Exploring Plasma Dynamics with Laboratory Magnetospheres

Mike Mauel and
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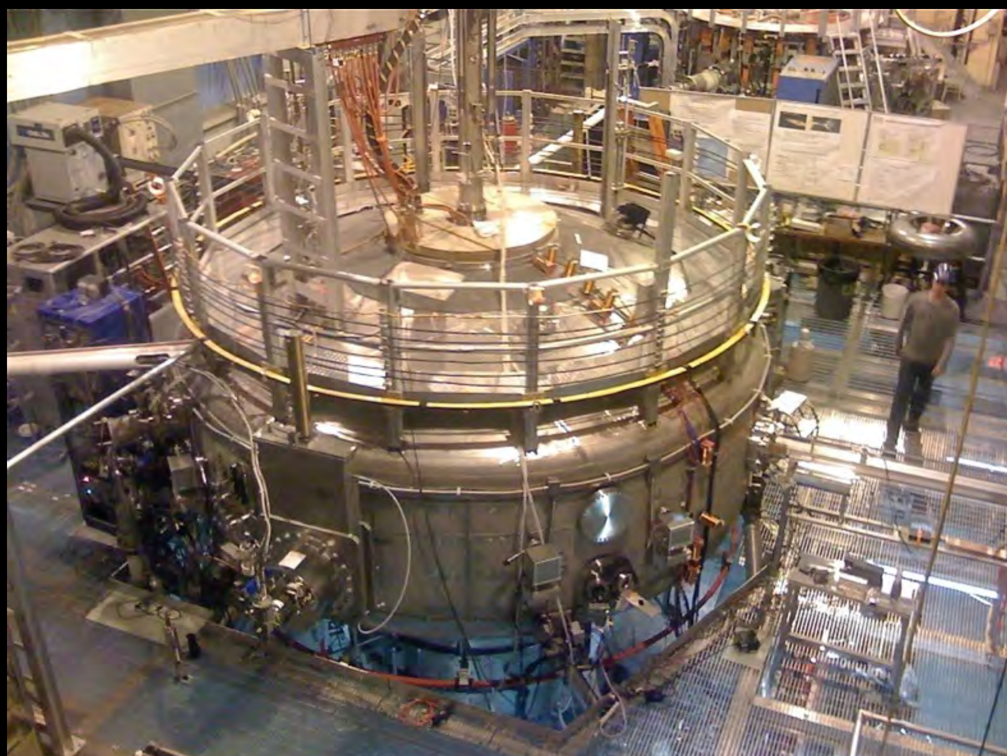
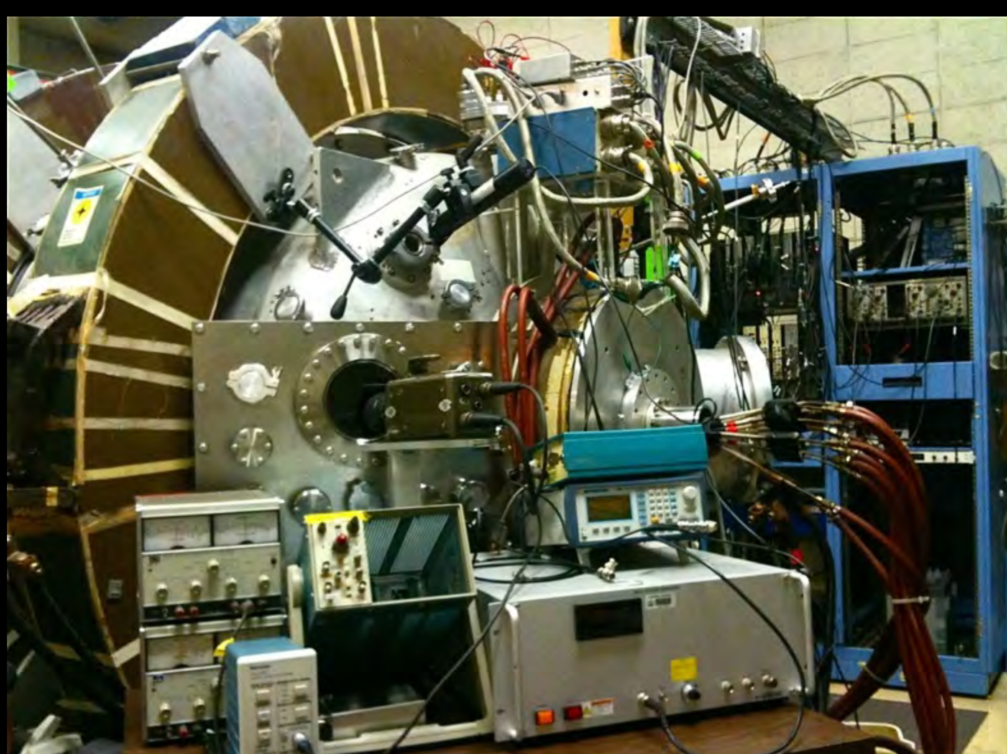
February 2014

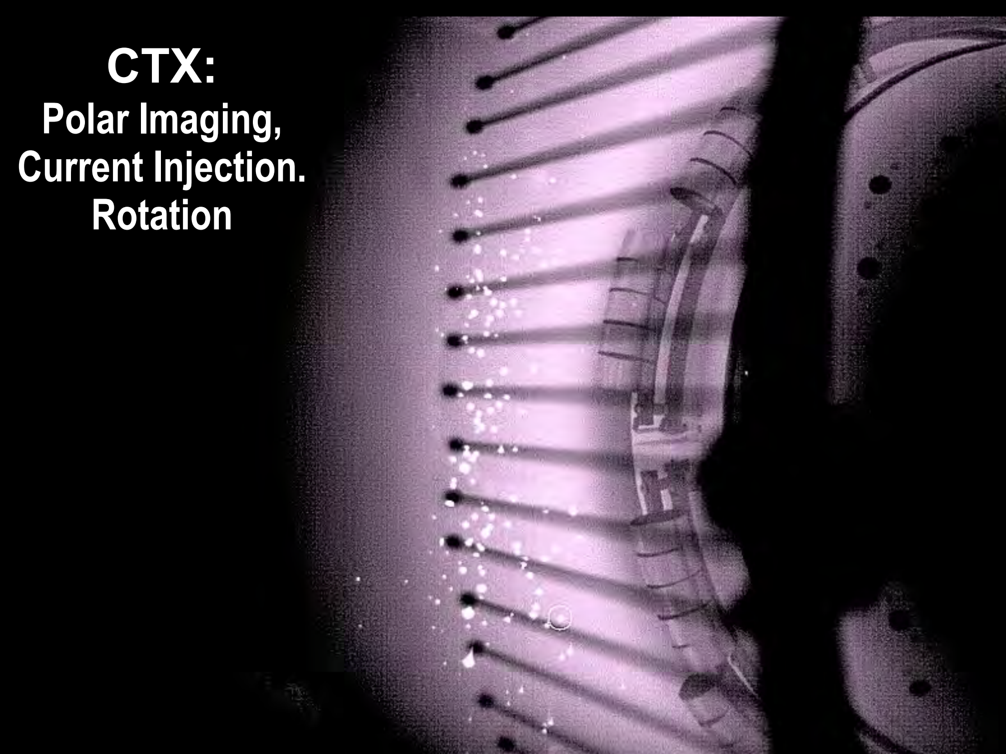
Motivation

- **Can space weather physics be applied to the laboratory?**
  - Very high plasma pressure, $\beta > 100\%$, steady-state, without toroidal field
  - Collisionless and semi-collisional dynamics well-represented by bounce-averaged transport (*i.e.* particle number per unit flux with constant energy invariants)
  - Fluctuations drive plasma to "canonical" profiles: stationary, marginally stable states, having minimum entropy generation
- **Can laboratory studies facilitate the study of space physics and technology?**
  - Controlled experiments in relevant magnetic geometry
  - Very strong, but small, dipole magnet inside a very large vacuum chamber making possible very large plasma experiments at relatively low cost
  - "Whole plasma" access for unparalleled imaging and diagnostic measurement
  - Injection of waves (ECH, "chorus", Alfvén, and ion-cyclotron waves), current, and particle/plasmoid gives unprecedented control over plasma properties and behaviors

Laboratory Magnetospheres: Facilities for Controlled Space Physics Experiments







Outline

- How does a laboratory magnetosphere work?
- Interchange disturbances and magnetic drift resonances
  - **Low frequency interchange turbulence: steady “canonical” profiles and bounce-averaged (flux-tube averaged) gyrokinetics**
  - **Three interchange instabilities: Fast drift-kinetic, centrifugal interchange, semi-collisional entropy modes**
- **Examples:** exploring plasma dynamics by injection of heat, particles, current, and magnetic perturbations by decreasing ion inertial lengths

LDX and CTX Team

R. Bergmann, A. Boxer, D. Boyle, D. Brennan, M. Davis, G. Driscoll, R. Ellis, ***J. Ellsworth,*** S. Egorov, D. Garnier, ***B. Grierson***, O. Grulke, C. Gung, A. Hansen, K.P. Hwang, V. Ivkin, ***J. Kahn, B. Kardon, I. Karim***, J. Kesner, S. Kochan, ***V. Korsunsky***, R. Lations, ***B. Levitt***, ***S. Mahar***, ***D. Maslovsky***, M. Mauel, P. Michael, ***E. Mimoun***, J. Minervini, M. Morgan, R. Myatt, G. Naumovich, S. Nogami, ***E. Ortiz***, M. Porkolab, S. Pourrahami, T. Pedersen, A. Radovinsky, ***A. Roach***, ***M. Roberts***, ***A. Rodin***, G. Snitchler, D. Strahan, J. Schmidt, J. Schultz, B. Smith, P. Thomas, P. Wang, ***H. Warren***, B. Wilson, ***M. Worstell***, P. Woskov, ***B. Youngblood***, A. Zhukovsky, S. Zweben

THE UNIVERSITY OF TOKYO

Dynavac

Ability Engineering Technology Inc.

American Superconductor

D.V. Efremov Institute

Office of Fusion Energy Sciences
Excellent Science Attractive Energy

IGC ADVANCED SUPERCONDUCTORS
A DIVISION OF INTERMAGNETICS GENERAL CORPORATION

Columbia University

AFOSR
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

NSF National Science Foundation
WHERE DISCOVERIES BEGIN

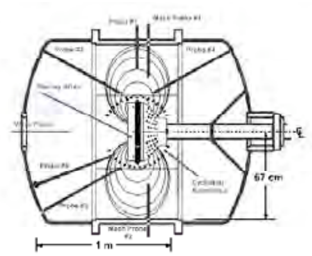
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

MIT PSFC

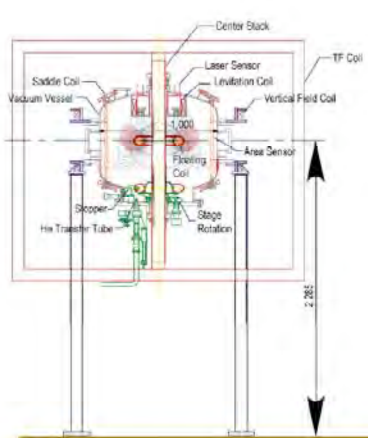

Jay Kesner
Darren Garnier

Laboratory Dipole Experiments Around the World



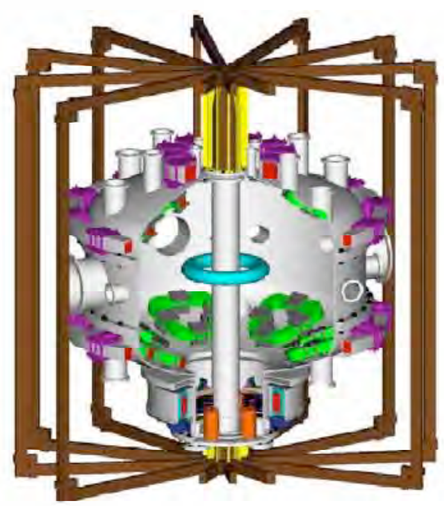
CTX (Columbia)

150 kA turns
(Not Levitated)
0.15 m



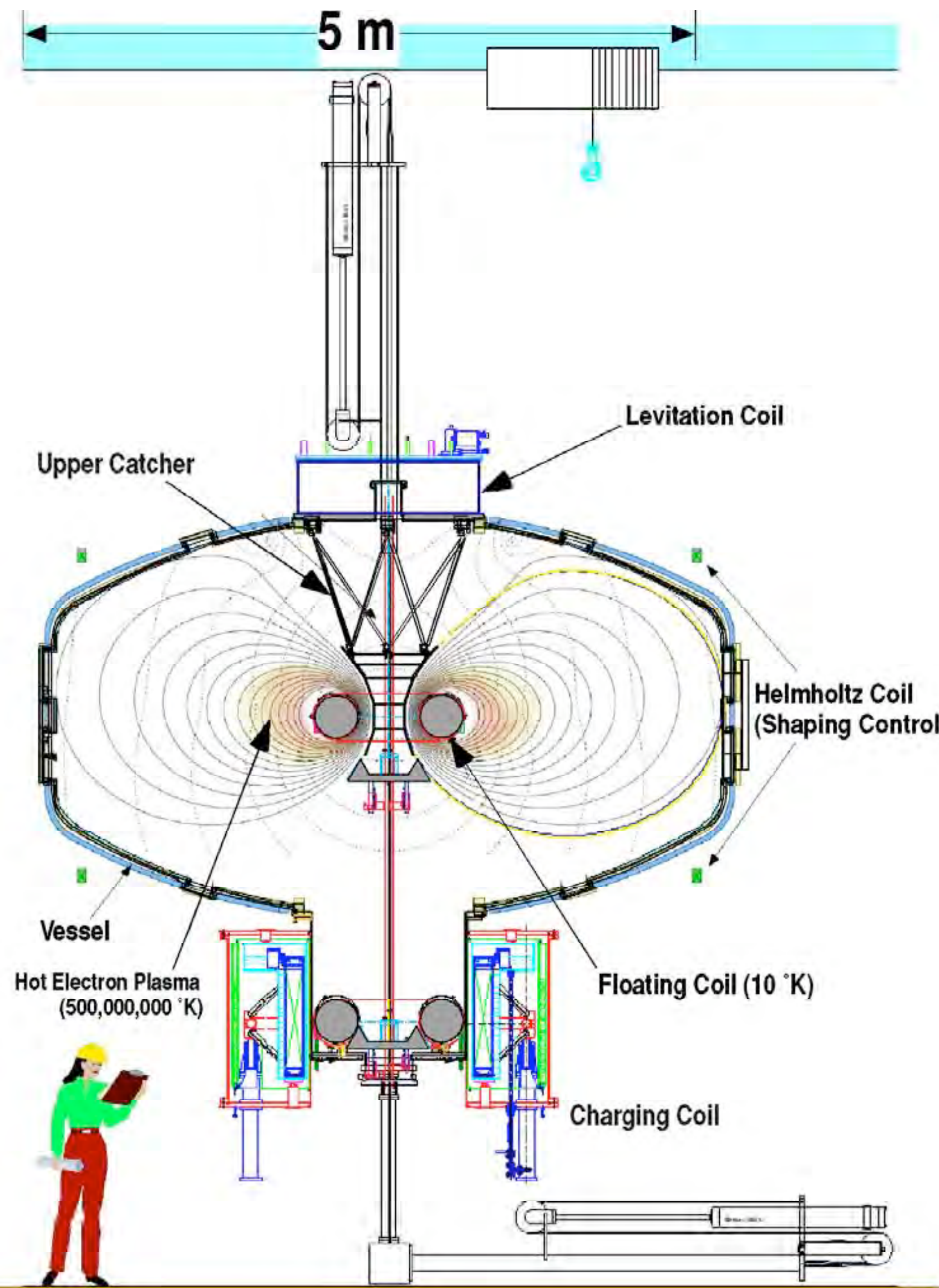
Mini-RT (Univ. Tokyo)

50 kA turns
17 kg
0.15 m



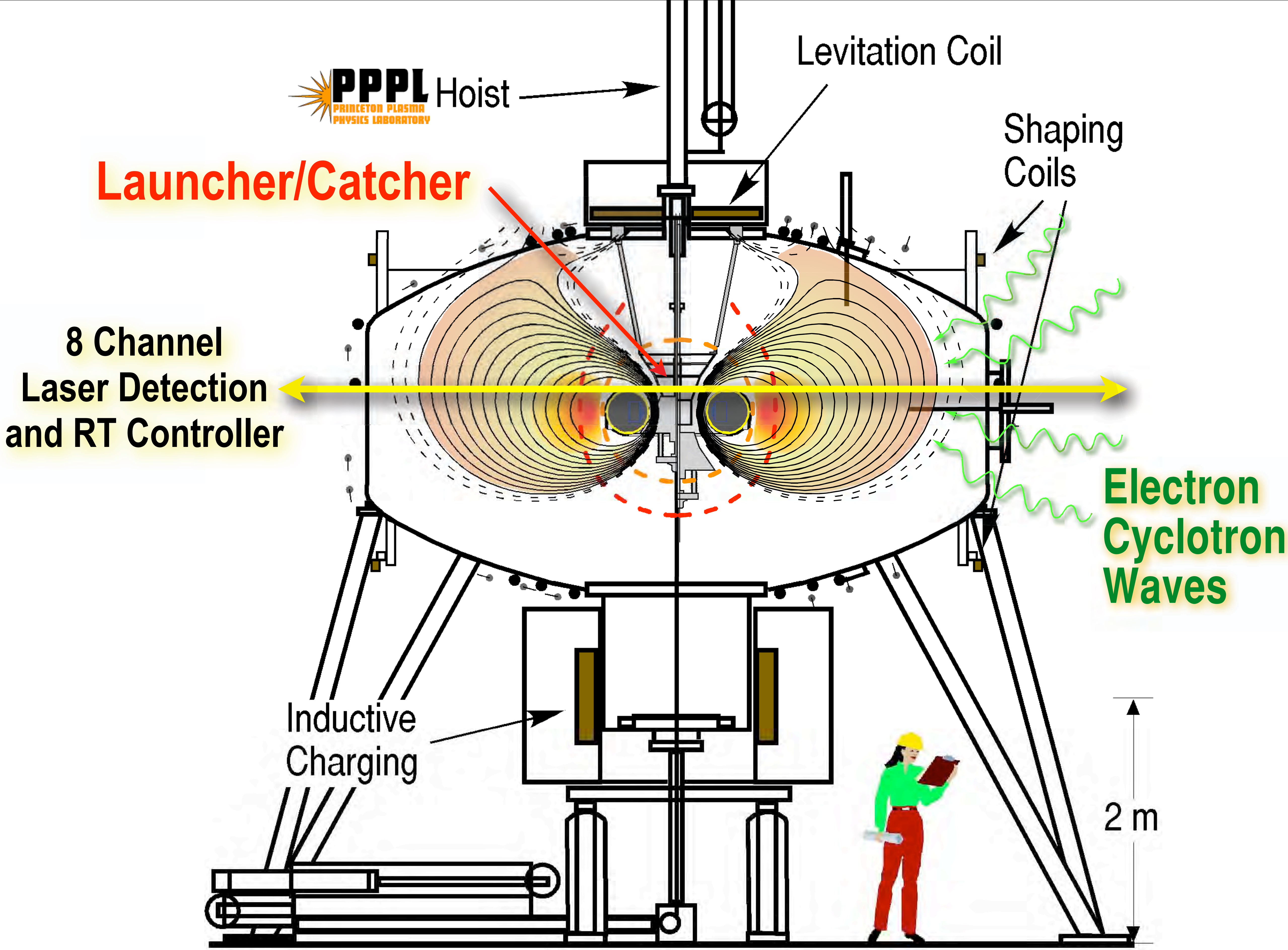
RT-1 (Univ. Tokyo)

250 kA turns
110 kg
0.25 m



LDX (Columbia-MIT)

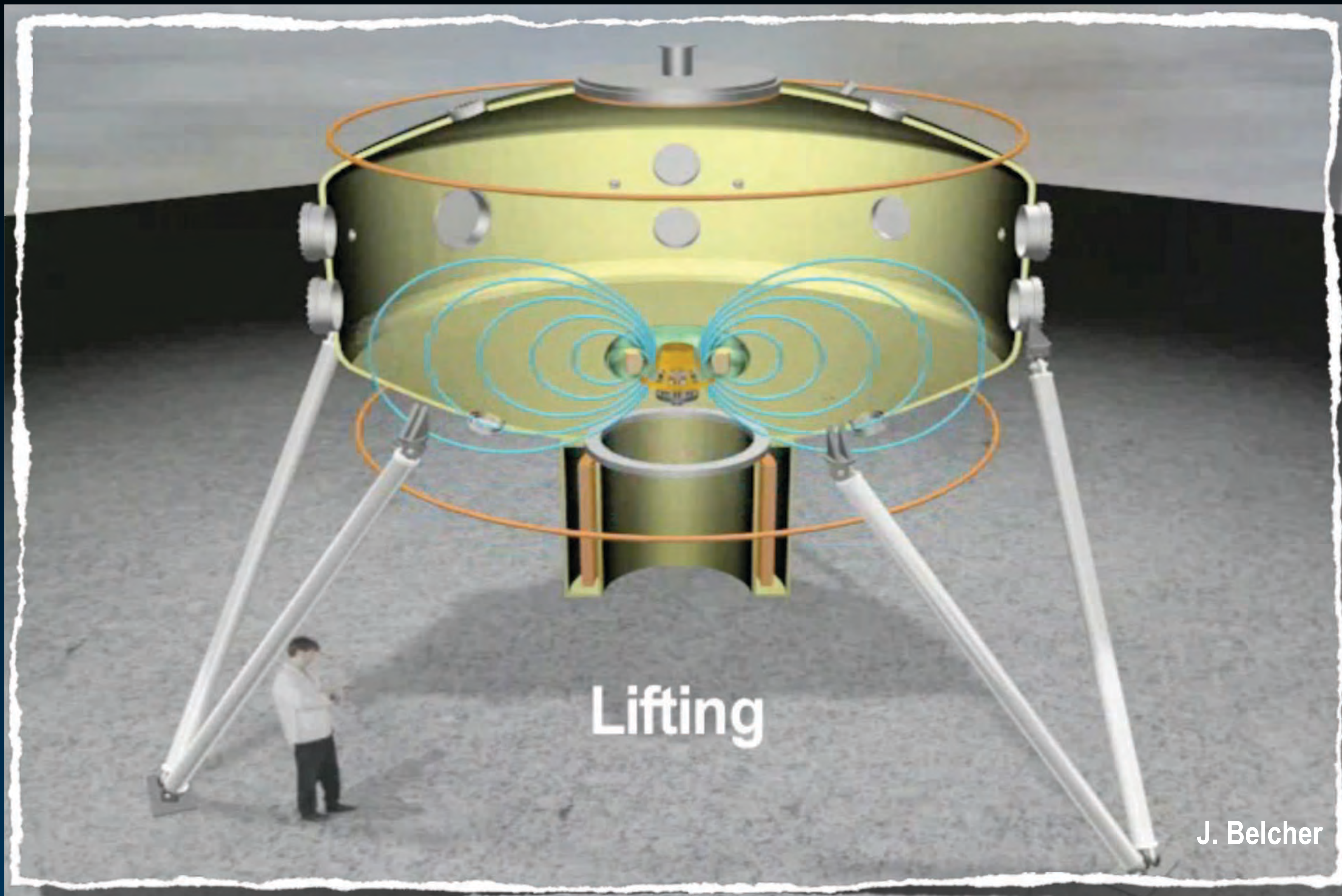
1200 kA turns
565 kg
0.34 m



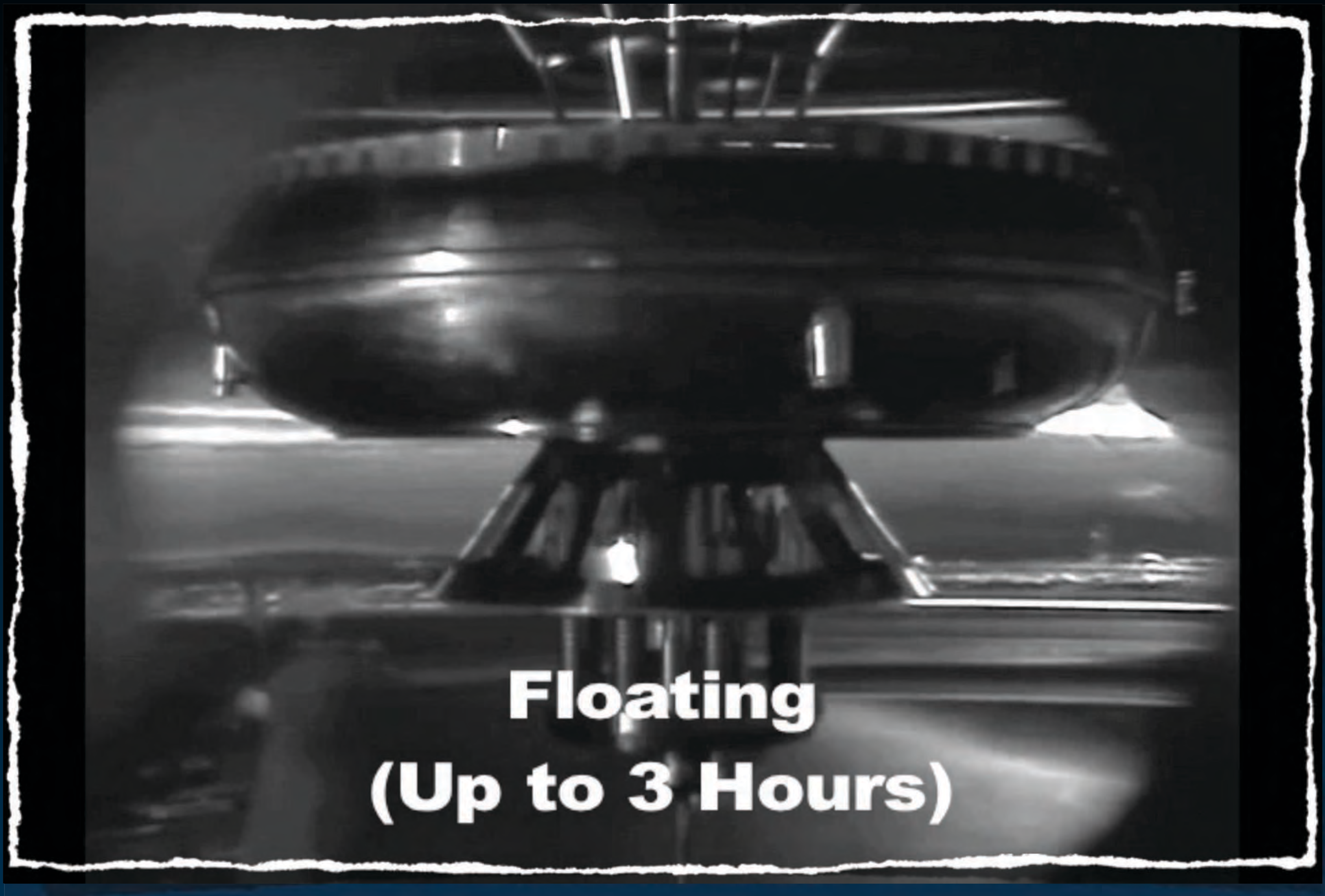
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

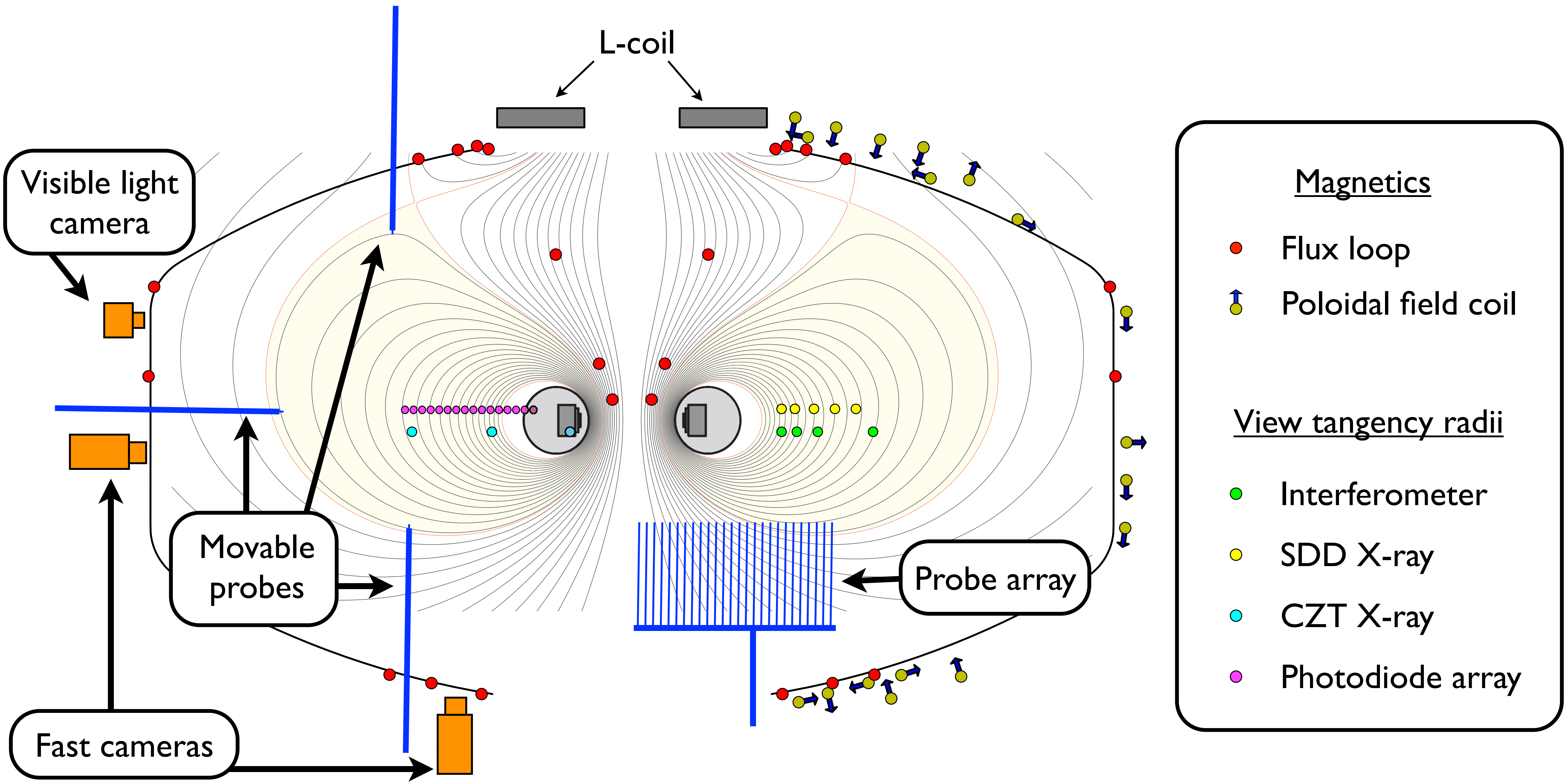
Lifting, Launching, Levitation, Experiments, Catching



