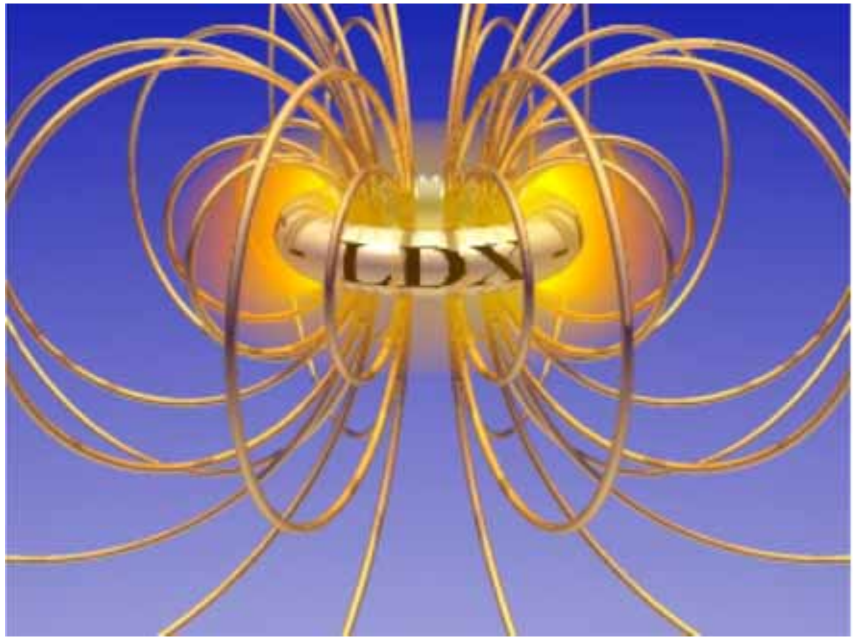


Campaign for Levitation in LDX

Columbia University

D.T. Garnier, M.E. Mauel, A.K. Hansen, E.E. Ortiz

Columbia University

A. Boxer, J. Ellsworth, I. Karim, J. Kesner,
P. Michael, A. Radovinsky, A. Zhukovsky,
R. Bergmann - *MIT PSFC*

2006 American Physical Society
Division of Plasma Physics Meeting

Synopsis

- Levitation will greatly change plasma behavior in LDX
  - Dominant loss channel removed -> better confinement
  - Higher background density with high beta -> more stable to HEI
  - Radial transport dominated (broader) profile -> more stable
- Levitation system nearly complete
  - Coil and control systems installation complete
  - Calibration and control algorithm development underway
  - Laser detection system nearly complete and undergoing refinement
  - Catcher system built and tested
- Levitation system testing in progress
  - 3 major tests completed give confidence in successful levitation

Levitation Campaign Milestones

- Integration of L-coil systems
- Development of Realtime control system
  - Test of L-coil electrical and thermal performance
- Development of Laser Detection System
  - Plasma "Noise" test
- Launcher Catcher Upgrade
  - Catcher Test Campaign
- Feedback Control Algorithm
  - Flight Tests

Hot Electron Interchange Stability

- Bulk plasma must satisfy MHD adiabaticity condition

Rosenbluth and Longmire, (1957)

$$\delta\left(p_b V^\gamma\right) = 0$$

where $V = \oint \frac{d\ell}{B}$

or

$$-\frac{d \ln p_b}{d \ln V} < \gamma^{-1}$$

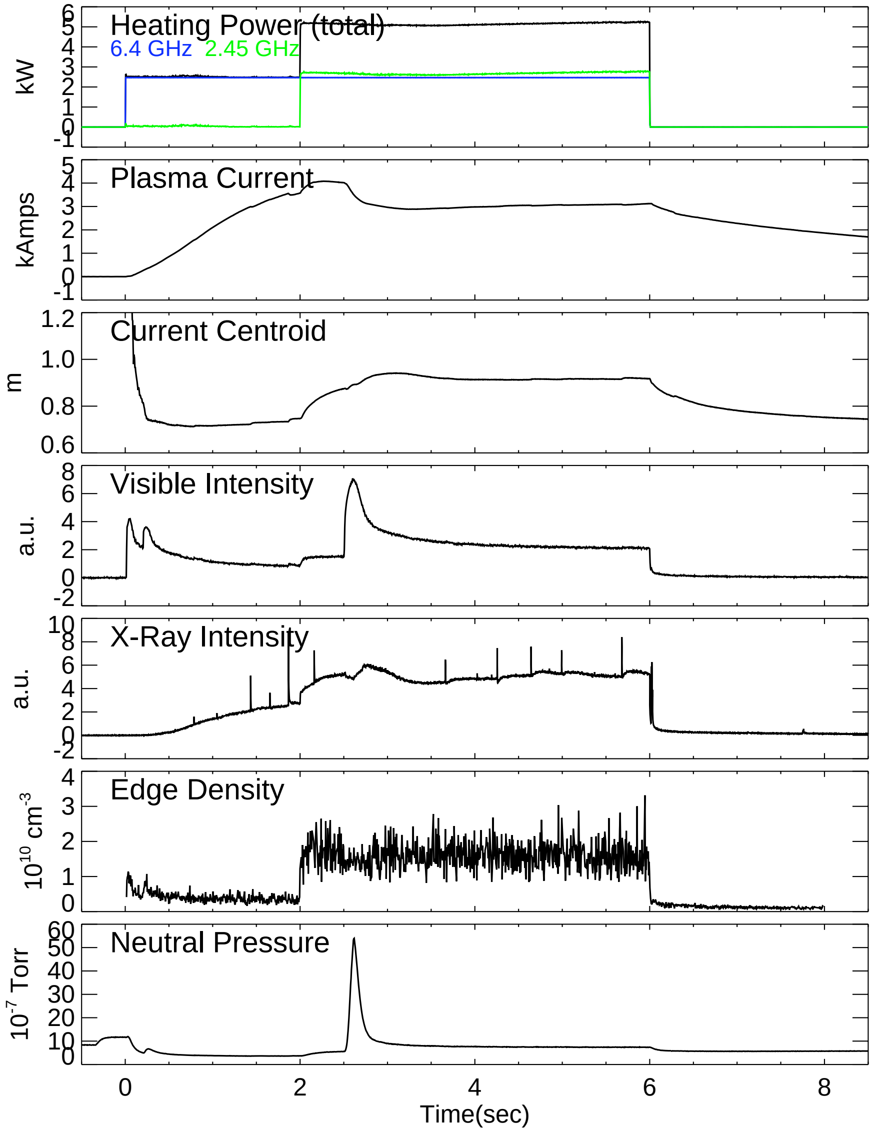
- Fast electron stability enhanced due to coupling of fast electrons to background ions

Krall (1966), Berk (1976)...

$$-\frac{d \ln \bar{n}_h}{d \ln V} < 1 + \frac{m_\perp^2}{24} \frac{\omega_{dh}}{\omega_{ci}} \frac{\bar{n}_i}{\bar{n}_h}$$

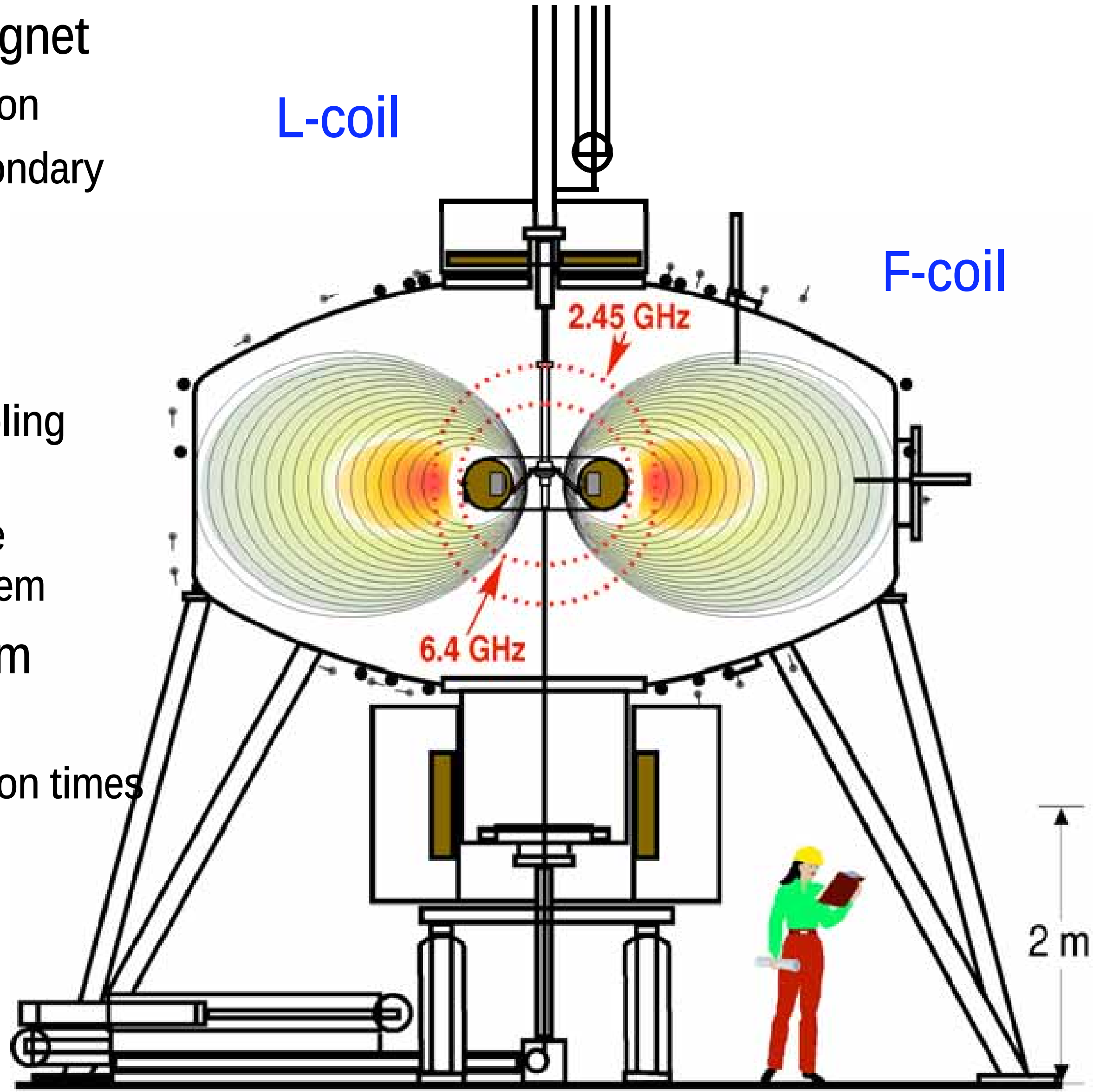
Increased Neutral Fueling Stabilizes HEI

- Stabilizes small HEI
  - More background density
  - Smaller hot electron fraction
- But loss of confinement
  - Pitch angle scattering to supports.
- Levitation changes
  - Pitch angle scattering gives more isotropic distribution
  - Collisions lead to broader radial profile
  - Higher overall confinement
  - Low frequency modes reduced?



