[KP1.116]


# Overview and Status of the Levitated Dipole Experiment (LDX)


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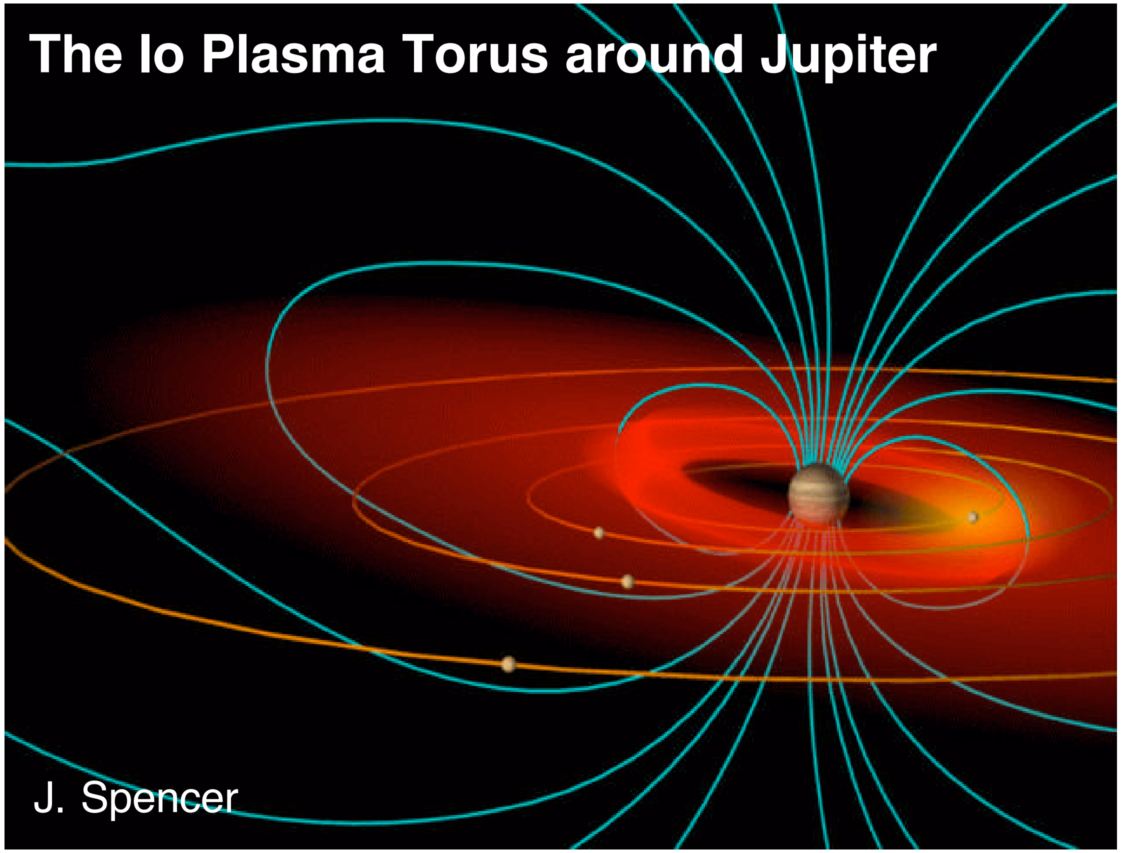
# Abstract

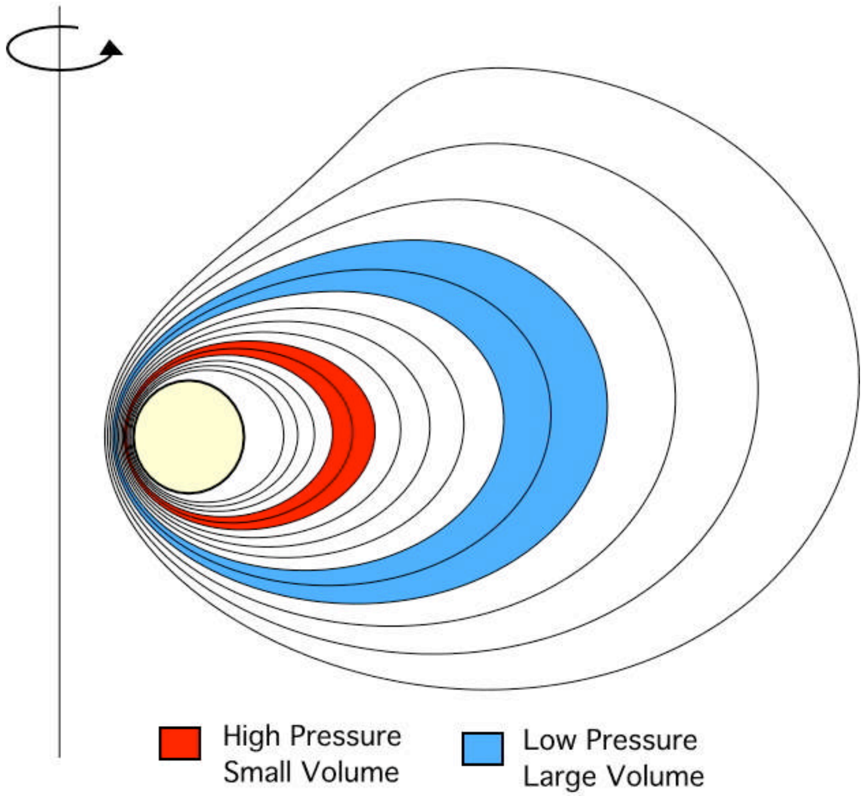

- The Levitated Dipole Experiment (LDX) is the first experiment designed to study high beta plasmas confined by a magnetic dipole with near classical energy confinement.
- The primary goal of the initial phase of LDX operation is the study of plasma behavior near marginal stability for interchange modes at high beta. Other areas of investigation include dipole confinement characteristics, the formation of convective cells within the closed field line geometry and the possibility of non-local transport.
- LDX consists of three superconducting magnets and highlights the role of innovative magnetic technology that makes possible explorations of entirely new confinement concepts. We describe the LDX machine design and detail the fabrication status of the superconducting floating-coil, charging-coil, and levitation-coil as LDX nears plasma operations.
- An overview of the project goals, overall program plan, and current status of the experiment are presented.

# Why is dipole confinement interesting?




- Simplest confinement field
- High-$\beta$ confinement occurs naturally in magnetospheres ($\beta$ ~ 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 $p_1 V_1^{\square} = p_2 V_2^{\square}$, then interchange does not change pressure profile.

For $\square = \dfrac{d \ln T}{d \ln n} = \dfrac{2}{3}$, 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.

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

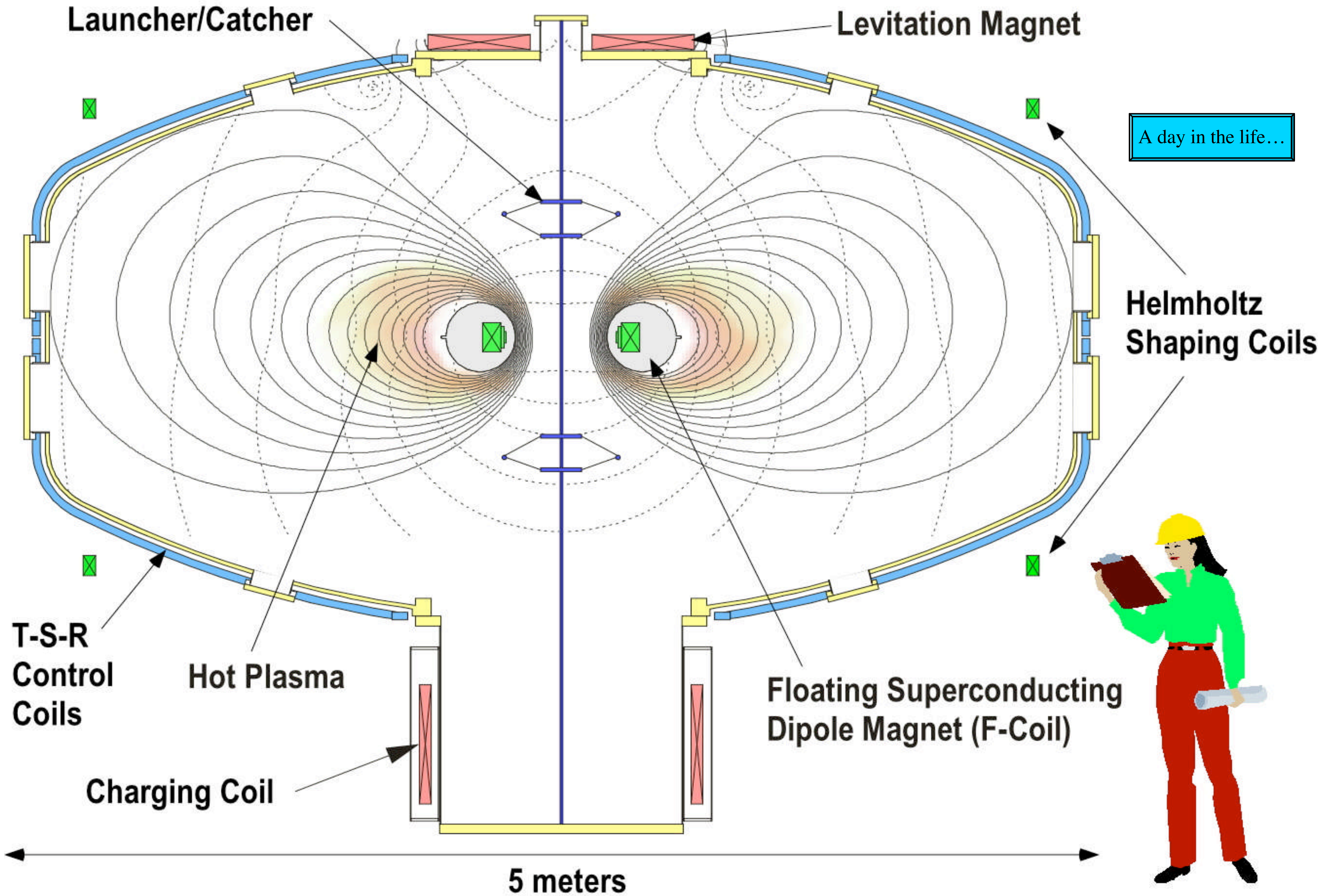
- **Equilibria exist at high-$\beta$ that are interchange and ideal MHD ballooning stable**
- **For marginal profiles with $\eta = 2/3$, dipoles also drift wave stable**
  - Near-classical confinement ?
  - Drift waves exist at other values of $\eta$, but with with reduced growth rates
- **No Magnetic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