First Levitated Dipole Plasma Experiment



Diagnostics



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    - **Low frequency interchange turbulence: steady "canonical" profiles and bounce-averaged (flux-tube averaged) gyrokinetics**
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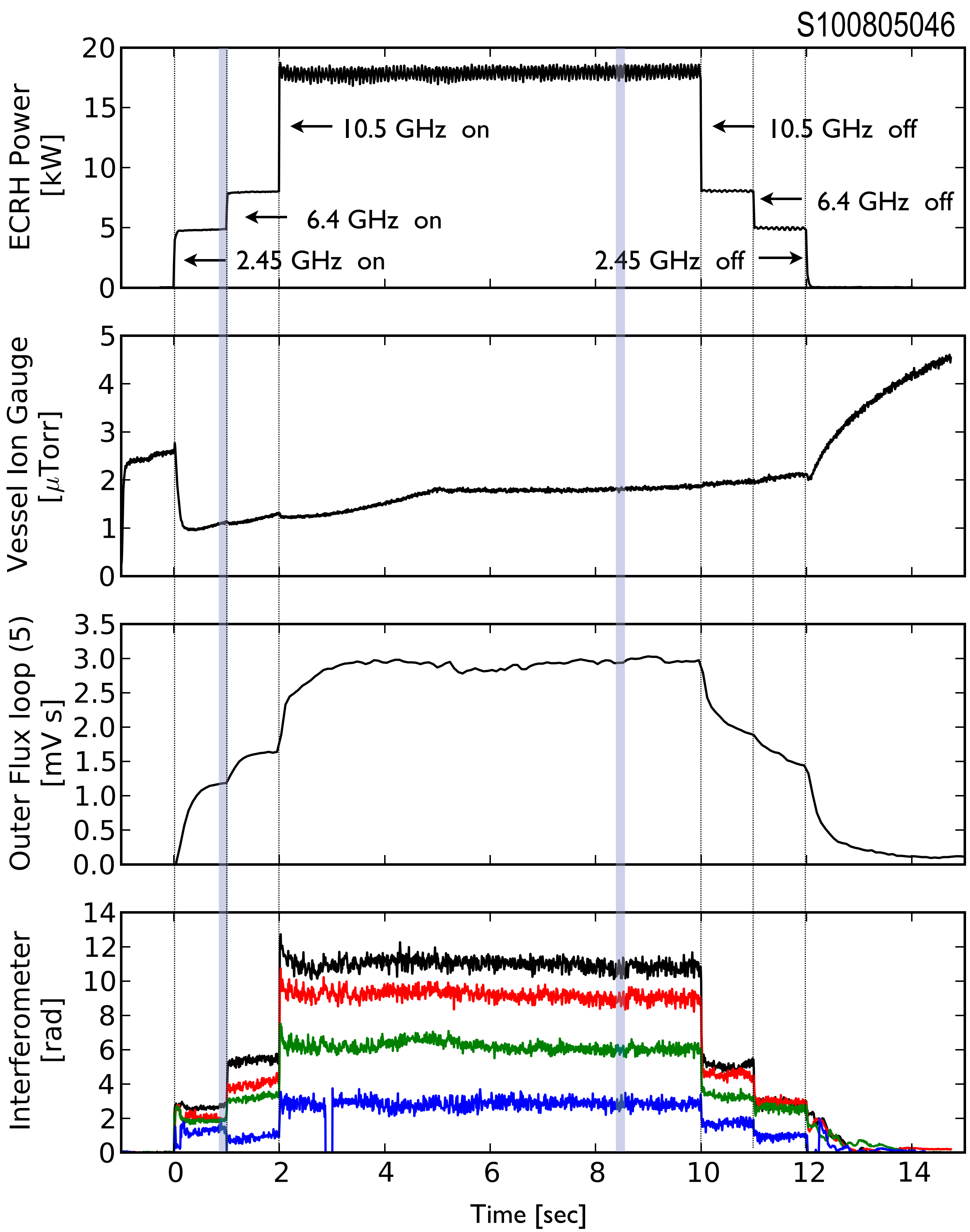
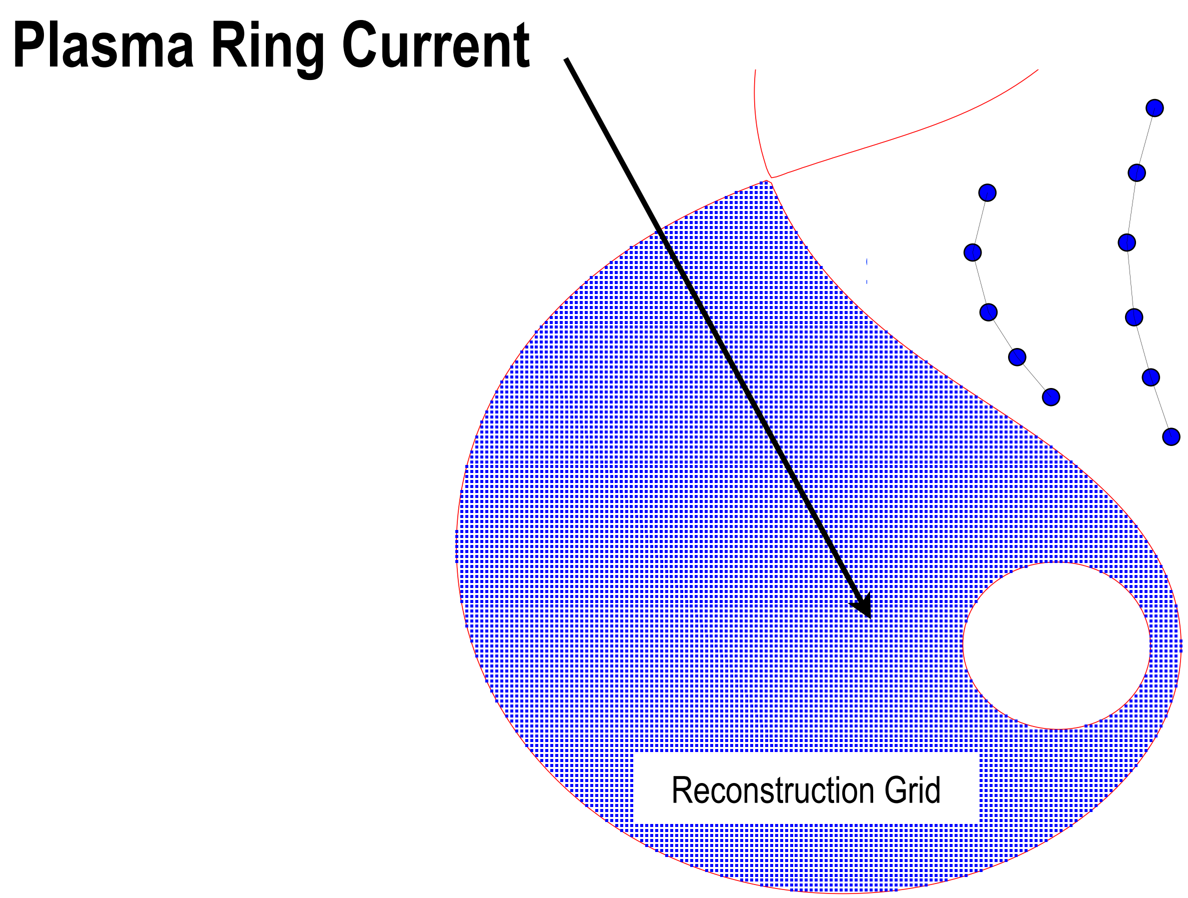
Example Plasma Experiment

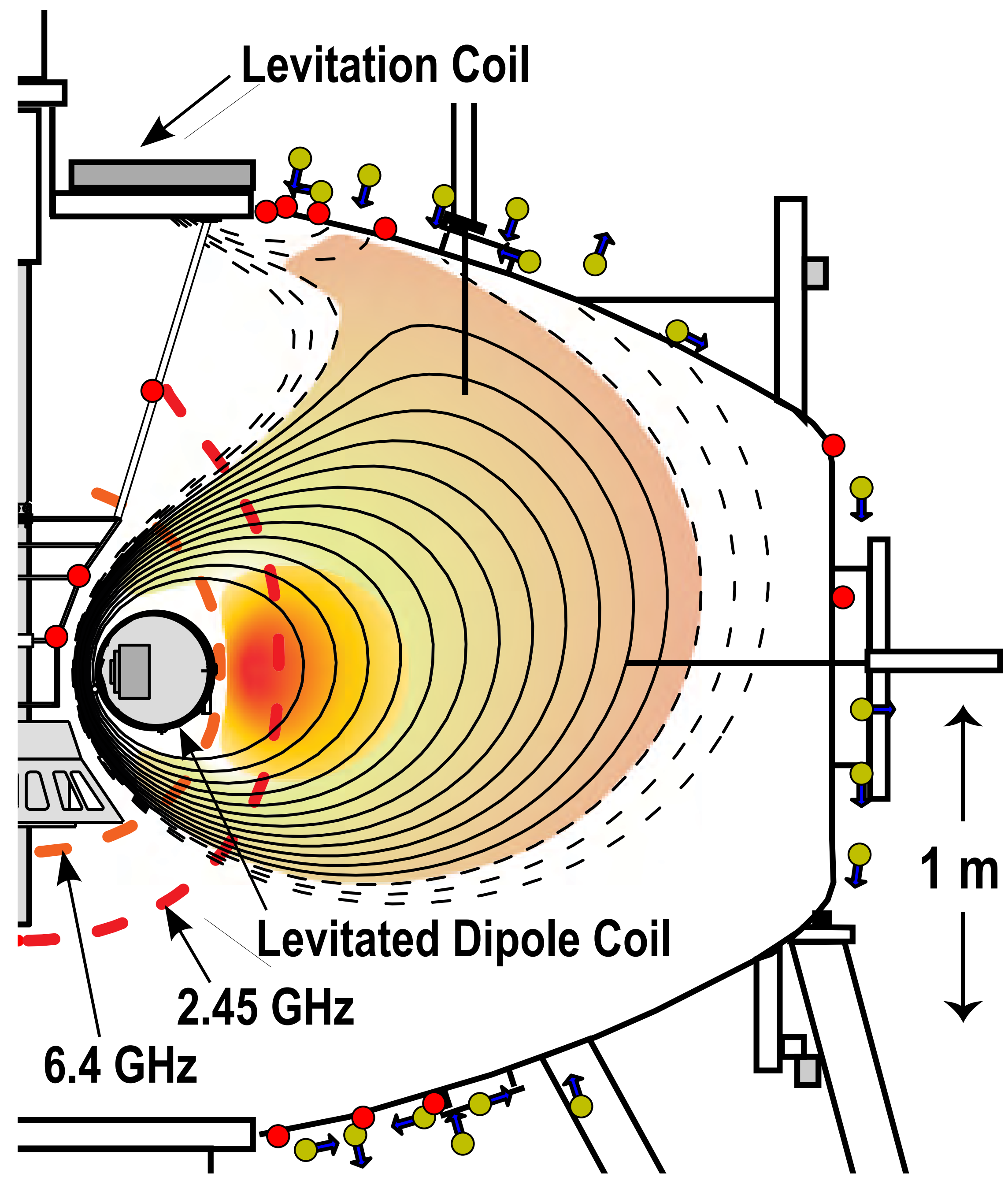
- 20 kW injected electron cyclotron waves
- Plasma energy 250 J (3 kA ring current)
- Peak β ~ 40% (70% achieved in RT-1)
- Hydrogen gas density 4×10^{10} cm^{-3}
- Peak plasma density 10^{12} cm^{-3}
- Energetic electrons 〈E〉 ~ 54 keV
- Peak 〈T〉 > 0.5 keV (thermal)
- Density proportional to injected power
- Sustained, dynamic, “steady state”



Measuring the Plasma Pressure from the Plasma Ring Current

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

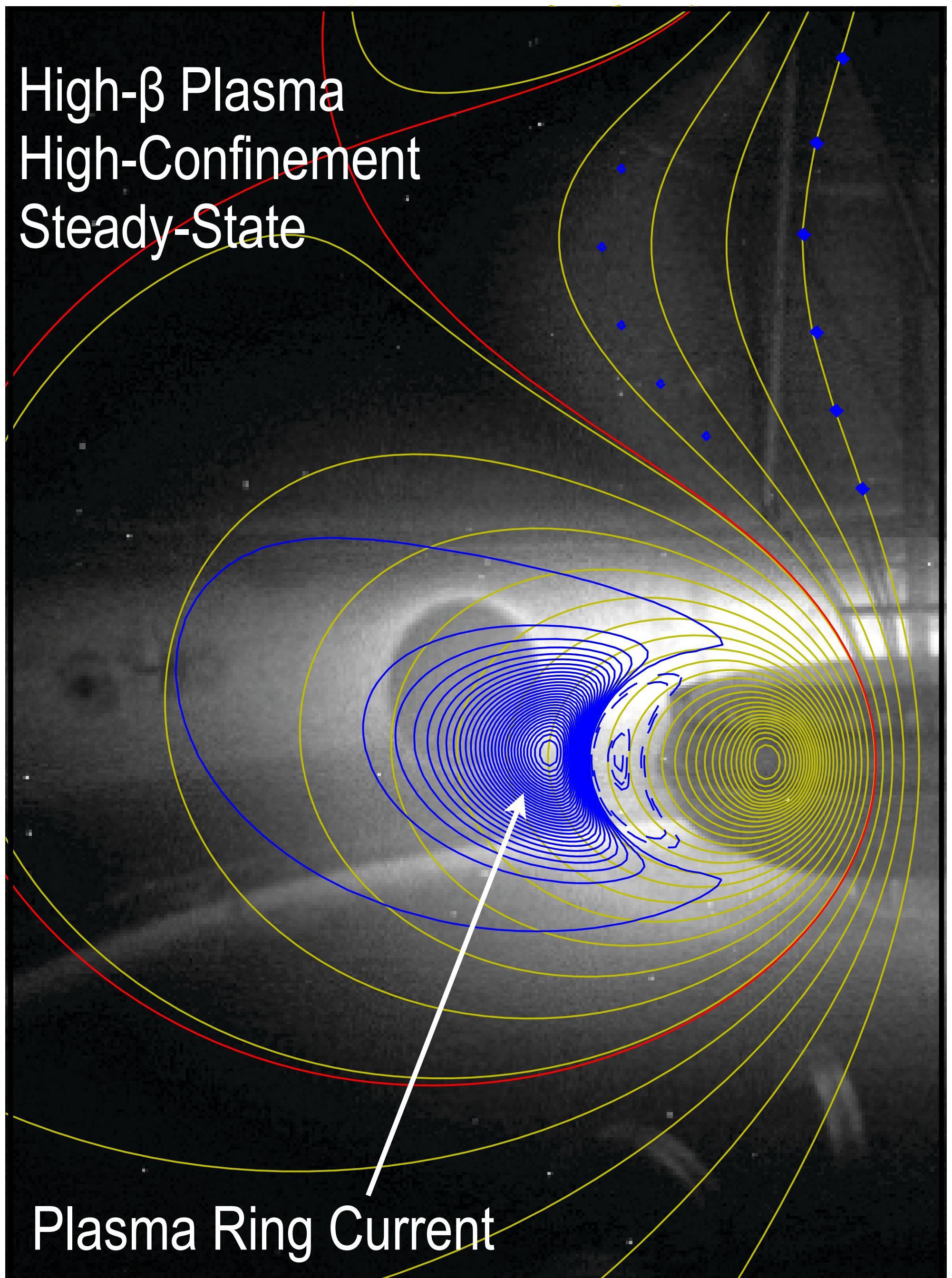




What is the plasma ring current distribution that fits magnetic sensor arrays?

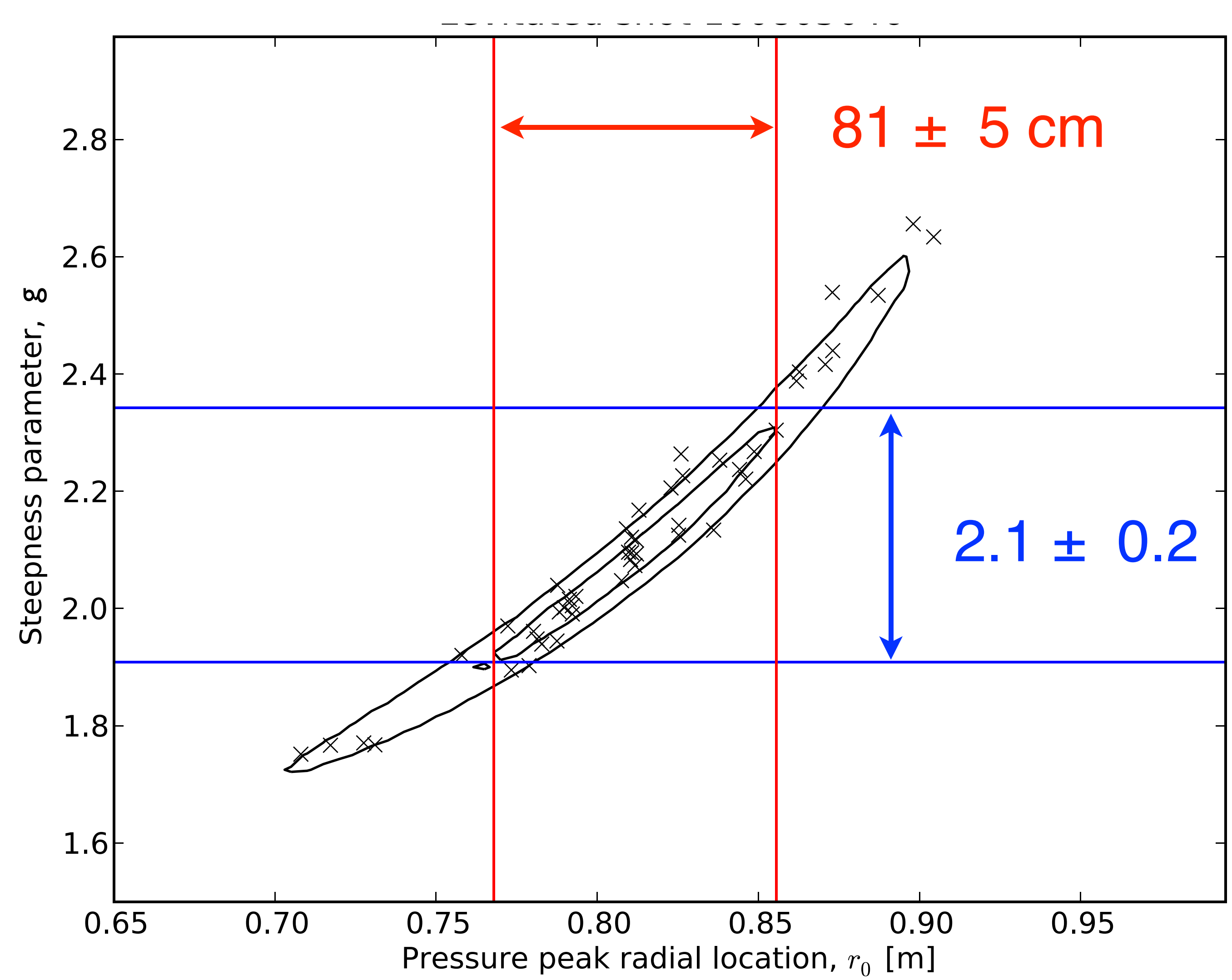
Measuring the Plasma Pressure from the Plasma Ring Current

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



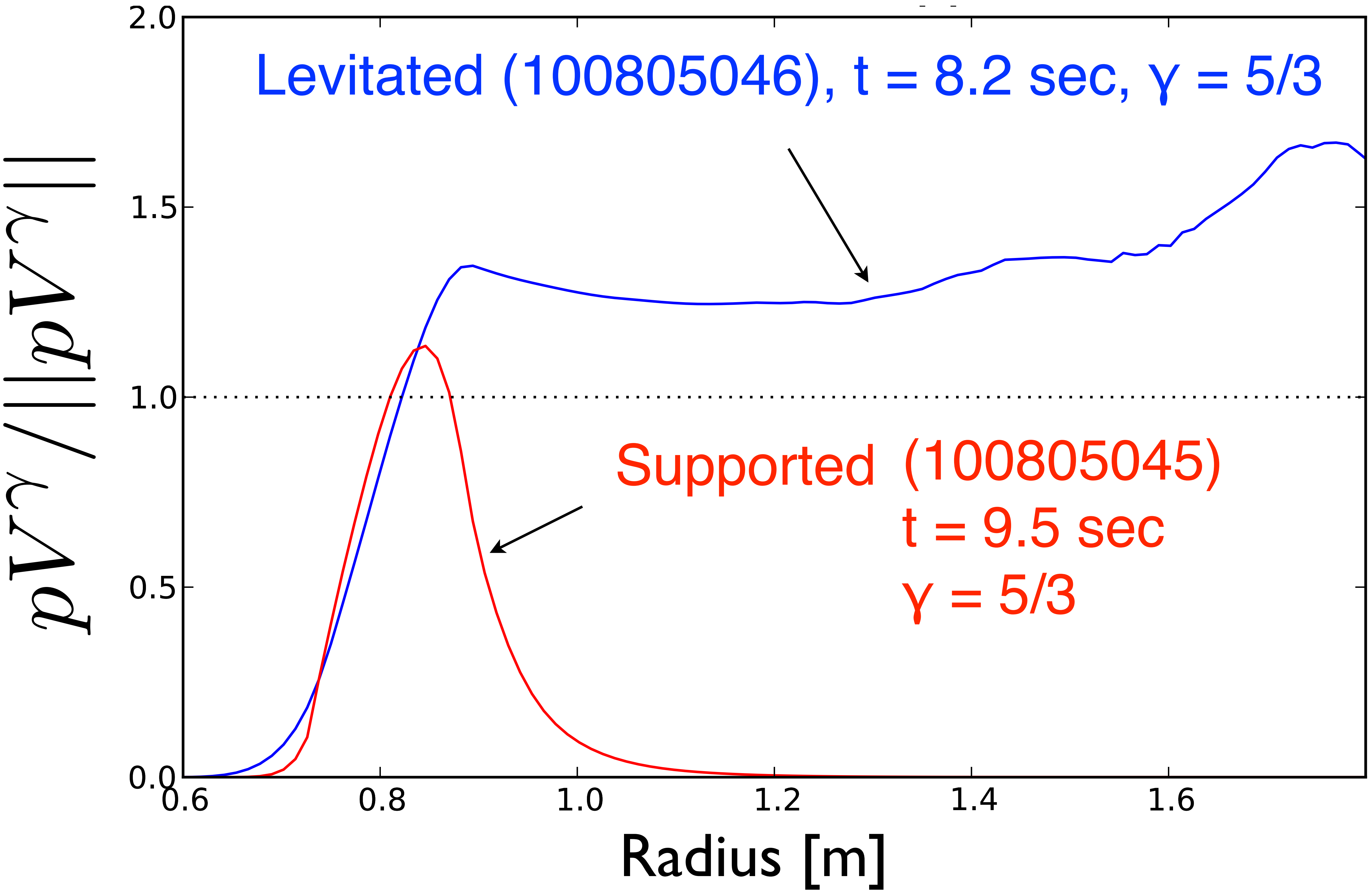
3 kA

Reconstruction Results in Very Good Accuracy of Pressure Profile

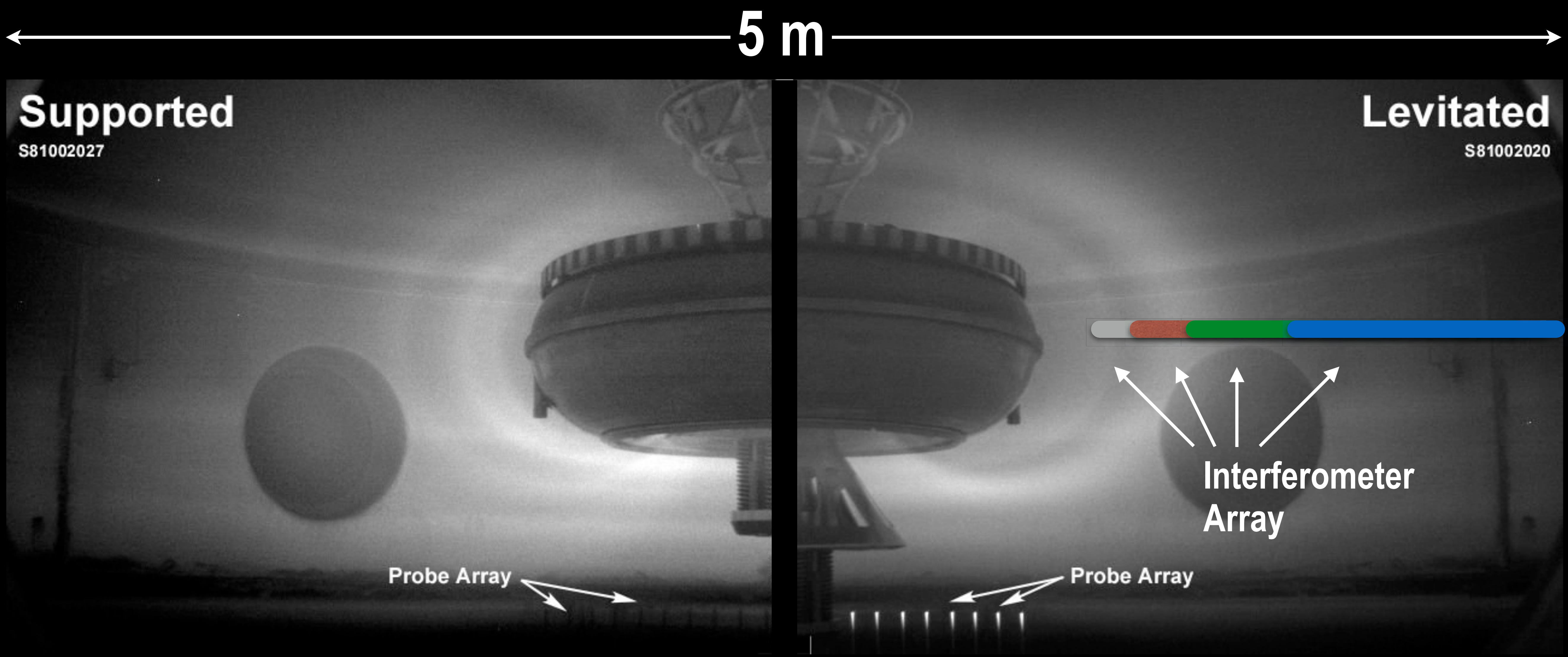


$$P_{||} \approx P_\perp$$

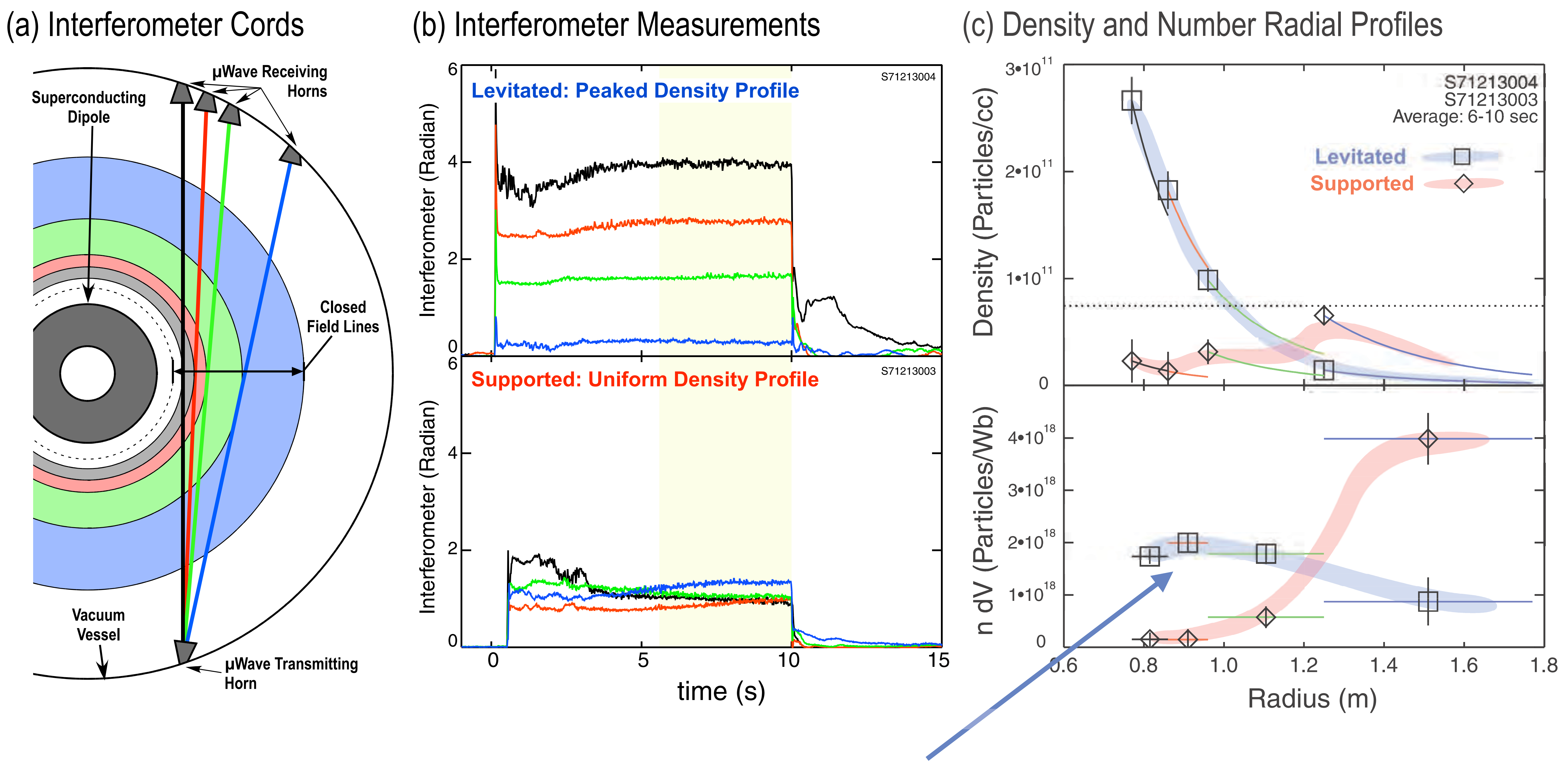
“Canonical” Profile: $\delta(PV^{\gamma}) \approx 0$



Measurement of Density Profile with Interferometry

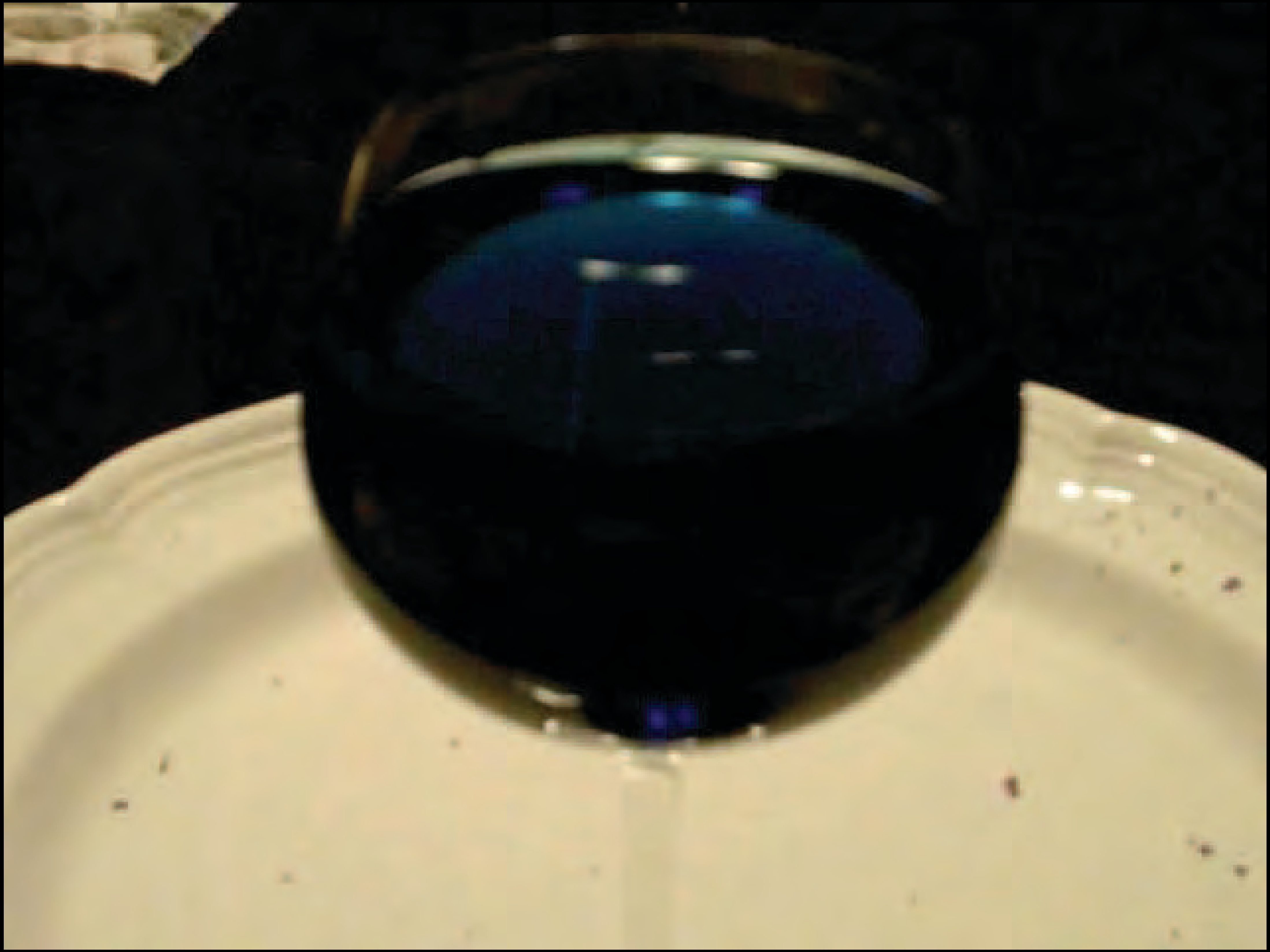


Measurement of Density Profile with Interferometry Show Equal Particle Number per Unit Magnetic Flux



