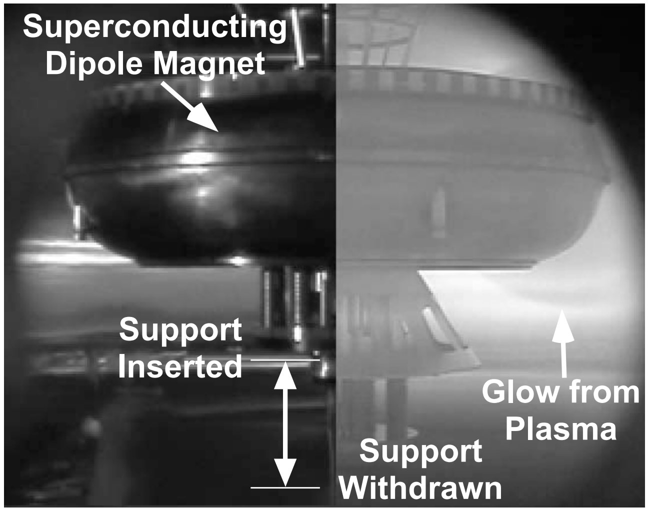
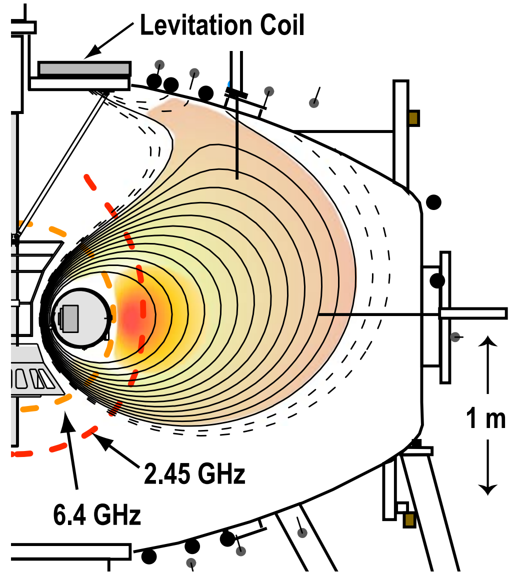




Improved Confinement During Magnetic Levitation in LDX

M. E. Maurel

For the LDX Experimental Team

Ryan Bergman, Alex Boxer, Matt Davis,
Jennifer Ellsworth, Darren Garnier, Brian Grierson,
Jay Kesner, Phil Michael, Paul Woskov

Columbia University

IN LVMINE TVO VIDEBIMVS LVMEN

MIT PSFC

50th Annual Meeting of the APS Division of Plasma Physics
Dallas, November 18, 2008

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 (τ_E > 60 msec), high peak β ~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)

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.**

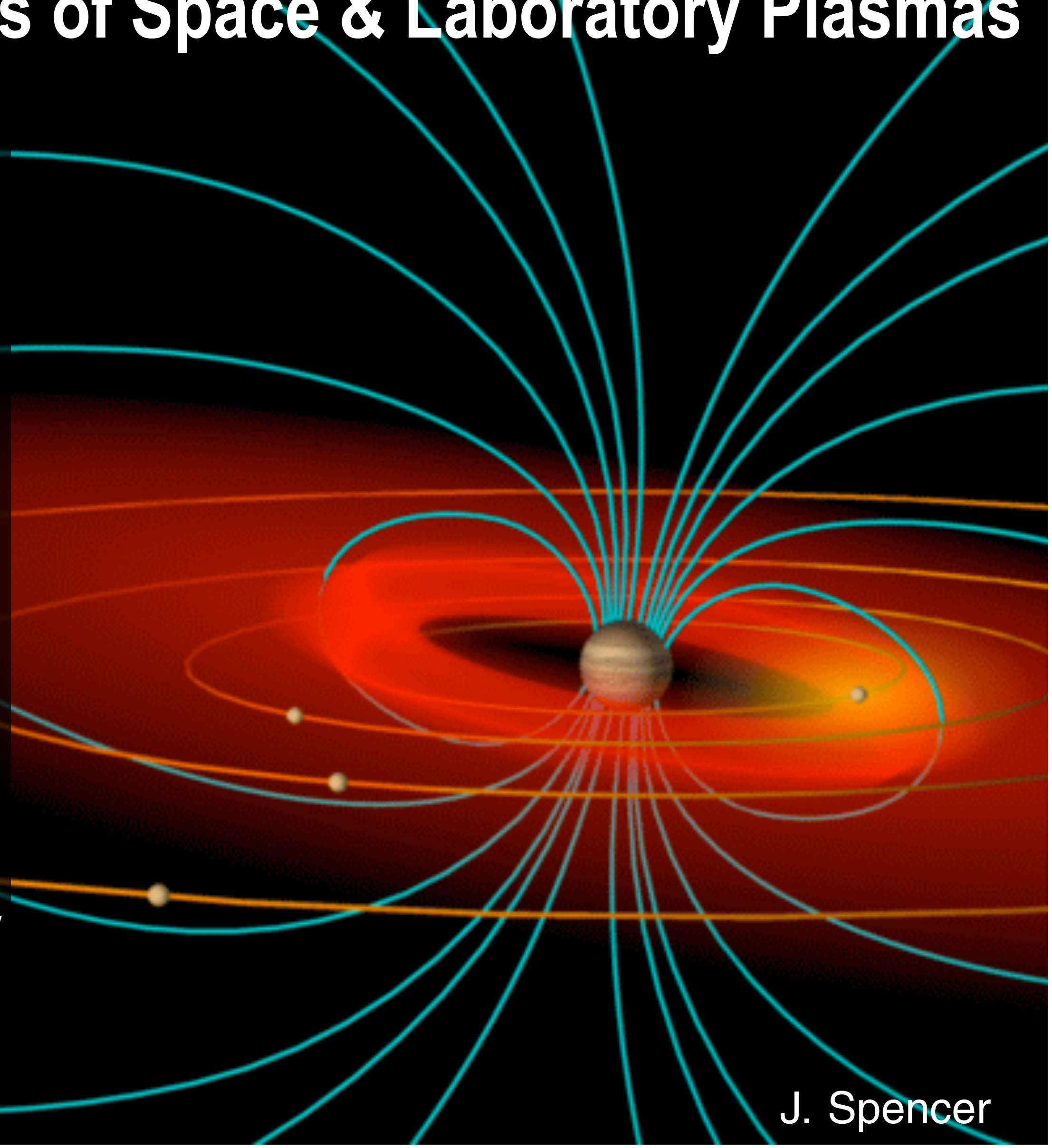
➡ **Multi-cord interferometry reveals dramatic (up to 10-fold) central peaking of plasma density during levitation.**

- **Low-frequency fluctuations are observed that likely cause density peaking though interchange mixing.**

- **This result is important and demonstrates the creation of "naturally" peaked density profiles in the laboratory.**

Levitated Dipole Confinement Concept:
Combining the Physics of Space & Laboratory Plasmas

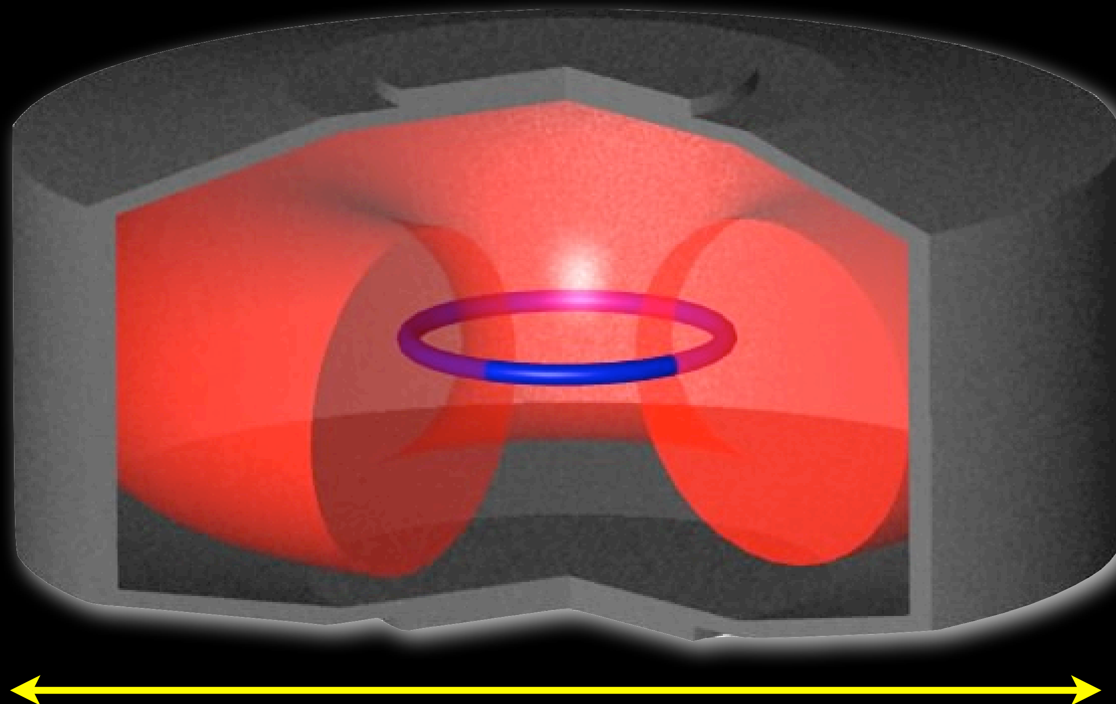
- Akira Hasegawa, 1987
- Three key properties of active magnetospheres:
  - **High beta**, with ~ 200% in the magnetospheres of giant planets
  - **Pressure and density profiles are strongly peaked**
  - And solar-driven activity **increases** peakedness



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)

What are Natural Profiles?

- In a strong, shear-free magnetic field, ideal MHD dynamics, $\mathbf{E}\cdot\mathbf{B} = 0$, is dominated by interchange motion with fluctuating potentials and fluctuating perpendicular $\mathbf{E}\times\mathbf{B}$ flows.

- Plasma interchange dynamics is effectively two-dimensional, characterized by **flux-tube averaged quantities**:

  - **Flux tube particle number**, $N = \int ds\ n/B \approx n\ \delta V$

  - **Entropy function**, $S = P\ \delta V^{\gamma}$, where $\gamma \approx 5/3$

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

➡ **Natural profiles** mean ***N* and *S* are homogeneous.** Interchange mixing drive $(N, S) \rightarrow$ uniform at the same rate.
Also, **natural profiles are "stationary"** since fluctuating potentials and $\mathbf{E}\times\mathbf{B}$ flows do not change (N, S).

What are Natural Profiles?

