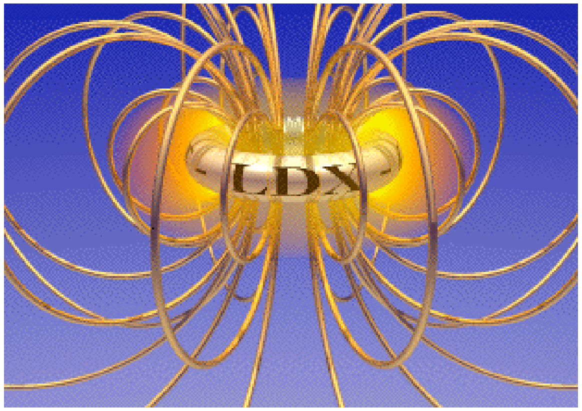

Overview and Experimental Program of the Levitated Dipole Experiment

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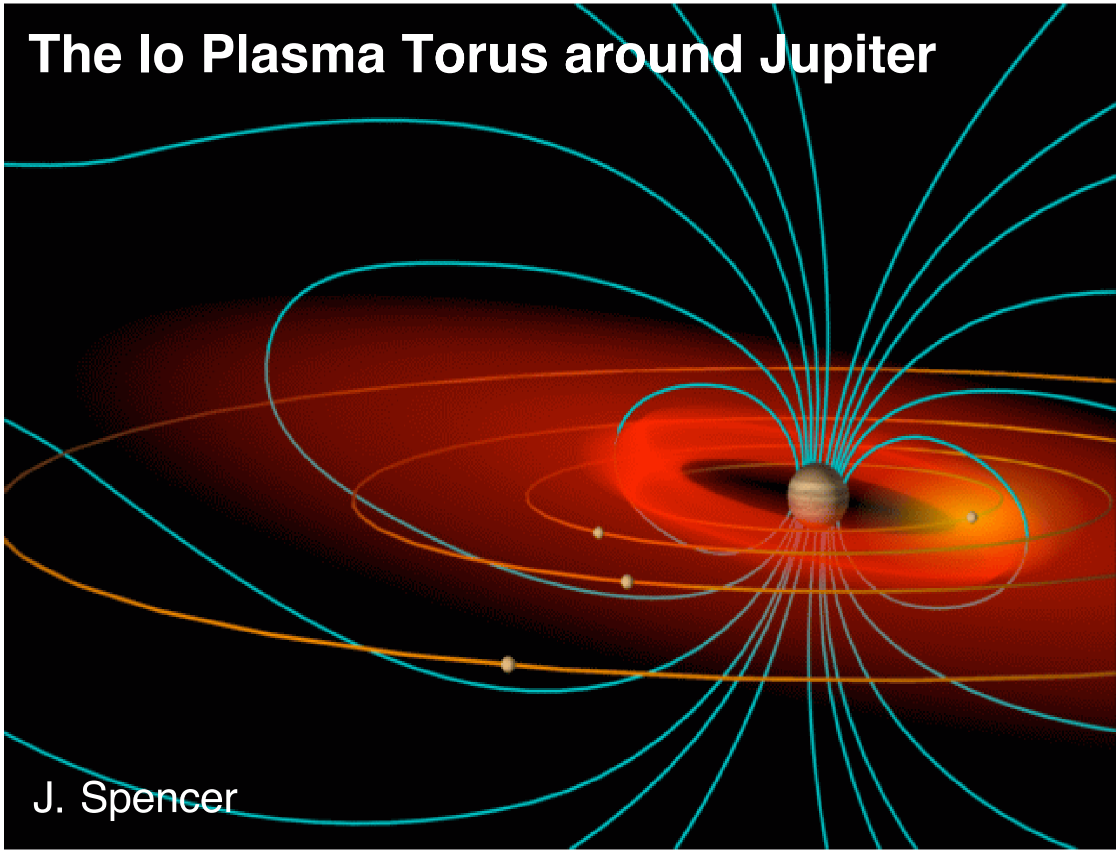
Abstract

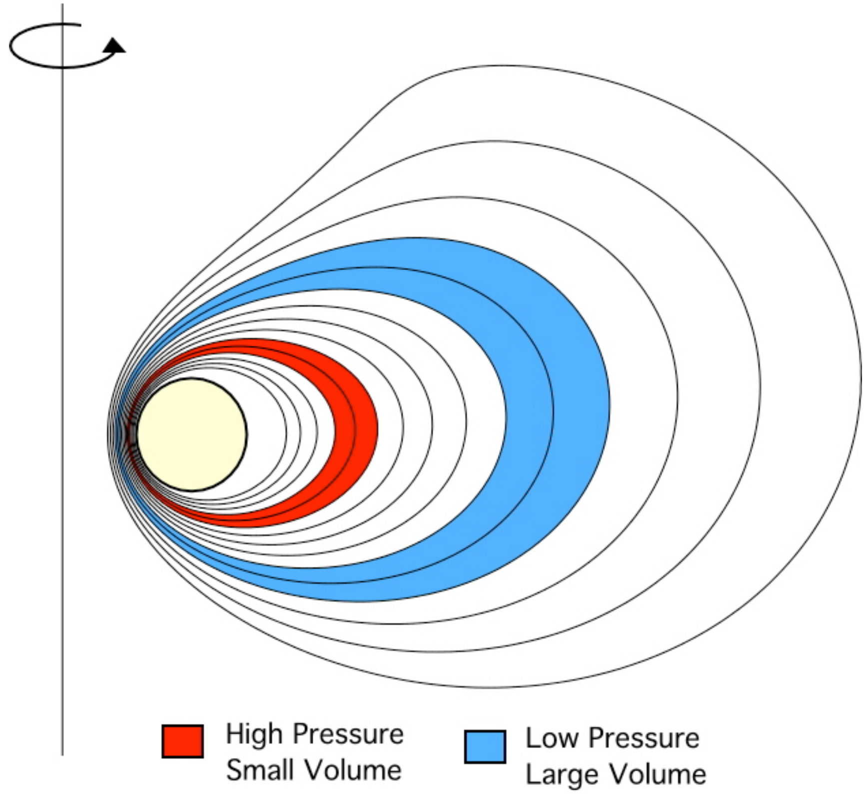
- The Levitated Dipole Experiment (LDX) is the first experiment to investigate the behavior of high-temperature plasma confined by a levitated magnetic dipole.
- LDX consists of a large, high-field, superconducting coil magnetically levitated within a large vacuum vessel. Since field lines pass through the inner bore of the floating coil, the plasma is not lost to the poles. High-temperature plasma having pressure comparable to the confining magnetic pressure $\beta \sim 1$ can be produced and studied.
- LDX will test recent theories showing unique equilibrium and stability properties of confined plasma with stationary profiles. The LDX physics plan includes the study of high-β plasma, investigation of dipole confinement characteristics, the formation of convective cells within the closed field line geometry, and the possibility of non-local transport.
- With its three super-conducting magnets, LDX highlights the role of innovative magnetic technology that makes possible explorations of entirely new confinement concepts.
- We describe the project goals, overall program plan, and current status of the experiment.

Why is dipole confinement interesting?



- Simplest confinement field
- High-β confinement occurs naturally in magnetospheres ($\beta \sim 2$ in Jupiter)
- Possibility of fusion power source with near-classical energy confinement
- Opportunity to study new physics relevant to fusion and space science

Dipole Plasma Confinement



If $p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$, then interchange does not change pressure profile.

For $\eta = \dfrac{d\ln T}{d\ln n} = \dfrac{2}{3}$, density and temperature profiles are also stationary.

- Toroidal confinement without toroidal field
  - Stabilized by plasma compressibility
    - Not average well
    - No magnetic shear
  - No neoclassical effects
  - No TF or interlocking coils
- Poloidal field provided by internal coil
  - Steady-state w/o current drive
  - $J_{||} = 0$ -> no kink instability drive

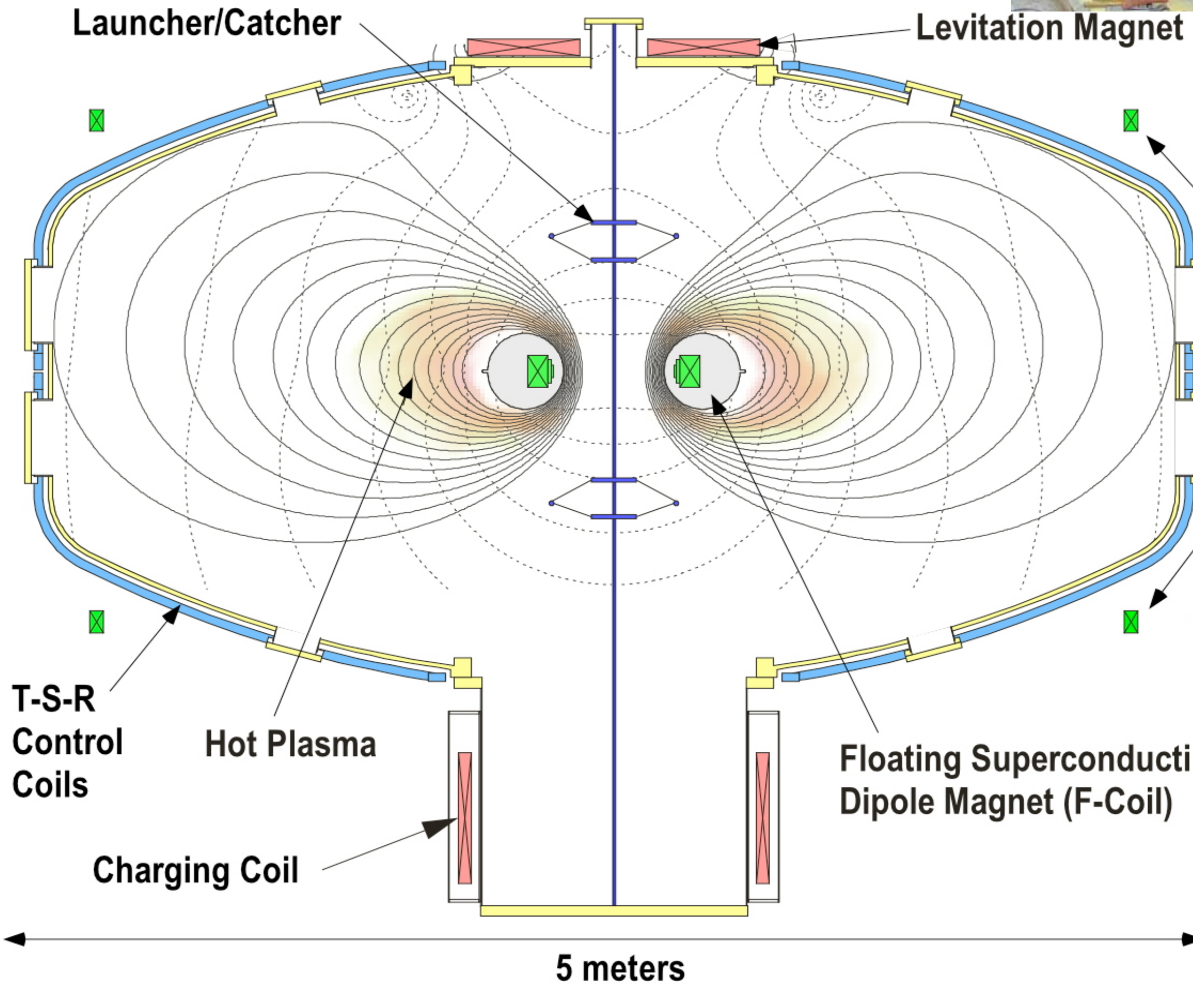
Dipole Confinement continued...

