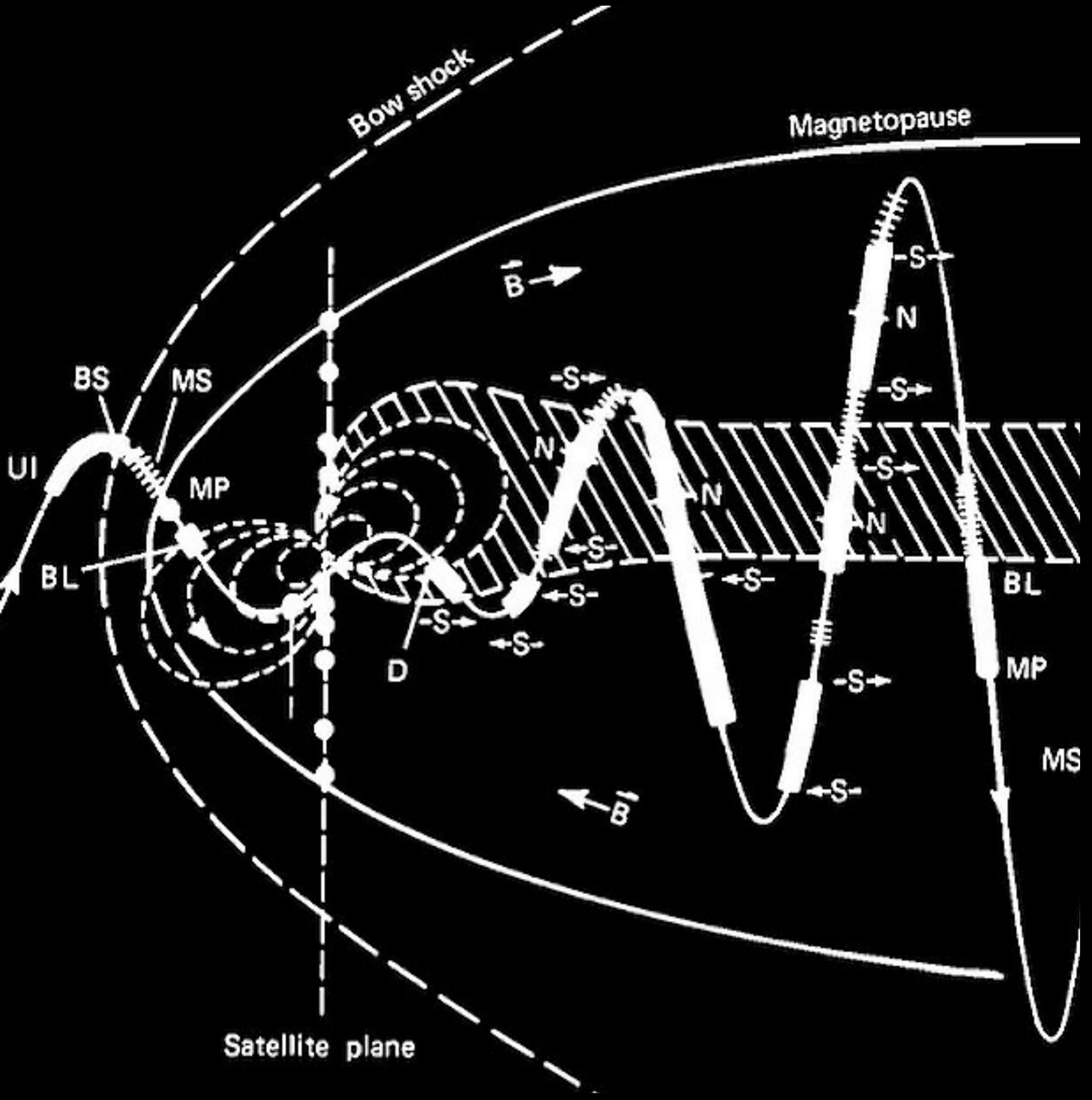
The Physics of the Laboratory Magnetosphere

Mike Mauel
Columbia University

with help from Darren Garnier, Jay Kesner, Masaki Nishiura, Barrett Rogers, Zensho Yoshida, and the students and scientists conducting research in support of the CTX, LDX, and RT-1 Laboratory Magnetospheres

57th Annual Meeting of the APS Division of Plasma Physics
November 16, 2015 • Savannah, GA

Akira Hasegawa invited to Voyager 2's encounter with Uranus
January 24, 1986



12 Hour Flyby

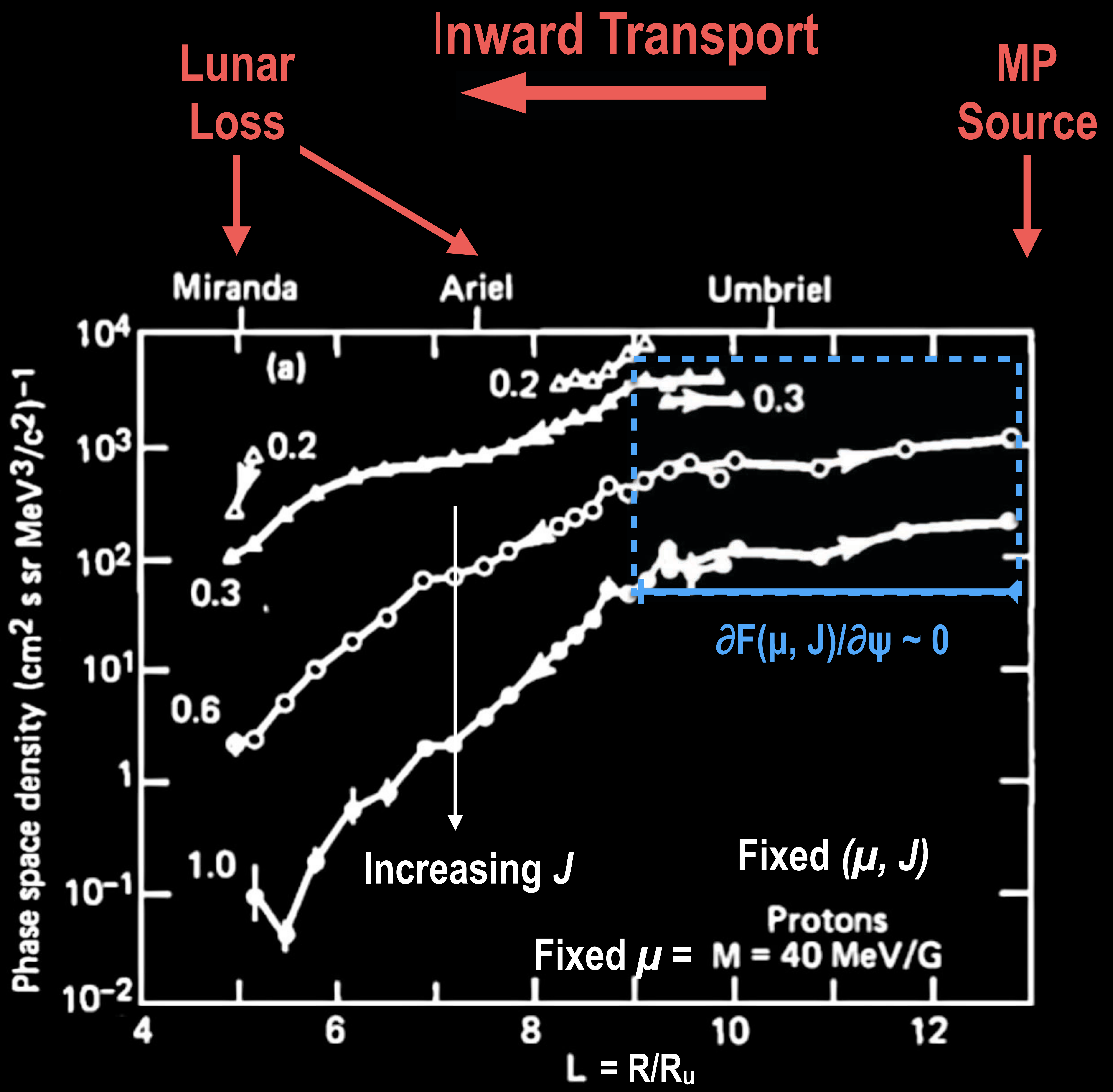
10 Newly Discovered Moons
Large, Tilted Magnetosphere
Long, Twisted Magnetotail
Substorm Injection
Inward diffusion and convection
Energetic Particles
Centrally-peaked Profiles
Plasma - Moon Interactions
…

Ed Stone, *JGR* **92**, 14,873 (1987)

Inward Transport of Energetic Particles

$F(\mu, J, \psi)$

Low-Energy-Charged Particles (LECP)
Protons: 10 keV – 150 MeV



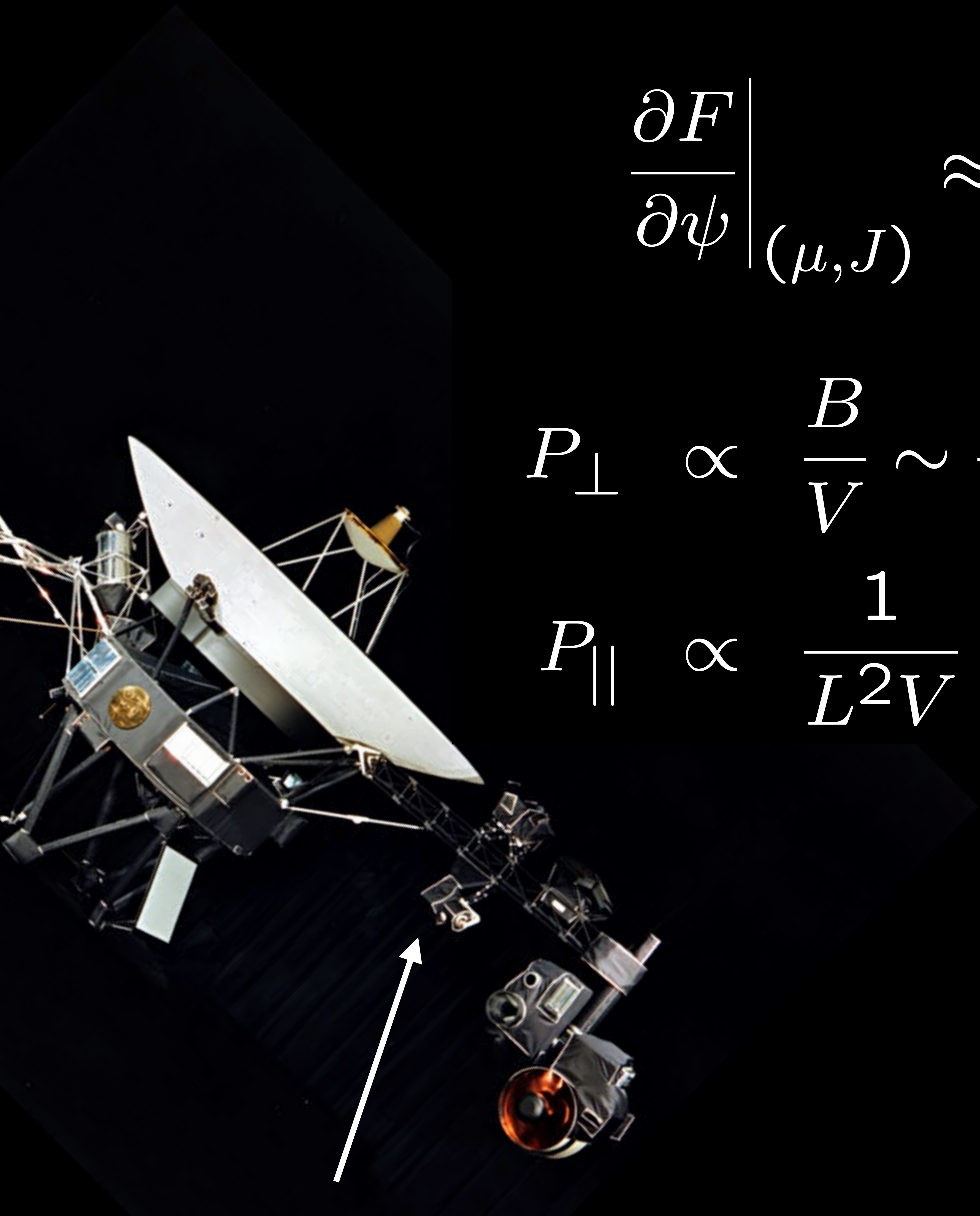
Chen, *et al.*, *JGR* **92**, 15,315 (1987)

Inward Transport Creates Centrally-Peaked Pressure

$$\left.\frac{\partial F}{\partial \psi}\right|_{(\mu,J)} \approx 0$$

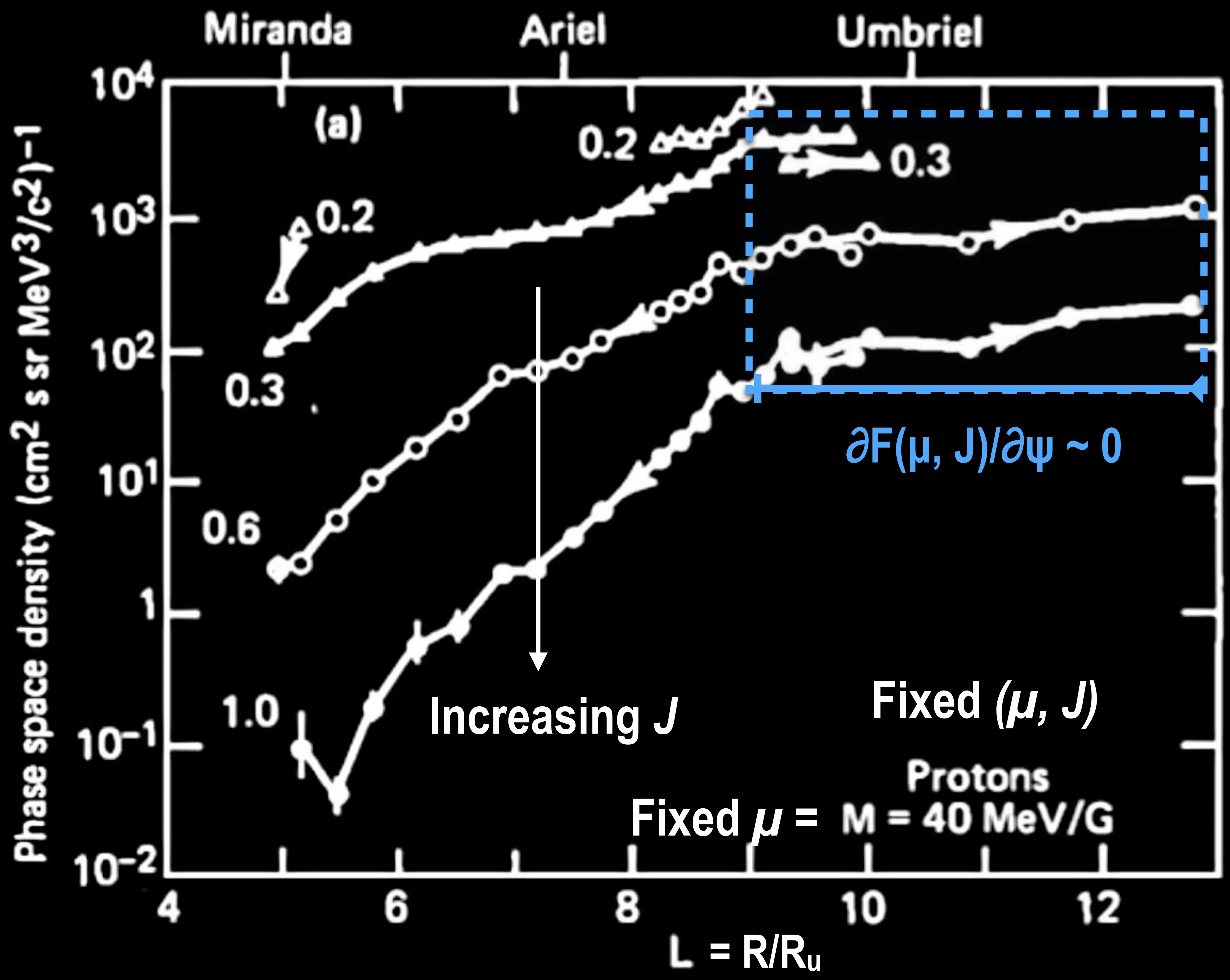
$$P_\perp \propto \frac{B}{V} \sim \frac{1}{L^7}$$

$$P_{||} \propto \frac{1}{L^2 V} \sim \frac{1}{L^6}$$



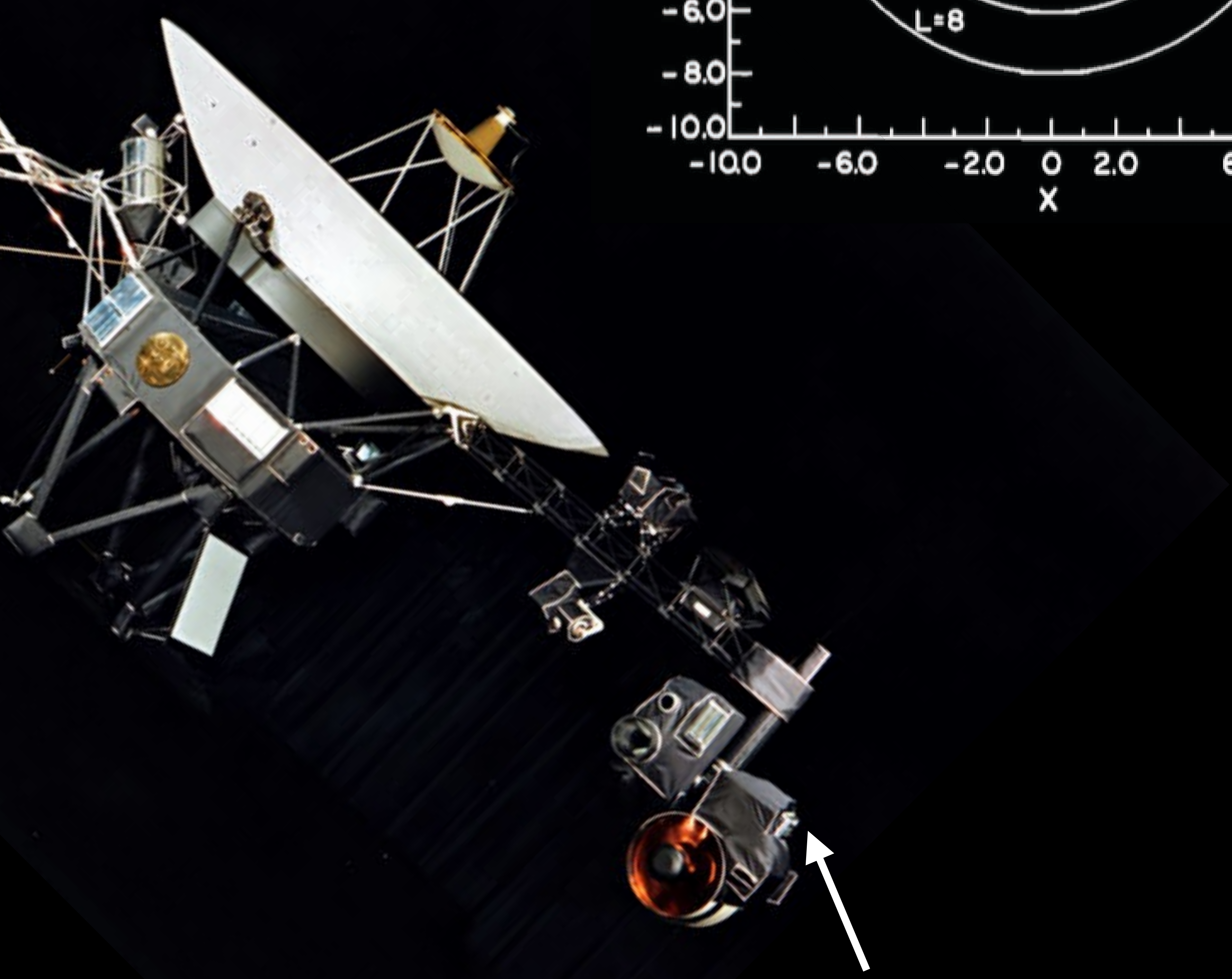
Low-Energy-Charged Particles (LECP)
Protons: 10 keV – 150 MeV

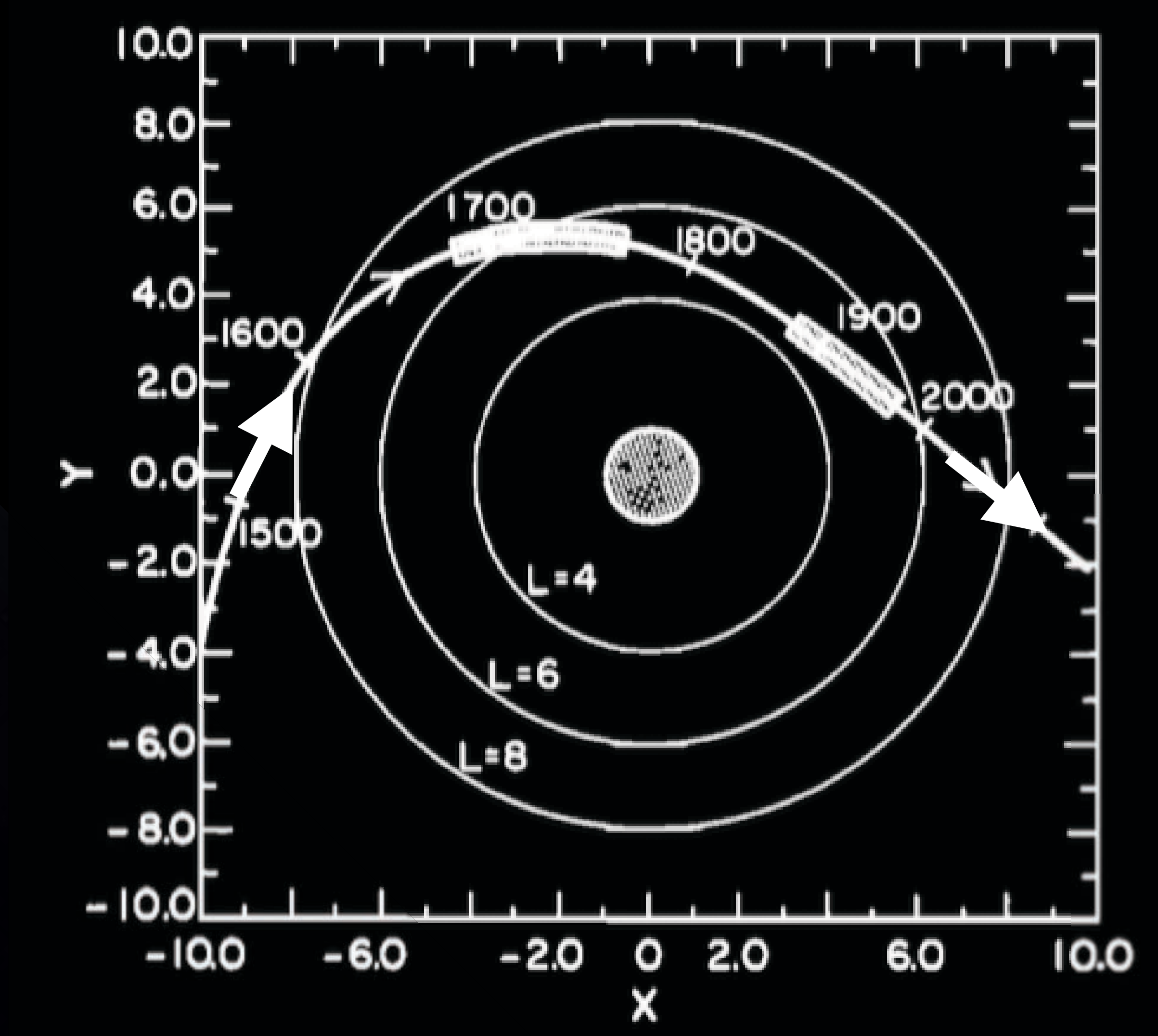
Inward transport of magnetospheric plasma *compresses* and *heats*...

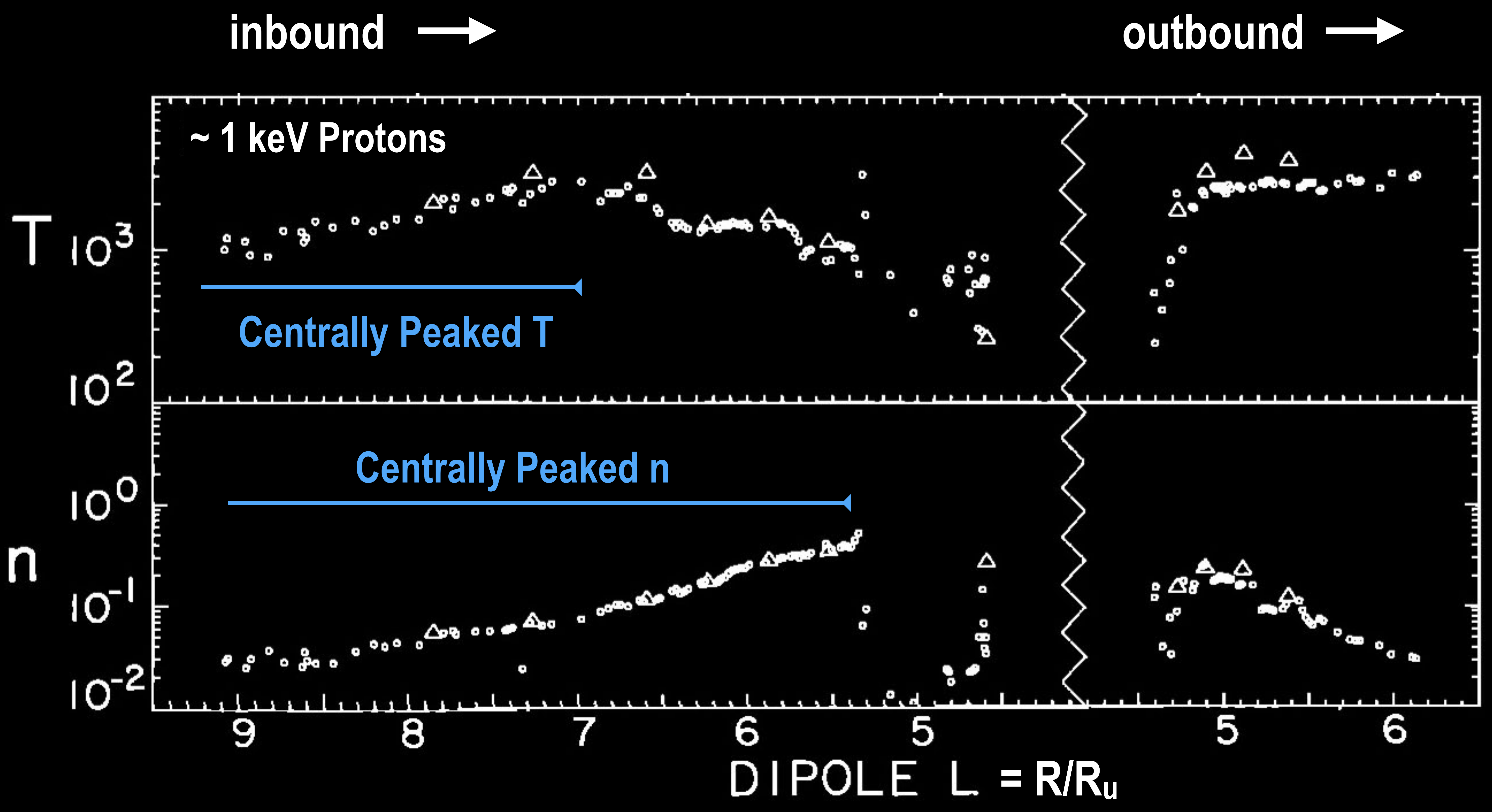


Chen, *et al.*, *JGR* **92**, 15,315 (1987)

Lower Energy (thermal) Plasma has Centrally-Peaked Temperature and Density







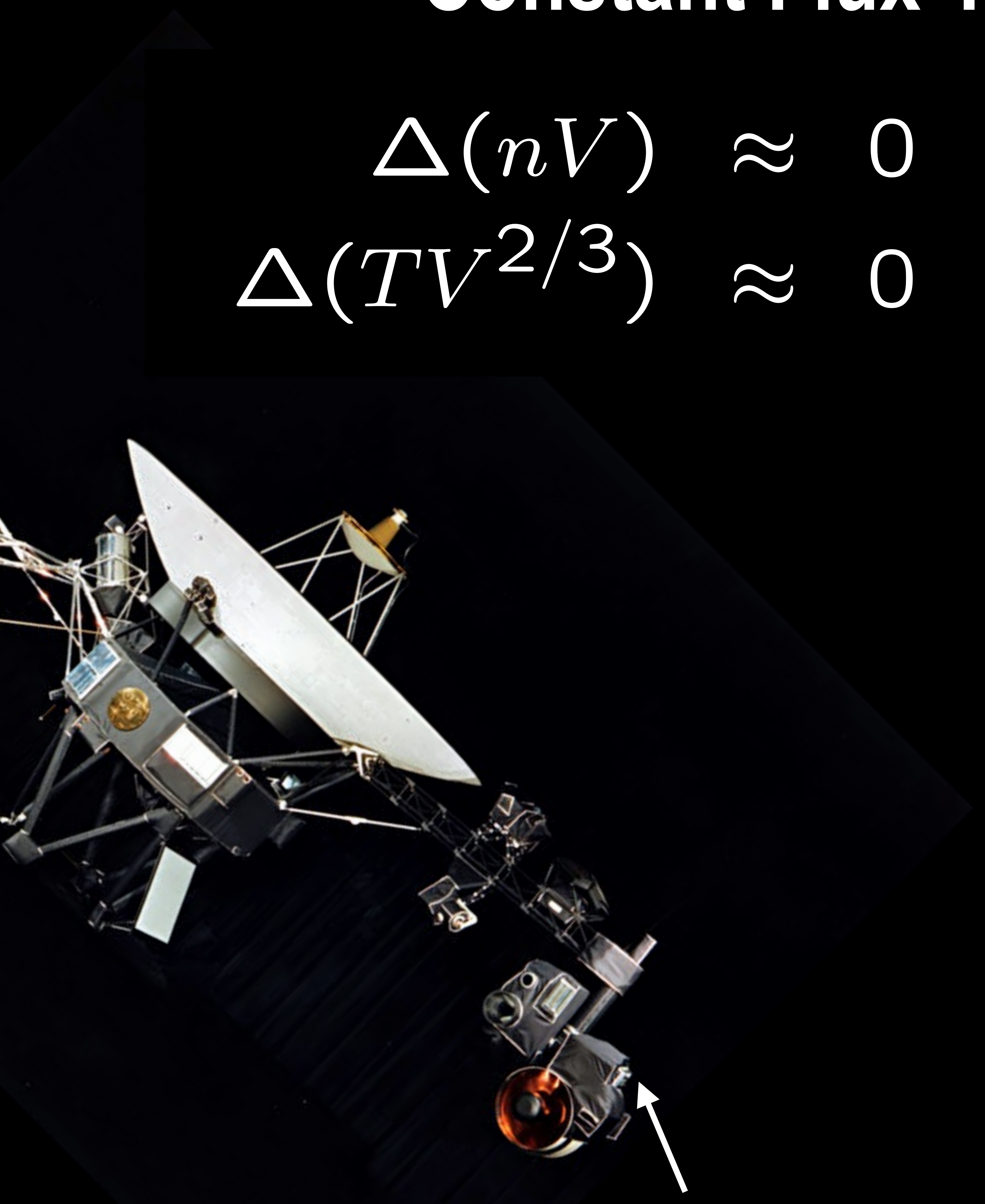
Plasma Science Experiment (PLS)
Ions and Electrons: 10 eV – 5.9 keV

Selesnick and McNutt, *JGR* **92**, 15,249 (1987)

Interchange Motion of Thermal Plasma Creates Regions with Constant Flux-Tube Content and Invariant Temperature

$$\Delta(nV) \approx 0$$
$$\Delta(TV^{2/3}) \approx 0$$

Flux-tube Volume = $V = \int \frac{dl}{B} \propto L^4$



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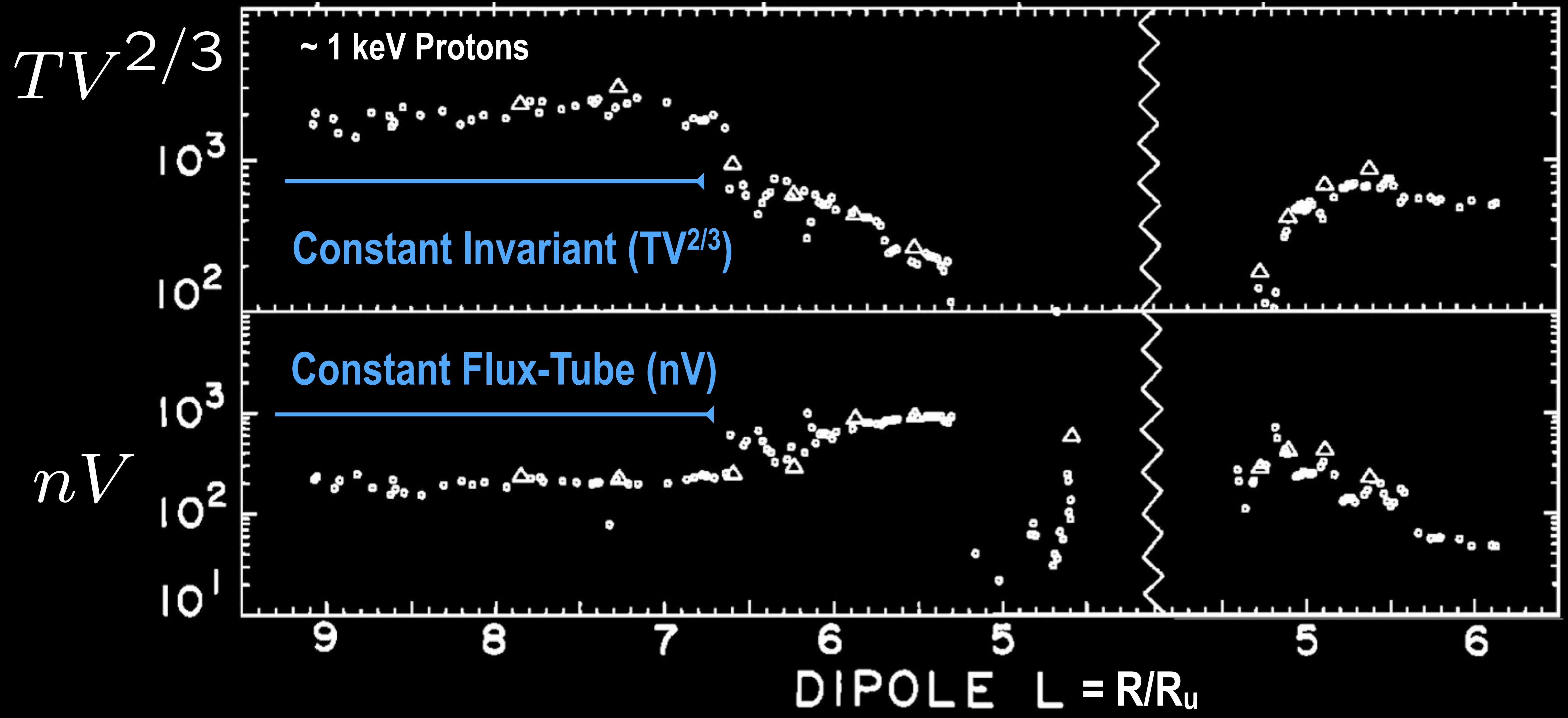


Selesnick and McNutt, *JGR* **92**, 15,249 (1987)

Magnetospheres are Nature's Laboratories for Magnetic Confinement Physics

Voyager 2 Encounters: Jupiter (1979), Saturn (1981), Uranus (1986), Neptune (1989)

Observations of magnetospheric radial transport and stability…

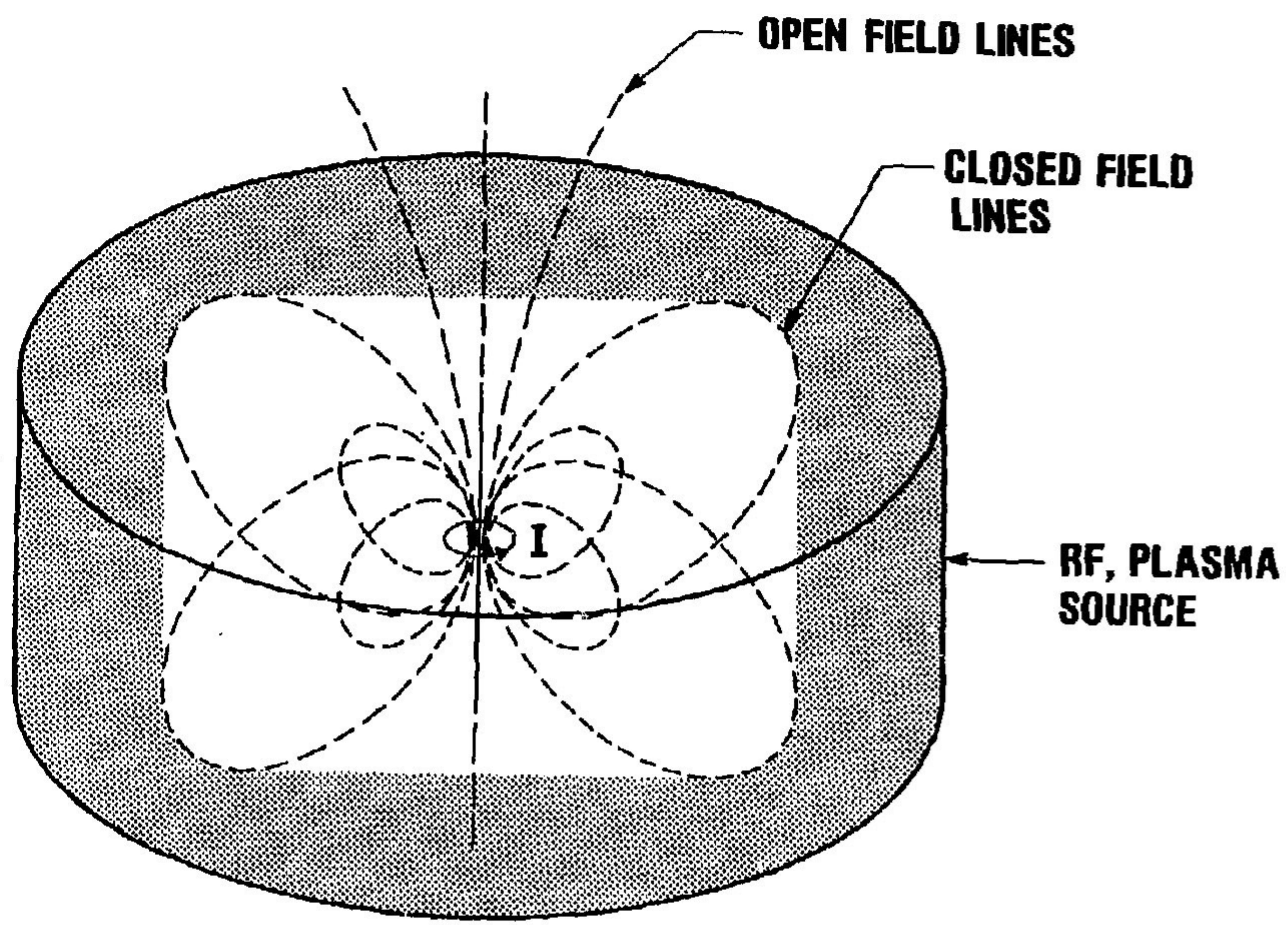
- ➡Inward transport of energetic particles preserve (μ, J) creating ***centrally-peaked pressure***
- ➡ Interchange motion of thermal plasma preserves flux-tube content (**n V**) and invariant temperature (**T $V^{2/3}$**) creating ***centrally peaked profiles***
- ➡ Marginally stable profiles $\Delta(P\,V^{5/3}) \sim 0$ ***at high beta***, $\beta \geq 1$

Stone and Lane, *Science*, **206**, 925 (1979)
Stone, *JGR* **88**, 8639 (1983)

Stone, *JGR* **92**, 14,873 (1987)
Stone and Miner, *Science*, **246**, 1417 (1989)

Does magnetospheric physics apply to magnetic confinement in the laboratory?

- ***Levitate*** a small, high-current superconducting current ring within a very large vacuum vessel
- ***Inject*** heating power and a source of plasma particles at outer edge (SOL)
- ***Somehow drive*** low-frequency fluctuations that create radial transport, preserve (μ, J), and sustain "centrally-peaked" profiles at marginal stability
- ***Achieve*** high beta, $\beta \geq 1$, steady-state, and link space and fusion studies



Akira Hasegawa, *Comments on Plasma Physics and Controlled Fusion* **11**, 147 (1987)

During the past decade, LDX and RT-1 have shown the physics of magnetospheric radial transport and stability ***does apply to the laboratory***

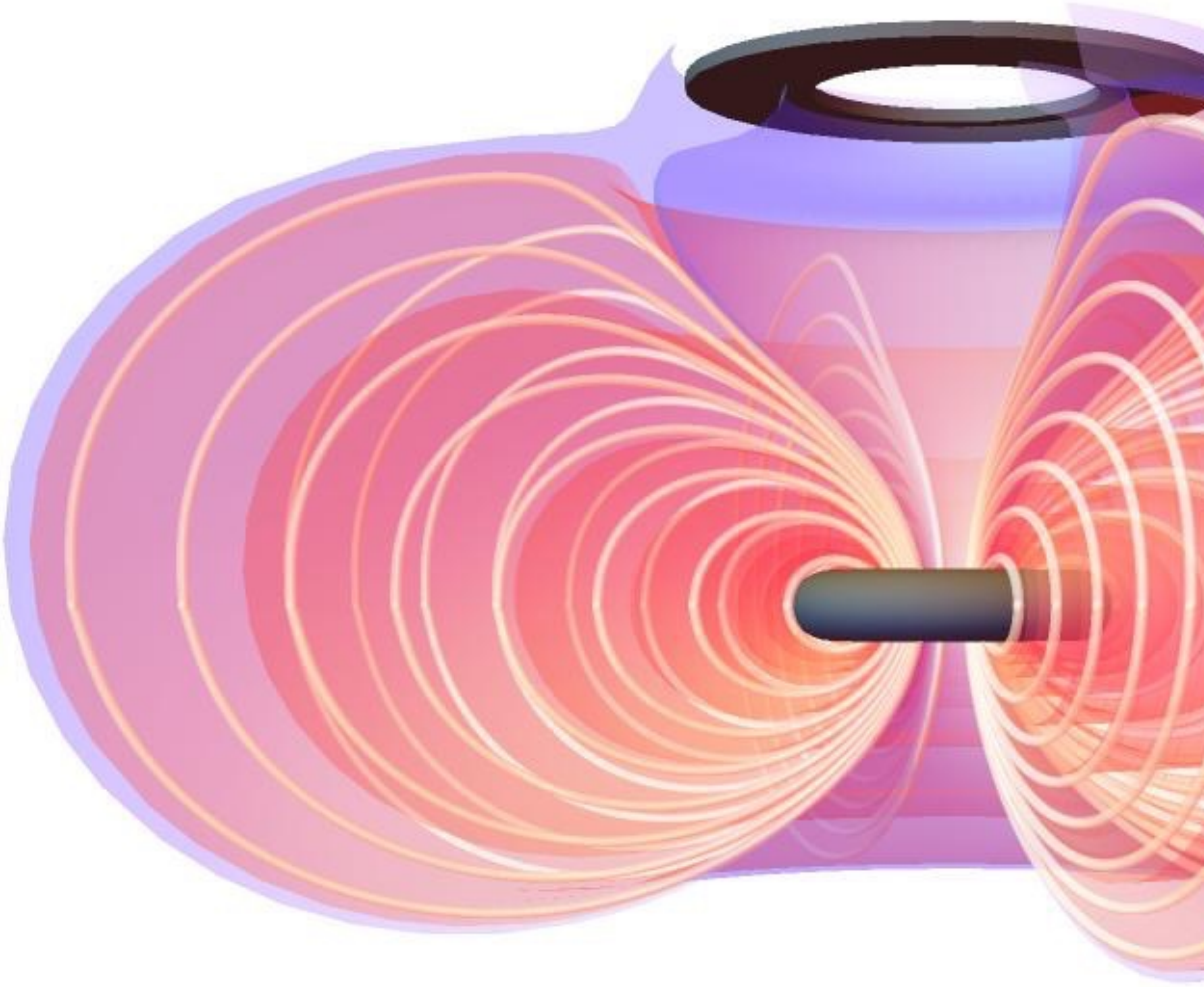
- ***Levitation creates a large confinement volume with plasma regulated by turbulent radial transport.***

- ***Density profiles are always centrally peaked***, and particle transport can be either ***inward*** or ***outward*** depending upon the location of the particle source.

- ***Interchange and entropy instabilities cause low-frequency fluctuations***, and

  Turbulent "self-organization" creates regions of ***nearly uniform*** flux-tube content (**n V**) and entropy density (**P** $V^{5/3}$).

- ***High local beta, β ~ 1, in steady state, can be achieved*** provided drift-resonant fast particle instabilities are stabilized.



LDX and RT-1 have also shown the laboratory magnetosphere is a simple and versatile configuration for ***fundamental study of toroidal magnetic confinement***

- ***Levitation is robust and reliable***

  Very good ***access*** for diagnostics, plasma heating and fueling.

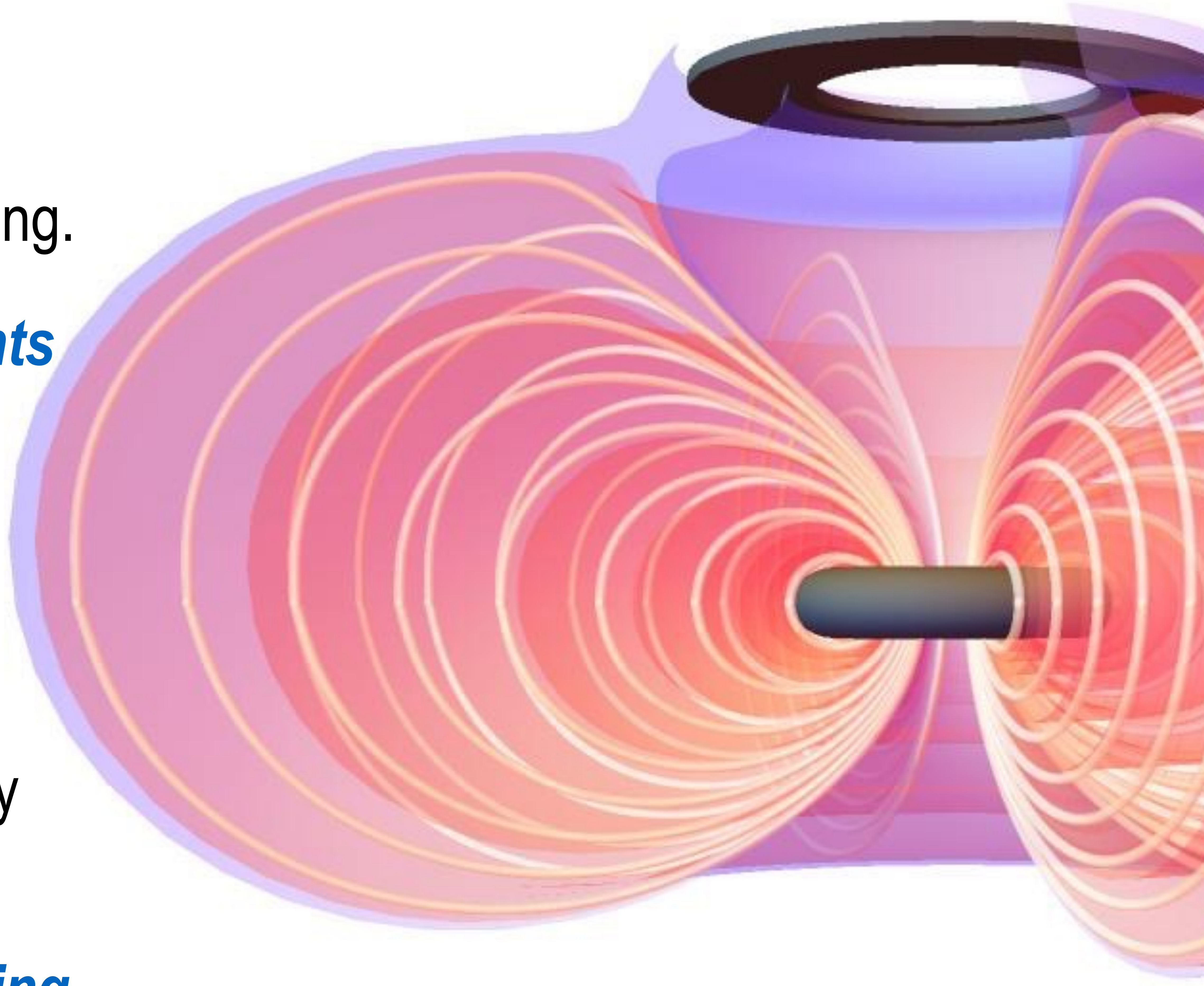
- ***Simple, axisymmetric torus with no field-aligned currents***

  Classical particle orbits with comparable passing and trapped dynamics .

  "***Good" confinement*** of heat, density, energetic particles.

- ***Radial transport processes*** relevant to space and to many toroidal confinement devices.

- ***Nonlinear gyrokinetics is a good model for understanding*** radial transport driven by interchange and entropy mode turbulence.



19 PhD Dissertations

Thomas Roberts, "Local Regulation of Interchange Turbulence in a Dipole-Confined Plasma Torus using Current Injection Feedback", Ph.D. Columbia University, (2015).

Matthew Worstell, "Symmetry Breaking and the Inverse Energy Cascade in a Plasma", Ph.D. Columbia University (2013).

Matt Davis, "Pressure profiles of plasmas confined in the field of a dipole magnet", Ph.D. Columbia (2013).

Sumire Kobayashi, "Gyrokinetic Simulations of Closed Field Line Systems", Ph.D. Dartmouth (2010).

Antoin Cerfon, "Analytic calculations of MHD equilibria and of MHD stability boundaries in fusion plasmas", Ph.D. MIT (2010).

Yoshihisa Yano, "Experimental analysis of he magnetic field structure on the high-beta plasmas in the magnetospheric plasma device," 2010, PhD, U. Tokyo

Jennifer Ellsworth, "Characterization of Low-frequency Density Fluctuations in Dipole-confined Laboratory Plasmas", Ph.D., MIT, (2010).

Brian Grierson, "Interchange Turbulence in a Dipole-Confined Plasma," Ph.D. Columbia (2009).

Alex Boxer, "Interchange Stationary Profiles in the Levitated Dipole Experiment (LDX)", Ph.D., MIT, (2008).

Alexie Kouznetsov, "Theoretical prediction of тau_E and β in a large aspect ratio LDX", Ph.D., MIT (2007).

Eugenio Ortiz, "Observation of Hot Electron Interchange Instability in a High Beta Dipole Confined Plasma", Ph.D. Columbia (2007).

Ishtak Karim, "Equilibrium and Stability Studies of Plasmas in a Dipole Magnetic Fields Using Magnetic Measurements", Ph.D., MIT, (2007).

Natalia Krasheninnikova, "Effects of hot electrons on the stability of a closed field line plasma," Ph.D. MIT (2006).

Haruhiko Saitoh, "Experimental Study on the Confinement of Electron Plasma and Formation of Flow of Neutral Plasma in an Internal Conductor System", Ph.D., Univ. Tokyo (2005).

Ben Levitt, "Global Mode Analysis of Centrifugal and Curvature Driven Interchange Instabilities," Ph.D. Columbia (2004).

Dmitry Maslovsky, "Suppression of Nonlinear Frequency Sweeping of Resonant Interchange Modes in a Magnetic Dipole with Applied Radio Frequency Fields," Ph.D. Columbia (2003).

John Tonge, "Particle Simulations of Instabilities in Space and Astrophysical Plasmas", Ph.D. UCLA (2002).

Andrei Simakov, "Plasma stability in a dipole magnetic field", Ph.D. MIT (2001).

