First Flight of the Levitated Dipole Experiment

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Abstract

In the past year, the first levitated experiments have been conducted in the Levitated Dipole Experiment (LDX). LDX, which consists of a 560 kg superconducting coil floating within a 5m diameter vacuum chamber, is designed to study fusion relevant plasmas confined in a dipole magnetic field.

In previous plasma run campaigns, conducted with the dipole coil held by thin supports, stable high beta plasma operations were demonstrated where the plasma kinetic energy is contained in population of energetic particles.

It was expected that levitated experiments would improve confinement by removing the primary loss of energy and particles along field lines. This in turn would lead to higher plasma density and broader radial profiles which should increase the stable operational space.

In February, the first flight of the floating dipole coil was achieved with 40 minutes of continuous levitation and three demonstration plasma shots. This first flight experiment demonstrated the operation of the digital feedback system that provides for stable levitation of the coil.

Further flights were undertaken this fall, leading to the first plasma experiments with the launcher fully removed from the plasma. Initial results confirm many of the expected behaviors.
Levitated Dipole Experiment

1.1 MA Floating dipole coil

- Nb3Sn superconductor
- Inductively charged by 10 MJ charging coil
- Up to 1 hour levitation using active feedback on upper levitation coil

Plasma

- Two component plasma created by multi-frequency ECRH

Diagnostics

- Magnetics - flux loops, Bp coils, Hall effect sensors
- Fast electrons - 4 Channel x-ray PHA, x-ray detector, Hard X-ray camera
- Bulk plasma - edge probes, interferometer, visible cameras, visible diode and array
- Fluctuations - Edge \( I_{\text{sat}} \) and \( V_f \) probes, Mirnov coils, visible diode array, interferometer
# Investigating the Dipole Concept

- **Stability:**
  - Can a dipole be stable at high $\beta$?

- **Energy Confinement:**
  - Sufficient to burn advanced fusion fuels?

- **Particle Confinement:**
  - Can convection decouple $\tau_p$ and $\tau_E$?

- **Engineering:**
  - Superconducting magnet surrounded by fusion plasma?

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**LDX Phase I**

- Investigating the Dipole Concept
- Stability:
  - Can a dipole be stable at high $\beta$?

**LDX Phase II Levitation**

- Investigating the Dipole Concept
- Energy Confinement:
  - Sufficient to burn advanced fusion fuels?

- Particle Confinement:
  - Can convection decouple $\tau_p$ and $\tau_E$?

- Engineering:
  - Superconducting magnet surrounded by fusion plasma?
Thin Supports Remain a Major Power Loss

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

Supports become “warm” during high-beta plasma operation.

(Elimination of supports, next step, will further enhance confinement.)
LDX Phase I - Hot Electron Results

• Stable high beta plasmas are created in LDX
  ▶ Large diamagnetic currents carried by fast electrons
  ▶ Imaging shows highly anisotropic plasma that with a localized peak near ECRH resonance (similar to radiation belts in magnetosphere)
  ▶ Magnetic reconstruction gives ~ 20% peak beta

• High beta requires sufficient neutral gas pressure
  ▶ 3 regimes found: (1) unstable, (2) high-\( \beta \), (3) afterglow
  ▶ Increasing gas pressure causes: (1) dramatic rise in density, (2) stabilization of the HEI, and (3) transition to high-\( \beta \) regime
  ▶ Hysteresis in gas fueling required to maintain stability
Unstable and Stable ECRH regimes

- Transitory unstable regime with small, localized plasma (anisotropic) and sparks caused by rapid radial loss of hot electrons to coil
- Bright ionization transition followed by steady large plasma with isotropic profile
**Typical Shot: Indicates 3 regimes**

- **Unstable Regime:**
  - Fast electron radial transport
  - Low density
  - Low diamagnetism (low $\beta$)

- **High Beta Regime:**
  - Large diamagnetic current
  - Measurable density.
  - $\beta$ loss events accompanied by xray bursts
  - Low frequency edge electric and magnetic fluctuations

- **Afterglow:** (no input power)
  - Low density
  - Slow diamagnetism decay
  - Quiescent with instability bursts
Controlling the High-\(\beta\) with Gas Puffing

- With sufficient neutral gas pressure, plasma enters high-\(\beta\) regime
- With insufficient neutral gas pressure, the plasma will become unstable (sometimes violently)
- A hysteresis is the observed thresholds implies the bifurcation of the low density unstable and stable high-\(\beta\) regimes
- Qualitatively consistent with theory of the Hot Electron Interchange Mode stability
LDX Phase I - Bulk Plasma Results

• Quasi-coherent background instability observed
  ▶ Global scale, bulk density and pressure fluctuations
  ▶ Several candidates for mode
    ★ Entropy mode
    ★ Interchange driven convective cells
    ★ Centrifugal driven mode

• Background fluctuations dependent on density profile
  ▶ Frequency of mode dependent on fueling rate/density profile steepness
  ▶ Fluctuation amplitude reduced with flatter density profile

• Ongoing investigation
Fueling dependent Core Low frequency mode

Visible array- Central Chord

Visible array- Central Chord

- Low frequency (few kHz) core fluctuation also affected by fueling
Next Step: Levitation

- Fast electron losses to supports eliminated
  - Pitch angle scattering reduce anisotropy, not beta
  - Anisotropy driven modes relax plasma without losses
- Bulk plasma confinement also improved
  - Stable fast electron fraction with lower neutral gas fueling?
- Radial transport driven profiles
  - Single peaked, broader (more stable) profiles

