Report on the Levitated Dipole eXperiment (LDX): An Uplifting Fusion Adventure

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Introduction to Magnetic Dipoles

Why would you build LDX?
Levitated Dipole Confinement Concept: Combining the Physics of Space & Laboratory

- Akira Hasegawa, 1987

- Two interesting properties of active magnetospheres:
  - **High beta**, with ~ 200% in the magnetospheres of giant planets
  - Pressure and density profiles are strongly peaked
  - “Invariant profiles” turbulent activity increases peakedness
What are Invariant Profiles?

- Invariant to adiabatic interchange of flux tubes
- Flux tube volume:
  \[ \delta V = \int \frac{d\ell}{B} = \text{constant} \]
- Invariant profiles:
  \[ n \delta V = \text{constant} \]
  \[ p \delta V^\gamma = \text{constant} \]
- Density and pressure profiles are flat
What are Invariant Profiles?

- **Flux tube volume:**
  \[
  \delta V = \int d\ell / B \approx R^4
  \]

- **Invariant profiles:**
  \[
  n\delta V = \text{constant}
  \]
  \[
  p\delta V^\gamma = \text{constant}
  \]

- **Density and pressure profiles are strongly peaked!**

"Natural" Profiles in LDX:

\[
\frac{\delta V_{\text{edge}}}{\delta V_{\text{core}}} \approx 50
\]
\[
\frac{n_{\text{core}}}{n_{\text{edge}}} \approx 50
\]
\[
\frac{P_{\text{core}}}{P_{\text{edge}}} \approx 680
\]
\[
\frac{T_{\text{core}}}{T_{\text{edge}}} \approx 14
\]
Testing a New Approach to Fusion and Laboratory Plasma Confinement

Levitated Dipole Fusion Concept

ITER

30 m

400-600 MW
D-T Fusion

Levitated Dipole Reactor


500 MW
D-D(He³) Fusion

60 m
Testing a New Approach to Fusion and Laboratory Plasma Confinement

Levitated Dipole Fusion Concept

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

Levitated Dipole Reactor


500 MW
D-D(He$^3$) Fusion

60 m
Design and Construction of LDX

Seemed simple enough at the time...
Lifting, Launching, Levitation, Experiments, Catching

J. Belcher
Floating Dipole Conceptual Design

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
Winding Pack and He Pressure Vessel

Advanced ITER Nb₃Sn conductor

... wound very carefully...
Lead Radiation Shields and Multi-Layer Insulation
Support Washer Stacks

- **Specification**
  - Hold heat leak to 5 K < 10 mW
  - Withstand 10g crash (5 Tons!)

- **Solution**
  - Stack of 400 4mil thick washers
  - 24 Stacks (~7000 coins)
  - Assembled, Sized and Installed
LDX Airbag Emergency Catcher

- NASA Pathfinder application research
  - NASA airbag research budget ~ 3 X total LDX budget!

Launcher / Catcher

- Tested to limit all accelerations to less than 5 g
Dilbert Levitation System

- Greatly simplified
  - Easily manufactured at low cost (even for Starbucks)
- Not reliable.
Levitation Control System Schematic

- Levitation Coil
- Rotation Indicators
- X-Y Sensing Laser Beams (green)
- Z-Tilt Sensing Laser Beams (red)
- Tilt-Slide-Rotate Control Coils
Digitally Controlled Levitation

- Levitated Cheerio Experiment II
- Uses LDX digital control system
- Modified PID feedback system
- Real-time graph shows position and control voltage
● Final LDX levitation control system contains added complexity
  ▶ Reliable levitation with over 80 hours of flight time
The Levitated Dipole Experiment (LDX)
LDX Operations and Results

Wow… it really works!
Levitated Dipole Plasma Experiments

Floating
(Up to 3 Hours)
Plasma Confined by a **Supported** Dipole

- 5 kW ECRH power
- \( I_p \sim 1.3 \text{ kA or 150 J} \)
- Cyclotron emission (V-band) shows fast-electrons
- Long, low-density “afterglow” with fast electrons
Fast Electrons: Anisotropic at ECRH Resonance
Fast Electrons: Anisotropic at ECRH Resonance

Shot 50701011

X-Ray
E > 40 keV
Plasma Confined by a **Levitated** Dipole

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

Flat or Hollow Density
*likely cause: parallel losses*

Hollow Number Profile!
Levitated plasmas show invariant profiles

Strongly Peaked Density!

Uniform Number Profile!
Edge probe array measures low frequency turbulence

- Array measures low frequency turbulent spectrum (0.1 - 10 kHz)
- Instantaneous ExB radial flow of 35 km/s
Low frequency fluctuations consistent with Turbulent Pinch

\[
\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi},
\]

where \( \langle S \rangle \) is the net particle source within the flux-tube, and the diffusion coefficient is \( D = R^2 \langle E_{\phi}^2 \rangle \tau_{cor} \) in units of \((V \cdot \text{sec})^2/\text{sec}\).
The dipole concept offers a unique avenue to study magnetic confinement bridging space and the laboratory.

The LDX device is highly innovative, superconducting magnetic confinement device with reliable operation.

LDX is fulfilling its physics mission:

- Demonstration of stable high beta plasmas
  - Significant plasma stored energy in the bulk plasma has been observed
- Demonstrated the formation of invariant “natural” density profiles in a laboratory dipole plasma.
  - Peaked profile formation likely the result of low frequency turbulent pinch
Next Steps

• Levitation System upgrades
  ▶ Incorporate magnetic signals
    ♦ remove influence of plasma diamagnetic current on levitation

• Diagnostic upgrades
  ▶ Improved fluctuation diagnostics to study turbulent transport
  ▶ Core temperature diagnostics to test effective adiabatic constant
    ♦ Including Thompson scattering system

• “Scotty, we need more power!”
  ▶ Higher power for higher density and temperatures
  ▶ 10 kW, 28 GHz gyrotron (with U Maryland collaboration)
  ▶ 200 kW ion heating (slow wave ICRH)
    ♦ 1 MW, 3-28 MHz Transmitter donated by GA to be installed with ARRA funding