Harren Warren, "Observation of Chaotic Particle Transport Driven by Drift-Resonant Fluctuations in the Collisionless Terrella Experiment," Ph.D. Columbia (1994).

and **10 M.S. Dissertations**

Outline

- ***Two laboratory magnetospheres***: LDX and RT-1, having large flux-tube expansion
- ***Particle transport and turbulent relaxation*** to centrally-peaked profiles (***LDX***)
    - Matt Davis (PhD *Columbia*) and Alex Boxer (PhD *MIT*)
- ***Understanding entropy mode turbulence*** near marginal stability (***GS2***)
    - Sumire Kobayashi (PhD *Dartmouth/Rogers*)
- ***Achieving record high local β*** by stabilizing fast electron interchange instability (***RT-1***)
    - Yoshihisa Yano (PhD *Univ Tokyo/Yoshida*)
- ***Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement***

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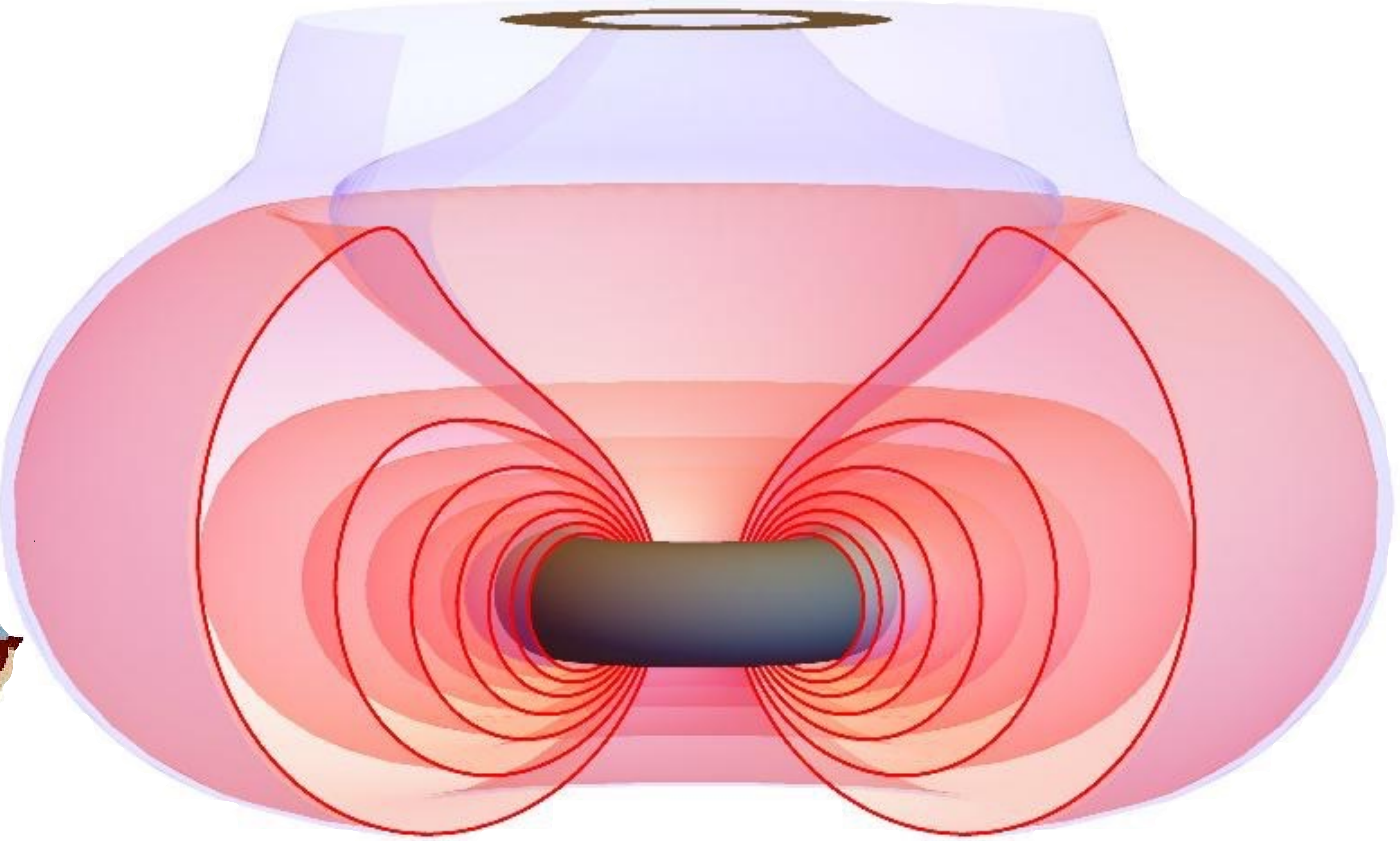
Two Laboratory Magnetospheres



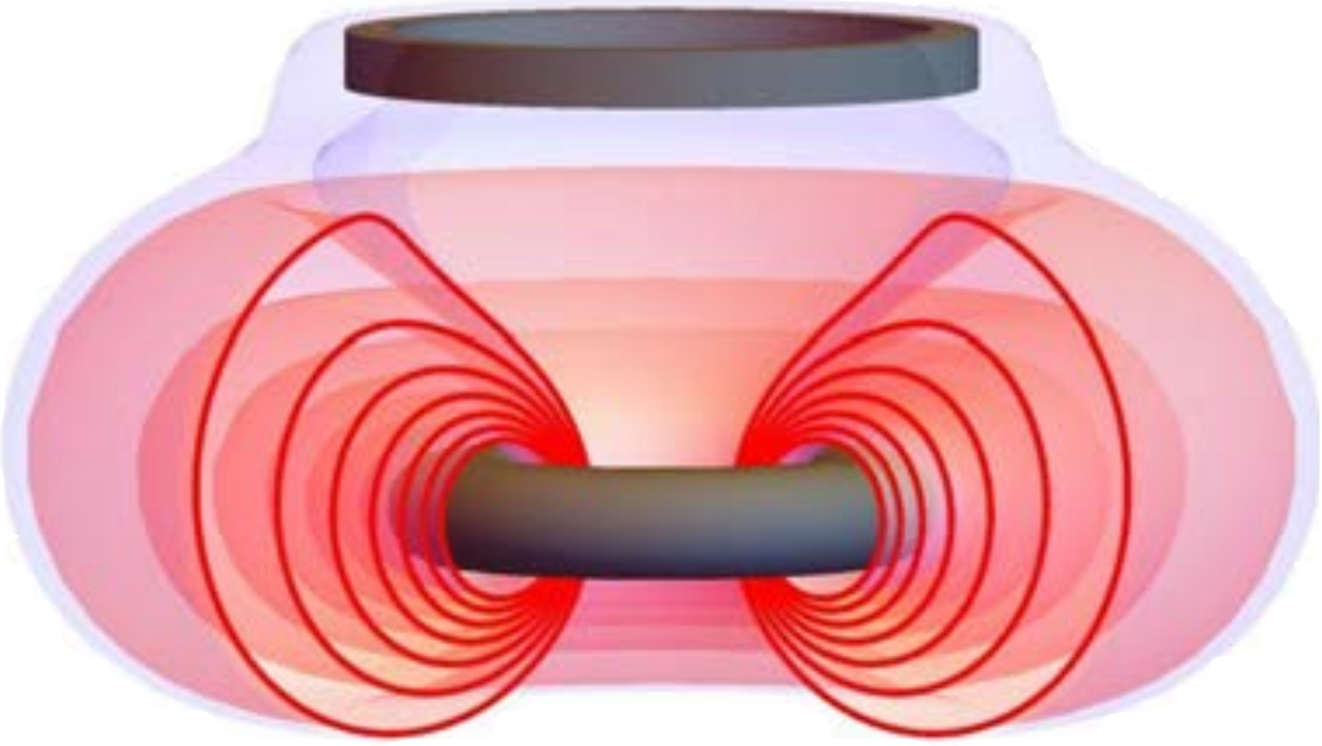
3.6 m

Levitated Dipole Experiment (LDX)

(1.2 MA · 0.41 MA m^2 · 550 kJ · 565 kg)

Nb_3Sn · 3 Hours Float Time

24 kW ECRH



1.8 m

Ring Trap 1 (RT-1)

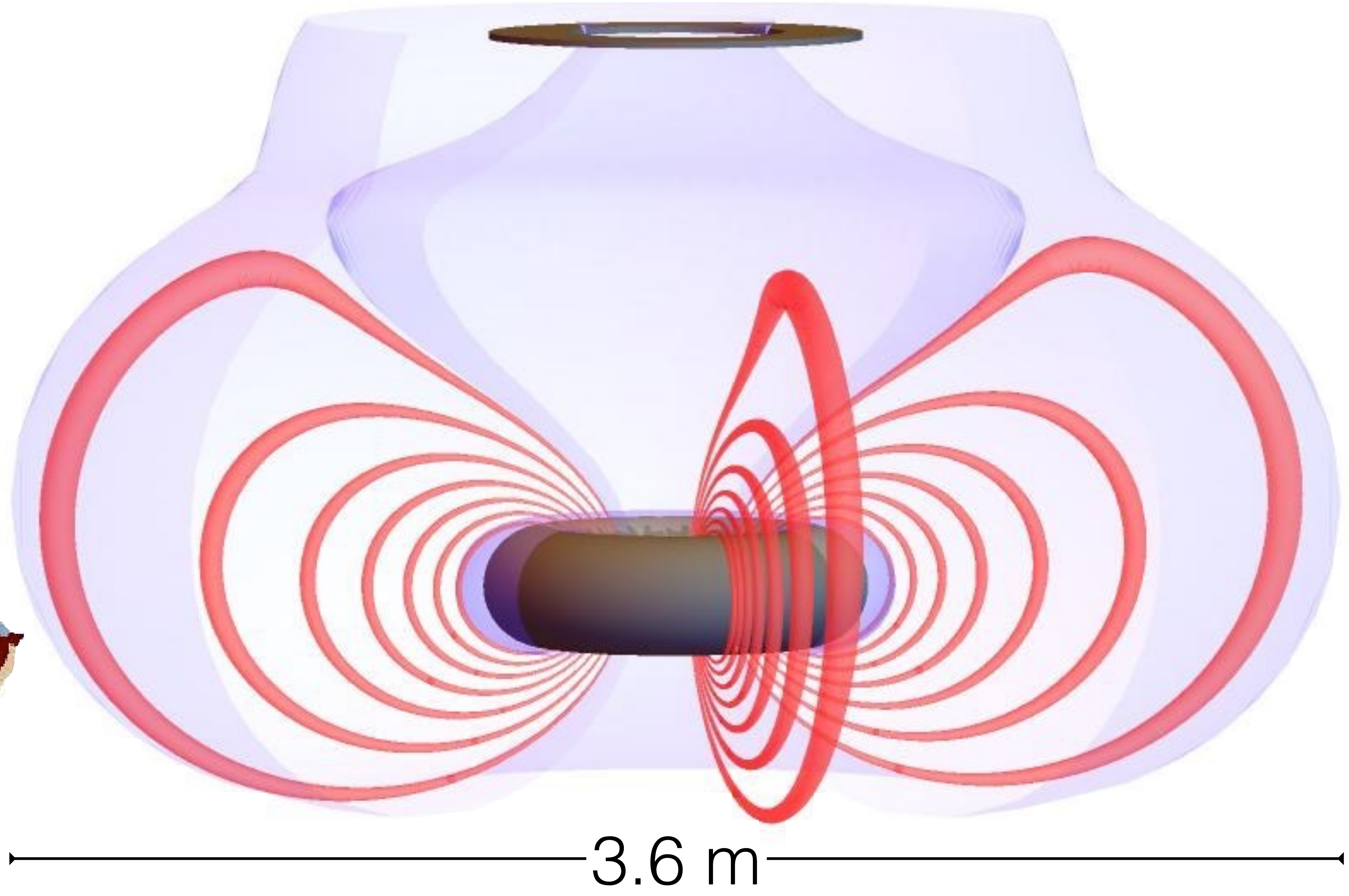
(0.25 MA · 0.17 MA m^2 · 22 kJ · 112 kg)

Bi-2223 · 6 Hours Float Time

50 kW ECRH

Laboratory Magnetospheres: Designed for Maximum Flux Tube Expansion

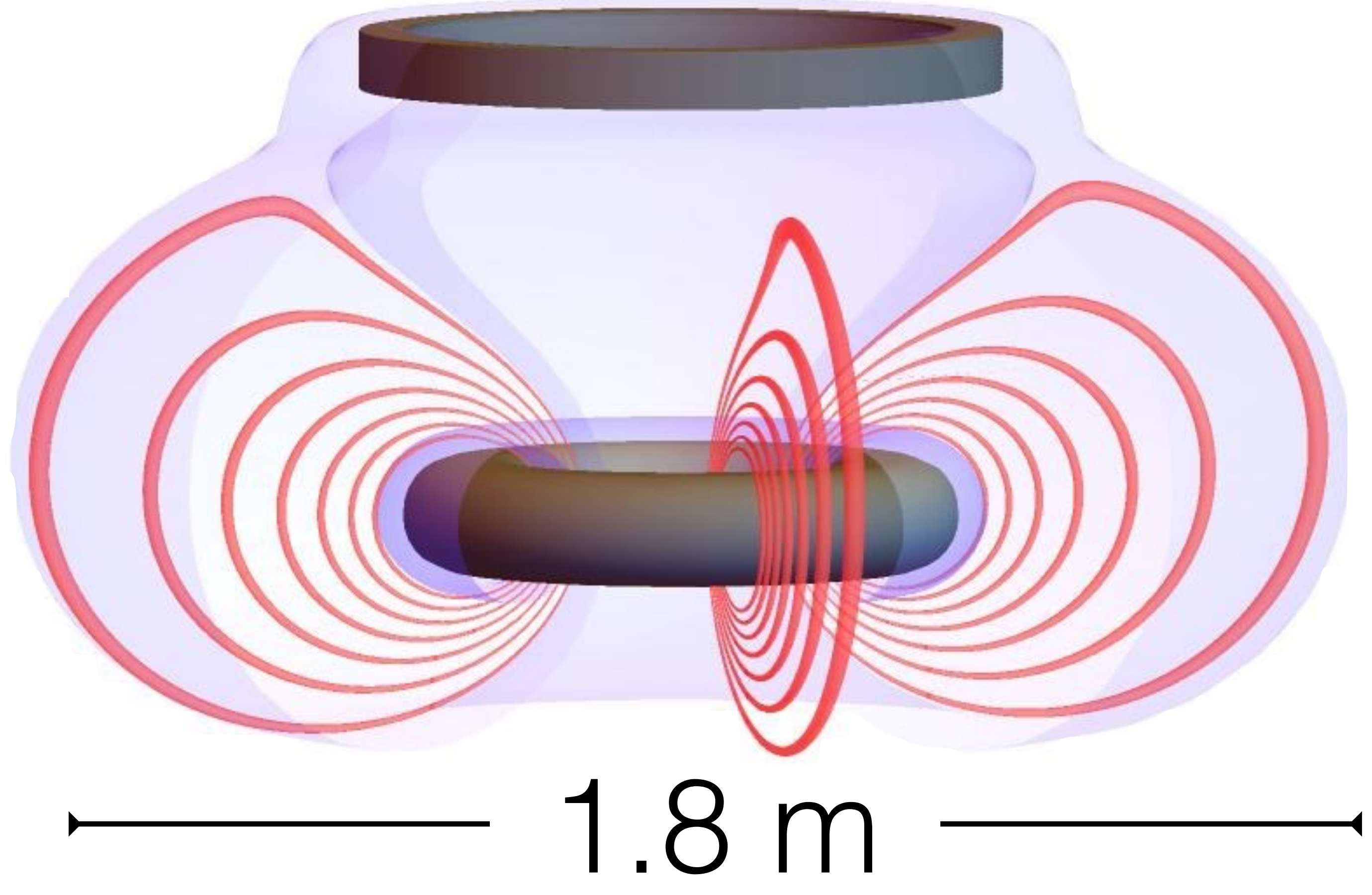
$$V = \int \frac{dl}{B} \propto L^4$$



Levitated Dipole Experiment (LDX)

Flux Tube Expansion:

δV(out)/δV(in) = 100



Ring Trap 1 (RT-1)

Flux Tube Expansion:

δV(out)/δV(in) = 40

Large Flux Tube Expansion Maximizes Plasma's Stable Pressure Gradient

Ideal MHD interchange instability limits plasma pressure gradient relative to the rate of **flux-tube expansion…**

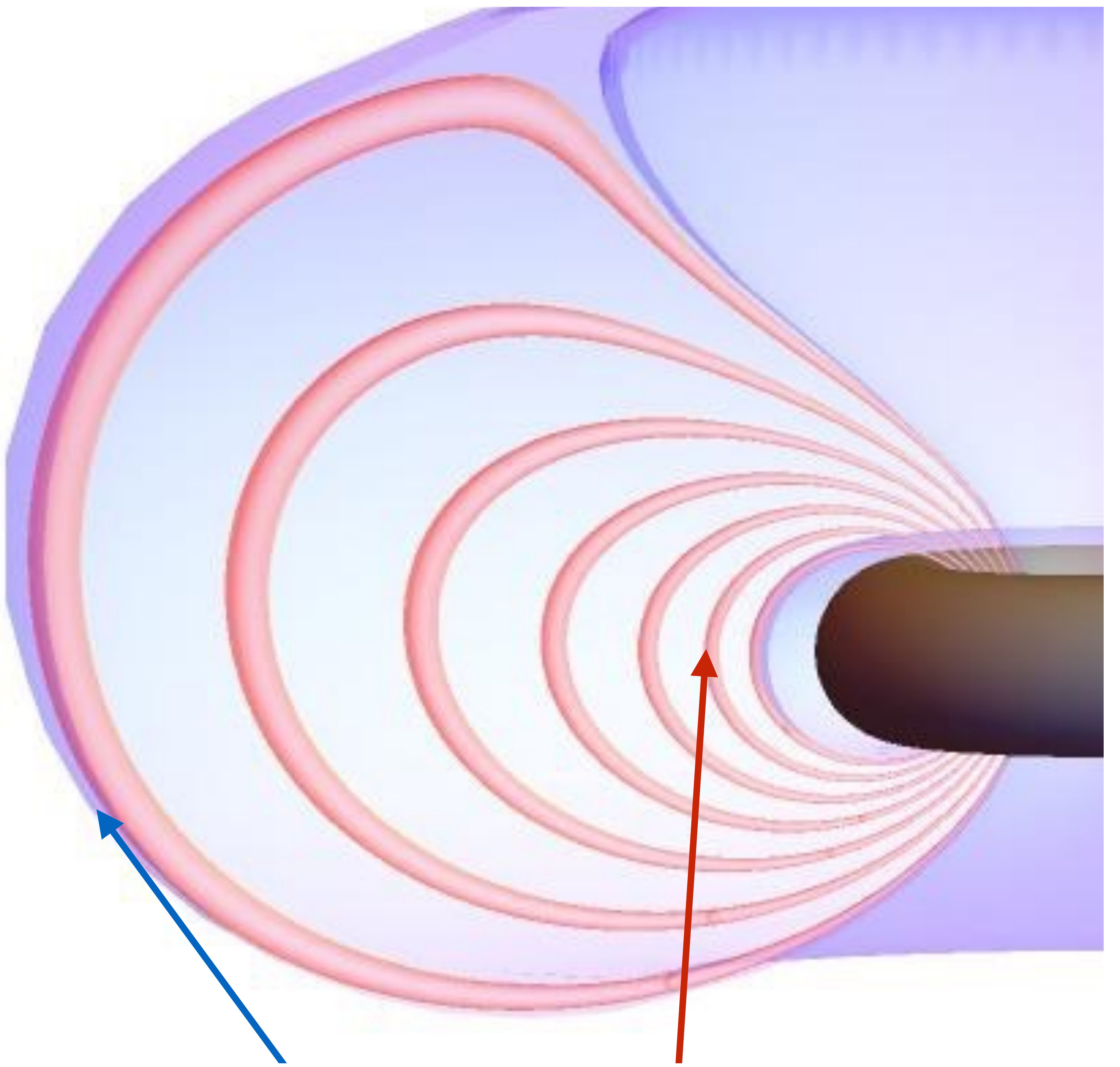
$$\Delta W_p = \Delta \left(P V^{5/3} \right) \frac{\Delta V}{V^{5/3}} > 0$$

and steep pressure gradients are MHD stable, ***even as β >> 1***.

MHD stability ***requires*** finite plasma pressure at edge.

$$\Delta W_p = \underbrace{\Delta P \Delta V}_{\text{Bad Curvature}} + \underbrace{\frac{5}{3}\frac{P}{V}(\Delta V)^2}_{\text{Compressibility}} > 0$$

Magnetosphere: Magnetopause plasma sustained by solar wind
Laboratory: Scrape-off-layer (SOL) maintained by escaping plasma

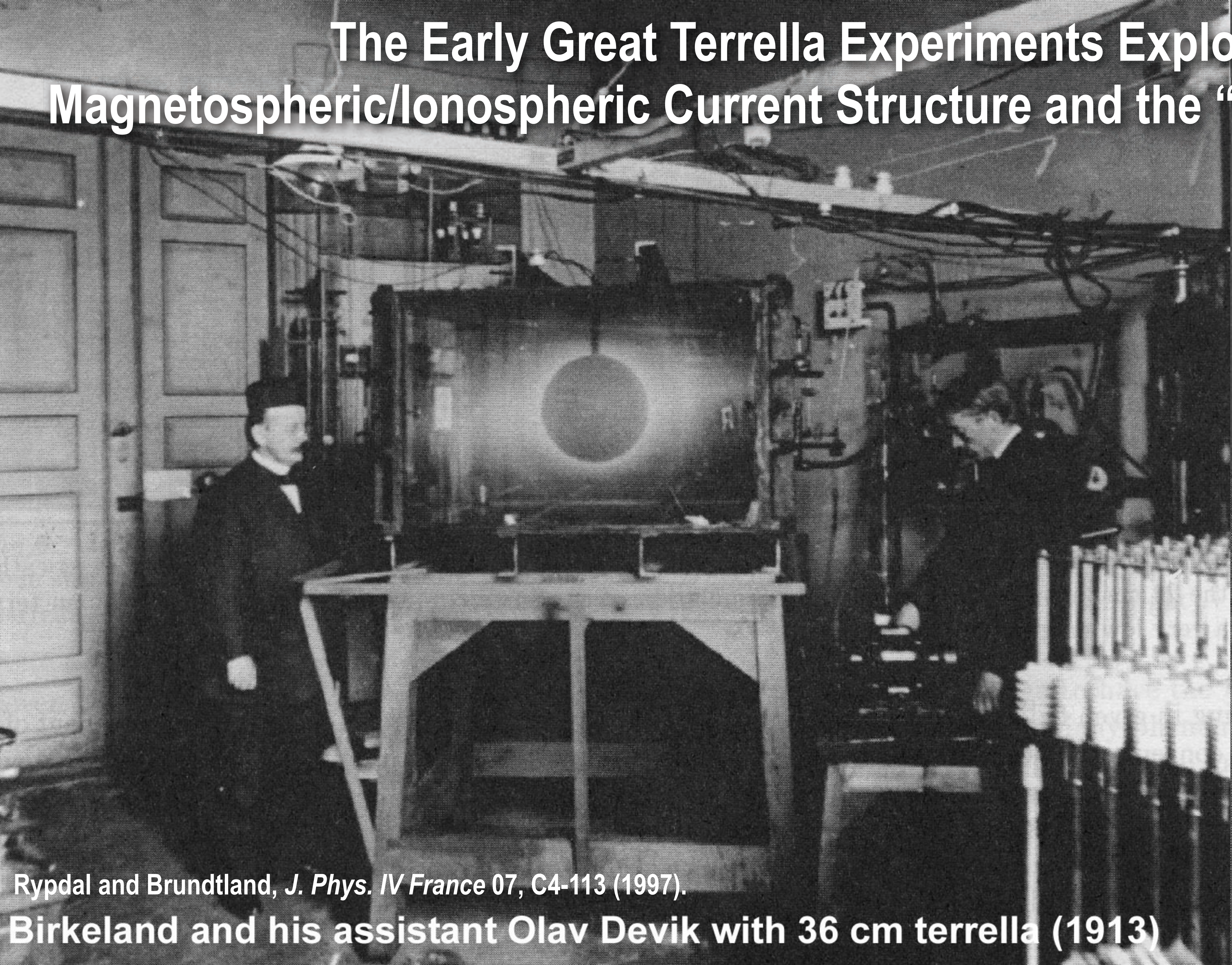


Edge pressure must rise in proportion to core pressure

$$\frac{P(core)}{P(edge)} \leq \left(\underbrace{\frac{V(edge)}{V(core)}}_{\text{Flux-Tube Expansion}} \right)^{5/3} \sim 2000$$

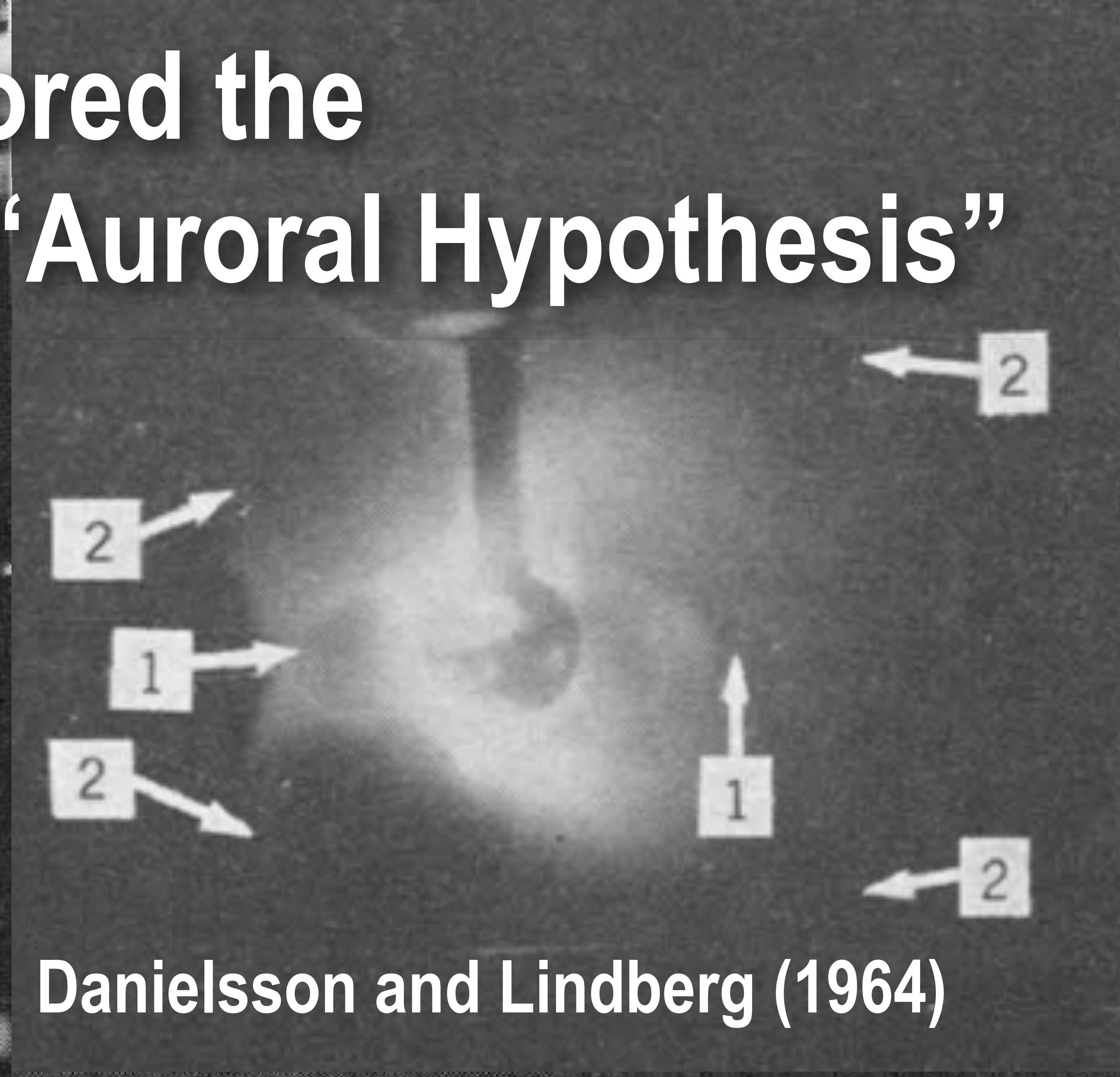
Rosenbluth and Longmire, "Stability of plasmas confined by magnetic fields," *Ann Phys*, **1**, 120 (1957)
Gold, "Motions in the magnetosphere of the Earth," *JGR*, **64** 1219 (1959)
Garnier, *et al.*, "Magnetohydrodynamic stability in a levitated dipole," *PoP*, **6**, 3431 (1999).
Krasheninnikov, *et al.*, "Magnetic dipole equilibrium solution at finite plasma pressure," *PRL*, **82**, 2689 (1999)

The Early Great Terrella Experiments Explored the Magnetospheric/Ionospheric Current Structure and the "Auroral Hypothesis"

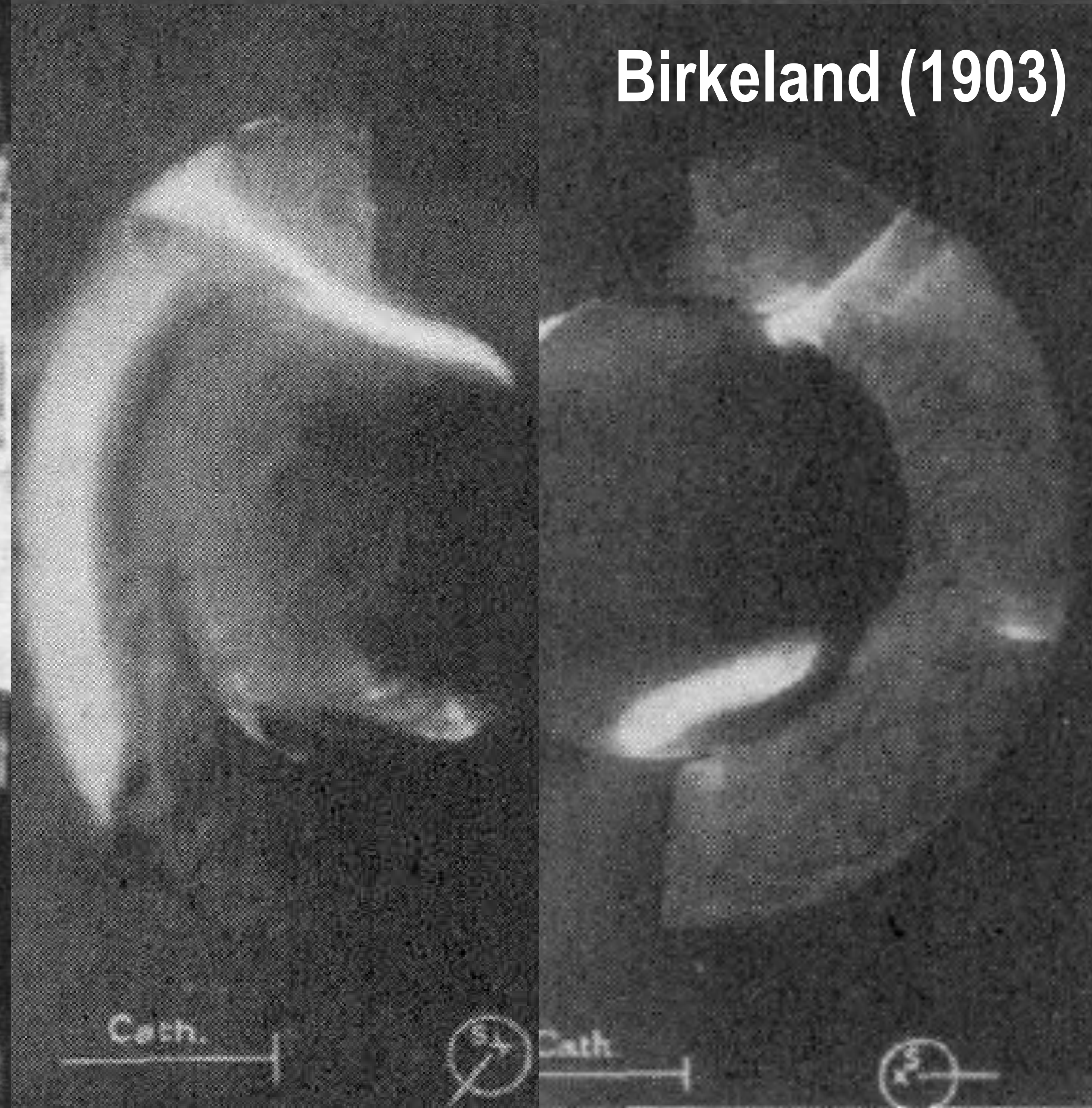


Rypdal and Brundtland, *J. Phys. IV France* 07, C4-113 (1997).

Birkeland and his assistant Olav Devik with 36 cm terrella (1913)

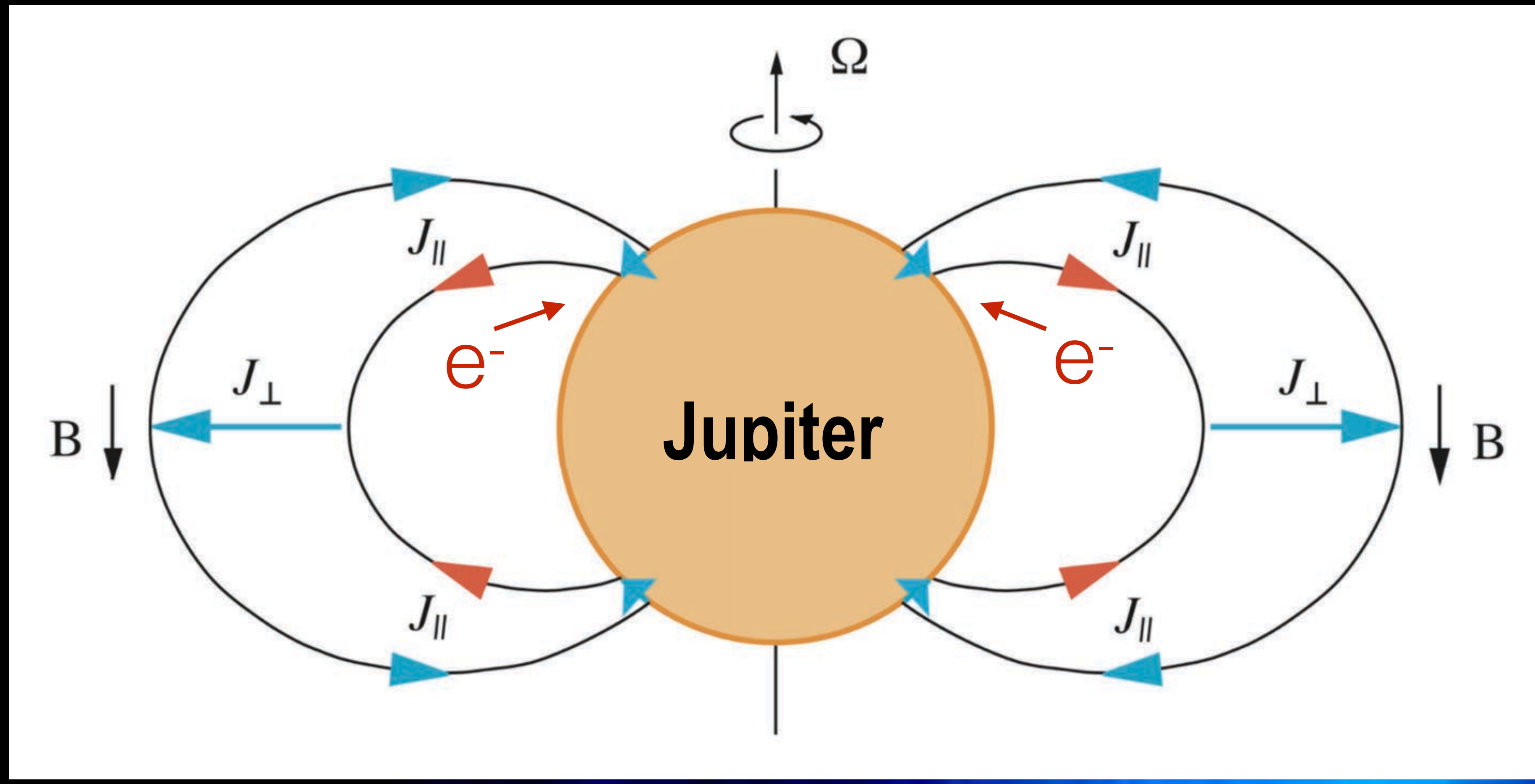


Danielsson and Lindberg (1964)



Birkeland (1903)

The Laboratory Magnetosphere Explores Stability and Transport *Without* Field-Aligned Currents and *Without* the Magnetospheric Dynamo



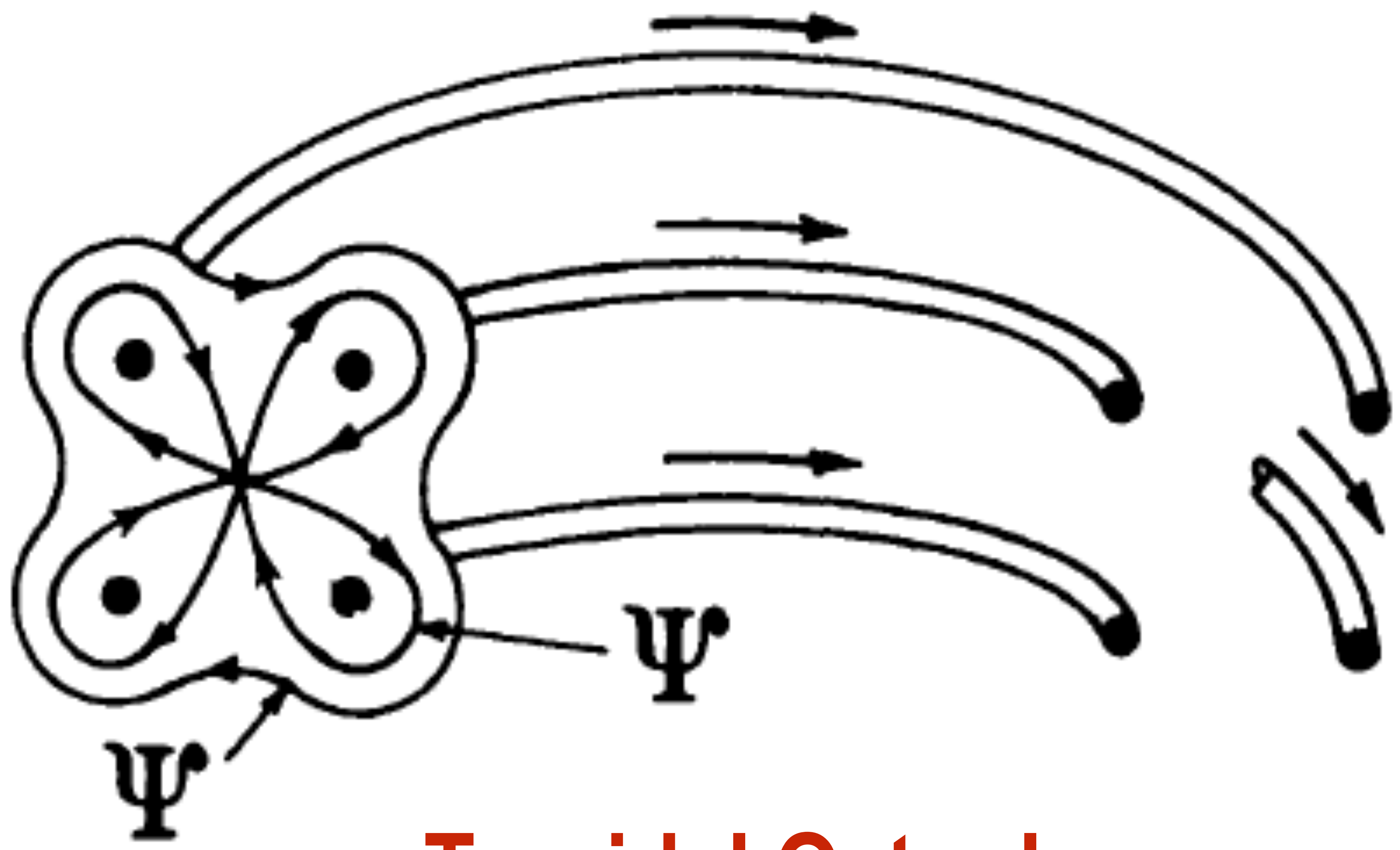
Magnetospheric Dynamo:
100 TW Auroral Power
Regulates Interchange Motion

Hill and Vasyliūnas, "Jovian auroral signature of Io's corotational wake," JGR, 107, 1464 (2002).

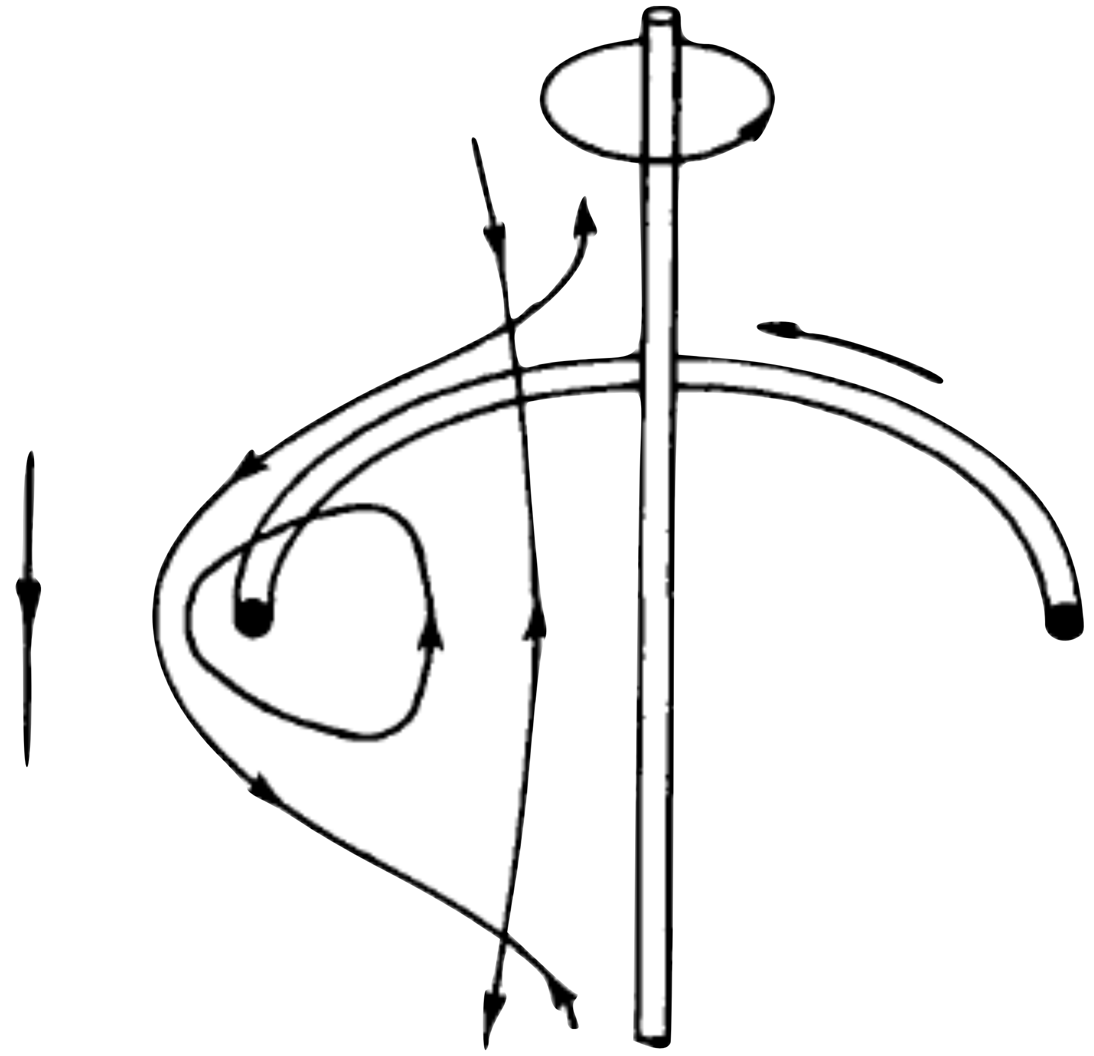
Hubble (Dec 9, 2000)

Internal Rings were used in Early Confinement Experiments to explore Stability and Transport with Good Curvature, Average Good Curvature, and Magnetic Shear

Yoshikawa, "Experiments on plasma confinement in internal-ring devices," *Nuc Fus* **13**, 433 (1973)



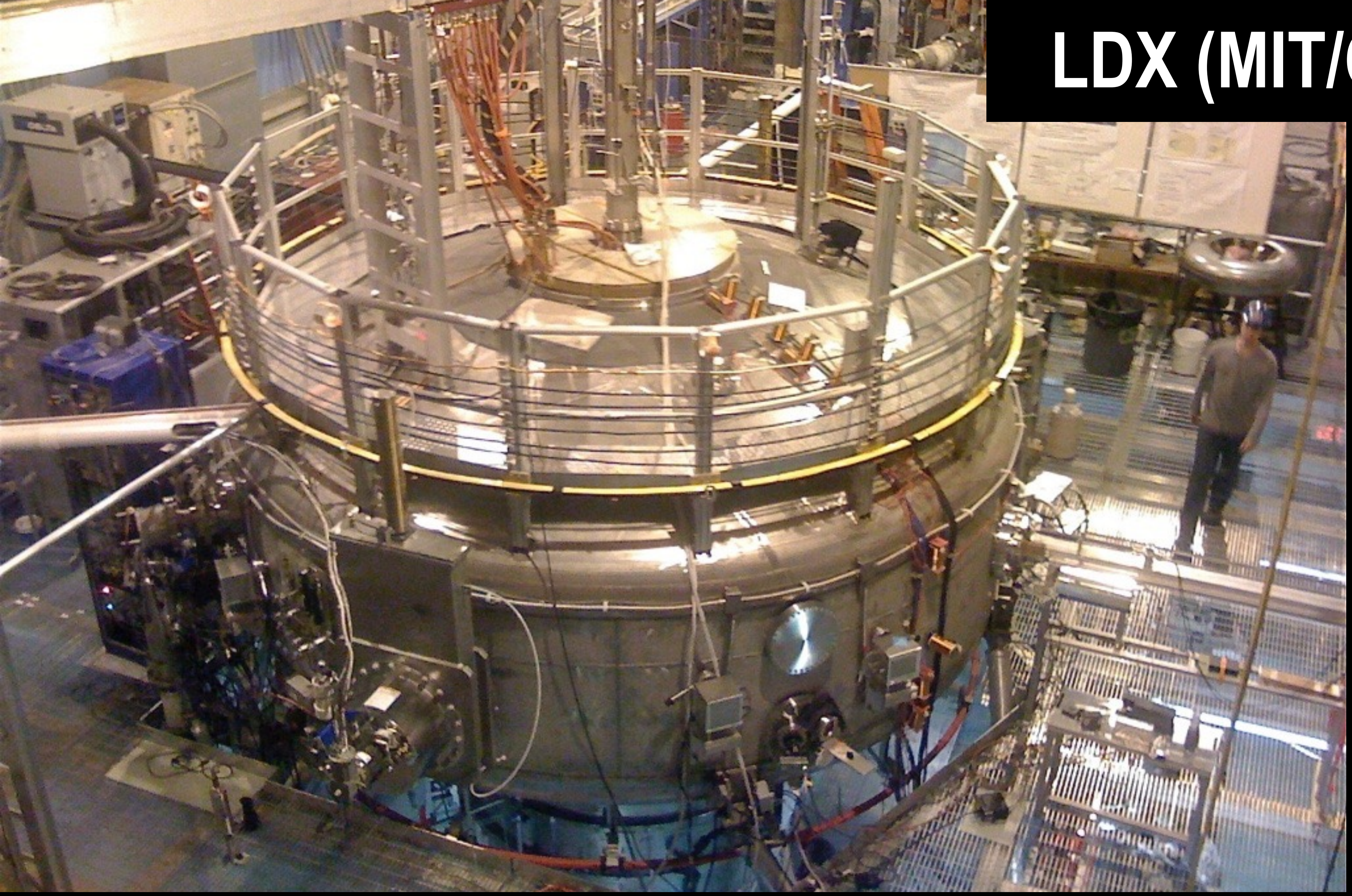
Toroidal Octuple
Good curvature
Magnetic shear

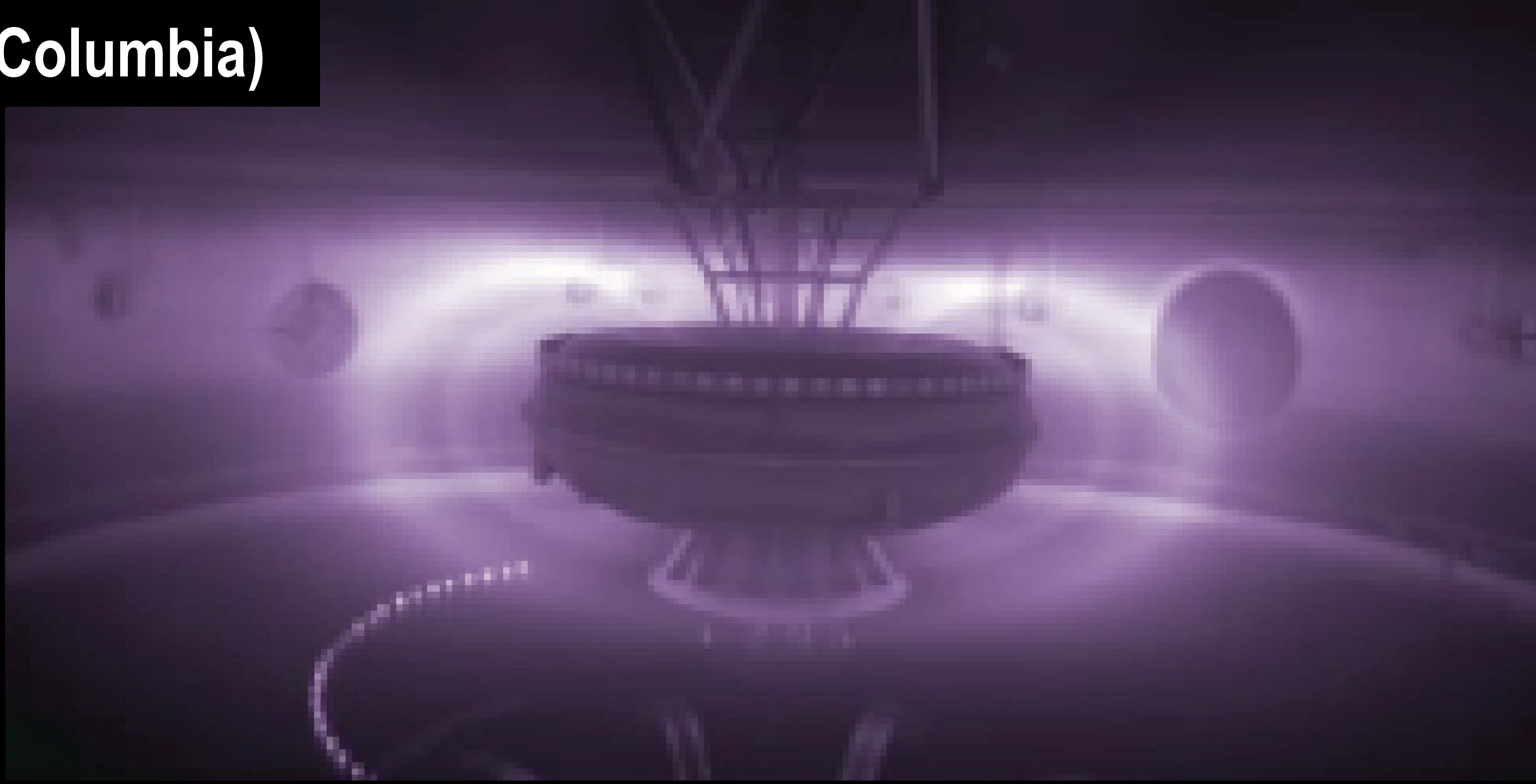


Spherator/Levitron
Average good curvature
Magnetic shear

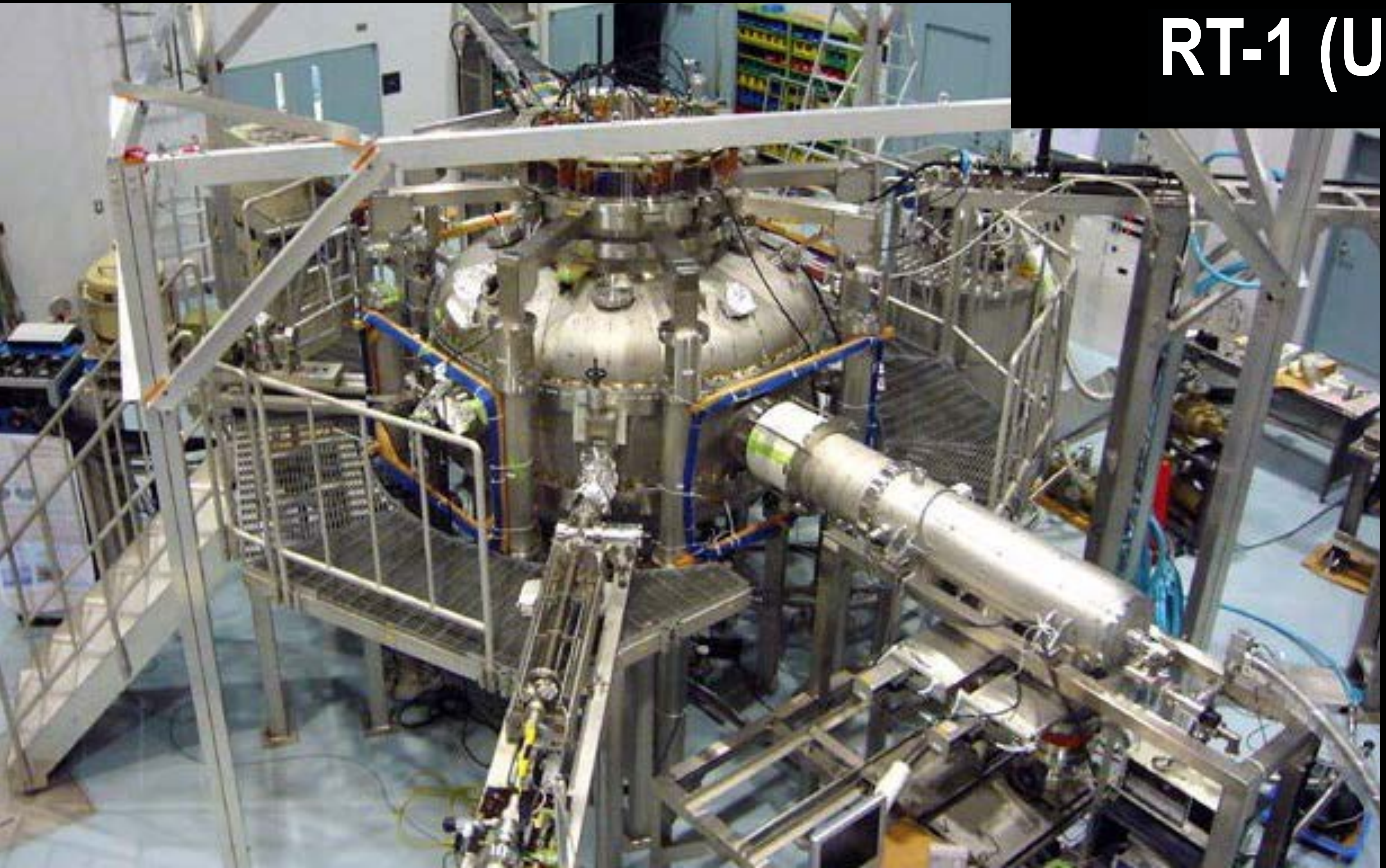
Laboratory Magnetospheres Explore Stability and Transport with the ***Large Flux-Tube Expansion Found in Space***