…see Kesner [KP1.118]

# LDX Experimental Goals

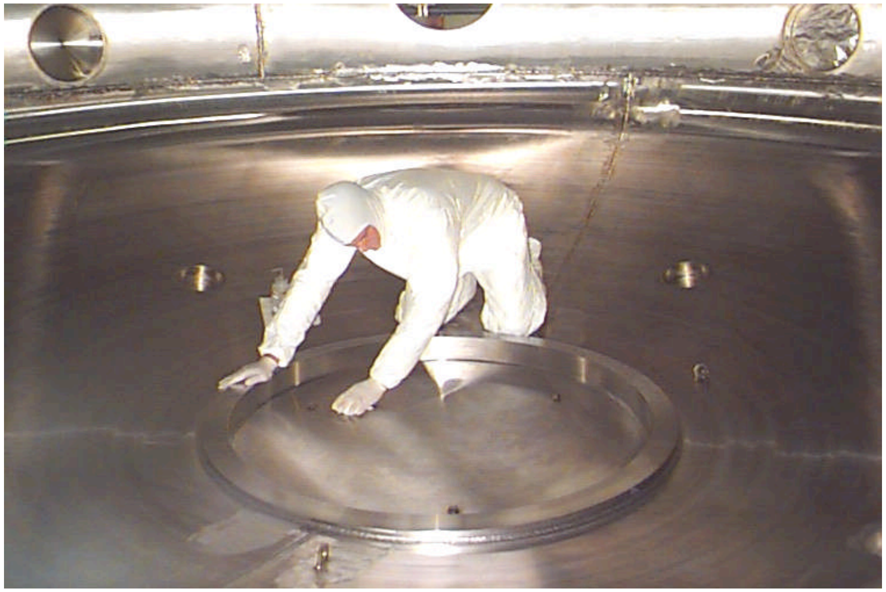
- Investigate high-beta plasmas stabilized by compressibility
  - Also the stability and dynamics of high-beta, energetic particles in dipolar magnetic fields
  - Examine the coupling between the scrape-off-layer and the confinement and stability of a high-temperature core plasma.
- Study plasma confinement 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 Experiment Cross-Section