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

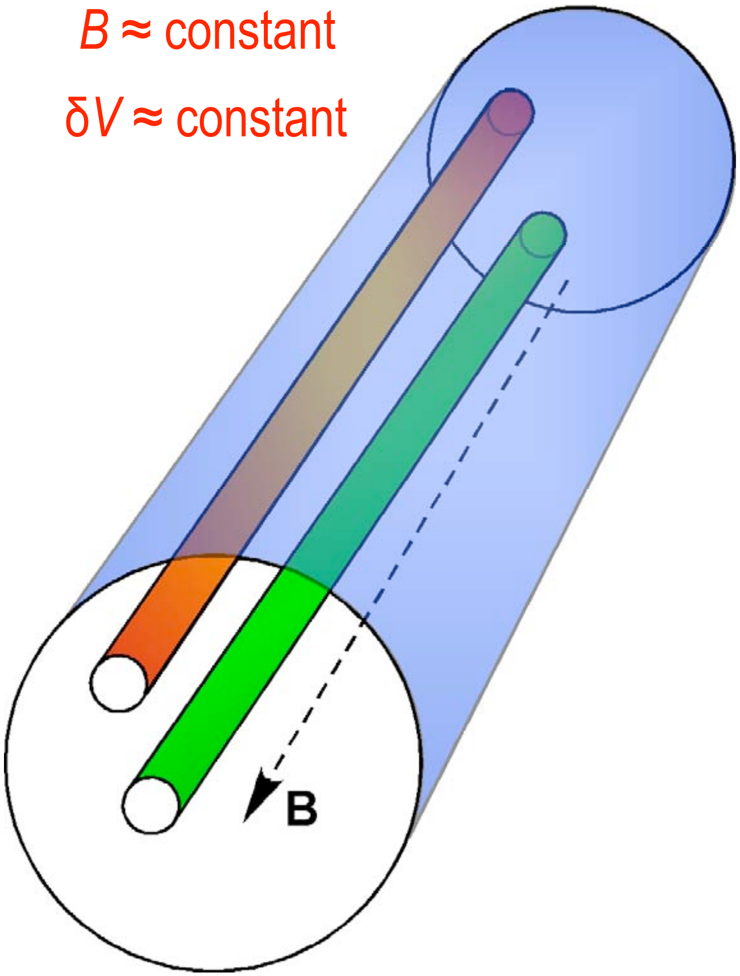
- Flux tube volume:
  - $\delta V = \int ds/B$ = constant

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

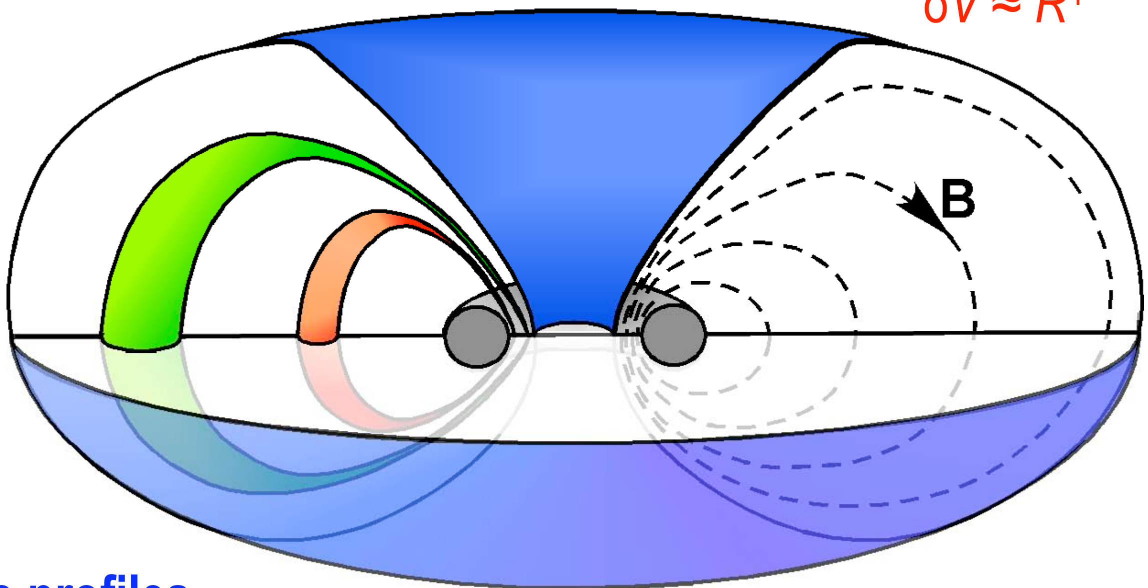
➡ Density, pressure, and temperature at edge and at core are equal.

$B \approx$ constant

$\delta V \approx$ constant



What are Natural Profiles?



- 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**.

"Natural" Profiles in LDX:

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

What are Natural Profiles?

- **Natural profiles are also marginally stable MHD profiles.**

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

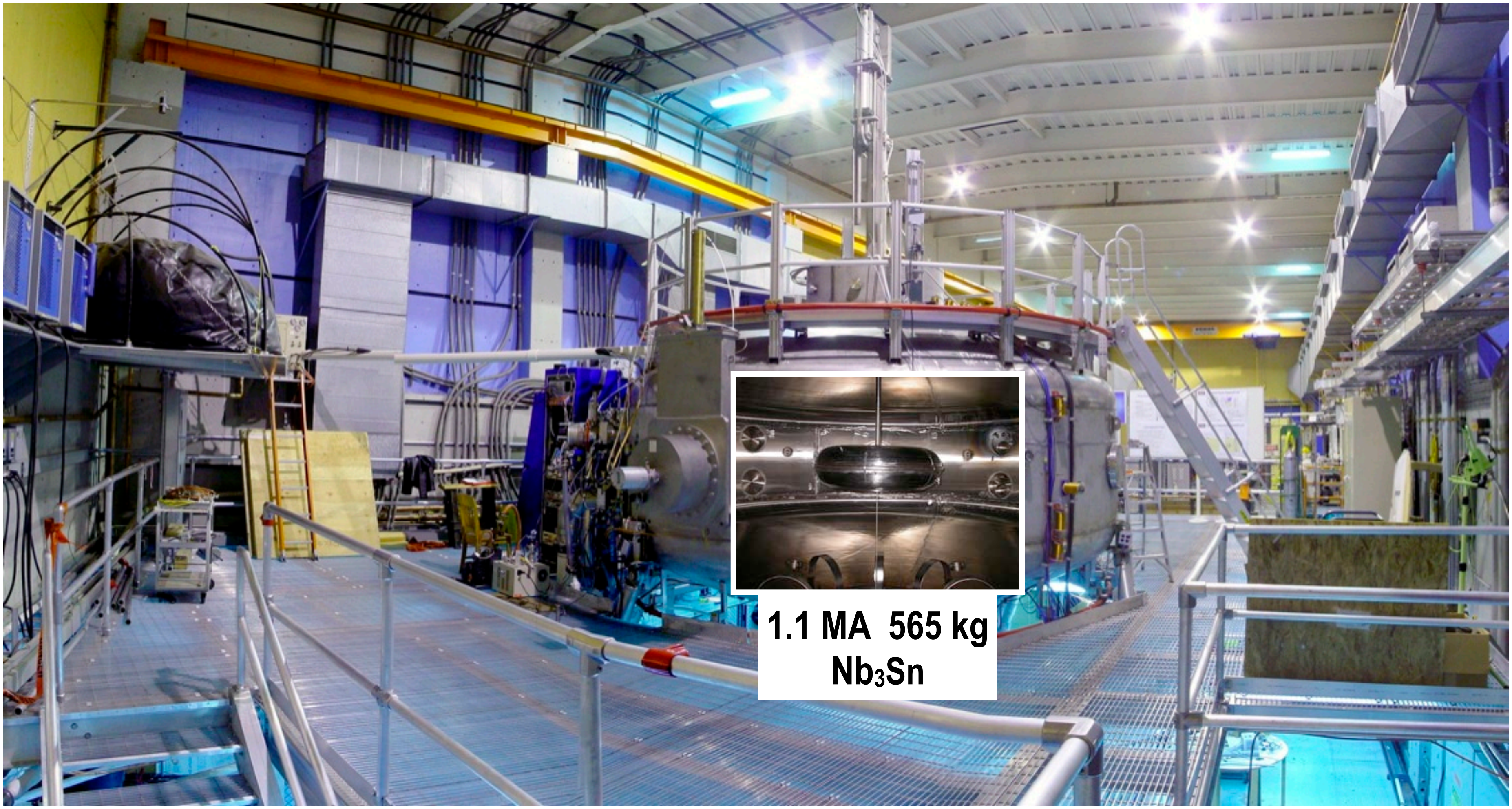
➡ **$S = P\,\delta V^{\gamma}$ = *constant*, is the T. Gold criterion (1959) for marginal stability of pressure-driven interchange mode in magnetosphere, and also Rosenbluth-Longmire (1957) and Bernstein, *et al.,* (1958).**

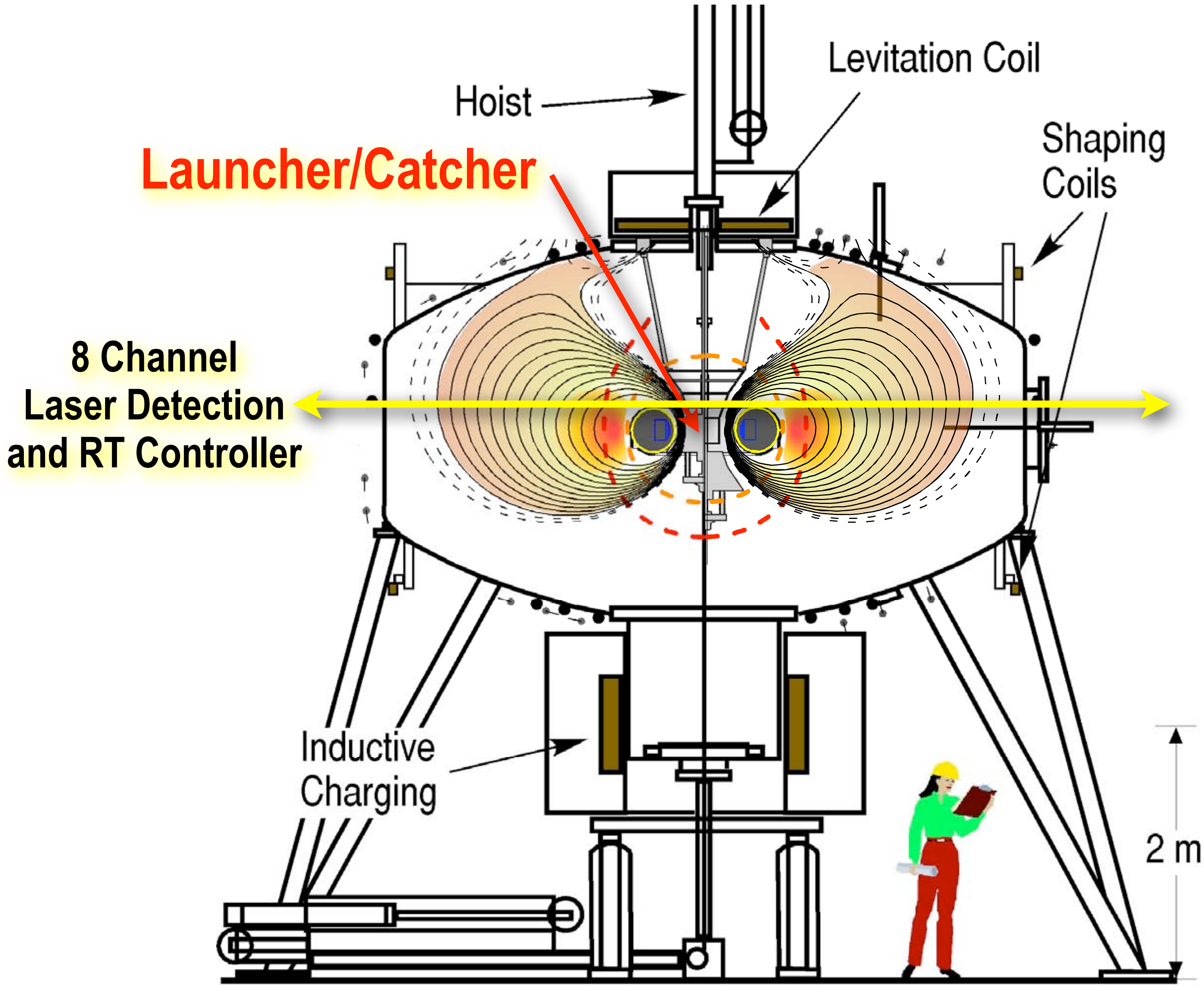
Outline

- LDX and magnetic levitation
- Levitation allows a dramatic peaking of central density and creation of natural dipole profiles.
- Improved particle confinement improves fast electron stability and creates higher stored energy.
- Low frequency fluctuations of density and potential have large-scales and are the likely cause of the naturally peaked profiles.