- Marginally stable profiles satisfy adiabaticity condition.
  - M.N. Rosenbluth and Longmire, ***Ann. Phys.*** 1 (1957) 120.

$$\delta(pV^{\gamma}) = 0, \ \text{where } V = \oint \frac{dl}{B}, \ \gamma = \frac{5}{3}$$

- Equilibria exist at high-β that are interchange and ideal MHD ballooning stable
- For marginal profiles with $\eta = 2/3$, dipoles also drift wave stable
  - Near-classical confinement ?
  - Drift waves exist at other values of η , but with with reduced growth rates
- No Magnetic Shear -> Convective cells are possible
  - For marginal profiles, convective cells convect particles but not energy.
    - Possible to have low τ_p with high τ_E .
  - Convective cells are non-linear solution to plasmas linearly unstable to interchange

LDX Experiment Cross-Section



Launcher/Catcher

Levitation Magnet

Helmholtz Shaping Coils

T-S-R Control Coils

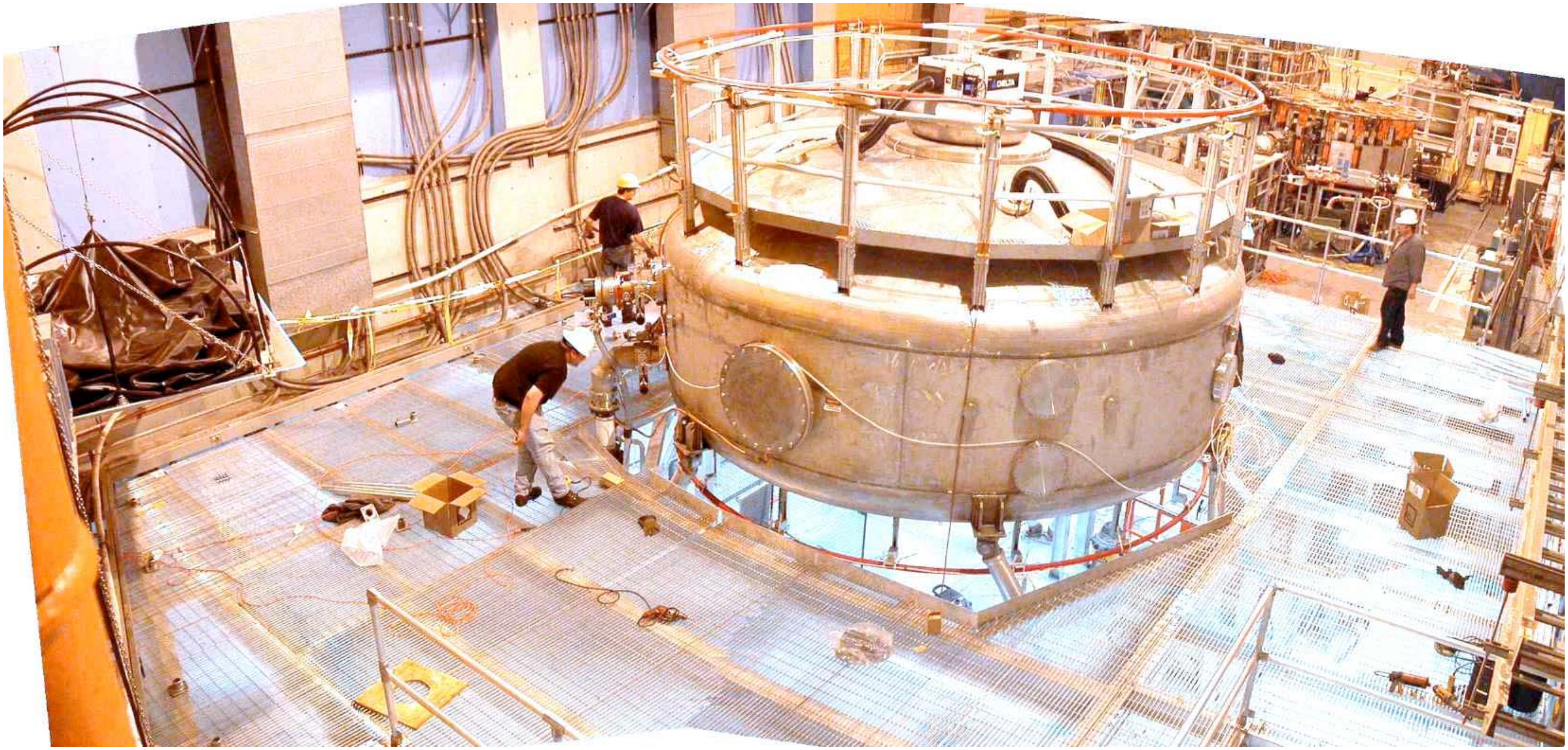
Hot Plasma

Floating Superconducting Dipole Magnet (F-Coil)

Charging Coil

5 meters

LDX Test Cell



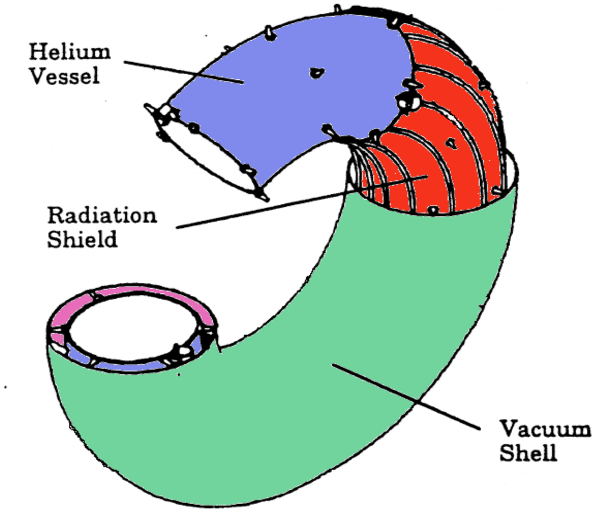
- MIT provided support stand installed May 2003
  - Doubles available space surrounding LDX
  - Provides safe and easy access to LDX diagnostic ports
  - Provision made for possible future lead shielding wall

LDX Vacuum Vessel

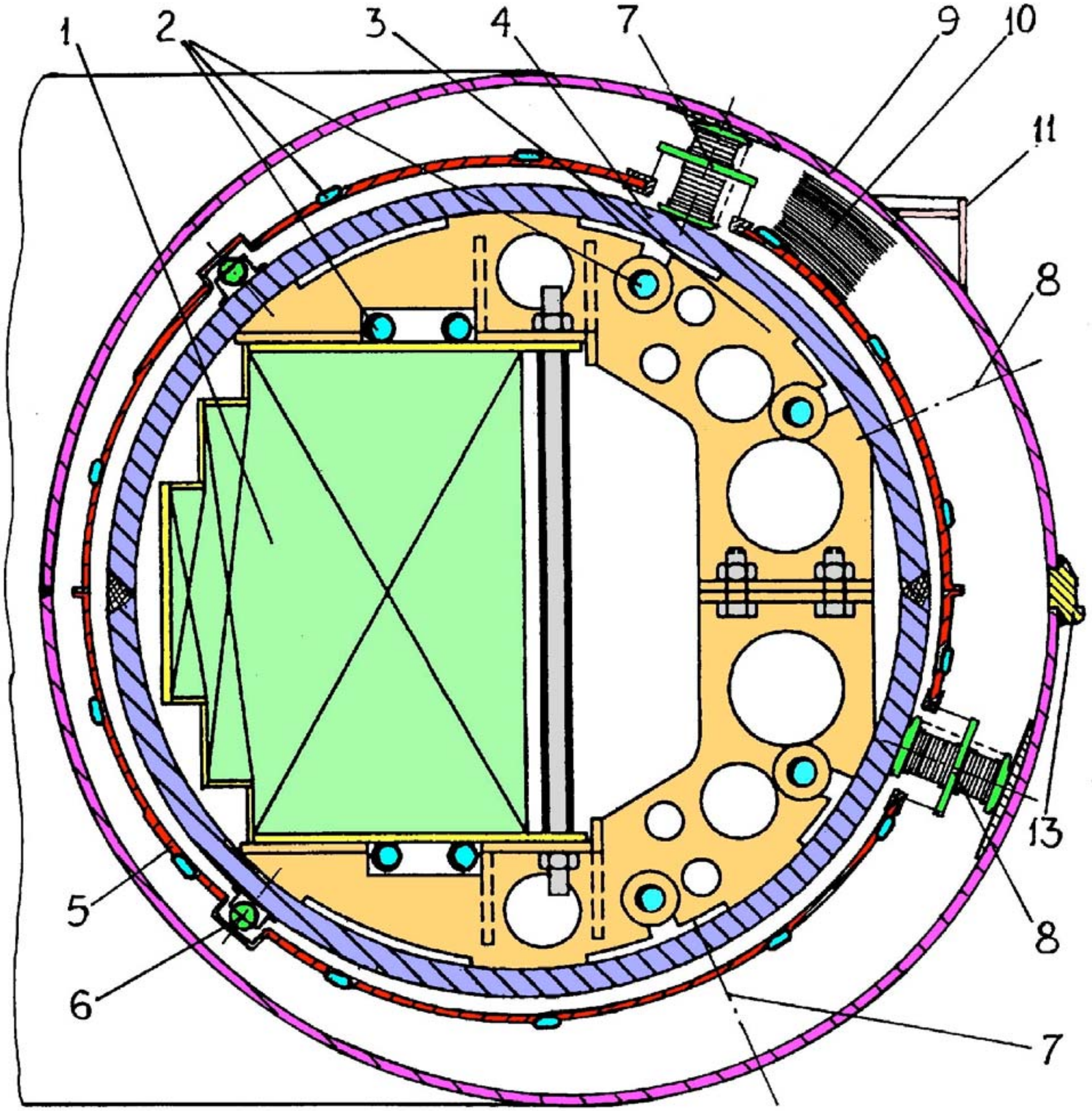
- Specifications
  - 5 meter (198”) diameter, 3 m high, elevated off chamber floor
  - 11.5 Ton weight
  - 7.5 x 10^{-8} Torr base pressure
- Manufactured by DynaVac
  - Completed Sept. 1999

