Fusion Turbulence without a Toroidal Field

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Columbia University and PSFC, MIT

Mixing in Fusion Plasmas
55th Annual Meeting of the APS Division of Plasma Physics
Denver, November 2013

Toroidal Confinement without Toroidal Magnetic Field is a New Paradigm for the Laboratory Study of Steady-State and High-Beta Transport

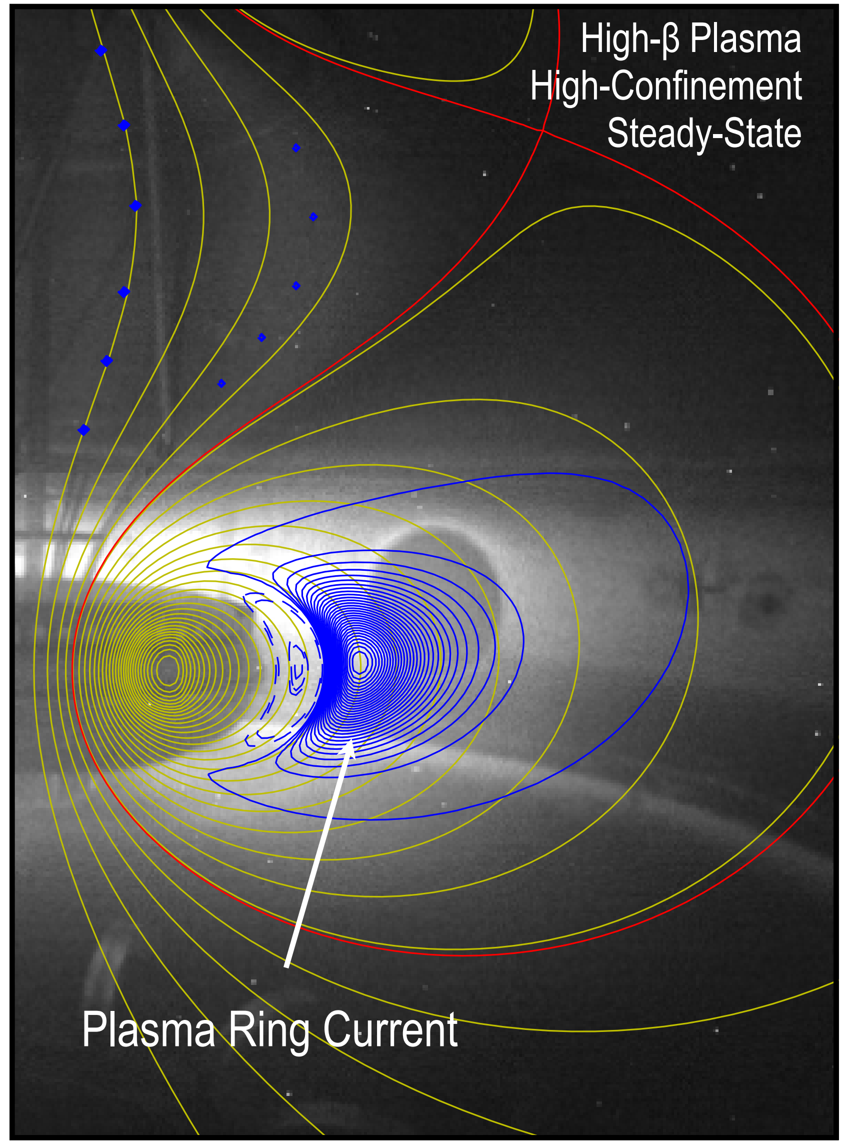
- Magnetospheric plasmas do not have toroidal field and nevertheless confine plasma at high beta.

  When a dipole is magnetically levitated, very high plasma pressure, $\beta > 50\%$, is achieved in the laboratory ***showing key connection between laboratory and space***

- By eliminating the toroidal field, a strong, but small, dipole magnet inside a very large vacuum chamber ***making possible very large plasma experiments at relatively low cost***

- Without a toroidal field, the rotational transform $\rightarrow \infty$; there is no average good curvature; and no magnetic shear.

  Stability stability results from plasma compressibility, $\omega^* \sim \gamma\omega_\kappa$; and the absence of streaming particles leads to flute-interchange modes.



Toroidal Confinement without Toroidal Magnetic Field is a New Paradigm for the Laboratory Study of Steady-State and High-Beta Transport

- Isentropic profiles, with $\delta(PV^\gamma) \sim 0$, have nearly equal diamagnetic and magnetic drifts, $\omega^* \sim \gamma\omega_\kappa$
- Passing and trapped particle dynamics are nearly equivalent
- Turbulence dominated by low-frequency interchange mixing, $k_{||} \sim 0$

➡ *Very high beta in steady-state can be reached in levitated dipole*

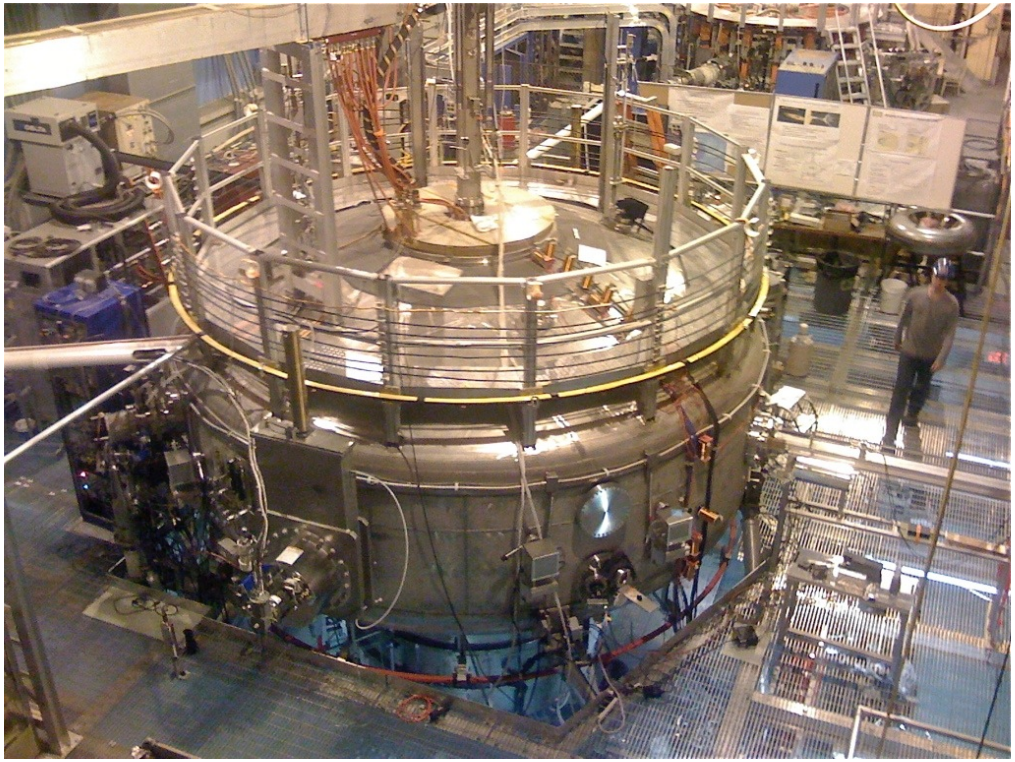
➡ *Turbulent mixing is 2D with inverse cascade and self-organization*

