Progress on Levitation in the Levitated Dipole Experiment

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Synopsis

- Levitation will likely greatly change operation of 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 prototype complete
  - Catcher system under construction
- Levitation system testing in progress
  - 3 major tests planned to give confidence in successful levitation

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

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

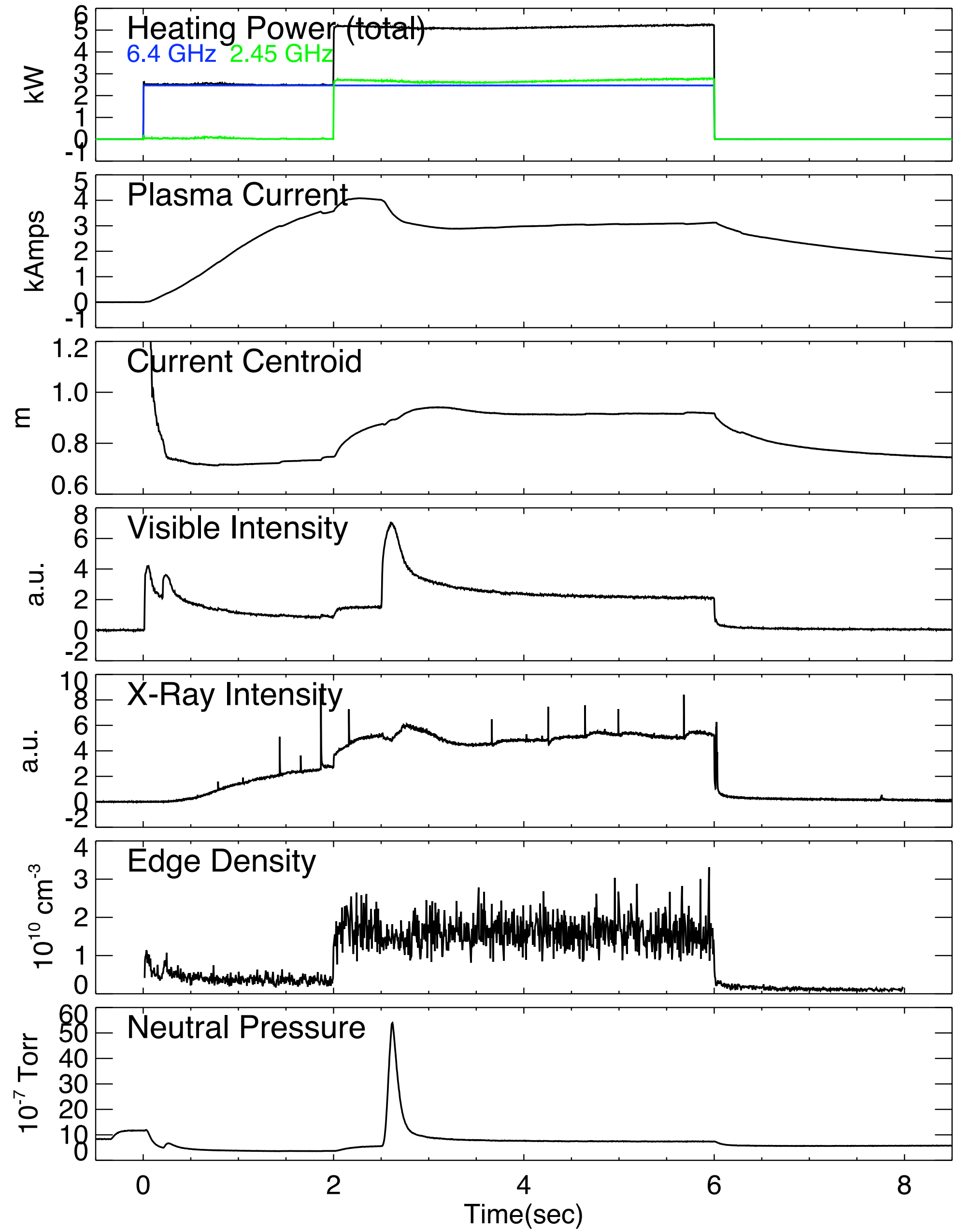
- Fast electron stability enhanced due to coupling of fast electrons to background ions

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

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

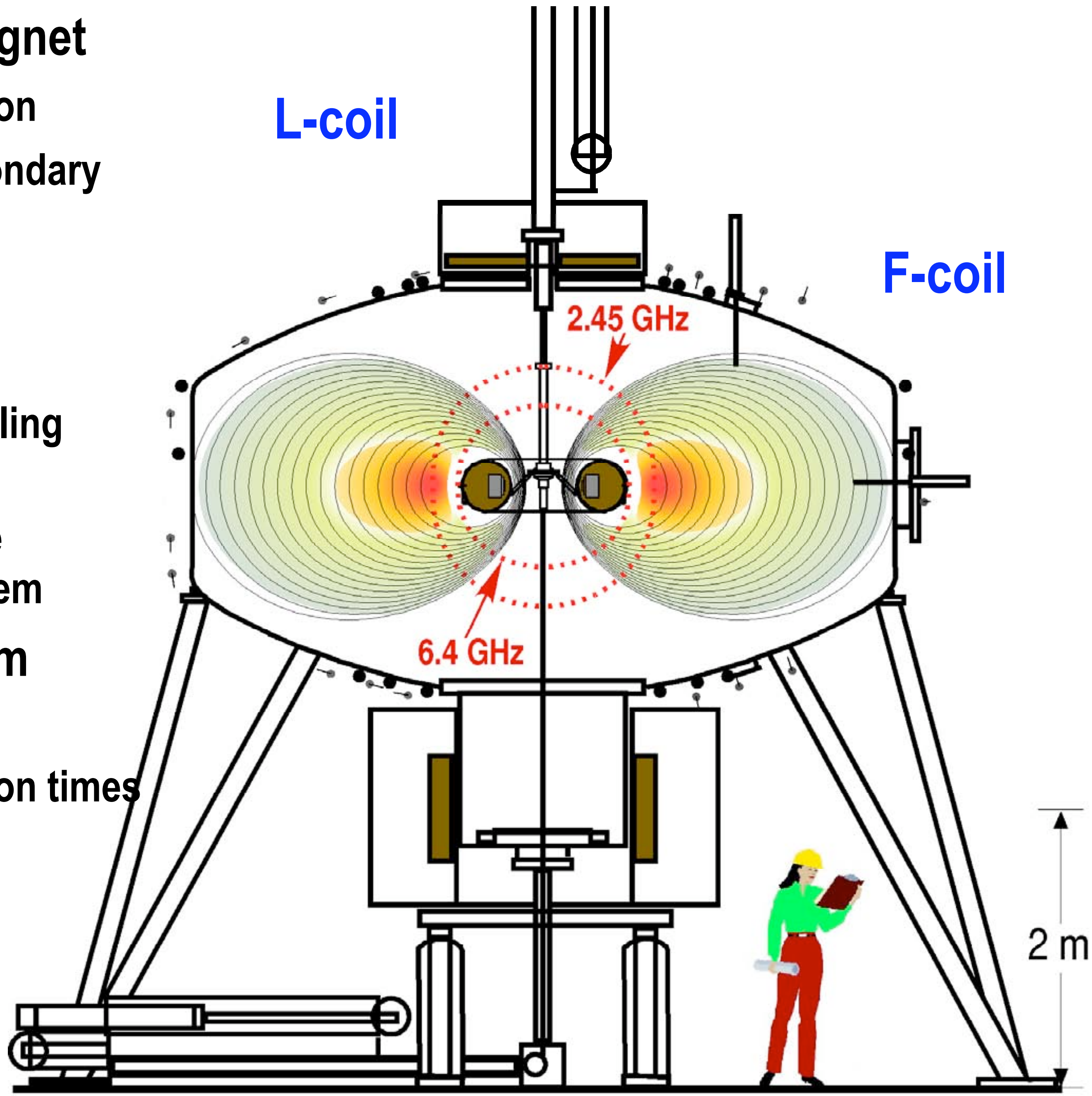
Increased Neutral Fueling Stabilizes HEI