LDX Floating Coil

- Unique high-performance Nb3Sn superconducting coil
  - 1.5 MA, 800 kJ
  - 1300 lbs weight
  - 8 hr levitation
  - Inductively charged
- Cryostat made from three concentric tori
  - Design < 1 Watt heat leak to Coil
  - Helium Pressure Vessel
  - Lead Radiation Shield
  - Outer Vacuum Shell
- Current Status
  - Final leak checking at MIT
    - Two leaks identified



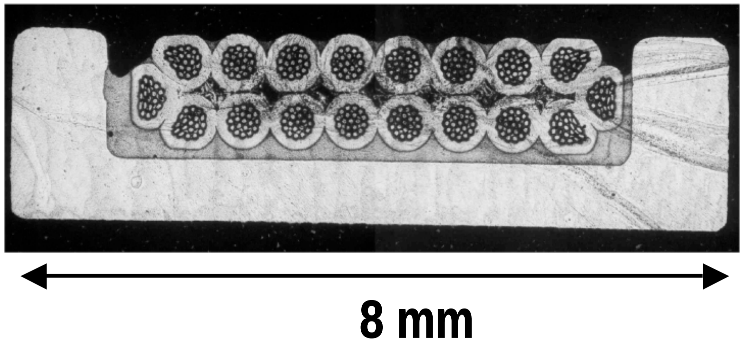
Floating Coil Cross-Section



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. Laser measurement surfaces
13. Outer structural ring

Floating Coil Winding Pack

Advanced Nb_3Sn react & wind conductor…



… wound very carefully…

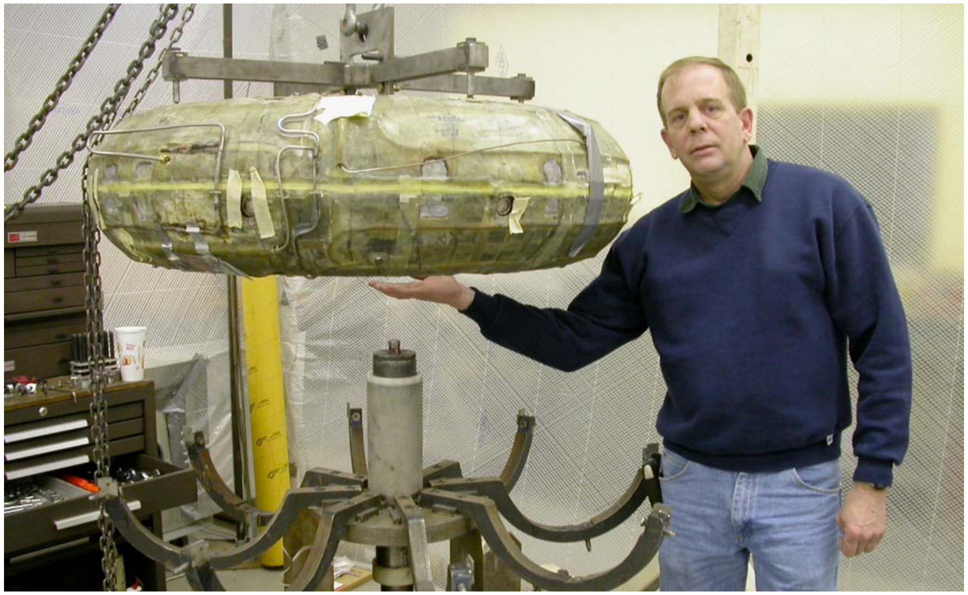
… epoxied and finally tested to full current (1.56 MA) and field (6 T) in 4.2K LHe bath.

F-Coil Helium Pressure Vessel

- Inconel 625 Pressure Vessel
  - 125 ATM at 300°K
  - 2-3 ATM cold
  - 1.5 kg He storage
  - Fully machined weight – 150 kg
- Completed construction at Ability Engineering Technology, South Holland, IL.
  - Pressure tested & code stamped
  - Leak test to vacuum @ 125 atm. for both vessel and heat exchanger
  - Covered in Al tape to give low emissivity at 4 K.

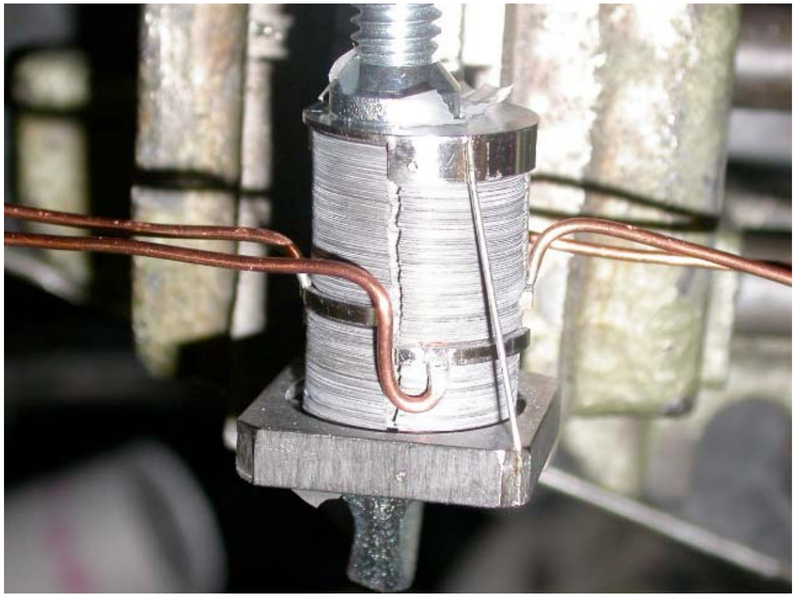
Thermal Radiation Shield

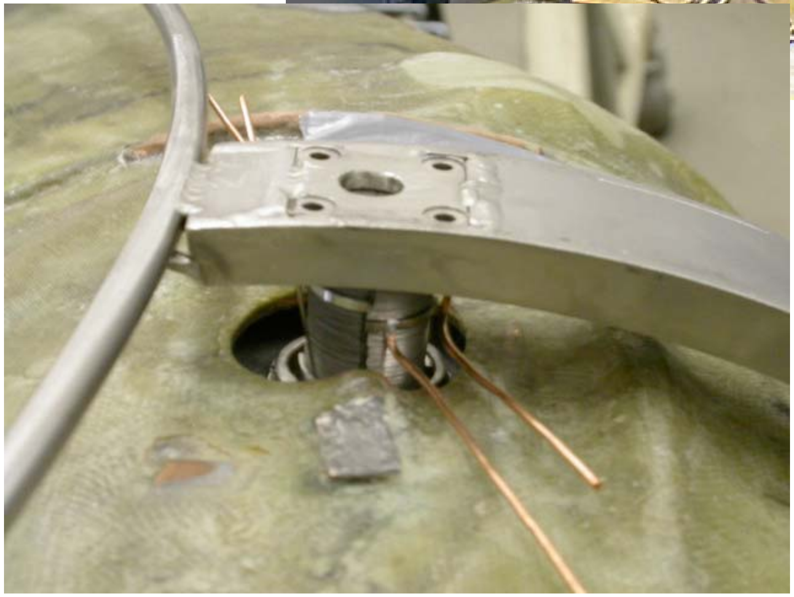
- "Cored" fiberglass composite construction
  - 2 fiberglass skins, 0.5mm thick and separated by core
  - Lead core panels provide thermal inertia at 20 K and intercept heat from vacuum vessel to 4 K helium vessel
  - Copper heat exchange tubing & conduction strips for cooldown
- Status
  - Fabrications and installation complete