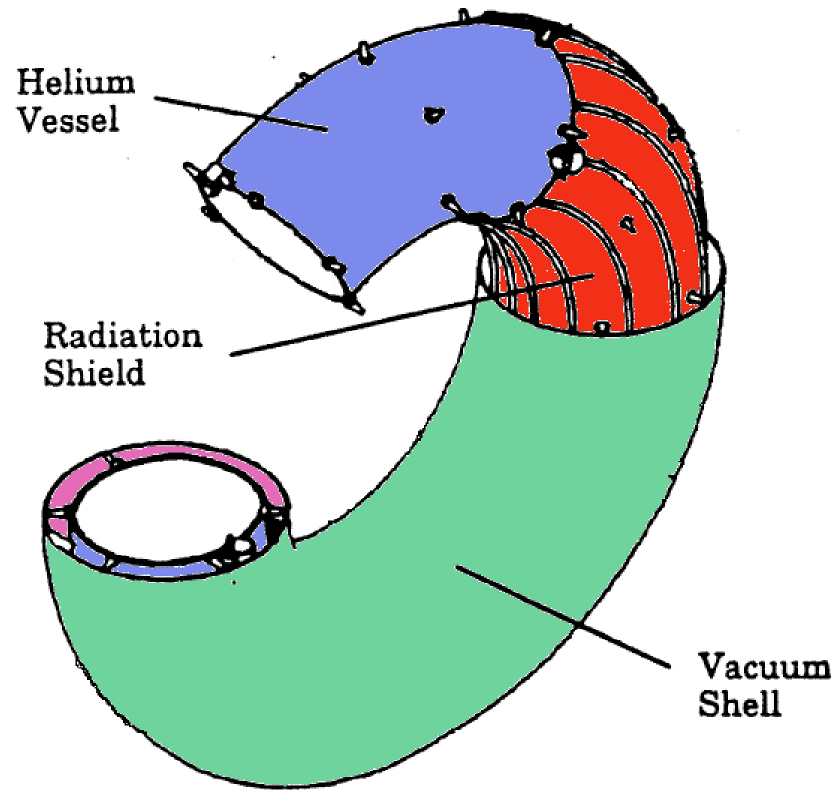
# LDX Vacuum Vessel

- 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

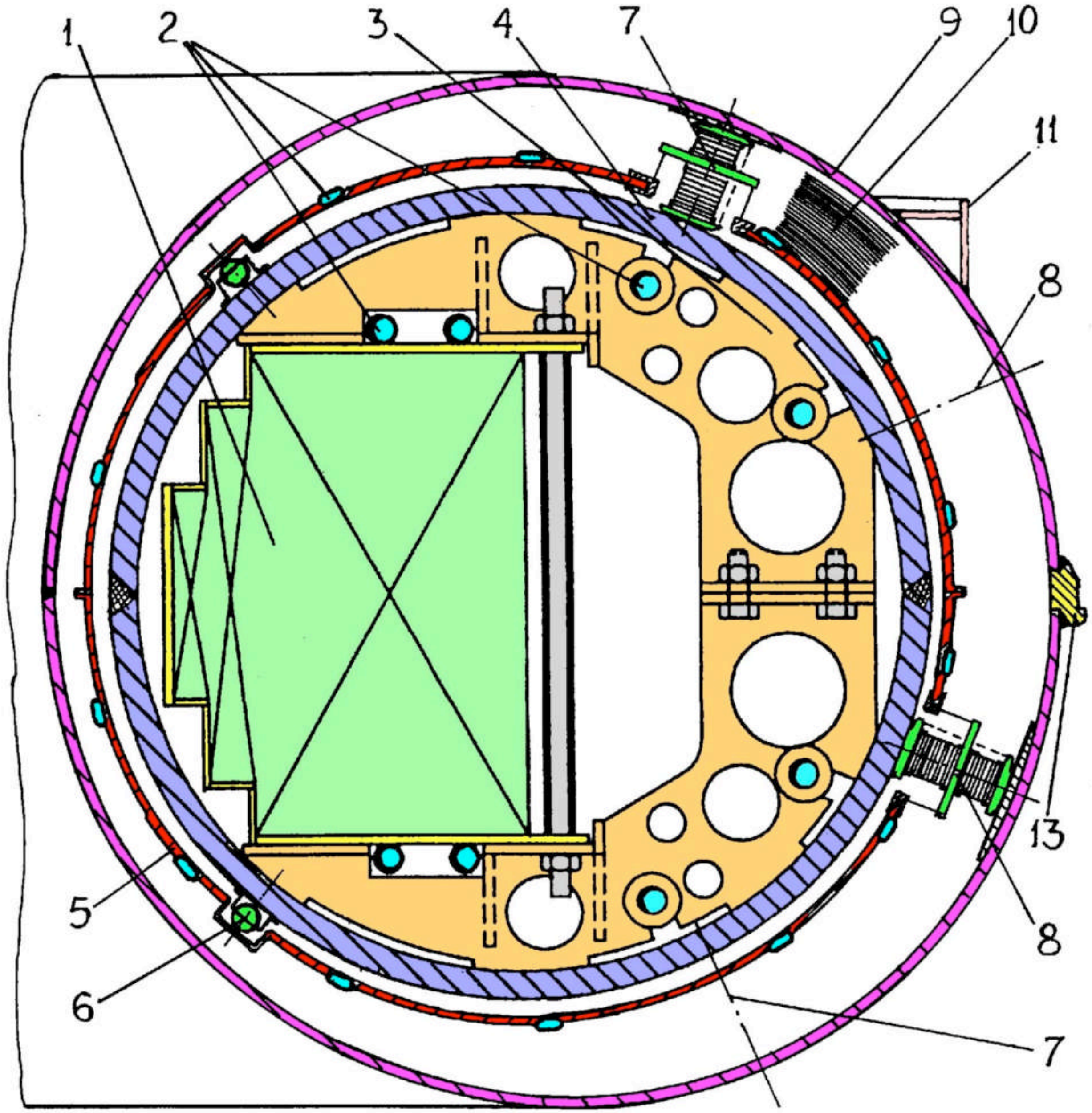


# LDX Floating Coil Overview

- 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



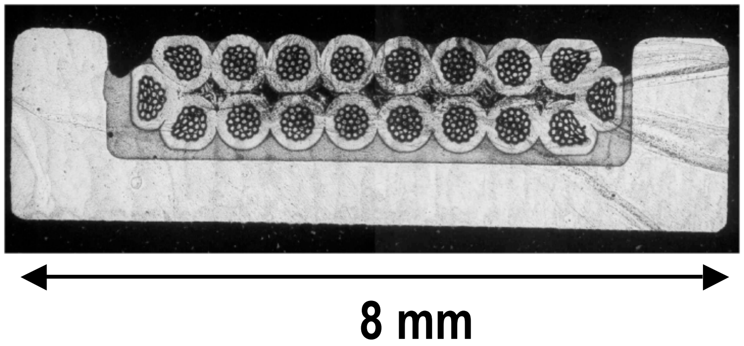
# Floating Coil Cross-Section

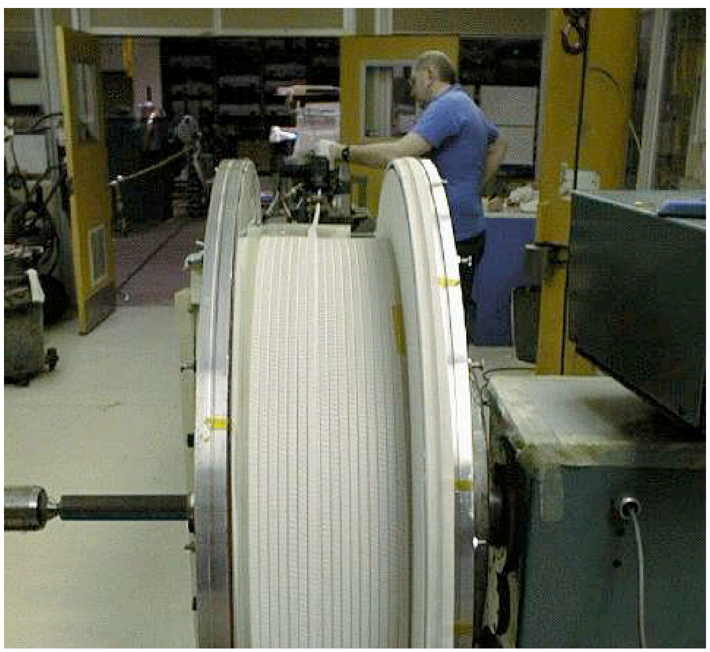



1. Magnet Winding Pack
2. Heat Exchanger tubing
3. Winding pack centering clamp
4. He Pressure Vessel (Inconel 625)
5. Thermal Shield (Lead/glass composite)
6. Shield supports (Pyrex)
7. He Vessel Vertical Supports/Bumpers
8. He Vessel Horizontal Bumpers
9. Vacuum Vessel (SST)
10. Multi-Layer Insulation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

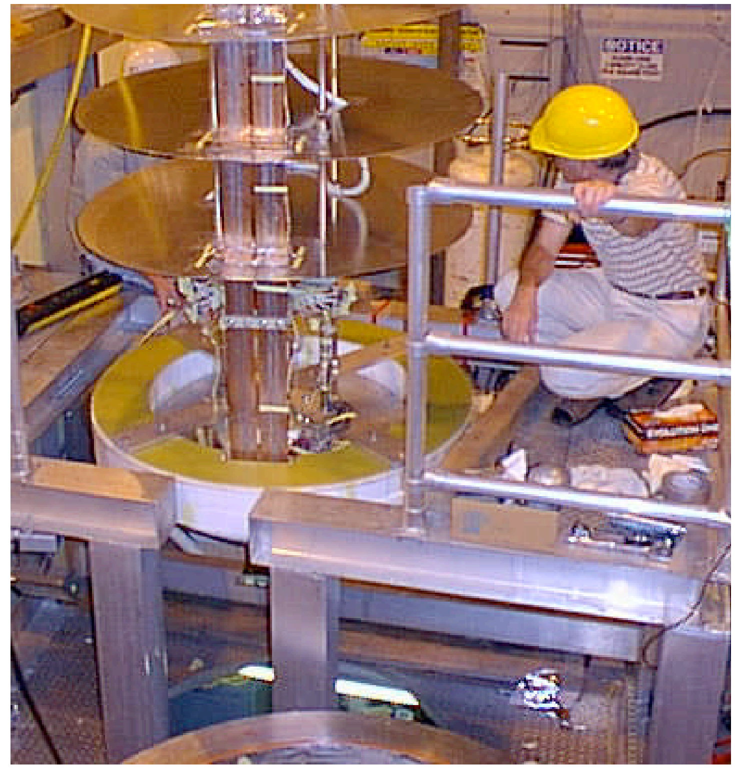
# Floating Coil Winding Pack

Advanced $Nb_3Sn$ react & wind conductor…



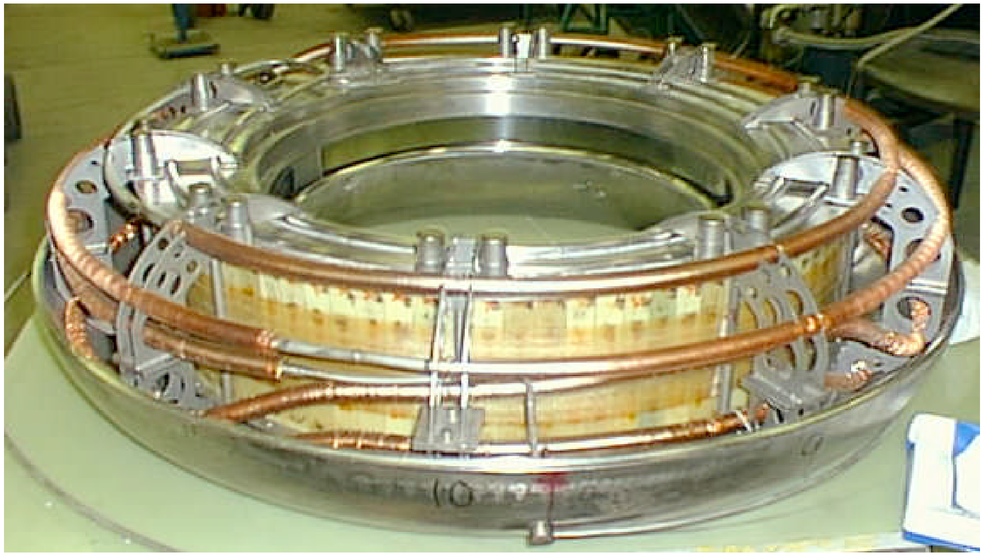
… wound very carefully…



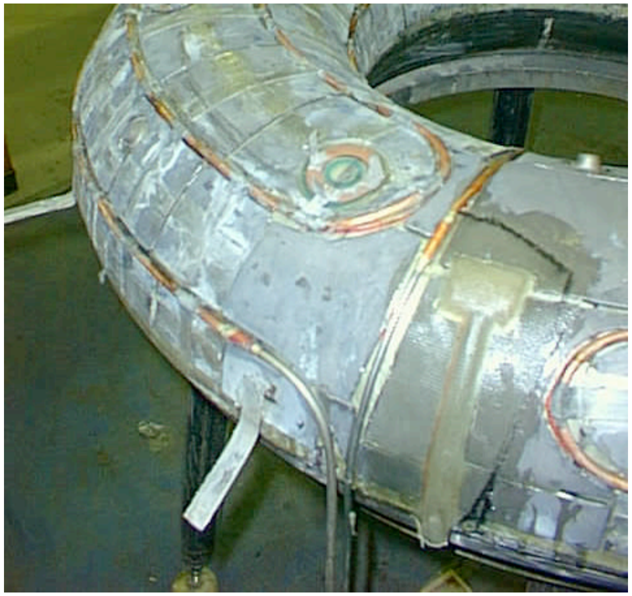
… epoxied and finally tested to full current (1.56 MA) and field (6 T) in 4.2K LHe bath.

# F-Coil Helium Pressure Vessel

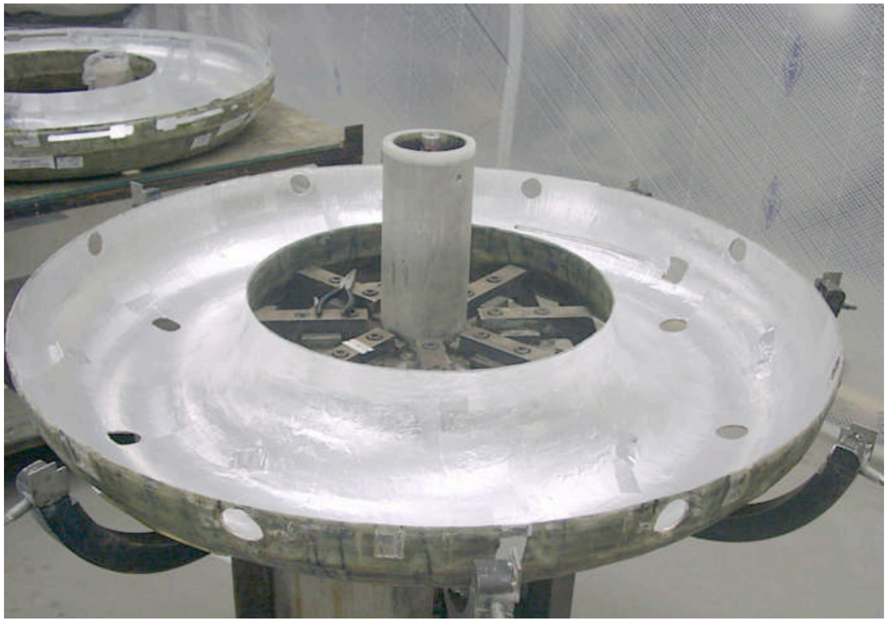
- Inconel 625 Pressure Vessel
  - 125 ATM at 300°K
  - 2-3 ATM cold
  - 1.5 kg He storage
  - Fully machined weight –~ 150 kg
- Completed construction at Ability Engineering Technology, South Holland, IL.
  - Pressure tested & code stamped
  - Leak test to vacuum @ 125 atm. for both vessel and heat exchanger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

