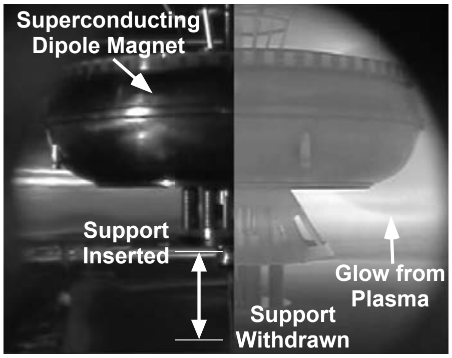
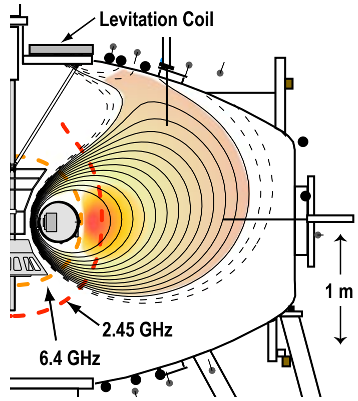



# Inward Turbulent Diffusion of Plasma in a Levitated Dipole

***LDX Experimental Team***
Ryan Bergman, Alex Boxer, Matt Davis,
Jennifer Ellsworth, Darren Garnier, Jay Kesner,
Mike Mauel, Phil Michael, Paul Woskov

Columbia University



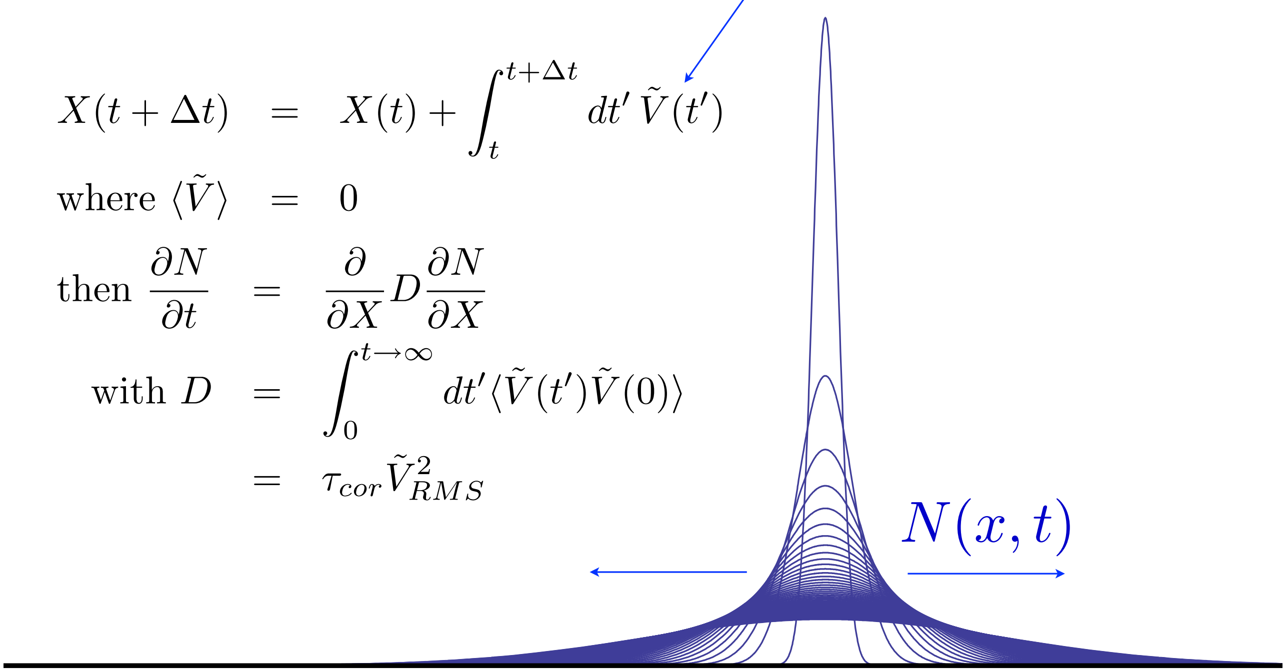
# Diffusion due to Random Velocity Fluctuations

$$X(t+\Delta t) = X(t) + \int_t^{t+\Delta t} dt' \, \tilde{V}(t')$$

$$\text{where } \langle \tilde{V} \rangle = 0$$

$$\text{then } \frac{\partial N}{\partial t} = \frac{\partial}{\partial X} D \frac{\partial N}{\partial X}$$

$$\text{with } D = \int_0^{t \to \infty} dt' \langle \tilde{V}(t') \tilde{V}(0) \rangle = \tau_{cor} \tilde{V}^2_{RMS}$$



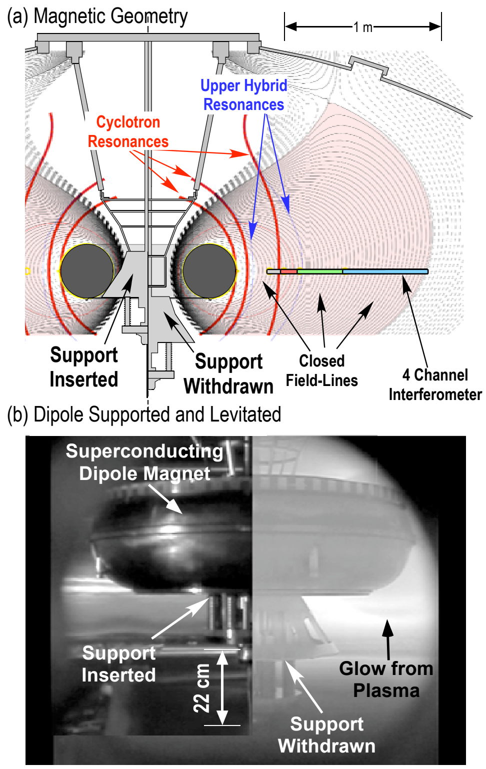
# Shake Sand on Plate



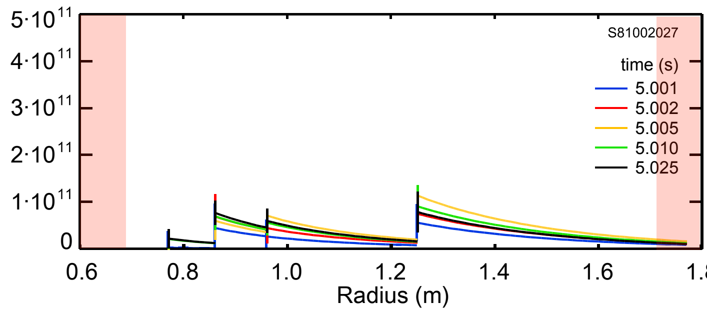
# Dye Stirred in Glass

# "Inward" Diffusion in Magnetized Plasma

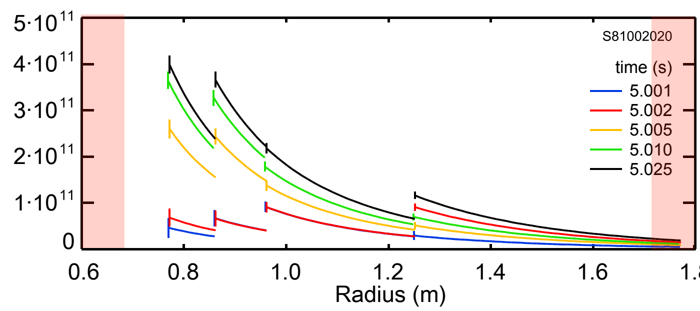
(Flux tube Motion due to Random Low-frequency **E×B** Fluctuations)




Supported: Density (Particles/cc)



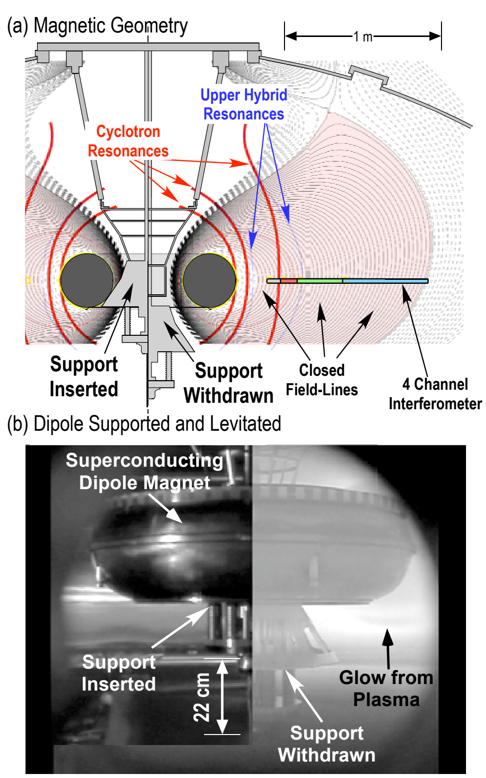

Levitated: Density (Particles/cc)






# "Inward" Diffusion in Magnetized Plasma

(Flux tube Motion due to Random Low-frequency **E×B** Fluctuations)



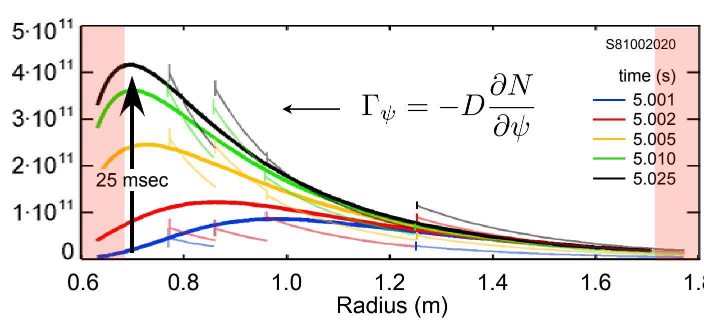

## Turbulent "Inward Pinch"

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi}$$

$$D_{\psi,\psi} = \lim_{t\to\infty} \oint_0^t dt \langle \dot{\psi}(t)\dot{\psi}(0)\rangle$$

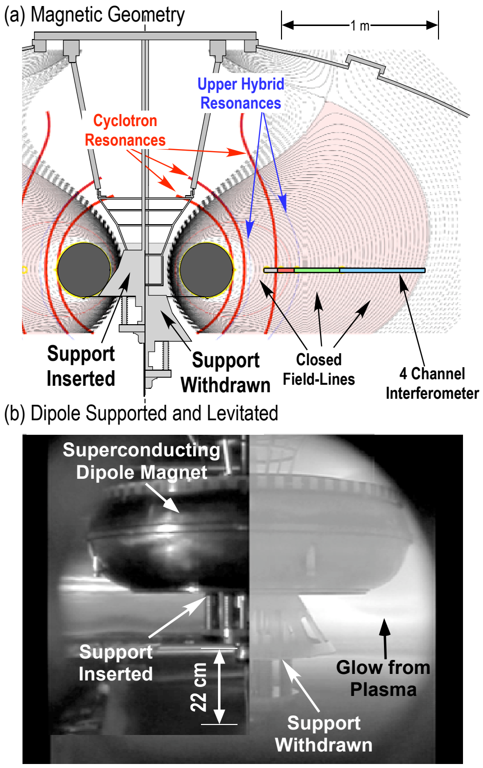
$$\equiv \langle \dot{\psi}^2 \rangle \tau_{cor} = R^2 \langle E_\phi^2 \rangle \tau_{cor}$$

Levitated: Density (Particles/cc)



# “Inward” Diffusion in Magnetized Plasma

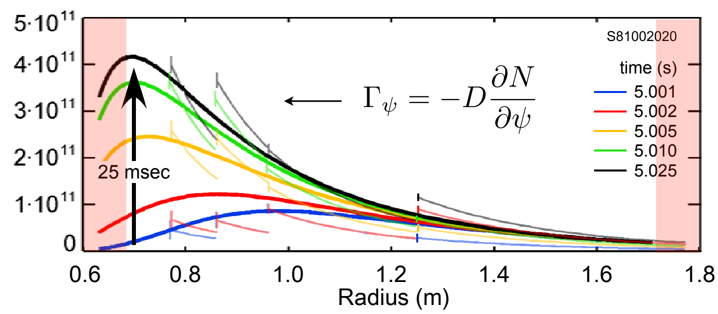
(Flux tube Motion due to Random Low-frequency **E×B** Fluctuations)




## Centrally peaked profiles result from turbulent interchange mixing: **Electrostatic Self-Organization**

Naturally peaked profiles **sustained steady-state** by microwave heating.

Levitated: Density (Particles/cc)






# TFTR

## Density Profile *q*-Scaling

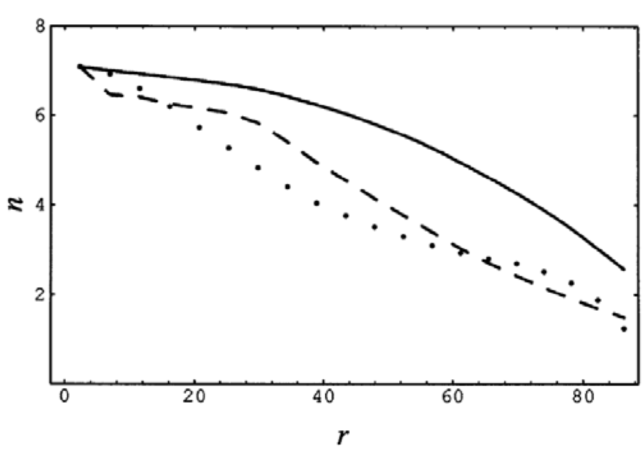



FIG. 1. Density in units of $10^{19}$ m$^{-3}$ as a function of minor radius in cm. The dots are data points from the supershot TFTR-76770, the dashed curve is proportional to $1/q$, and the solid curve is calculated from Eq. (1).

