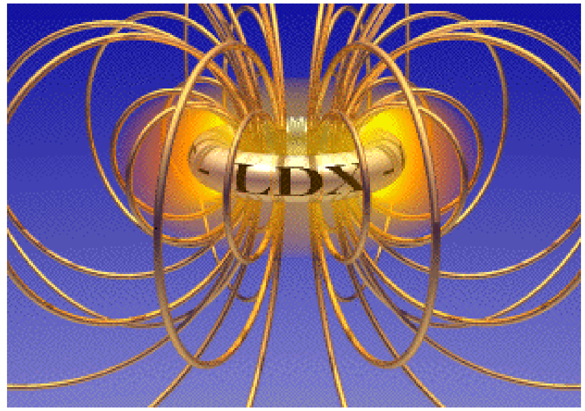

Levitation Control System for the Levitated Dipole Experiment

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Abstract

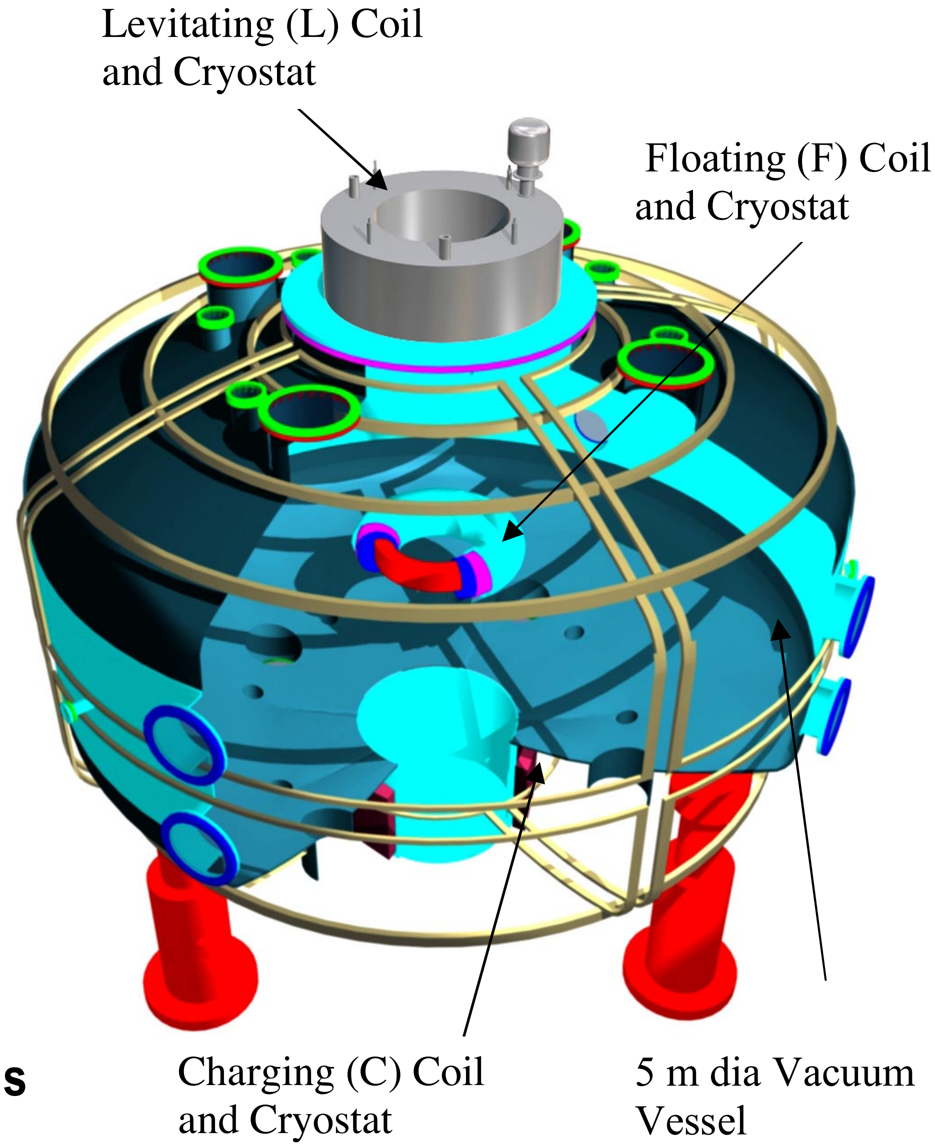
- The confining field in the Levitated Dipole Experiment (LDX) is provided by a 1/2 ton levitated superconducting dipole magnet. This floating coil is charged with 1.5 MA current and will be levitated continuously for the eight hour experimental run day.
- Earnshaw's theorem states that there exists no statically stable configuration for levitation of magnets. In LDX, the floating coil is levitated by a smaller dipole levitation coil 1.5 meters above. This configuration is unstable vertically, but stable in tilt or horizontal motion.
- The position of the coil will be monitored with a set of eight laser position detectors giving redundant measurements of the five degrees of freedom of the floating coil.
- The levitation will then be stabilized by feedback control of the current in the levitation coil. The feedback system is a digital system running on a real time operating system platform. This system is programmed, monitored, and controlled by a second computer using Matlab Simulink. The system is currently being tested on a small model and a larger test is planned before LDX operation.
- Results from these tests and optimizations are presented.

Outline

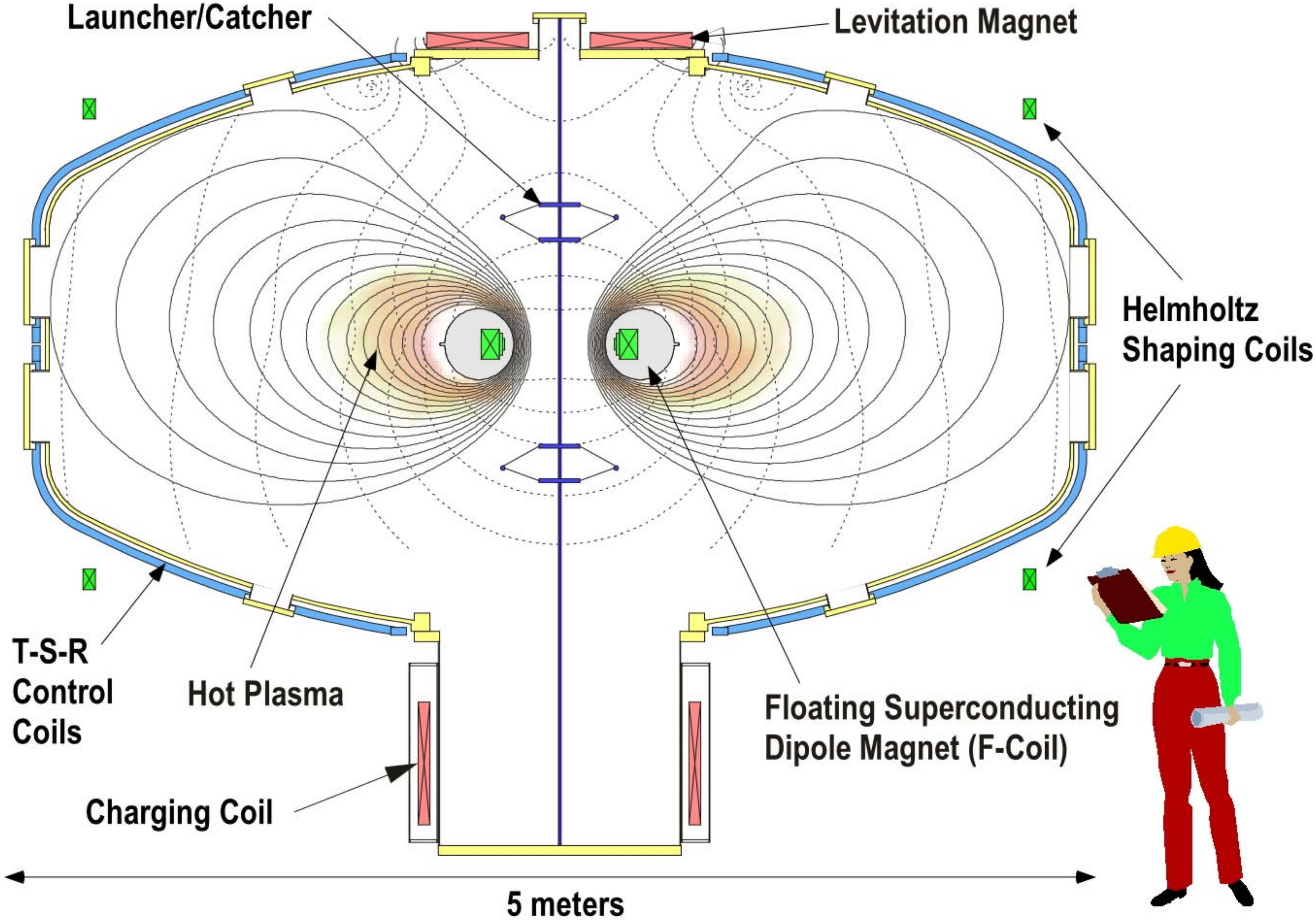
- Introduction to LDX
- Coil Systems
  - F-coil
  - L-coil
  - TSR coils
- Levitation Physics
- Levitation Control System
  - Hardware
    - Optical detection system
    - Digital real-time control computer
  - Simulation
  - Cheerio Model
- Conclusions