- 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



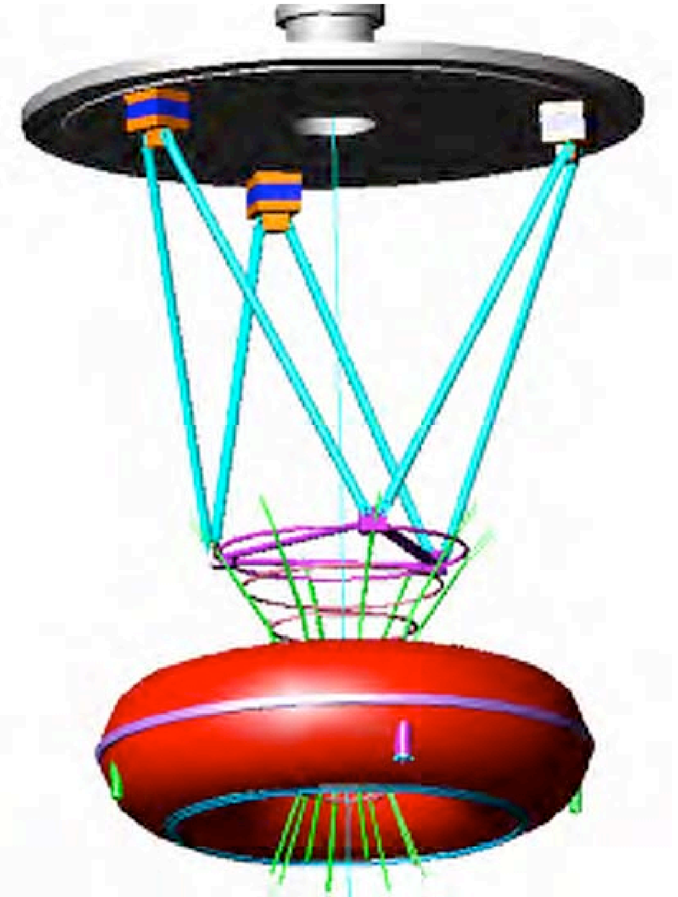
LDX Levitation Basics

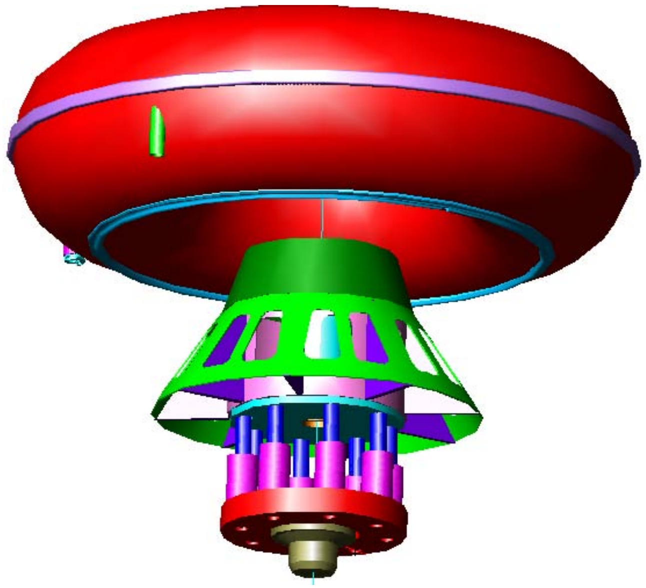
- Levitation by upper lift magnet
  - Unstable only to vertical motion
  - Mostly undamped stable secondary modes
- HTS lift magnet
  - First in US Fusion program
  - Much reduced power and cooling requirements
  - AC heating introduces unique requirements for control system
- Large 5 m diameter vacuum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



Generation II Catcher

- New catcher under construction
  - Lightweight cone that will accelerate to match F-coil fall without large impulse
  - Partial F-coil deceleration while launcher mass accelerates
  - Limit all accelerations to less than 5 g

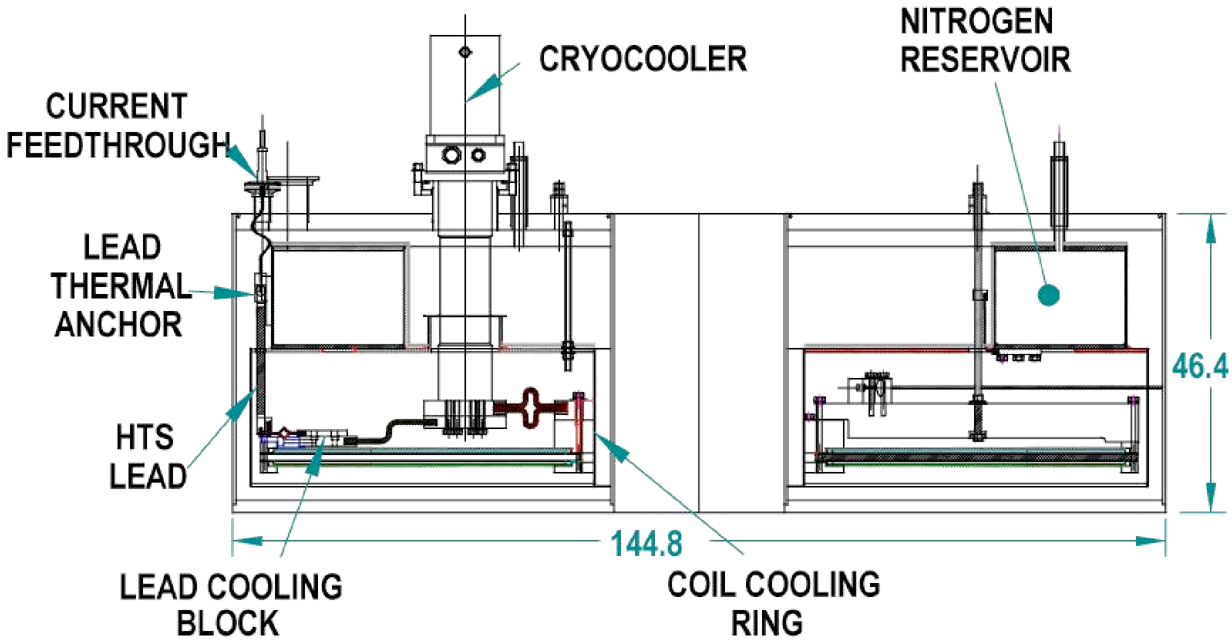




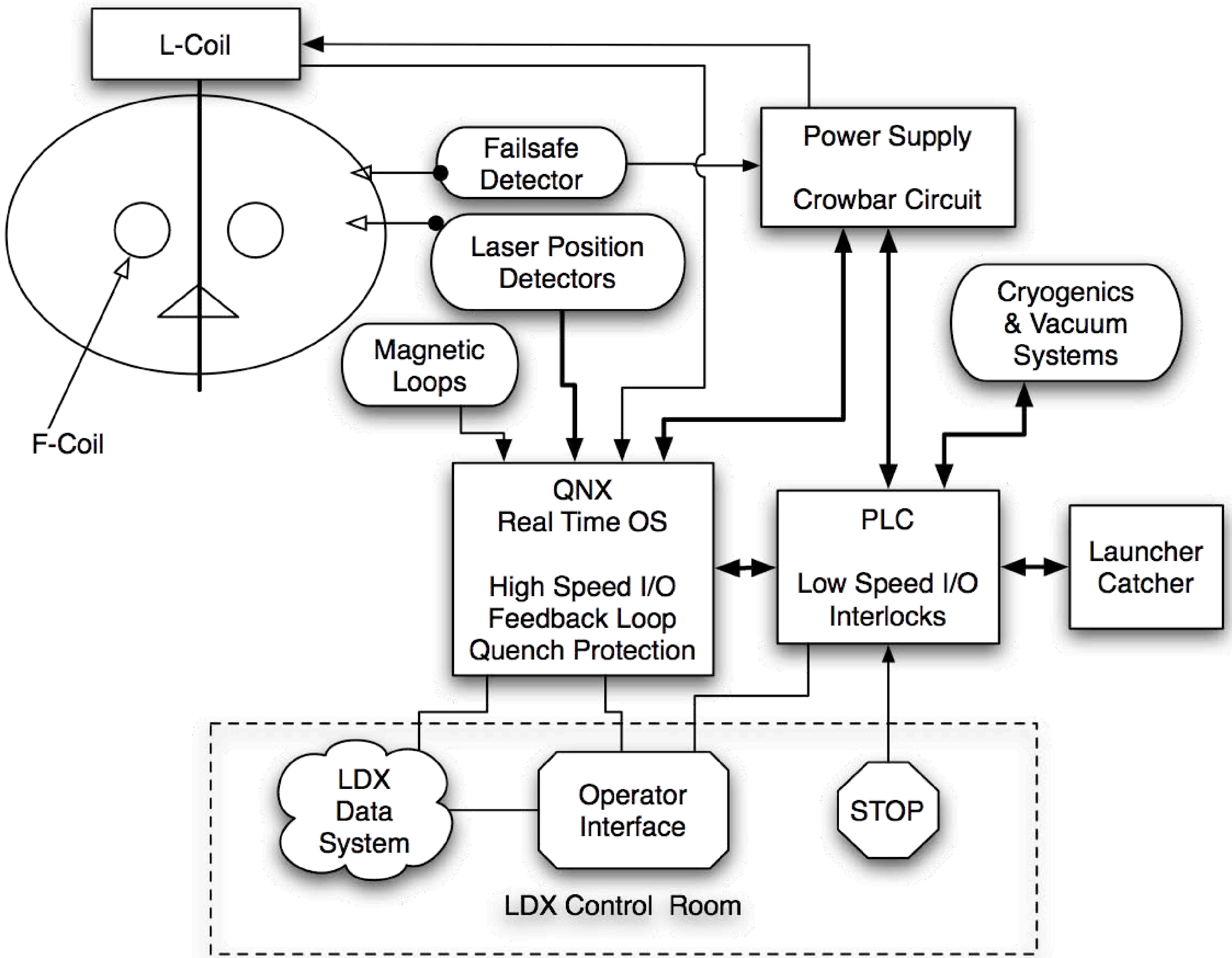
- Upper space frame
  - Limit upward motion
  - Align radial motion for fall to catcher

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.



