Controlling Interchange Instabilities in the Levitated Dipole Experiment

Darren Garnier
For the LDX Team

2006 US-Japan MHD Control Workshop
JAEA, Naka, Japan
Monday, February 6, 2006
Synopsis

- We observe a fast growing flute-like mode that drives rapid radial transport of plasma particles and energy
  - Identified as the “hot electron interchange” (HEI) mode
  - When stabilized, LDX plasmas reach a high-$\beta$ operational regime
- The most effective experimental control for the mode is the neutral gas fueling
  - Higher neutral gas pressure stabilizes the mode
  - Destabilizes it (sometimes dramatically)
  - Observed hysteresis in required fueling consistent with simplified theory
- Other controls, and other control problems in LDX
Dipole stability derives from plasma compressibility

- Toroidal system without toroidal field
- Closed field lines
  - no magnetic shear
  - “bad curvature”
- Adiabatically invariant pressure profile is marginal to MHD interchange
  \[ \delta(pV^\gamma) = 0 \]
- Kinetic stability:

If \( p_1 V_1^\gamma = p_2 V_2^\gamma \), then interchange does not change pressure profile.

For \( \eta = \frac{d \ln T}{d \ln n} = \frac{2}{3} \), density and temperature profiles are also stationary.
• Superconducting dipole magnet I > 1 MA

• Large 5 m diameter vacuum vessel

• Expansive diagnostic access

• Dipole supported by three thin spokes

• Two ECRH heating frequencies provide up to 5 kW power
The Levitated Dipole Experiment (LDX)
The Levitated Dipole Experiment (LDX)
Plasma Diagnostic Set

• Magnetic equilibrium
  ‣ flux loops, Bp coils, Hall effect sensors

• Fast electrons
  ‣ 4 Channel x-ray PHA, x-ray detector, Hard X-ray camera

• Core parameters
  ‣ interferometer, visible cameras, visible diode and array

• Fluctuations
  ‣ Edge $I_{\text{sat}}$ and $V_f$ probes, Mirnov coils, visible diode array, interferometer

• Edge parameters
  ‣ swept probes
Typical LDX Plasma

• Setup for Shot 50701014
  ‣ Small D$_2$ gas pre-fill
  ‣ ECRH power for 12 seconds

• Three regimes observed
  ‣ Short initial unstable
  ‣ Stable high-β
  ‣ Afterglow
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
Fast Electrons: Anisotropic at ECRH Resonance
Fast Electrons: Anisotropic at ECRH Resonance

Shot 50701011

X-Ray
E > 40 keV
Characteristics of the Stable (High-$\beta$) Regime

• Quasi steady state

• Bulk plasma has 10x increased density
  ▶ Edge density $\sim 10^{10}$ cm$^{-3}$
  ▶ Peak density near ECRH cutoff $\sim 10^{11}$ cm$^{-3}$

• Fast electron population with 100-200 keV energies

• Significant diamagnetic current $> 3$ kA
  ▶ Afterglow indicates the current is carried by fast electrons
  ▶ Magnetic reconstruction:
    ▶ Peak local beta: $\sim 20\%$
    ▶ Stored energy: 330 J (with 5 kW of input power)
LDX Parameters in high-$\beta$ Regime

ECH creates a hot electron component within a background plasma.

**Hot Electron Plasma**
- Density: $n_{\text{eh}} << n_{\text{eb}}$
- Temperature: $T_{\text{eh}} \gg T_{\text{eb}}$
  - Hot electron energy > 50 keV, $\omega_{\text{dh}} \sim 1$-10 MHz
- Pressure
  - Core 200 Pa.
  - $\beta_{\text{max}} \sim 20\%$
- Confinement
  - Stored energy $\sim 200$ J, $\tau_{E} \sim 50$ msec.

**Background Plasma**
- Density
  - Core: <nl> $\sim 1$-5 x 10$^{16}$ m$^{-3}$
    - $n_{\text{cutoff}}(2.45 \text{ GHz}) = 7.6 \times 10^{16}$ m$^{-3}$ @ $R_0=0.78$ m
    - $n_{\text{cutoff}}(6.4 \text{ GHz}) = 5.2 \times 10^{17}$ m$^{-3}$ @ $R_0=0.60$ m
  - Edge density 1-2 x 10$^{16}$ m$^{-3}$
- Temperature:
  - Edge temperature $\sim 10$-20 eV, $\omega_{*b} \sim 1$-10 KHz
- Pressure
  - Edge 0.01 Pa
  - $P_{\text{Core}}/P_{\text{edge}} \sim 10000$
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
High-\(\beta\) Plasma Begins Upon HEI Stabilization

Rapid Ionization and Density Rise = Stability

In unstable regime, quasi-continuous HEI instability prevents plasma build-up ...

- Chaotic Radial Transport
- Intermittent Bursts
- Edge Potential Fluctuations
- Drift Resonant Energy (keV)

PhotoDet (A.U.)
X-Ray (A.U.)
Edge Isat (A.U.)
Mirnov (A.U.)