➡ *Strong turbulent pinch drives stationary profiles towards $\eta \sim 2/3$*

Outline

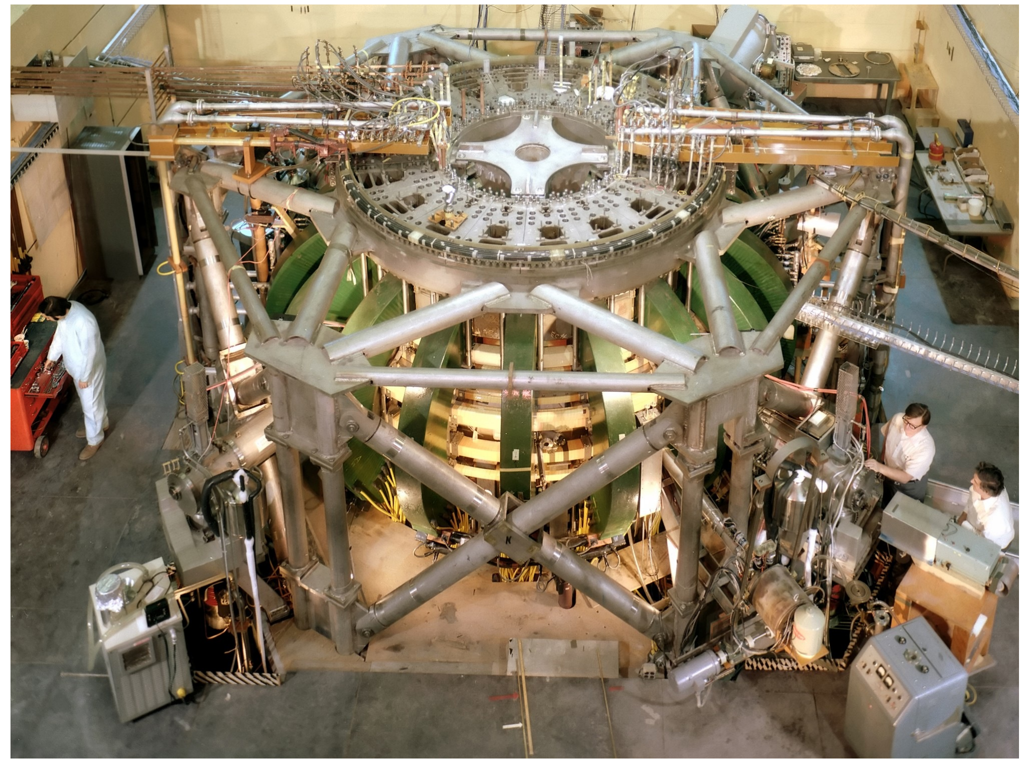
- What are the differences and similarities between the turbulent pinch in
  - **Tokamak** L-mode (with $\omega^* \sim (R/a)\,\omega_\kappa >> \gamma\omega_\kappa$ and *unequal* trapped-passing dynamics)
  - **Magnetic dipole** in laboratory and space (near isentropic, $\delta(PV^\gamma) \sim 0$, with $\omega^* \sim \gamma\omega_\kappa$ and *similar* trapped-passing dynamics)
- What are the differences and similarities between the spatial structure and spectrum of low-frequency fluctuations?

Turbulent Pinch is a Fundamental Process found in Toroidal Magnetic Systems Including Tokamaks and Planetary Magnetospheres



Levitated Dipole Experiment (LDX)

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

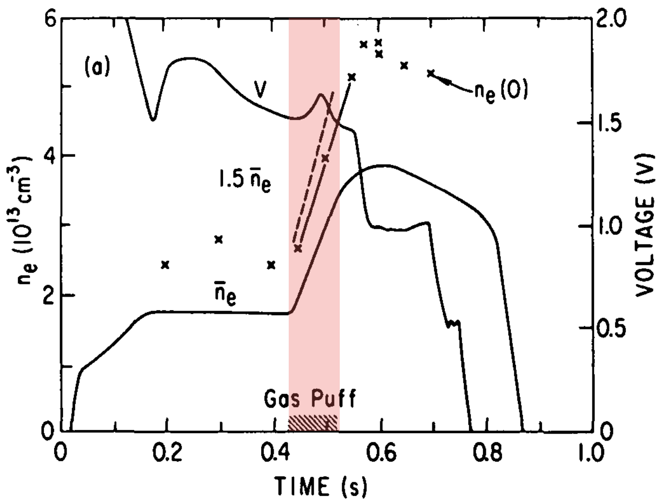


Princeton Large Torus (PLT)

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

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



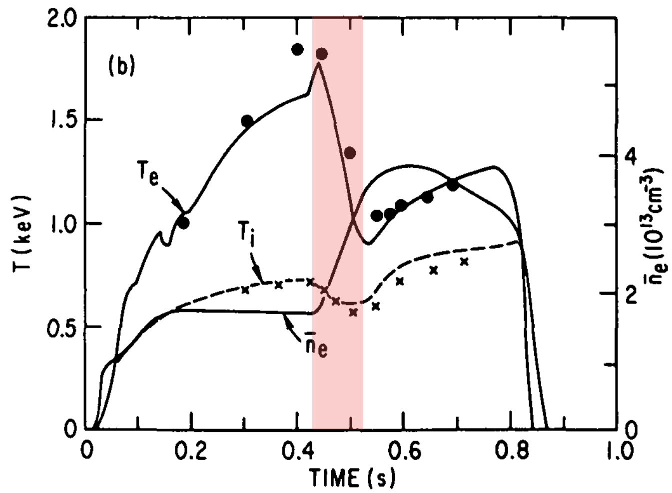
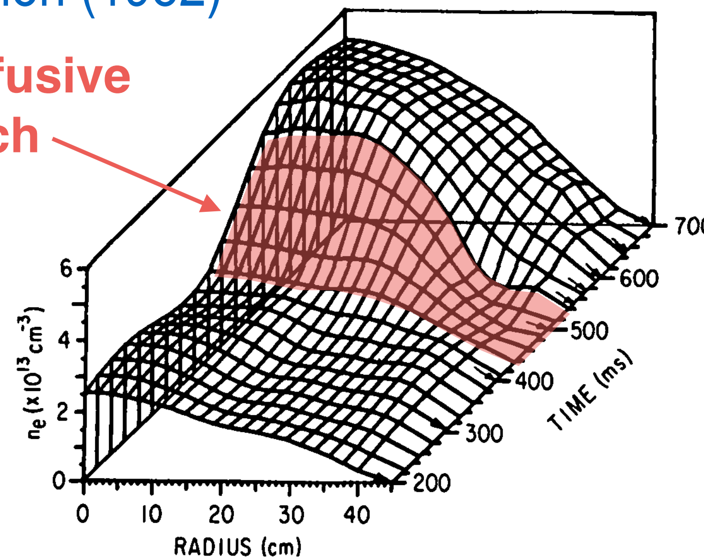
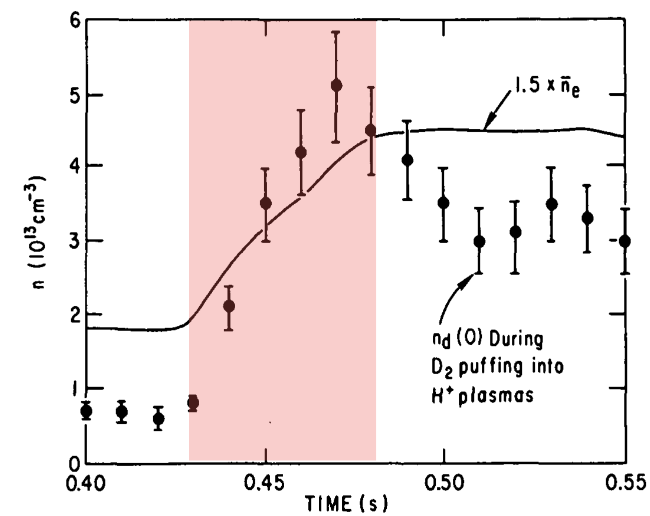