Expectation of improved stability and confinement

- Contrast with supported operation will further understanding of unstable/high-$\beta$ regime bifurcation.
Levitation Control System

- **4500 A / 50 V Power supply**
  - Resistive coil allows for rapid shutdown

- **Realtime digital control computer**
  - Allows different control methods to be implemented
  - Matlab/Simulink Opal-RT development environment
  - 4 kHz feedback loop
  - Failsafe backup for upper fault

- **Programmable Logic Controller**
  - Slow fault conditions
  - Interlocks
  - Coil and Bus temperature and resistance monitoring

- **Optical link to control room**
  - User interface
  - LDX data system
New levitation coil has been installed

- Levitation coil is used to support floating coil and to feedback on f-coil position
  - 80 turn water cooled Cu coil
  - 4500 A power supply and bus work complete
Upper Catcher / Space frame

- **Upper catcher**
  - Limit upward motion
  - Align radial motion for fall to catcher

- **Space frame structure**
  - Allows internal magnetic flux loops near plasma
Phase II Launcher / Catcher

- Lightweight cone to minimize impulse on F-coil contact
- Partial F-coil deceleration while launcher mass accelerates
- Limit all accelerations to less than 5 g
• Ring placed on floating coil to occult laser beams
  ▸ Horizontal lasers pass through small ports (4 of 8 shown here)
  ▸ Alternating bands of specular reflective silver and rough stainless steel to allow rotation monitoring
Laser Position Detector

- Occultation detection
- COTS - Keyence
- Extensive testing
  - Plasma light not important
  - Vibration somewhat important
  - ECRF electrical isolation pickup noise measured
    - 2.4 GHz reduces laser power… interferes with power regulator circuit in LED laser?
    - Wire grid screens installed
Full Levitation

- **Steady state levitation**
  - 22 cm separation between catcher mechanism and dipole coil
  - Z position control to 0.1 mm
- **Statistics**
  - 7 successful launches
  - > 2 hours total levitation

- **Control algorithm**
  - P - I - D - A control of voltage
    - PS voltage feedback fast
    - Small operating space of reliable gains
  - Full state control under development
    - (Extended) Kalman filter
    - Optimal control
Dipole Dynamics - 45 minute flight

Slow toroidal rotation oscillation undamped 6 minute period
Dipole Dynamics - Launch

6 mm excursion caused by launcher residual magnetism

Stable modes damp in 10 s
Levitated Plasma Operations Have Begun

- Launcher fully extracted past plasma LCFS
- 5 kW ECRH Input power
- Marked changes compared to similar supported operation
  - Higher density for less neutral pressure
  - Flatter density profiles
  - HEI stability
  - Eliminated observed quasi-coherent mode
  - Fast electron buildup changed
HEI relaxation - Supported

Energy lost to (non-disruptive) HEI relaxation events
No HEI observed when Levitated

Much lower operating neutral pressure allowable

Much different beta buildup (Heating accessibility?)
6.4 GHz Heating (Supported)

- **Total Heating Power**: Reaches steady state in 2 s
- **Diamagnetic Flux**:
- **Gas fueling rate**: Fueling greatly effects stored energy and density gradient
- **Chord average density**: Strong density gradient at core
- **Density Fluctuation Level**

Time (sec)
6.4 GHz Heating (Levitated)

- **Total Heating Power**: Reaches steady state in ~ 10s
- **Diamagnetic Flux**:
- **Gas fueling rate**: Fueling has minimal effect on density and beta
- **Chord average density**: Flat core density (ECRH cutoff?)
- **Density Fluctuation Level**: Broadband density fluctuations unaffected by levitation
Gas Puff (Supported)

- Total Heating Power
- Diamagnetic Flux
- Gas fueling rate
- Neutral Pressure
- Mirnov Fluctuation Level
- Mirnov TFD

Notes:
- Neutrals ruin fast electron confinement (pitch angle scattering)
- Quasi-coherent mode reduced by gas puffing
Gas Puff (Levitated)

- **Total Heating Power**: Stepwise increase, indicating a controlled heating process.
- **Diamagnetic Flux**: Smooth rise and fall, showing stable magnetic properties.
- **Gas fueling rate**: Sharp increase, possibly related to a gas injection event.
- **Neutral Pressure**: Gradual increase, indicating gas pressure build-up.
- **Mirnov Fluctuation Level**: Slight fluctuations, indicating stability in plasma behavior.
- **Mirnov TFD**: No evidence of quasi-coherent mode, suggesting stable or non-coherent behavior.

**Key Observations**:
- Reduced effect of pitch angle scattering.
- No evidence of quasi-coherent mode.
Synopsis

• Full levitation achieved
  ▸ Several hours of levitation with new Cu upper levitation coil
  ▸ Levitation control system well developed
  ▸ One run (11/8/2007) with launcher removed past plasma LCFS

• Embarking on experimental phase of project
  ▸ Levitation allows access to higher density, high beta plasmas
  ▸ Focus on stability, control and confinement of bulk plasma
  ▸ Initial plasma run gives evidence of several expectations
    ✷ Elimination of parallel loss channel for background and fast electrons
    ✷ Flatter radial profiles
    ✷ Better stability to hot electron interchange mode