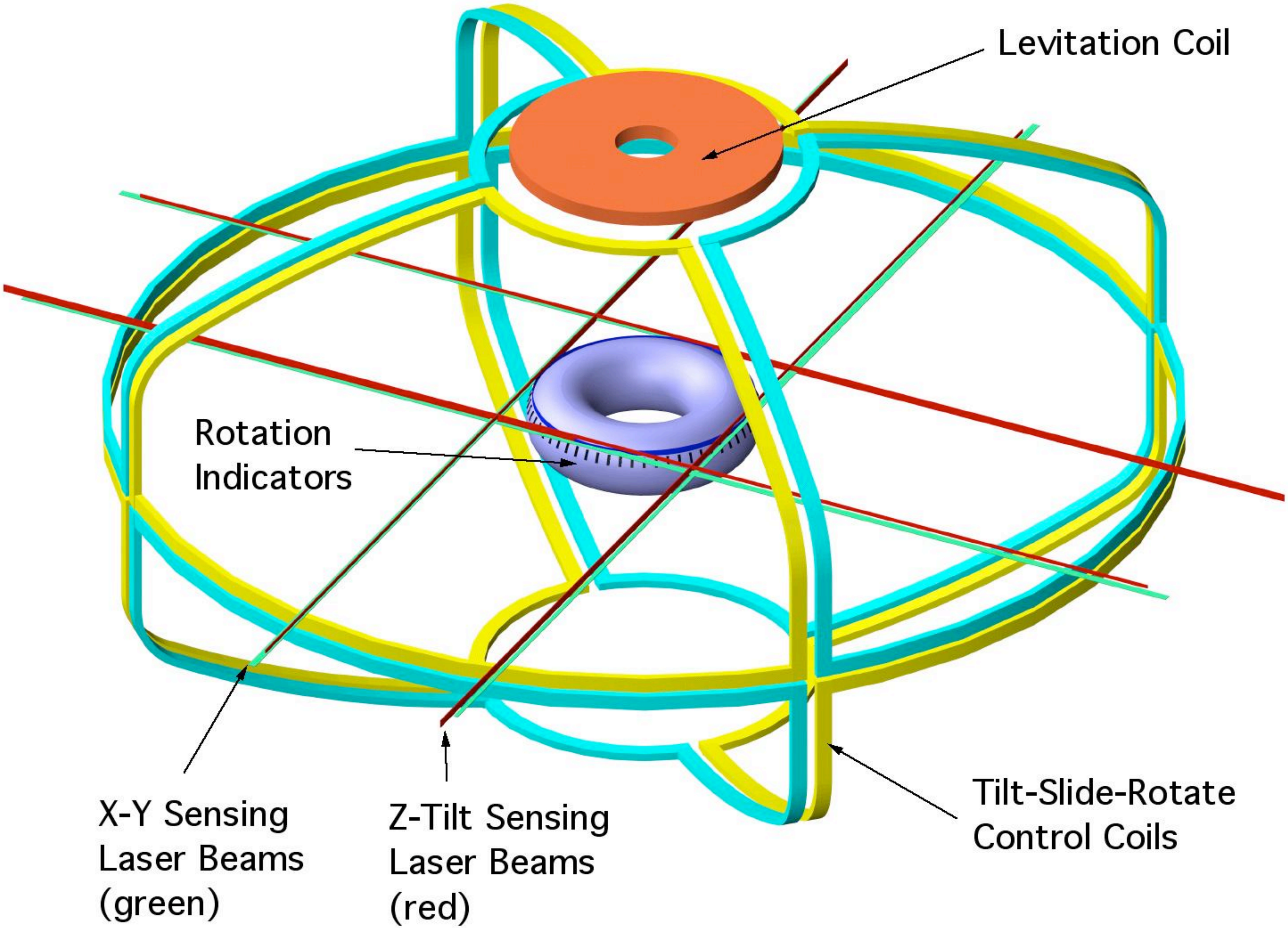
Levitation Control System



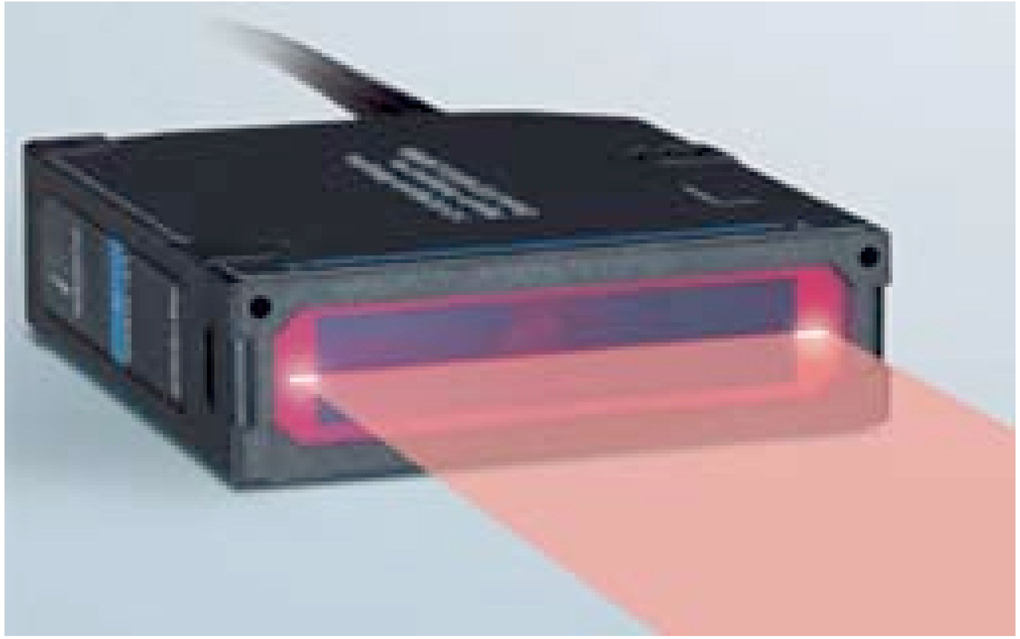
LDX Control System Description

- 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

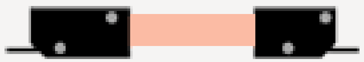
Levitation Control System Schematic



Optical Position Detection System



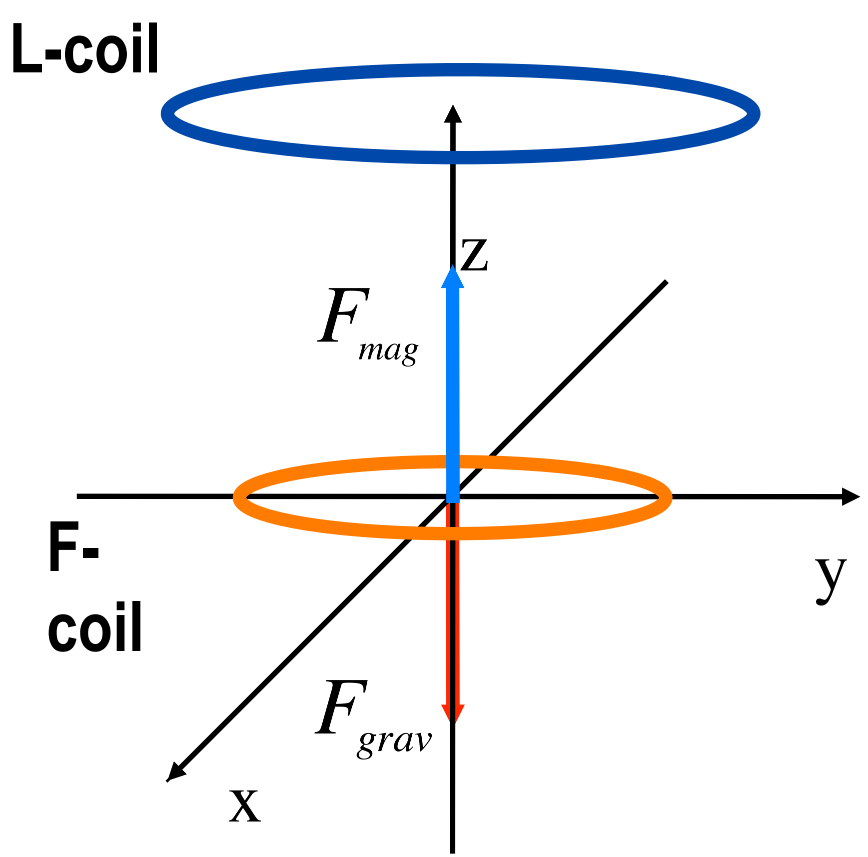
- Position/Attitude Sensing
  - Occulting system of 8 beams
    - Provides measurement of 5 degrees of freedom of coil with redundancy in each measurement
  - Specification
    - ± 1 cm detection range
    - 5 μm resolution
    - 5 kHz frequency response
  - Keyence LH-300 COTS units
    - Exceed all 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

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: $M_{LF} = M_{LF}(\vec{x}_{1\to 5})$

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

Feedback: Optimized Voltage PID

- Because of the L-coil inductance, we cannot change IL instantaneously. We can control the voltage=L*dIL/dt, instantaneously (or as fast as the power supply allows us to change its voltage):