FIG. 2. (a) Time evolution of the loop voltage, V, the line-average density $\bar{n}_e$, and the central electron density, $n_e(0)$ during the density rise. (b) Time evolution of the central electron temperature from $2\omega_{ce}$ (——), and from TVTS (●), with the time evolution of the central ion temperature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



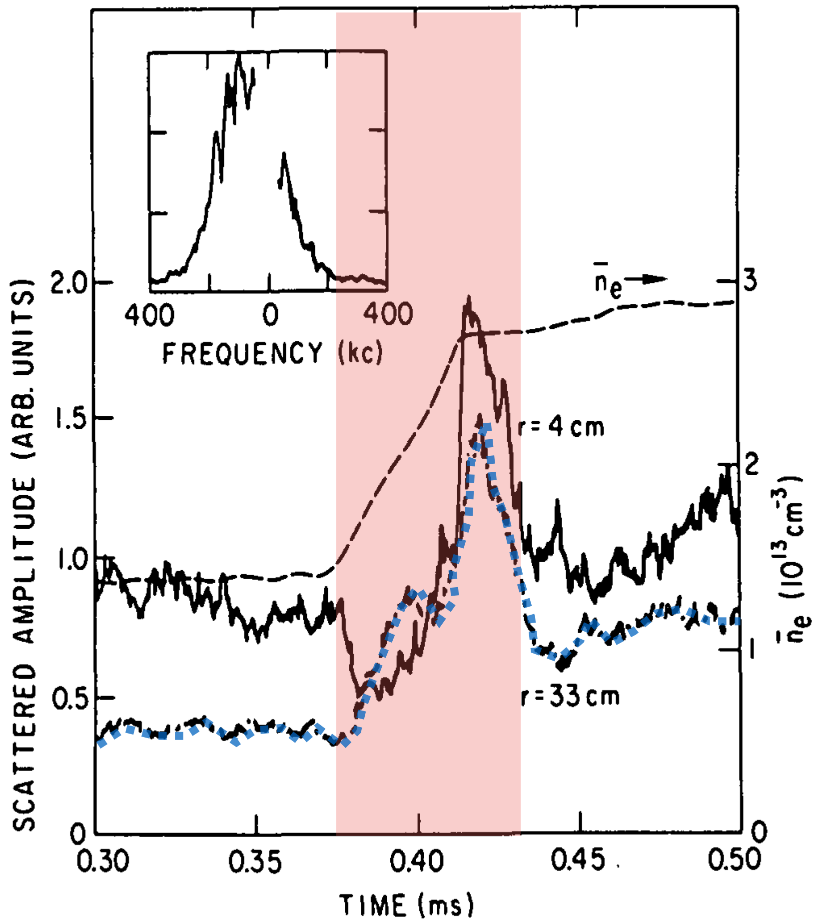


Inward Turbulent Pinch "*is necessary to model the experimental results*" of peaked density from edge gas source

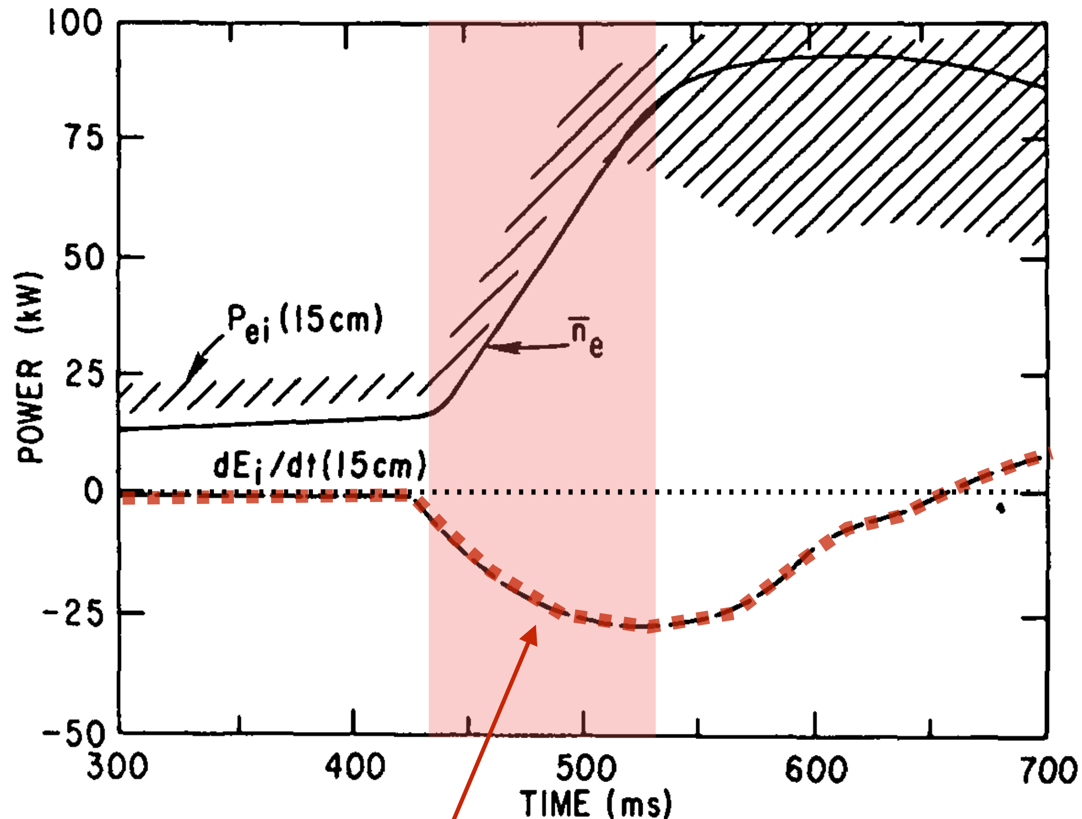
A (*Historic*) Density Rise Experiment on PLT

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

Low Frequency Gyrokinetic Theory provide a Framework for Understanding Turbulent Transport

- Low frequency fluctuations in strongly magnetized plasma, $\omega << \omega_b << \omega_c$, conserve constants of motion.
- **Turbulent equipartition across flux tube volumes** possible *provided a sufficiently broad turbulent spectrum resonates with particles*
- **Magnetic geometry** relates turbulent diffusion in magnetic-flux-space to diffusive and pinch terms in coordinate-space.
- **Dipole geometry**:
  - Birmingham, *J. Geophysical Res.*, 1969
  - 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
  - Isichenko, *et al.*, *Phys. Rev. Lett., 1995*
  - Baker and Rosenbluth*, Phys. Plasmas*, 1998; Baker, *Phys. Plasmas*, 2002

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

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

Diffusion Coefficient

$$D_\psi = \lim_{t\to\infty} \int_0^t dt\, \langle \dot{\psi}(t)\dot{\psi}(0)\rangle \equiv \langle \dot{\psi}^2 \rangle \tau_c$$
$$= R^2 \langle E_\varphi^2 \rangle \tau_c$$

Adiabatic Radial Transport

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

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

Turbulent Pinch in Toroidal Laboratory Plasmas

When the turbulent spectrum is sufficiently broad to interact with (nearly) all particles, *independent of energy and pitch-angle*, then ...

