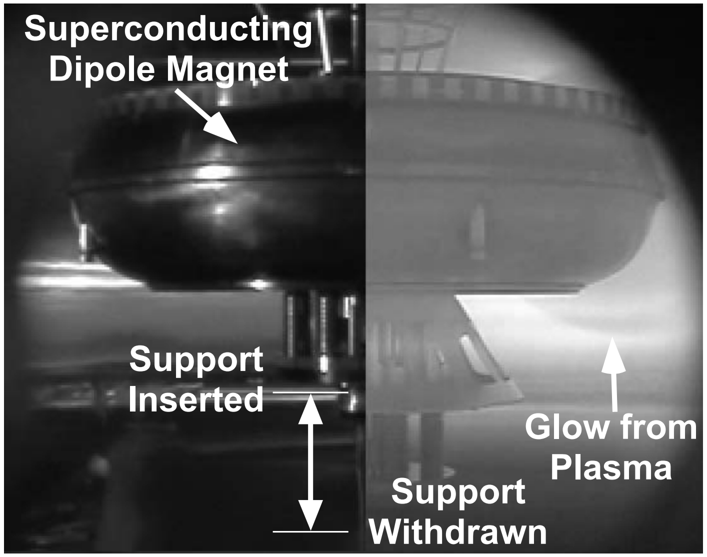
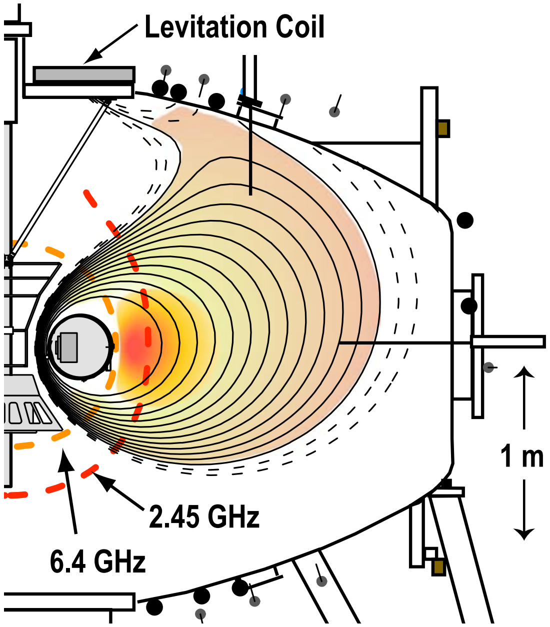




Inward Turbulent Diffusion of Plasma in a Levitated Dipole

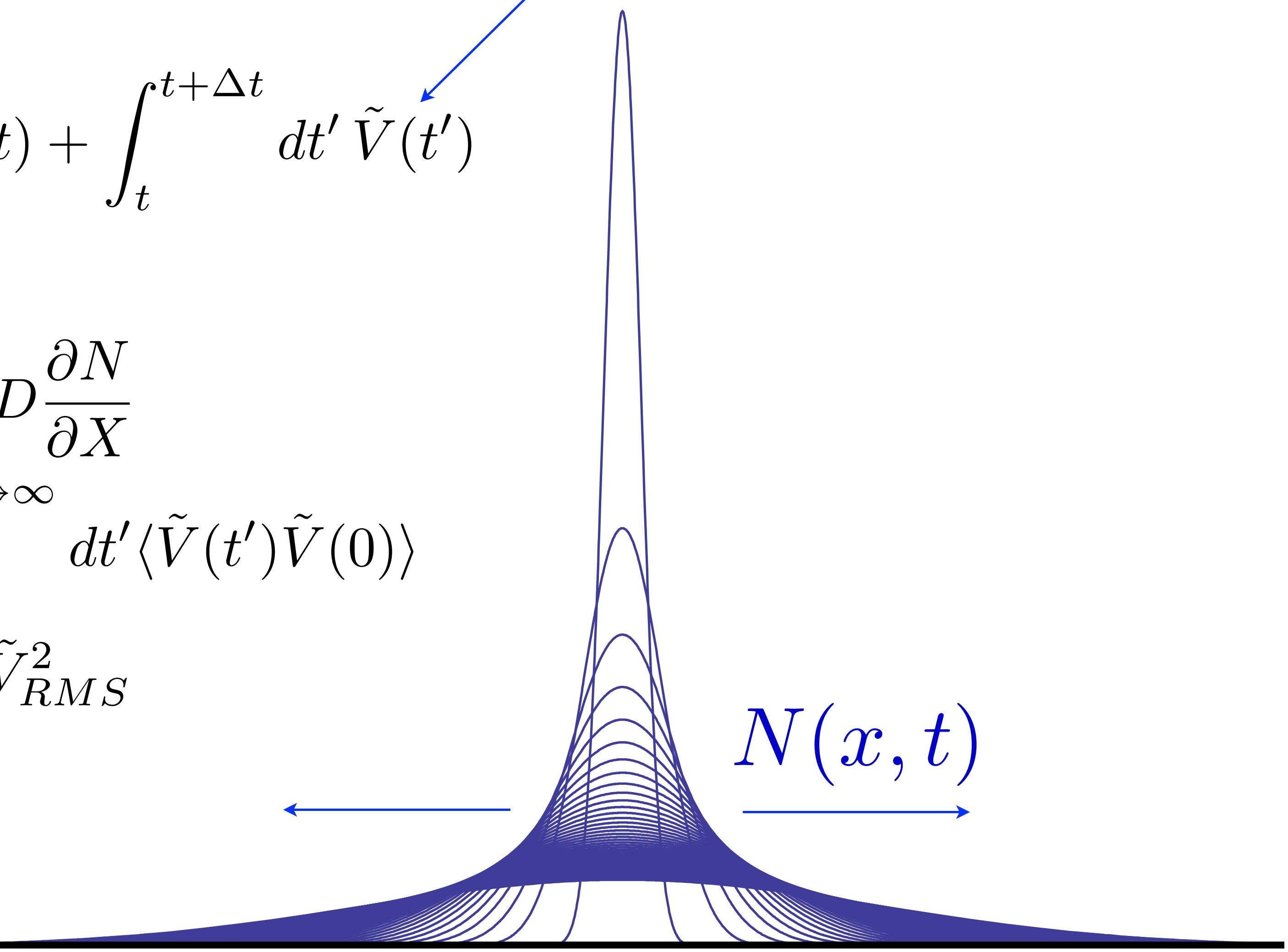
Columbia University

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

“Outward” Particle Diffusion

(Brownian Motion due to Random Velocity Fluctuations)

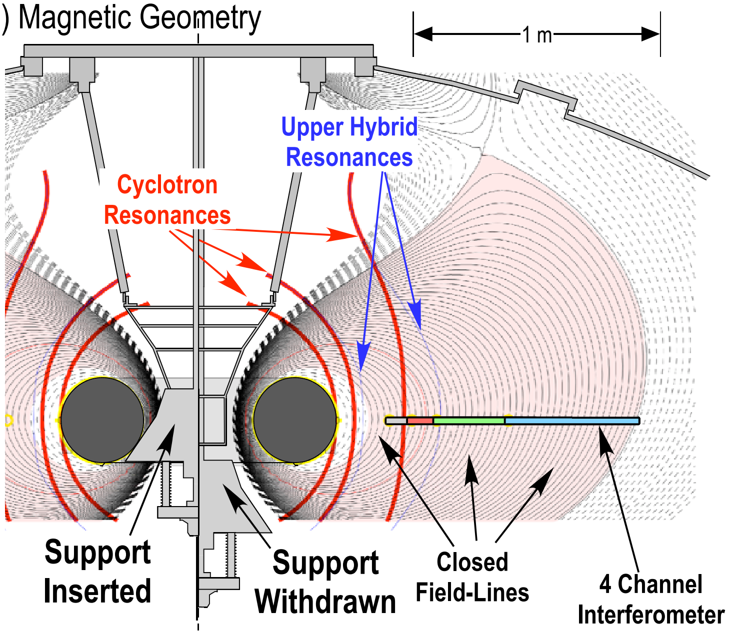
$$\begin{aligned}
X(t+\Delta t) &= X(t) + \int_t^{t+\Delta t} dt'\, \tilde{V}(t') \\
\text{where } \langle \tilde{V} \rangle &= 0 \\
\text{then } \frac{\partial N}{\partial t} &= \frac{\partial}{\partial X} D \frac{\partial N}{\partial X} \\
\text{with } D &= \int_0^{t\to\infty} dt' \langle \tilde{V}(t') \tilde{V}(0) \rangle \\
&= \tau_{cor} \tilde{V}_{RMS}^2
\end{aligned}$$



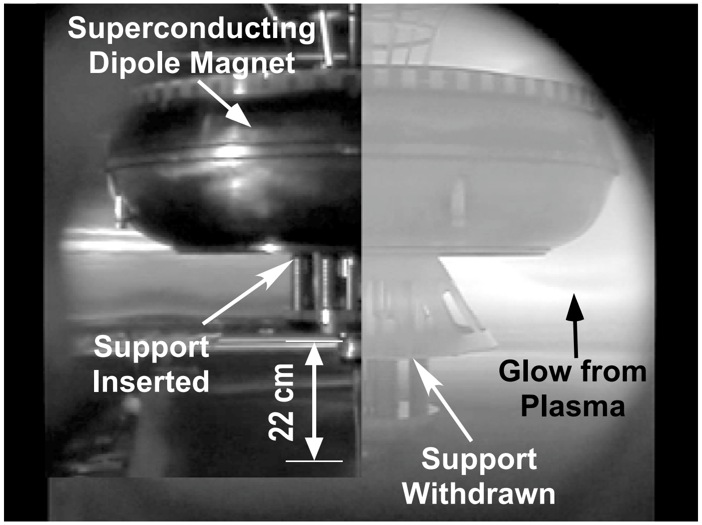
“Inward” Diffusion in Magnetized Plasma

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

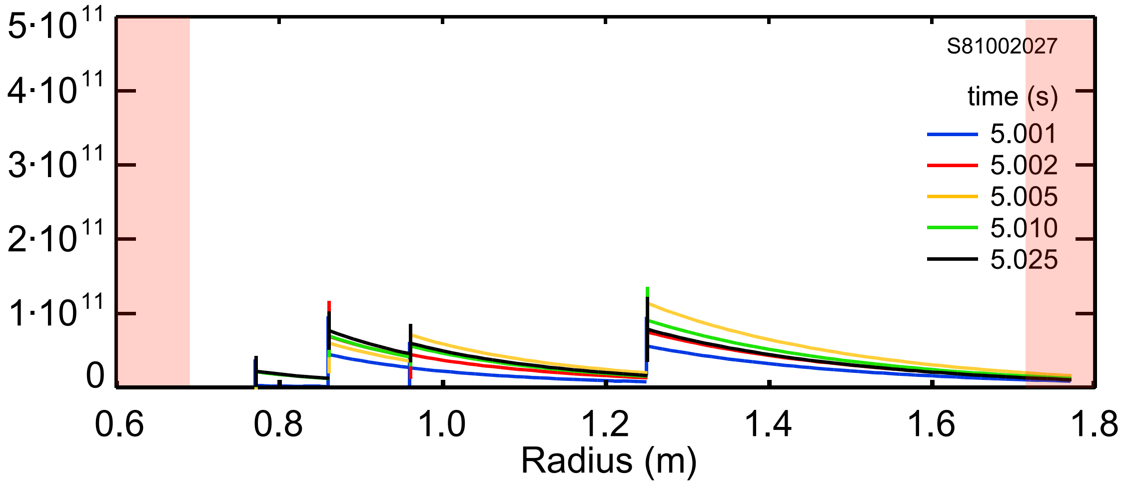
(a) Magnetic Geometry



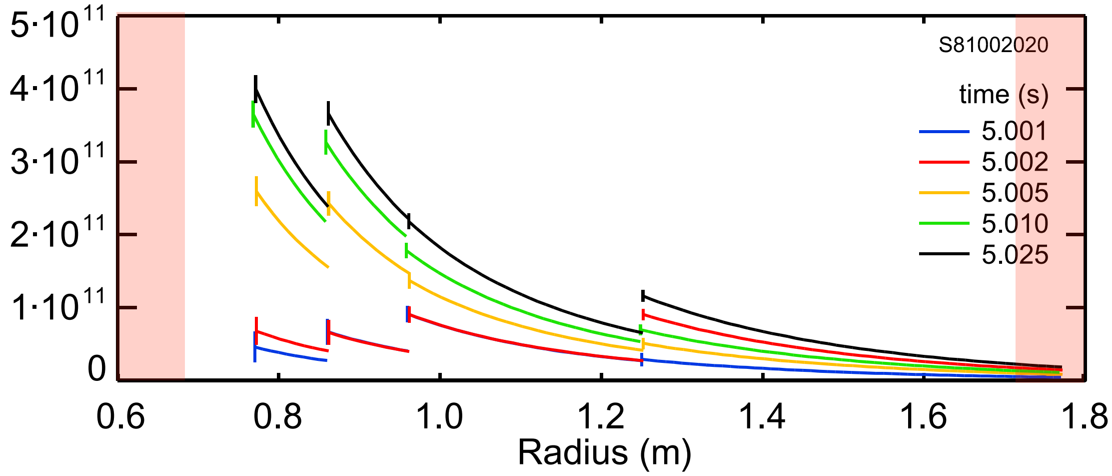
(b) Dipole Supported and Levitated



Supported: Density (Particles/cc)



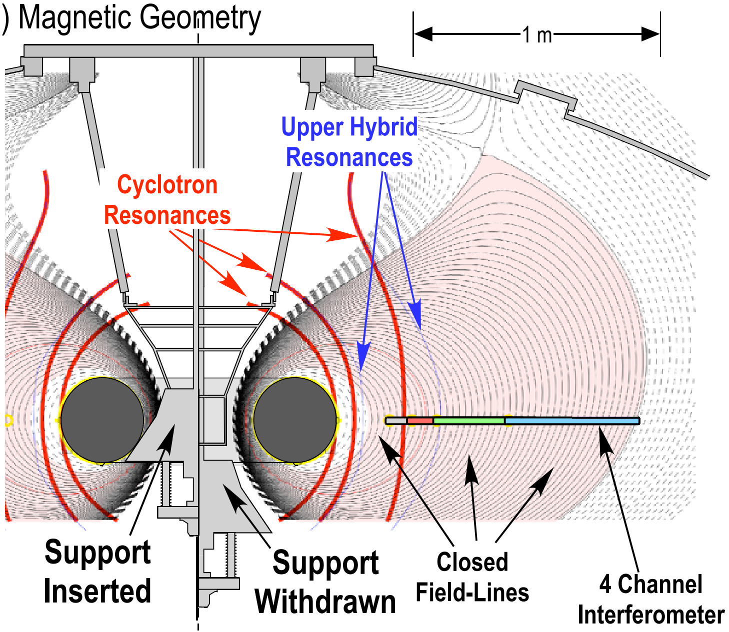
Levitated: Density (Particles/cc)



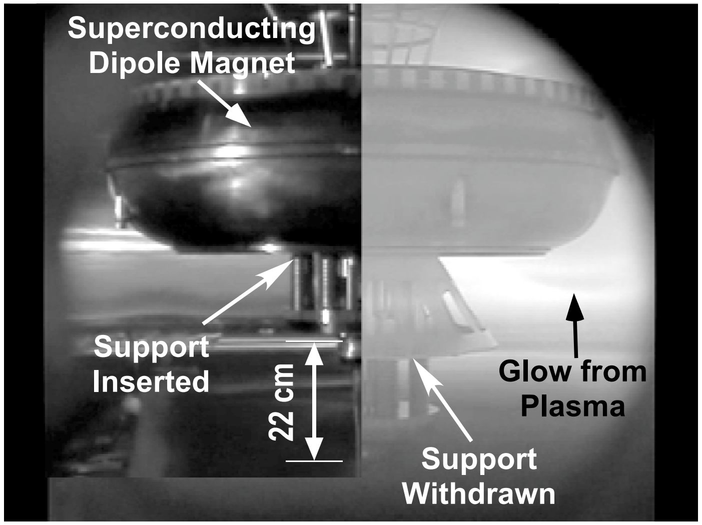
“Inward” Diffusion in Magnetized Plasma

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

(a) Magnetic Geometry



(b) Dipole Supported and Levitated

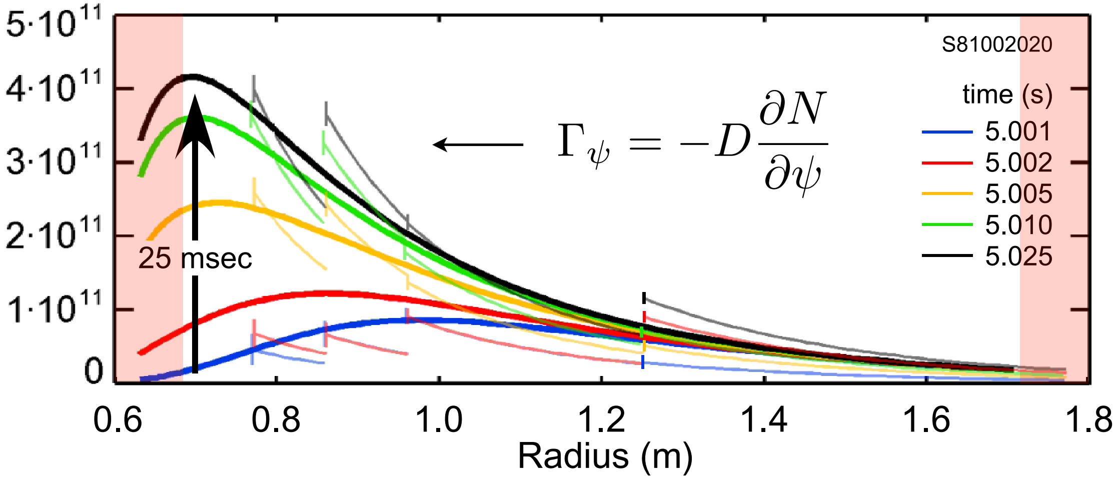


Turbulent “Inward Pinch”

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

$$\begin{aligned} D_{\psi,\psi} &= \lim_{t\to\infty} \oint_0^t dt \langle \dot{\psi}(t)\dot{\psi}(0)\rangle \\ &\equiv \langle \dot{\psi}^2 \rangle \tau_{cor} = R^2 \langle E_\phi^2 \rangle \tau_{cor} \end{aligned}$$

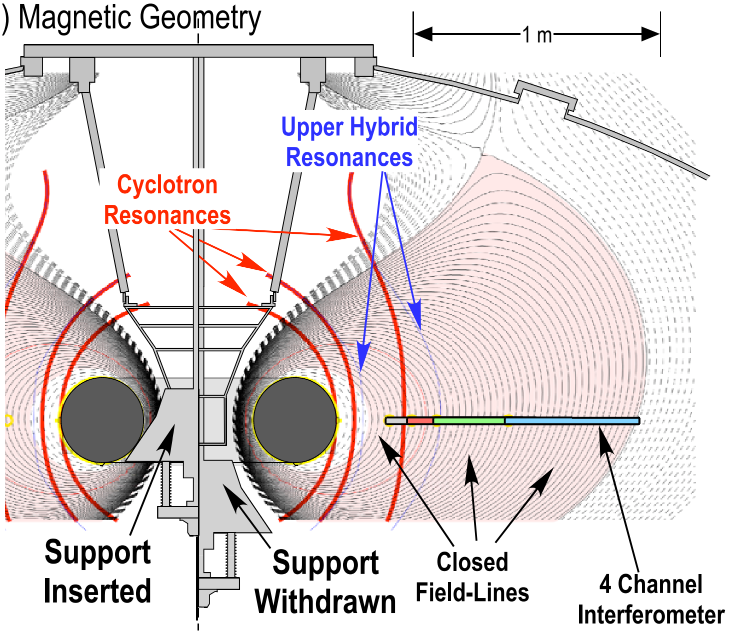
Levitated: Density (Particles/cc)



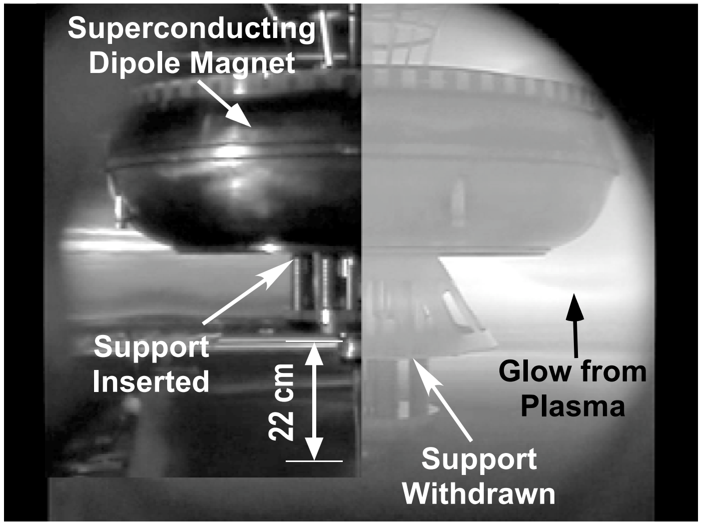
“Inward” Diffusion in Magnetized Plasma

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

(a) Magnetic Geometry



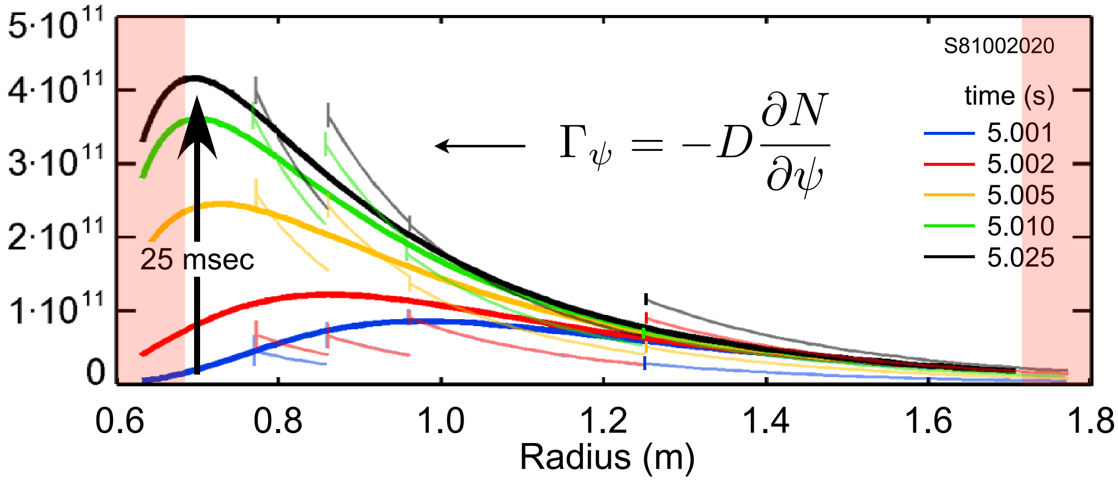
(b) Dipole Supported and Levitated



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

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

Levitated: Density (Particles/cc)



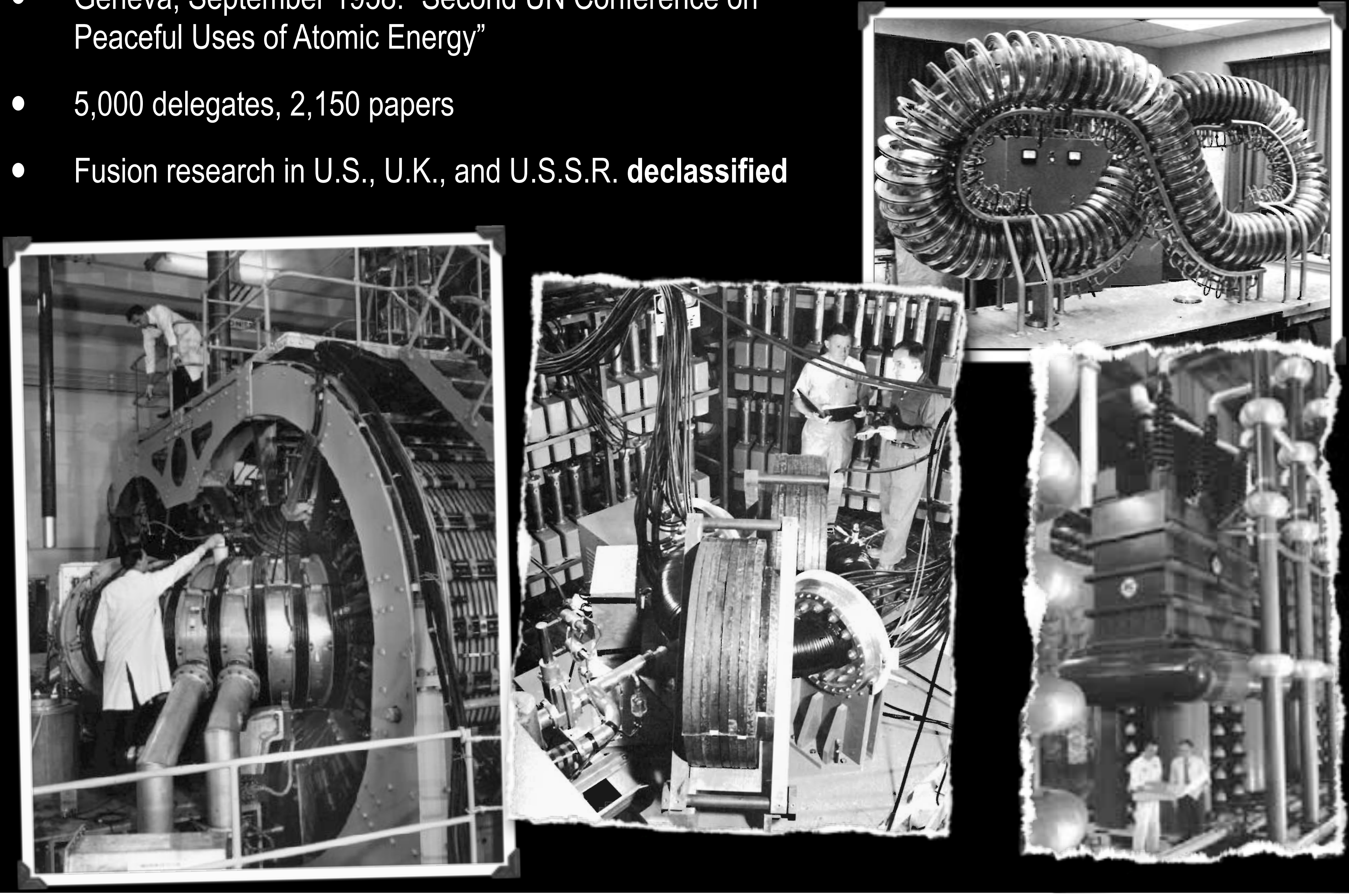
Outline

- Plasma confinement in a dipole magnetic field: **Laboratory Magnetosphere**
- Transport due to low-frequency fluctuations: **Electrostatic Self-Organization**
- 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**, $G = P\delta V^{\gamma}$
- On-going research…