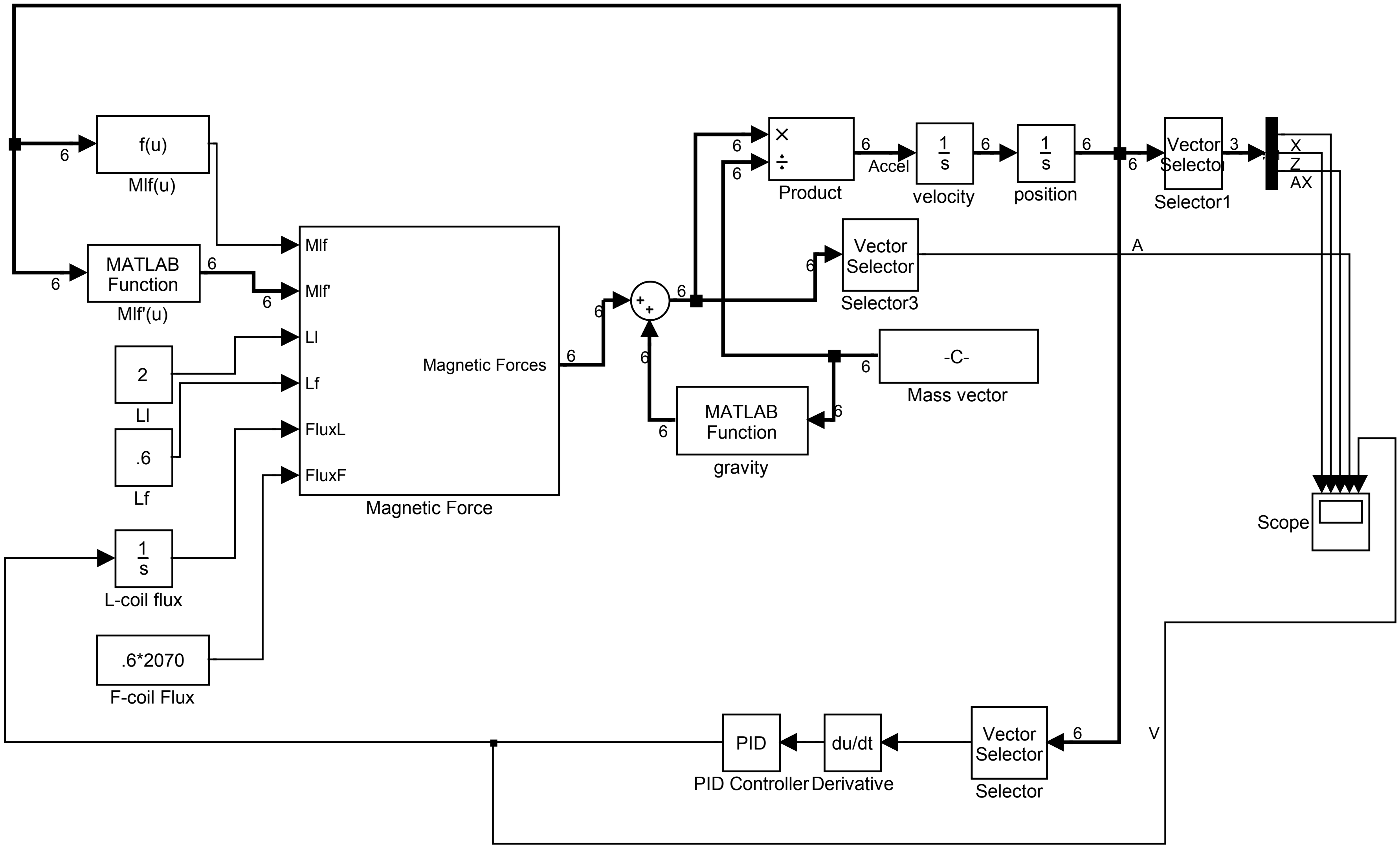
$$V_L(t) = -b_0\varepsilon(t) - b_1\varepsilon'(t) - b_2\varepsilon''(t)$$

- Include an integral term to automatically adjust for DC losses:

$$V_L(t) = -b_{-1}\int \varepsilon(t)dt - b_0\varepsilon(t) - b_1\varepsilon'(t) - b_2\varepsilon''(t)$$

- The b parameters are optimized to get the best stabilization:
  - Put feedback expression into equation of motion to find most stable, critically damped solution
- Technique used to estimate required currents / voltages for L-coil
- Similar technique (using only derivative gain) used to determine required current for damping Rock & Roll motion using TSR coils
  - ~ 200 Amp turns required…

Basic Simulink Levitation Model



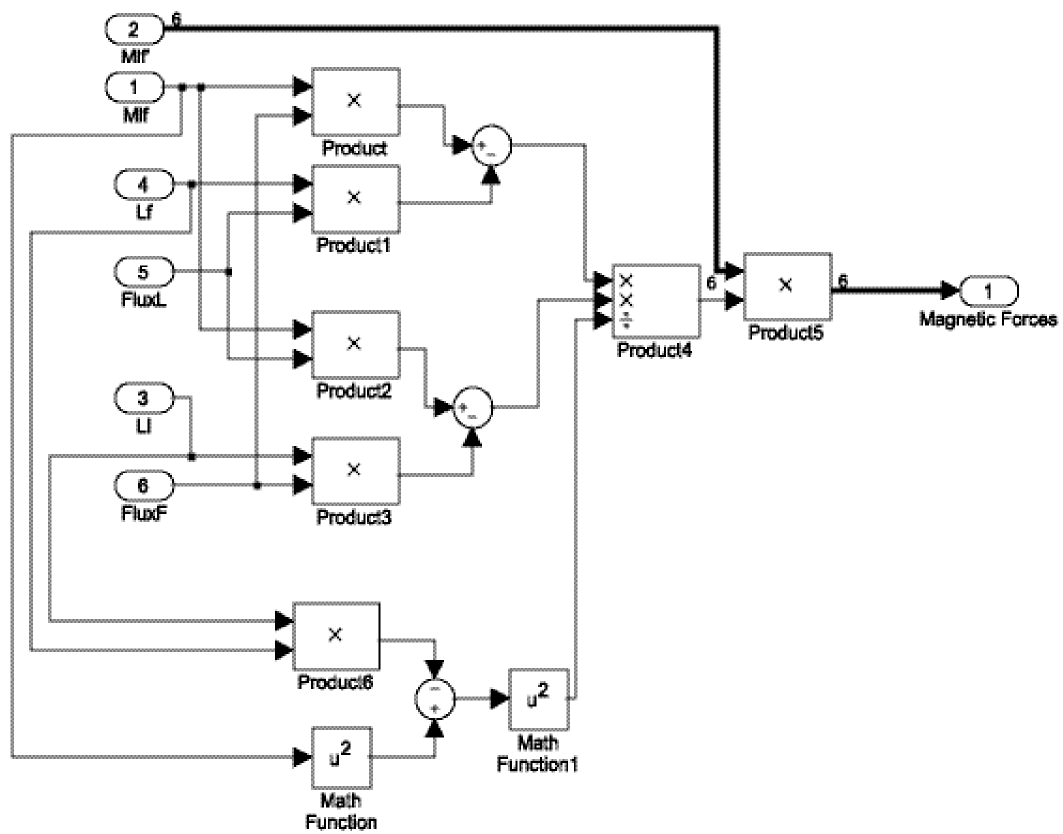
- **This basic model simulates 6 degrees of freedom of F-coil with L-coil levitation using voltage feedback control.**