Dipole

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

Tokamak (for Trapped Particles)

$$D_\psi = R^2 \langle E_\theta^2 \rangle (B_p^2 / B^2) \tau_c$$

Flux-Tube **Particle** Number Transport:

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

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

Geometry of Magnetic Flux Tubes, δV, Determines Pinch

Dipole

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

Tokamak (Trapped Particles)

$$D_\psi = R^2 \langle E_\theta^2 \rangle (B_p^2 / B^2) \tau_c$$

Flux-Tube Number Transport:

$$\cancel{\frac{\partial(\bar{n}\delta V)}{\partial t}} = \cancel{\langle S \rangle} + \frac{\partial}{\partial \psi} D_\psi \frac{\partial(\bar{n}\delta V)}{\partial \psi} = 0$$

Steady-state *without* internal source, zero net flux condition:

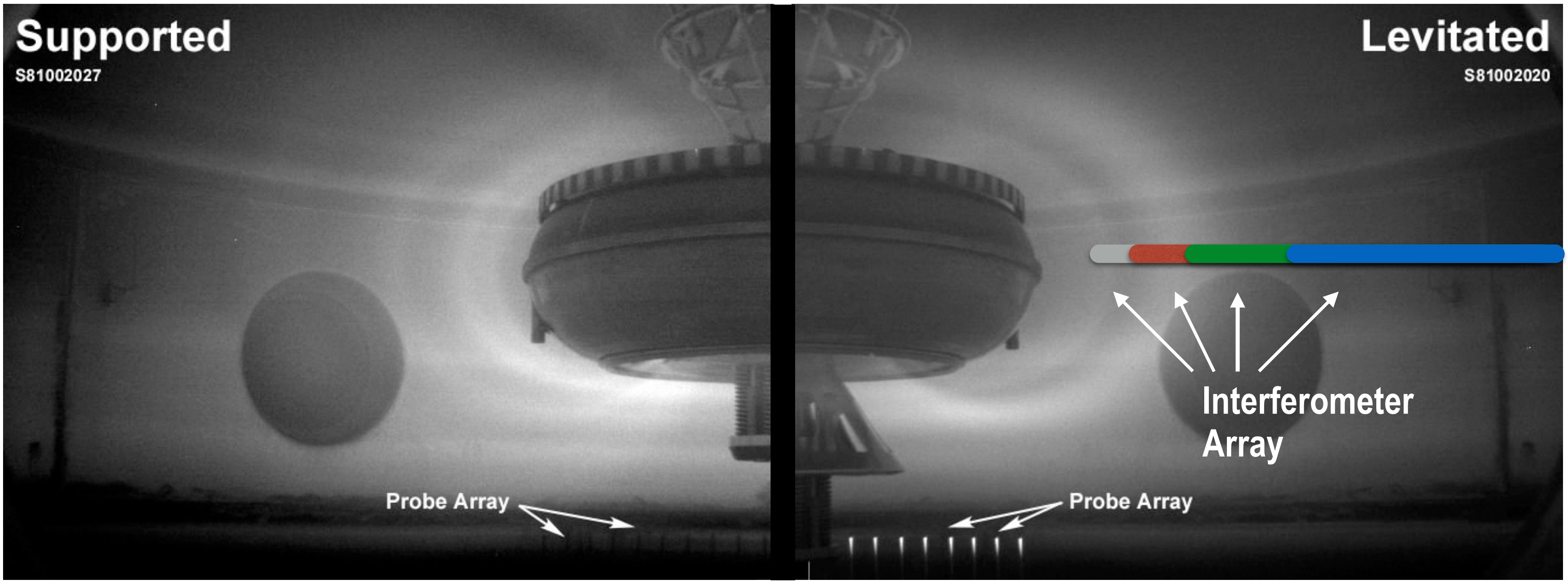
$$\bar{n} \propto \frac{1}{\delta V} \sim \begin{cases} 1/R^4 & \text{Dipole} \\ 1/q & \text{Tokamak (Trapped Particles)} \end{cases}$$

… and particles can move **inward against a density gradient**.

Quantitative Verification of Inward Turbulent Convection

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

5 m



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

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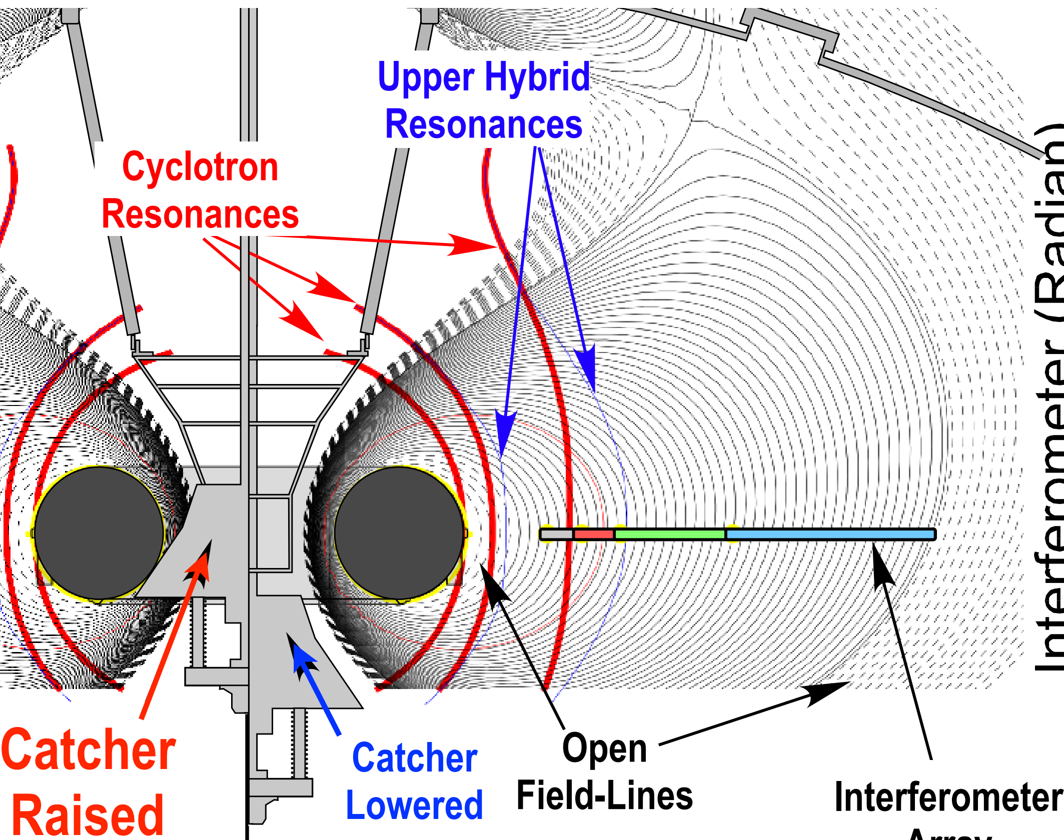
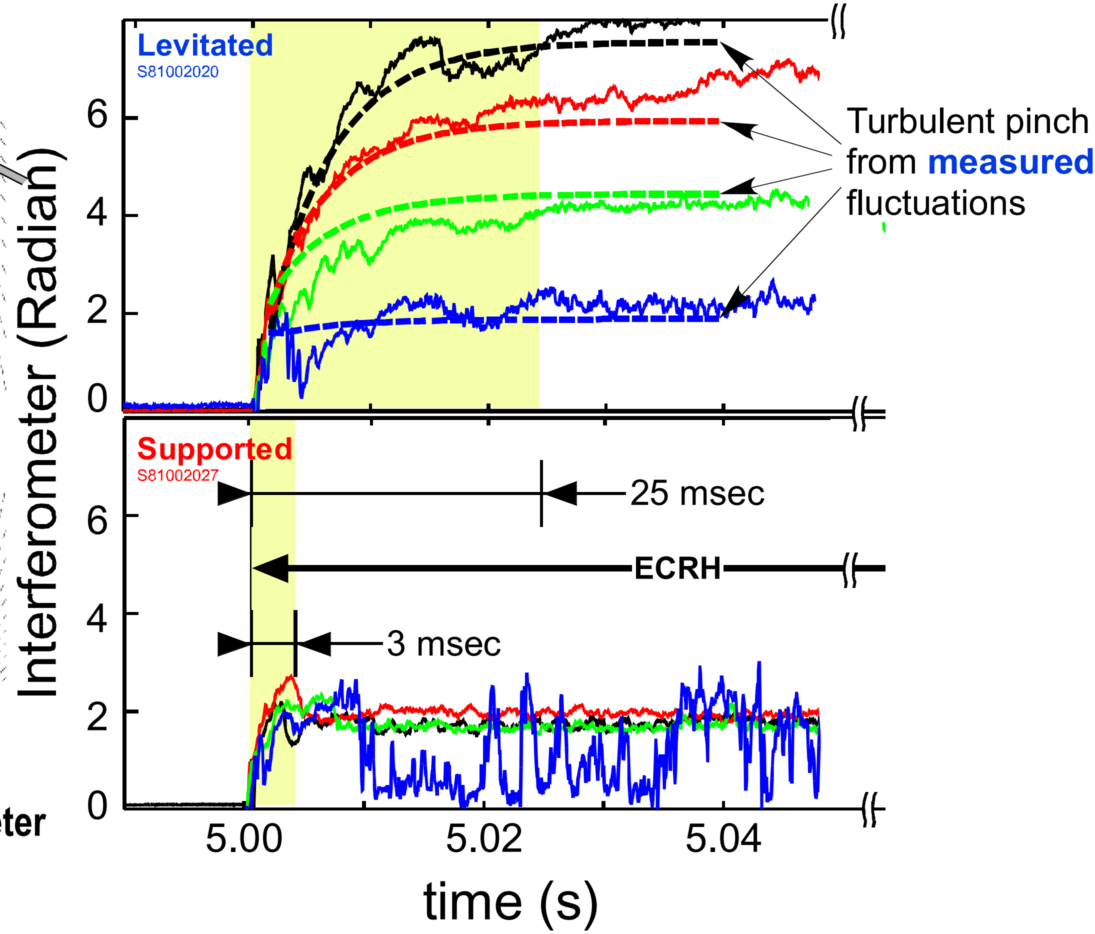


