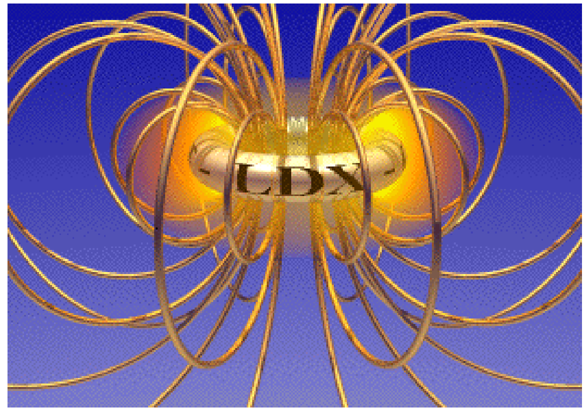


# Status of the LDX Project

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*Columbia University*

for the LDX Team

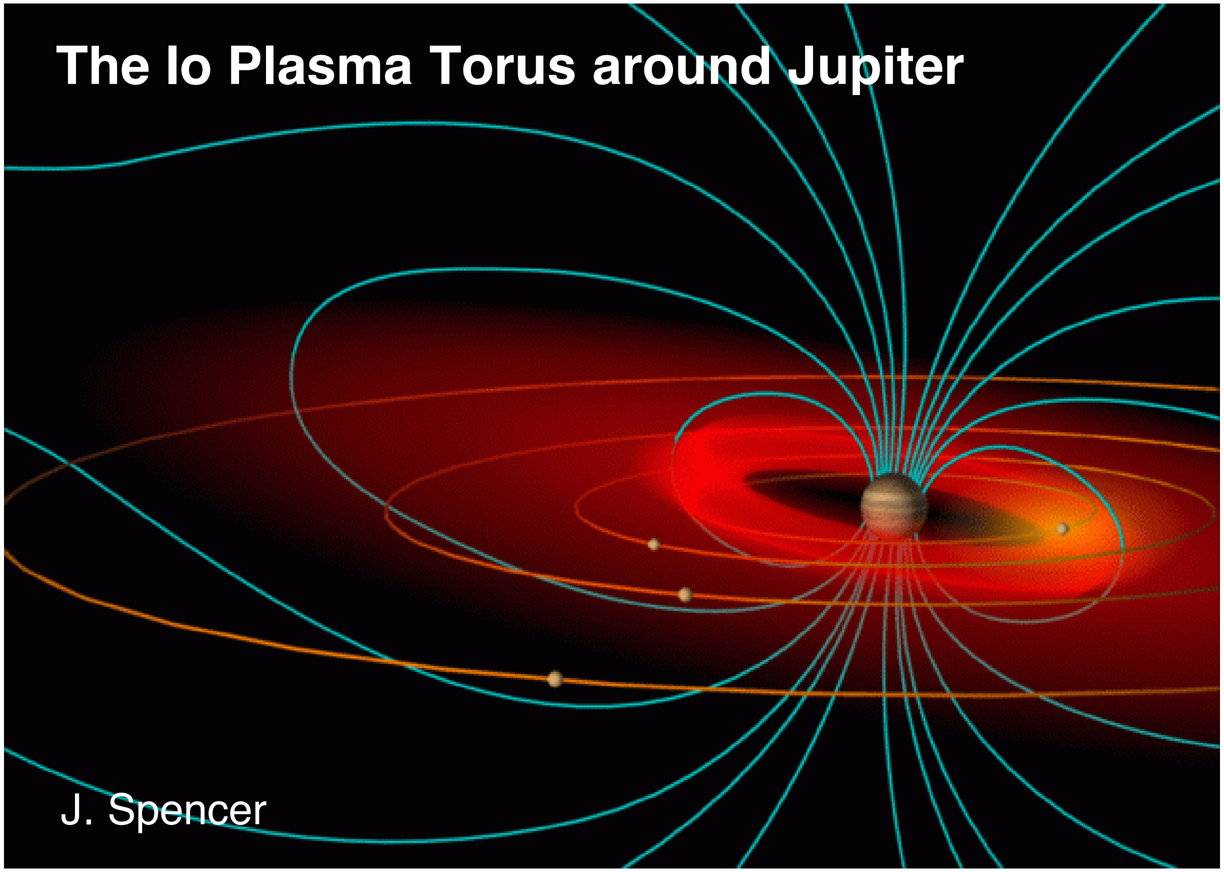
Columbia University

*Presented at the*
*Innovative Confinement Concepts Workshop 2000*
*Berkeley, California, February 24, 2000*