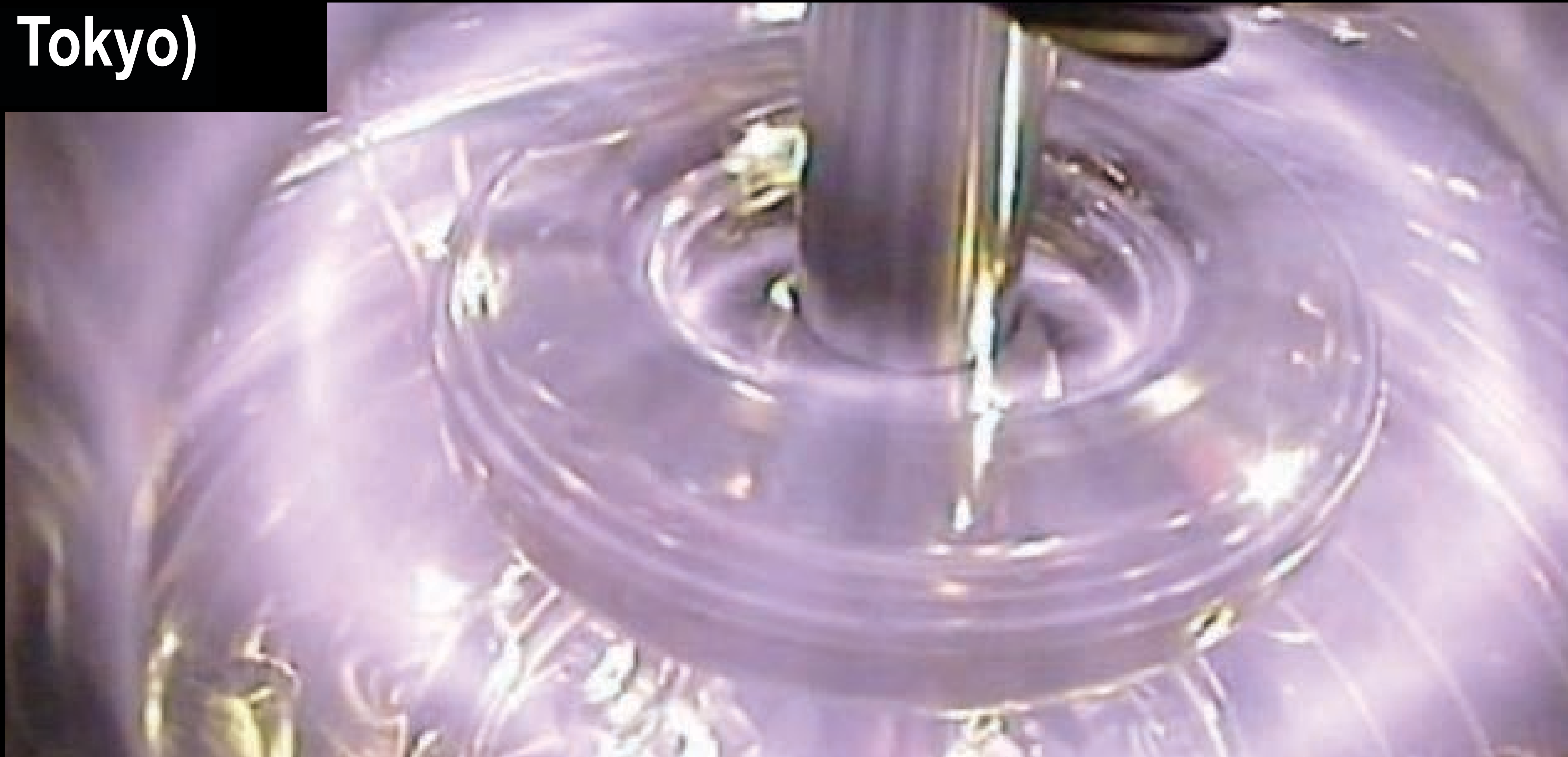
LDX (MIT/Columbia)



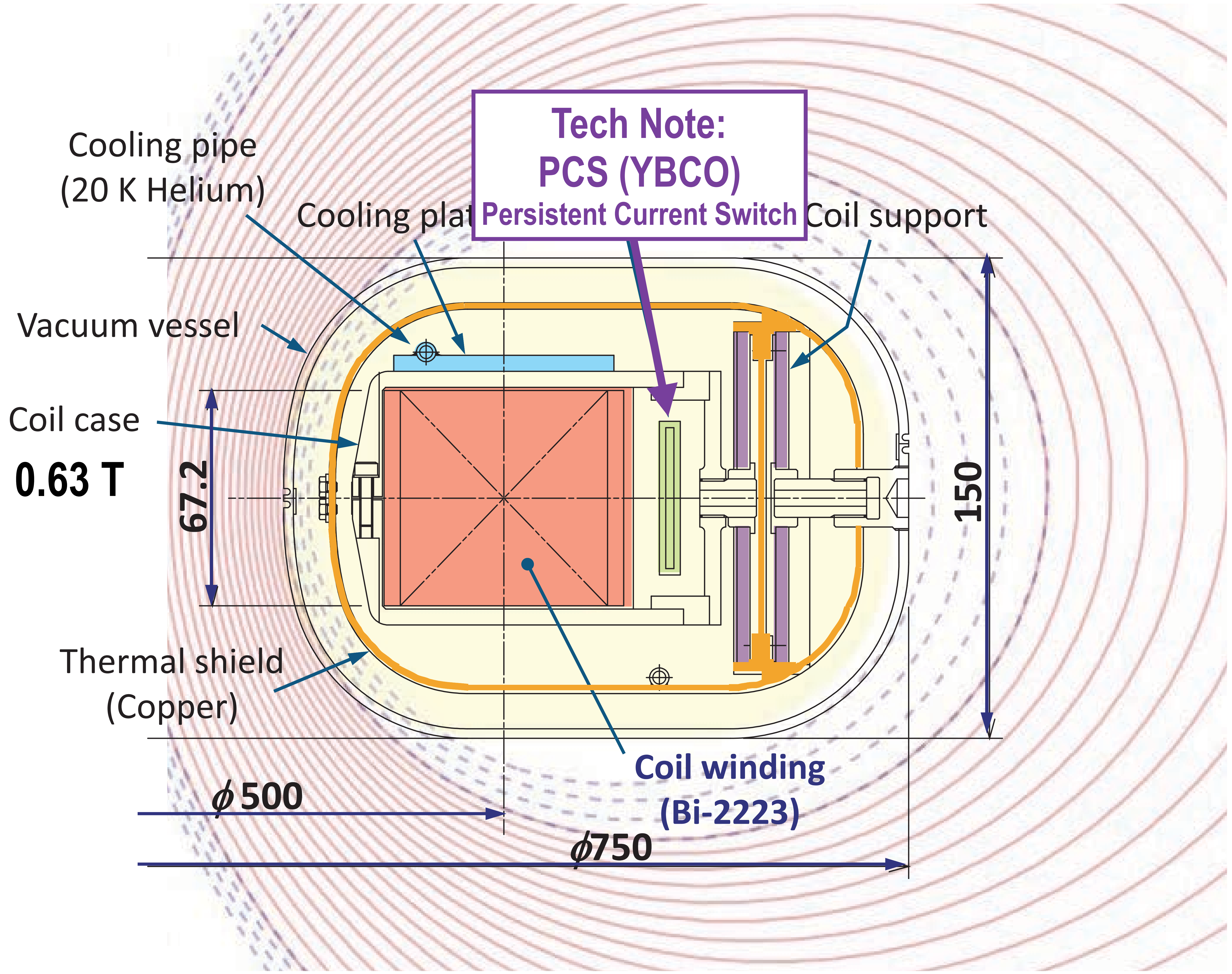


RT-1 (U Tokyo)



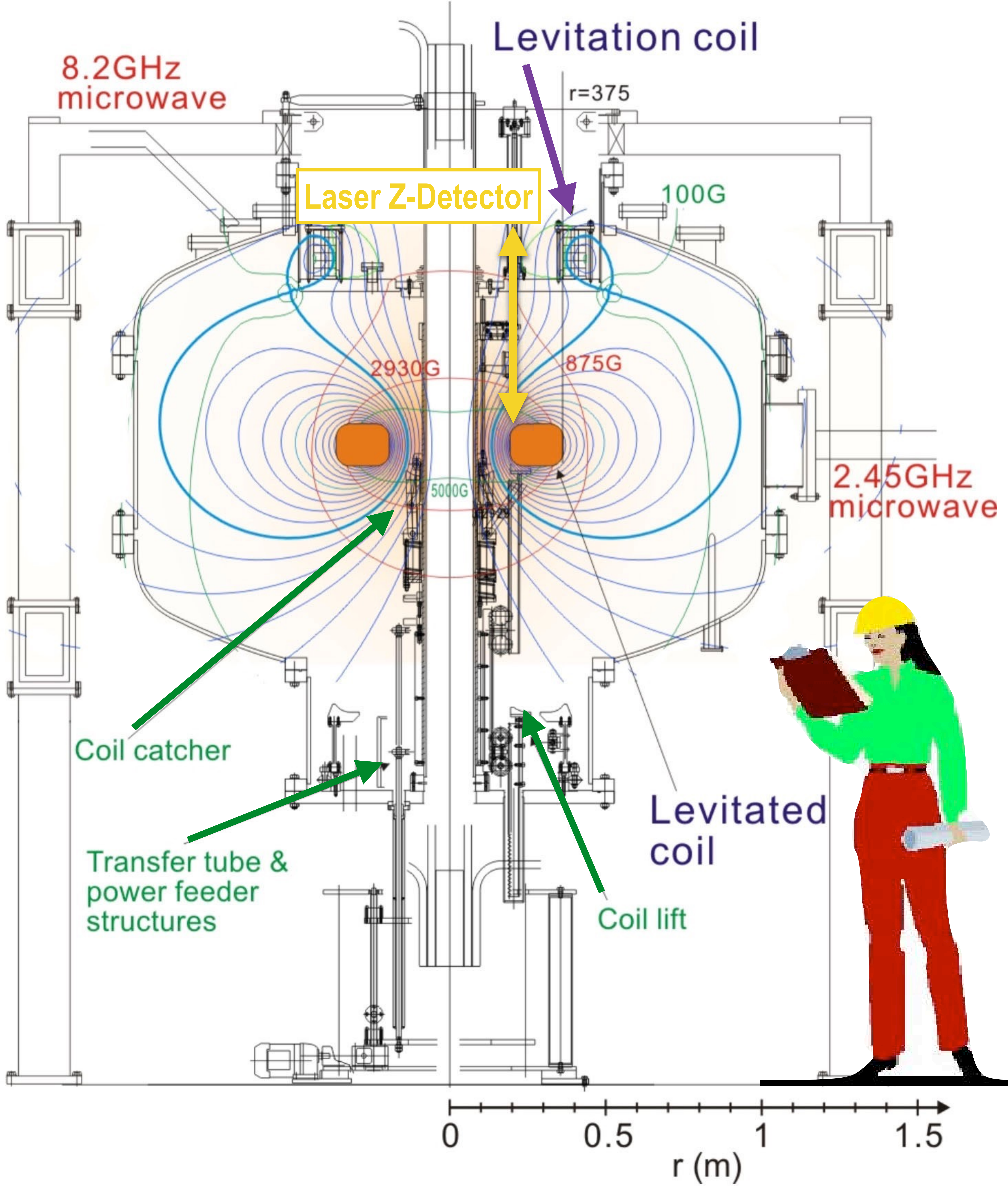


Ring Trap 1 (RT-1)

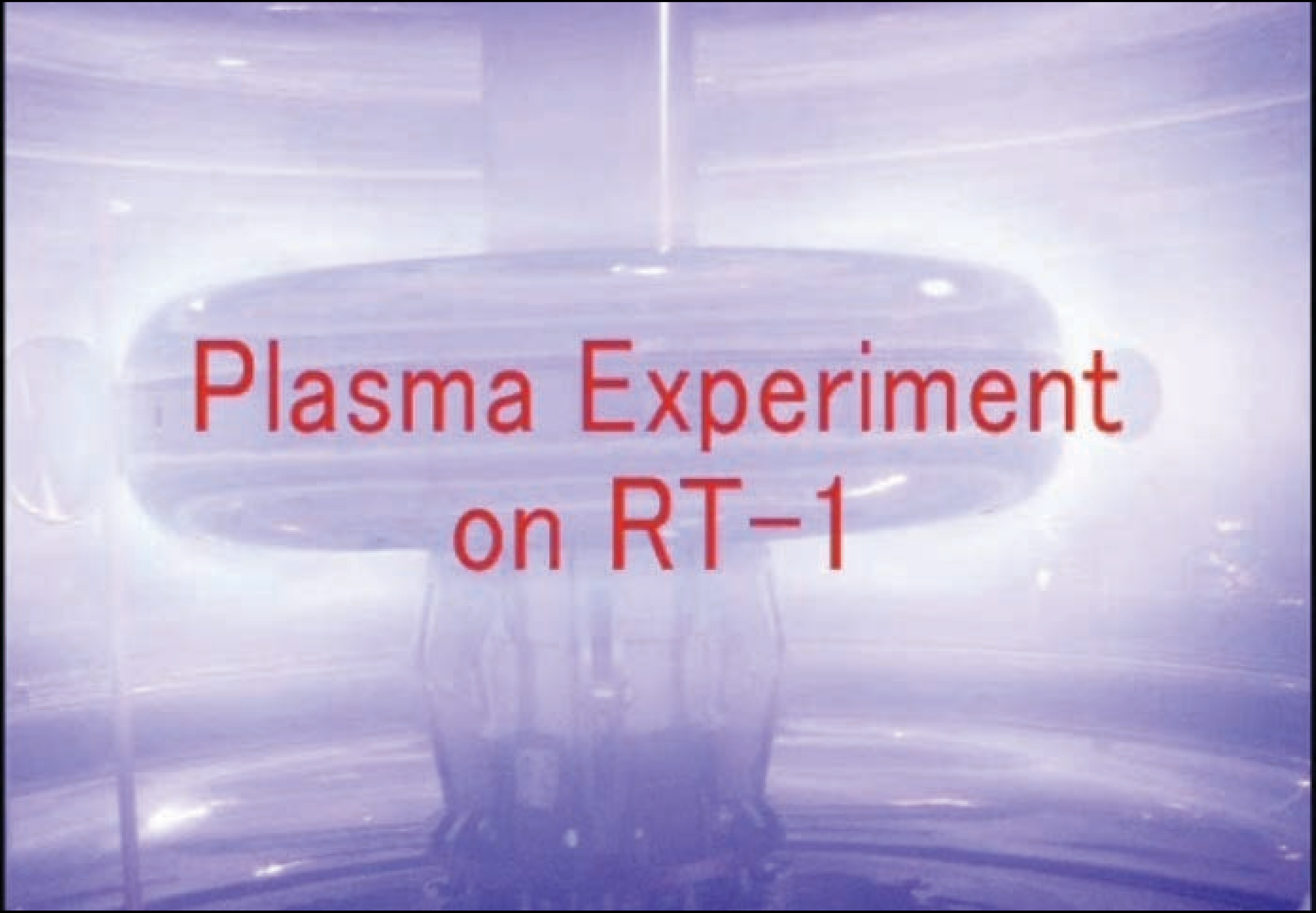


(0.25 MA · 0.17 MA m² · 22 kJ · 112 kg)

Bi-2223 · 6 Hours Float Time

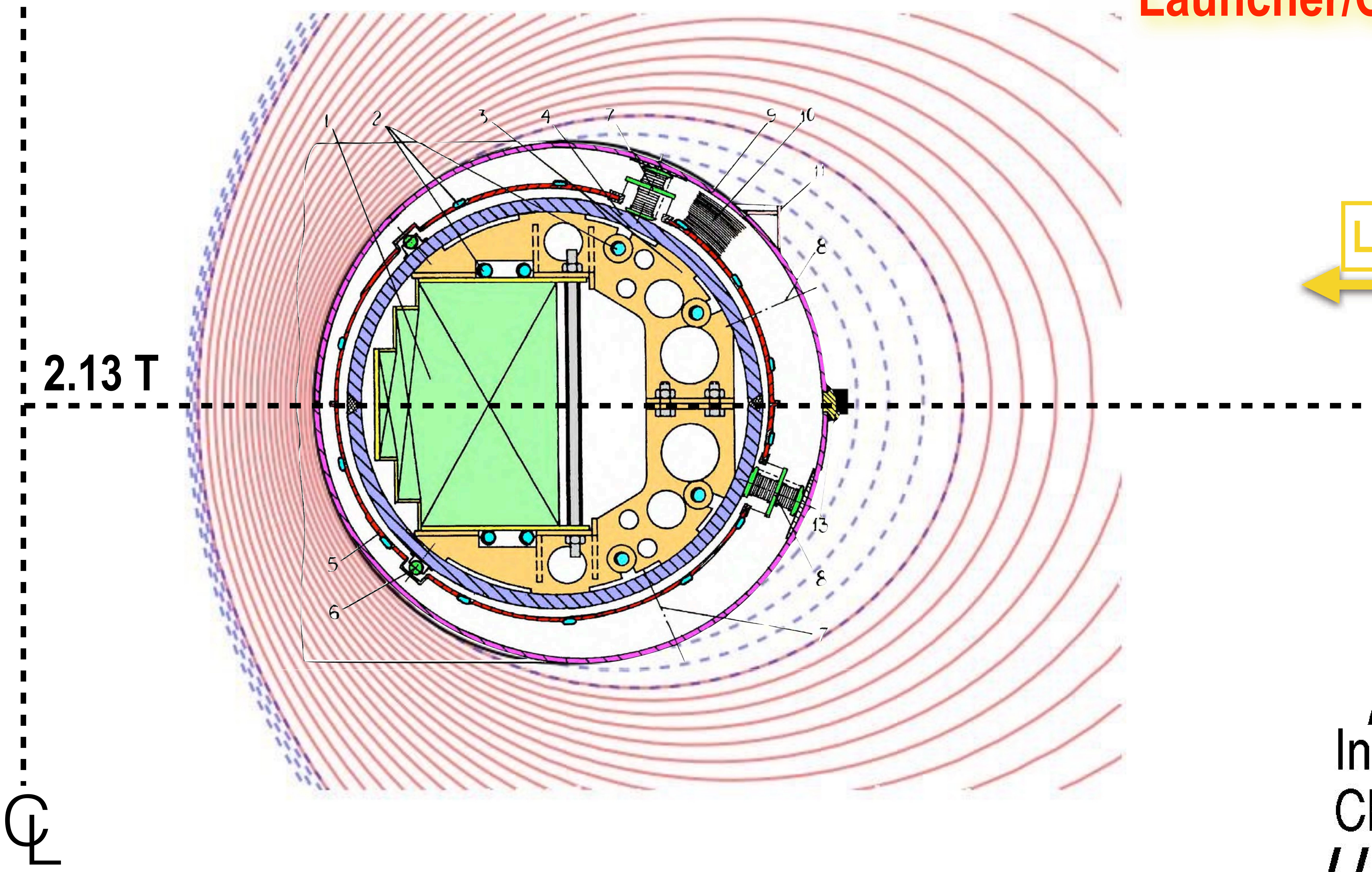


Launching/Catching Superconducting Ring



Levitated Dipole Experiment (LDX)

×20 Larger Magnet Energy
×20 Larger Plasma Volume



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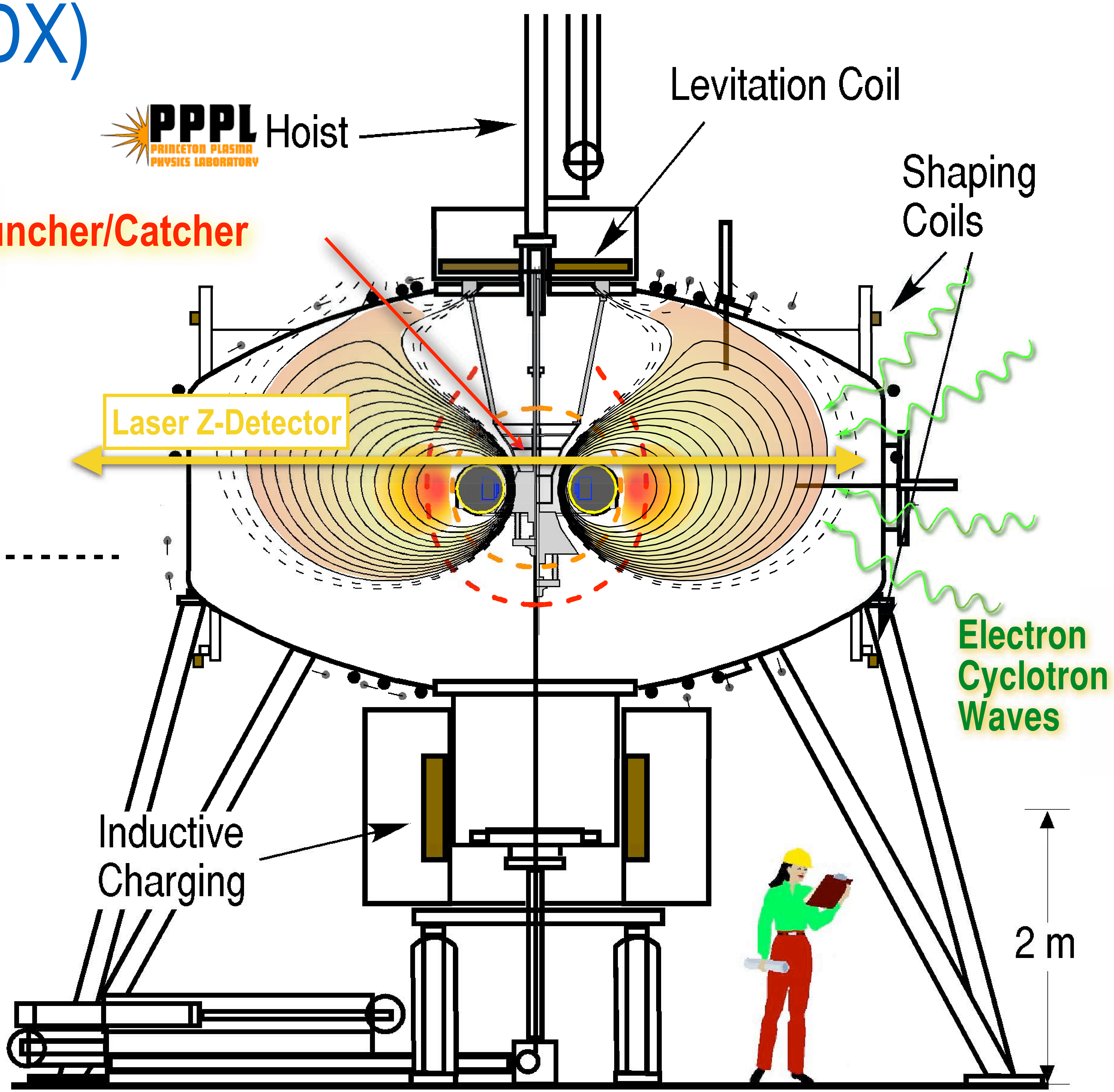
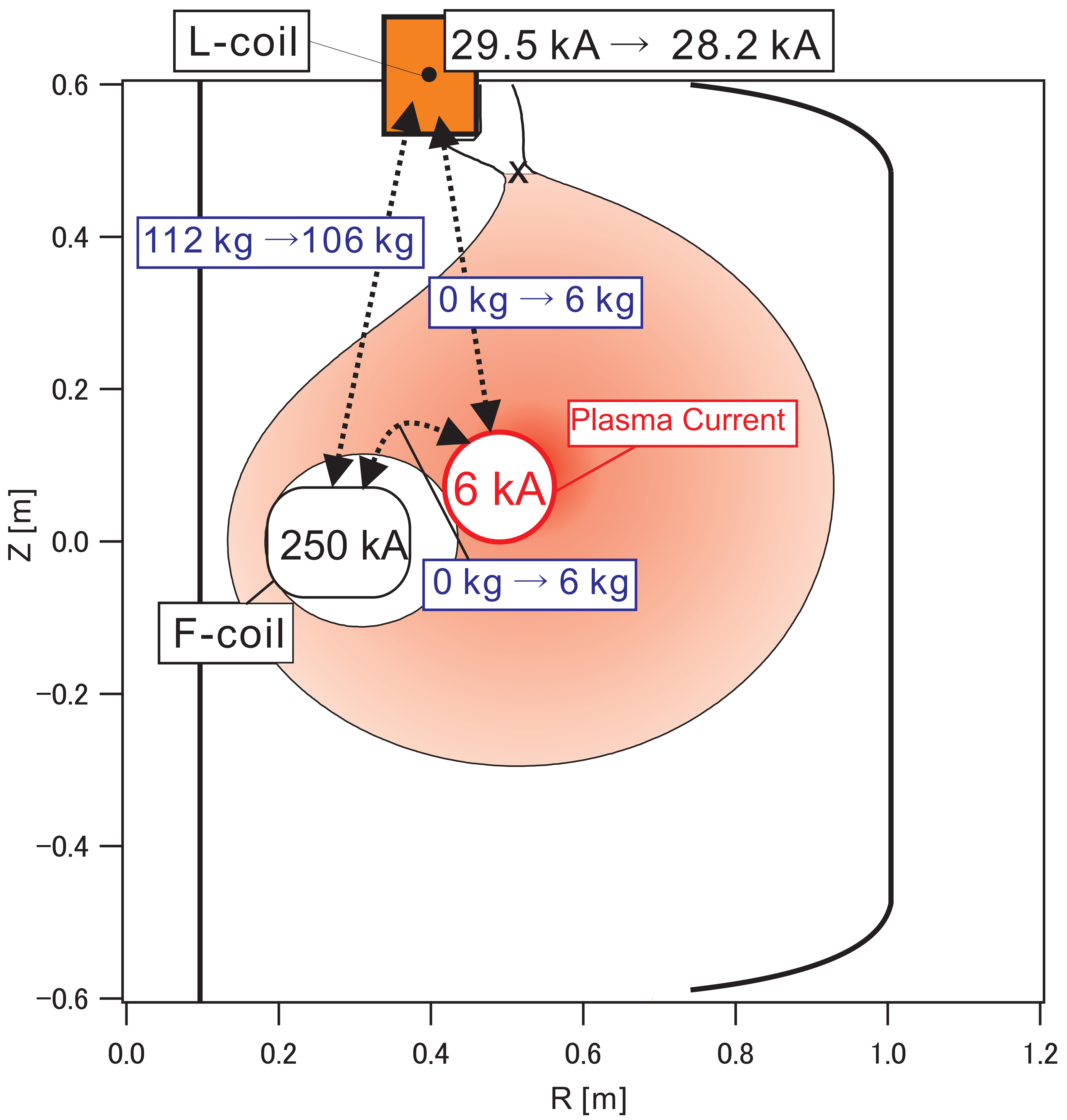
Nb_3Sn · 3 Hours Float Time

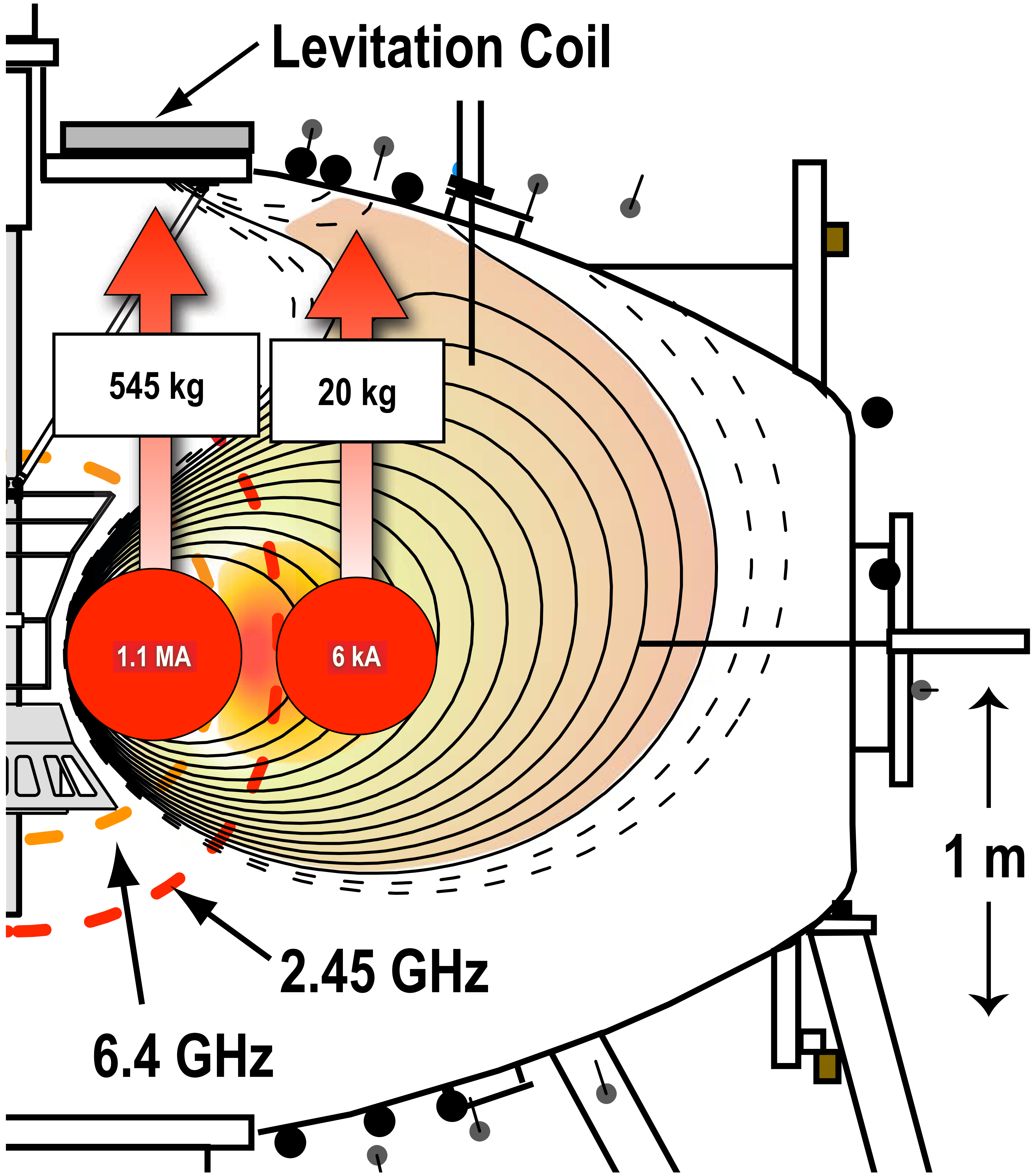


Tech Note:

Routine and Reliable Levitation with Upper "Attractive" Levitation Coil

Excellent Control (± 4mm) even with High β Plasma Ring Current

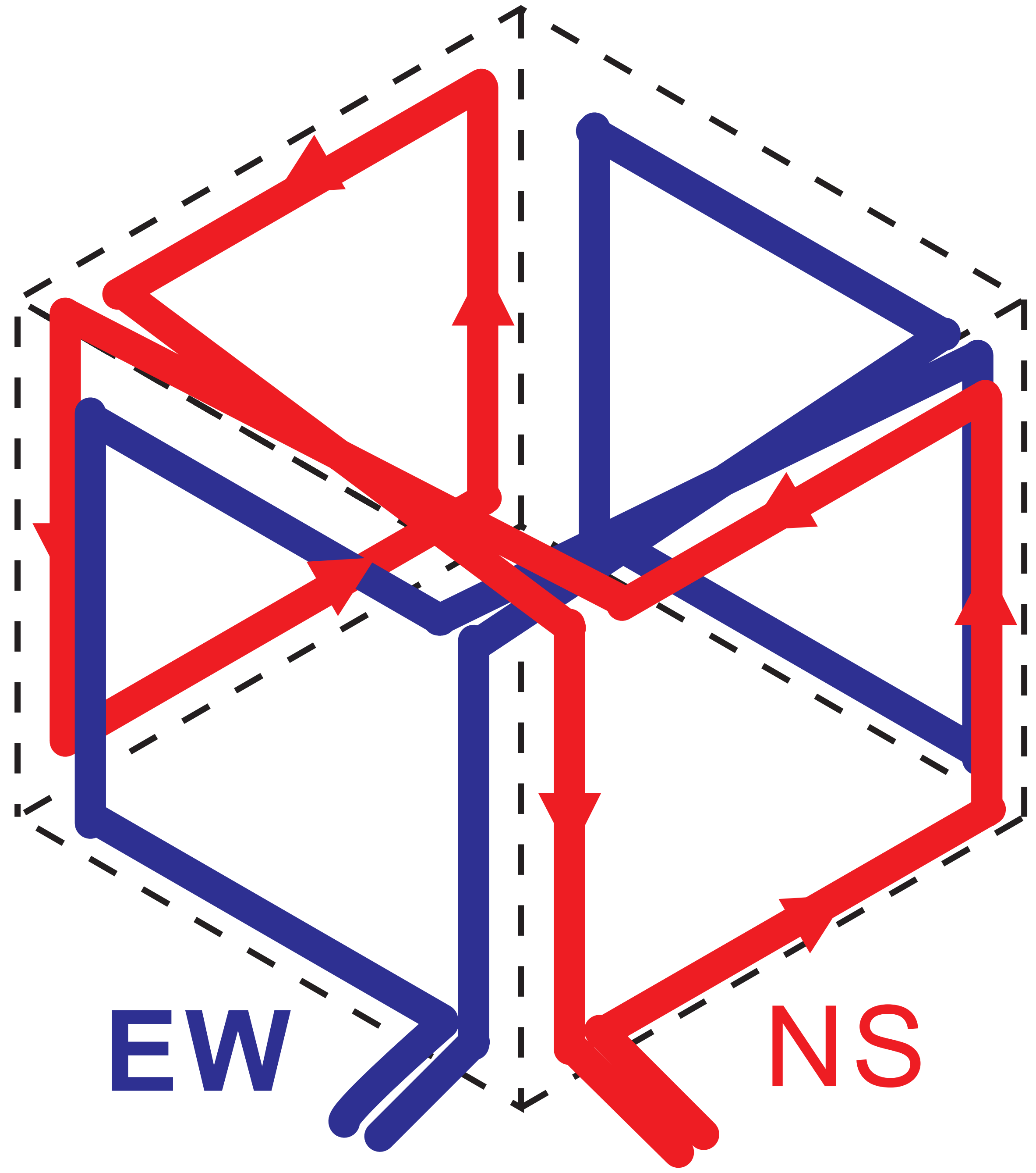




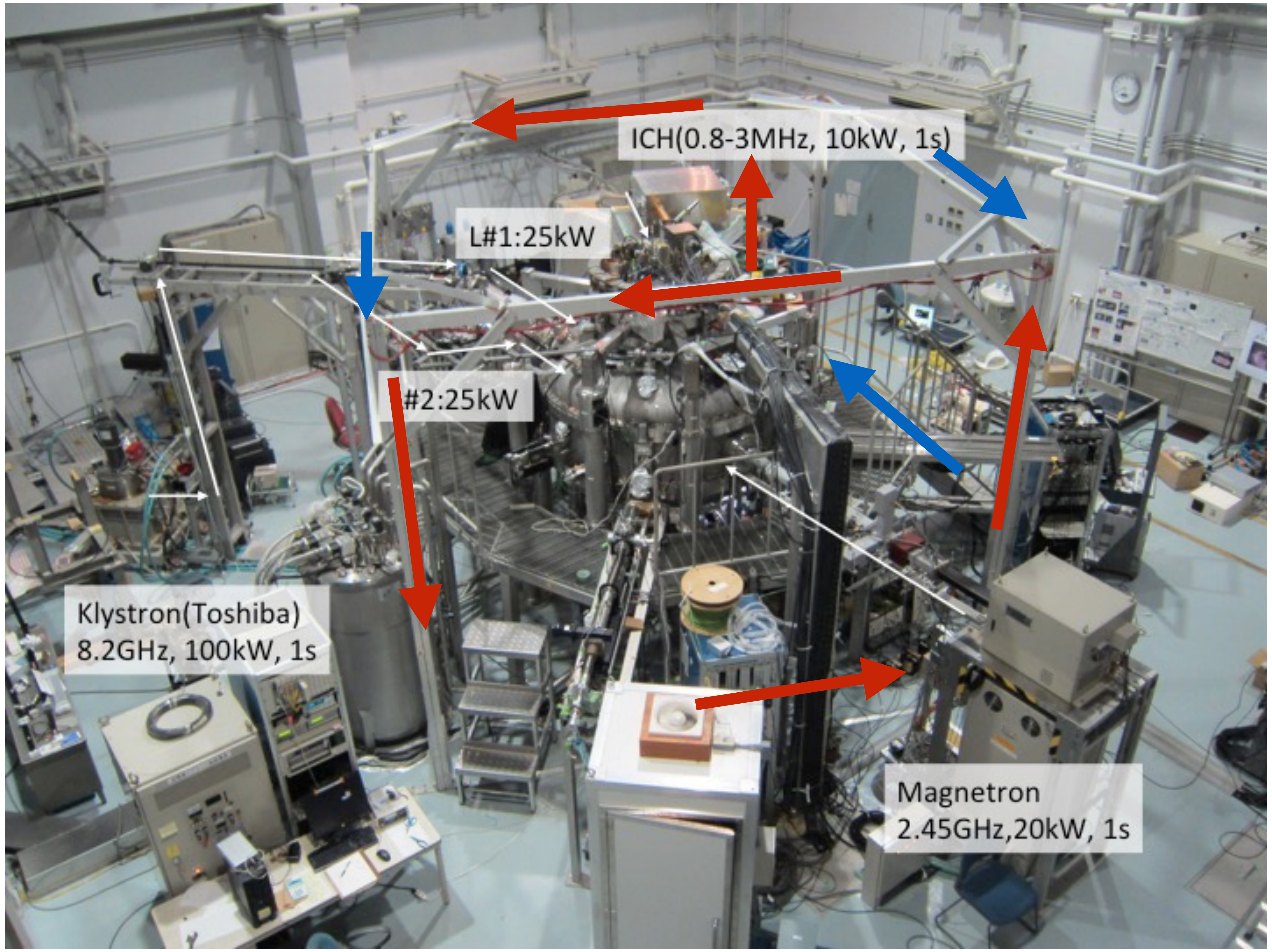
Levitation coil current *decreases* under feedback control for high β plasma.

Tech Note:
Without a Toroidal Field, Suppression of Horizontal Magnetic Field-Errors Improves Confinement

Earth's Field nulled to 0.05 G



4.5 m Correction Cube on RT-1



Yoshihisa Yano and Z. Yoshida, "Improvement of Field Accuracy and Plasma Performance in the RT-1 Device," *Plasma Fusion Res* **4**, 039 (2009).
Ryutov, Kesner, and Mauel, "Magnetic field perturbations in closed-field-line systems with zero toroidal magnetic field," *Phys. Plasmas*, **11**, 2318 (2004).

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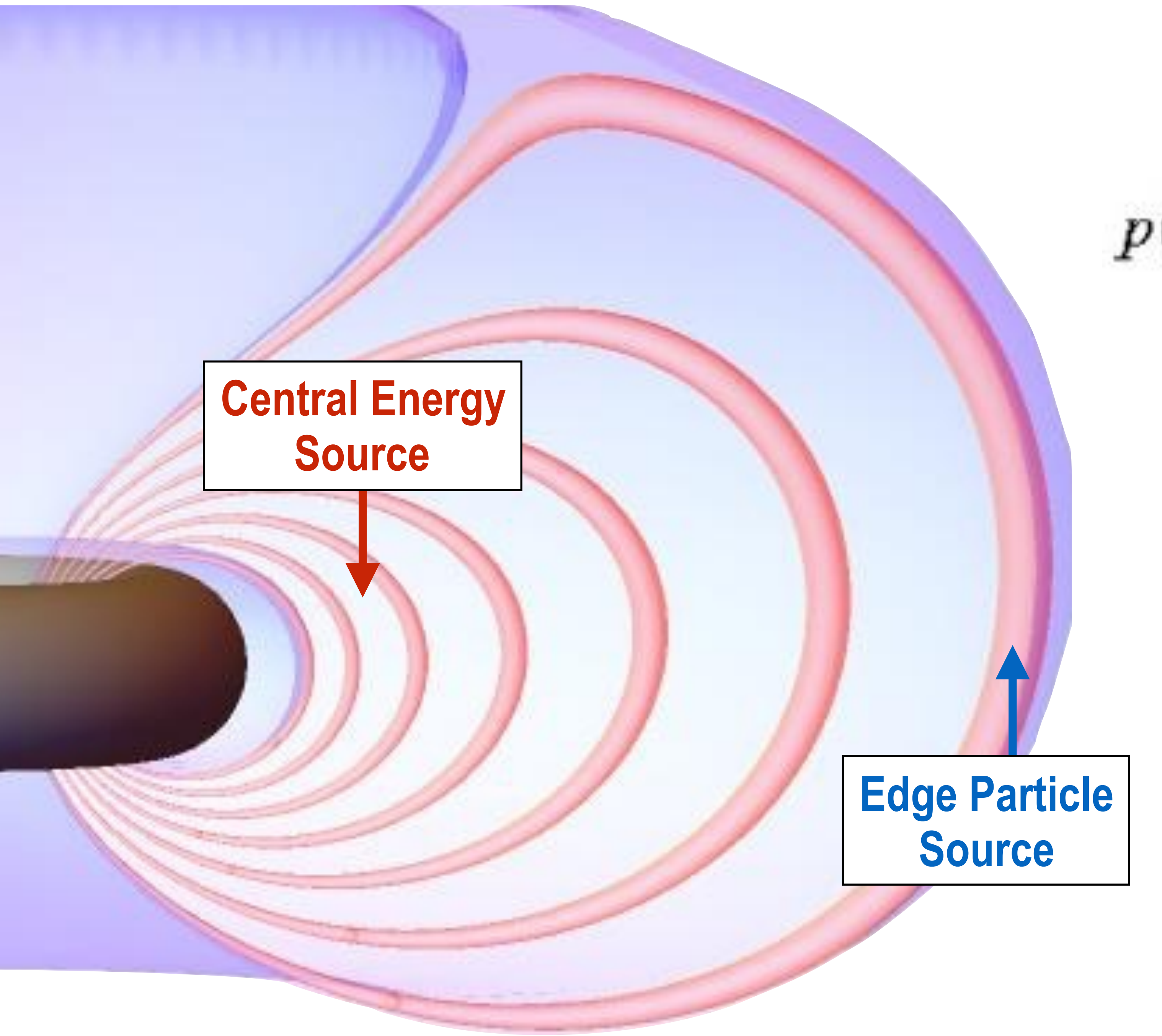
Solar wind drives radial diffusion in planetary magnetospheres.

In the laboratory, Central heating excites instability, and Centrally-Peaked Pressure and Density are the Final State of Turbulent Self-Organization



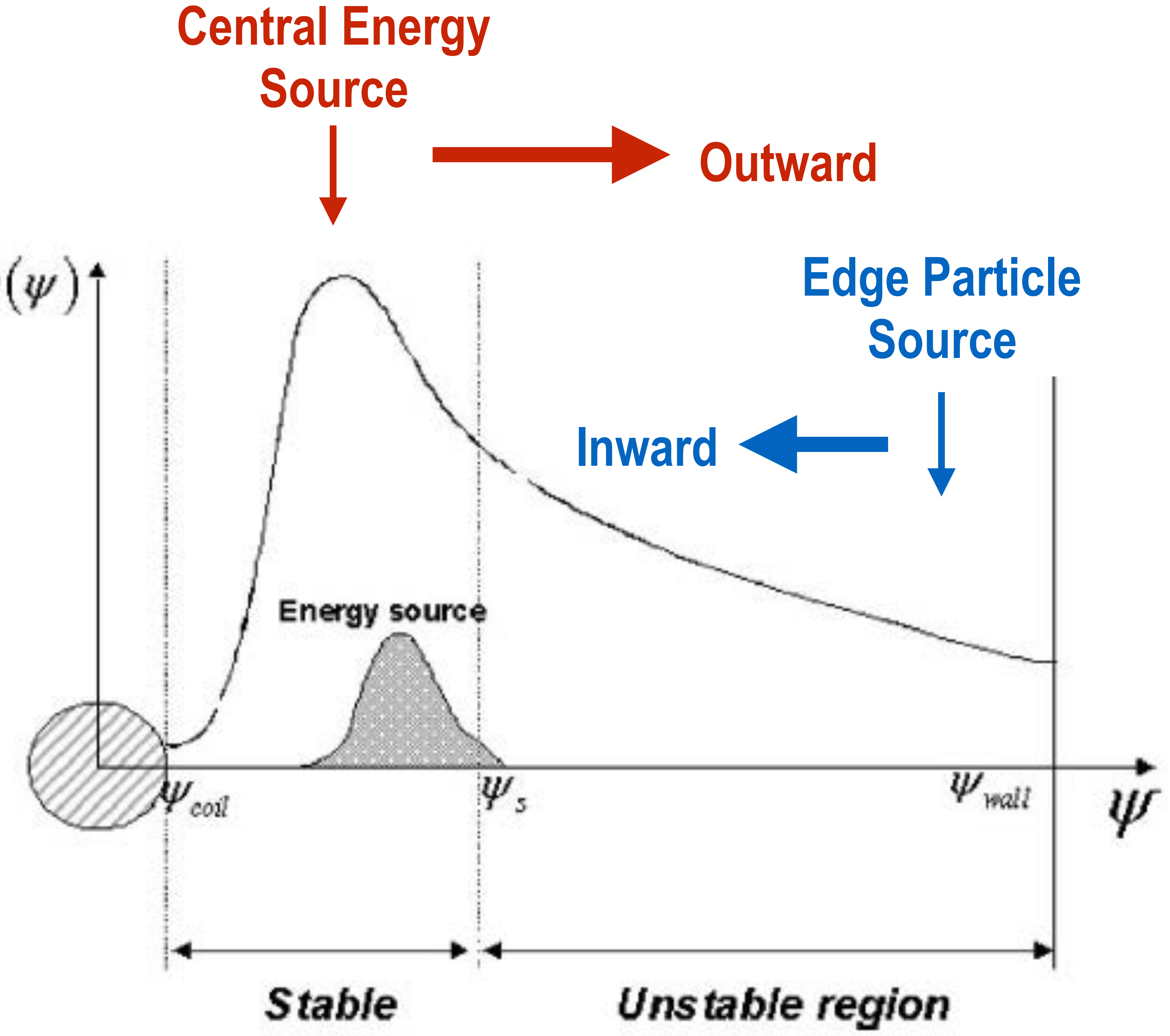


FIG. 1. The LDX schematic profile.

Quasilinear MHD Interchange Turbulence

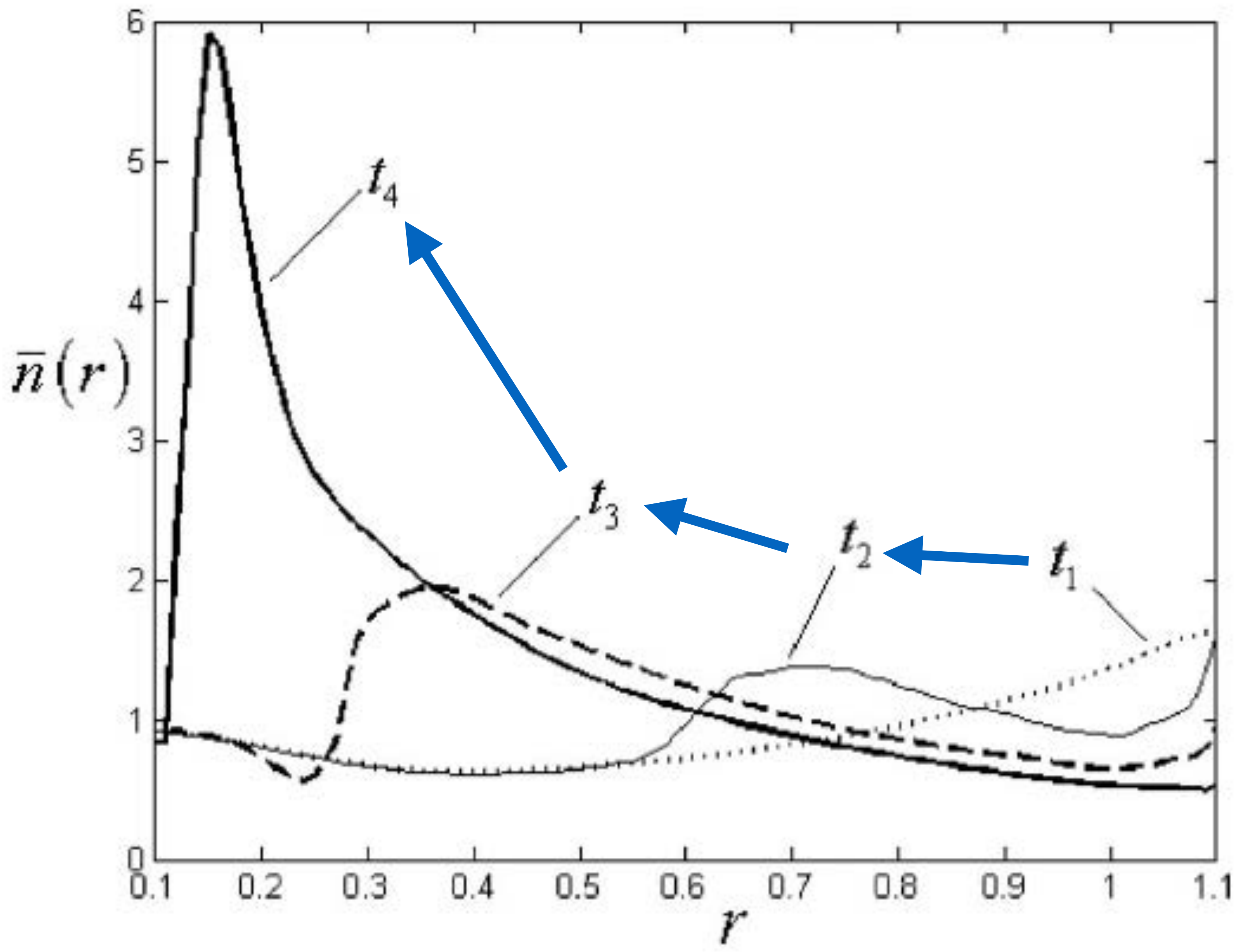


FIG. 5. The snapshots of the "self-organizations" process. Time t_1: before an instability is excited; t_2–t_4: different stages of self-organization.

Alexie Kouznetsov (PhD MIT/Freidberg), *et al*, "Quasilinear theory of interchange modes in a closed field line configuration," *Phys Plasmas*, **14**, 102501 (2007)

John Tonge (PhD UCLA/Dawson), *et al.*, "Kinetic simulations of the stability of a plasma confined by the magnetic field of a current rod," *Phys Plasmas* **10**, 3475 (2003).

Entropy Modes have changed the way we think about Turbulent Self-Organization

The MHD interchange mode limits *pressure* gradients, but entropy modes drive turbulent "self-organization" even when MHD interchange is stable.

Entropy Modes regulate *density* and *temperature* gradients, driving $\eta \rightarrow 2/3$.

$$\Delta\,(nV) \sim 0 \quad \text{and} \quad \Delta\left(TV^{2/3}\right) \sim 0 \quad \text{and} \quad \eta = \frac{\Delta \ln T}{\Delta \ln n} = \frac{2}{3}$$

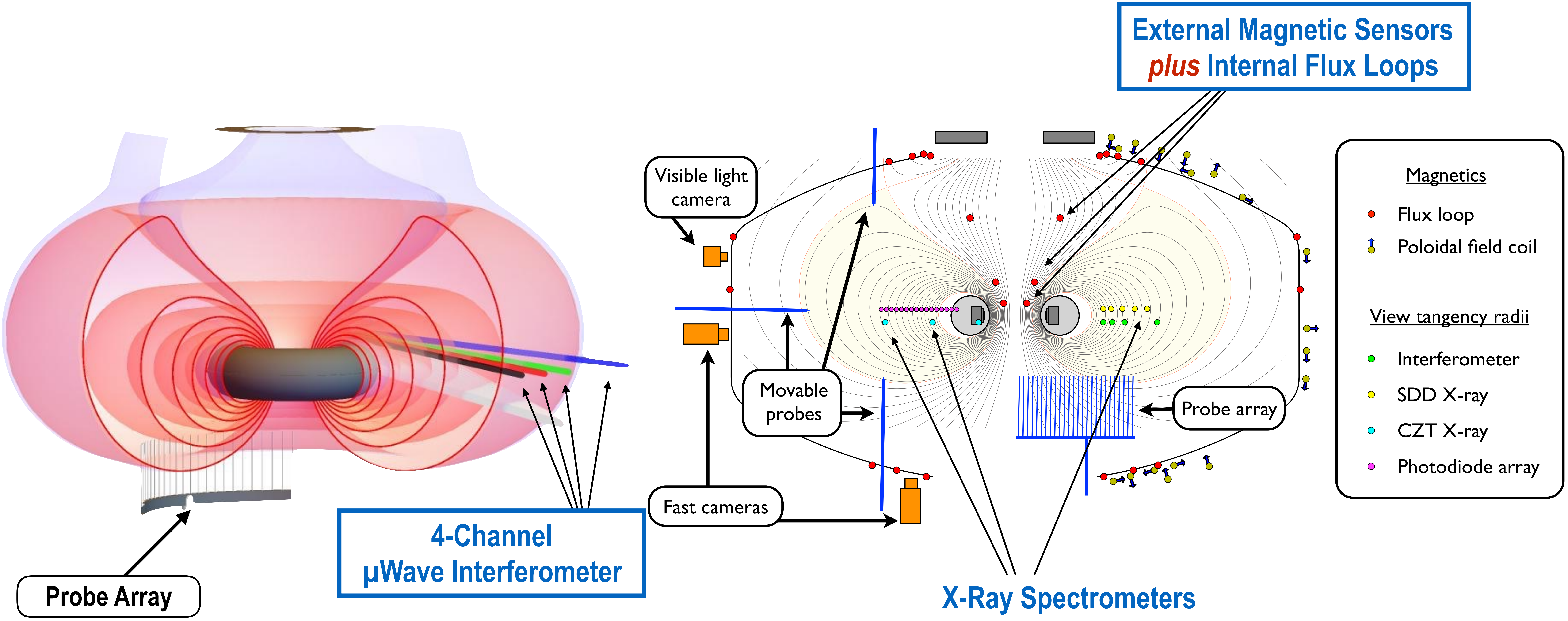
Entropy mode transport depends upon the relative gradients of density and temperature profiles, and **η determines the direction of particles flux…**

- When η > 2/3 (a "**warm core**"), particles pinch **inward** & temperature **outward**.
- When η < 2/3 (a "**cool core**"), particles **outward** & temperature pinches **inward**.

