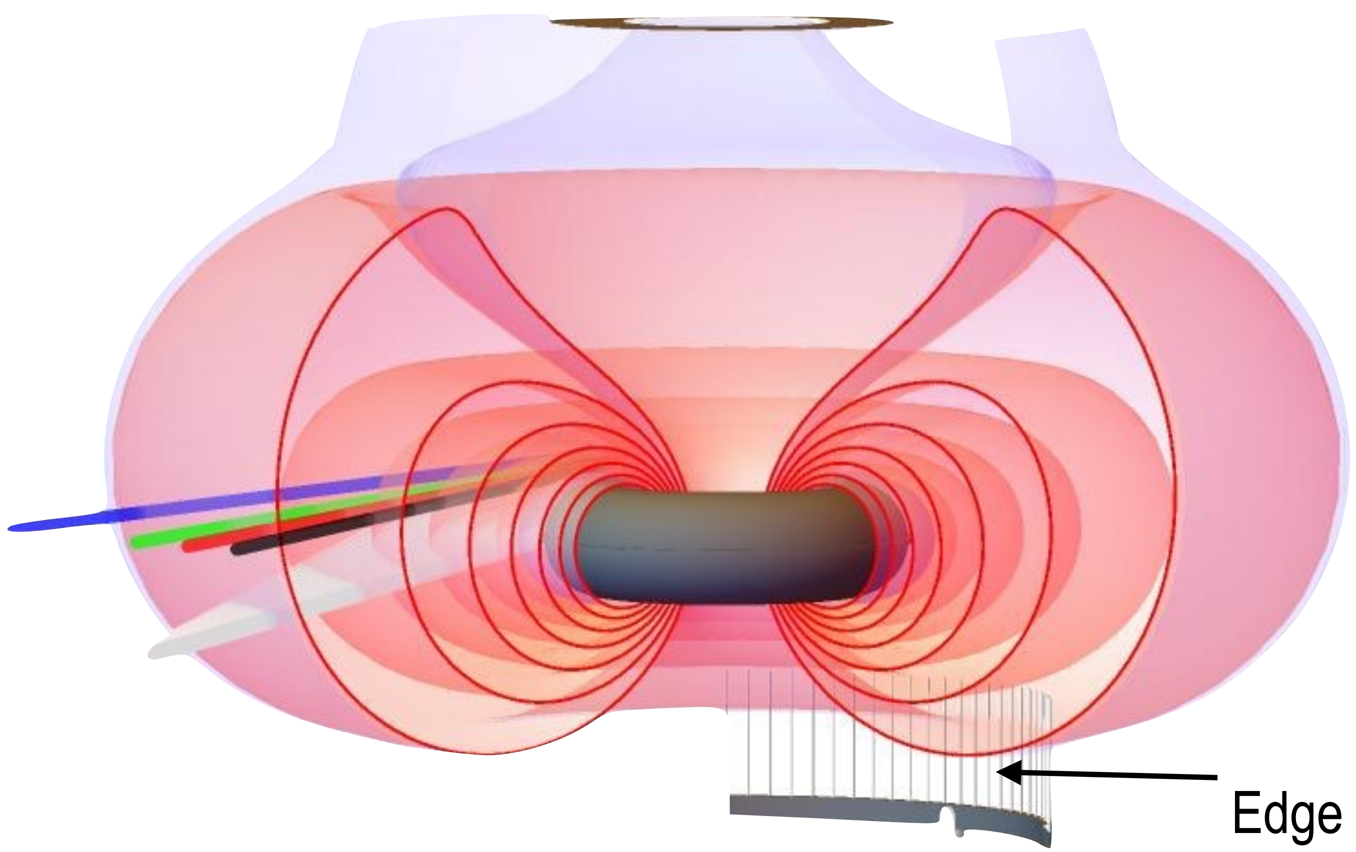
Well-modeled with global, nonlinear Bounce-Averaged drift-kinetic simulation…



High β build-up after Stabilization of Fast Electron Instability



The Radial Diffusion Coefficient is Measured by Ensemble Correlation of the Measured Radial E×B Velocity



Edge Probe Array Measures Radial **E×B** Velocity

$$\mathbf{E} \cdot \mathbf{B} = 0$$

$$\dot{\psi}(t) = R E_\varphi(t) = \nabla\psi \cdot \mathbf{E} \times \mathbf{B}$$

$$D_\psi = \lim_{t\to\infty} \int_0^t dt' \langle \dot{\psi}(t') \dot{\psi}(0) \rangle \equiv R^2 \langle E_\varphi^2 \rangle \tau_c$$

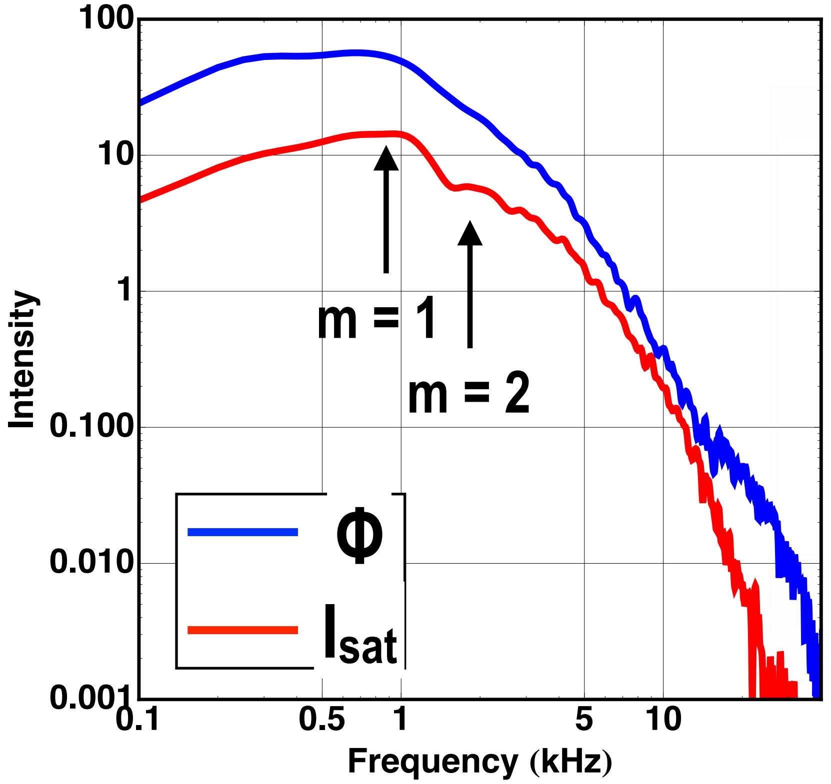
$$\frac{\partial}{\partial t}(nV) = \underbrace{\langle S \rangle}_{\text{Source}} + \frac{\partial}{\partial \psi} D_\psi \frac{\partial}{\partial \psi}(nV)$$

Radial Diffusion due to Interchange/Entropy Turbulence

Alex Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet,” *Nat Phys* **6**, 207 (2010).