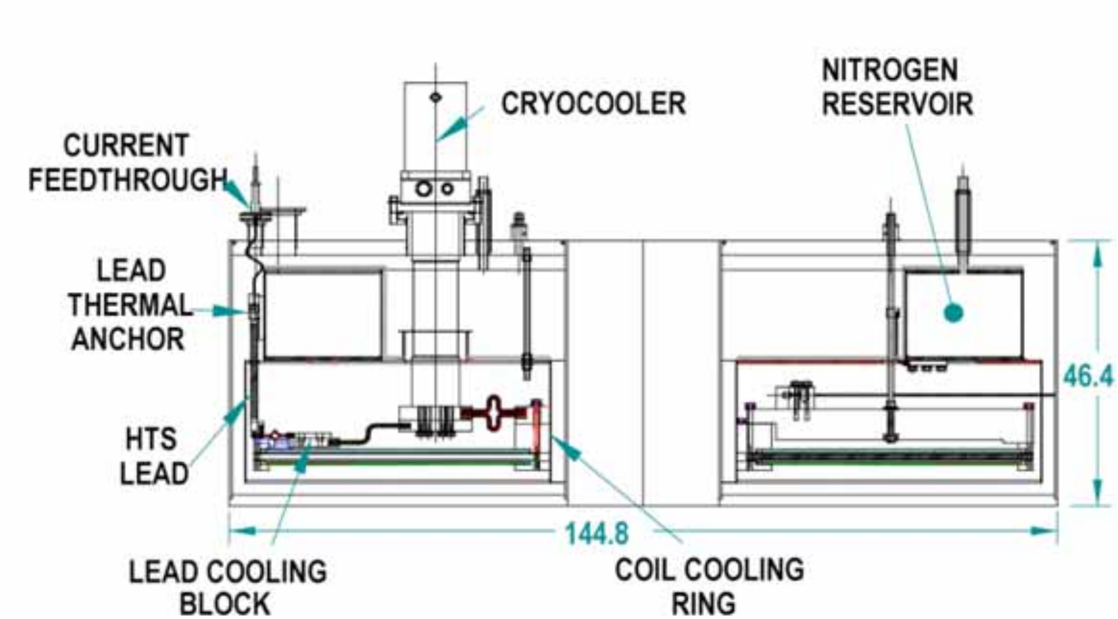
LDX Levitation Basics

- Levitation by upper lift magnet
  - Unstable only to vertical motion
  - Mostly undamped stable secondary modes
- HTS lift magnet
  - First in US Fusion program
  - Much reduced power and cooling requirements
  - AC heating introduces unique requirements for control system
- Large 5 m diameter vacuum vessel
  - Eddy current times << levitation times
- Laser position detection
  - Many secondary diagnostics
- Digital feedback system



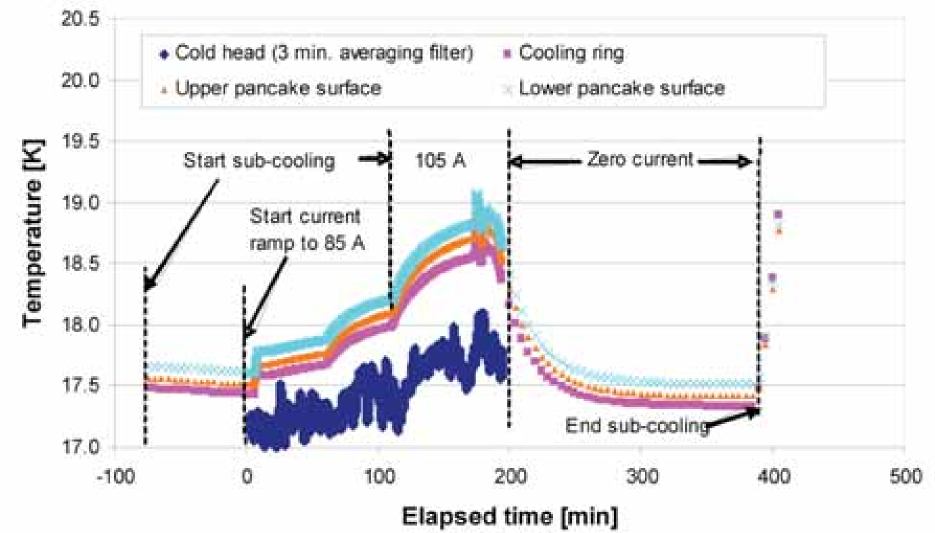
L-Coil Design

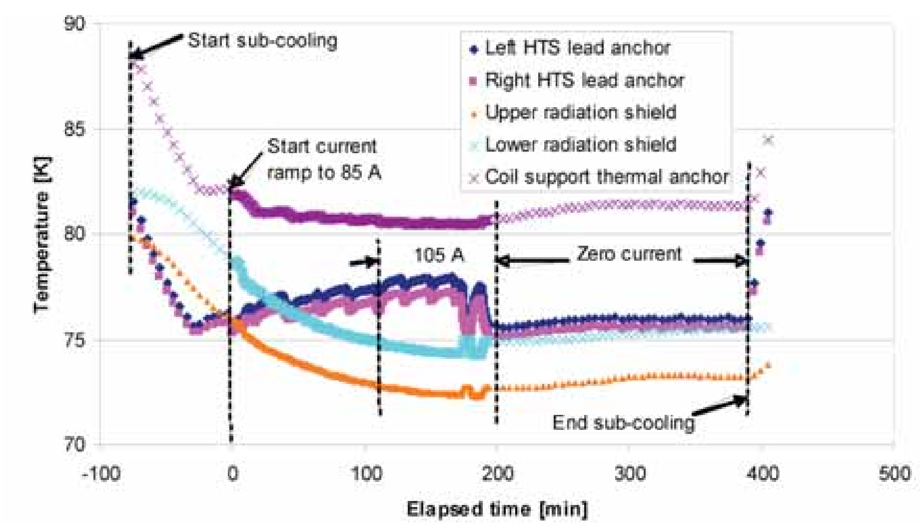
- High Temperature Superconductor.
  - Negligibly power consumption compared to resistive equivalent.
  - Nominal 105 A current, with ± 1 A, 1 Hz position control ripple.
  - Easier to manage position control ac loss than for LTS.
  - Funded by SBIR, first HTS coil in US fusion energy program.
- Optimized, disk-shape geometry for F-coil levitation.
  - Double pancake winding.
  - Center support and cooling plate.
- Conduction cooled coil.
  - Low maintenance, moderate cost, high conductor performance.
  - Estimated 12 W hysteresis loss.
  - One-stage cryocooler for coil.
    - 20W @ 20K
  - Liquid nitrogen reservoir for radiation shield.



L-coil Heating Stress Test

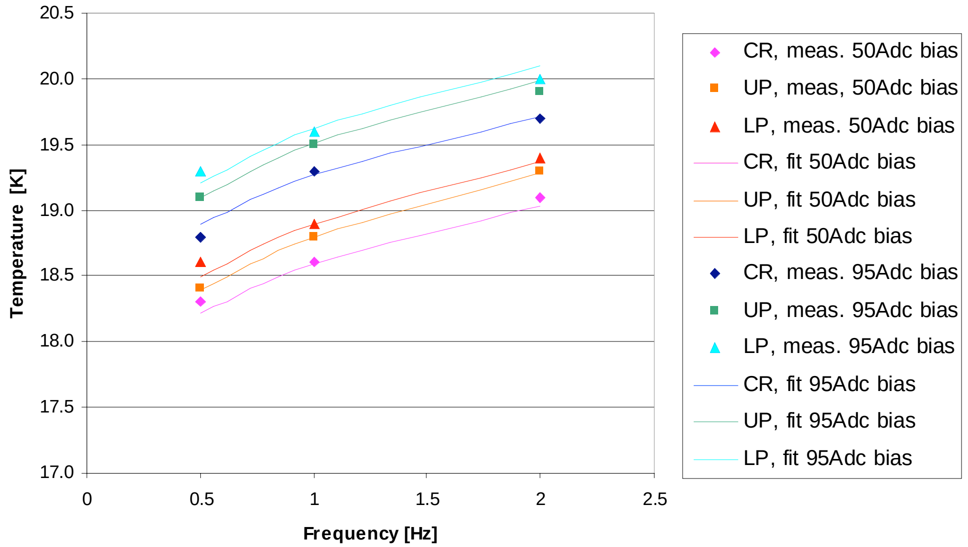
- Steady State Test
  - 90-min, 1Hz, ±1-A ripple with 105-Adc bias test performed on Apr. 5, 2006
  - Demonstrates the thermal stability of HTS coil in expected levitation operation
    - Well below theoretical quench point at ~40 K
- Sub-cooling demonstrated
  - Evacuation of LN2 reservoir to 500 Torr.
  - Gives greater operational margin at warm end of HTS leads

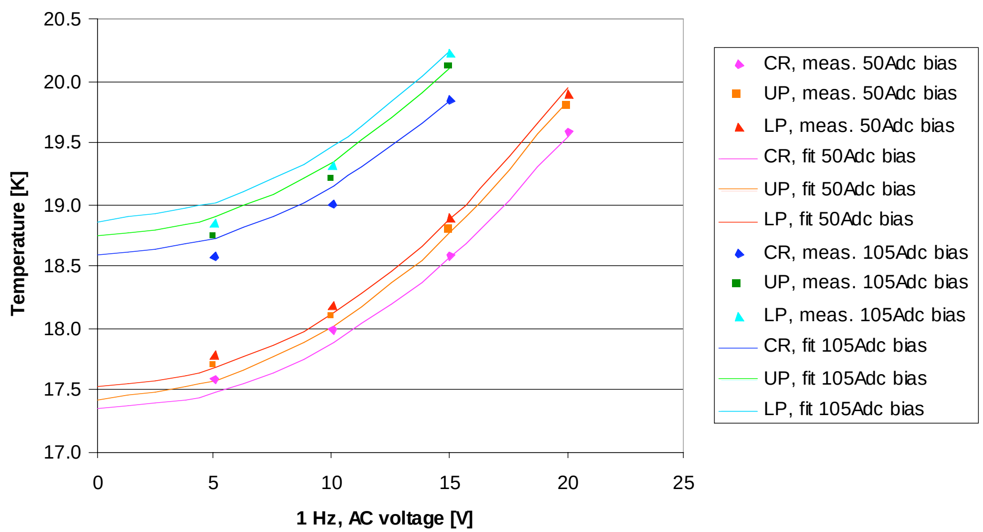




L-coil Heating Model

- Semi-empirical model estimates the steady-state temperature rise at the L-coil during electrical excitation
  - over the range from 0-A dc to 105-A dc bias current
  - ac excitation at frequency from ½-Hz to 2-Hz
  - AC ripple 0-Vac and 20-Vac.
  - accurate to within approximately 0.2-K over the entire fitting range.



