Turbulent Transport in a Laboratory Magnetospheric Dipole

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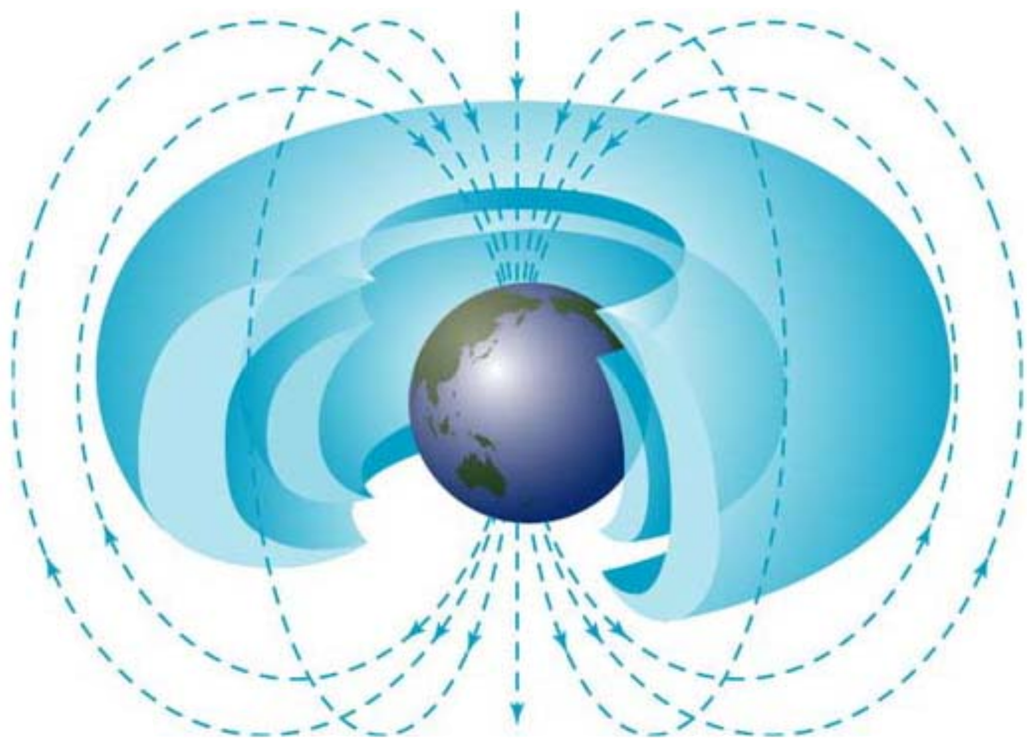
Physics of dipole plasma confinement established by early space exploration

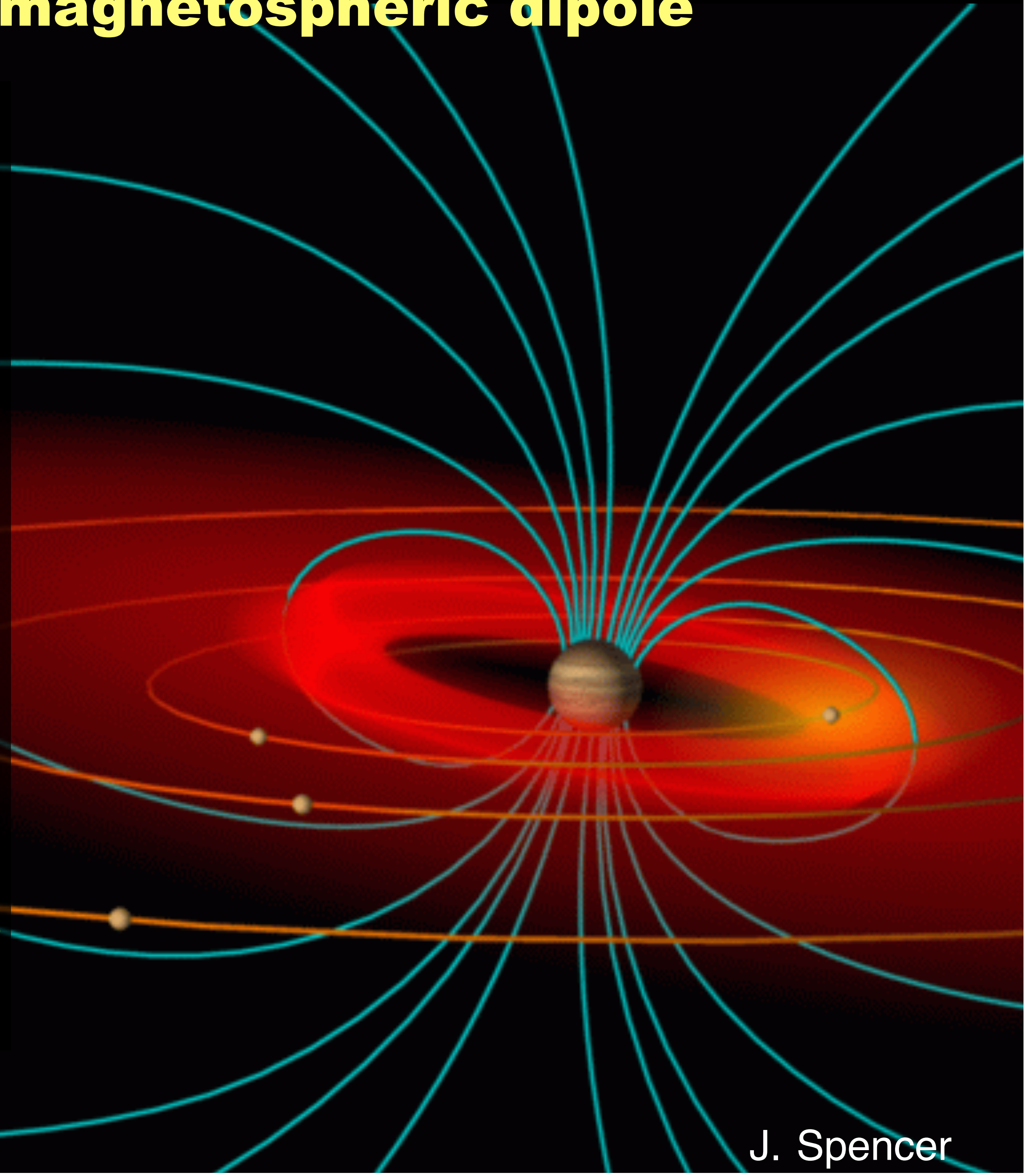
- More than 50 years of magnetospheric exploration: Earth, Jupiter, Saturn, Uranus, and Neptune
- Confinement and stability based on magnetic compressibility
- Gold (1959): Plasma pressure is centrally peaked with $p \sim 1/V^{\gamma} \sim R^{-20/3}$
- Melrose (1967): Plasma density is centrally peaked with $\langle n \rangle \sim 1/V \sim R^{-4}$
- Farley (1970): Random solar-driven fluctuations cause strong inward pinch and adiabatic heating of radiation belts



$$V = \oint \frac{d\ell}{B} \propto R^4$$

Observation of high β in outer planets prompted study of laboratory magnetospheric dipole

- Two interesting properties of active magnetospheres:
  - Pressure and density profiles are strongly peaked
  - High beta: β ~ 100% in magnetosphere of Jupiter
- Akira Hasegawa, 1987
  - Can the physics of collisionless space plasmas be applied to collisional fusion plasma confinement ?



J. Spencer

Dipole MHD stability sets interchange invariant profiles

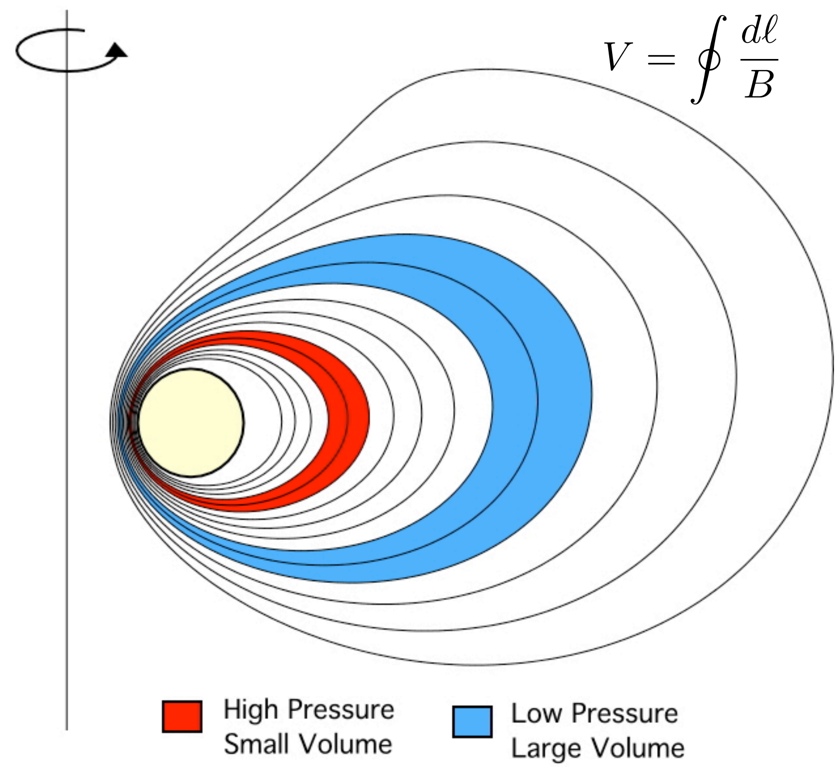
- **MHD stability from plasma compressibility**

If $p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$, then interchange does not change pressure profile.

- **Even as β > 1, interchange, not ballooning, limits pressure gradients (*Garnier, PoP, 1999*)**

- **Including rotationally-driven centrifugal modes, MHD constrains density and temperature profiles, and**

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



Dipole drift-kinetic stability shows importance of interchange dynamics even for MHD-stable plasmas

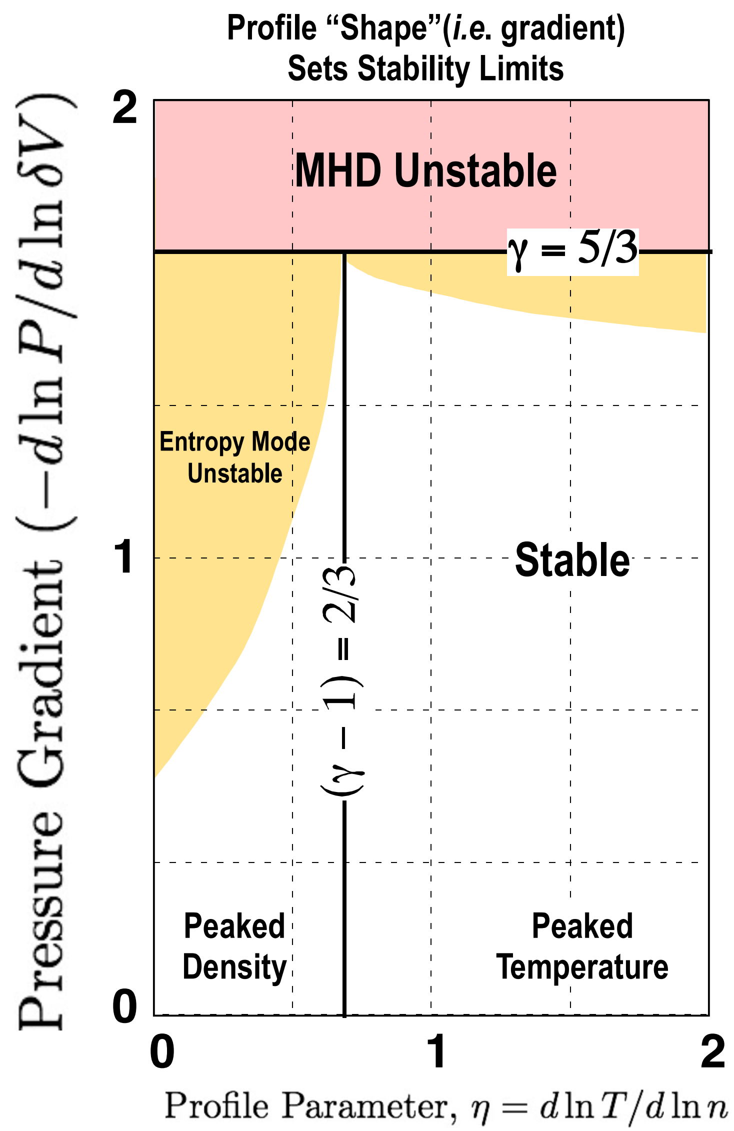
- **Entropy mode** (*Kesner, Hastie, PoP 2002*) changed our thinking: not simply MHD, but drift-kinetic fluctuations depend upon η
- Entropy modes occur for MHD stable plasmas when either the density or temperature profiles are not "stationary", with η ~ 2/3.
- Dipole fluctuations are interchange like