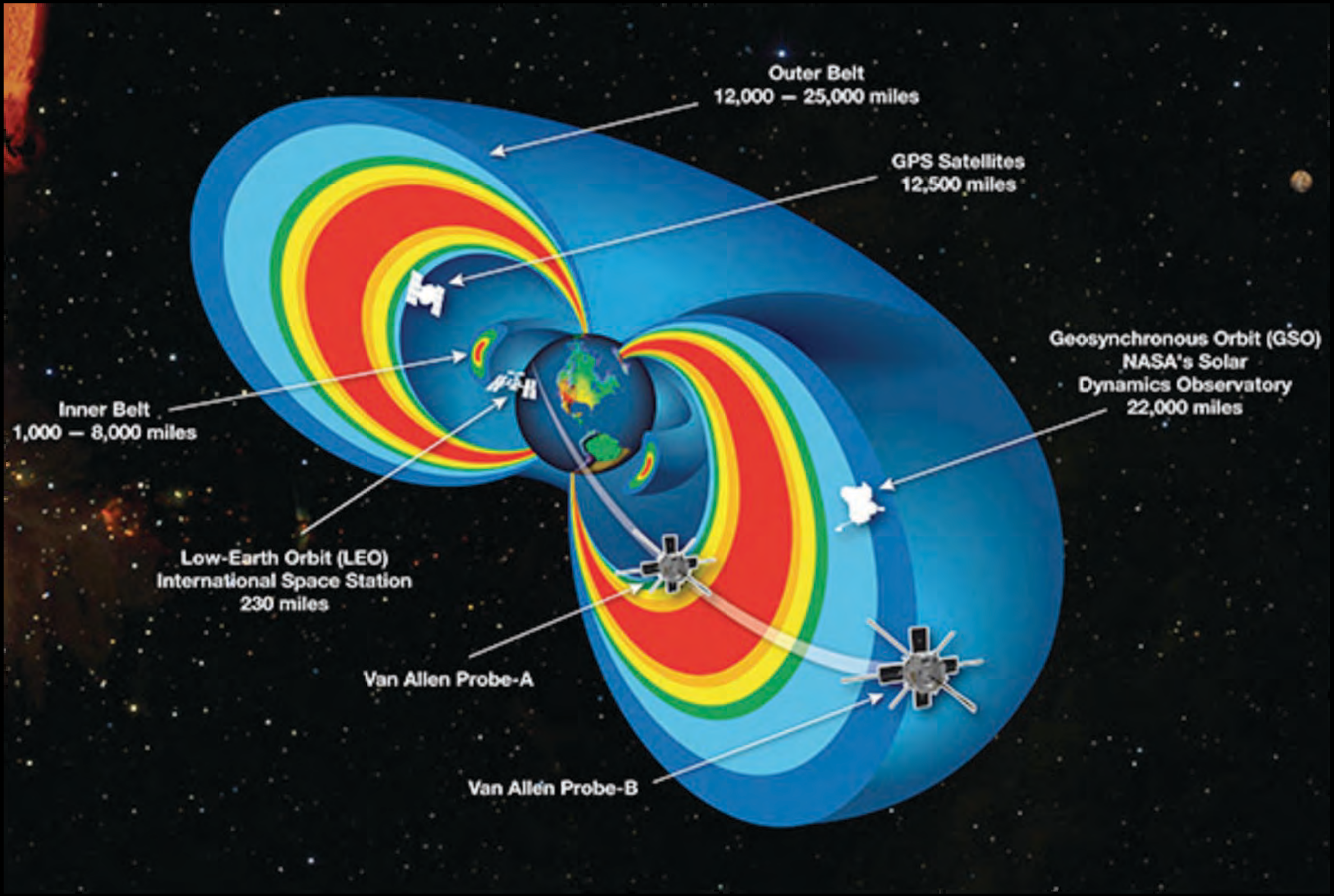
“Canonical” Profile: $\delta(nV) \approx 0$

Self-Organized Mixing: Dye Stirred in Glass



Our Space Environment is Complex and Highly Variable

With Concurrent Plasma Processes and Important Questions to Answer



Van Allen Probes (A&B) Launched August 2012

Discovered **New** 3rd Radiation Belt (2 MeV e^-) then annihilated by passage of interplanetary shock

ScienceExpress, Baker, *et al.*, 28 Feb 2013

JOURNAL OF GEOPHYSICAL RESEARCH, SPACE PHYSICS VOL. 74, NO. 9, MAY 1, 1969

Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation

THOMAS J. BIRMINGHAM

E×B

$$\left\{ \dot{\psi} = \nabla\psi \cdot \mathbf{V} = \frac{\partial \Phi}{\partial \varphi} = -RE_\varphi \right.$$

Diffusion Coefficient

$$\left\{ \begin{aligned} D_\psi &= \lim_{t\to\infty} \int_0^t dt \, \langle \dot{\psi}(t)\dot{\psi}(0) \rangle \equiv \langle \dot{\psi}^2 \rangle \tau_c \\ &= R^2 \langle E_\varphi^2 \rangle \tau_c \end{aligned} \right.$$

Adiabatic Radial Transport

$$\left\{ \frac{\partial F}{\partial t} = S + \frac{\partial}{\partial \psi}\bigg|_{\mu,J} D_\psi(\mu,\, J)\, \frac{\partial F}{\partial \psi}\bigg|_{\mu,J} \right.$$

Collisionless Radiation Belt Particles

NORAD OV3-4 (1966) validated physics of inward pinch and adiabatic heating of drift-resonant radiation belt particles. Farley, *et al.*, *Phys. Rev. Lett.*, 1970

INNER MAGNETOSPHERIC MODELING WITH THE RICE CONVECTION MODEL

FRANK TOFFOLETTO, STANISLAV SAZYKIN, ROBERT SPIRO and RICHARD WOLF

Department of Physics and Astronomy, Rice University, Houston, TX 77005, U.S.A.

Semi-collisional Plasmasphere and Ring Current

TABLE I

Comparison of equations of ideal MHD with those used in the RCM

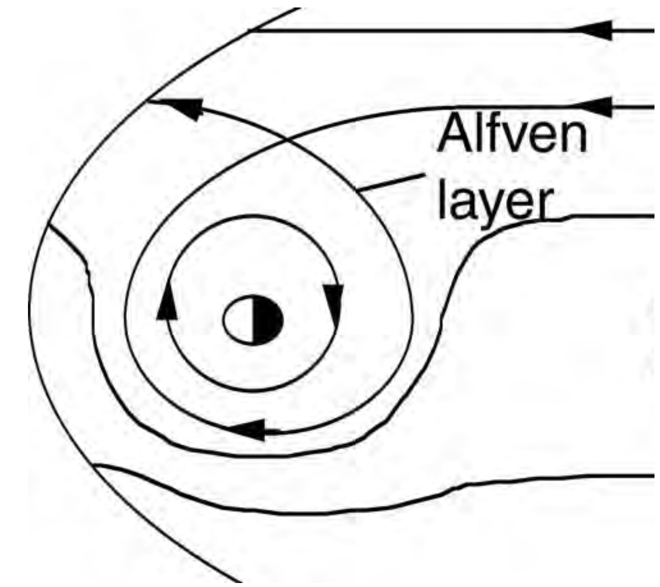
Ideal MHD	RCM
$\frac{\partial\rho}{\partial t} \quad \nabla \quad \rho v / \quad 0$	$\frac{\partial}{\partial t} \quad \vec{v}_k \ \lambda_k \ \vec{x} \ t / \ \nabla / \eta_k \quad S \ \eta_k / - L \ \eta_k /$
$\frac{\partial}{\partial t} \quad \vec{v} \quad \nabla / \ \rho \vec{v} / \quad \vec{j} \times \vec{B} - \nabla P$	$\vec{j}_k \times \vec{B} \quad \nabla P_k$
$\frac{\partial}{\partial t} \quad \vec{v} \quad \nabla / \ P \rho^{-5 \ 3} / \quad 0$	$P \quad \frac{2}{3} \sum_k \eta_k \lambda_k V^{-5 \ 3} \quad \lambda_k \quad constant$
$\nabla \quad \vec{B} \quad 0$	Part of the magnetic field model.
$\nabla \times \vec{B} \quad \pi_0 \vec{j}$	Included in magnetic field, but $\vec{j} \ / \ \sum_k \vec{j}_k$.
$\nabla \times \vec{E} \quad -\frac{\partial \vec{B}}{\partial t}$	Included implicitly in mapping.
$\vec{E} \quad \vec{v} \times \vec{B} \quad 0$	$\vec{E} \quad \vec{B} \quad 0$ and $\vec{E}_\perp \quad \vec{v}_k \times \vec{B} \quad \frac{\nabla W \ \lambda k \ \vec{x} \ t /}{q_k}$

For each species and invariant energy λ, η is conserved along a drift path.

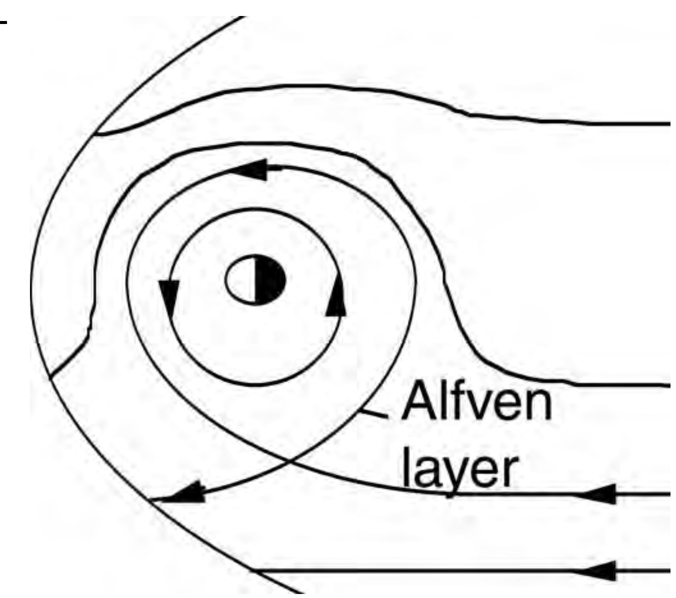
Specific Entropy

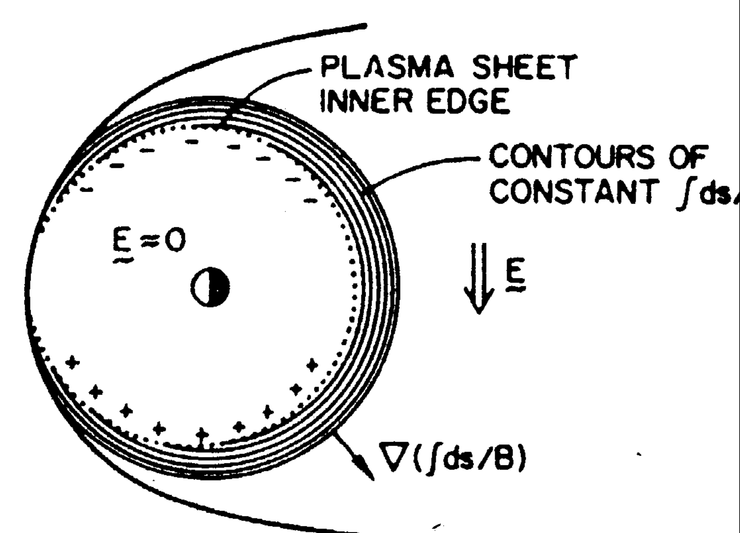
$$pV^{\gamma} = \frac{2}{3}\sum_s |\lambda_s| \eta_s$$

Ions



Electrons





Space Science Reviews **107:** 175–196, 2003.

Bounce-Averaged Turbulent Mixing in Toroidal Laboratory Plasmas

For isentropic mixing and when the turbulent spectrum is sufficiently broad to interact (nearly equally) with all particles, independent of energy and pitch-angle, the curvature pinch dominates.

***Diffusion of flux-tube particle number*, *nδV*, …**

$$\frac{\partial(\bar{n}\delta V)}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D_\psi \frac{\partial(\bar{n}\delta V)}{\partial \psi}$$

$$= \langle S \rangle + \frac{\partial}{\partial \psi} \left[\underbrace{D_\psi \delta V}_{\text{Diffusion}} \frac{\partial \bar{n}}{\partial \psi} + \bar{n} \underbrace{D_\psi \frac{\partial \delta V}{\partial \psi}}_{\text{Pinch Velocity}} \right]$$

Diffusion of Energy/Entropy, $P\delta V^\gamma$, …

$$\frac{\partial(\bar{P}\delta V^\gamma)}{\partial t} = \langle H \rangle + \frac{\partial}{\partial \psi} D_\psi \frac{\partial(\bar{P}\delta V^\gamma)}{\partial \psi}$$

"Canonical" Profiles of Magnetized Plasma

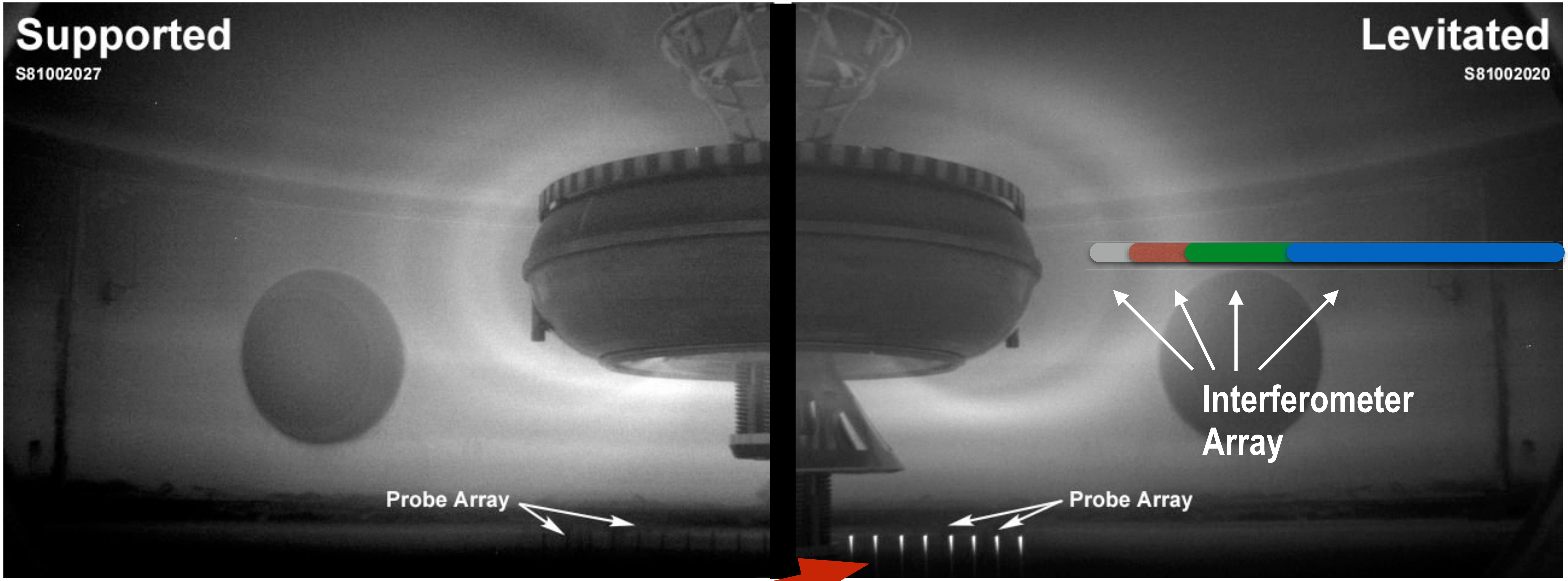
$$\delta(nV) \approx 0 \quad \& \quad \delta(PV^{\gamma}) \approx 0$$

- Low frequency fluctuations in strongly magnetized plasma, $\omega_d \sim \omega << \omega_b << \omega_c$, conserve *energy* or *Lagrangian invariants* of the flow.
- **Turbulent mixing across flux tube volumes "self organizes"** magnetized plasma to **canonical profiles**, which are nearly stationary $\delta(nV) \approx 0$ and $\delta(PV^{\gamma}) \approx 0$.
- **Flux-tube geometry** determines curvature diffusive & pinch terms in coordinate-space.
- **Space (*i.e.* Dipole) geometry**:
  - ➡ Birmingham, *J. Geophysical Res.*, 1969
  - Harel, Wolf, *et al., J. Geophys. Res.*, 1981
  - Kobayashi, Rogers, and Dorland, *Phys. Rev. Lett.*, 2010
  - Kesner, *et al., Plasma Phys. Control. Fusion*, 2010; Kesner, *et al.*, *Phys. Plasmas*, 2011.
- **Tokamak geometry**:
  - ➡ Coppi, *Comments Plasma Phys. Controll. Fus.,* 1980
  - Yankov, *JETP Lett.*, 1994 and Isichenko, *et al.*, *Phys. Rev. Lett., 1995*
  - Baker and Rosenbluth, *Phys. Plasmas*, 1998; Baker, *Phys. Plasmas*, 2002
  - Garbet, *et al., Phys. Plasmas,* 2005

Quantitative Verification of Turbulent Particle Pinch

*Using only **measured electric field** fluctuations,*
Space weather diffusion model is verified with levitated dipole

5 m



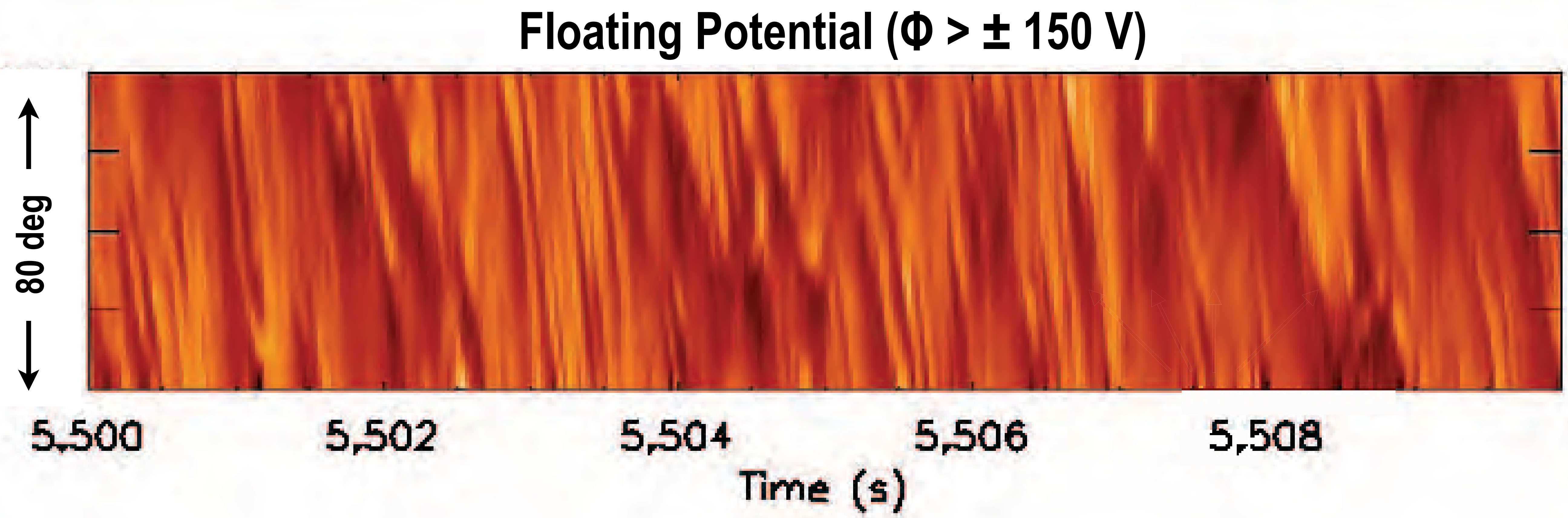
Edge Probe Array:

$$D = \lim_{t \to \infty} \int_0^t dt \langle \dot{\psi}(t) \dot{\psi}(0) \rangle \equiv \langle \dot{\psi}^2 \rangle \tau_c$$

$$D_\psi = R^2 \langle E_\varphi^2 \rangle \tau_c$$

Quantitative Verification of Turbulent Particle Pinch

*Using only **measured electric field** fluctuations,*
Thomas Birmingham's diffusion model is verified with levitated dipole



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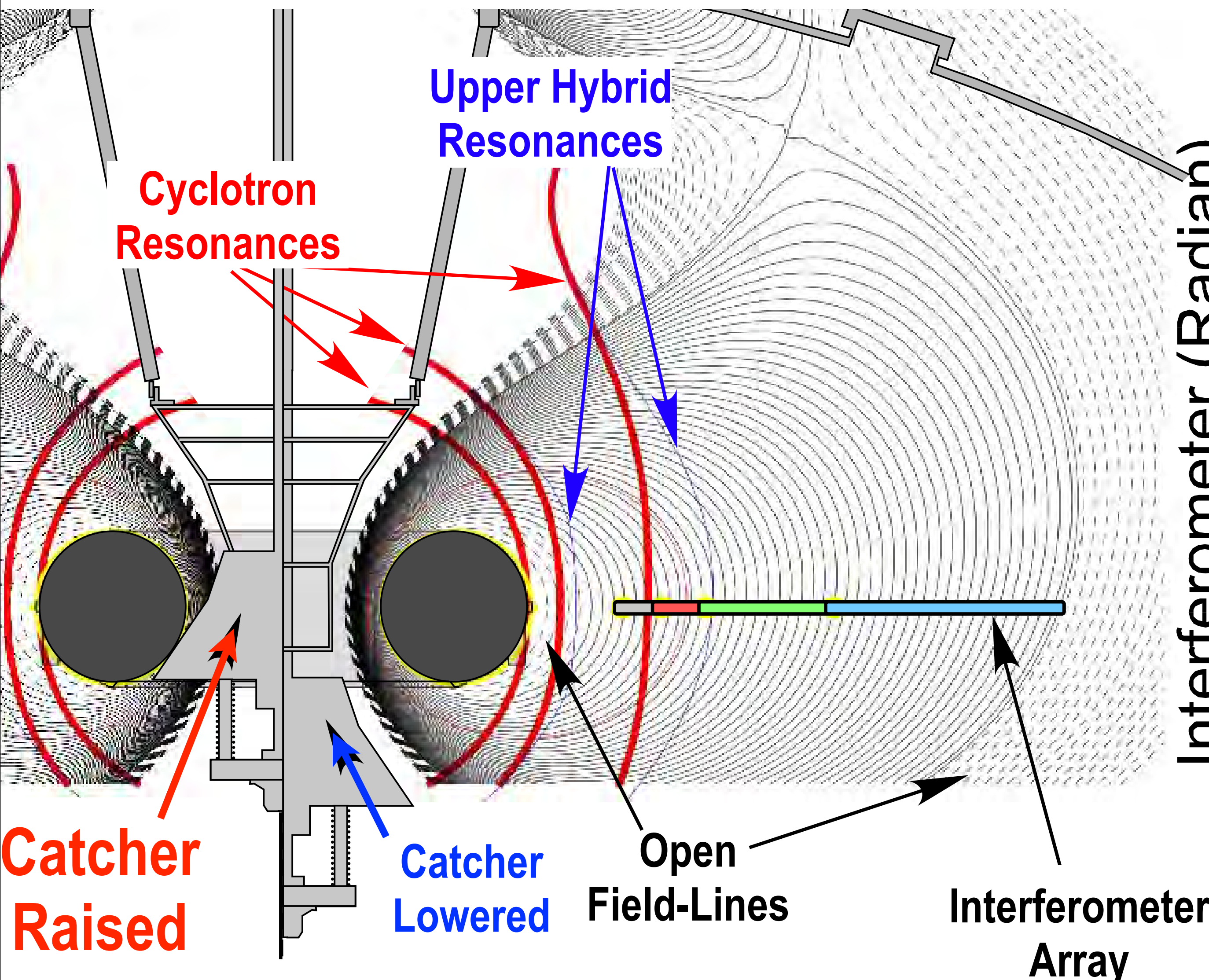
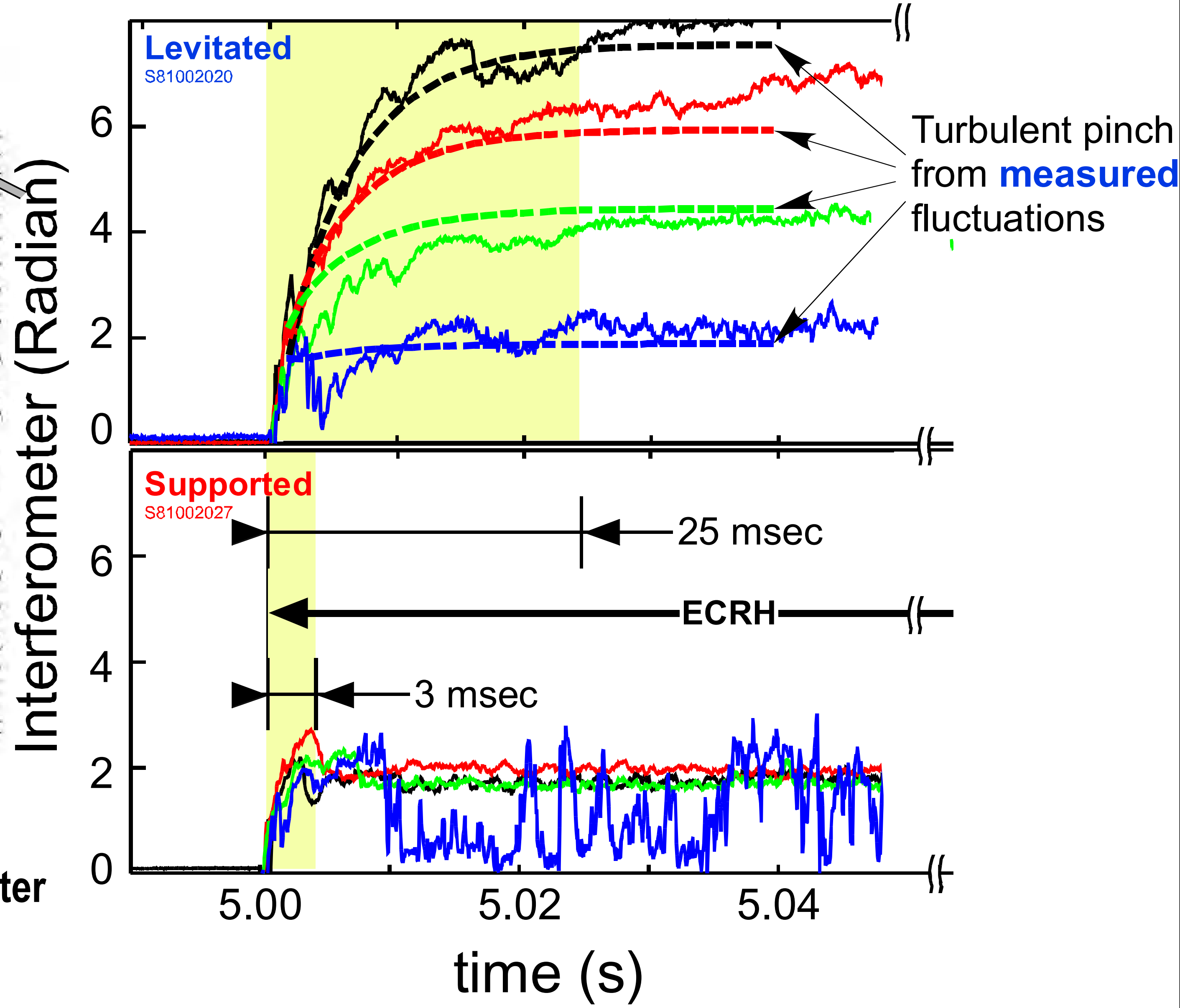
$$D_\psi = R^2 \langle E_\varphi^2 \rangle \tau_c$$

Quantitative Verification of Inward Turbulent Pinch

$$\frac{\partial(\bar{n}\delta V)}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D_\psi \frac{\partial(\bar{n}\delta V)}{\partial \psi}$$



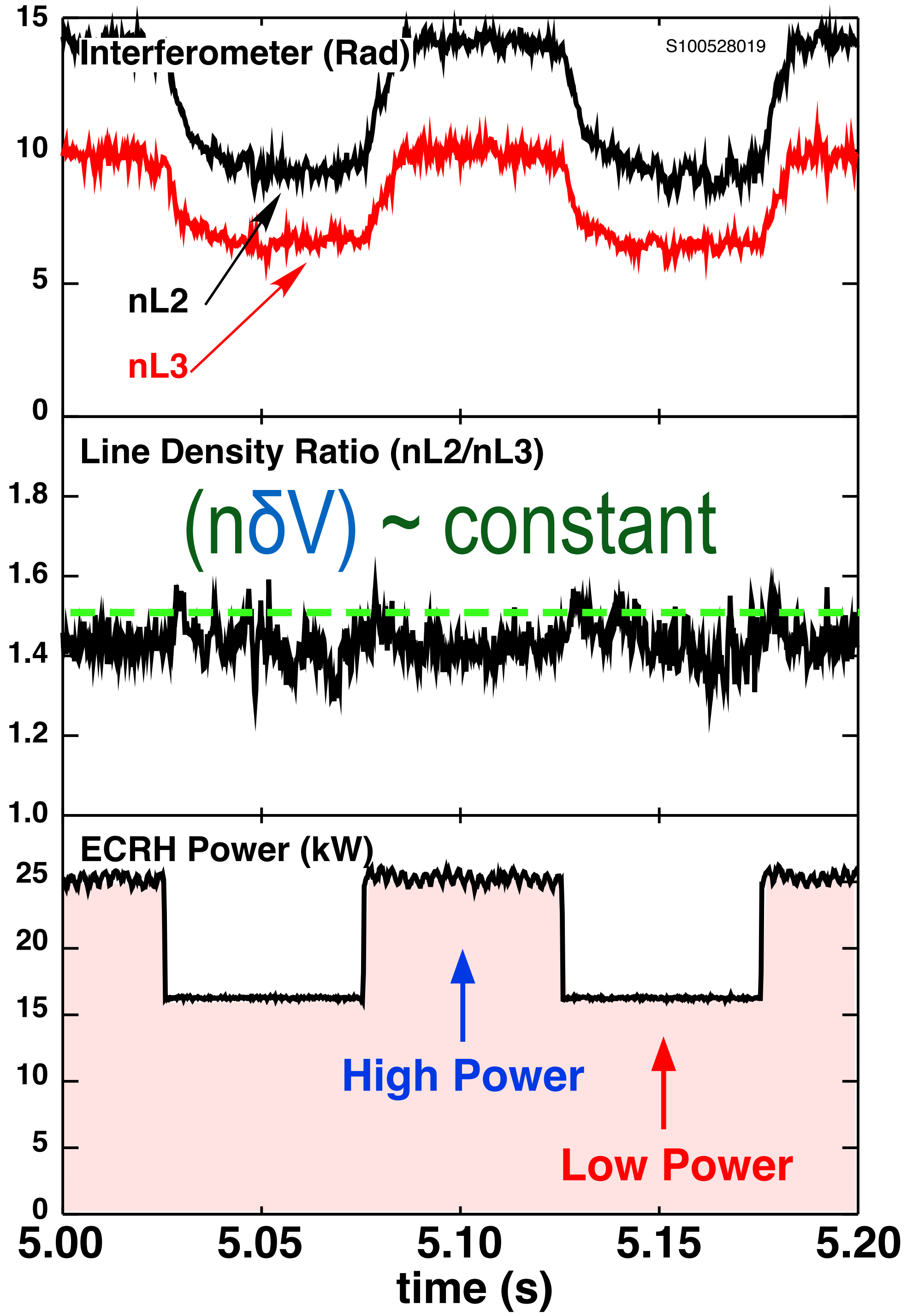
With levitated dipole, inward turbulent transport sets profile evolution

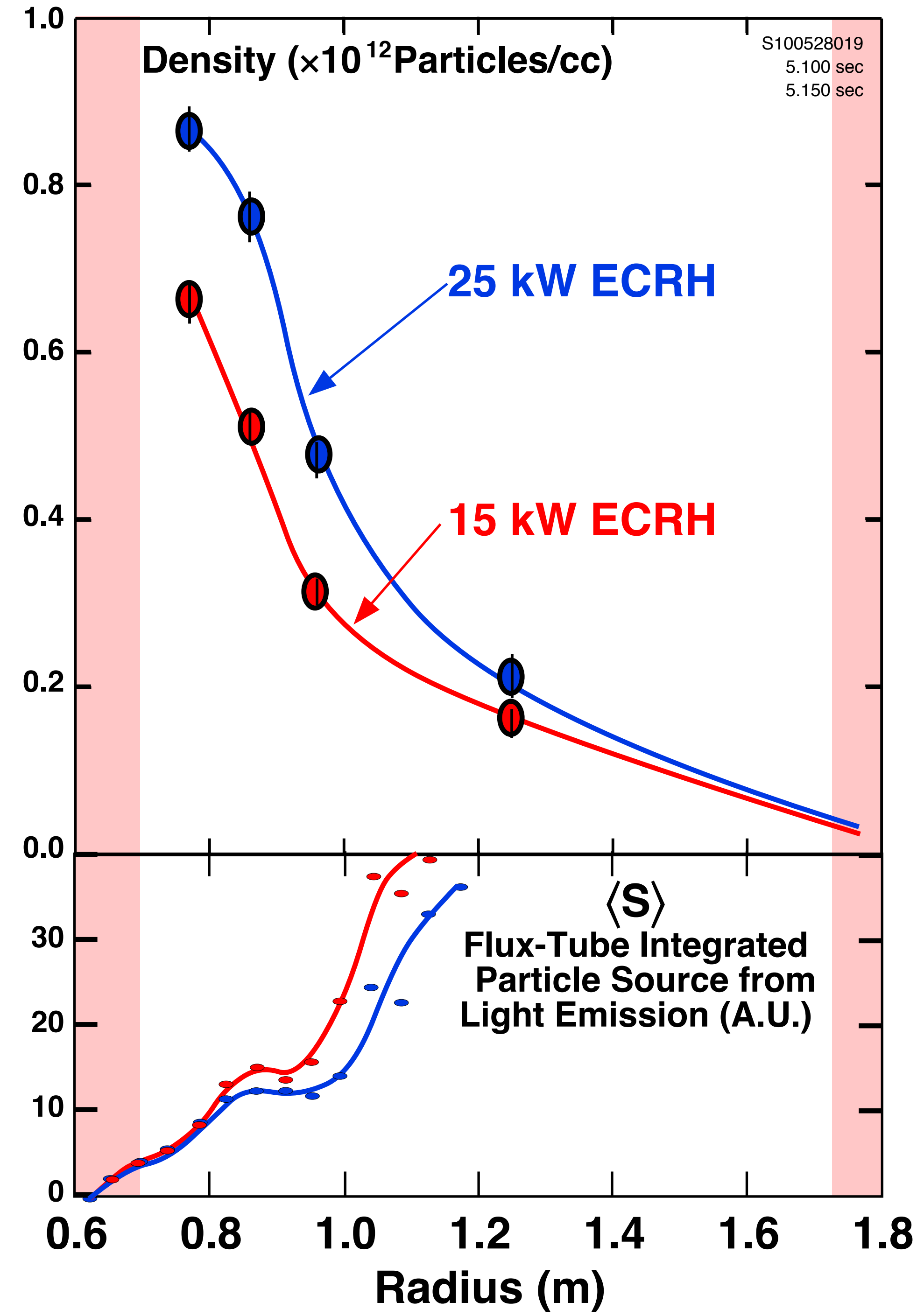


Alex Boxer, *et al.*, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nature Phys* **6**, 207 (2010).