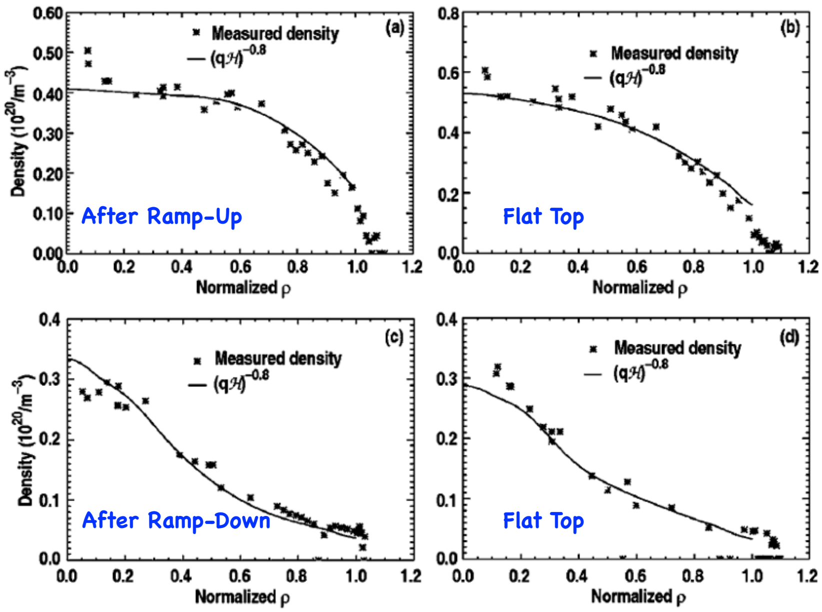
V. Yankov, 1994

- The pinch effect [is the result] of a turbulent **uniform distribution of particles over some phase-space surfaces** specified by the **geometry of the magnetic field** and **by invariants is introduced**.
- Large-scale electrostatic modes lead to a turbulent uniform distribution $nq = const$ with a maximum particle density at the center of the column.
- Leading to a natural explanation of the self-consistency of profiles.

# DIII-D: Ip Ramps (L-Mode)

(Dan Baker, 2002)

Lagrangian Transport Description with Preserved Adiabatic Invariants




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

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

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

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



# Outline

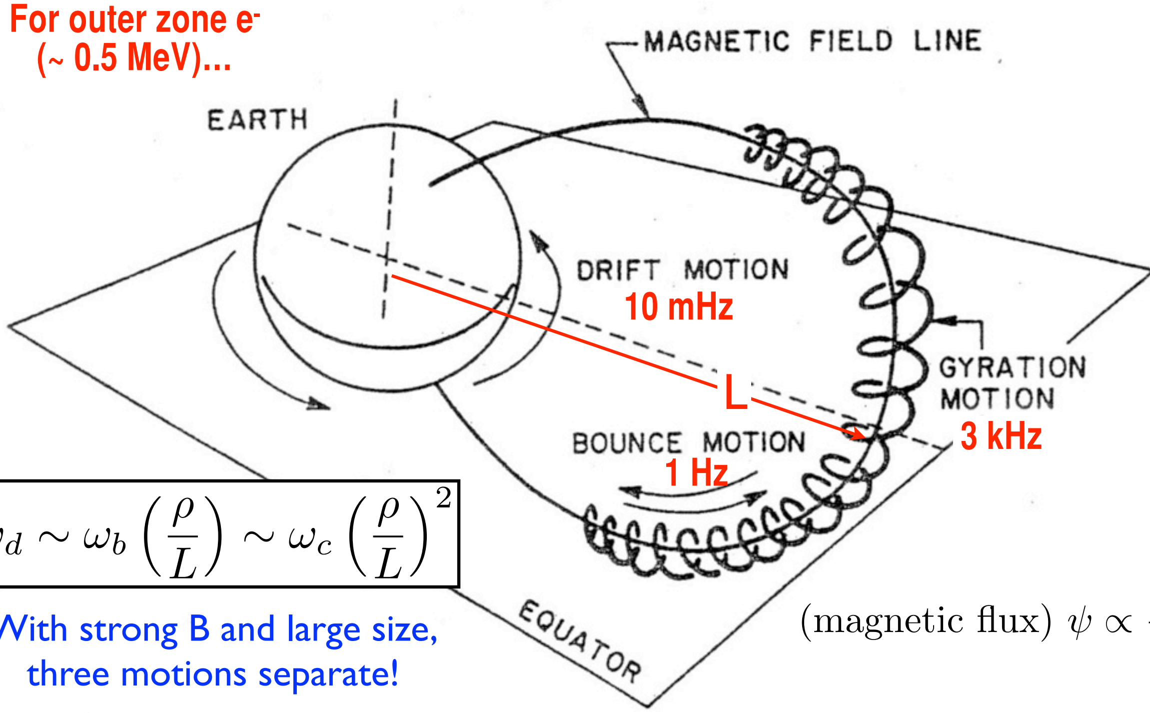
- Plasma transport due to low-frequency fluctuations in a magnetospheric/dipole field: ***The Turbulent Pinch***
- Levitated Dipole Experiment (LDX)
- Comparing discharges confined by a **Supported** and **Levitated** superconducting magnet
- Observation of the **turbulent inward particle pinch** and measurement of random **E×B** motion at edge.
- Turbulent transport of **entropy density**, G = PδV$^{\gamma}$
- New research tools for LDX
- *Tritium-suppressed fusion*

# Particle Dynamics Characterized by Adiabatic Invariants: Gyration (μ), Bounce (J), and Drift (ψ)

Northrup and Teller, "Stability of the Adiabatic Motion of Charged Particles in the Earth's Field," Phys Rev (1960)

Warren, *et al.* "On Arnol'd diffusion in a perturbed magnetic dipole field," *GRL* (1992)

**For outer zone $e^-$ (~ 0.5 MeV)...**



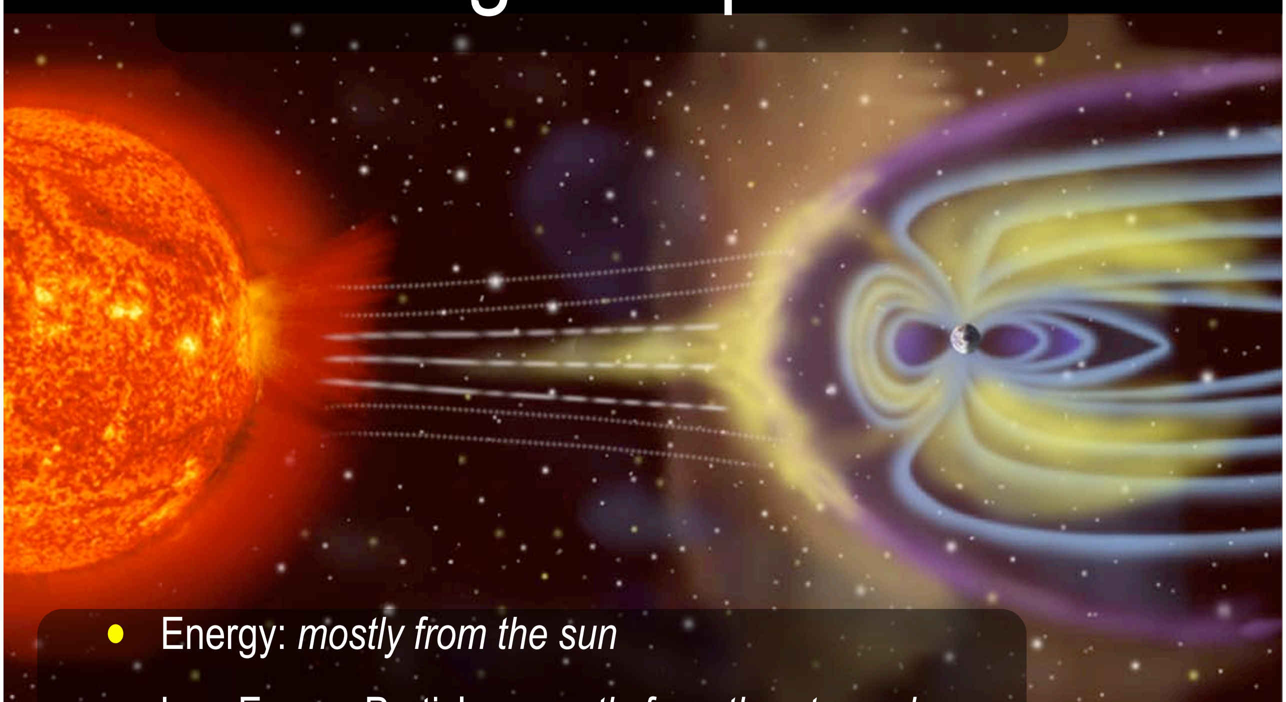

$$\omega_d \sim \omega_b \left(\frac{\rho}{L}\right) \sim \omega_c \left(\frac{\rho}{L}\right)^2$$

With strong B and large size, three motions separate!

$$(\text{magnetic flux})\ \psi \propto \frac{1}{L}$$



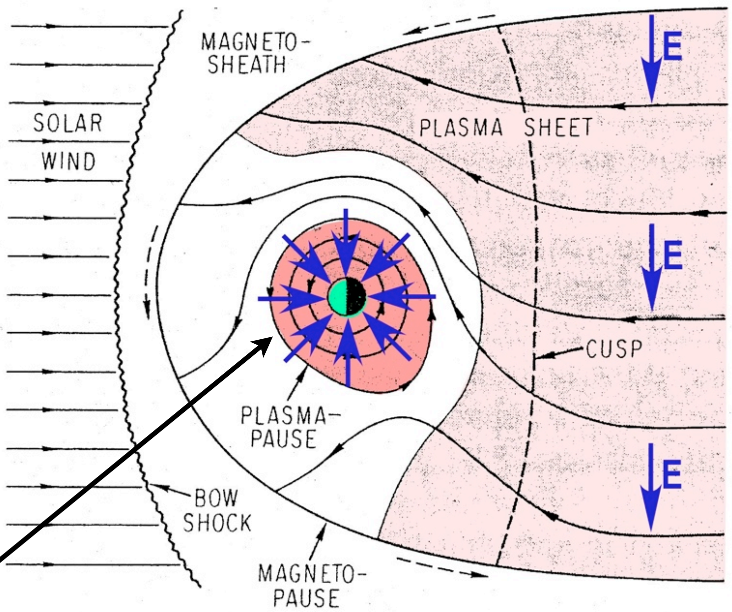
# Magnetosphere



- Energy: *mostly from the sun*
- Low Energy Particles: *mostly from the atmosphere*
- High Energy Particles: *mostly from outer boundary*

# Structure of Magnetosphere

## *Electric Field*




**Plasma Sheet Convection**

**Plasmasphere Co-Rotation**

$$\delta\Phi \sim -\overbrace{E_c\left(\frac{R_e^2}{L}\right)}^{\text{Axisymmetric}} + \underbrace{E_c L \sin\phi}_{m=\pm 1} + \ldots$$

T. Birmingham, *JGR* (1969)



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

Collisionless Random Electric Convection

$$\frac{\partial\langle\bar{Q}\rangle(\alpha, M, J, t)}{\partial t} = \frac{\partial}{\partial\alpha}\left[\overline{D_{\alpha\alpha}}\,\frac{\partial\langle\bar{Q}\rangle}{\partial\alpha}\right] \quad (5)$$

$$\overline{D_{\alpha\alpha}} \approx \frac{c^2\mu^2}{4\alpha^2}(\pi)^{1/2}\tau_c\mathfrak{a} \quad (18)$$

α = magnetic flux, ψ

dipole field. We describe **E** by the potential $V$

$$V = \frac{A(t)r}{\sin^2\vartheta}\sin\phi \quad (2)$$

$A$ being a positive, time-dependent amplitude. The form equation 2 is the fundamental ($m = 1$) asymmetric mode in *Fälthammar*'s [1965] Fourier expansion of a general longitudinally dependent potential. Since $r\sin^{-2}\vartheta$ and $\phi$ are both constant on dipole field lines, **B** lines are equipotentials, and **E·B** is zero. In the $\vartheta = \pi/2$, equatorial plane

A reasonable direction to proceed, in view of the paucity of direct experimental evidence of electric fields and their time variations, is to assume that the autocorrelation $\langle\delta A(t-\tau)\,\delta A(t)\rangle$ has the form

$$\langle\delta A(t-\tau)\,\delta A(t)\rangle = \mathfrak{a}\exp -\frac{\tau^2}{\tau_c^2} \quad (16)$$

from dawn to dusk, and is random on the time scale on which the solar wind executes time variations of large spatial extent. (The correlation time $\tau_c$ is thus typically one hour.)

# Random Interchange Motion

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

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

Correlation Time

T. Birmingham, *JGR* (1969) →

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

$$\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi}$$

Flux tube particle number



# Stationary Turbulent Profiles:

## *Connection with Magnetic Geometry*

- Plasma interchange dynamics is characterized by **flux-tube averaged quantities**:
  - **Flux tube particle number**, ***N*** = ∫ ds ***n***/*B* ≈ *n* δ*V*
  - **Entropy density**, *G* = *P* δ$V^{\gamma}$, where γ ≈ 5/3

  (***n***, *P*) ⇔ (***N***, *G*) are related by **flux tube volume (*geometry*)**, δ*V* = ∫ ds/*B*

- Random fluctuations cause radial diffusion or plasma “flux-tubes”. Interchange mixing flattens ∂[***N*** *and G*]/∂ψ → 0 **at the same rate**.