# Outline

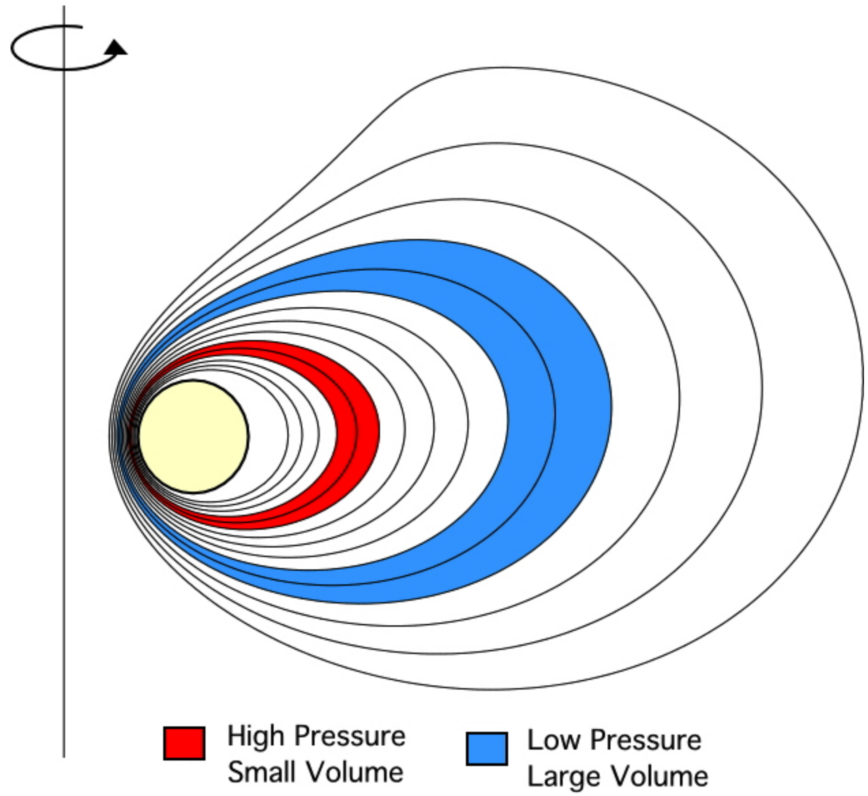
- Short introduction to LDX
  - Intro to Dipole physics
  - Goals of LDX program
- "A day in the life" of LDX
  - LDX Machine Design
  - Construction Progress of Major Components
- Experimental Plan and Schedule

# Why is dipole confinement interesting?




- Simplest confinement field
- High-$\beta$ 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**