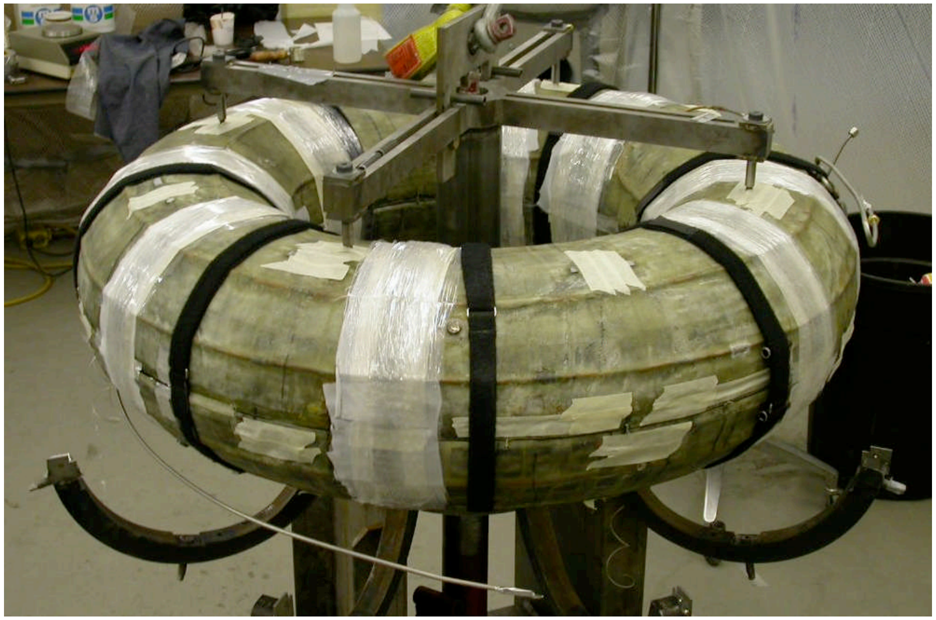


# Thermal Radiation Shield



- "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
  - Major fabrication and fit-up complete
  - Currently undergoing final assembly procedure





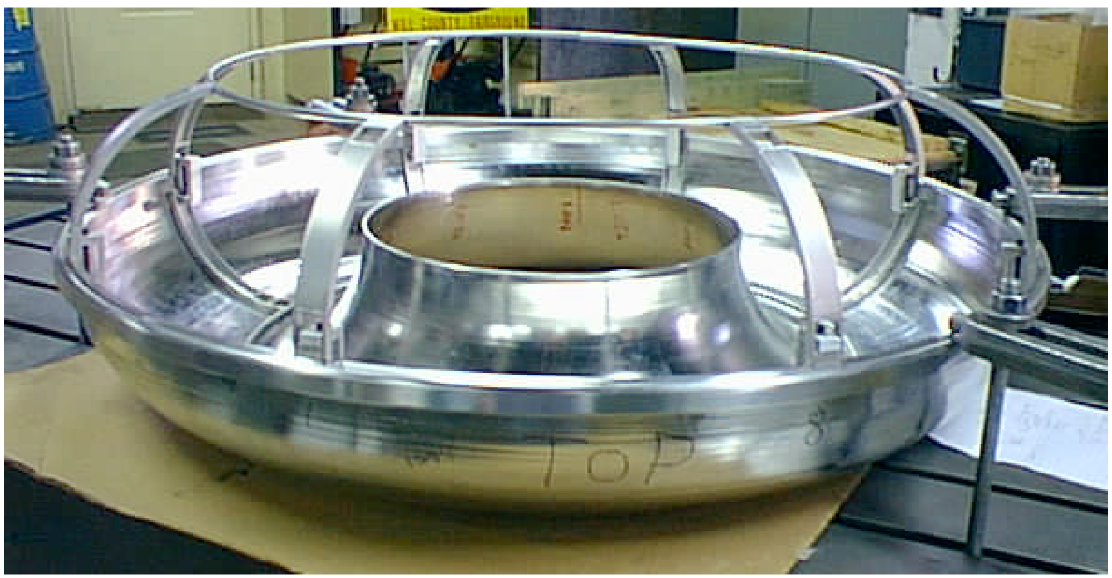
# Support Washer Stacks

- 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
  - Awaiting integration into F-coil cryostat

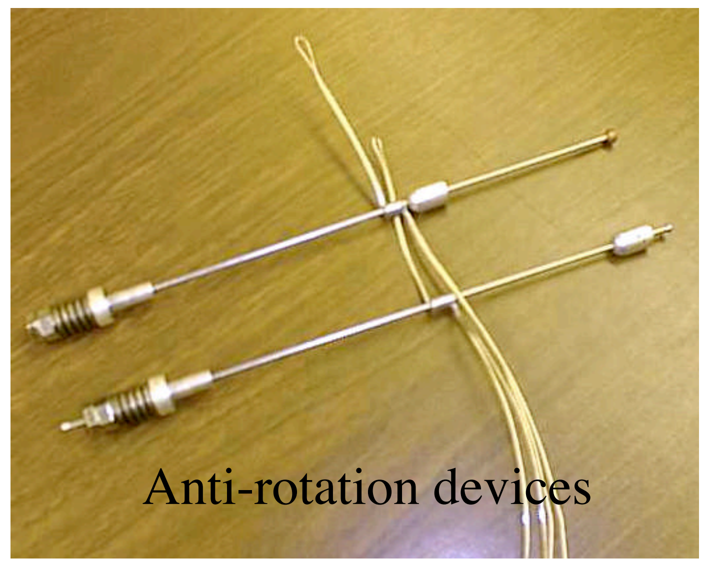
# Floating Coil Cryostat

- Low heat leak anti-rotation devices complete and tested
- Unique low heat-leak LHe feedthoughs tested
- Electrical feedthrough complete
- Support space frame complete and fitted
- Currently installing feedthroughs in vacuum shell

Inverted Cryogenic Feedthrough



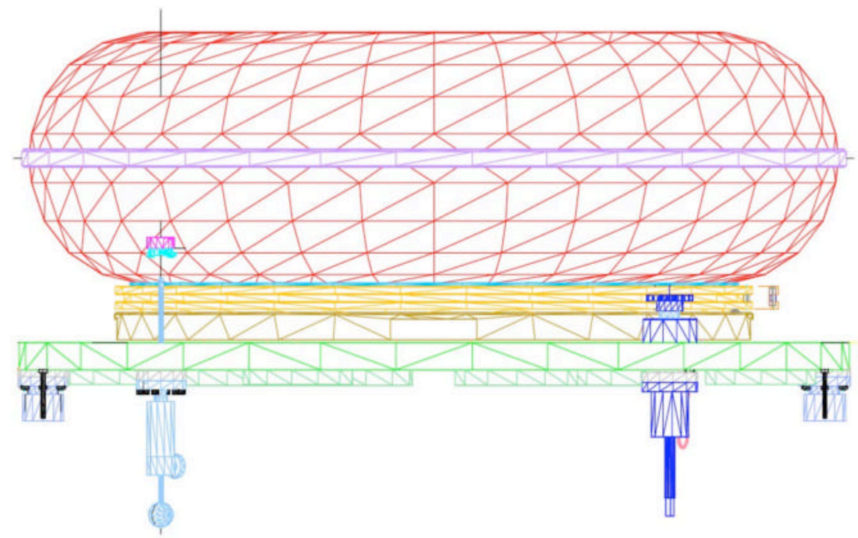
Cryostat vacuum vessel and support space frame

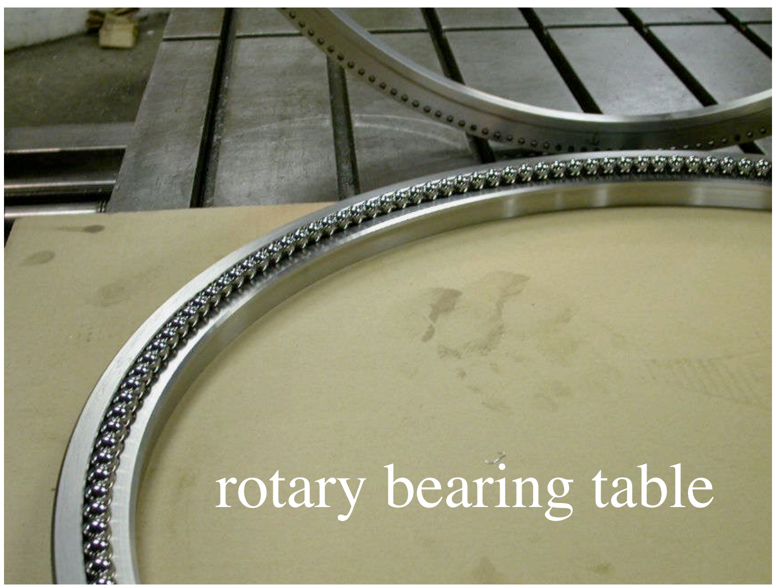


Anti-rotation devices

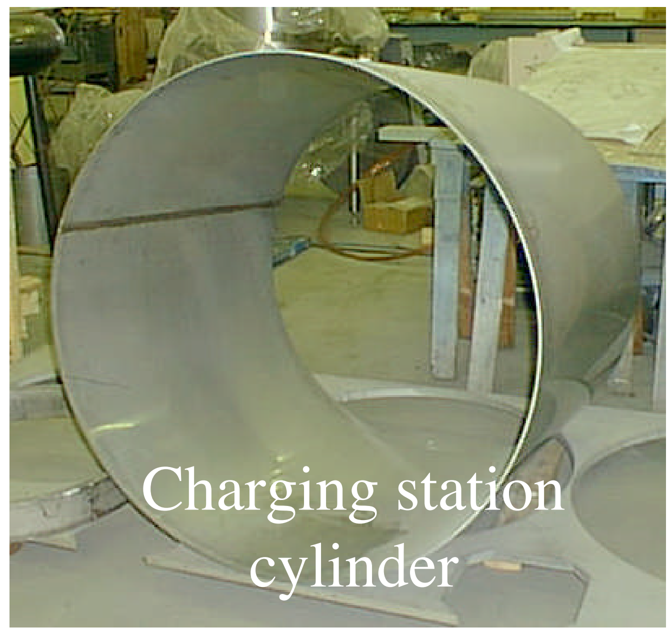
# Floating Coil Charging Station

- Rotary bearing table
  - Fixes radial motion but allows azimuthal alignment of feedthroughs
- Vacuum jacketed cryogenic feedthroughs
- Electrical connection for magnet temperature measurement
- Design complete
  - Currently being machined