➡ **Steady turbulent profiles** imply ***N*** **and** ***G*** **are homogeneous.**

- **Natural profiles are “stationary”** since fluctuating **E**×**B** flows do not change (***N***, *G*).

## Natural Profiles are also Marginally Stable Profiles

➡ *N = constant*, is the D. B. Melrose criterion (1967) for stability to centrifugal interchange mode in rotating magnetosphere.

➡ $G = P\,\delta V^{\gamma}$ = *constant*, is the T. Gold criterion (1959) for marginal stability of pressure-driven interchange mode in magnetosphere, and also Rosenbluth-Longmire (1957) and Bernstein, *et al.*, (1958).

➡ Self-Organization is possible: *e.g.* steep central pressure gradients excites instability that drives inward turbulent particle pinch while relaxing pressure to $P\,\delta V^{\gamma}$ = *constant*



# Natural Profiles in Solenoidal Geometry

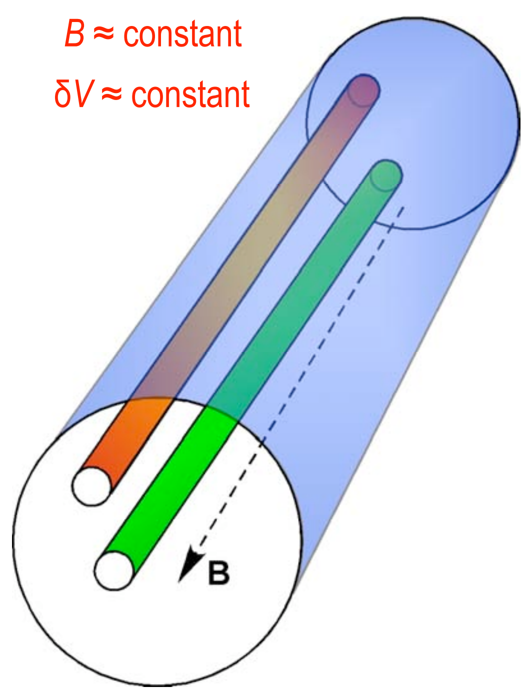
**Theta-pinch, large aspect ratio solenoid, …**

- Flux tube volume:
  - $\delta V = \int ds/B$ = constant
  - $\delta V = \int ds/B = (q\mathcal{H})^{-0.8}$ (*tokamak*)
- Natural profiles:
  - $n\,\delta V$ = constant
  - $P\,\delta V^{\gamma}$ = constant
  - **Density and pressure profiles are flat**

➡ Density, pressure, and temperature at edge and at core are equal ***unless interchange mixing is suppressed.***

$B \approx$ constant

$\delta V \approx$ constant

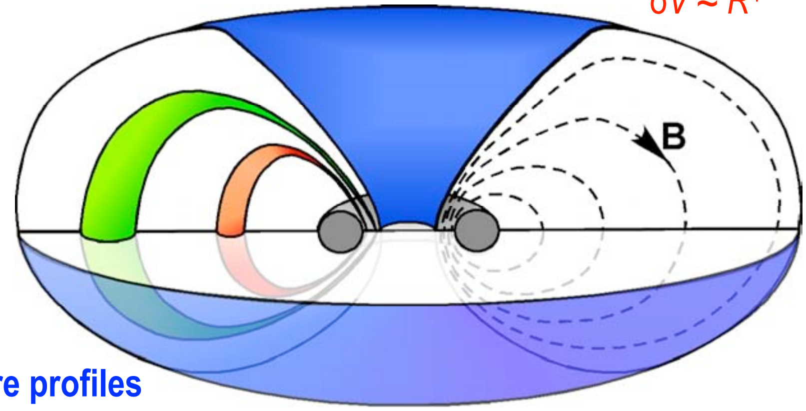


# Natural Profiles in Dipole Geometry

- Flux tube volume:
  - $\delta V = \int ds/B \approx R^4$
- Natural profiles:
  - $n\,\delta V$ = constant
  - $P\,\delta V^{\gamma}$ = constant
  - **Density and pressure profiles are strongly peaked!**

➡ Density, pressure, and temperature at edge and at core are **not equal**.

***Interchange mixing sustains peaked profiles.***




***"Natural" Profiles in LDX:***

$$\delta V_{edge}/\delta V_{core} \approx 50$$
$$n_{core}/n_{edge} \approx 50$$
$$P_{core}/P_{edge} \approx 680$$
$$T_{core}/T_{edge} \approx 14$$



# Electrostatic Self-Organization

**Heat injection creates *super-critical gradients* creating global turbulent fluctuations that *relax gradients* while *driving particles inward*.**

*JETP Letters, Vol. 82, No. 6, 2005, pp. 356–365.*

**Self-Consistent Turbulent Convection in a Magnetized Plasma**

**V. P. Pastukhov* and N. V. Chudin**

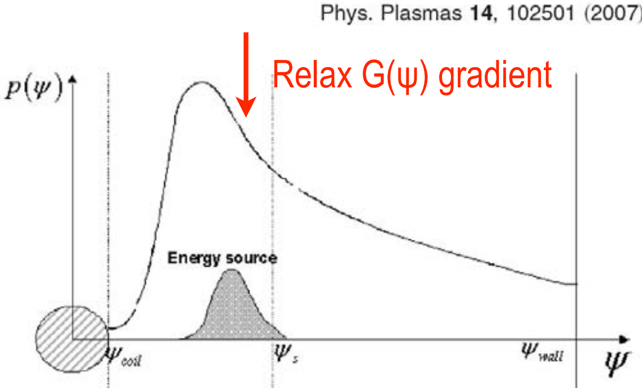
***Russian Research Centre Kurchatov Institute, pl. Akademika Kurchatova 1, Moscow, 123182 Russia***

**Quasilinear theory of interchange modes in a closed field line configuration**

A. Kouznetsov, J. P. Freidberg, and J. Kesner

*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

Phys. Plasmas **14**, 102501 (2007)



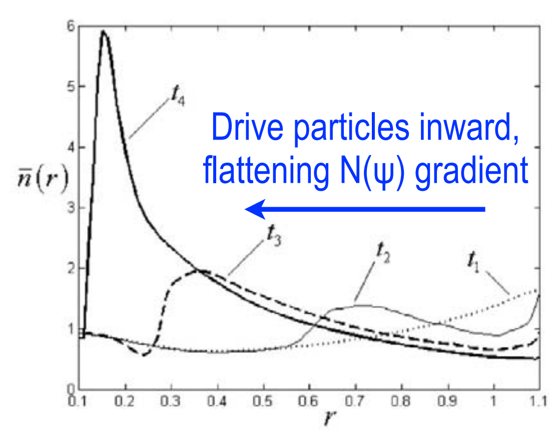
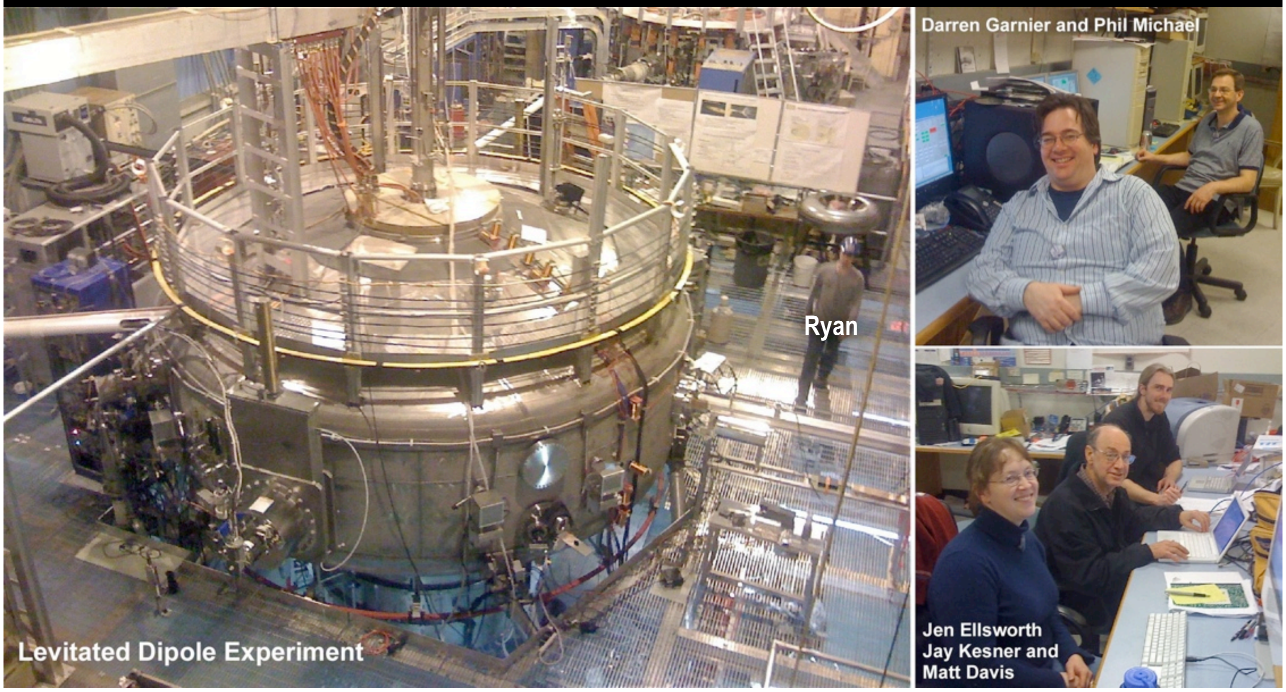




FIG. 5. The snapshots of the "self-organizations" process. Time $t_1$: before an instability is excited; $t_2$–$t_4$: different stages of self-organization.

# LDX Experiment






## Levitated Dipole Experiment (LDX)

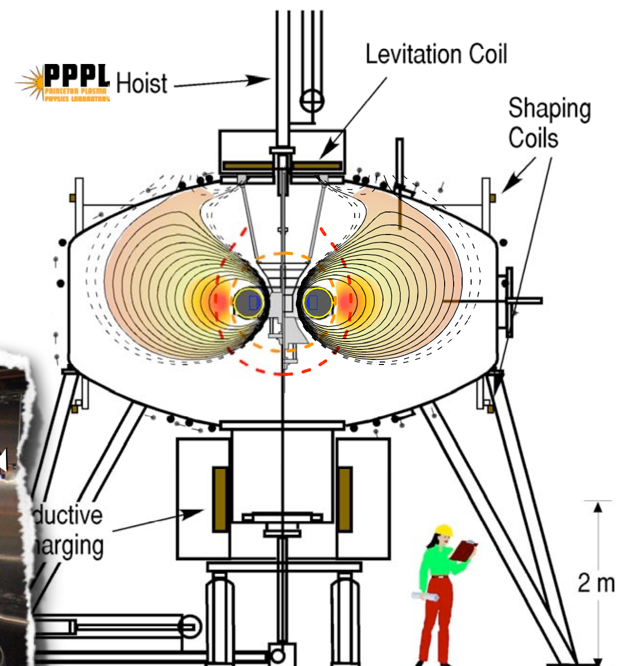
- Project start: 1999
- Launch/Mission: August 2004 to Present.
- Weight: 565 kg (floating coil)

- Key diagnostics:

Magnetic Loops
(Ring Current)

Microwave Interferometers
(Plasmasphere)

Probes
(Edge Dynamics & Structure)

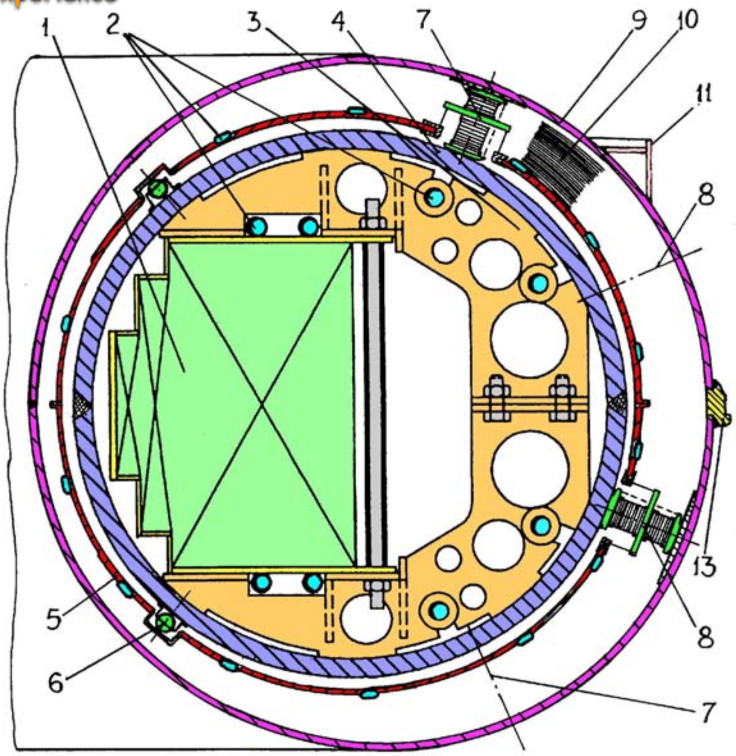




3 hr float time

plus Optical and X-Ray Imagers
(Plasmasphere and Ring Current)