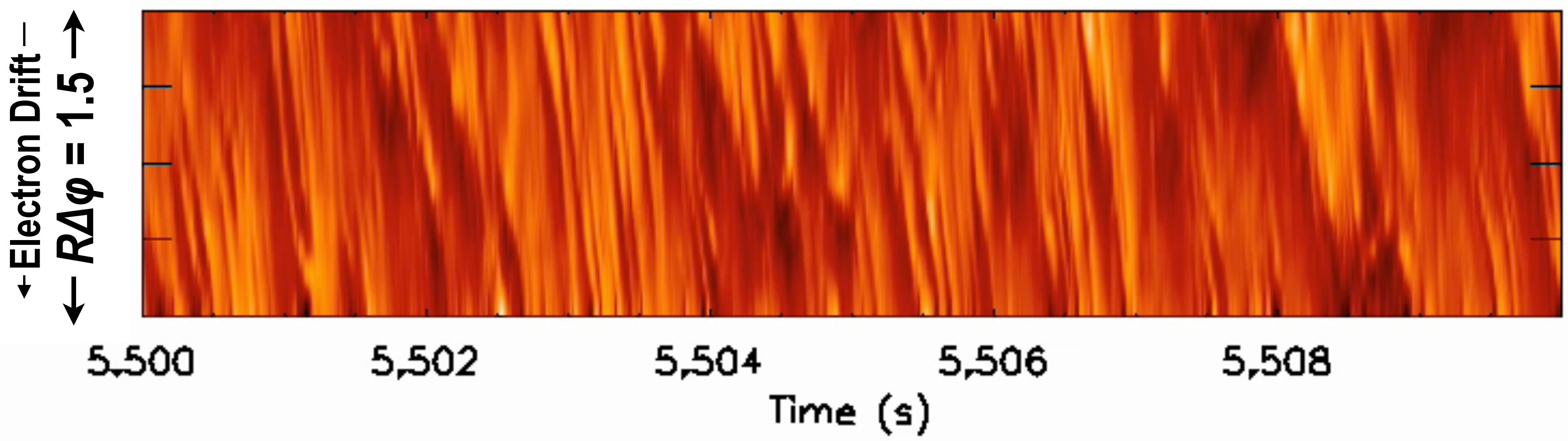
Turbulent Fluctuations Propagate in Electron Drift Direction
(during edge gas fueling)

Edge Fluctuation Spectrum



$|E_\varphi| \sim 55$ V/m (RMS) $\tau_C \sim 16$ μsec

Floating Potential (Φ > ± 100 V)



$\omega \approx m\,\omega_d \sim 2\,\pi\, m\ 700$ Hz

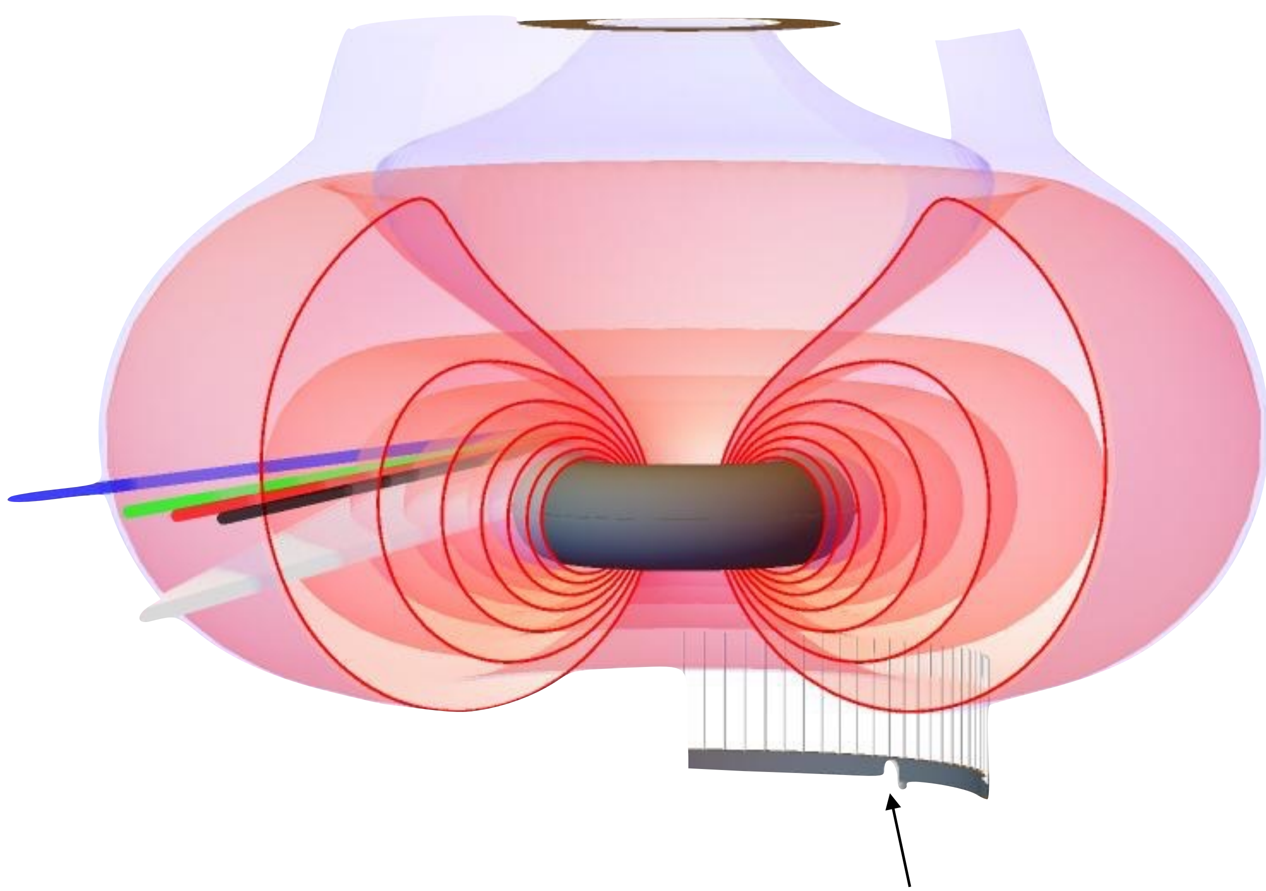
$m = 1, 2, 3, 4, 5, 6, \ldots$

Inverse mode structure cascade,
chaotic mode dynamics, …

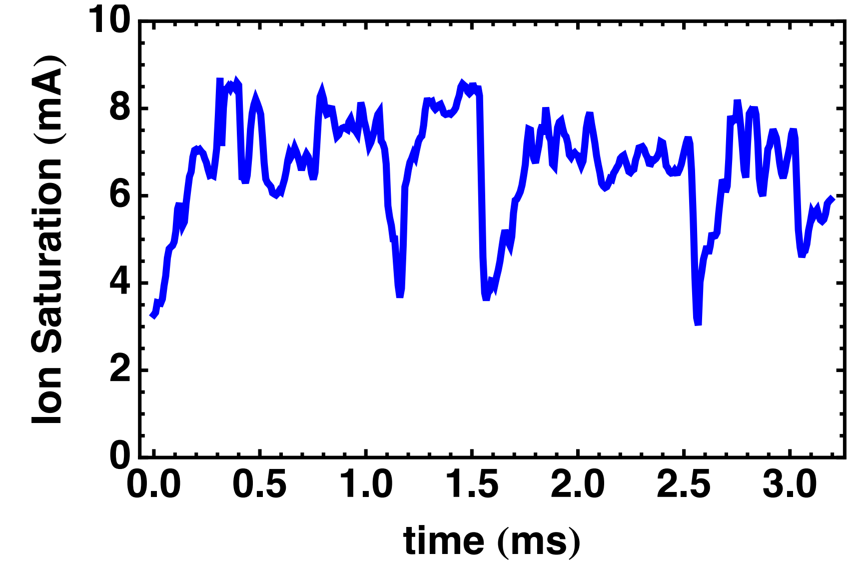
Jen Ellsworth, *Characterization of Low-Frequency Density Fluctuations in Dipole-Confined Laboratory Plasmas*, PhD MIT (2010).