LDX: Experimental Overview

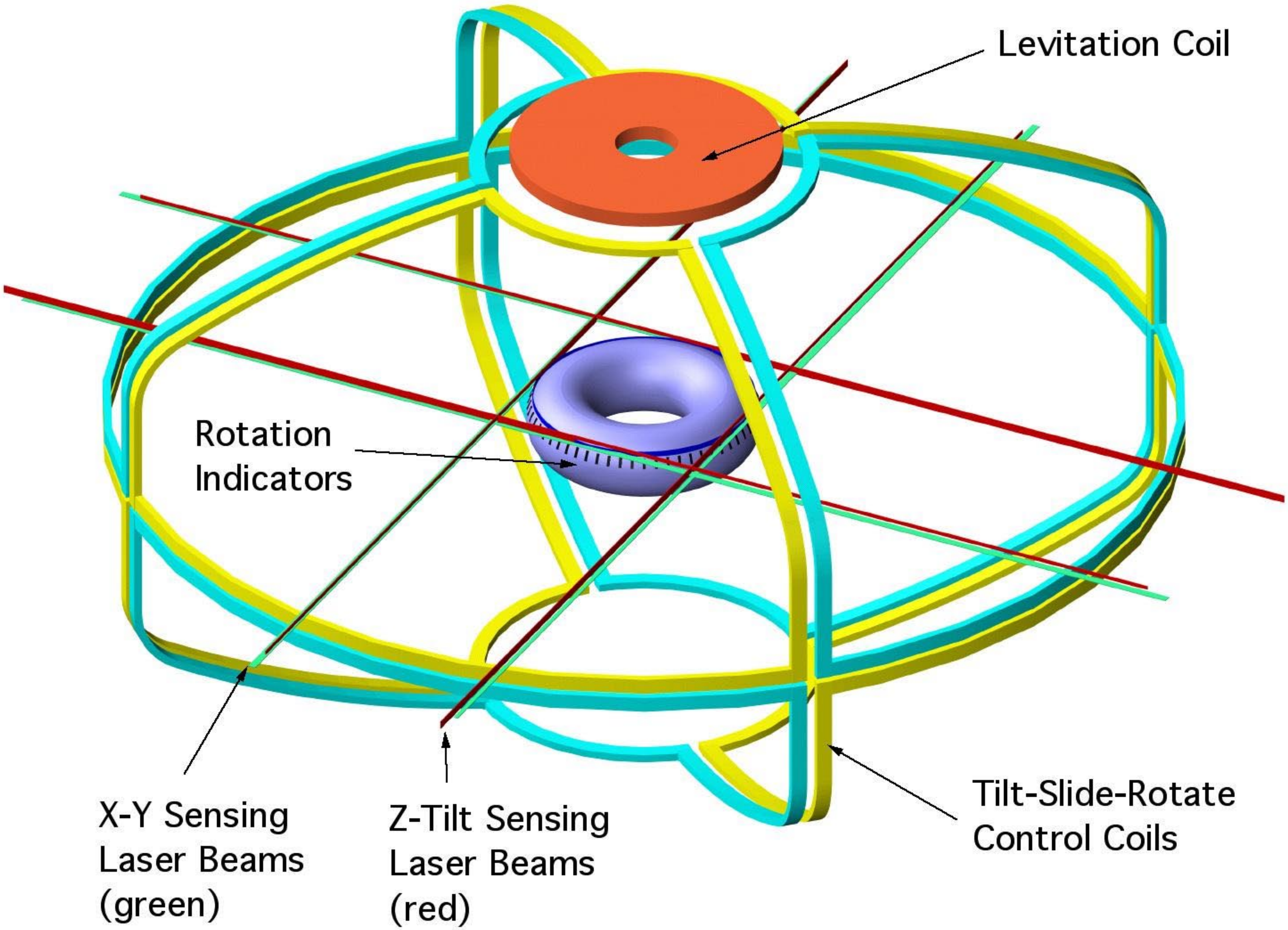
- LDX consists 3 major components:
  - a high performance super conducting floating coil
  - charging coil
  - vacuum vessel
- Other components include
  - Plasma heating system (multi-frequency ECRH)
  - Levitation coil
  - Control system & coils
  - Launcher/Catcher system
  - Plasma shaping (Helmholtz) coils
  - Plasma diagnostic systems