# Floating Coil Cross-Section

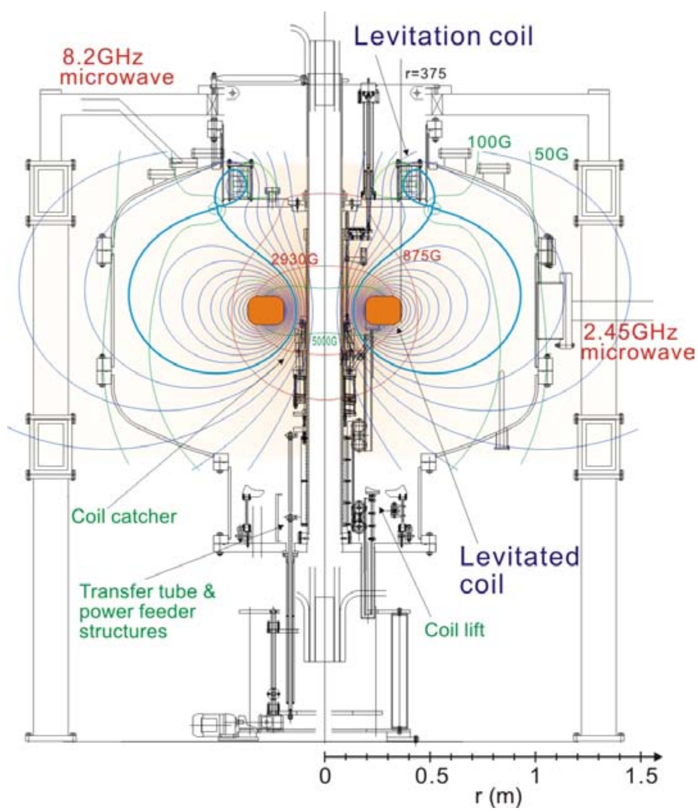
FM-1b Experience

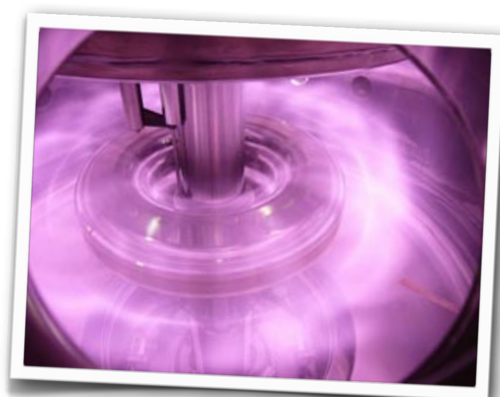


1. Magnet Winding Pack
2. Heat Exchanger tubing
3. Winding pack centering clamp
4. He Pressure Vessel (Inconel 625)
5. Thermal Shield (Lead/ glass composite)
6. Shield supports (Pyrex)
7. He Vessel Vertical Supports/Bumpers
8. He Vessel Horizontal Bumpers
9. Vacuum Vessel (SST)
10. Multi-Layer Insulation
11. Laser measurement surfaces
13. Outer structural ring



# RT-1 (University of Tokyo)



1/3-scale as LDX
High-beta (40%)
10 keV electrons
0.2 sec hot electron confinement-time

### Previous Result using a Supported Dipole:

## High-beta ($\beta$ ~ 26%) plasma created by multiple-frequency ECRH with sufficient gas fueling

- Using 5 kW of long-pulse ECRH, plasma with trapped fast electrons ($E_h$ > 50 keV) were sustained for many seconds.

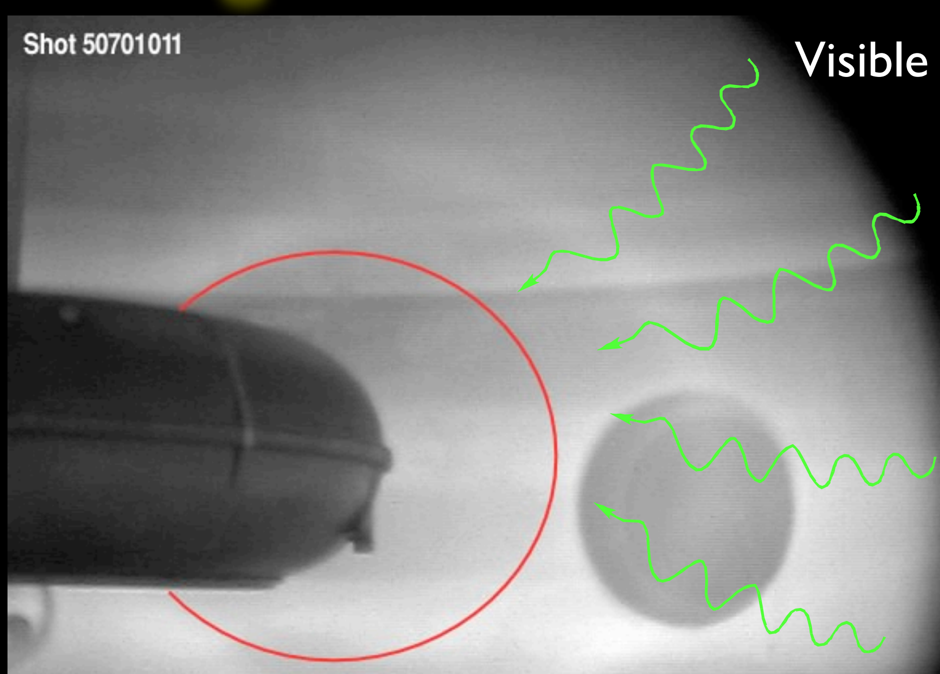
➡ Magnetic equilibrium reconstruction and x-ray imaging showed high stored energy > 300 J ($\tau_E$ > 60 msec), high peak $\beta$ ~26%, and anisotropic fast electron pressure, $P_\perp/P_{||}$ ~ 5.

- Stability of the high-beta fast electrons was maintained with sufficient gas fueling (> $10^{-6}$ Torr) and plasma density.

- D. Garnier, *et al., PoP*, (2006)

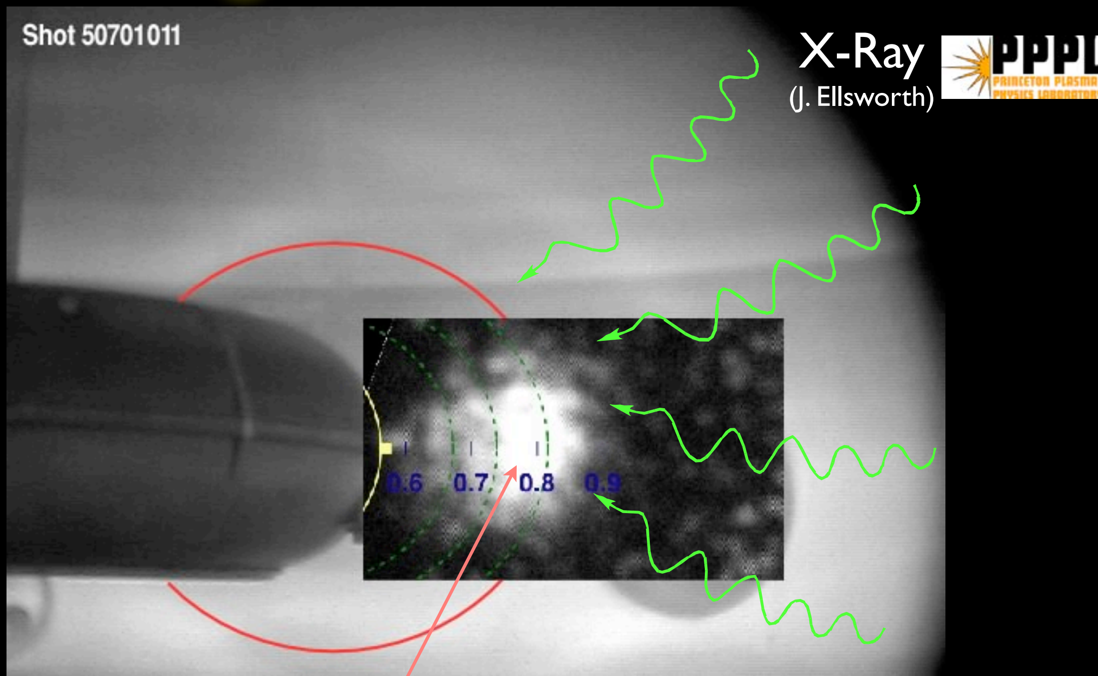


# LDX High-Beta Plasma Torus




"Artificial Radiation Belt"
with ECRH

# LDX High-Beta Plasma Torus

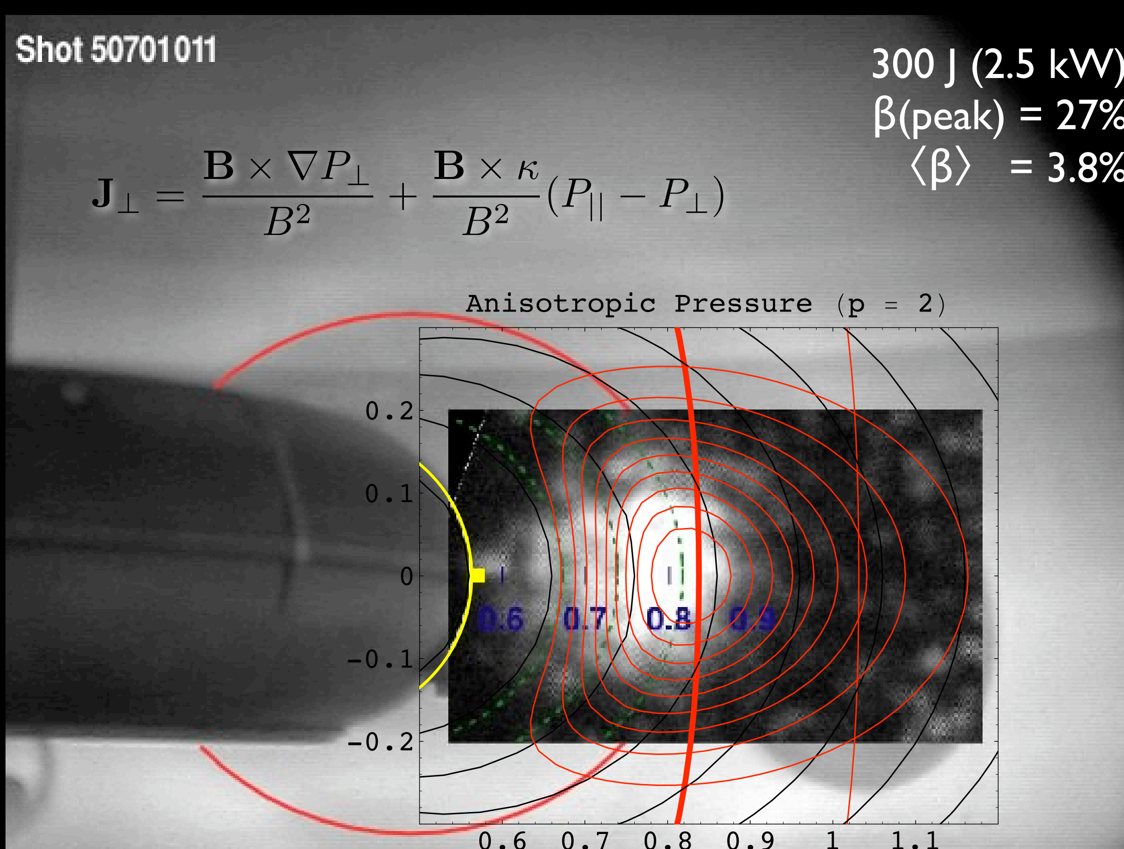



High-Beta
Trapped Electrons

“Artificial Radiation Belt”
with ECRH

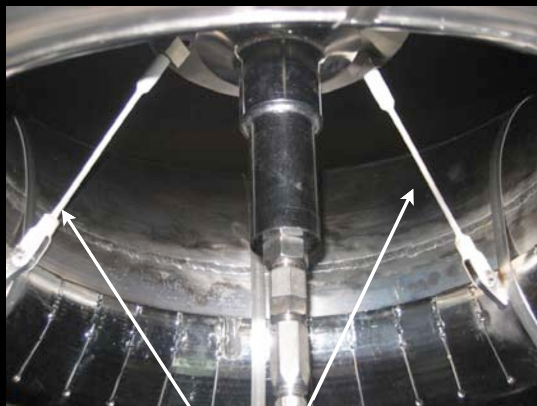


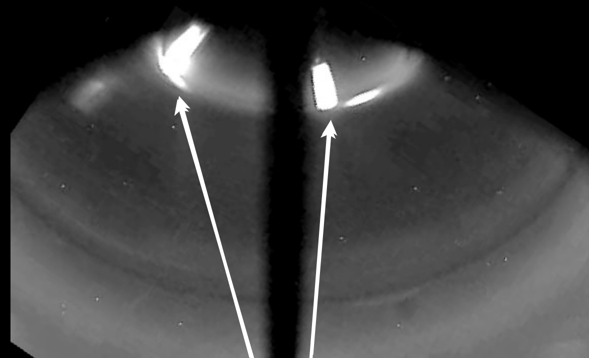
# Best Fit Equilibrium Constrained by X-Ray Camera




