Improved Confinement During Magnetic Levitation in LDX

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For the LDX Experimental Team
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Columbia University

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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, $P_\perp/P_\parallel \sim 5$.

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

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

J. Spencer

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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


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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**, $N = \int ds \frac{n}{B} \approx n \delta V$
  - **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 $(N, S)$. 

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What are Natural Profiles?

- Flux tube volume:
  \( \delta V = \int \frac{ds}{B} = \text{constant} \)

- Natural profiles:
  \( n \delta V = \text{constant} \)
  \( P \delta V = \text{constant} \)
  \( \text{Density and pressure profiles are flat} \)

\( B \approx \text{constant} \)
\( \delta V \approx \text{constant} \)

Density, pressure, and temperature at edge and at core are equal.
What are Natural Profiles?

- Flux tube volume:
  - \( \delta V = \int ds/B \approx R^4 \)

- Natural profiles:
  - \( n \delta V = \text{constant} \)
  - \( P \delta V = \text{constant} \)
  - Density and pressure profiles are strongly peaked!

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

“Natural” Profiles in LDX:

\[
\begin{align*}
\frac{\delta V_{\text{edge}}}{\delta V_{\text{core}}} & \approx 50 \\
n_{\text{core}}/n_{\text{edge}} & \approx 50 \\
P_{\text{core}}/P_{\text{edge}} & \approx 680 \\
T_{\text{core}}/T_{\text{edge}} & \approx 14
\end{align*}
\]
What are Natural Profiles?

- Natural profiles are also marginally stable MHD profiles.

\[ N = \text{constant}, \] is the D. B. Melrose criterion (1967) for stability to centrifugal interchange mode in rotating magnetosphere.

\[ S = P \delta V = \text{constant}, \] 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

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The Plasma Science & Fusion Center (PSFC) is recognized as one of the leading university research laboratories in the physics and engineering aspects of magnetic confinement fusion.

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12 m

8 Channel Laser Detection and RT Controller
Lifting, Launching, Levitation, Experiments, Catching
Levitated Dipole Plasma Experiments

Floating
(Up to 3 Hours)
Levitated Dipole Plasma Experiments

Levitation:
✓ Proven reliable and safe!
✓ Over 40 hours of “float time” (>150,000 sec!)
✓ Cyrostat performance: 3 hours between re-cooling!
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 $\sim 10^{-6}$ Torr
- Fast electron instability, $\sim 0.5$ s
- $I_p \sim 1.3$ 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

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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”  

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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

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Naturally Peaked Profiles Observed at Full Power

Supported

Levitated

Closed Field Lines

Density (Particles/cc)

n dV (Particles/Wb)

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Naturally Peaked Profiles Established Rapidly

- Very short 1/2 second heating pulses. Plasma beta remains low, \( \beta < 4\% \)

- Plasma density rises much more rapidly than plasma pressure.

- **Question:** How quickly are natural profiles established?
Naturally Peaked Profiles Established Rapidly

Short 15 msec Density Rise
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 \((f \sim 1 \text{ kHz and } < 20 \text{ kHz})\) 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 \((E \sim 200 \text{ V/m})\) 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

Supported

Levitated

![Graphs showing fluctuation spectrum for supported and levitated conditions.](image-url)
Comparing the Turbulent Fluctuation Spectrum: Supported/Levitated

**Supported**

![Graph showing supported fluctuations]

- Gas Puffer Rate
- Line Density Fluctuations

**Levitated**

![Graph showing levitated fluctuations]

- Line Density Fluctuations

"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

Floating Potential (Φ > ± 150 V)

15 kW High-β Discharge

ω ~ Ω m = ΩR k, with

Ω/2π ~ 1 kHz

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

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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!

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