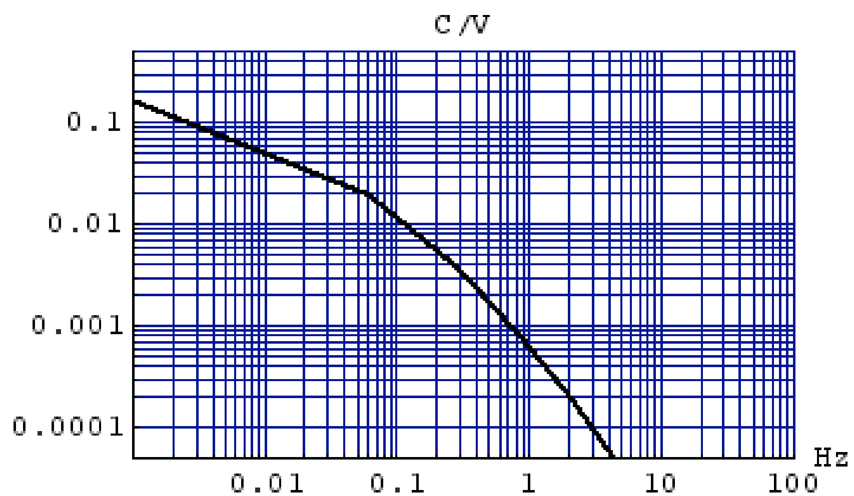


L-coil Electrical Model

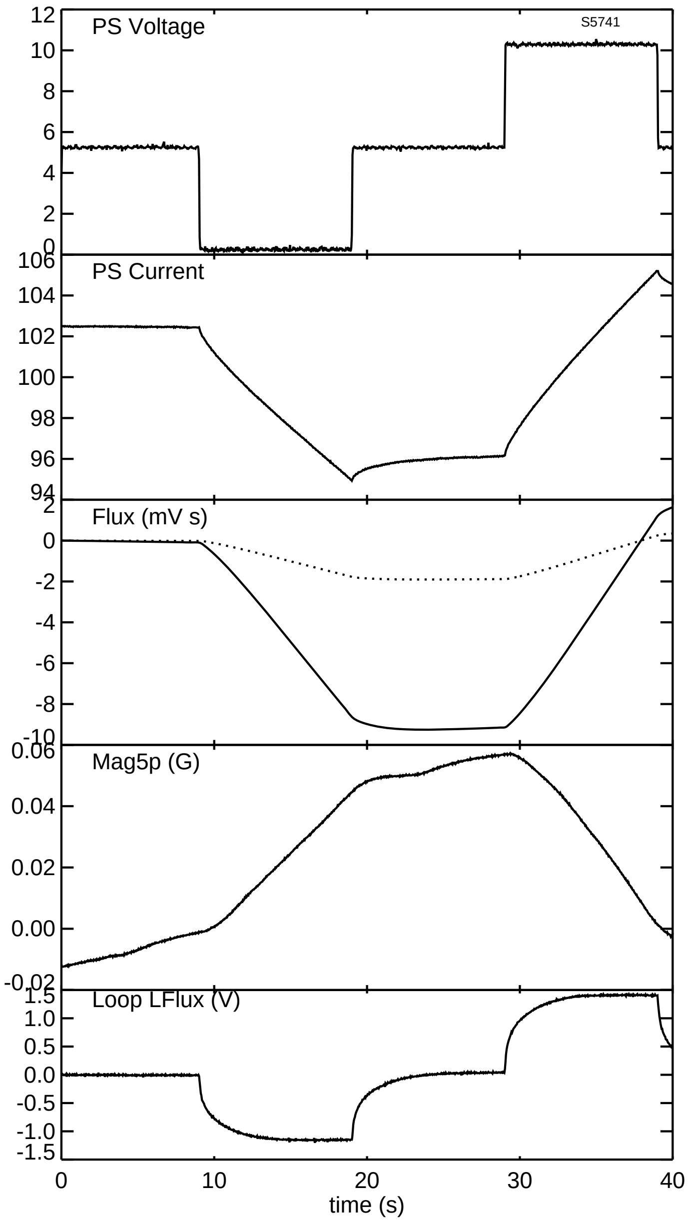
- Semi-empirical fitted model
  - Takes into account known short and eddy currents in L-coil
  - Also models vacuum vessel eddy currents
- Parameters matched to electrical open loop gain tests

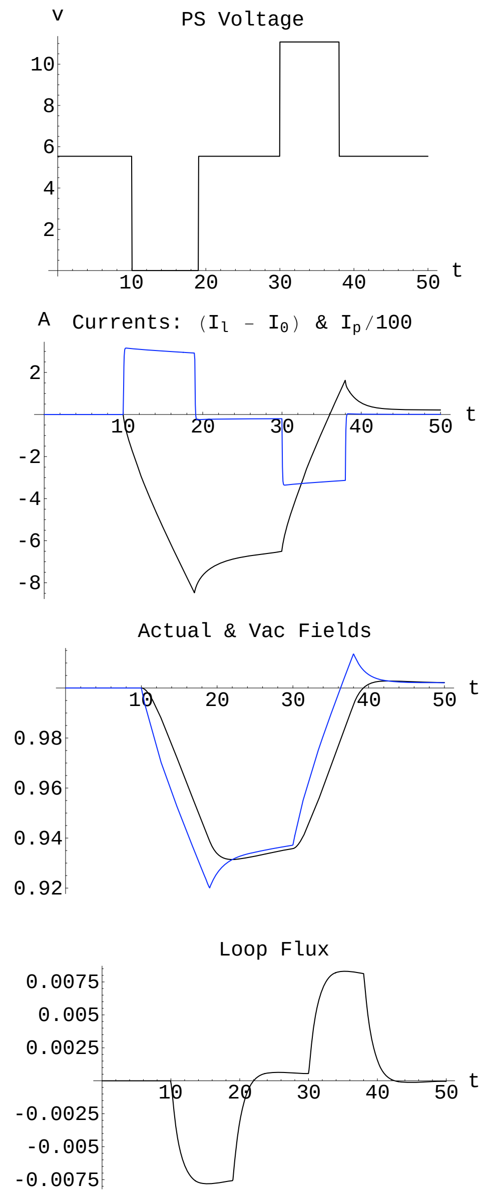
Transfer function

$$\left(\frac{0.000989(s+0.339)(s+25.2)}{(s+0.008)(s+0.4)(s+0.654)(s+22.4)}\right)$$