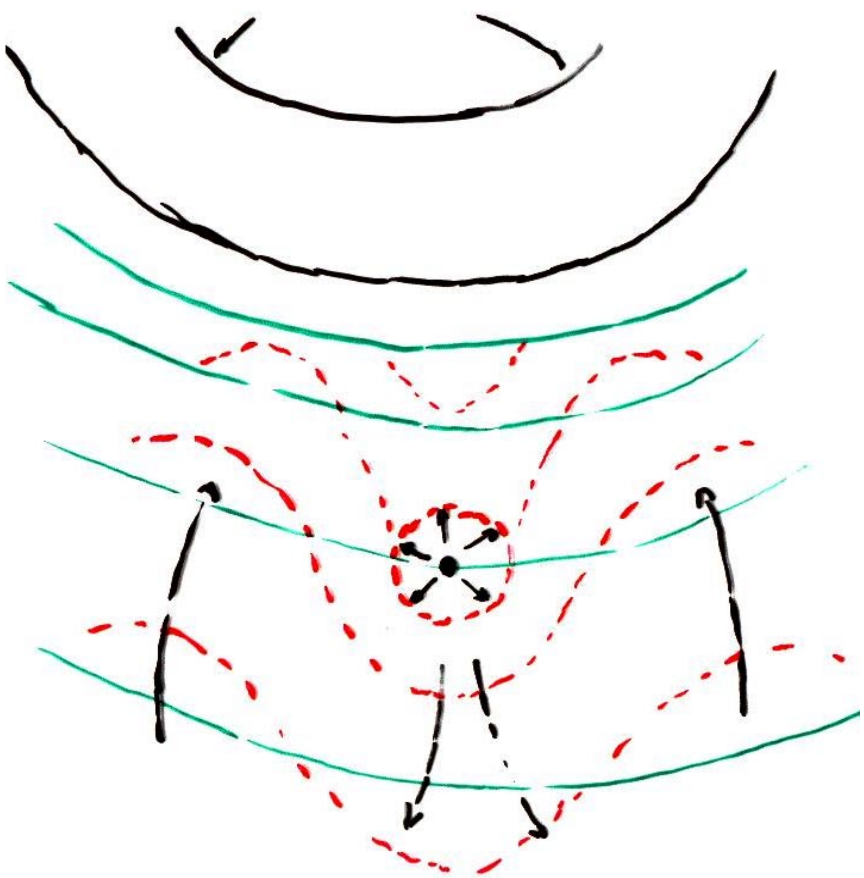
# Dipole Confinement continued...

- **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-$\beta$ that are interchange and ideal ballooning stable**
- **For marginal profiles with $\eta \leq 2/3$, dipoles are also drift wave stable.**
  - Near-classical confinement ?
- **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 $\tau_E$ .
  - But, good curvature region near ring, convective cells can cause anomalous transport

# Convective Cells



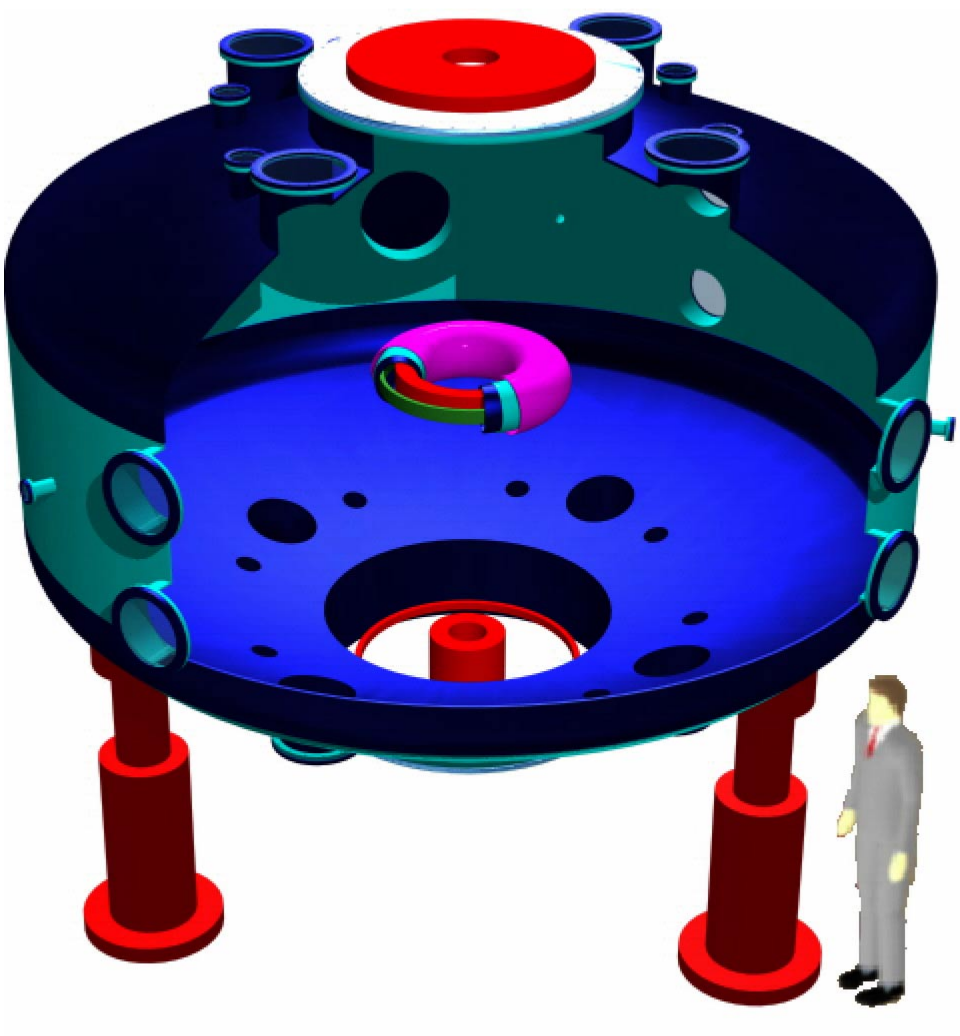
- How are they formed?
  - Are they the nonlinear saturation of interchange modes?
  - How asymmetric does the heating profile need to be to drive them?
- Do they degrade energy confinement?
  - Can we have high energy confinement with low particle confinement?
- Explore methods for driving and limiting.
  - Current drive ?