Happy Anniversary:

51 ~~50~~ Years of Declassified Fusion Research

- Geneva, September 1958: “Second UN Conference on Peaceful Uses of Atomic Energy”
- 5,000 delegates, 2,150 papers
- Fusion research in U.S., U.K., and U.S.S.R. **declassified**

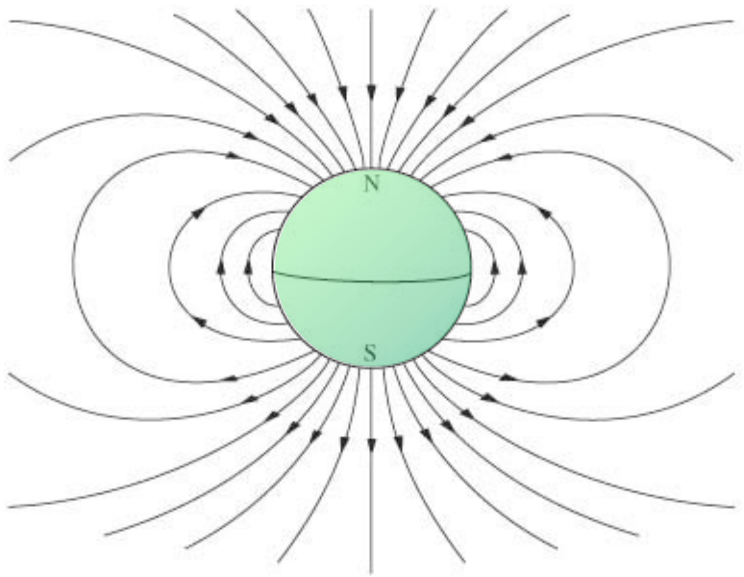


Happy Anniversary

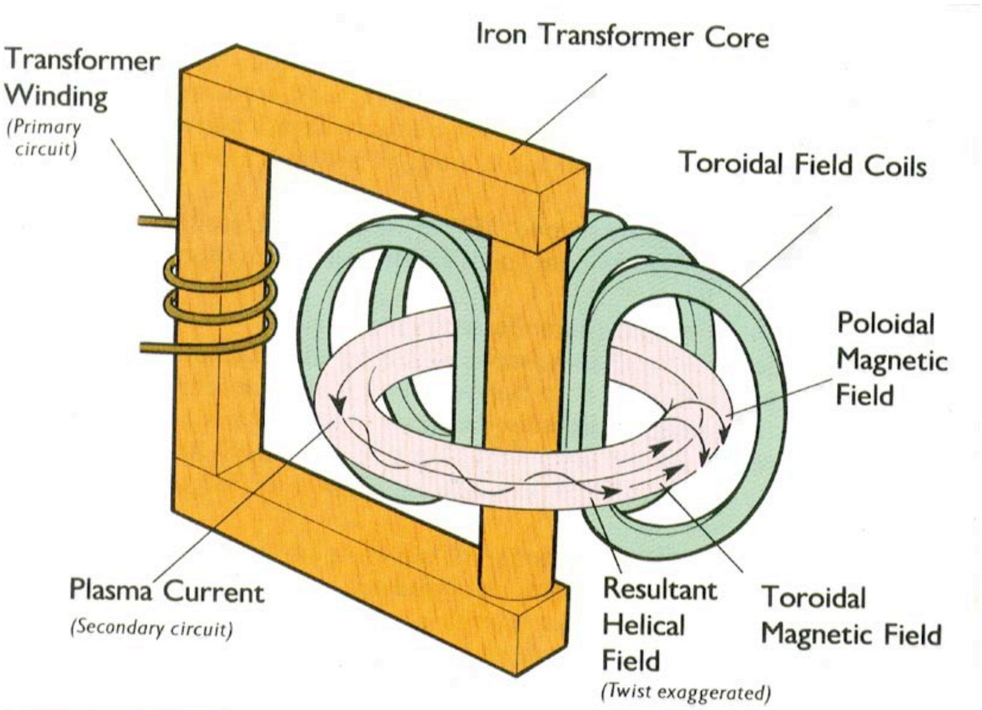
NASA founded October 1, 1958

Discovery of the radiation belts
Explorer 1 (January 31, 1958) and
Explorer III (March 26, 1958)

Space & Laboratory Magnetic Confinement

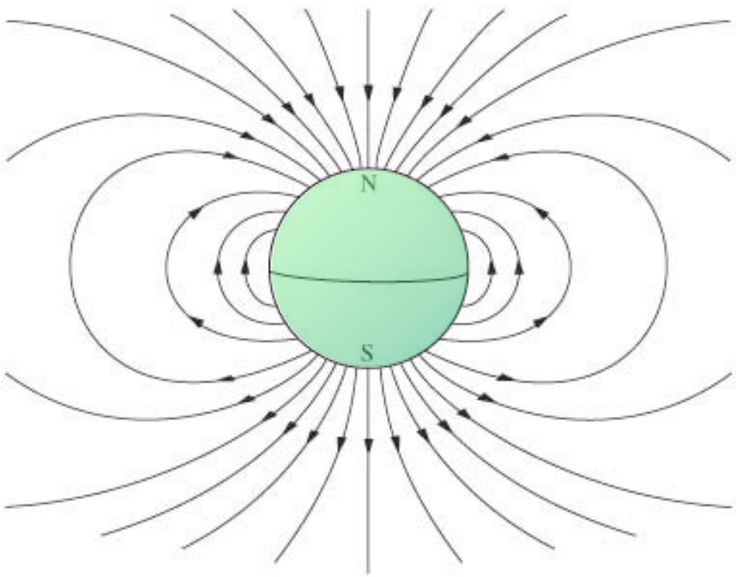


$$B(r,\theta,\phi) = \frac{M}{r^3}\sqrt{1+3\cos^2\theta}$$

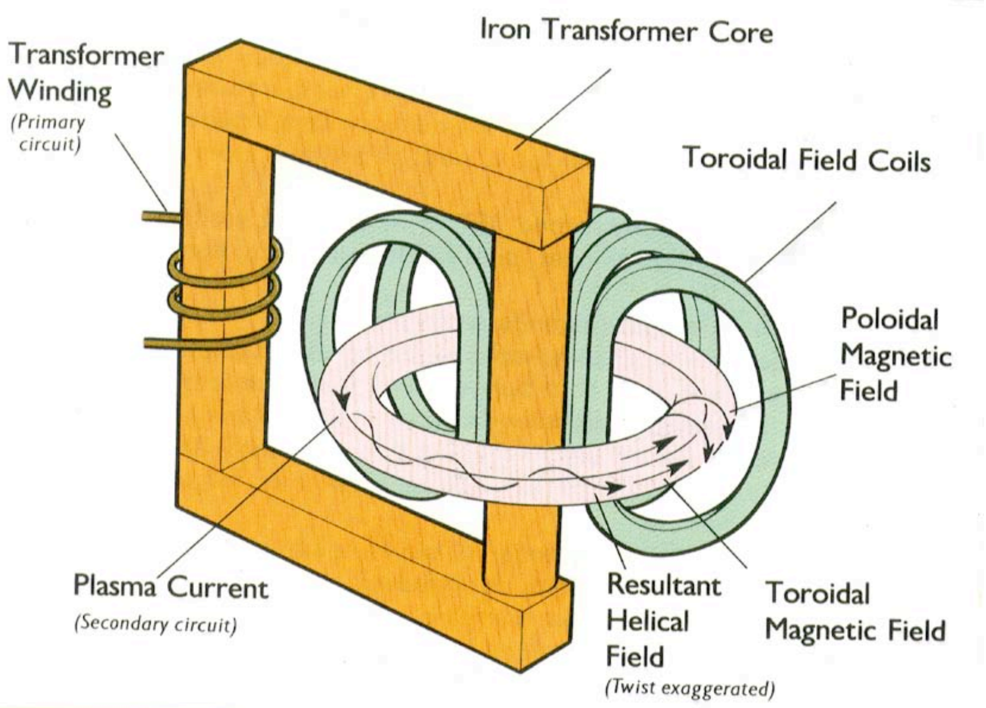


Internal "coil" Large **external** confinement volume	**External** coil Small **internal** confinement volume
Internal (planetary) particle source; **B-lines contact polar caps**	Particles fueled from edge; **B-lines form nested surfaces**
No rotational transform No magnetic shear	Rotational transform **required** Magnetic shear (toroidal field)
Gravity and rotation important	Rotation and plasma flow important
Dynamics driven from sun; Energy flux from sun	Dynamics driven by self-generated instability; Energy from applied heating (RF, beams)

Space & Laboratory Magnetic Confinement



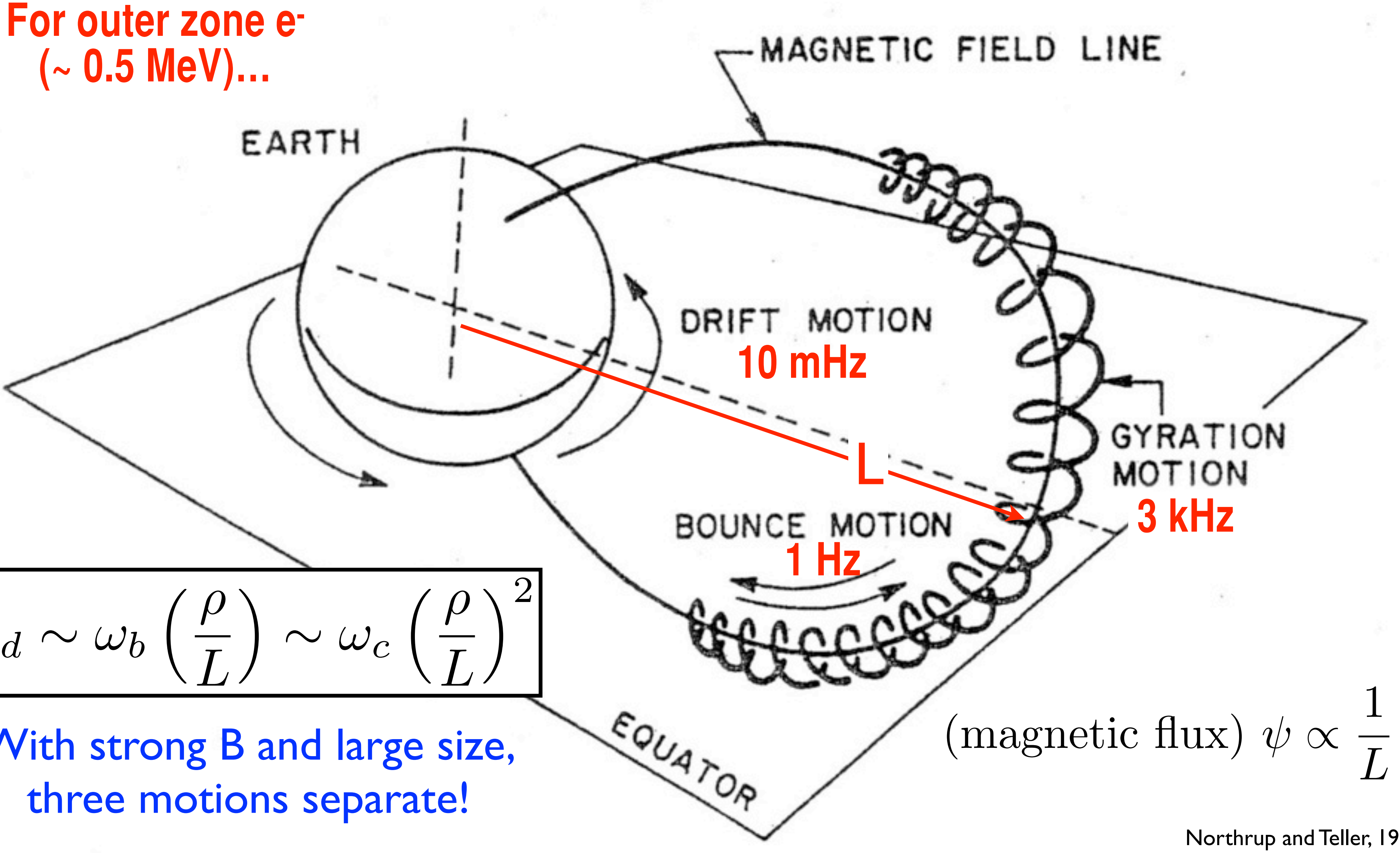
$$B(r,\theta,\phi) = \frac{M}{r^3}\sqrt{1+3\cos^2\theta}$$



- How well are particles and energy confined?
- What are the plasma profiles? How do they change?
- How can we describe/predict plasma dynamics?

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

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



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

With strong B and large size, three motions separate!

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

Northrup and Teller, 1960

Low-Frequency **E×B** Dynamics

(1D, $k_\perp \rho \ll 1$, Gyrokinetics!)

Low-frequency fluctuations mean…

"interchange dynamics"

- Conservation of (μ, J): $\omega \lll \omega_b \lll \omega_c$
- No parallel electric field: $\mathbf{E} \cdot \mathbf{B} = 0$
- Fluctuating cross field motion is **E×B**
- Entire "flux tubes" of plasma interchange during turbulent mixing

$$
\begin{aligned}
N(\psi, \varphi) &= \int d\mu dJ \, F(\mu, J, \psi, \varphi) = \oint \frac{dl}{B} n = \langle n \rangle \delta V \\
&= \text{Number of particles with a ``fluxtube'' } (\delta\psi)
\end{aligned}
$$

Low-Frequency **E×B** Dynamics

(1D, $k_\perp \rho \ll 1$, Gyrokinetics!)

$$\mathbf{V} = \delta\mathbf{E}\times\mathbf{B} = -\hat{\varphi}R\frac{\partial\Phi}{\partial\psi} + \overbrace{\frac{\hat{\psi}}{RB}}^{\text{Radial Transport}}\frac{\partial\Phi}{\partial\varphi}$$

"Interchange Dynamics"

$$\begin{aligned} \dot{\mu} &= 0 \; (\omega \ll \omega_c) \\ \dot{J} &= 0 \; (\omega \ll \omega_b) \end{aligned}$$

2D Gyrokinetic Phase Space

$$\left\{ \begin{aligned} \dot{\psi} &= \nabla\psi\cdot\mathbf{V} = \frac{\partial\Phi}{\partial\varphi} = -RE_\varphi \;\; (\propto \delta\mathbf{E}\times\mathbf{B}) \\ \dot{\phi} &\approx \omega_d(\mu,\, J,\, \psi) + \omega_E(\psi) \end{aligned} \right.$$

2D Fluxtube Dynamics

A. Chan, L. Chen, R. White, *GRL* (1989)

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

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

α = magnetic flux, ψ

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

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

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 ϕ are both constant on dipole field lines, **B** lines are equipotentials, and **E**·**B** is zero. In the $\vartheta = \pi/2$, equatorial plane

Collisionless Random Electric Convection

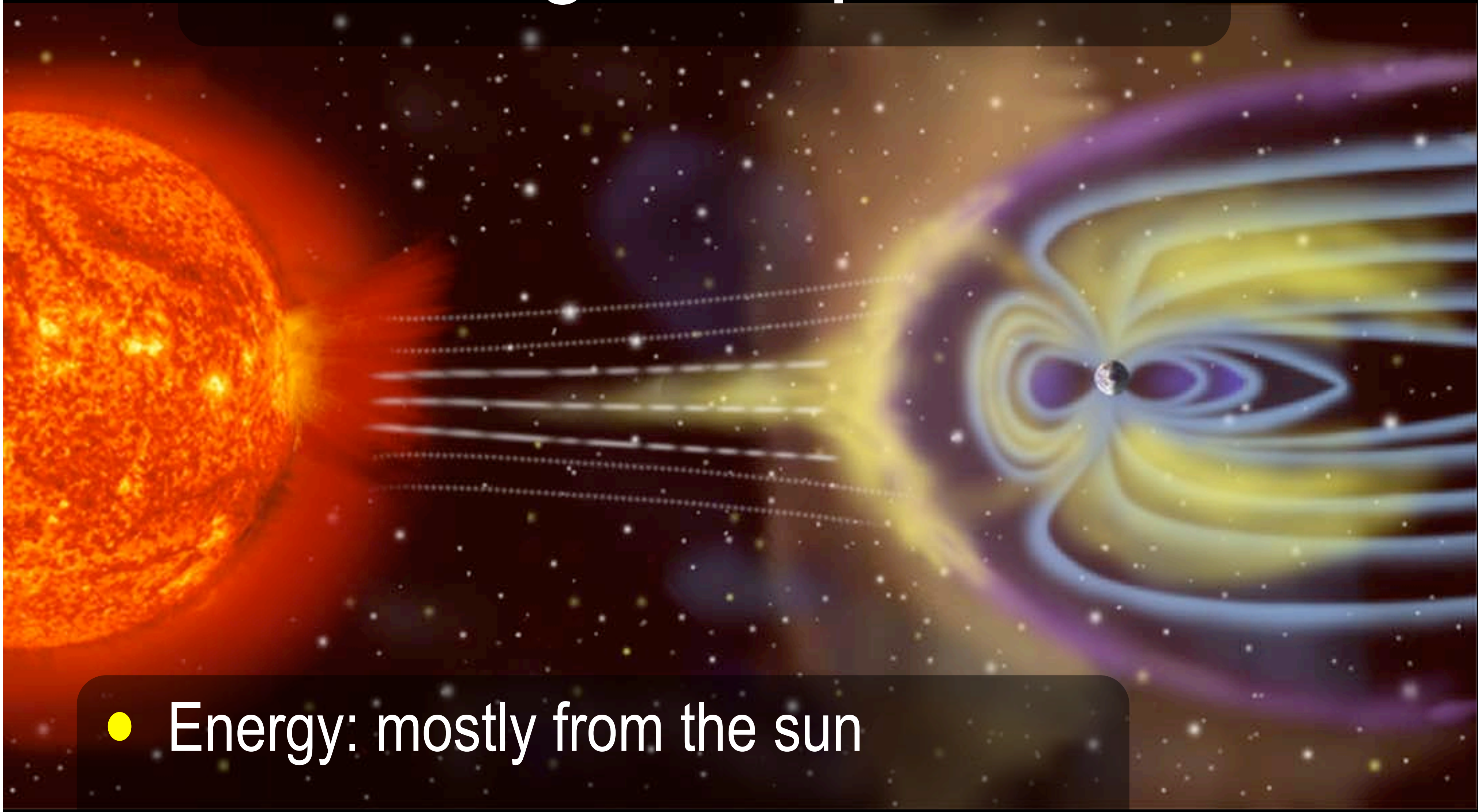
$$\boxed{\overline{D_{\alpha\alpha}} \approx \frac{c^2\mu^2}{4\alpha^2}(\pi)^{1/2}\tau_c\mathfrak{A}} \qquad (18)$$

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

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

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 τ_c is thus typically one hour.)

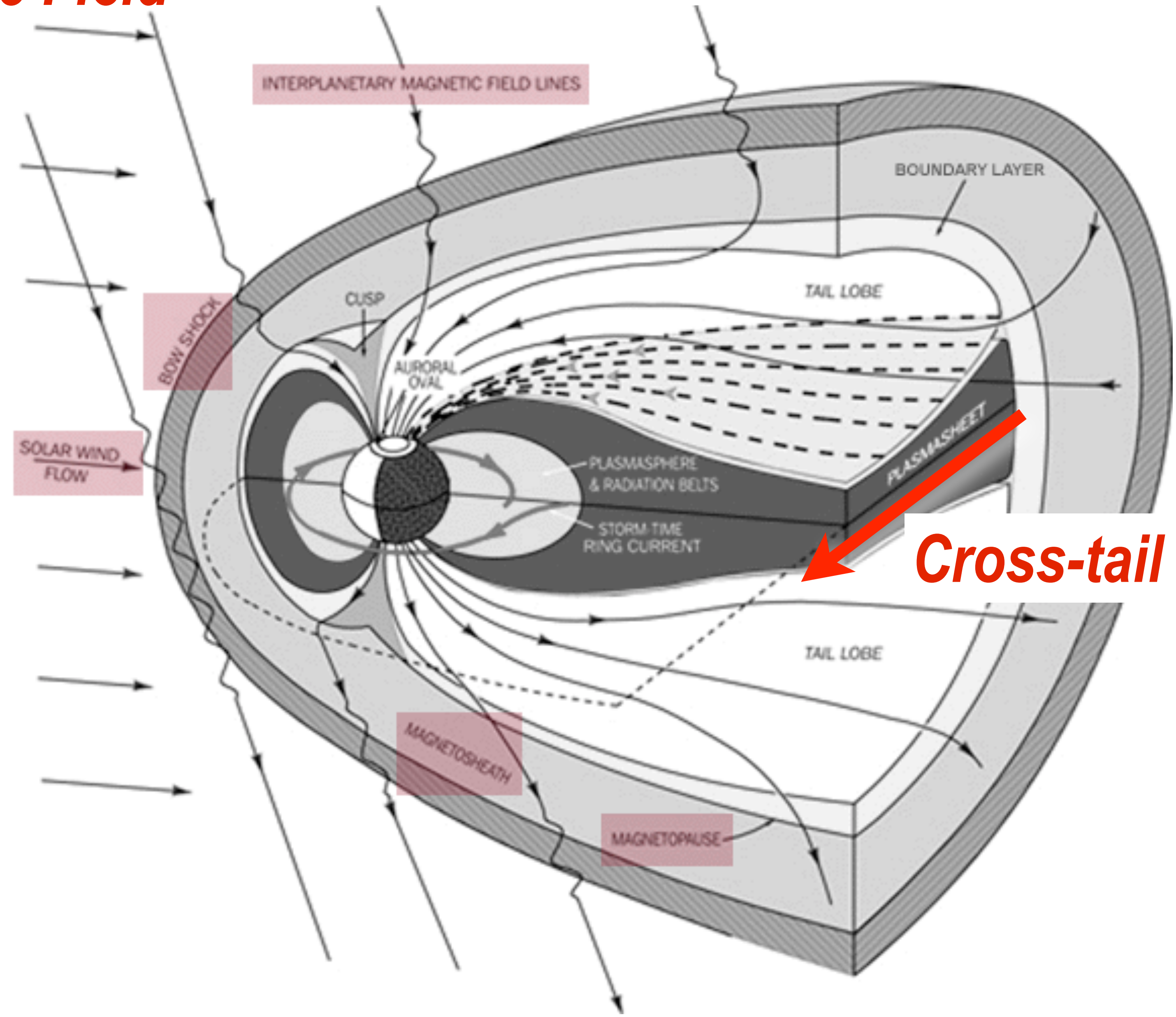
Magnetosphere



- Energy: mostly from the sun
- Particles: mostly from the atmosphere

Structure of Magnetosphere

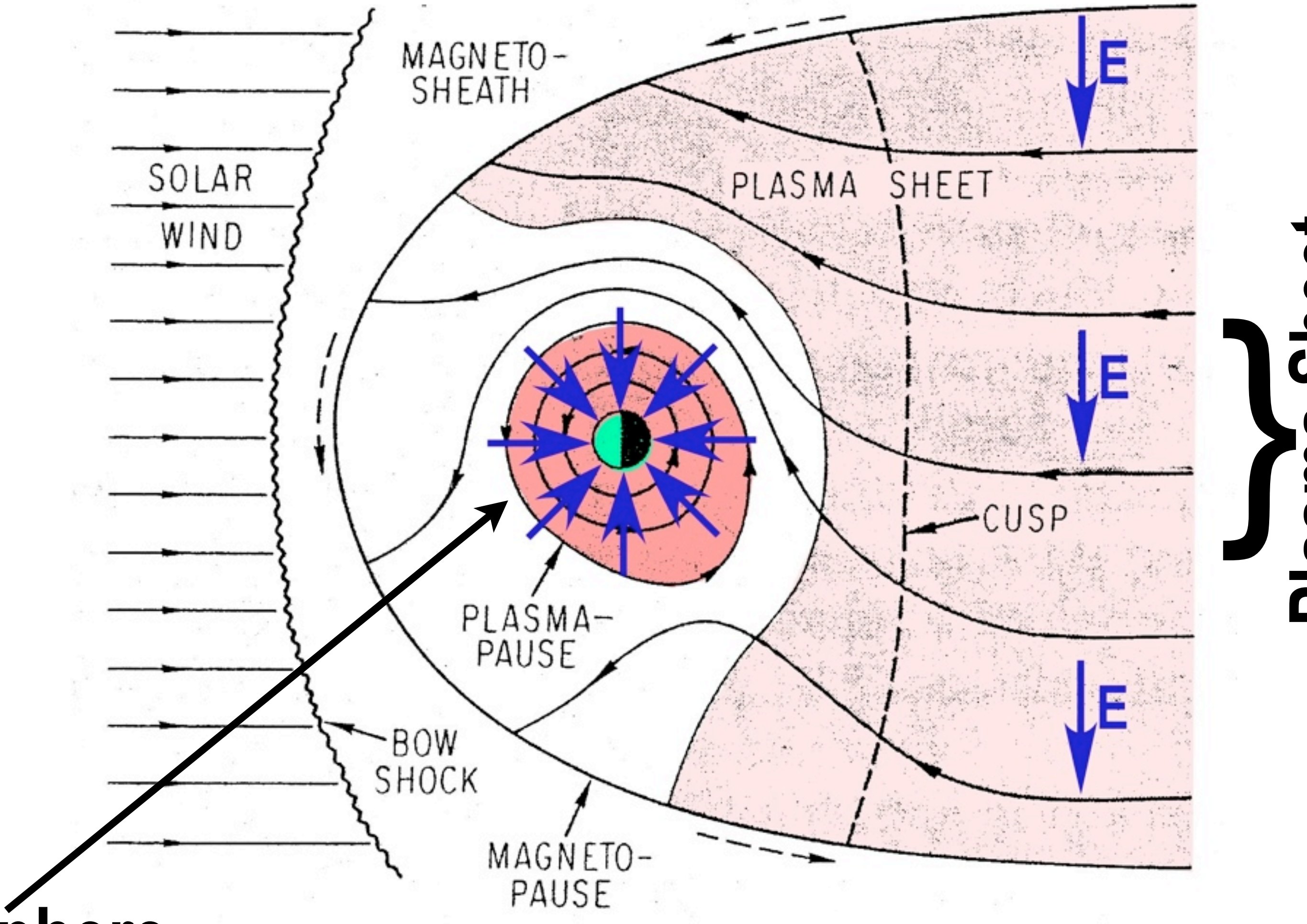
Magnetic Field



Cross-tail current

Structure of Magnetosphere

Electric Field



Plasma Sheet Convection

Plasmasphere Co-Rotation

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

T. Birmingham, *JGR* (1969)

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)

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

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

Flux tube
particle number

Natural Profiles

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

  $(n, P) \Leftrightarrow (N, G)$ are related by **flux tube volume**, $\delta V = \int ds/B$

- Random fluctuations cause radial diffusion or plasma "flux-tubes". Interchange mixing flattens $\partial[N$ and $G]/\partial\psi \rightarrow 0$ **at the same rate**.