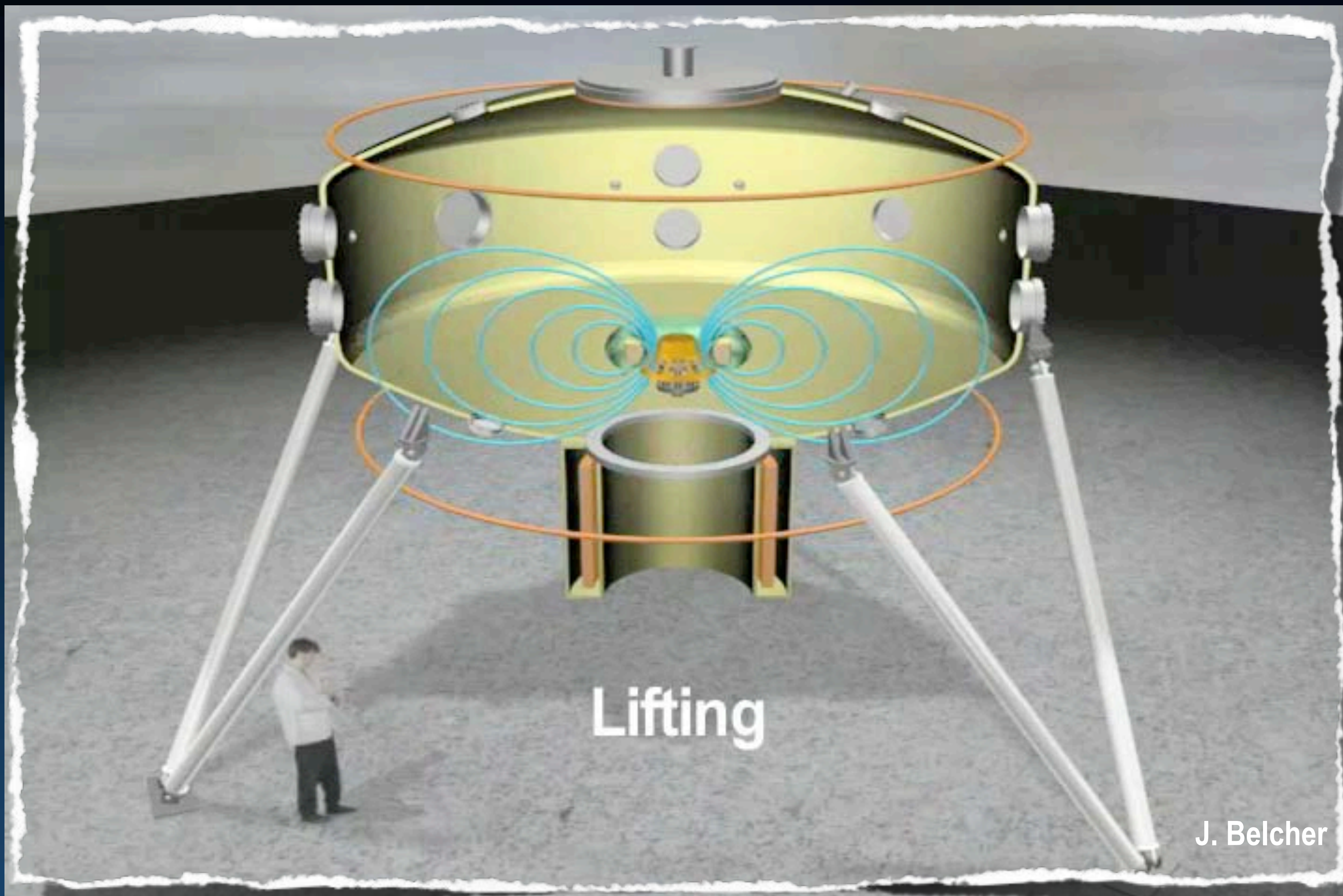
Levitated Dipole Experiment

MIT-Columbia University



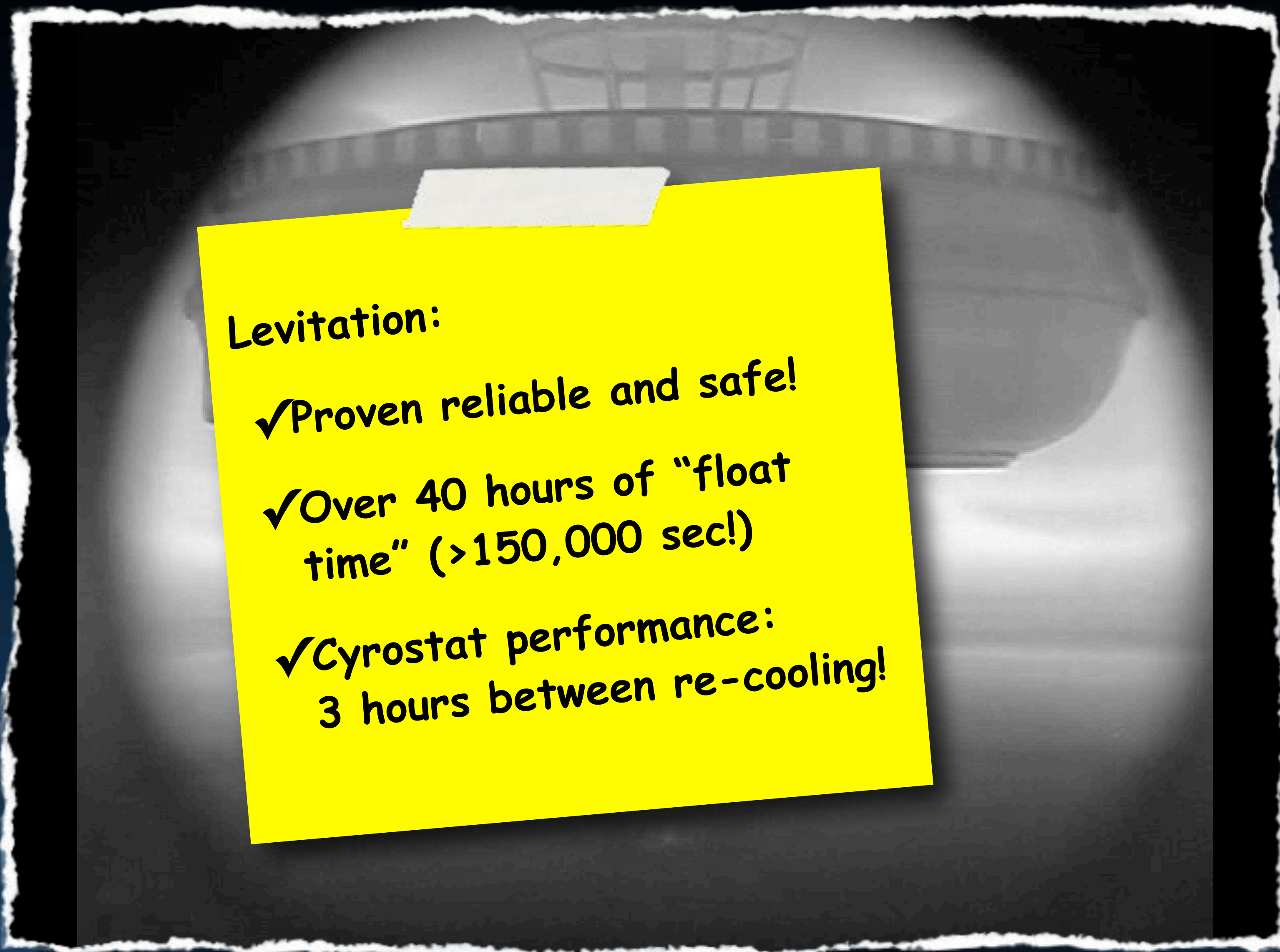

Levitation Coil
Hoist
Shaping
Coils
Launcher/Catcher
8 Channel
Laser Detection
and RT Controller
Inductive
Charging
2 m