Levitation Physics - Simulink Model

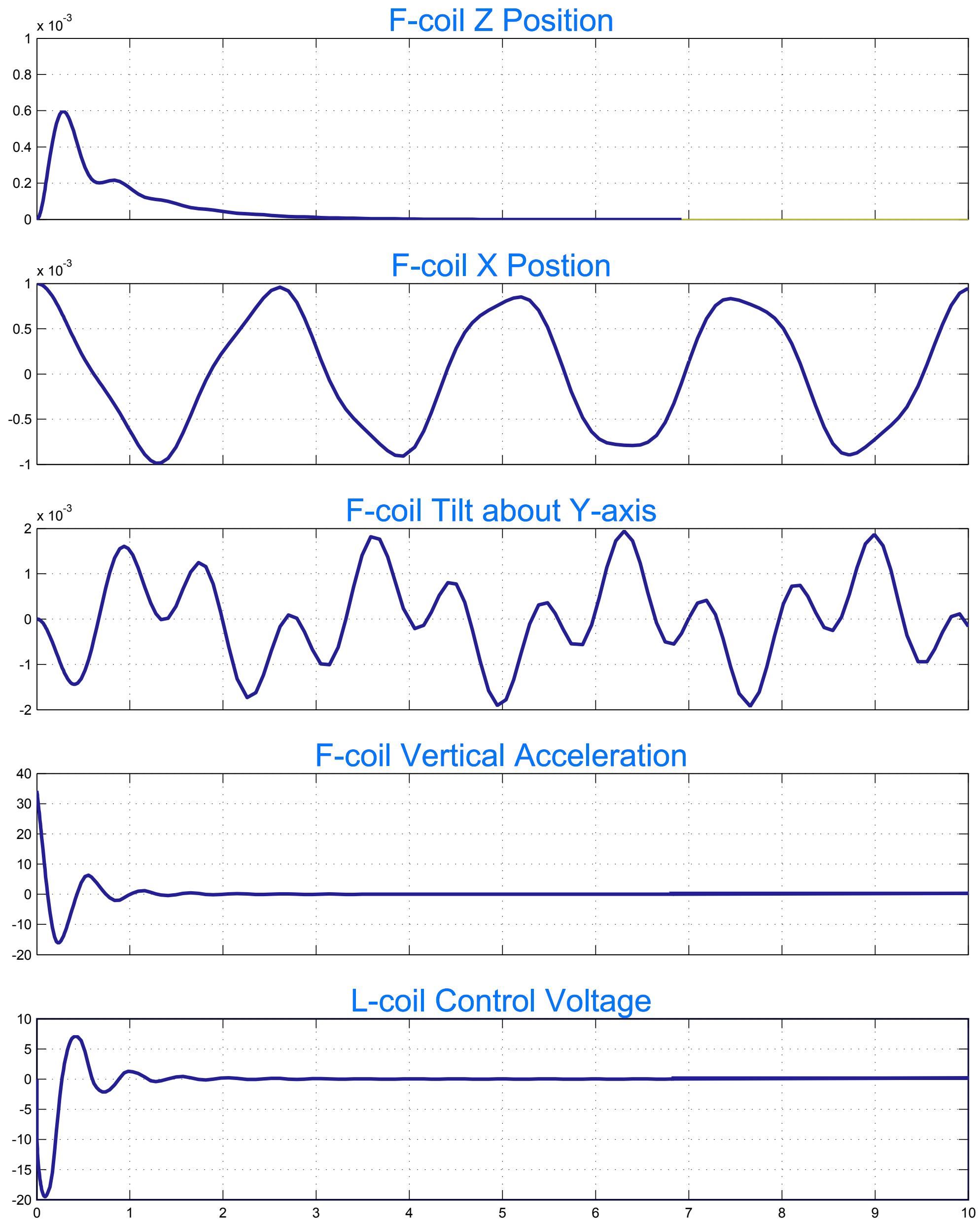
… solving for the magnetic force on the F-coil due to the L-coil in terms of the flux gives:

$$F_{magnetic} = \vec{\nabla} M_{LF} \frac{(M_{LF}\Phi_F - L_F\Phi_L)(M_{LF}\Phi_L - L_L\Phi_F)}{(L_L L_F - M_{LF}{}^2)^2}$$

This equation translated to a Simulink model might look like:



Basic Levitation Model Results

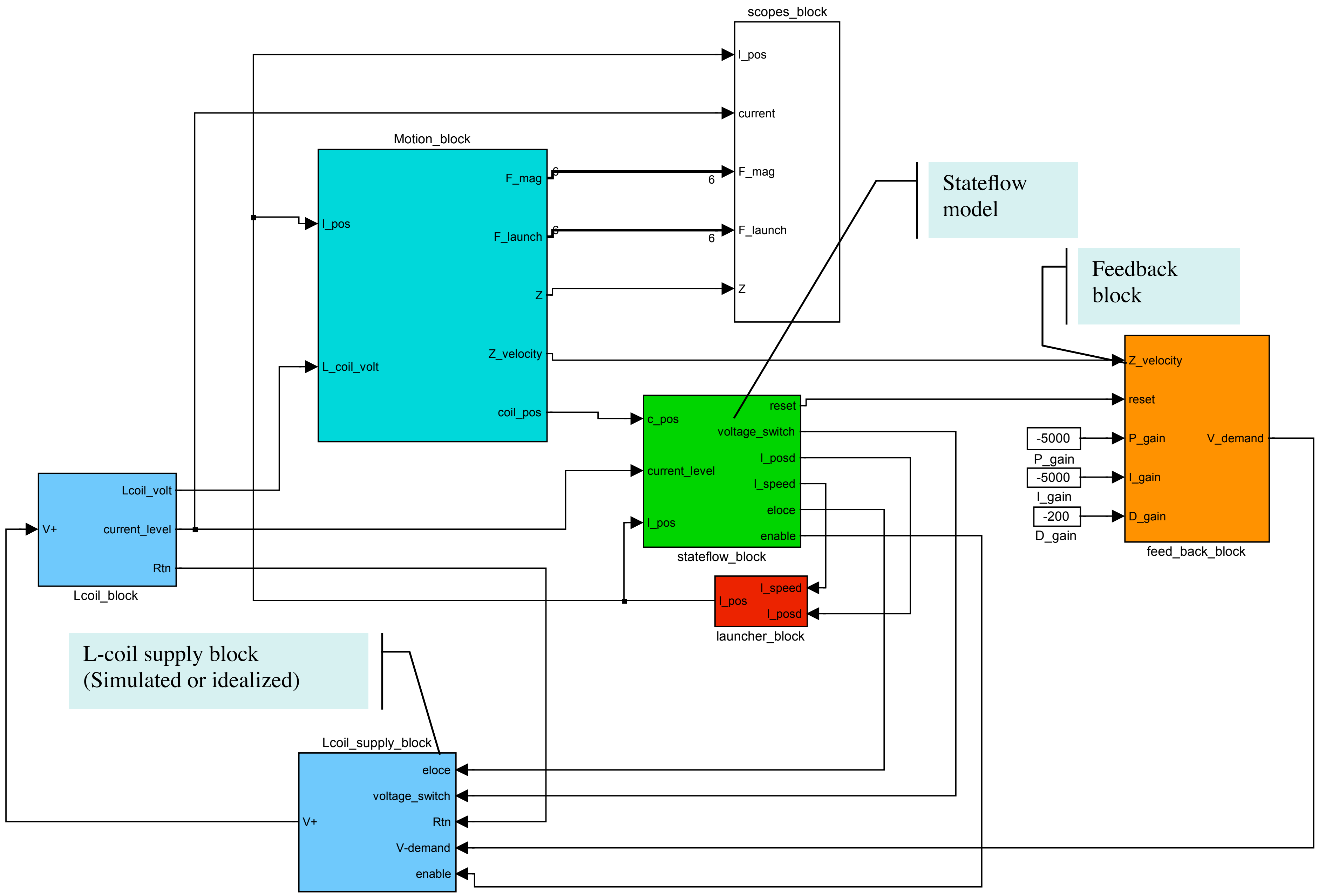


- Control parameters as calculated from analytic optimization for voltage PID loop
    - Simulations stay within L-coil supply specifications
- Simulink works!
    - Results match previous numerical simulations
    - Analytic analysis eigenmodes are 1.0 and 0.4 Hz
- On to implementation!