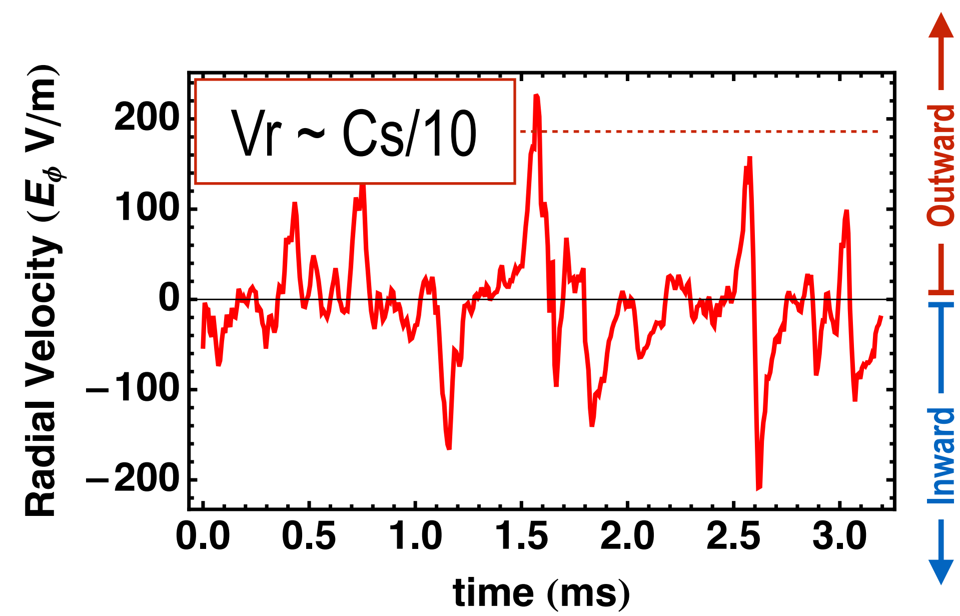
Grierson, Worstell, and Mauel, "Global and local characterization of turbulent and chaotic structures in a dipole-confined plasma," *Phys Plasmas* **16**, 055902 (2009).

Edge Transport is “Bursty”: Outward Warm Filaments and Inward Cool Filaments



Probe Array:
Floating Potential, E_φ
Ion Saturation Current
Radial **E×B** Flux





$RE_\varphi \sim \Delta\Phi/\Delta\varphi$

Jen Ellsworth, *Characterization of Low-Frequency Density Fluctuations in Dipole-Confined Laboratory Plasmas*, PhD MIT (2010).
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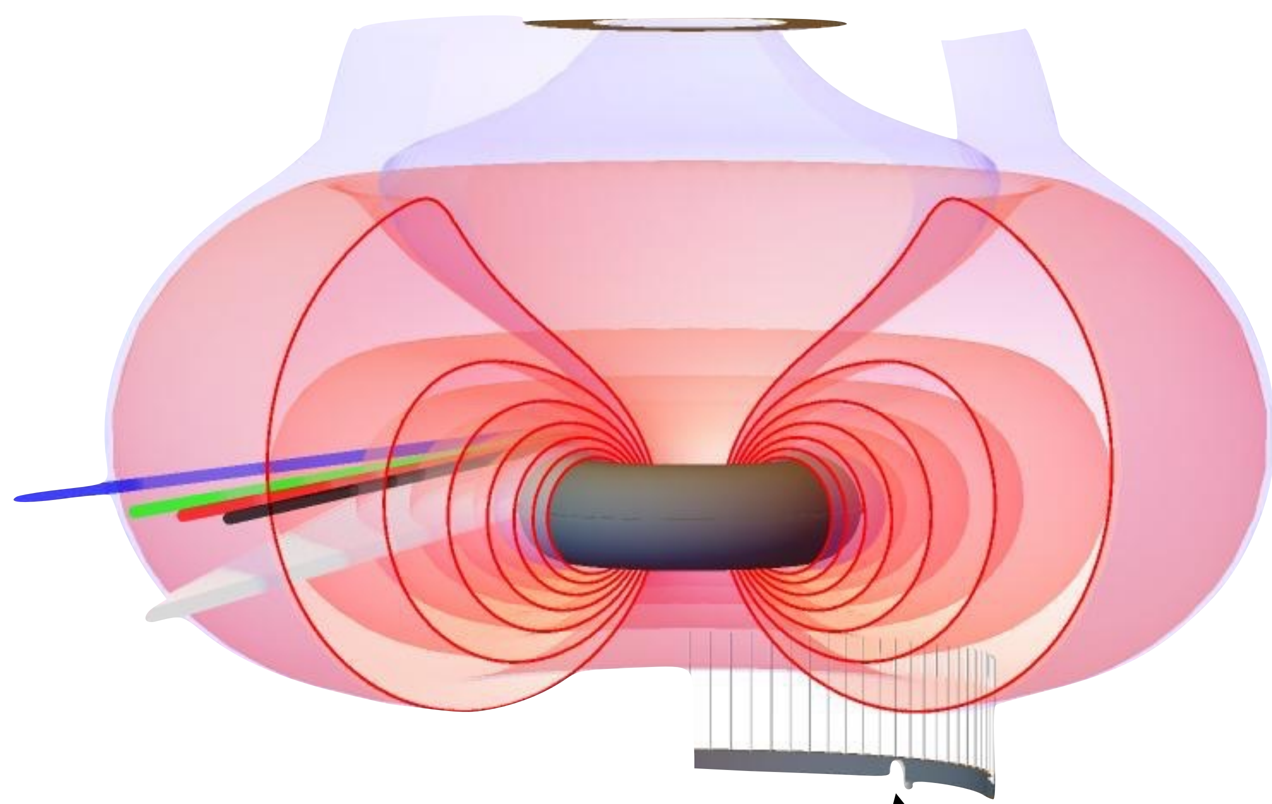
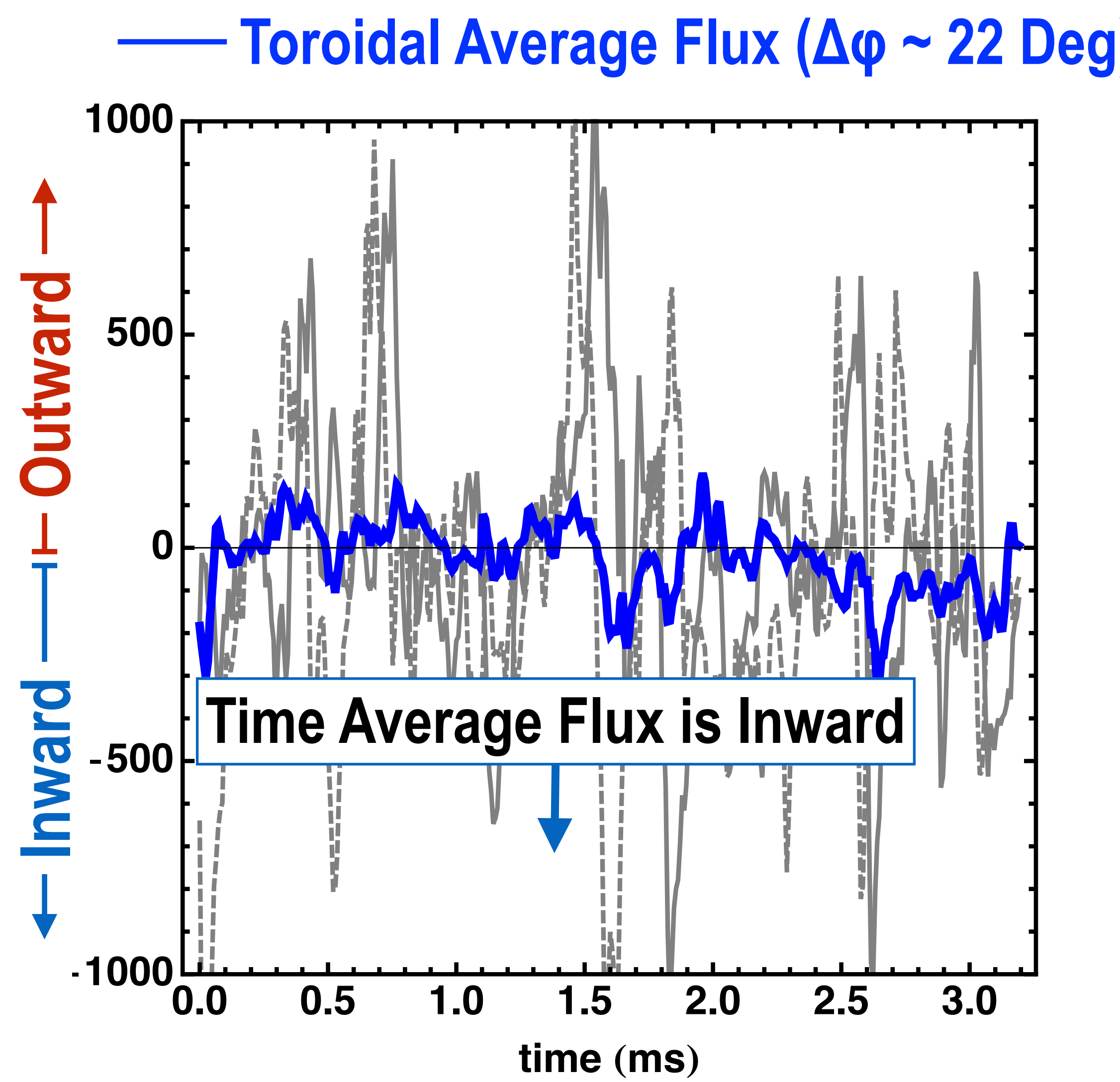