LDX Experiment Cross-Section

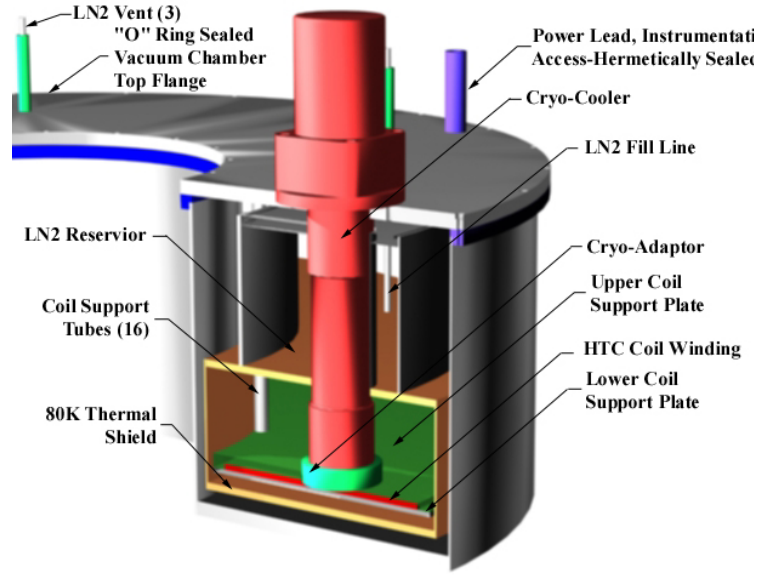


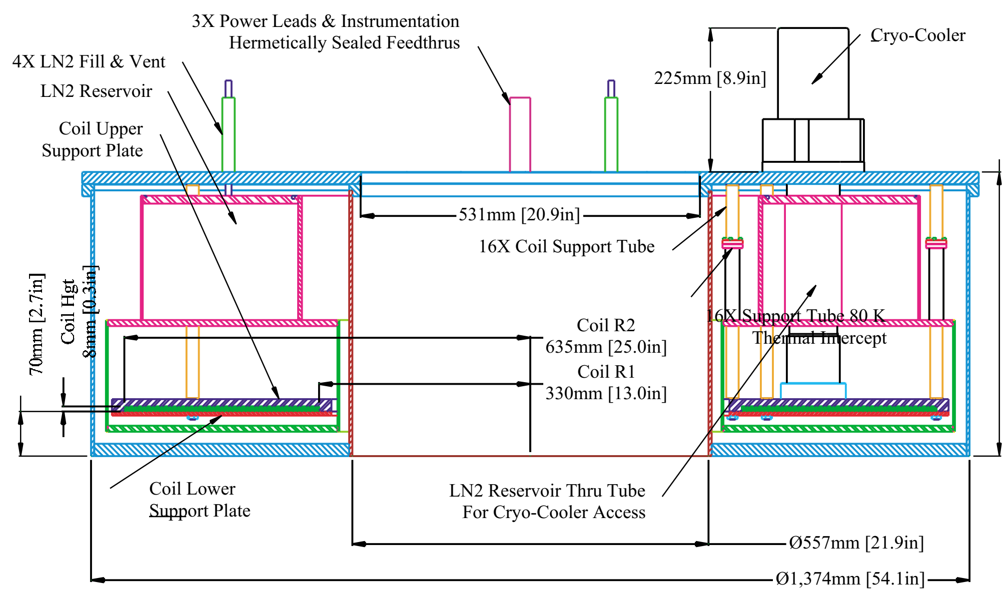
Levitation Control System Schematic



High T_c Superconducting Levitation Coil

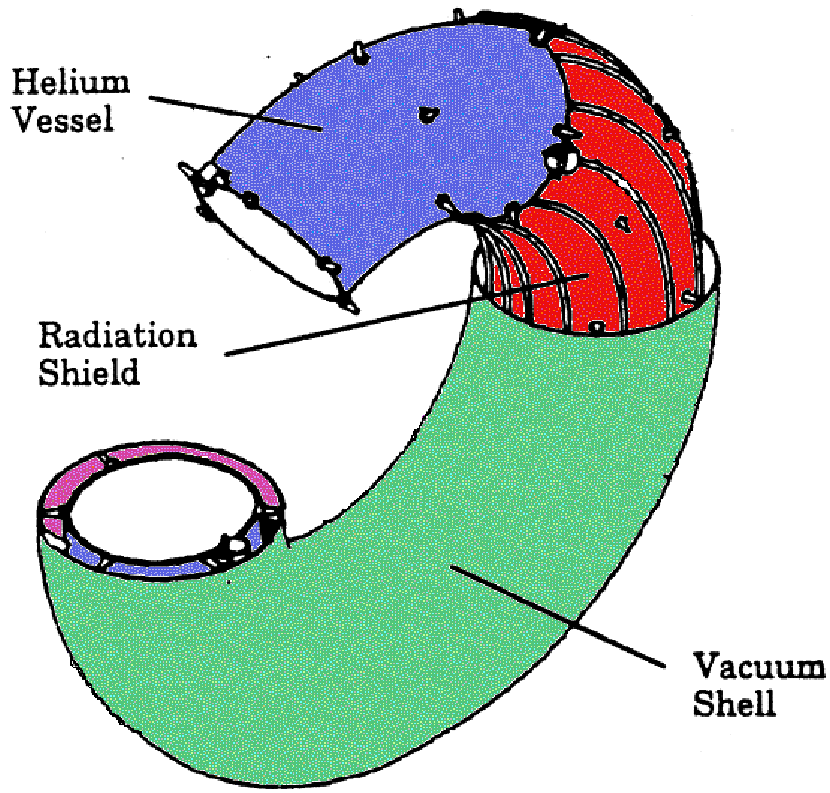
- SBIR collaboration with American Superconductor to build first HTS coil in the fusion community.
- Uses 7kmof BSSCO-2223 conductor
  - 1128 turns 1-in-hand wound
  - 37 Joints
- Max field 0.8 Tesla
- 20 kJ stored energy can be dumped in < 1 second.
- Cryostat is cooled with cryocooler 30W cooling capacity at 20° K
- Feedback gain selected for 5 Hz frequency response
  - Limit heating to < 20W AC losses
- Manufacturing underway at Everson Electric



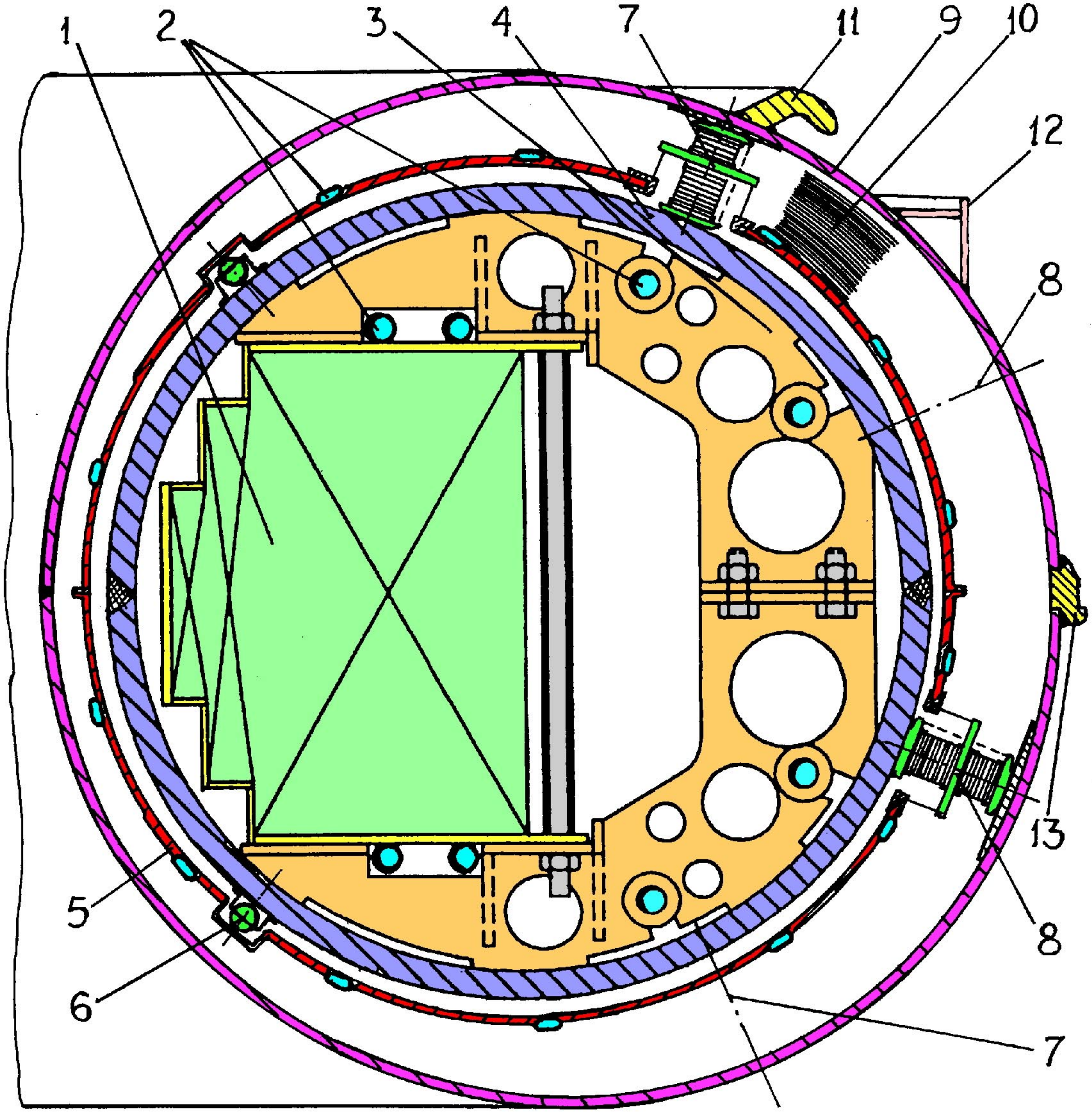


LDX Floating Coil

- Unique high-performance Nb3Sn superconducting coil
  - 1.5 MA-turns, 800 kJ
  - 580 kg weight
  - 8 hr levitation
- Successfully tested
  - July 2000: Tested on-site at MIT above design current
- Cryostat under construction



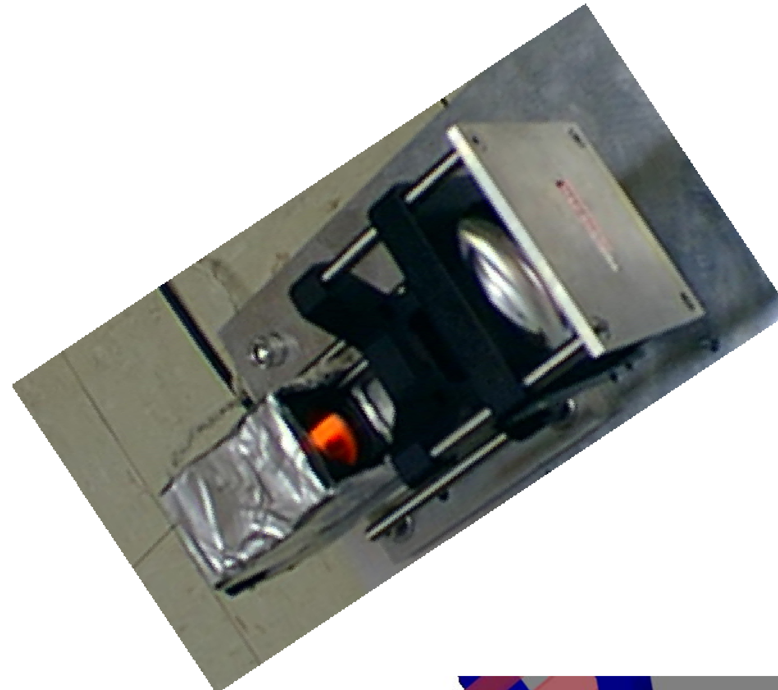
F-Coil Cross-Section

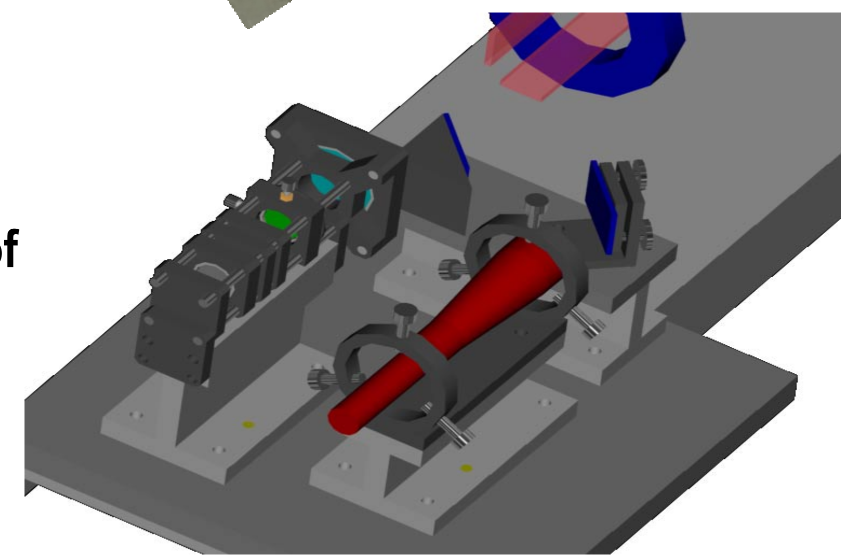


1. Magnet Winding Pack
2. Heat Exchanger tubing
3. Winding pack centering clamp
4. He Pressure Vessel (Inconel 625)
5. Thermal Shield (Lead/glass composite)
6. Shield supports (Pyrex)
7. He Vessel Vertical Supports/Bumpers
8. He Vessel Horizontal Bumpers
9. Vacuum Vessel (SST)
10. Multi-Layer Insulation
11. Utility lifting fixture
12. Laser measurement surfaces
13. "Visor" limiter attachment