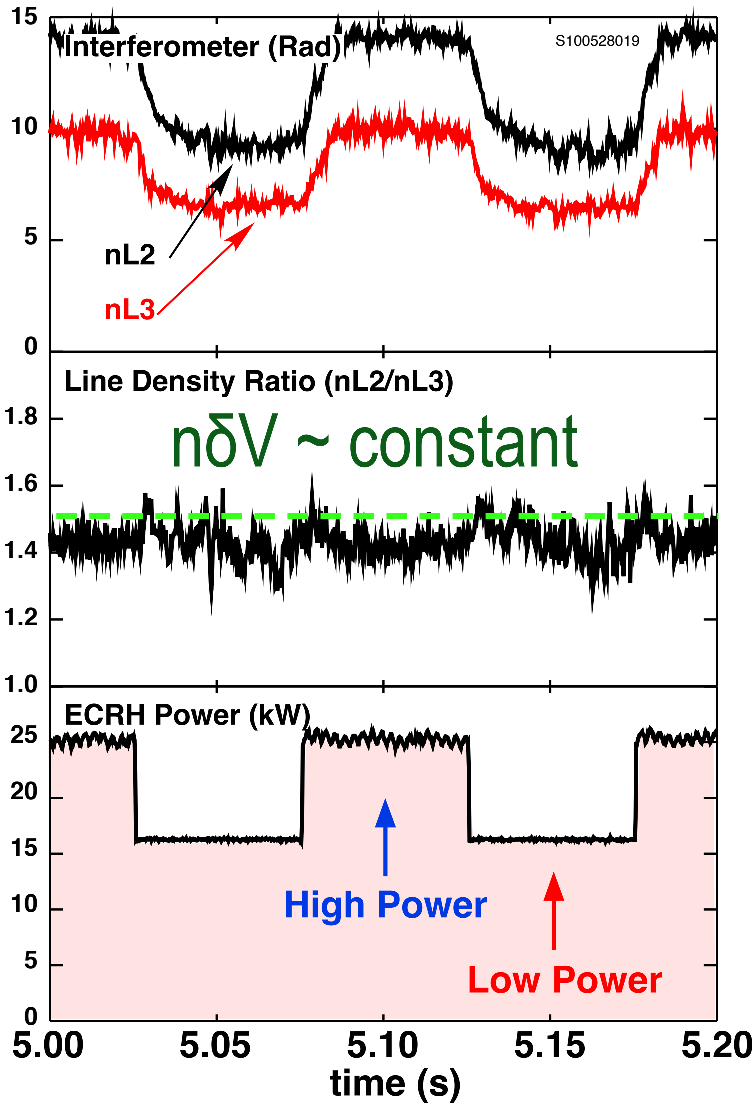
With levitated dipole, inward turbulent transport sets profile evolution

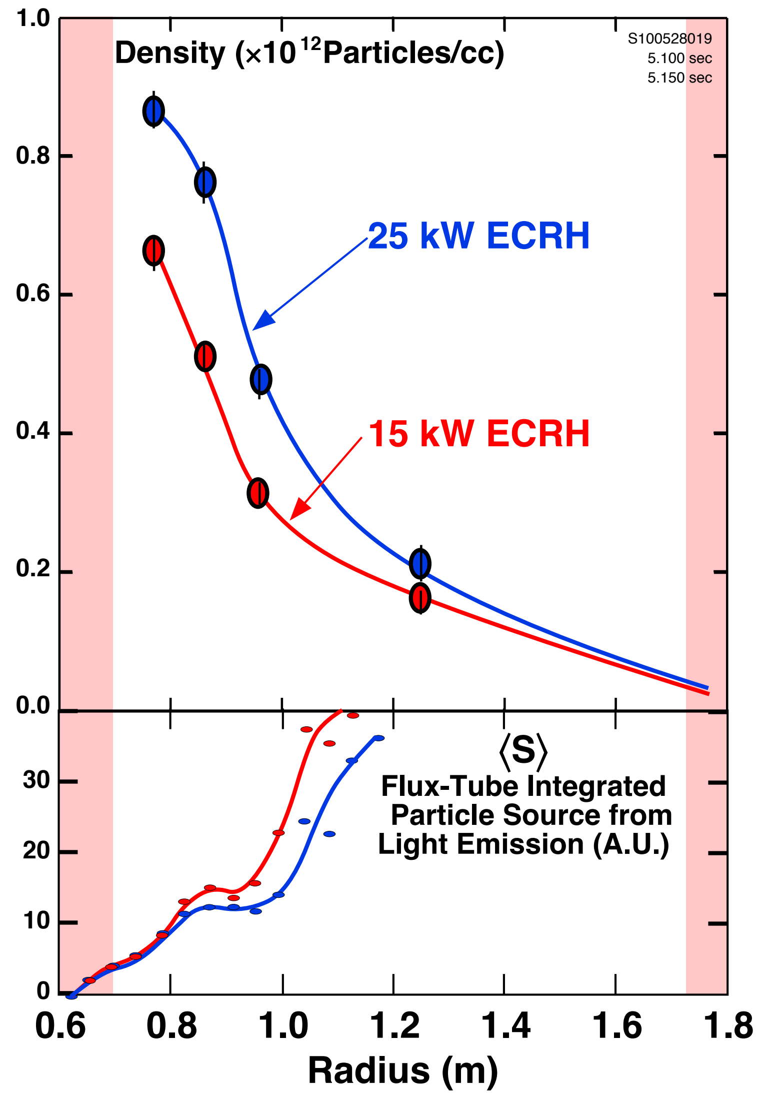


Alex Boxer, *et al.*, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nature Phys* **6**, 207 (2010).