➡ **Natural profiles** mean ***N* and *G* are homogeneous.**

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

Natural Profiles in Solenoidal Geometry

Solenoid, theta-pinch, large aspect ratio torus, …

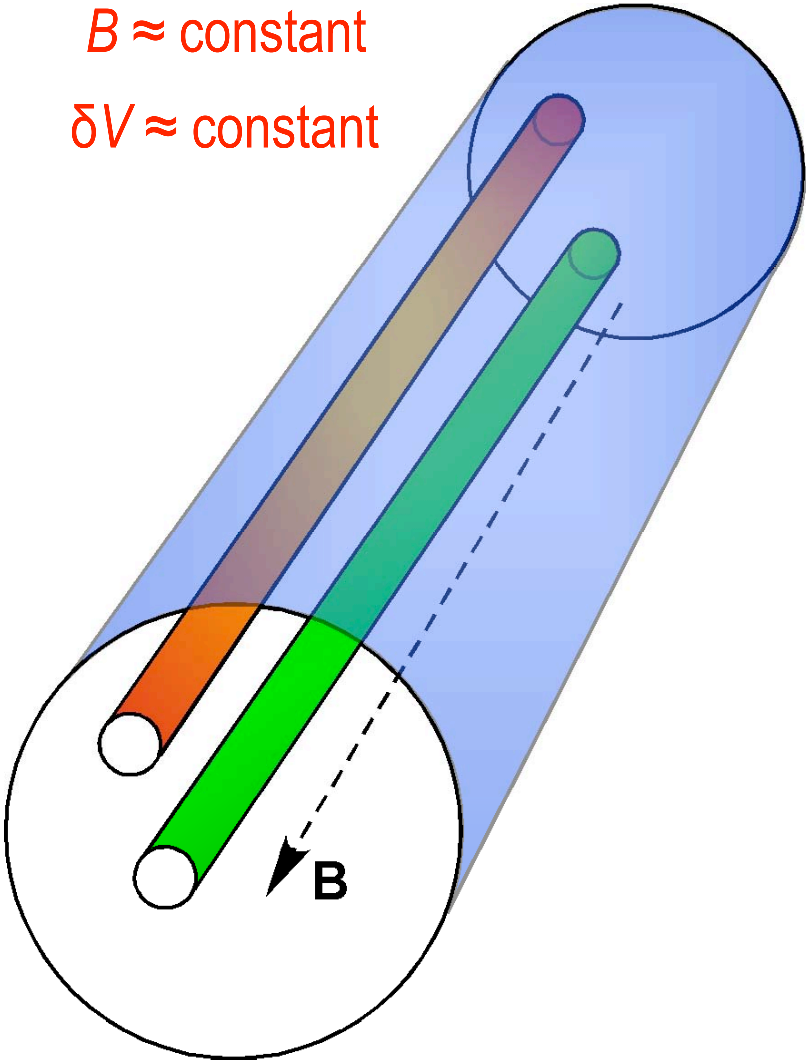
- Flux tube volume:
  - $\delta V = \int ds/B =$ constant

- Natural profiles:
  - $n\,\delta V =$ constant
  - $P\,\delta V^{\gamma} =$ constant
  - **Density and pressure profiles are flat**

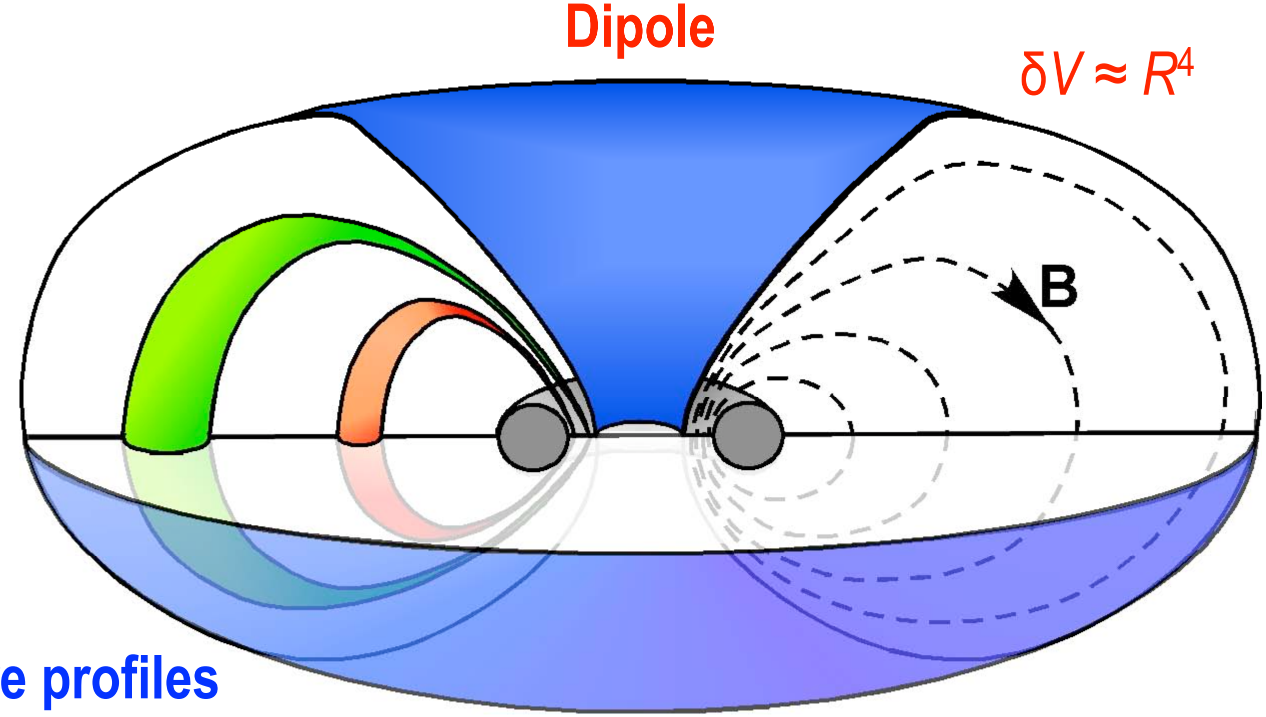
➡ Density, pressure, and temperature at edge and at core are equal ***unless interchange mixing is suppressed.***

$B \approx$ constant

$\delta V \approx$ constant



Natural Profiles in Dipole Geometry



$B \approx 1/R^3$

$\delta V \approx R^4$

- Flux tube volume:
  - $\delta V = \int ds/B \approx R^4$
- Natural profiles:
  - $n\,\delta V = \text{constant}$
  - $P\,\delta V^\gamma = \text{constant}$
  - **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:

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

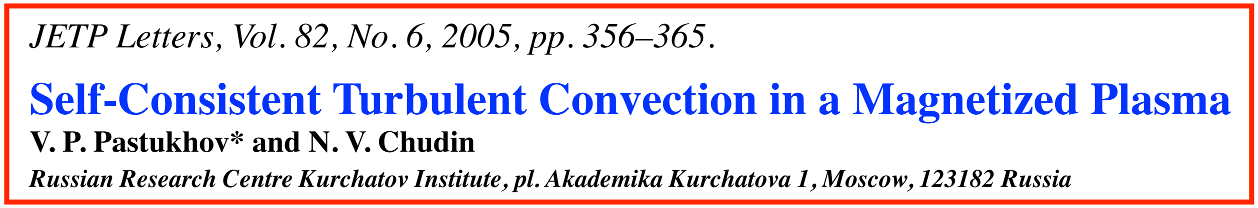
Natural Profiles are also Marginally Stable Profiles

➡ $N =$ *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).

Electrostatic Self-Organization

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

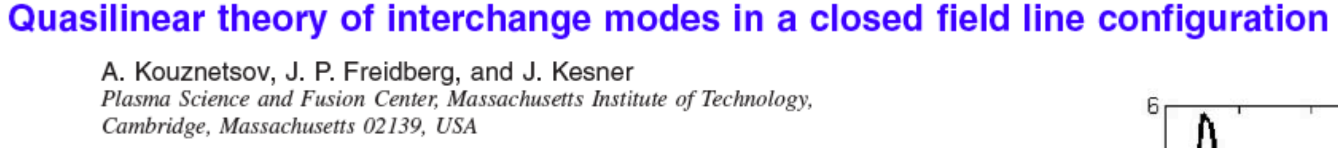


JETP Letters, Vol. 82, No. 6, 2005, pp. 356–365.

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

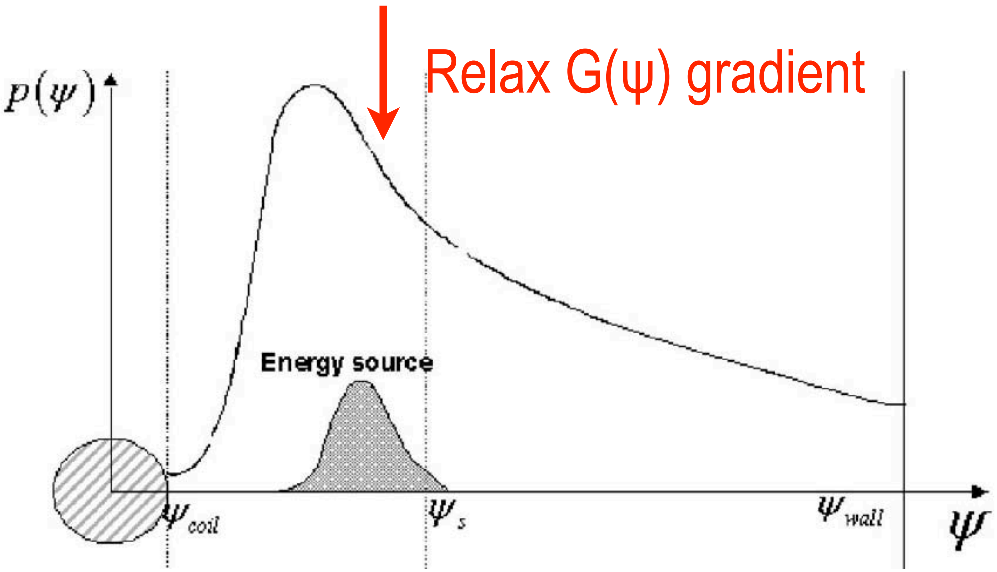


Quasilinear theory of interchange modes in a closed field line configuration

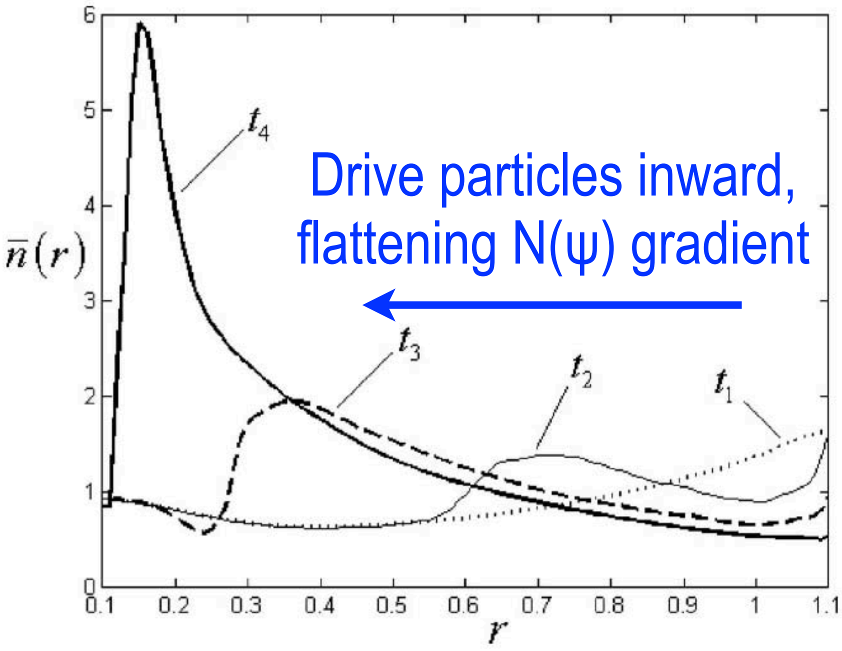
A. Kouznetsov, J. P. Freidberg, and J. Kesner

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

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



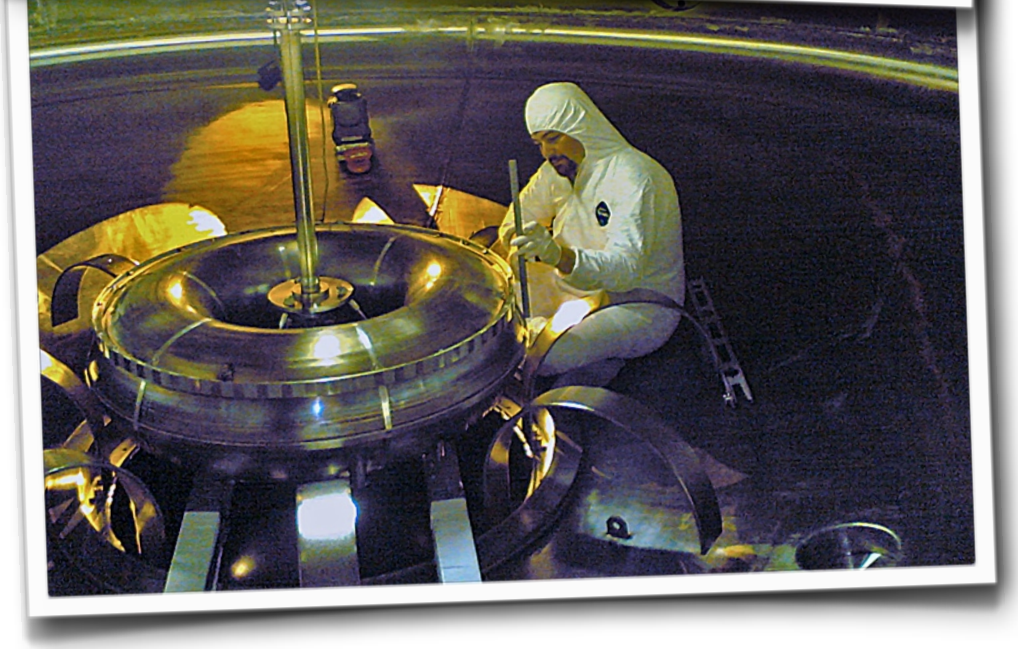
Relax G(ψ) gradient



Drive particles inward, flattening N(ψ) gradient

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.

Two Examples:
Plasma Dynamics Study



IMAGE

“Imager for Magnetopause-to-Aurora Global Exploration”

Launch: March 25, 2000
First satellite dedicated to global imaging of the Earth’s magnetosphere

LDX

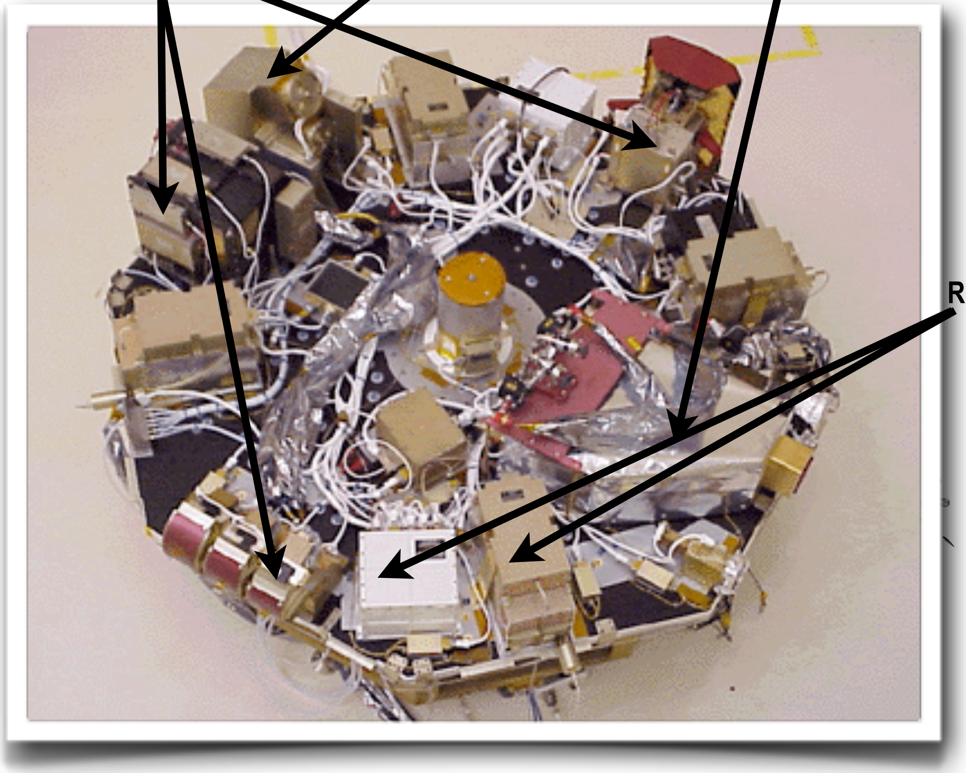
“Levitated Dipole Experiment”

Launch: August 13, 2004
First laboratory experiment dedicated to testing the applicability of space plasma physics for fusion energy

IMAGE Spacecraft

- Project start: 1997
- Launch/Mission: March 2000 to Dec 2005
- Weight: 494 kg

- Key diagnostics:

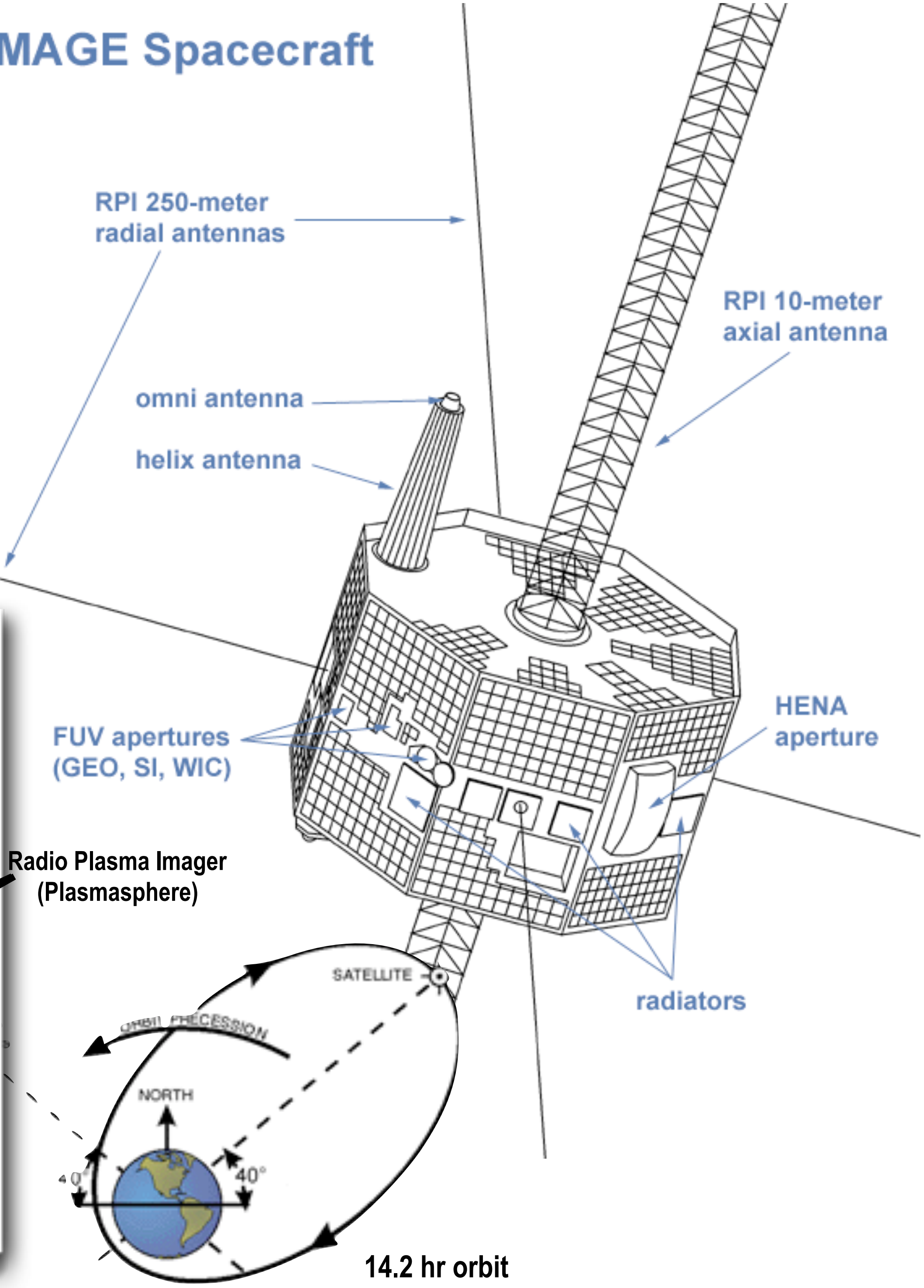


Extreme-Ultraviolet Imager
(Plasmasphere)

Neutral Atom Imagers
(Ring Current)

Far-Ultraviolet Imager
(Aurora)

Radio Plasma Imager
(Plasmasphere)



14.2 hr orbit

Levitated Dipole Experiment (LDX)