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

# Thin Supports were a Major Power Loss…



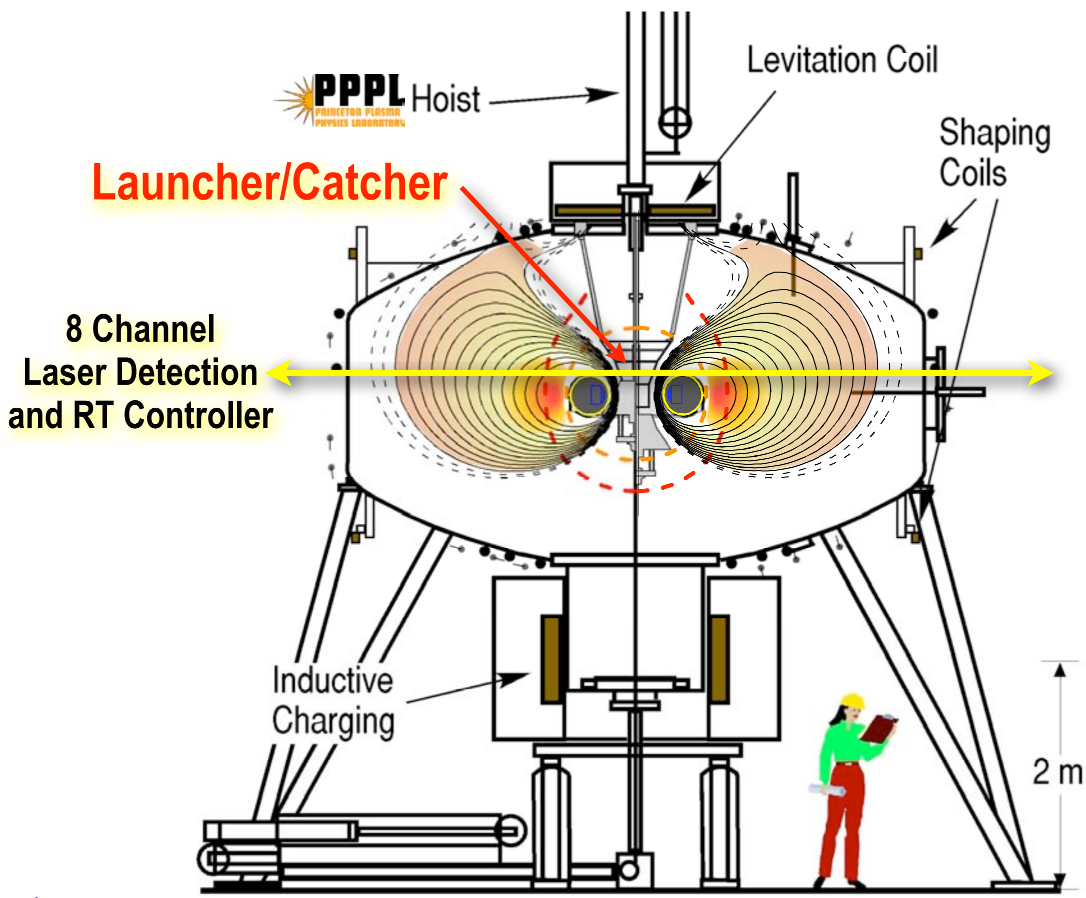


Three high-strength, alumina-coated spokes support dipole during Phase I experiments

Supports become "very warm" during high-beta plasma operation

***Elimination of supports, next step, will further enhance confinement, density, …***

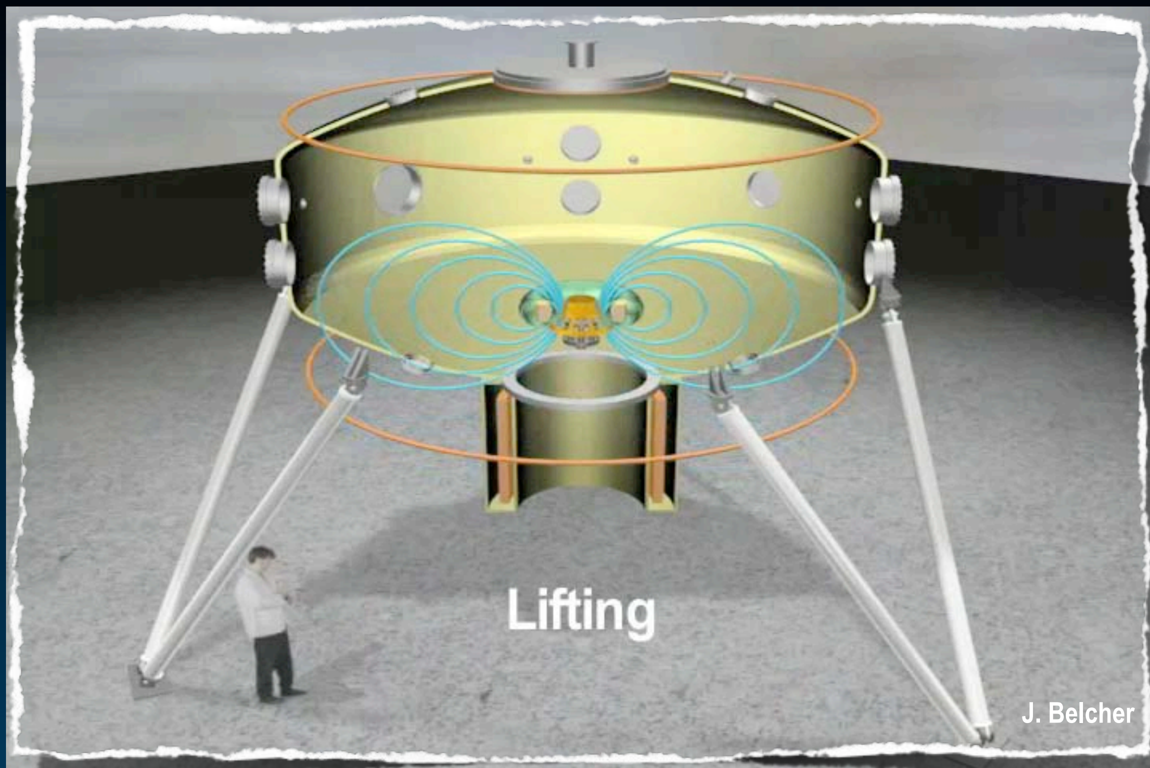





Columbia University in the City of New York

MIT Massachusetts Institute of Technology

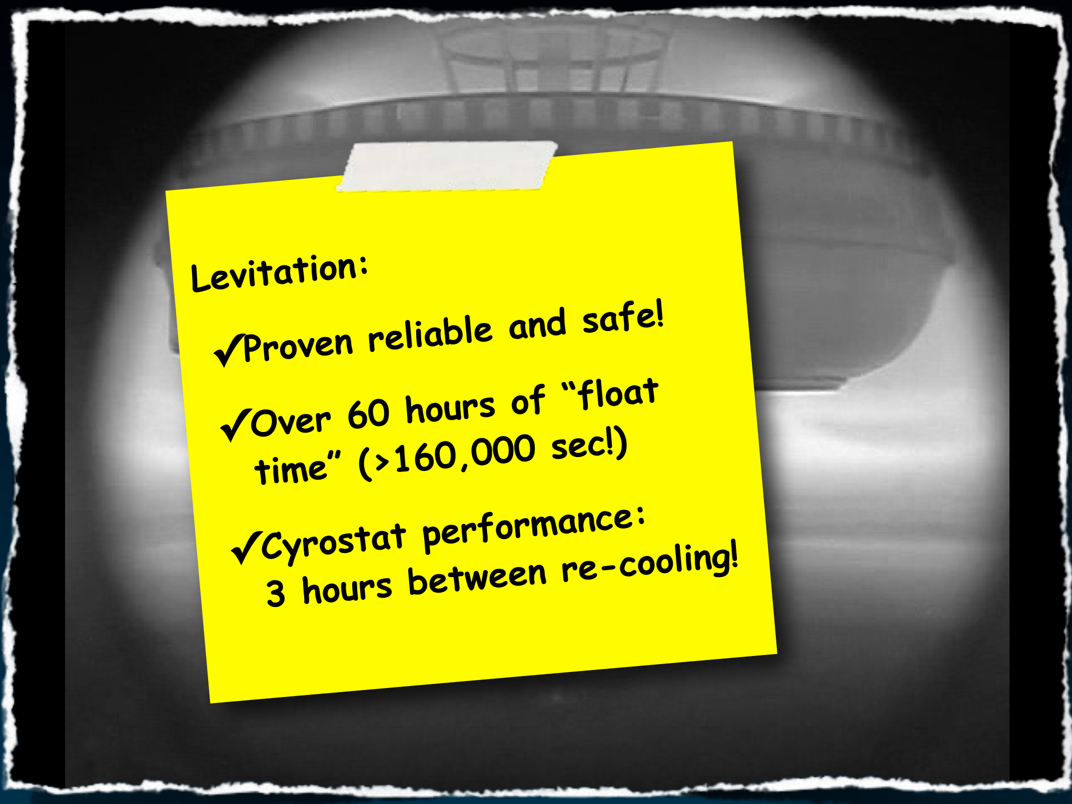
# Lifting, Launching, Levitation, Experiments, Catching






# Levitated Dipole Plasma Experiments

## Levitated Dipole Plasma Experiments






## New Result with Levitated Dipole:

# Centrally peaked density profiles and Increased plasma pressure occur during levitation

- Magnetic levitation eliminates parallel losses, and plasma profiles are determined by radial transport processes.

➡ Multi-cord interferometry reveals dramatic (up to 10-fold) central peaking of plasma density during levitation.

- Profile peaking occurs rapidly, allowing direct measurement of the inward particle pinch.

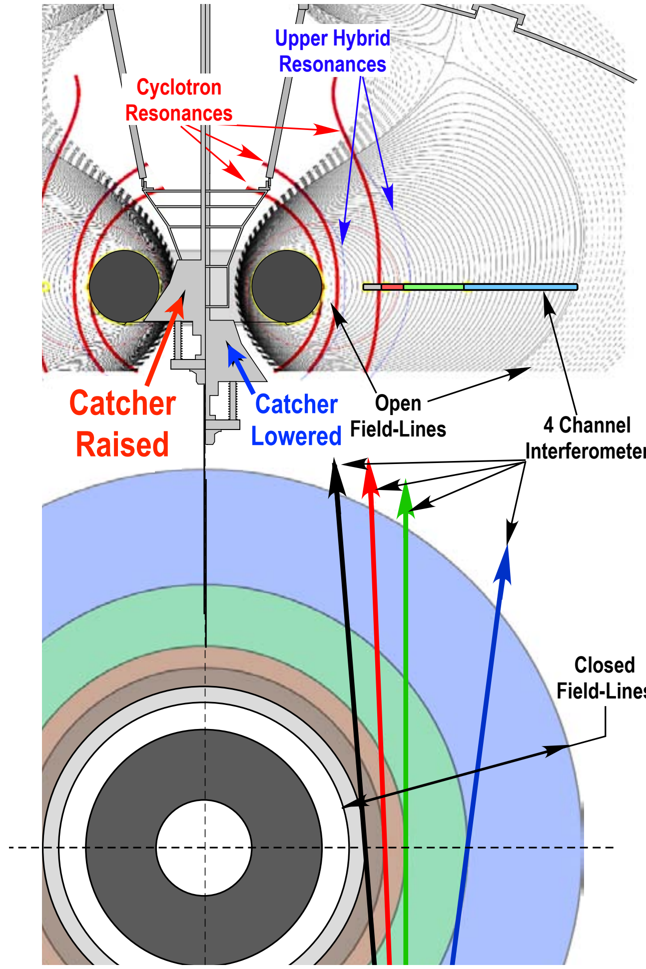
- Low-frequency fluctuations are observed with an intensity consistent with the observed inward pinch.

- The turbulent pinch is associated with increased plasma pressure consistent with constant entropy density, $G = P\delta V^{\gamma}$, and high thermal electron temperature, $T_e > 300$ eV.