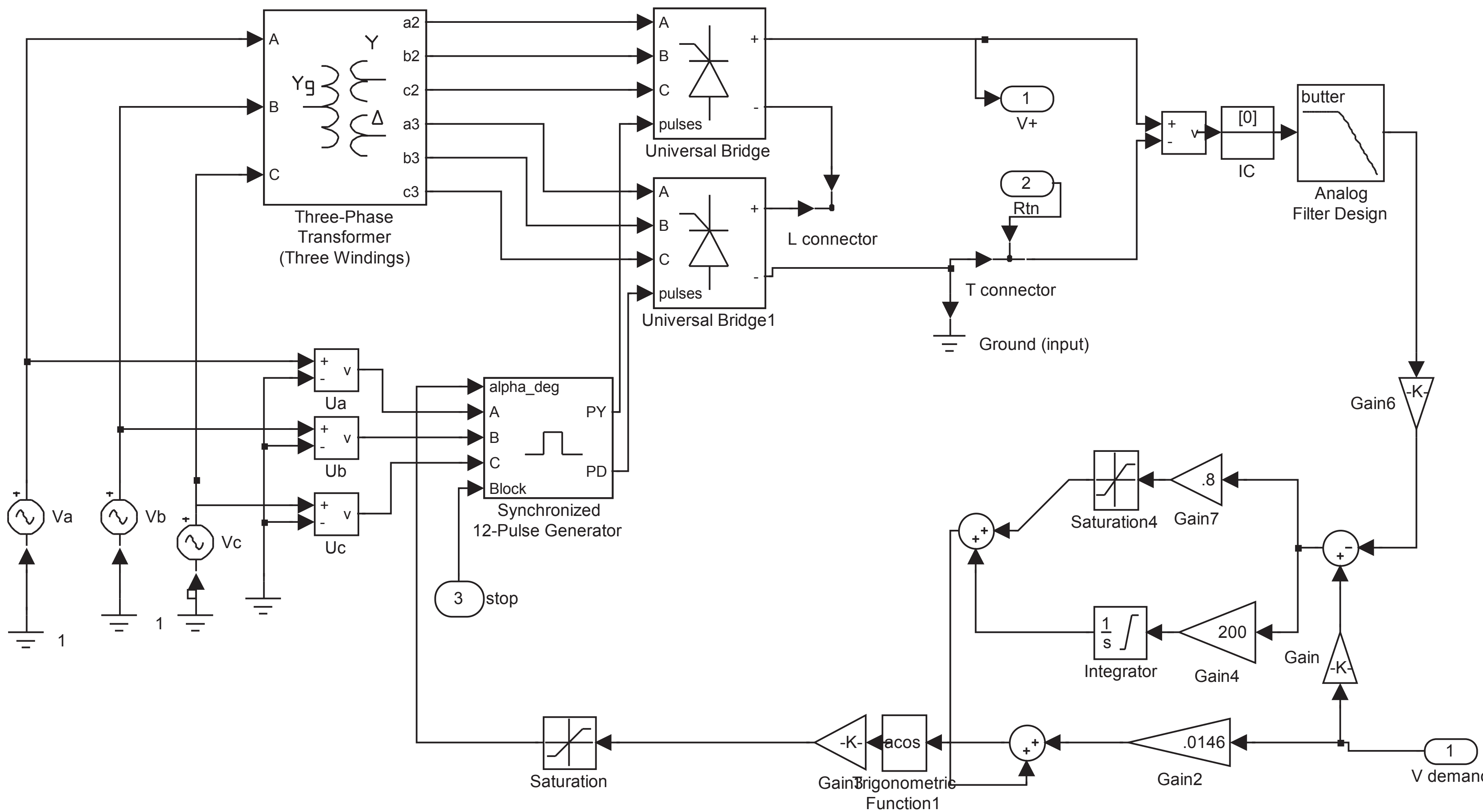
LDX Control System State Machine

- Design of simple levitation controllers requires linear approximation of dynamics near operational point
- But magnetic forces are go like L^3
- Use a state machine to ensure safe operation of system while not near flight status
  - Simulink Stateflow handles state machine in LDX control design

System Simulink/Stateflow Model

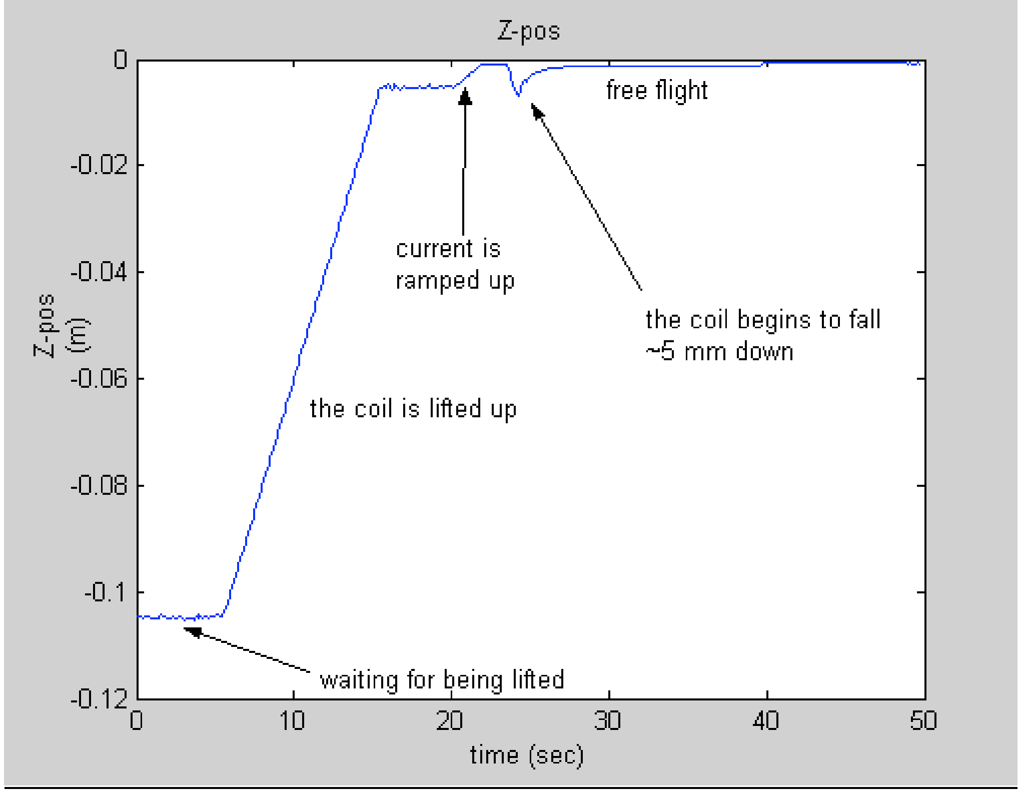


L-coil Power Supply Simulation



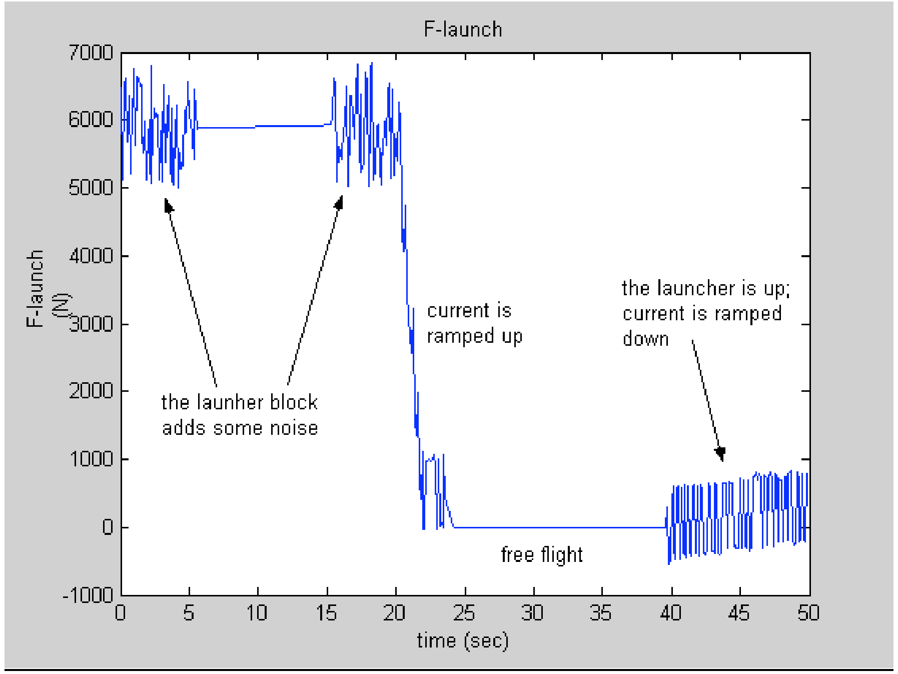
- Model of 12 pulse switch regulated power supply for L-coil
  - Uses Simulink Power System Blockset
- Internal voltage control feedback loop

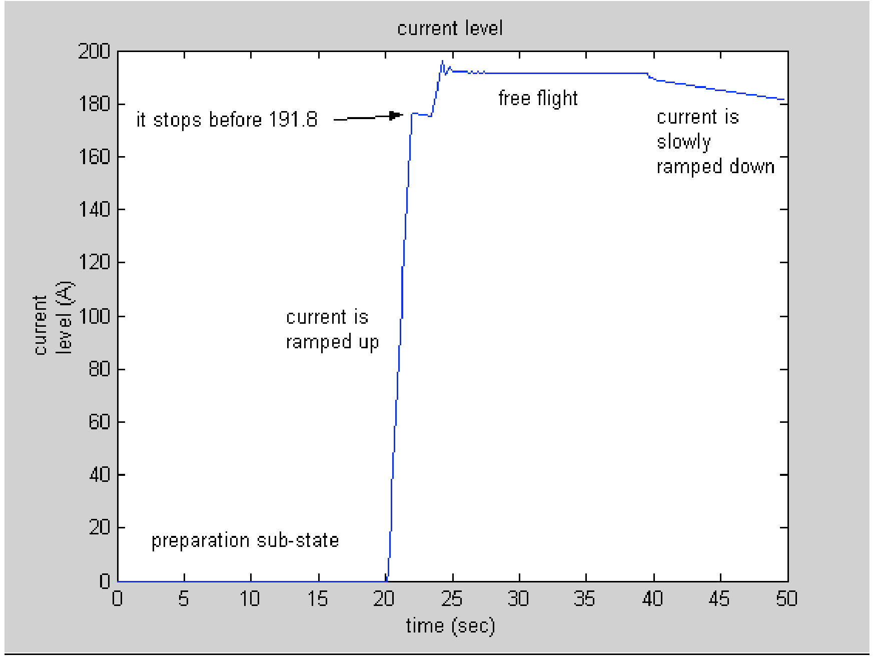
State System Simulation

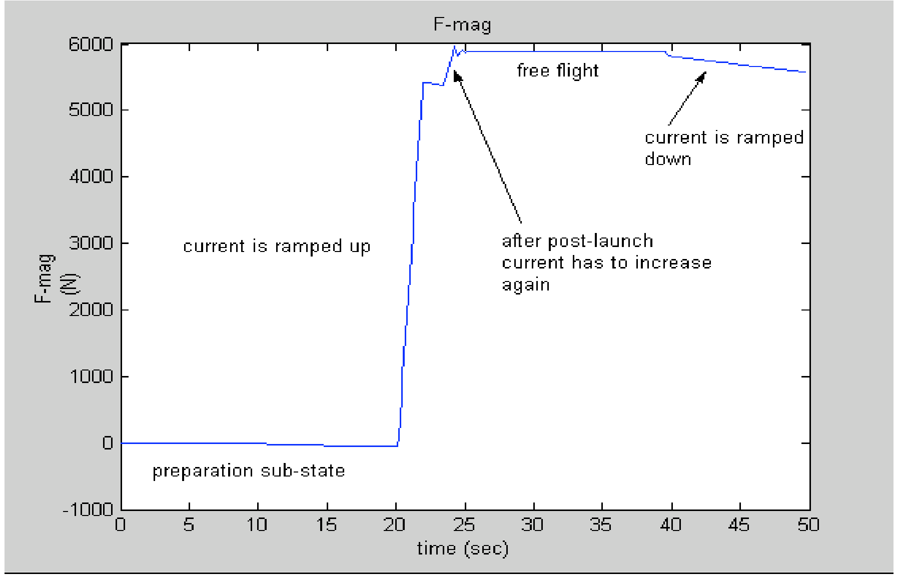


- Complete functional model
  - Includes human check wait states
  - Automatic failure modes tested
- Z Position Graph
  - Shows launcher in action
  - Current ramp of L-coil
  - Pre-flight check
  - (Premature) launch
  - Free flight