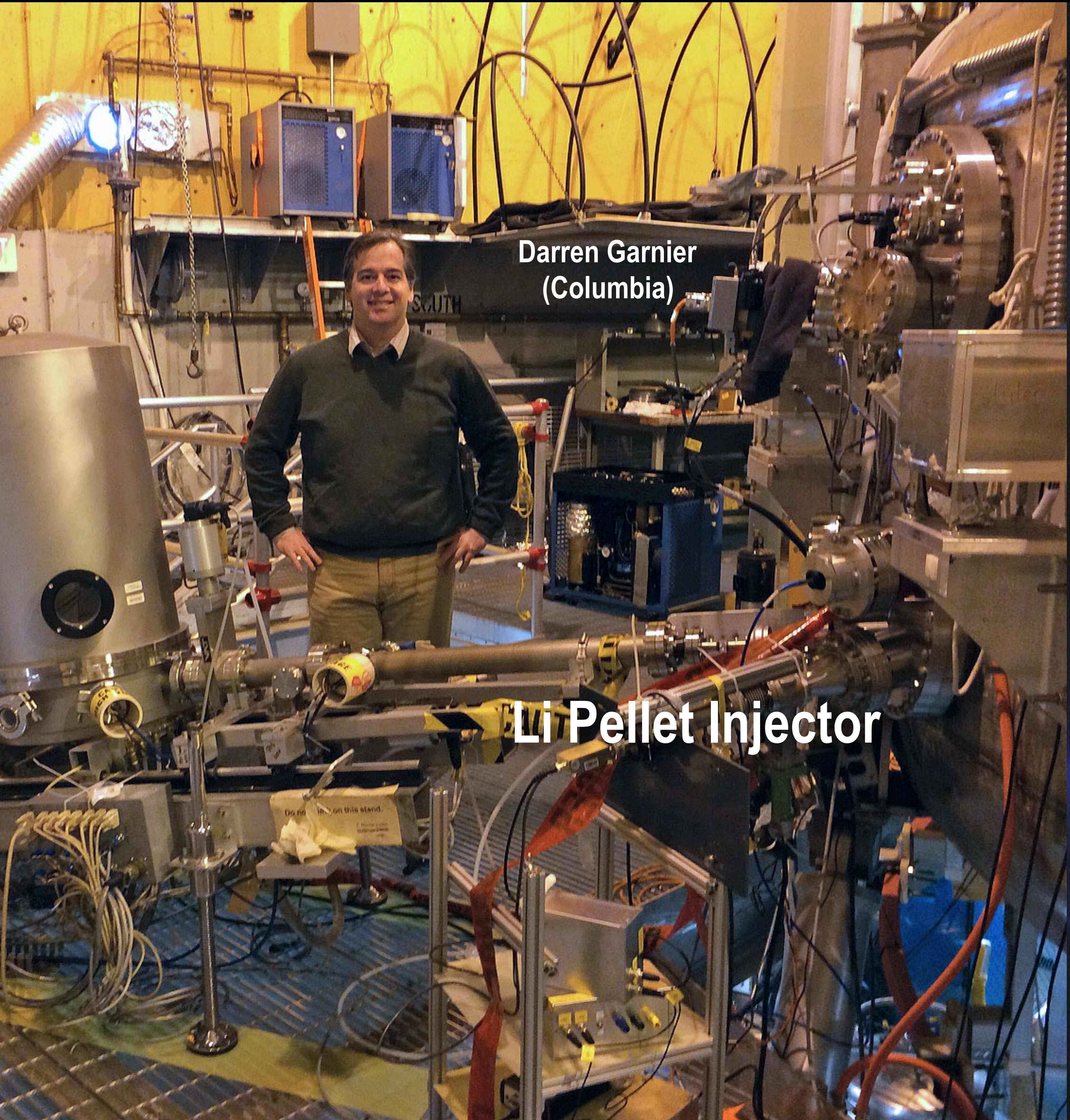
Probe Array:
Floating Potential, E_φ
Ion Saturation Current
Radial **E×B** Flux