# 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 Overview

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

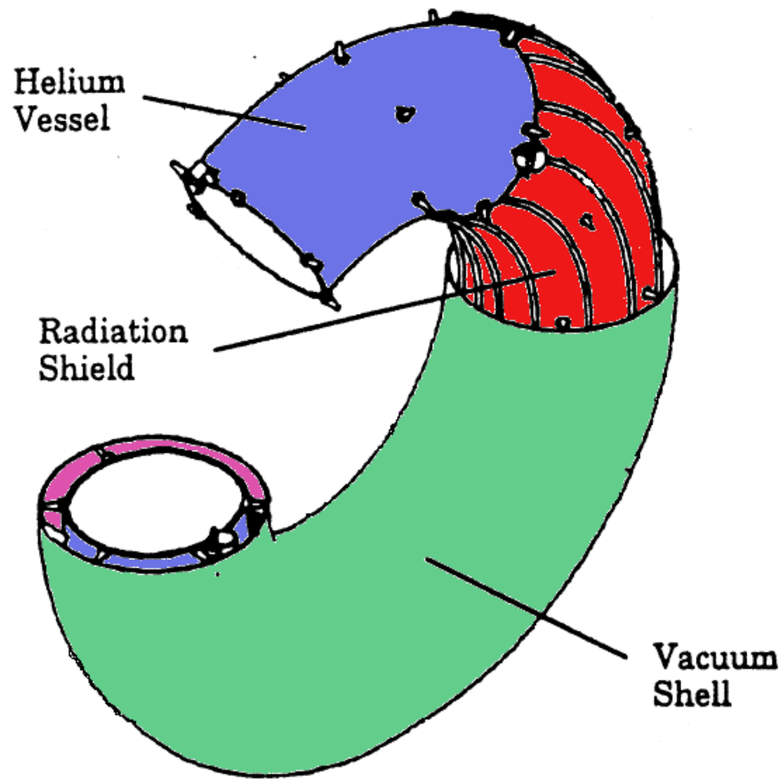


# LDX Vacuum Vessel

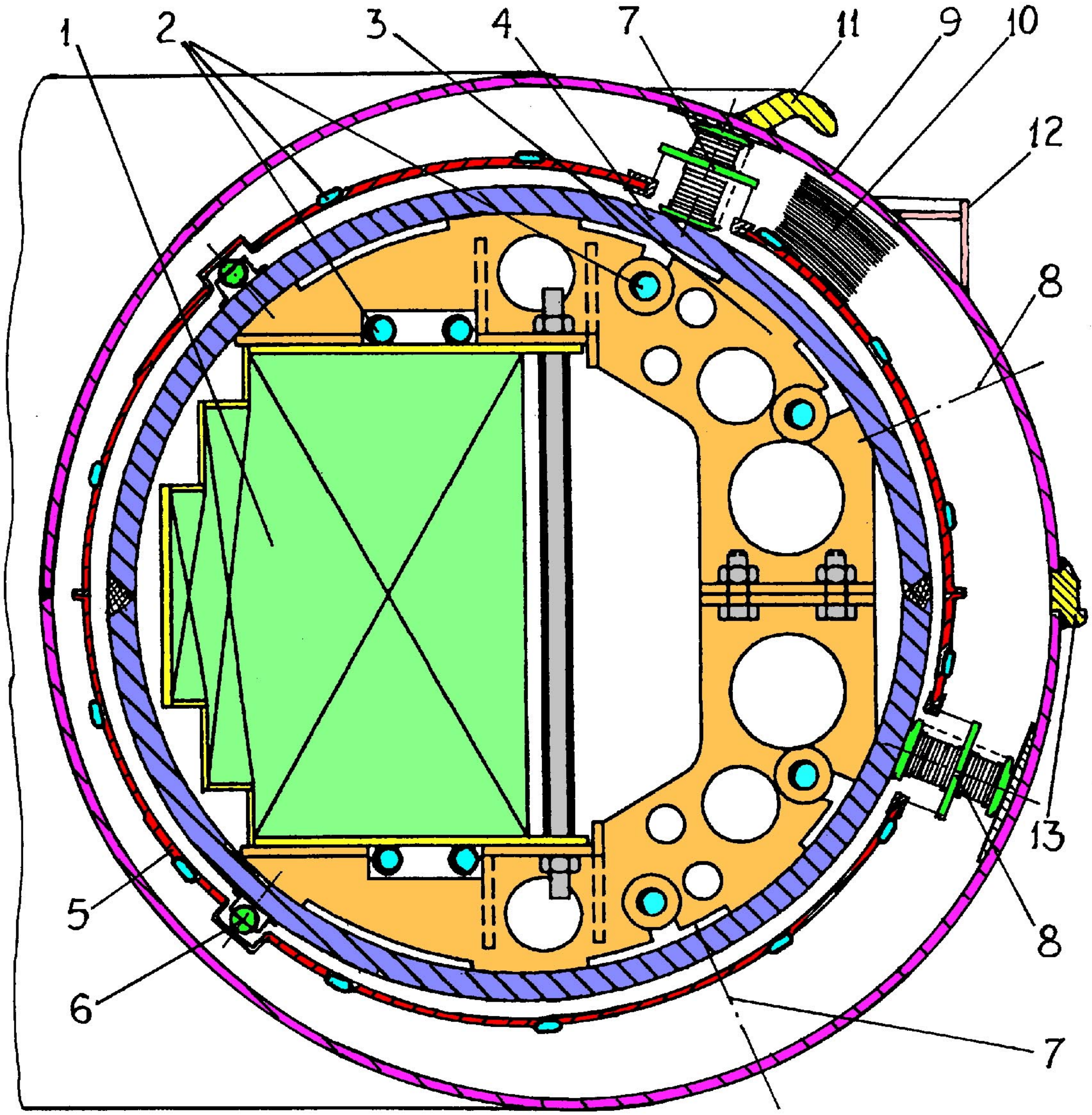
- Vacuum Vessel
  - Specifications
    - 5 meter (198") diameter, 3 m high, elevated off chamber floor
    - 11.5 Ton weight
  - Manufactured by Vacuum Technology Associates / DynaVac
- Ports
  - 2 50" ports (for floating ring installation)
  - 2 24" ports for cryopumping
  - 10 16.5" horizontal diagnostic ports
  - 8 10" horizontal ports
  - 8 laser alignment ports
  - Room for more!
- Construction Complete!
  - Pumped down and leak checked

# 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 3 concentric tori
  - Design < 1 Watt heat leak
  - Helium Pressure Vessel
    - Holds 1.5 kg of He
    - 125 Atm at room temperature
    - Cooling tube heat exchanger
  - Lead Radiation Shield
    - 75 kg Pb, good thermal capacity
  - Outer Vacuum Shell
    - Laser alignment surface