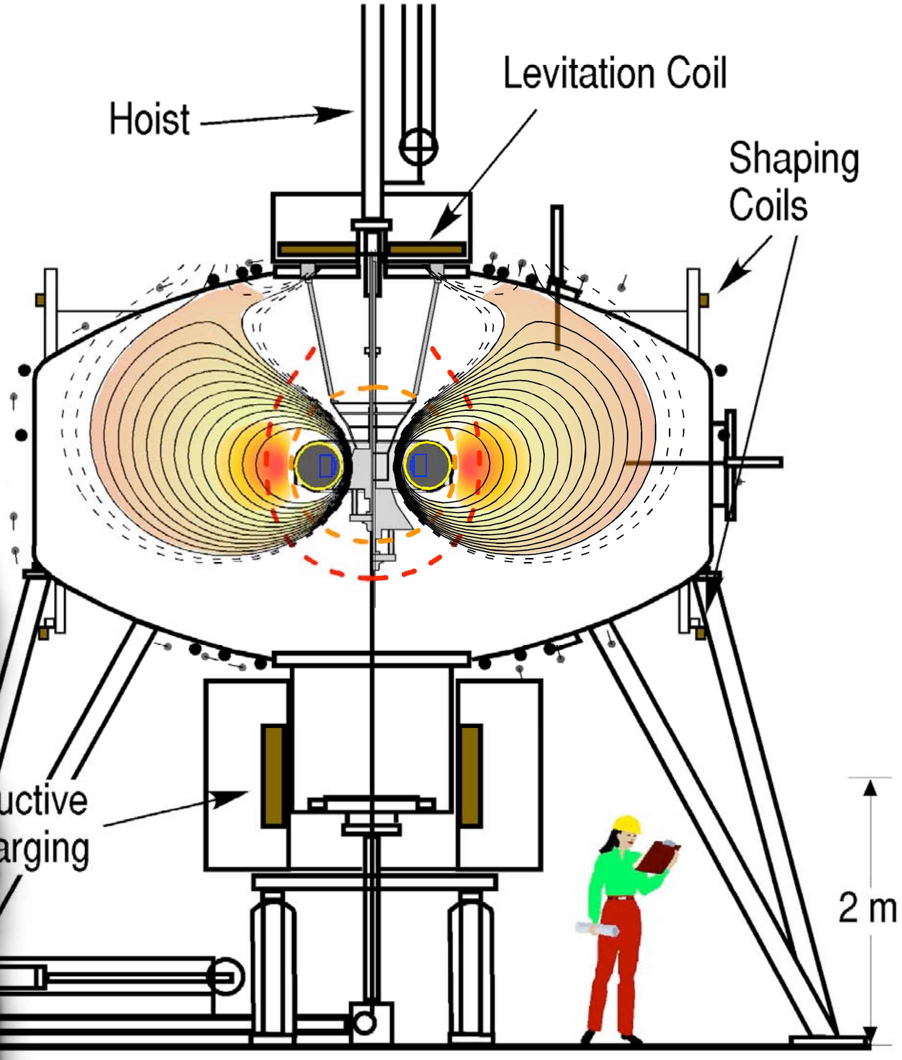
- Project start: 1999
- Launch/Mission: August 2004 to Present.
- Weight: 565 kg (floating coil)

- Key diagnostics:

Probes (Edge Dynamics & Structure)

Magnetic Loops (Ring Current)

Microwave Interferometers (Plasmasphere)



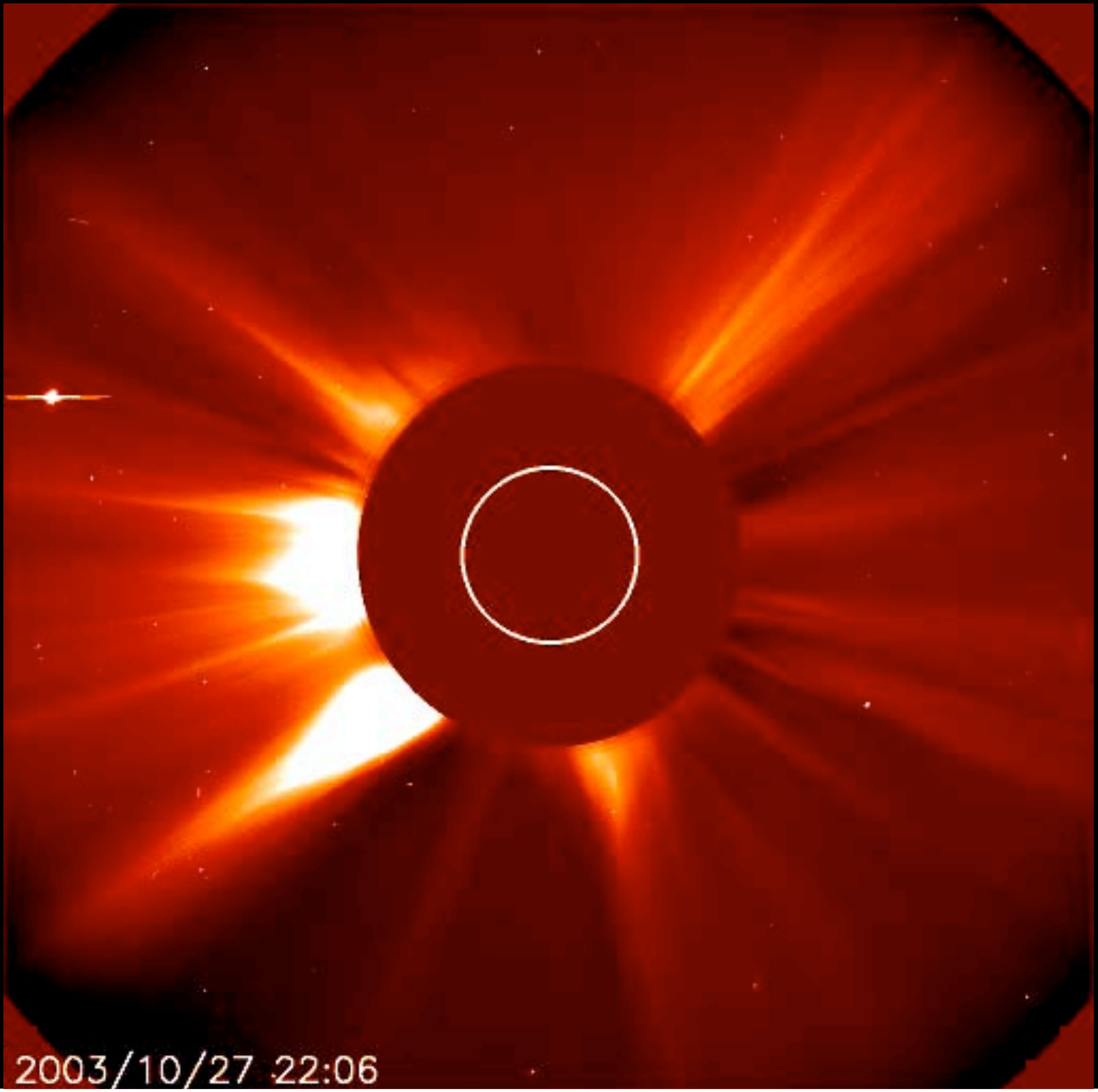
3 hr float time

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

Variable Solar Particle and Energy Flux

(SOHO: October 27-30, 2003)

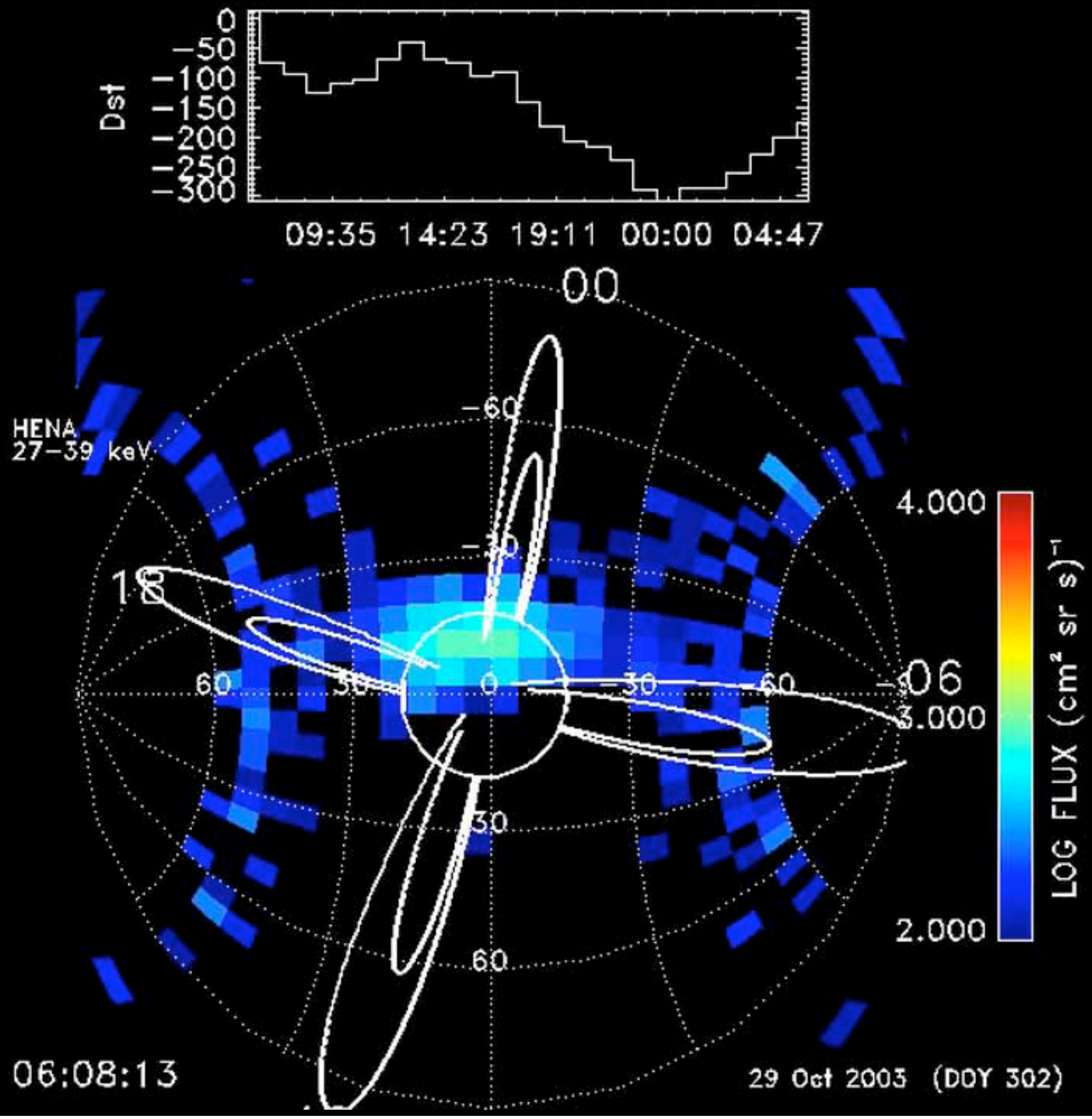
Coronal Mass Ejections especially frequent at Solar Maximum



Solar and Heliospheric Observatory

IMAGE: Ring Current

Charge Exchange Neutrals from Energetic Protons

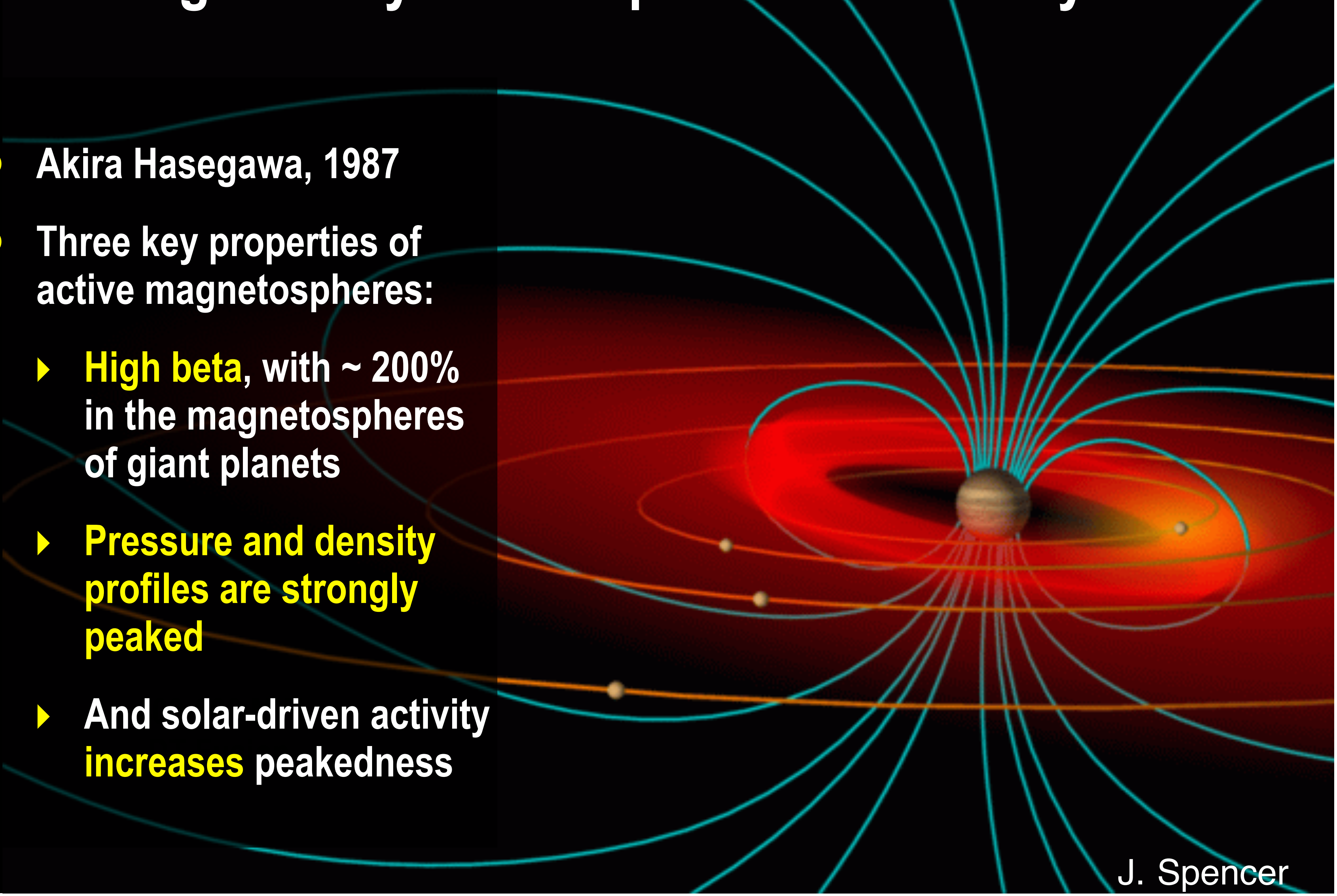


Log Scale!

Oct 29, 2003:
Magnetic Storm

Levitated Dipole Confinement Concept:

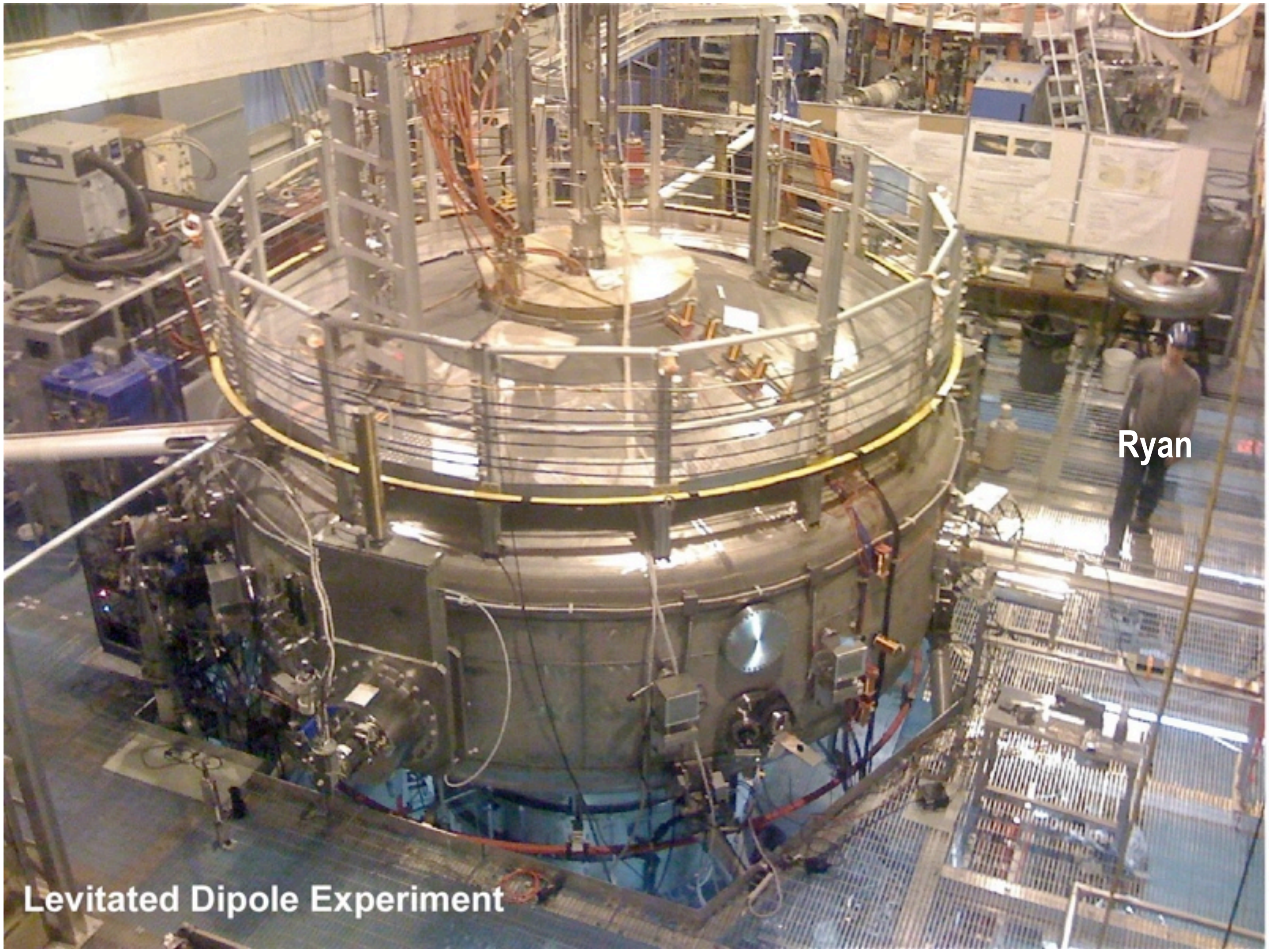
Combining the Physics of Space & Laboratory Plasmas



- Akira Hasegawa, 1987
- Three key properties of active magnetospheres:
  - **High beta**, with ~ 200% in the magnetospheres of giant planets
  - **Pressure and density profiles are strongly peaked**
  - And solar-driven activity **increases** peakedness

J. Spencer

LDX Experiment



Ryan

Levitated Dipole Experiment

Darren Garnier and Phil Michael

Jen Ellsworth
Jay Kesner and
Matt Davis

Previous Result using a Supported Dipole:

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

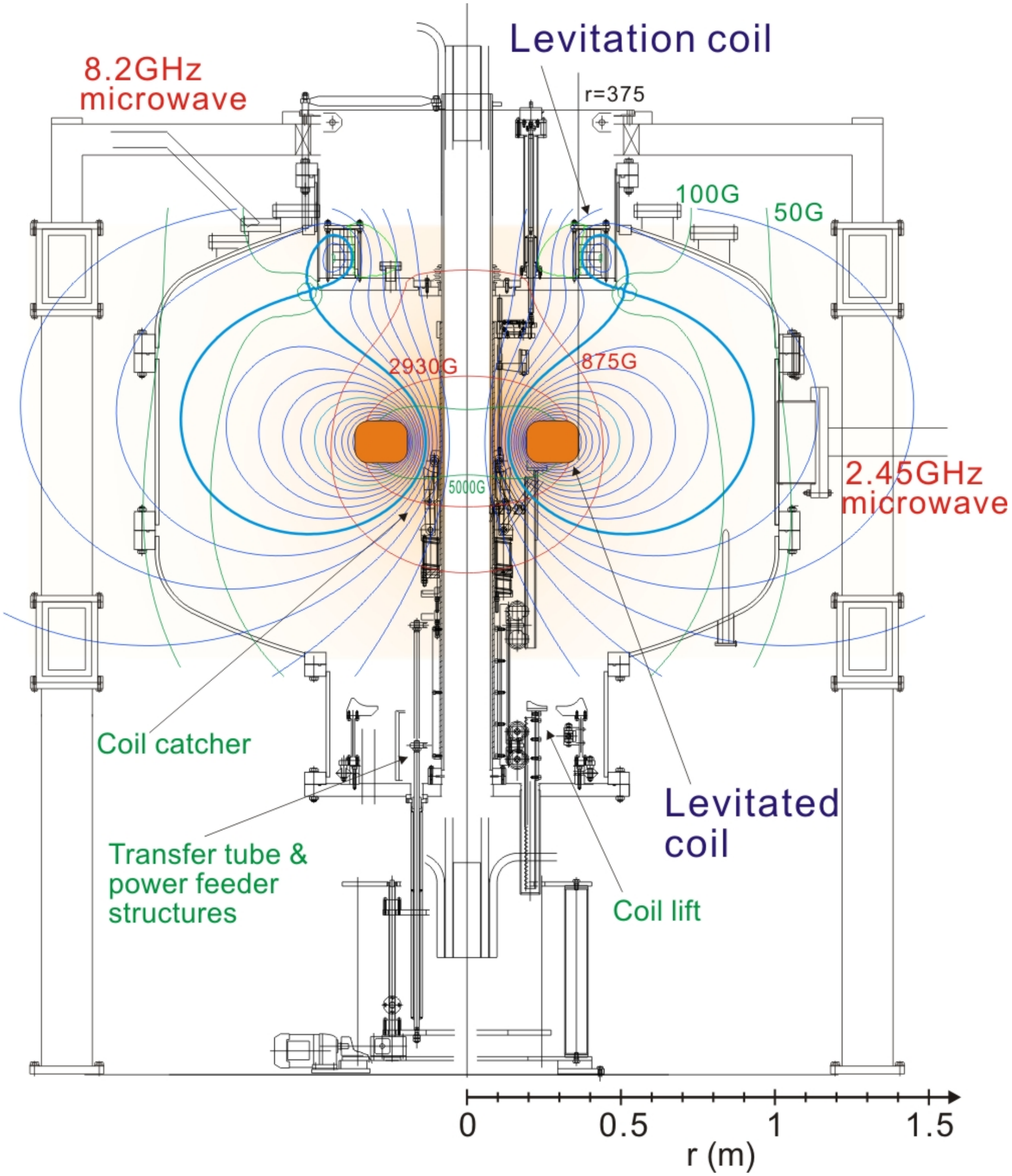
- Using 5 kW of long-pulse ECRH, plasma with trapped fast electrons ($E_h > 50$ keV) were sustained for many seconds.

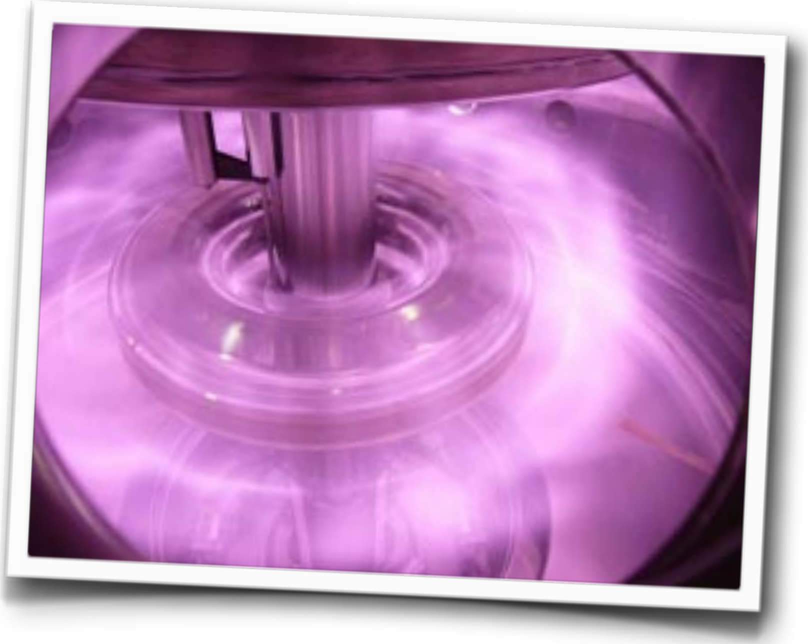
➡ Magnetic equilibrium reconstruction and x-ray imaging showed high stored energy > 300 J ($\tau_E > 60$ msec), high peak $\beta \sim 26\%$, and anisotropic fast electron pressure, $P_\perp / P_{||} \sim 5$.