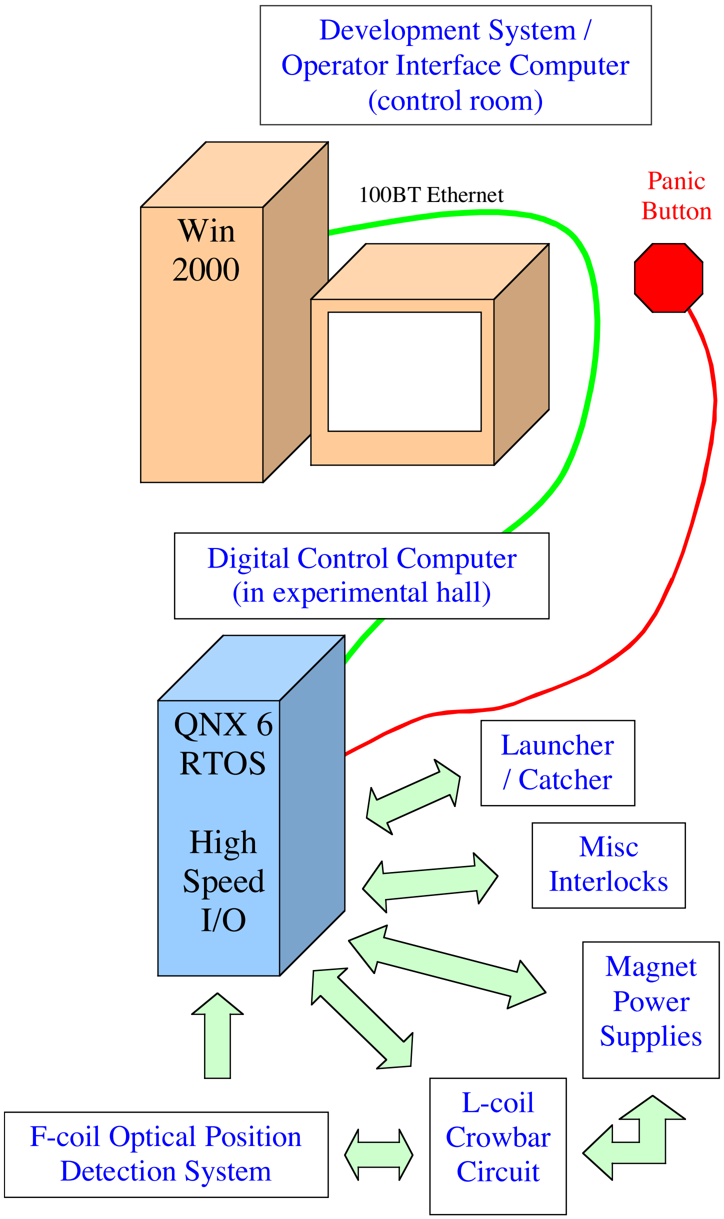
Optical Position Detection System

- 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
  - Current Status
    - Tests of 1st channel of optical system performed August 2001
- Rotation Sensing
  - Reflecting system to sense final degree of freedom
  - Nonaxisymmetry systematic noise correction





Digital Control System Schematic

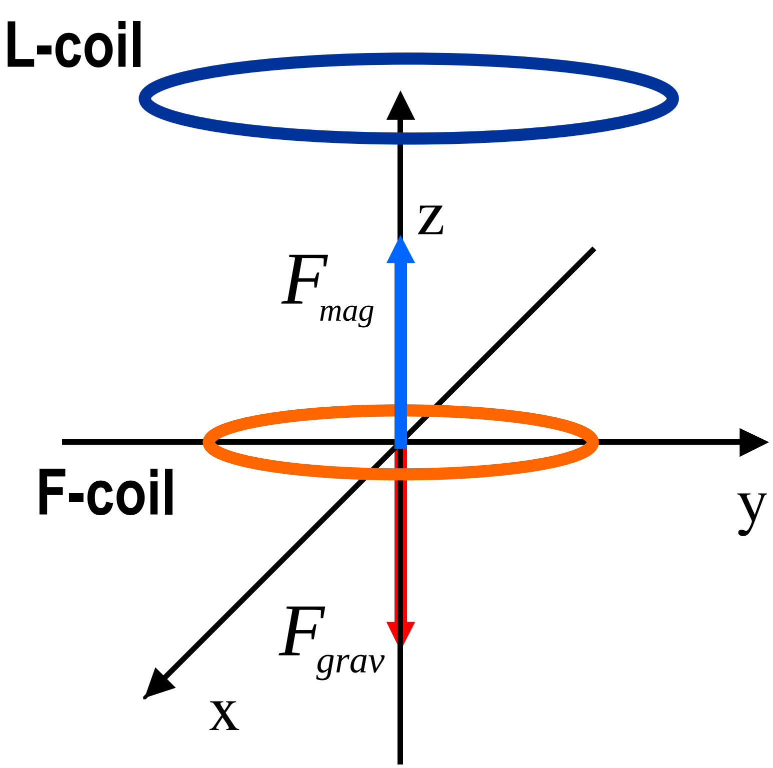


- **Design Requirements**
  - All digital process control
  - Mathworks Matlab/Simulink design tool and visualization software
  - Process control on hard real-time operating system based computer
- **Modular QNX Neutrino based system Real-time system**
  - Opal-RT RT-Lab interface to Simulink with hardware drivers
  - Multiple I/O boards
    - 32 Analog Inputs
    - 16 Analog Outputs
    - 64 Digital I/0 channels
  - 50 kHz maximum hardware synchronized loop update rate
  - System is upgradable in both number of channels and processing power

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

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:

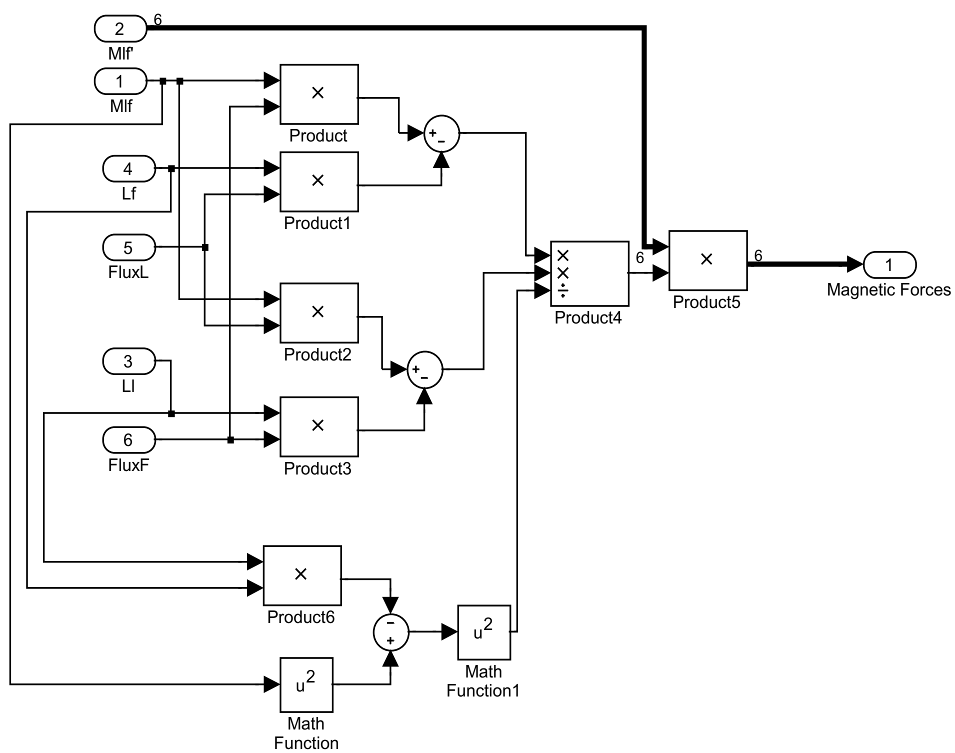
$$\Phi_L = M_{LF} I_F I_L + L_L I_L = \int V_L(t)\,dt$$