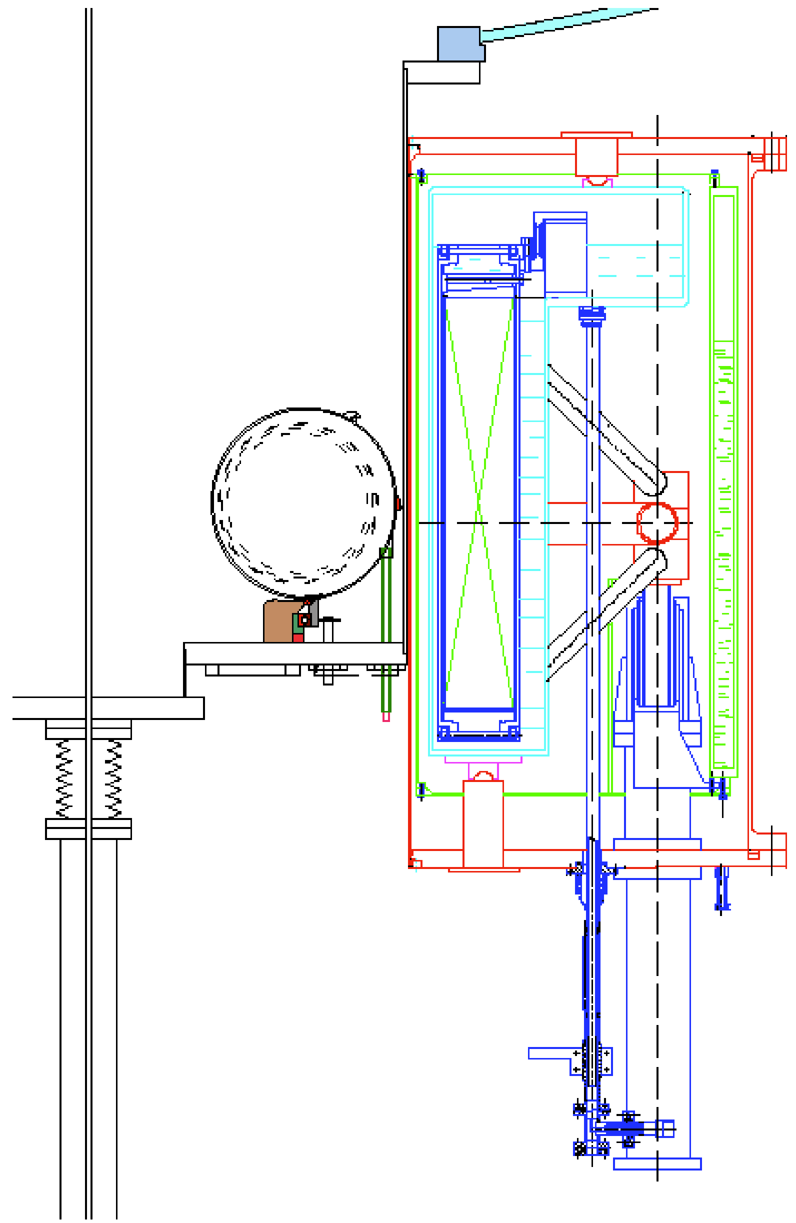
rotary bearing table



Charging station cylinder

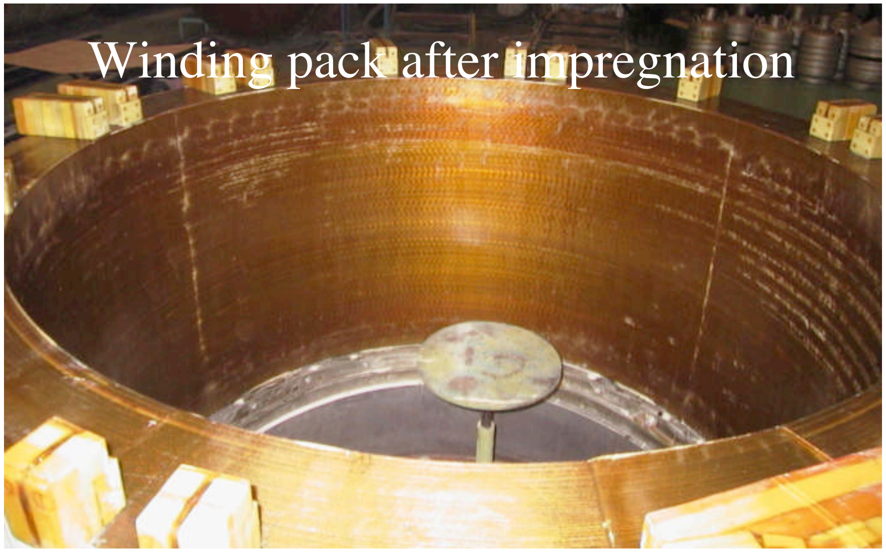
# Superconducting Charging Coil

- 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.
- Being built at Efremov Institute in St. Petersburg, Russia
  - Winding and impregnation of coil complete
  - Pre-loading and HV insulation tests successful
  - Cryostat assembly underway
  - Testing and Delivery this winter