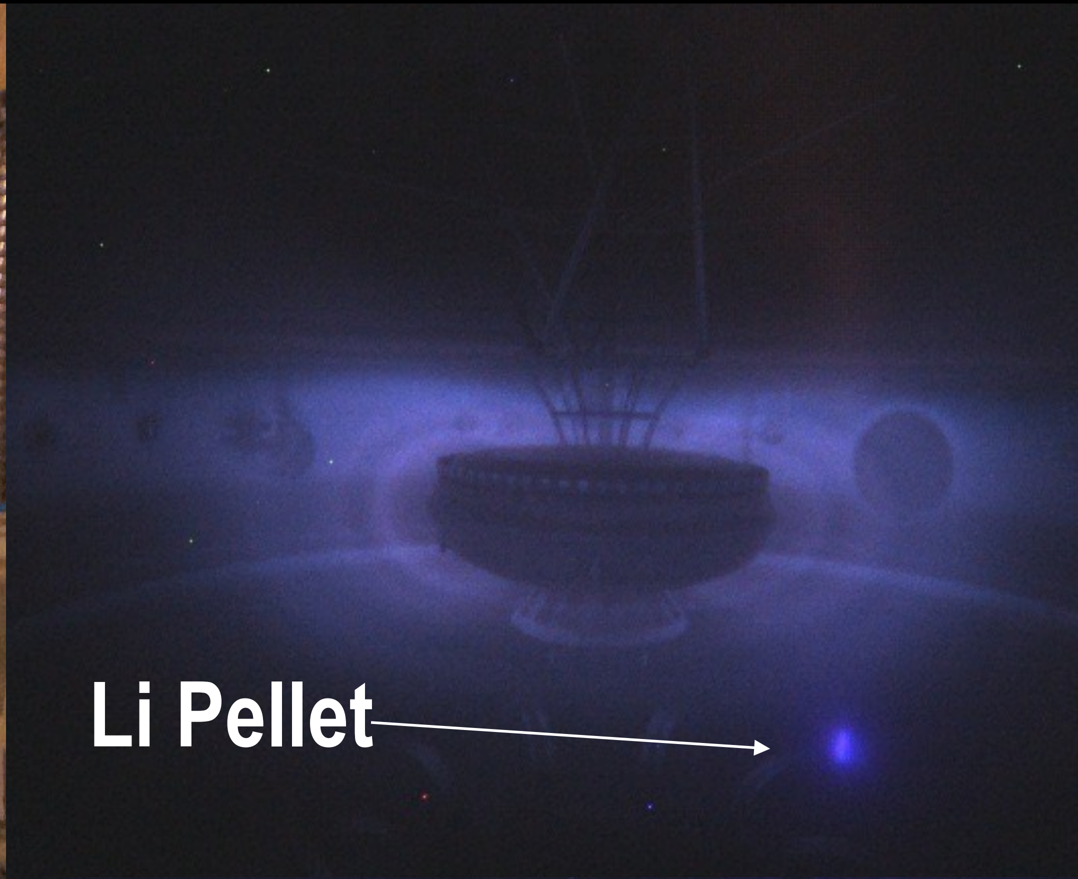


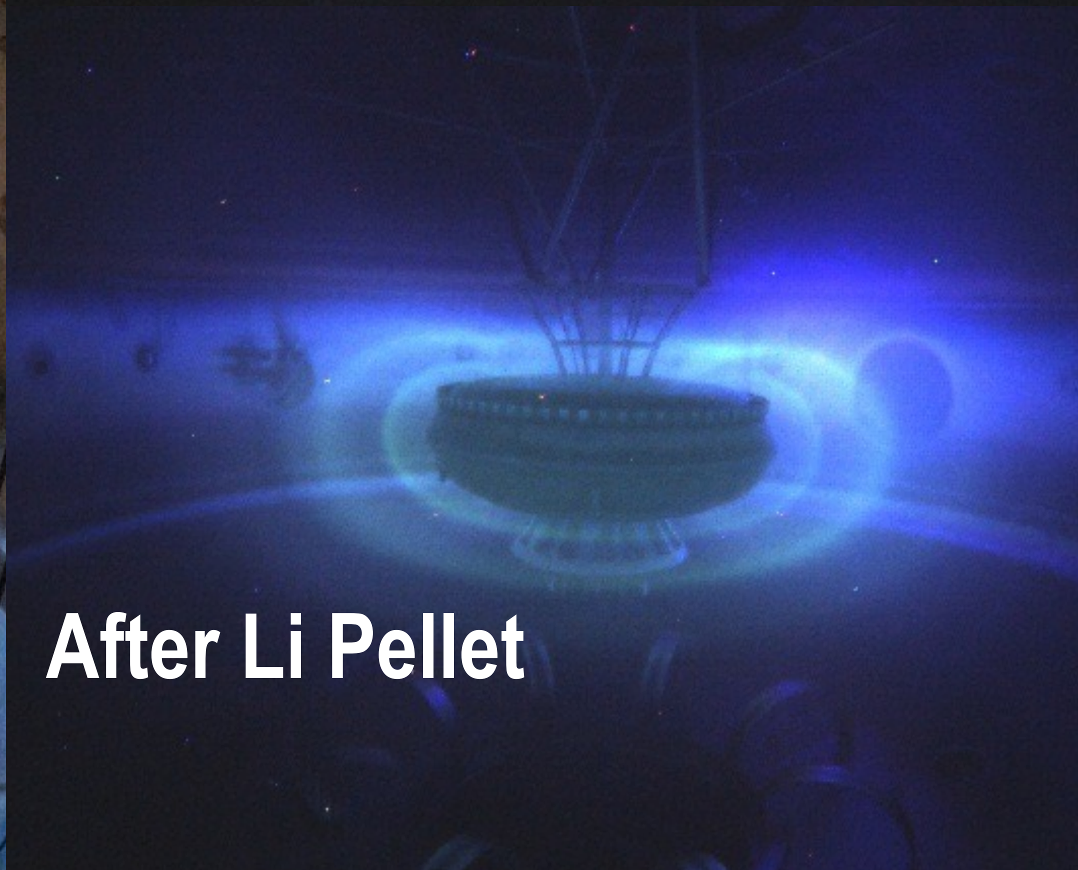
Radial Flux ~ $(E_\varphi/B) \times I_{sat}$

Jen Ellsworth, *Characterization of Low-Frequency Density Fluctuations in Dipole-Confined Laboratory Plasmas*, PhD MIT (2010).
Grierson, *et al.*, "Transport Induced by Large Scale Convective Structures in a Dipole-Confined Plasma," *PRL* **105**, 205004 (2010).

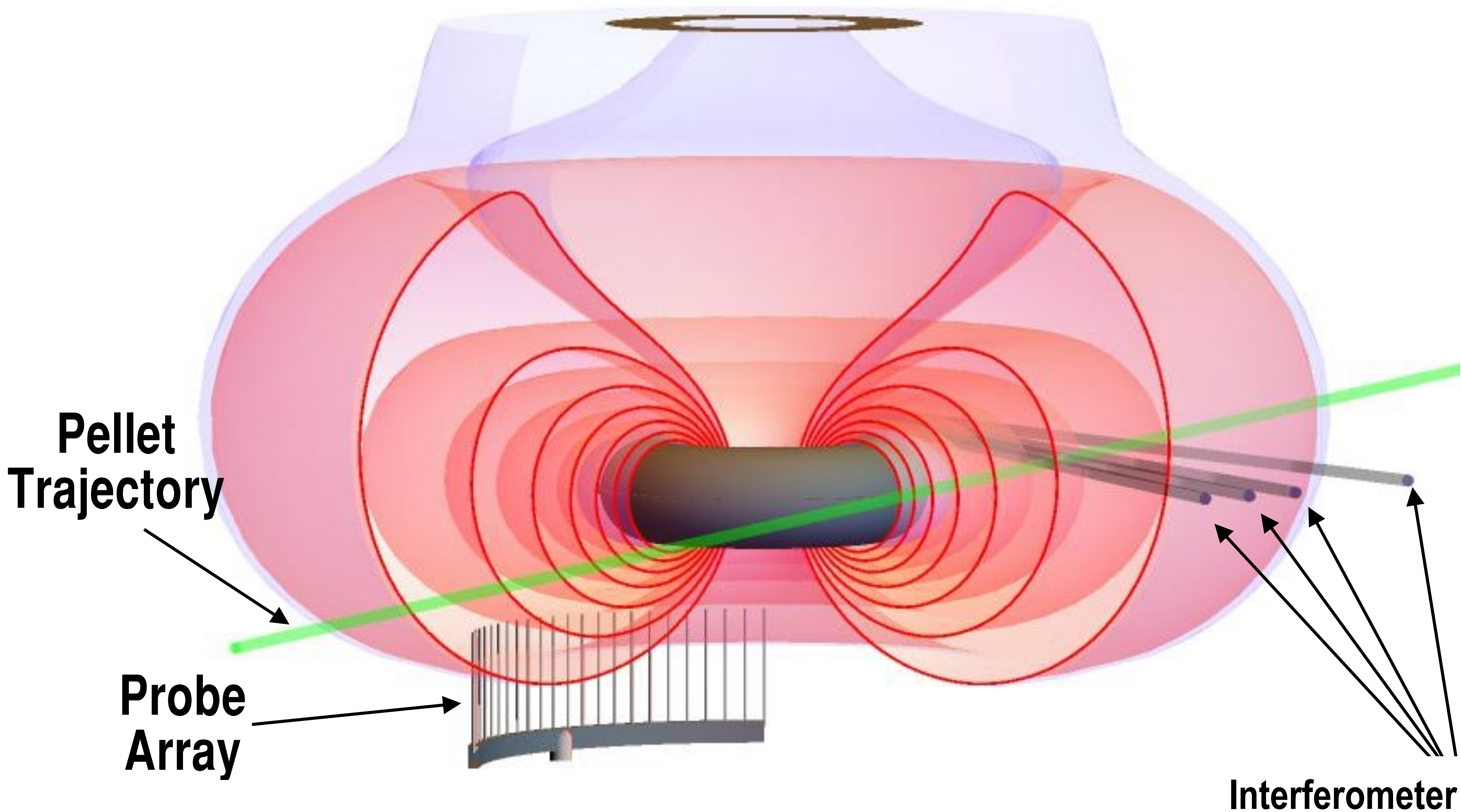
High Speed Pellet Injection Cools Core & Creates Internal Fueling and *Reverses* the Direction of Particle Diffusion