L-coil System Model Comparison to Data

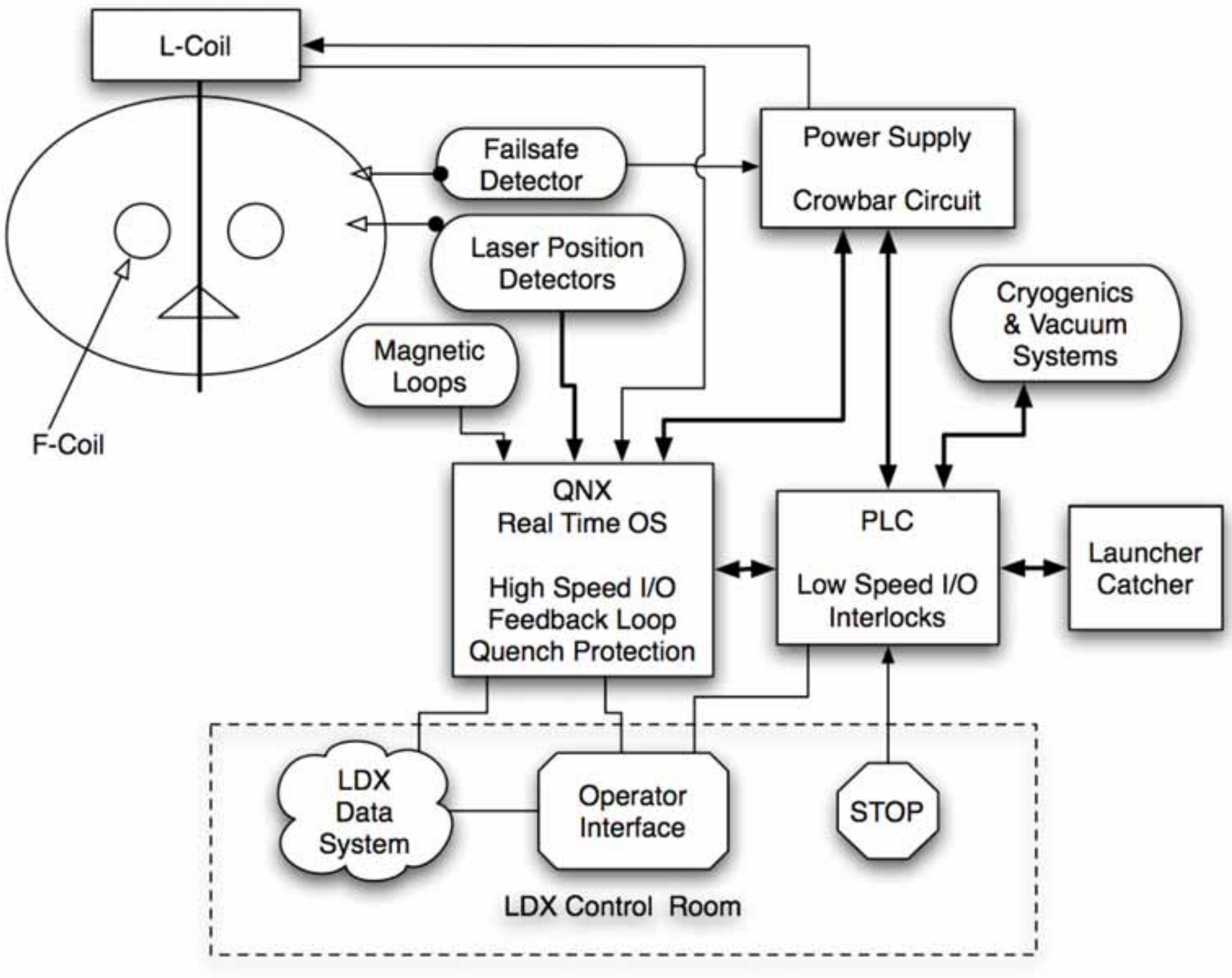




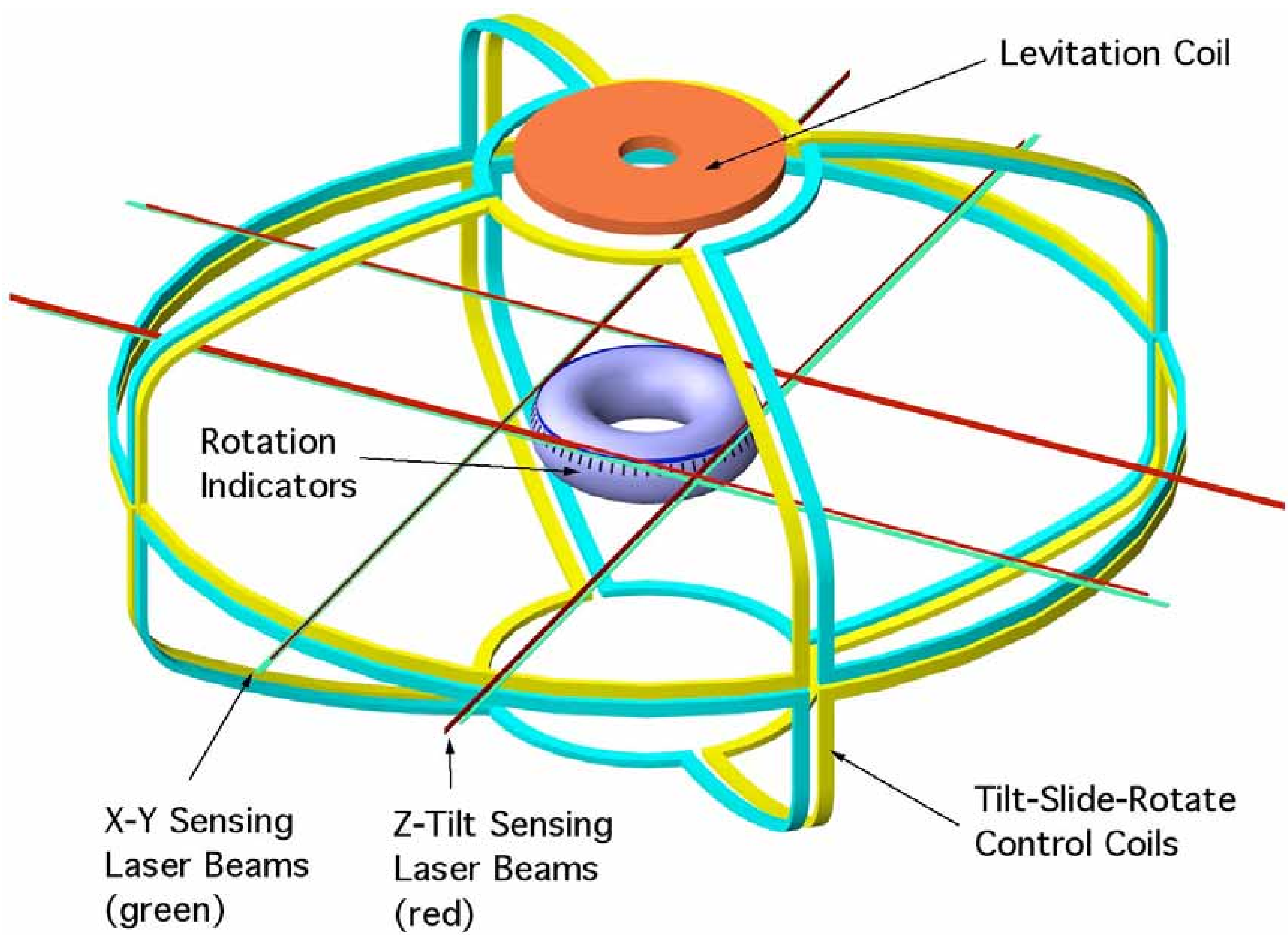
LDX Control System Description

- 150A, +/- 100V Power Supply
  - Integrated dump resistor for rapid discharge
- Realtime digital control computer
  - Matlab/Simulink Opal-RT development environment
  - 4 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

Levitation Control System



Levitation Control System Schematic

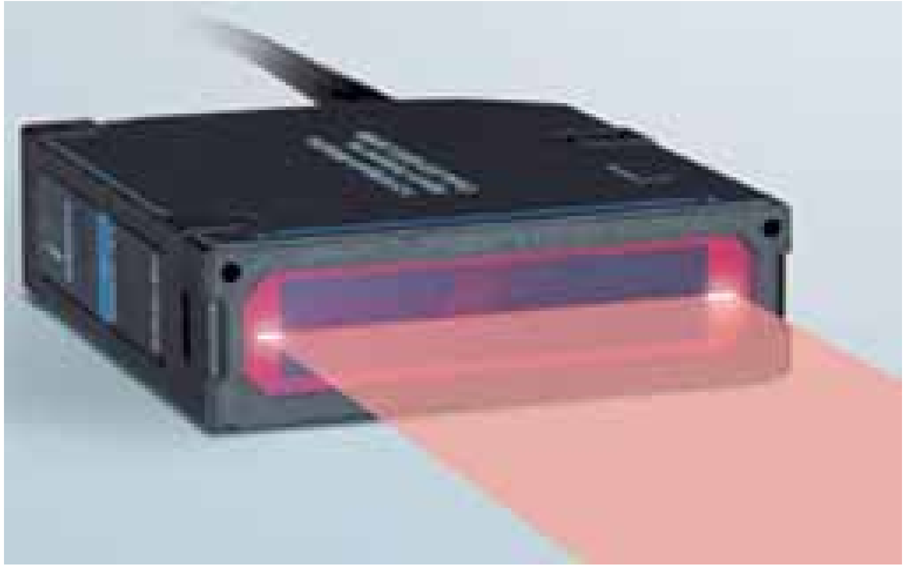


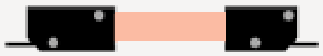
Laser Alignment Ring

- 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

Optical Position Detection System

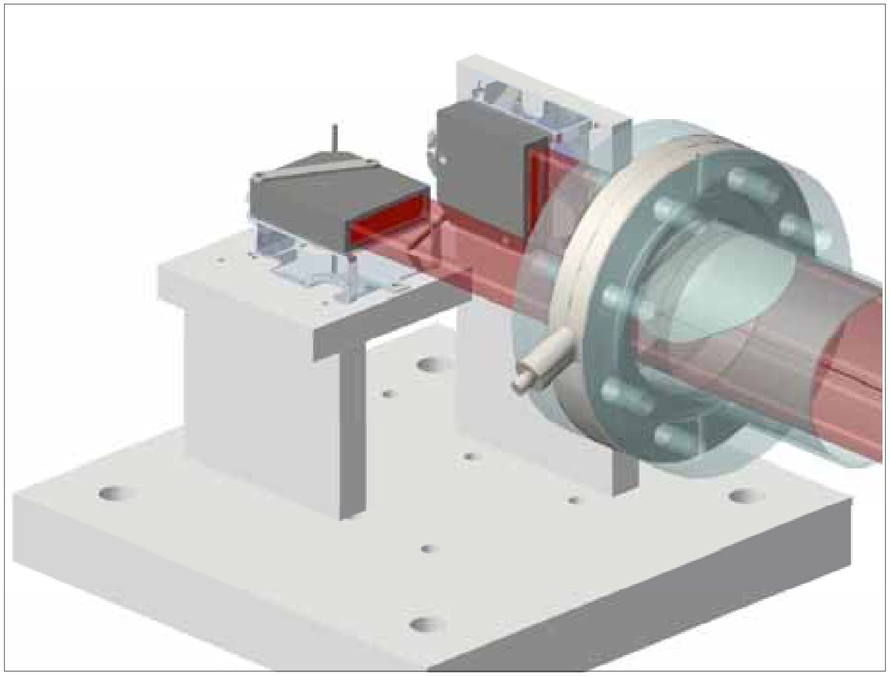
- Position/Attitude Sensing
  - Occulting system of 8 beams
    - Provides measurement of 5 degrees of freedom of coil with redundancy in each measurement
  - Specification
    - ± 1 cm detection range
    - 5 μm resolution
    - 5 kHz frequency response
  - Keyence LH-300 COTS units
    - Exceed all specifications
    - Procured with 2 channels installed on prototype mounting hardware
      - Require plasma test for final mount production OK
- Rotation Sensing
  - Reflecting system to sense final degree of freedom
  - Remove Nonaxisymmetry systematic noise correction

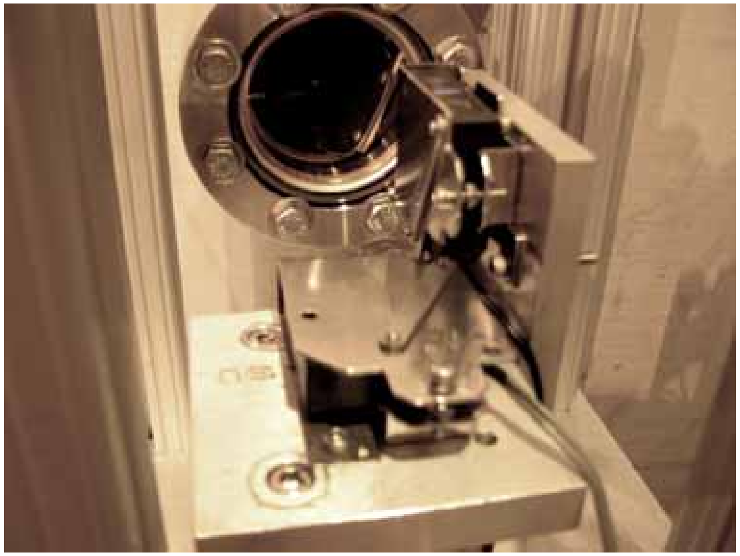


Status		Displays received light intensity (A-10)
When entire area beam is received		1000
When half the area beam is interrupted		500
When entire area beam is interrupted		0