# F-Coil Cross-Section



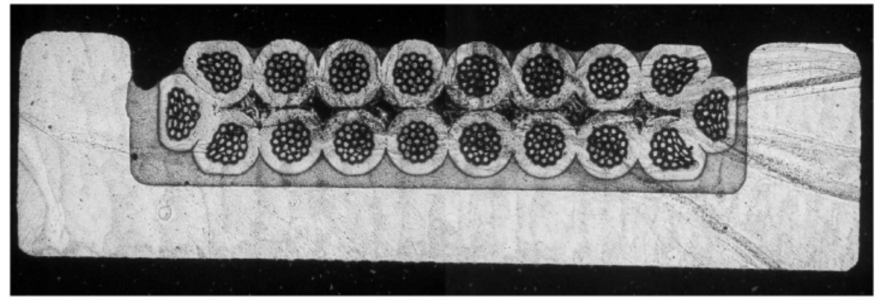

1. **Magnet Winding Pack**
2. **Heat Exchanger tubing**
3. **Winding pack centering clamp**
4. **He Pressure Vessel (Inconel 625)**
5. **Thermal Shield (Lead/glass composite)**
6. **Shield supports (Pyrex)**
7. **He Vessel Vertical Supports/Bumpers**
8. **He Vessel Horizontal Bumpers**
9. **Vacuum Vessel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

# F-Coil Superconductor

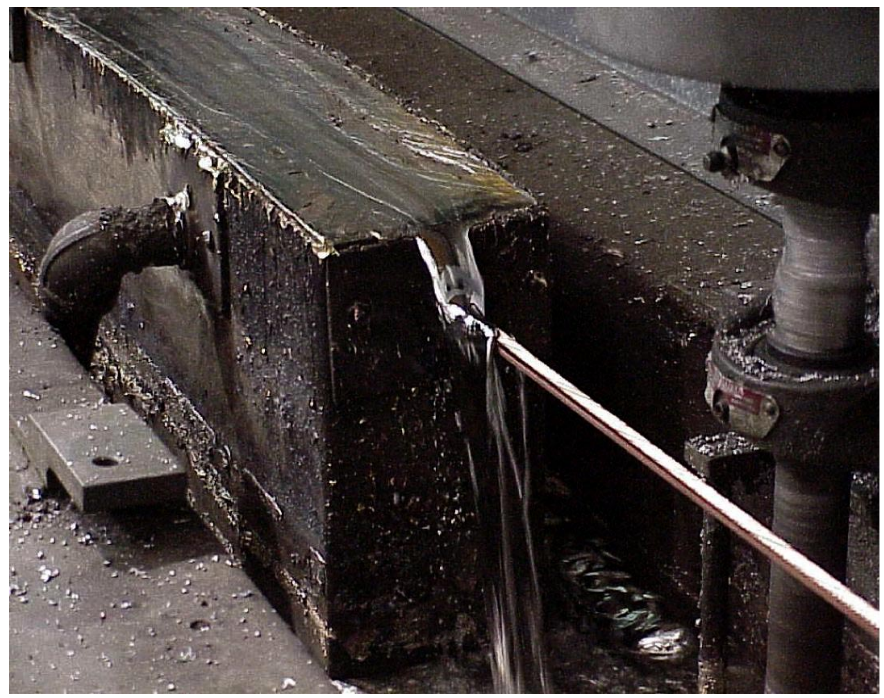
- Nb3Sn cable-in-channel superconductor manufactured in collaboration between industry, universities and national laboratories

| | |
|---|---|
| Contracted Vendor | IGC-AS |
| Strand production and testing | IGC |
| Cabling | LBL |
| Heat treatment | BNL |
| Soldering into Cu channel | IGC |
| Conductor sample testing | BNL |
| Conductor quality assurance | MIT/Everson |

- "State of the Art" conductor now complete
  - Samples tested and meet performance requirements
    - > 2000 Amps @ 6T and 10K
  - Currently being wound at Everson Electric on magnet coil form.