More Full Simulation Results

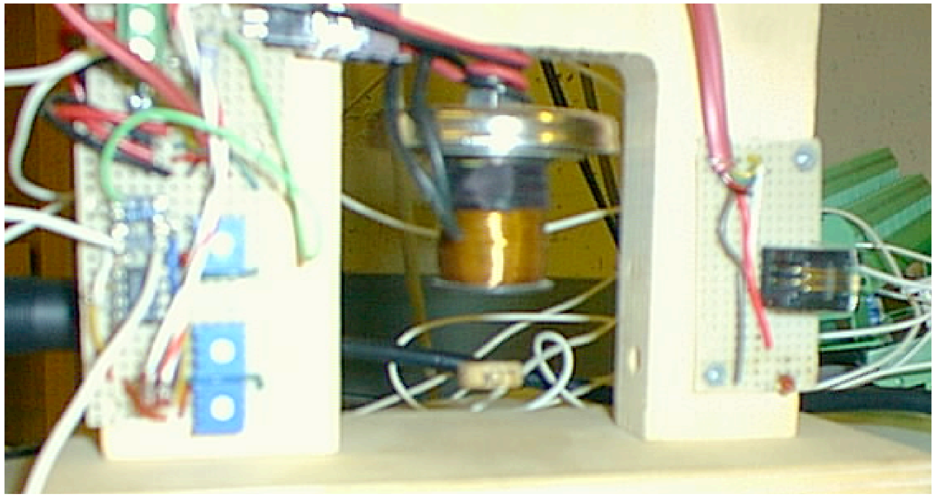


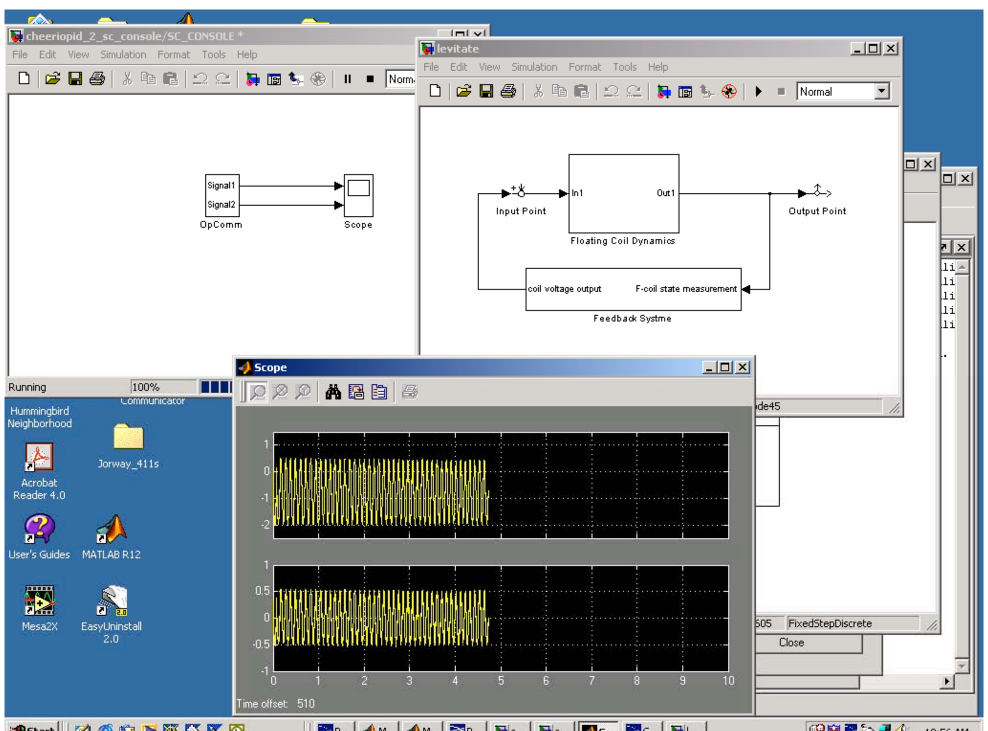




- Vibrating launcher spring
- L-coil supply voltage ripple
  - ~ 40 volt ripple
  - Current ripple is < 50mA
  - No filtering required
- Some state machine bugs…

LCX II: Digitally Controlled Levitation

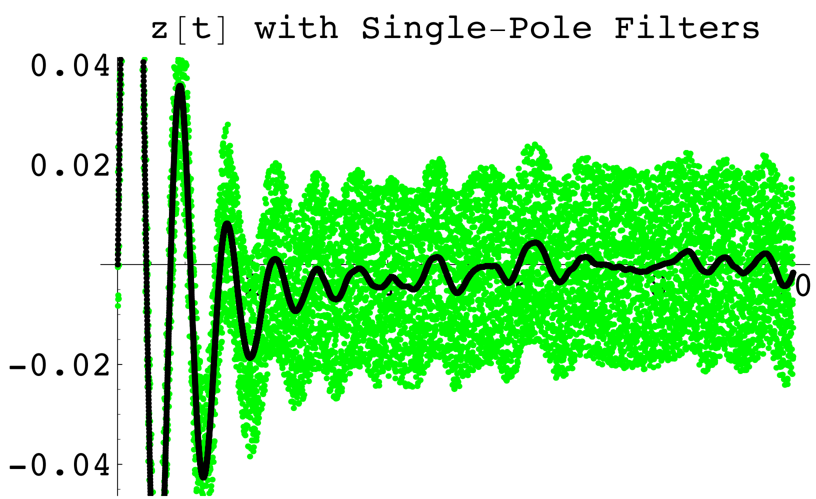


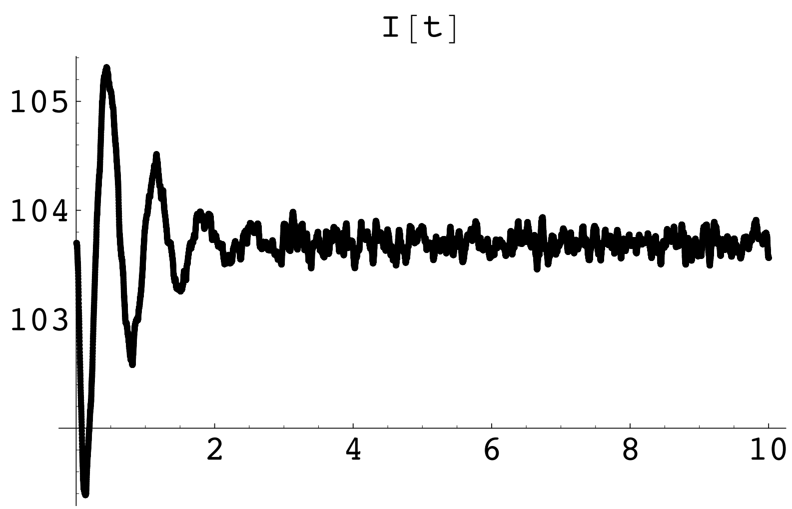


- Levitated Cheerio Experiment II
- Uses LDX digital control system
  - LCX I was analog demonstration
- Modified PID feedback system
  - Low pass filter added for high frequency roll-off of derivative gain
  - Integral reset feature for launch transition
- Dynamic model block replaced by I/O and estimators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