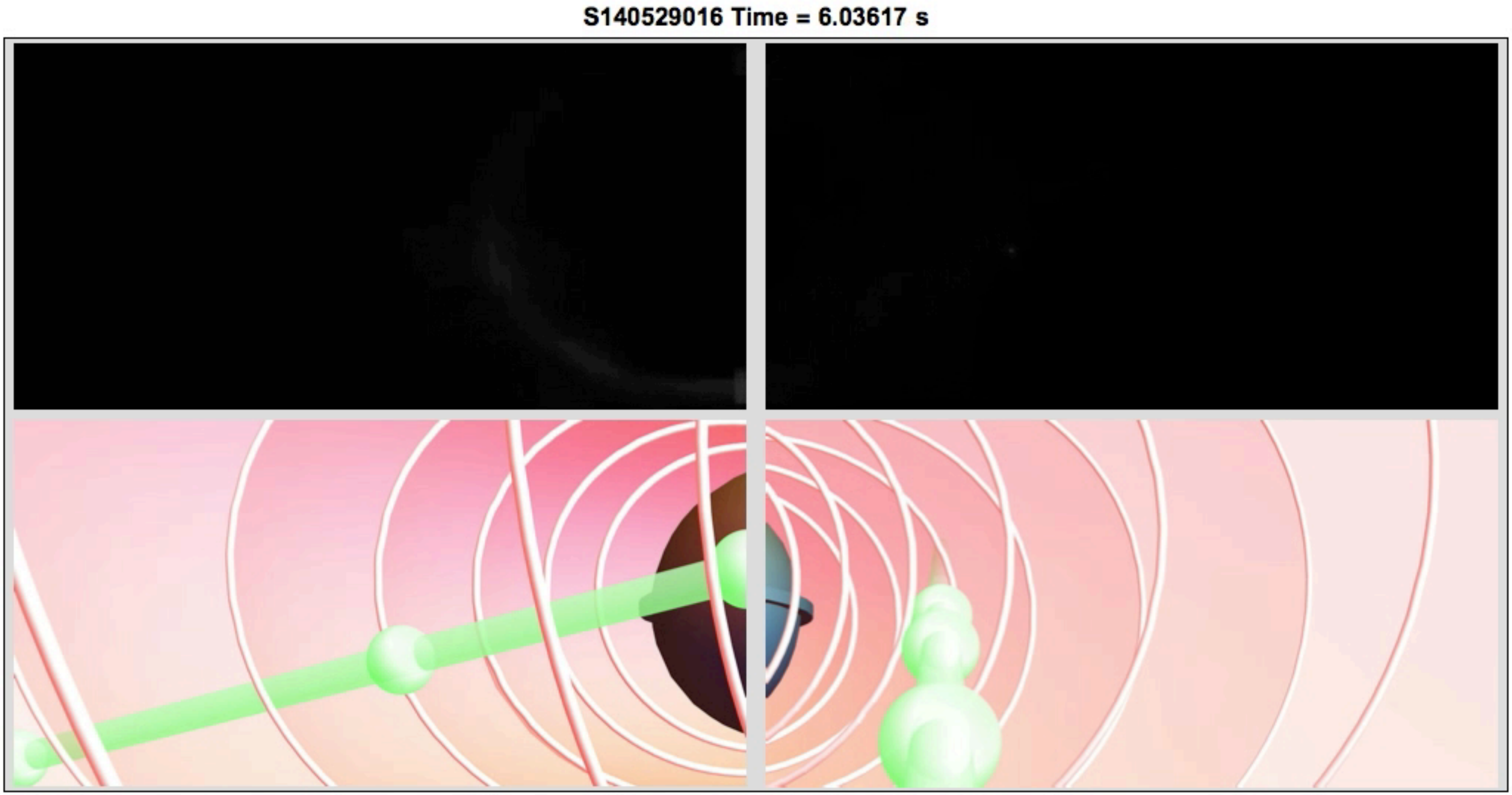


Li Pellet Injection Provides Large Internal Particle Source for Transient Transport Study



×5 Peak Density
×3 Electrons
÷3 Energy

Li Pellet Injection Provides Large Internal Particle Source for Transient Transport Study