Heating modulation demonstrates robust inward pinch towards invariant 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.





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

Flux-Tube Plasma **Energy/Entropy** Transport:

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

Geometry of Magnetic Flux Tubes, δV, Determines Stability

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

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

$$\frac{\partial(\bar{P}\delta V^\gamma)}{\partial \psi} = e\bar{n}\,\delta V^\gamma \big(\langle \omega^* \rangle - \gamma \langle \omega_\kappa \rangle\big)$$

$$\approx \begin{cases} 0 & \text{Dipole (marginally stable)} \\ e\bar{n}\delta V^\gamma \langle \omega^* \rangle & \text{Tokamak (avg good curvature)} \end{cases}$$

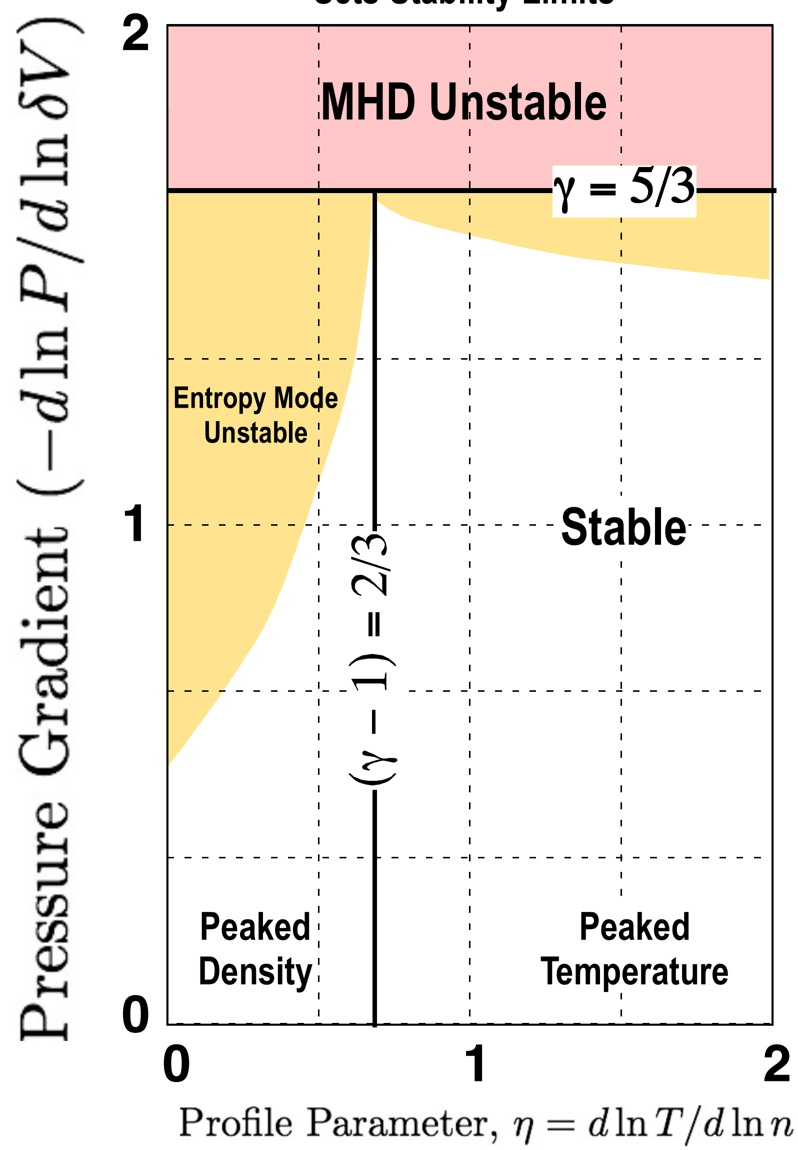
While energy/entropy flux is **always outward in a tokamak**,
depending upon the location of the heating source ‹*H*›,
Energy flux **in a dipole can be inward (magnetosphere) or outward**.

Low frequency fluctuations dominate plasma dynamics: MHD interchange & Entropy modes

- Interchange modes set pressure and density gradient limits in dipole-plasma (*not* ballooning-drift)
- ***Entropy mode*** (Kesner, Hastie, *POP*, 2002) ***changed our thinking:*** not just pressure and density gradients, but also $\eta = d(\ln T)/d(\ln n)$
- 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)

$$k_\perp \gg k_{||}$$

Profile "Shape"(*i.e.* gradient) Sets Stability Limits



Turbulence drives plasma to steep profiles and creates Turbulent Self-Organization in Dipole Geometry

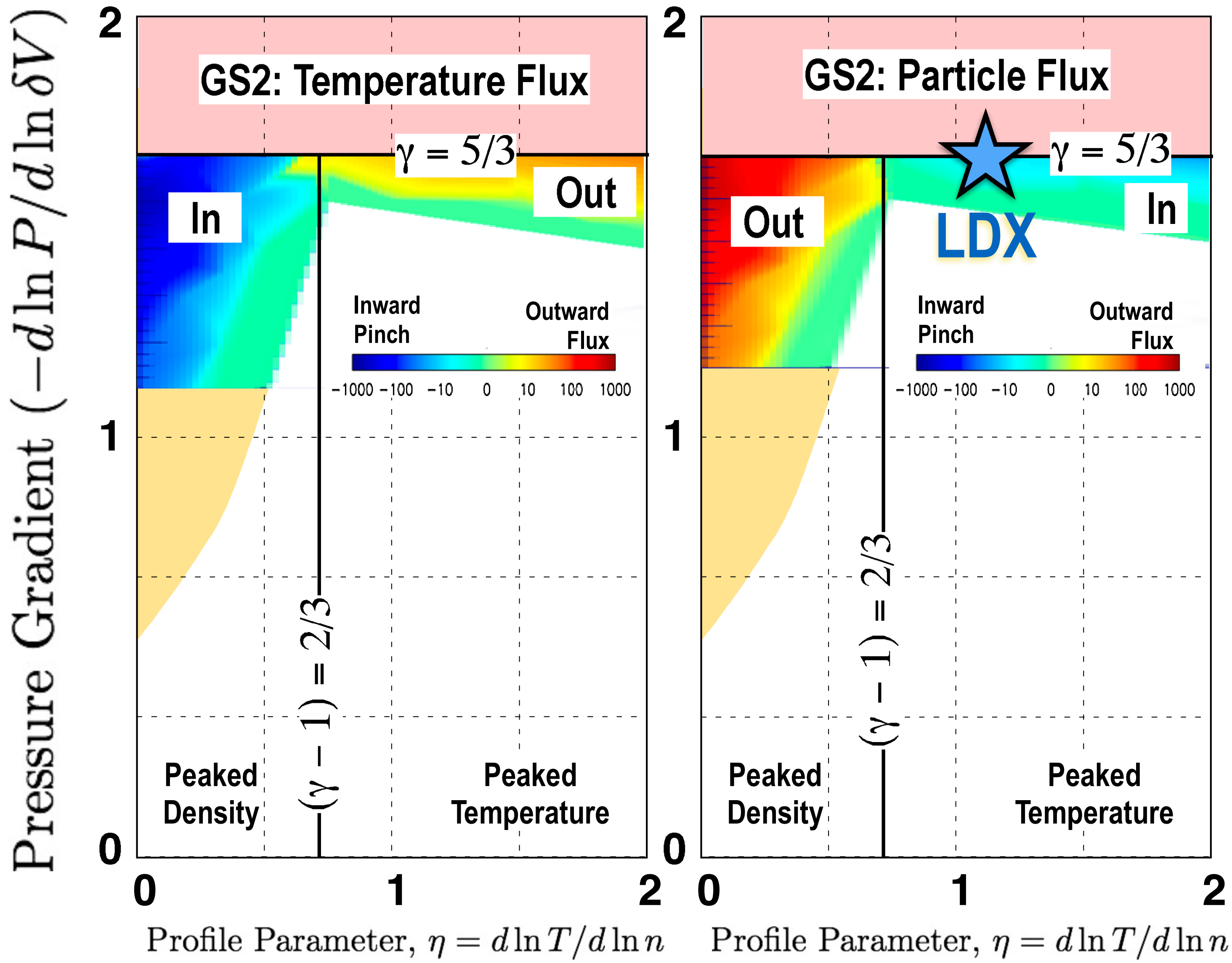
Gyrokinetic (GS2) simulations show turbulence drives particles or heat to maintain uniform entropy density