Sumire Kobayashi, Rogers, and Dorland, "Particle Pinch in Gyrokinetic Simulations of Closed Field-Line Systems," *PRL*, **105**, 235004 (2010).
Kesner, Garnier, and Mauel, "Fluctuation driven transport and stationary profiles," *Phys Plasmas*, **18**, 050703 (2011).
Garbet, *et al.*, "Turbulent fluxes and entropy production rate," *Phys Plasmas*, **12**, 082511 (2006)

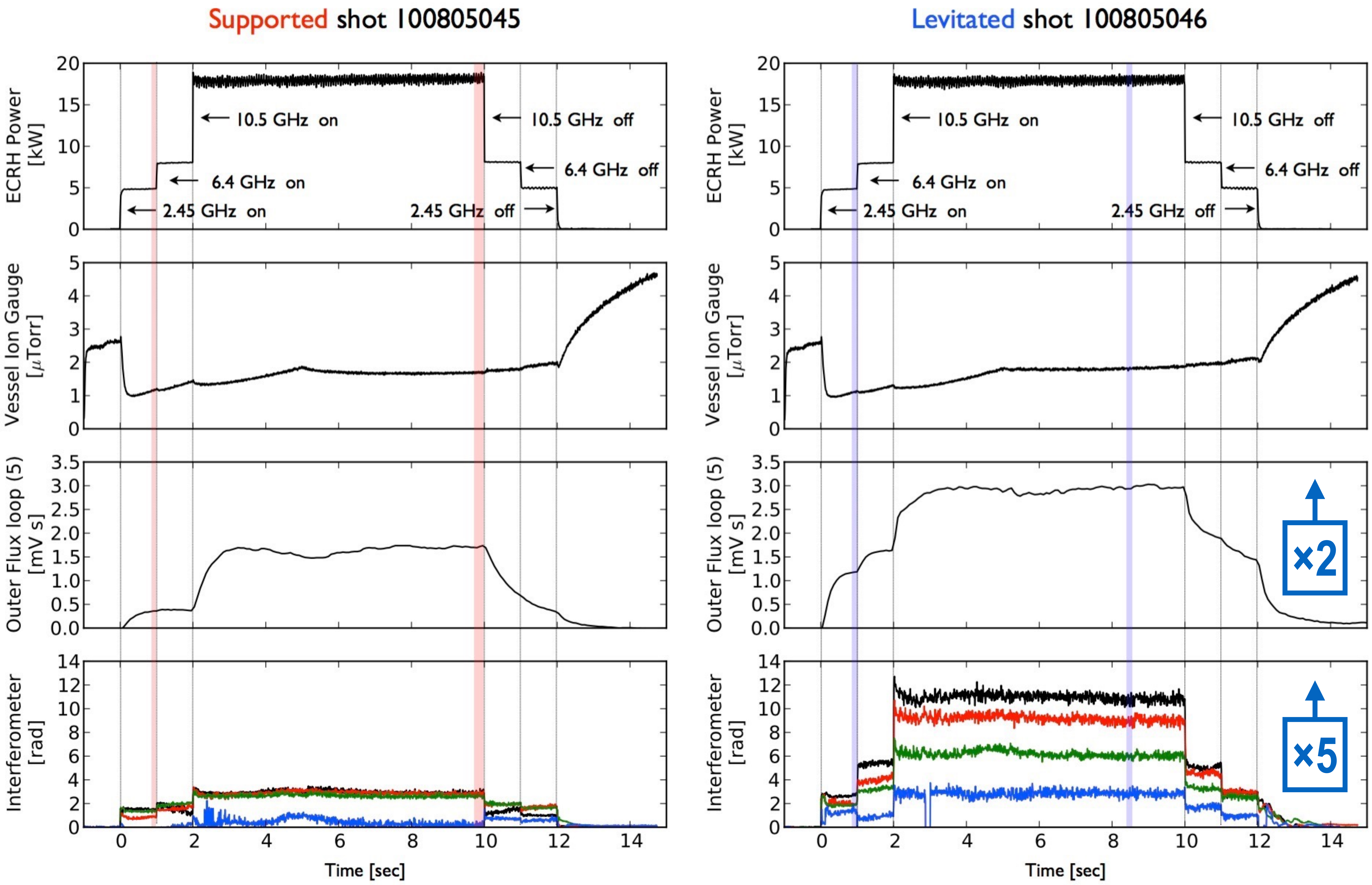
Measurement of Pressure and Density Turbulent Self-Organization in LDX

Matt Davis (PhD Columbia) and Alex Boxer (PhD MIT)




Levitated
Good confinement
Some Energetic Electrons
Supported
Poor confinement
Energetic Trapped Electrons

Example Plasma Discharges: **Supported** vs. **Levitated** Coil



18 kW ECRH

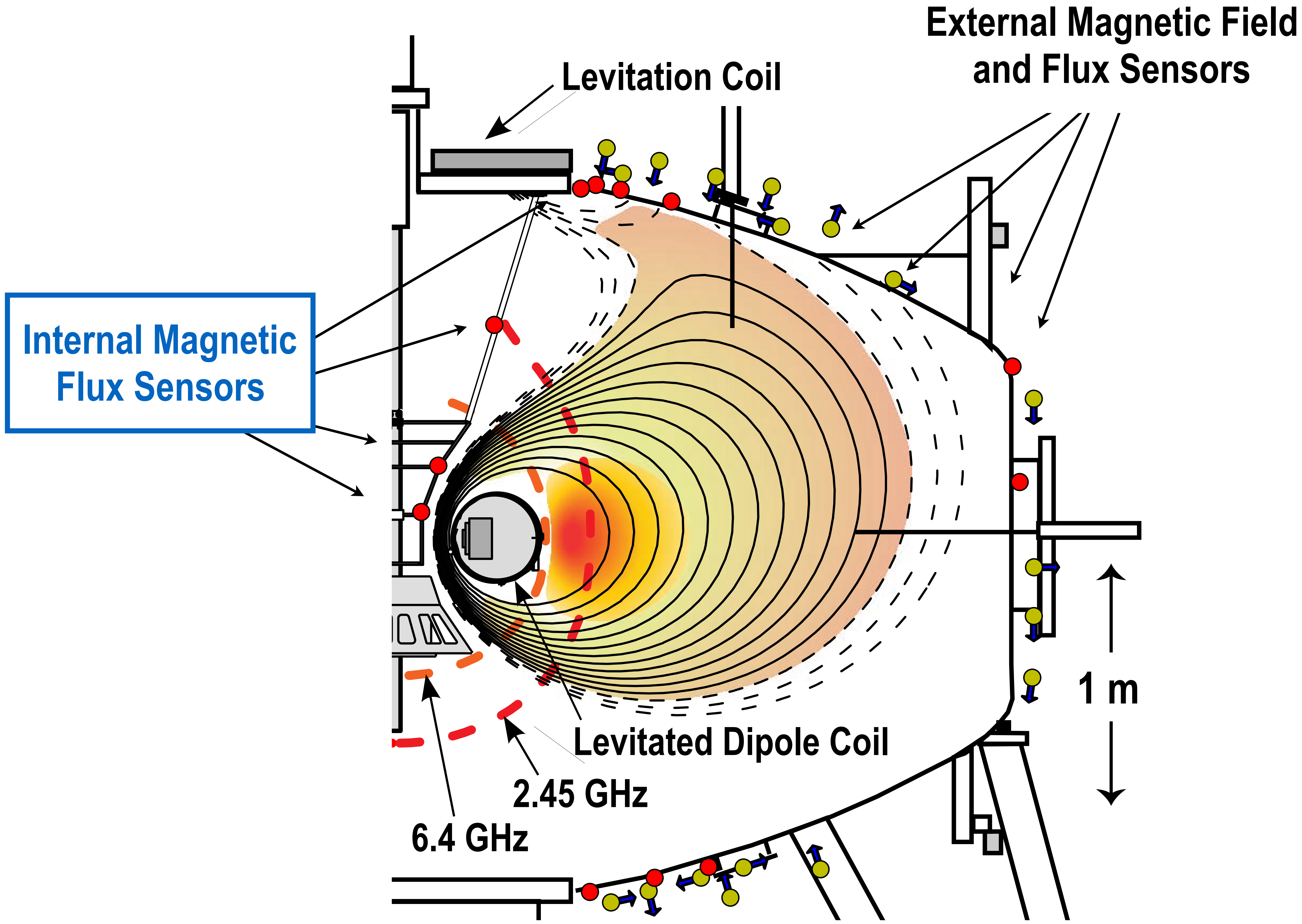
***Actively* Controlled Neutral Pressure**

Flux from Plasma Ring Current

Plasma Line Density

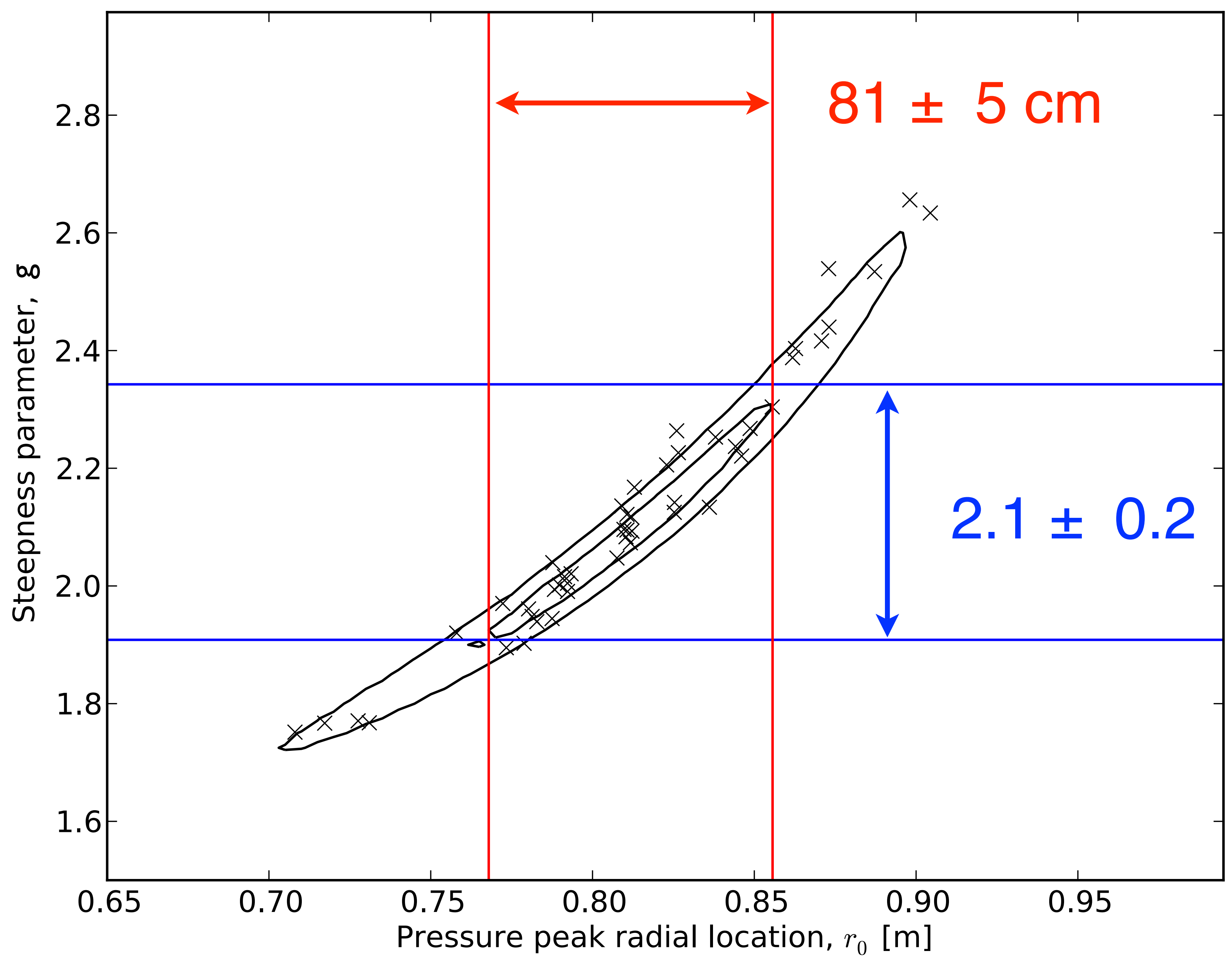
Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

Accurate Reconstruction of the Plasma Pressure from the Plasma Ring Current Requires Internal Magnetic Sensors



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

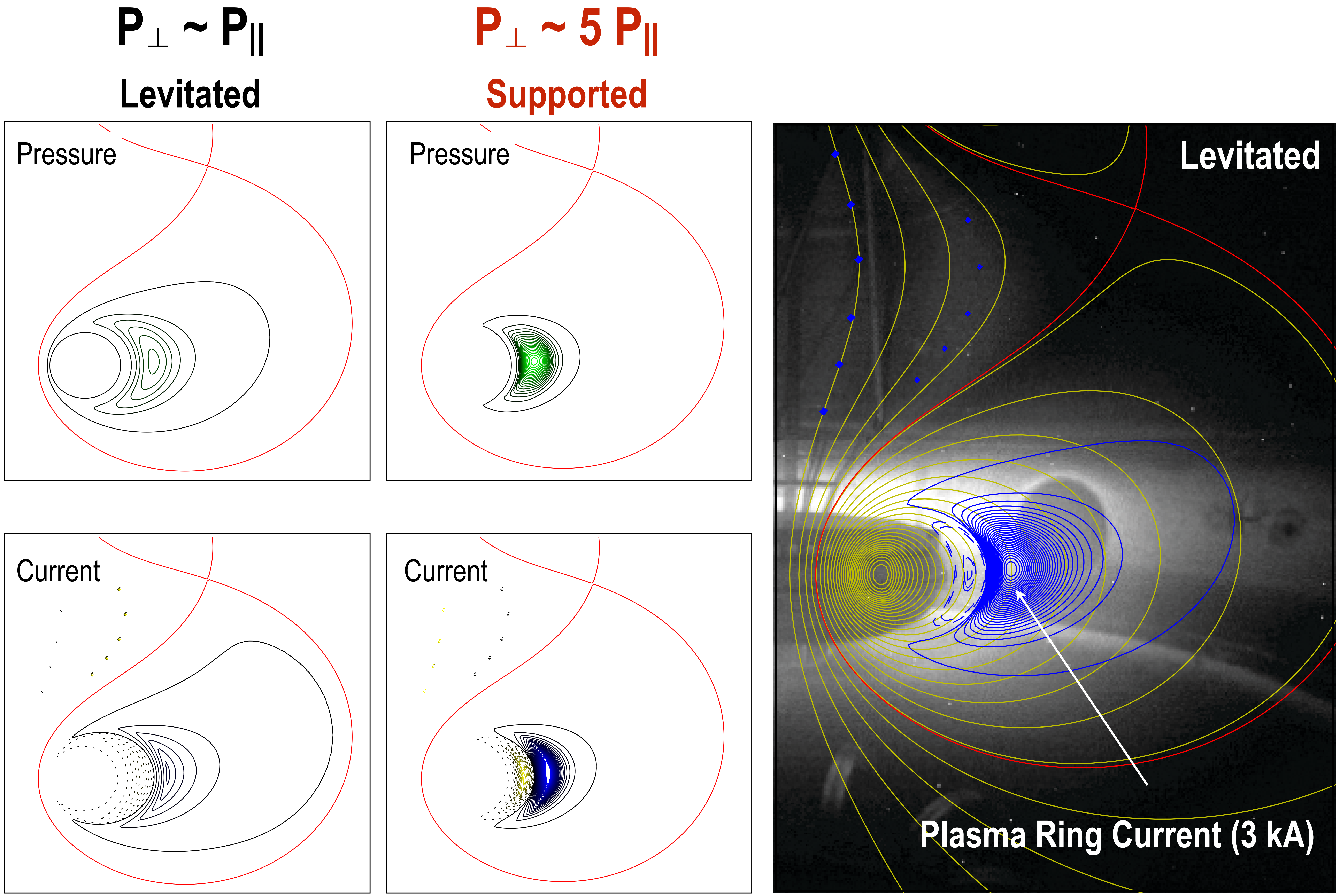
Reconstruction Results in Very Good Accuracy of Pressure Profile



$P_{\perp} \sim P_{\|}$

Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

Levitated Coil: Broad Isotropic Pressure Profile
Supported Coil: Narrow Anisotropic Pressure Profile

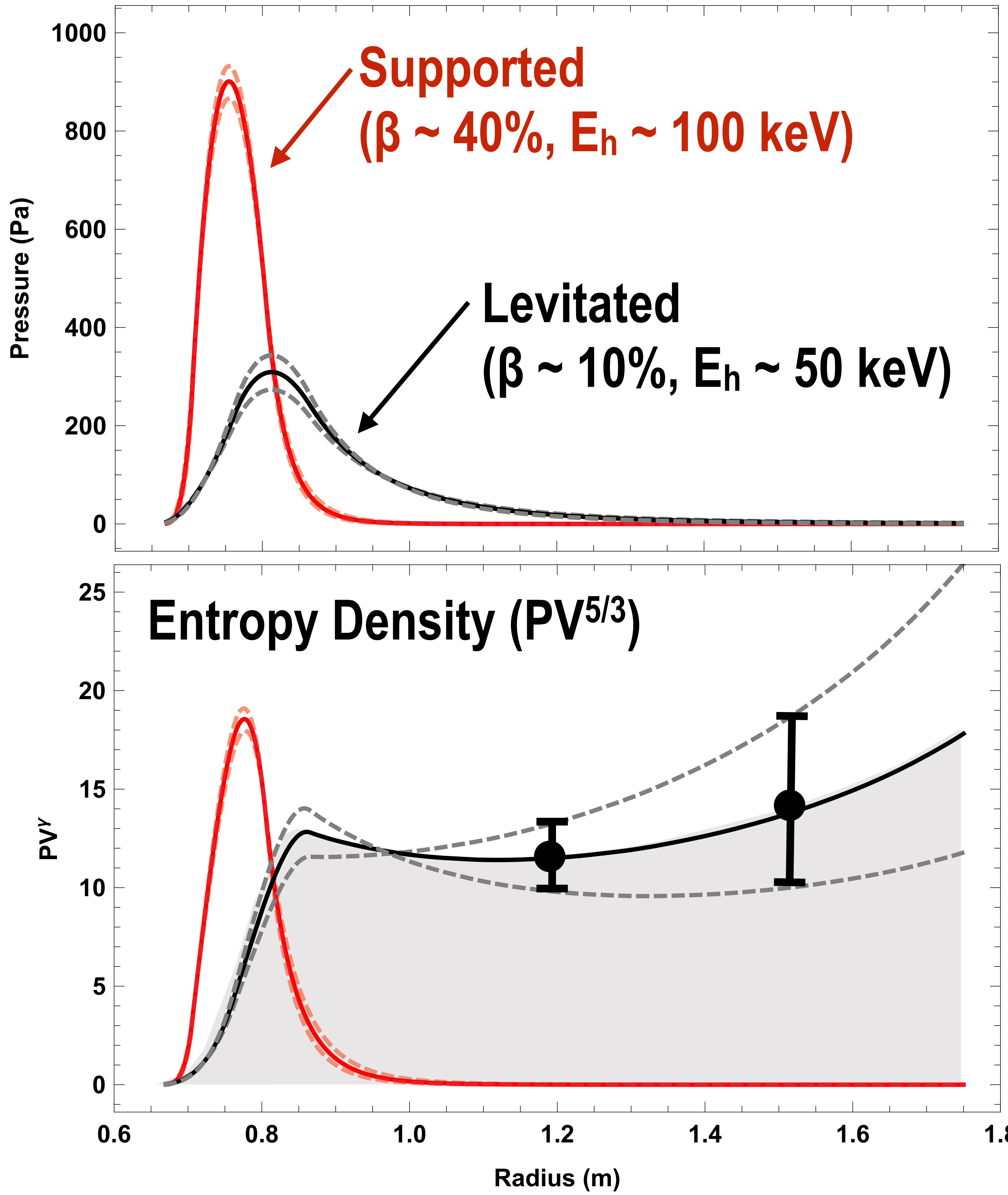


Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

Levitated Coil: Broad Isotropic Pressure Profile
Supported Coil: Narrow Anisotropic Pressure Profile

- **Supported**:
  - High peak beta, β ~ 40%
  - No thermal confinement
  - Ideal MHD ***unstable***
- **Levitated**:
  - Peak beta, β ~ 10%
  - Broad profile shows good thermal confinement
  - Marginally ***stable*** $\Delta(PV^{5/3}) \geq 0$

Supported: No Thermal Confinement (only energetic trapped electrons)

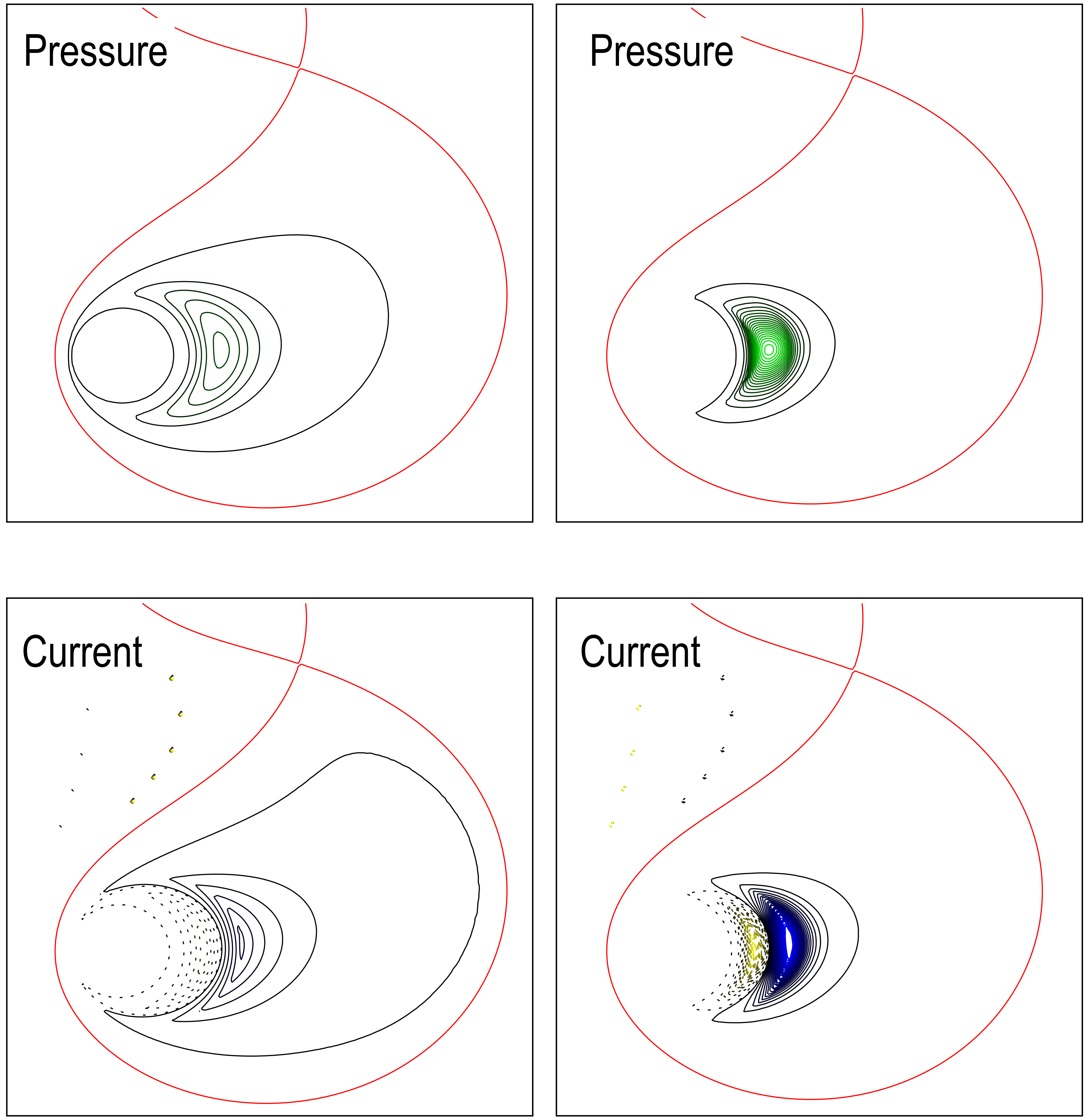


$P_\perp \sim P_{||}$

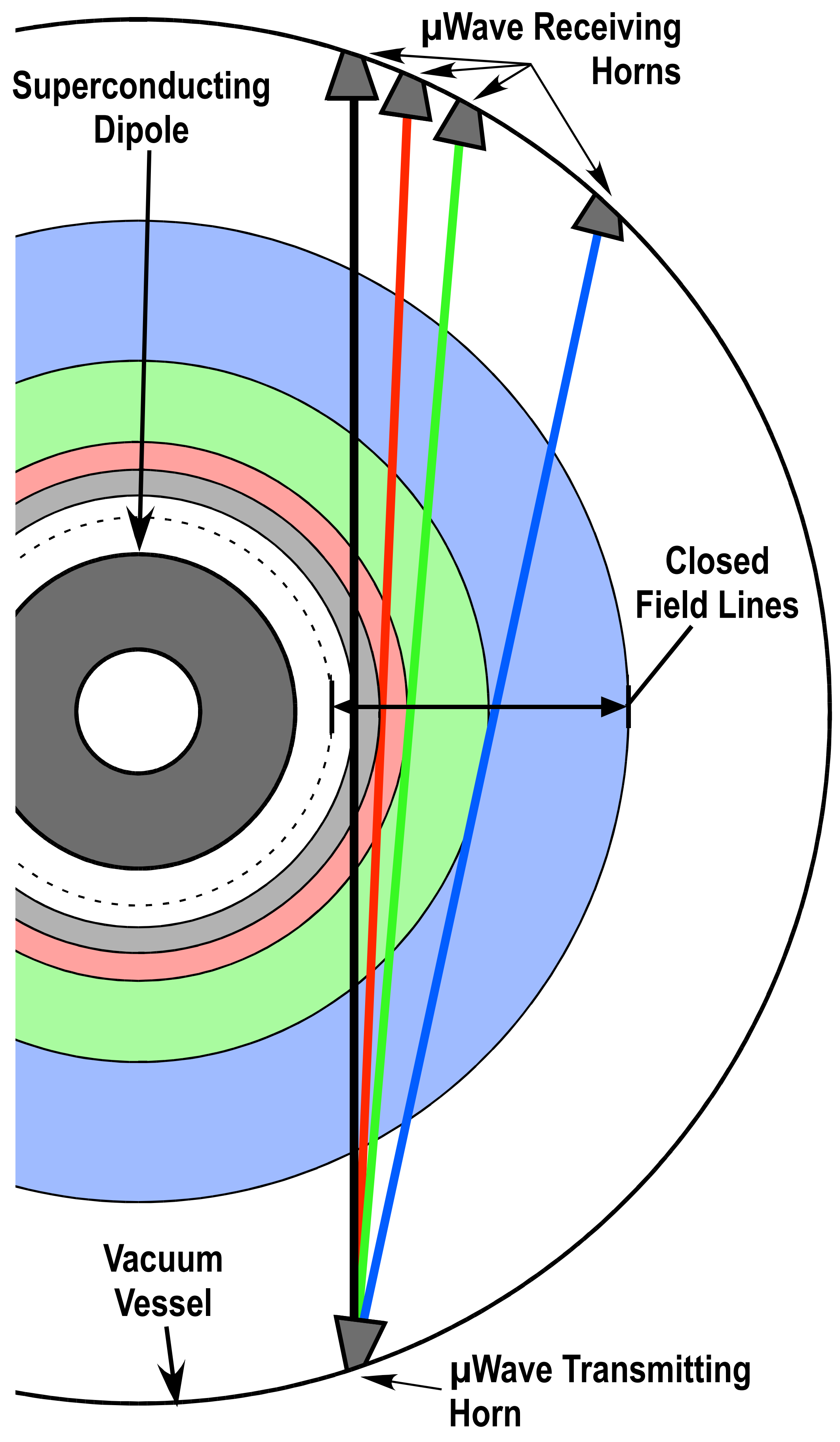
Levitated

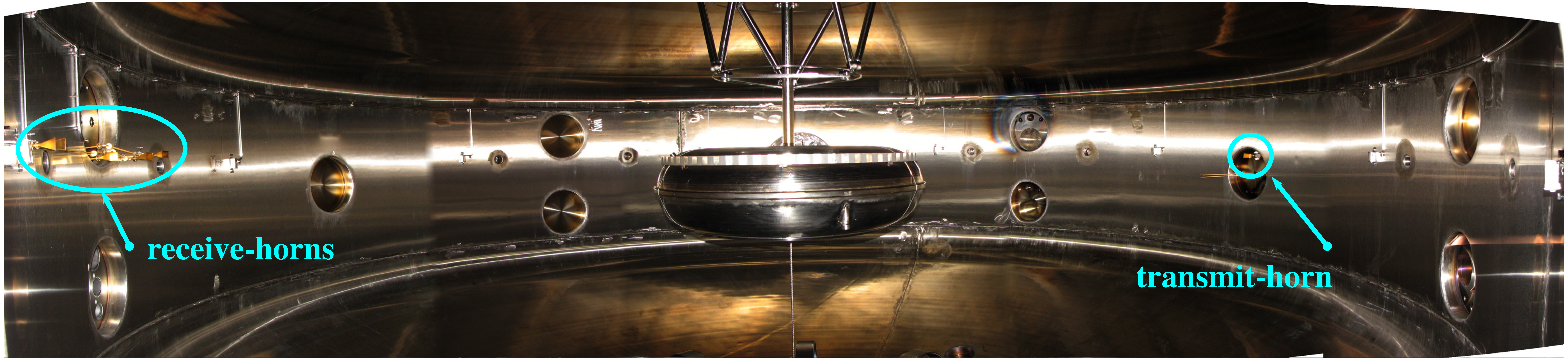
$P_\perp \sim 5\,P_{||}$

Supported



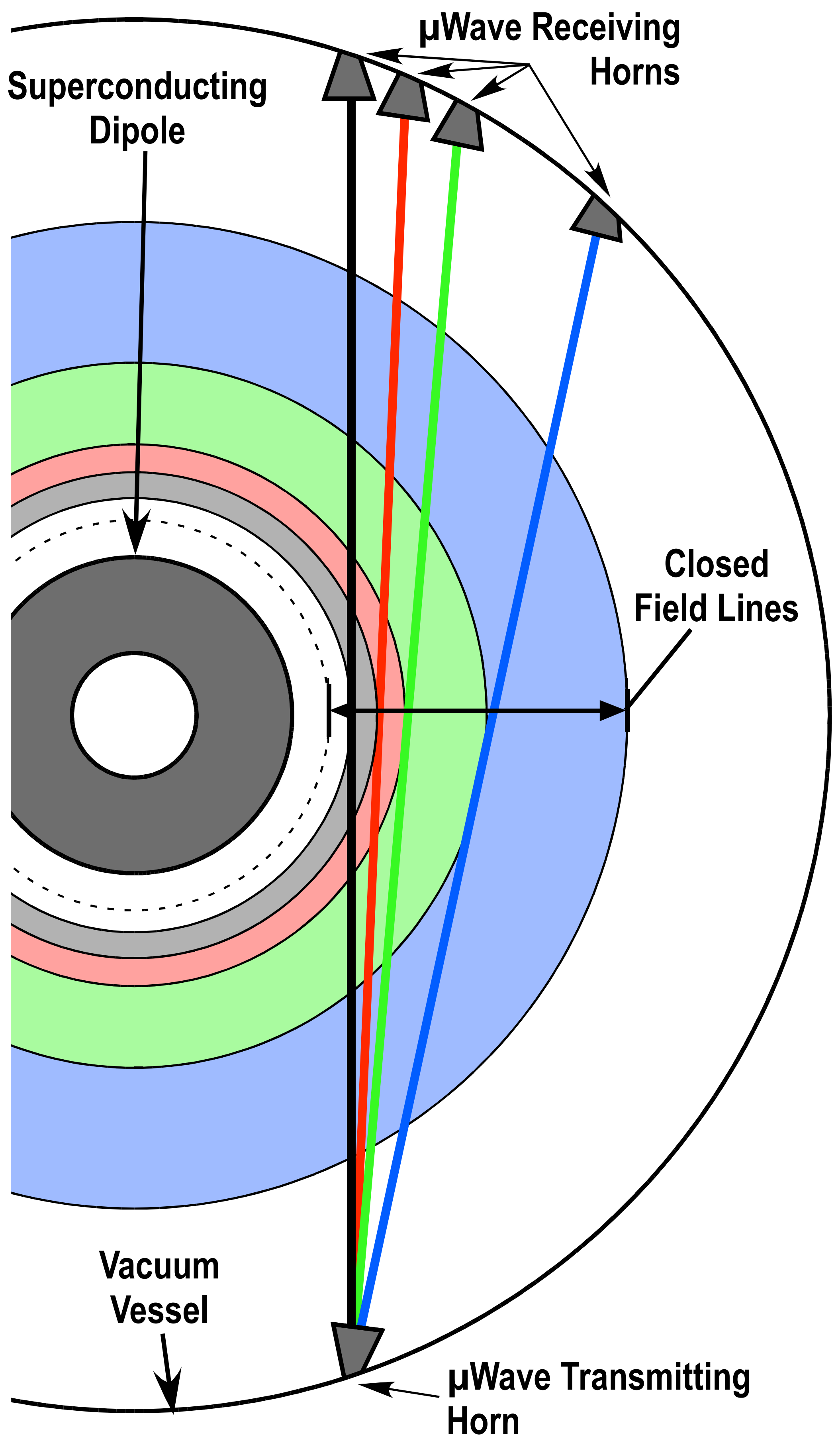
Multichannel Microwave Interferometer

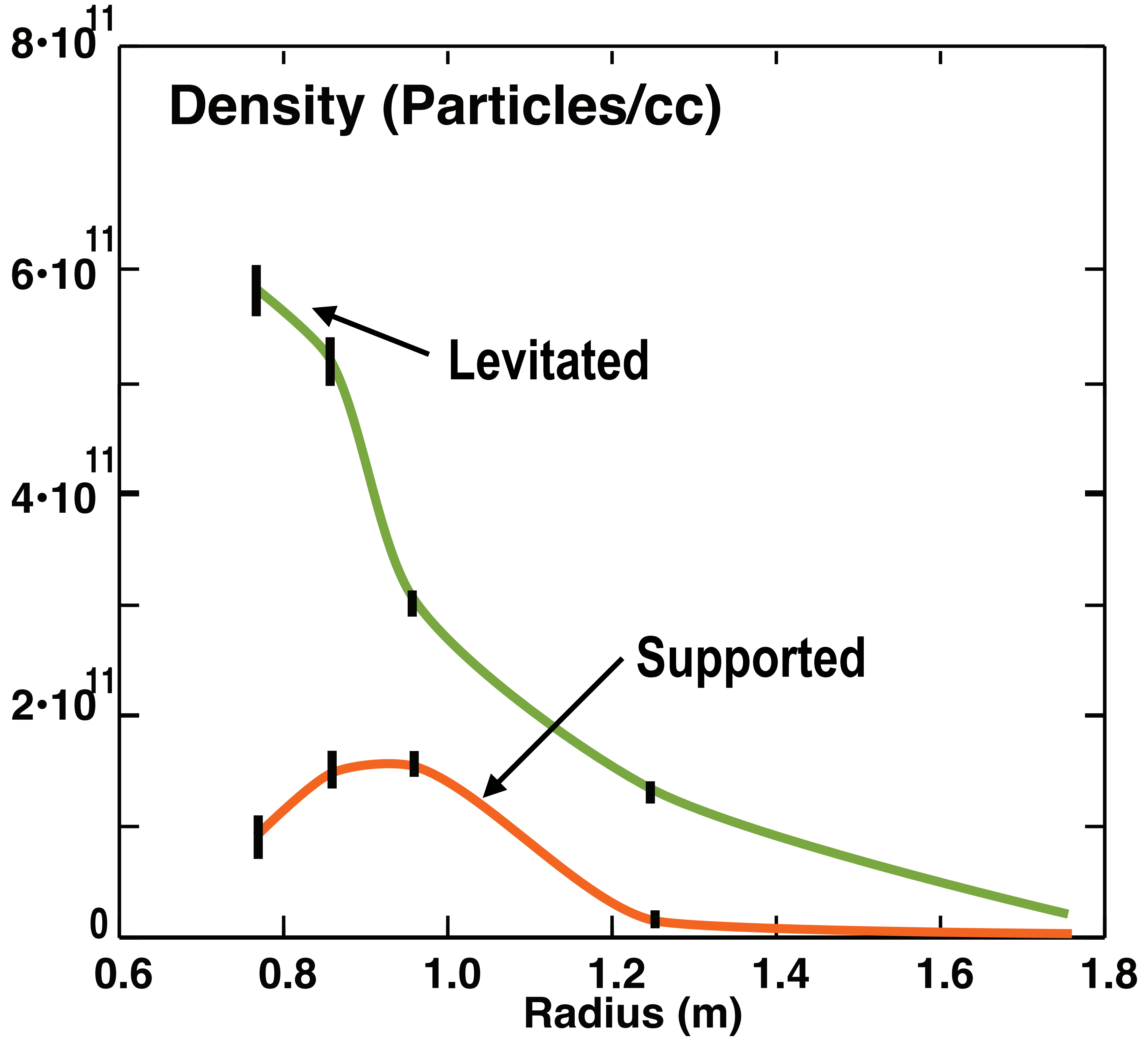


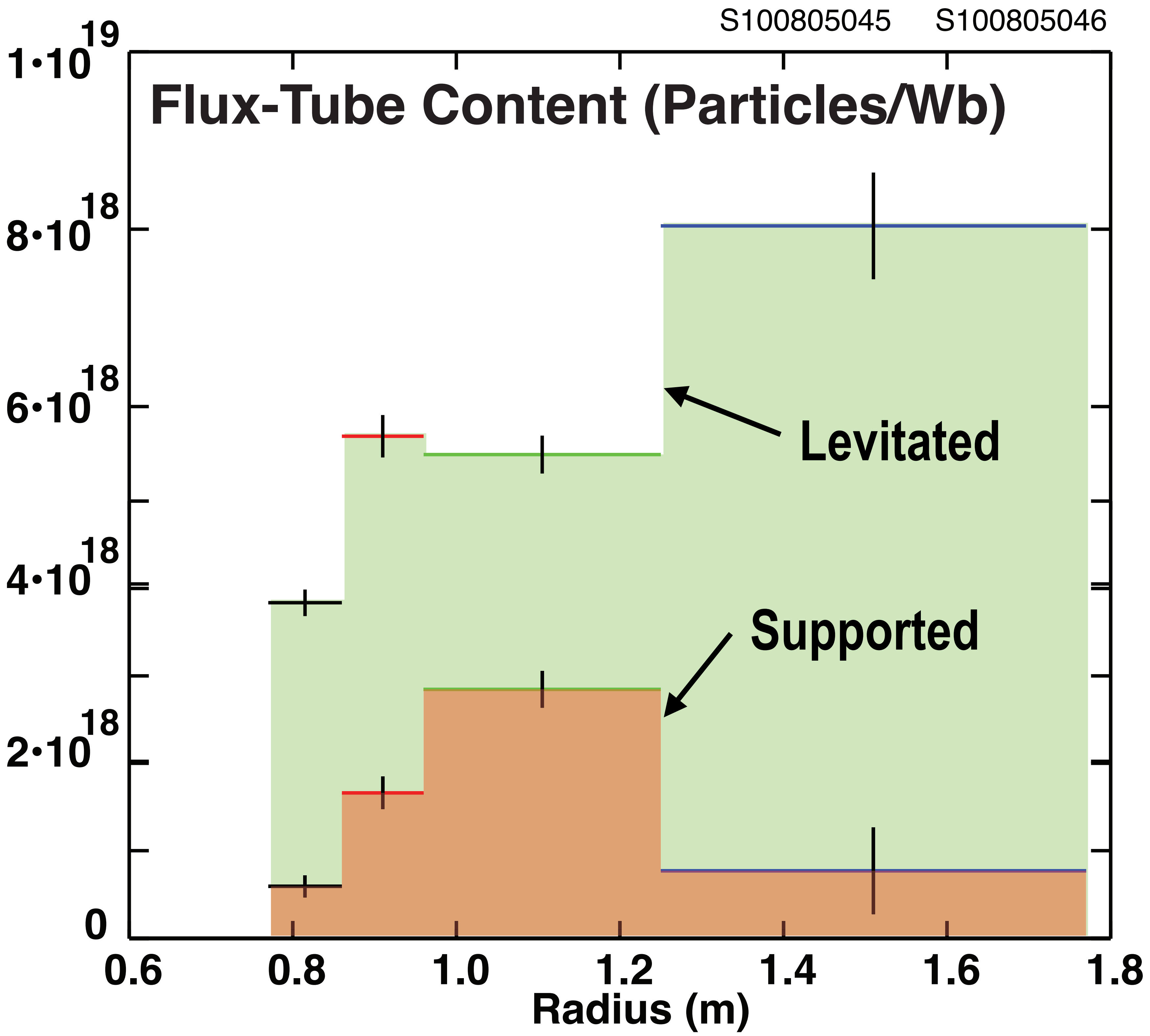


Boxer, *et al.*, "Multichannel microwave interferometer for the levitated dipole experiment," *Rev Sci Instrum* **80**, 043502 (2009).

Levitated Coil creates Centrally-Peaked Density Profile
Supported Coil shows Poor Particle Confinement

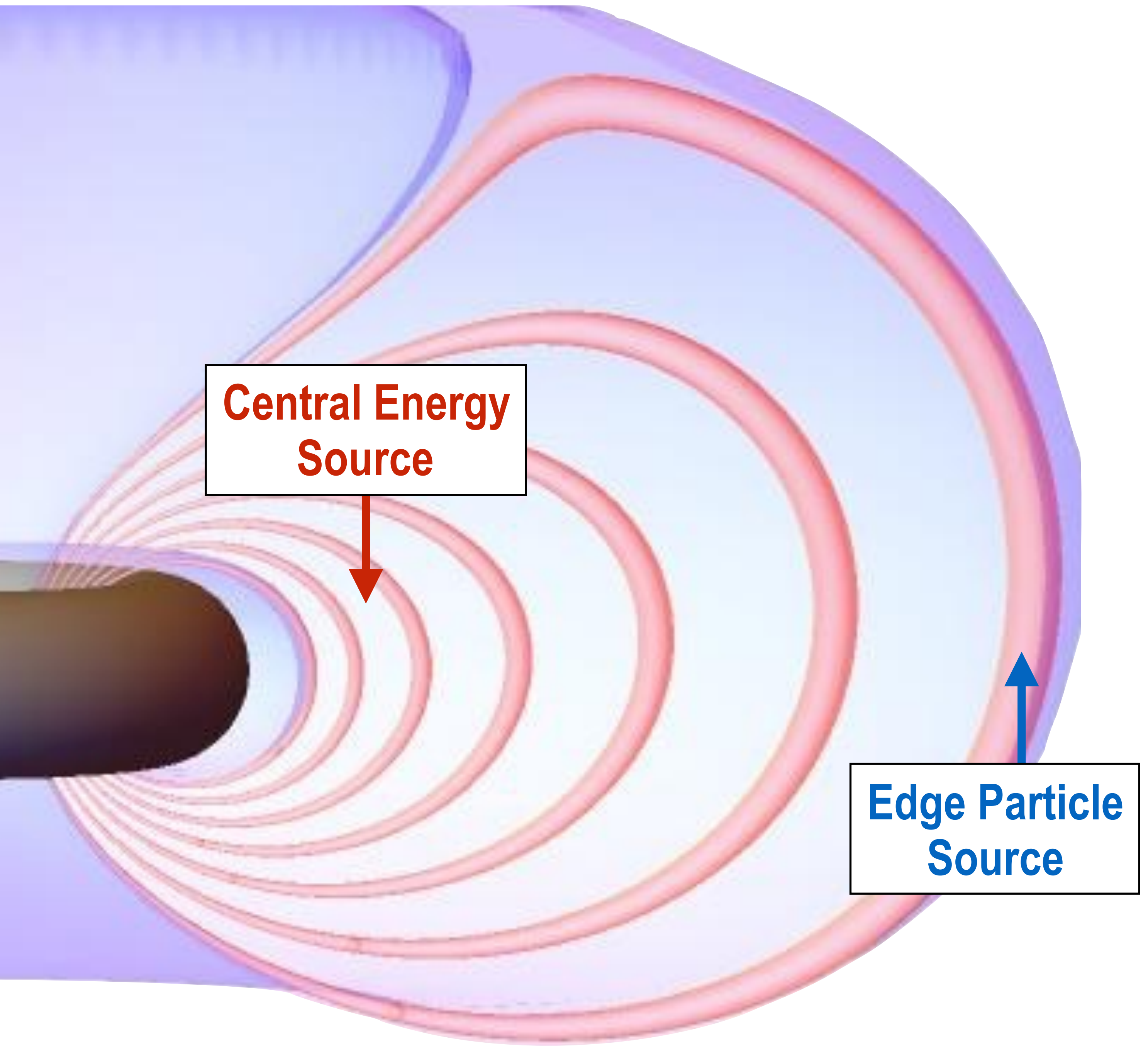


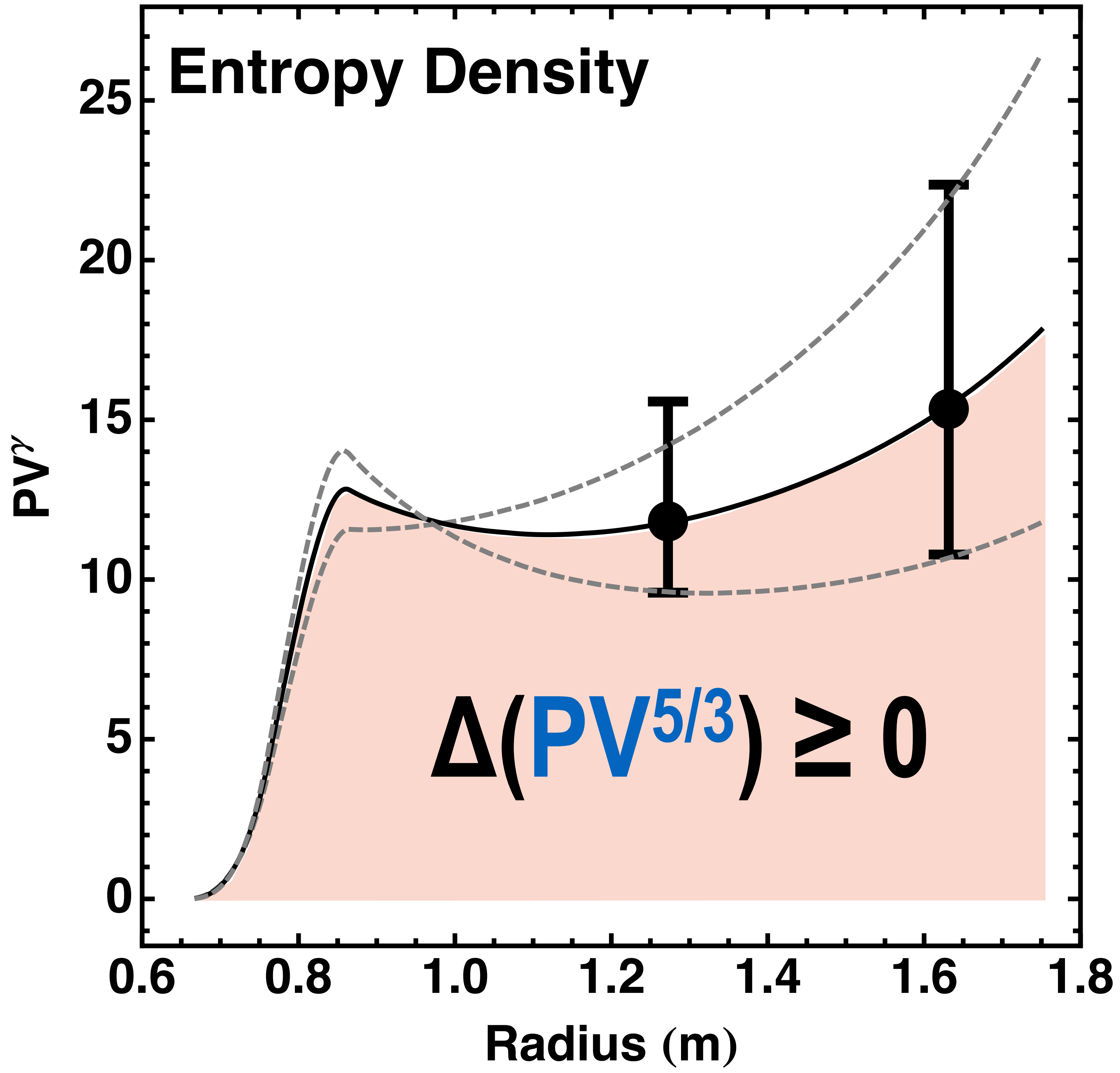


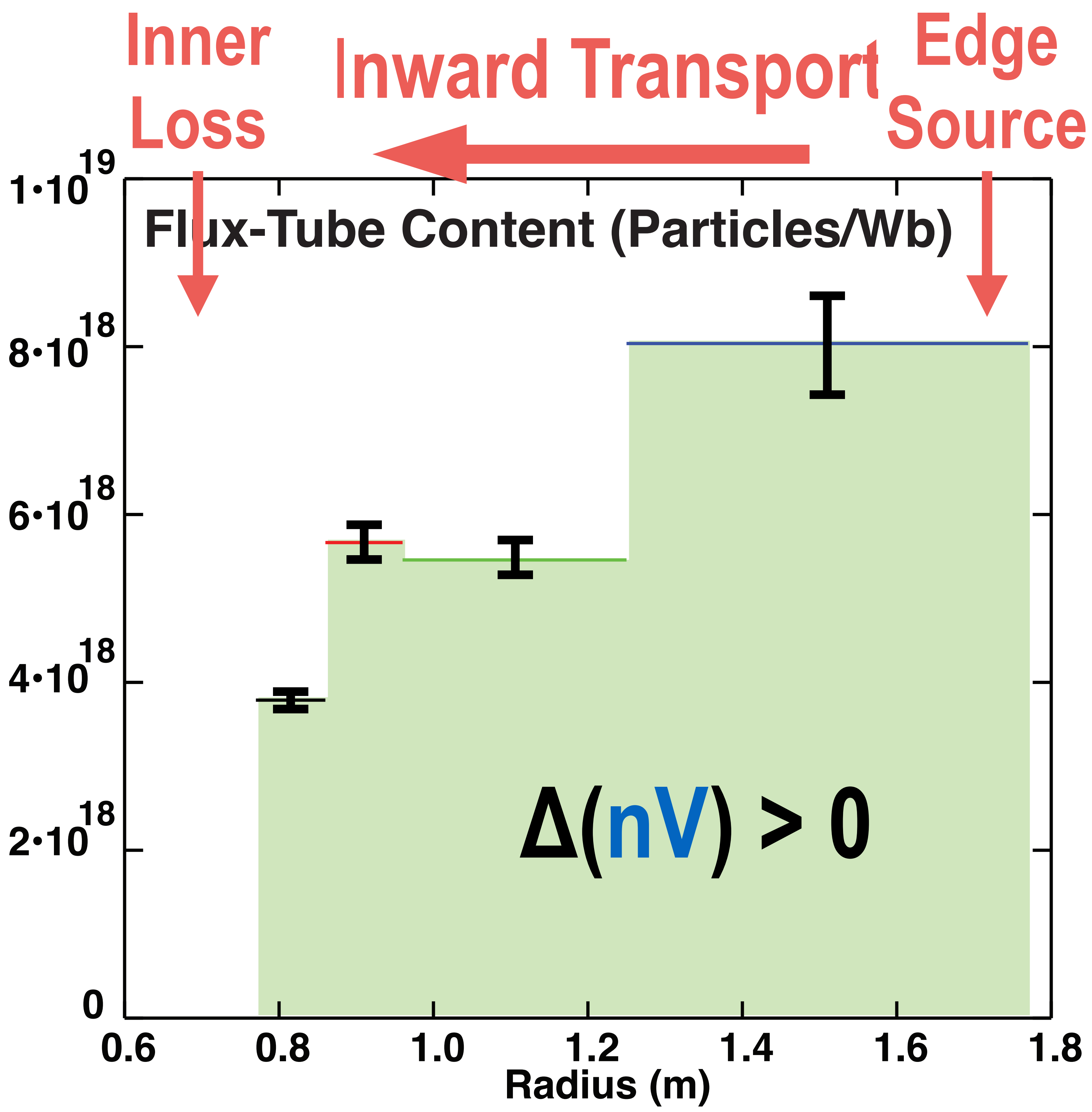


Boxer, *et al.*, "Multichannel microwave interferometer for the levitated dipole experiment," *Rev Sci Instrum* **80**, 043502 (2009).