Support Washer Stacks

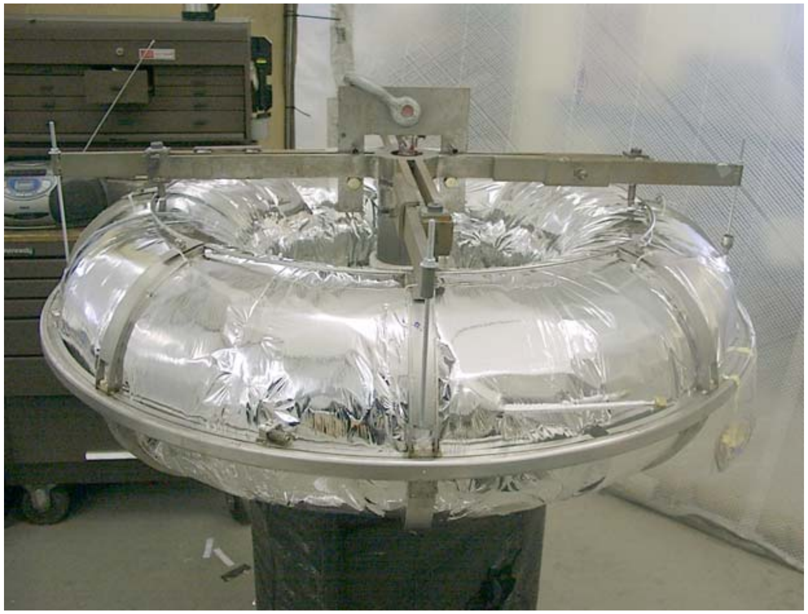
- Specification
  - Hold heat leak to 5 K < 10 mW
  - Withstand 10g crash (5 Tons!)
- Solution
  - Stack of 400 4mil thick washers
- Status: Complete!
  - Prototype testing complete
  - 24 Stacks (~7000 coins) Assembled, Sized and Installed





F-coil Multilayer Insulation (MLI)

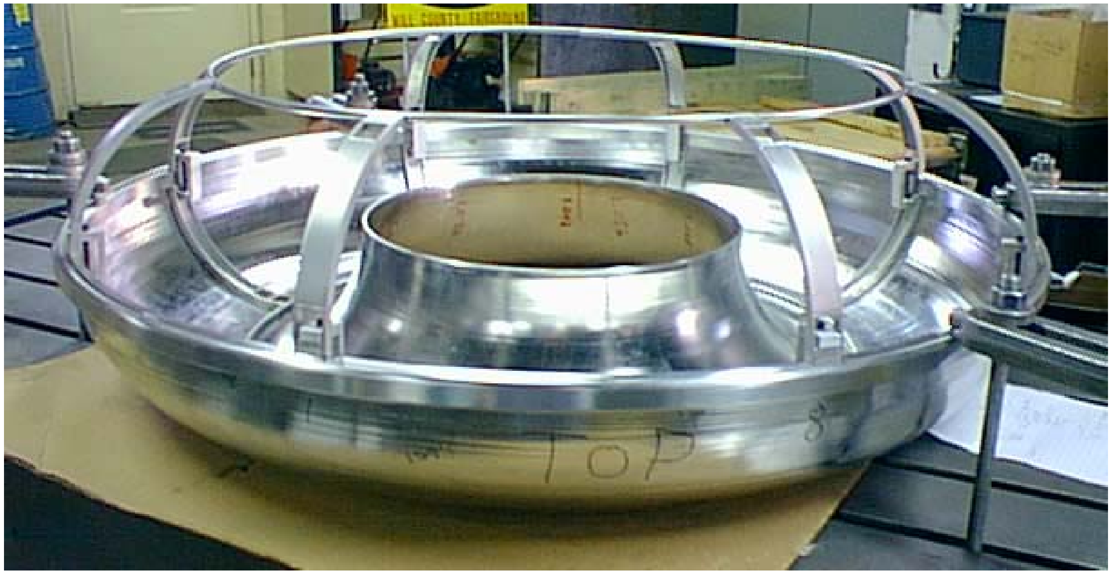
- F-coil Multilayer Insulation (MLI)
  - Alternating layers of Remay spun polyester fabric and 0.0005” double aluminized Mylar film
  - MLI system developed at Fermilab for use on the Superconducting Supercollider.
  - Low heat leak and simplified application make it ideal for toroidally shaped cryostat
  - Up to 96 layers applied by hand
    - Initial 36 layers made from individually fitted “bow ties” to minimize joint defects



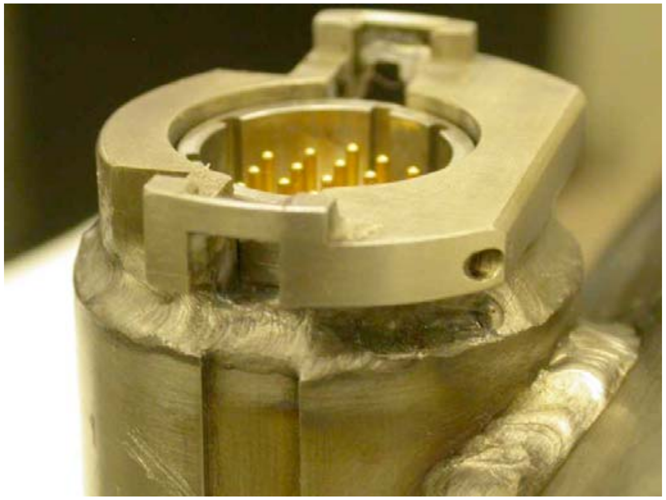
Outer Floating Coil Cryostat

- Low heat leak anti-rotation devices complete, tested and installed
- Unique low heat-leak LHe feedthoughs tested
- Electrical feedthrough complete
- Support space frame complete and installed
- Currently repairing internal helium leaks
- Final welds procedure tested


Inverted Cryogenic Feedthrough



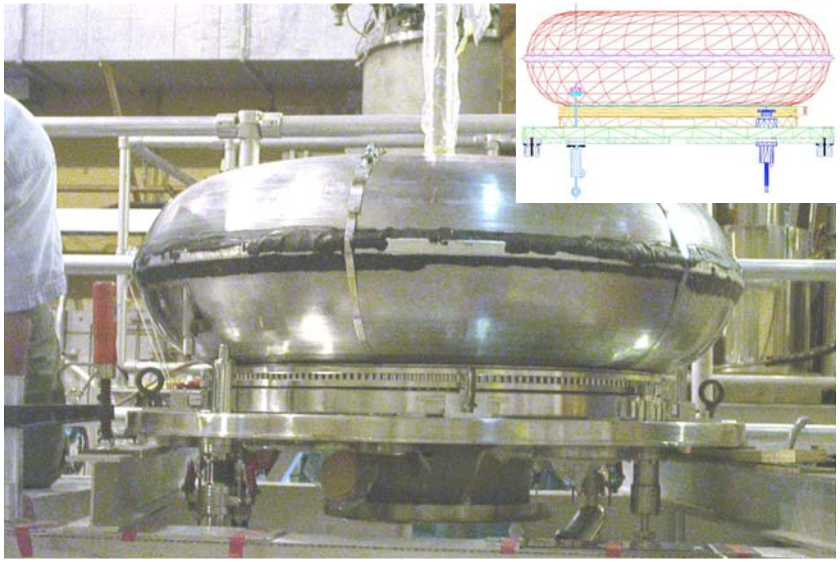
Cryostat vacuum vessel and support space frame

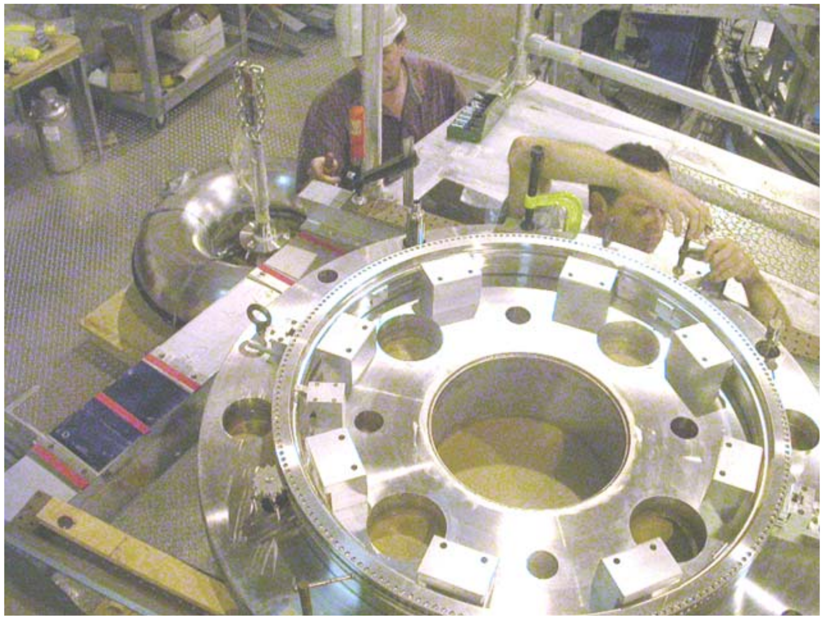


Electrical feedthrough

Floating Coil Charging Station

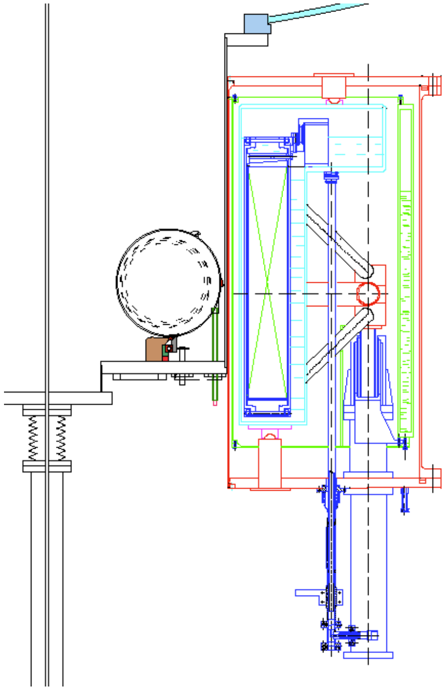
- Rotary bearing table
  - Fixes radial motion but allows azimuthal alignment of feedthroughs
- Vacuum jacketed cryogenic feedthroughs
- Electrical connection for magnet temperature measurement
- Status: Acceptance tests complete.