Lifting, Launching, Levitation, Experiments, Catching



Levitated Dipole Plasma Experiments

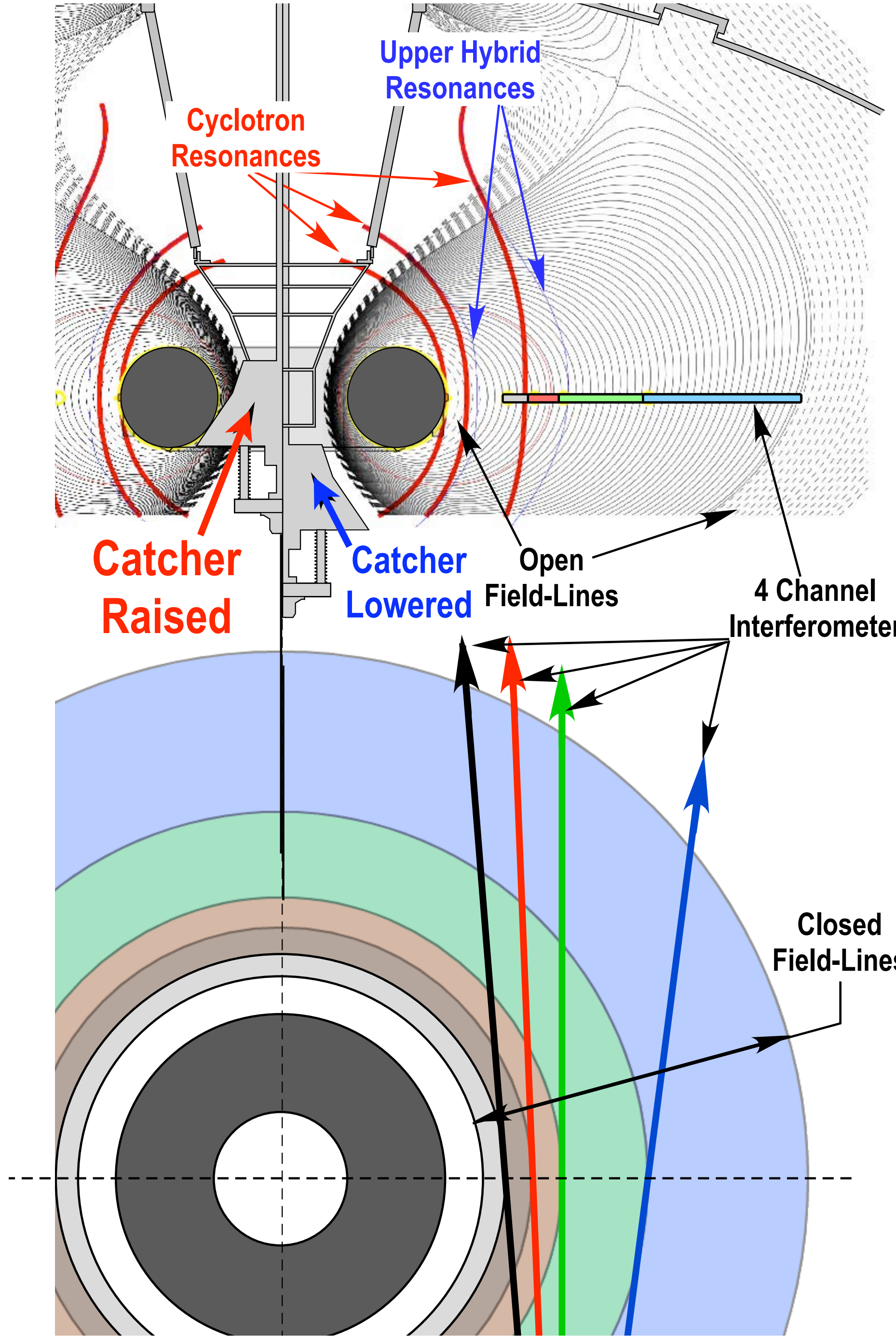
Levitated Dipole Plasma Experiments



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

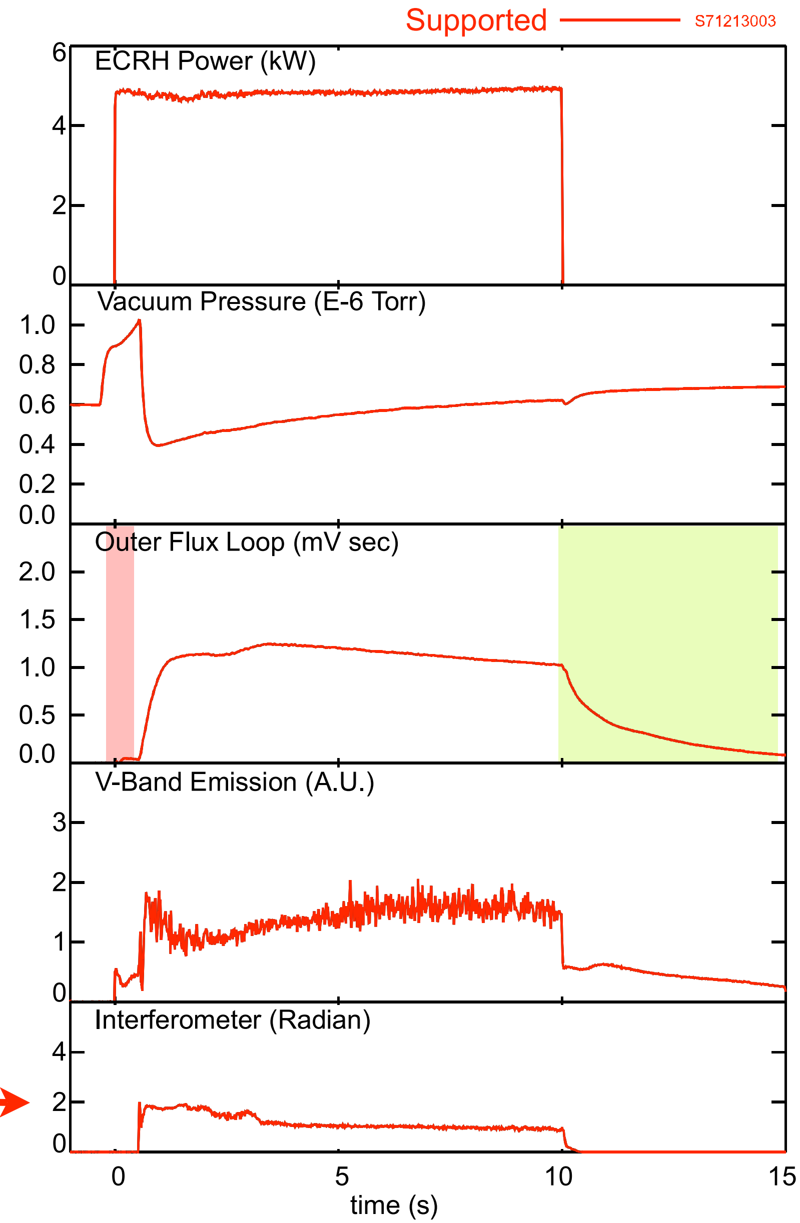
Alex Boxer, MIT PhD, (2008)



Plasma Confined by a Supported Dipole

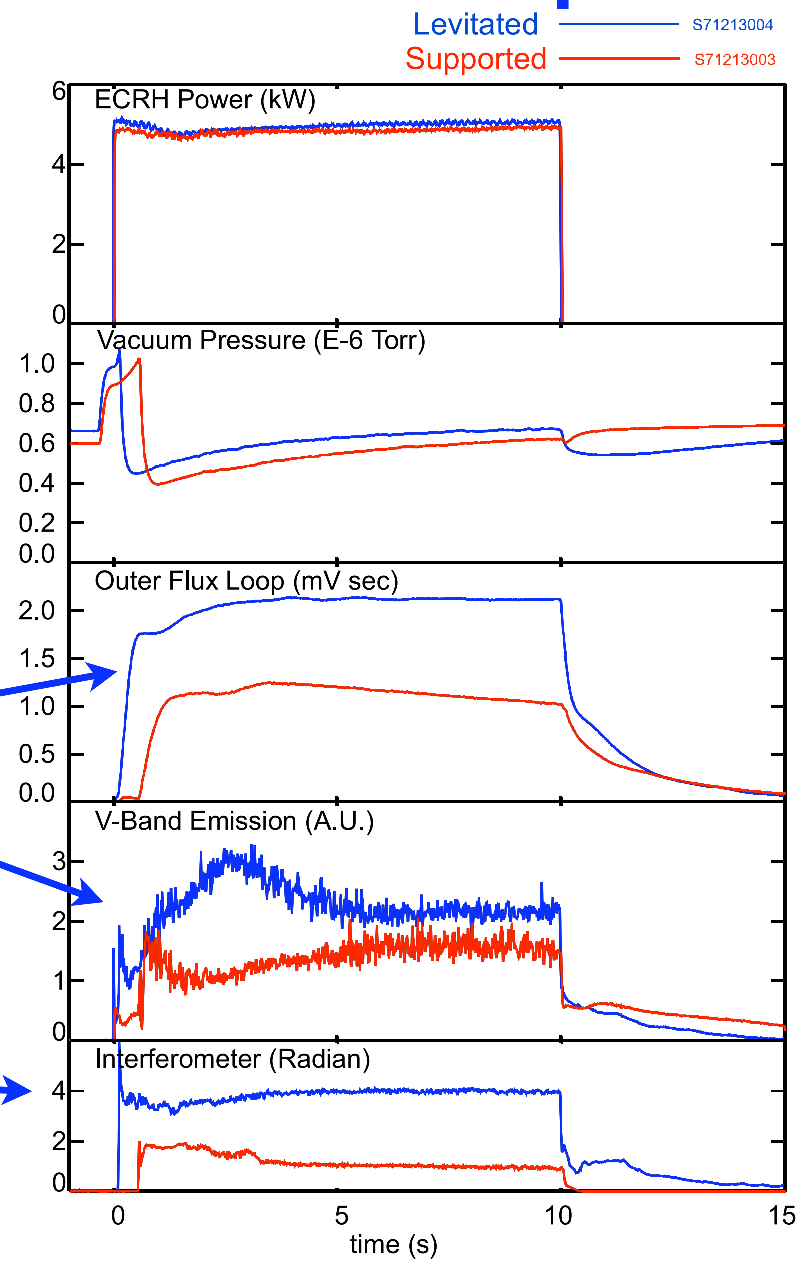
- 5 kW ECRH power
- D_2 pressure ~ 10^{-6} Torr
- Fast electron instability, ~ 0.5 s
- Ip ~ 1.3 kA or 150 J
- Cyclotron emission (V-band) shows fast-electrons
- Long, low-density “afterglow” with fast electrons

➡ **1×10^{13} cm^{-2} line density**

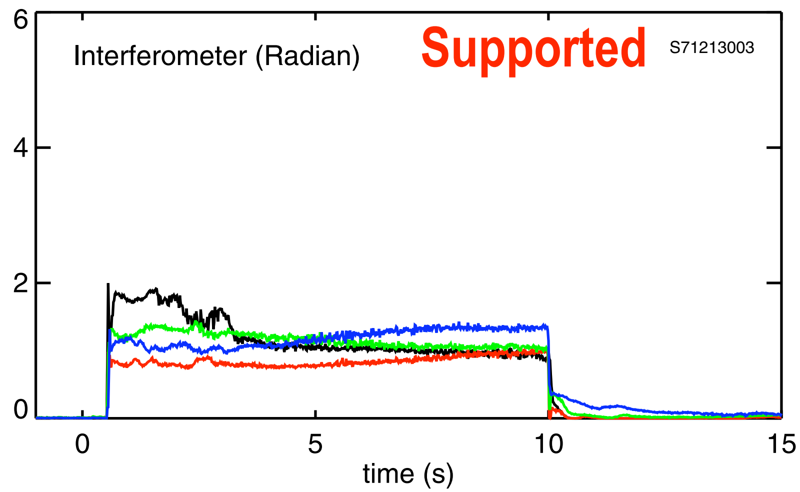


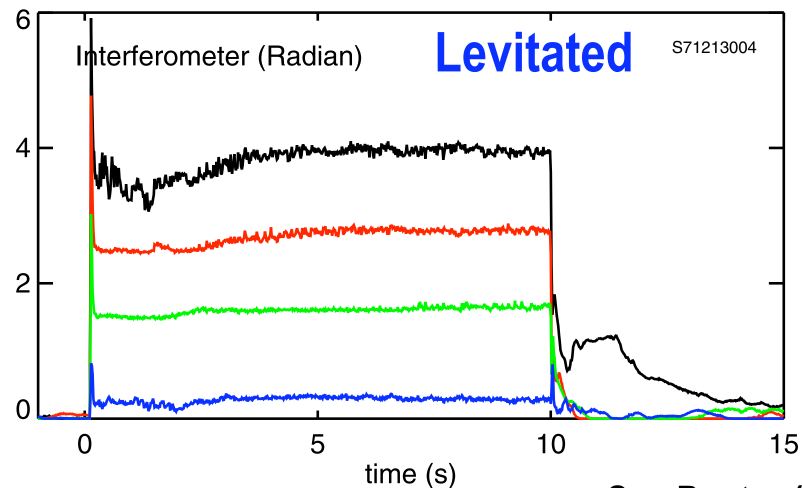
Plasma Confined by a Levitated Dipole

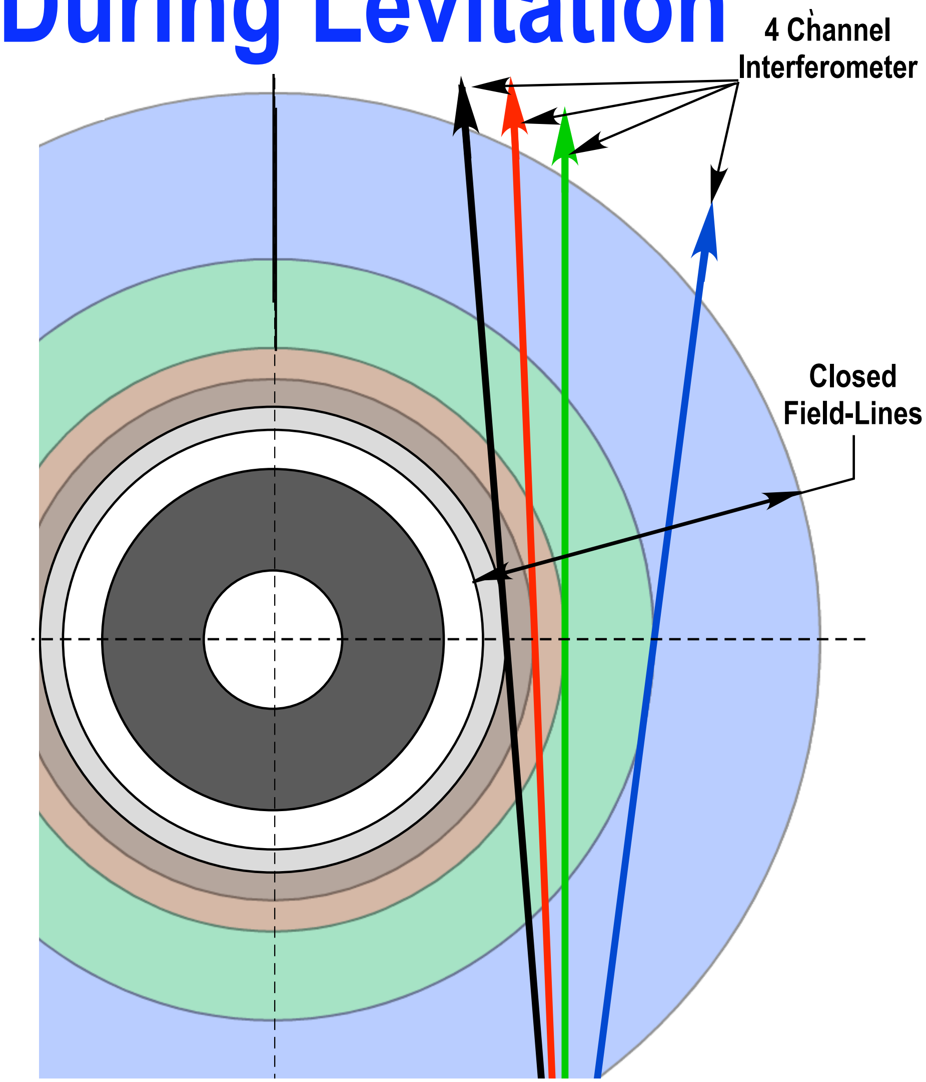
- Reduced fast electron instability
- 2 x Diamagnetic flux
- Increased ratio of diamagnetism-to-cyclotron emission indicates **higher thermal pressure**.
- Long, higher-density “afterglow” shows improved confinement.
- **3 x line density**