Pressure and Density Profiles ***During Levitation*** Indicate ***Marginally Stable Pressure*** ($PV^{5/3}$) and Flux-Tube Content (nV) ***Decreasing Inward***







Warm Core: $\Delta(nV) > 0$ and $\Delta(TV^{2/3}) < 0$

$\eta > 2/3$

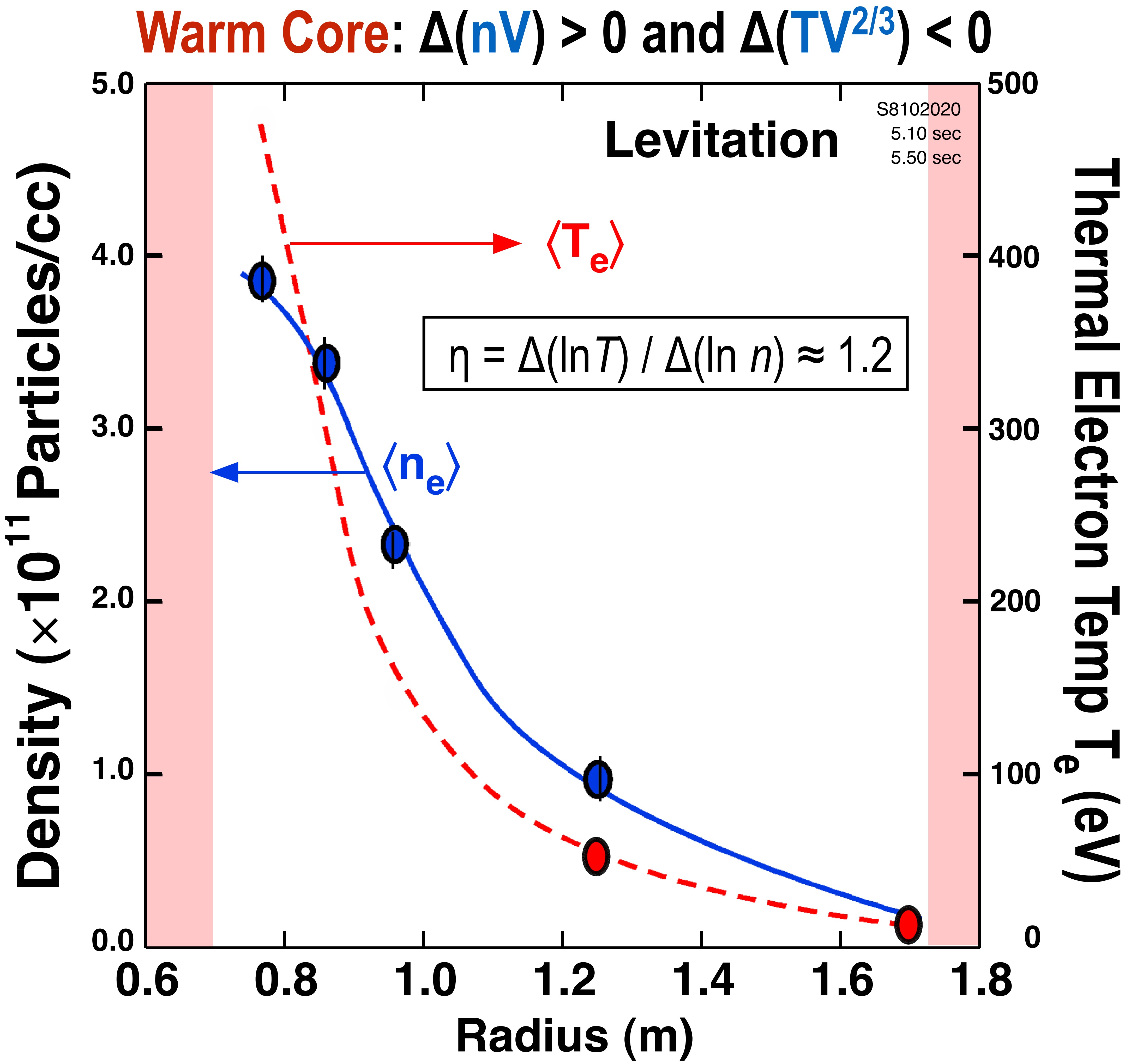
$$\eta = \frac{\Delta \ln T}{\Delta \ln n}$$

Alex Boxer, *et al.*, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nat Phys* **6**, 207 (2010).
Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

Edge fueling and central ECRH creates a "warm core" with η > 2/3

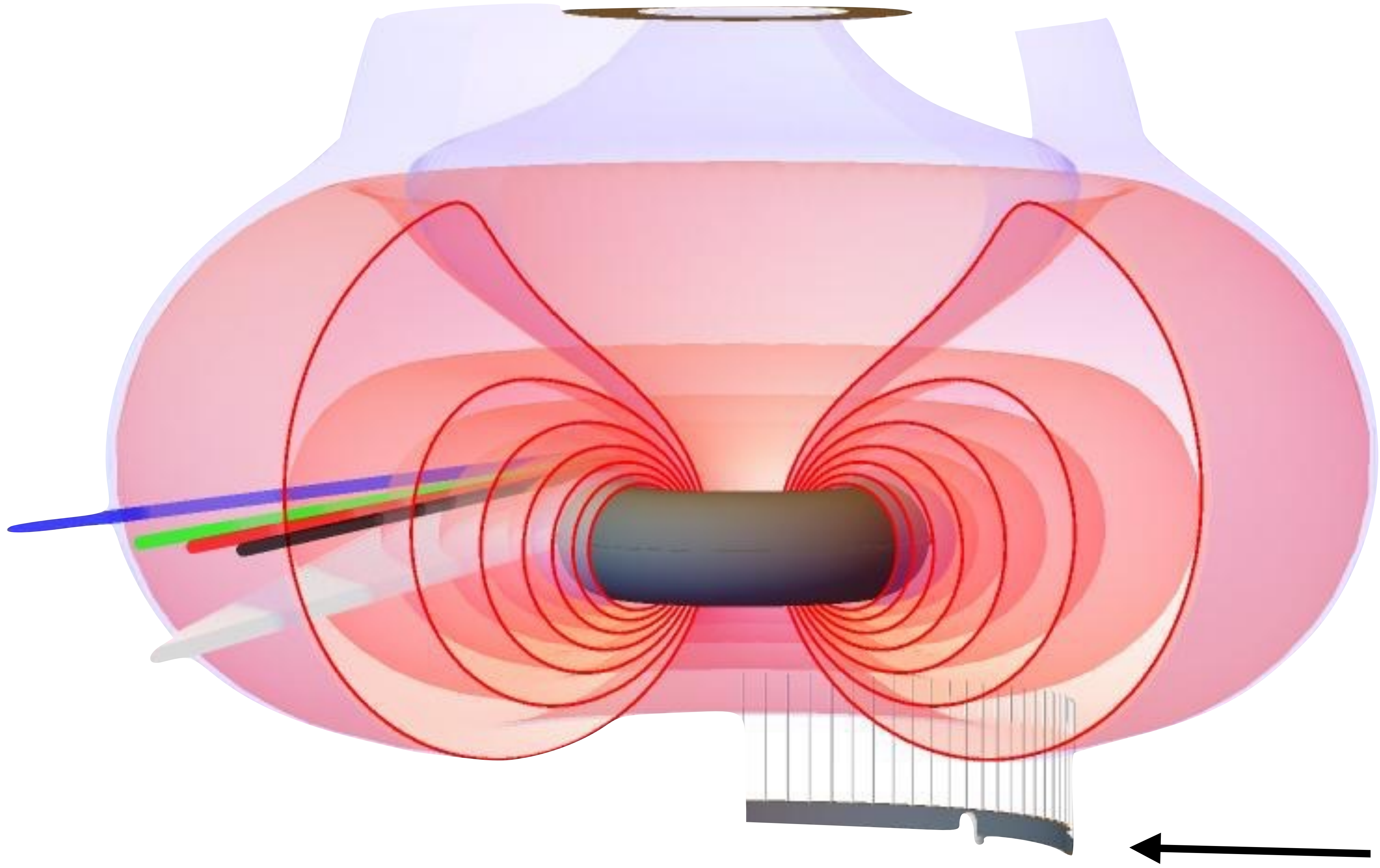
Example thermal profile: Short-pulse heating before appearance of energetic electrons…

- 11 kW ECRH creates thermal plasma energy: $W_{th} \approx 100$ J.
- Measured *edge* $T_e \approx 15$ eV, density profile, and stored energy, imply ***central*** **T_e ~ 500 eV**
- "**Warm core**" with η > 2/3 ~ 1.2
- $\rho^* \sim 0.02$, $\omega_d/2\pi \approx 0.8$ kHz
- Semi-collisional thermal electrons: $2\pi\, v_e/\omega_b \sim 0.006$ (Thermal electrons bounce > 100 times in a collision time.)

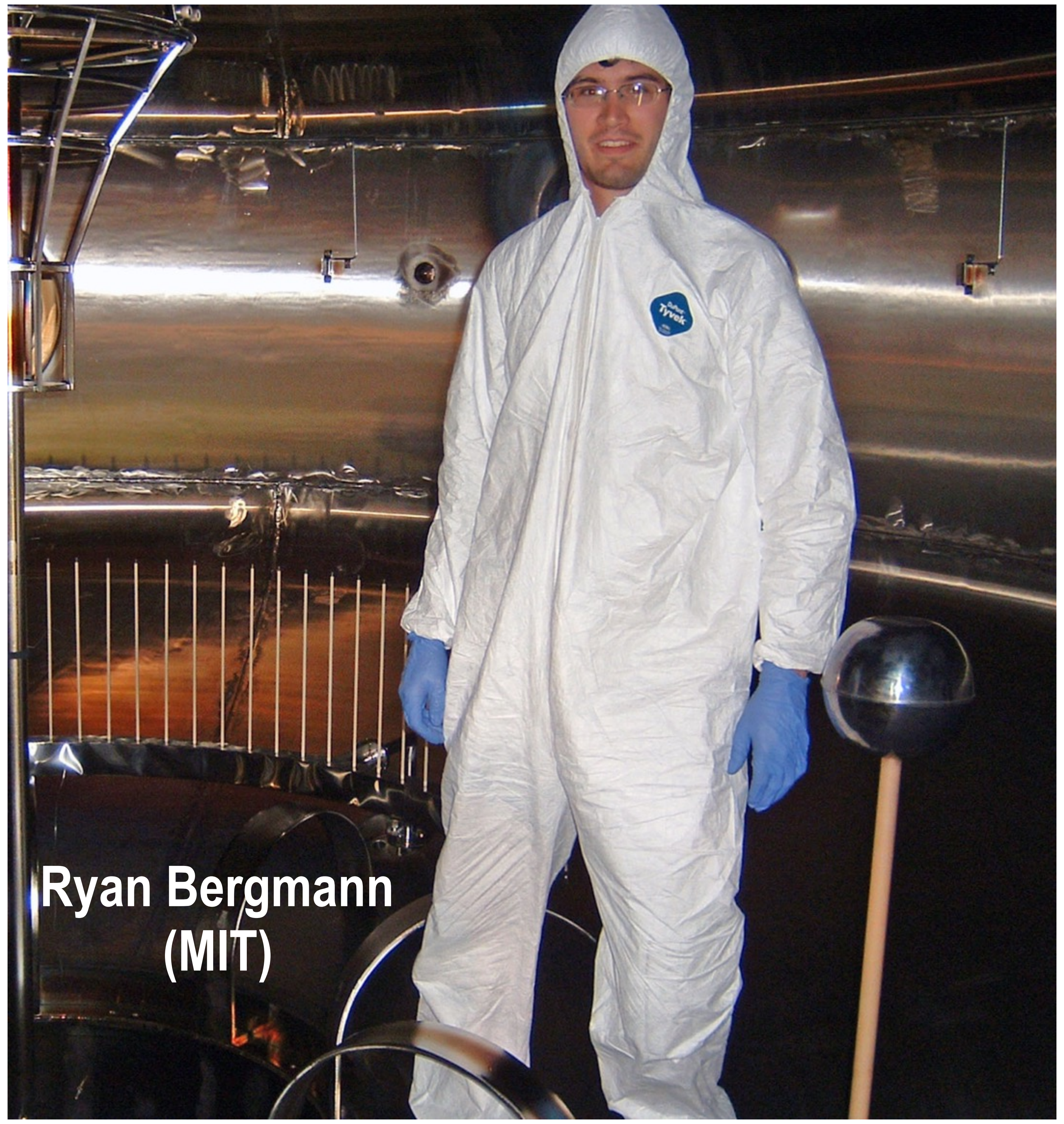


Alex Boxer, *et al.*, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nat Phys* **6**, 207 (2010).
Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

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



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



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

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

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

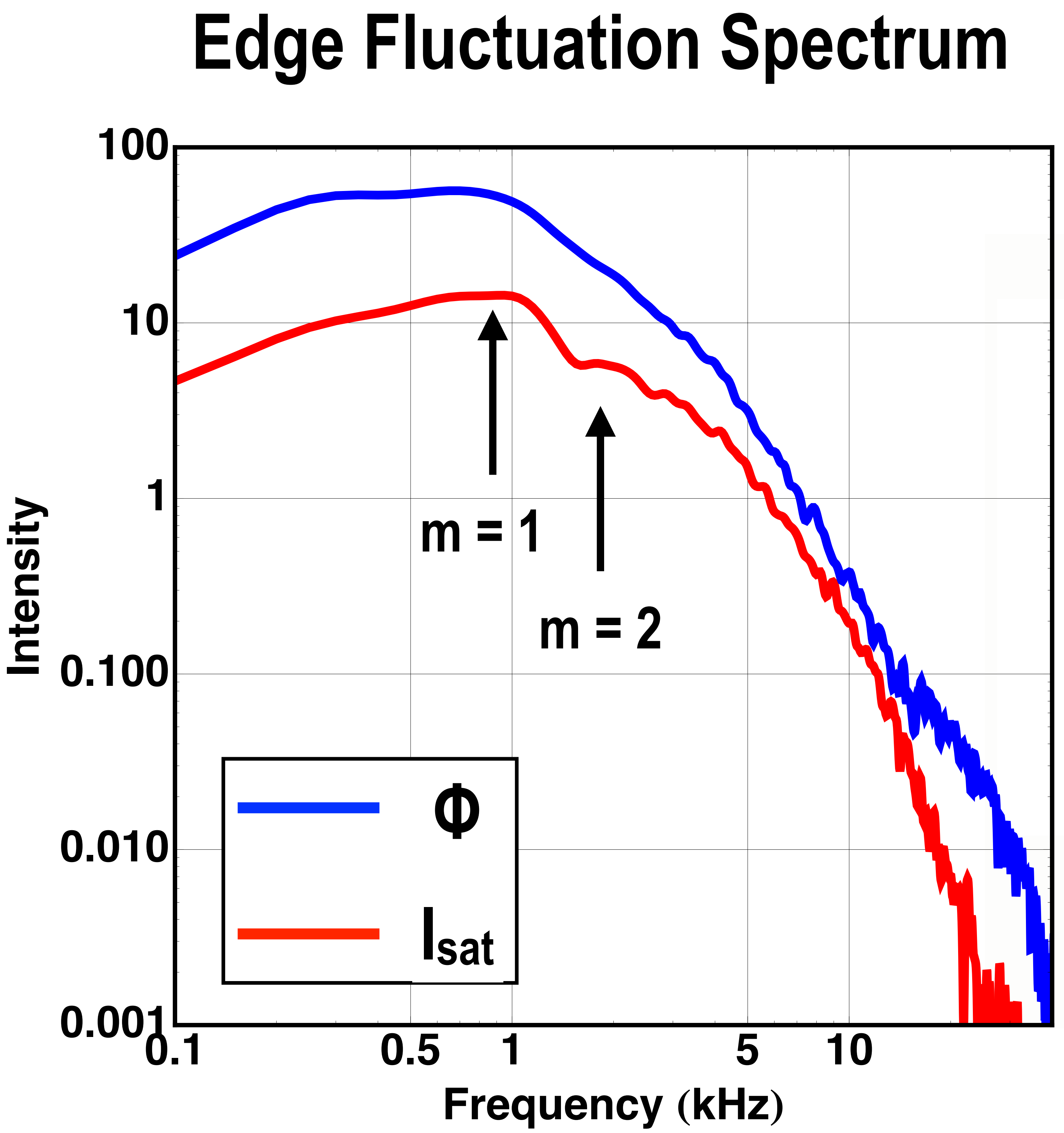
$$\frac{\partial}{\partial t}(nV) = \underbrace{\langle S \rangle}_{\text{Source}} + \frac{\partial}{\partial \psi} D_\psi \frac{\partial}{\partial \psi}(nV)$$

Radial Diffusion due to Interchange/Entropy Turbulence

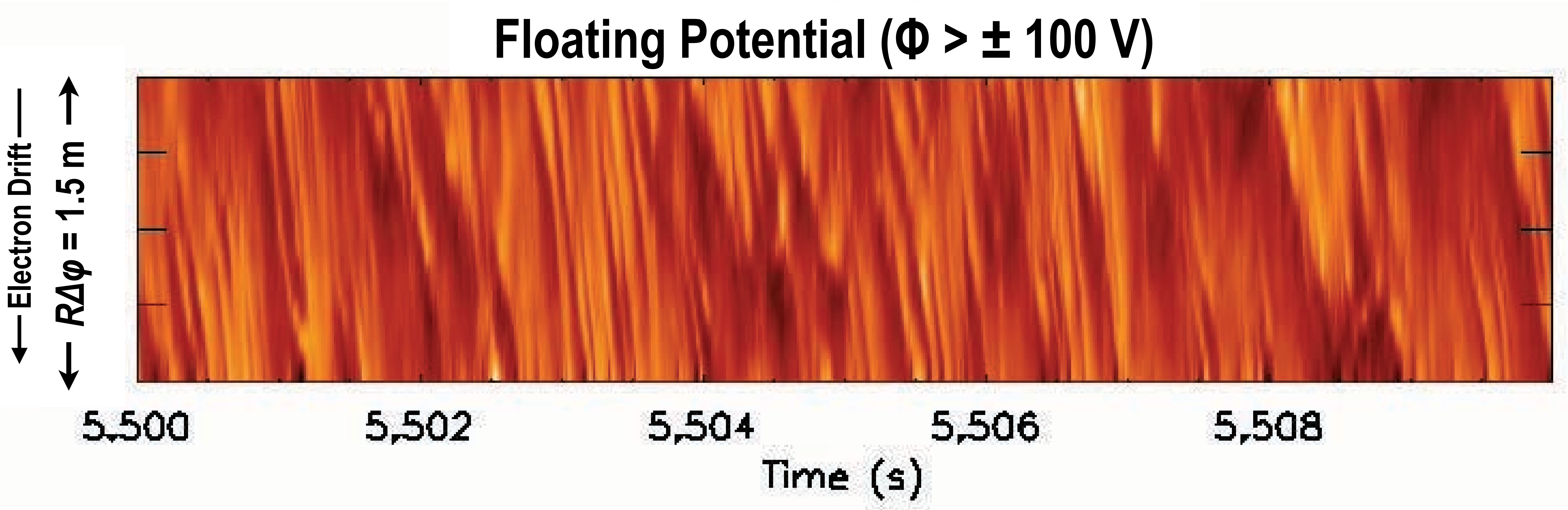
Alex Boxer, *et al.*, “Turbulent inward pinch of plasma confined by a levitated dipole magnet,” *Nat Phys* **6**, 207 (2010).

Turbulent Fluctuations Propagate in Electron Drift Direction

(during edge gas fueling)



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



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

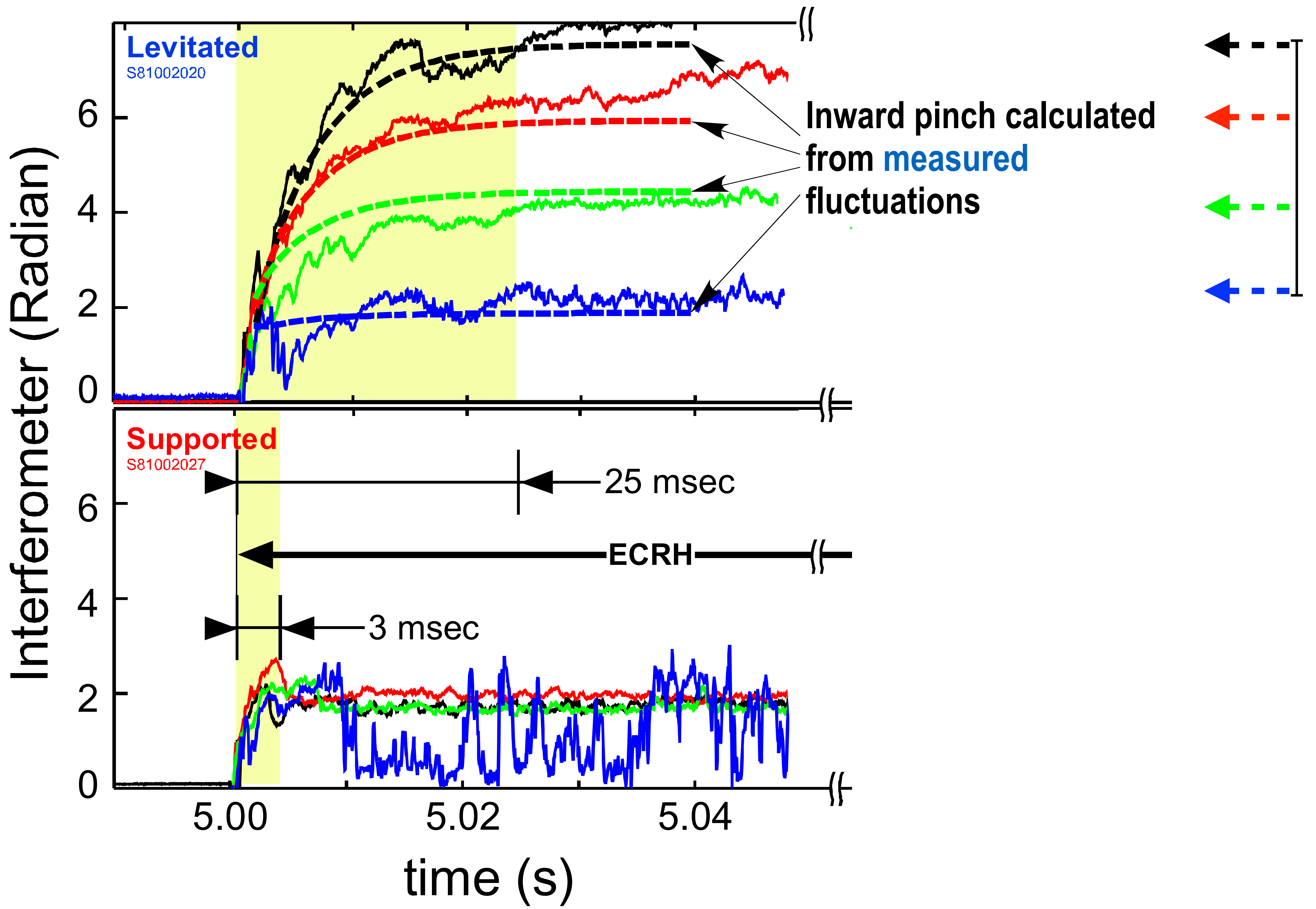
$m = 1, 2, 3, 4, 5, 6, \ldots$

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).

Rate of Inward Diffusion Agrees using Measured Interchange Diffusion Coefficient

With levitated dipole, inward turbulent transport sets profile evolution



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

$D_\psi \sim 0.047$ (Wb^2/s)

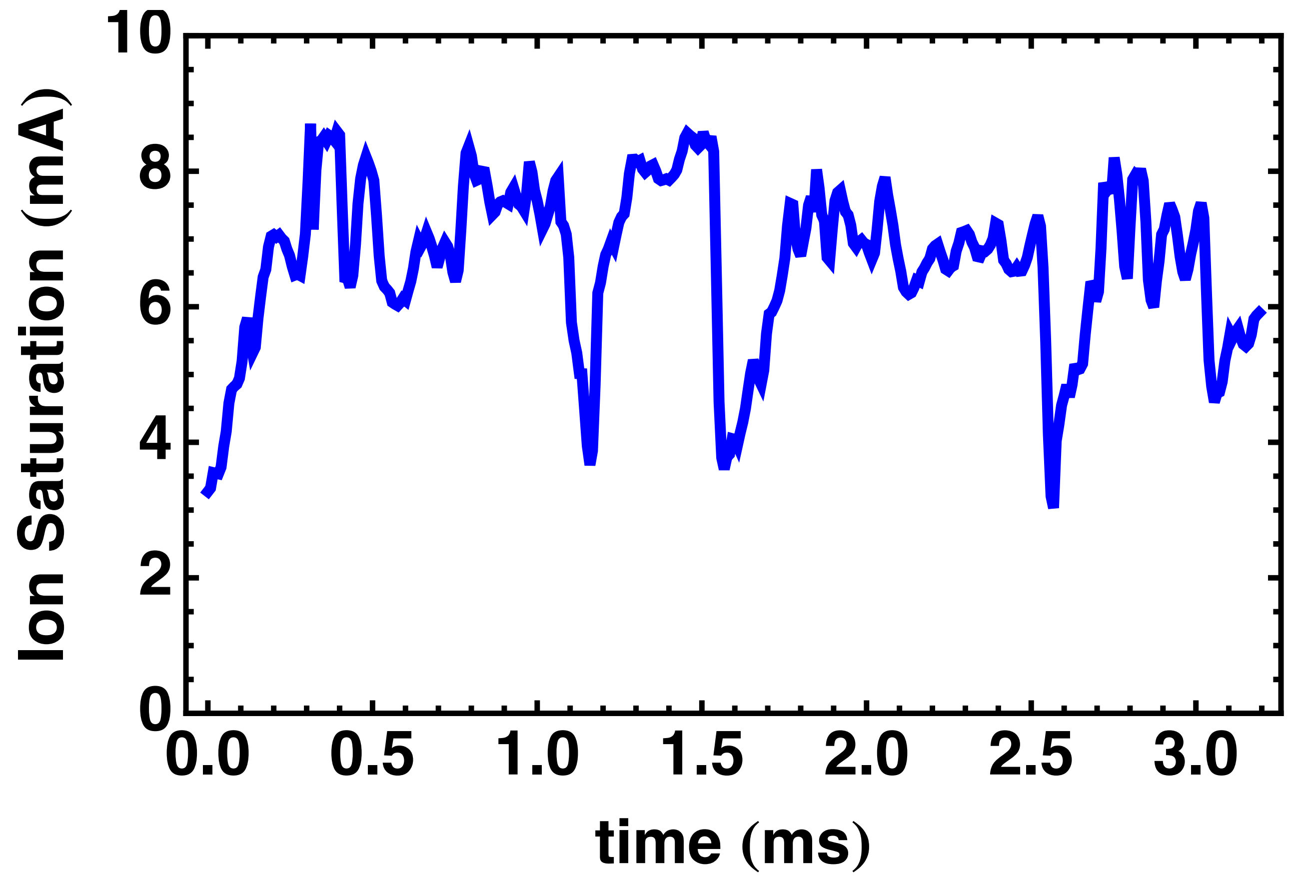
$|E_\varphi| \sim 55$ V/m (RMS) $\tau_c \sim 16$ µsec

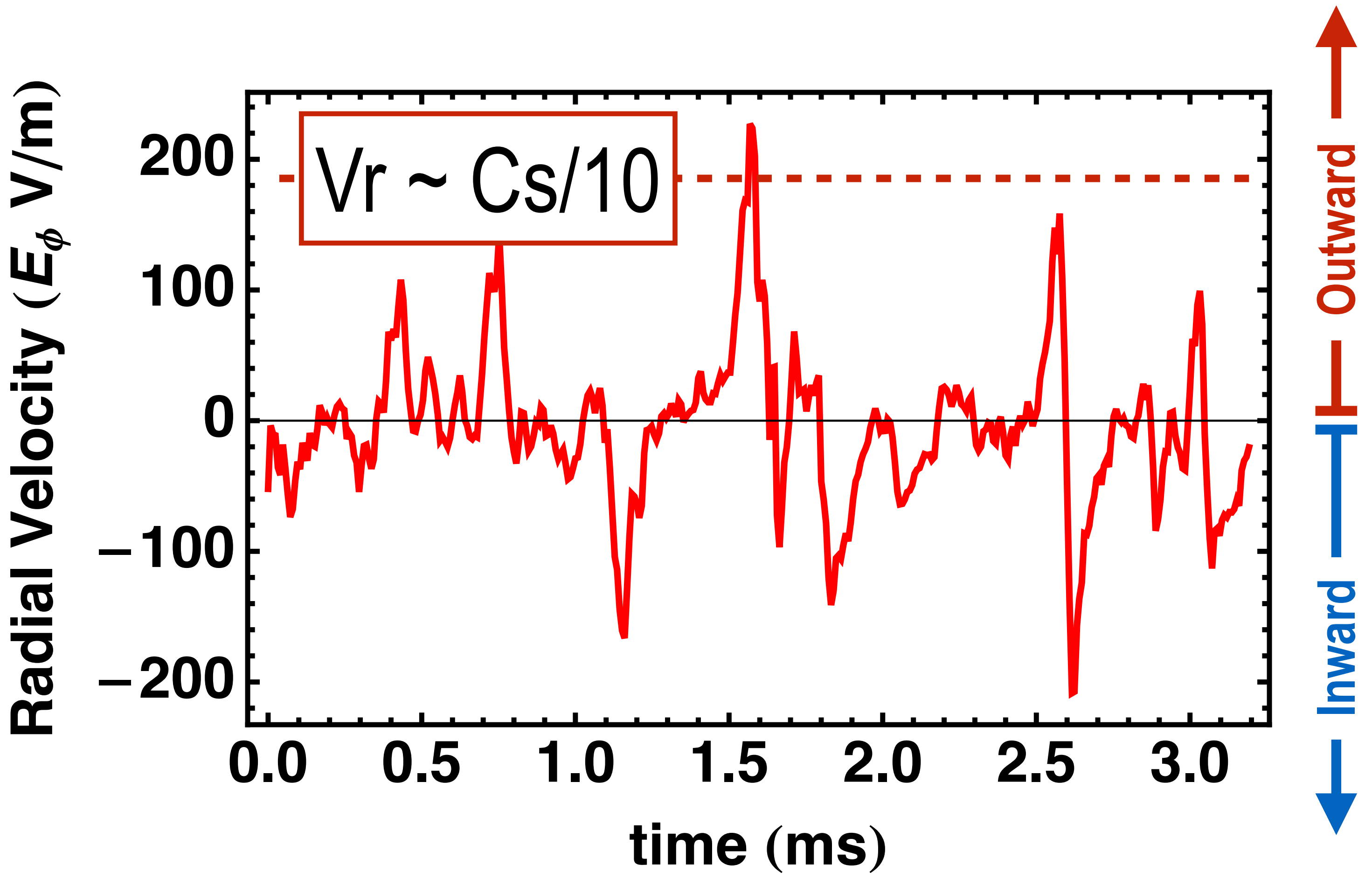
$$D_\psi = R^2 \langle E_\varphi^2 \rangle \tau_c$$

Thomas Birmingham, "Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation," *JGR*, **74**, (1969).
Alex Boxer, *et al.*, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nature Phys* **6**, (2010).

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

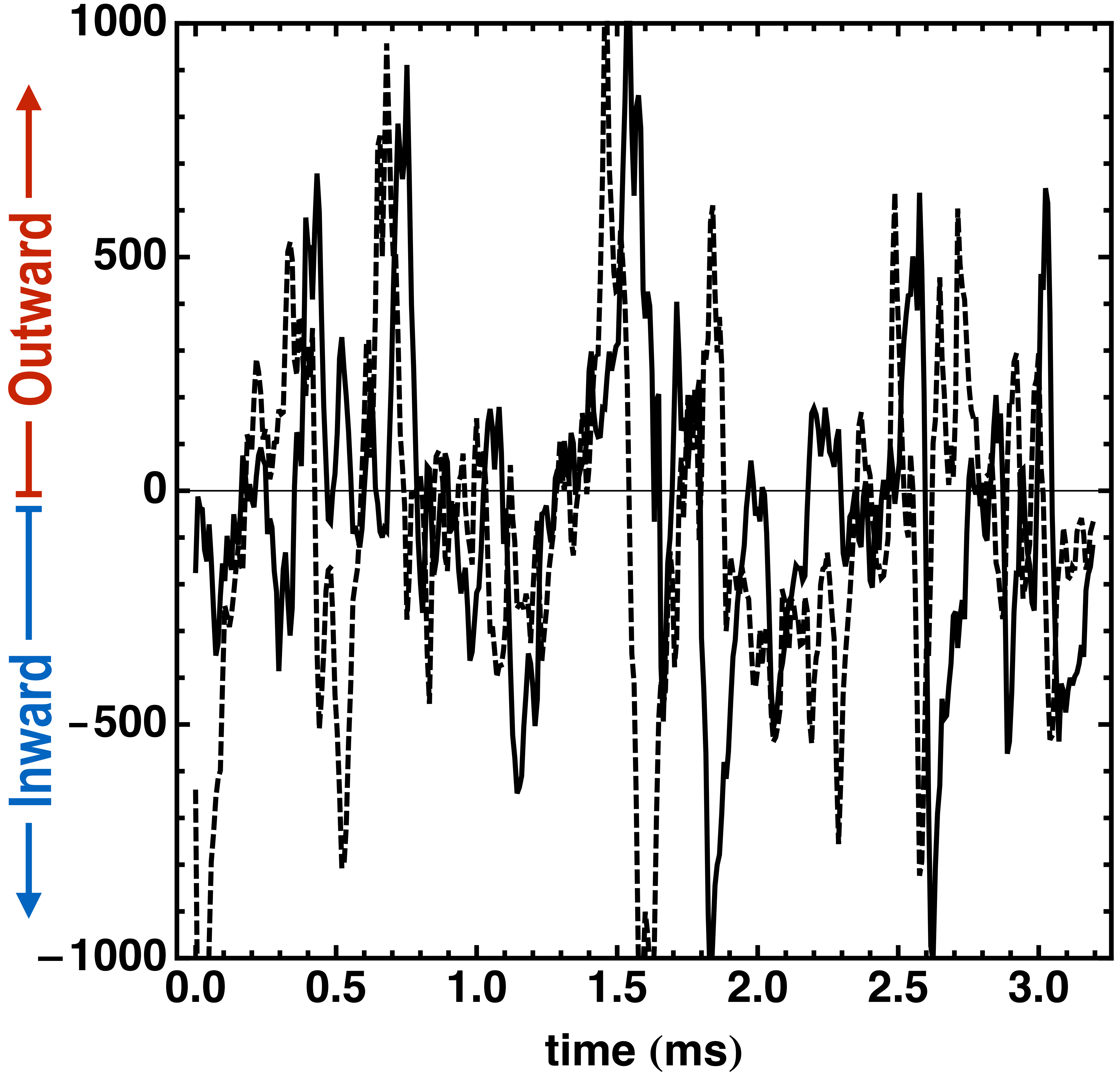
Probe Array:
Floating Potential, E_φ
Ion Saturation Current
Radial **E**×**B** Flux





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

“Bursty” Inward/Outward Filaments



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

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).

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

Probe Array:
Floating Potential, E_φ
Ion Saturation Current
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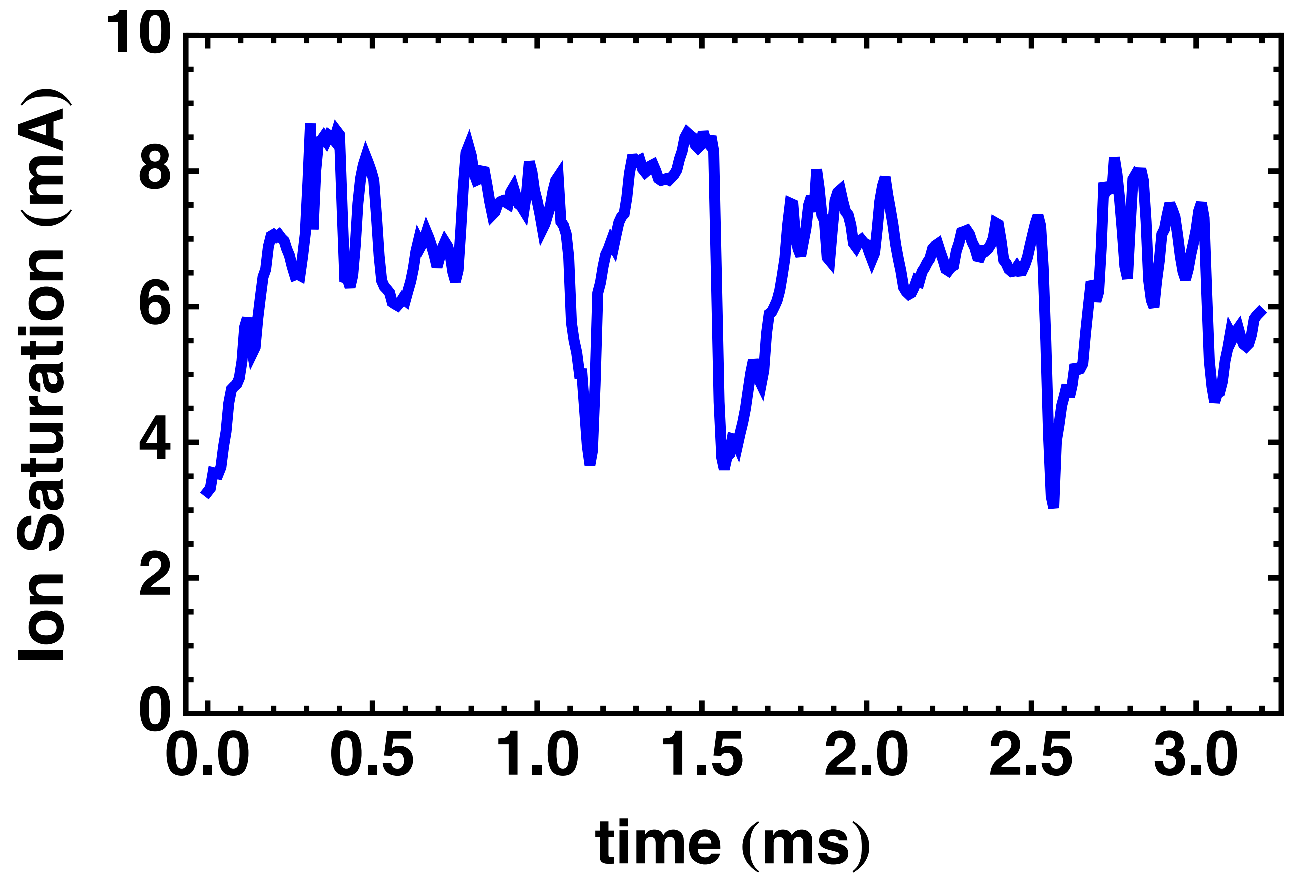
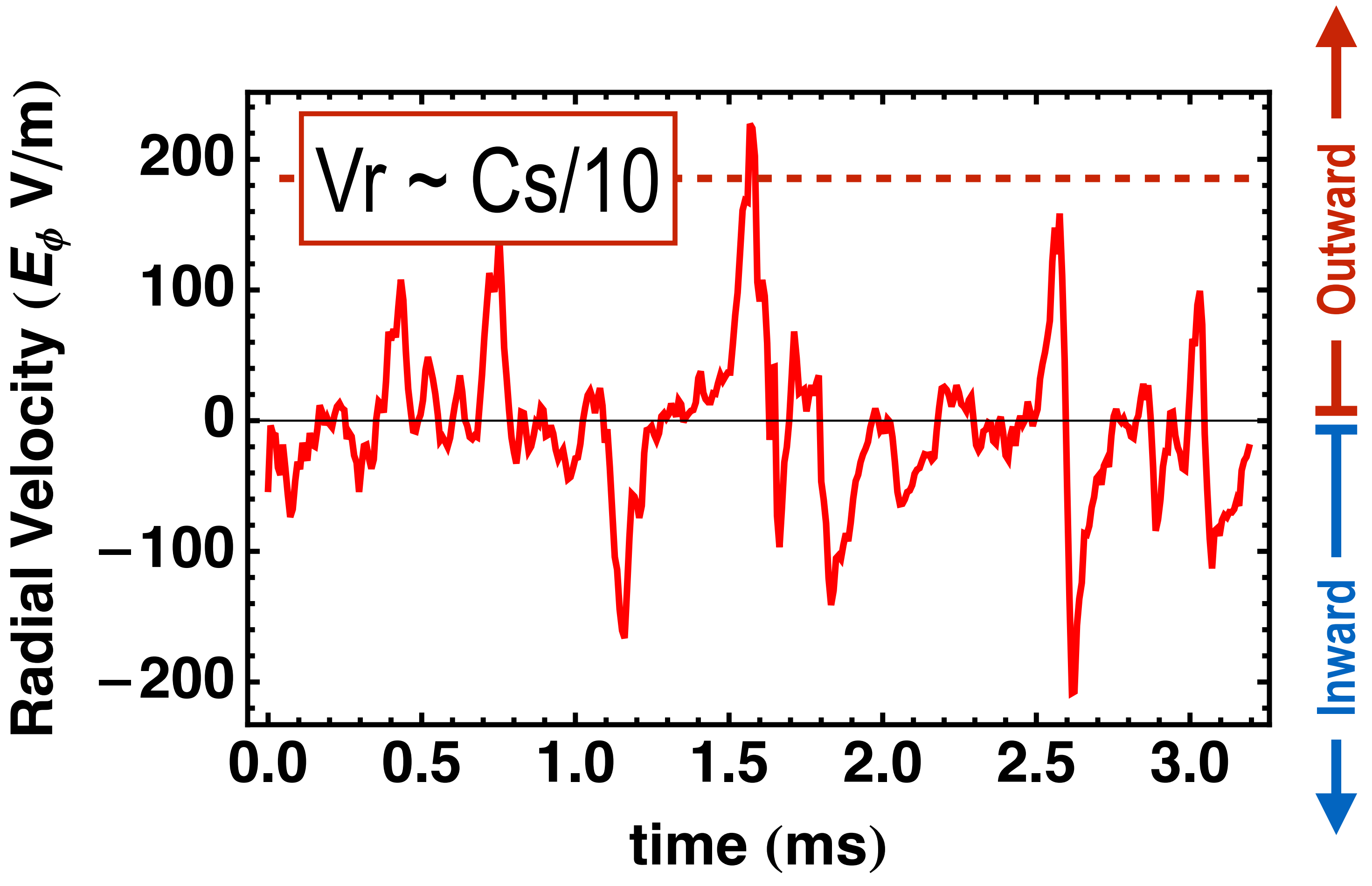
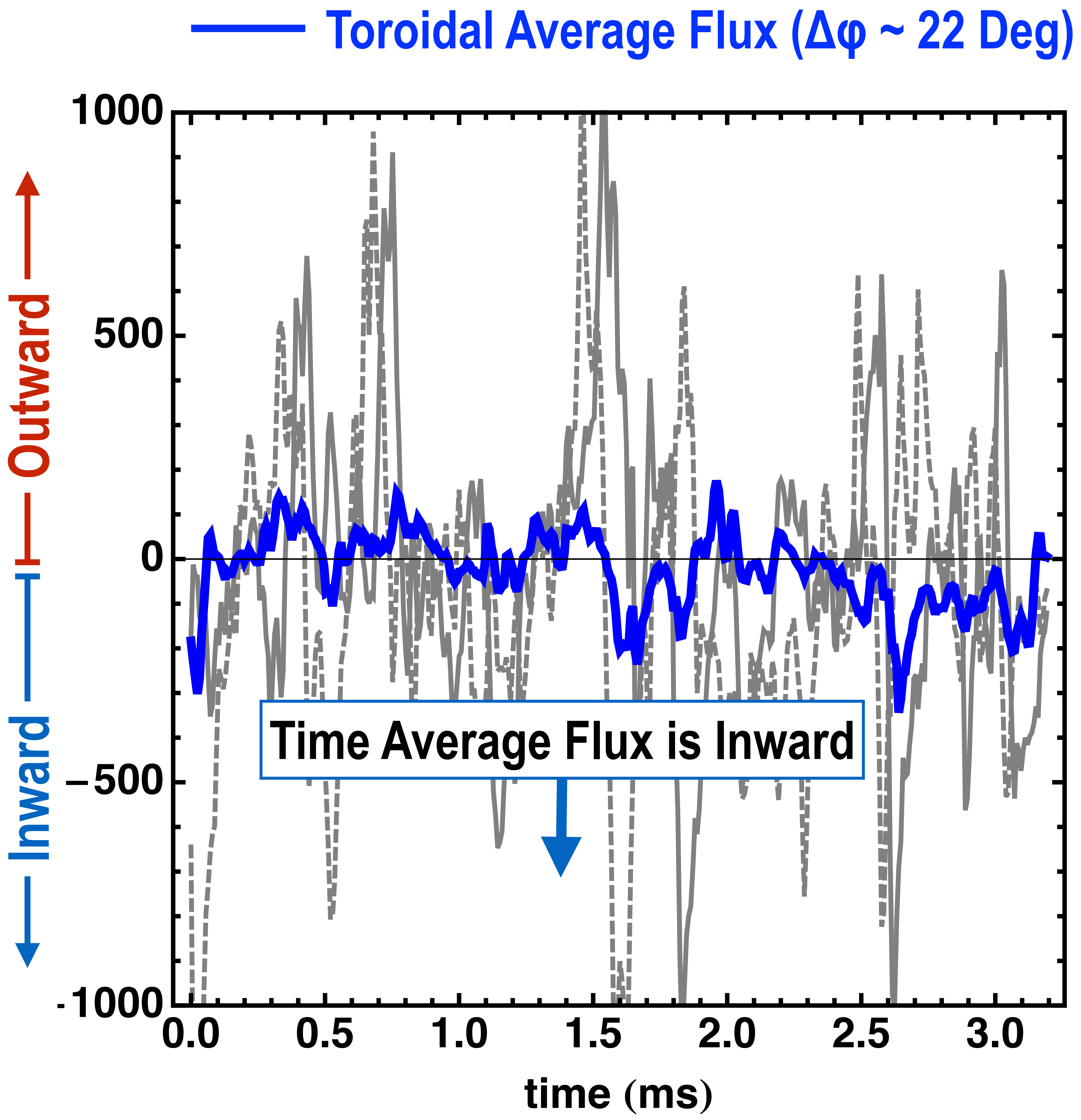




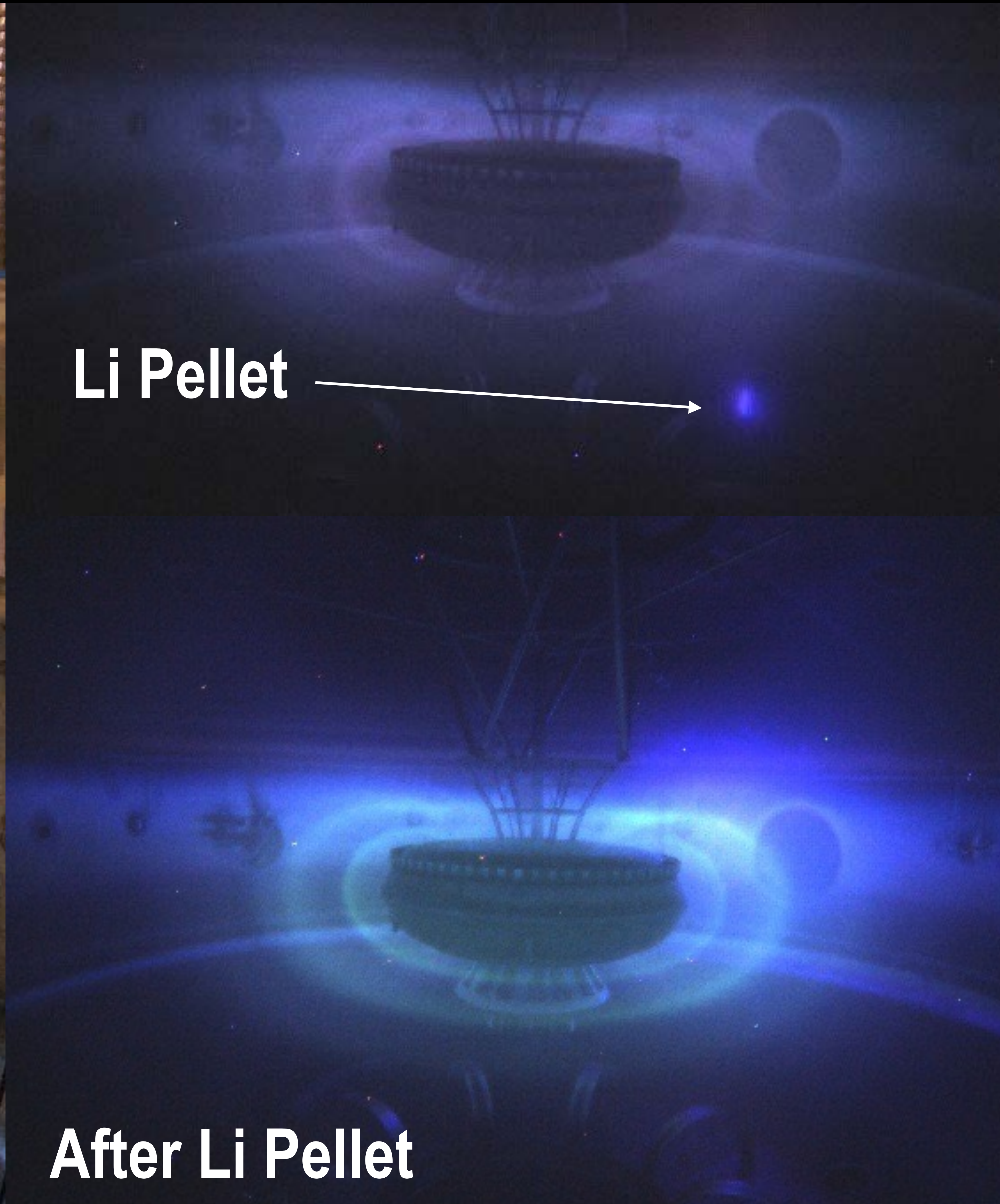
$RE_\varphi \sim \Delta\Phi/\Delta\varphi$



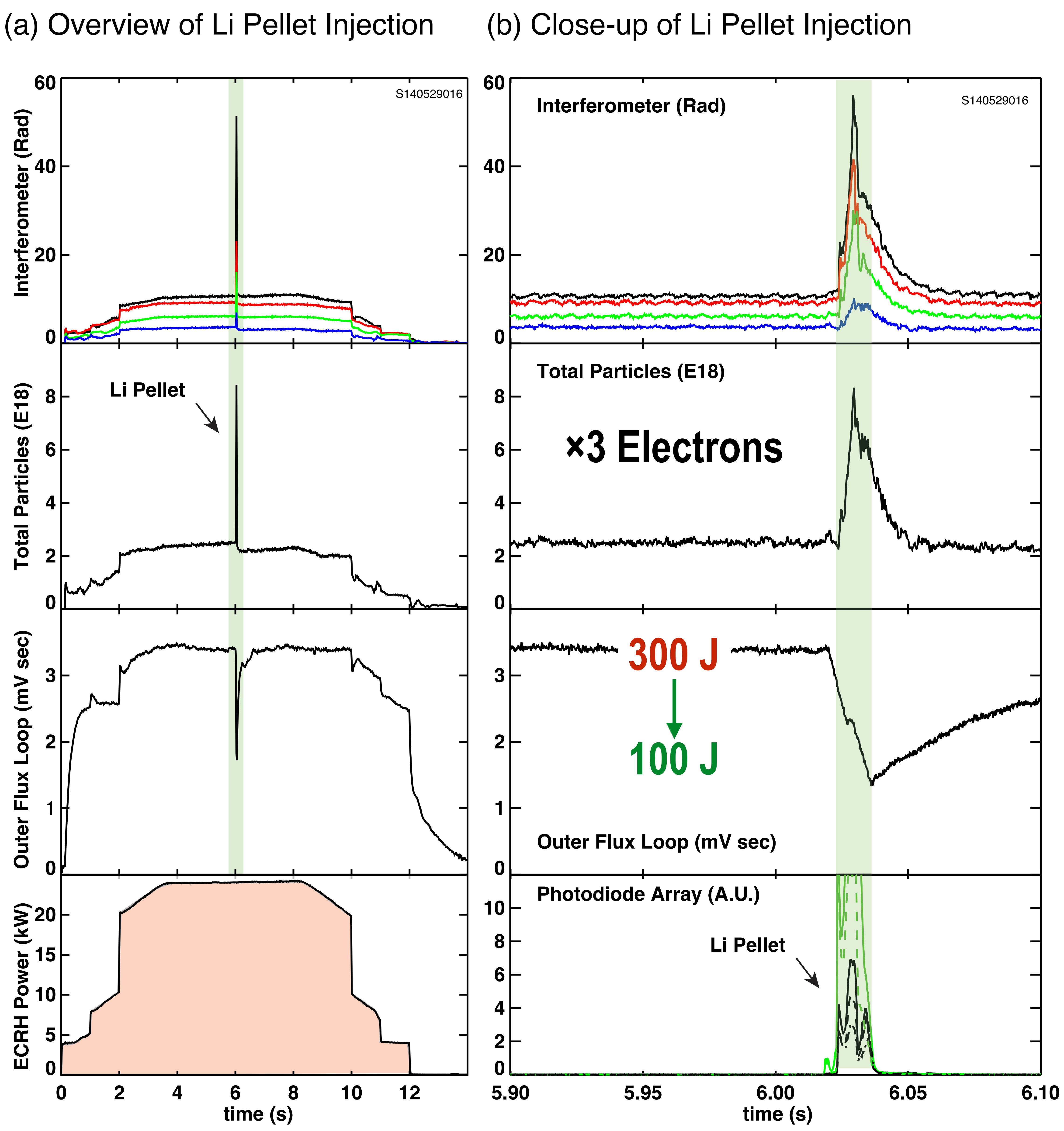
Radial Flux ~ $(E_\varphi/B) \times I_{sat}$

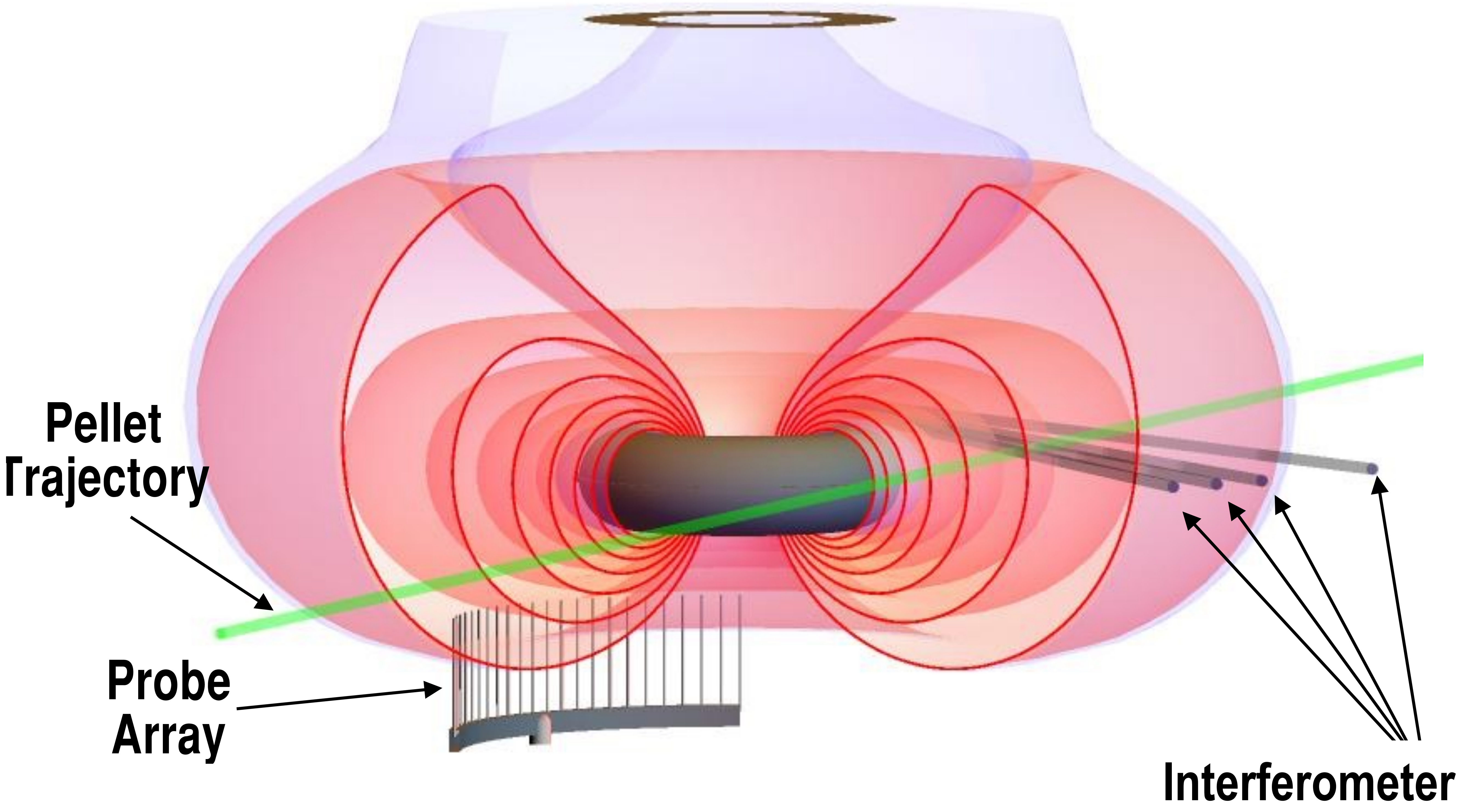
Jen Ellsworth, *Characterization of Low-Frequency Density Fluctuations in Dipole-Confined Laboratory Plasmas*, PhD MIT (2010).
Grierson, *et al.*, "Transport Induced by Large Scale Convective Structures in a Dipole-Confined Plasma," *PRL* **105**, 205004 (2010).