0.0 0.2 0.4 0.6 0.8 1.0 1.2
Edge Potential Fluctuations

0.804 0.805 0.806 0.807 0.808
Drift Resonant Energy (keV)

Mirnov (A.U.)

Outward Transport
HEI Instability Can Terminate High-\(\beta\) Plasma

Intense HEI instability resonates with fast electrons causing **rapid** radial transport…

Inward Transport

Outward Transport

**Edge Potential Fluctuations**
High fueling needed to stabilize HEI, increase density, and increase beta
- Unstable regime evolves gas from vessel walls by surface heating
- Once stable, less fueling is needed to maintain stability
  - Without continued puffing, plasma pumps required gas from chamber
HEI ⇒ Hysteresis in Gas Requirements

- High fueling needed to stabilize HEI, increase density, and increase beta
  - Unstable regime evolves gas from vessel walls by surface heating
- Once stable, less fueling is needed to maintain stability
  - Without continued puffing, plasma pumps required gas from chamber
Hysteresis in evolution of stability limit

- Unstable regime has high $f_h$ and 40 keV electrons
- Increased gas fueling $\Rightarrow$ stabilization $\Rightarrow f_h$ to drop by 1/10
- In high-$\beta$ regime, fast electrons heat $\Rightarrow$ higher stability limit
Hysteresis in evolution of stability limit

- Unstable regime has high $f_h$ and 40 keV electrons
- Increased gas fueling $\Rightarrow$ stabilization $\Rightarrow f_h$ to drop by $1/10$
- In high-$\beta$ regime, fast electrons heat $\Rightarrow$ higher stability limit
Hysteresis in evolution of stability limit

- Unstable regime has high $f_h$ and 40 keV electrons
- Increased gas fueling $\Rightarrow$ stabilization $\Rightarrow f_h$ to drop by 1/10
- In high-$\beta$ regime, fast electrons heat $\Rightarrow$ higher stability limit
Hysteresis in evolution of stability limit

- Unstable regime has high $f_h$ and 40 keV electrons
- Increased gas fueling $\Rightarrow$ stabilization $\Rightarrow f_h$ to drop by $1/10$
- In high-$\beta$ regime, fast electrons heat $\Rightarrow$ higher stability limit
Hysteresis in evolution of stability limit

- Unstable regime has high $f_h$ and 40 keV electrons
- Increased gas fueling $\Rightarrow$ stabilization $\Rightarrow f_h$ to drop by 1/10
- In high-$\beta$ regime, fast electrons heat $\Rightarrow$ higher stability limit
Hysteresis in evolution of stability limit

- Unstable regime has high $f_h$ and 40 keV electrons
- Increased gas fueling $\Rightarrow$ stabilization $\Rightarrow$ $f_h$ to drop by 1/10
- In high-β regime, fast electrons heat $\Rightarrow$ higher stability limit
Pre-programmed Optimization

- Careful programming of puffing rate gave highest plasma stored energy
  - Maintain small but stable neutral
- Stored energy increases with less neutrals
  - Less pitch angle scattering of fast electrons
- Small puff before afterglow to (nonlinearly) stabilize initial HEI in afterglow
- Feedback system planned for next run...
Other Controls on HEI stability

- Weak trend with total ECRH power
  - More power requires more neutrals
- Heating profile has dramatic effect
- Plasma shaping also has dramatic effect
  - Smaller plasmas need higher neutral pressure
Other control issues: Low frequency mode

Visible array- Central Chord

Visible array- Central Chord

- Low frequency (few kHz) core fluctuation also effected by fueling
Levitation Control System

- 150A, +/- 100V Power Supply
  - Integrated dump resistor for rapid discharge
- Realtime digital control computer
  - Matlab/Simulink Opal-RT development environment
  - 5 kHz feedback loop
  - Failsafe backup for upper fault
- Programmable Logic Controller
  - Slow fault conditions
  - Vacuum & Cryogenic monitoring
  - PS user interface
- Optical link to control room
  - User interface
  - LDX data system
Summary

- Stable high-$\beta$ plasmas are created in LDX in supported operation
  - Plasma energy is carried by fast electrons in a highly localized peak near ECRH resonance
- High requires sufficient neutral gas pressure to stabilize hot electron interchange mode
  - Demonstrable hysteresis in threshold levels for transition to and from unstable regime is consistent with theory
- Plasma confinement is optimized when fueling is controlled
- Other interesting control problems in the near future
  - Including first levitation!
LCX II: Digitally Controlled Levitation

- Levitated Cheerio Experiment II
- Uses LDX digital control system
  - Test at 10 times the frequency required
- Modified PID feedback system
  - Low pass filter added for high frequency roll-off of derivative gain
  - Stimulated work on Kalman filtering system for LDX control
- Real-time graph shows position and control voltage
  - Wiggles indicate non-linearly stable rolling mode…