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:



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:

$$I_L(t) = I_0 - a_0 \int \varepsilon(t)\,dt - a_1 \varepsilon(t) - a_2 \dot{\varepsilon}(t)$$

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):

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

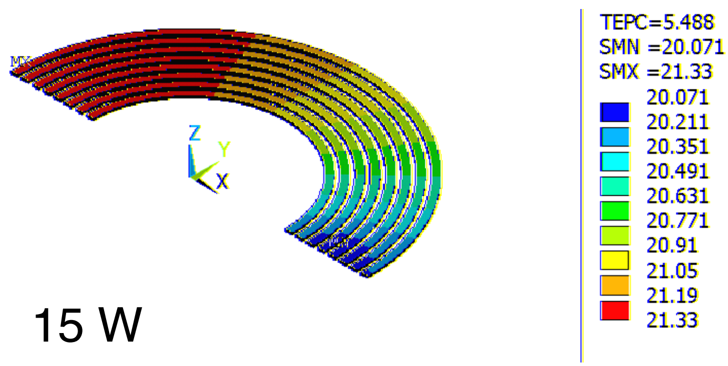
- Include an integral term to automatically adjust for DC losses:

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

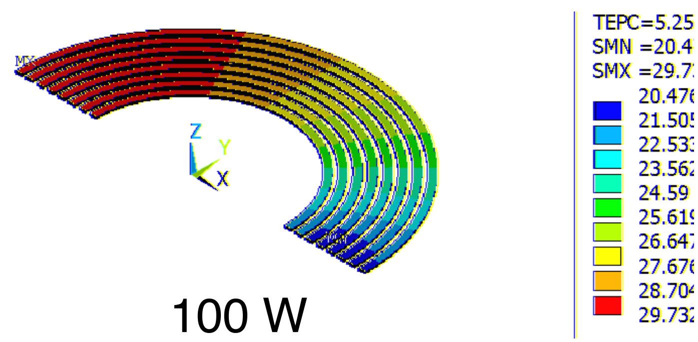
- The b parameters are optimized to get the best stabilization:
  - Put feedback expression into equation of motion to find most stable, critically damped solution
- Technique used to estimate required currents / voltages for L-coil
- Similar technique (using only derivative gain) used to determine required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

L-coil Heating

- **Heating at 20K dominated by AC losses[1]**
  - **F-coil vertical oscillation of 1 mm at 1 Hz ⇒ ±1 A 1 Hz oscillation in L-coil current ⇒ 20 W heating**
- **Suppress feedback gains at high frequencies to limit AC losses**
  - **Derivative terms in feedback are particularly noise sensitive**
  - **Very high frequencies (1/ω< 15 msec) are shielded by vessel**
- **Current design for L-coil has cryocooler with 30 W capacity at 20 K**
  - **Finite element analysis [2] shows that internal temperature differences can be kept below 10 K if heating power is less than 100 W**



15 W

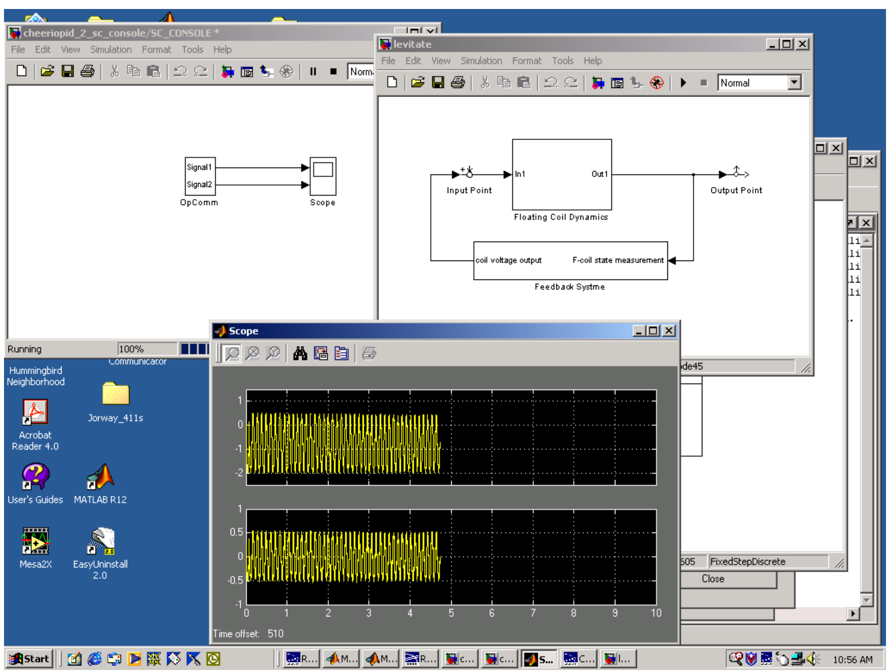


100 W

[1] J. H. Schultz et al., presented at ASC conference, September 2000

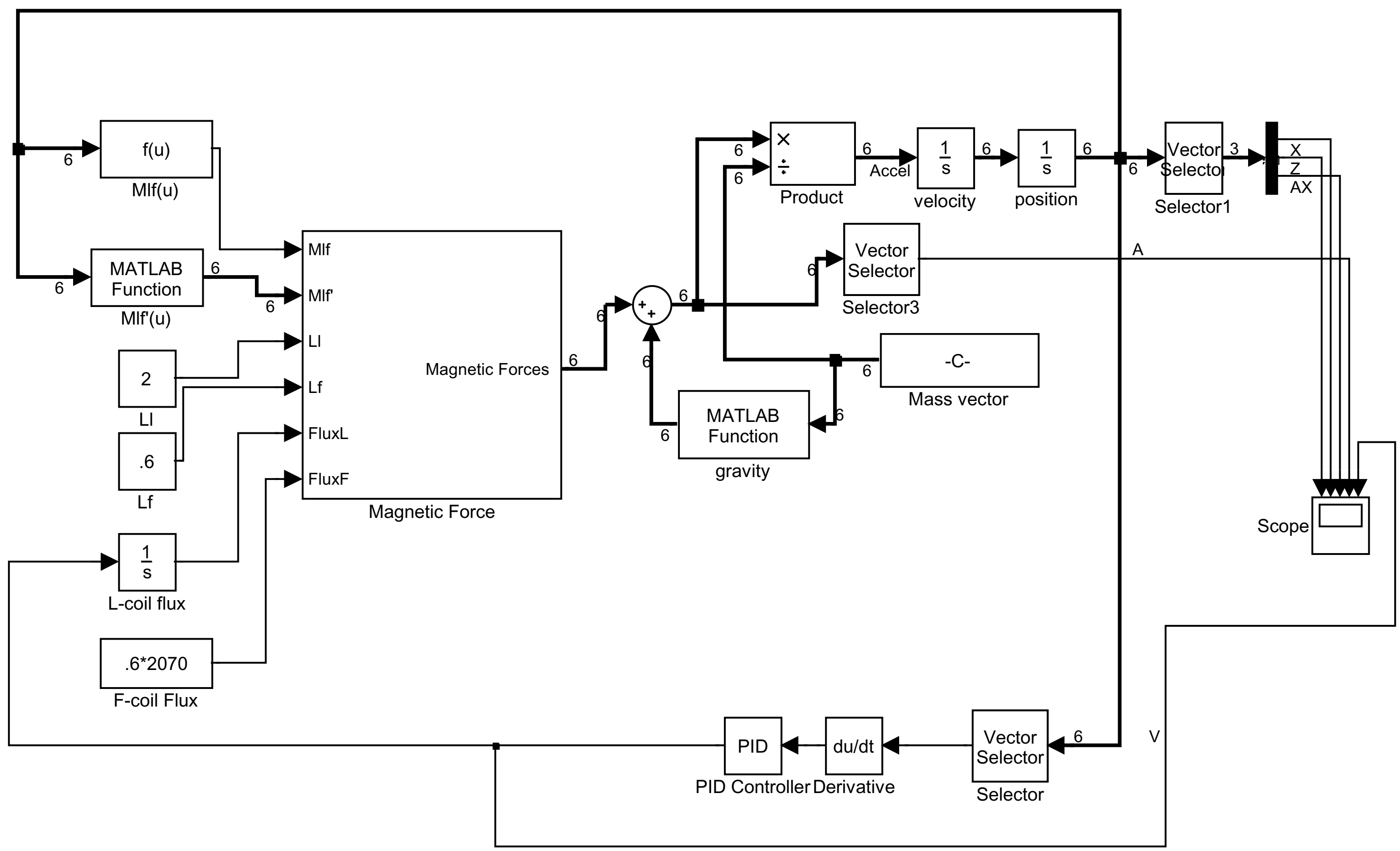
[2] R. L. Myatt, Myatt Consulting, Inc.