Laser Position Detector Testing

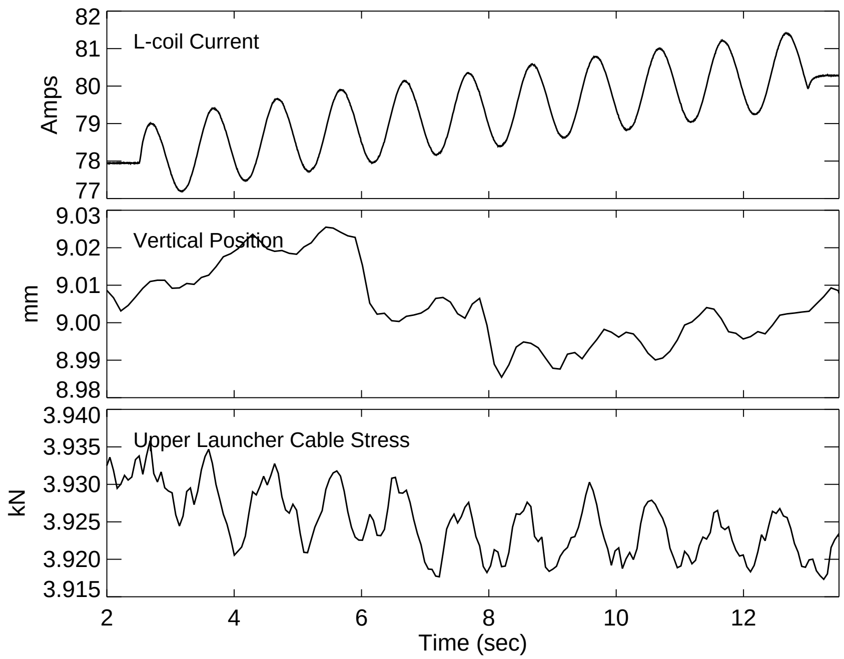
- Prototype mounting and amplifiers in place for July 2006 plasma run
  - RF electrical pickup noise measured
  - Plasma light not important
  - Vibration somewhat important
  - Measured motion of F-coil on stiff spring of fixed launcher
- Further development since
  - Better vibration immunity (higher frequency)
  - Reduced electrical noise

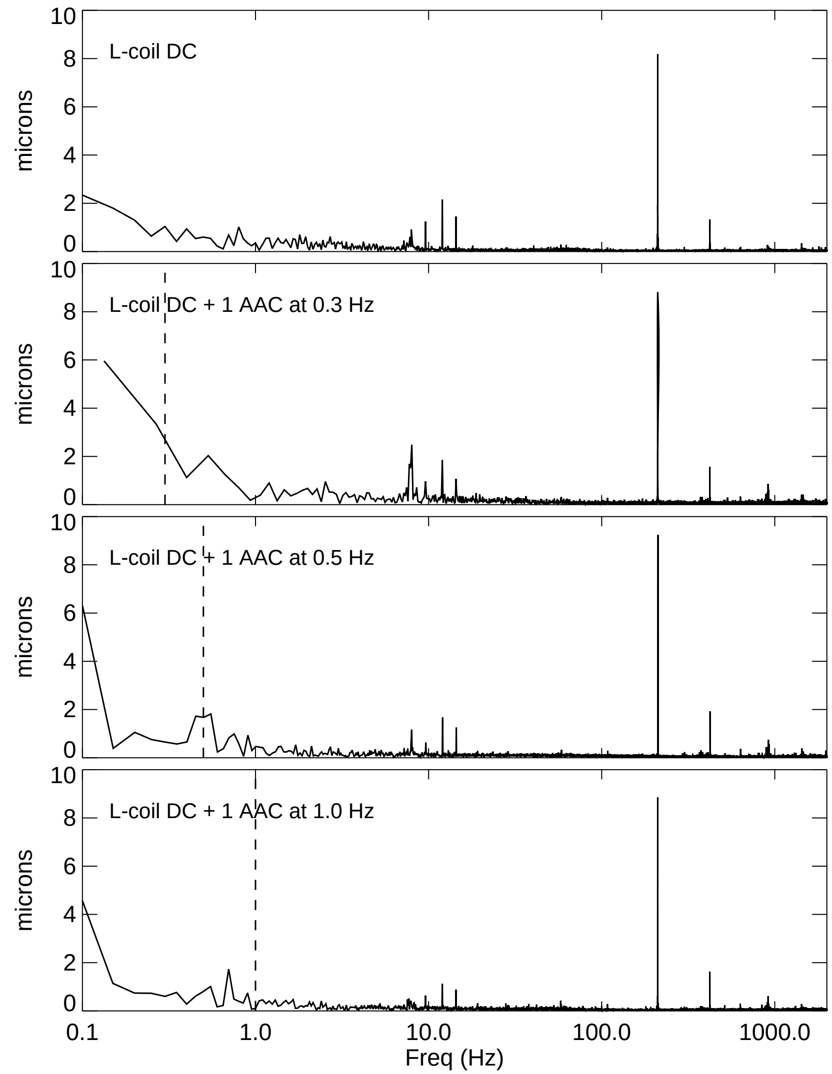




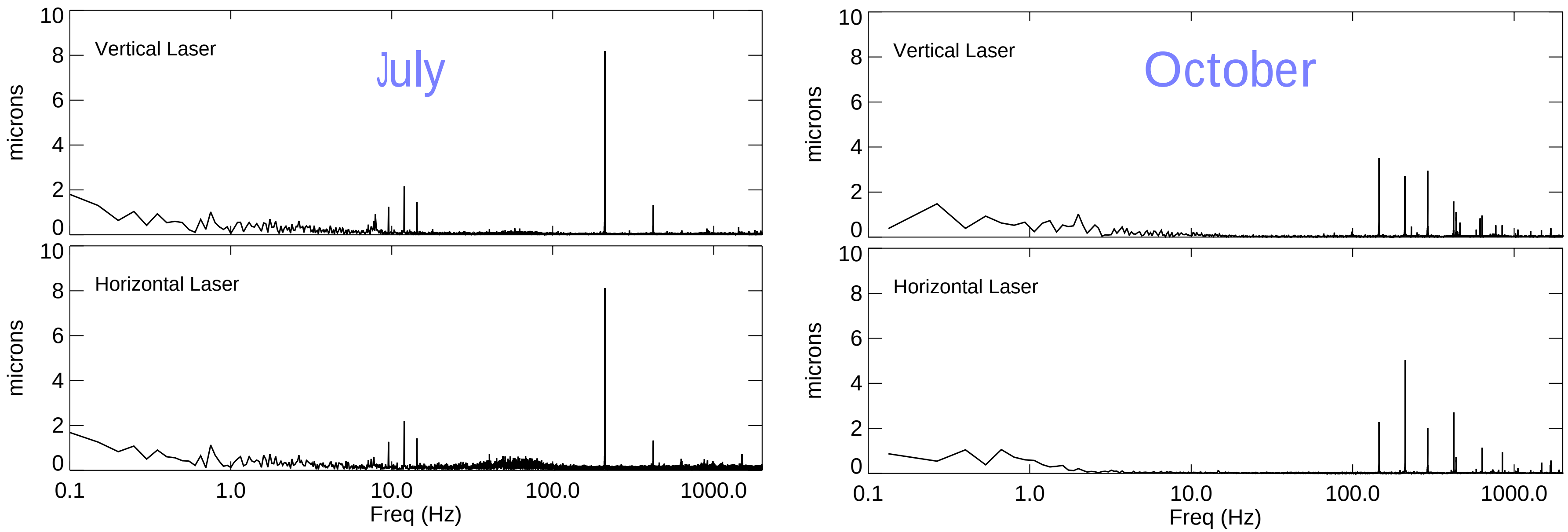
Supported F-coil Motion

- Observed motion of F-coil due to L-coil interaction
  - F-coil supported (with stiff spring)
  - motion smaller than nominal resolution of detectors



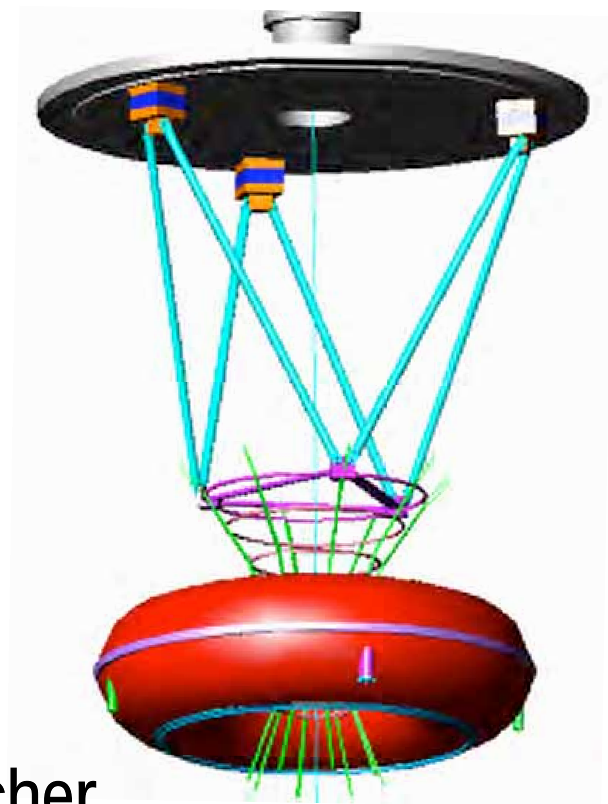


Improved noise isolation



- Steady development of mount hardware has reduced noise in system.
  - Reduced electrical noise at 200 Hz with better cabling
  - Removing rubber mounts increased vibrational mode frequencies