Multi-Cord Interferometer Shows Strong Density Peaking During Levitation







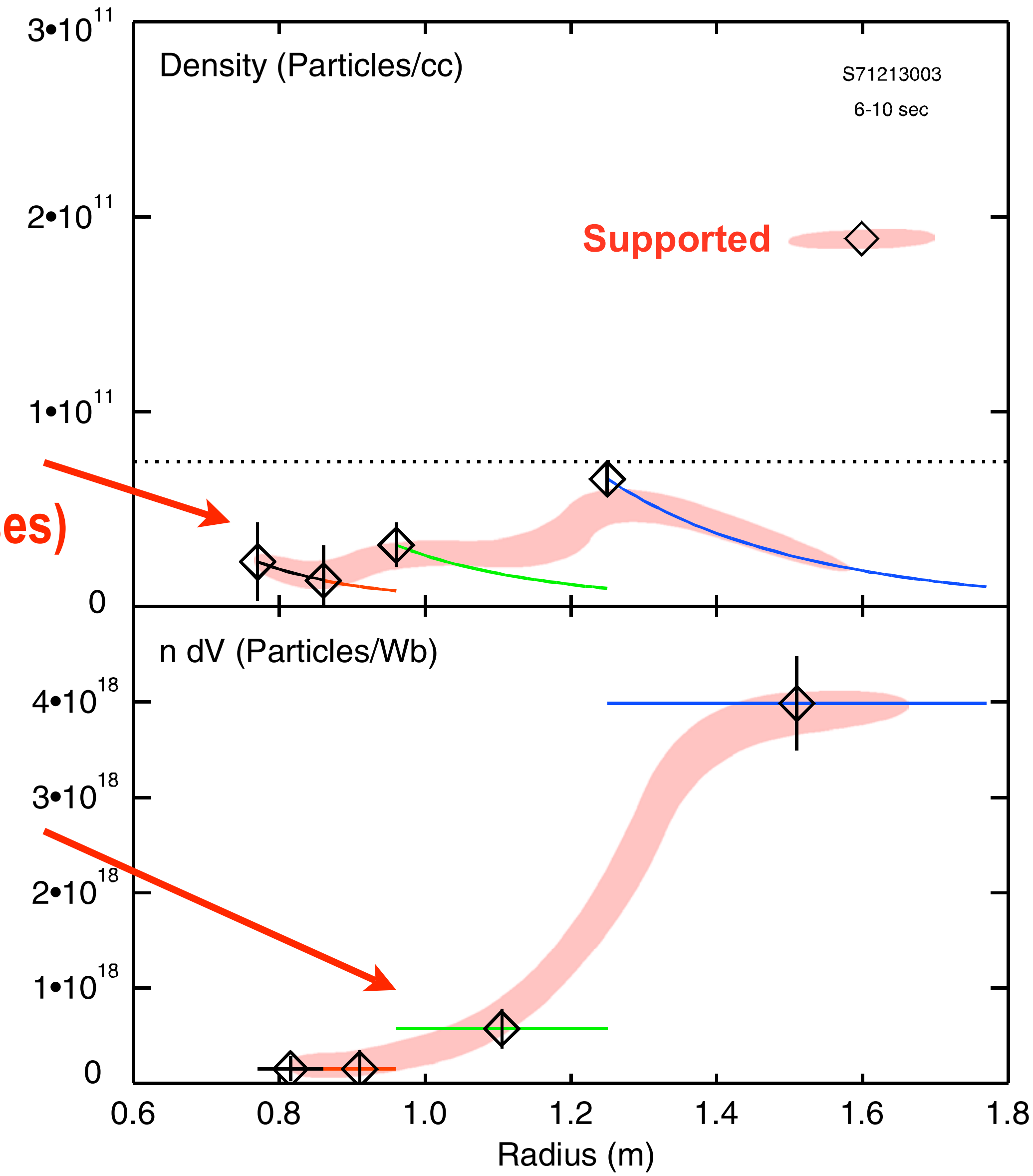
See Poster (NOW!) CP6.00084:

Boxer, et al., "Evidence of ``Natural'' Density Profiles in a Dipole-Confined Plasma"

Inversion of Chord Measurements

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

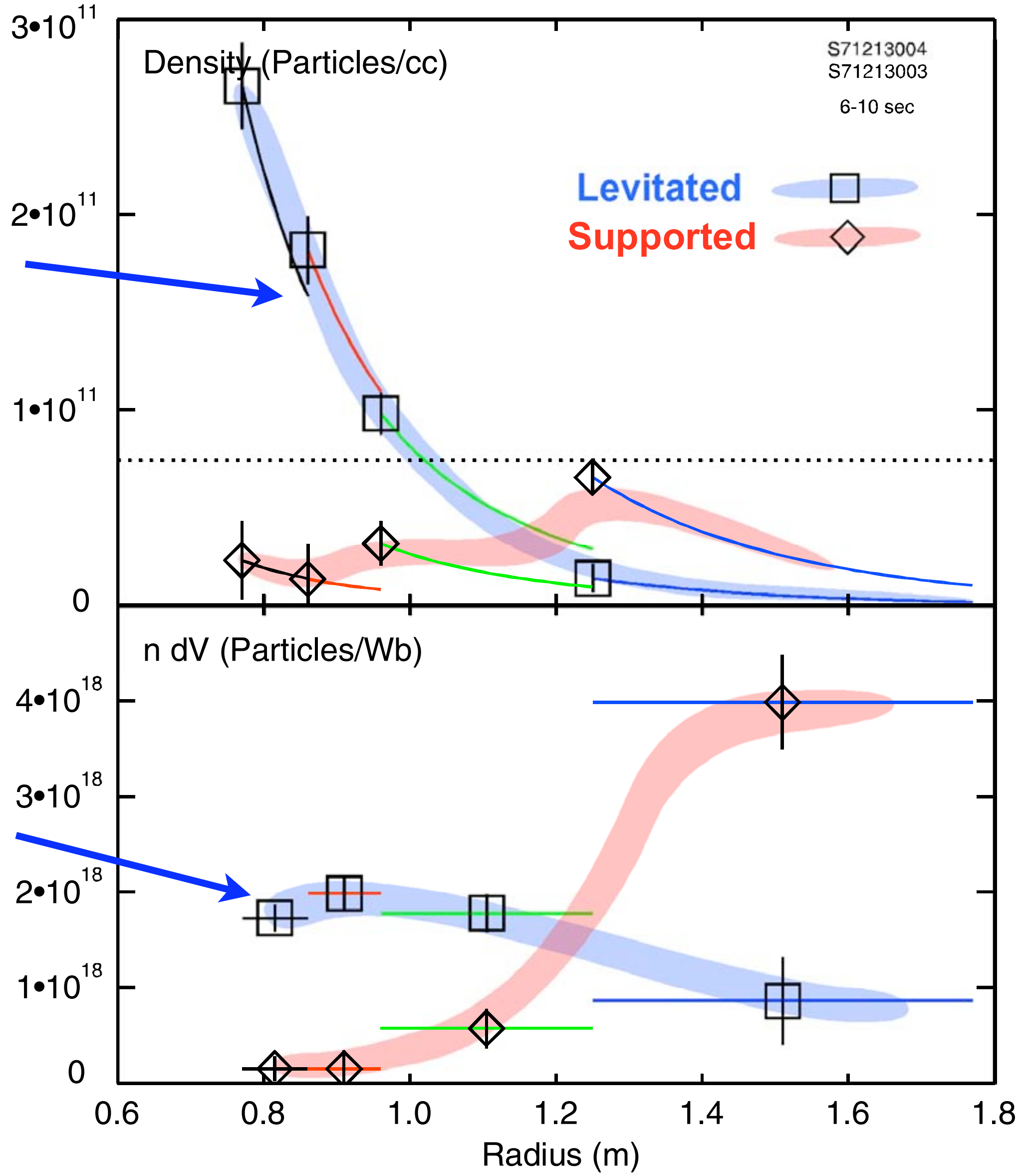
Hollow Number Profile!



Inversion of Chord Measurements

Strongly Peaked Density!

Uniform Number Profile!