# Charging Coil Winding Pack

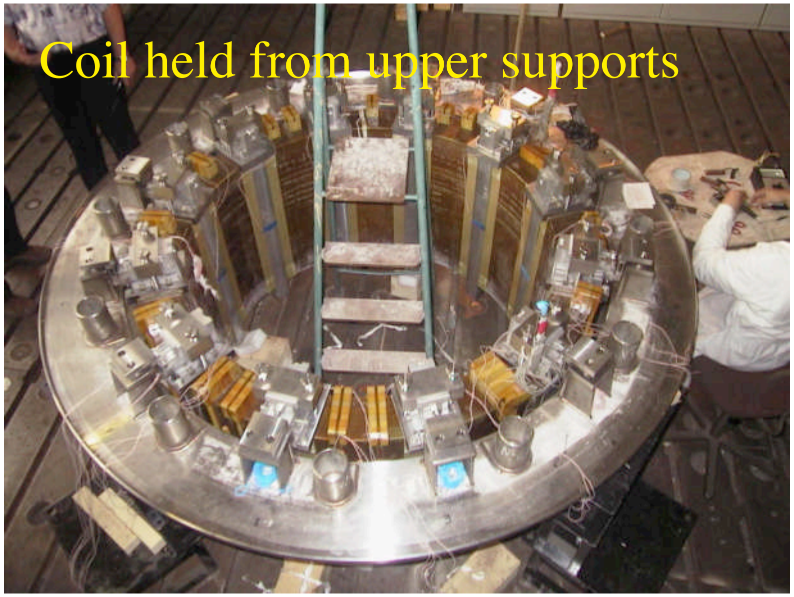
Winding 37 km of superconducting cable



Winding pack after impregnation

Electrical tests after
100 T of axial preload

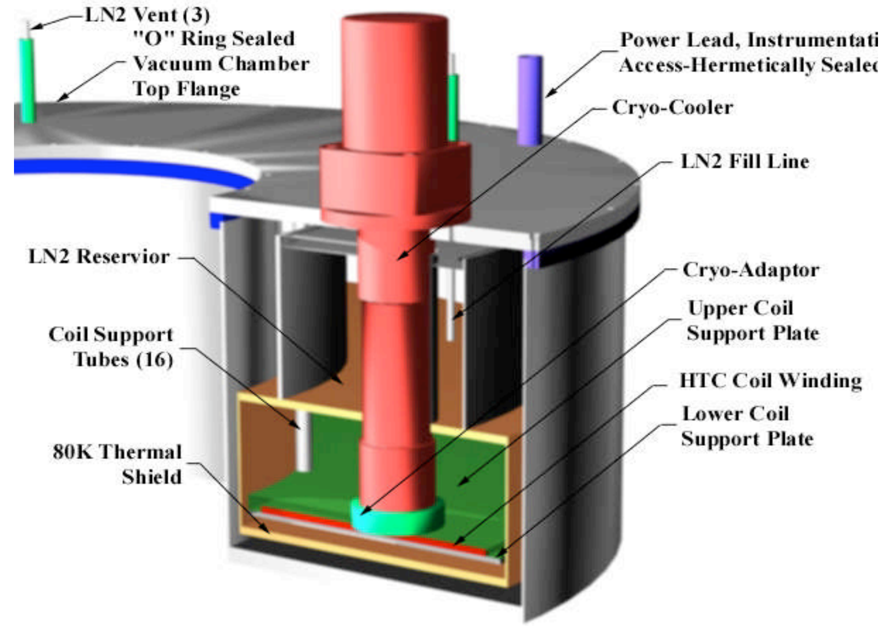
# Charging Coil Cryostat

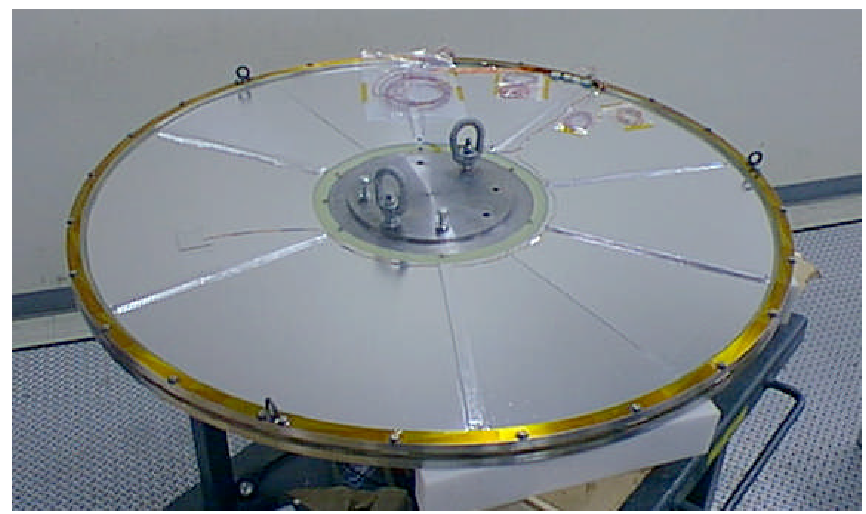



He can currently being welded closed

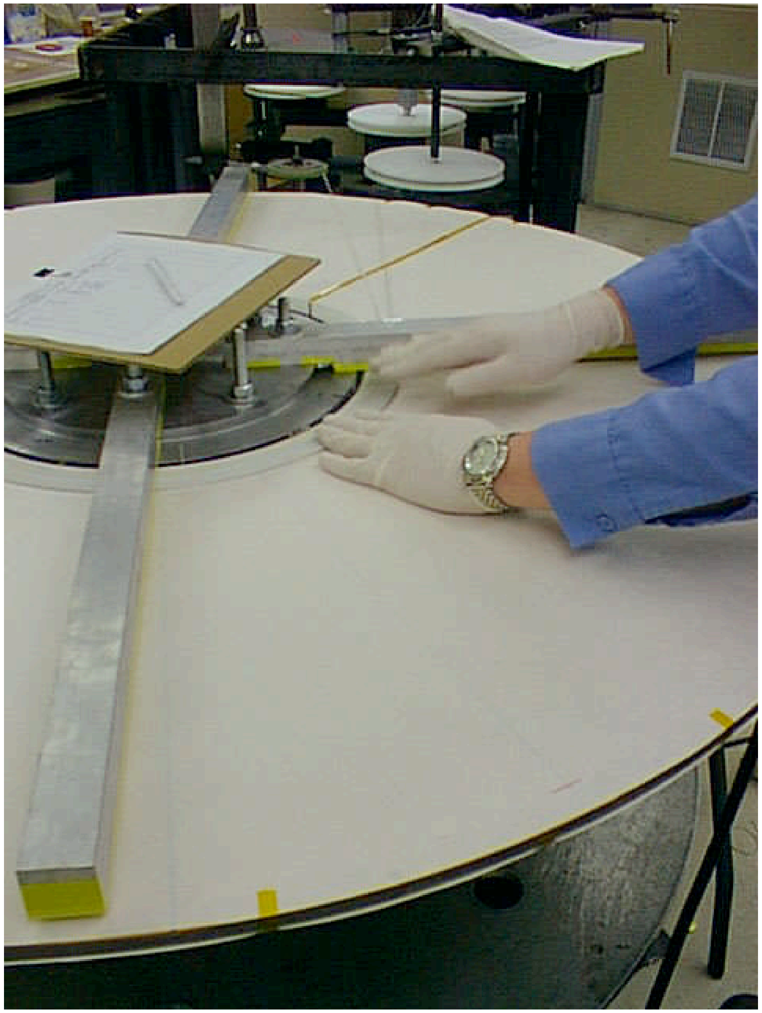

# High $T_c$ Superconducting Levitation Coil

- 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.
- Winding pack complete
  - 77° K superconducting tests successful
  - Cryostat currently under construction at Everson Electric

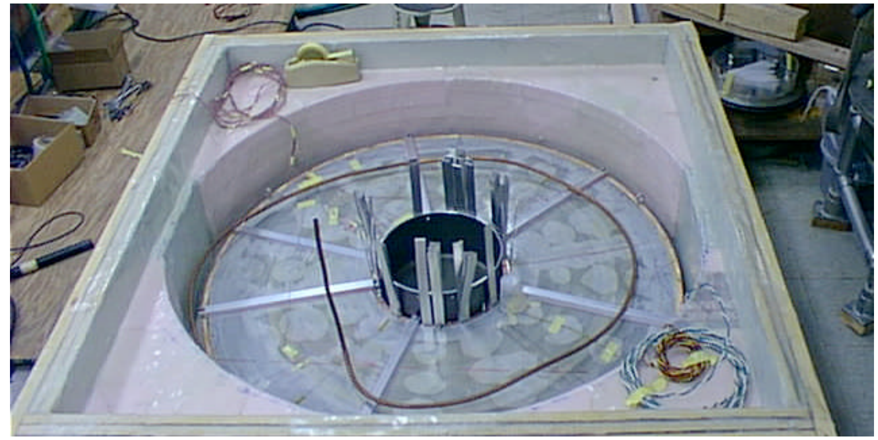


# Levitation Coil Progress



105 layers wound of very
small and fragile HTS

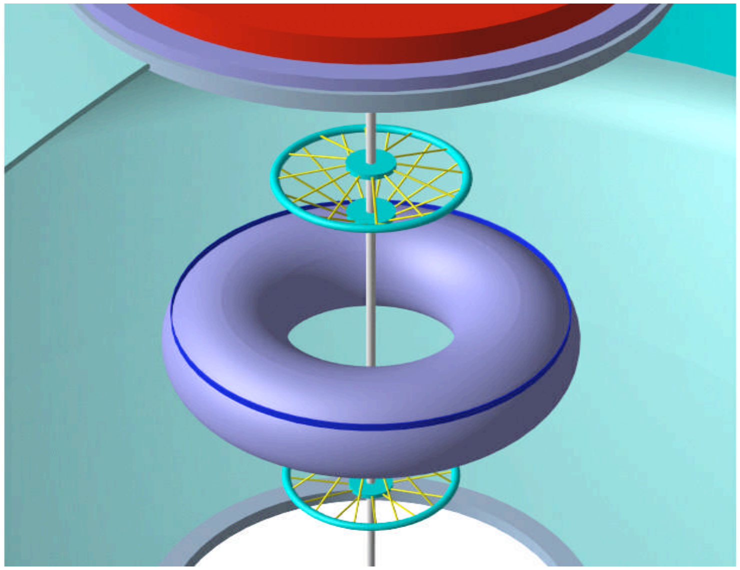


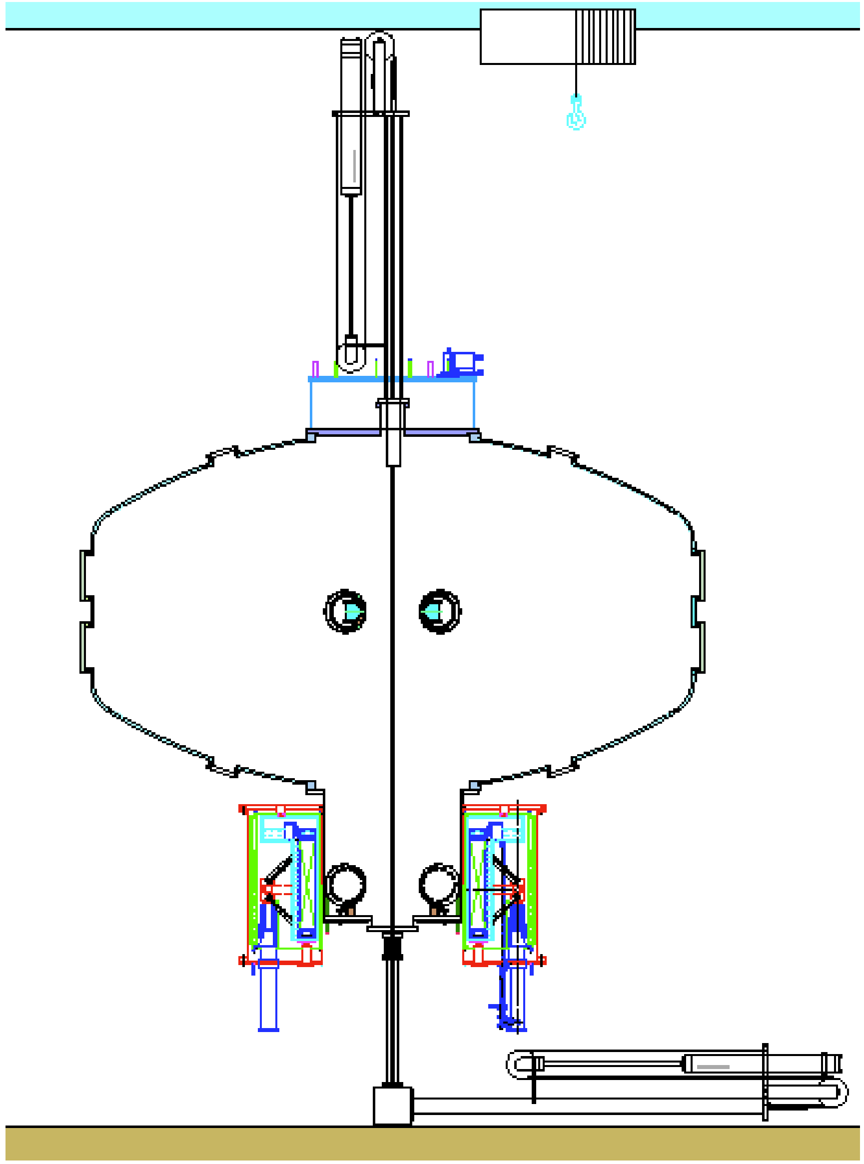
Magnet in temporary cryostat for 77 K test