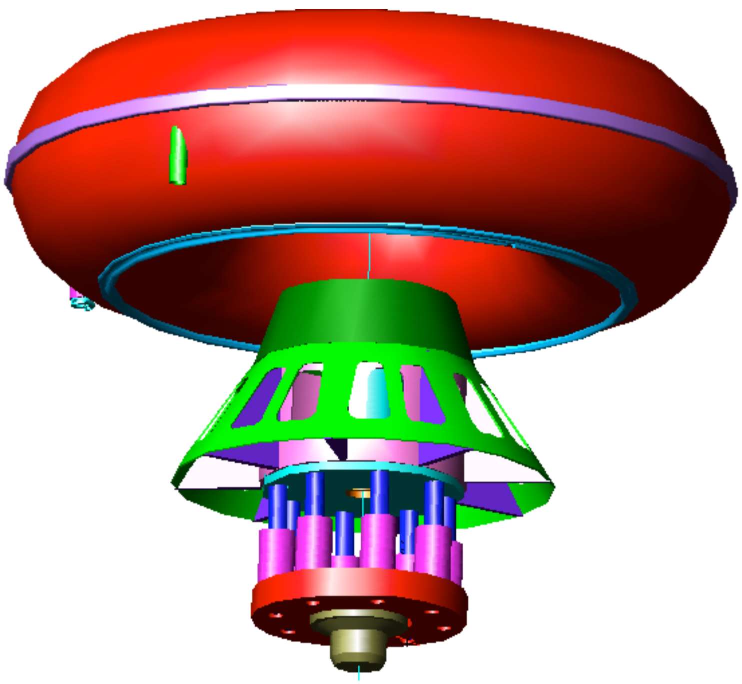
Upper Catcher / Space frame



- Upper catcher
  - Limit upward motion
  - Align radial motion for fall to catcher
- Space frame structure
  - Allows installation of new internal magnetic flux loops near plasma

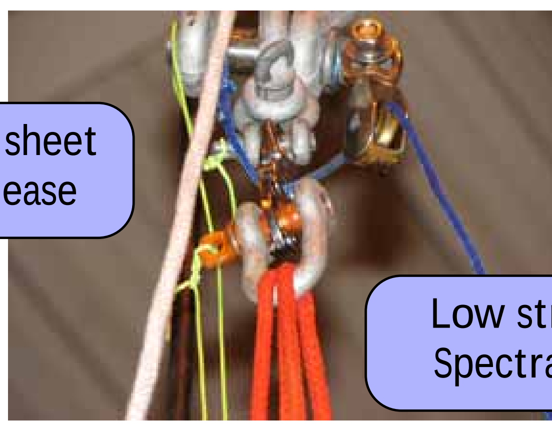
Generation II Catcher

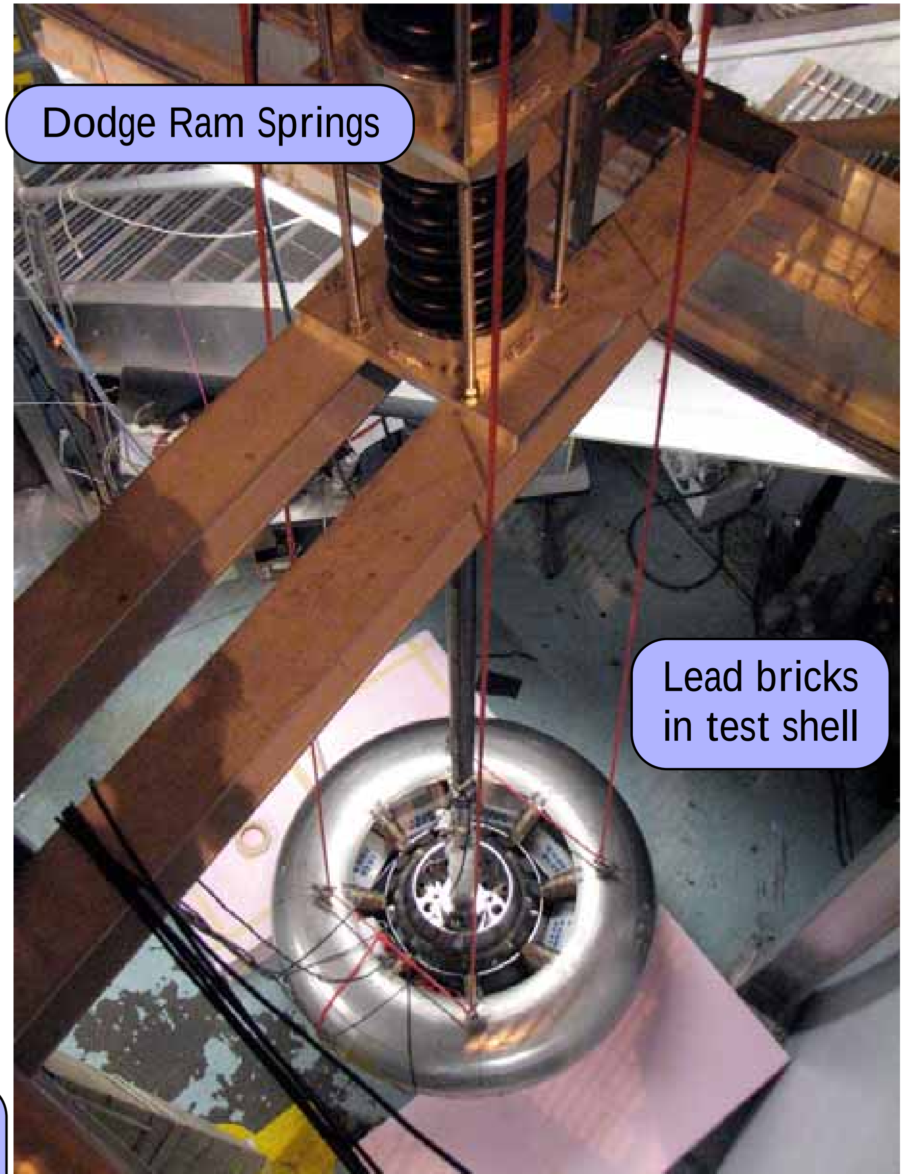
- New catcher constructed and tested
  - Lightweight cone to minimize impulse on F-coil contact
  - Partial F-coil deceleration while launcher mass accelerates
  - Limit all accelerations to less than 5 g



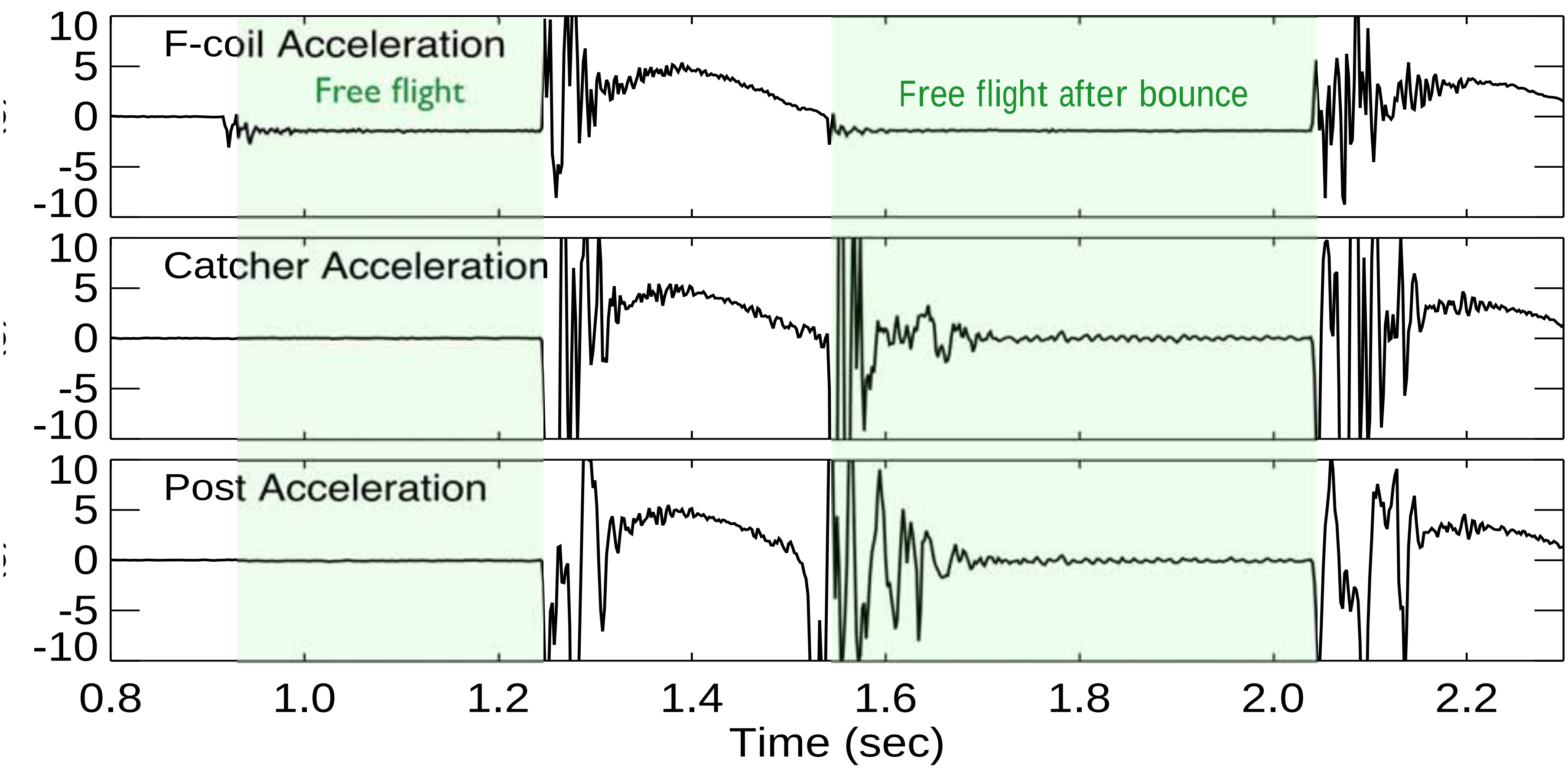
Catcher Drop Test

- Accurately test catcher outside of vacuum vessel
  - Uses “practice” f-coil made from lead bricks
- Results
  - Works as expected with no deformation of f-coil ring