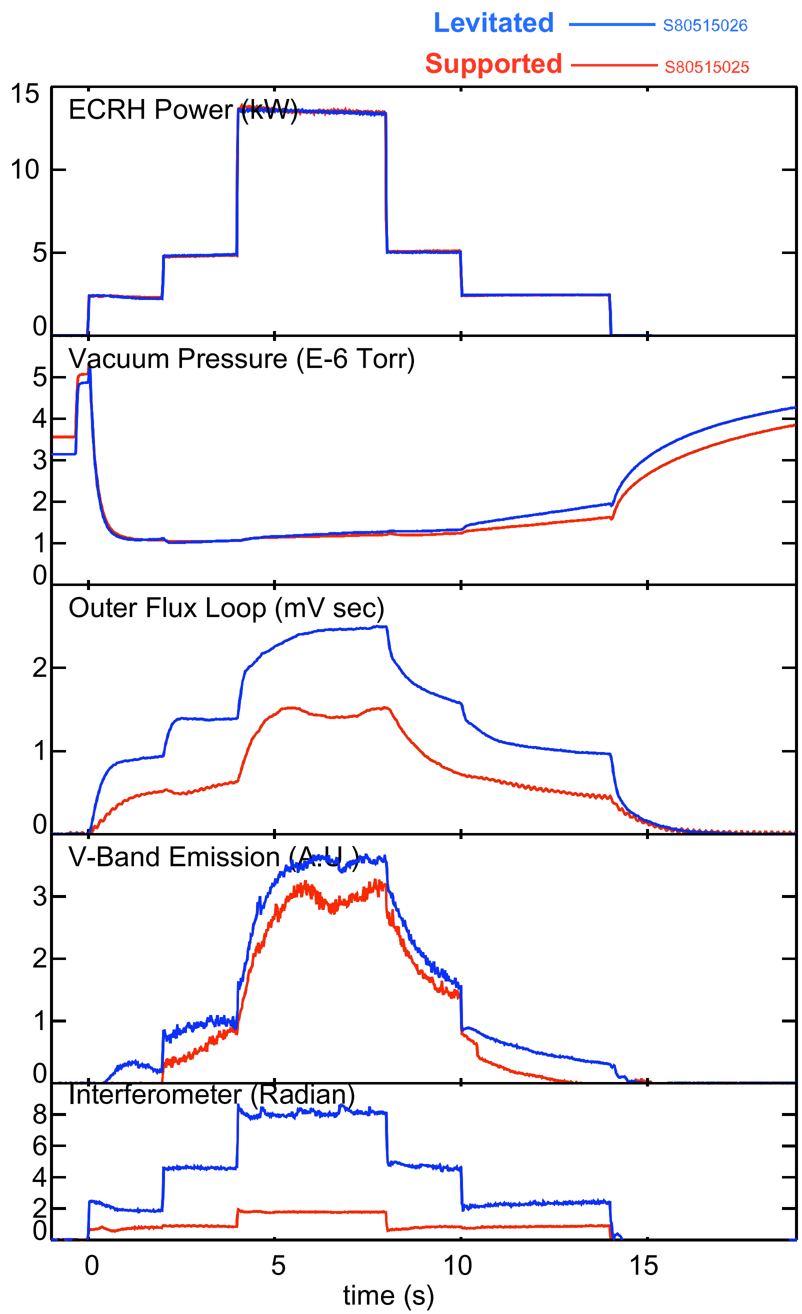


Levitation Always Causes More Peaked Profiles Relative to Supported Discharges

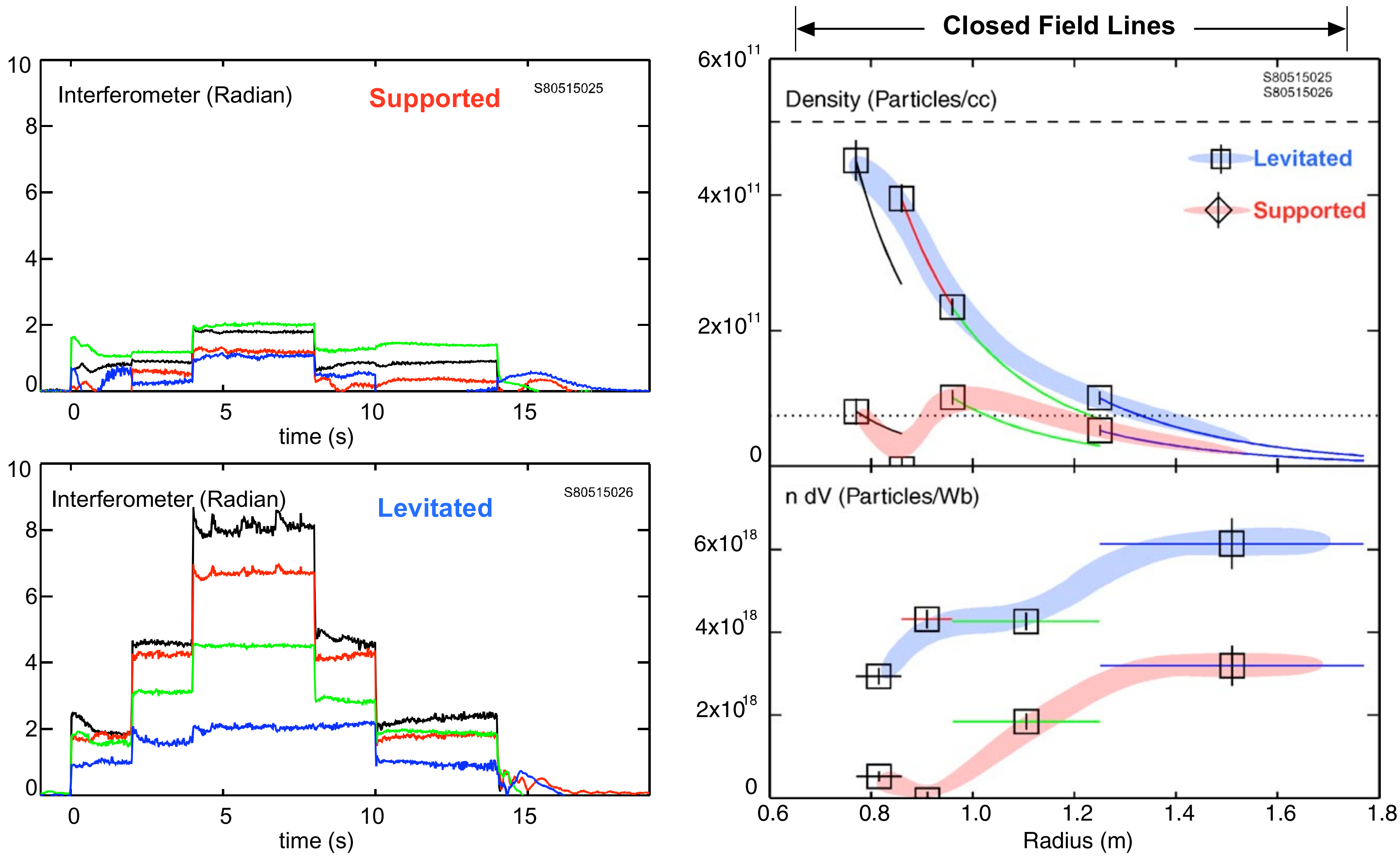
- Comparison of density profiles for levitated and supported discharges always show more peaked profiles during levitation.
- Natural density profiles are created regardless of plasma pressure (*i.e*. both low and high beta).
- Natural density profiles are established quickly, within 15 msec.

Naturally Peaked Profiles Observed at Full Power

- **Full power: 15 kW ECRH**
  (2.45 GHz, 6.4 GHz, 10.4 GHz)
- **~2 x Diamagnetism**
  (β ~ 18% during levitation)
- **Cyclotron emission suggests increased β is due to warm thermal plasma *not fast electrons***
- **4 x Line Density**



Naturally Peaked Profiles Observed at Full Power

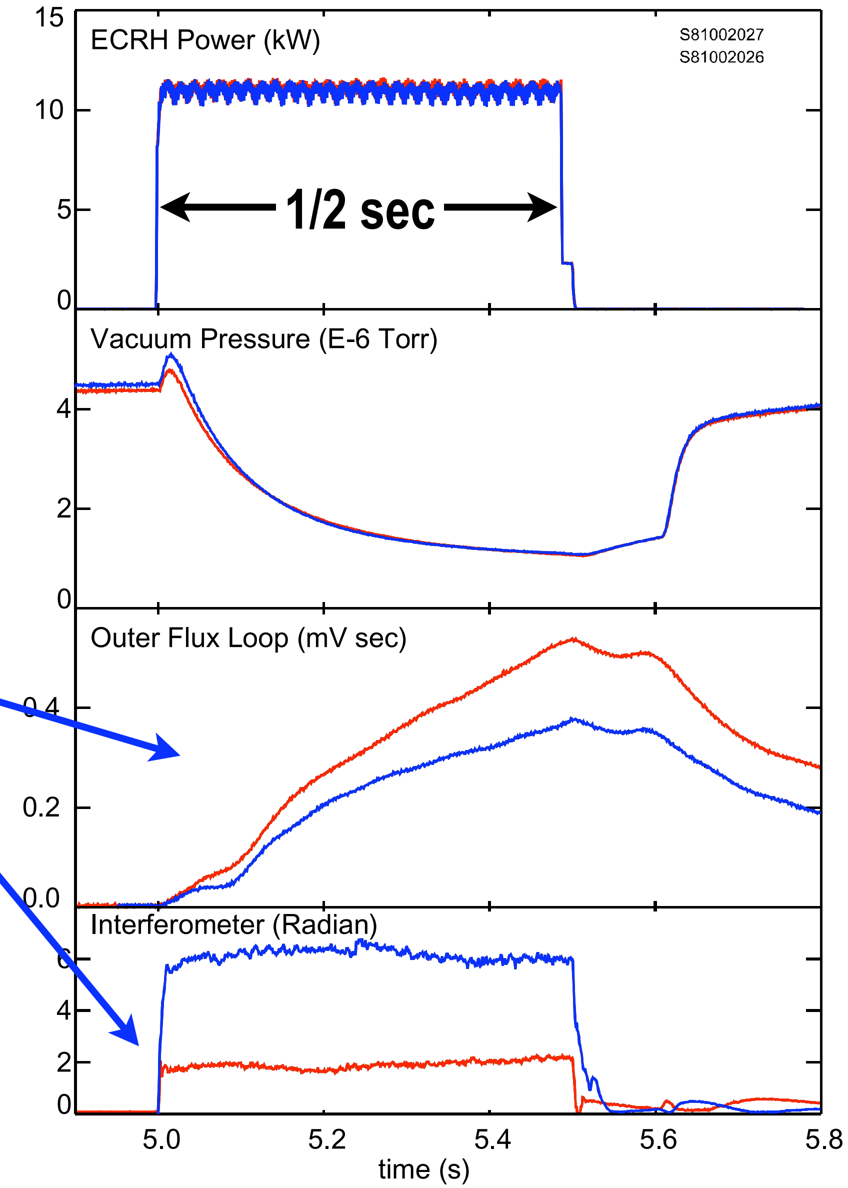


Naturally Peaked Profiles Established Rapidly

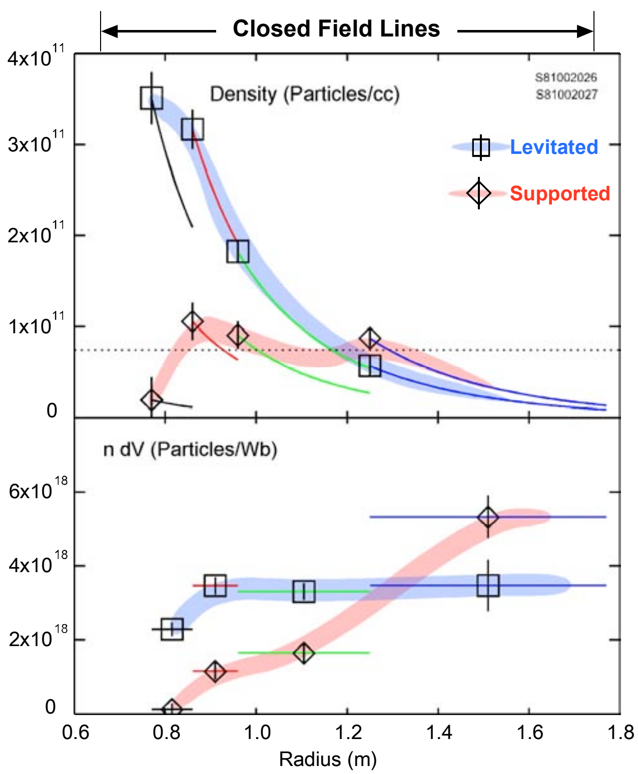
- **Very short 1/2 second heating pulses. Plasma beta remains low, β < 4%**