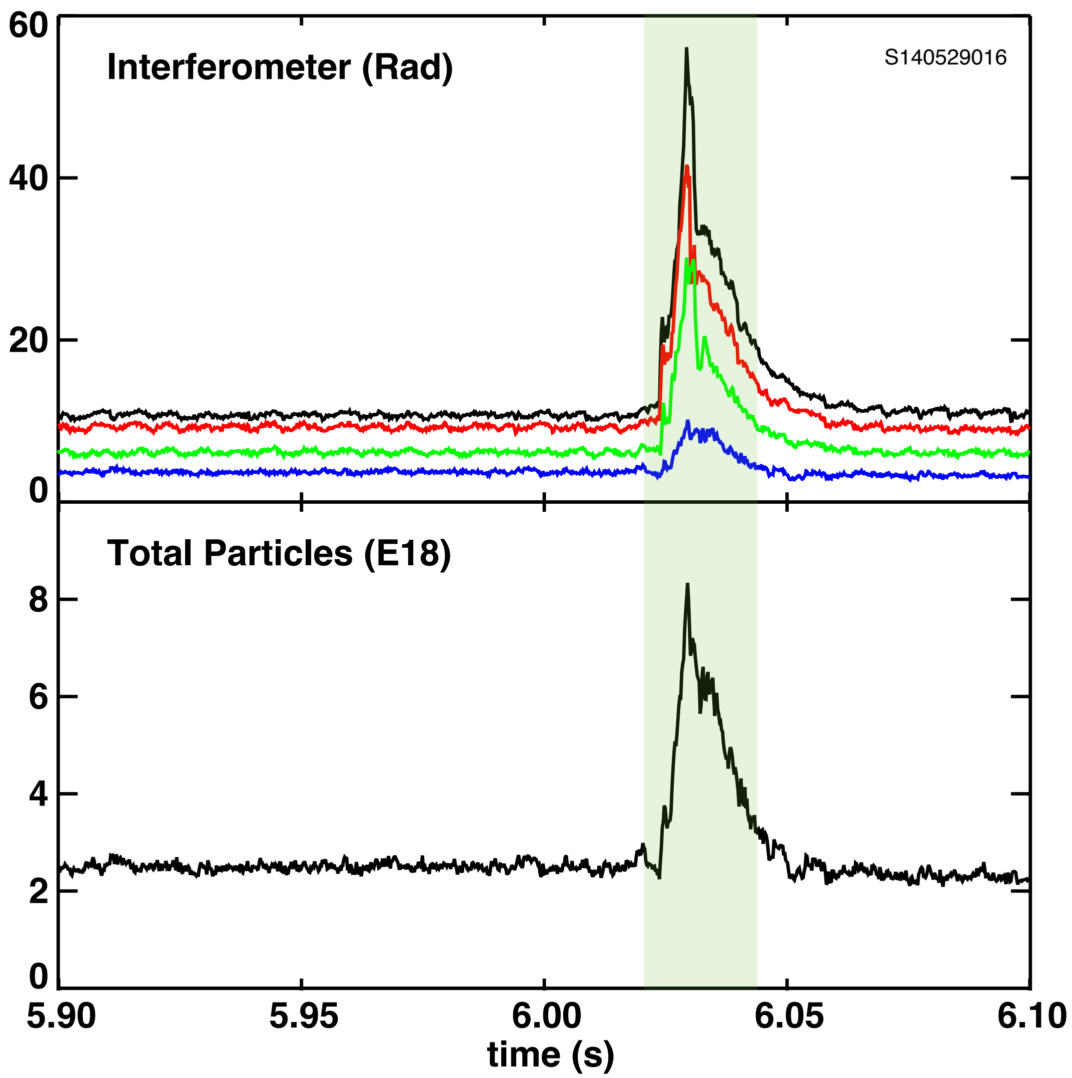


×5 Peak Density
×3 Electrons
÷3 Energy

17 ms traveling at 225 m/s

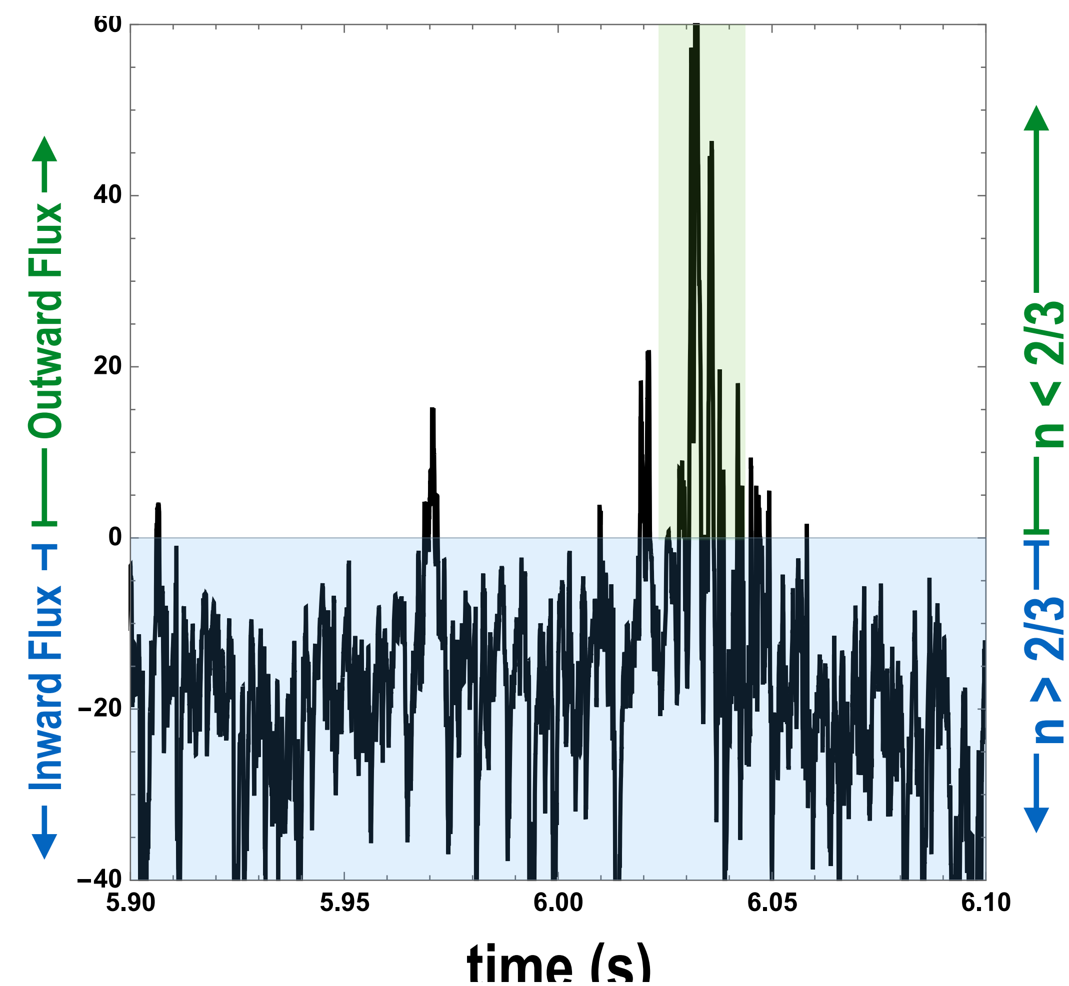
“Cool Core”/Li Pellet Fueling *Reverses* Direction of Particle Flux

(Creating outward burst of “planetary wind”)