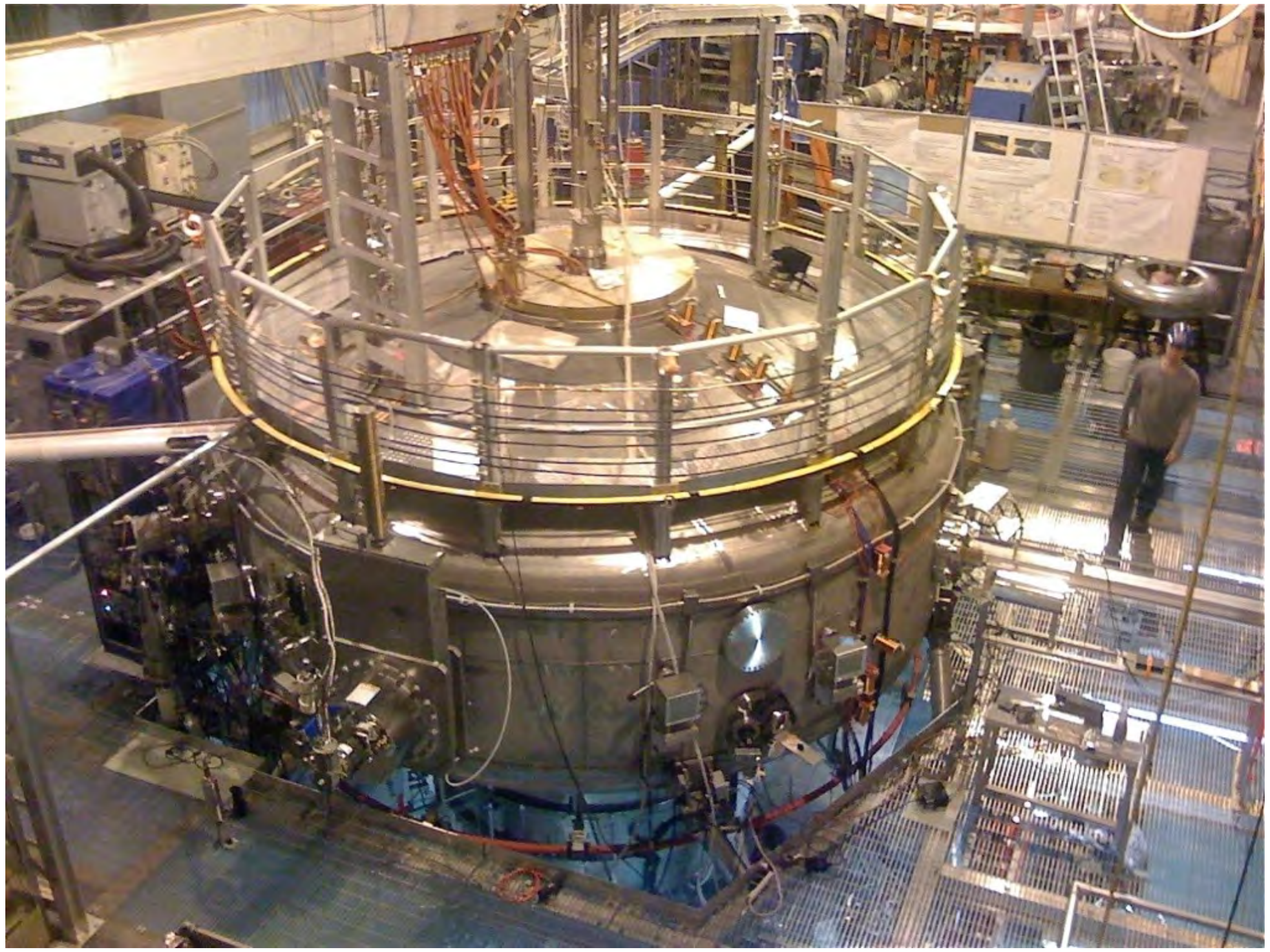
Heating or gas modulation demonstrates (**Robust**) inward pinch & **Natural** "canonical" profile

- Density increases with power (T ~ constant). Density **profile shape is unchanged** near ($n\delta V$) ~ constant.
- Gas source moves radially outward. **Inward pinch required** to increase central density.



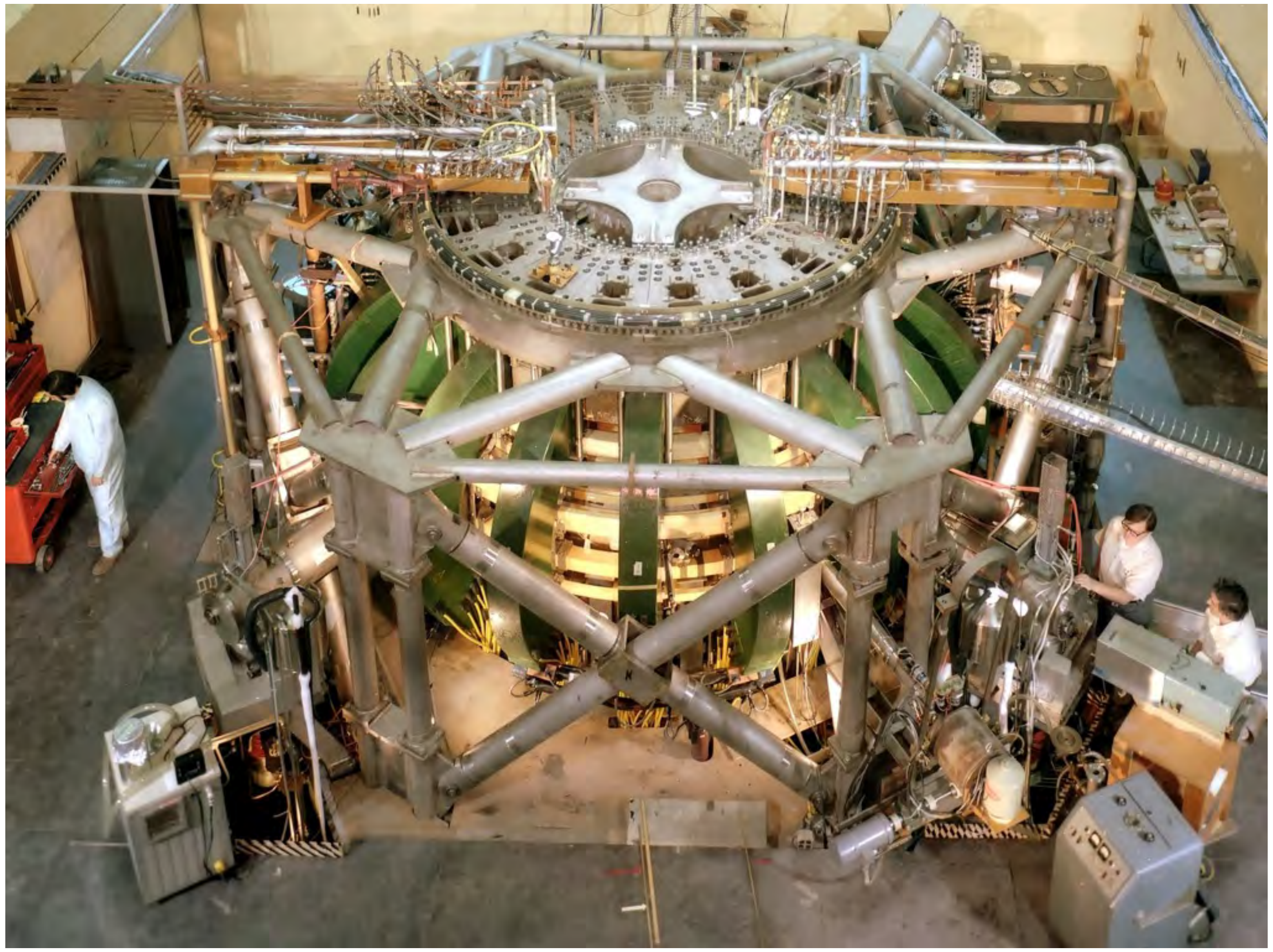


Turbulent Pinch is a Fundamental Process found in Toroidal Magnetic Systems Including Tokamaks and Planetary Magnetospheres (but, different…)



Levitated Dipole Experiment (LDX)

1.2 MA Superconducting Ring
Steady-State
25 kW ECRH
1 MW ICRF (unused)



Princeton Large Torus (PLT)

17 MA Copper Toroid
1 sec pulses
750 kW Ohmic
75 kW LHCD
2.5 MW NBI & 5 MW ICRF

A (*Historic*) Density Rise Experiment on PLT

Jim Strachan, et al., Nuc. Fusion (1982)

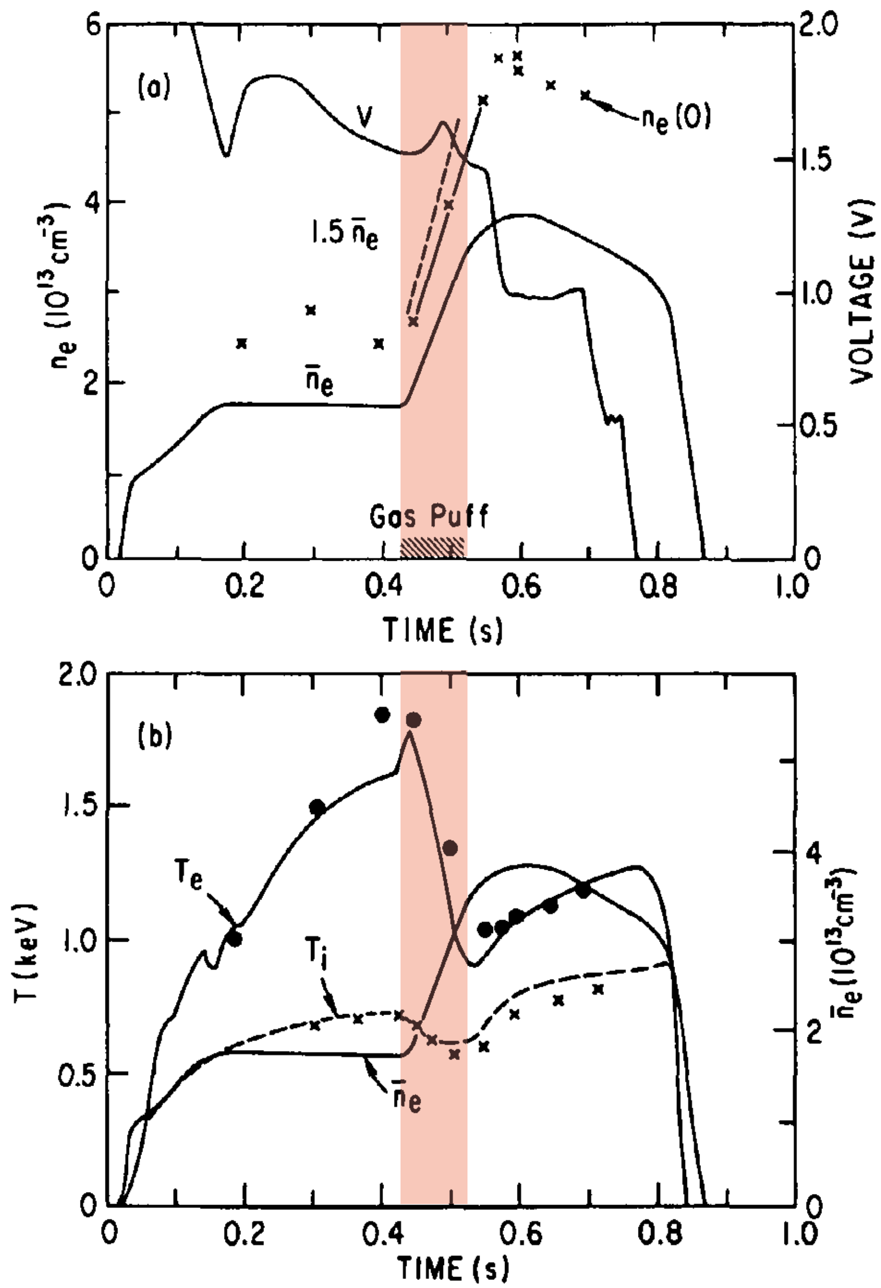
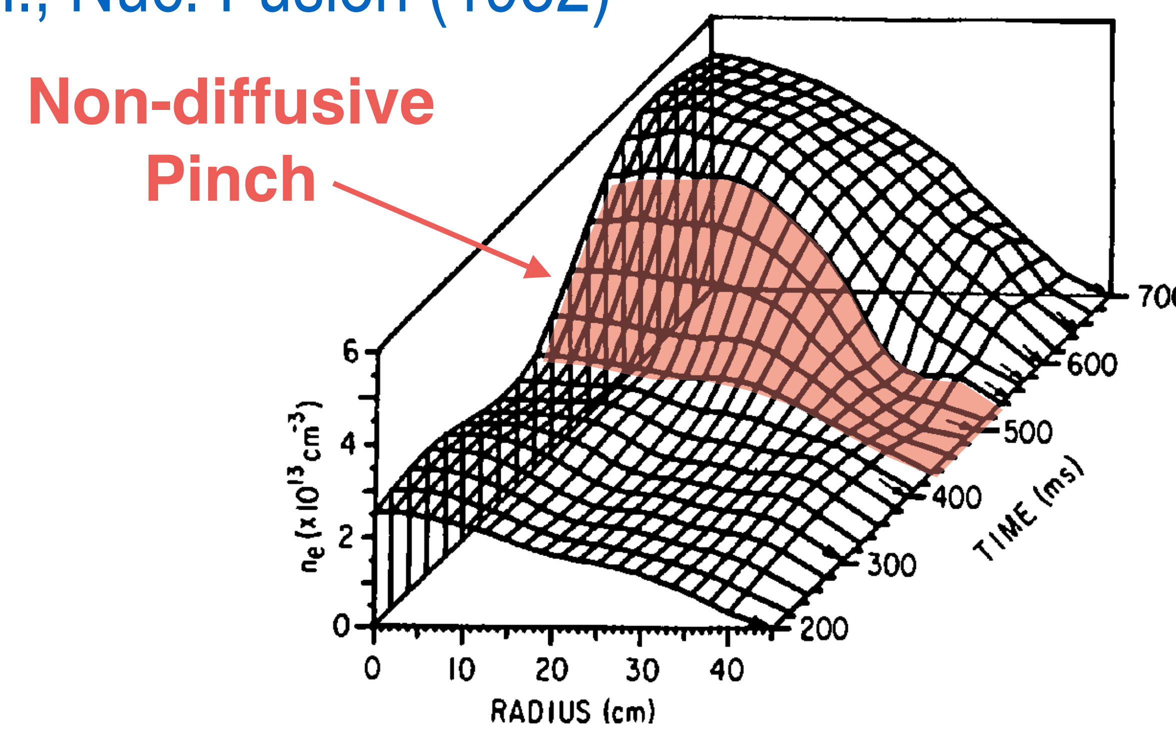
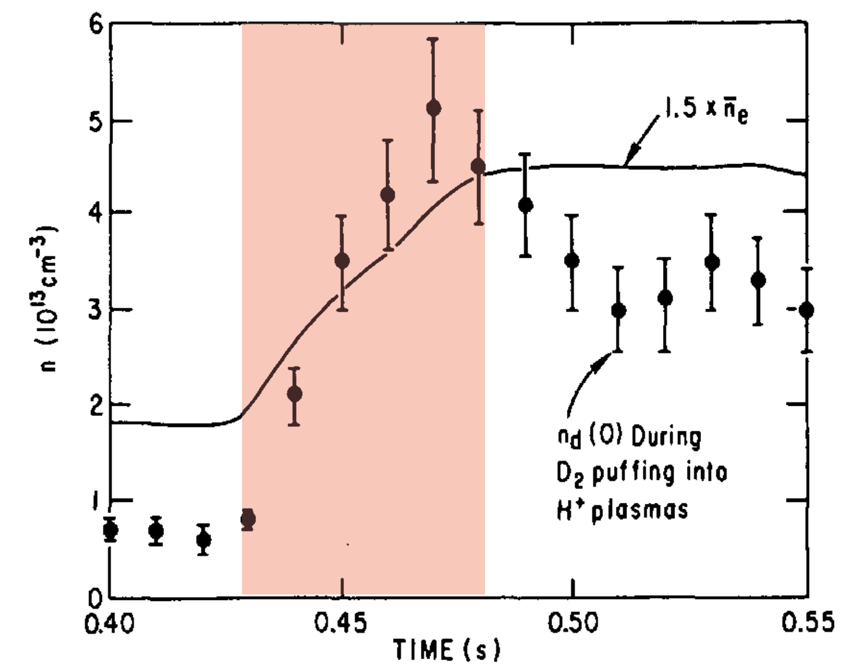


FIG.2. (a) Time evolution of the loop voltage, V, the line-average density $\bar{n}_e$, and the central electron density, $n_e(0)$ during the density rise. (b) Time evolution of the central electron temperature from $2\omega_{ce}$ (——), and from TVTS (●), with the time evolution of the central ion temperature from neutrons (- -), and from charge exchange (X) during the density rise.



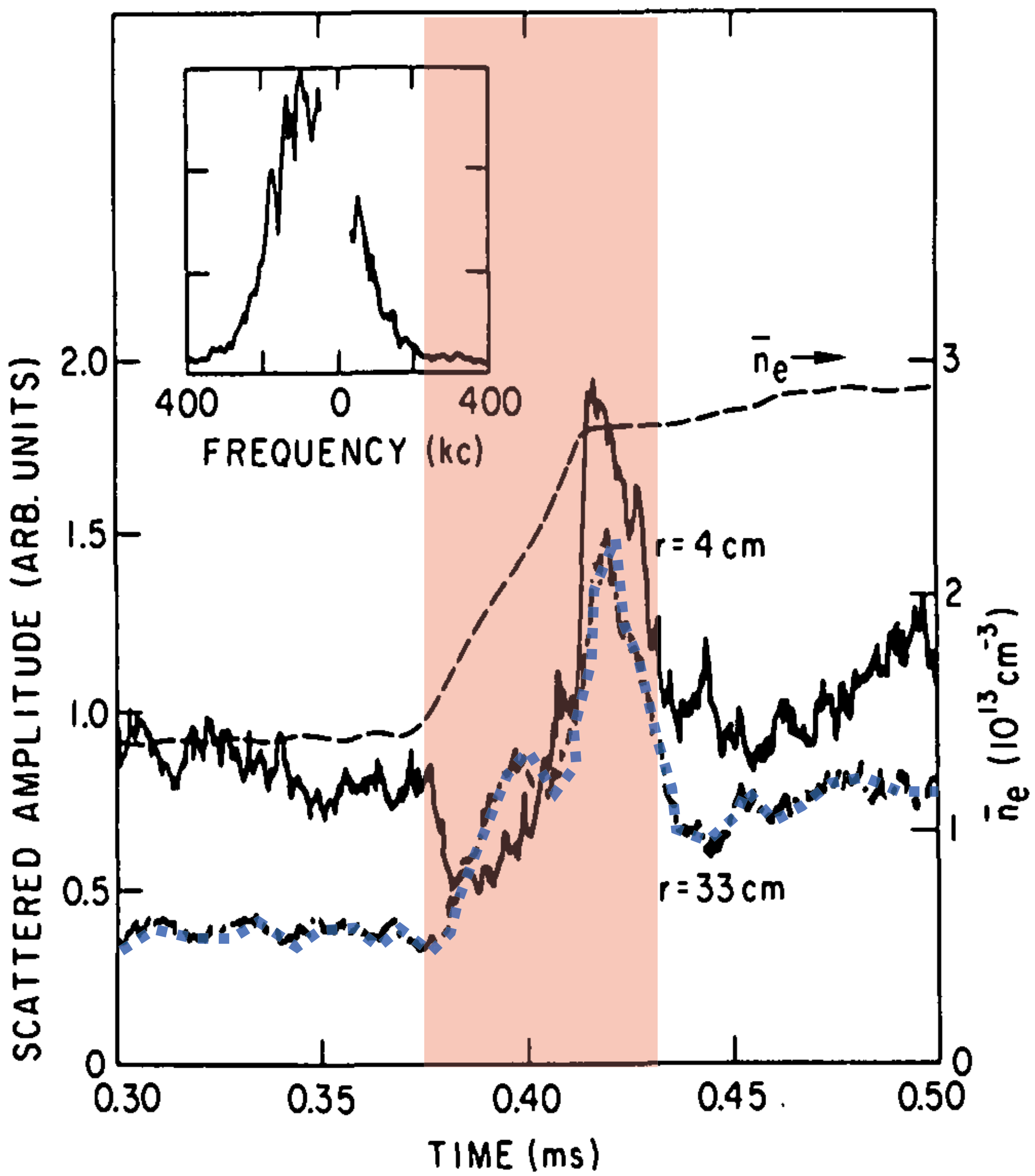


Inward Turbulent Pinch "*is necessary to model the experimental results*" of peaked density from edge gas source

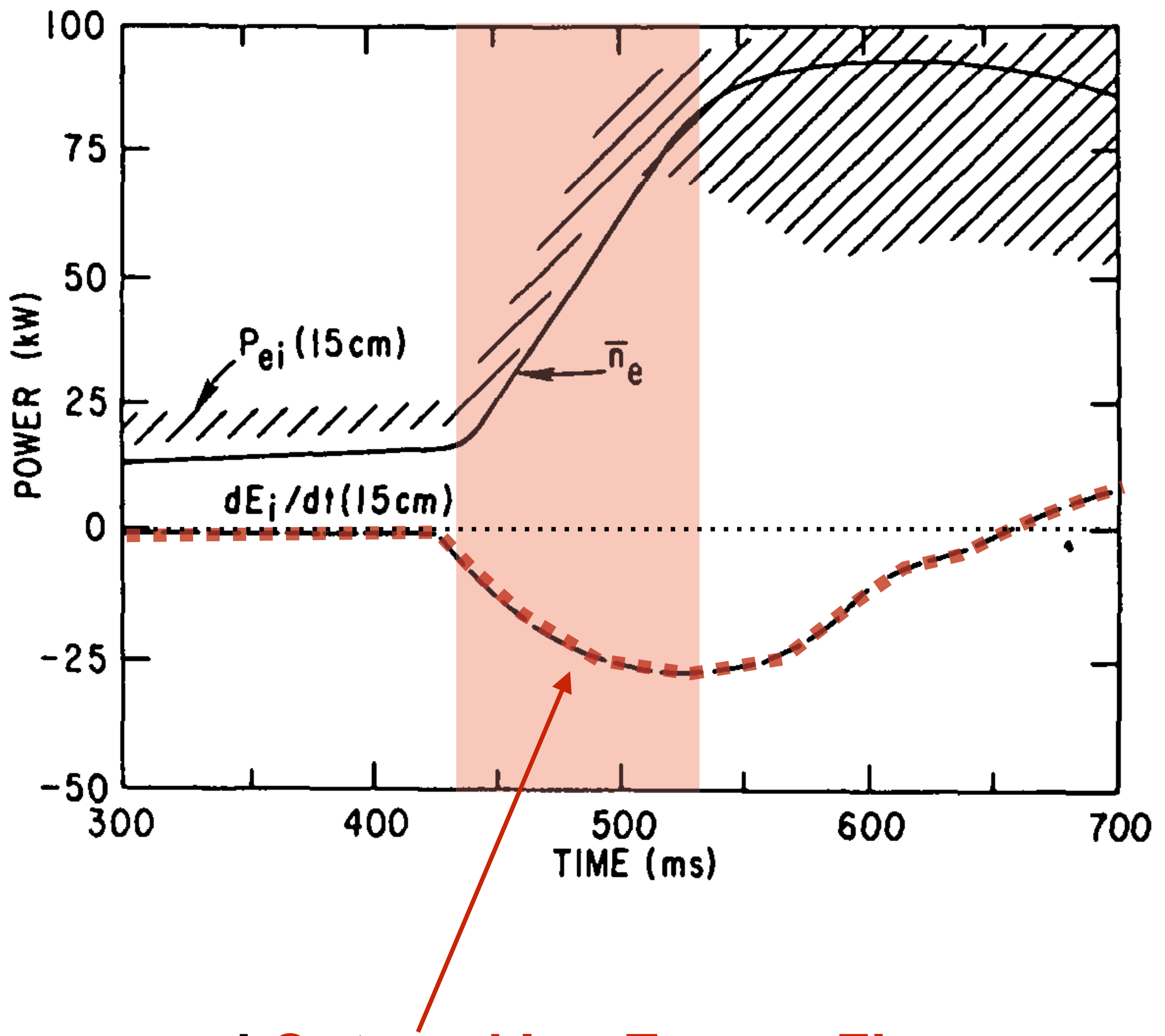
A (*Historic*) Density Rise Experiment on PLT

Jim Strachan, et al., Nuc. Fusion (1982)

Enhanced Turbulent Fluctuation Intensity…



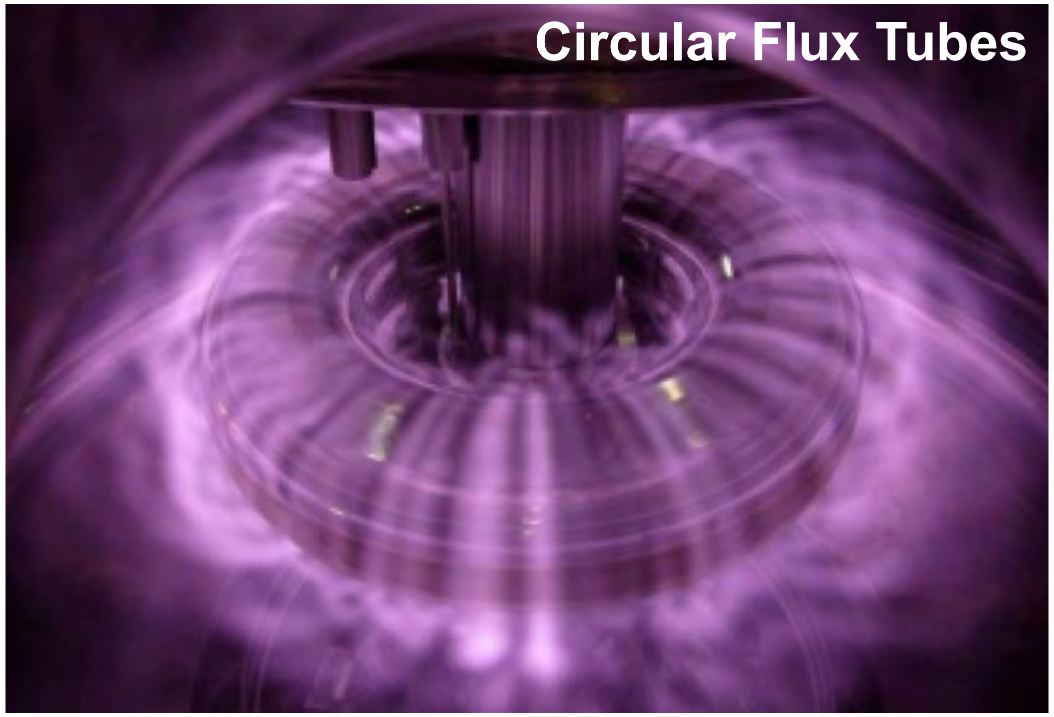
… Causing Central Ion Cooling

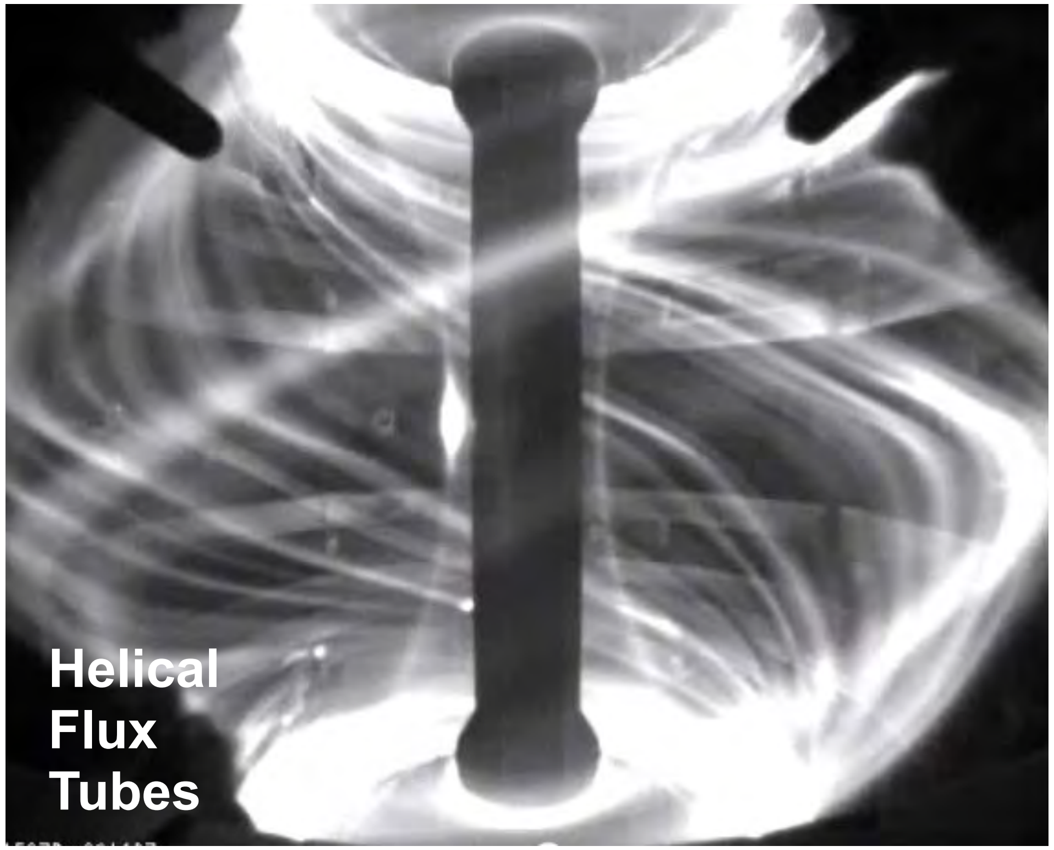


but gas puff intensifies turbulence and Outward Ion Energy Flux accompanies Inward Turbulent Particle Pinch