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

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

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

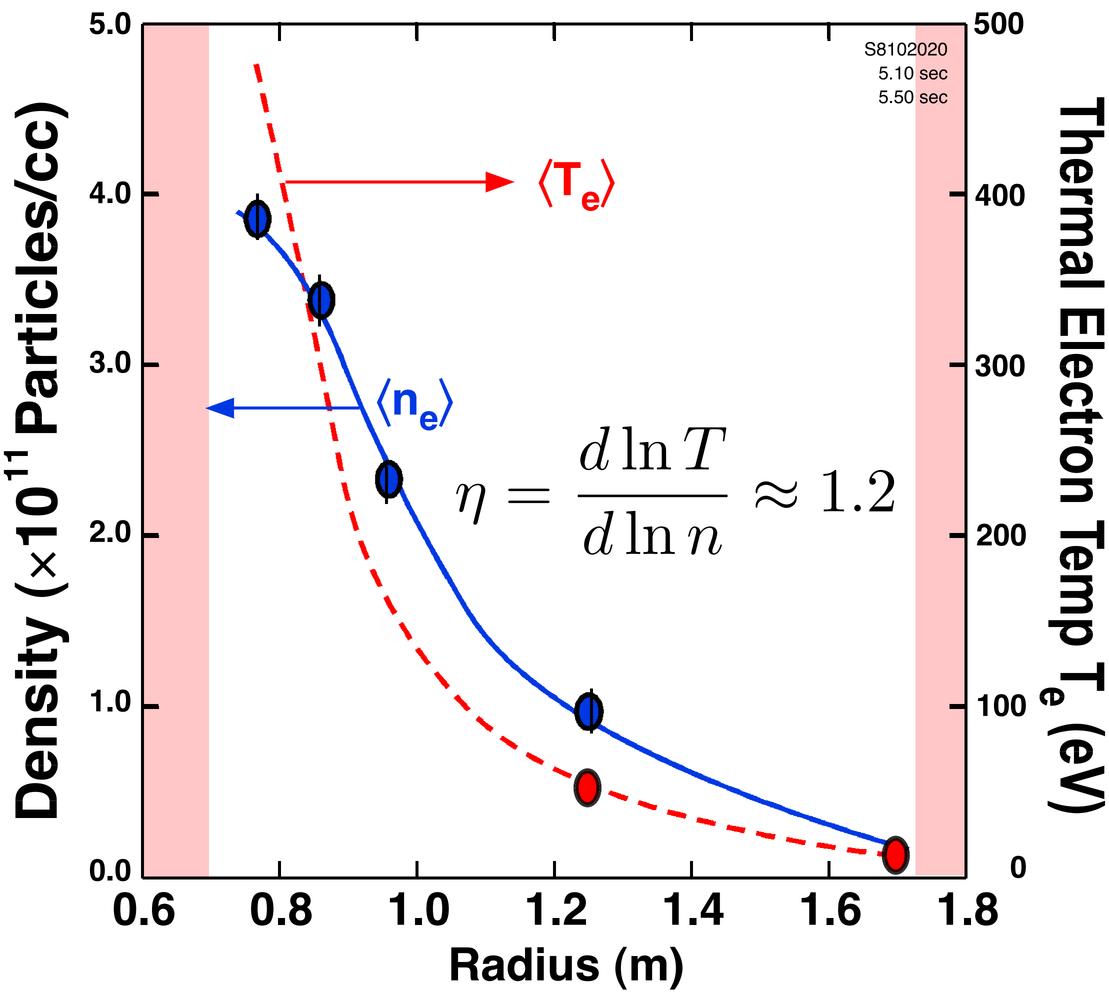
Kobayashi, Rogers, Dorland, *PRL* (2010)



Turbulent Pinch Maintains Centrally-Peaked Temperature

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

- Thermal plasma energy about 100 J with 11 kW of ECRH.
- Measured edge temperature (14 eV), density profile, and stored energy, …
  central T_e ~ 0.5 keV
- Outward thermal flux sustains inward particle flux, η ~ 1.2

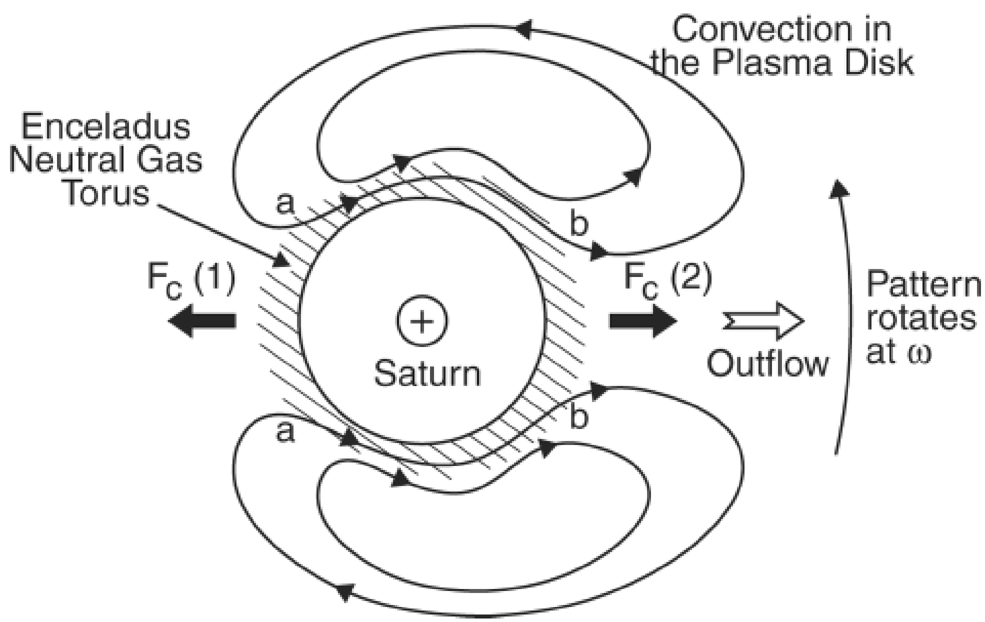


Boxer, *et al.*, *Nature Phys.* (2010)