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



Li Pellet Injection Provides Internal Particle Source and Cools Plasma Core

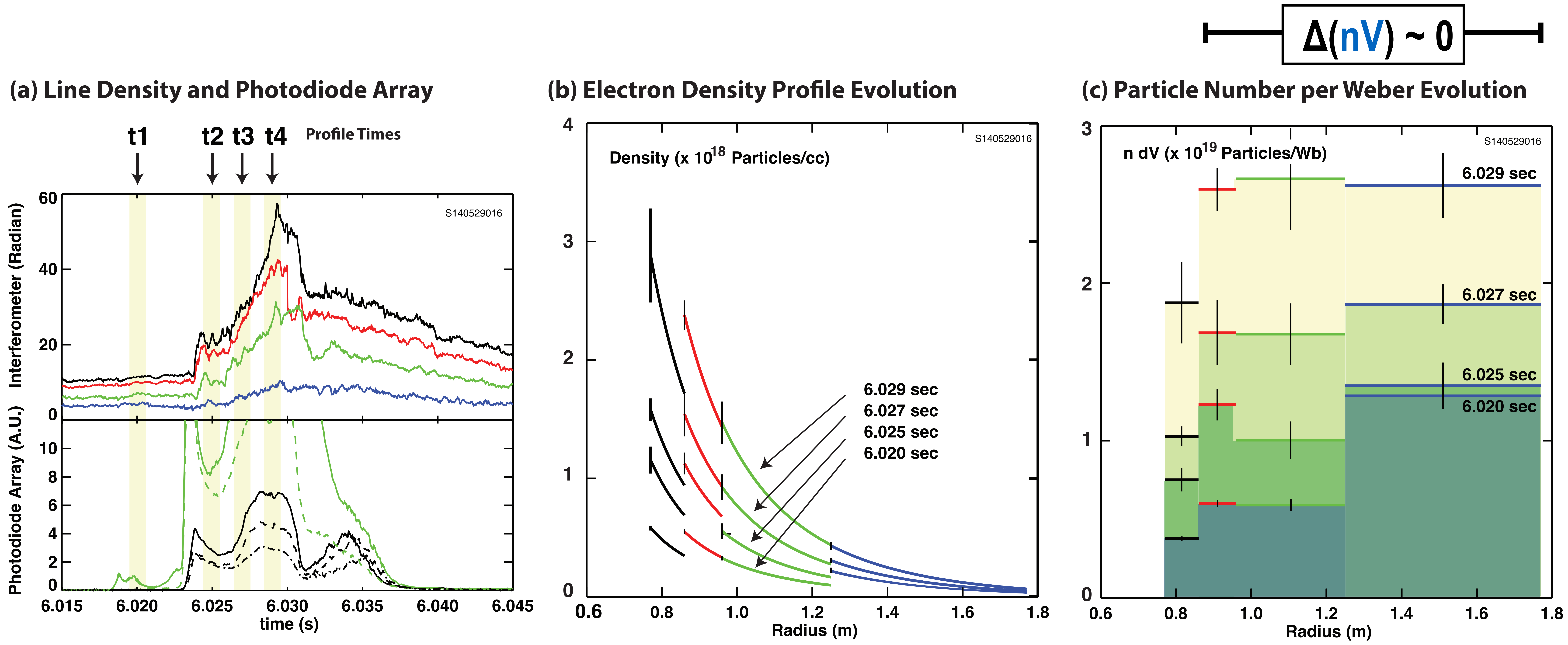




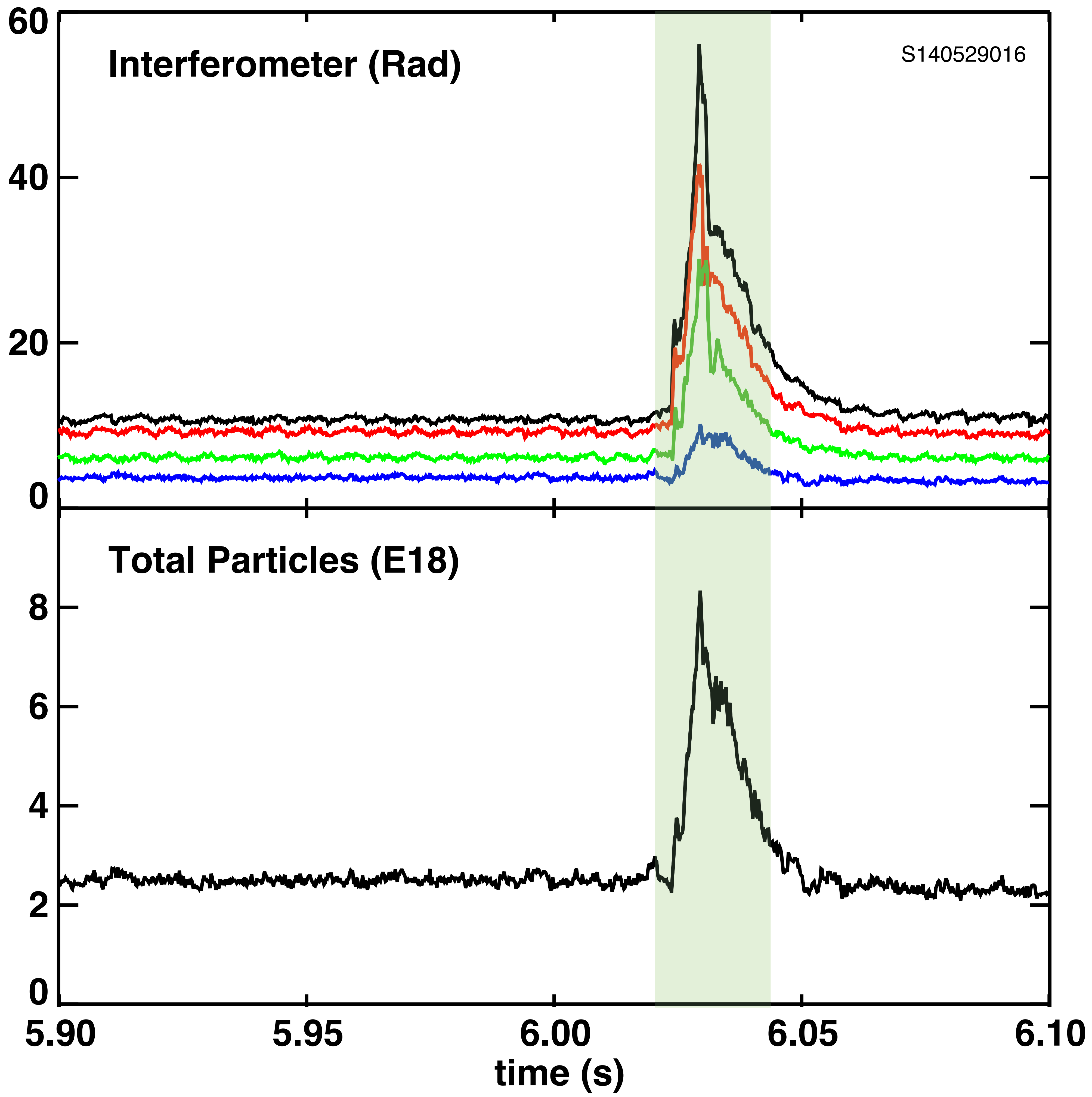
×3 Electrons
÷3 Energy

Li-Pellet Injection Increases Central Density (×5), **Cools Core Temperature**, and Decreases η < 2/3

η > 2/3 ("**warm core**"/edge fueling) becomes η < 2/3 ("**cool core**"/pellet fueling)

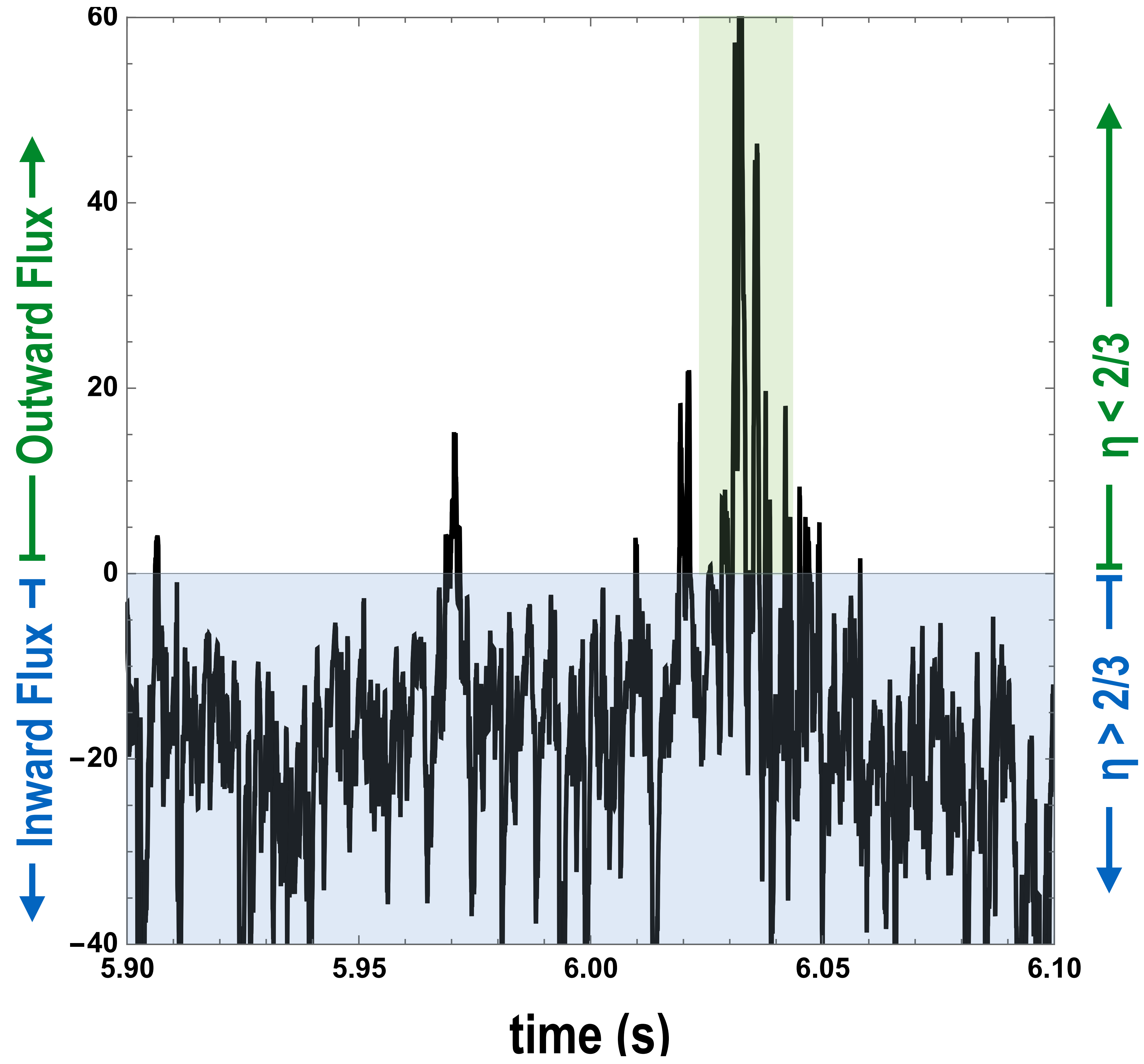


“Cool Core”/Li Pellet Fueling *Reverses* Direction of Particle Flux



Average Radial Particle Flux from Edge Probe Array

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

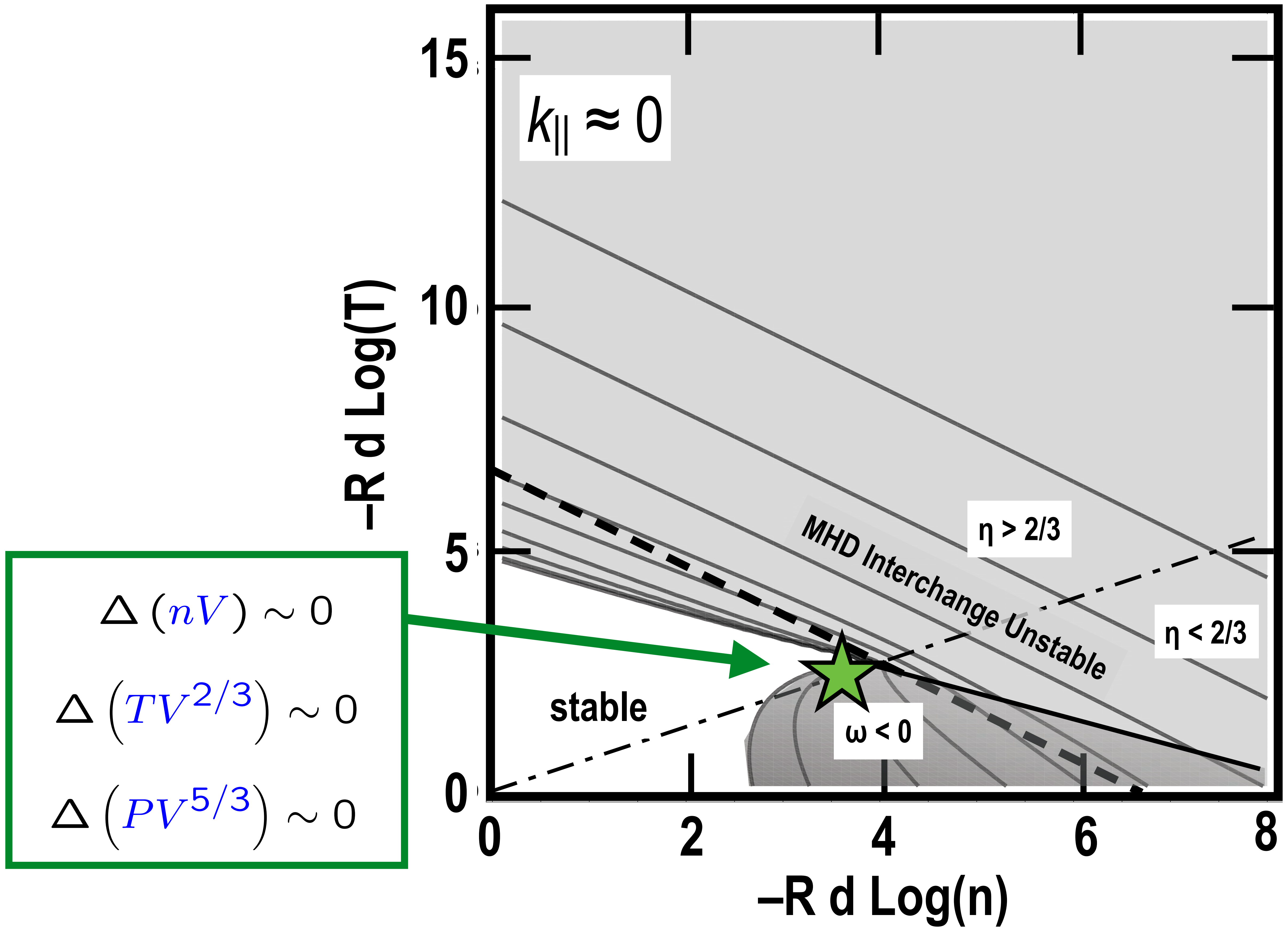


Outline

- *Two laboratory magnetospheres*: LDX and RT-1, having large flux-tube expansion
- *Particle transport and turbulent relaxation* to centrally-peaked profiles (*LDX*)
    - Matt Davis (PhD *Columbia*) and Alex Boxer (PhD *MIT*)
- ***Understanding entropy mode turbulence*** near marginal stability (***GS2***)
    - Sumire Kobayashi (PhD *Dartmouth/Rogers*)
- *Achieving record high local β* by stabilizing fast electron interchange instability (*RT-1*)
    - Yoshihisa Yano (PhD *Univ Tokyo/Yoshida*)
- *Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement*

Physics Tools Used to Understand Magnetic Confinement in Tokamaks can be Applied to the Laboratory Magnetosphere

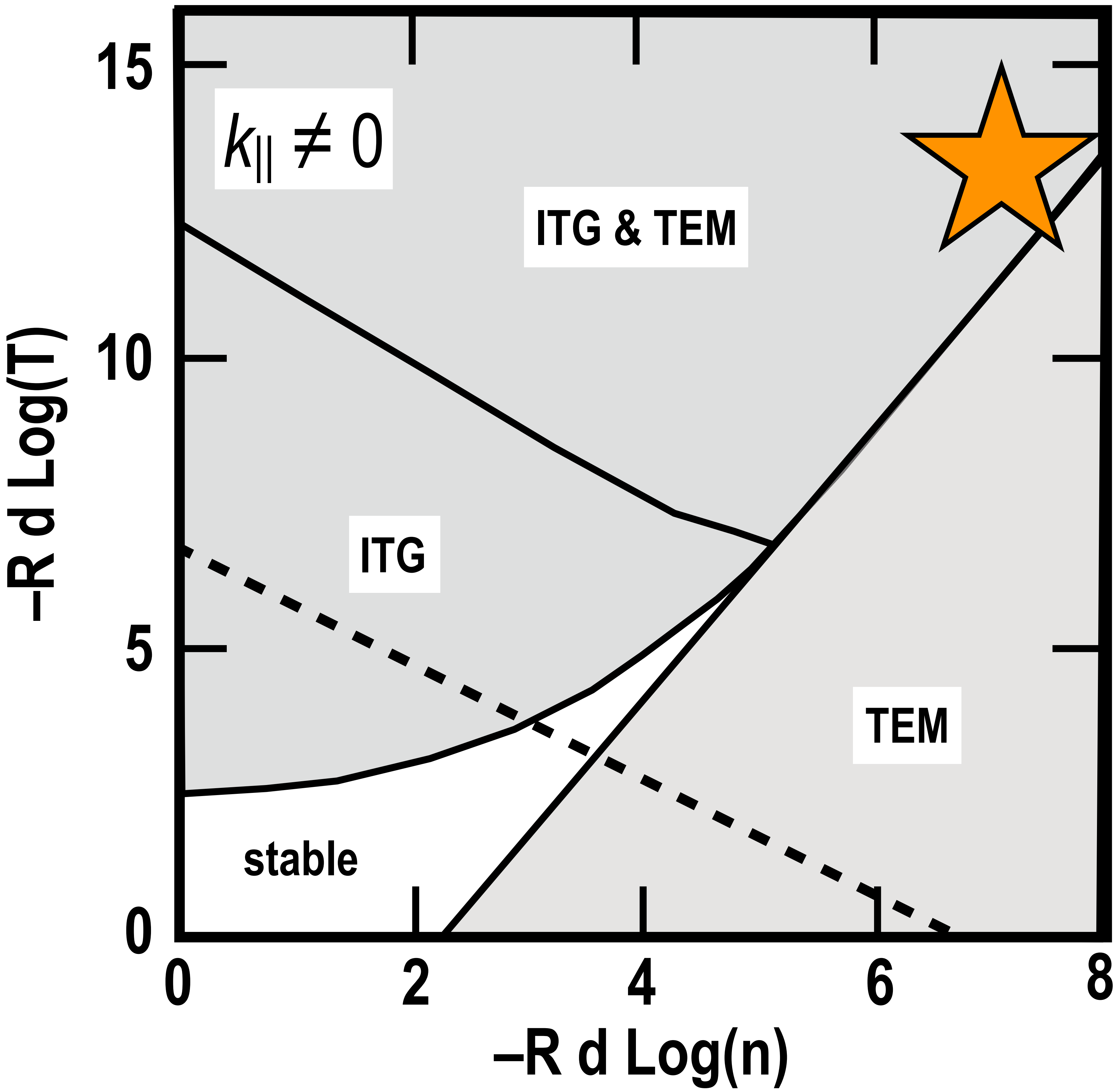
(a) Dipole Interchange-Entropy Modes



Weak gradients: $\omega_p^* \sim \omega_d$

Stable by compressibility and field line tension

(b) Tokamak ITG-TEM Modes



Steep gradients: $\omega_p^* >> \omega_d$

Stable by average good curvature and magnetic shear

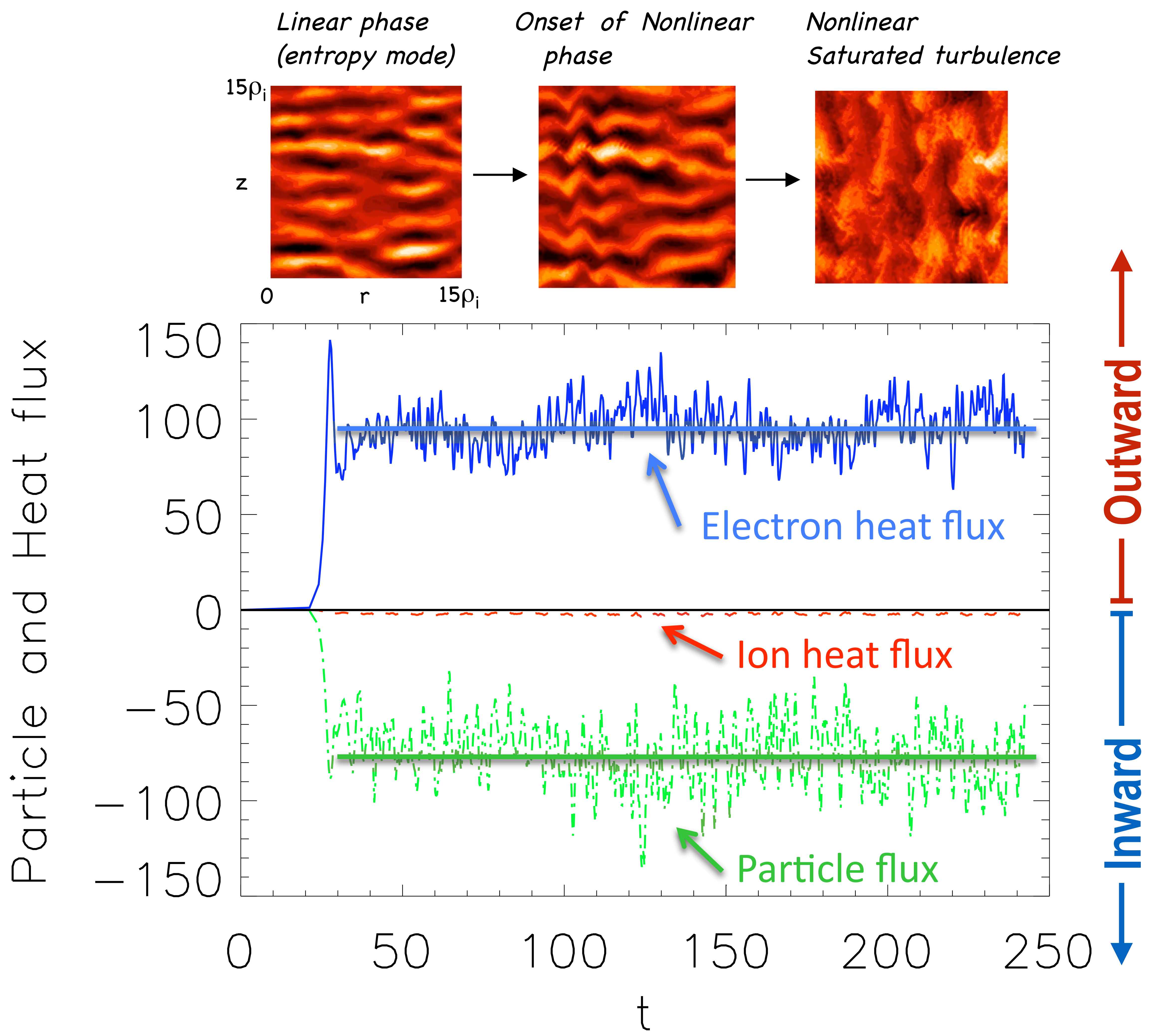
From Ricci, et al., *Phys Plasma*, **13**, 062102 (2006)

X. Garbet, *Comptes Rendus Physique* **7**, 573 (2006)

Gyrokinetic Simulations of Closed Field Line Systems

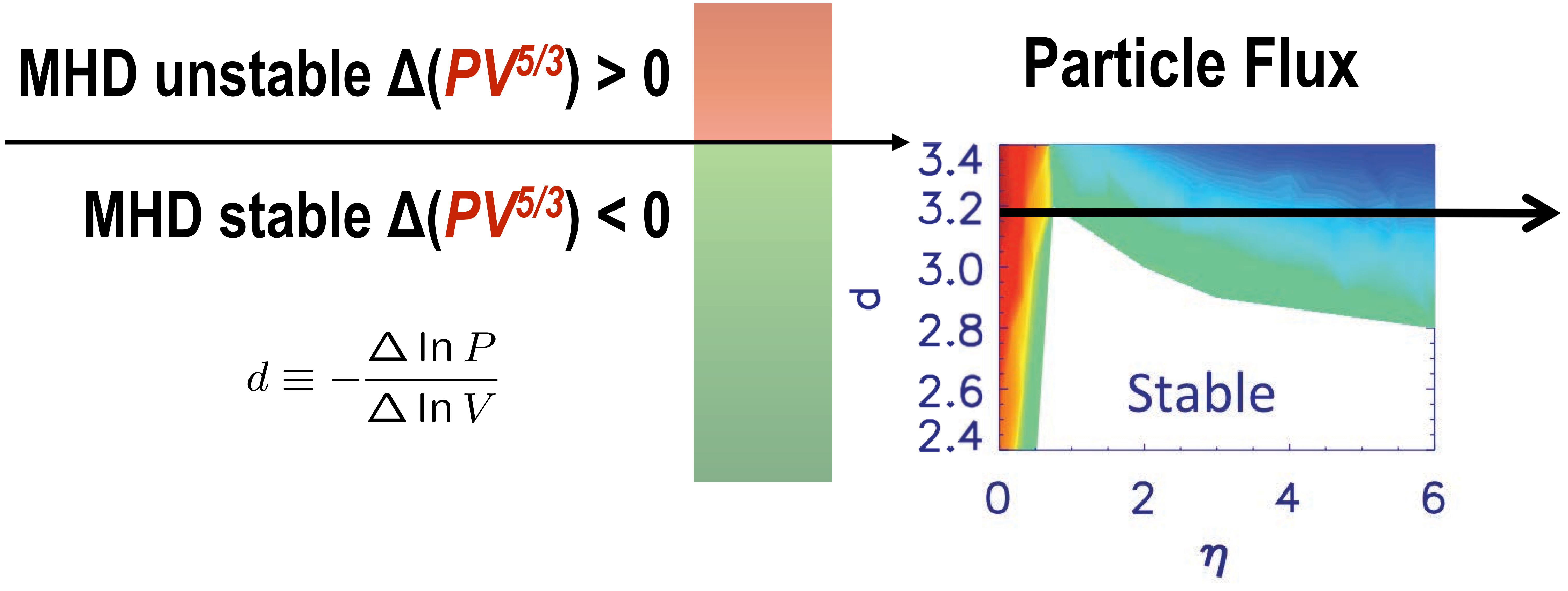
Sumire Kobayashi (PhD Dartmouth)

- 5D Gyrokinetic (GS2) simulations and quasilinear theory of entropy mode turbulence consistent with observations.
- "***Warm Core***", η > 2/3, creates inward particle pinch and outward heat transport.
- "***Cool Core***", η < 2/3, creates outward particle pinch and inward heat flux.
- ***Furthermore***: Nonlinear simulations show zonal flows, with significant transport reduction, appear at low collisionality.

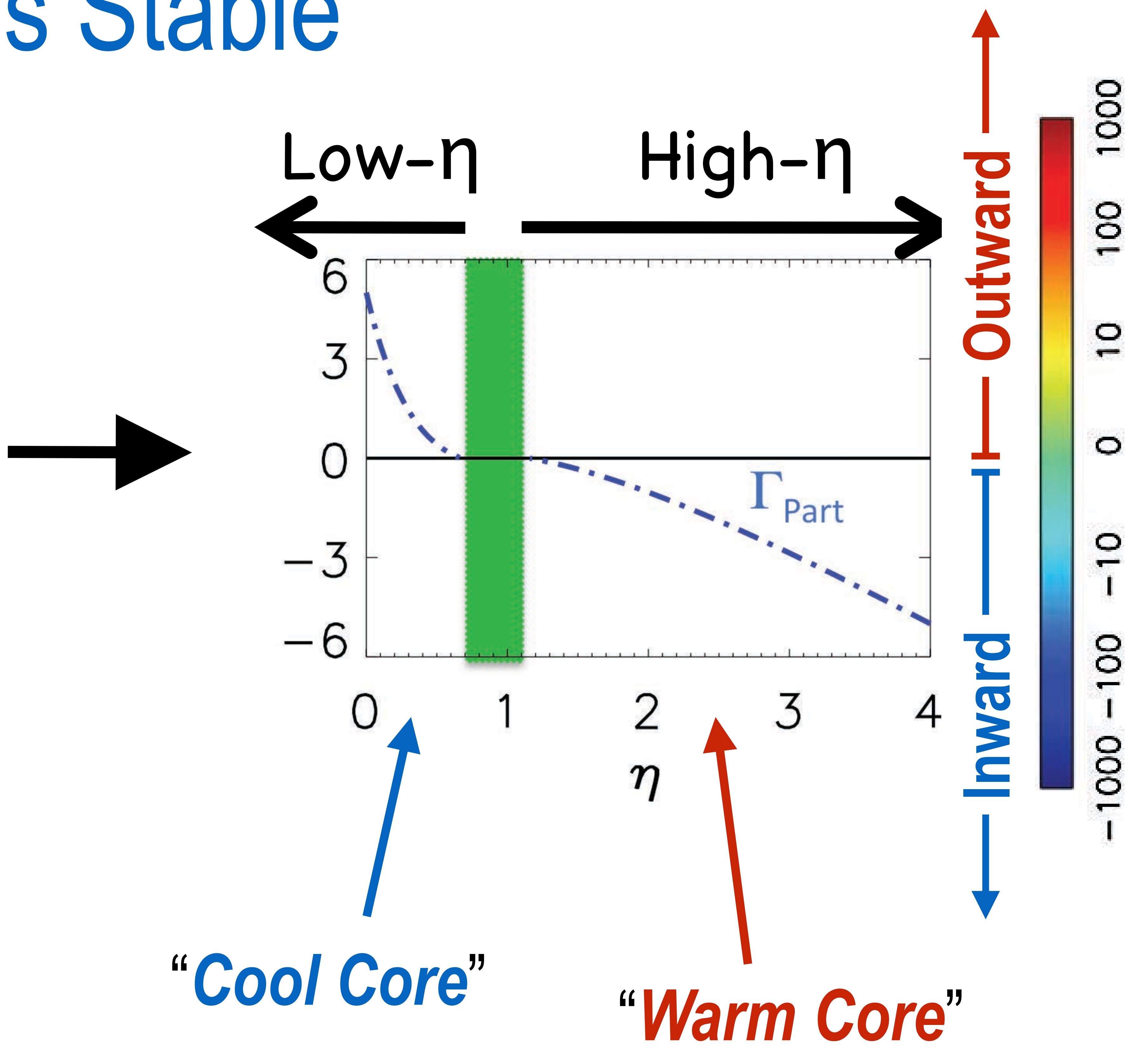


Sumire Kobayashi, Rogers, and Dorland, "Particle Pinch in Gyrokinetic Simulations of Closed Field-Line Systems," PRL, 105, 235004 (2010).
Sumire Kobayashi, Rogers, and Dorland, "Gyrokinetic Simulations of Turbulent Transport in a Ring Dipole Plasma," PRL 103, 055003 (2009).

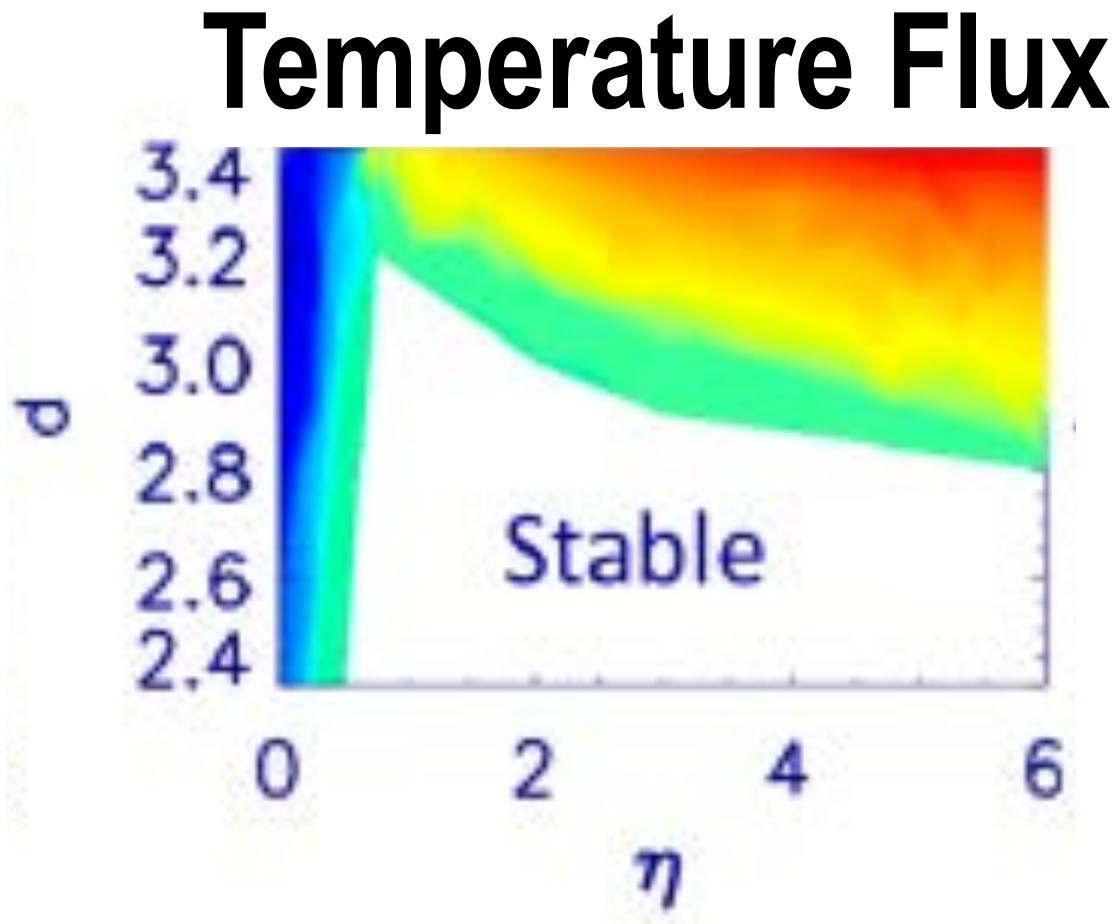
GS2 show Entropy Modes Drive Turbulent "Self-Organization" *even* when MHD Interchange is Stable



$$d \equiv -\frac{\Delta \ln P}{\Delta \ln V}$$

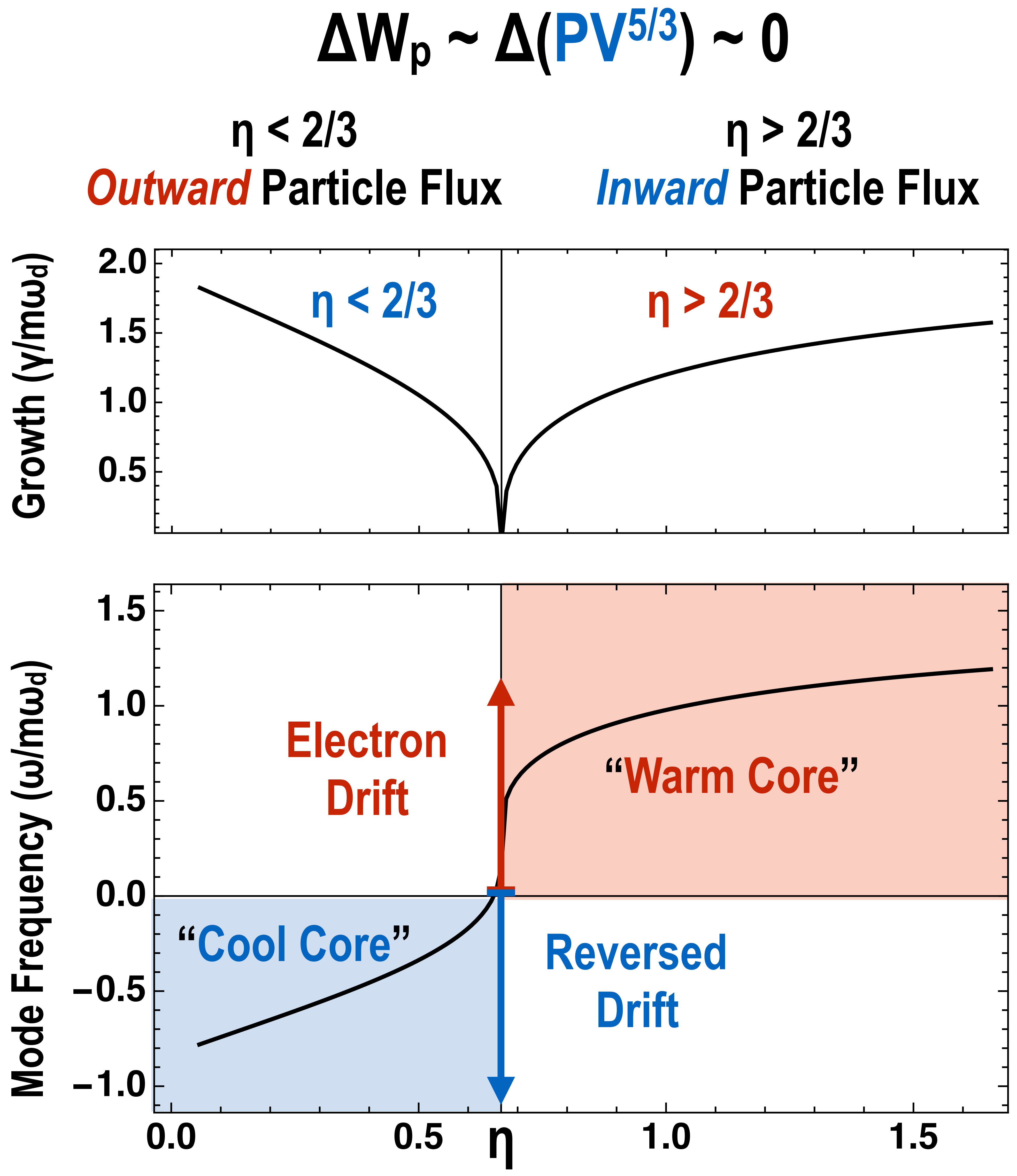


- "***Warm Core***", η > 2/3, creates inward particle pinch and outward heat transport.
- "***Cool Core***", η < 2/3, creates outward particle pinch and inward heat flux.



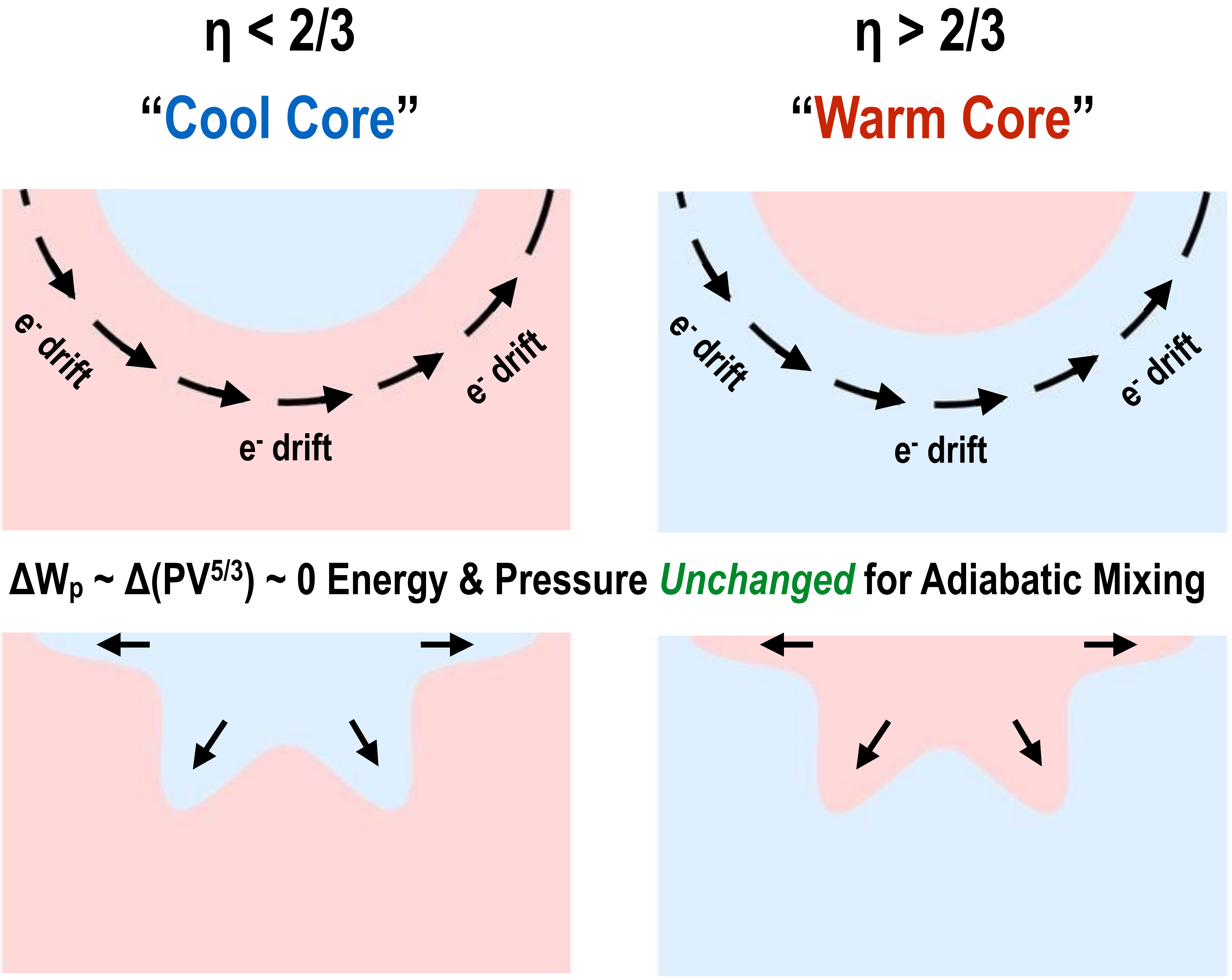
Sumire Kobayashi, Rogers, and Dorland, "Particle Pinch in Gyrokinetic Simulations of Closed Field-Line Systems," PRL, 105, 235004 (2010).
Sumire Kobayashi, Rogers, and Dorland, "Gyrokinetic Simulations of Turbulent Transport in a Ring Dipole Plasma," PRL 103, 055003 (2009).

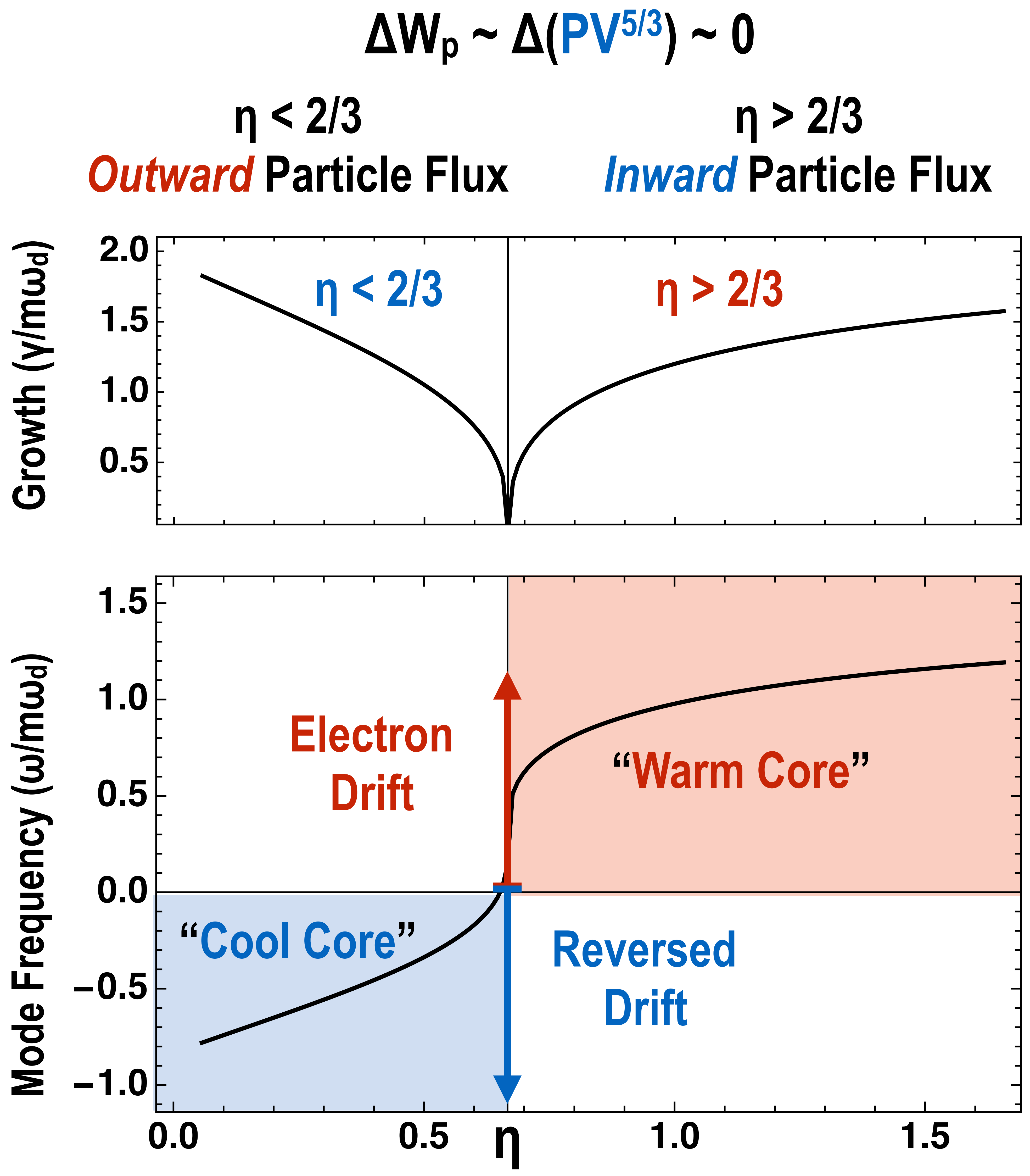
When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η



Ricci, *et al.*, "Gyrokinetic linear theory of the entropy mode in a Z pinch," **13**, 062102 (2006).

When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η



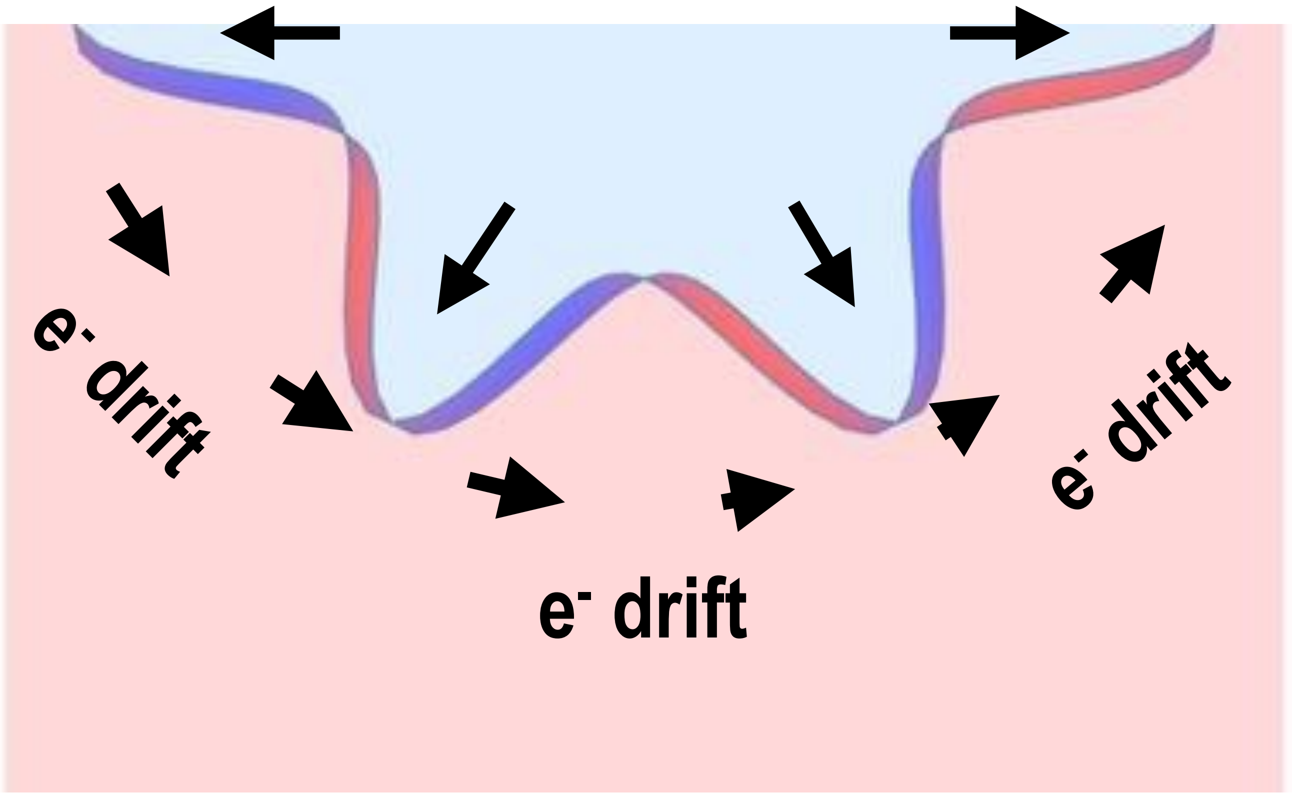


Ricci, *et al.*, "Gyrokinetic linear theory of the entropy mode in a Z pinch," **13**, 062102 (2006).