Superconducting Charging Coil

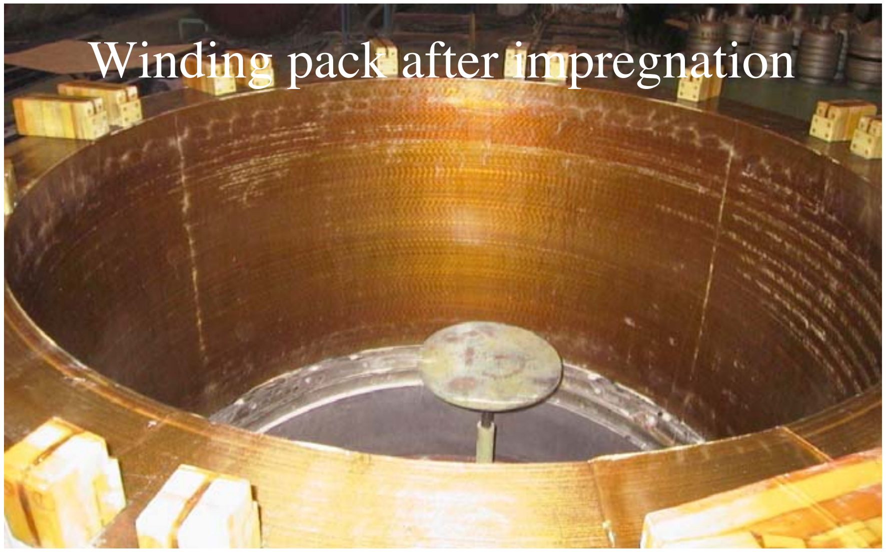
- Large superconducting coil
  - NbTi conductor
    - 4.5°K LHe pool-boiling cryostat with LN2 radiation shield
  - 1.2 m diameter warm bore
  - 5.6 T peak field
  - 12 MJ stored energy
  - Cycled 2X per day
  - Ramping time for F-Coil < 30 min.



- Built and tested at SINTEZ Efremov Institute in St. Petersburg, Russia
  - Received at MIT 9/03.

Charging Coil Winding Pack

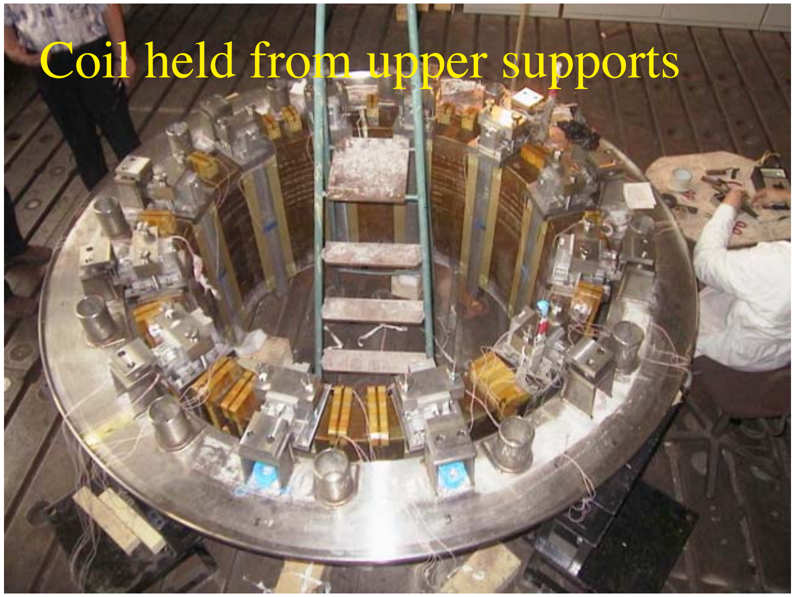
Winding 37 km of superconducting cable



Winding pack after impregnation

Electrical tests after
100 T of axial preload

Charging Coil Cryostat Construction


Coil held from upper supports

He can currently being welded closed


Vapor cooled leads installed


LN2 cooled copper shield ready for installation next

C-coil Cryostat Assembly

Inner LN2 can installed

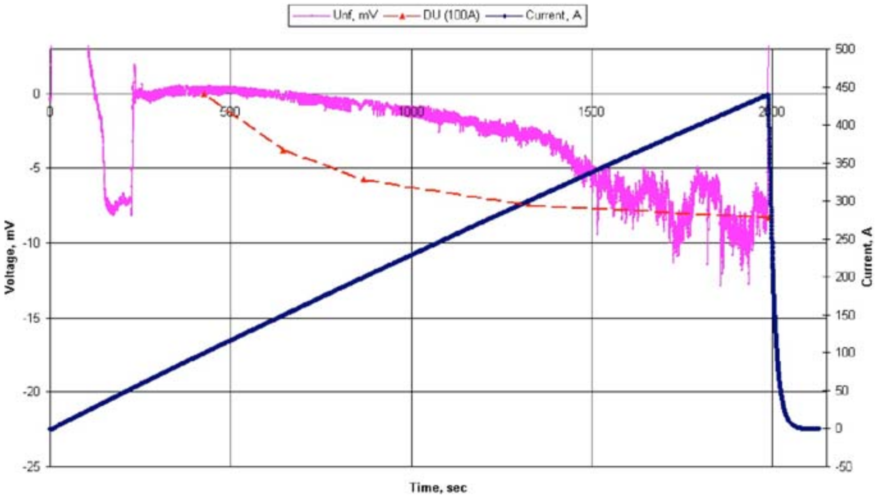
Installation of monocrystalline Al coated SS sheets

LHe can installed on LN2 cooled struts

Outer vacuum vessel lowered over assembly (with outer LN2 can installed)

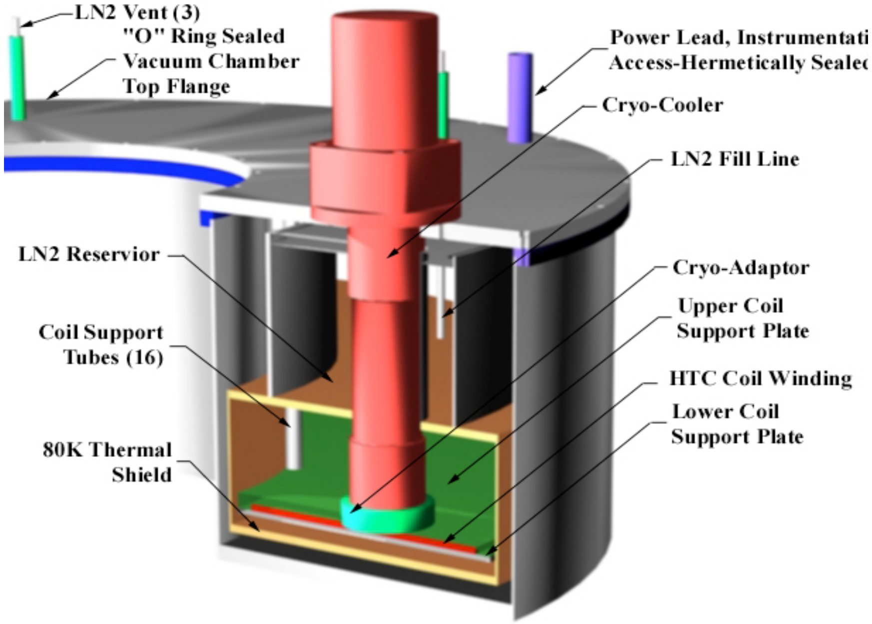
C-coil Acceptance Tests

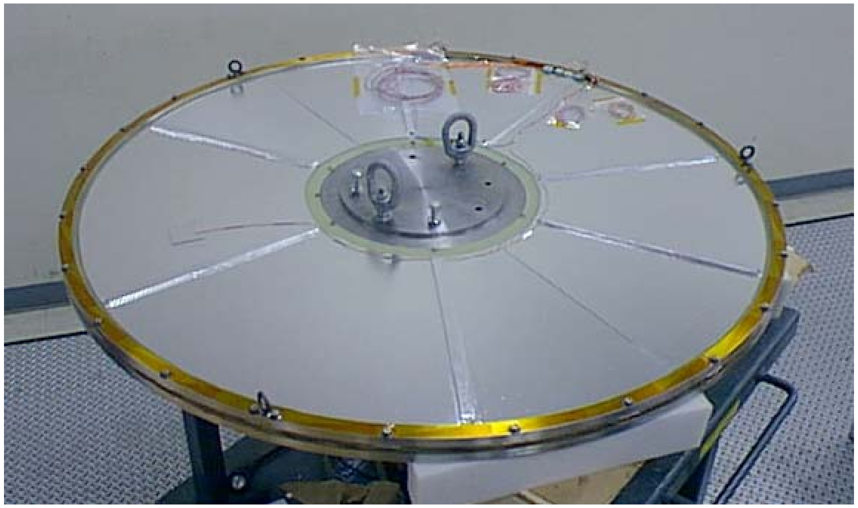
- Vacuum, cryogenic and magnetic tests completed
  - Tests completed 3/8/03
  - Vacuum and cryogenic tests indicate small He leak
    - Causes acceptable increase in cryogen consumption
  - 3 Magnetic tests showed magnet quench at 440 A (4.3T peak field)
    - No training observed
    - Safe operating point at 425A (roughly 80% of nominal design point)
  - Tests indicate Charging coil will meet all LDX physics objectives
  - Received at MIT
    - Installation procedures underway