But, Toroidal Confinement **without Toroidal Field** is different…

- **Dipole…**
  - Interchange (***not drift-ballooning***) sets limits
  - $\beta \sim 100\%$ with $\omega^* \sim \omega_d$ (***isentropic***, $\delta(PV^\gamma) \sim 0$)
  - Flux-tubes convect globally without bending
  - No toroidally circulating particles
  - Peaked profiles with flux tube volume $\boldsymbol{\delta V \sim R^4}$
- **Tokamak…**
  - Ballooning and kinks set pressure limit
  - $\beta \sim \varepsilon/q \approx 5\%$ with $\omega^* >> \omega_d$ (***non-isentropic***)
  - Short radial scale of drift waves fluctuations
  - Passing ≠ trapped particles
  - Flat profiles with $\boldsymbol{\delta V \sim qR}$





Outline

- How does a laboratory magnetosphere work?
- Interchange disturbances and magnetic drift resonances
  - **Low frequency interchange turbulence: steady “canonical” profiles and bounce-averaged (flux-tube averaged) gyrokinetics**
  - **Three interchange instabilities: Fast drift-kinetic, centrifugal interchange, semi-collisional entropy modes**
- **Examples:** exploring plasma dynamics by injection of heat, particles, current, and magnetic perturbations by decreasing ion inertial lengths

Interchange (or Entropy) Instabilities Always Dominate Turbulent Mixing

- Familiar magnetospheric convection, *e.g.* Saturnian convection

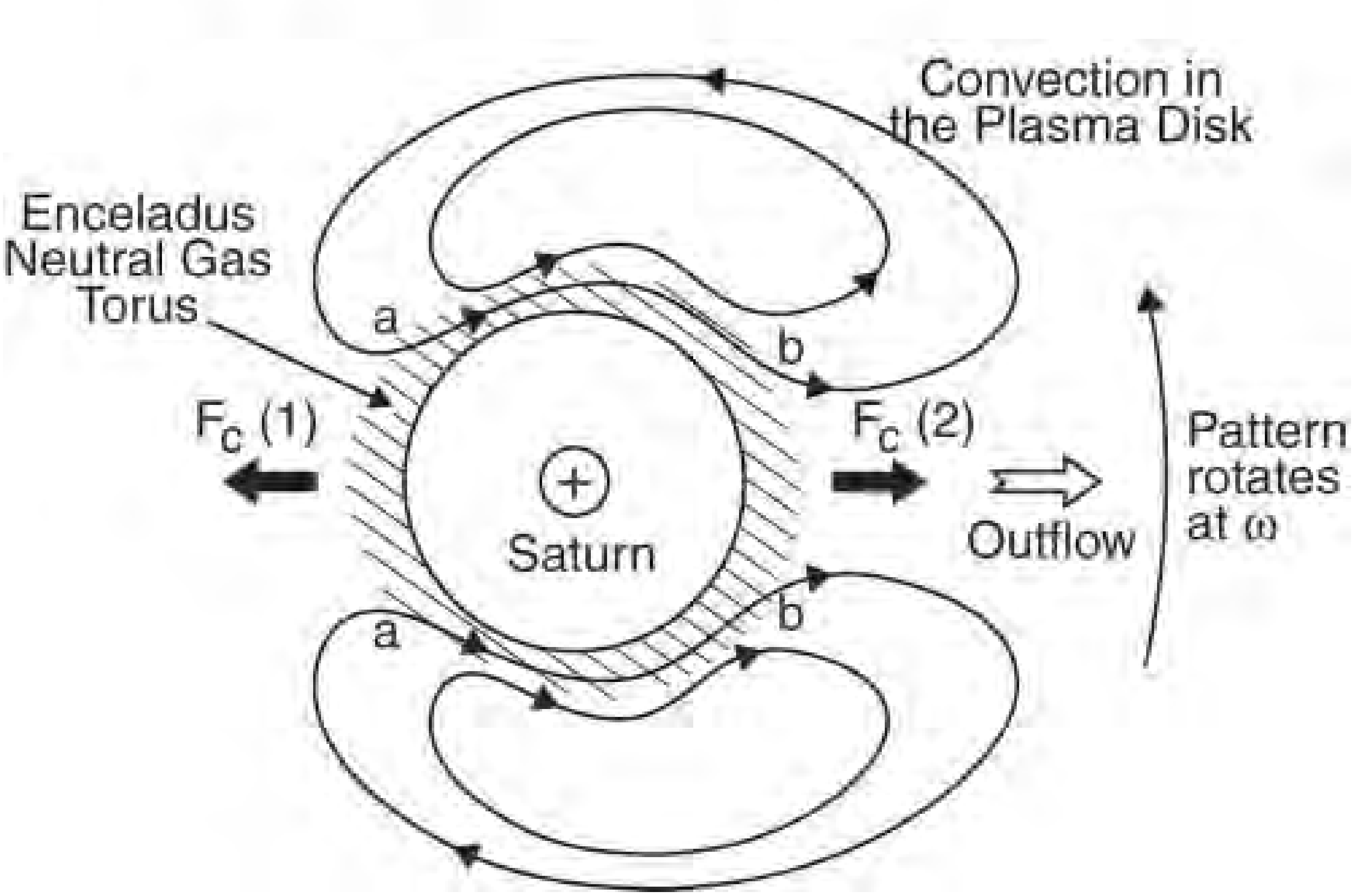
- Three modes in the laboratory with ***same global structure*** but different frequencies:

  - Fast electron gyrokinetic interchange: Collisionless ($\omega_d \tau_{col} > 10^3$) with ($\mu$, J) invariance; frequency chirping

  - Centrifugal interchange Mach ~ 1: Semi-collisional ($\Omega\ \tau_{col} \sim 1$) with (nV) invariance

  - Interchange/entropy modes: Semi-collisional ($\omega_d \tau_{col} \sim 1$) with ($PV^\gamma$) & (nV) invariance

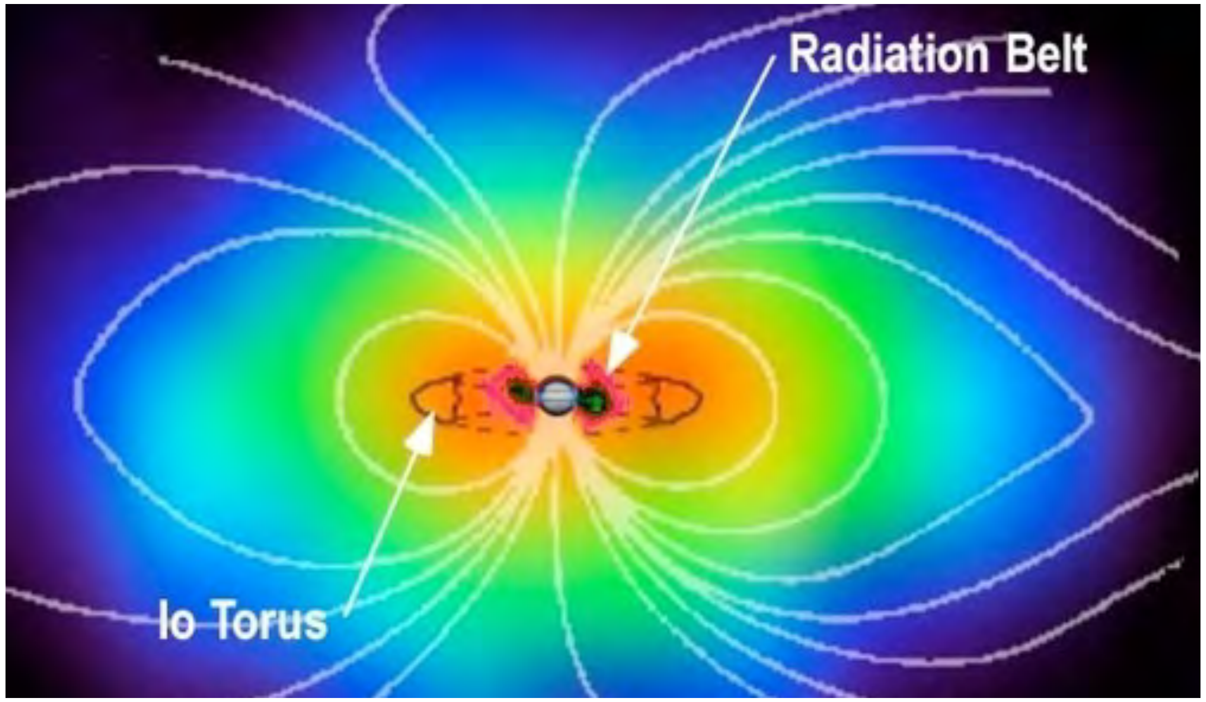
Gurnett, et al., *Science* **316**, 442 (2007)



$\delta(PV^\gamma) \sim \delta(nV) \sim 0$

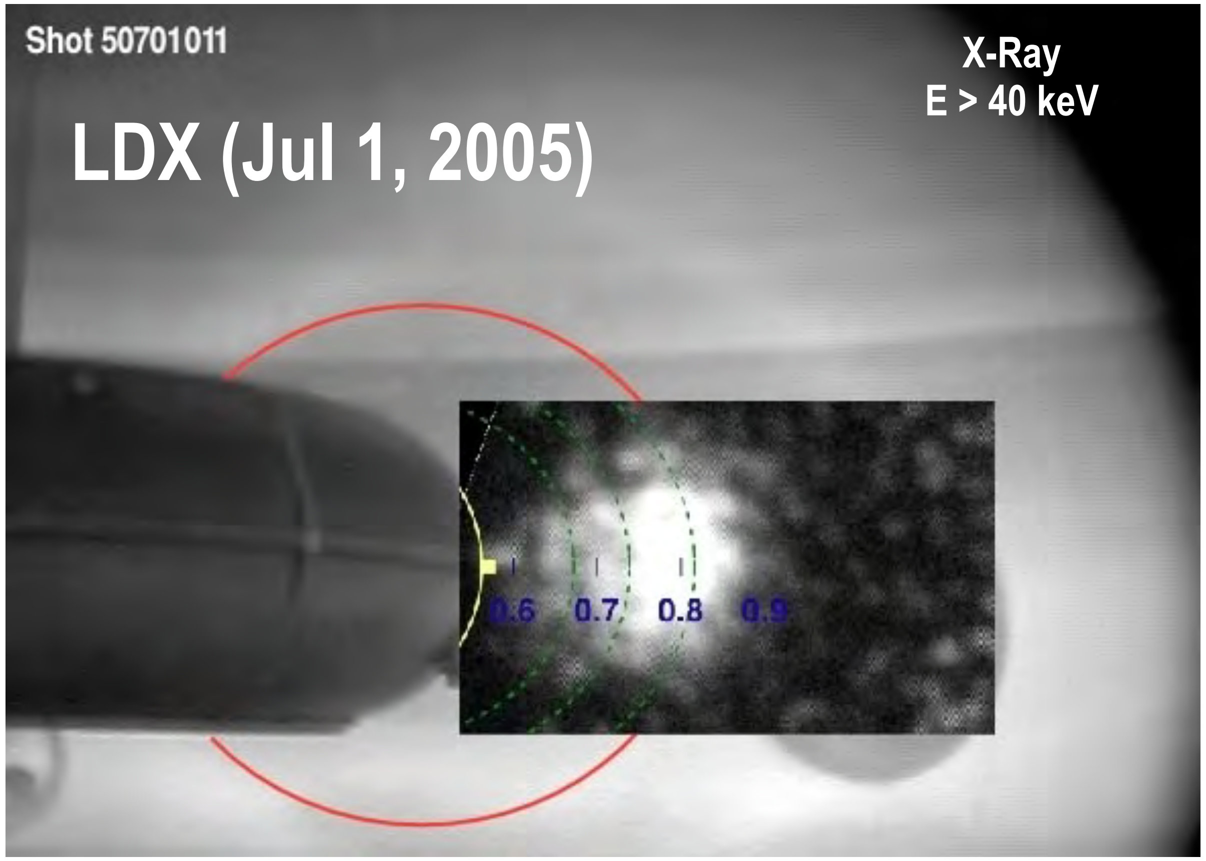
Trapped energetic particles very well confined by dipole magnetic field

Cassini at Jupiter (Dec 30, 2000)

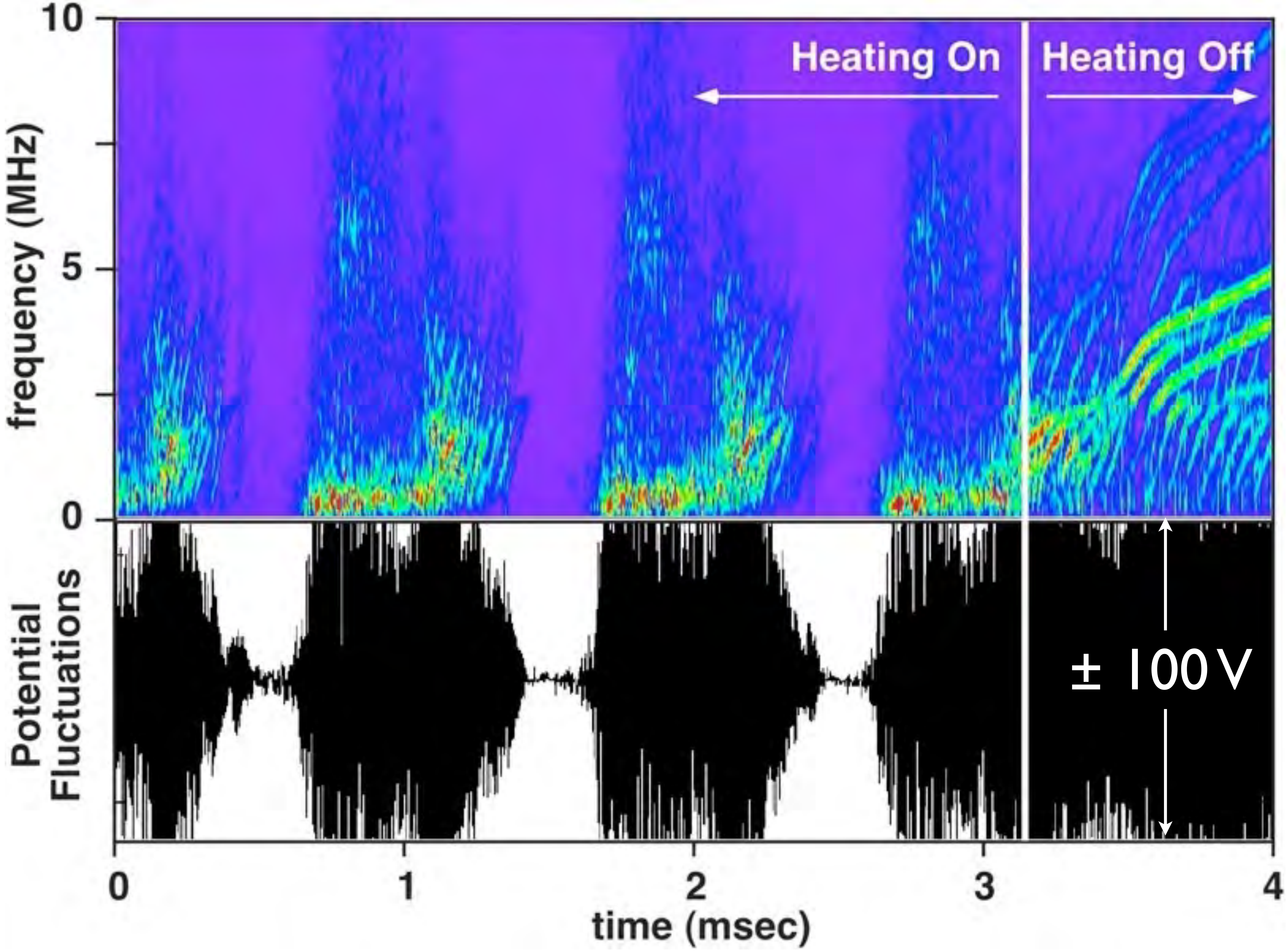


The natural high beta in planetary magnetospheres can be achieved in the laboratory. Steady-state.

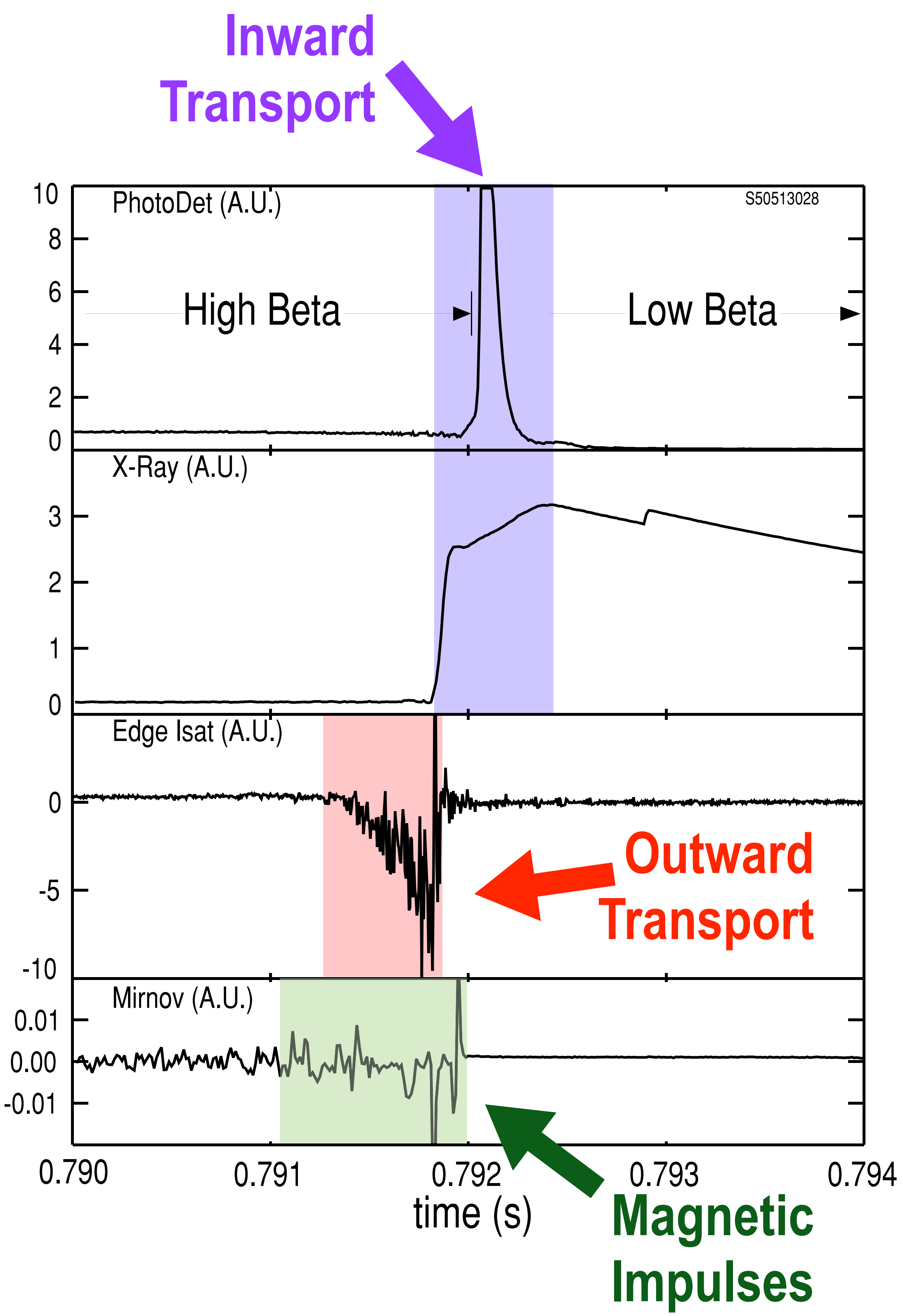
- Garnier, POP (1999) shows equilibria with $\beta > 100\%$ possible
- Garnier, POP (2006) reports peak beta 20% achieved
- Garnier, NF (2009) reports peak beta doubles with levitation
- ➡ Saitoh, JFE (2010) reports peak beta 70% achieved in RT-1



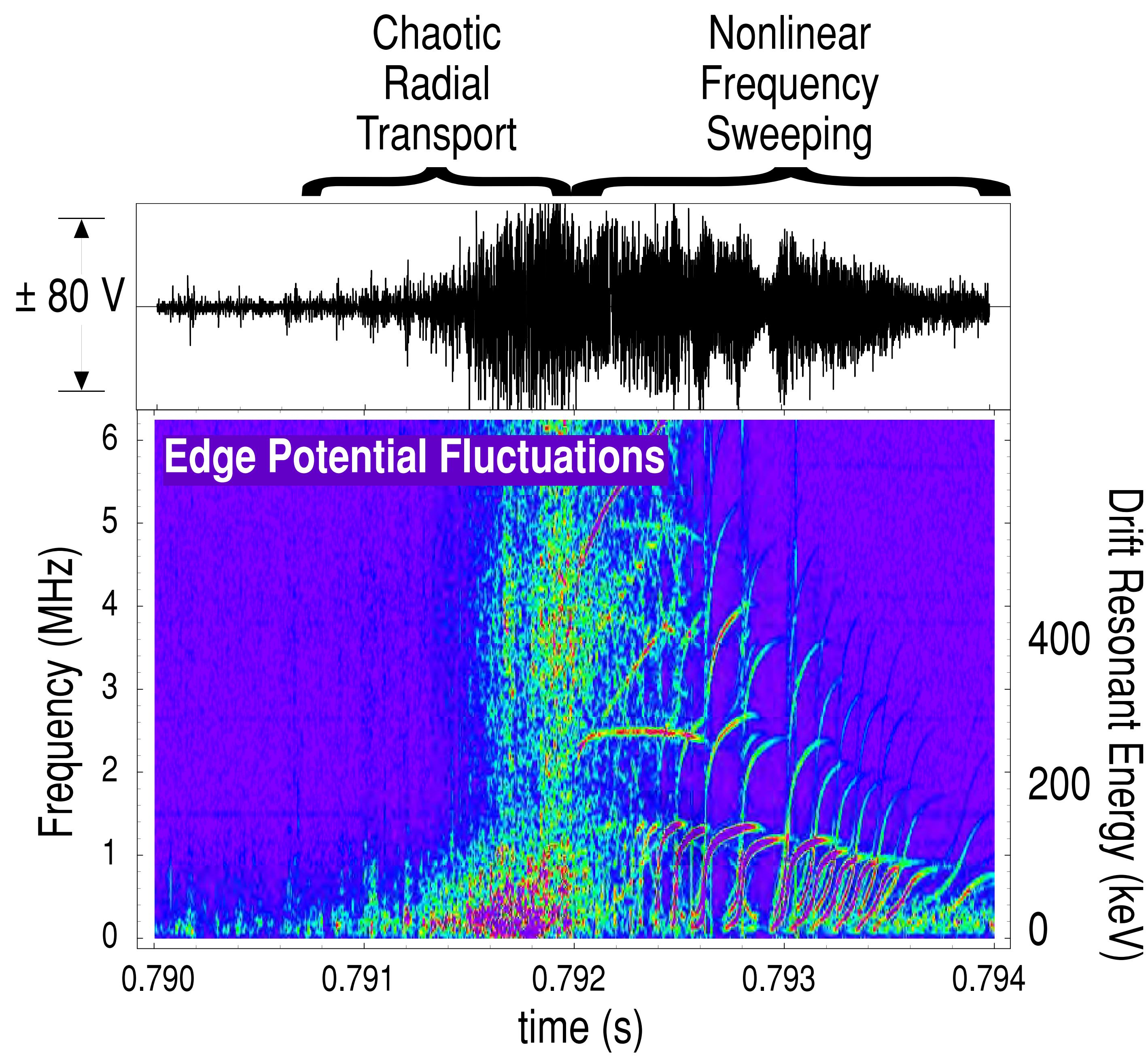
Drift-Resonant (Hot Electron) Interchange Instability



Kinetic Interchange Drift Mode can also appear in LDX with β ~ 40% "Artificial Radiation Belt"

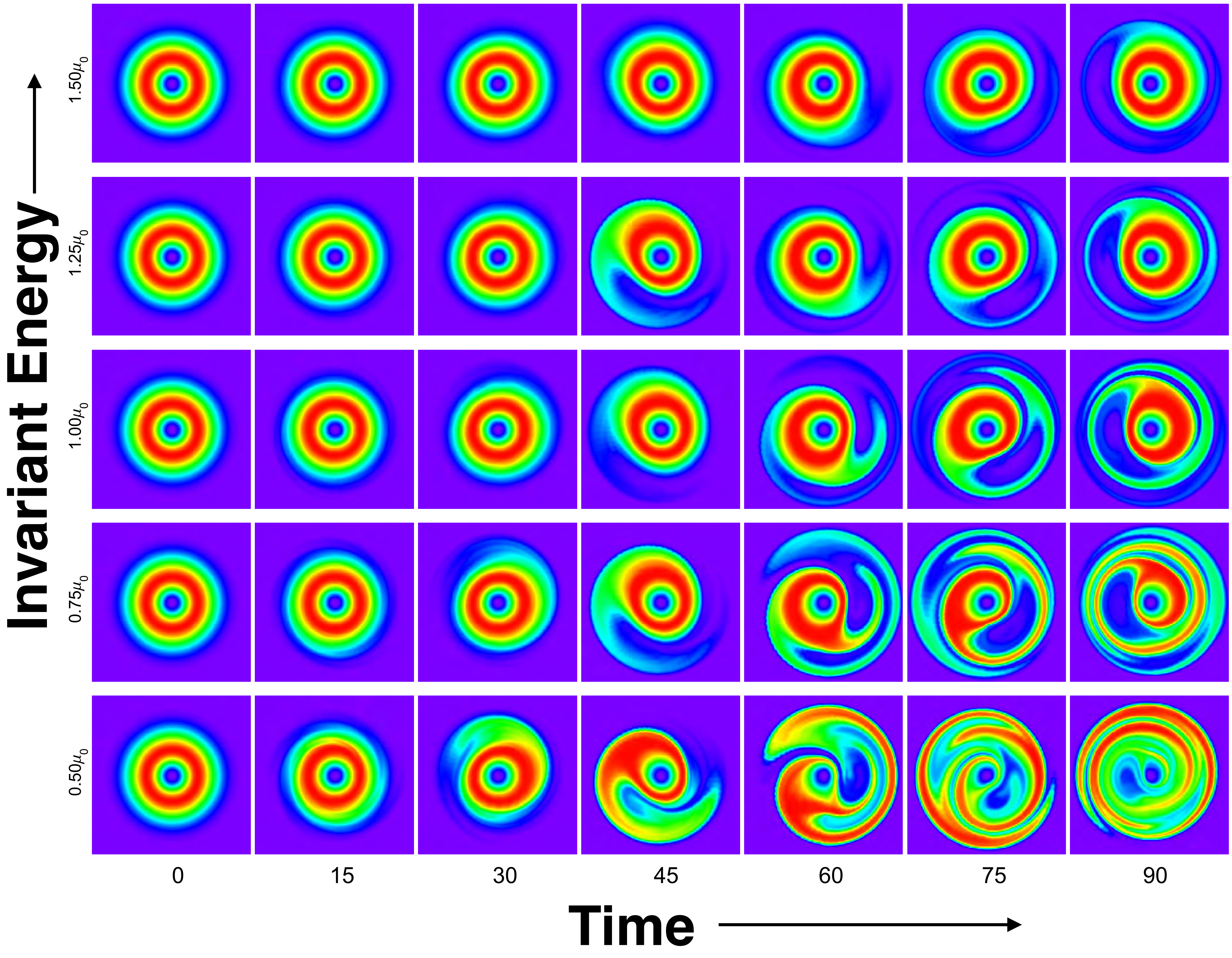


Fast drift-resonant instability resonates with fast electrons causing rapid radial transport…



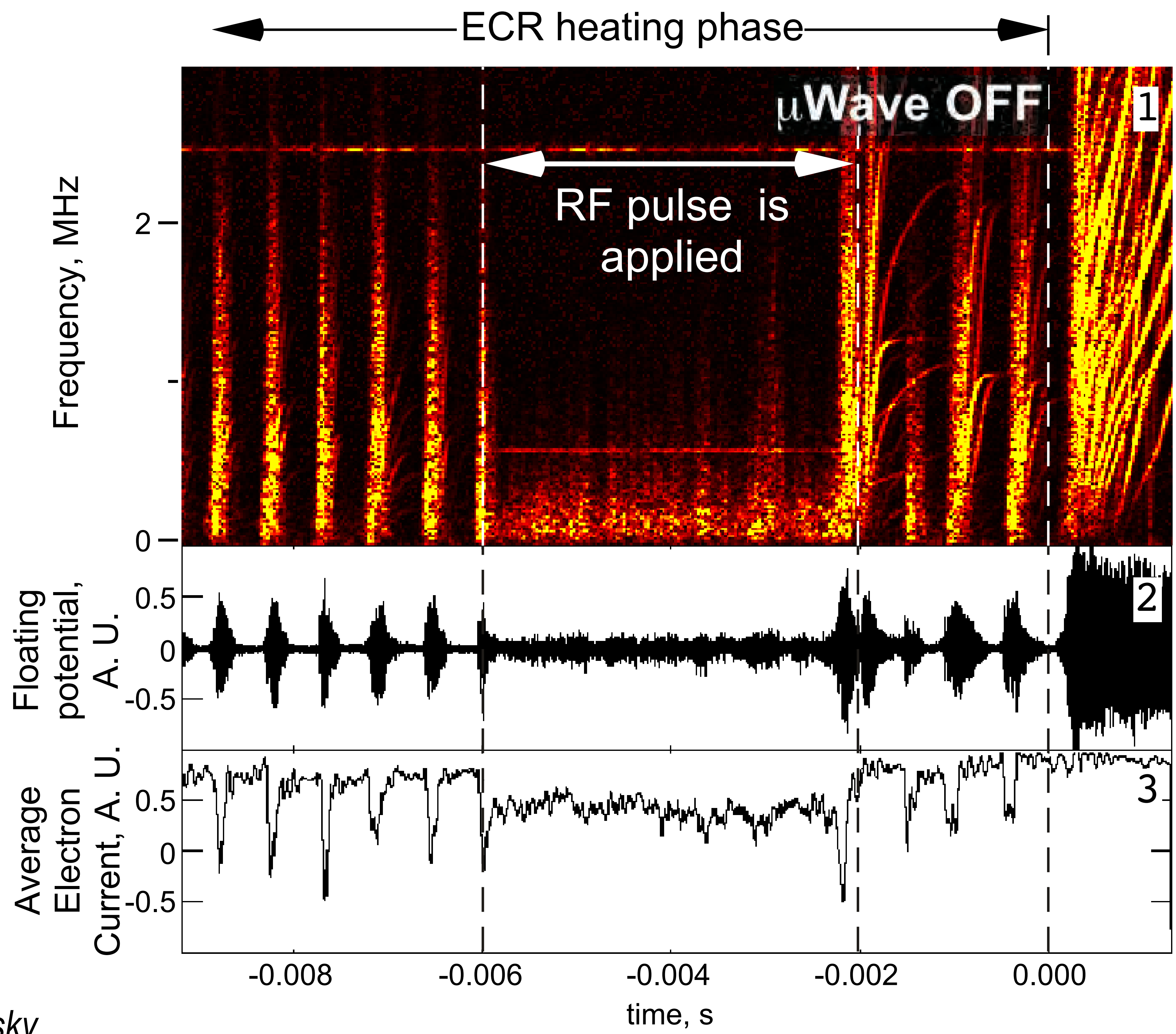
Interchange Drift Resonance (μ, J) ~ $1/L^2$