Noise reduction necessary

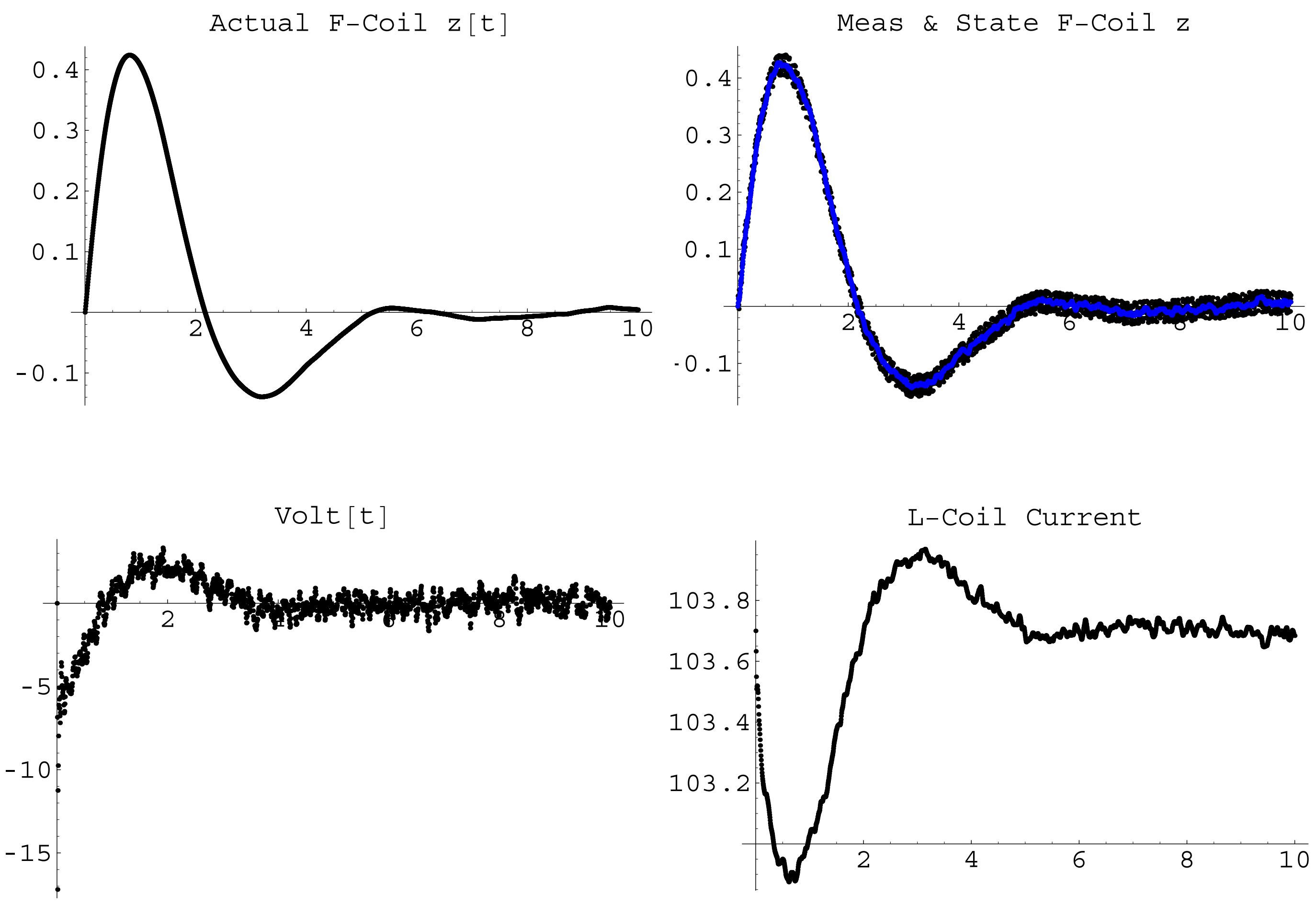
- Noise reduction necessary for derivative gains
- Multipole filter noise reduction limited due to added phase delay





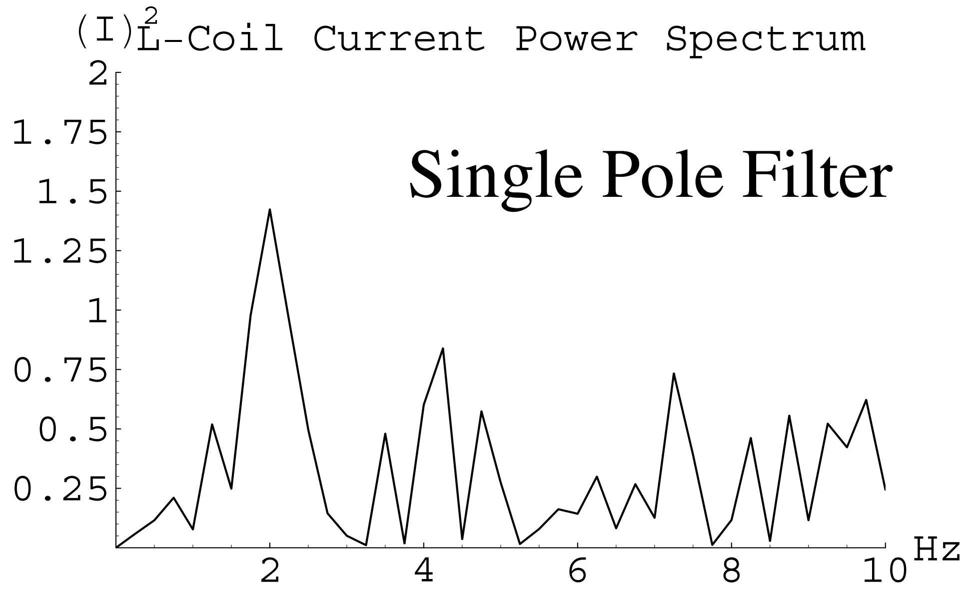
Kalman Filter Simulation

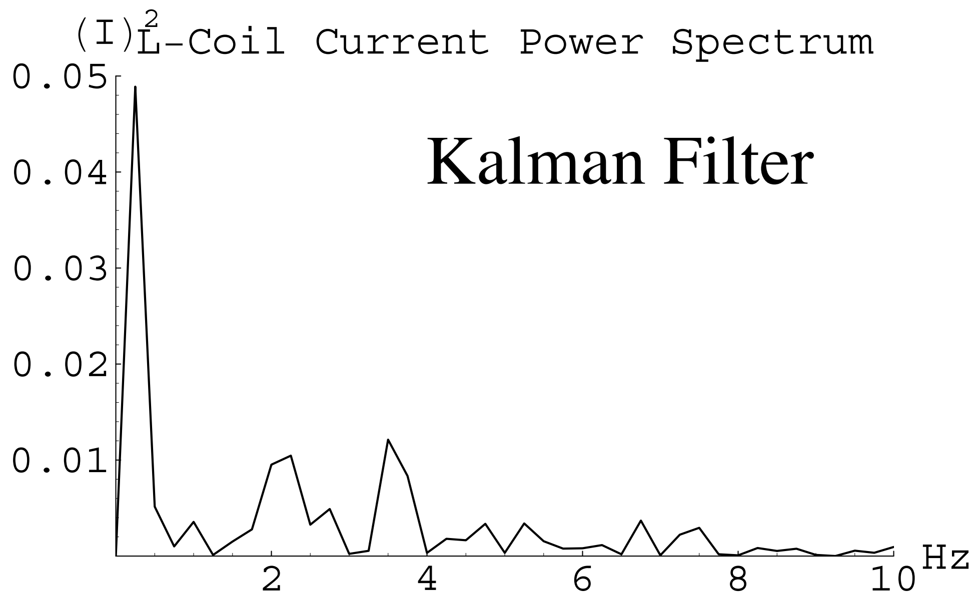
- Kalman filter can be used to reduce noise with minimal latency
  - Uses a physics based predictor that tracks the real motion and is updated with every time step



Kalman Filter Reduces L-coil AC Losses

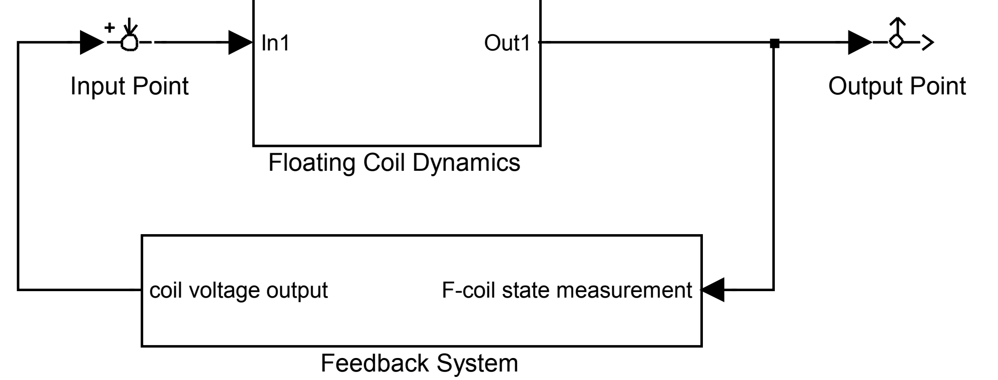
- **Kalman filter results**
  - Improved filter greatly reduces noise in system
  - Reduced noise leads to reduced AC heating of L-coil
- **Kalman filter with simple feedback sufficient**
  - Simulations show this method should meet our requirements for stable levitation





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
  - MIMO System Simulation
  - Optimal control with balance of minimization of noise and L-coil heating explicitly
  - Ensure control system won't add noise to stable modes
- Further state machine testing



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
    - Gather data to determine HTS coil quench detection algorithm
  - Calibrate “transfer function” of L-coil System
    - Check state space model for unknown system variables
- 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
- Levitation Test
  - First levitation with nearby supports and safety lines
- Levitated Plasma Operations begin