Low-Frequency Convection Motions in Dipoles are Global

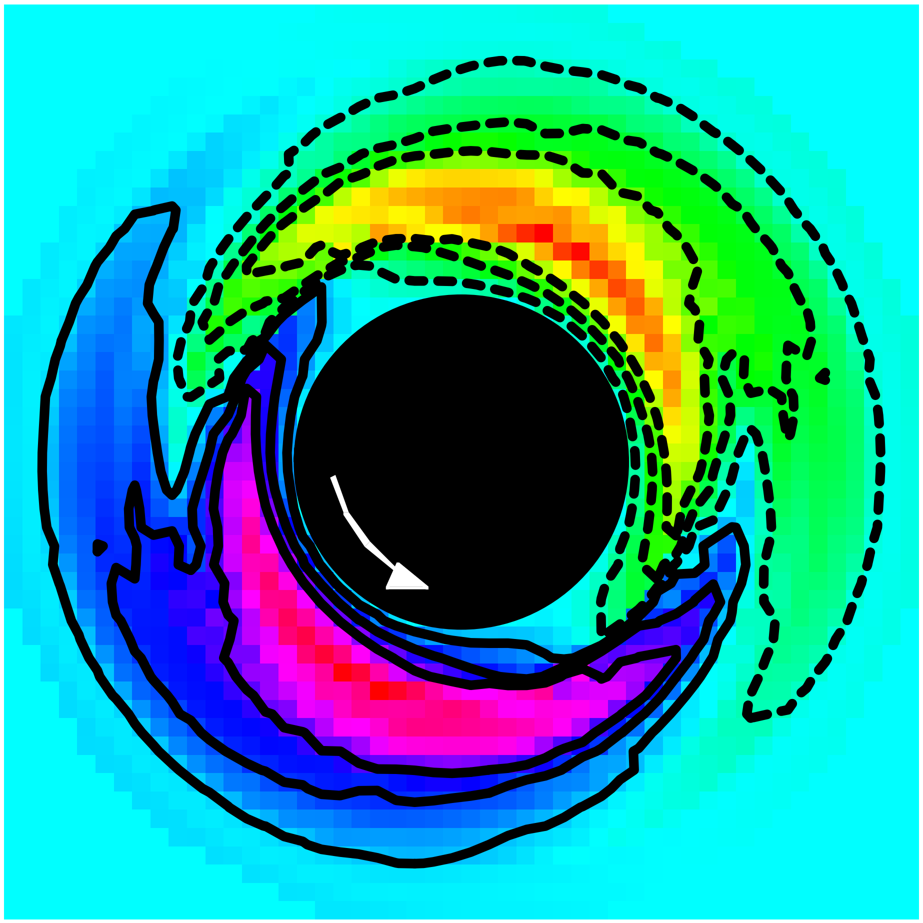
Exploring the physics of low-frequency turbulent convection

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



CASSINI: Observations of Circulating interchange mixing of Saturn's Magnetosphere

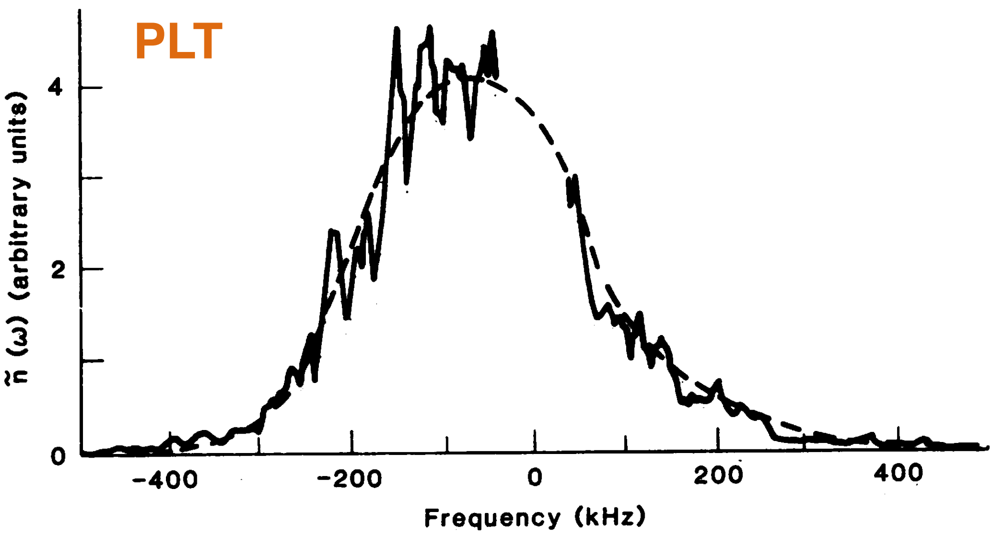
Levitt, et al., Phys Rev Lett 94, 175002 (2005).



Streamfunction during Mach ~ 1 rotation showing plasma mixing from centrifugal mode

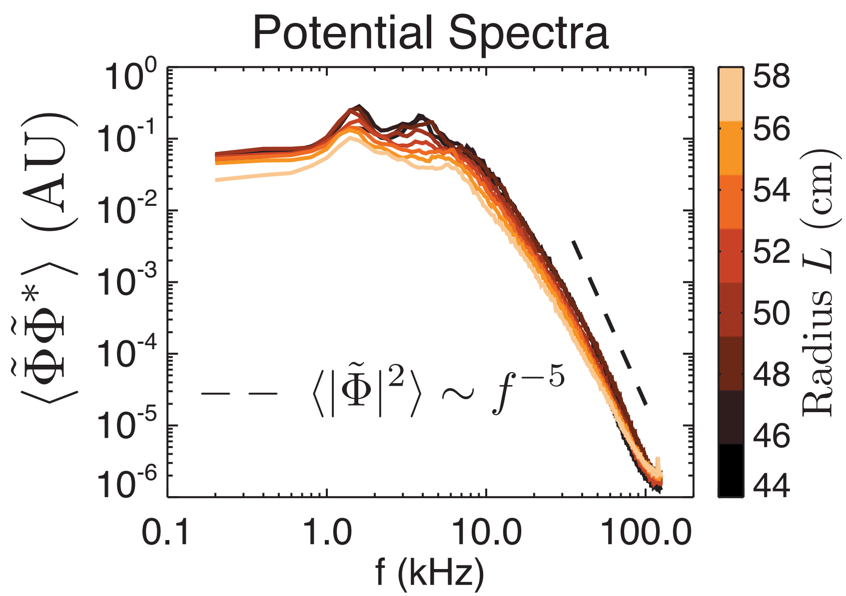
Dipole Observations Show Global Low-Frequency Turbulence Structure, 2D Inverse Cascade, and Self-Organization

Surko and Slusher, *Science* **221**, 817 (1983)



- Broad spectrum
- $\omega \sim \omega^{*}\,(a/\rho_i)$
- $\lambda \sim \rho_i$
- Ballooning-Drift

Grierson, *et al.*, *Phys Plasmas* **16**, 055902 (2009)
Boxer, *et al.*, *Nature Phys* **6**, 207 (2010).



- Broad spectrum
- $\omega \sim 0$ (in plasma frame)
- $\lambda \sim R >> \rho_i$
- Interchange, $k_{||} = 0$

Summary
Fusion Turbulence without a Toroidal Field

- Toroidal confinement without toroidal field is a **new paradigm for the study of steady-state and high-beta transport**
  - Very high pressure connecting space and laboratory plasma dynamics
  - Very large plasma experiments at relatively low cost
  - Whole plasma access for imaging and experimental control
- Strong inward turbulent particle **pinch verified by satellite and laboratory observations**
- Observations show global low-frequency turbulence structure, 2D inverse cascade, and self-organization

Presentations at DPP 55th

(Last Monday)

- CP8.00025 **Controlled Space Physics Experiments using Laboratory Magnetospheres** (Mike Mauel, *et al.*)
- CP8.00026 **Flux Tube Dynamics Following Pellet Release Experiments in Laboratory Magnetospheres** (Darien Garnier, *et al.*)
- CP8.00027 **Active Feedback Control of Global Turbulence with Multiple Localized Controllers** (Max Roberts, *et al*.)
- CP8.00028 **Profile Consistency and Turbulent Particle Pinch in Dense Plasma** (Jay Kesner, *et al*.)
- CP8.00029 **Symmetry Breaking and the Inverse Energy Cascade in a Plasma** (Matt Worstell, *et al*.)
- CP8.00030 **Interchange turbulence in a dipole-confined plasma** (Bo Li, *et al*.)