Completion of cryogen free cooling structure

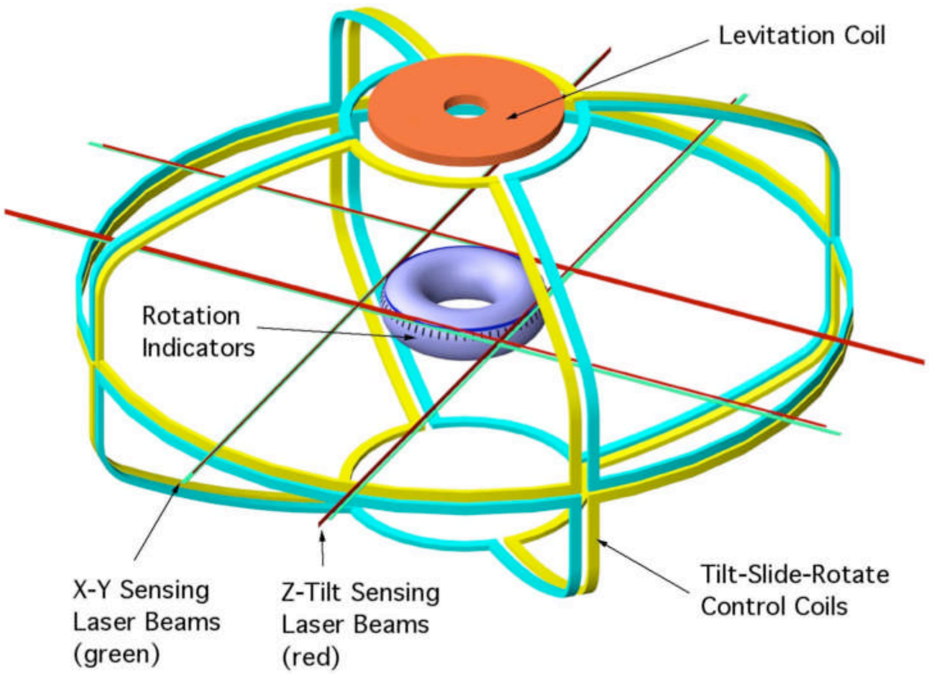
# Launcher/Catcher

- Launcher/Catcher can be used in both supported and levitated operation
  - Central rod limits fault motion of floating coil without interrupting plasma.
  - Designed at PPPL
  - Installation and Testing underway

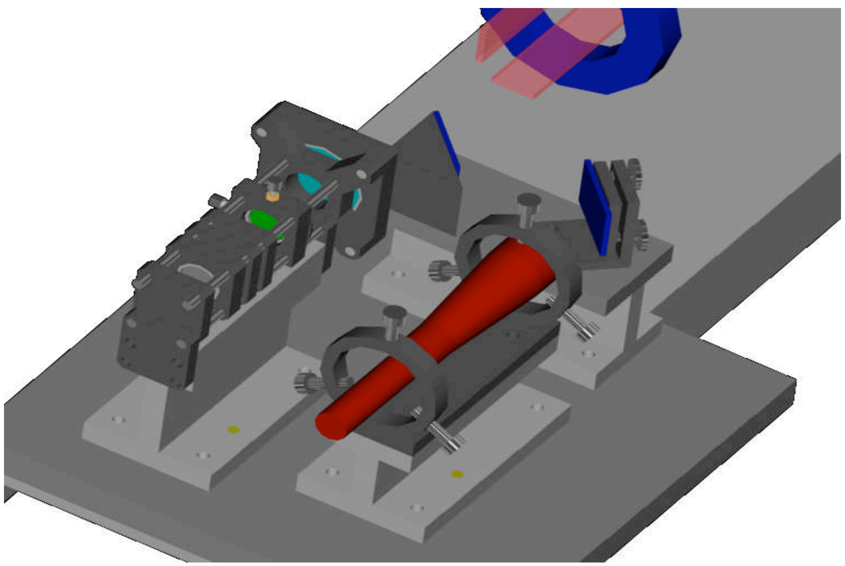




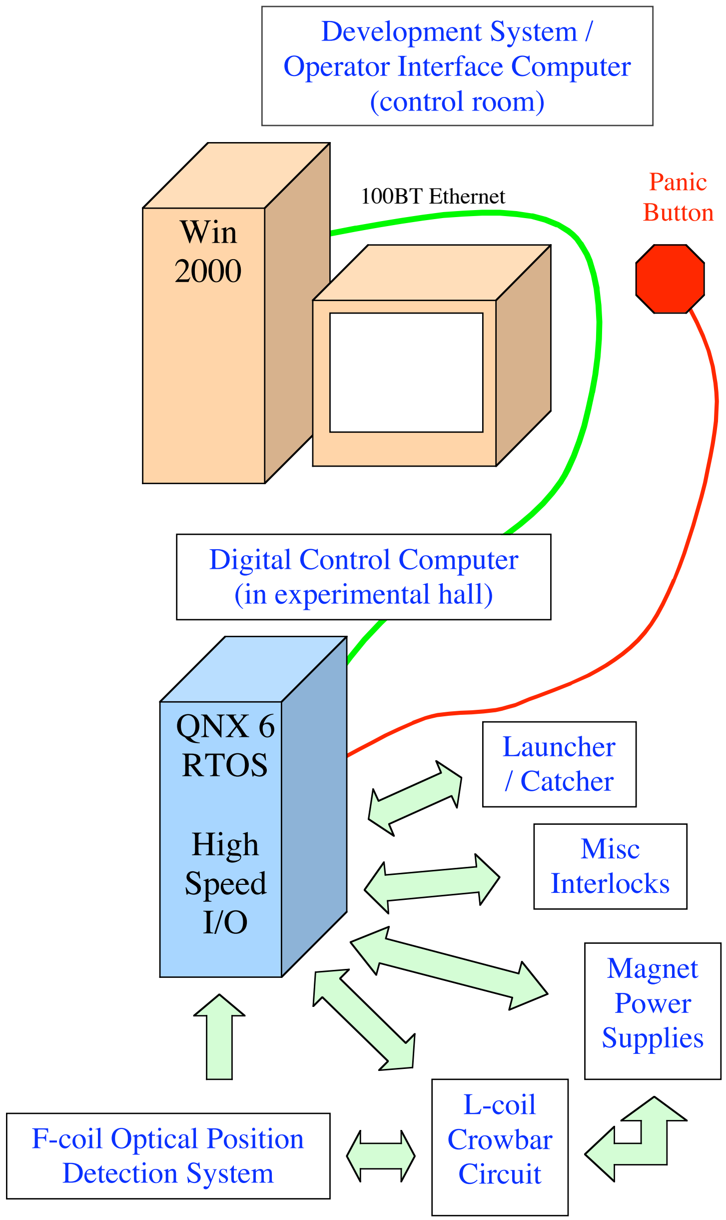
# Levitation Control System



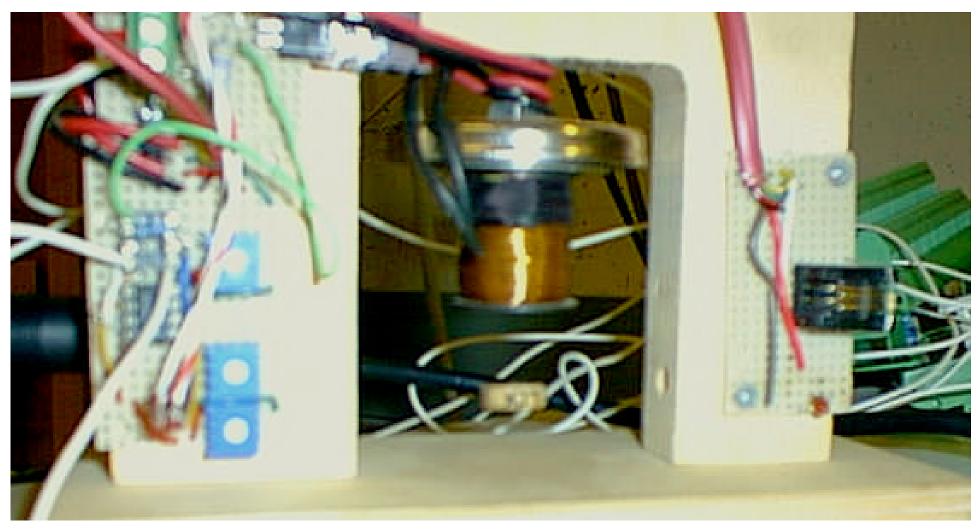

- Levitation from above
  - Requires stabilization of vertical motion by feedback
  - Other motions are stable
- Levitation control system
  - Optical detection system measures position and attitude of floating coil with 10 μm resolution
  - Digital control system