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

- Marginally stabile profiles

$$n \propto V^{-1} \text{ and } p \propto V^{-\gamma}$$

$$\eta = \frac{d \ln T}{d \ln n} \to \gamma - 1 = \frac{2}{3}$$



Dipole profiles dynamics show strong pinch from turbulent mixing

- Natural or "Invariant" profiles are stationary solutions to adiabatic transport equations

$$\frac{\partial(nV)}{\partial t} = \frac{\partial}{\partial\psi} D^{\psi\psi} \frac{\partial(nV)}{\partial\psi} + \langle S \rangle$$

$$\frac{\partial}{\partial\psi}\left(D^{\psi\psi} V \frac{\partial n}{\partial\psi} + n D^{\psi\psi} \frac{\partial V}{\partial\psi} \right)$$

dipole geometry has large pinch term

$$\frac{\partial(pV^{\gamma})}{\partial t} = \frac{\partial}{\partial\psi} D^{\psi\psi} \frac{\partial(pV^{\gamma})}{\partial\psi} + \langle H \rangle$$

Kouznetsov, Freidberg, Kesner, Phys. Plasmas. (2007)

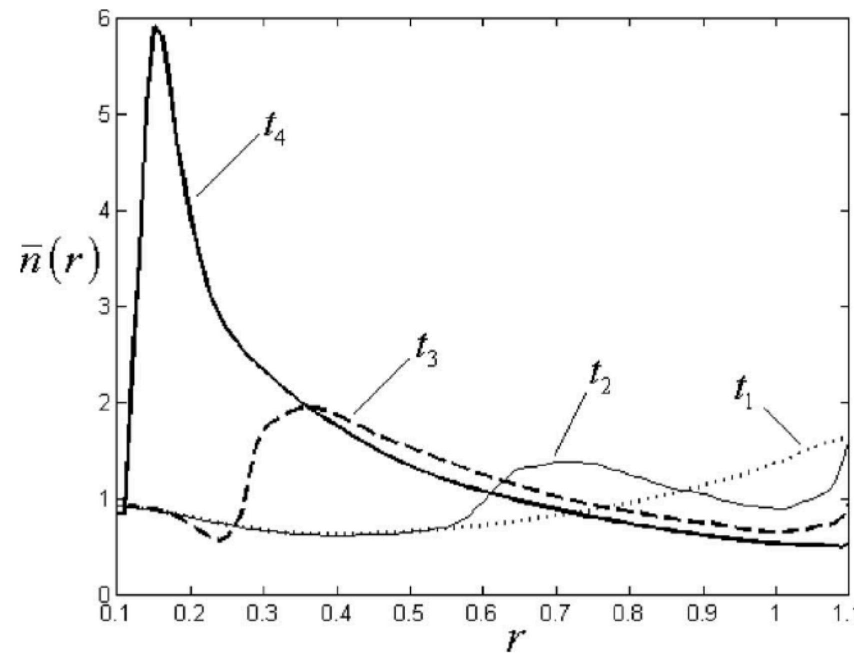
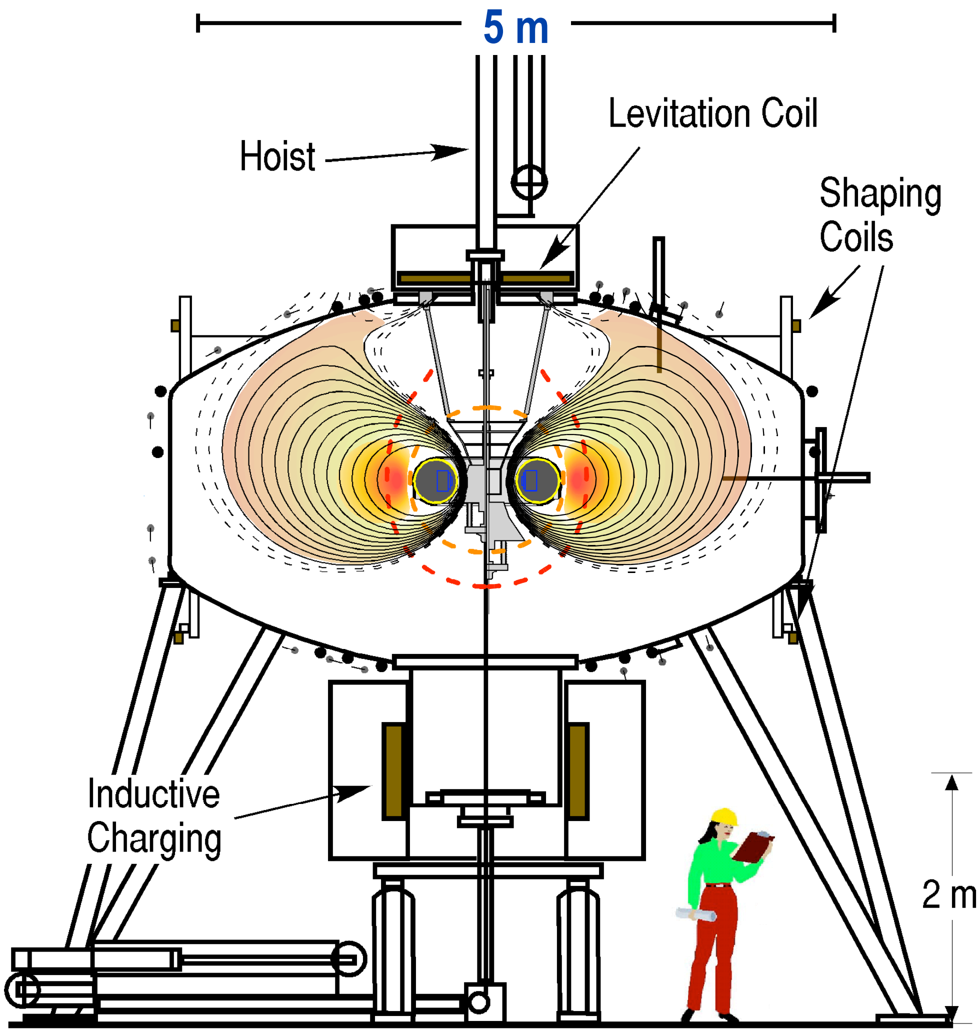


FIG. 5. The snapshots of the "self-organizations" process. Time t_1: before an instability is excited; t_2–t_4: different stages of self-organization.

Superconducting Levitated Dipole Experiments

LDX (MIT - USA)

Nb_3Sn Dipole 1.2 MA
Inductively Charged
3 Hour Float Time 25 kW CW ECRH



Components of a Levitated Dipole Experiment:

- Strong superconducting dipole for long-pulse, quasi-steady-state experiments
- Large vacuum chamber for unequalled diagnostic access and large magnetic compressibility
- Upper levitation coil for robust axisymmetric magnetic levitation
- Lifting/catching fixture for re-cooling, coil safety, and physics studies
- ECRH for high-temperature, high-beta plasmas

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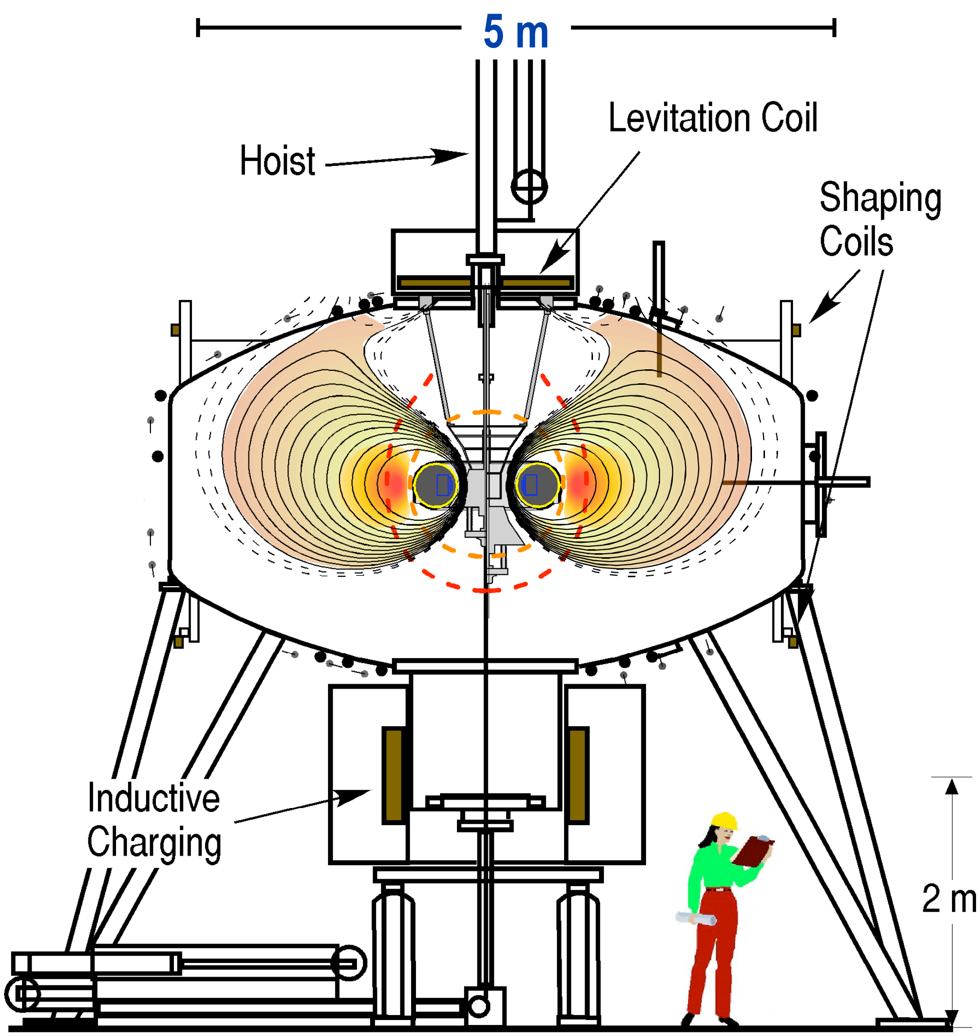
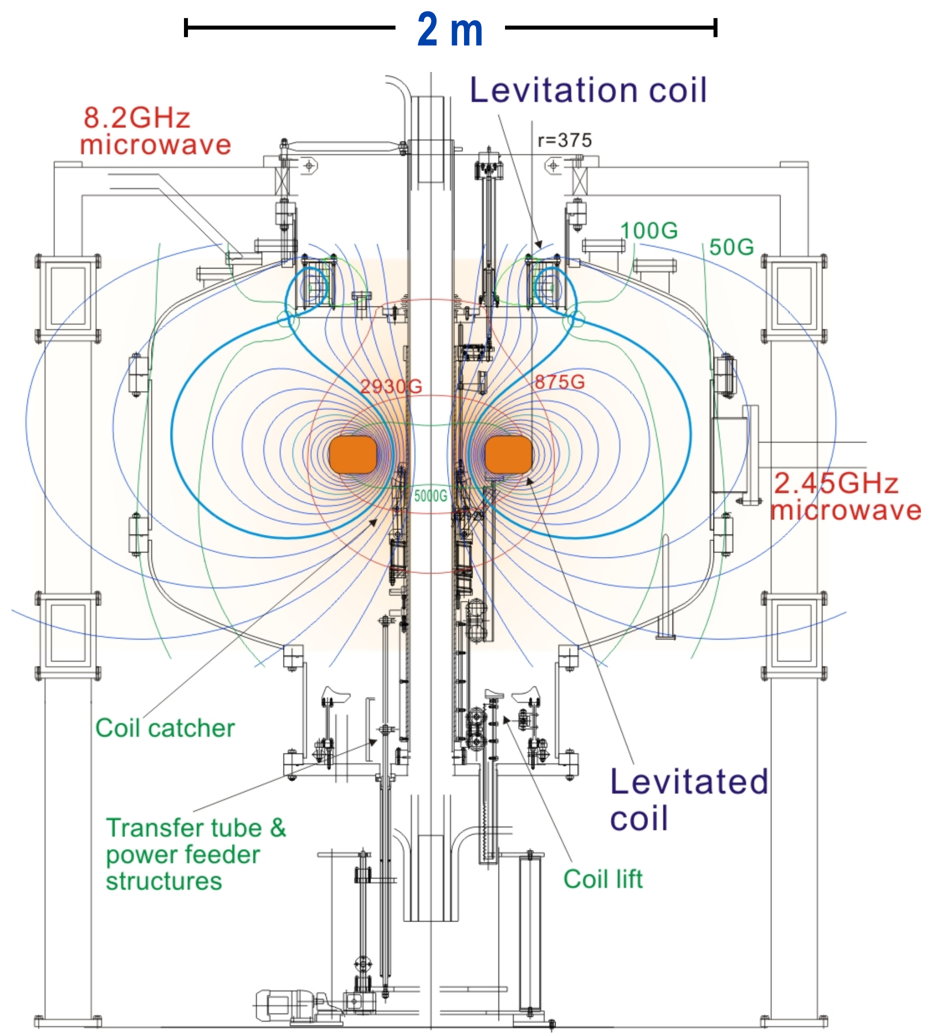