# Density Profile with/ without Levitation

- *Procedure*:
  - Adjust levitation coil to produce equivalent magnetic geometry
  - Investigate multiple-frequency ECRH heating
- *Observe*: Evolution of density profile with 4 channel interferometer
- *Compare*: Density profile evolution with supported and levitated dipole

*Alex Boxer, MIT PhD, (2008)*

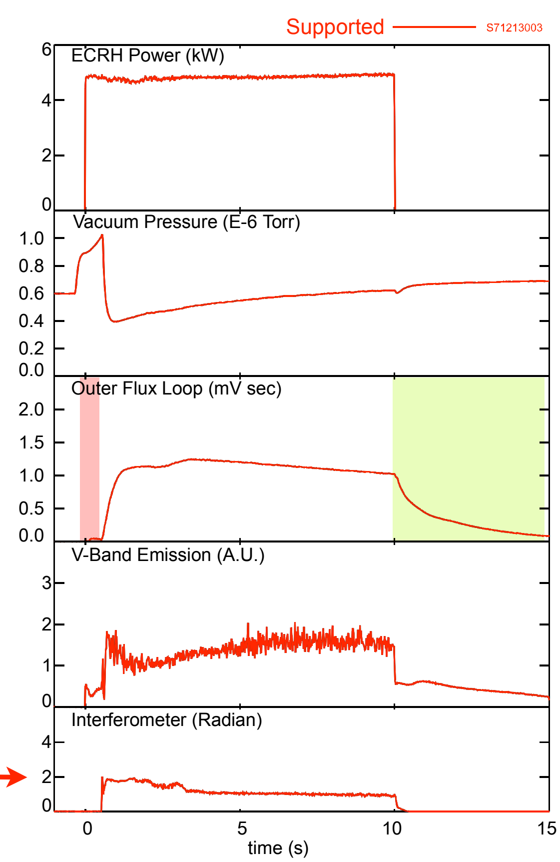





# Plasma Confined by a Supported Dipole

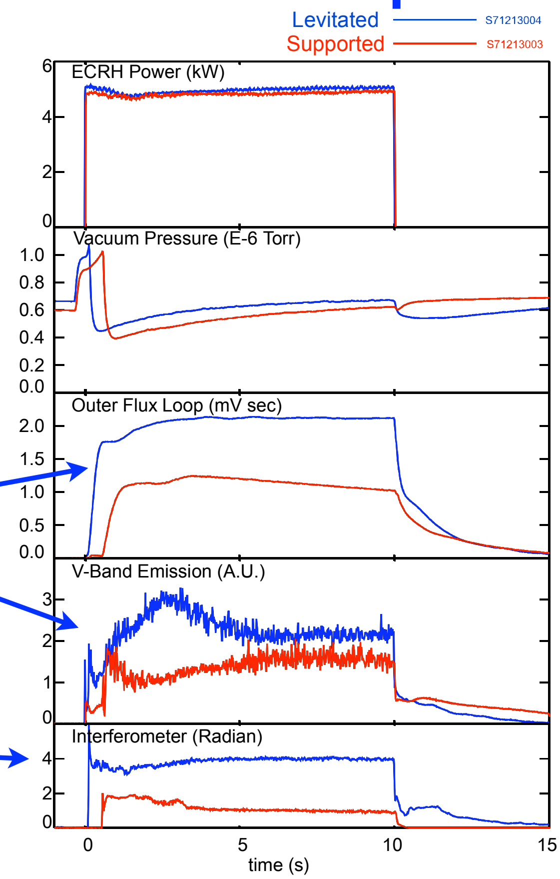
- 5 kW ECRH power
- $D_2$ pressure ~ $10^{-6}$ Torr
- Fast electron instability, ~ 0.5 s
- Ip ~ 1.3 kA or 150 J
- Cyclotron emission (V-band) shows fast-electrons
- Long, low-density "afterglow" with fast electrons

➡ $1 \times 10^{13}$ $cm^{-2}$ line density



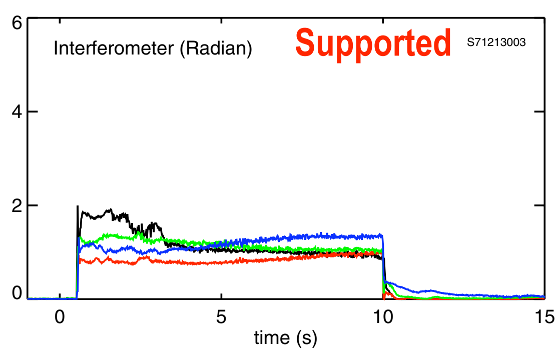
# Plasma Confined by a Levitated Dipole

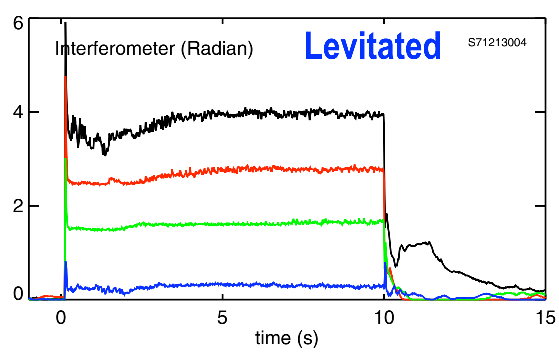
- Reduced fast electron instability
- 2 x Diamagnetic flux
- Increased ratio of diamagnetism-to-cyclotron emission indicates **higher thermal pressure**.
- Long, higher-density “afterglow” shows improved confinement.
- **3 x line density**

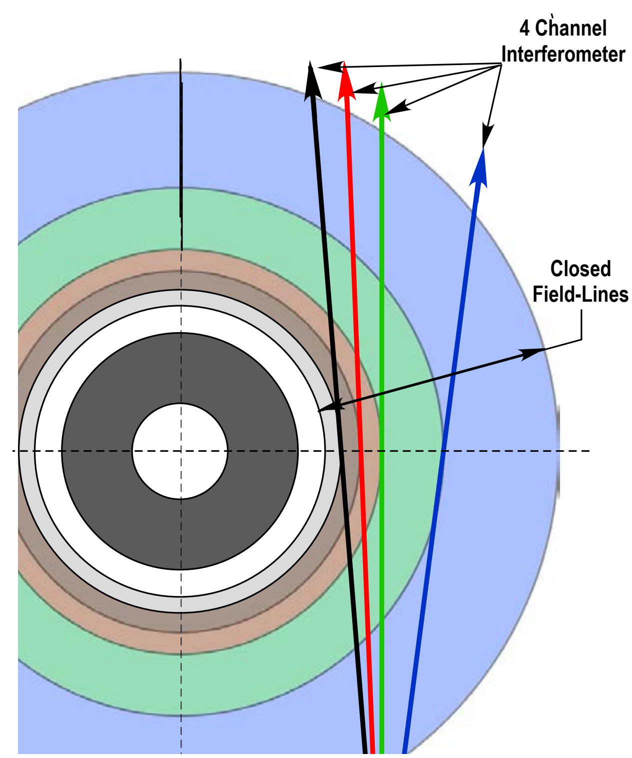




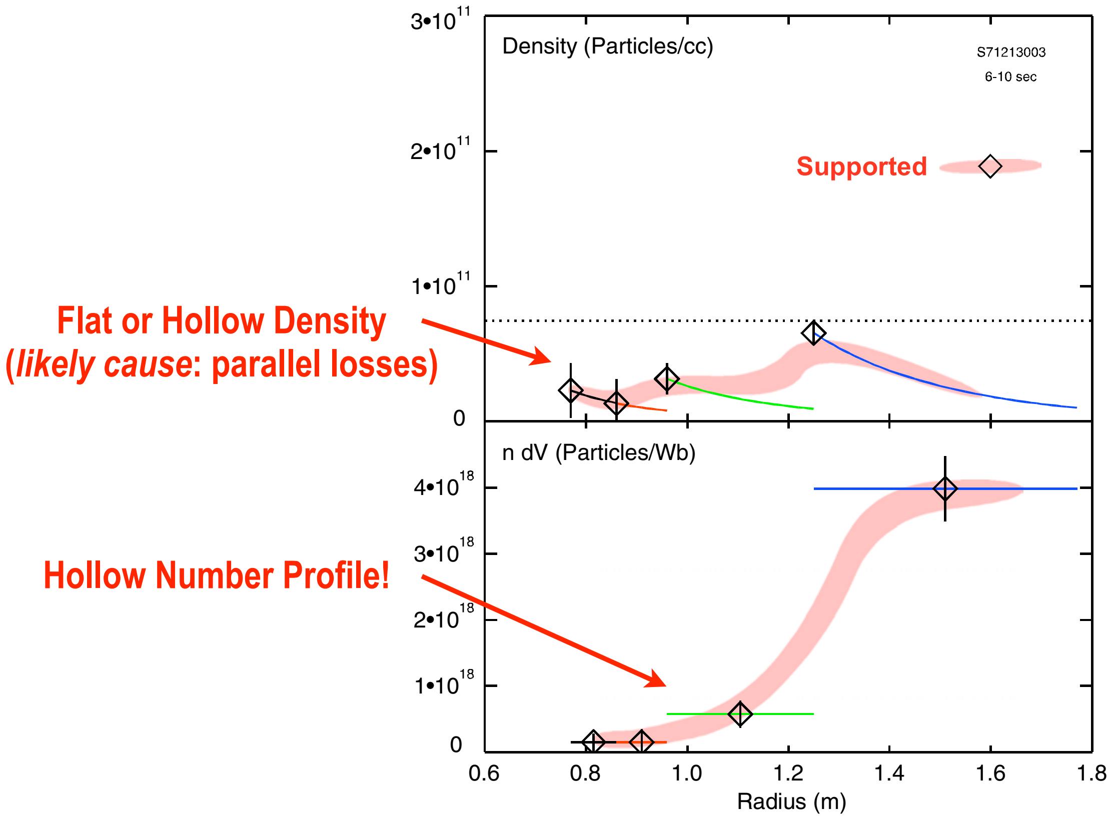

# Multi-Cord Interferometer Shows Strong Density Peaking During Levitation



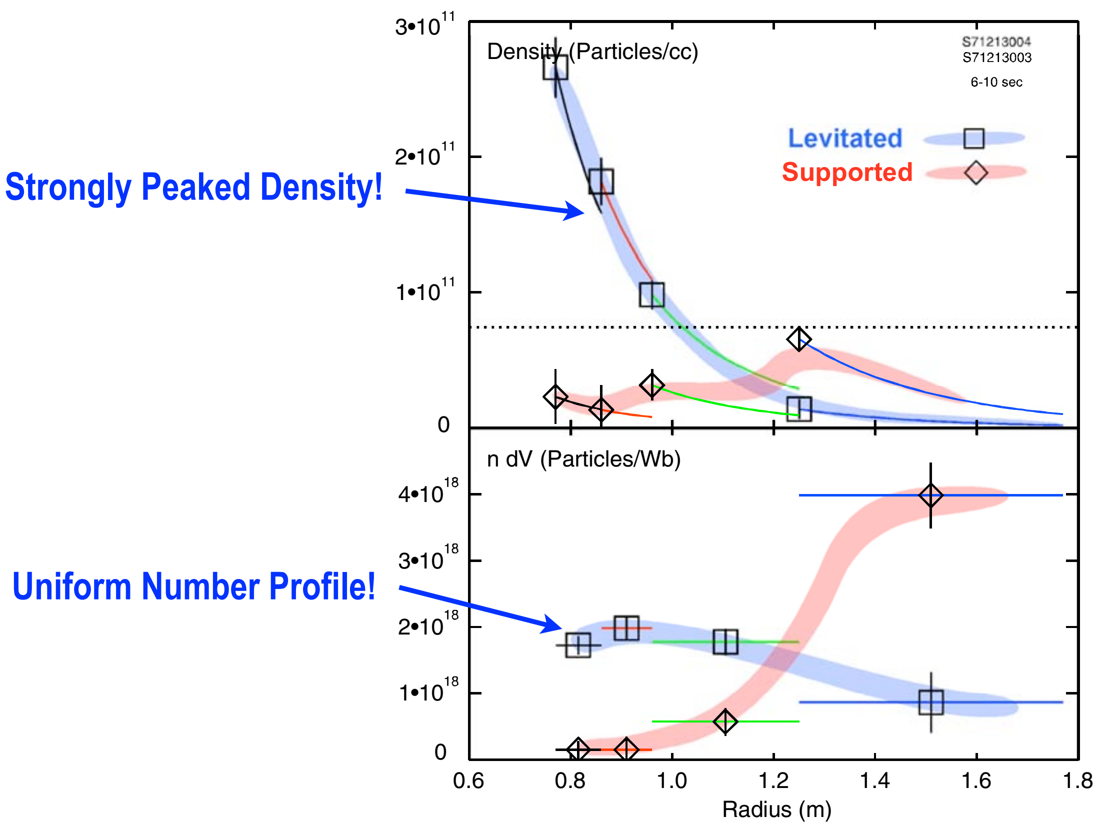



# Inversion of Chord Measurements






# Inversion of Chord Measurements



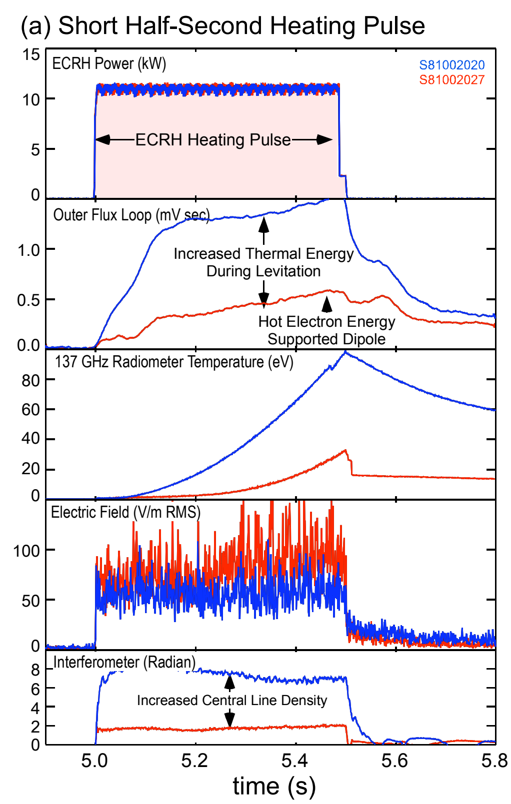
# Levitation Always Causes More Peaked Profiles Relative to Supported Discharges

- **Comparison of density profiles for levitated and supported discharges always show more peaked profiles during levitation.**
- **Natural density profiles are created regardless of plasma pressure (*i.e.* both low and high beta).**
- **Natural density profiles are established rapidly, within ~20 msec.**
- **Natural density profiles are sustained steady-state by microwave heating.**