- 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)

RT-1 (University of Tokyo)



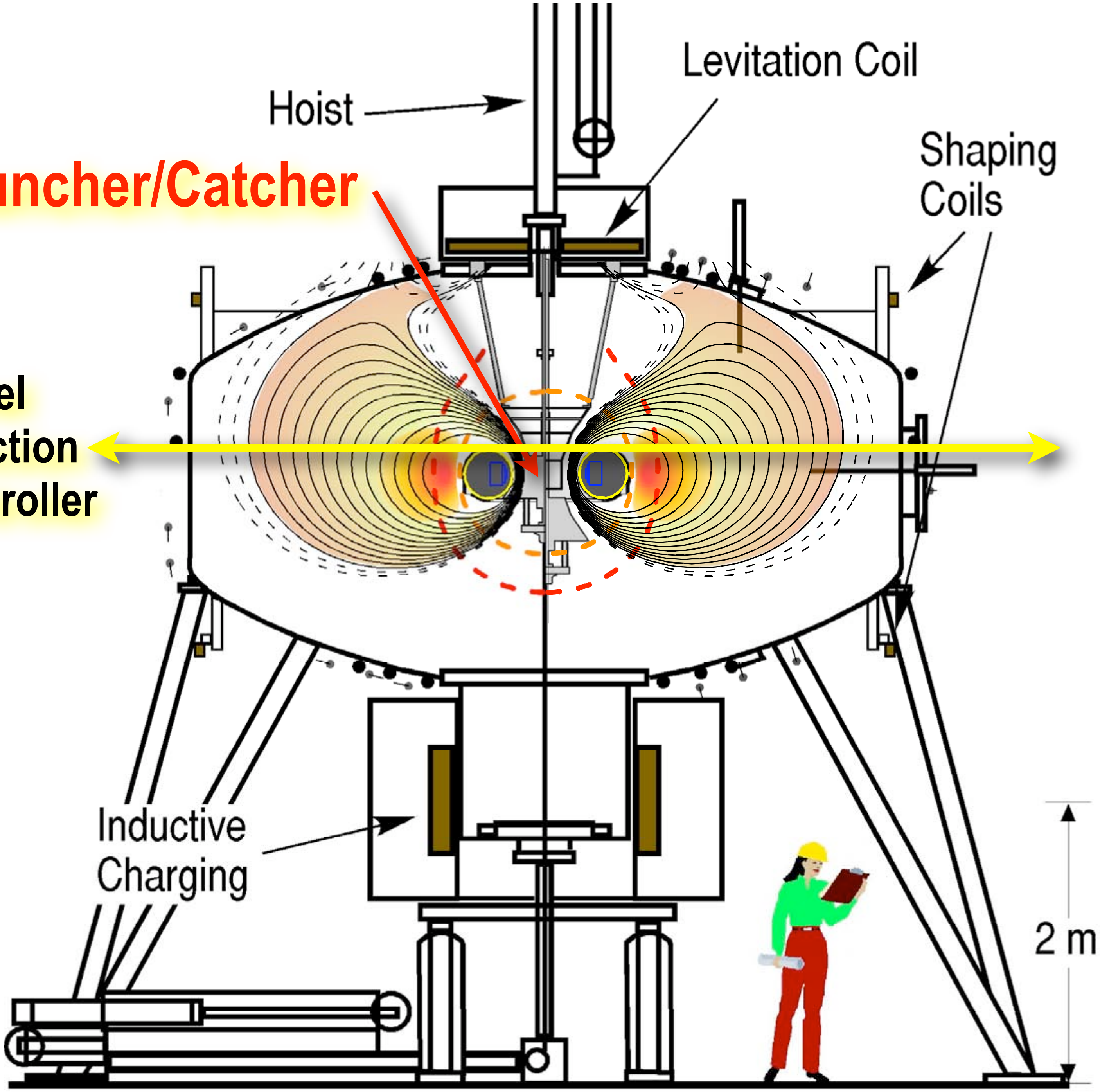


1/3-scale as LDX

High-beta (40%)

10 keV electrons

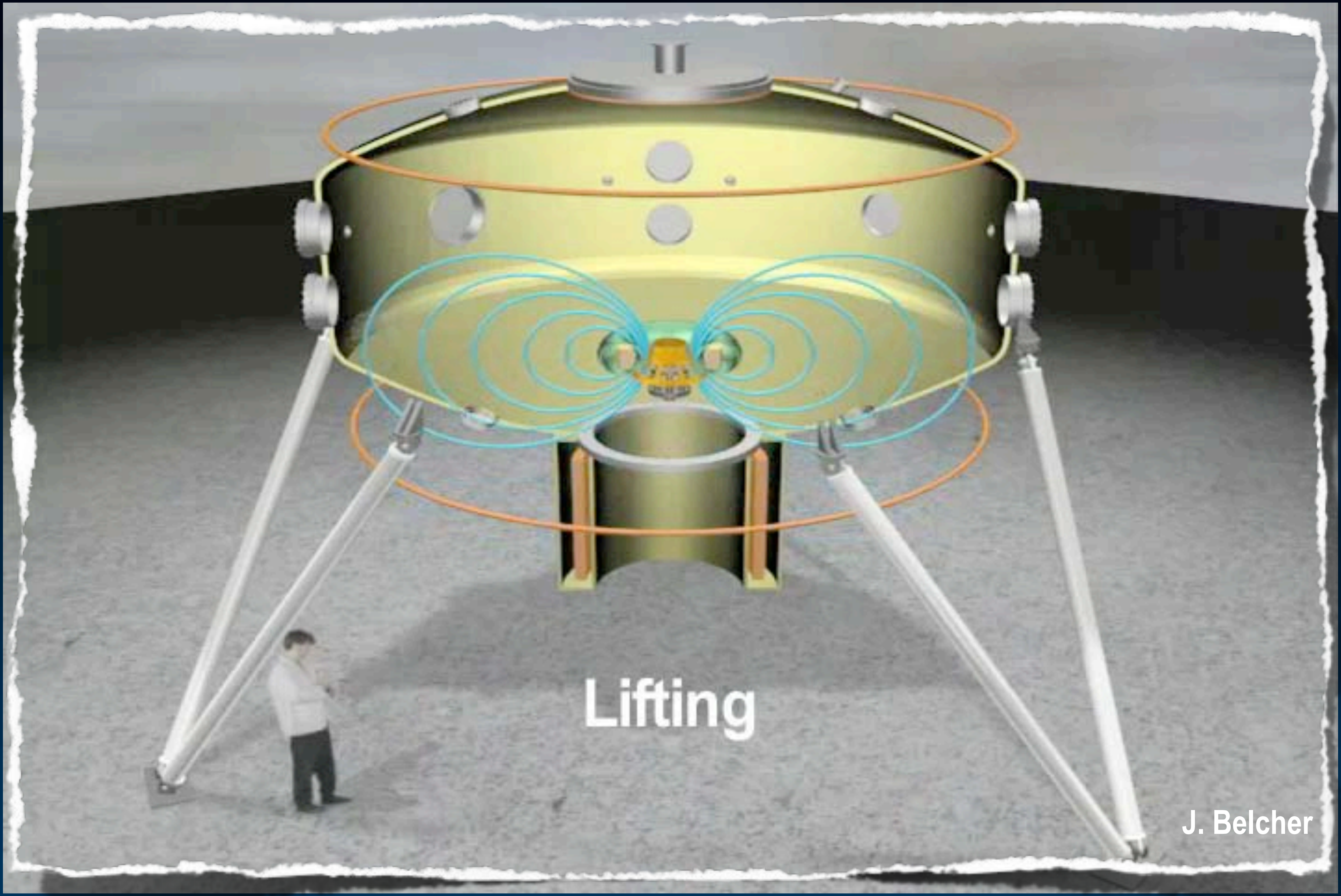
0.2 sec hot electron confinement-time



Launcher/Catcher

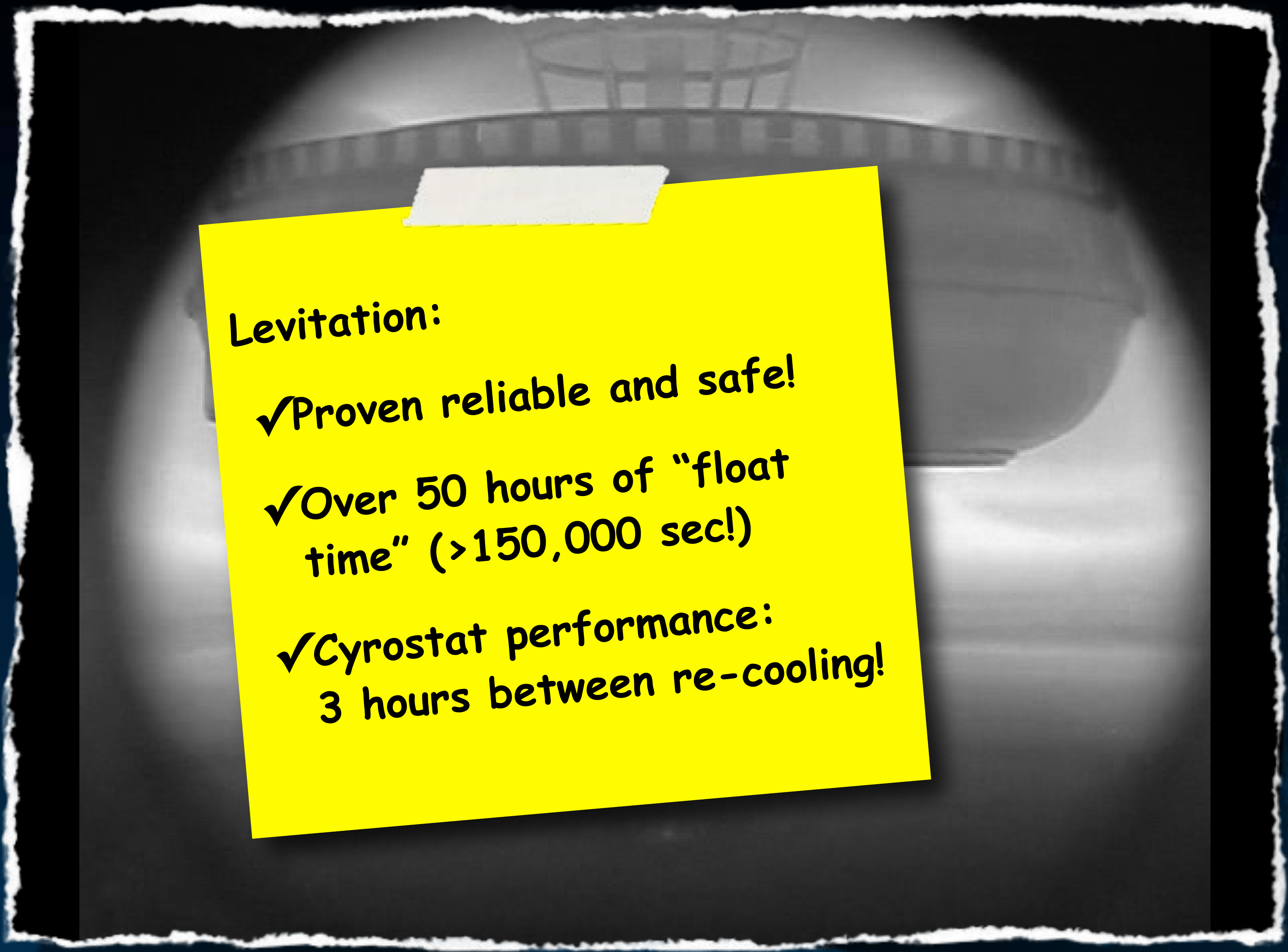
8 Channel Laser Detection and RT Controller

Lifting, Launching, Levitation, Experiments, Catching



Levitated Dipole Plasma Experiments

Levitated Dipole Plasma Experiments



Levitation:

- ✓Proven reliable and safe!
- ✓Over 50 hours of “float time” (>150,000 sec!)
- ✓Cyrostat performance: 3 hours between re-cooling!

New Result with Levitated Dipole:

“Naturally” peaked density profiles 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.

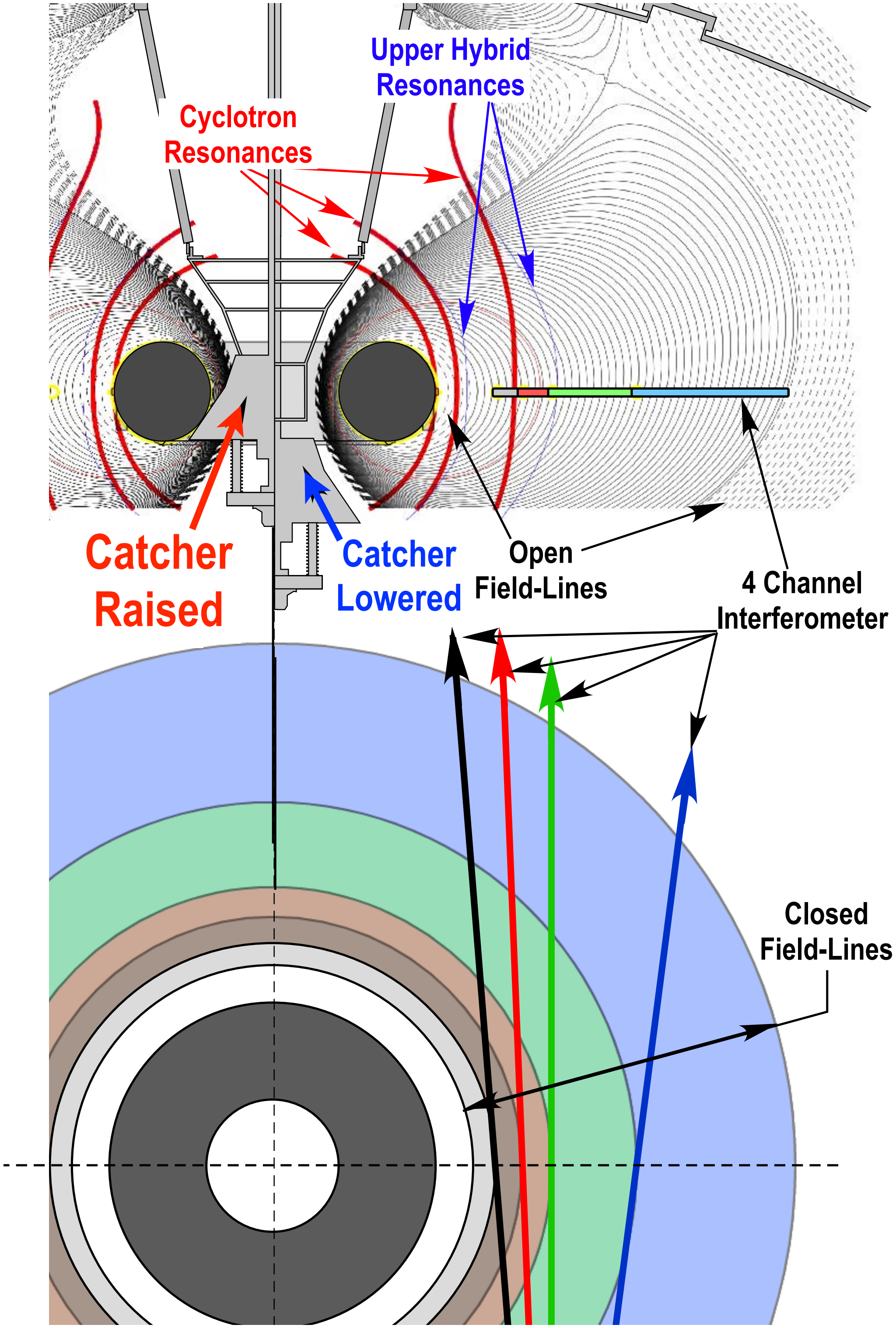
- Low-frequency fluctuations are observed with an intensity consistent with the observed inward pinch.

- 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

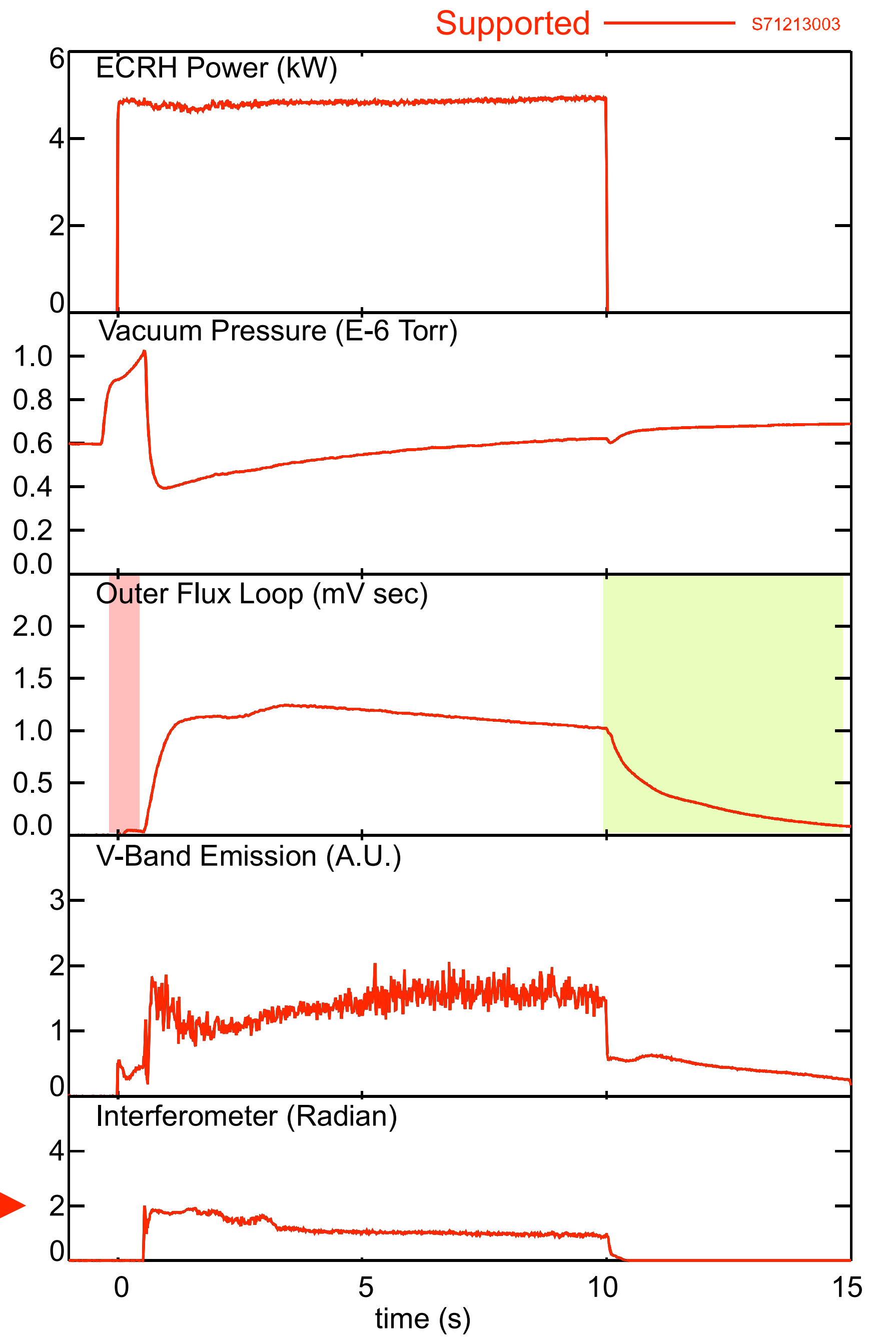
Alex Boxer, MIT PhD, (2008)



Plasma Confined by a Supported Dipole

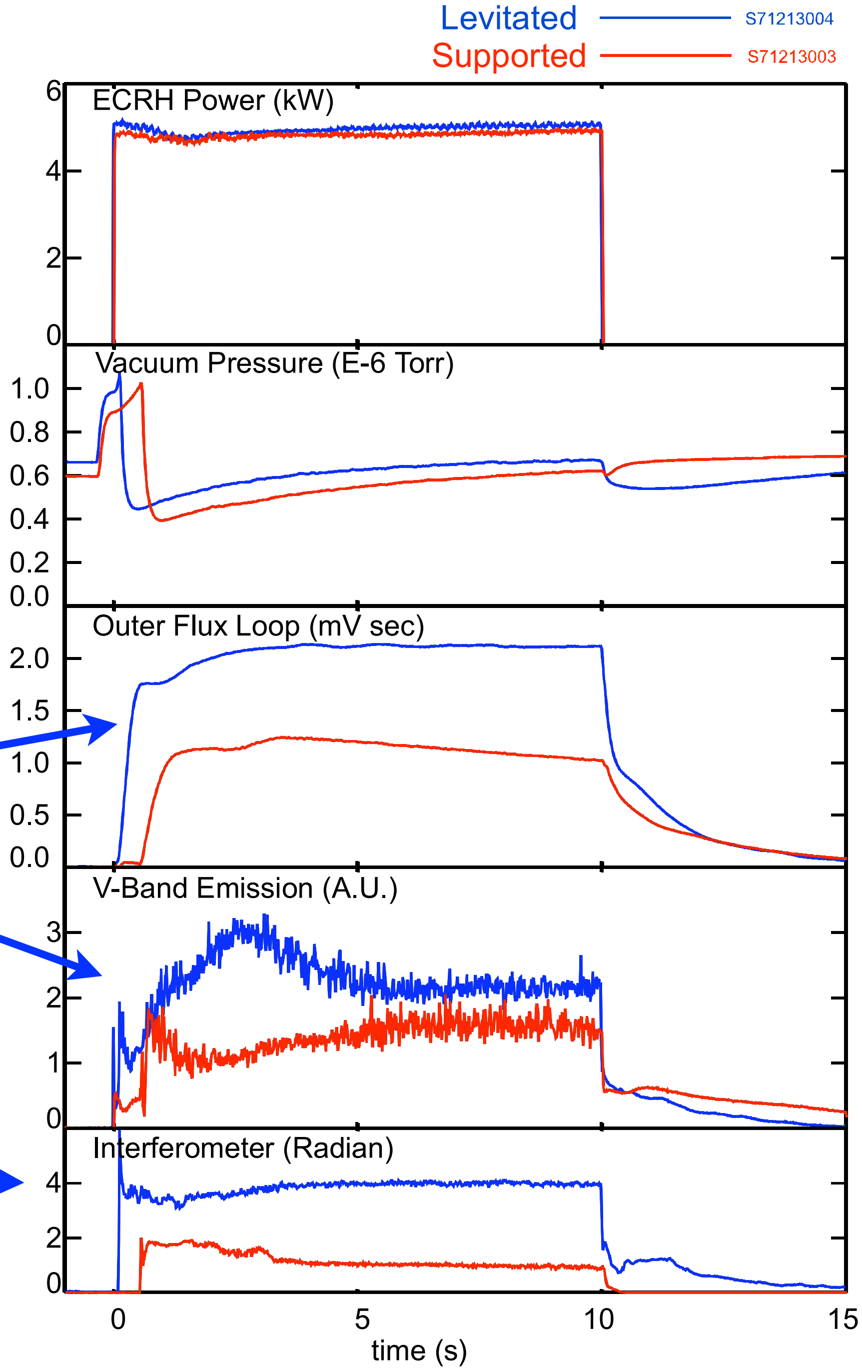
- 5 kW ECRH power
- D_2 pressure ~ 10^{-6} Torr
- Fast electron instability, ~ 0.5 s
- Ip ~ 1.3 kA or 150 J
- Cyclotron emission (V-band) shows fast-electrons
- Long, low-density "afterglow" with fast electrons

➡ **1×10^{13} cm^{-2} line density**

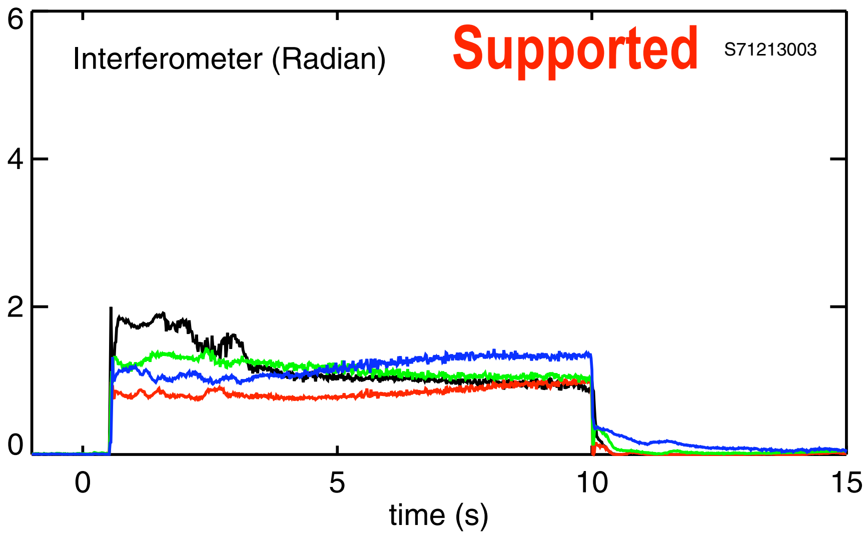


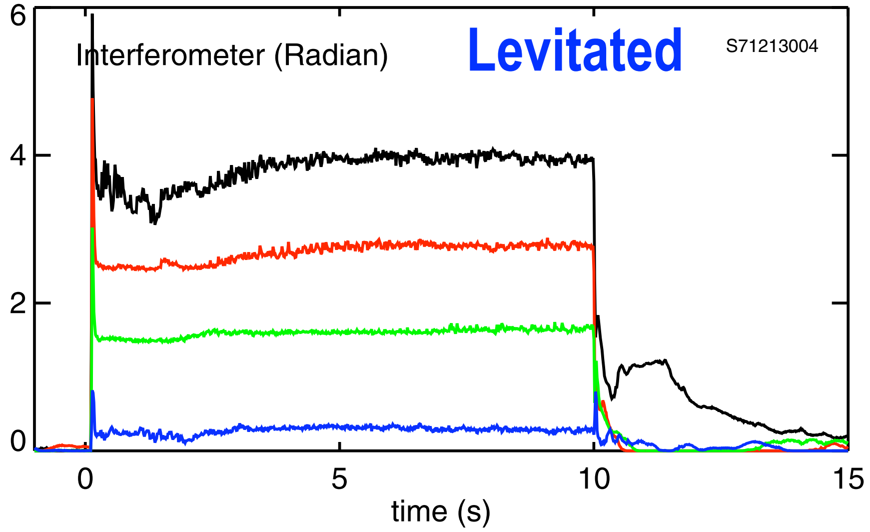
Plasma Confined by a Levitated Dipole

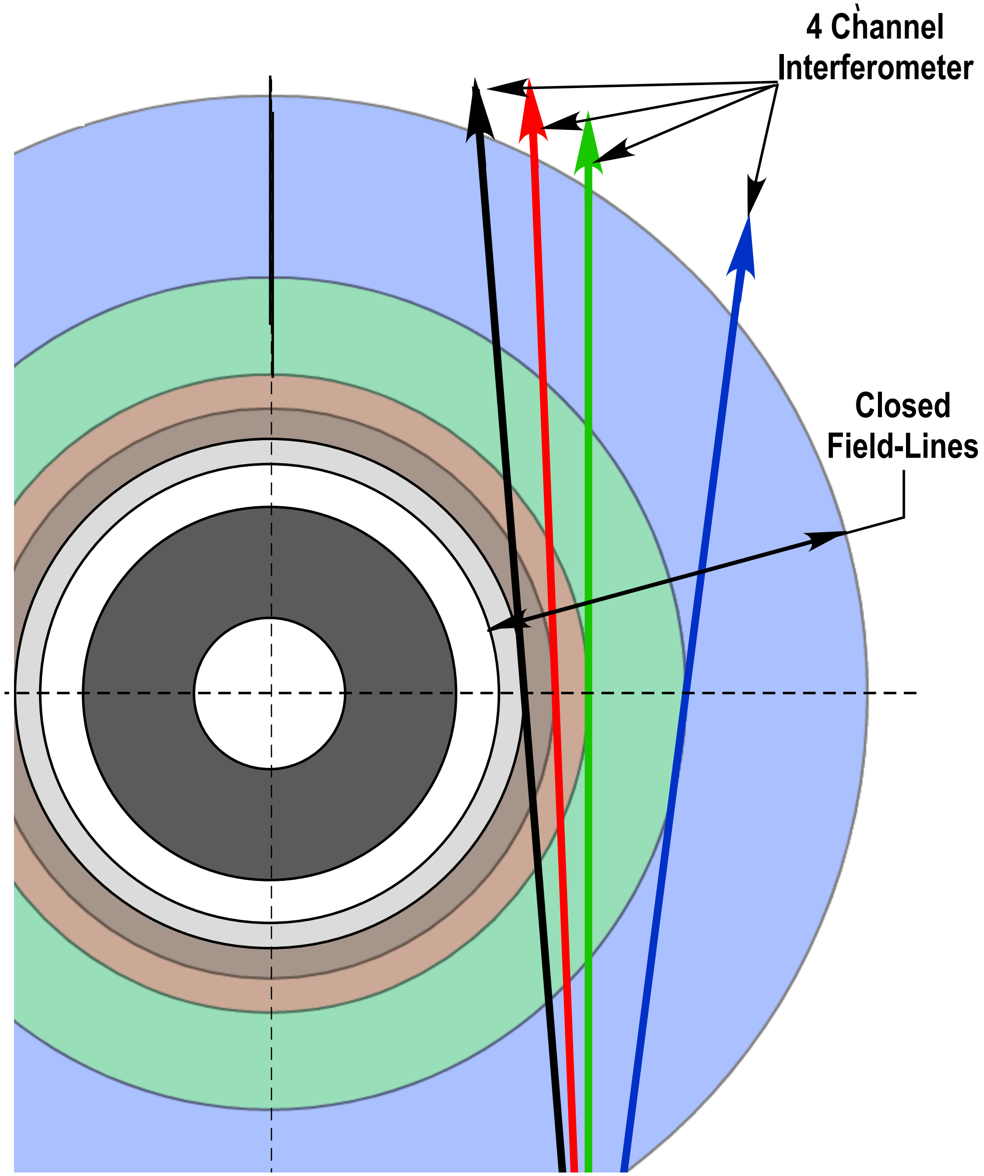
- Reduced fast electron instability
- 2 x Diamagnetic flux
- Increased ratio of diamagnetism-to-cyclotron emission indicates **higher thermal pressure**.
- Long, higher-density “afterglow” shows improved confinement.
- **3 x line density**