RT-1 (U. Tokyo - Japan)

HTS Bi-2223 Dipole 0.25 MA
Electrically Charged w/SC Switch
6 Hour Float Time 45 kW CW ECRH



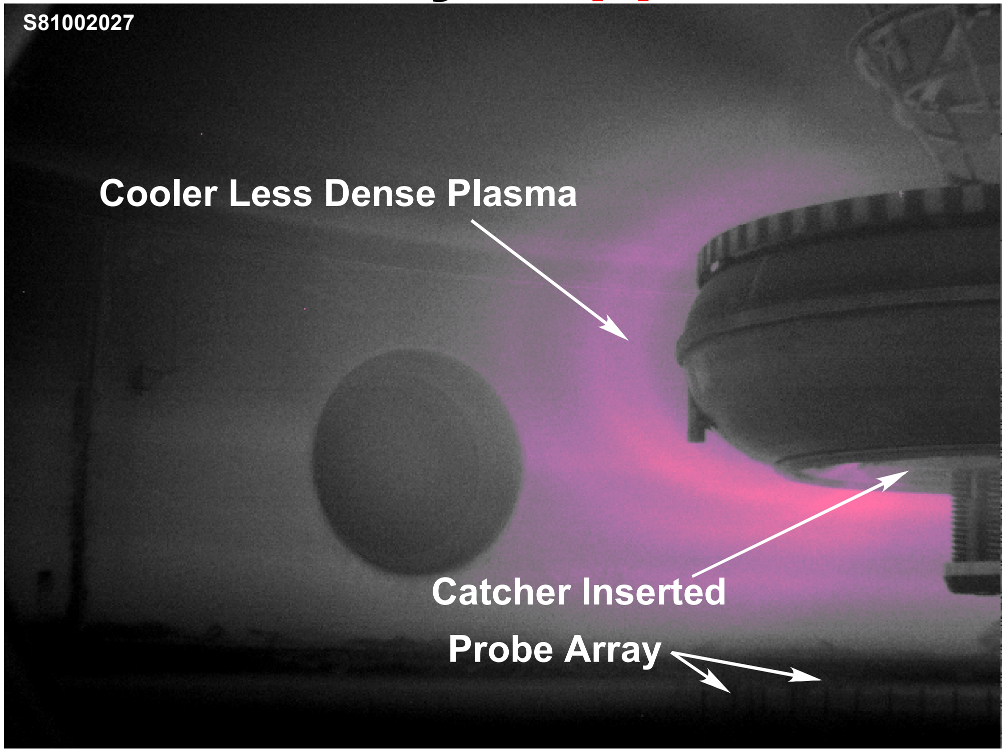
Levitated dipoles reproduce magnetospheric observations

- ECRH generates very high-beta plasmas consisting of centrally-peaked well-confined energetic electrons and warm collisional plasma…
  - Peak local beta observed ~ 50% (RT-1 reaches 70%)
  - Global energy confinement times up to 60 ms. LDX show levitated plasmas contain 40-70% of stored energy in collisional plasma.

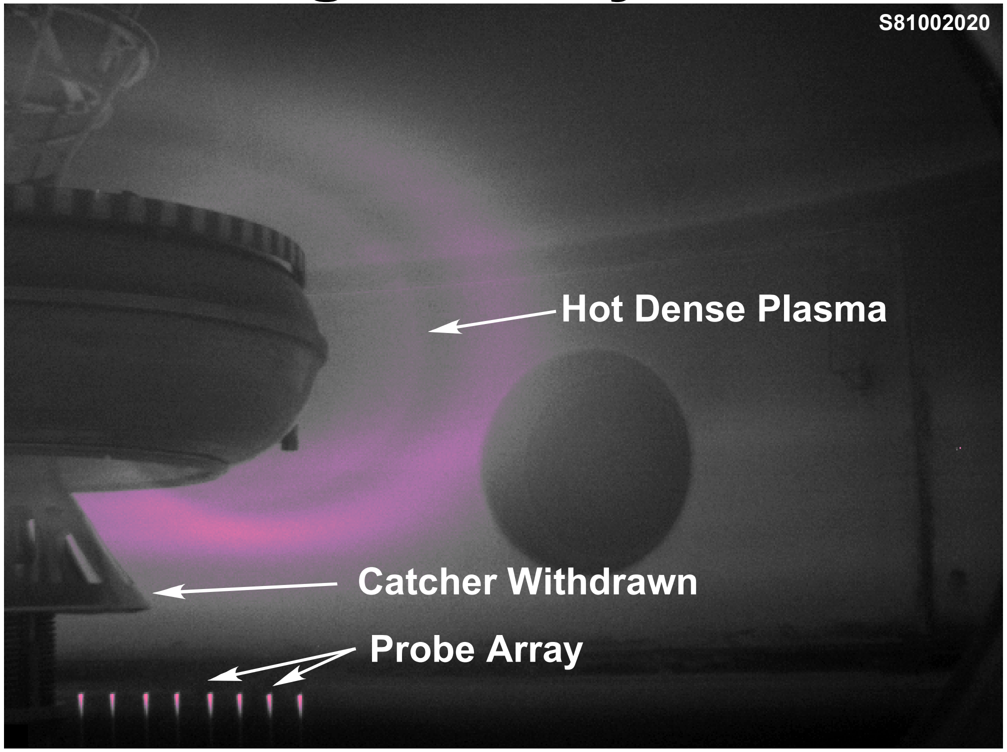
- Plasma density profiles are centrally peaked caused by a strong inward turbulent particle pinch…
  - Near invariant density profiles measured with multi-chord interferometer
  - Rate of inward pinch (~ 25 ms) observed in LDX to be consistent with fluctuations measurements

Supported vs. Levitated

Mechanically Supported



Magnetically Levitated

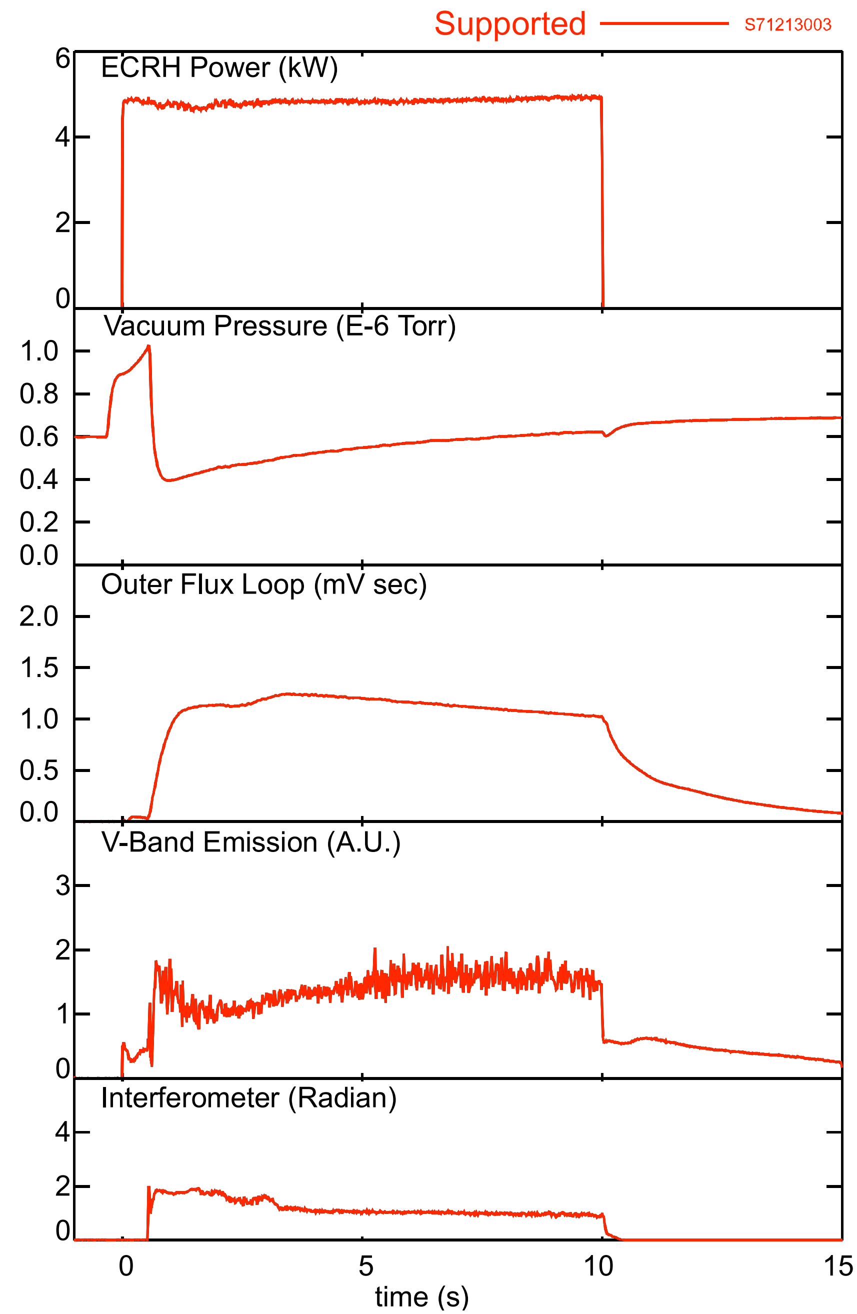


- Removing catcher eliminates losses to supports
  - Source region moves outward, edge probes see plasma losses
- Radial transport determines profiles for levitated plasmas