# Digital Feedback System



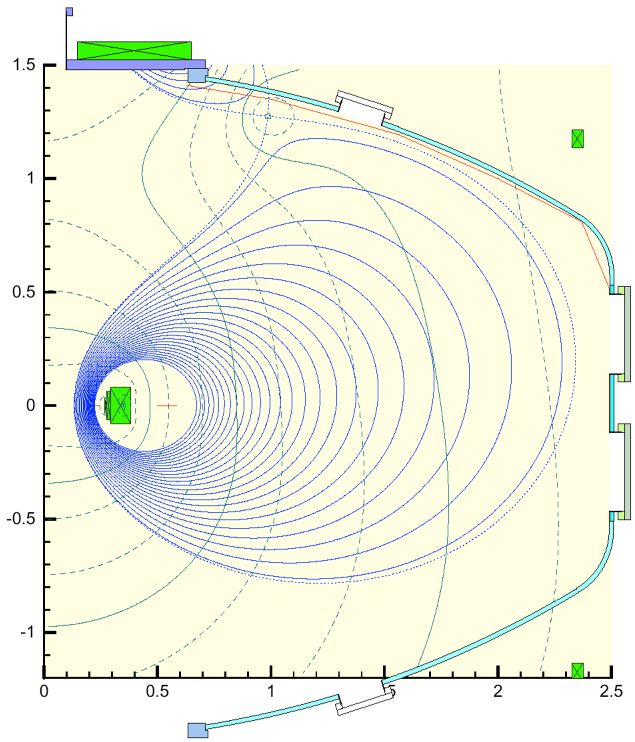

- **Design Requirements**
  - All digital process control
  - Mathworks Matlab/Simulink design tool and visualization software
  - Process control on hard real-time operating system based computer
- **Modular Opal-RT / QNX Neutrino Real-time system implemented**
  - Hardware/Software testing with desktop model - LCX II

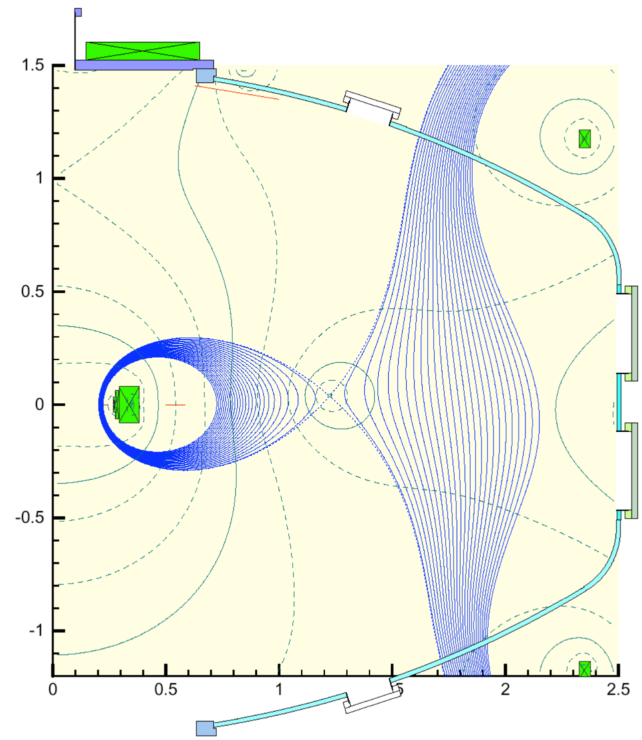


# Helmholtz Shaping Coils

$$\frac{P_{core}}{P_{edge}} \approx \left(\frac{V_{edge}}{V_{core}}\right)^{\gamma} \text{ where } V \equiv \oint \frac{dl}{B}, \text{ and } \gamma = 5/3$$

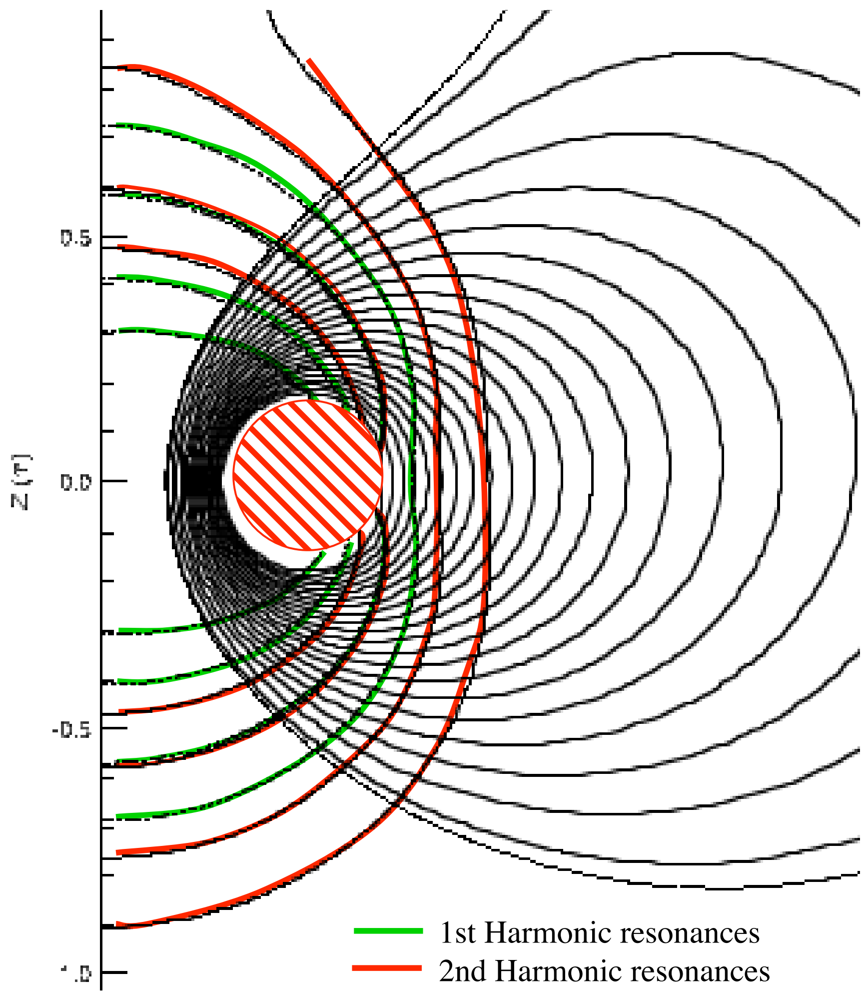
| | | | |
|---|---|---|---|
| Helmholtz Coil: | 0 kA | Helmholtz Coil: | 80 kA |
| Compression Ratio: | 228 | Compression Ratio: | 14 |
| Adiabatic Pressure Ratio: | 8500 | Adiabatic Pressure Ratio: | 85 |



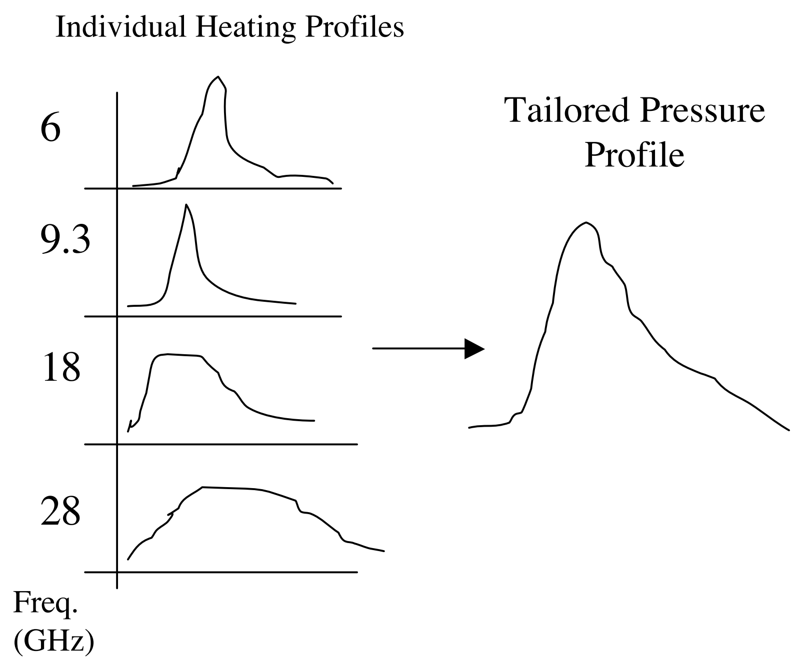




**Compressibility can be adjusted to change marginal stable pressure by factor of 100!**

# Multi-frequency ECRH on LDX




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



# 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

# Initial Plasma Diagnostic Set

- Magnetics (flux loops, hall probes)
  - Plasma equilibrium shape
  - magnetic $\beta$ & stored energy
  - Mirnov coils for magnetic fluctuation measurements
- Interferometer
  - Density profile and macroscopic density fluctuations
- X-ray pulse height energy analyzer
  - Hot electron energy distribution / profile
- Hard X-Ray Camera (in collaboration with PPPL)
- XUV arrays
  - Instabilities and 2-D profiles
- $D_\alpha$ camera
- Edge probes
  - Edge plasma density and temperature

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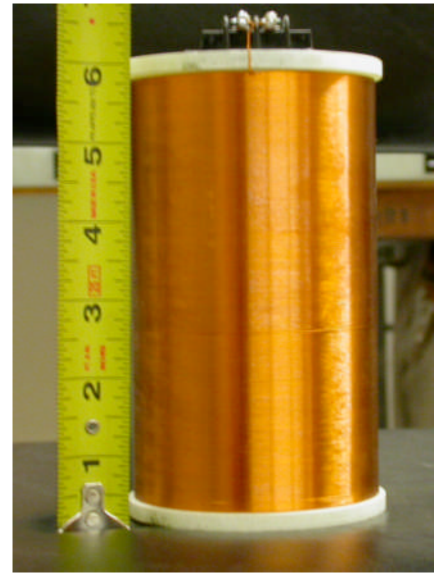

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# LDX Experimental Plan

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

# 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-$\beta$ 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 nearing completion of construction
- First plasma early spring
- Check www.psfc.mit.edu/ldx/ for a copy of this poster and updates on progress