Multi-Cord Interferometer Shows Strong Density Peaking During Levitation



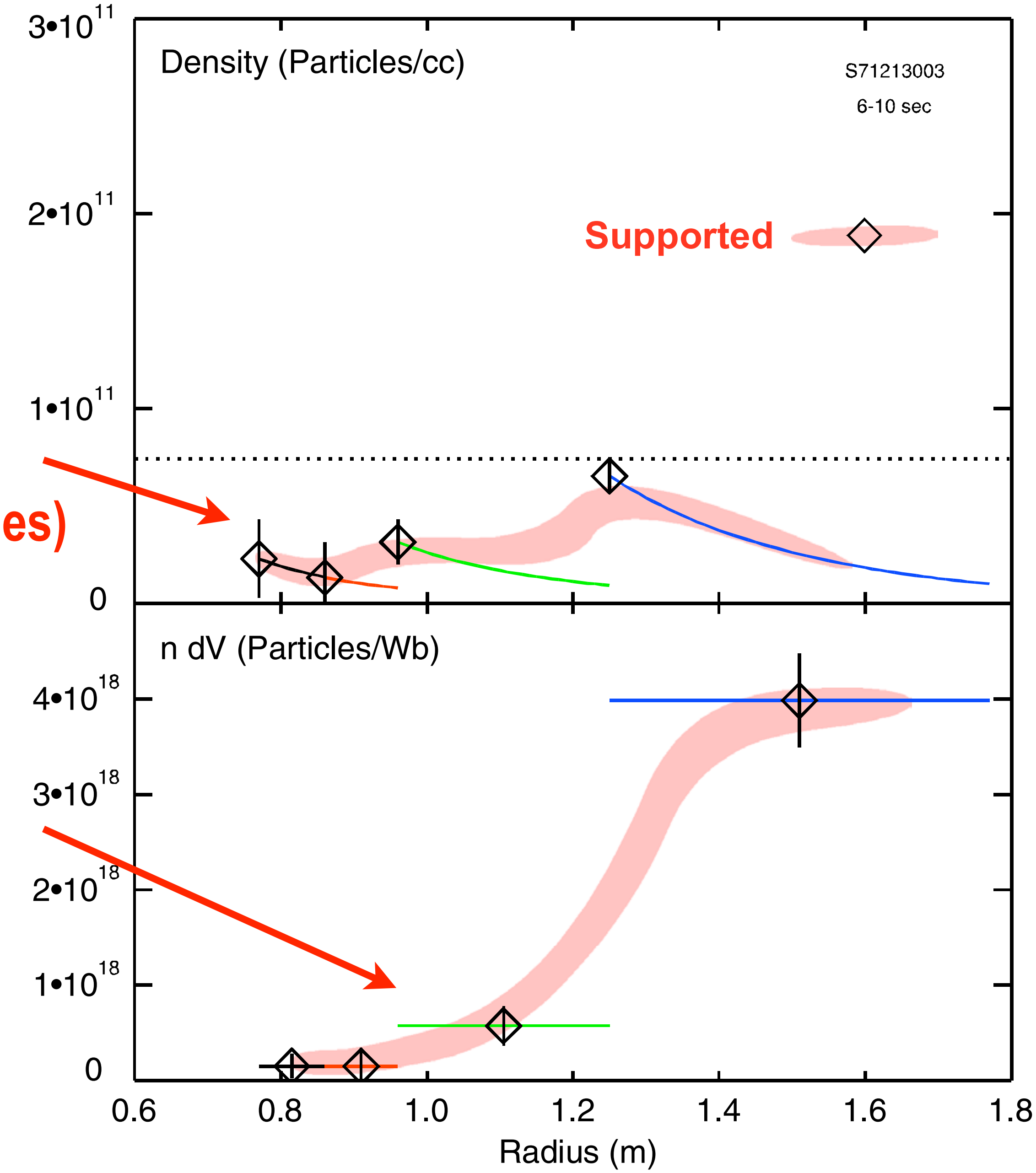




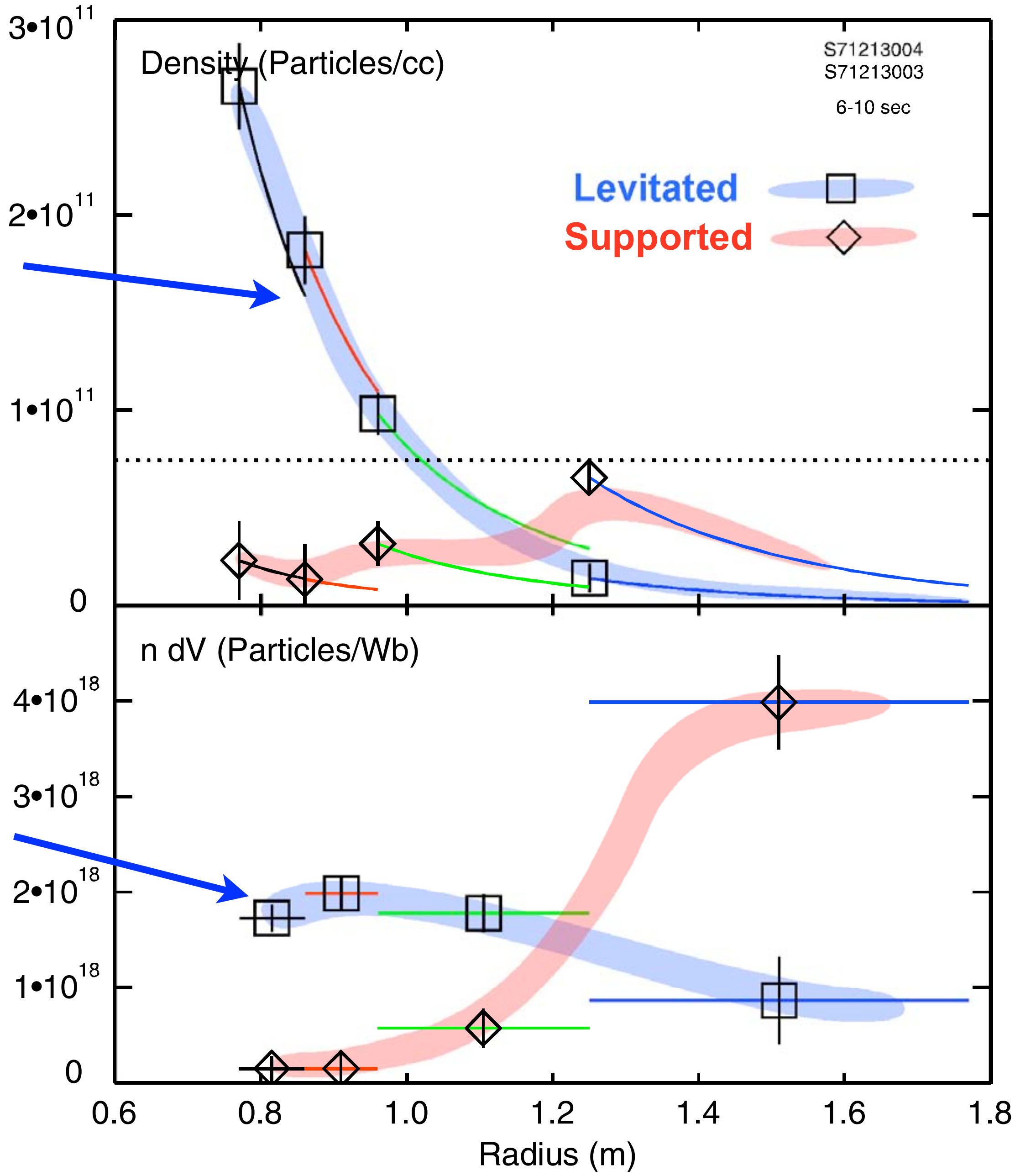
Inversion of Chord Measurements

Flat or Hollow Density
(*likely cause*: parallel losses)

Hollow Number Profile!



Inversion of Chord Measurements



Strongly Peaked Density!

Uniform Number Profile!

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.

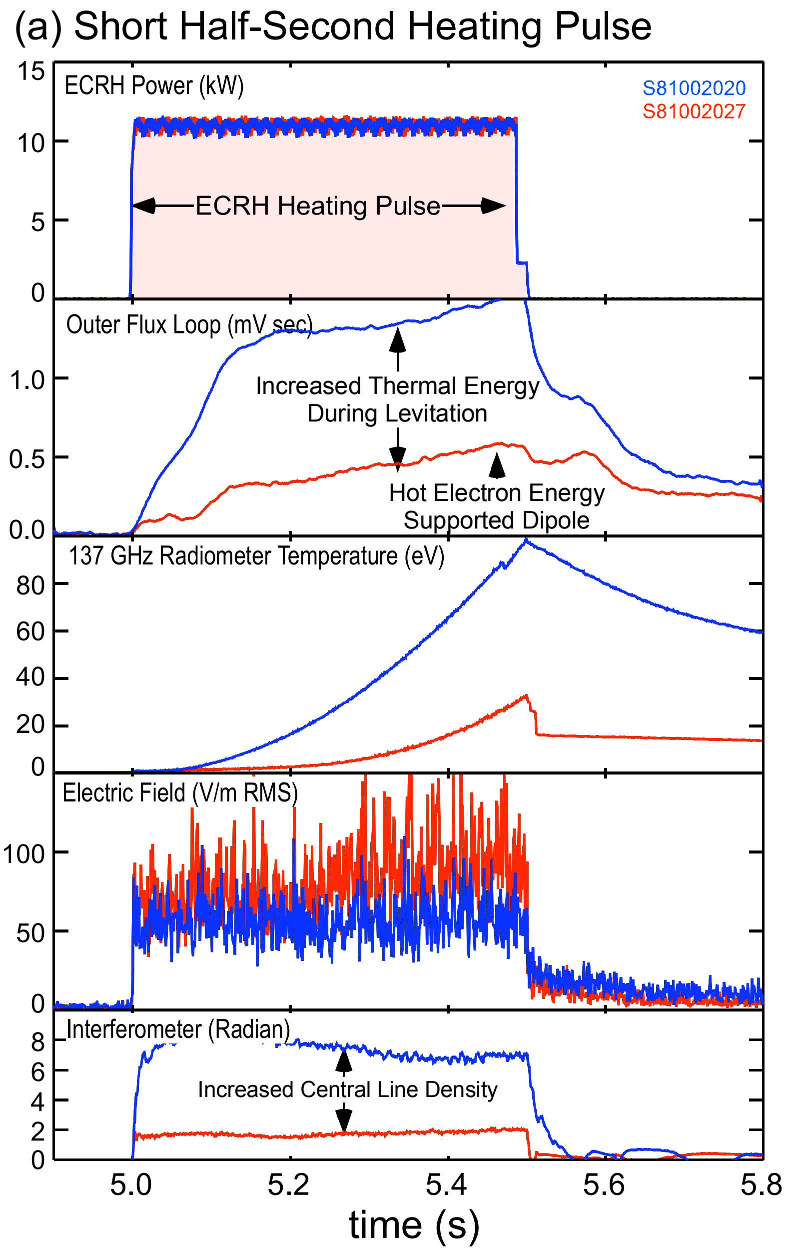
- Natural density profiles are created regardless of plasma pressure (*i.e*. both low and high beta).

- Natural density profiles are established rapidly, within ~20 msec.

- Natural density profiles are sustained steady-state by microwave heating.

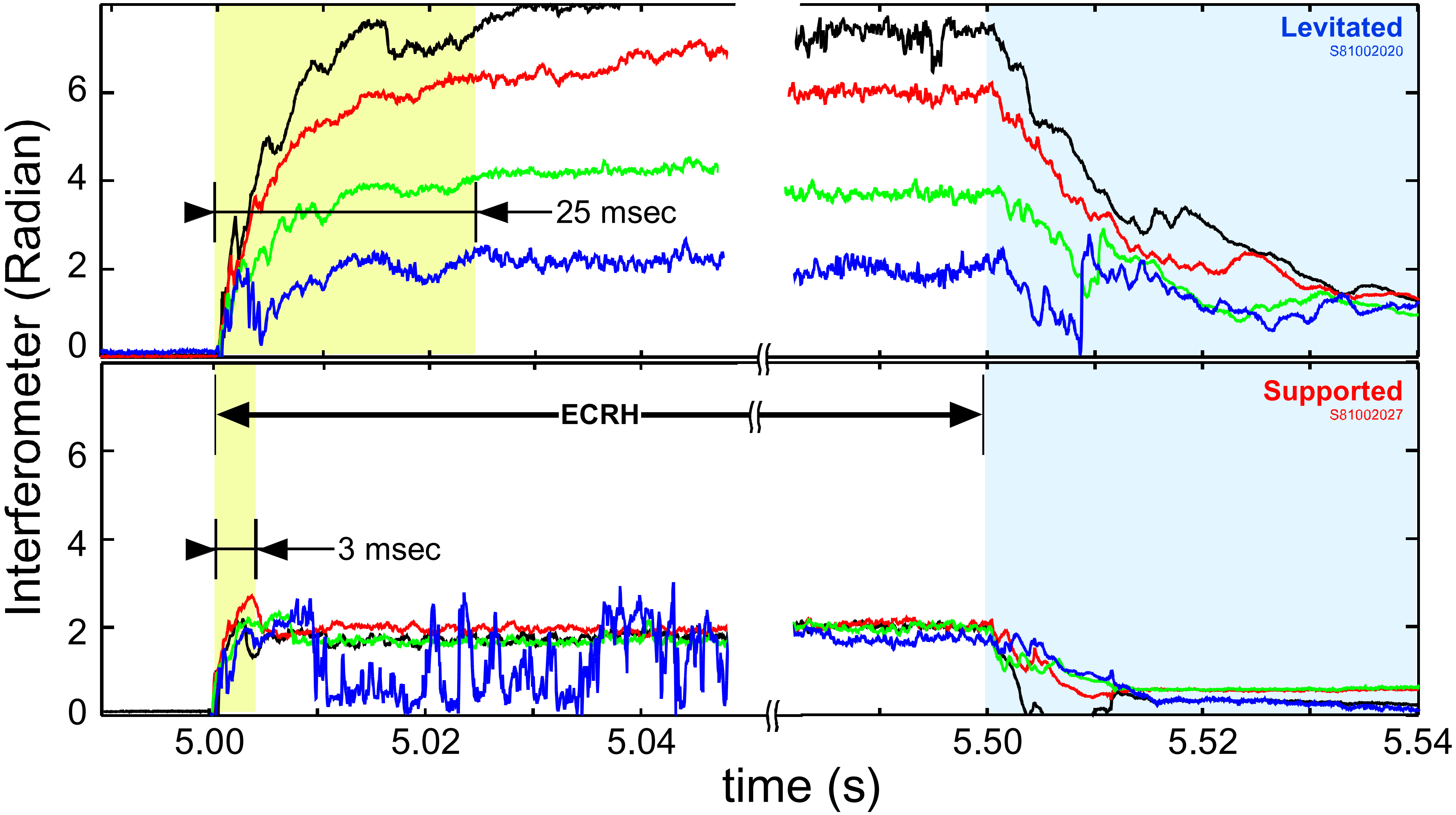
Natural Density Profiles Established Rapidly

- 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.



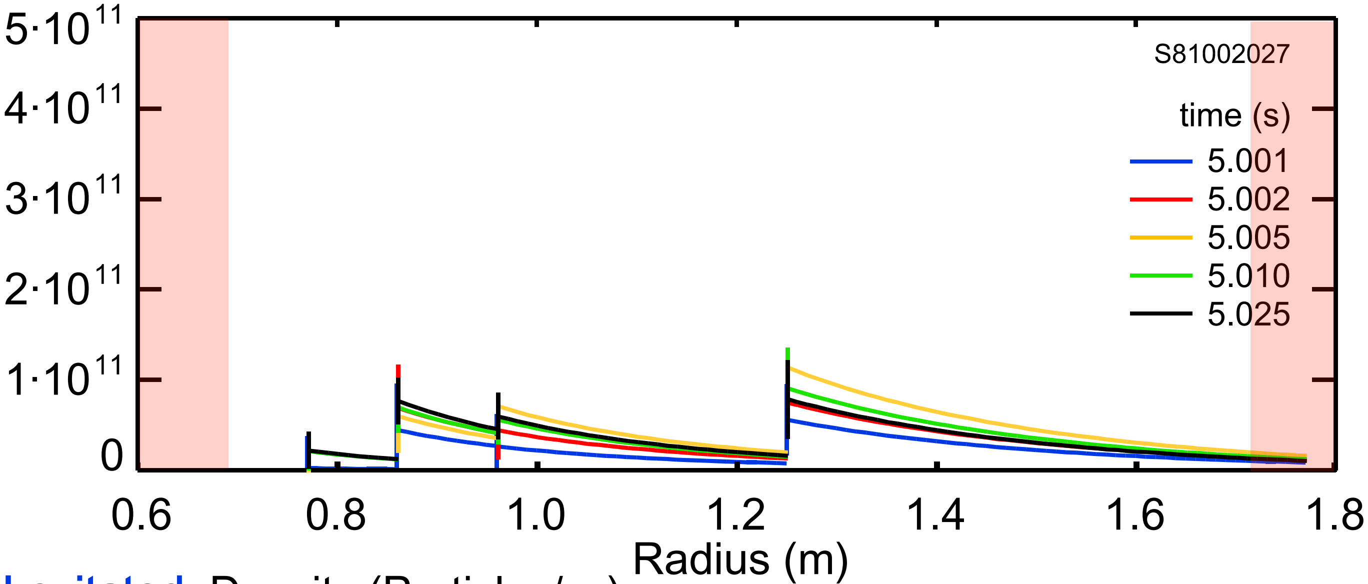
Naturally Peaked Profiles Established Rapidly

Line Density from Supported and Levitated Plasma

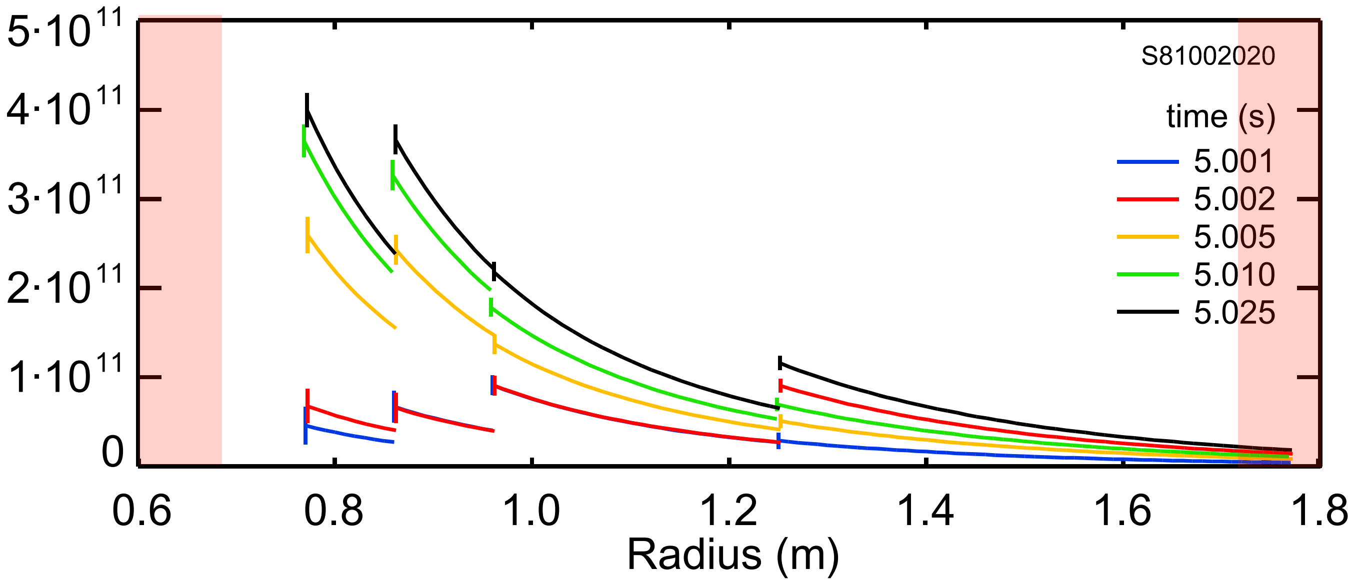


Naturally Peaked Profiles Established Rapidly

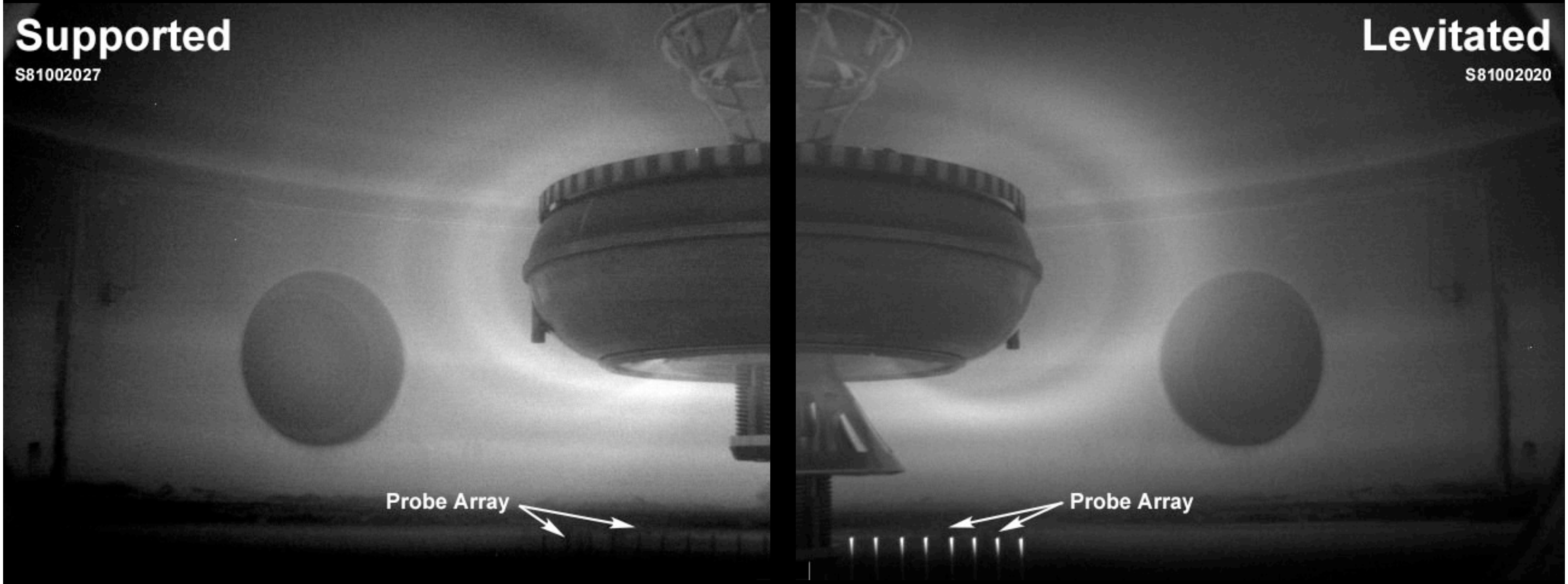
Supported: Density (Particles/cc)