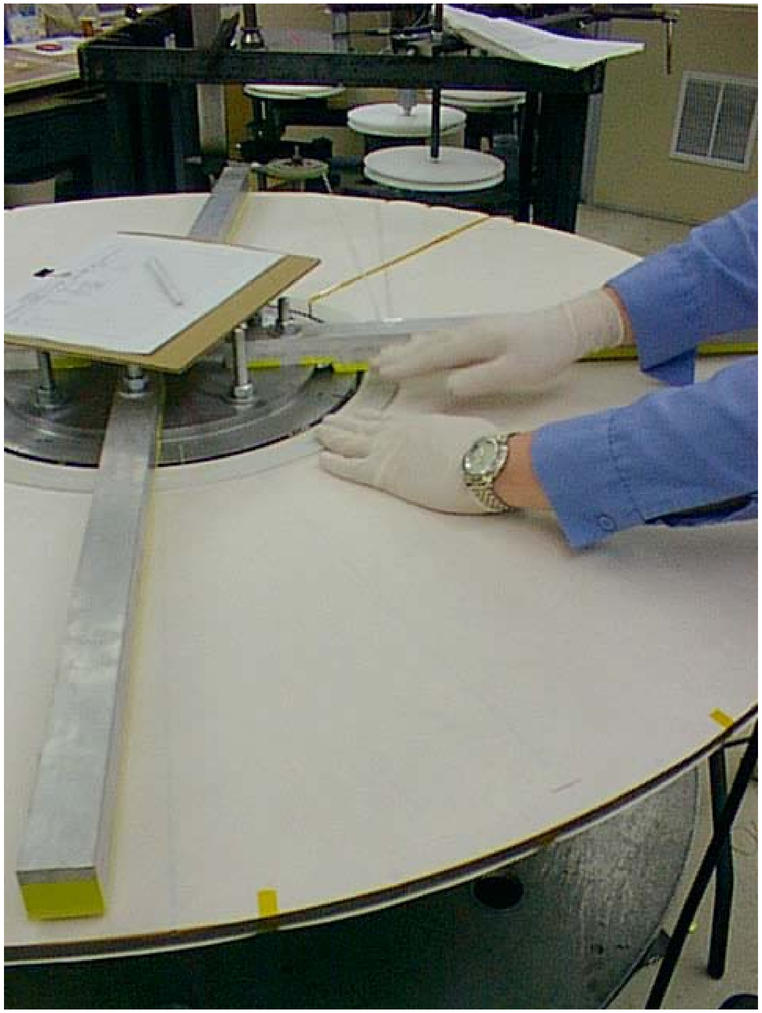
High T_c Superconducting Levitation Coil

- SBIR collaboration with American Superconductor
  - First HTS coil in the fusion community
  - Uses available BSSCO-2223 conductor
- Operational temp 20-25° K
- Feedback gain selected for 5 Hz mode frequency
  - < 20 W AC loss
- 20 kJ stored energy
  - Emergency dump in < 1 second.
- Coil Completed & Tested
  - 77° K superconducting tests successful
  - 20° K tests complete
  - Preliminary assessment: GOOD!



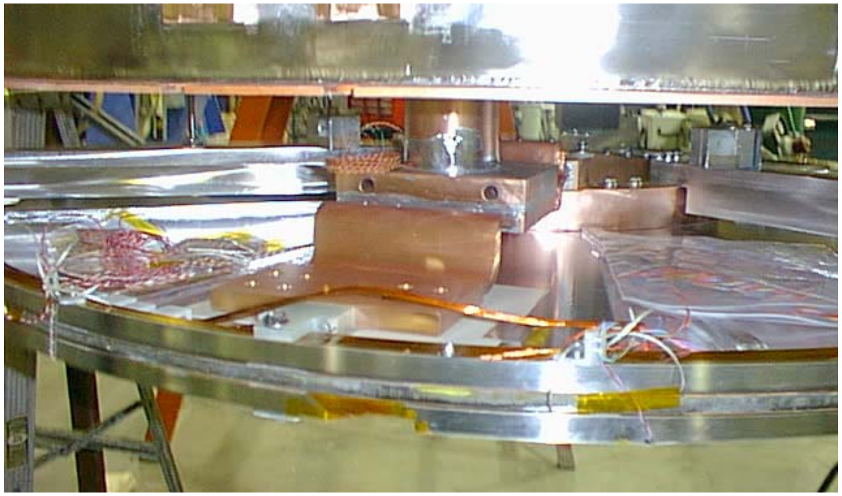


Levitation Coil Construction



105 layers wound of very small and fragile HTS

Completion of cryogen free cooling structure

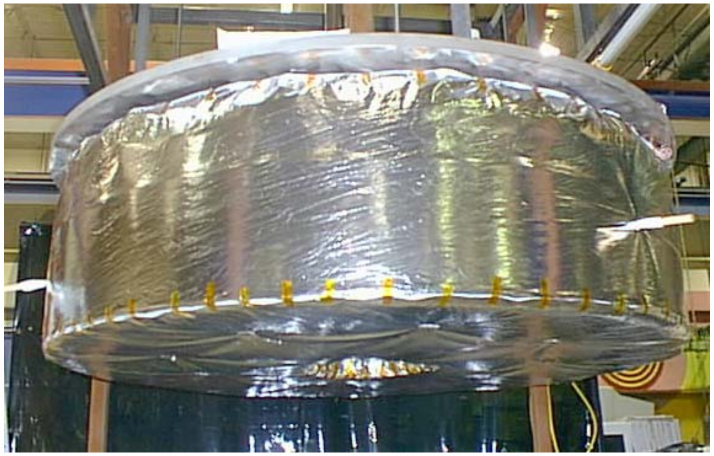


Coil in first stage of cryostat assembly

L-coil Cryostat Construction

Installation of HTS leads and "cold finger" conduction cooling from cold head.

Assembly of coil, cold head, nitrogen can and copper thermal shield

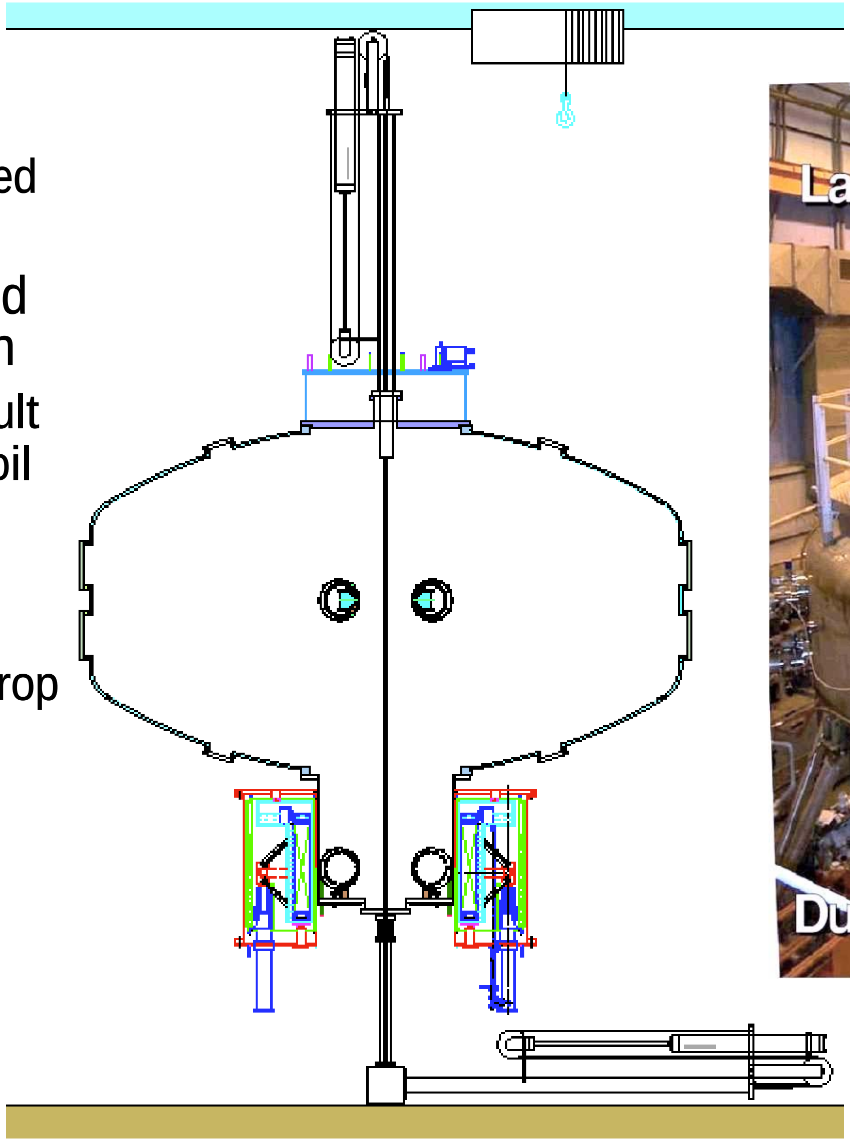


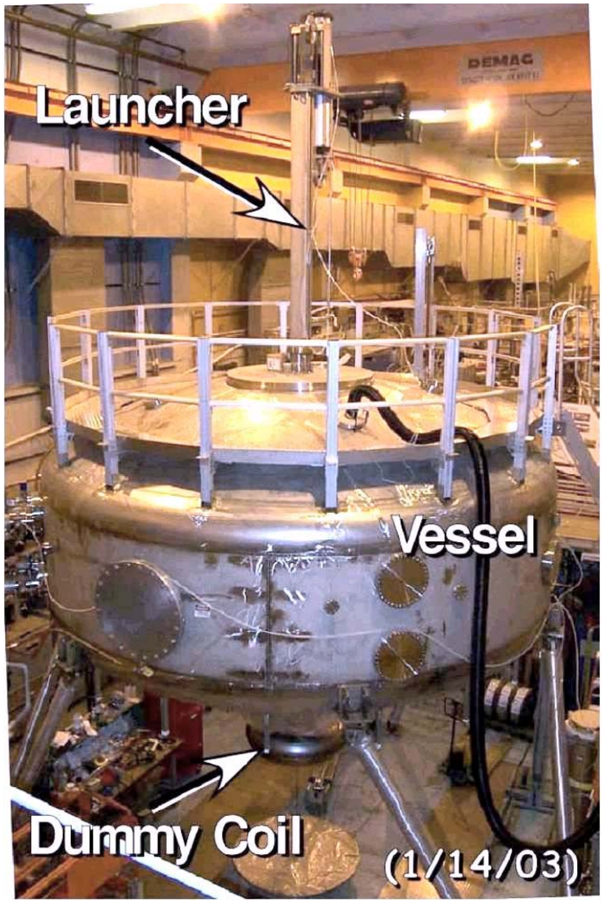
Multilayer Insulaiton (MLI) installed

Received L-coil undergoing tests…

Launcher/Catcher

- Bellows feedthrough
  - High vacuum required
  - Long (> 2m) motion
- Used in both supported and levitated operation
  - Central rod limits fault motion of floating coil without interrupting plasma.
  - Integral shock absorbers to keep drop deceleration < 10g
- Status
  - Built and tested for Phase 1 (supported) operations