Plasma Confined by a Supported Dipole

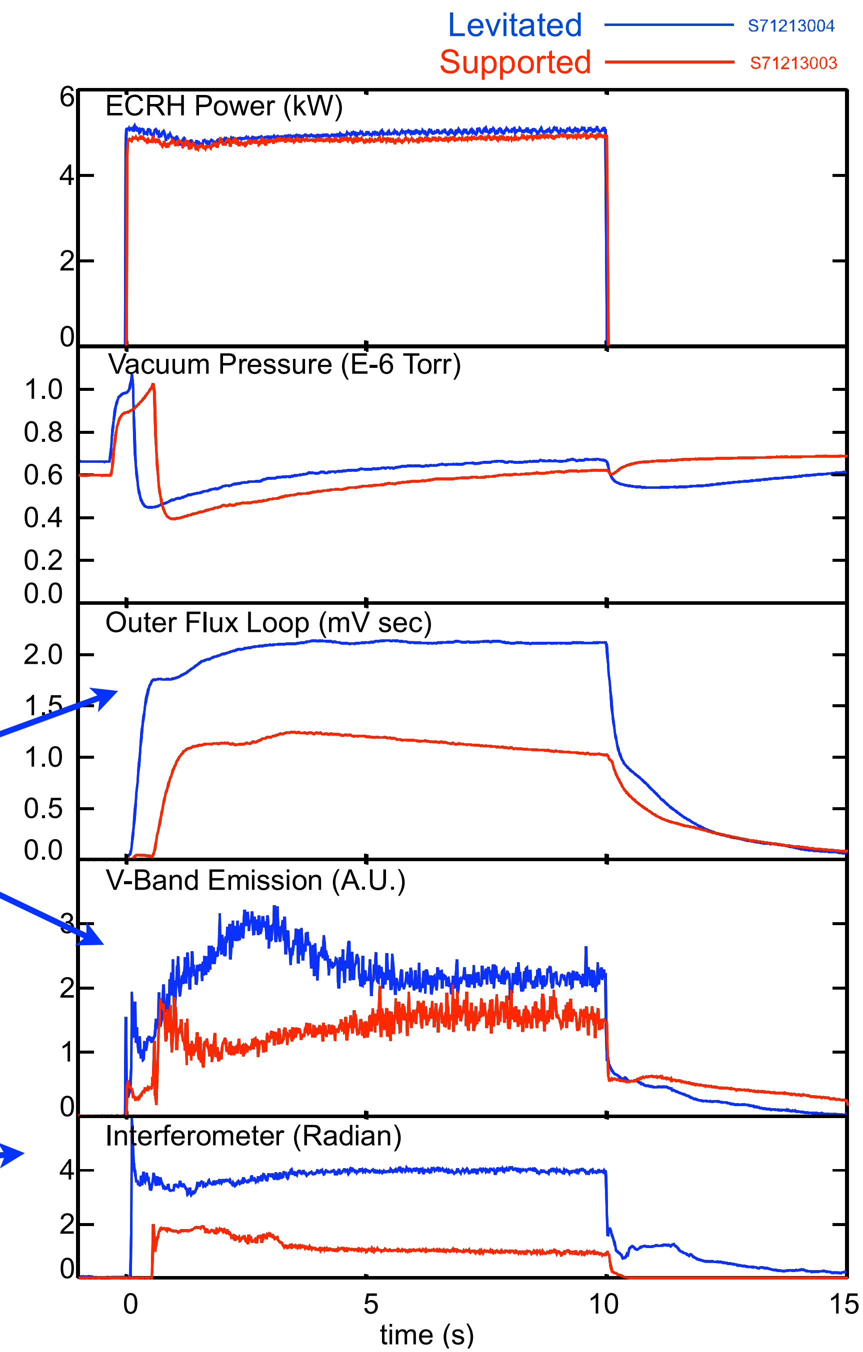
- 5 kW ECRH power
- Ip ~ 1.3 kA or 150 J

- Cyclotron emission (V-band) shows fast-electrons
- Long, low-density "afterglow" with fast electrons



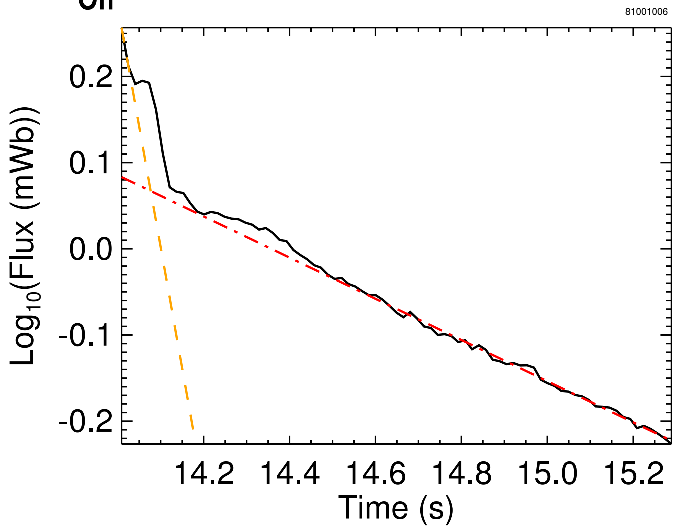
Plasma Confined by a **Levitated** Dipole

- **Reduced fast electron instability**
- **2-3 x Diamagnetic flux**
- **Increased ratio of diamagnetism-to-cyclotron emission indicates higher thermal pressure.**
- **Long, higher-density "afterglow" shows improved confinement.**
- **3-5 x line density**

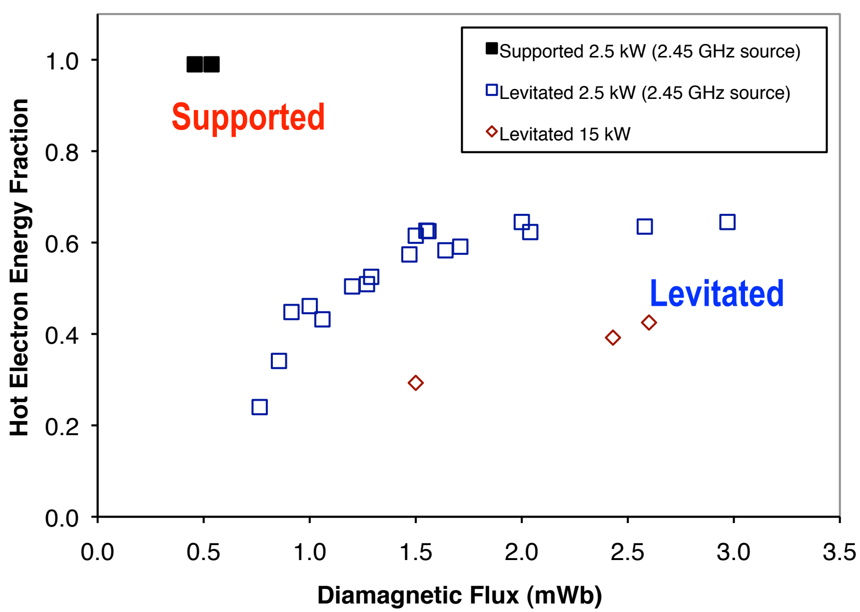


Energy confinement time and β values

Flux Decay of “Ring Current” with ECRH Off

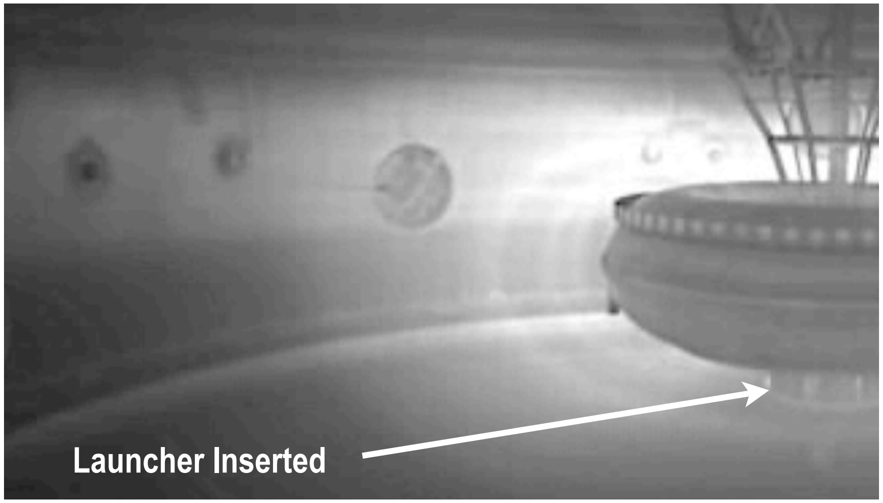


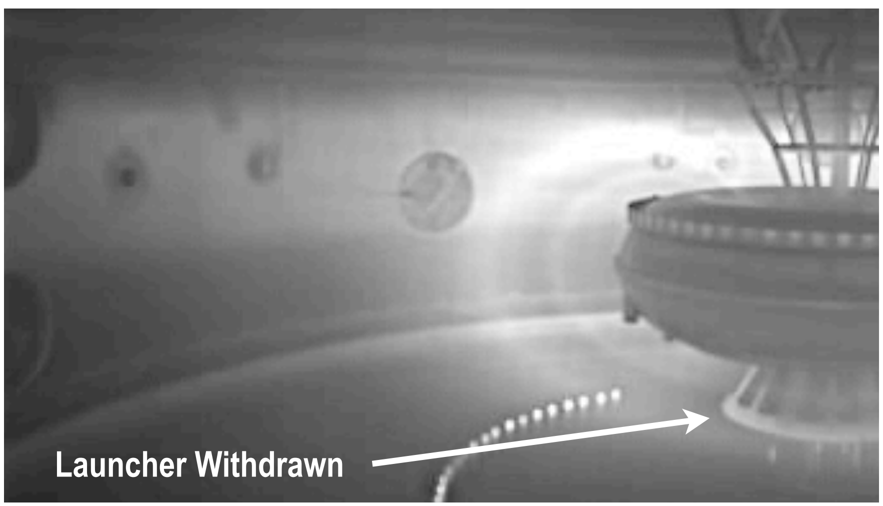
Hot Electron Fraction on LDX

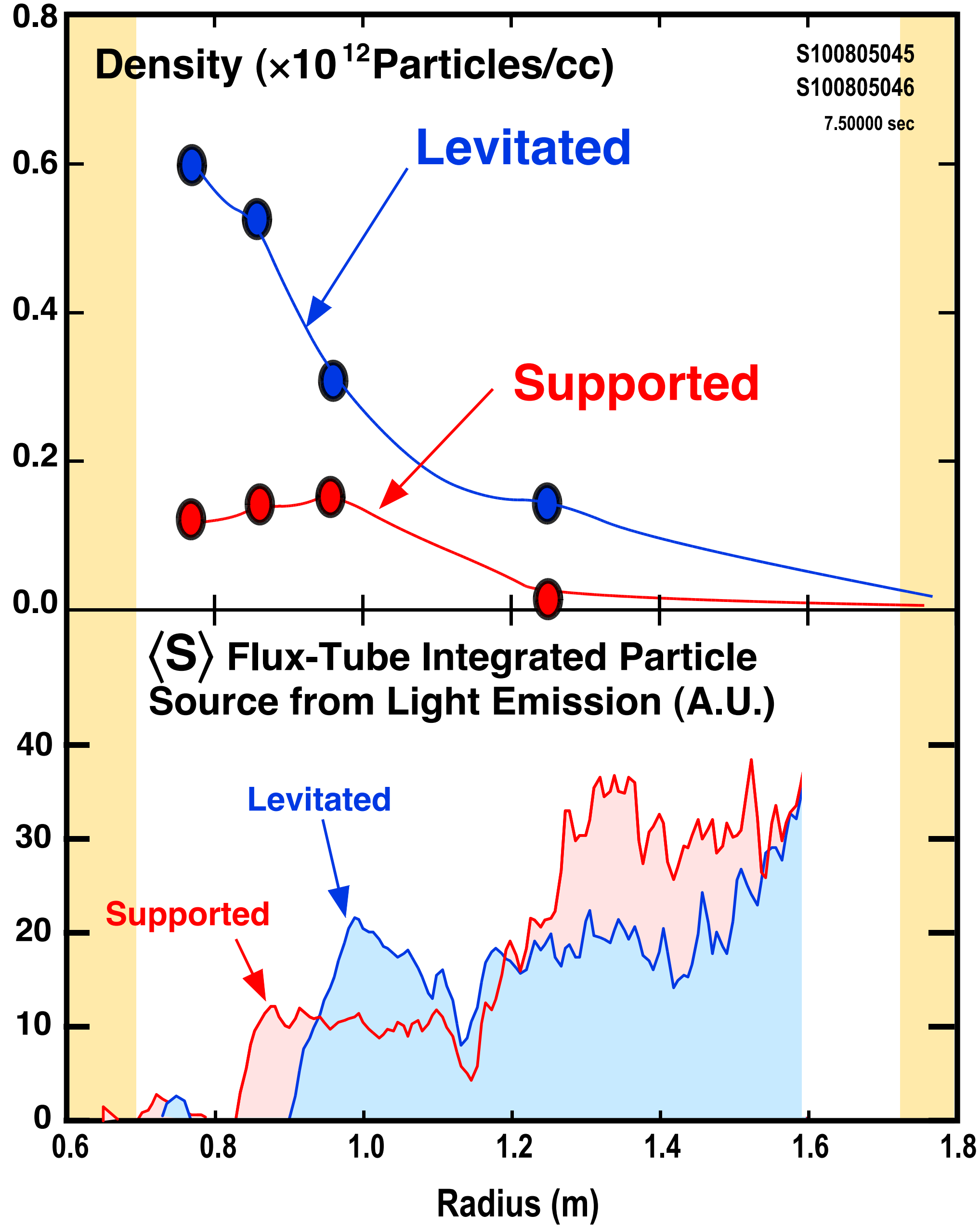


- Plasma pressure profile measured with magnetic reconstruction
  - Peak plasma beta ~ 50%
- Energy confinement time estimated from from stored energy and injected RF power
  - τ_E magnetics ~ 60 ms.
    - τ_E is shorter than that estimated from diamagnetic decay time of thermal component ~ 150 ms.
- Ratio of fast to slow decay gives estimate of bulk plasma energy content
  - 40-70% stored energy in bulk plasma