Levitated: Density (Particles/cc)



Neutrals Appear to Recycle at Outer Edge

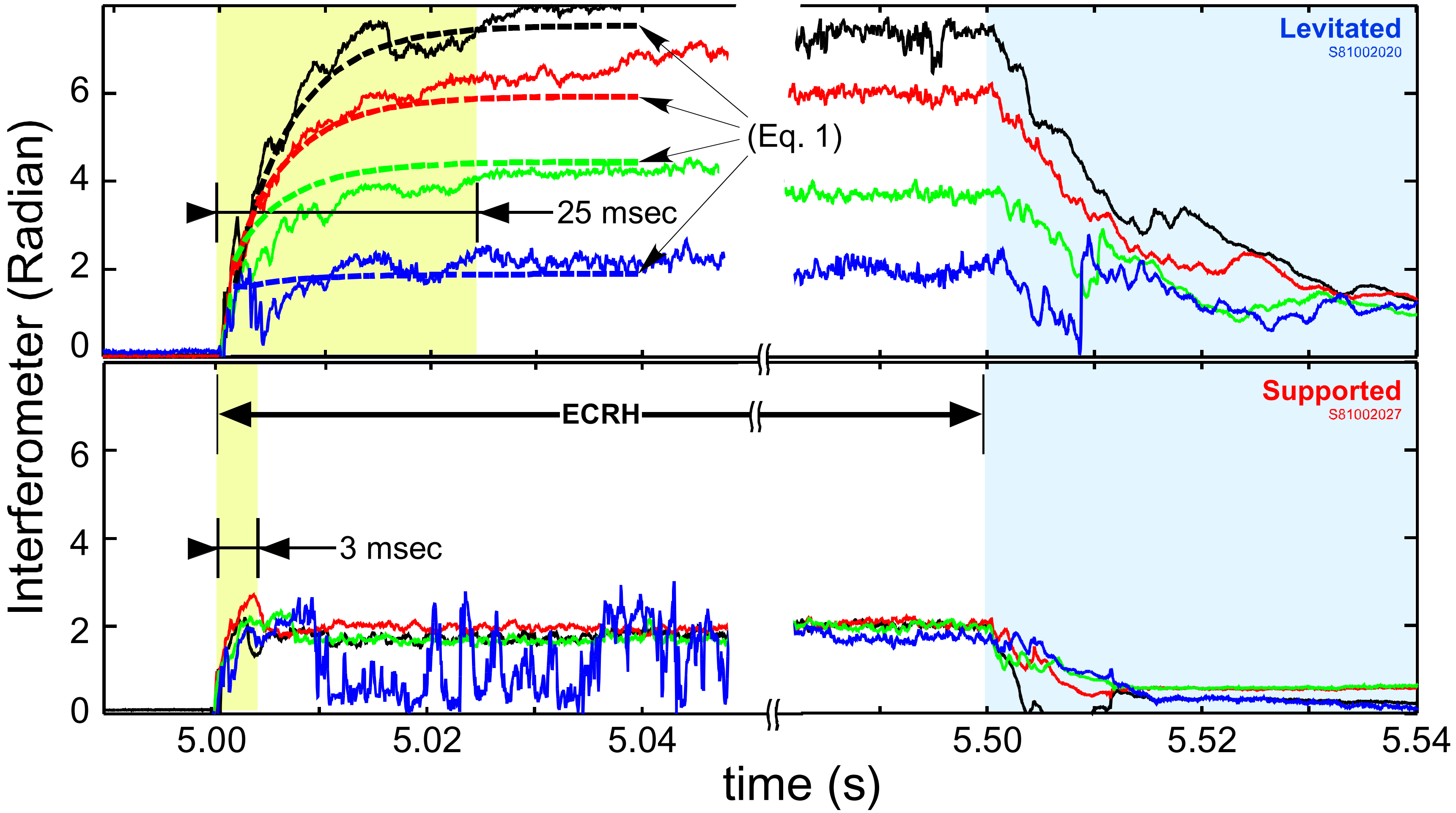


Naturally Peaked Profiles Established Rapidly

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

D ≈ 0.05 Weber^2/s ***across the profile*** and S ≈ 0

Line Density from Supported and Levitated Plasma



Turbulent Radial Diffusion Implies an Inward Pinch

- Turbulent particle pinch links magnetic geometry and particle transport
- When flux-tube volume, $\delta V(\psi)$, varies rapidly with radius, then the turbulent pinch is large

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

Look!

$$\Gamma_\psi = -D \frac{\partial N}{\partial \psi} = -D \delta V \frac{\partial \langle n \rangle}{\partial \psi} + \boxed{V_\psi \langle n \rangle}$$

$$\text{where } V_\psi \equiv -D \frac{\partial \delta V}{\partial \psi}$$

This is Big

LDX:
$D \approx 0.05$ Weber^2/s
V (pinch) ~ 45 m/s (core) and 400 m/s (edge)

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, µwave interferometry, and fast video cameras.**

- **The structure of these fluctuations are complex, turbulent, and still not well 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.**

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

Interchange Particle Diffusion

For "Random Motion"...

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

Cross Correlation Function

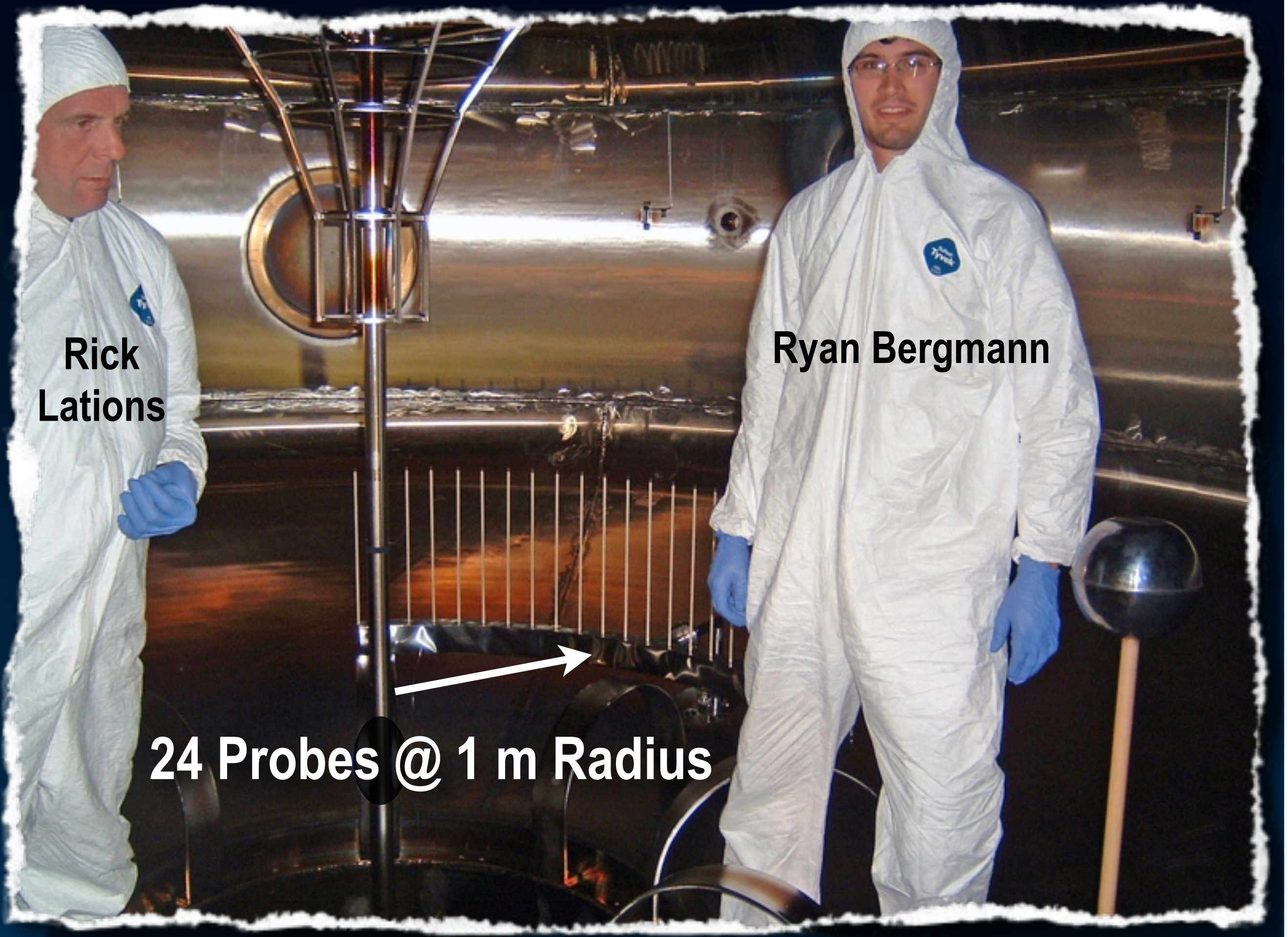
$$D = R^2 \langle E_\varphi^2 \rangle \tau_c$$

Measured at edge

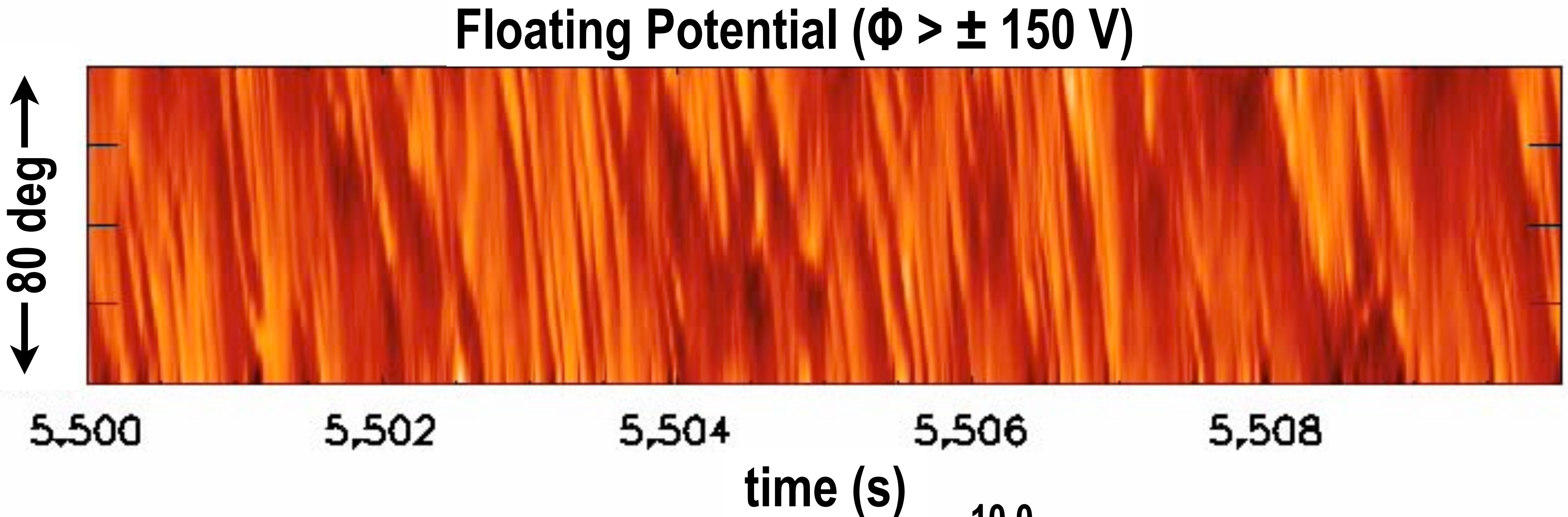
$$\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi}$$

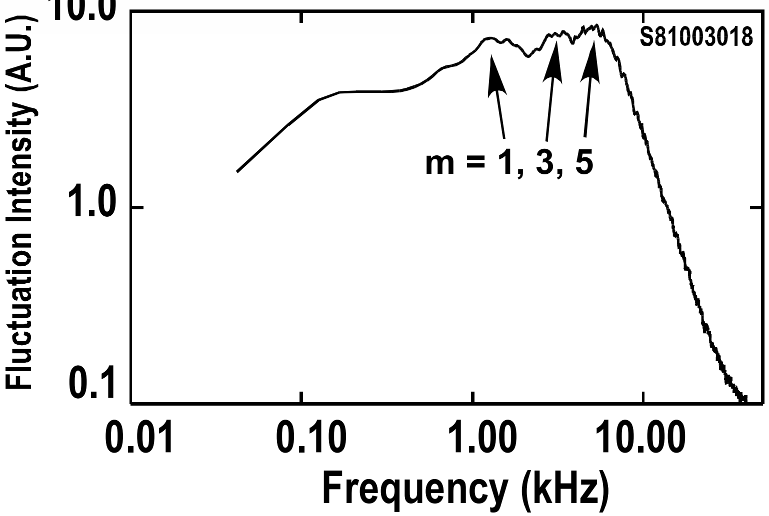
Floating Potential Probe Array

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



Floating Potential Probe Array



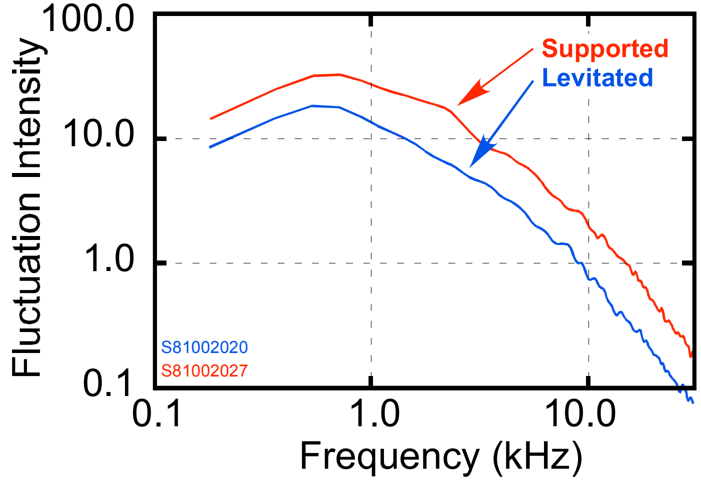


15 kW High-β Discharge

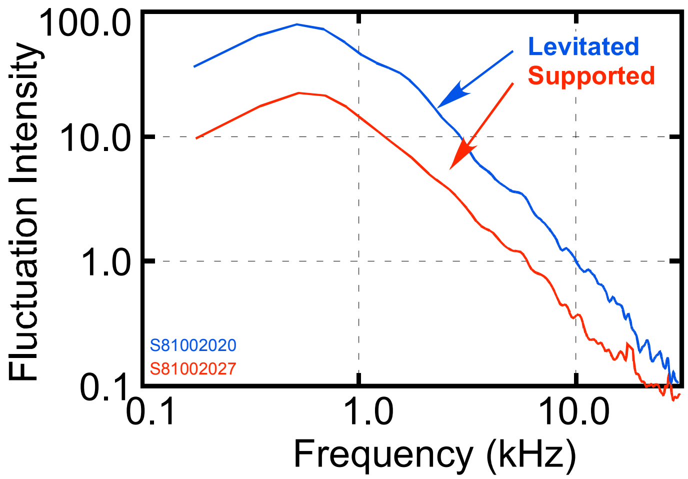
$\omega \sim \Omega\, m = \Omega R\, k$, with

$\Omega/2\pi \sim 1$ kHz

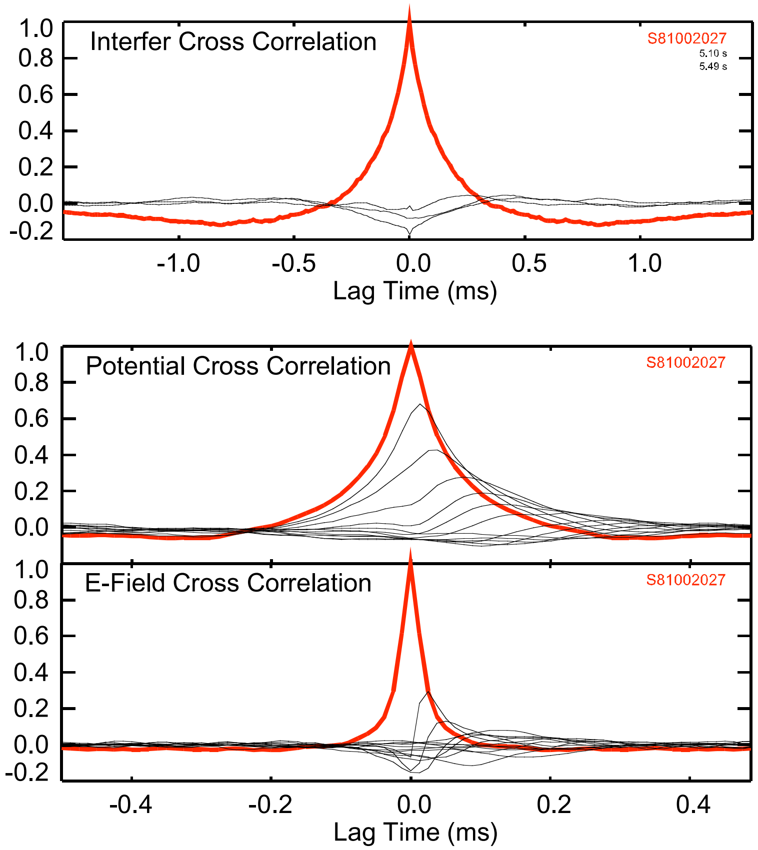
(a) Edge Floating Potential Fluctuations



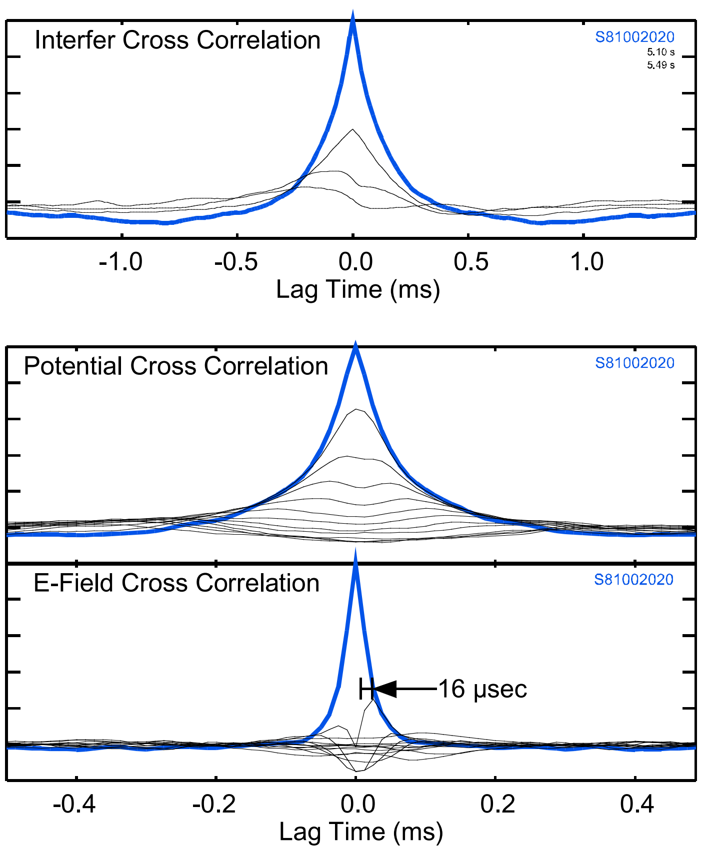
(b) Inner Interferometer Fluctuations



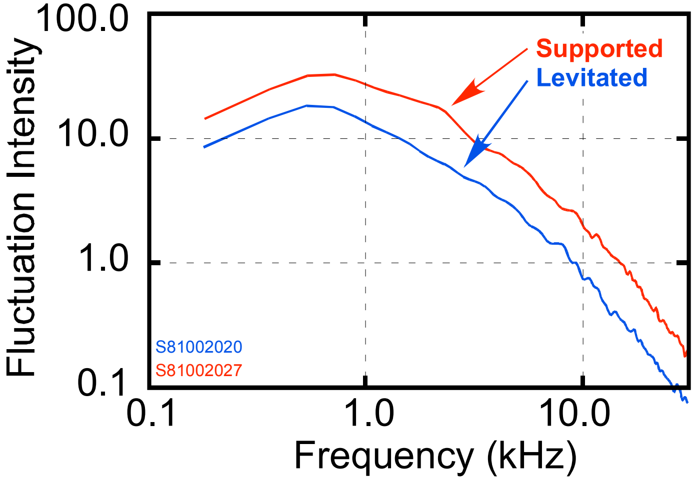
(c) **Supported** Dipole Correlations



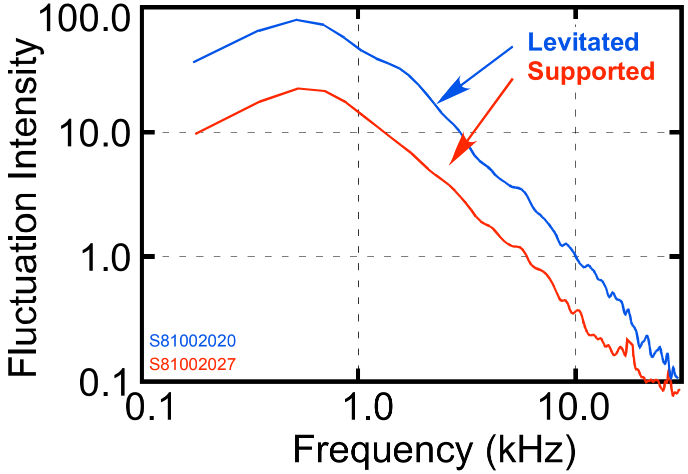
(d) **Levitated** Dipole Correlations



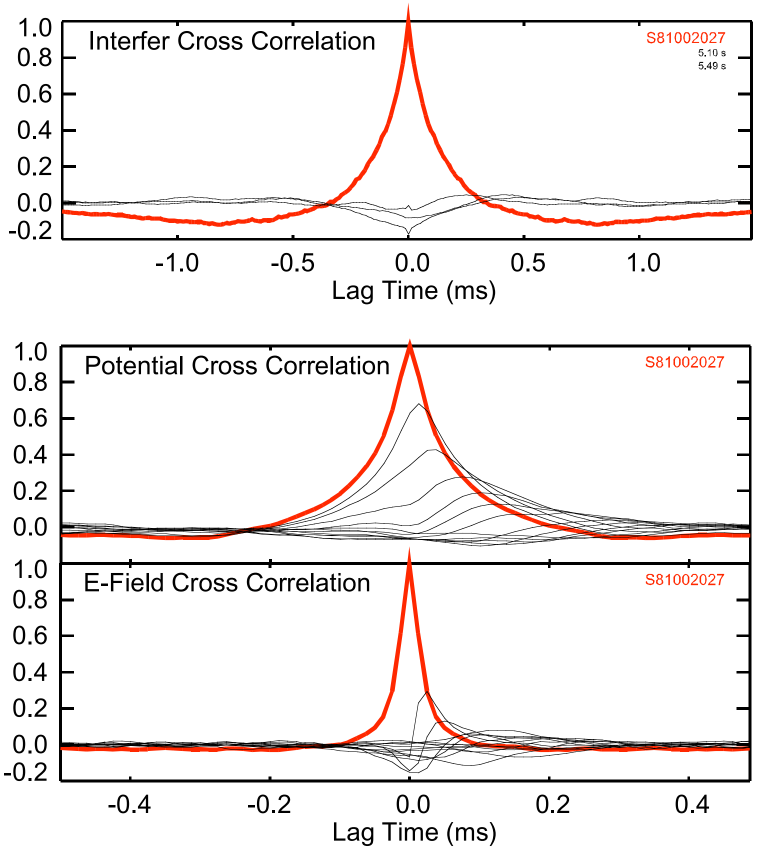
(a) Edge Floating Potential Fluctuations