Well-modeled with global, nonlinear Bounce-Averaged gyrokinetic simulation…



"Chorus" Injection Fills-in Phase-Space Holes

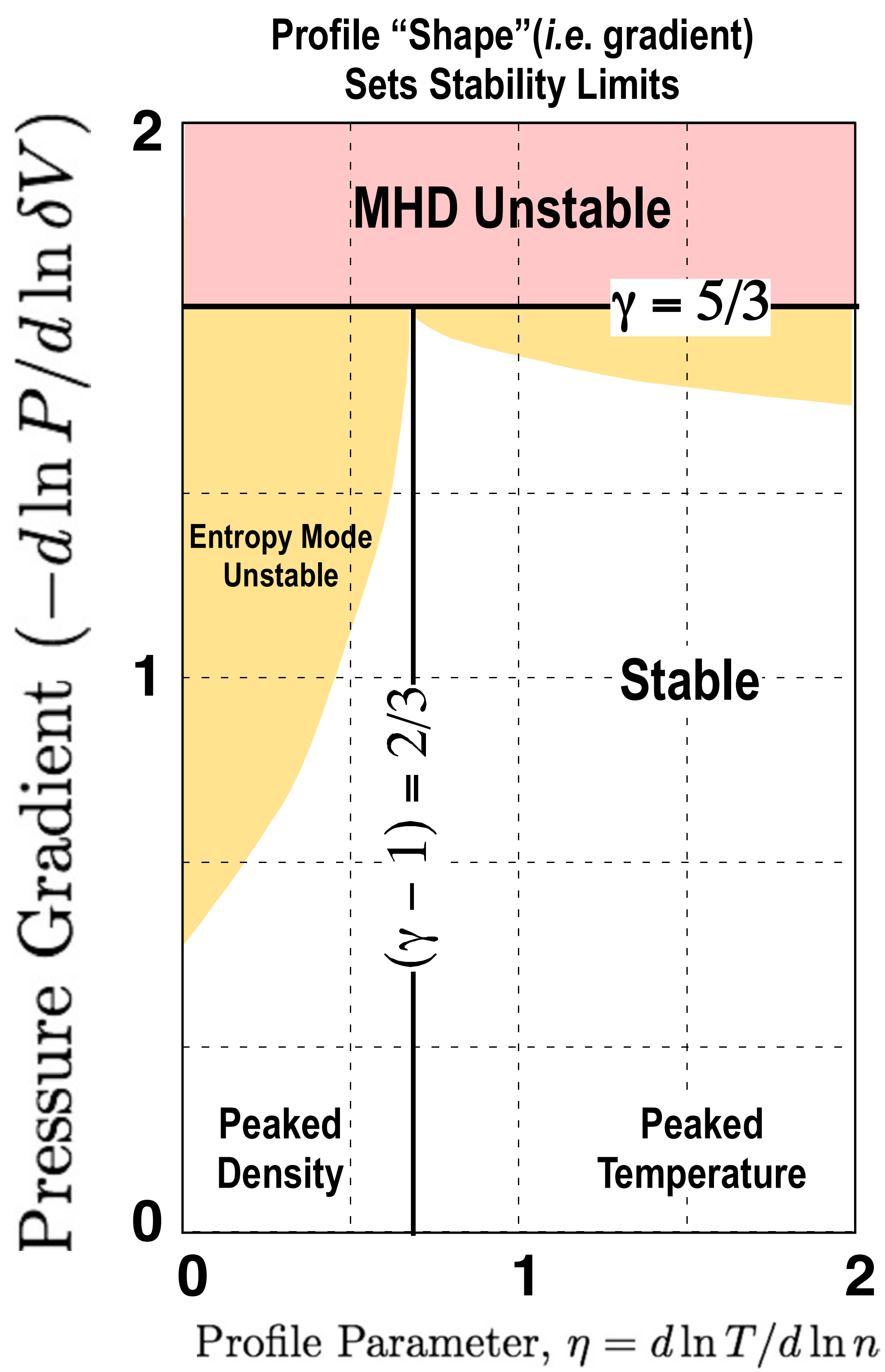
Well-modeled with global, nonlinear Bounce-Averaged gyrokinetic simulation…



Dmitri Maslovsky

Low frequency interchange & Entropy modes dominate Semi-collisional thermal plasma dynamics

- Interchange modes set pressure and density gradient limits in dipole-plasma (*not* ballooning-drift)
- ***Entropy mode changed our thinking:*** not just pressure and density gradients, also η = d(ln*T*)/d(ln*n*) (Kesner, *POP*, 2000; Kesner, Hastie, *POP*, 2002)
- Entropy modes generate zonal flows and self-regulate transport levels (Ricci, Rogers, Dorland, *PRL*, 2006)
- Fluctuations disappear with flat density profiles (Garnier, *JPP*, 2008; Kobayashi, et al., *PRL*, 2009)
- ***Measurements show fluctuations throughout plasma*** (*Nature-Physics*, 2010); inverse energy cascade (*POP*, 2009); intermittency (*PRL*, 2010)



Turbulence drives plasma to steep profiles and creates "Canonical" Profiles: Self-Organization

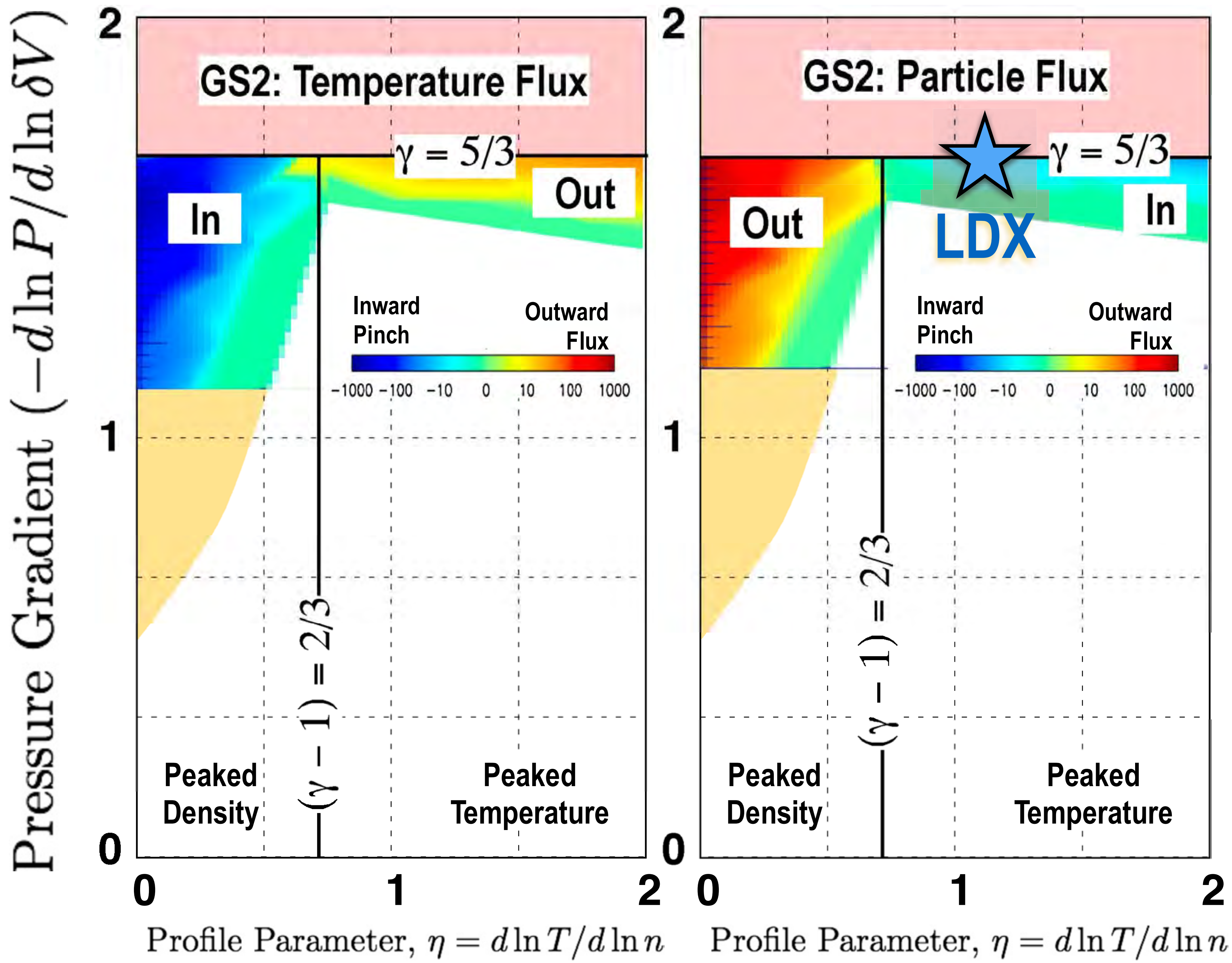
Gyrokinetic (GS2) simulations show turbulence drives particles or heat to maintain uniform entropy density

Kobayashi, Rogers, Dorland, *PRL* (2010)

$$\eta = \frac{d\ln T}{d\ln n} \rightarrow \frac{2}{3}$$

$$-\frac{d\ln n}{d\ln \delta V} \rightarrow 1$$

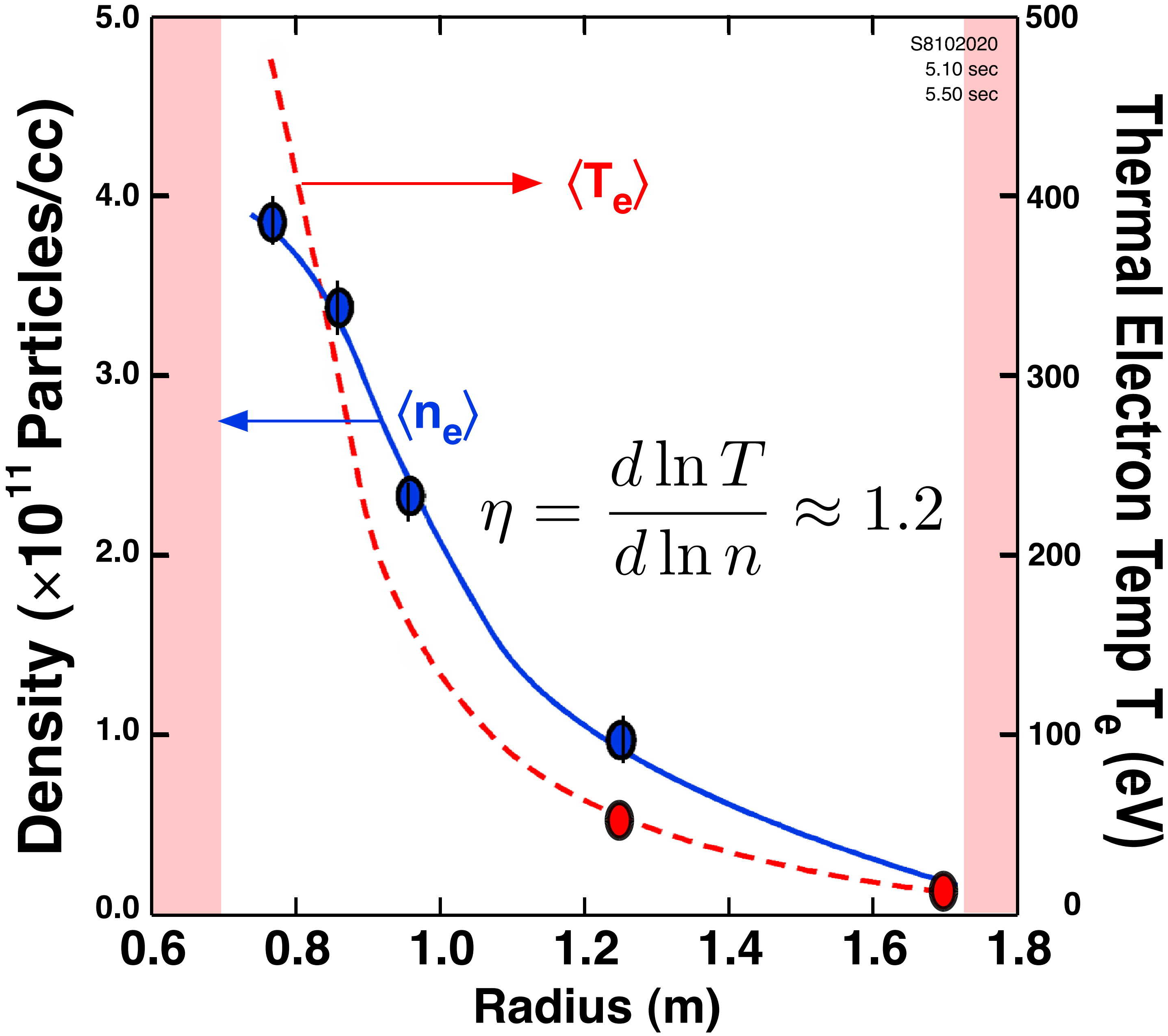
$$-\frac{d\ln P}{d\ln \delta V} \rightarrow \frac{5}{3}$$



Turbulence Maintains Centrally-Peaked Self-Organized "Canonical" Profiles

- Thermal plasma energy $W_{th} \approx 100$ J with 11 kW ECRH.
- Measured *edge* $T_e \approx 14$ eV, density profile, and stored energy, require *central* $T_e \sim 0.5$ keV
- Outward thermal flux sustains inward particle flux, $\eta \sim 1.2$

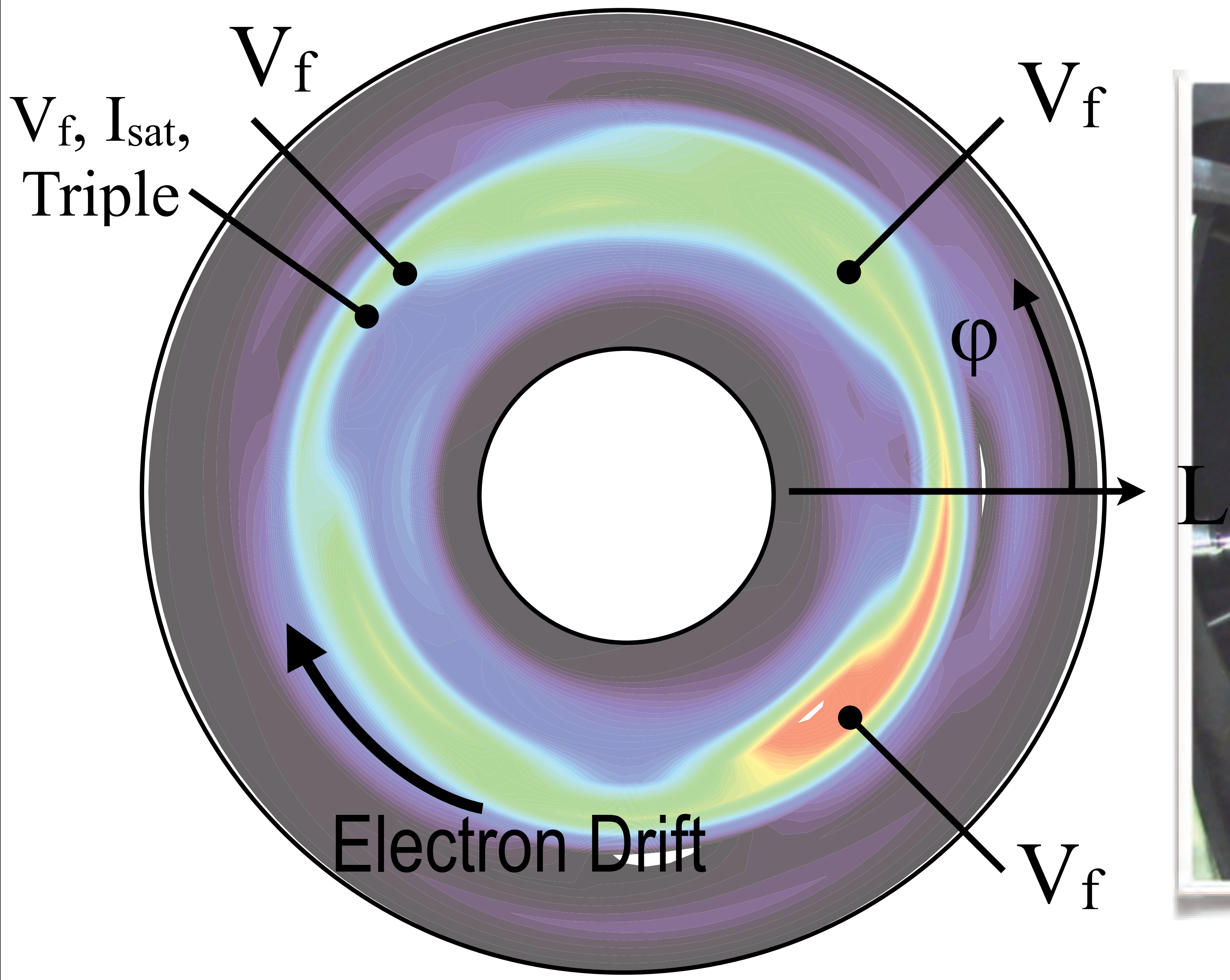
$$-\frac{d \ln P}{d \ln \delta V} = \gamma = \frac{5}{3}$$

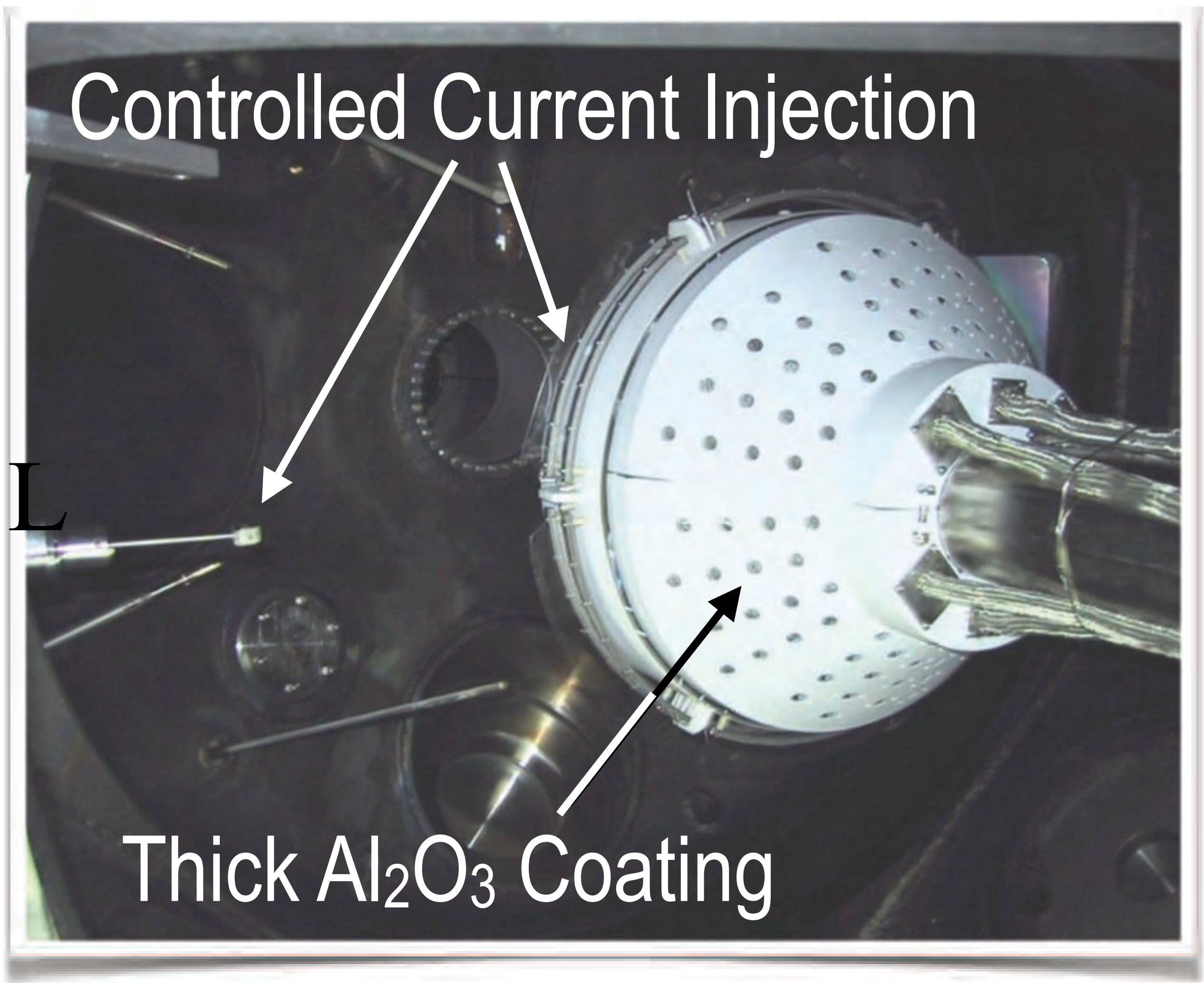


Boxer, *et al.*, *Nature Phys.* (2010)

Polar Imaging of Plasma Dynamics

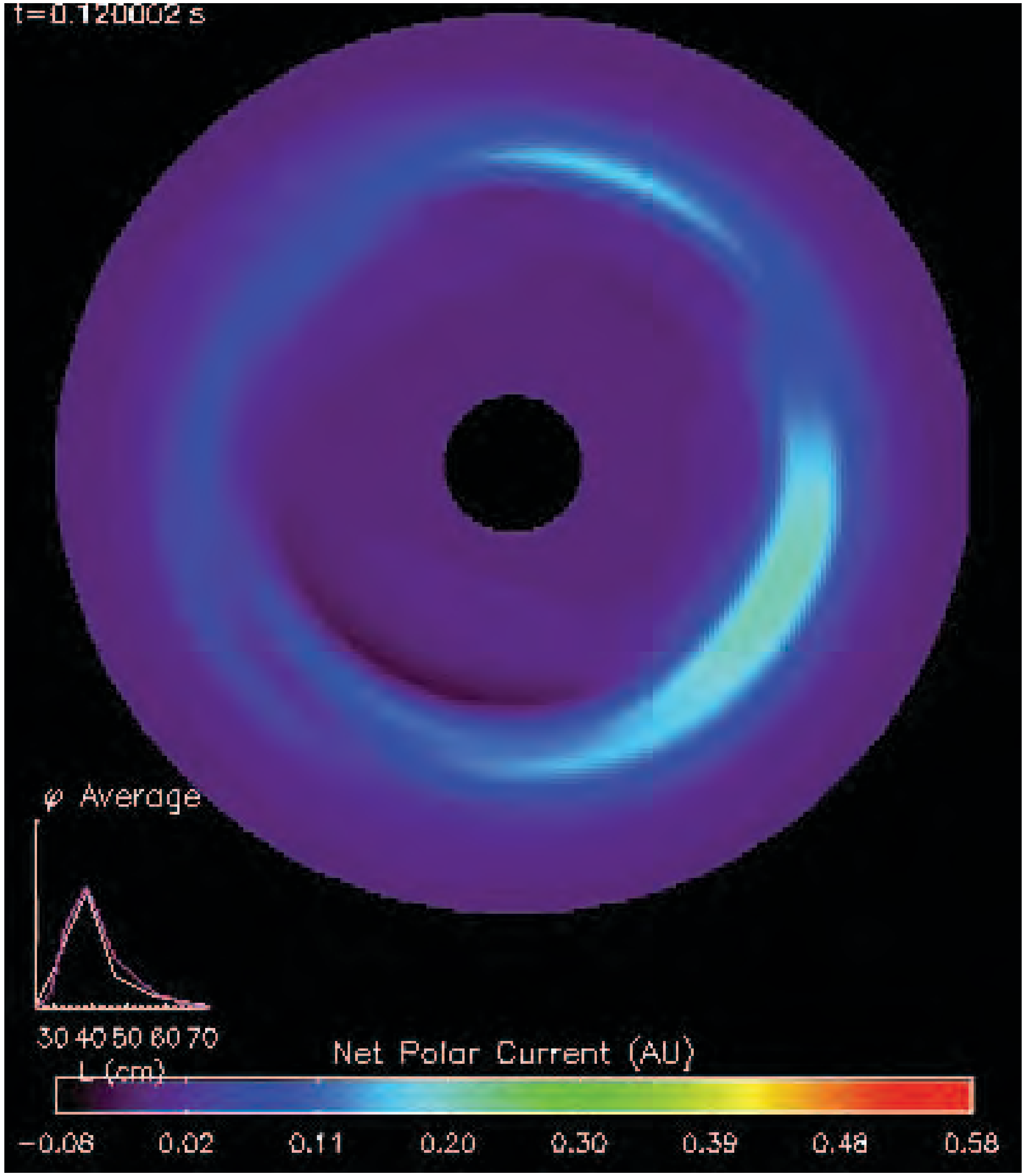
Investigations of Interchange/Entropy Mode Turbulence





High Speed Imaging of Interchange/Entropy Mode Turbulence at 0.5 Mfps

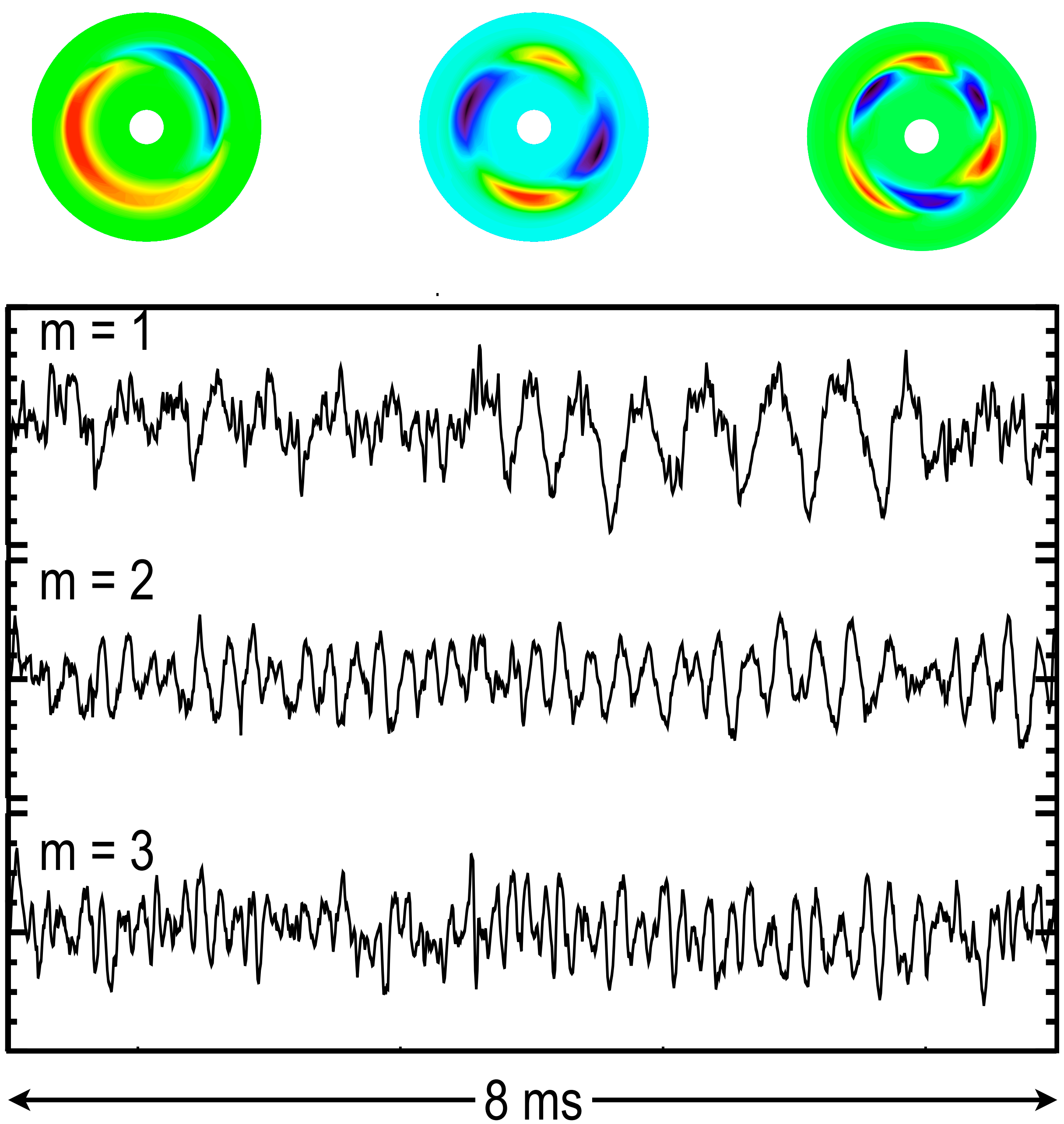
- Detectors biased to collect ion current
- Visualize turbulence
- Density fluctuations rotate in electron drift direction with random amplitude and phase modulations
- Compute turbulence cascade and compare with nonlinear simulations



Brian Grierson

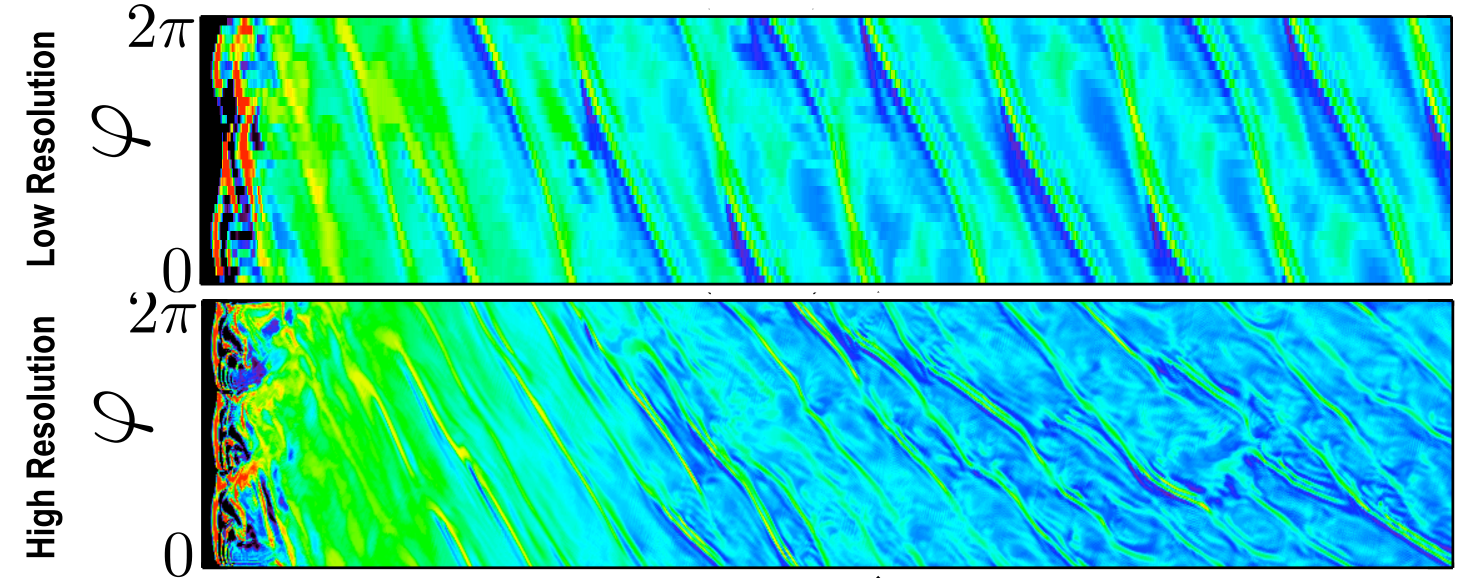
Low-Frequency Turbulent Convection: Detailed Observation of Particle Transport Process