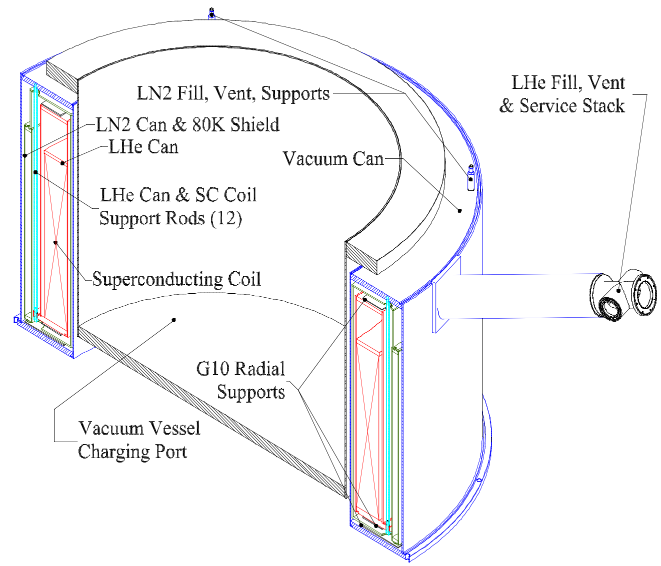


8 mm

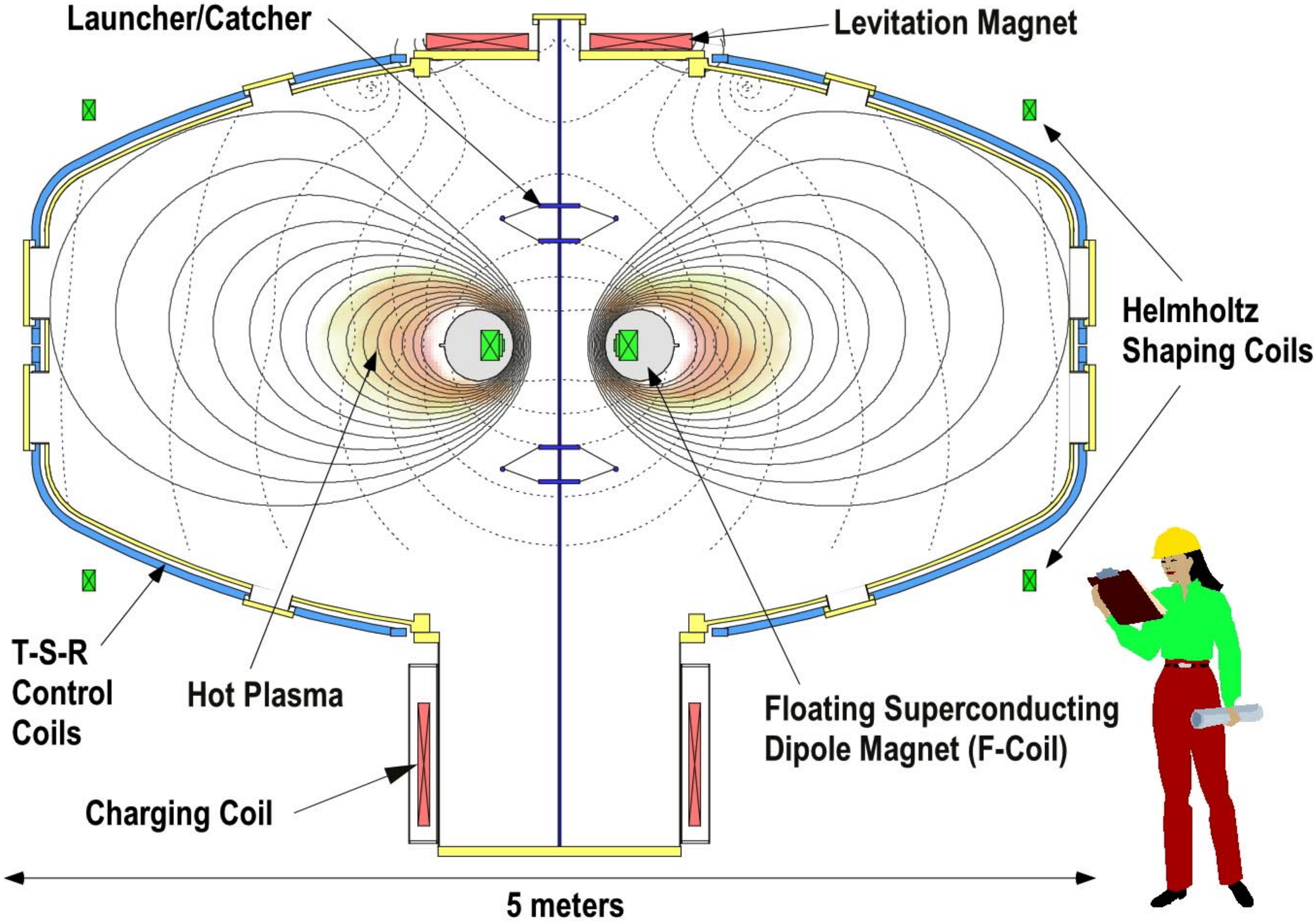


# Superconducting Charging Coil

- 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
  - 11.2 MJ stored energy
- Cycled 2X per day
  - Charging time for F-Coil < 30 min.