When $T_e \gg T_i$, Linear Theory Shows Entropy Mode ***Reverses*** Direction with η

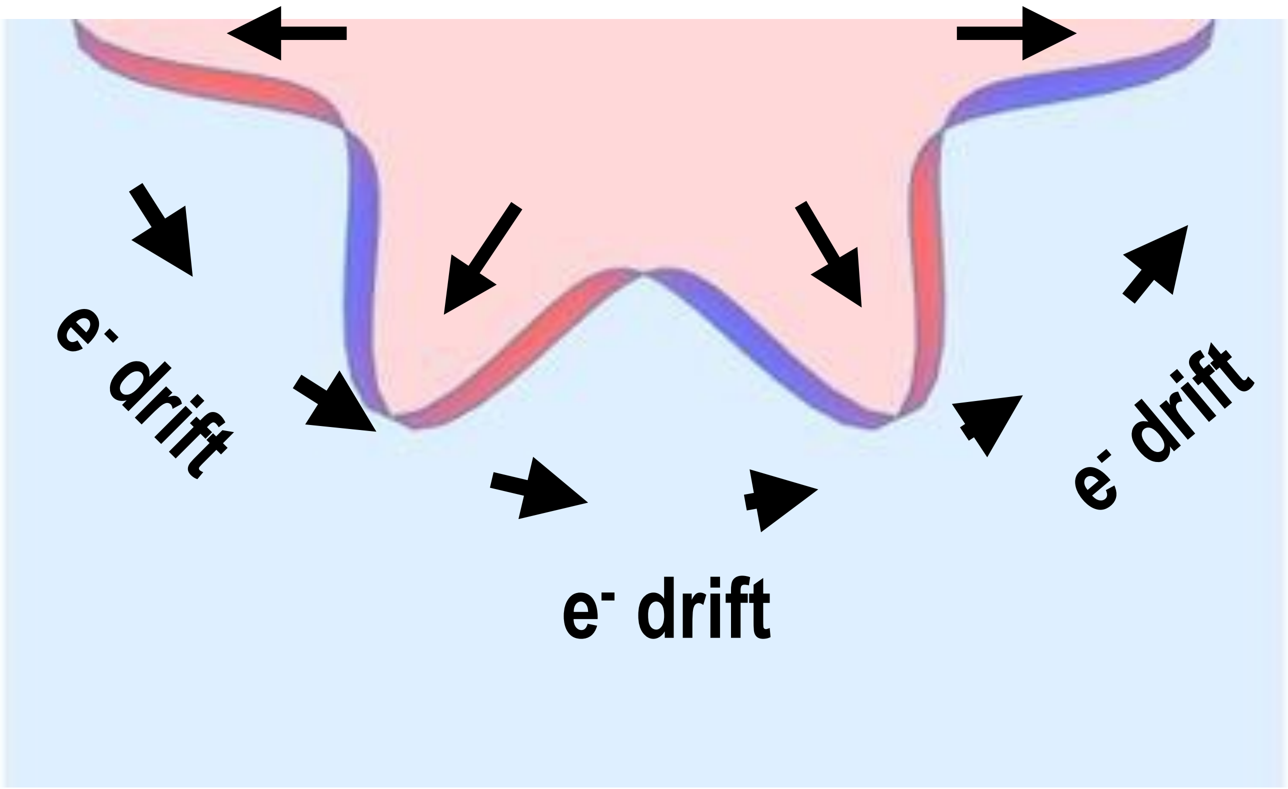
η < 2/3

"Cool Core"

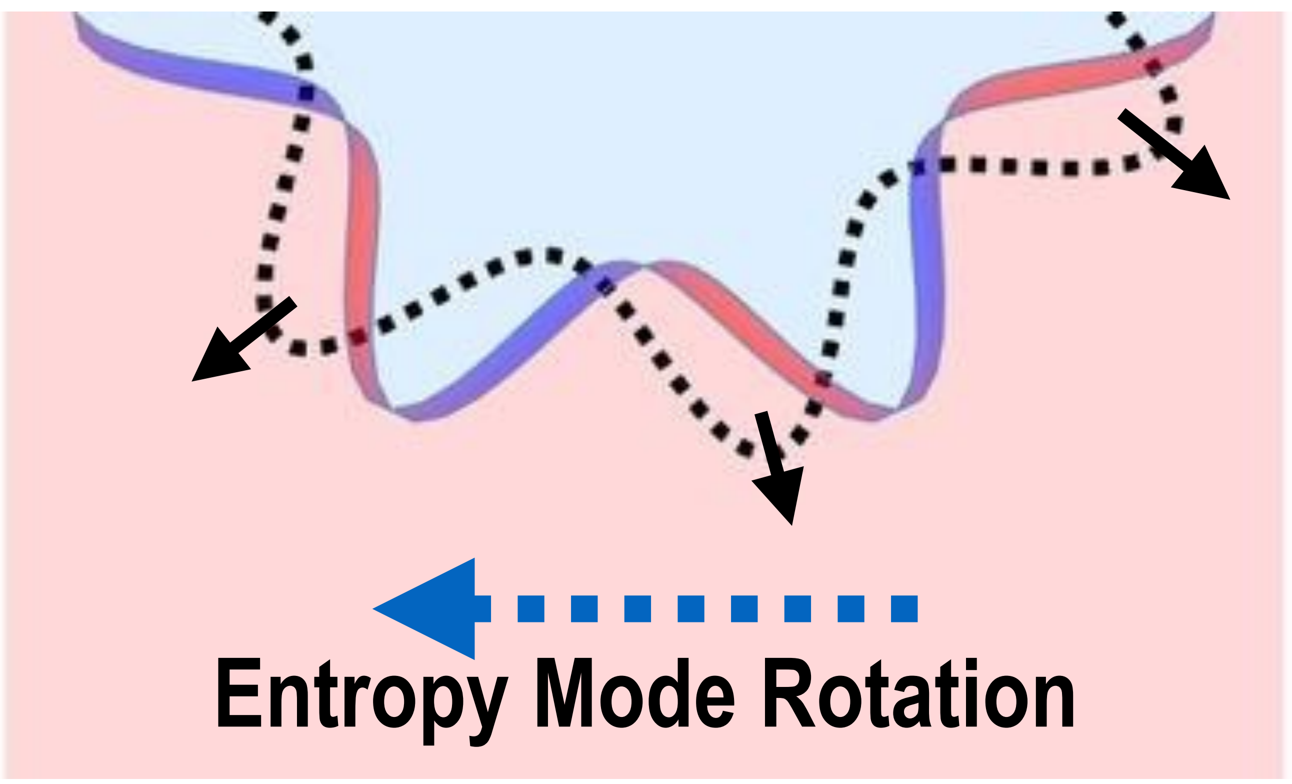


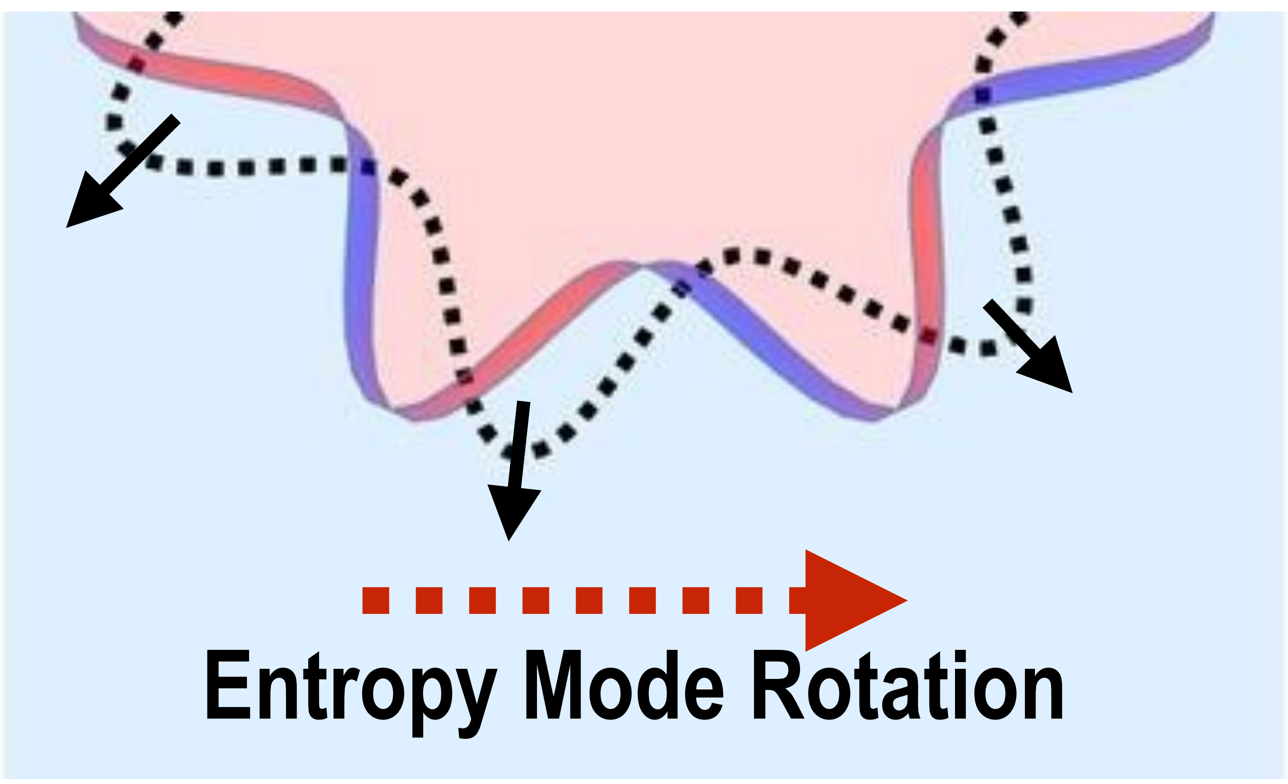
η > 2/3

"Warm Core"



Drift-Kinetic *Heat* moves toroidally from Warm to Cool Flux-Tubes

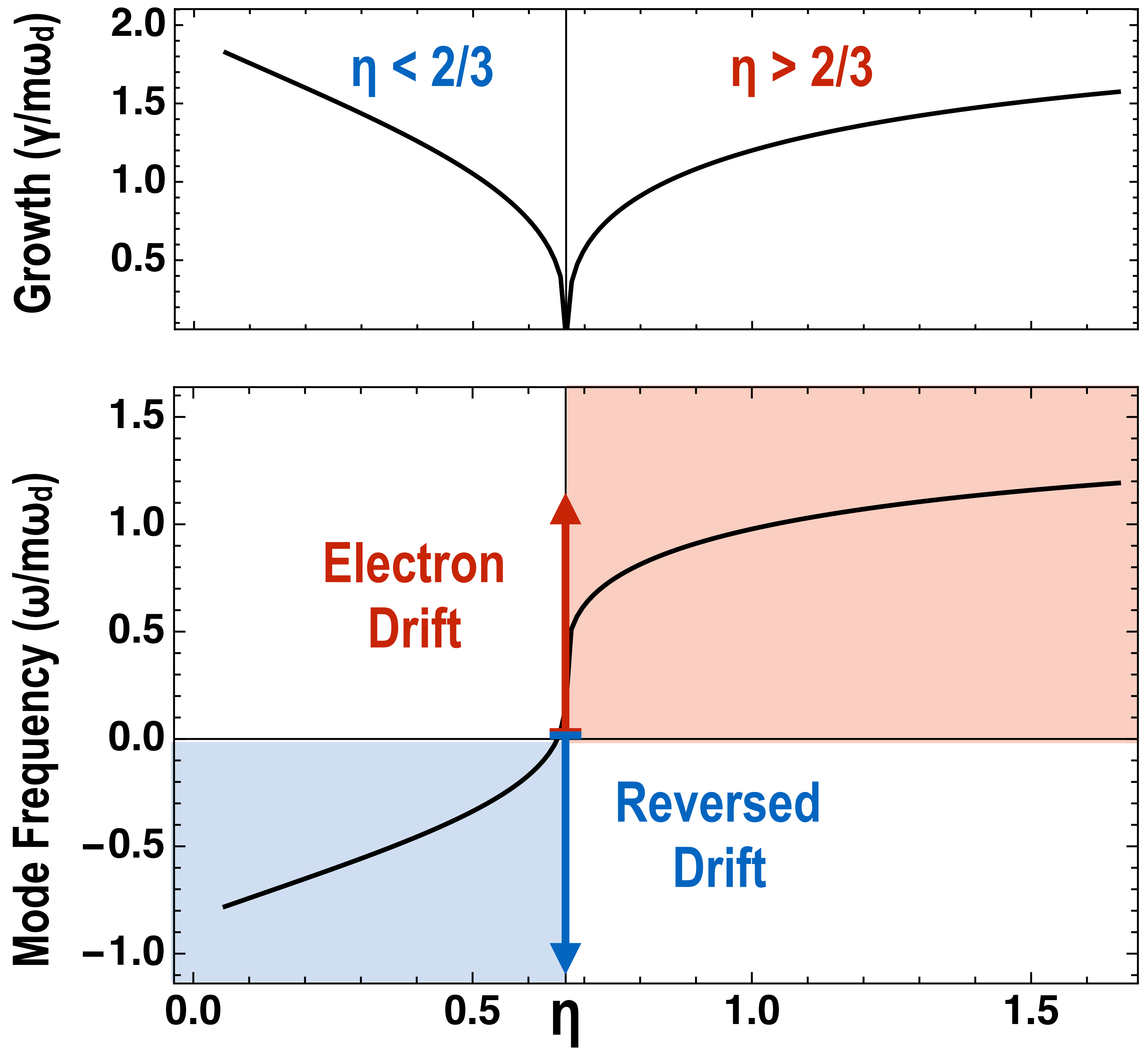




$\Delta W_p \sim \Delta(PV^{5/3}) \sim 0$

η < 2/3: ***Outward*** **Particle Flux**

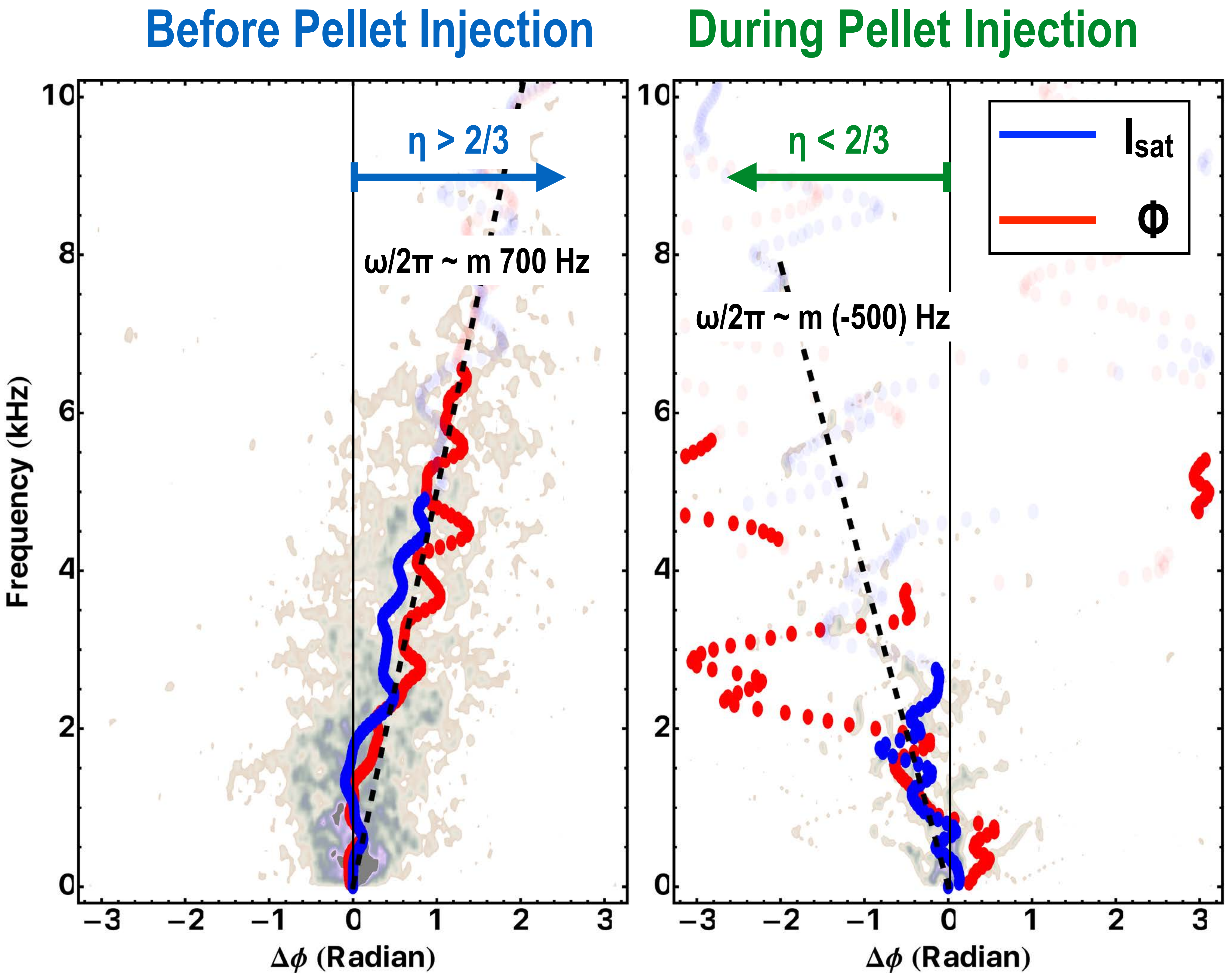
η > 2/3: ***Inward*** **Particle Flux**



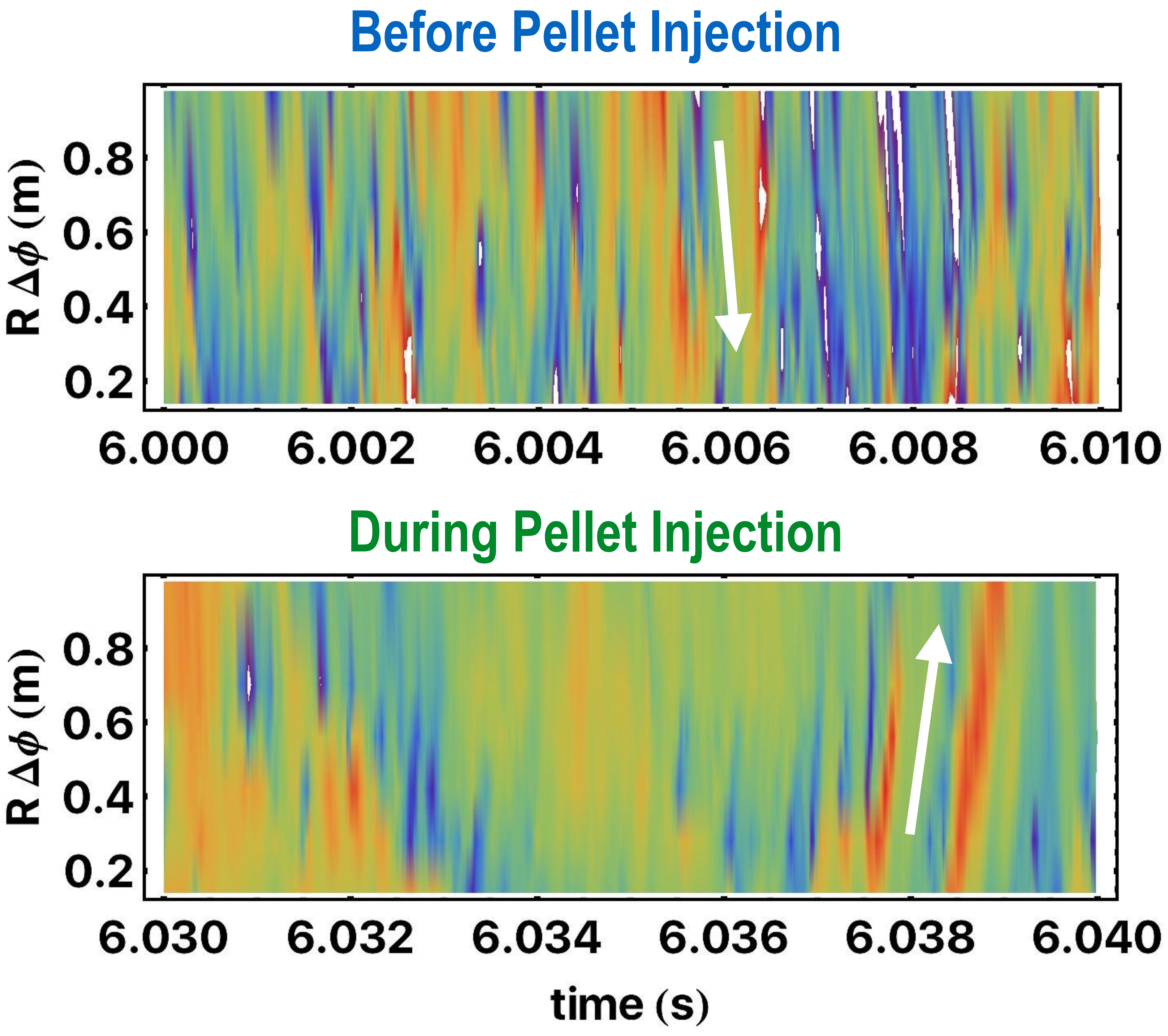
Ricci, *et al.*, "Gyrokinetic linear theory of the entropy mode in a Z pinch," **13**, 062102 (2006).

Dispersion Measurements during Pellet Injection agree with Linear Theory
Entropy Modes ***Reverse*** Direction with ***Reversal*** of Particle Flux

Ensemble-Averaged Entropy Mode Dispersion



Potential Fluctuations Reverse Direction



Outline

- *Two laboratory magnetospheres*: LDX and RT-1, having large flux-tube expansion
- *Particle transport and turbulent relaxation* to centrally-peaked profiles (***LDX***)
  - Matt Davis (PhD *Columbia*) and Alex Boxer (PhD *MIT*)
- *Understanding entropy mode turbulence* near marginal stability (***GS2***)
  - Sumire Kobayashi (PhD *Dartmouth/Rogers*)
- ***Achieving record high local β*** by stabilizing fast electron interchange instability (***RT-1***)
  - Yoshihisa Yano (PhD *Univ Tokyo/Yoshida*)
- *Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement*

Stable Toroidal Plasmas at Very High Local β are Characteristics of the Giant Magnetospheres and Predicted for the Laboratory Magnetosphere

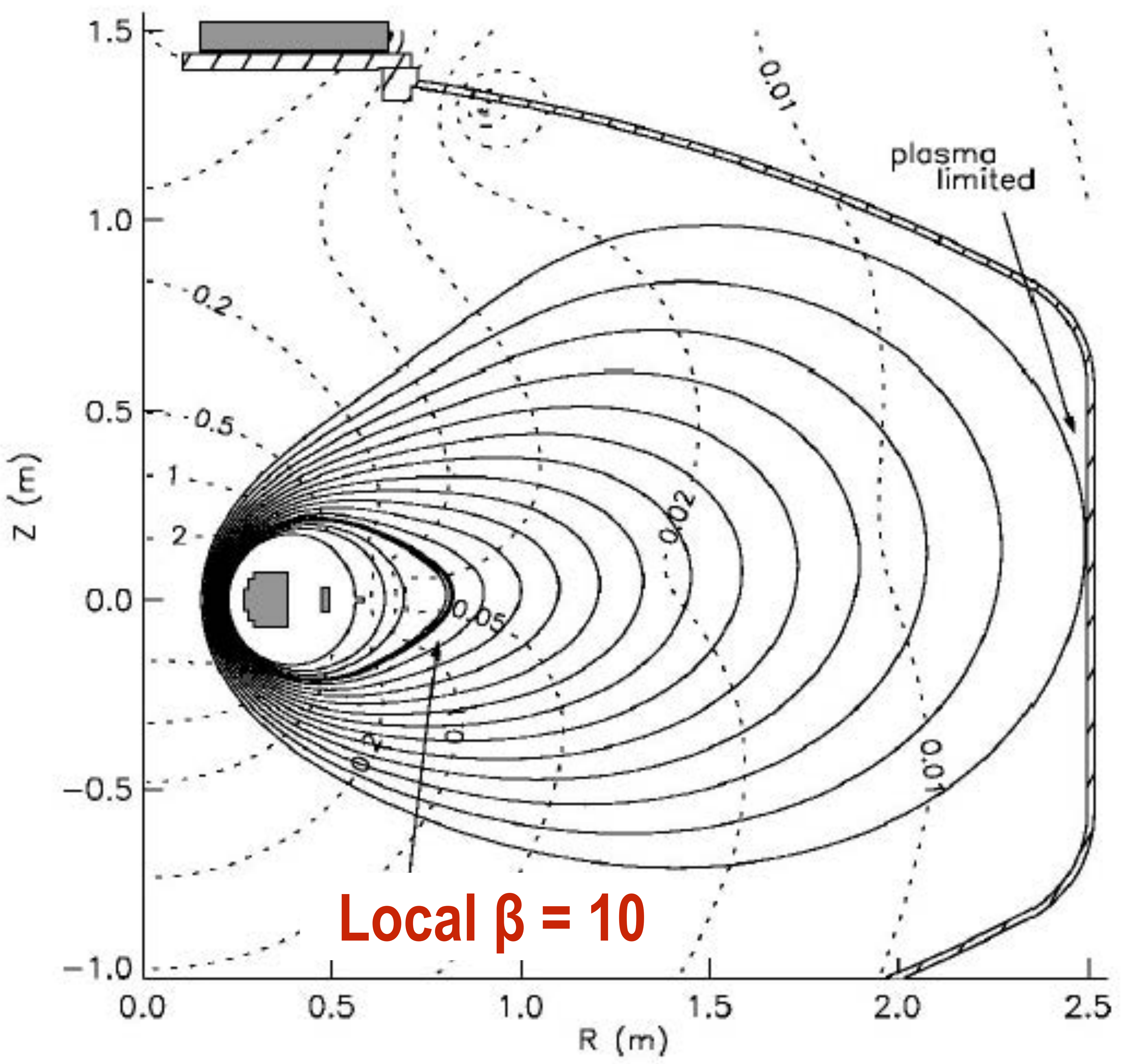
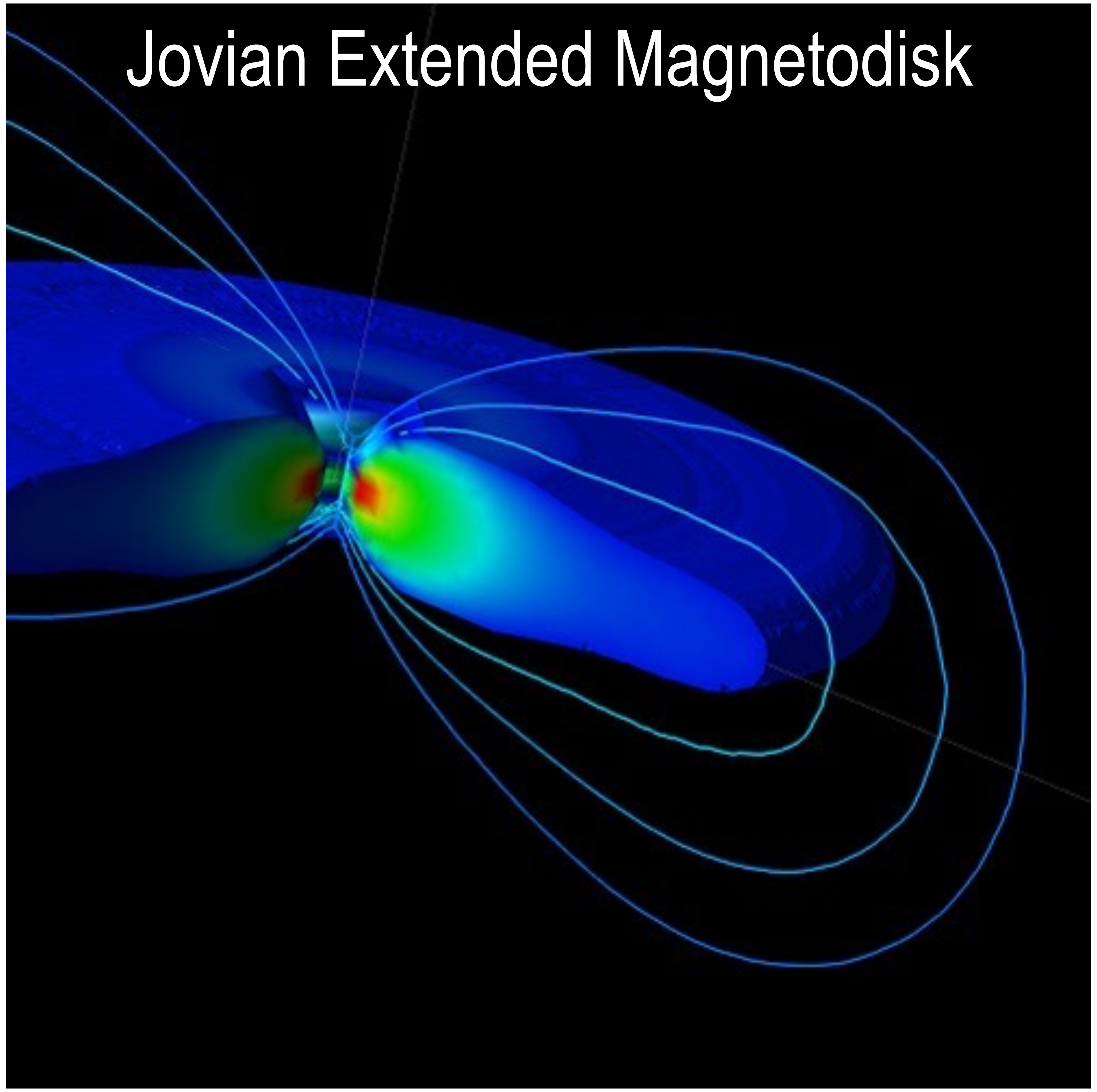


FIG. 2. High β equilibrium ($\beta_{max} = 10$) solution in the LDX geometry.



Garnier, Kesner, and Mauel, "Magnetohydrodynamic stability in a levitated dipole," *Phys Plasmas* **6**, 3431 (1999).

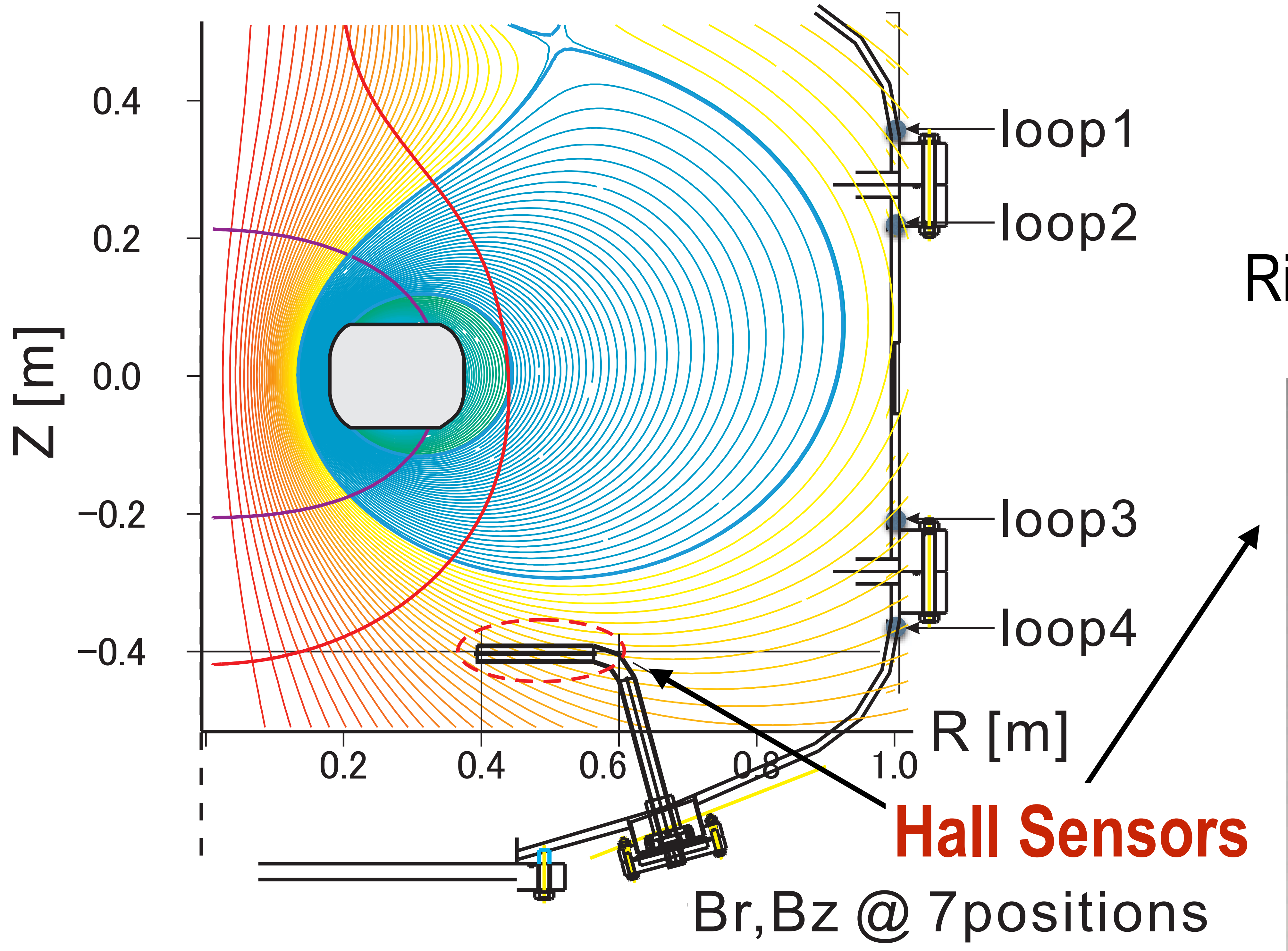
Shiraishi, Ohsaki, and Yoshida, "Relaxation of a quasisymmetric rotating plasma: A model of Jupiter's magnetosphere," *Phys Plasmas* **12**, 092901 (2005)

Measuring Record Peak β ~ 1 with Internal Hall Probe in RT-1

(Yoshihisa Yano, PhD Univ Tokyo)

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

Equilibrium Profile Reconstruction



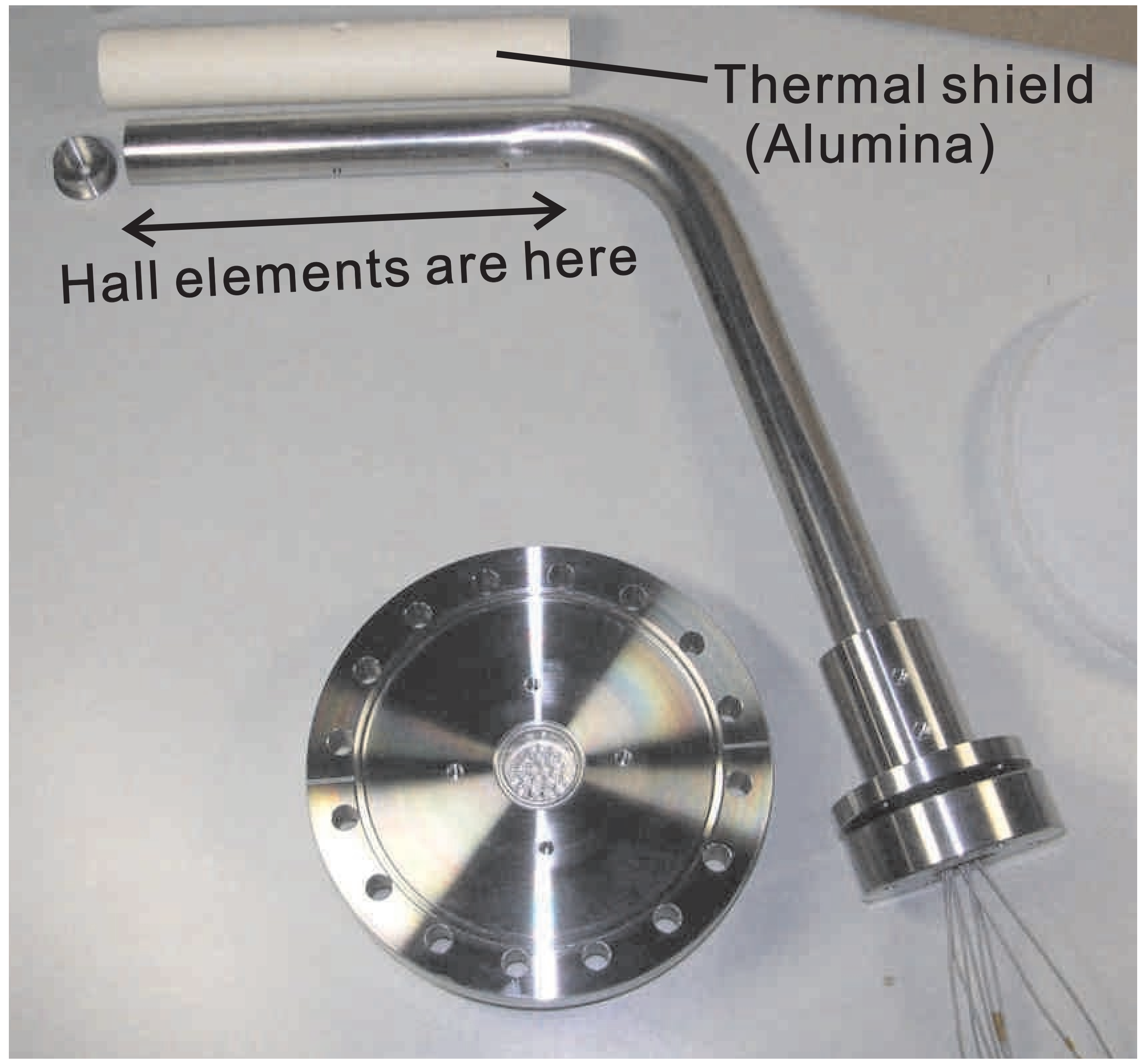
Dessler-Parker-Sckopke Relationship:

Earth's Magnetosphere Energy = 0.54 GJ/A × I_{RC}

LDX's Plasma Energy = 0.12 J/A × I_{RC}

Plasma Ring Current ~ Energy ~ Peak Beta

Internal **Hall Probe** for Accurate Ring Current Profile Reconstruction

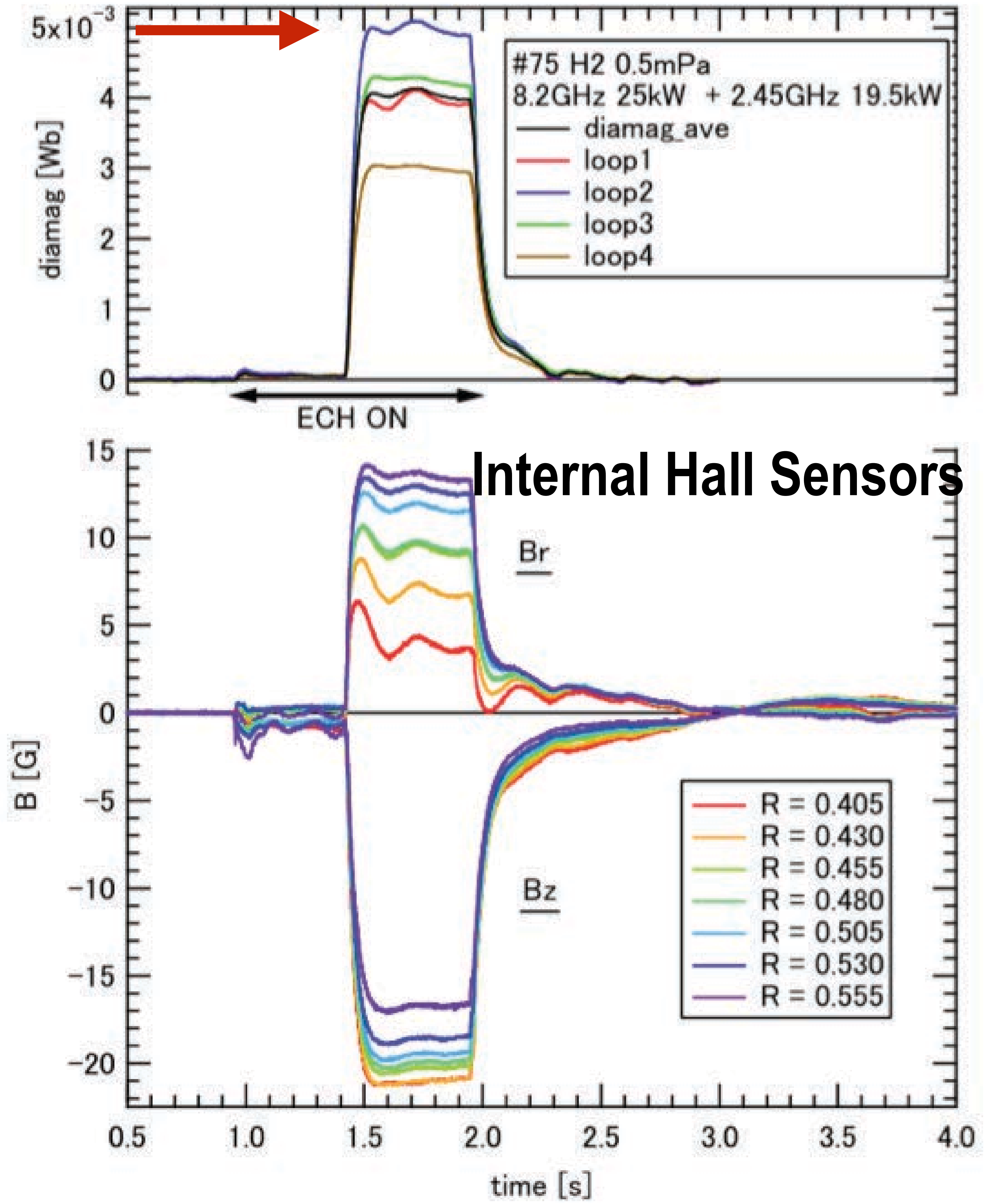


Measuring Record Peak β ~ 1 with Internal Hall Probe in RT-1

(Yoshihisa Yano, PhD Univ Tokyo)

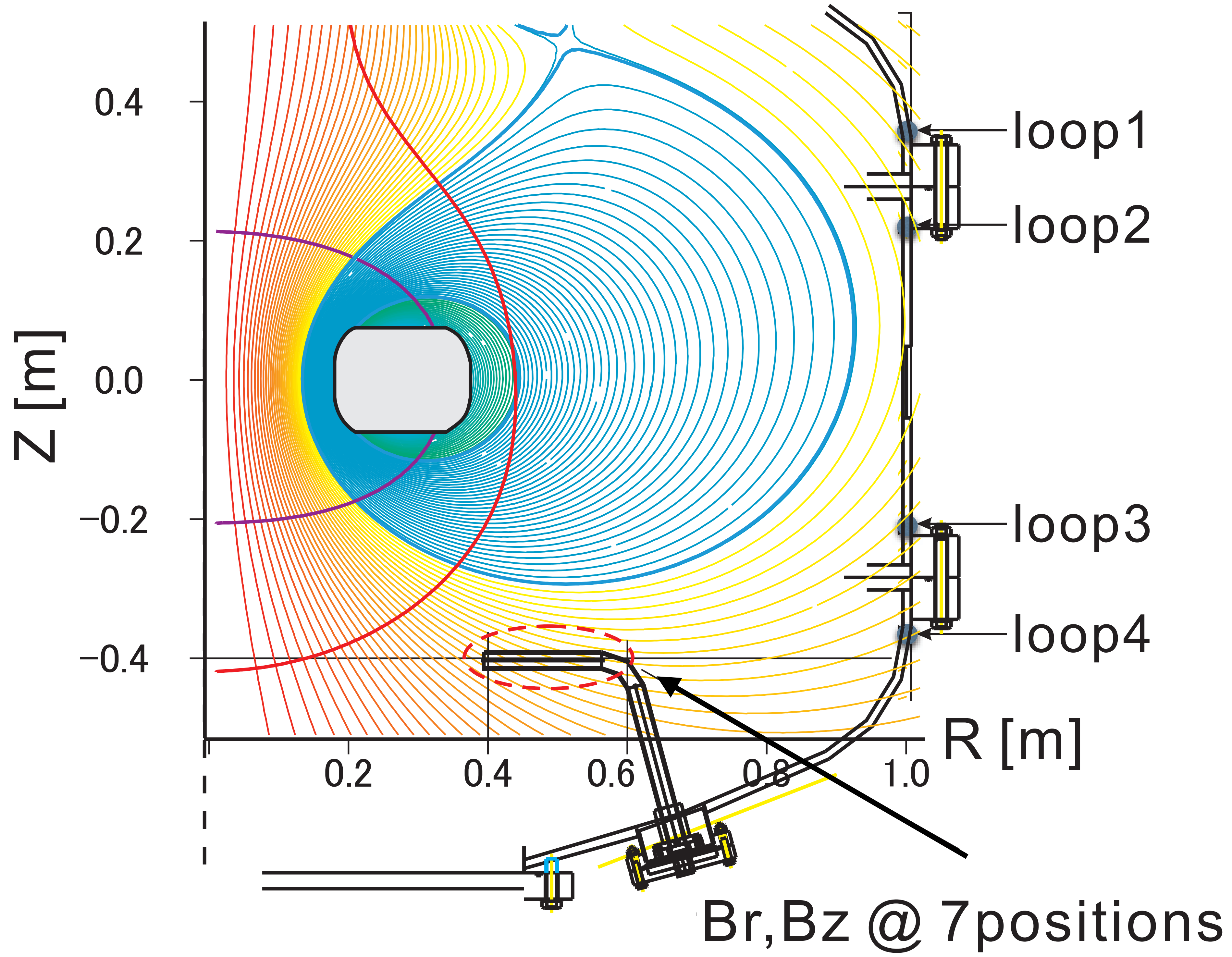
80% Peak β
5 mWb

25 kW 8.2 GHz
19 kW 2.45 GHz



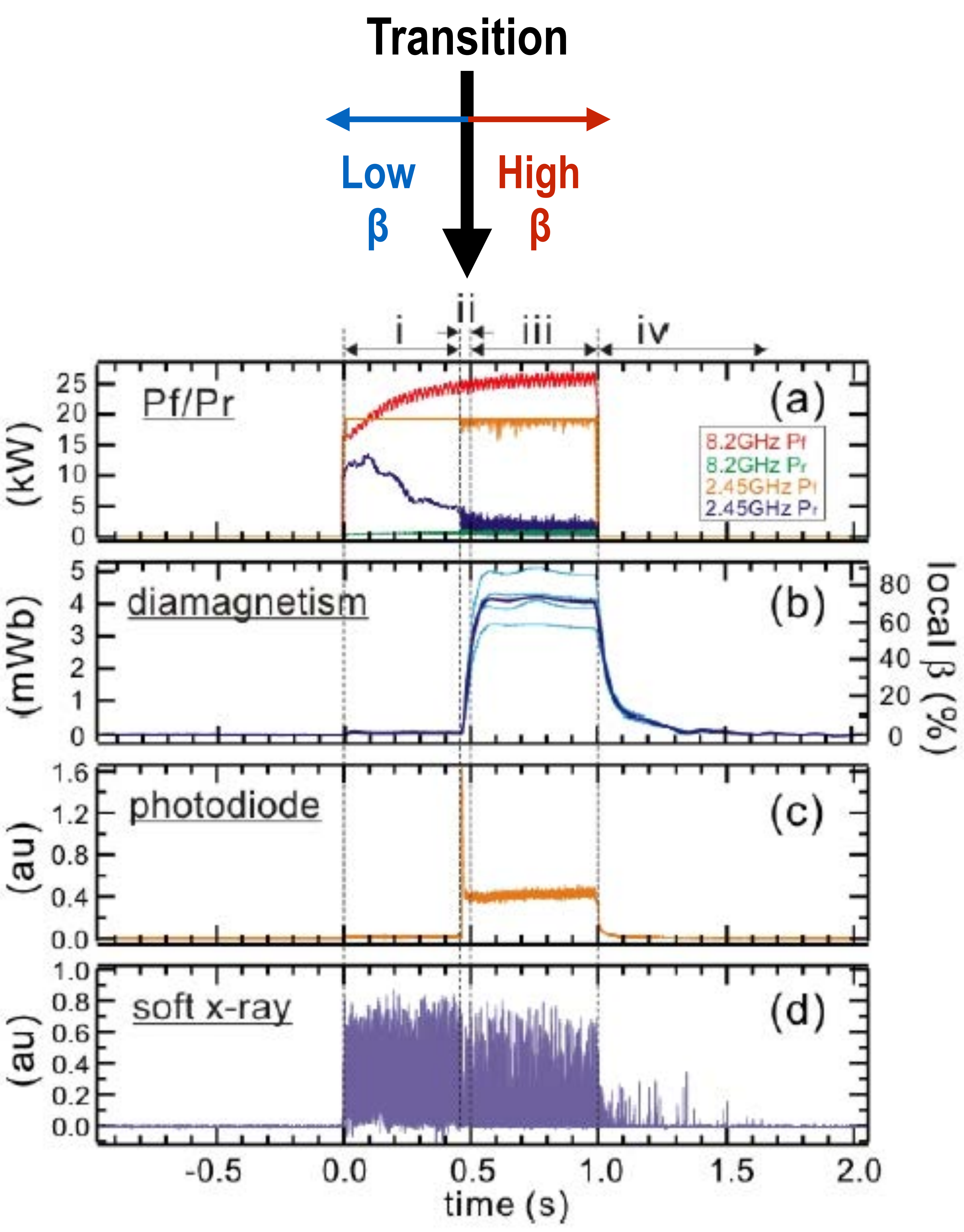
$$\beta \approx 0.18\Delta\Psi \ \ (\mathrm{mWb}^{-1},\ \text{Peak-local})$$

Equilibrium Profile Reconstruction



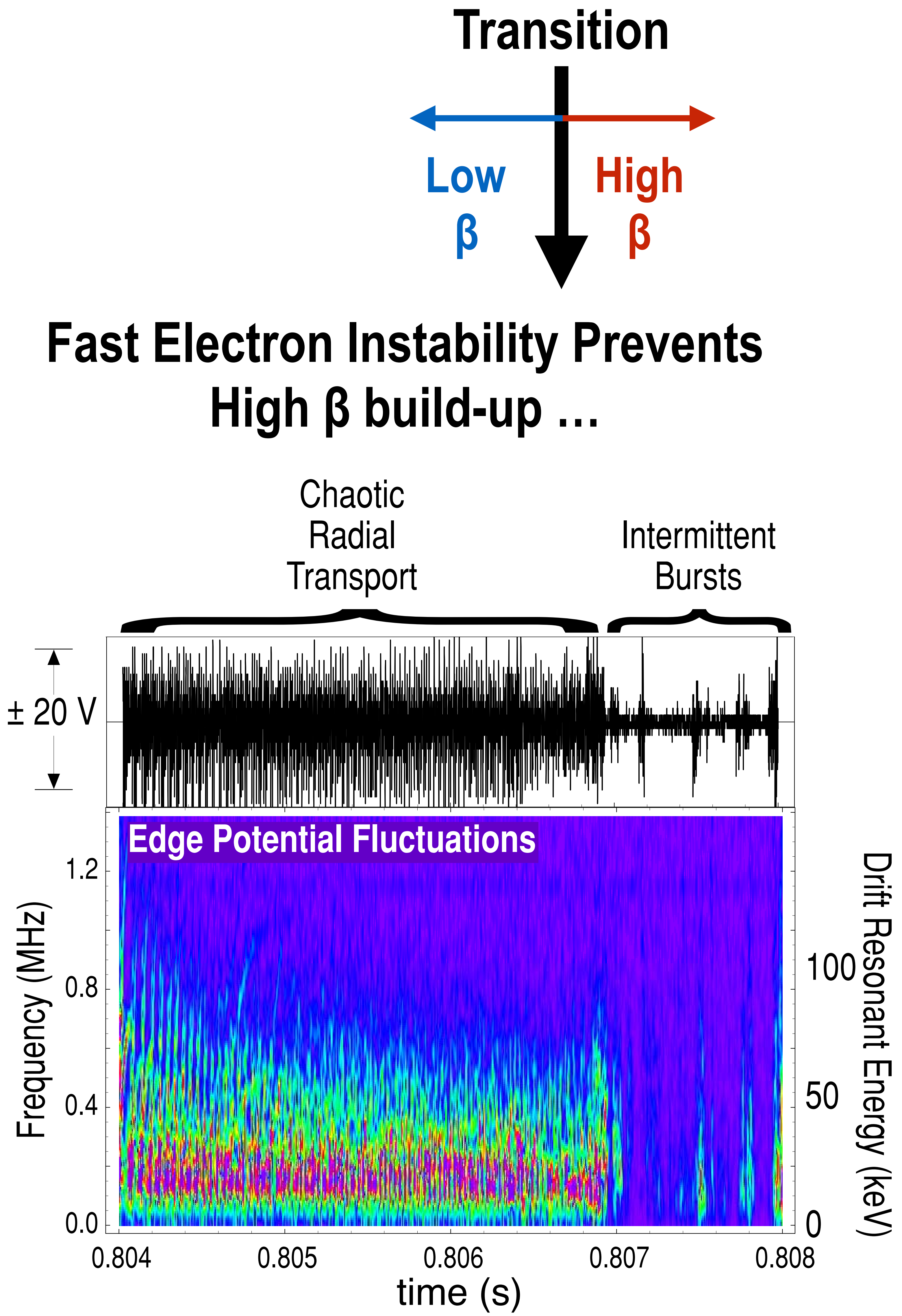
Nishiura, et al., "Improved beta (local beta >1) and density in electron cyclotron resonance heating on the RT-1 magnetosphere plasma," Nuc Fus 55, 053019 (2015).
Saitoh, et al., "Observation of a new high-β and high-density state of a magnetospheric plasma in RT-1," Phys Plasmas 21, 082511 (2014).
Saitoh, et al., "High-β plasma formation and observation of peaked density profile in RT-," Nuc Fus 51, 063034 (2011).

Hot Electron Interchange (HEI) Instability Must be Stabilized to Achieve High β



RT-1

Fast Electron Instability Prevents High β build-up ...