Plasma particle pinch illuminated by levitation

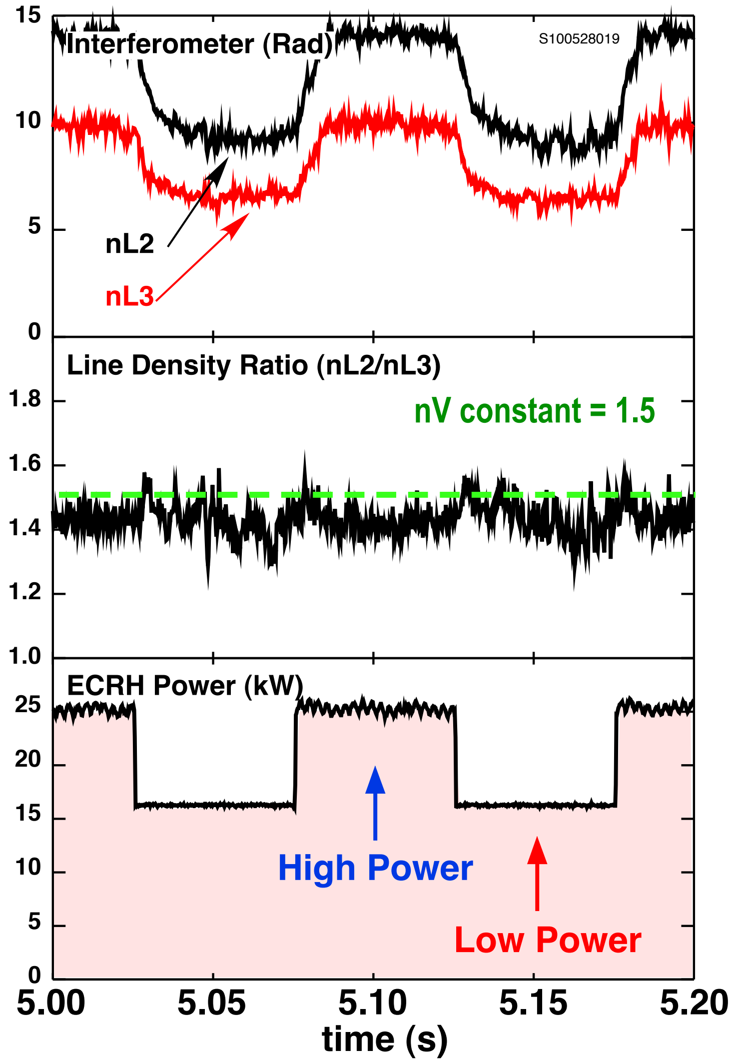


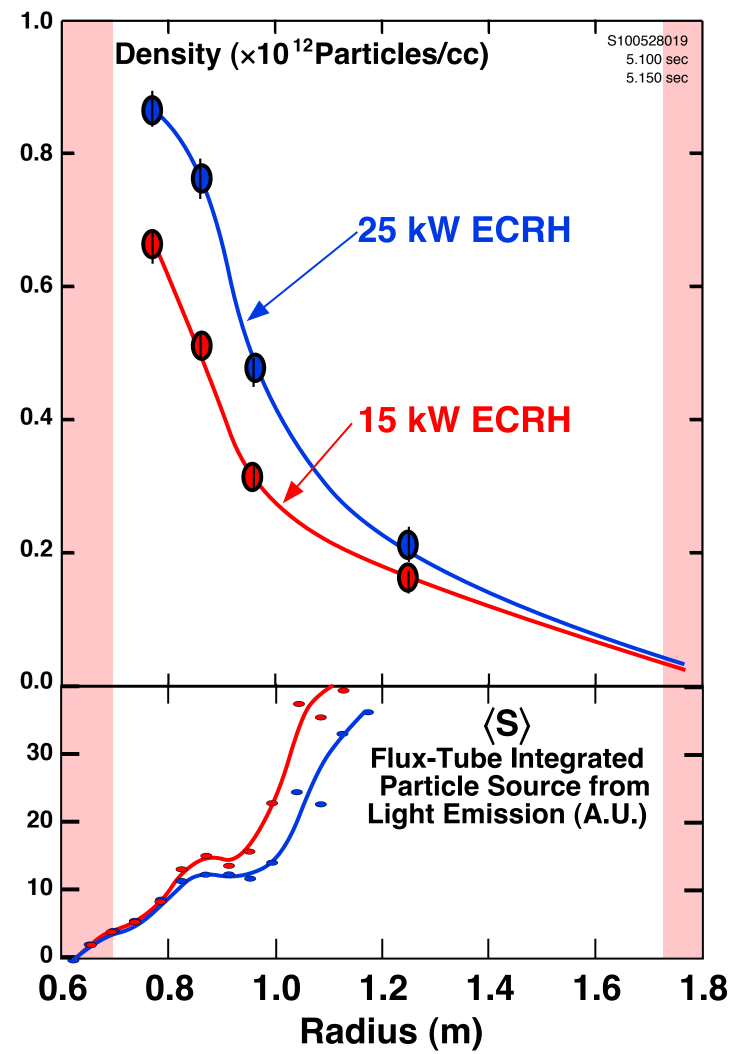




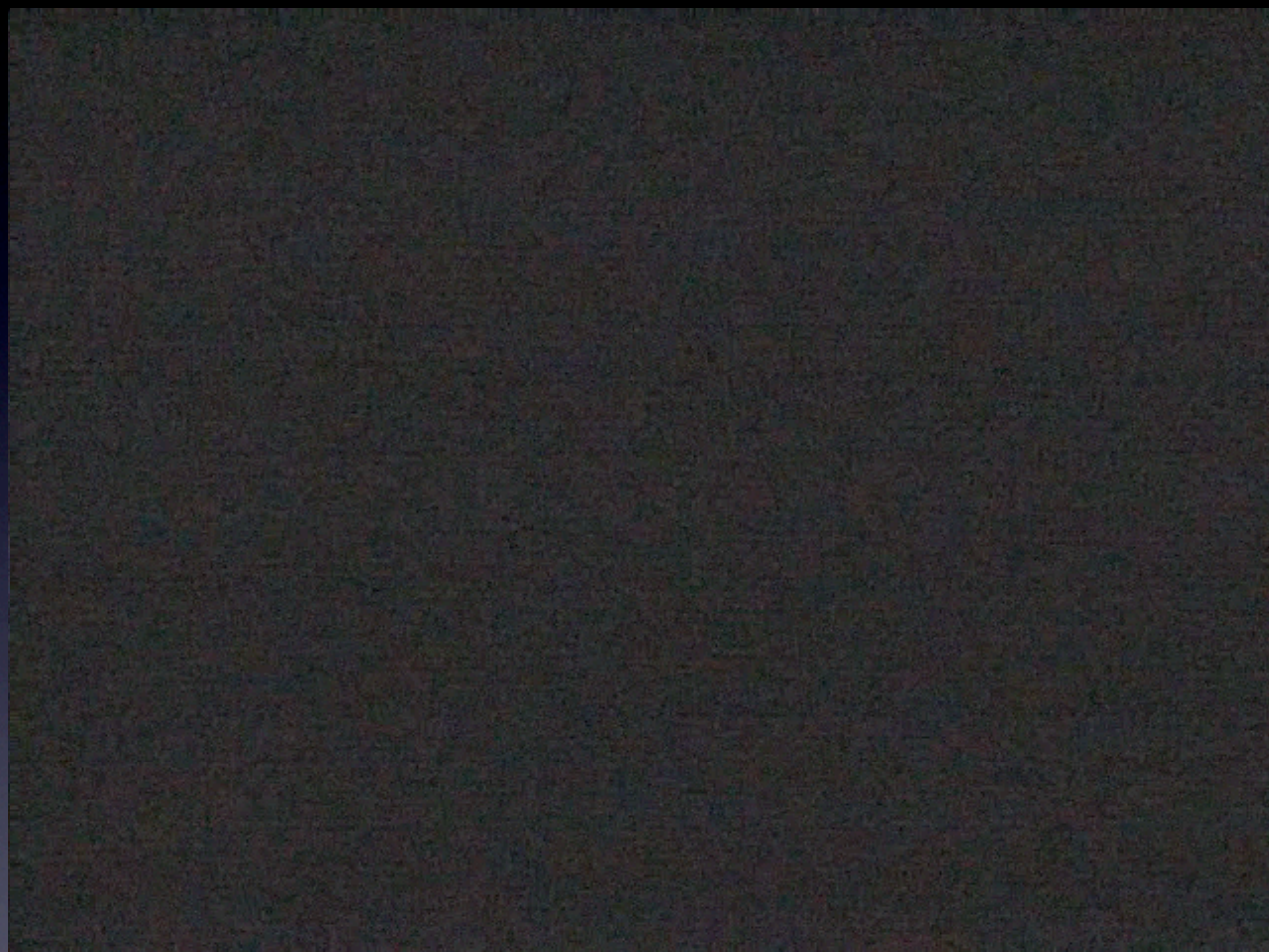
Heating modulation demonstrates robust inward pinch towards invariant profile

- 10 Hz 10 kW (10.5 GHz) ECH modulation
  - Density modulation follows power: profile shape remains unchanged near nV=constant
  - Source moves radially outward, requiring pinch to create increased central density