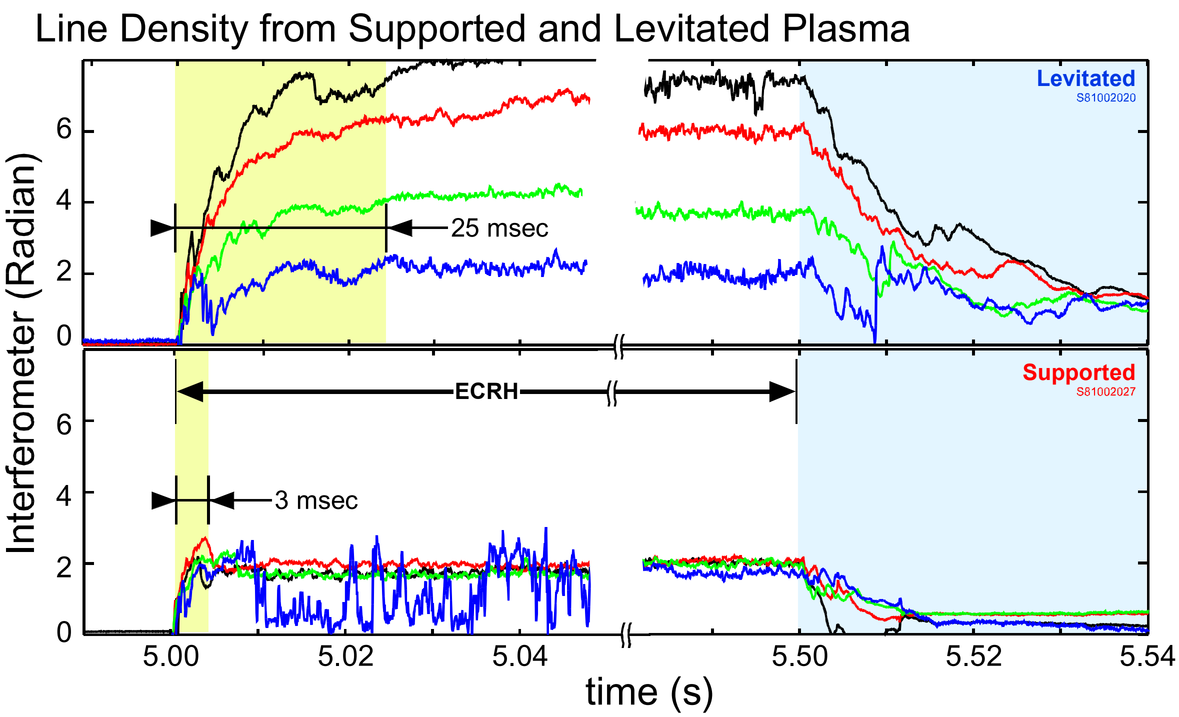


# Natural Density Profiles Established Rapidly

- Levitation vs. Supported comparisons provide an opportunity to directly observe the effects of turbulent transport, as the parallel losses are switched off/on.
- Short 1/2 second heating pulses minimize influence of hot electrons on plasma dynamics.
- Turbulent fluctuations are established quickly as the ECRH is switched on. Fluctuations diminish after ECRH is switched off.



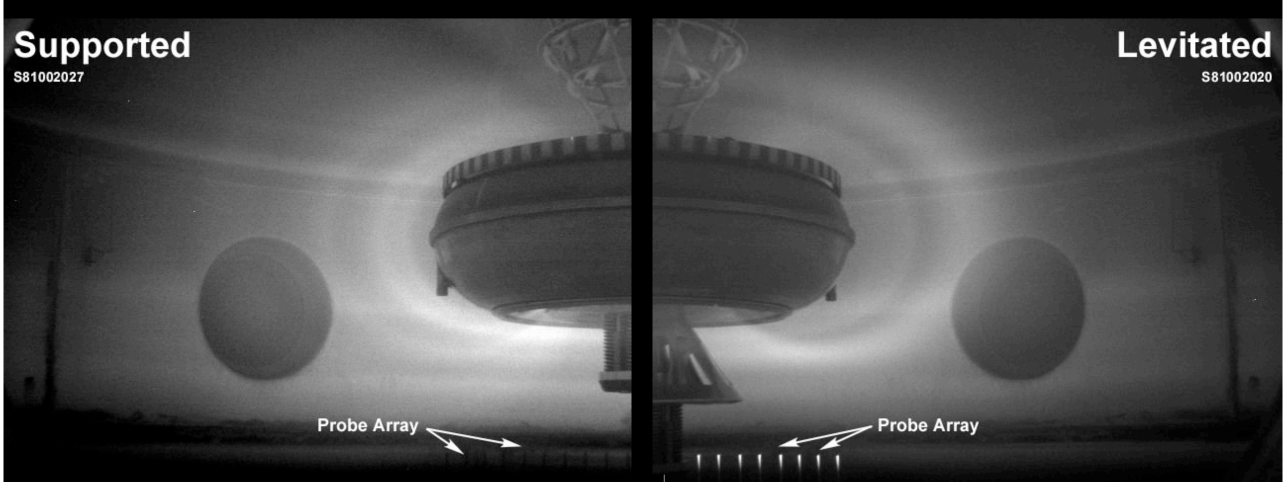
# Naturally Peaked Profiles Established Rapidly






# Neutral Source Appears at Outer Edge

## (Levitation Shields Neutrals from Core)



# Floating Potential Probe Array

- Edge floating potential oscillations
- 4 deg spacing @ 1 m radius
- 24 probes
- Very long data records for excellent statistics!!




# Low-Frequency Fluctuations are Observed throughout Plasma and Probably Cause Naturally Peaked Profiles

- **Low-frequency fluctuations (*f* ~ 1 kHz and < 20 kHz) are observed with edge probes, multiple photodiode arrays, interferometry, and fast video cameras.**
- **The structure of these fluctuations are complex, turbulent, and *not understood*.**
- **Edge fluctuations can be intense (*E* ~ 200 V/m) and are dominated by long-wavelength modes that rotate with the plasma at 1-2 kHz**
- **High-speed digital records many seconds long enable analysis of turbulent spectra in a single shot. We find the edge fluctuations are characteristic of viscously-damped 2D interchange turbulence.**
- **See Brian Grierson, *et al.* "Global and local characterization of turbulent and chaotic structures in a dipole-confined plasma," *Phys Plasmas* (2009).**

# Plasma ExB Motion

$$\mathbf{V} = -\hat{\varphi} R \frac{\partial \Phi}{\partial \psi} + \frac{\hat{\psi}}{RB} \frac{\partial \Phi}{\partial \varphi} \, .$$

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

Measured
at edge



# Random Interchange Particle Diffusion

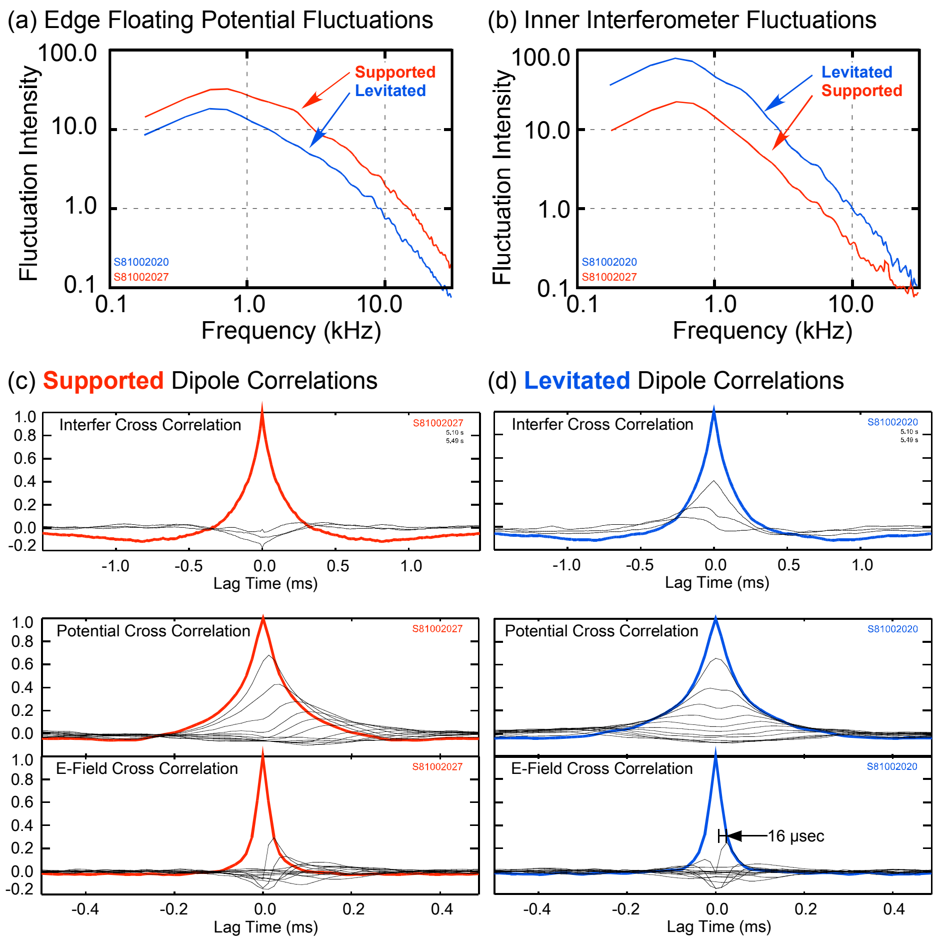
$$D = \lim_{t \to \infty} \int_0^t dt \langle \dot{\psi}(t) \dot{\psi}(0) \rangle \equiv \langle \dot{\psi}^2 \rangle \tau_c$$

Cross Correlation Function

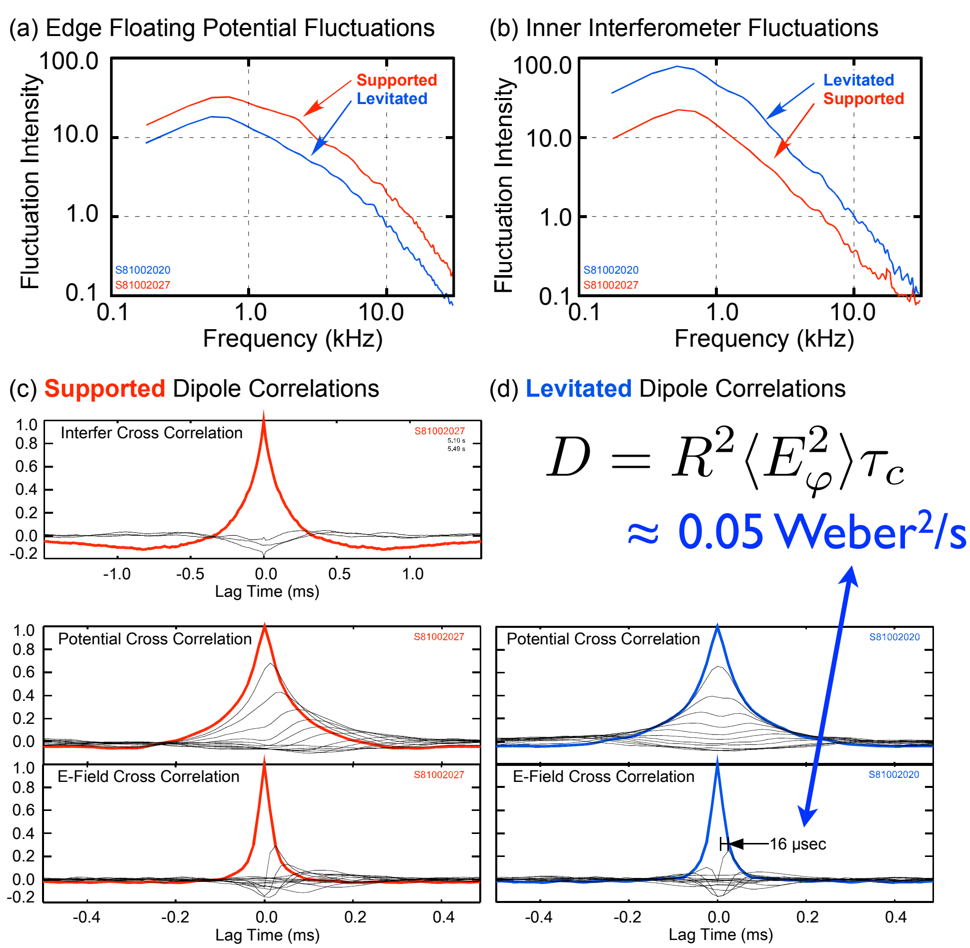
$$D = R^2 \langle E_{\varphi}^2 \rangle \tau_c$$

Measured
at edge

$$\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi}$$


(a) Edge Floating Potential Fluctuations
Supported
Levitated
Fluctuation Intensity
Frequency (kHz)
S81002020
S81002027
(b) Inner Interferometer Fluctuations
Levitated
Supported
Fluctuation Intensity
Frequency (kHz)
(c) Supported Dipole Correlations
(d) Levitated Dipole Correlations
Interfer Cross Correlation
Lag Time (ms)
Potential Cross Correlation
E-Field Cross Correlation
16 μsec
Lag Time (ms)