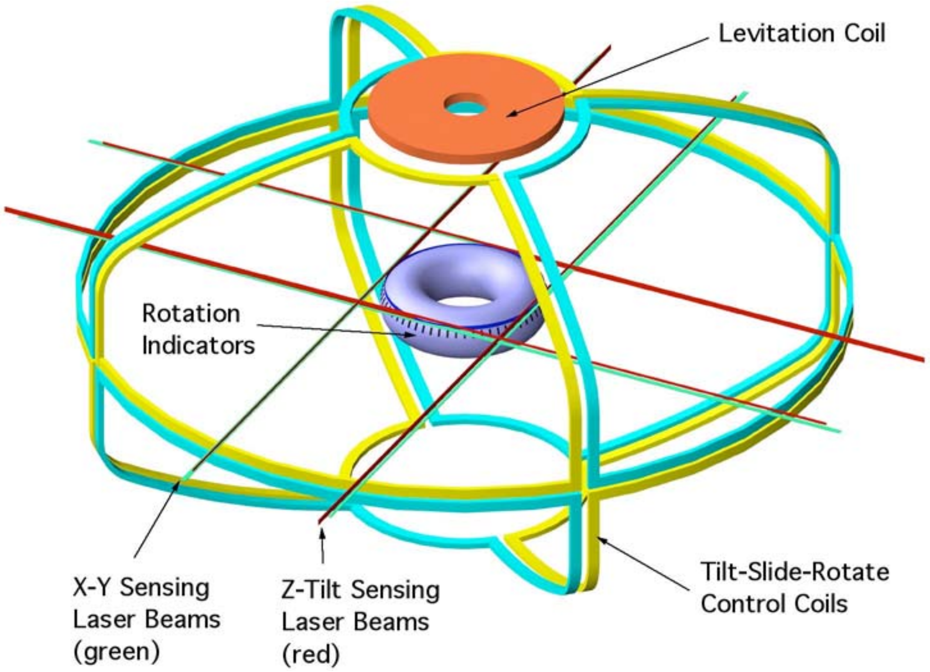




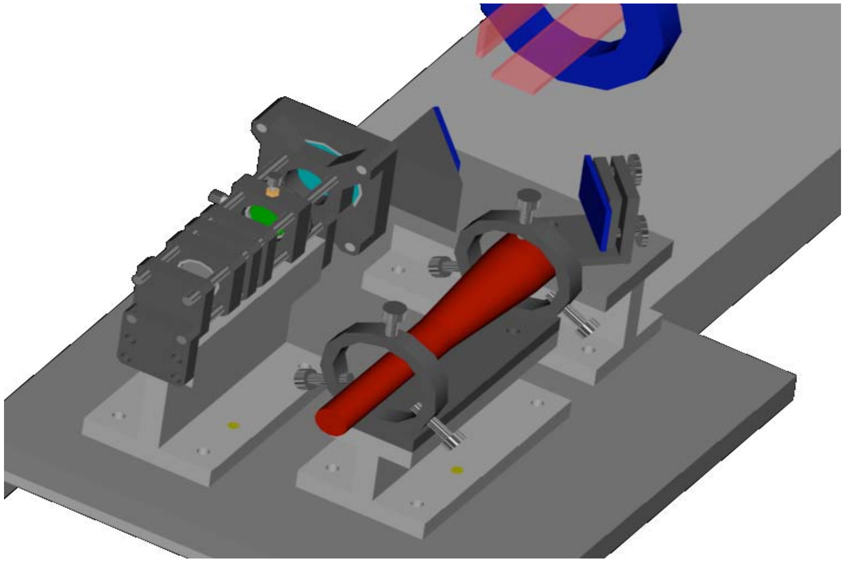
Launcher Fixture - Phase 1

- The floating coil rests on a conformal ring.
- Field lines close to the coil intercept the lifting fixture at the spokes.
- Shown:
  - Support loaded with dummy shell of same dimensions as those of the floating coil system.
  - Dummy shell lifted into operating position within the vacuum chamber.
- Not shown:
  - 1” wide boron nitride shields over spokes.

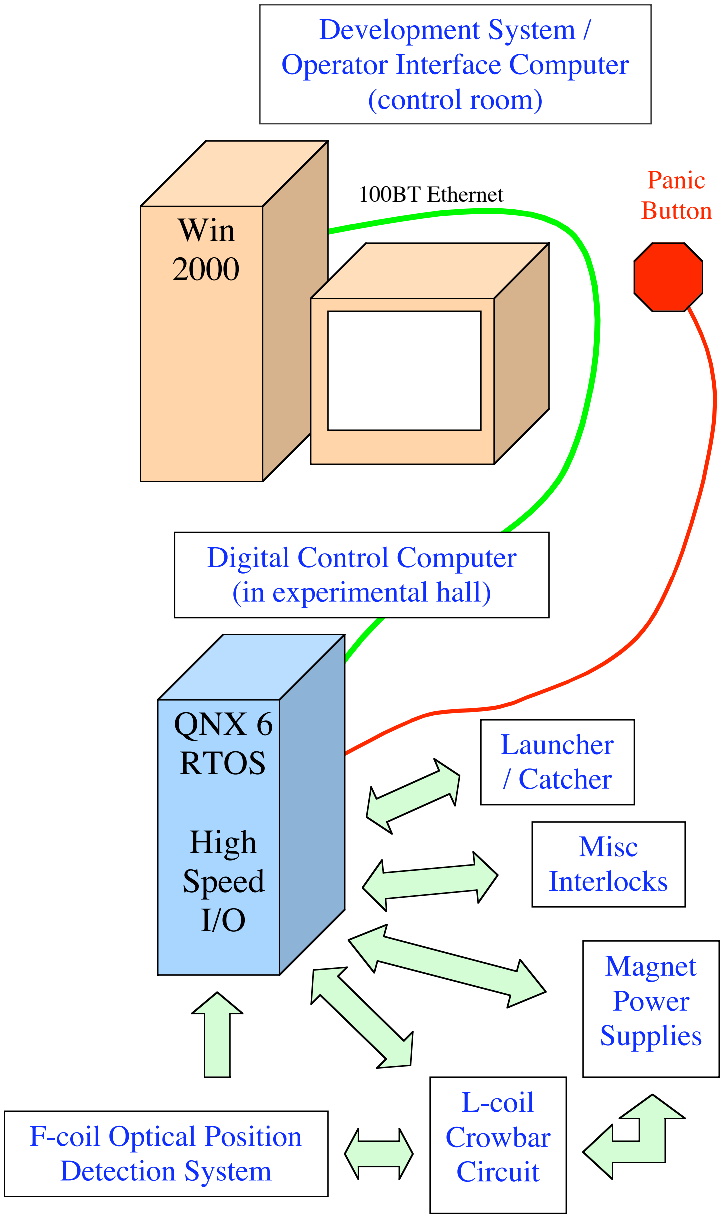
Levitation Control System



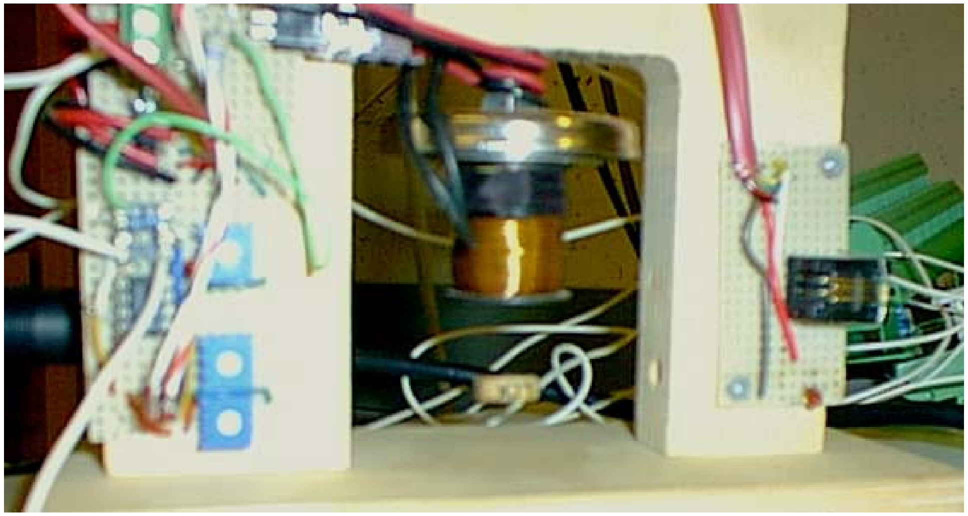
- Levitation from above
  - Requires stabilization of vertical motion by feedback
  - Other motions are stable
- Levitation control system
  - Optical detection system measures position and attitude of floating coil with 10 μm resolution
  - Digital control system



Digital Feedback System



- 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 Opal-RT / QNX Neutrino Real-time system implemented
  - Hardware/Software testing with desktop model - LCX II



LDX Experimental Goals

- Investigate high-beta plasmas stabilized by compressibility
  - Also the stability and dynamics of high-beta, energetic particles in dipolar magnetic fields
  - Examine the coupling between the scrape-off-layer and the confinement and stability of a high-temperature core plasma.
- Study plasma confinement in magnetic dipoles
  - Explore relationship between drift-stationary profiles having absolute interchange stability and the elimination of drift-wave turbulence.
  - Explore convective cell formation and control and the role convective cells play in transport in a dipole plasma.
  - The long-time (near steady-state) evolution of high-temperature magnetically-confined plasma.
- Demonstrate reliable levitation of a persistent superconducting ring using distant control coils.