Catcher Worst Case ~ 5g



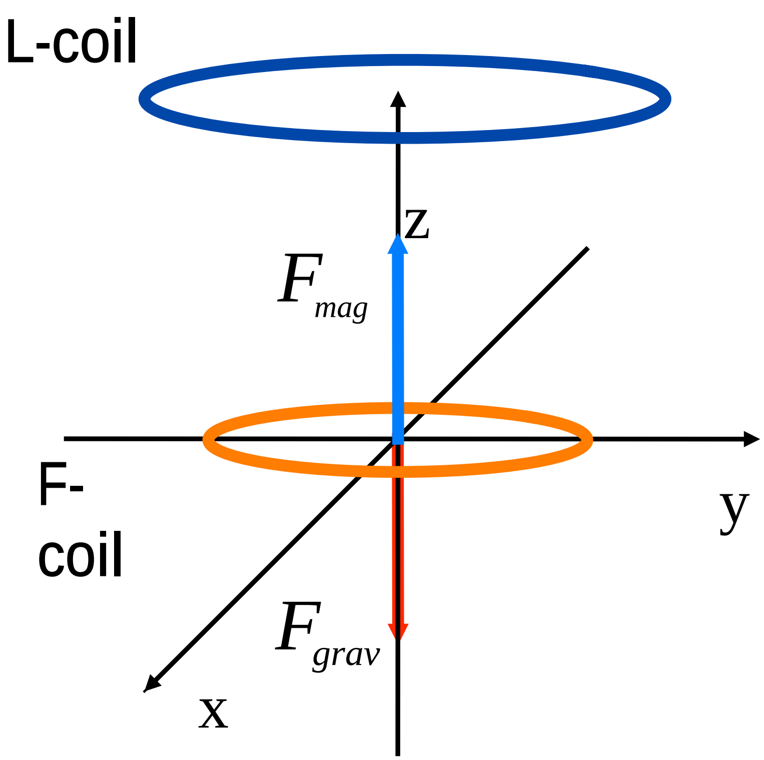
Drop Test Results

- F-coil acceleration in acceptable range
  - ~ 5g
- Small (and expected) plastic deformation of lightweight cone
  - ~ 3 mm
  - future drops will be elastic
- Installation imminent

Levitation Physics

We can choose a Lagrangian formulation of the equation of motion so the constraints above can be easily incorporated:

$$L = \tfrac{1}{2}\sum_{i=1}^{6} m_i \dot{x}_i^{\,2} - M_{LF} I_F I_L - \tfrac{1}{2} L_F I_F^{\,2} - \tfrac{1}{2} L_L I_L^{\,2} - mgz$$



Where: $M_{LF} = M_{LF}(\vec{x}_{1\to5})$

F-coil is a superconducting loop, so its flux is conserved, whereas we can vary the flux in the L-coil by applying our control voltage:

$$\Phi_F = M_{LF} I_F I_L + L_F I_F = \text{constant}$$

And:

$$\Phi_L = M_{LF} I_F I_L + L_L I_L = \int V_L(t)\,dt$$

Feedback stabilization

- The upward force on the F-coil is proportional to the radial magnetic field at its position, generated by the L-coil.
  - Hence, it is proportional to the current in the L-coil.
- Without feedback, the vertical position is unstable because dBR/dz>0, so if the F-coil moves up, the upward electromagnetic force will increase, and the coil will move even further up.
- If we detect a small increase in vertical position, and decrease the L-coil current appropriately, we can bring the coil back to its original position.
- Simple Approach: Use proportional-integral-derivative (PID) feedback:

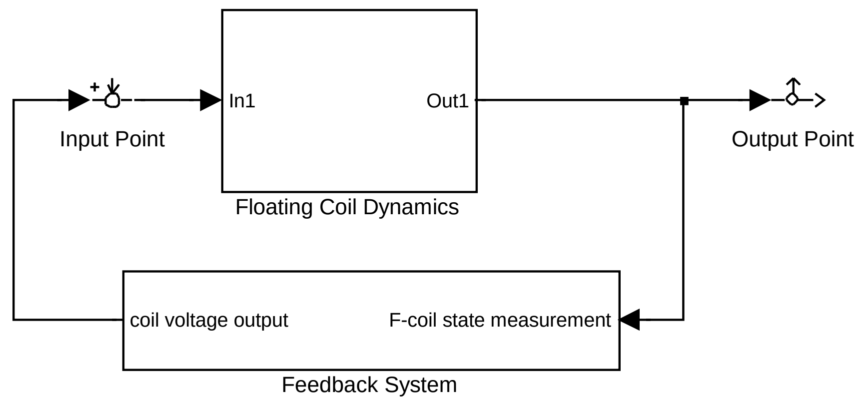
$$I_L(t) = I_0 - a_0 \int \varepsilon(t)dt - a_1 \varepsilon(t) - a_2 \varepsilon'(t)$$

Automatic correction to I_0

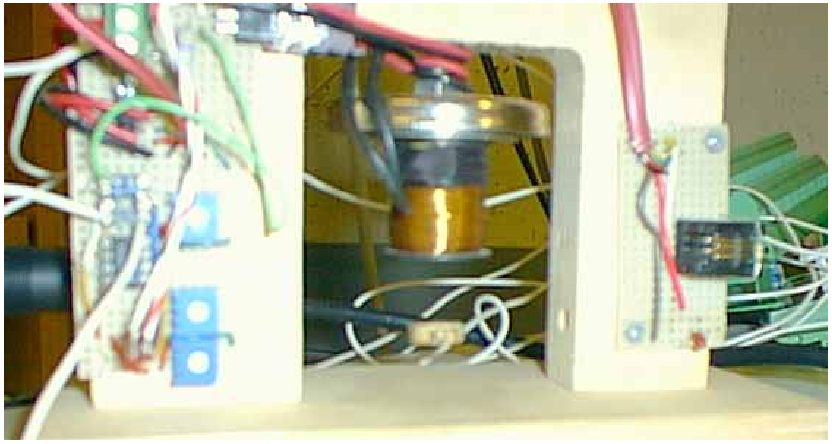
Damping term, acts like friction

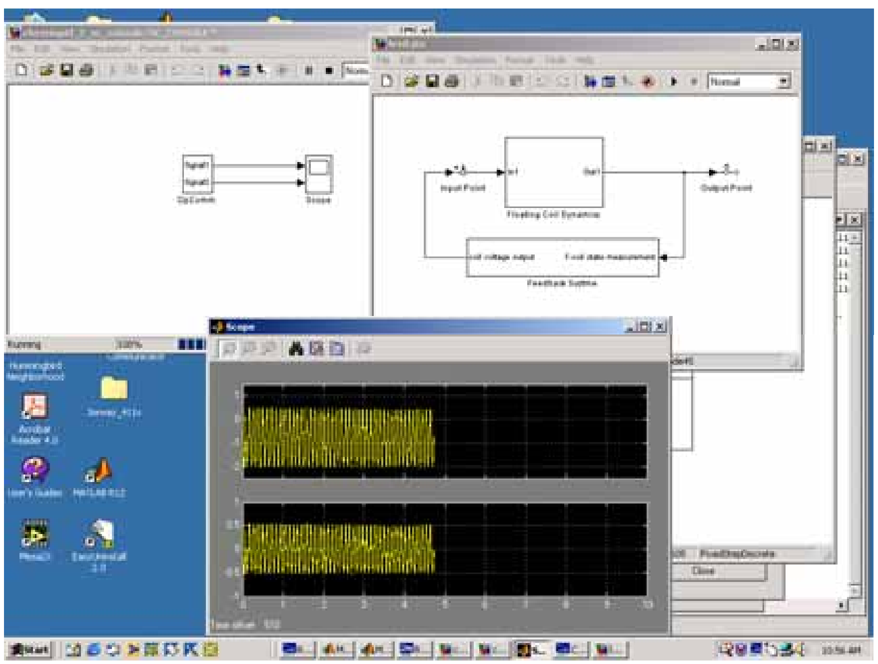
Control System Development

- Integrated test results
  - System identification to ensure observed behavior matches system model
  - Identification of model parameters
- Formal check of observability and controllability
- Optimal Control Theory
  - Optimal control with balance of minimi noise and L-coil heating explicitly
  - Ensure control system won't add noise to stable modes
- Further state machine testing



LCX II: Digitally Controlled Levitation

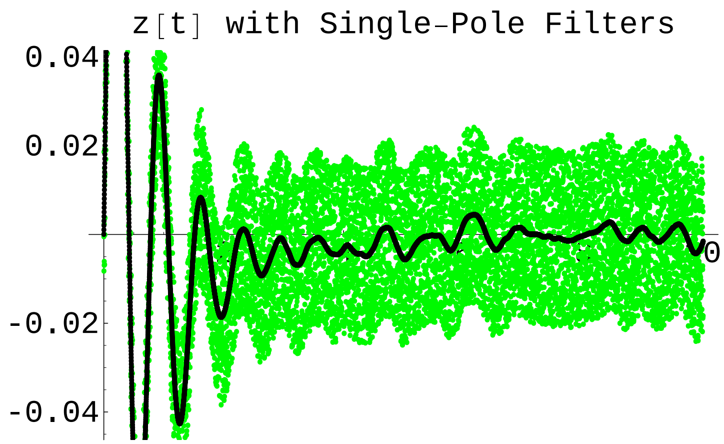


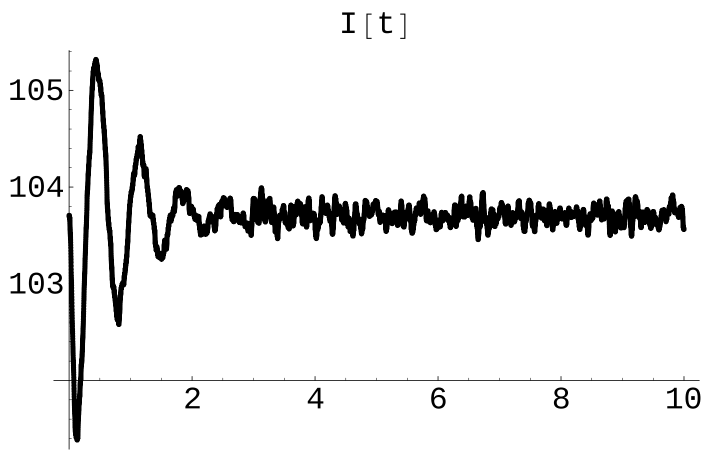


- Levitated Cheerio Experiment II
- Uses LDX digital control system
  - LCX I was analog demonstration
- Modified PID feedback system
  - Low pass filter added for high frequency roll-off of derivative gain
  - Integral reset feature for launch transition
- Dynamic model block replaced by I/O and estimators
- Real-time graph shows position and control voltage
  - Wiggles indicate non-linearly stable rolling mode…