Well-modeled with global, nonlinear Bounce-Averaged gyrokinetic simulation…

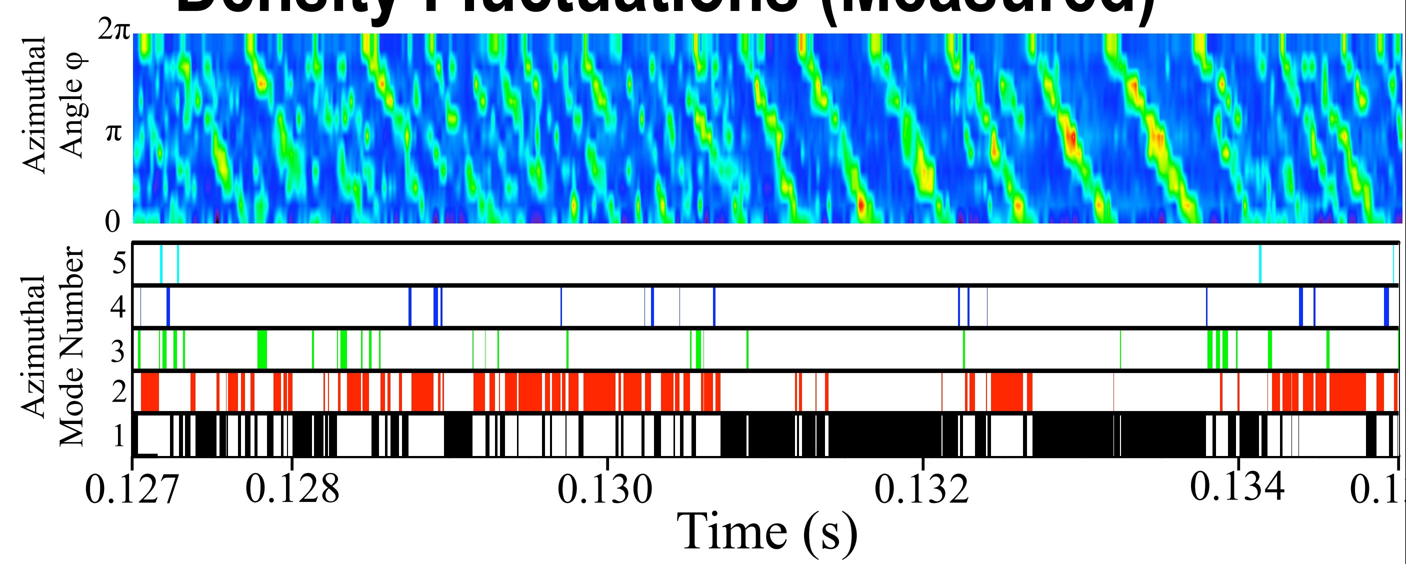


Convective Structures Dynamics

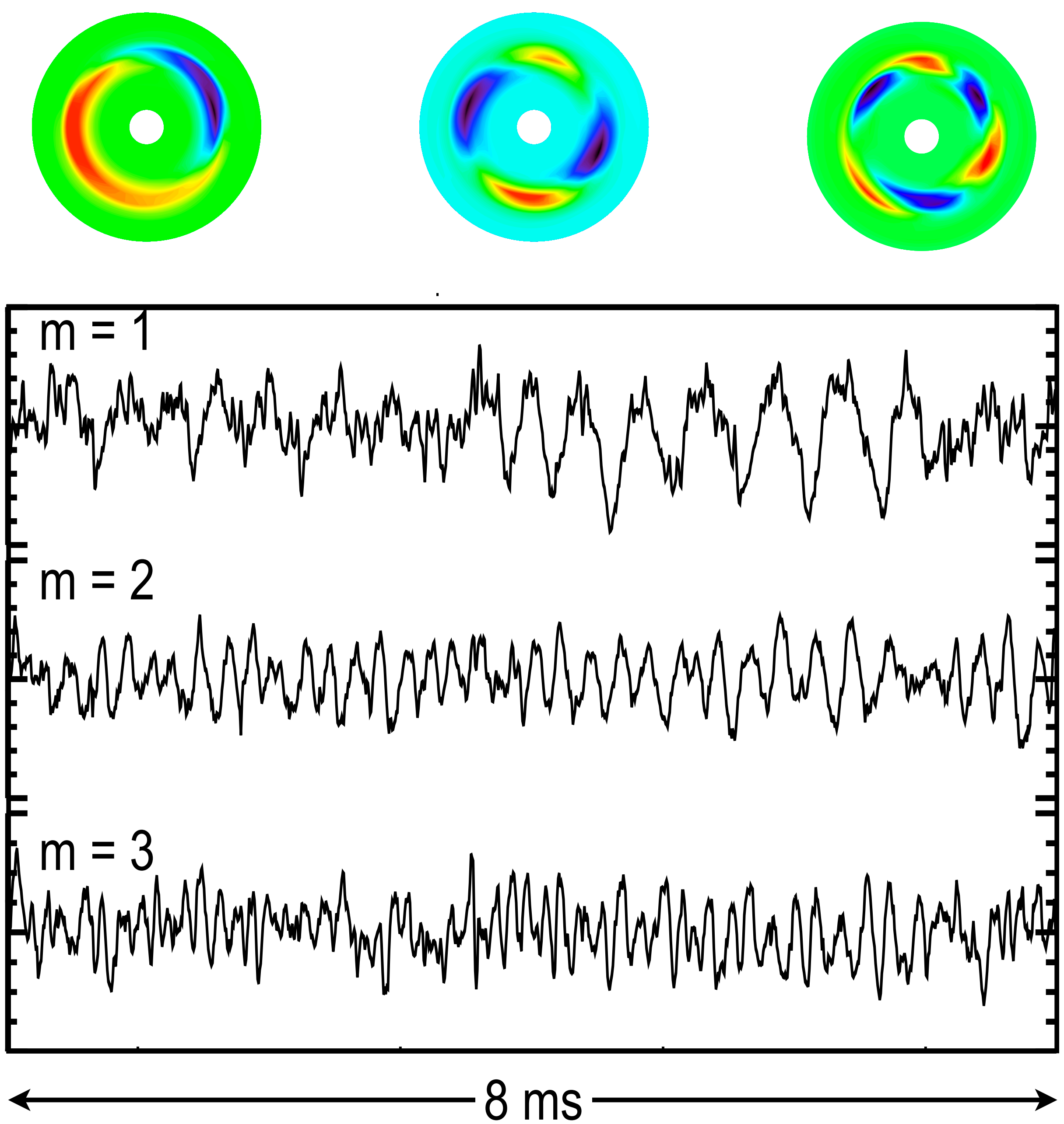
Density Fluctuations (Simulation)



Density Fluctuations (Measured)

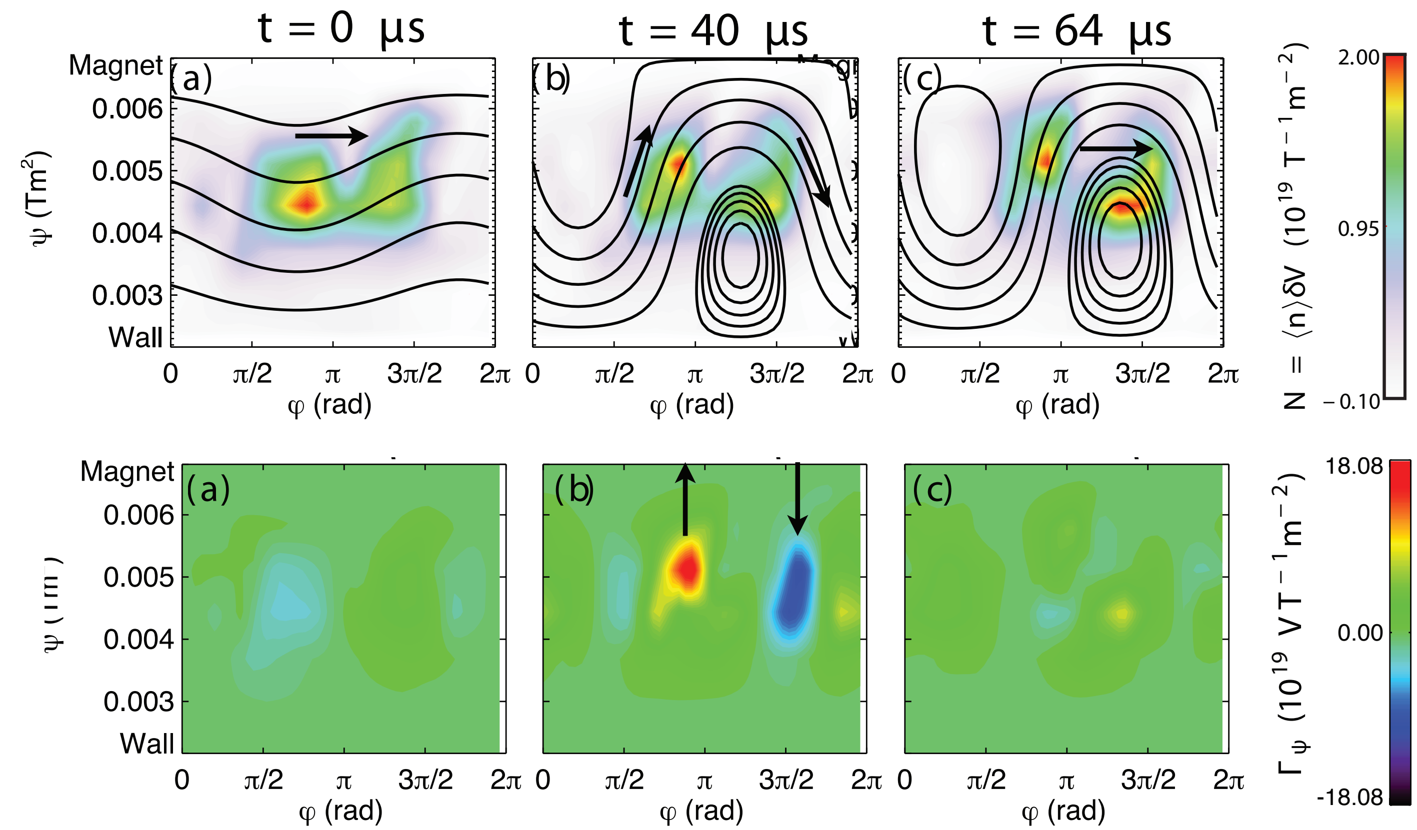


Low-Frequency Turbulent Convection: Detailed Observation of Particle Transport Process



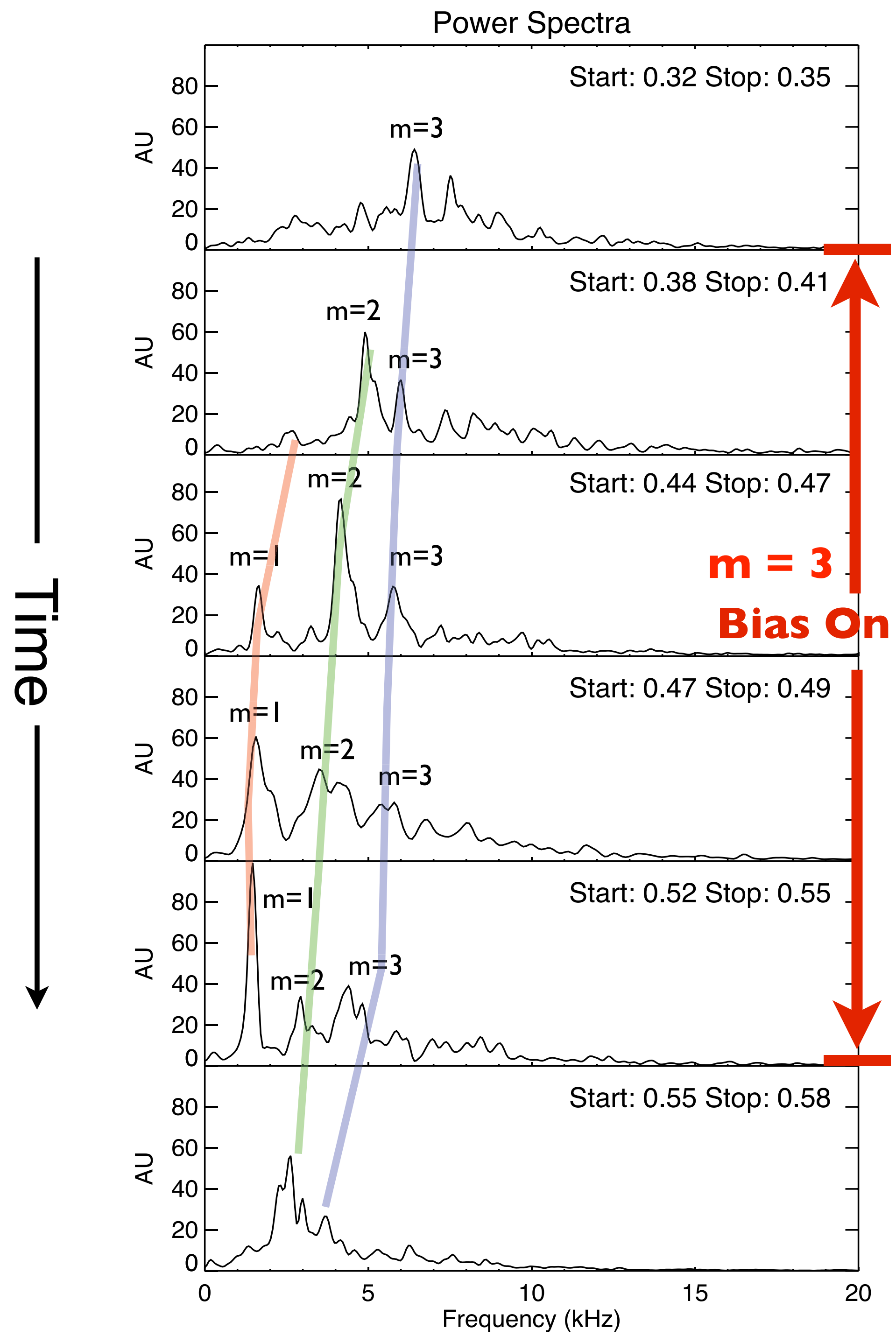
Convective Structures Dynamics

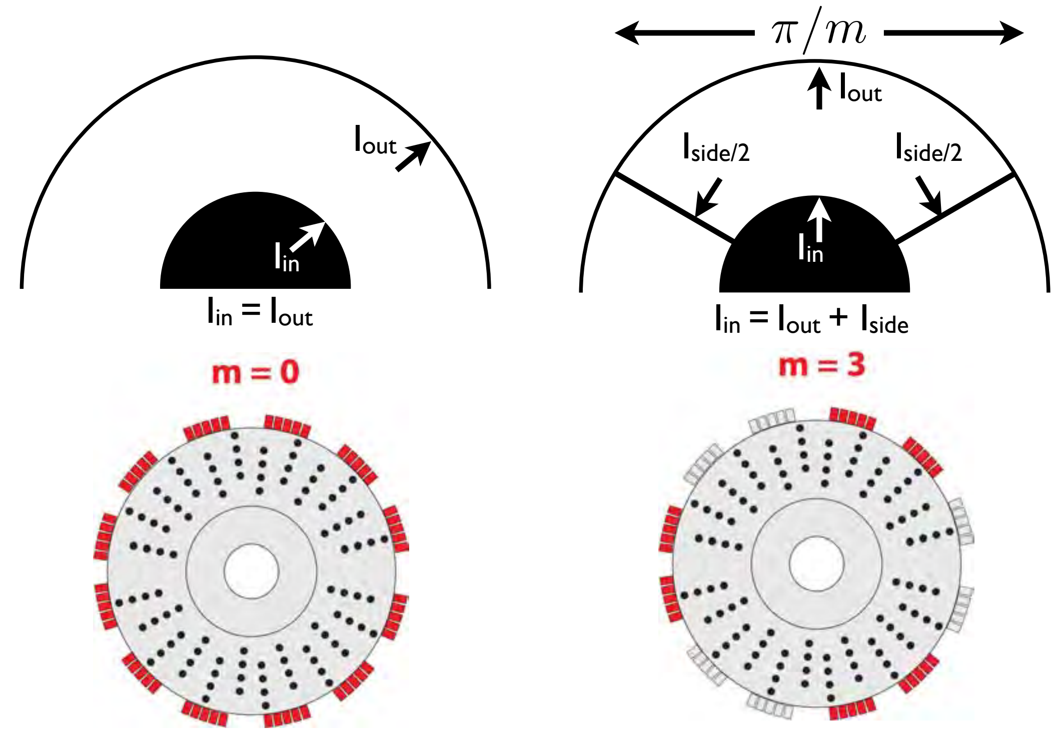
Interchange Transport of "**Inward**" and "**Outward**" Moving Plasma-Filled Flux Tubes

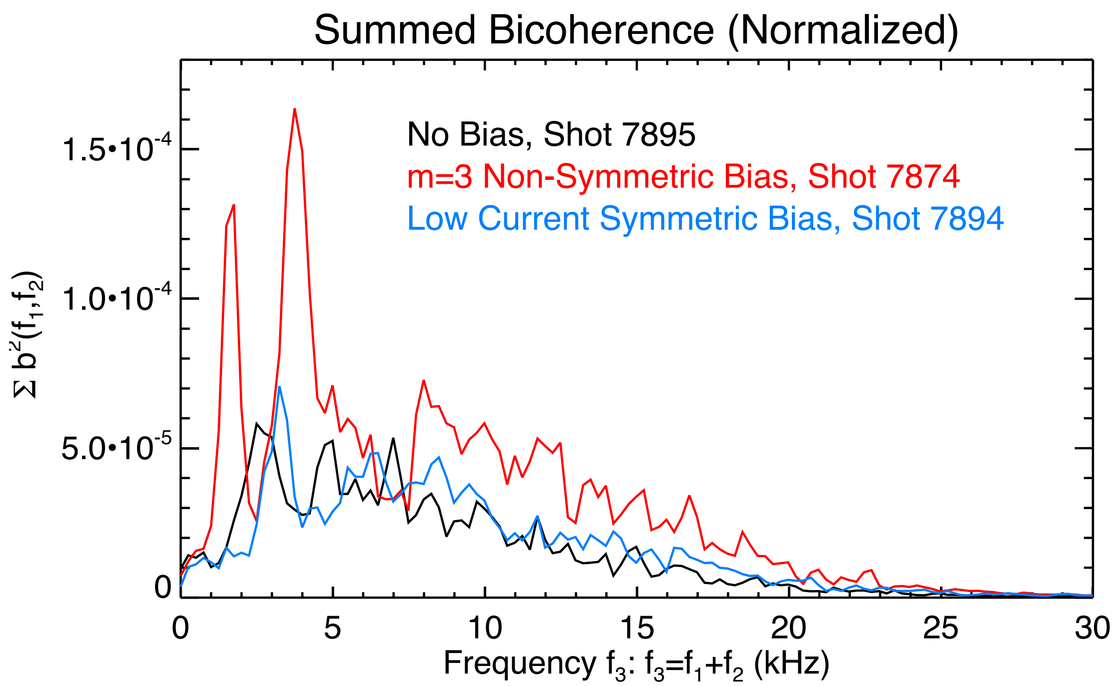


Chaotic Interaction between Convective E×B Streamlines and Plasma Density Perturbations

Symmetry Breaking and the 2D Inverse Energy Cascade.

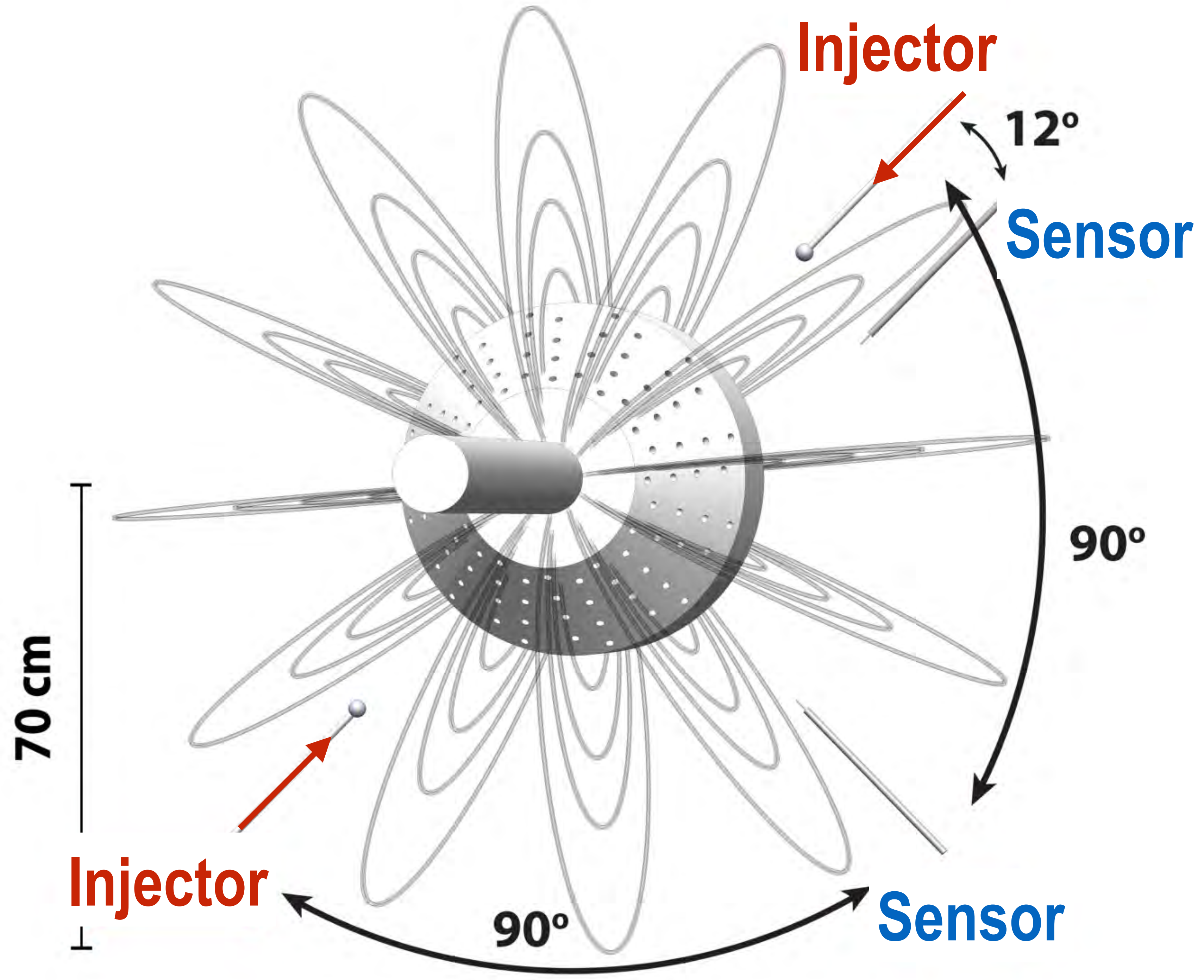






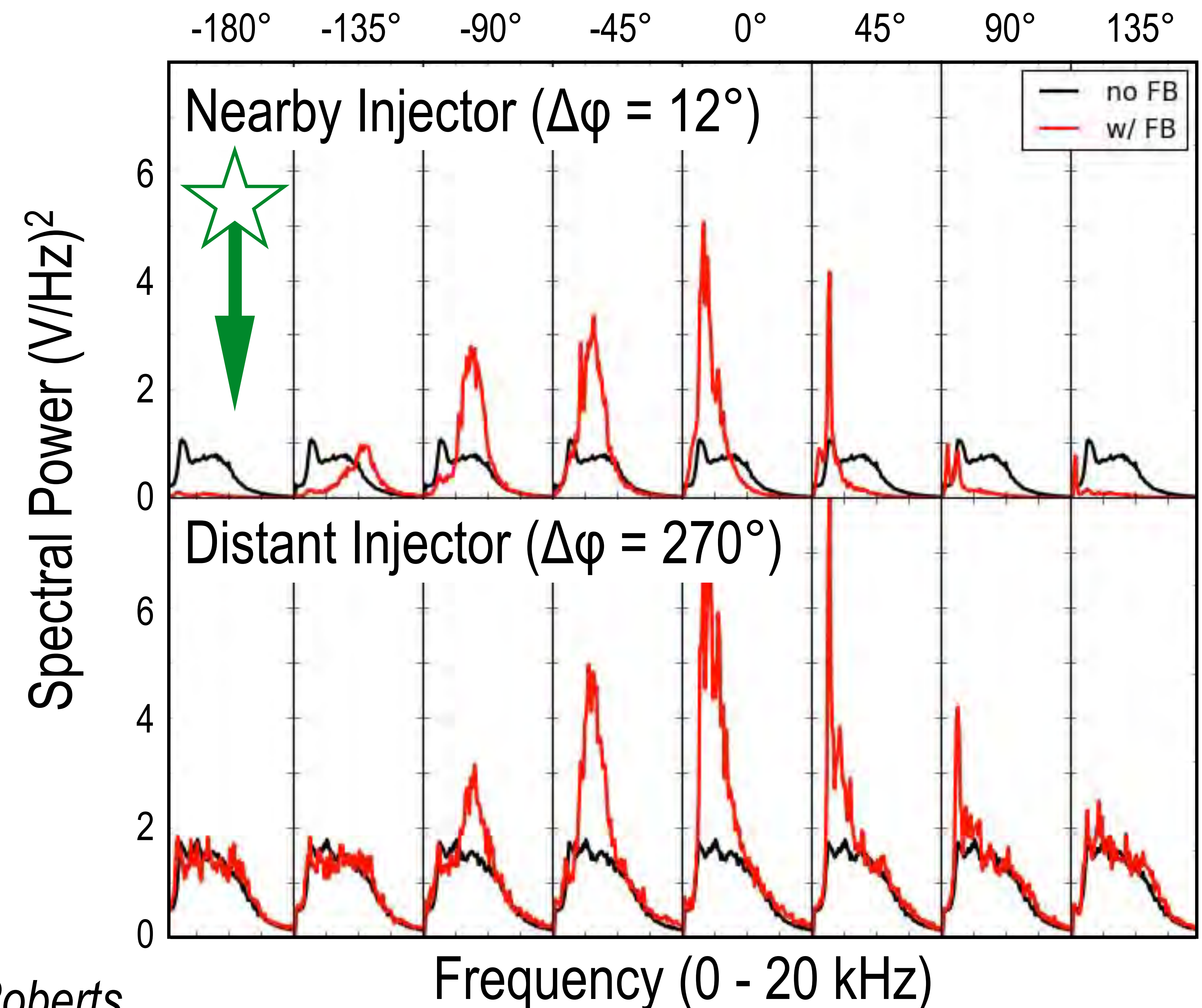
Matt Worstell

Local Current Injection to Explore Interchange/ Entropy Mode Turbulence



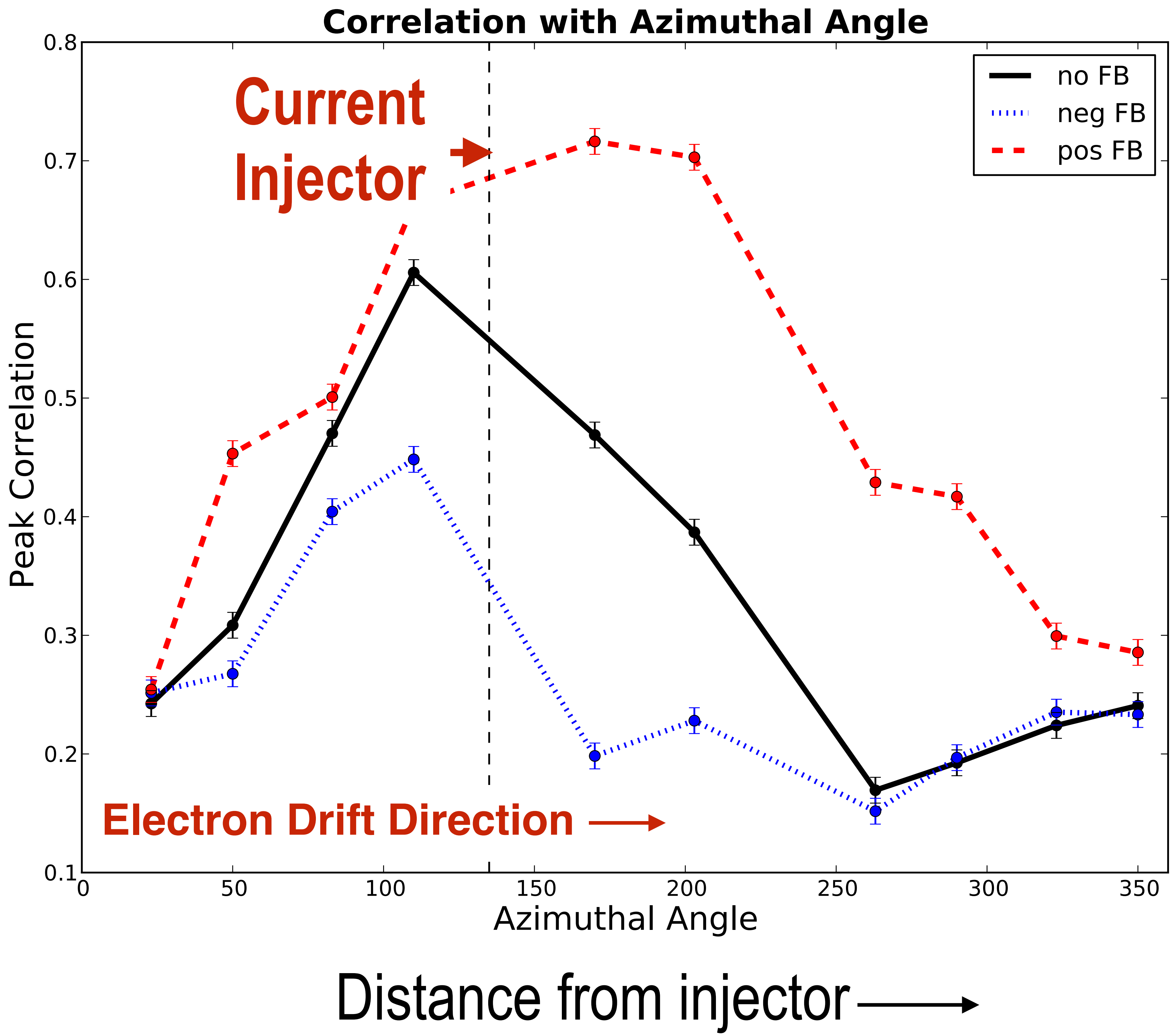
$$\int \frac{ds}{B} \nabla \cdot \mathbf{J}_\perp = \int \frac{ds}{B} \nabla \cdot \mathbf{J}_{prb} \propto I_{prb}\, \delta(\psi - \psi_{probe}) \delta(\varphi - \varphi_{prb})$$

Current Injection results in Global Amplification or *Local* Suppression of m = 1 Entropy Modes



Max Roberts

Current Injection results in Global Amplification or Local Suppression of m = 1 Entropy Modes