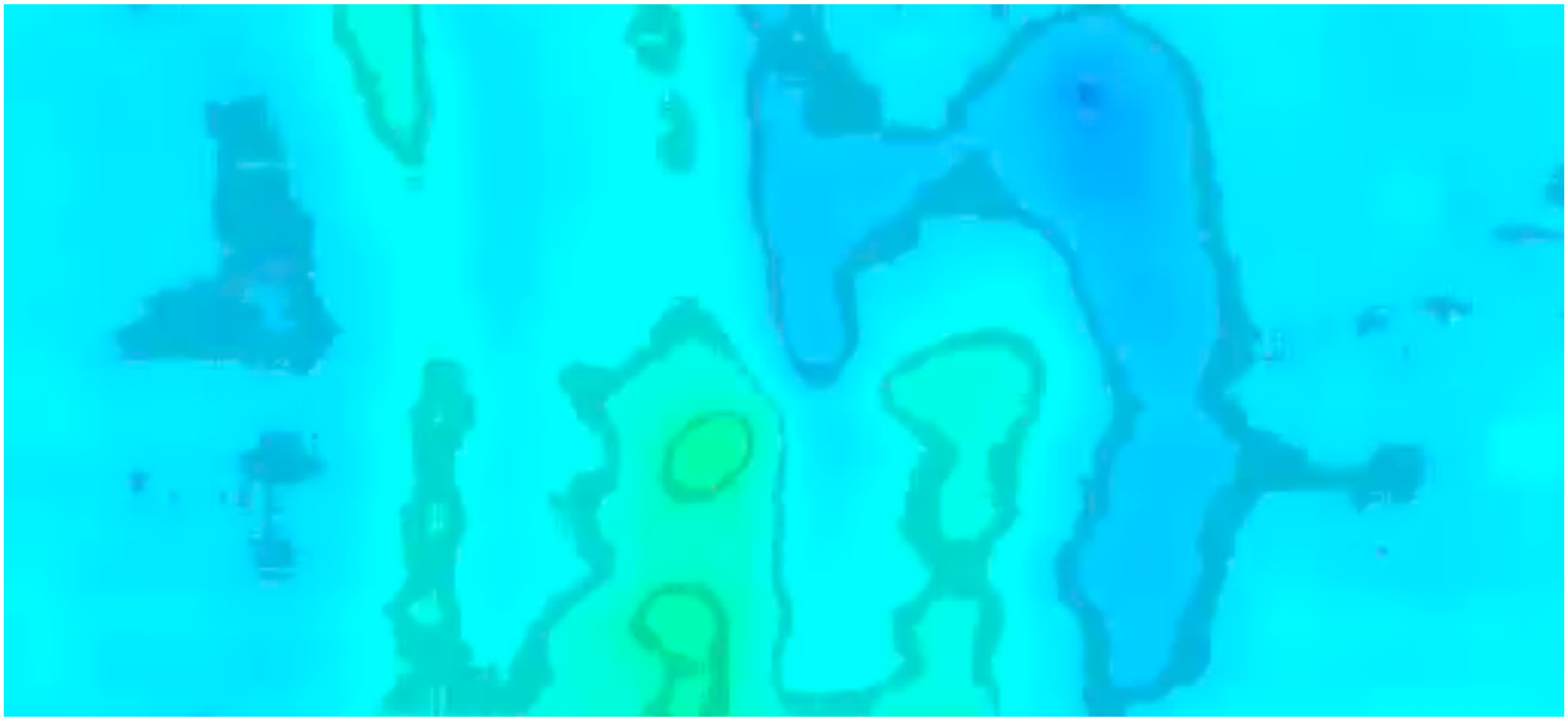


Dipole plasmas are dominated by low frequency turbulence



Top-view visible fast camera fluctuations

- Low coherence large structures observed



ϕ

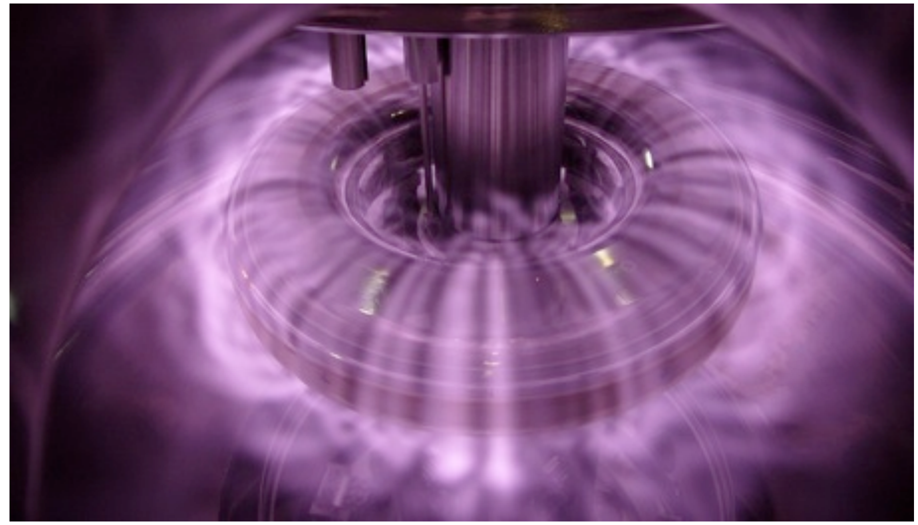
coil

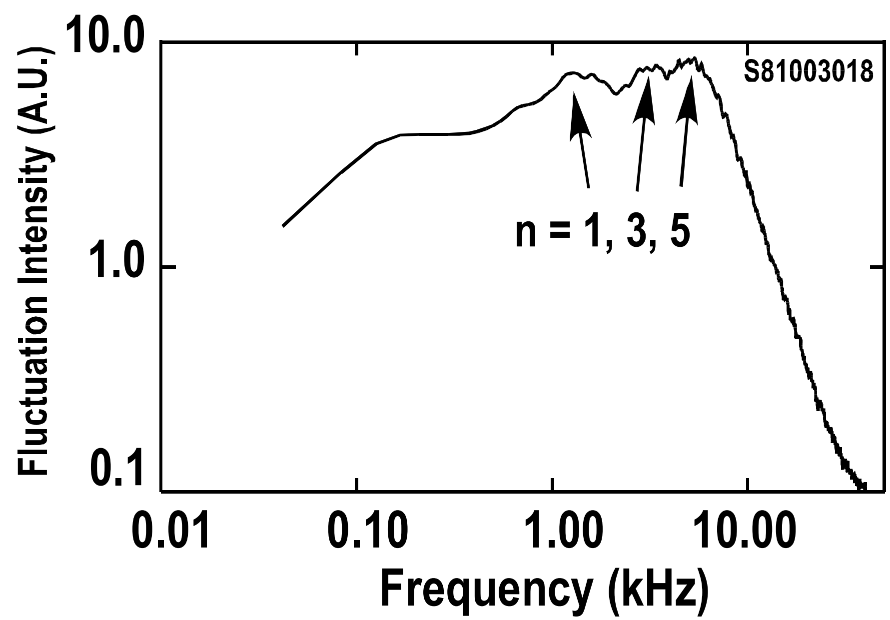
r

Character of low frequency turbulence

- Observed turbulence in magnetospheric dipole experiments are:
  - Interchange like
  - Low frequency (0.1-10 kHz)
    - near zero in plasma frame
  - Broad k spectrum
    - peaked at lower modes
    - often with quasi-coherent low order modes
  - Bursty
    - distinctly non-gaussian PDFs
  - Exhibit inverse cascade of power from high frequency to low
    - Grierson, et al. PoP 2009

- RT-1 low frequency density fluctuations

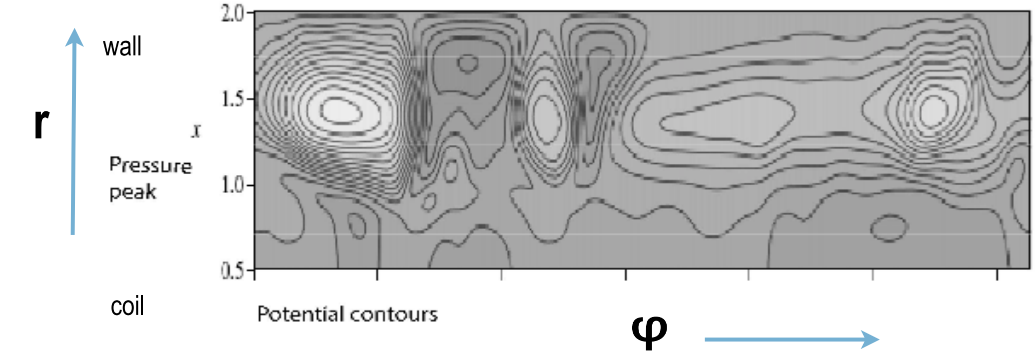




Observed turbulence consistent with simulations

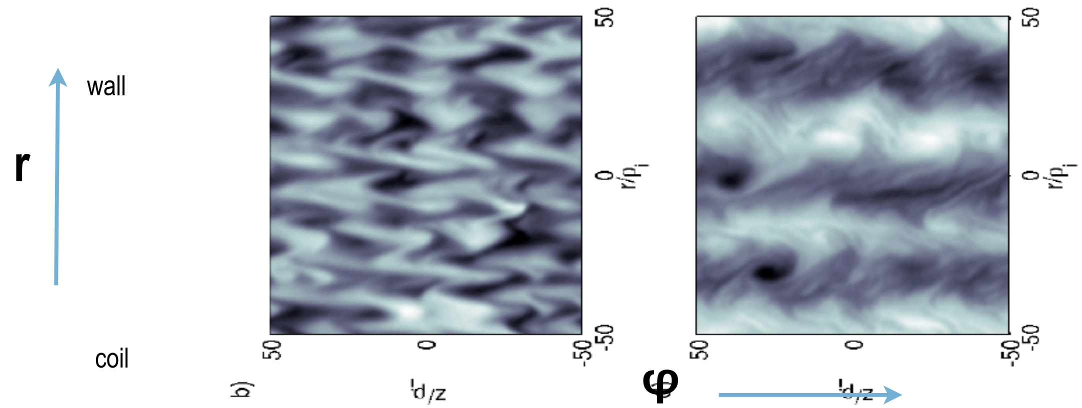
- Non-linear evolution of MHD interchange instabilities lead to large scale convective cells
- Gyrokinetic studies of entropy mode also show broad spectrum
  - $k_{\perp} \rho_s < 1$

Reduced MHD Interchange



Pastukhov, Chudin, Pl Physics 27 (2001) 907.

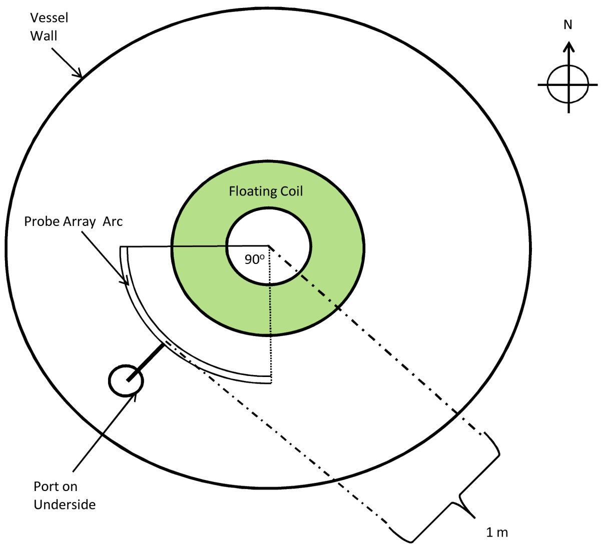
GS2 Drift Mode (entropy mode)

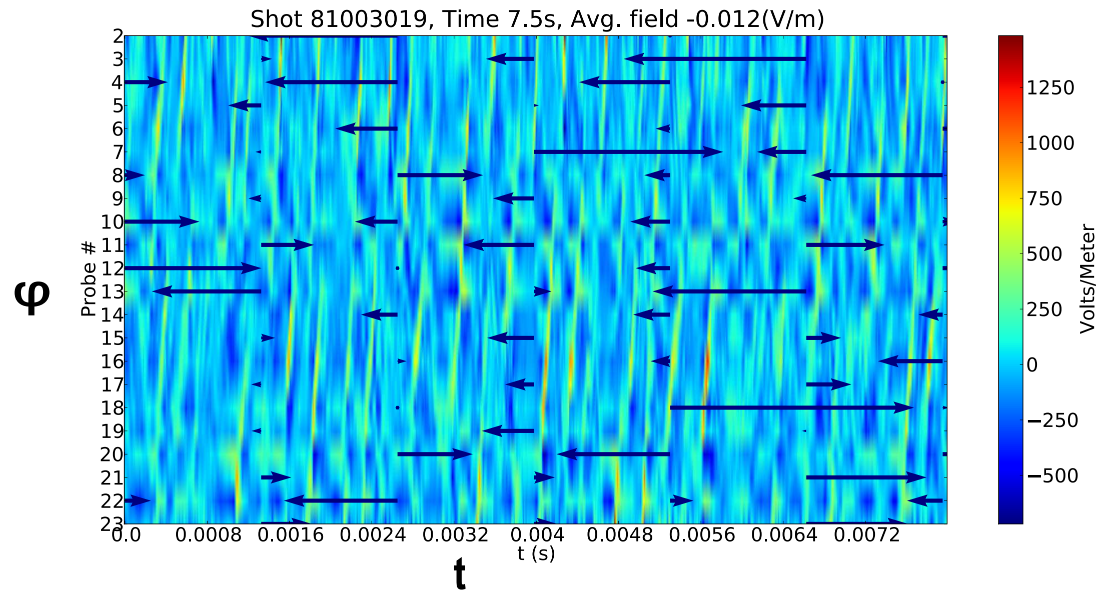


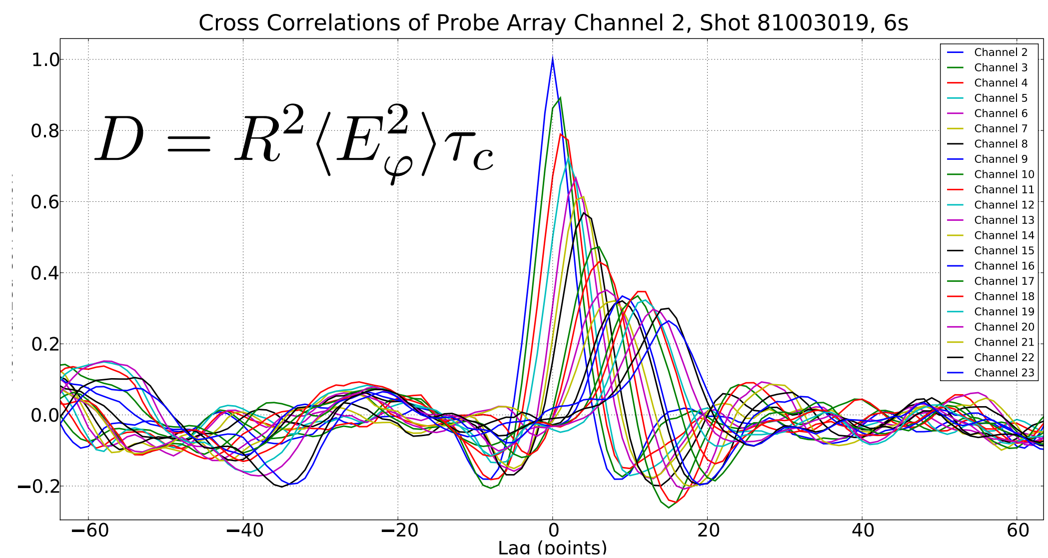
Ricci, Rogers, Dorland, PRL 97, 245001 (2006).