Noise reduction necessary

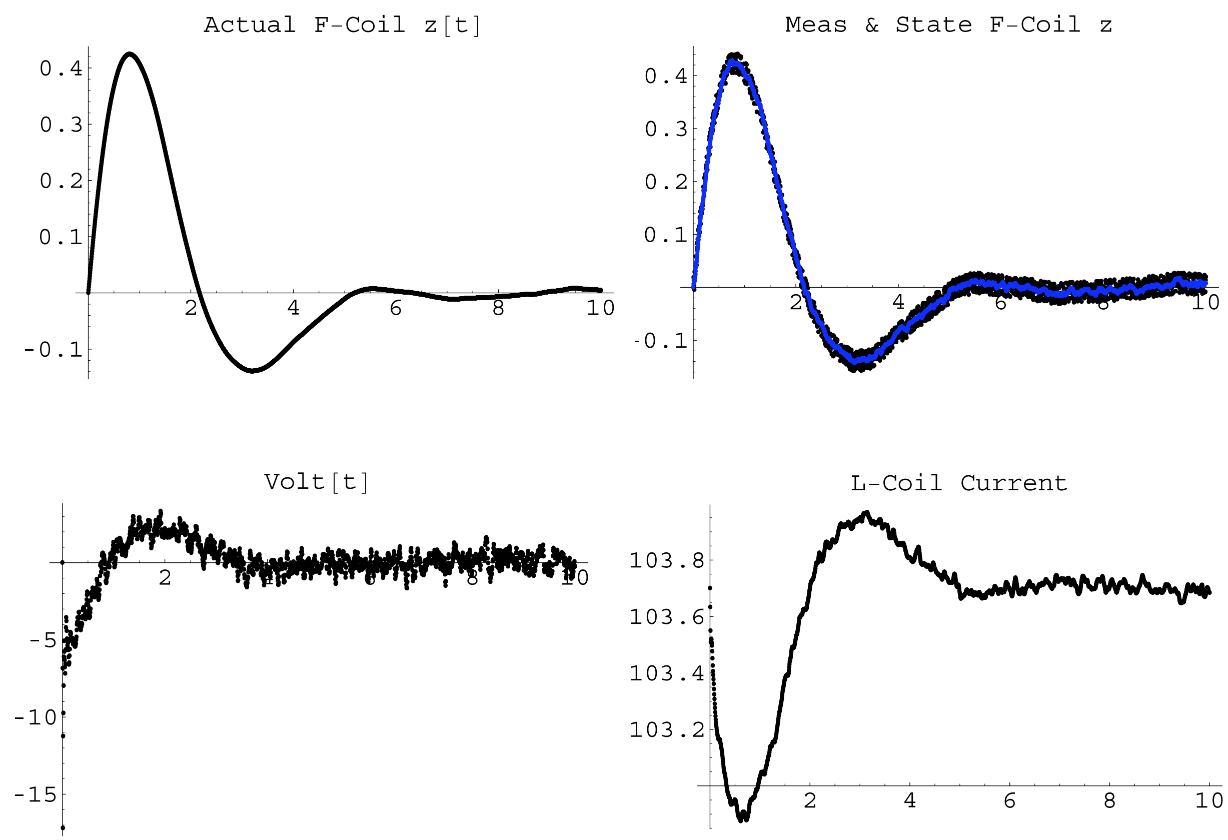
- Noise reduction necessary for derivative gains
- Multipole filter noise reduction limited due to added phase delay





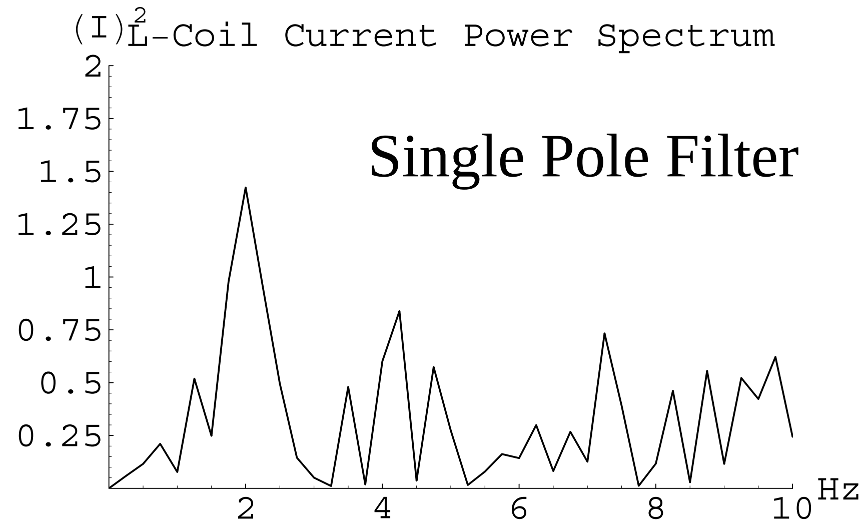
Kalman Filter Simulation

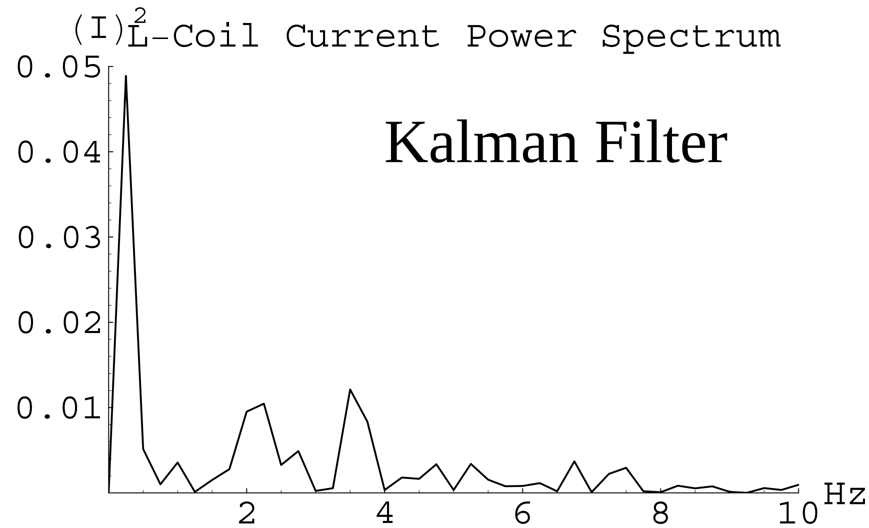
- Kalman filter can be used to reduce noise with minimal latency
  - Uses a physics based predictor that tracks the real motion and is updated with every time step



Kalman Filter Reduces L-coil AC Losses

- Kalman filter results
  - Improved filter greatly reduces noise in system
  - Reduced noise leads to reduced AC heating of L-coil
- Kalman filter with simple feedback sufficient
  - Simulations show this method should meet our requirements for stable levitation

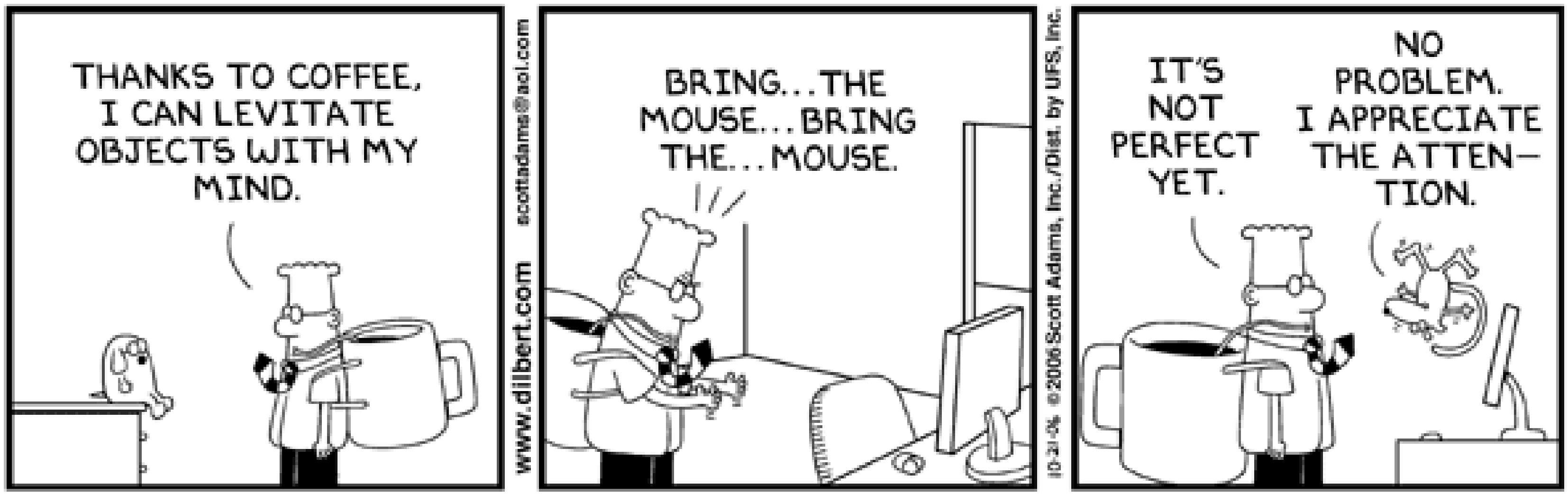




2006 Levitation Test Program

- ✓ System integration test
  - Test inter-operation of cryogenic and two control systems
- ✓ L-coil Integrated Performance Test
  - Test L-coil cryogenic performance under worst-case operation point
    - Also gather data to determine HTS coil quench detection algorithm
  - Calibrate “transfer function” of L-coil System
- ✓ Integrated System Plasma Test
  - Characterize noise on levitation diagnostics in plasma environment
  - Operate L-coil systems at 1/2 current with plasma present
    - Calibrate system using measured lift forces
- ✓ Catcher Drop Test
  - Operated successfully from worst-case scenario
    - Measured acceleration in acceptable range
- Levitation Test Next

Alternative Levitation System



- Greatly simplified
  - Reduced cost
  - Easily manufactured
    - numerous local vendors: Starbucks, Dunkin' Donuts, etc.
- Implementation likely to be "challenging"