LCX II: Digitally Controlled Levitation



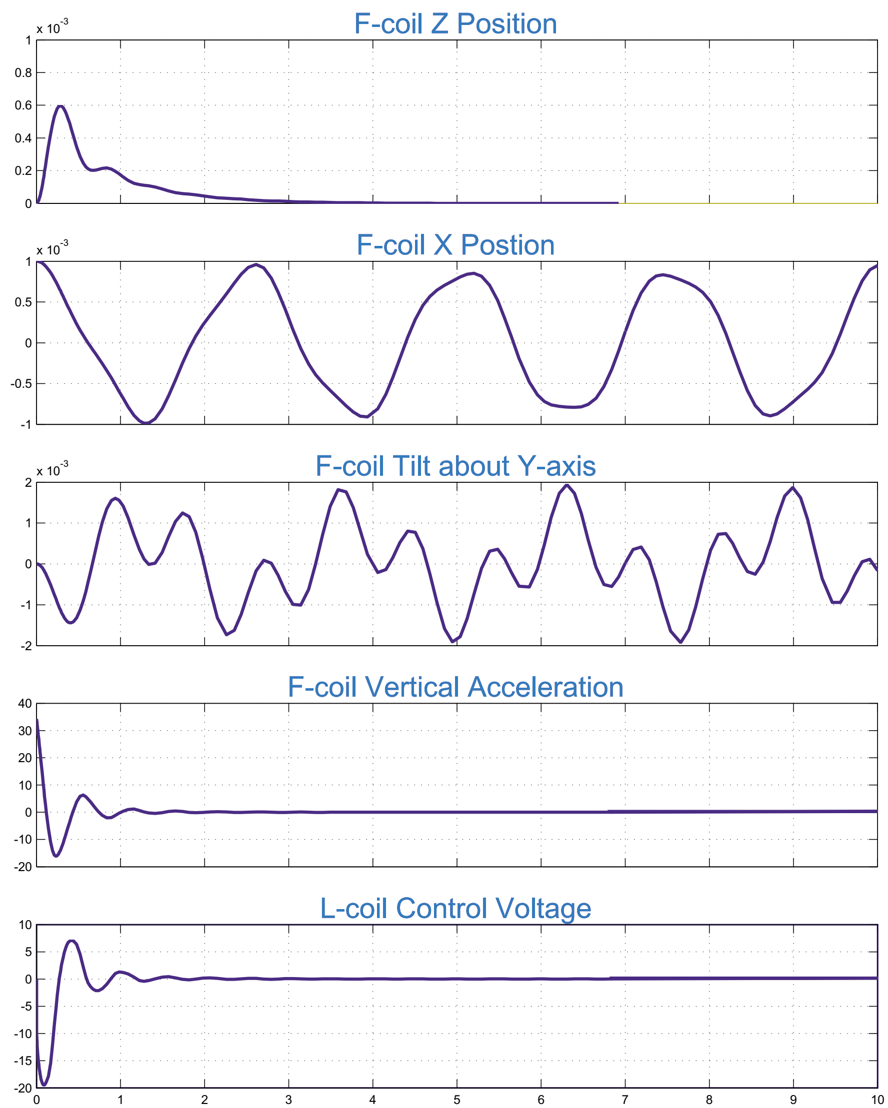
- Levitated Cheerio Experiment II
- Uses LDX digital control system
  - LCX I was analog demonstration
- Modified PID feedback system
  - Low pass filter added for high frequency roll-off of derivative gain
  - Integral reset feature for launch transition
- Dynamic model block replaced by I/O and estimators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

Basic Simulink Levitation Model



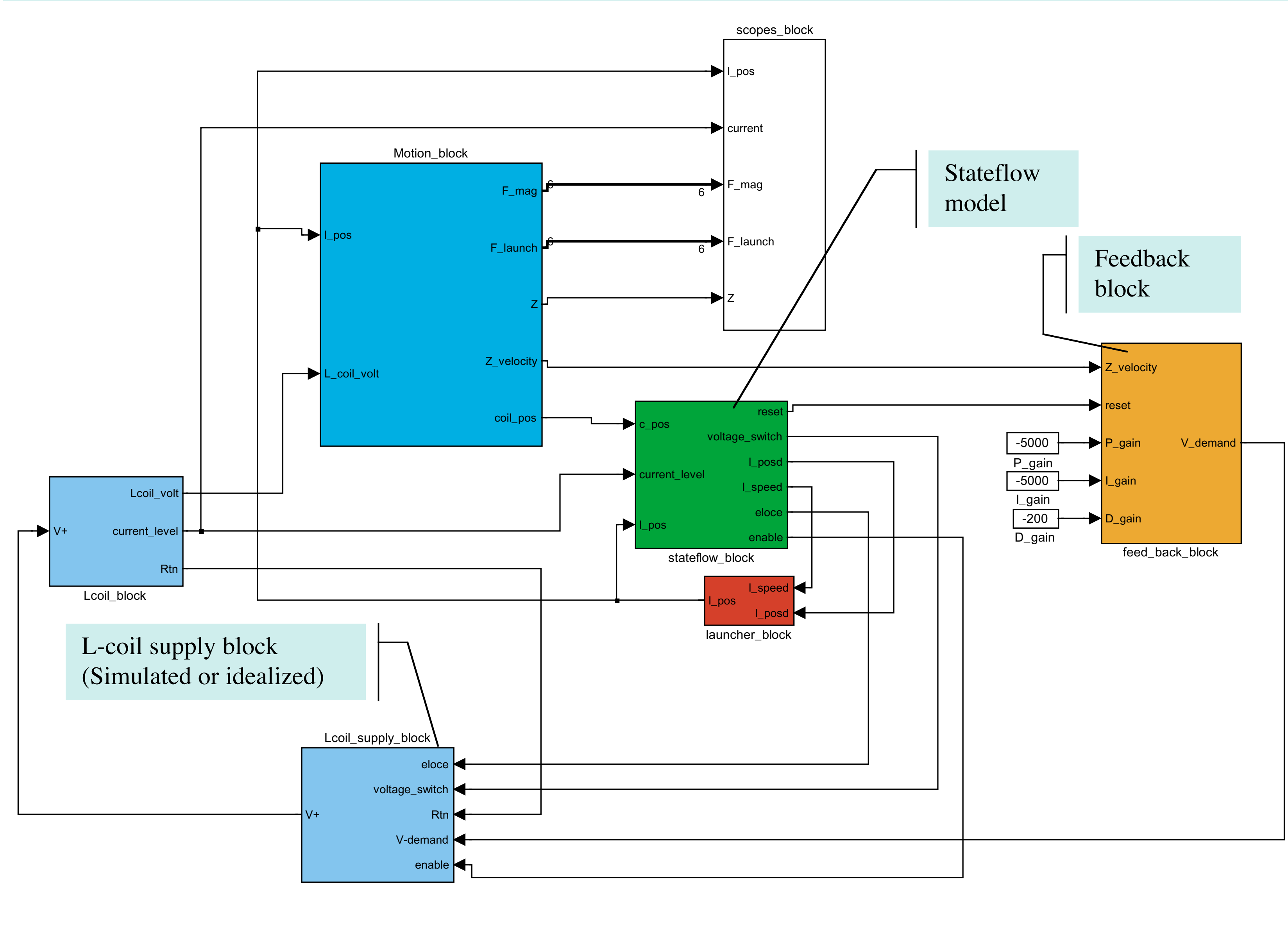
- This basic model simulates 6 degrees of freedom of F-coil with L-coil levitation using voltage feedback control.