Average Radial Particle Flux from Edge Probe Array

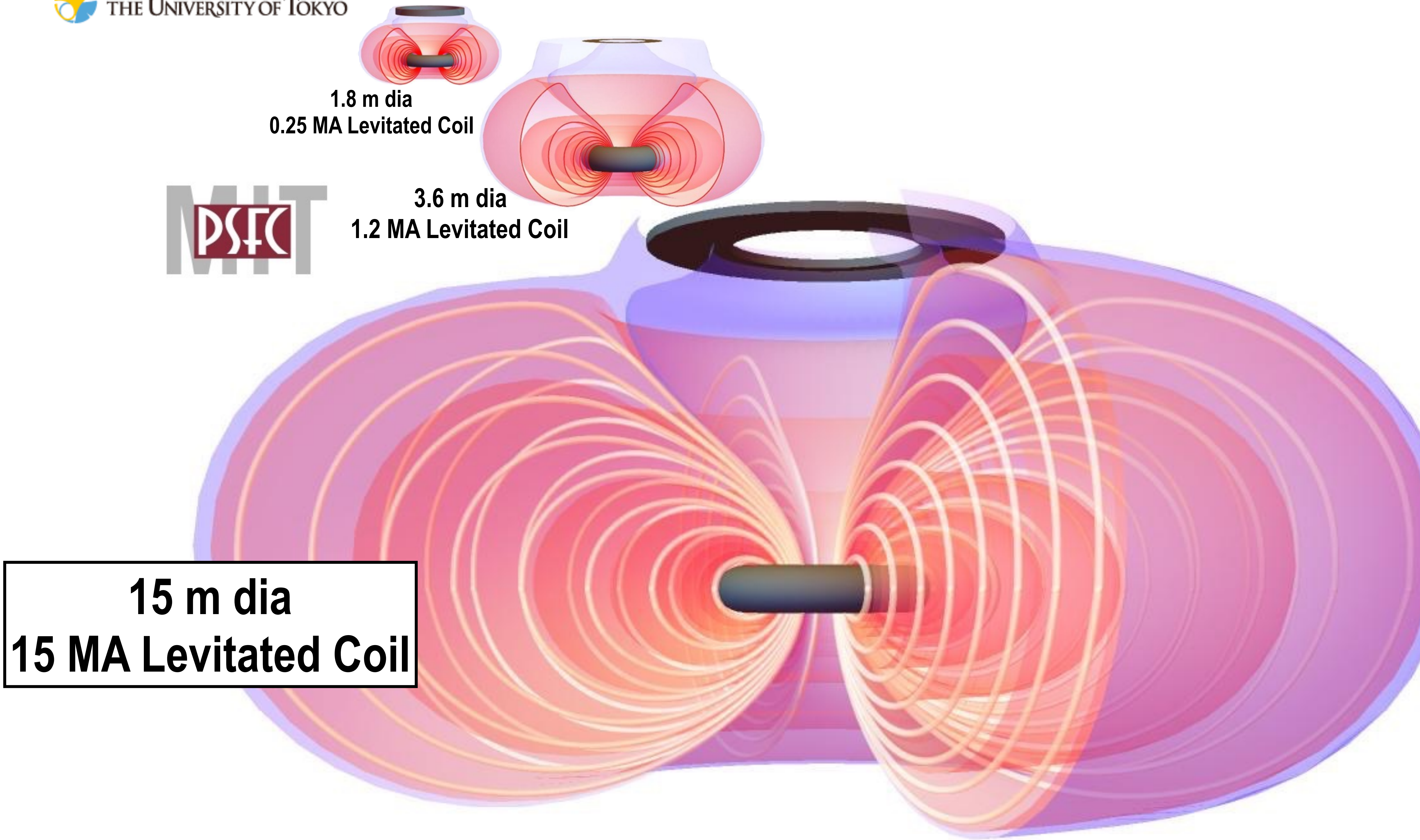
$$\langle \Gamma_\psi \rangle = \langle \langle R E_\phi I_{sat} \rangle \rangle_{(\Delta\phi, \Delta t)}$$



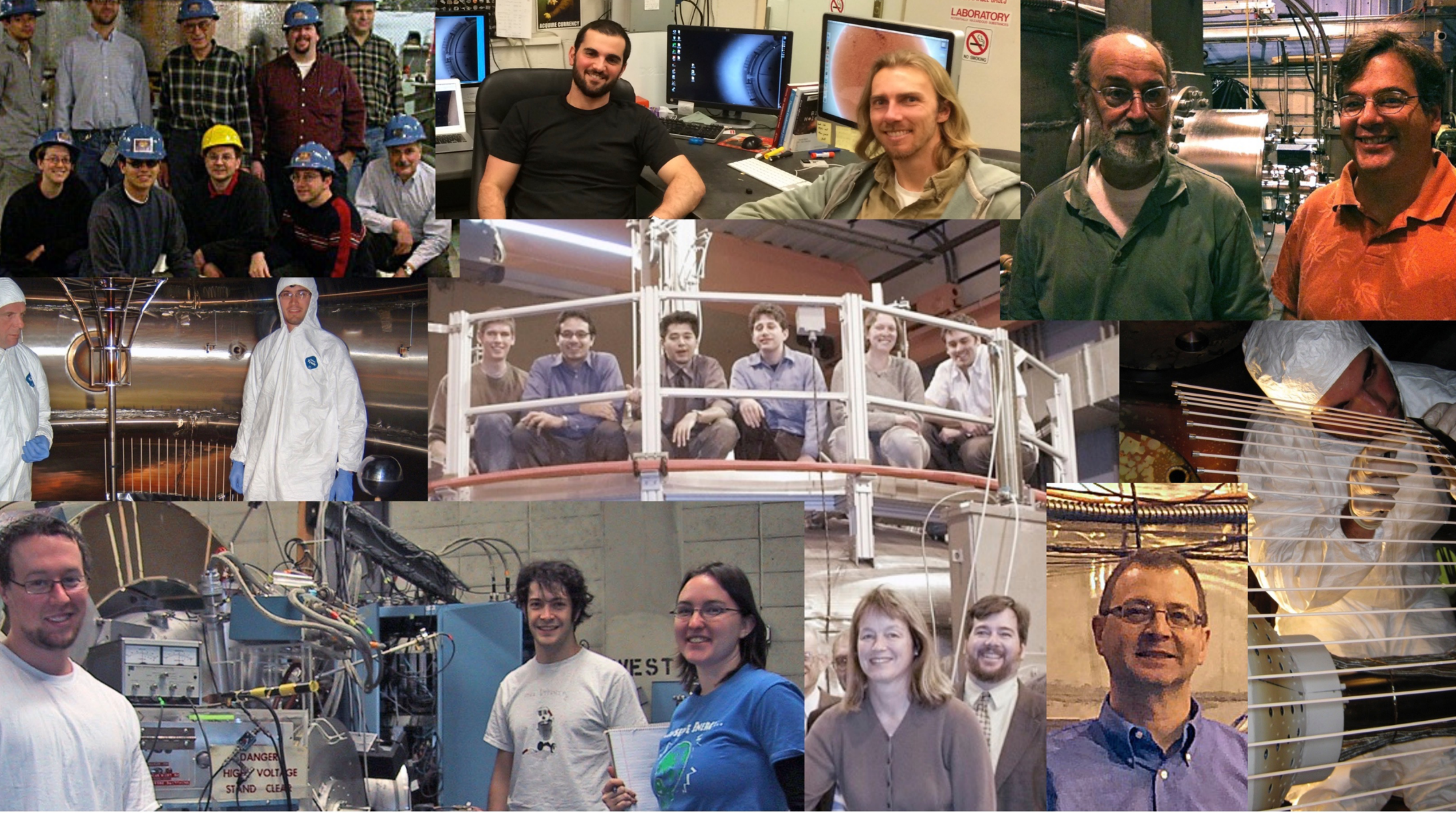
Physics of the Laboratory Magnetosphere: *Frontier Questions …*

- **Beyond ECRH and accessibility limits: high density and warm ions…**
  - What are the stability and transport properties of a high-density plasma torus with $T_i \sim T_e$?
  - How does Alfvén magnetic turbulence couple to interchange and entropy mode turbulence?
  - Whistler waves interactions with energetic particles, when $\omega_{pe} >> \omega_{ce}$
- **Develop and understand "whole plasma" predictive models of magnetized plasma transport with precision measurements of an axisymmetric high-β torus…**
  - How do particle and heat sources influence the self-organized profiles? What are the roles of momentum input? Zonal flows? T_i/T_e ratio? Ionic mass and impurities?
  - Are reduced dimension models effective to predict the saturated turbulence transport?
  - Can improved diagnostics give precision observation of plasma turbulent self-organization?
  - How do we understand core-edge connections, both boundary interfaces, and SOL flows?
- **Magnetospheric configuration toroidally confines non-neutral, single-component plasma…**
  - Can a levitated dipole be used to study exotic and electron-positron plasmas?
- **With a small superconducting magnetic, can we create and study very large confined plasma …**

We can create the world's *largest* magnetized plasma for the study of basic plasma processes…



A Large Space Chamber Could be Filled with a Laboratory Magnetosphere



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