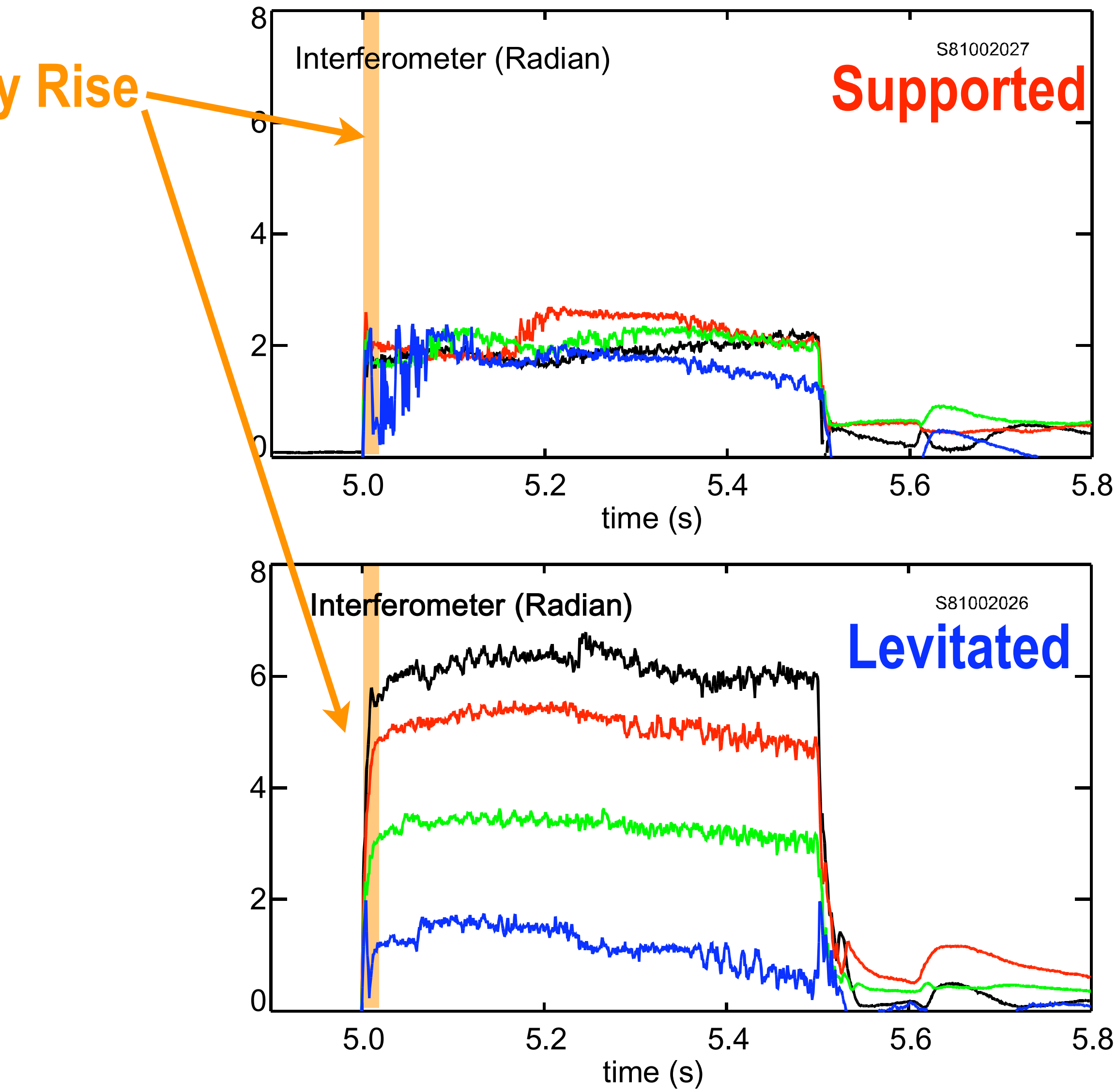
➡ **Plasma density rises much more rapidly than plasma pressure.**

- ***Question*: How quickly are natural profiles established?**



Naturally Peaked Profiles Established Rapidly



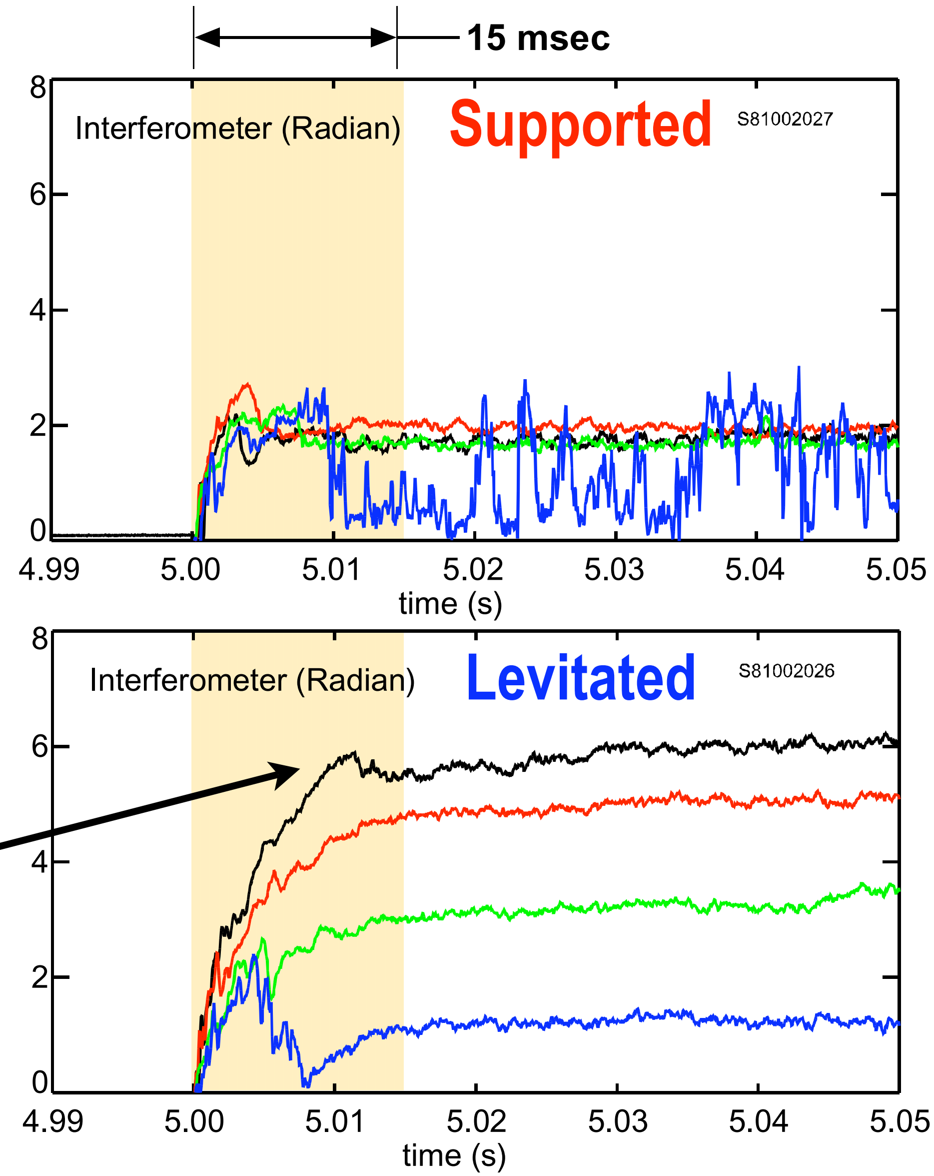


Naturally Peaked Profiles Established Rapidly

- Initially (~ 4 msec), density rises equally for supported and levitated discharges

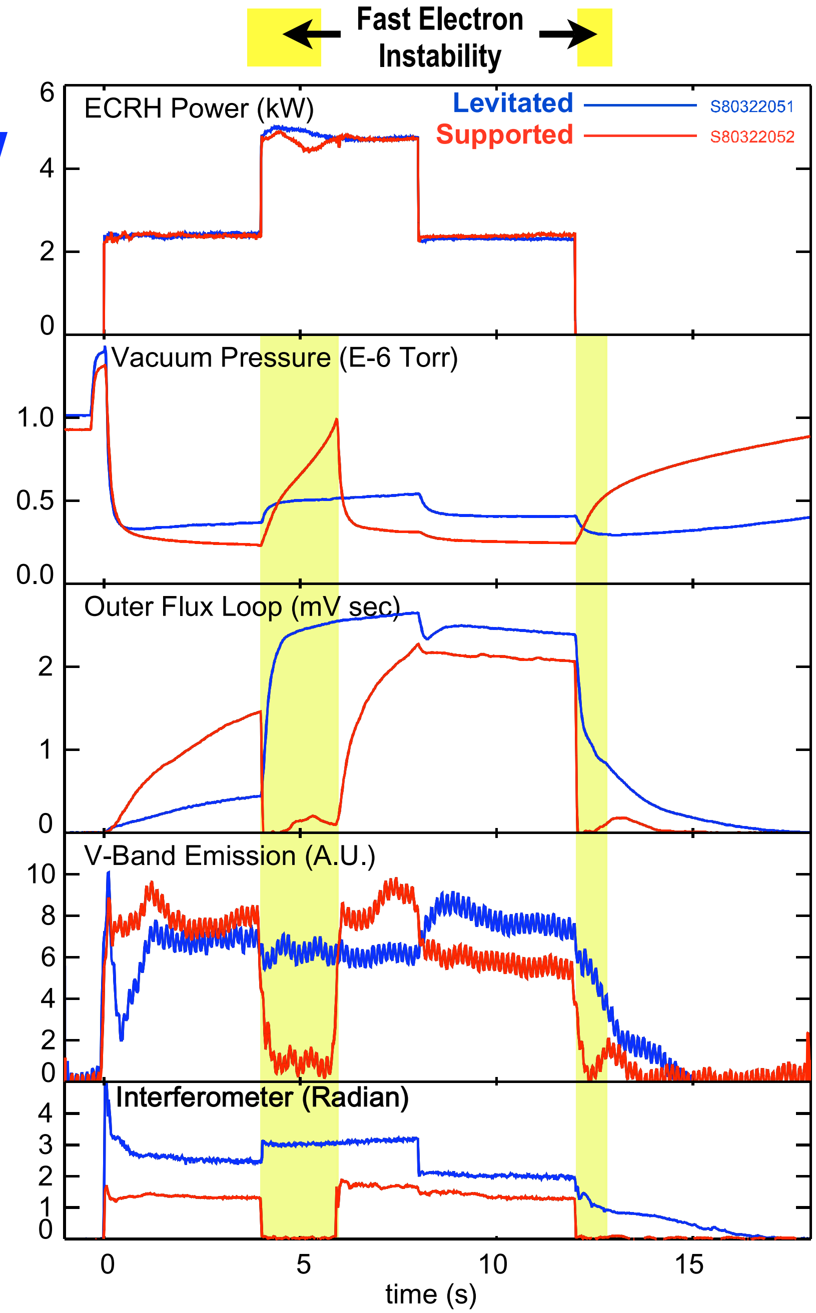
- Only when levitated, central density continues to increase

- Natural profiles are created in less than 15 msec!



Improved Particle Confinement Improves Fast-Electron Stability

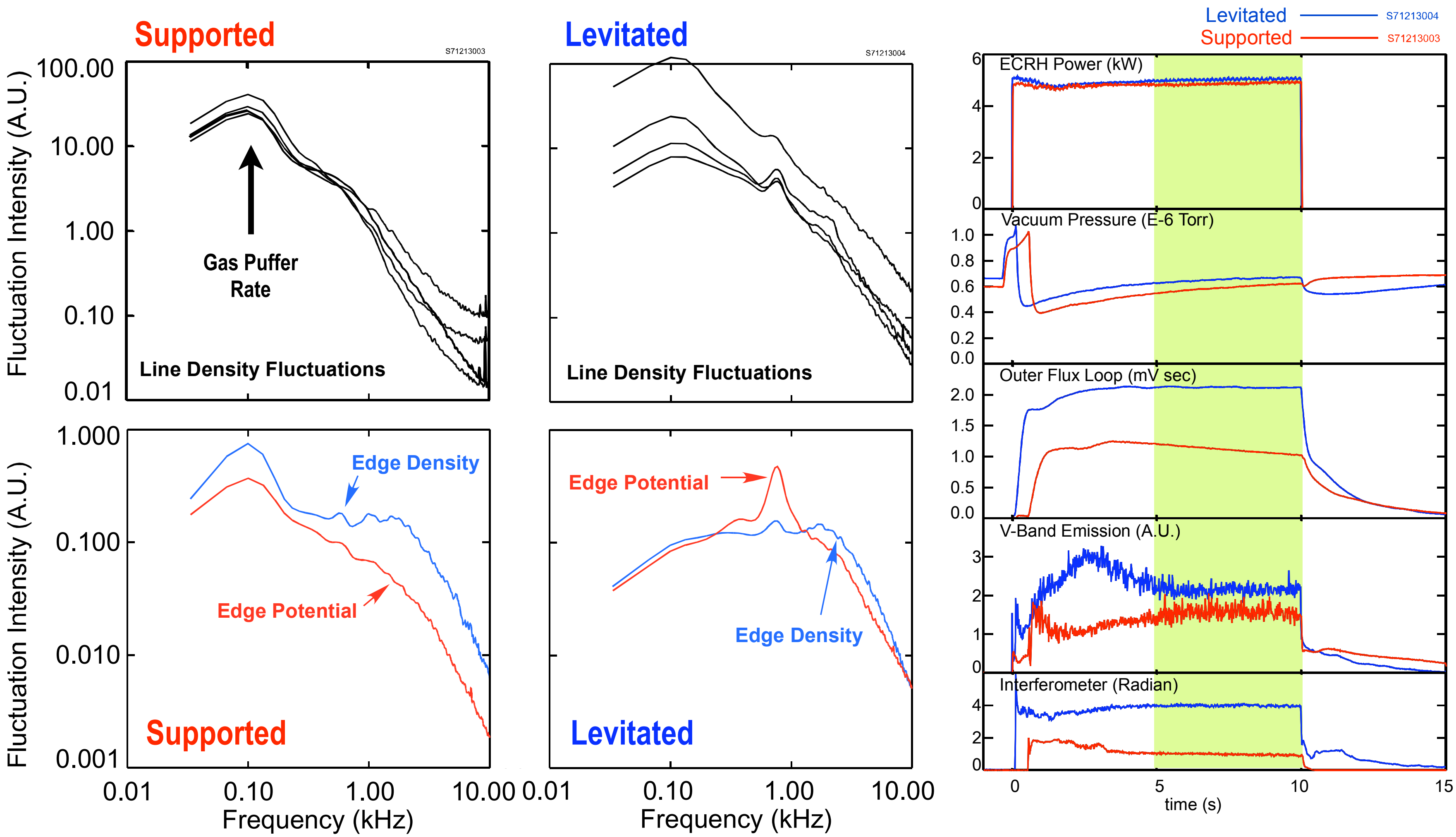
- High-β start-up and stability require sufficient plasma density to stabilize fast-electron instabilities.
- Supported:
  - Reduced particle confinement requires high gas fueling for stability.
  - At low-pressure, fast-electron instability causes rapid extinction of pressure and density.
- Levitated:
  - Good particle confinement gives robust stability for global instability.
  - Global plasma instability never observed during LDX levitation.