Basic Levitation Model Results

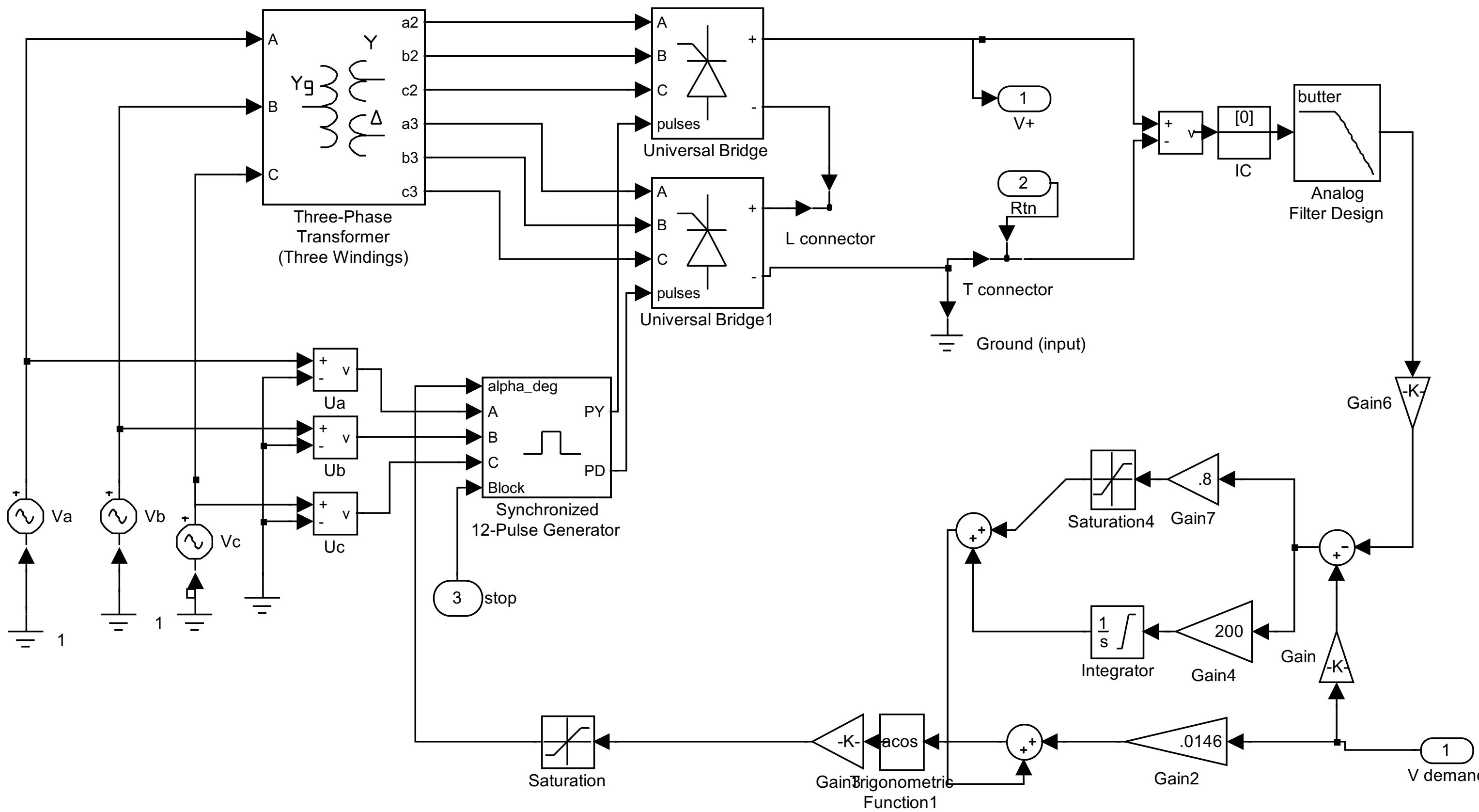


- Control parameters as calculated from analytic optimization for voltage PID loop
  - Simulations stay within L-coil supply specifications
- Simulink works!
  - Results match previous numercal simulations
  - Analytic analysis eigenmodes are 1.0 and 0.4 Hz
  - Single afternoon of work
- On to implementation!

System Simulink/Stateflow Model

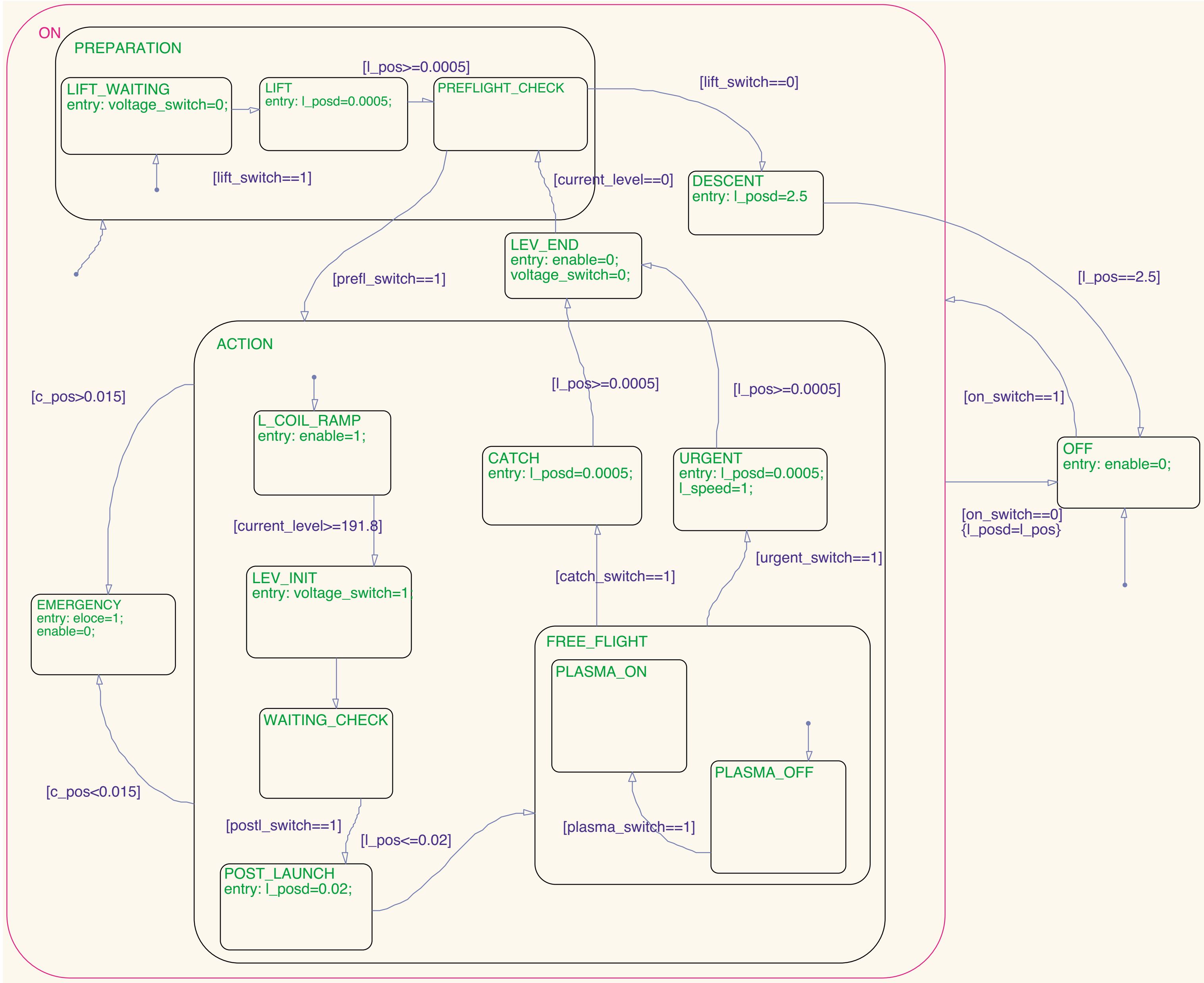


L-coil Power Supply Simulation

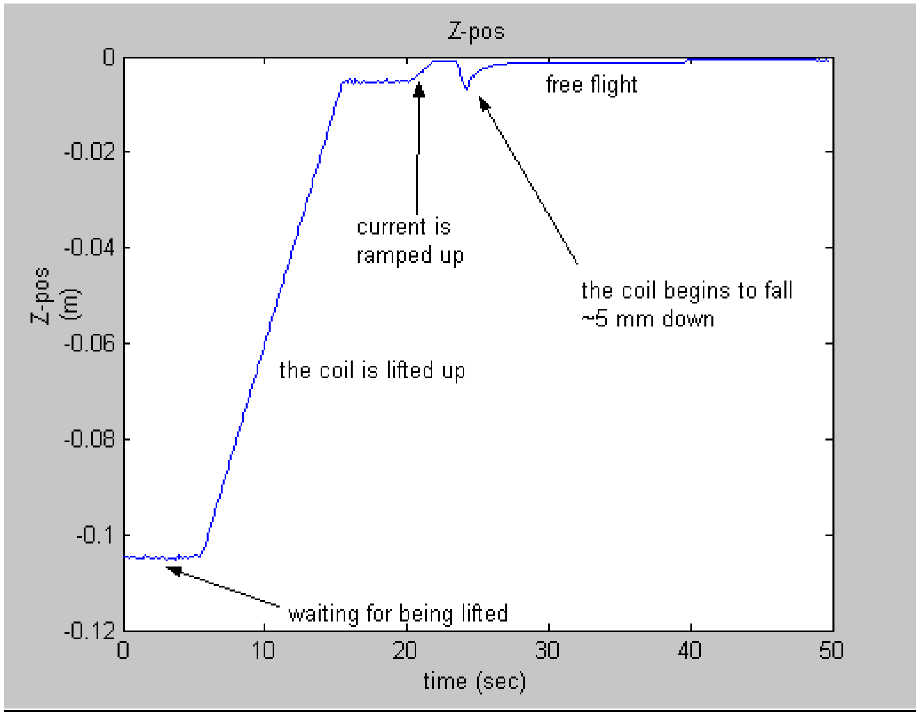


- Model of 12 pulse power supply for L-coil
  - Uses Simulink Power System Blockset
  - Will upgrade to use Opal-RT Artemis for extensive simulation
- Internal voltage control feedback loop
  - Possible to use phase control directly in our completed system