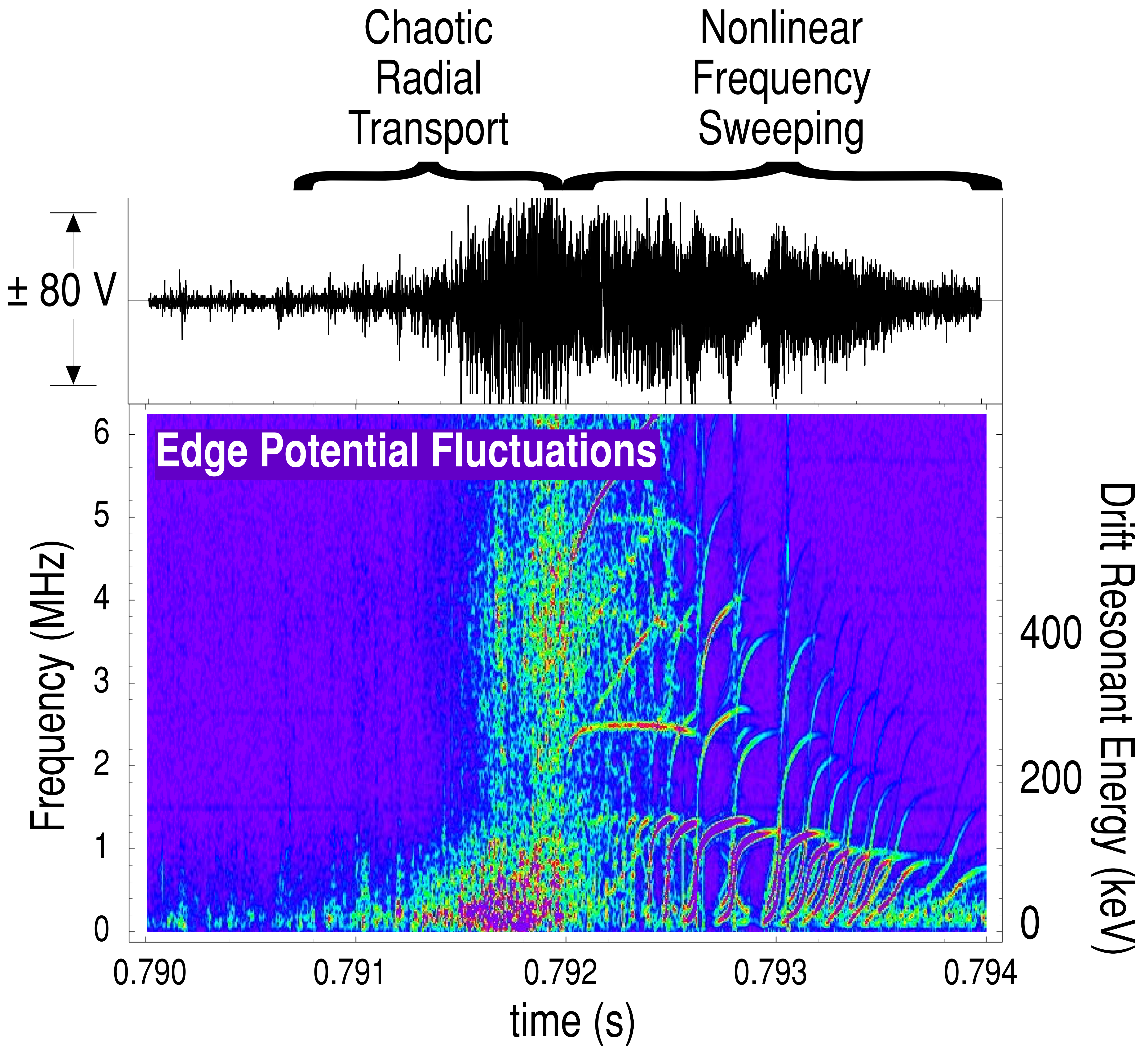


LDX

Achieving High β with ECRH Requires Stabilization of Hot Electron Interchange Mode and Creates a stable ***"Artificial Radiation Belt"***

- ECRH *always* generates energetic electrons
- Hot Electron Interchange (HEI) modes appear with both supported and levitated magnets whenever the plasma density is too low.
- HEI instabilities are drift-resonant ($\omega \sim m\omega_{dh} \sim 1$ MHz), have global structures, with nonlinear frequency chirping.
- Transport preserves phase-space density F(μ, J).
- Can be stabilize with dense, colder plasma:

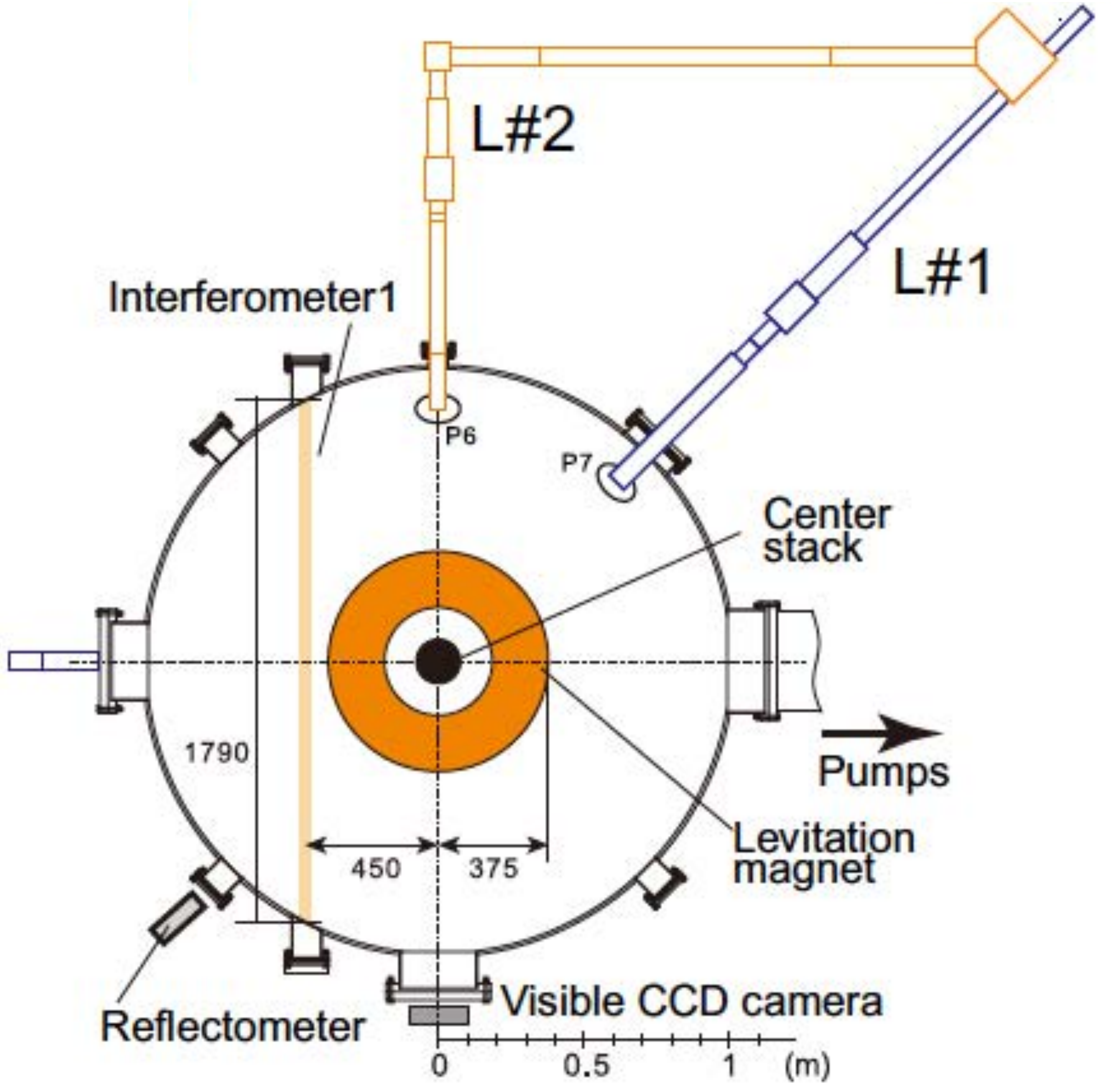
$$-\frac{d \ln n_{hot}}{d \ln V} > 1 + \underbrace{\frac{m_\perp^2}{24} \frac{\omega_{dh}}{\omega_{ci}} \frac{n_{ion}}{n_{hot}}}_{\text{Cold Density Stabilization}}$$



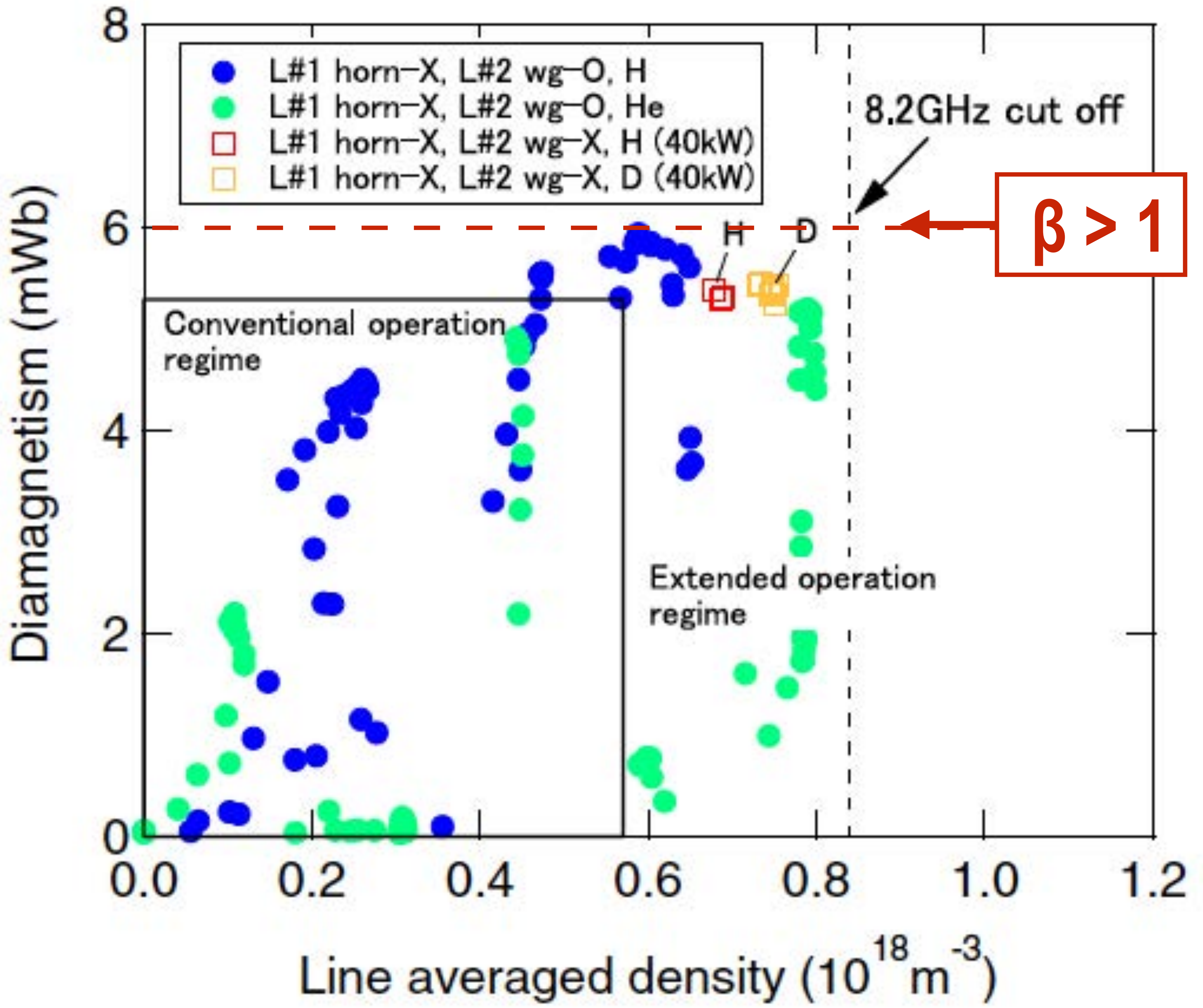
(Six PhD Dissertations: Warren, Maslovsky, Levitt, Krasheninnikova, Grierson, Ortiz)

RT-1 Achieved Record Peak β > 1 with 50 kW ECRH 8.2 GHz Heating

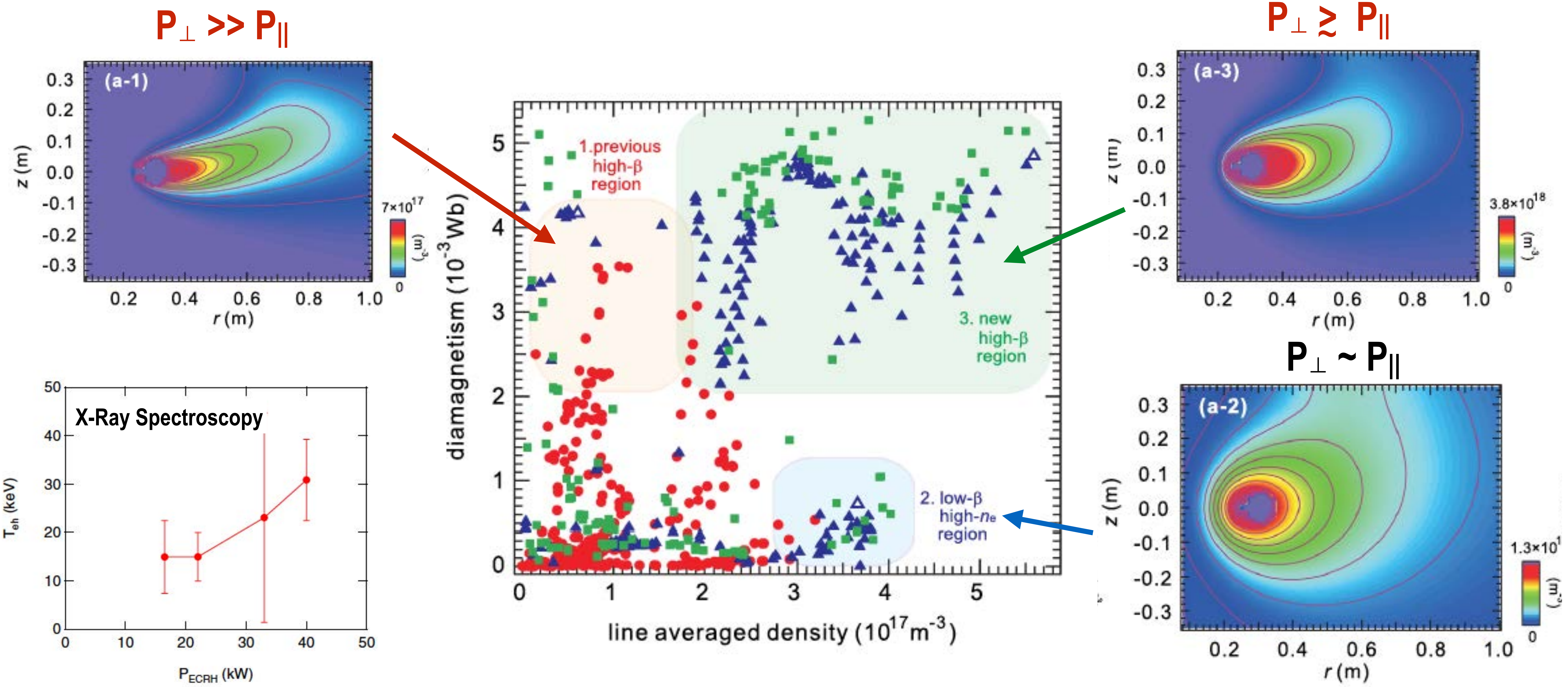
Higher μWave frequency makes higher density accessible.
Higher μWave power creates higher peak local β.



Higher Power and Higher Density



RT-1 has ***Three Regimes*** of High-β Operation depending upon Background Neutral Density and ECRH Power



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Saitoh, et al., "Observation of a new high-β and high-density state of a magnetospheric plasma in RT-1," Phys Plasmas 21, 082511 (2014).

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Experiment, Theory, and Simulation
Link Transport Physics of Planetary and Laboratory Magnetospheres

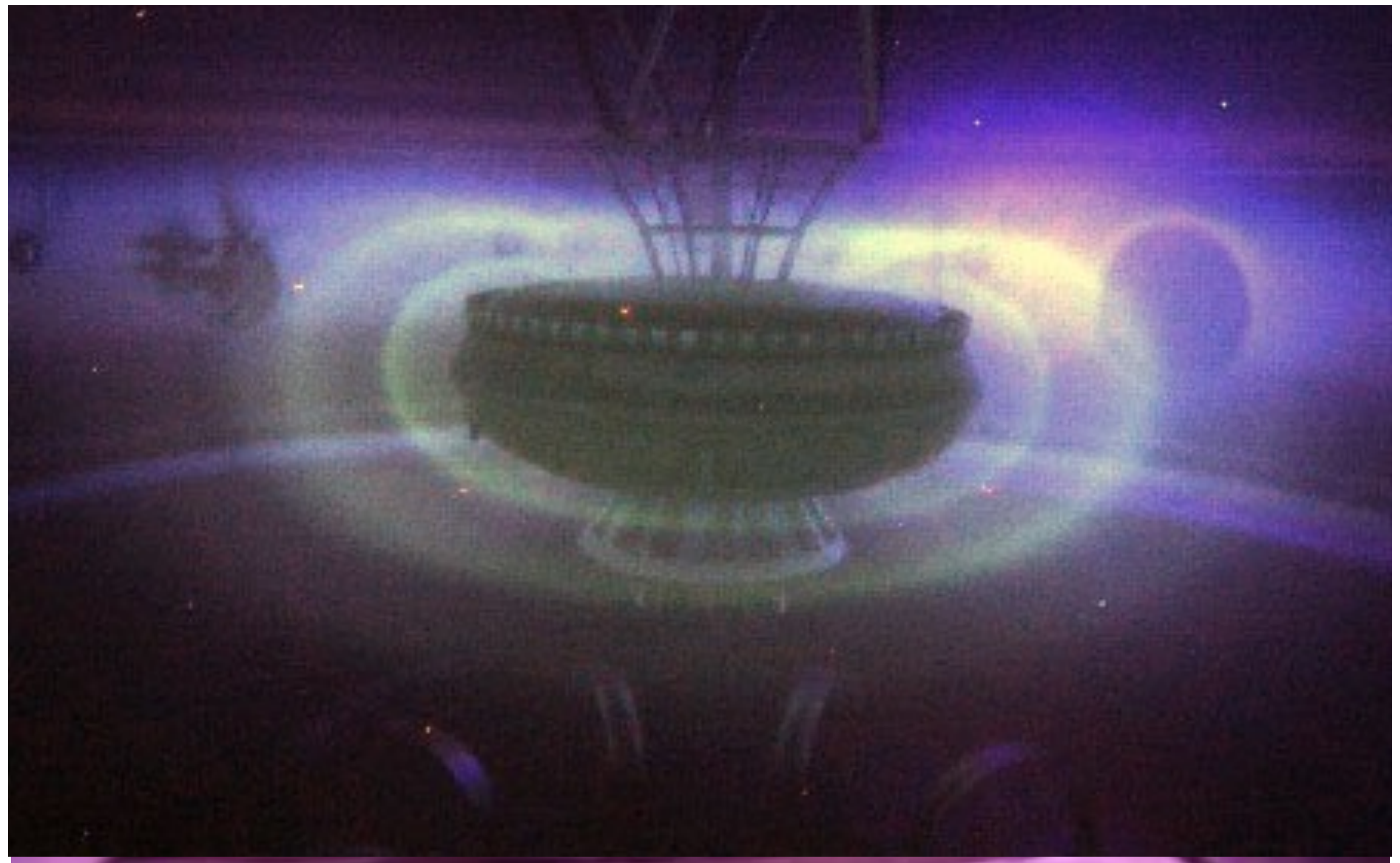
- ***Density profiles are always centrally peaked***, and particle transport can be either ***inward*** or ***outward*** depending upon the location of the particle source.

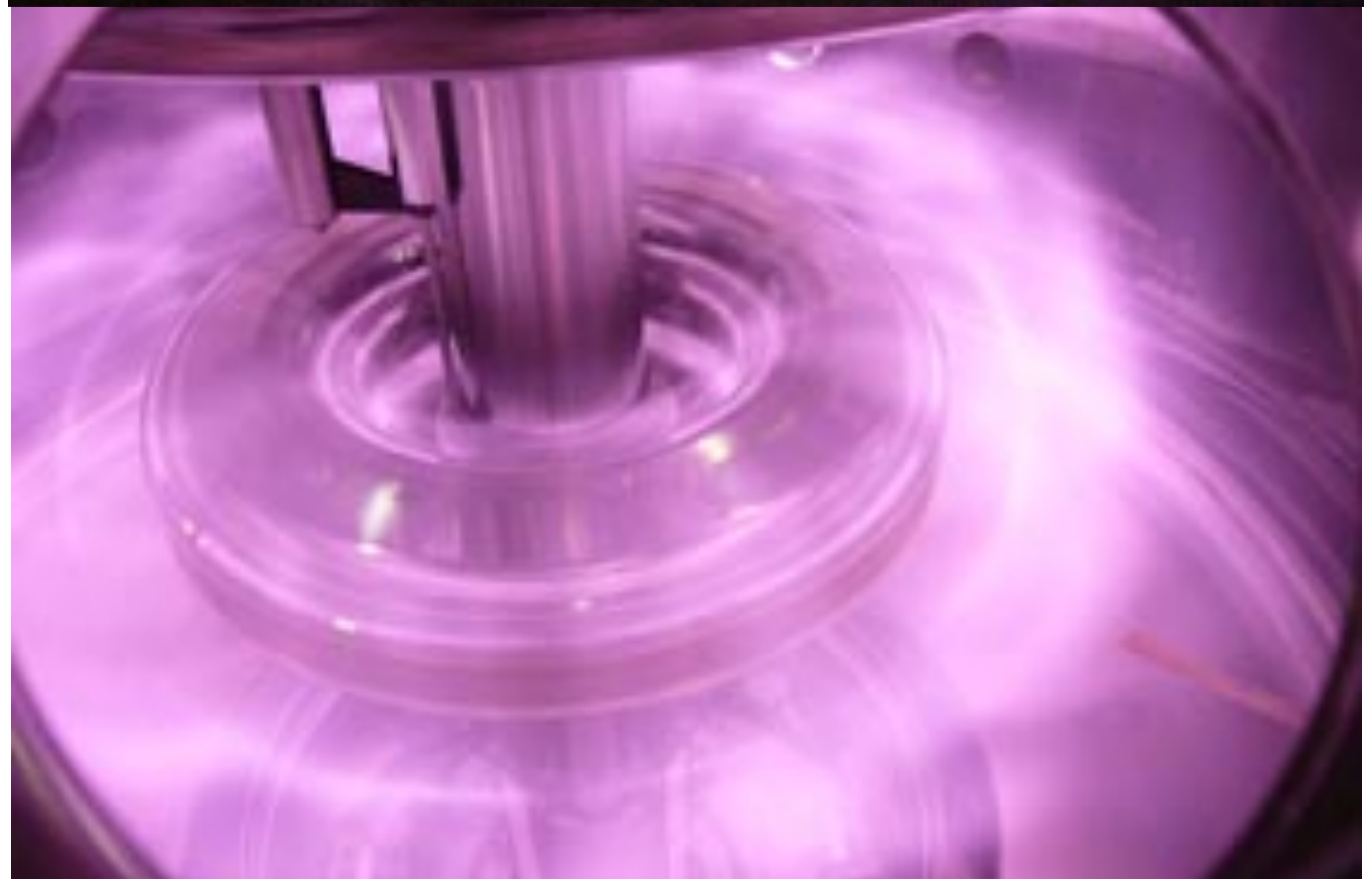
- ***Turbulent "self-organization"*** is characterized by *nearly* uniform flux-tube content, $\Delta(\mathbf{nV}) \sim 0$, invariant temperature, $\Delta(\mathbf{TV}^{2/3}) \sim 0$, and entropy density, $\Delta(\mathbf{PV}^{5/3}) \sim 0$.

  - ***Space***: Turbulence driven by solar wind and planetary rotation

  - ***Lab***: Interchange and entropy instabilities drive fluctuations

- ***High local beta, β ~ 1, "artificial radiation belt" in steady state***

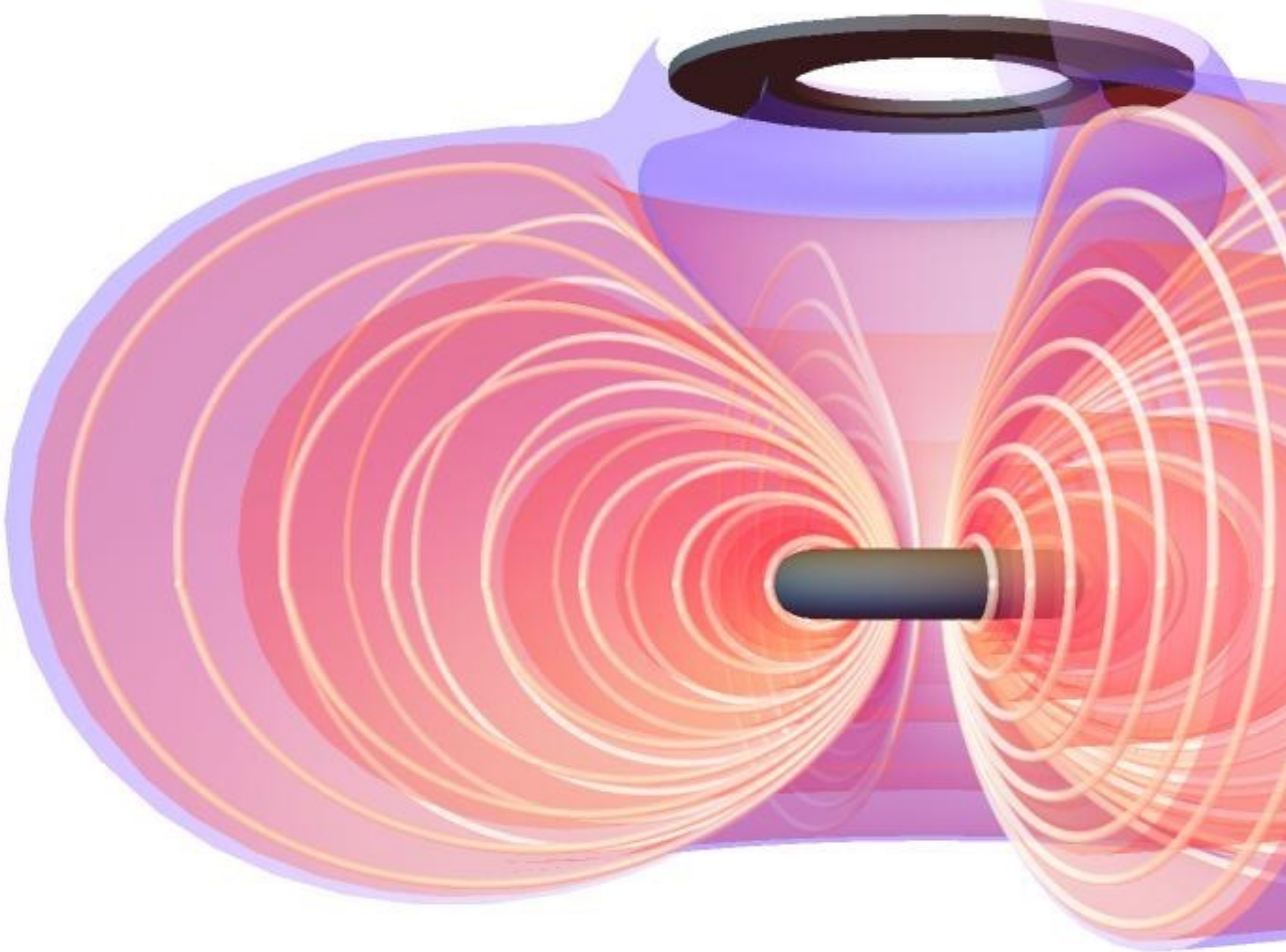




The Axisymmetric Plasma Torus is a *New Paradigm* for the Laboratory Study of Steady-State and High-Beta Plasma Transport

- ***Levitation is robust and reliable*** with very good access for diagnostics, plasma heating and fueling.
- ***Simple, axisymmetric torus with no field-aligned currents*** with classical particle orbits and good confinement of heat, density, and energetic particles.
- ***Fascinating radial transport processes*** relevant to space and to many toroidal confinement devices: *up-gradient pinch, zonal flows, bursty interchange filaments, avalanches* …

Nonlinear gyrokinetics appears to provide a good model for predicting radial transport driven by interchange and entropy instabilities

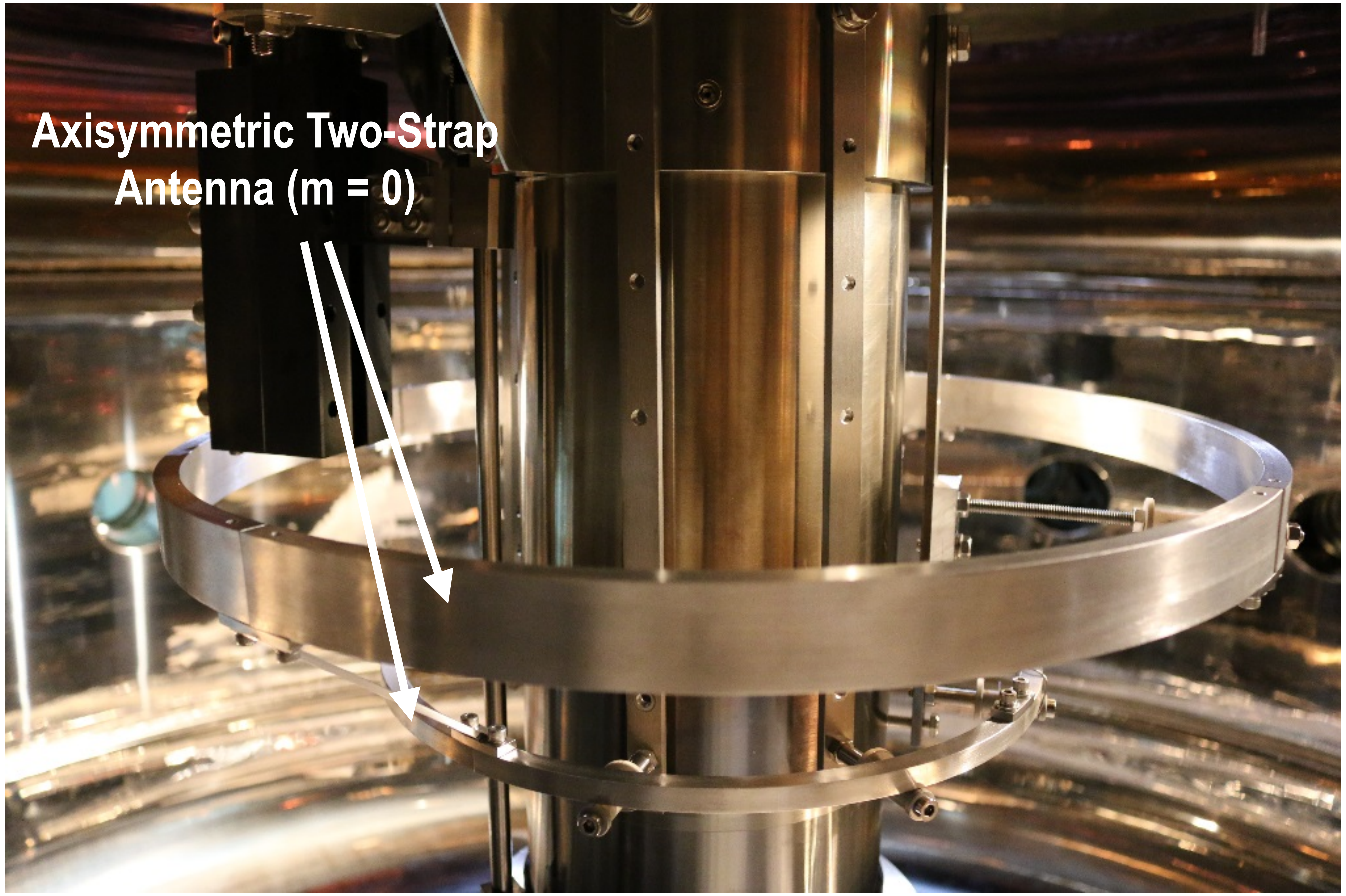


Physics of the Laboratory Magnetosphere: *Frontier Questions …*

- **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 …**

First Successful Test of Wave Heating in Ion Cyclotron Range of Frequencies

- ***Frontier opportunity:*** reach high density with finite ion temperature allows $T_e \sim T_i$
- Whistler waves ($\omega_{pe} >> \omega_{ce}$) trapping
- Alfvén waves ($c/\omega_{pi}L << 1$) resonances and dynamics at high beta
- FLR, ion drift-orbit bifurcation, ion mass/ isotope
- Does high power drive zonal flows and create transport barriers in a dipole plasma torus?



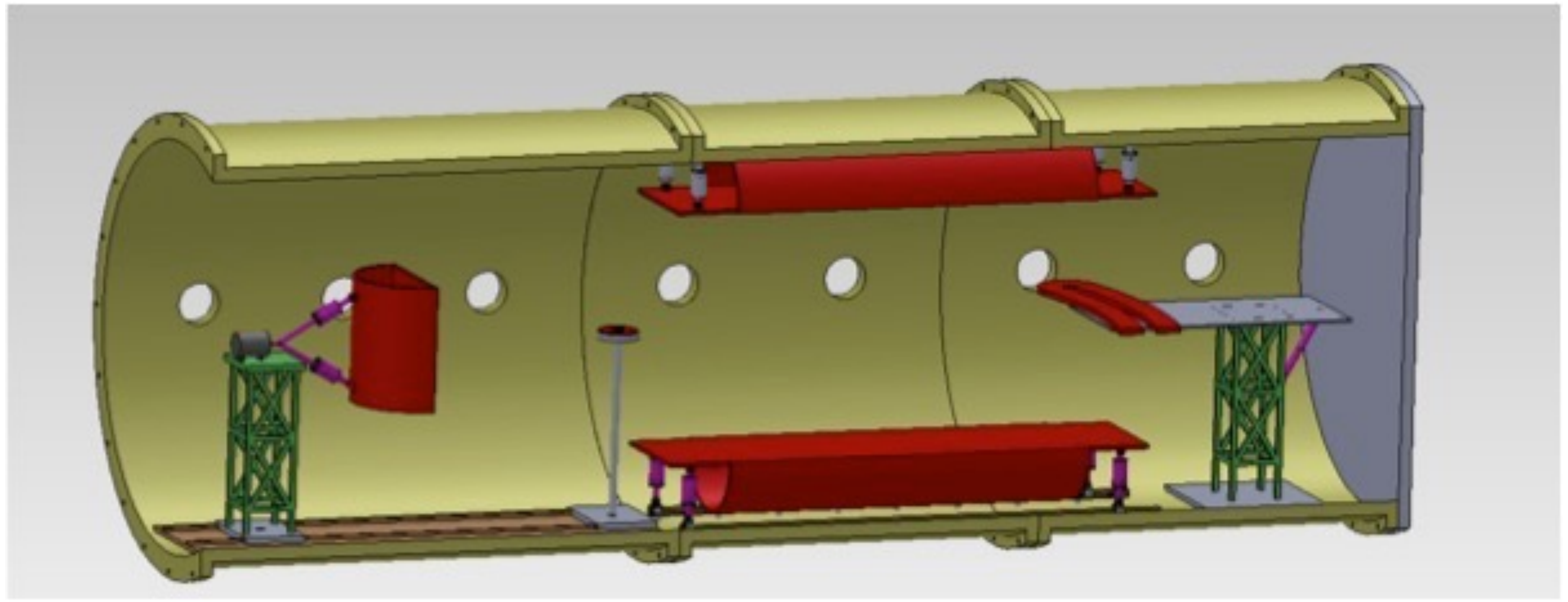
Observed increase of T_i with 10 kW of ICRF heating at 2MHz

JP12.00120 (**Tue, Afternoon**): Toshiba Mushiake, *et al.*, "Measurement of RF electric field … using a Pockels detector in RT-1"
NP12.00044 (**Wed, Morning**): Masaki Nishiura, *et al*. "Wave Heating in Ion Cyclotron Ranges of Frequencies in RT-1"

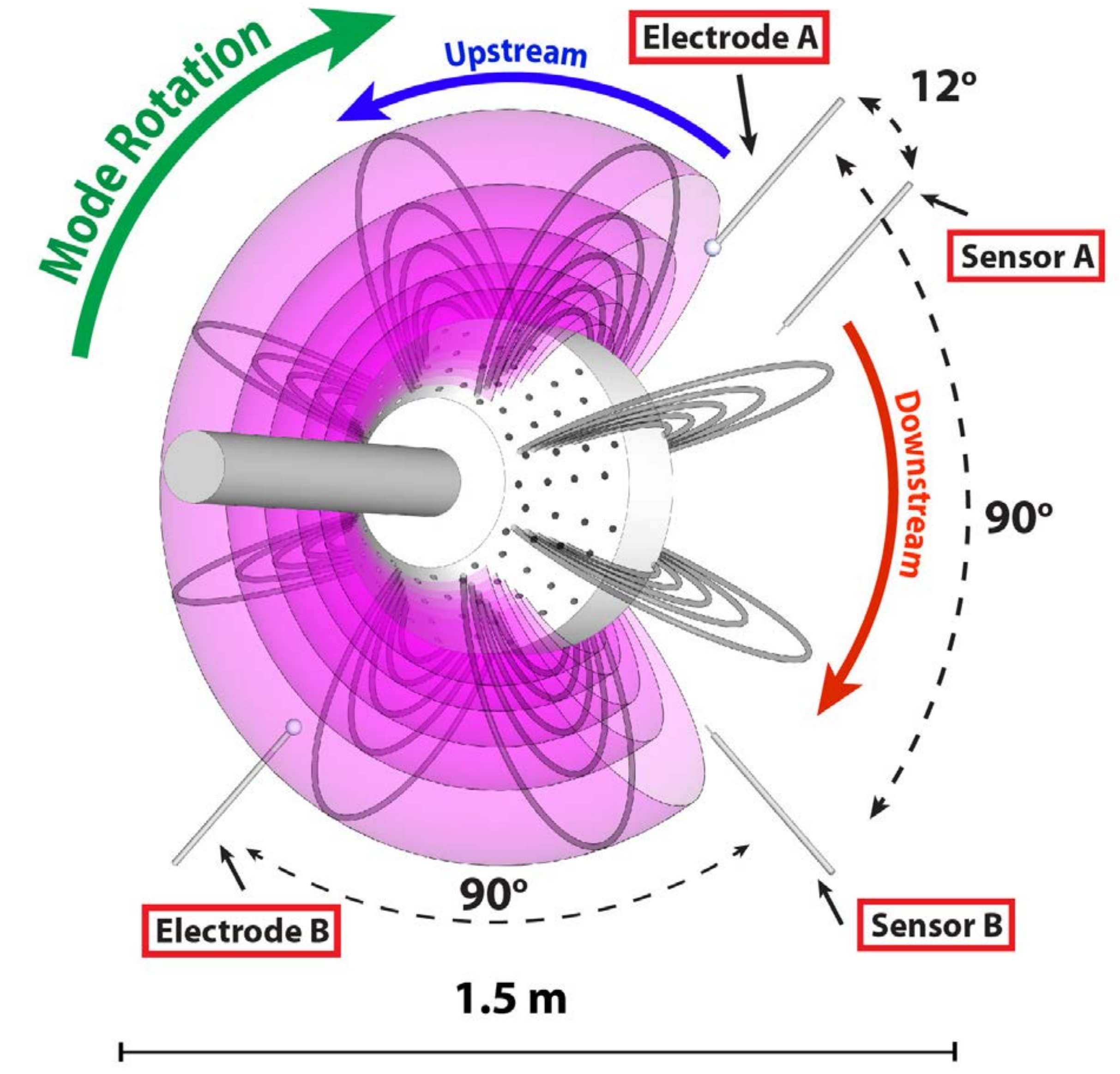
Laboratory Magnetospheres for Space Science and Astrophysics

- **Harbin Institute of Technology**
  - CO7.00014 (**Mon, Afternoon**): Wang Zhibin, *et al.*, Computational Design of the Plasma Sources in Harbin Dipole eXperiment (HDX)
  - CO7.00015 (**Mon, Afternoon**): Qingmei Xiao, *et al.*, "Design of magnetic field configuration in Space Plasma Environment Research Facility (SPERF)"
- **Wisconsin Plasma Astrophysics Lab**
  - NP12.00128 (**Wed, Morning**): Douglass Endrizzi, *et al.*, "Astrophysically Relevant Dipole Studies at (WiPAL),"
- **Collisionless Terrella Experiment** (Columbia Univ)
  - JP12.00039 (**Tue, Afternoon**): Alexander Battey, *et al.*, "Multiple-Probe Excitation and Control of Low-Frequency Fluctuations in a Laboratory Magnetosphere"
  - PP12.00053 (**Wed, Afternoon**): Melissa C. Abler, *et al.*, "Effects of Multi-Point Current-Injection Feedback on Interchange Turbulence in a Dipole-Confined Plasma"

Space Plasma Environment Research Facility

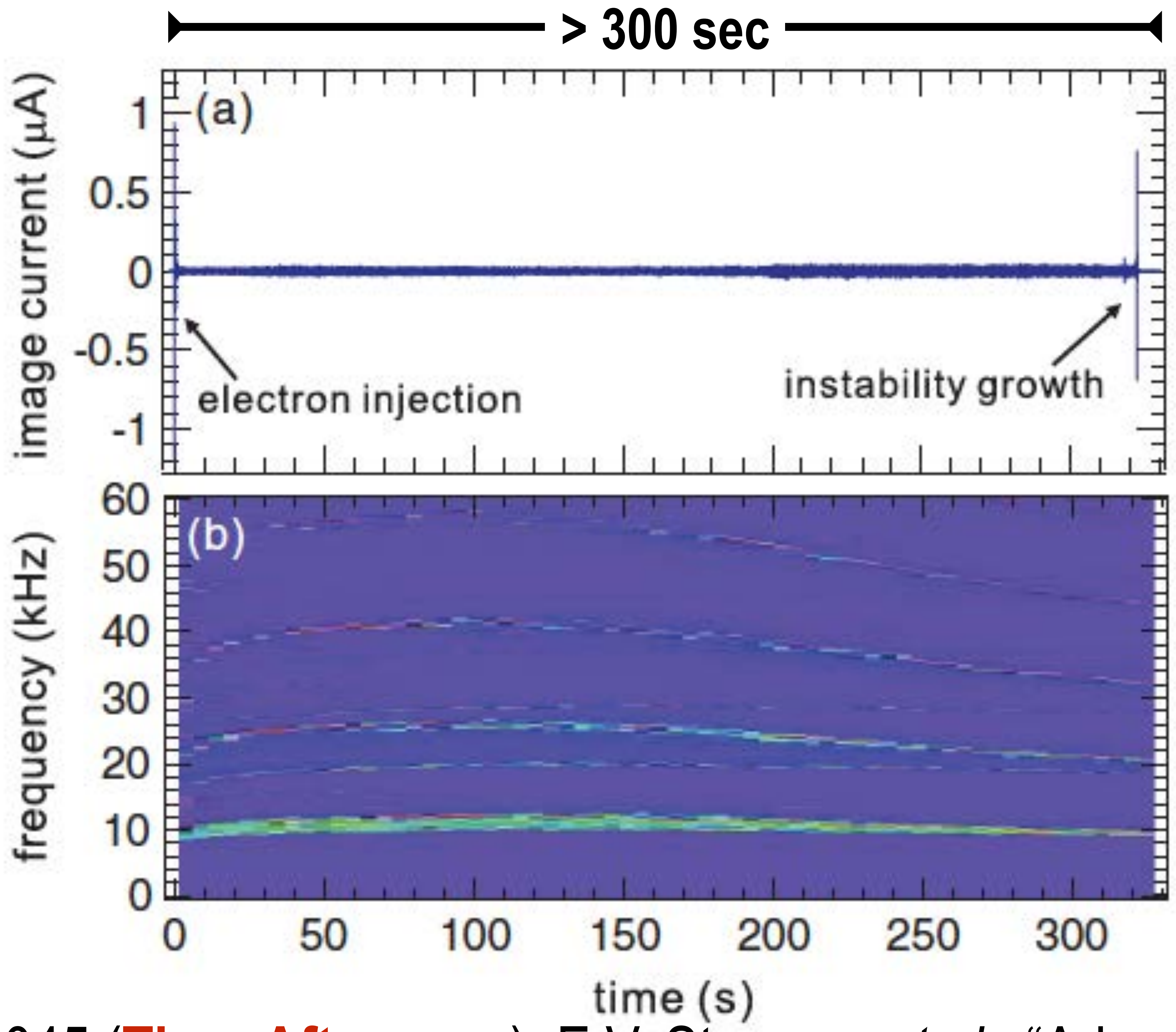


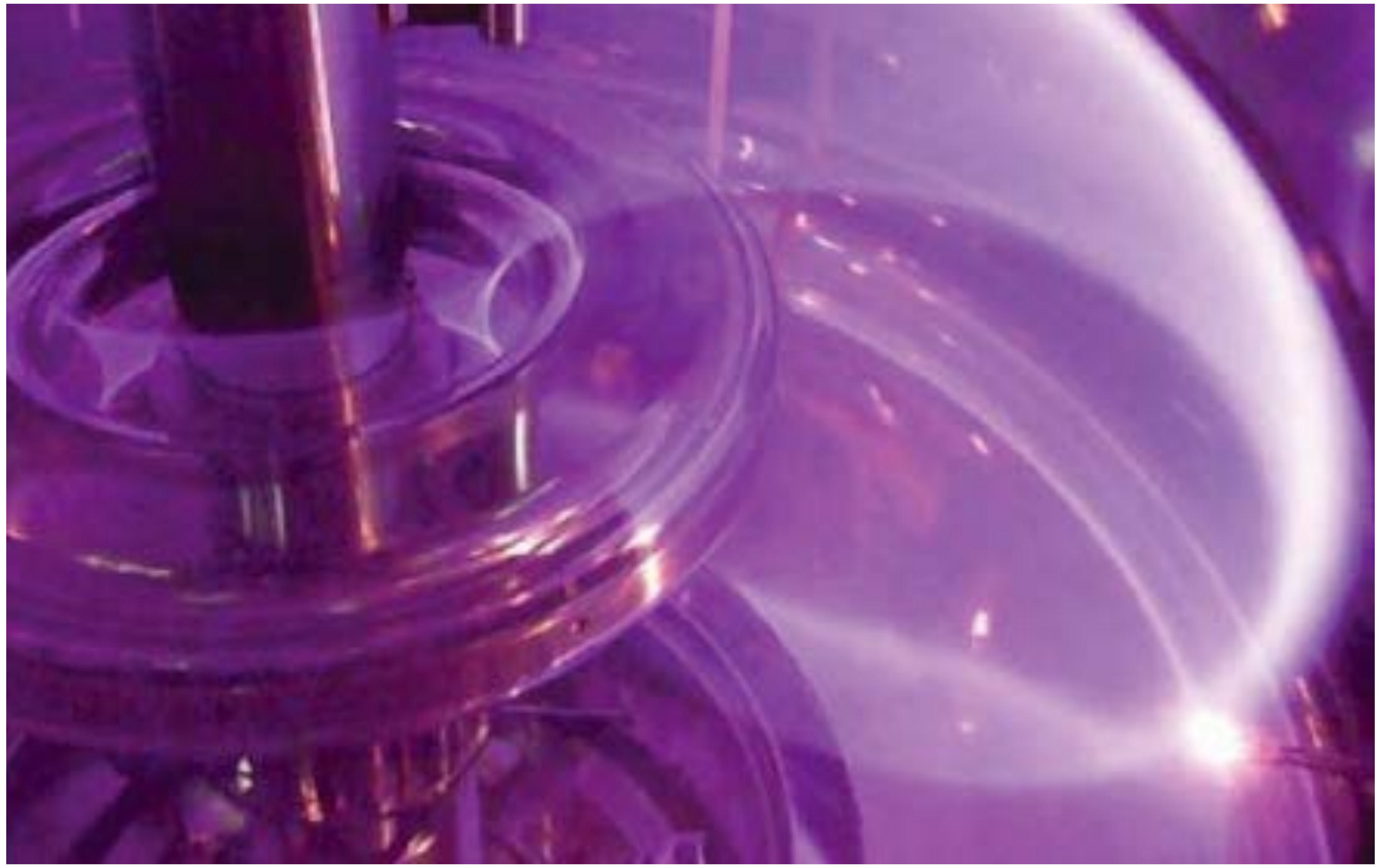
Driving the Magnetospheric Dynamo with Active Current Injection



Toroidal Confinement of Pure-Electron and Positron Plasmas

Yoshida, *et al.*, “Magnetospheric Vortex Formation: Self-Organized Confinement of Charged Particles,” *Phys Rev Lett* **104**, 235004 (2010).





UP12.00045 (**Thur, Afternoon**): E.V. Stenson, *et al.*, “Advancements toward matter-antimatter pair plasmas in the laboratory”

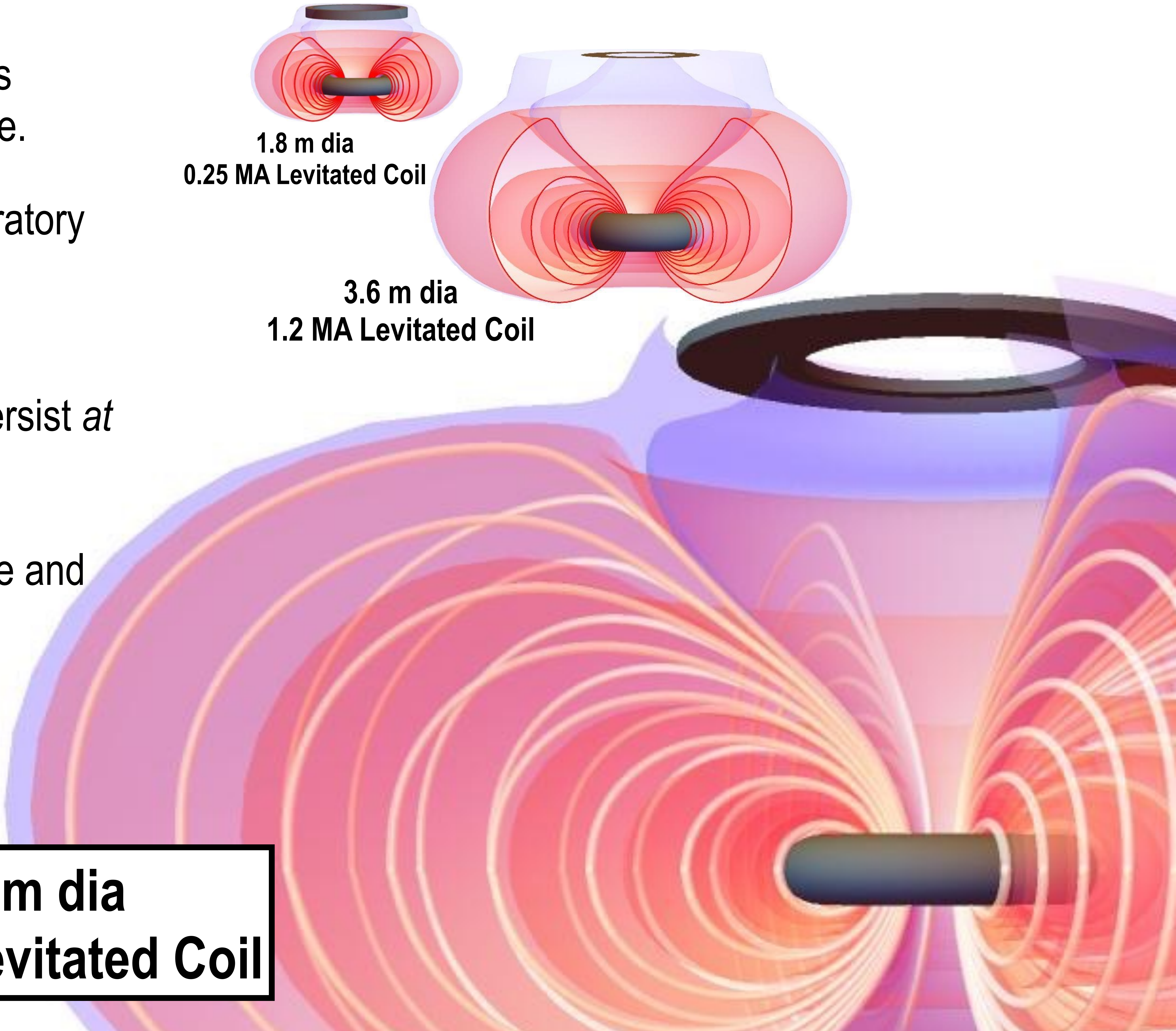
APEX/PAX (*A Positron Electron Experiment/Positron Accumulation Experiment*) aims create and magnetically confine a laboratory electron-positron pair plasma for fundamental studies.

Hasegawa's 1987 Question: Does magnetospheric physics apply to fusion magnetic confinement in the laboratory?

- ✓ LDX, RT-1, theory and simulation do not show any limitations preventing the scaling of stable high-β equilibria to larger size.
- ➡ However, the answer to Hasegawa's question we need laboratory tests with high power heating and high plasma density. (*We can do these experiments using existing facilities.*)
- ➡ If turbulent self-organization and centrally-peaked profiles persist *at large size*, …

  With only a small superconducting magnetic, we could create and study very large confined plasma for …

  - ➡ **Fundamental plasma physics**
  - ➡ **Space science and technology**
  - ➡ **Fusion energy confinement science**



ACQUIRE CURRENCY
FLAMMABLE GASES
LABORATORY
NO SMOKING
DANGER
HIGH VOLTAGE
STAND CLEAR
WEST