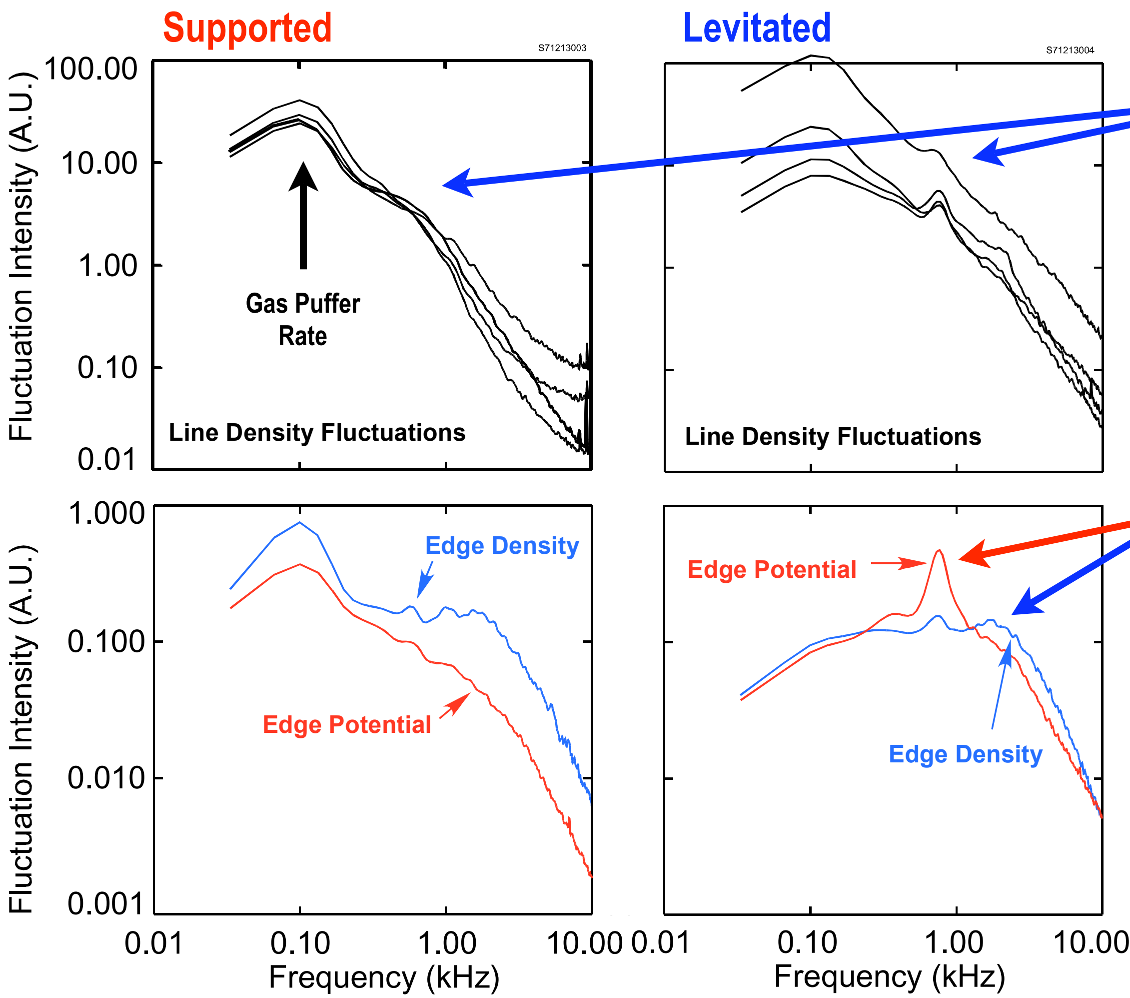
Low-Frequency Fluctuations are Observed throughout Plasma and Probably Cause Naturally Peaked Profiles

- **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.**

Comparing the Turbulent Fluctuation Spectrum: Supported/Levitated



Comparing the Turbulent Fluctuation Spectrum: Supported/Levitated



"Large Scale" fluctuations seen across profile

Possible Evidence of "Stationary" Density Profile?

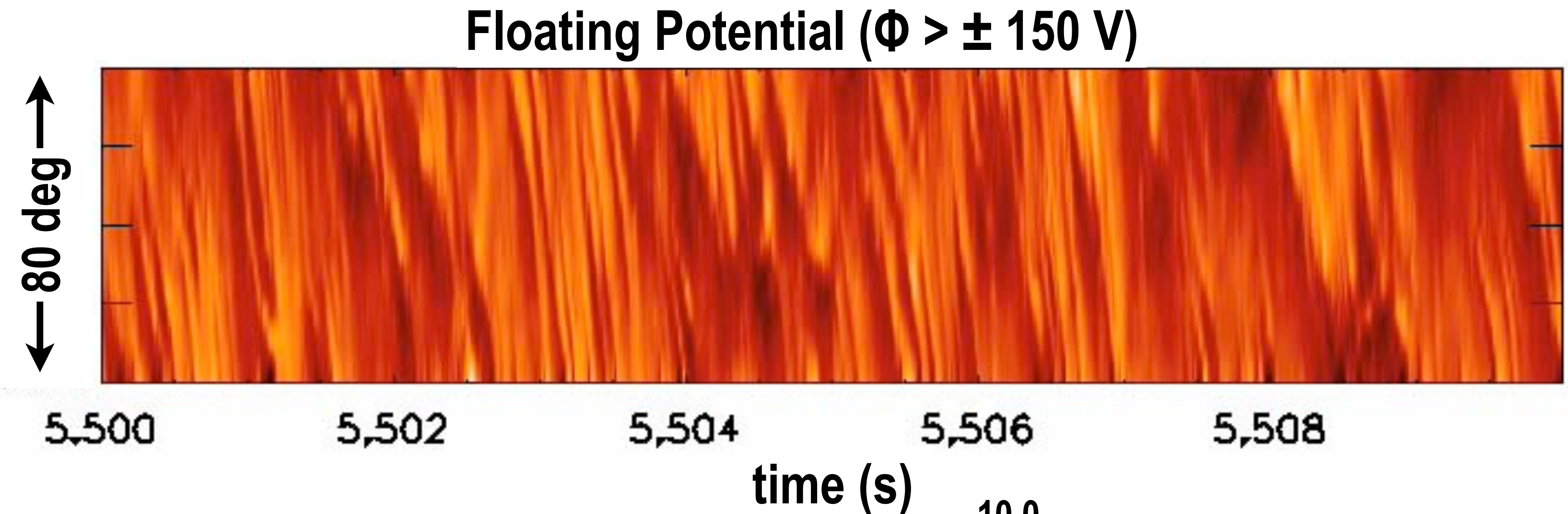
Strong E×B flows (*i.e.* potential fluctuations) with *reduced* density fluctuations.

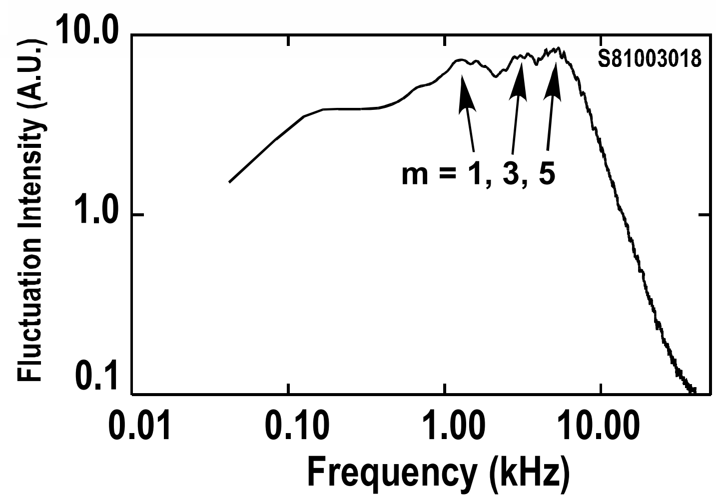
Floating Potential Probe Array

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

See Poster (NOW!) CP6.00087:
Bergmann, et al., “Observation of low-frequency oscillations in LDX with an angular electrostatic probe”

Floating Potential Probe Array





15 kW High-β Discharge

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

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

See Poster (NOW!) CP6.00087:

Bergmann, et al., “Observation of low-frequency oscillations in LDX with an angular electrostatic probe”

Edge Potential Fluctuations are Characteristic of 2D Interchange Turbulence in a Rotating Plasma

- **Millions of recorded samples are sufficient to compute converged auto-spectra and bi-spectra of potential fluctuations in a single shot.**

- **Edge fluctuations have: (i) dispersion dominated by plasma rotation, (ii) damping characteristic of a scale-independent viscosity, and (iii) nonlinear power coupling from small-to-large scales (as in 2D turbulence).**

➡ **See Brian Grierson's invited talk:**

"*Global and Local Characterization of Turbulent and Chaotic Structures in a Dipole-Confined Plasma*".
Basic Plasma Session UI1, 3:30pm Thursday.

Next Steps in LDX Dipole Confinement Physics

- Do natural pressure profiles, $P \sim 1/\delta V^{\gamma}$, develop? ***Install soft x-ray filter array for warm plasma profile measurements.***
- What are the spatial structures of the convective flows? ***Install a reflectometer and complete high-speed optical tomography studies.***
- Create higher density plasma with additional heating options:
  - **100 kW pulsed 4.6 GHz**
  - **20 kW CW 28 GHz gyrotron (*See P. Woskov's Poster*)**
  - **1 MW CW ICRF heating**
- What is the effect of magnetic field errors on confinement? ***Install non-axisymmetric trim/error coils.***

Summary

- The mechanics of magnetic levitation is proven reliable.

- 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.

- Improved particle confinement improves hot electron stability and creates higher stored energy.

- Fluctuations of density and potential show large-scale circulation that is the likely cause of peaked profiles.

LDX Experimental Team

Poster Session CP6: NOW!