Stateflow diagram of Control System

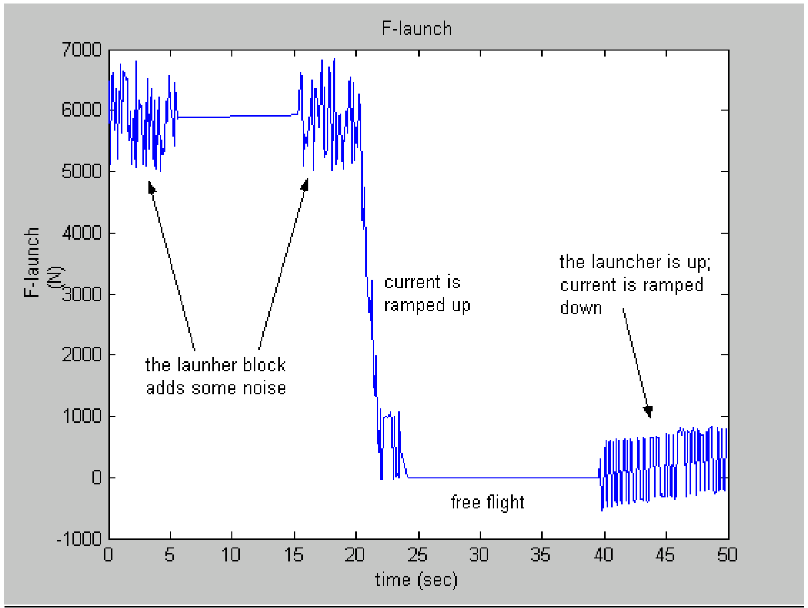


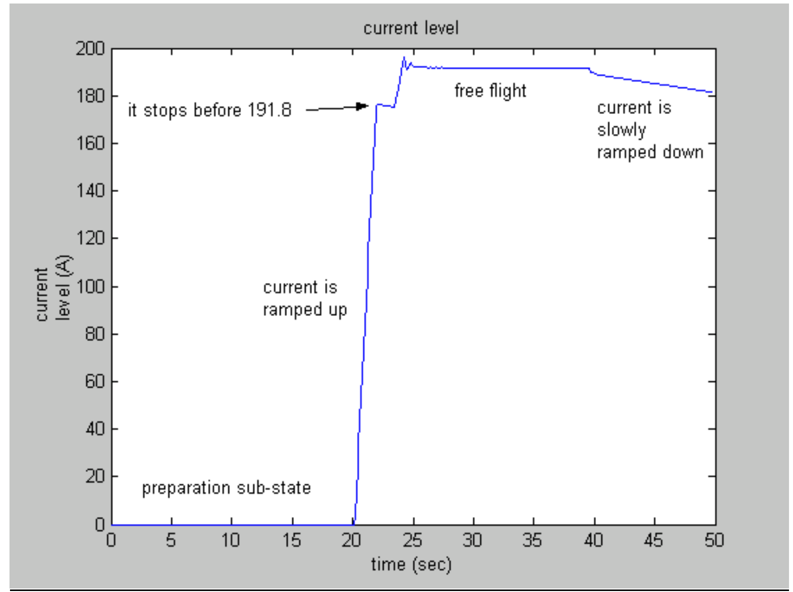
State System Simulation

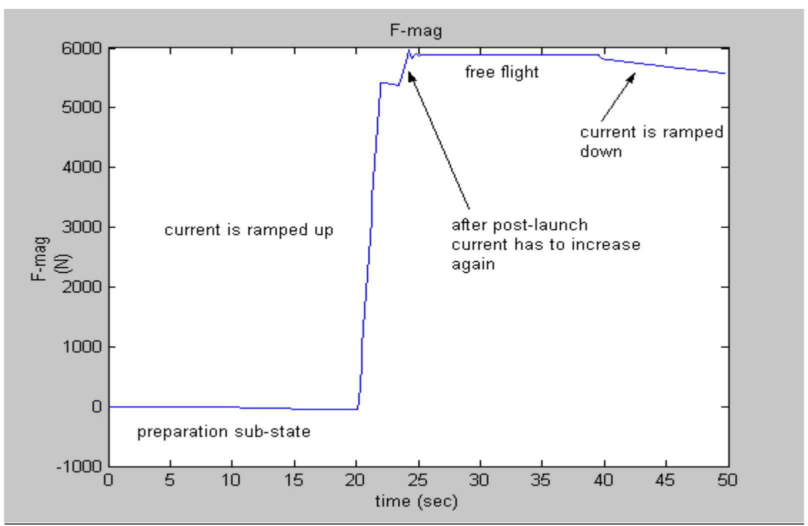


- Complete functional model
  - Includes human check wait states
  - Automatic failure modes tested
- Z Position Graph
  - Shows launcher in action
  - Current ramp of L-coil
  - Pre-flight check
  - (Premature) launch
  - Free flight

More Full Simulation Results

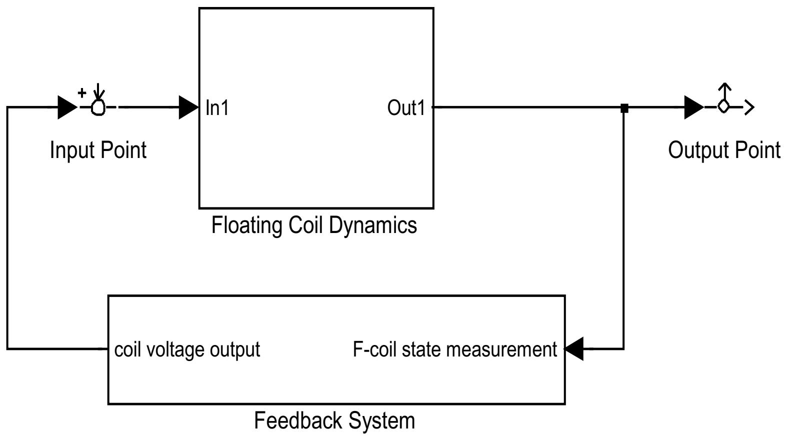


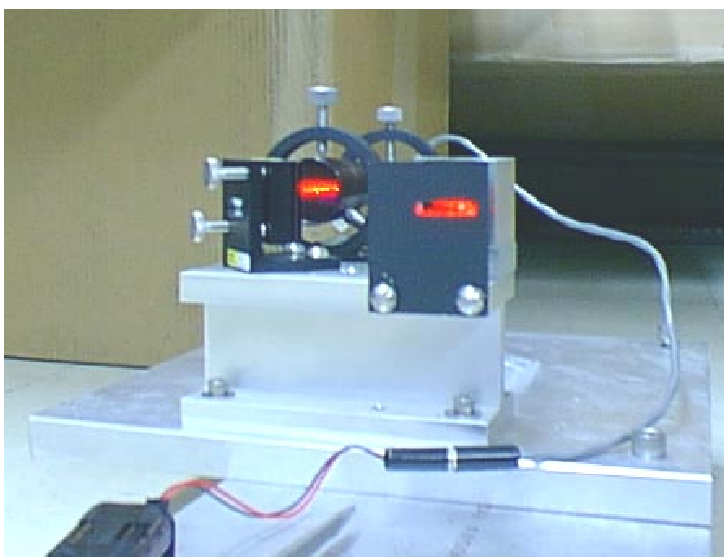




- **Vibrating launcher spring**
- **L-coil supply voltage ripple**
  - **~ 40 volt ripple**
  - **Current ripple is < 50mA**
  - **No filtering required**
- **Some state machine bugs…**

Future Development





- Optimal Control Theory
  - Use Matlab control system toolbox
  - Characterize system
  - Develop optimal feedback control algorithm
- Hardware Integration
- Testing program
  - Use light small aspect ratio magnet
  - optical system calibration
  - Integrated supply test
- Further algorithmic / state machine testing

Conclusions

- Levitation Control System Design Complete
- Control coils designed, specified, and being purchased
  - Modern HTS L-coil… first in Fusion research!
  - Modest power supply requirements specified
  - TSR coil size specified (and very modest)
- Digital Control System Under Development
  - Computer hardware / software in place
  - Several demonstrations / simulations made to show feasibility
- Hardware implementation being designed and tested
  - 1st channel of optical system under evaluation
- Control algorithms under development