LDX Experimental Plan

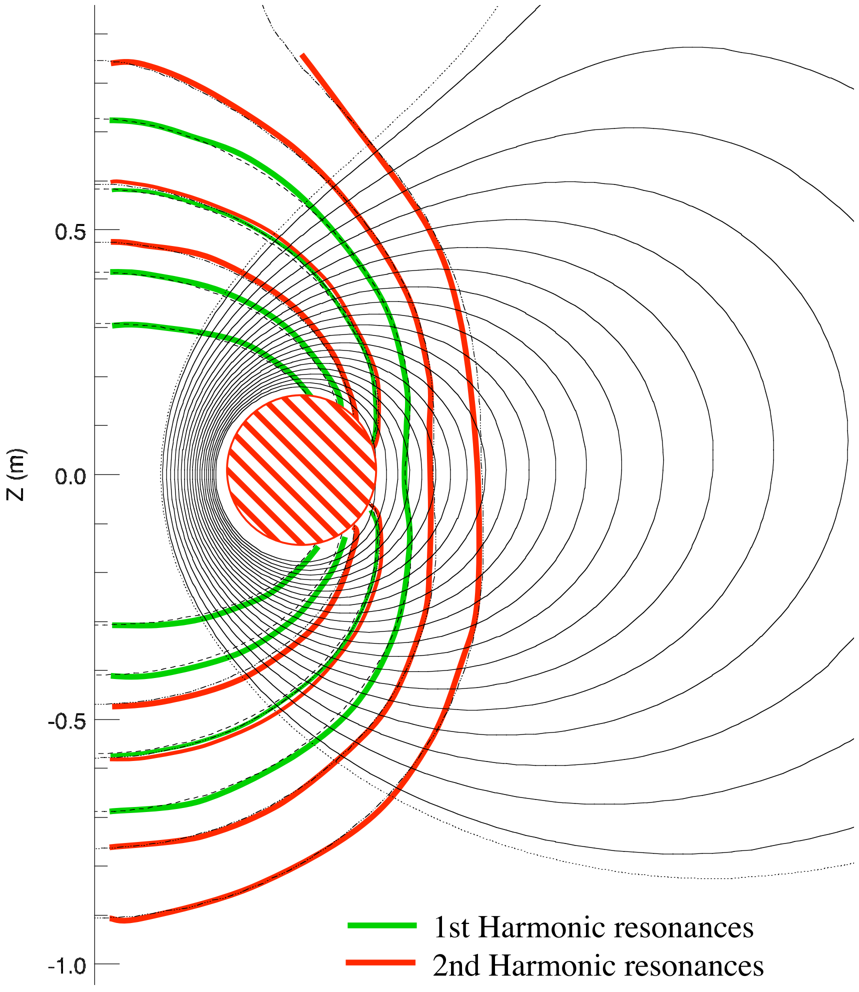
- Supported Dipole Hot Electron Plasmas
  - High- β Hot Electron plasmas with mirror losses
  - ECRH Plasma formation
  - Instabilities and Profile control
- Levitated Dipole Hot Electron Plasmas
  - No plasma losses to supports
  - β enhancement
  - Confinement studies
- Thermal Plasmas
  - Thermalization of hot electron energy with gas puffs / pellets
  - Convective cell studies
  - Concept Optimization / Evaluation

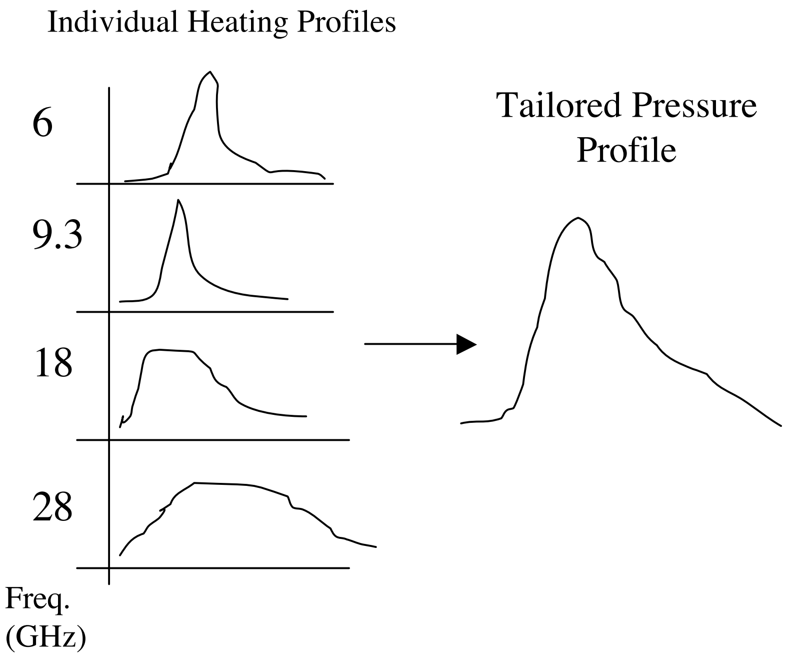
Initial Supported Hot Electron Plasmas

- Low density, quasi steady-state plasmas formed by multi-frequency ECRH with mirror-like losses from supported dipole
  - Areas of investigation
    - Plasma formation & density control
    - Pressure profile control with ECRH
    - Supercritical profiles & instability
    - Compressibility Scaling
    - ECRH and diagnostics development
  - Unique to supported operation
    - B field scaling
    - Floating ring potential control

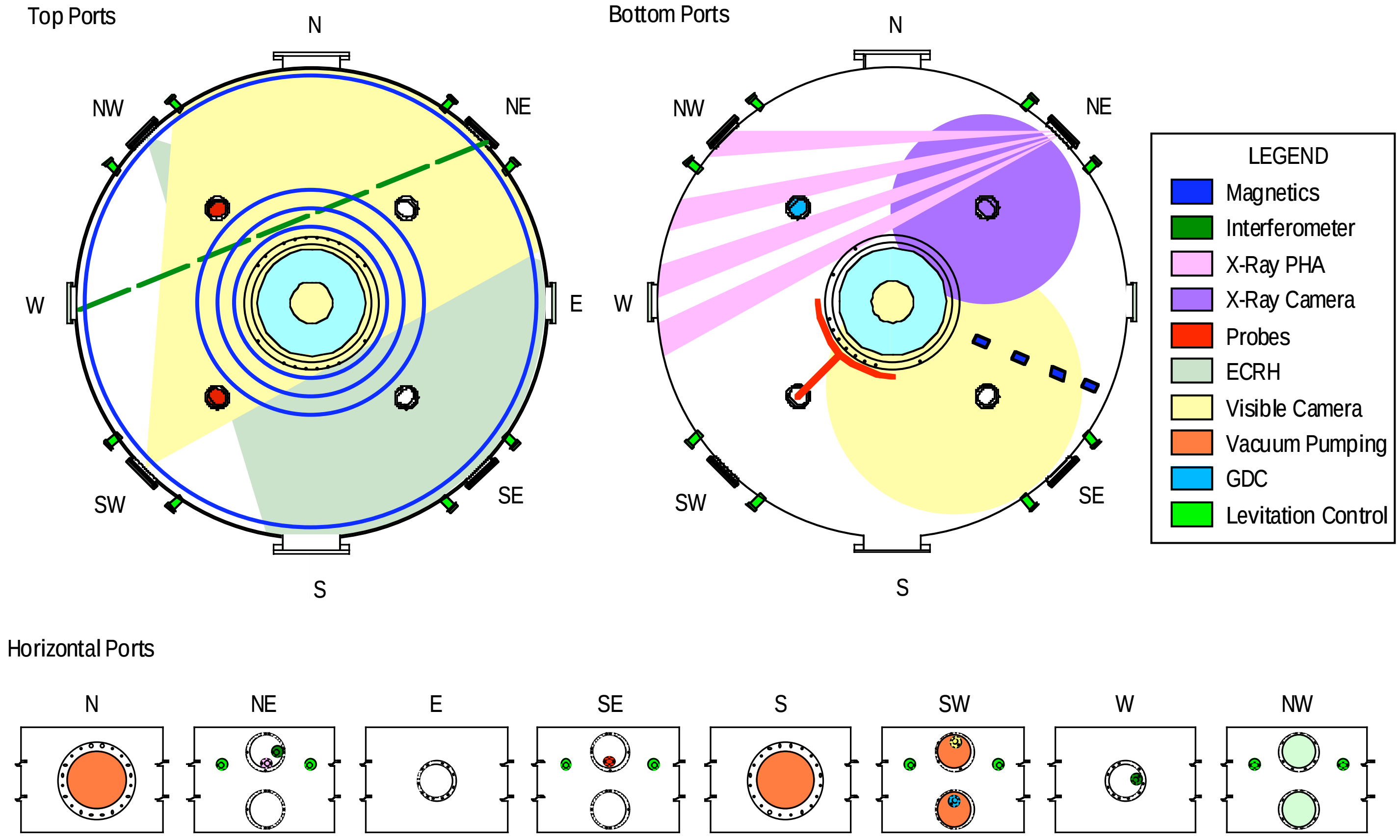
Multi-frequency ECRH on LDX

- Multi-frequency electron cyclotron resonant heating
  - Effective way to create high-β hot electron population
  - Tailor multi-frequency heating power to produce ideal (stable) pressure profile with maximum peak β.





Initial Plasma Diagnostic Set



- Magnetics (flux loops, hall probes)
  - Plasma equilibrium shape
  - Mirnov coils for magnetic fluctuations
- Interferometer
  - Density profile and macroscopic density fluctuations
- X-rays diagnostics
  - PHA hot electron energy distribution / profile
  - Hard X-Ray Camera
- D_α camera
- Edge probes
  - Edge plasma density and temperature
  - Fluctuations

Conclusions

- LDX is the first experiment to investigate plasmas stabilized by compressibility with near-classical confinement
  - Capable of directly testing effects of compressibility, pressure profile control and axisymmetry on plasma stability and confinement
  - Relevant to both space and laboratory fusion plasma physics
- Initial diagnostic set and experimental plan to focus on stability of high-β hot electron plasmas in supported and levitated operation
- LDX is a "world class" superconducting fusion experiment with sophisticated magnet technology
  - Three unique superconducting magnet systems are received at MIT and nearly completed
- Check www.psfc.mit.edu/ldx/ for updates on progress