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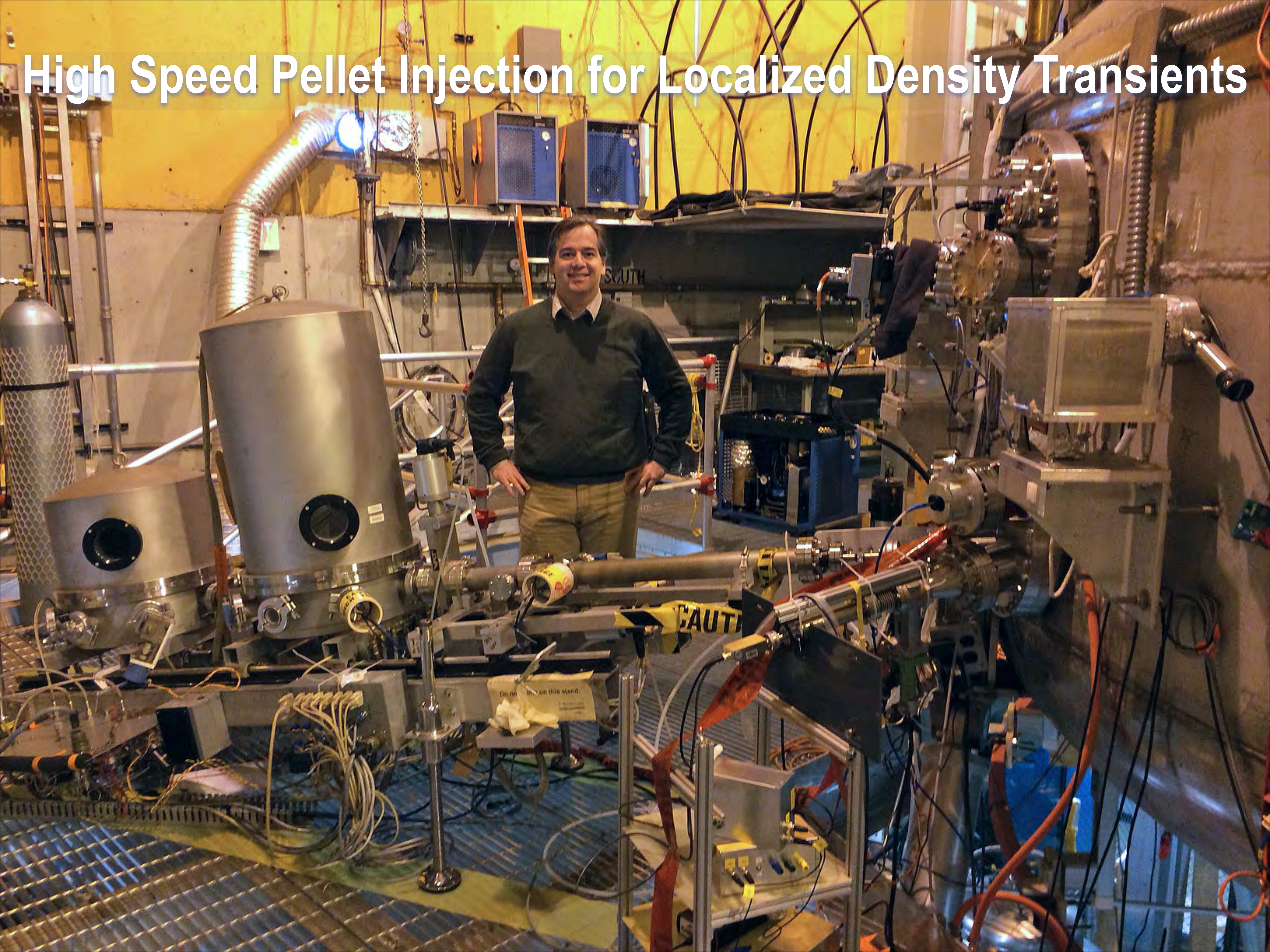
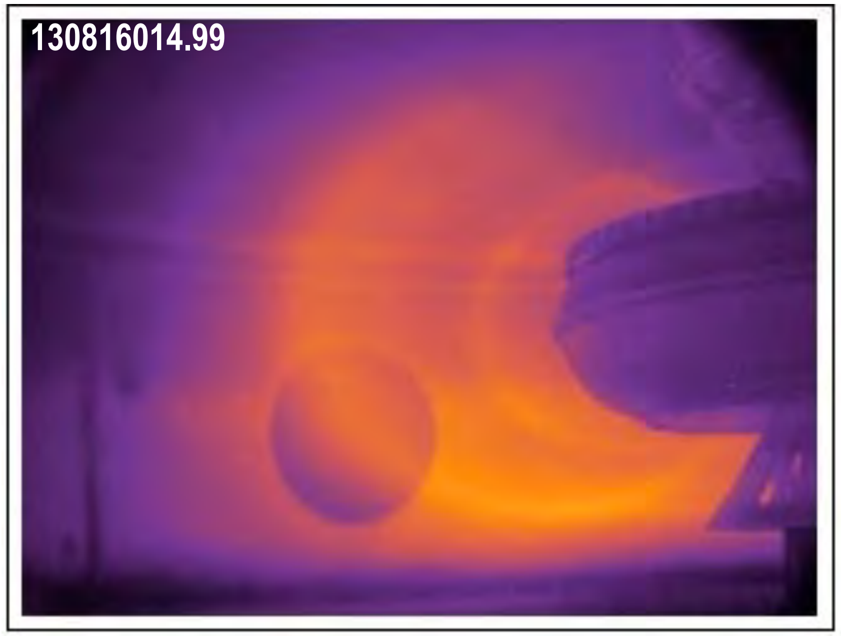
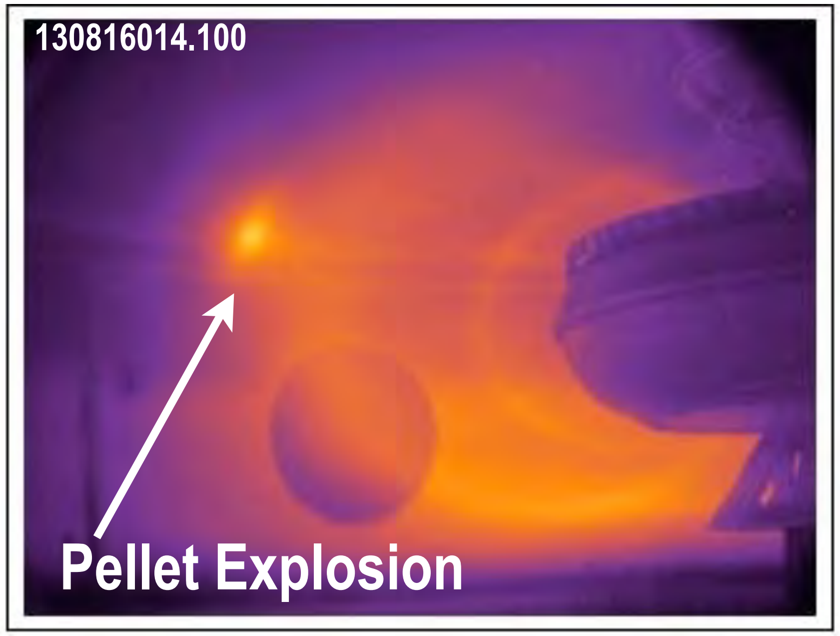
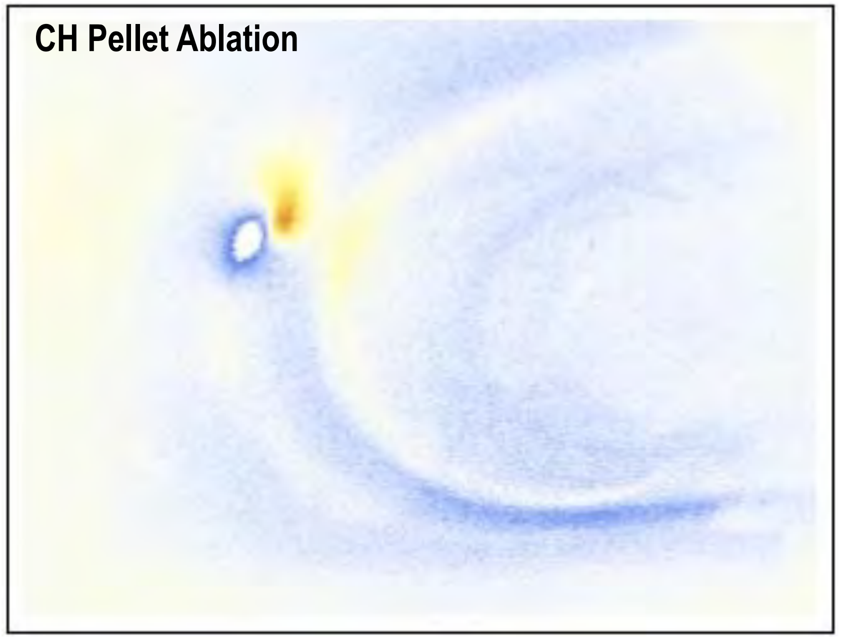
High Speed Pellet Injection for Localized Density Transients

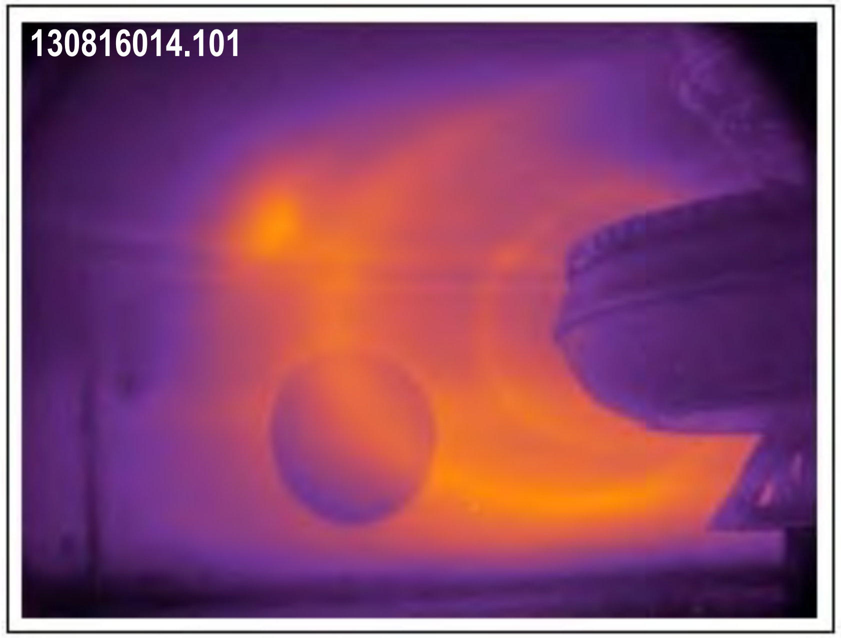


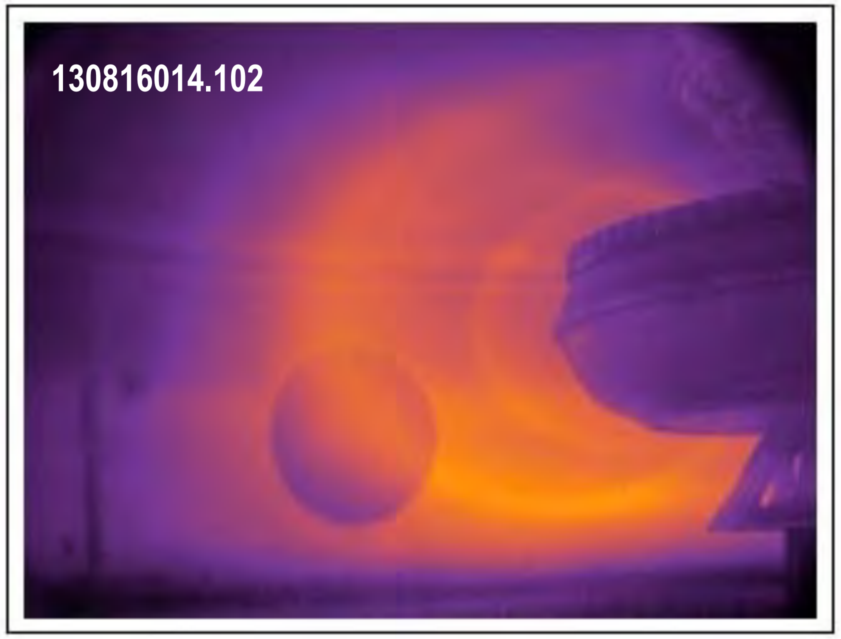
Flux Tube Dynamics Following Pellet Release Experiments in Laboratory Magnetospheres

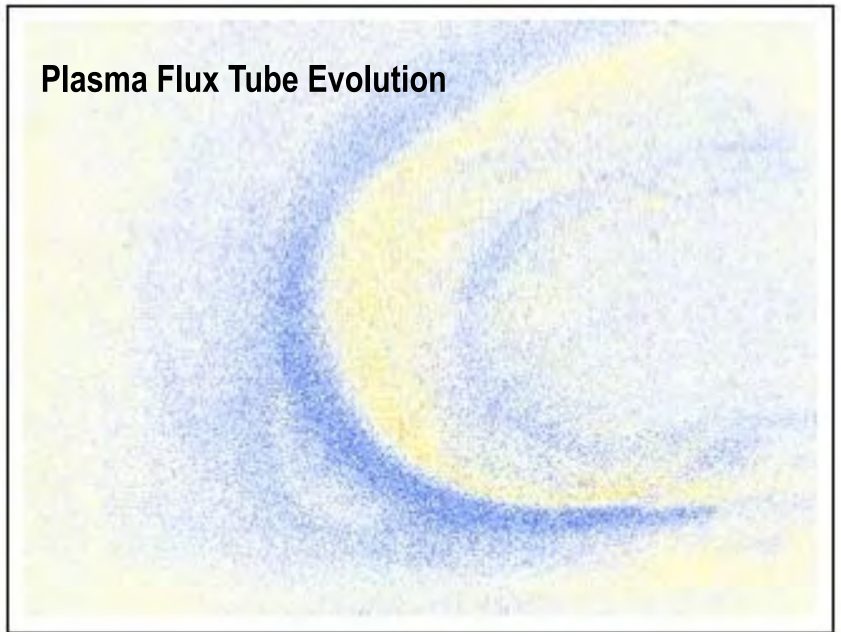




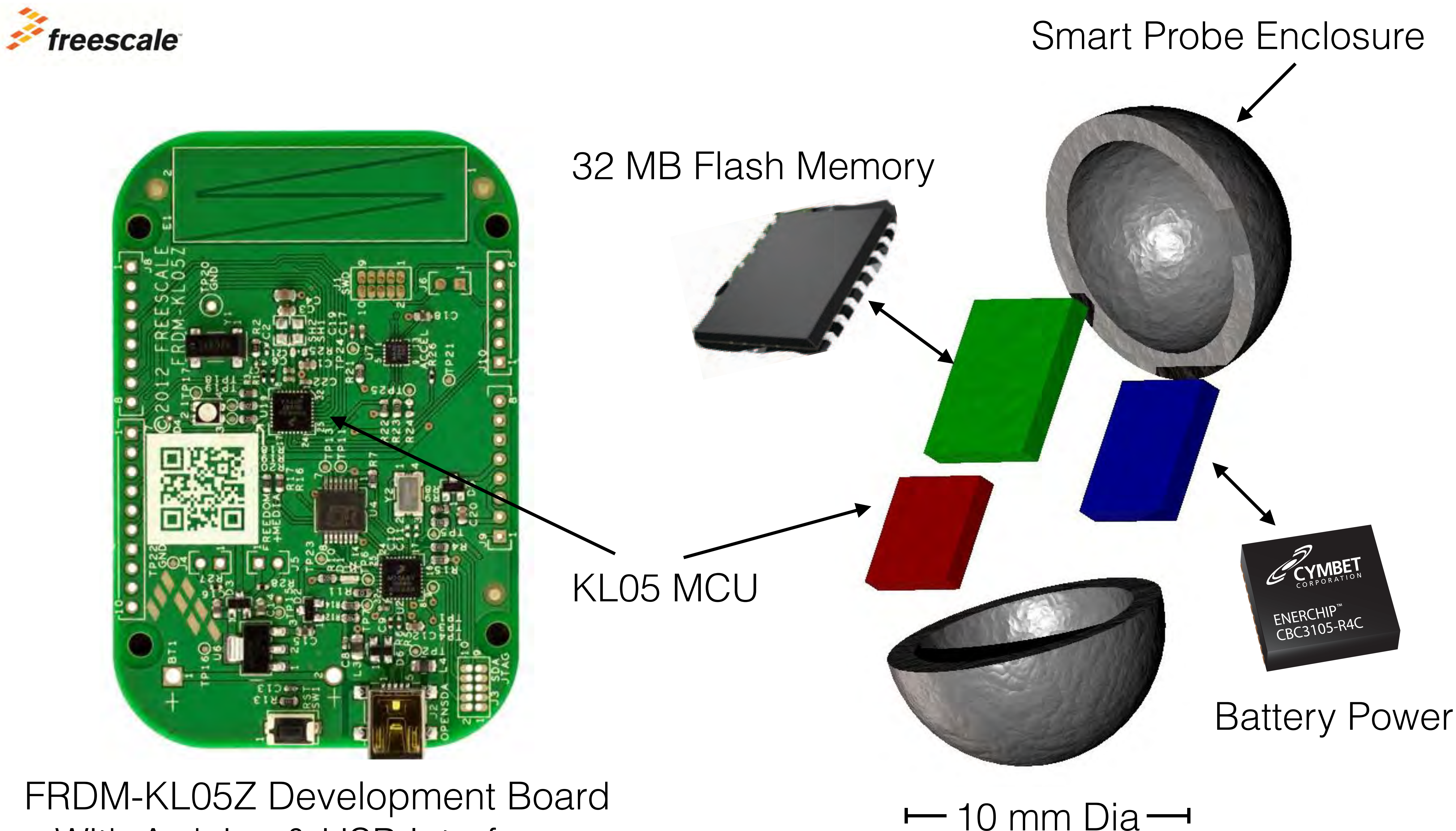






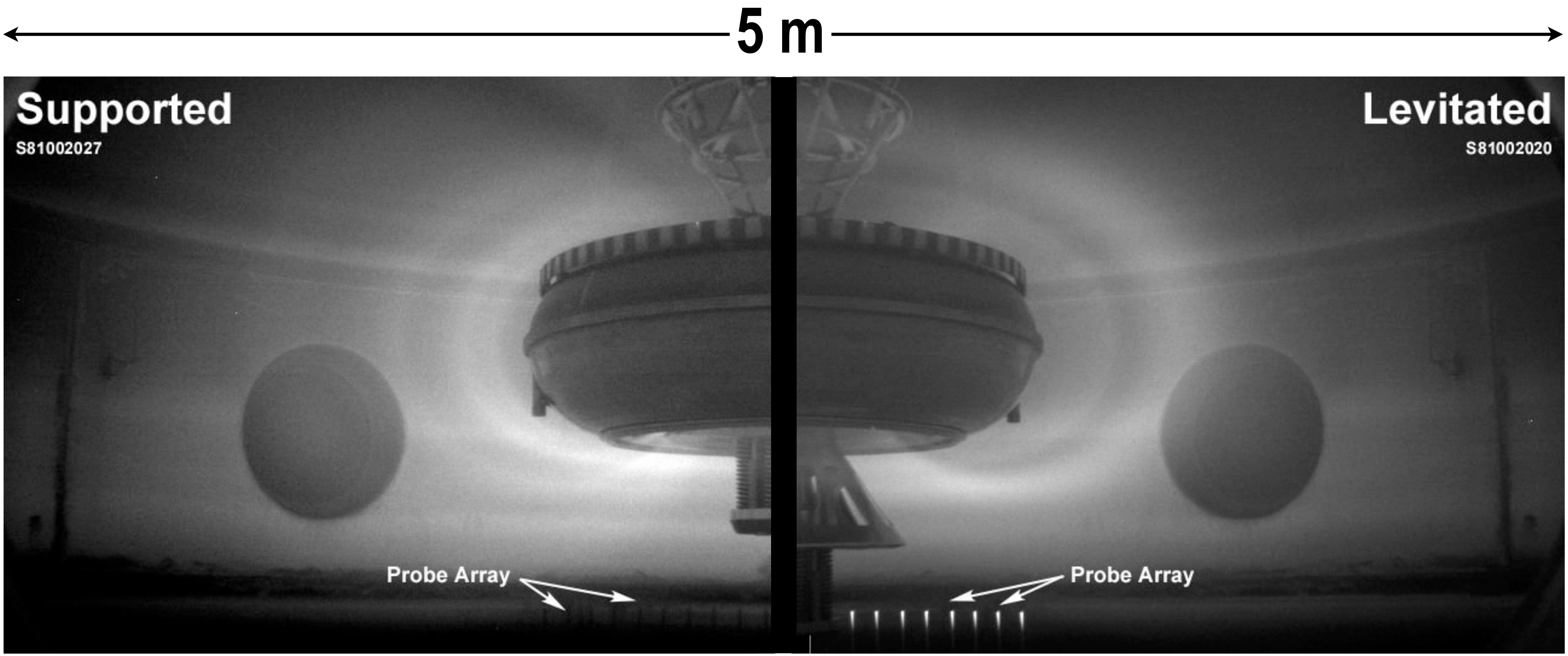


Low-cost “Smart-Probes” for Multiple-Point *in situ* Measurements



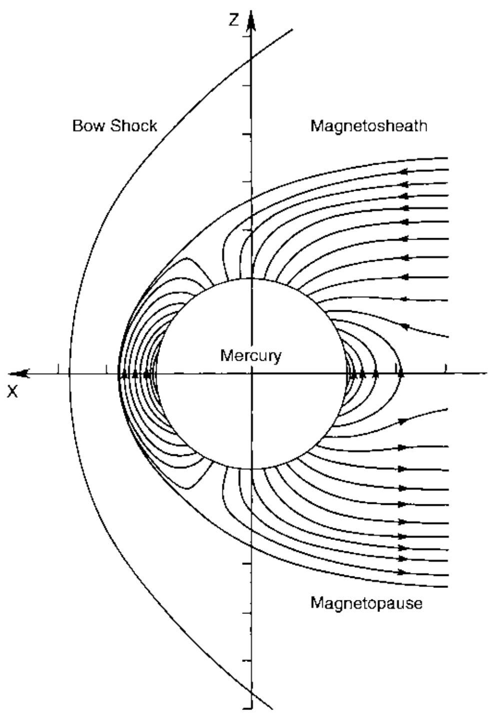
FRDM-KL05Z Development Board
With Arduino & USB Interfaces
3-axis accelerometer

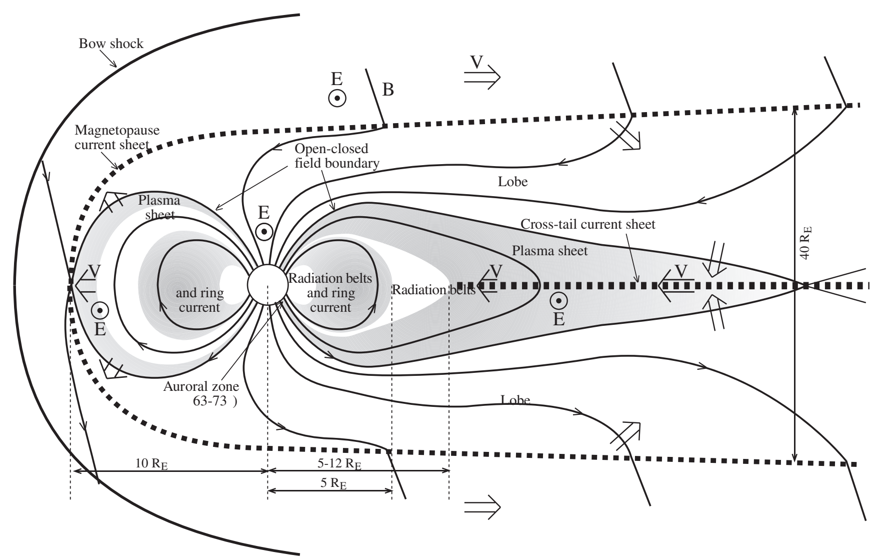
World's Largest Lab Magnetosphere

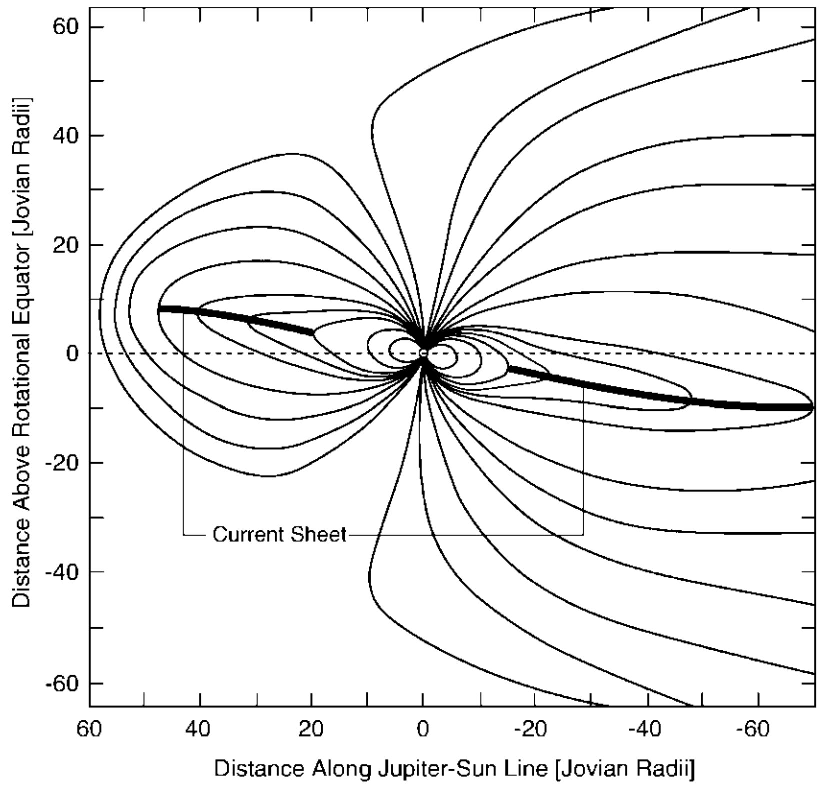


Size matters:
At larger size, trapped particle energy, intensity of "artificial radiation belt", and plasma density significantly increase

High Density and Large Size are required for Controlled Investigations of Alfvén Wave Dynamics





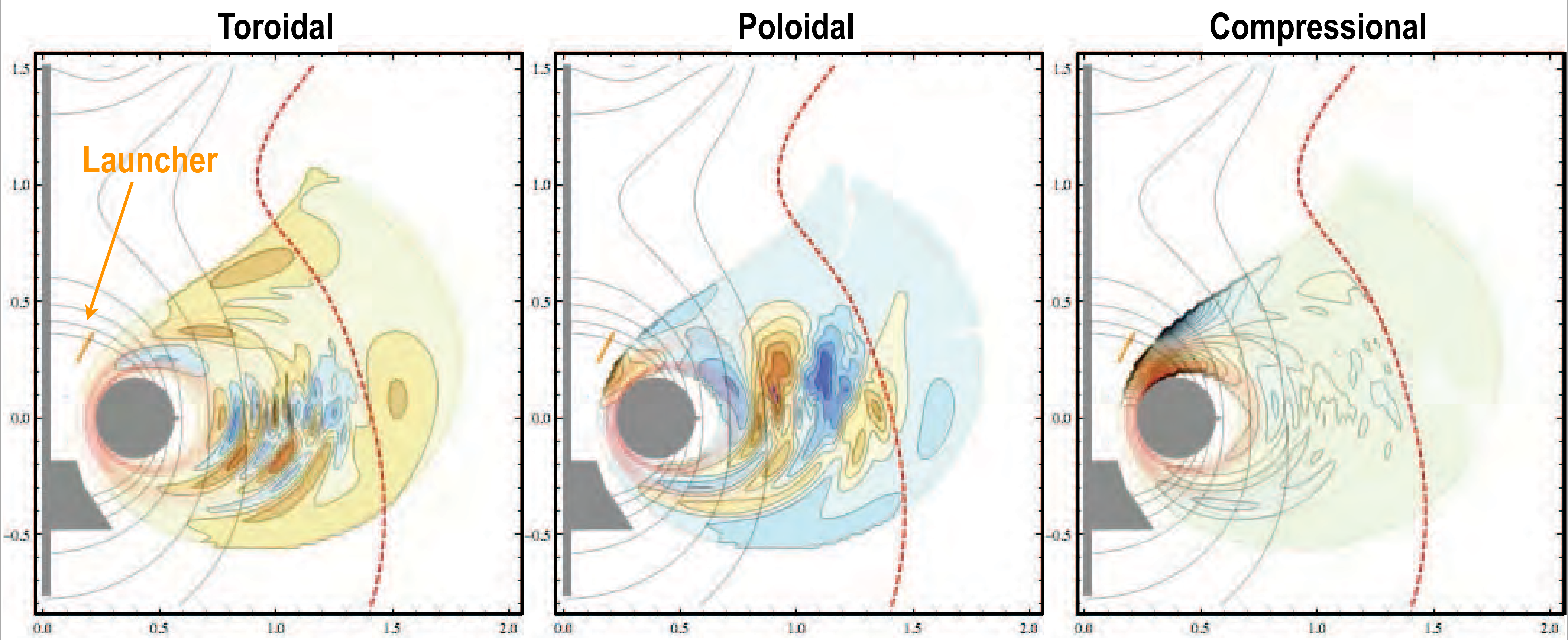


$$\frac{V_A}{L} \sim f_A \ll f_{ci} \rightarrow \frac{c/\omega_{pi}}{L} \ll 1$$

	Mercury	Earth	Jupiter
Size	2 R	10 R	100 R
Density (c / ω	0.1	0.003	0.00001
Comments	V	Alfvén Resonances	Propagating Alfvén

Alfvén Wave Excitation in LDX: Opportunity for a Many Important Experiments

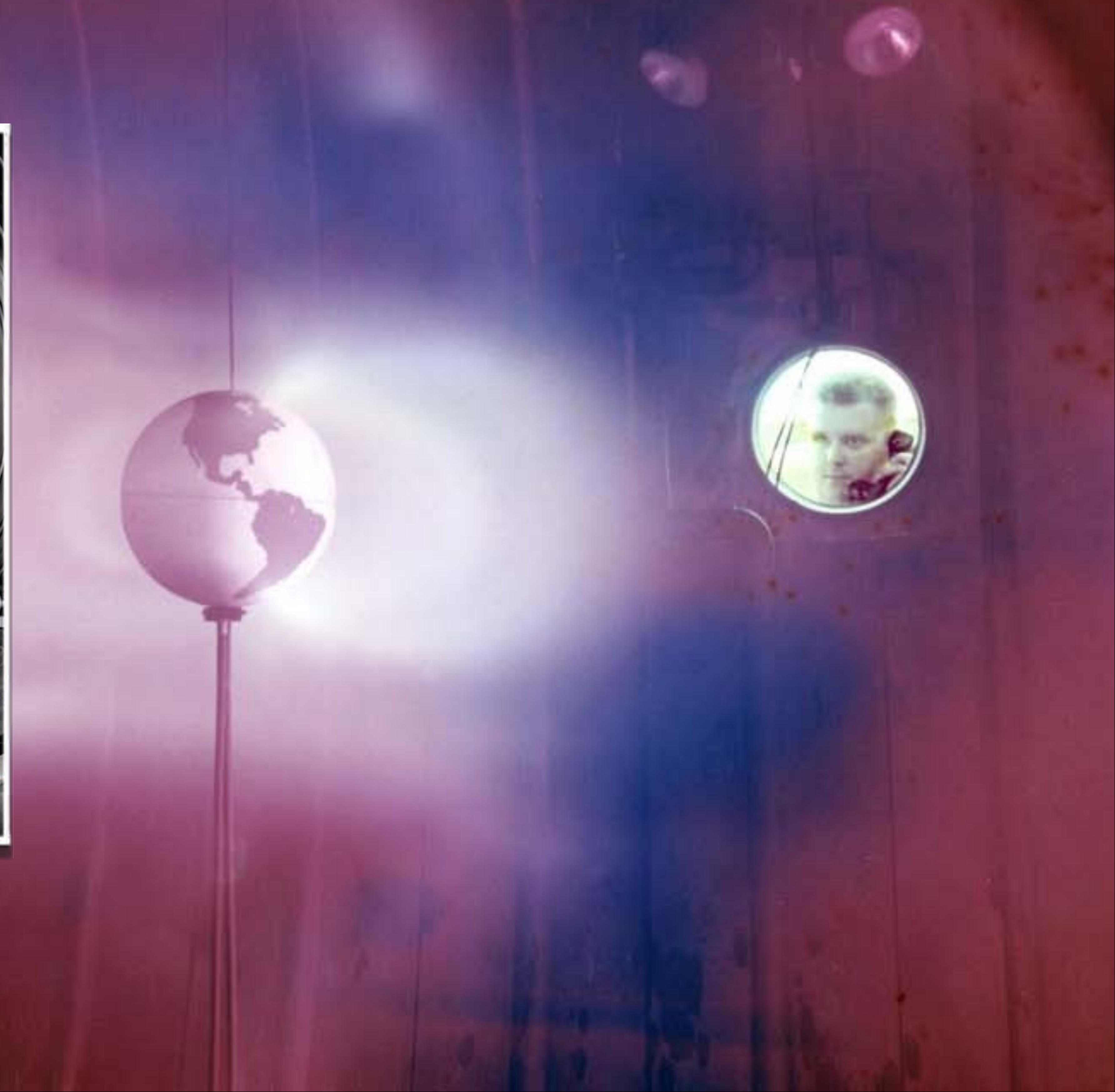
- Alfvén Wave Spectroscopy and Resonances
- Toroidal-Poloidal Polarization Coupling
- Alfvén Wave interactions with Radiation Belt Particles
- Ion Cyclotron Resonance and FLR



Example: 200 kHz m = 2 Polar Launcher

NASA's early effort in Laboratory Testing and Validation can be Significantly Advanced with Modern Modeling and Diagnostics

NASA Glenn #5 (1966)



A Large Space Chamber Could be Filled with a Laboratory Magnetosphere

Laboratory Magnetospheres are Unique Opportunities for Controlled Plasma Science Experiments

- Laboratory magnetospheres are facilities for ***conducting controlled tests*** of space-weather models in relevant magnetic geometry and for ***exploring*** magnetospheric phenomena by ***controlling the injection of heat, particles, and perturbations***
- Semi-collisional and trapped ***"artificial radiation belt"*** dynamics and transport have been studied.
- Larger laboratory magnetospheres significantly increase trapped particle energy, intensity of "artificial radiation belt", and plasma density. Allowing new controlled tests of ***complex Alfvén wave interactions*** in the magnetosphere.
- ***Very large plasmas*** can be produced in the laboratory, continuously, with low power and great flexibility. ***Verification and discovery*** of critical plasma science.
- ***Outlook***: We can build/operate the ***largest laboratory plasma on Earth***