(b) Inner Interferometer Fluctuations



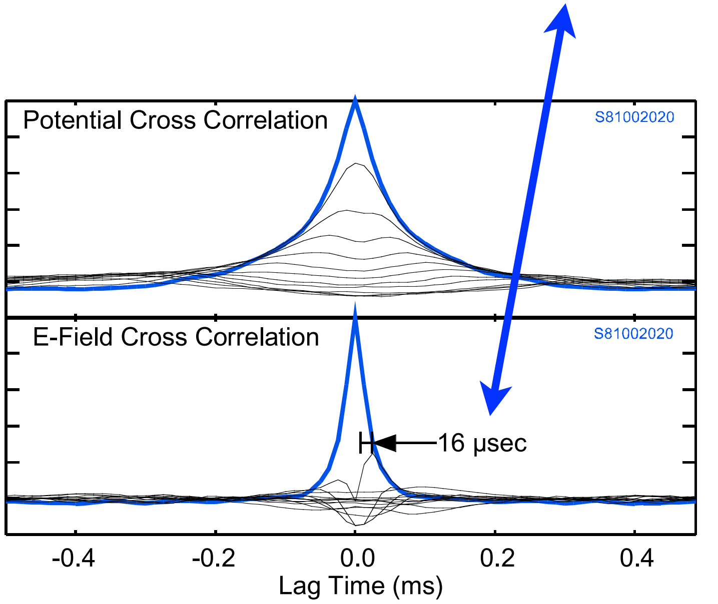
(c) **Supported** Dipole Correlations



(d) **Levitated** Dipole Correlations

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

$\approx$ 0.05 Weber^2/s



Saturday, November 14, 2009

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

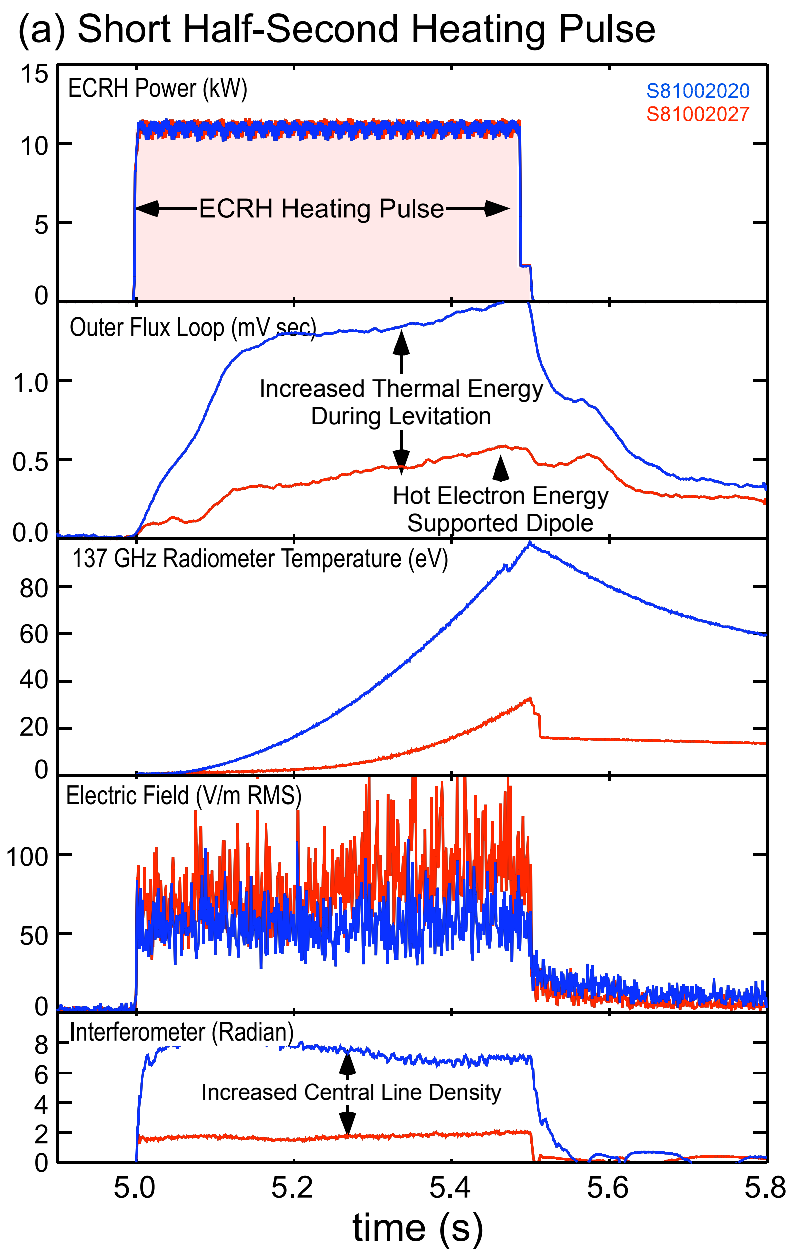
- Flux-tube density and entropy density have identical dynamics for a plasma with an adiabatic closure, $G = P\delta V^{\gamma}$

$$
\begin{aligned}
\frac{\partial N}{\partial t} - \frac{\partial}{\partial \varphi}\left(N\frac{\partial \Phi}{\partial \psi}\right) + \frac{\partial}{\partial \psi}\left(N\frac{\partial \Phi}{\partial \varphi}\right) &= S \\
\frac{\partial G}{\partial t} - \frac{\partial}{\partial \varphi}\left(G\frac{\partial \Phi}{\partial \psi}\right) + \frac{\partial}{\partial \psi}\left(G\frac{\partial \Phi}{\partial \varphi}\right) &= H
\end{aligned}
$$

- (N, G) ~ constant implies peaked density and pressure profiles

- Edge T_e ~ 15 eV, implies central T_e ~ 500 eV with measured diamagnetism and measured density profile

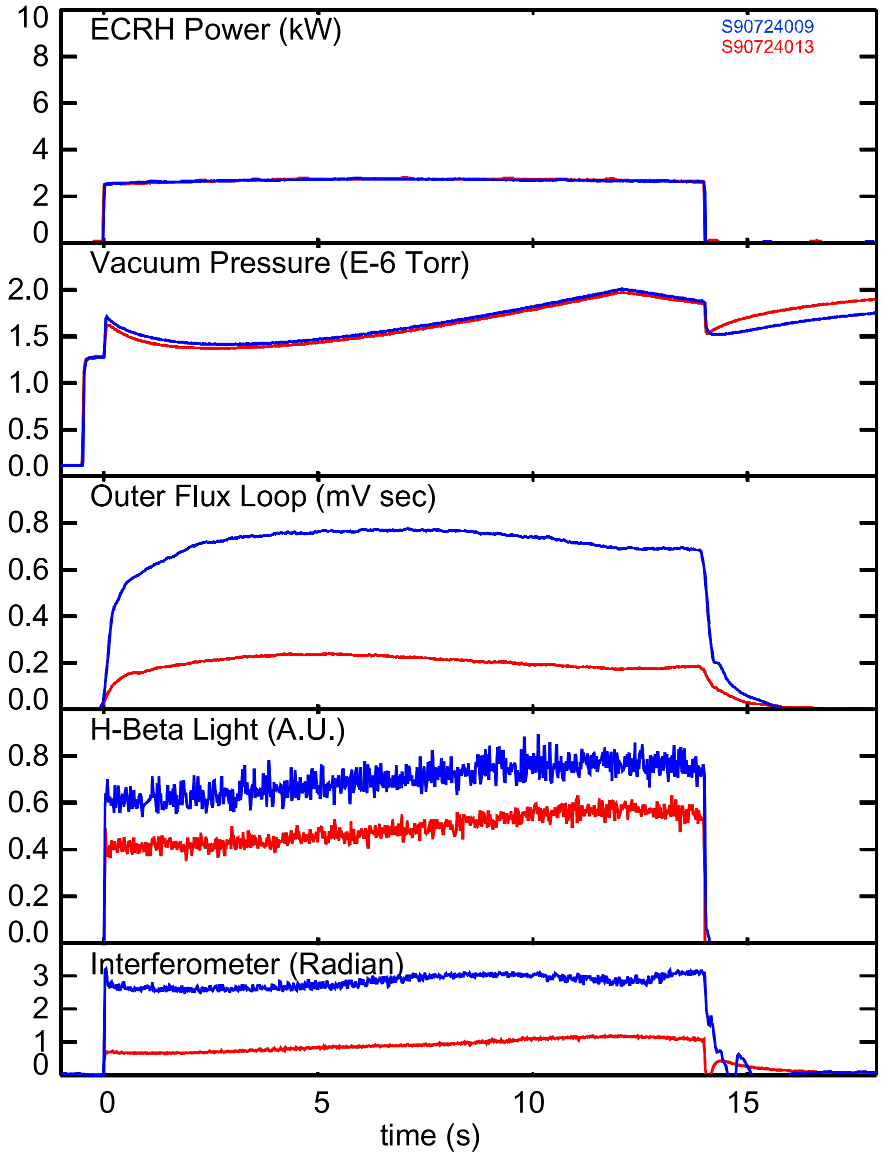
- Thermal stored energy of 60 J (this example levitated discharge, 2 µTorr D_2)



(a) Short Half-Second Heating Pulse

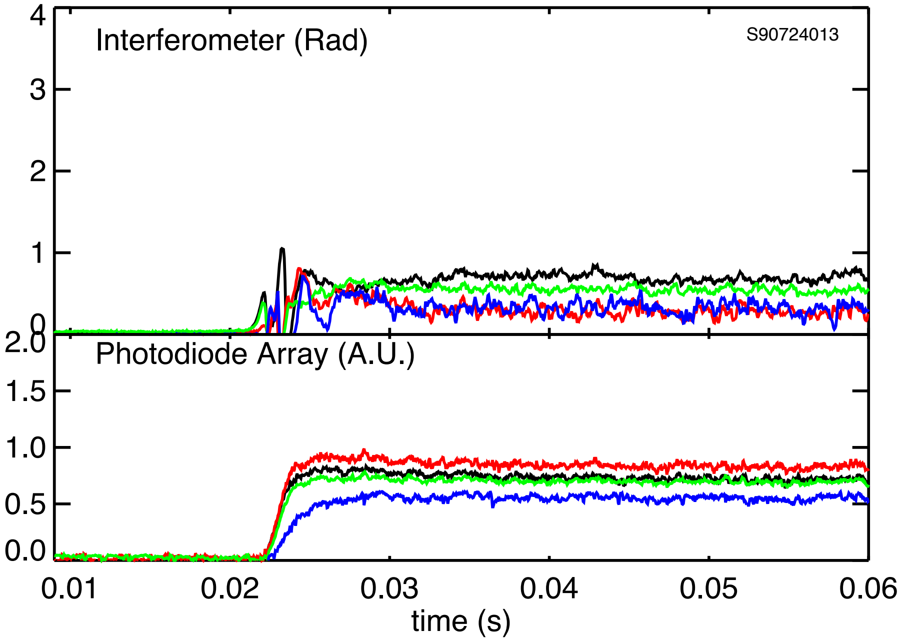
Another Example: Low-Power, Lower-Pressure

- 2.5 kW at 2.45 GHz
- Quasi-steady-state profiles, fluctuations, and parameters
- 0.6 mV·s (60 J) thermal energy
- Turbulent diffusion and turbulent pinch consistent with edge electric field fluctuations and "recycling" inner SOL.

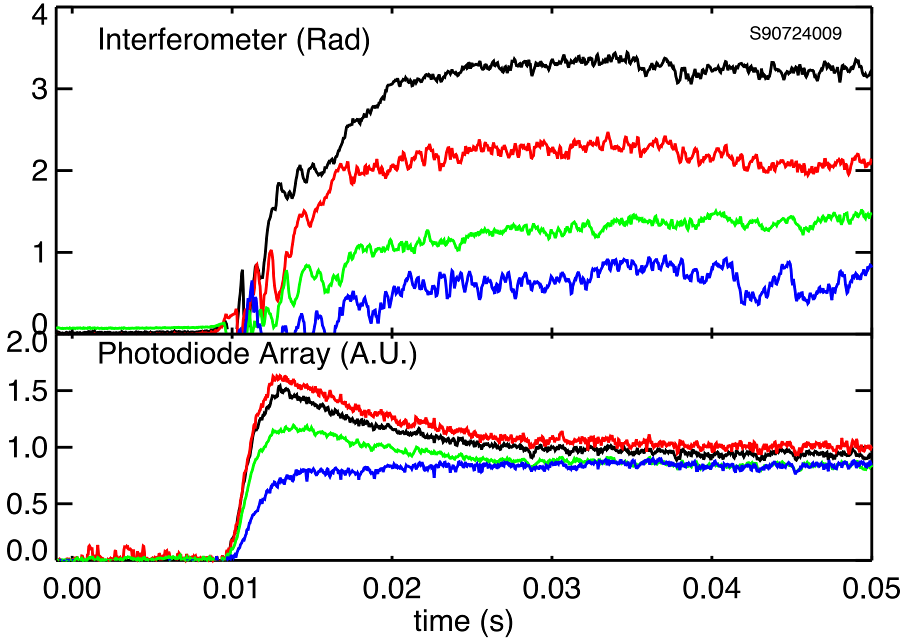


Turbulent Diffusion

Supported



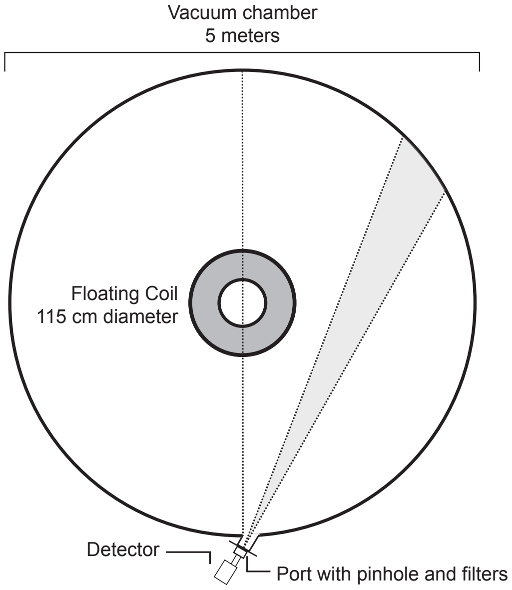
Levitated



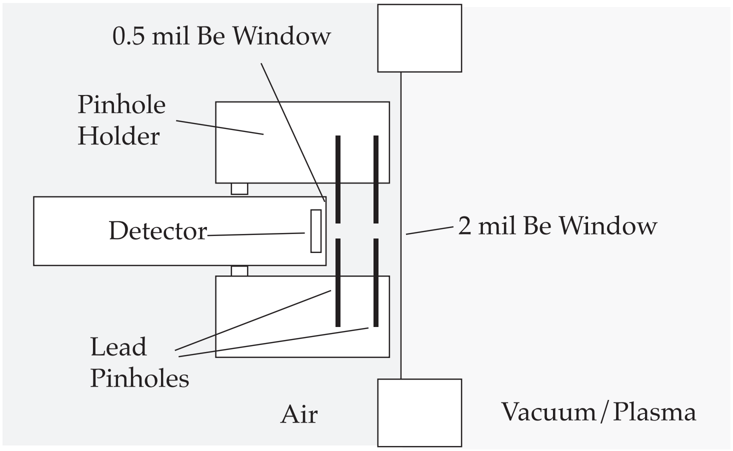
$D \approx 0.09\ \mathrm{Weber}^2/\mathrm{s}$

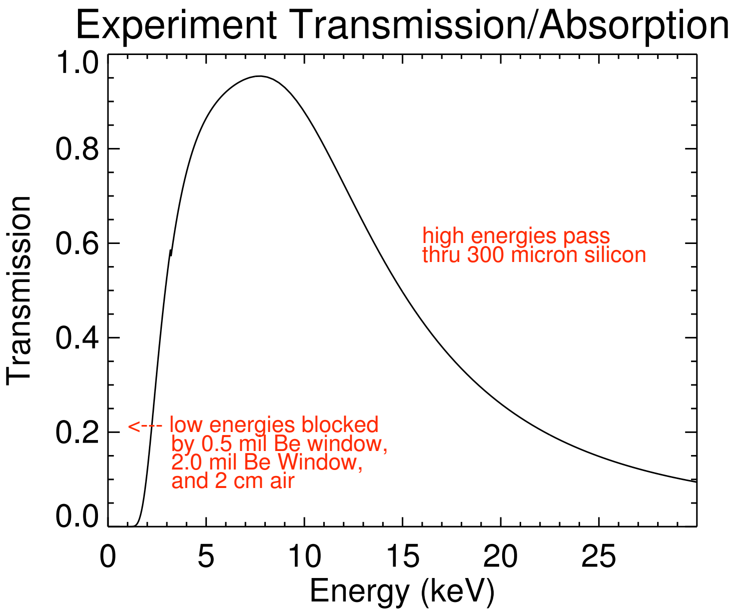
SI(PIN) X-Ray Spectrum

(Amptek XR-100Cr)



The detector viewed the plasma through a 2 mil Be port window, 2 cm of air and a 0.5 mil Be window built on the detector. The view was in the equatorial plane with a tangent radius between 80 and 90 cm.

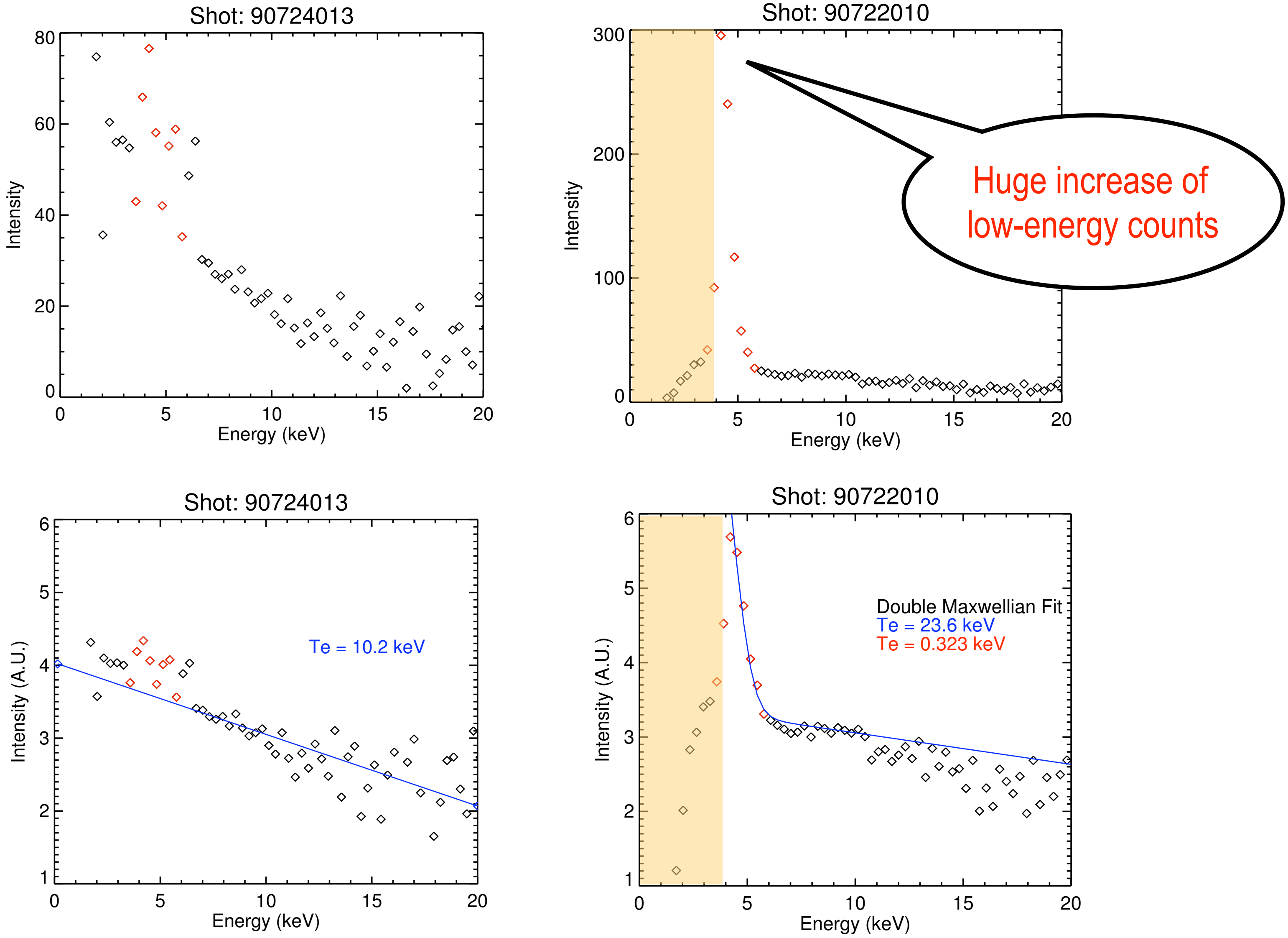




SI(PIN) X-Ray Spectrum

(Amptek XR-100Cr)

Supported **Levitated**



Huge increase of low-energy counts

M. Davis
(Preliminary)

Transport Work in Progress…

- Improve diagnostics of density evolution, transients, and particle source profile
- Understand transport boundaries: inner and outer edges
- Improve internal fluctuation structure measurements and better model transport/correlations due to fluctuation spectrum, drift-resonance effects.
- Measure and understand entropy dynamics and evolution. (12-Channel Thomson scattering soon.)
- Study and understand transport rate changes as a function of plasma, fueling, power, and spectral variations.

28 GHz 10 kW CW Gyrotron

(University of Maryland)

28 GHz ECRH system is being rapidly implemented on LDX

Will be available for next plasma campaign this year

Views of recent (last week) 28 GHz ECRH system installation activity at LDX

TSW2500 1 MW CW RF Transmitter

(General Atomics)

Higher-density plasmas will (i) improve our ability to diagnose parameters and measure profiles, (ii) better differentiate between edge and core dynamics, and (iii) allow study of the density profiles that evolve from a fully-recycling inner edge at the levitated dipole. Most importantly, the RF Power System will determine whether or not the favorable stability and confinement results achieved so far at low-density can be scaled.

Summary

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

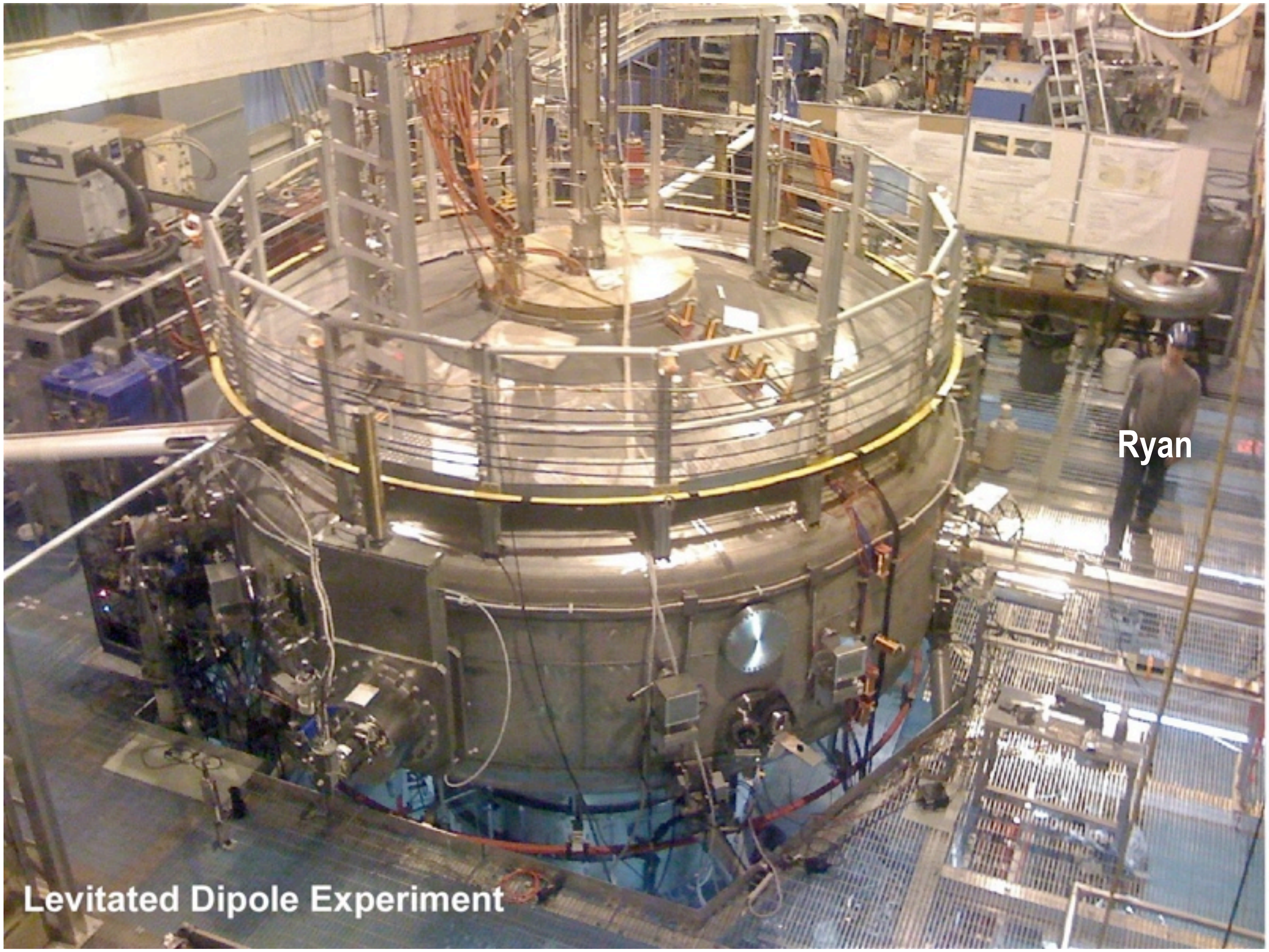
  LDX has demonstrated the formation of natural density profiles in a laboratory dipole plasma and the applicability of space physics to fusion science.

- 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_φ 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 Experimental Team



Levitated Dipole Experiment

Darren Garnier and Phil Michael

Jen Ellsworth
Jay Kesner and
Matt Davis