PIC: Tonge, Leboeuf, Huang, Dawson, 10 PoP. (2003) 3475.
Quasilinear MHD: Kuznetzov, Friedberg, Kesner PoP 2008

Edge probes used to estimate diffusion operator







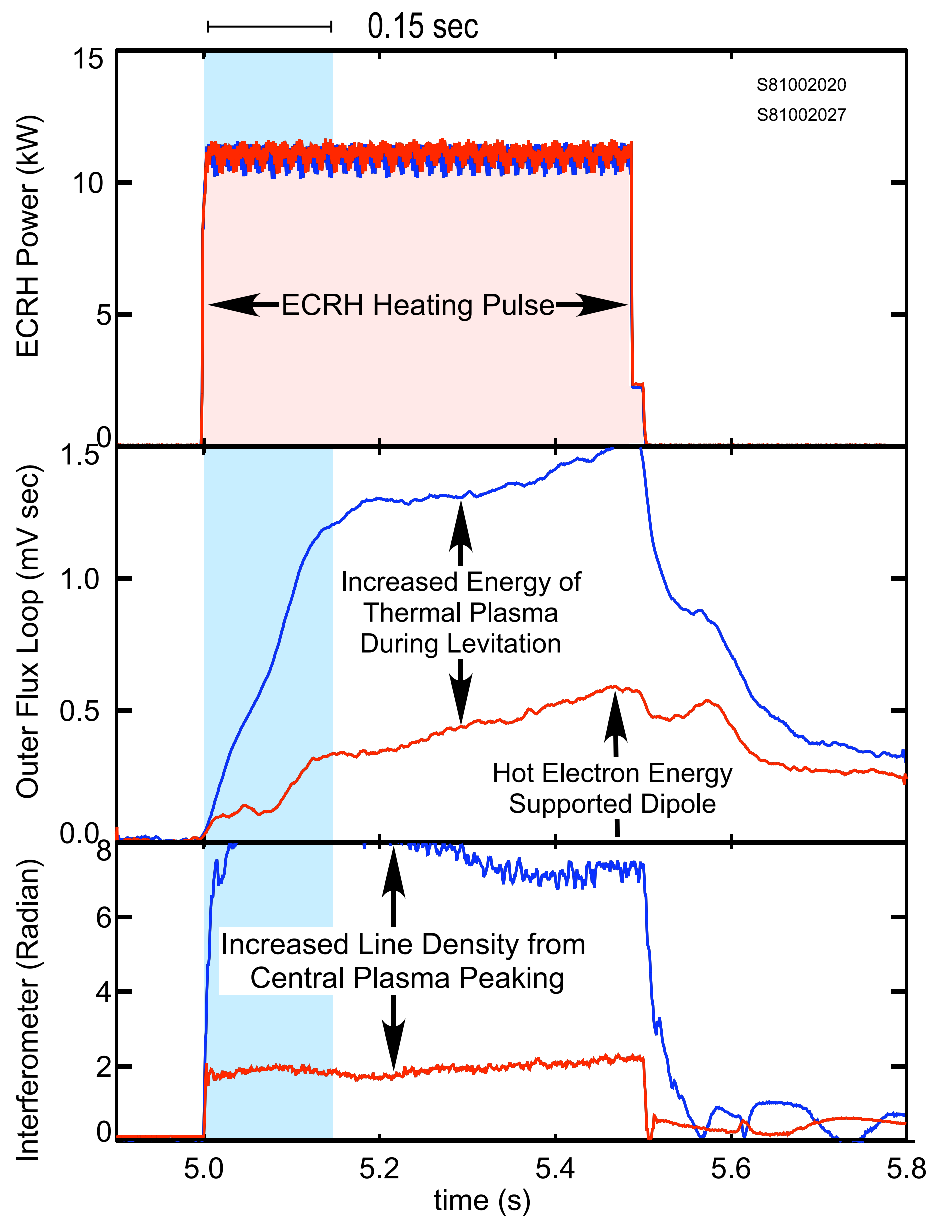
$$D = R^2 \langle E_\varphi^2 \rangle \tau_c$$

- **Instantaneous ExB radial flow of 35 km/s**

$$\frac{\partial(nV)}{\partial t} = \frac{\partial}{\partial \psi} D^{\psi\psi} \frac{\partial(nV)}{\partial \psi} + \langle S \rangle$$

Thermal Plasma Profiles Established Quickly

- With a levitated dipole, thermal plasma profiles are established quickly, well before energetic electrons.
- Within 0.15 sec, thermal plasma energy reaches 100 J.
- Density profile is established in the first 20 msec.
- Turbulence is responsible for inward particle pinch with centrally-peeked density profiles

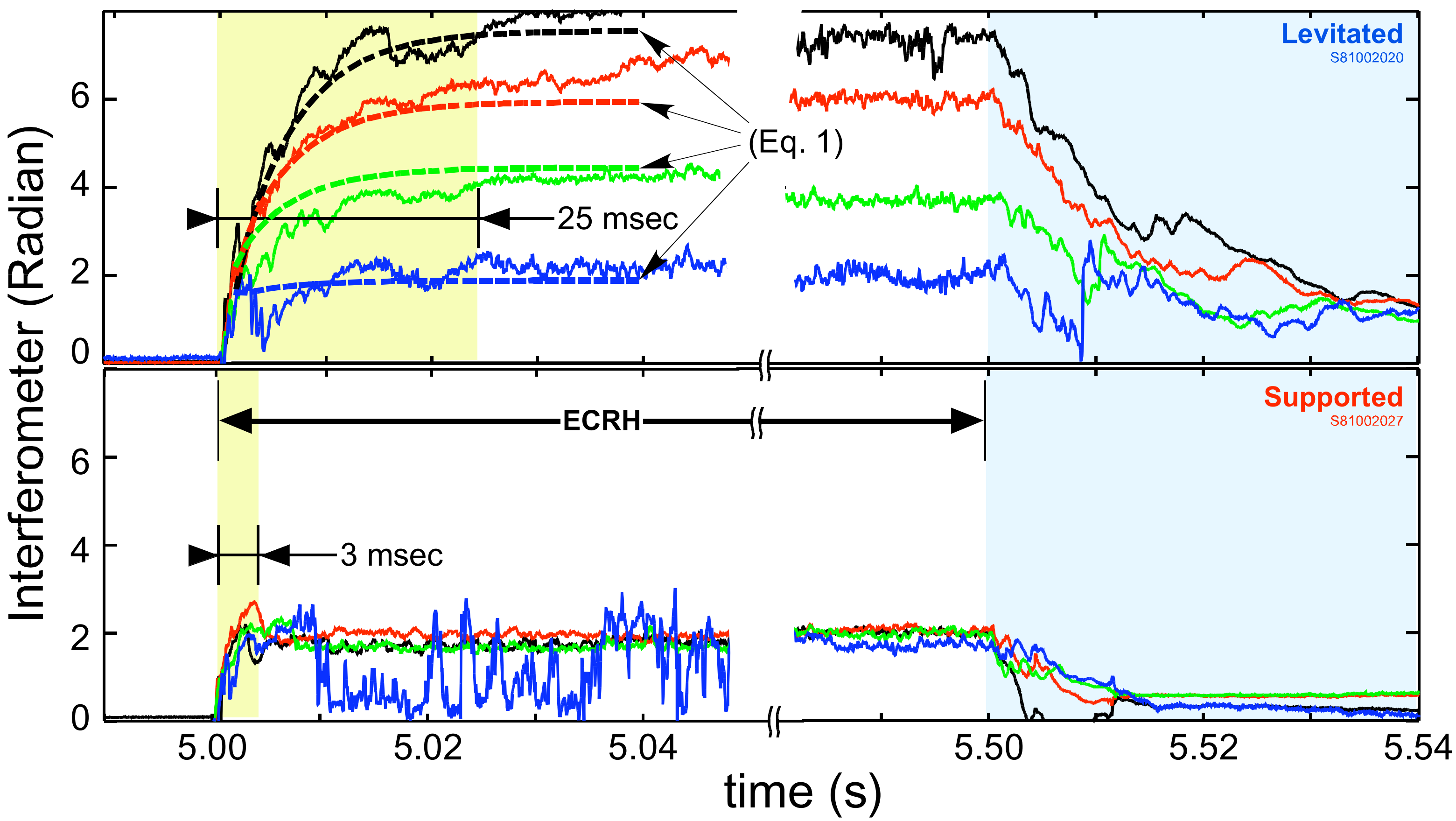


Boxer, *Nature-Physics* (2010)

Measured low frequency fluctuation intensity and spectrum reproduces observed turbulent pinch

$$\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi} \,, \qquad (1)$$

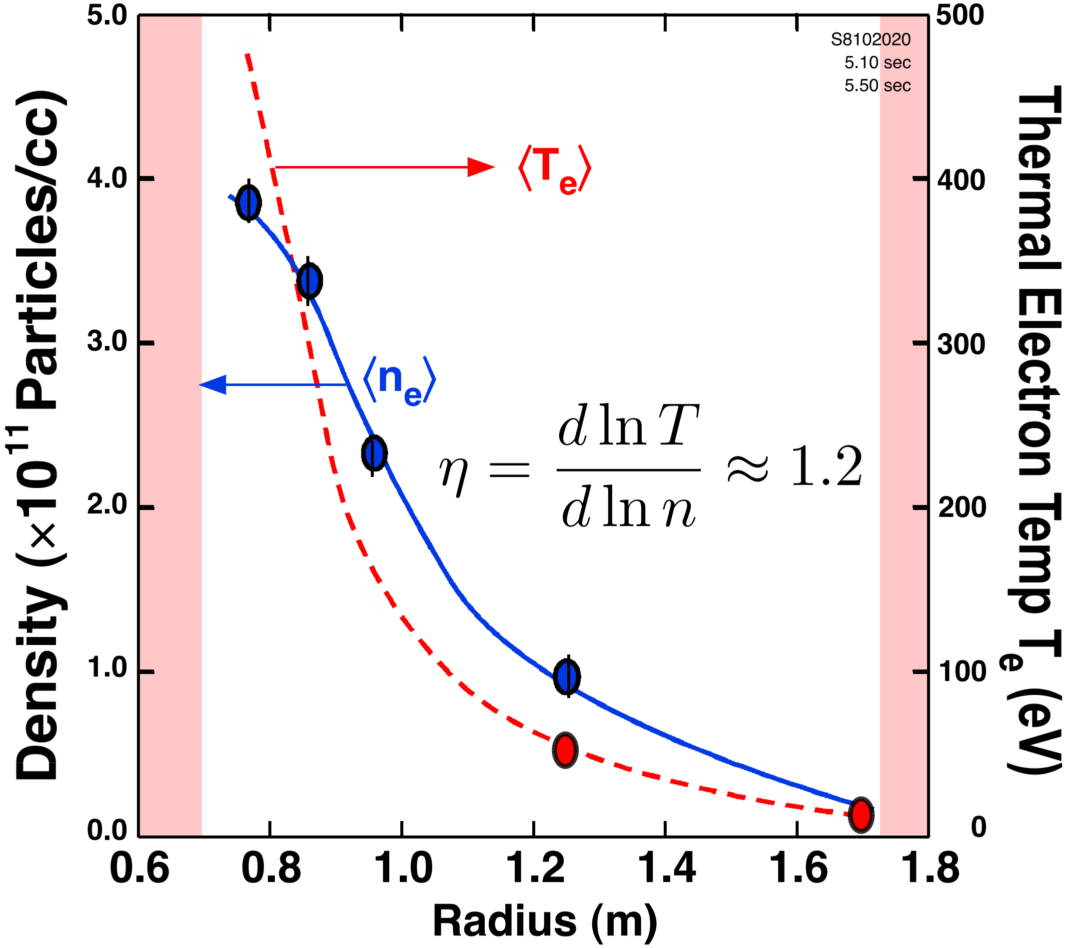
where $\langle S \rangle$ is the net particle source within the flux-tube, and the diffusion coefficient is $D = R^2 \langle E_\varphi^2 \rangle \tau_{cor}$ in units of $(\mathrm{V} \cdot \mathrm{sec})^2/\mathrm{sec}$.