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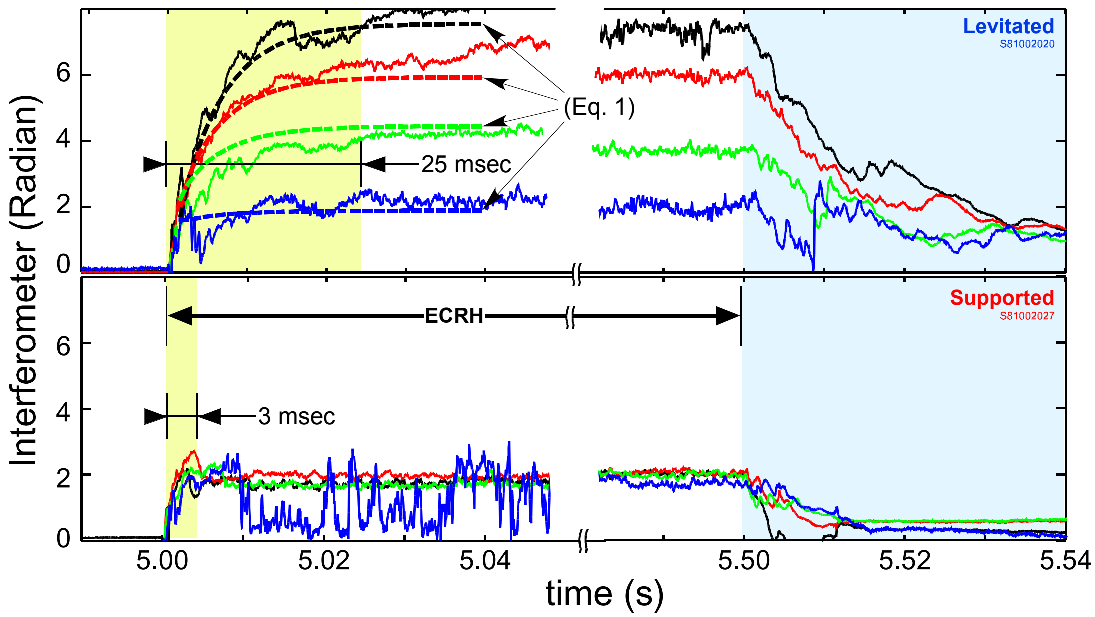
Frequency (kHz)
(c) Supported Dipole Correlations
(d) Levitated Dipole Correlations
Interfer Cross Correlation
Lag Time (ms)
$D = R^2 \langle E_\varphi^2 \rangle \tau_c$
≈ 0.05 Weber²/s
Potential Cross Correlation
E-Field Cross Correlation
16 μsec
Lag Time (ms)

# Naturally Peaked Profiles Established Rapidly

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi} \qquad (1)$$

$D \approx 0.05$ Weber$^2$/s ***across the profile*** and $S \approx 0$

Line Density from Supported and Levitated Plasma






# Turbulent Particle Pinch is associated with Turbulent Entropy Pinch: Pressure Peaking

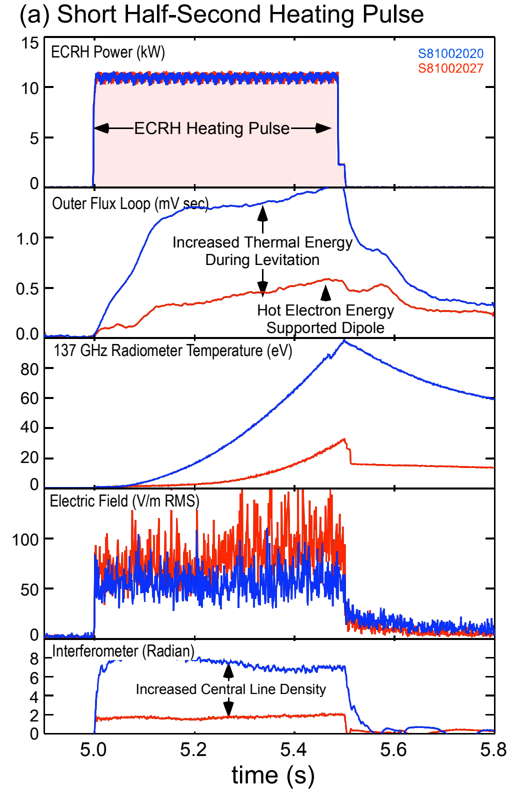
- Flux-tube density and entropy density have identical dynamics for a plasma with an adiabatic closure, $G = P\delta V^{\gamma}$

$$\frac{\partial N}{\partial t} - \frac{\partial}{\partial \varphi}\left(N\frac{\partial \Phi}{\partial \psi}\right) + \frac{\partial}{\partial \psi}\left(N\frac{\partial \Phi}{\partial \varphi}\right) = S$$

$$\frac{\partial G}{\partial t} - \frac{\partial}{\partial \varphi}\left(G\frac{\partial \Phi}{\partial \psi}\right) + \frac{\partial}{\partial \psi}\left(G\frac{\partial \Phi}{\partial \varphi}\right) = H$$

- ($N$, $G$) ~ constant implies peaked density and pressure profiles (**if $\gamma > 1$**)
- Edge $T_e$ ~ 15 eV, implies central $T_e$ ~ 500 eV with measured diamagnetism and measured density profile
- Thermal stored energy of 60 J (this example levitated discharge, 2 μTorr $D_2$)

(a) Short Half-Second Heating Pulse



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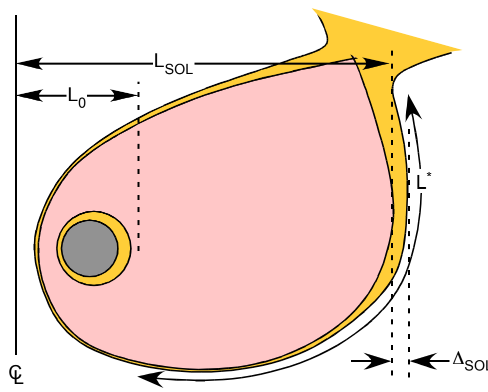
Adiabatic mixing implies core parameters determined by edge & compressibility:

$T_e/T_p \sim (4\gamma-3)C_v^{\gamma-1} > 50$

- ($N$, $G$) ~ constant implies peaked density and pressure profiles (**if $\gamma > 1$**)
- Edge $T_e \sim 15$ eV, implies central $T_e \sim 500$ eV with measured diamagnetism and measured density profile
- Thermal stored energy of 60 J (this example levitated discharge, 2 μTorr $D_2$)






# Next Steps in LDX Dipole Confinement Physics

- **Do natural pressure profiles, $P \sim 1/\delta V^{\gamma}$, develop?** ***Soft x-ray diagnostics (installed) and Thomson scattering (SSPX) for warm plasma pressure profile measurements.***
- **What are the spatial structures of the convective flows?** ***Install additional interferometer channels, reflectometer, and complete high-speed optical tomography analysis (in progress).***
- **Higher density plasma with additional heating options:**
  - ✓ **10 kW CW 28 GHz gyrotron (*1st experiments successful*)**
  - **1 MW CW ICRF heating (*TSW2500 from GA, starting…*)**
- **What is the effect of magnetic field errors on confinement?** ***Install non-axisymmetric trim/error coils. Induce ~15 kA plasma current to create very weak rotational transform.***

# Fusion Fuels

- Back to The Future (July 3, 1985)
  Fuel: banana, beer

- Spider-Man 2 (June 30, 2004)
  Fuel: tritium

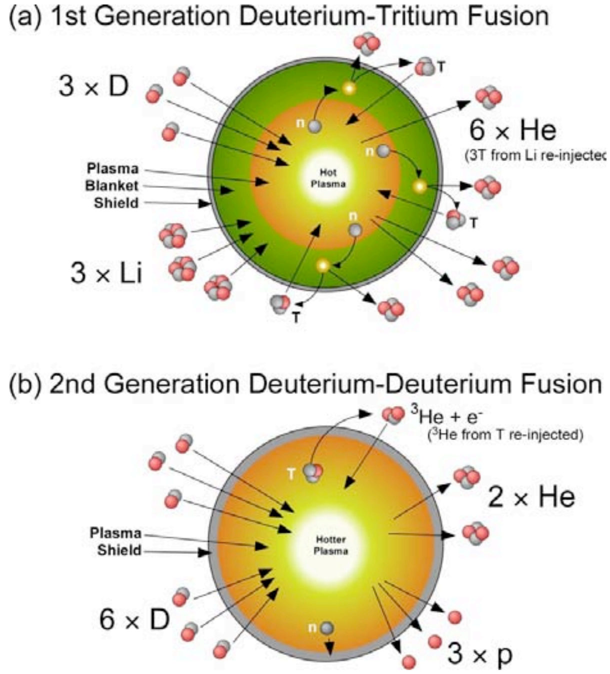


**Fuel: $^{3}$He**


- **Opened July 19, 2009. (Written and directed by Duncan Jones, son of David Bowie.)**
- **It is the near future. Astronaut Sam Bell is living on the far side of the moon, completing a three-year contract with Lunar Industries to mine Earth's primary source of energy, Helium-3. It is a lonely job, made harder by a broken satellite that allows no live communications home. Taped messages are all Sam can send and receive.**

# Deuterium-Fueled Power Plants with Tritium Suppression

John Sheffield and Mohamed Sawan, *Fus. Sci. Tech.* (2008)



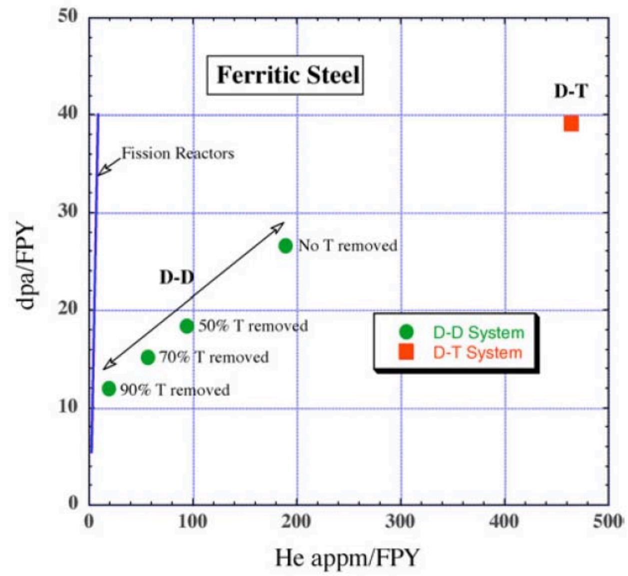




Fig. 1. dpa and He production rates in ferritic steel for D-T and D-D systems for the first wall of a ferritic steel/$H_2O$ shield.

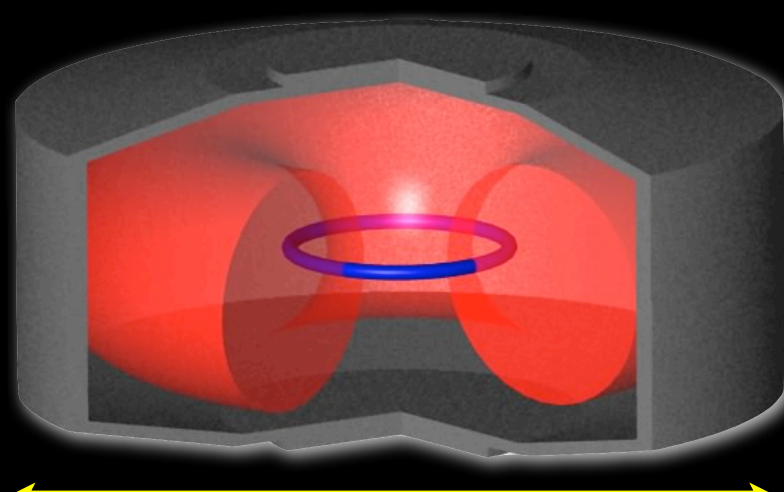


# Levitated Dipole Confinement Concept:

## Combining the Physics of Space & Laboratory Plasmas

- Steady state
- Non-interlocking coils
- Good field utilization
- Possibility for $\tau_E > \tau_p$
- Advanced fuel cycle
- Internal ring

**Levitated Dipole Reactor**

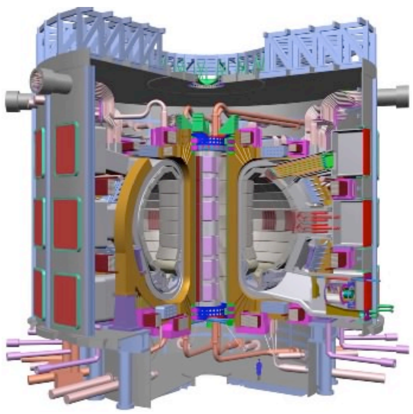
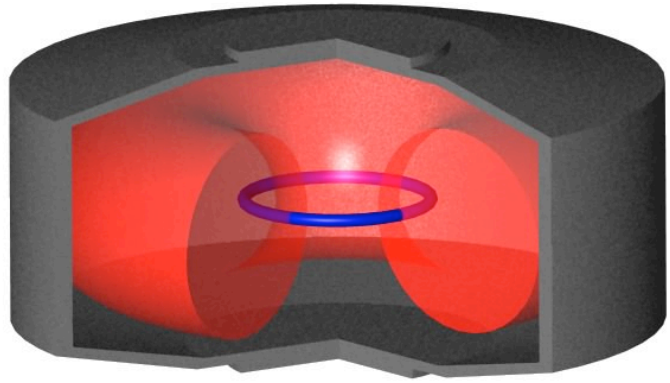


60 m

500 MW
DD(He3) Fusion

Kesner, et. al. *Nuclear Fusion* (2004)

# Dipole Fusion Concept

| ITER<br>1st Generation Reactor | Levitated Dipole<br>2nd Generation Reactor |
|---|---|
|  |  |
| 30 m | 60 m |
| 400-600 MW<br>DT Fusion | 500 MW<br>DD(He3) Fusion |

Kesner, et. al. Nucl. Fus. 2004



# Summary

- Levitation eliminates parallel particle losses and allows a dramatic peaking of central density.

  LDX has demonstrated the formation of natural density profiles in a laboratory dipole plasma and the applicability of space physics to fusion science.

- Random fluctuations of density, light emission, potential, and electric field provide evidence of random E×B motion that causes interchange mixing and an turbulent inward pinch.

- Intensity of $E_\varphi$ fluctuations measured at edge can account for inward diffusion.

- Increased stored energy consistent with adiabatic entropy density profile: *a necessary physics requirement for dipole fusion.*


LDX Dedication
October, 2004
MIT - PSFC
Columbia University