Turbulent Pinch Maintains Centrally-Peaked Temperature

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

- **Within 0.15 sec, thermal plasma energy reaches 100 J with 11 kW of ECRH.**
- **With measured edge temperature (14 eV), measured density profile, and measured thermal stored energy…**
- **Stationary pressure and temperature profiles characterize the inward particle pinch**



Boxer, *Nature-Physics* (2010)

Turbulence drives plasma to very steep profiles and creates strong inward particle pinch in dipole geometry

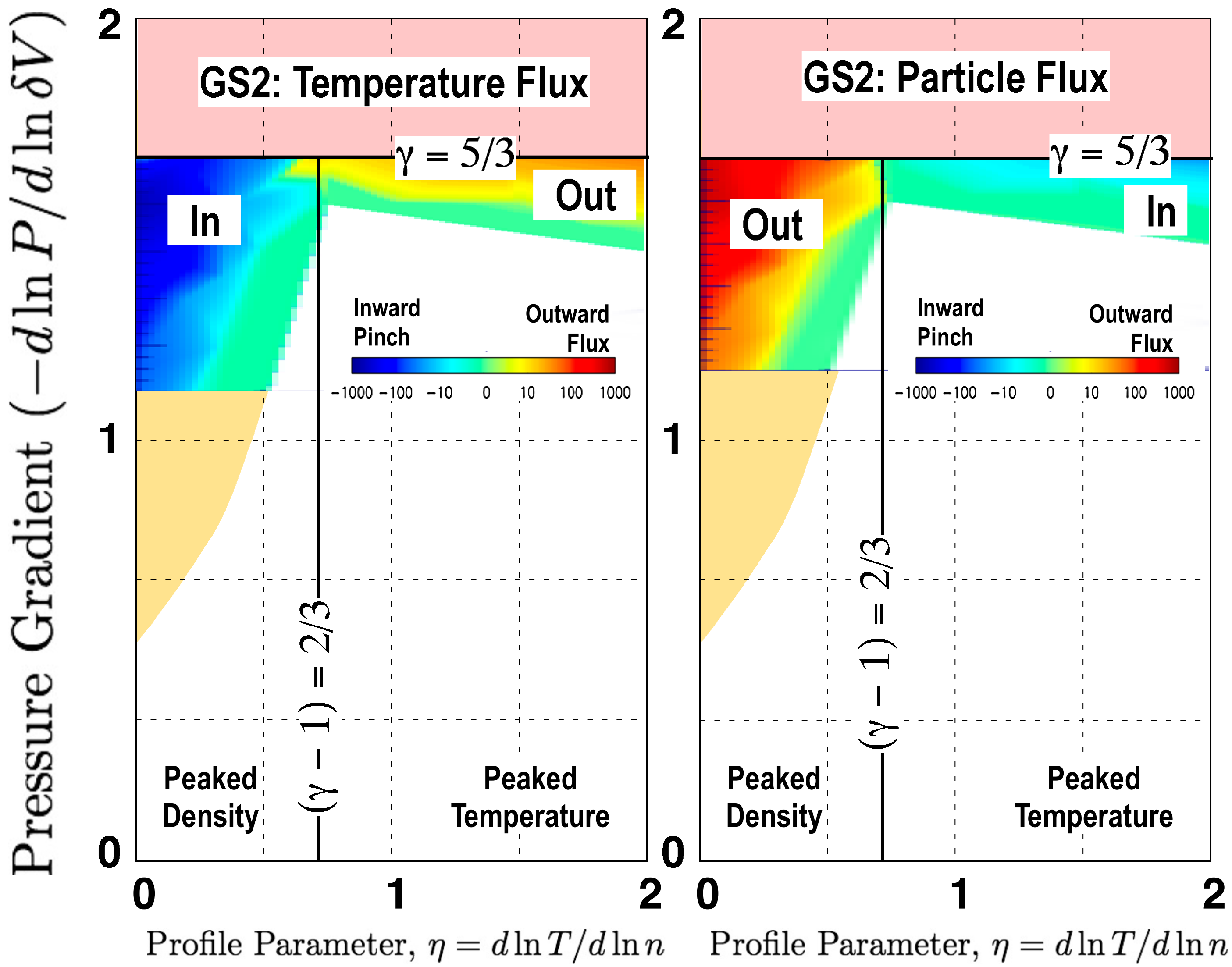
Gyrokinetic (GS2) simulations show turbulence drives particles or heat to maintain uniform entropy density:

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

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

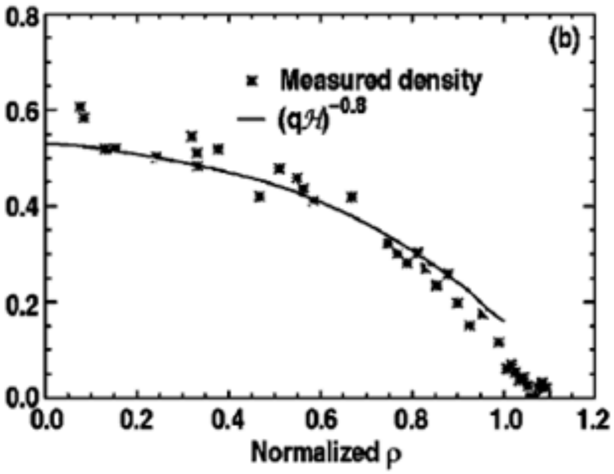
$$-\frac{d\ln n}{d\ln \delta V} \rightarrow 1$$

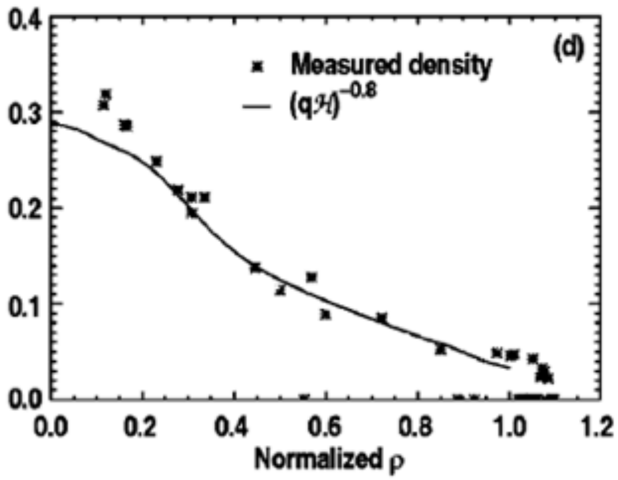
$$-\frac{d\ln P}{d\ln \delta V} \rightarrow \frac{5}{3}$$



Tokamaks (with magnetic shear): n ~ V ~ 1/q

- Baker and Rosenbluth (1998), Baker (2002)
- DIII-D L-mode density profiles





Lagrangian Transport Description with Preserved Adiabatic Invariants leads to profiles with equal number of particles per flux tube

$$\frac{\partial f_{\mathrm{M}}}{\partial t} = \frac{\partial}{\partial \psi}\left(D^{\psi\psi} \frac{\partial f_{\mathrm{M}}}{\partial \psi} \right),$$

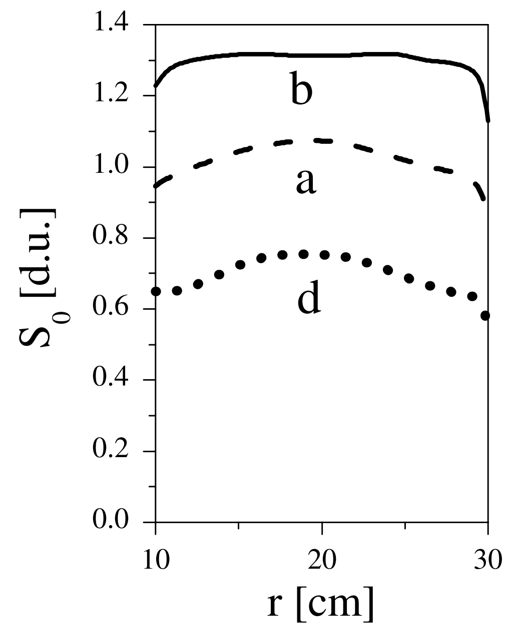
$$\Gamma = -D^{\psi\psi} \int d\mu \, dJ \left. \frac{\partial f_{\mathrm{M}}}{\partial \psi} \right|_{J,\mu}$$

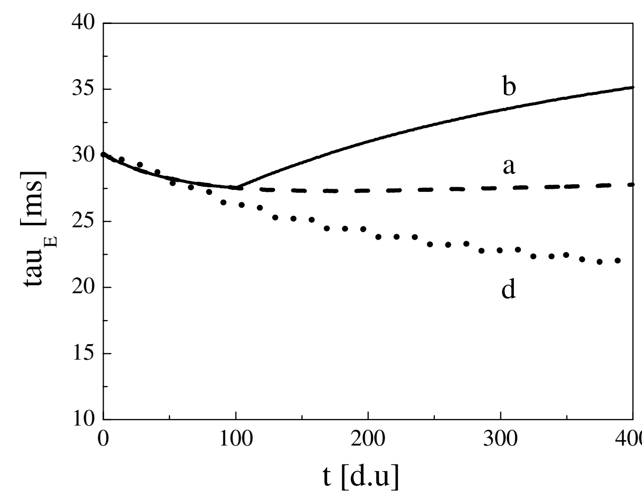
$$\frac{1}{n}\frac{\partial n}{\partial \rho} \approx \xi \left\{ q\mathcal{H} \frac{\partial}{\partial \rho} \frac{1}{q\mathcal{H}} \right\},$$

$$\text{or} \quad n(\rho) \propto (q\mathcal{H})^{-\xi}$$

Controlling pV^γ profile improves energy confinement

- Pastukhov and Chudin
  - Reduced MHD simulation of tokamak turbulence
- Improvement in confinement due to control of entropy profile
  - Case b has $S = pV^\gamma$ flat
- Consistent with experimental result of off-axis ECH heating experiments on T-10 and ASDEX





Pastukhov *et al*. Plasma Phys. Control. Fusion **53** (2011) 054015

Summary

- **The magnetospheric levitated dipole bridges space and laboratory magnetic confinement**
  - Large flux expansion allows steep profiles to be formed with turbulent transport
- **Superconducting levitated dipoles achieve stable, high-beta, well-confined, plasmas**
  - Error field corrected, optimized RT-1 plasmas show peak local ~ 70%.
  - Global energy confinement time ~ 60 ms. LDX shows 40-70% of stored energy in "warm" collisional electron population
- **"Natural" invariant density profiles self-generate in a laboratory dipole confined plasmas**
  - LDX and RT-1 demonstrate peak profiles near nV = constant, driven by low-frequency fluctuations
  - Stored energy is consistent with expectations, demonstrating good confinement and "stationary" profiles in LDX

The Levitated Dipole Experiment (LDX)