- Fabrication Status
  - Under contract with Efremov Institute, St. Petersburg, Russia
  - Expected delivery Winter 00/01.
    - "Critical Path" item for project.

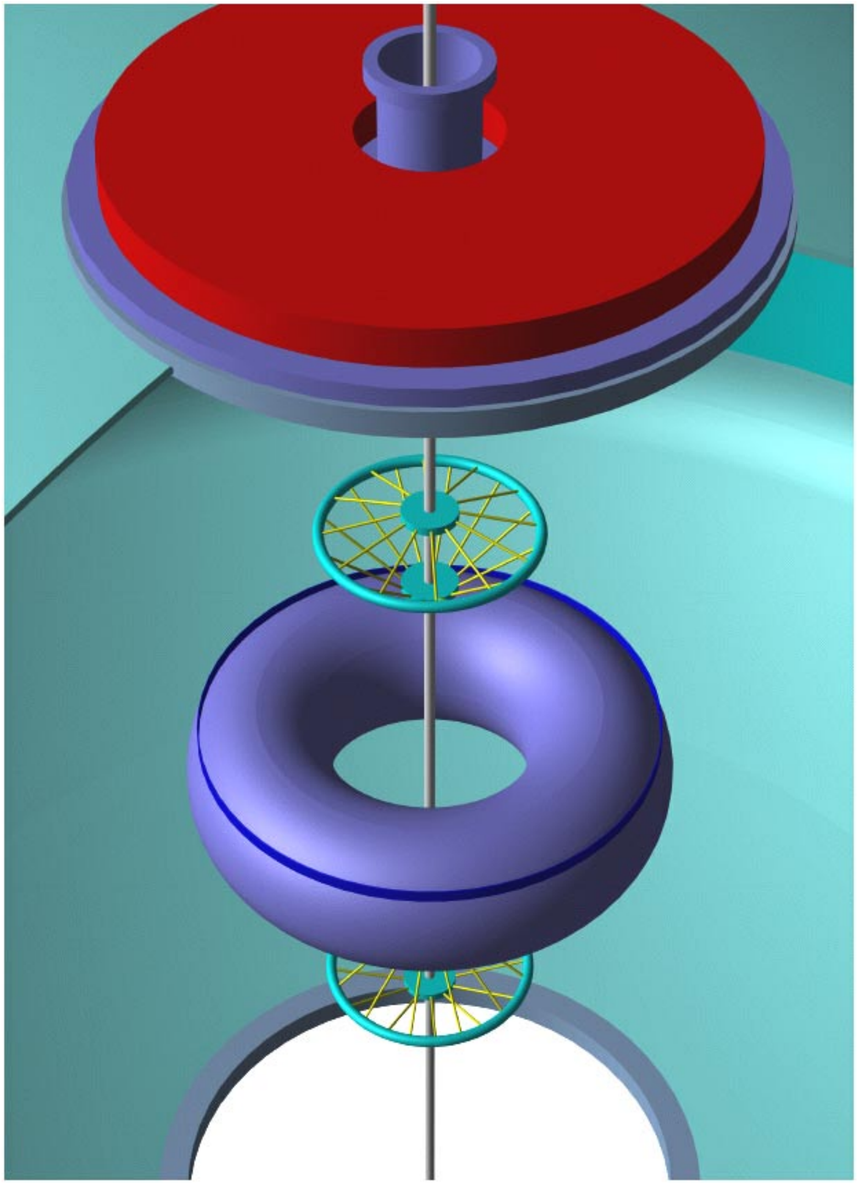



# LDX Experiment Cross-Section

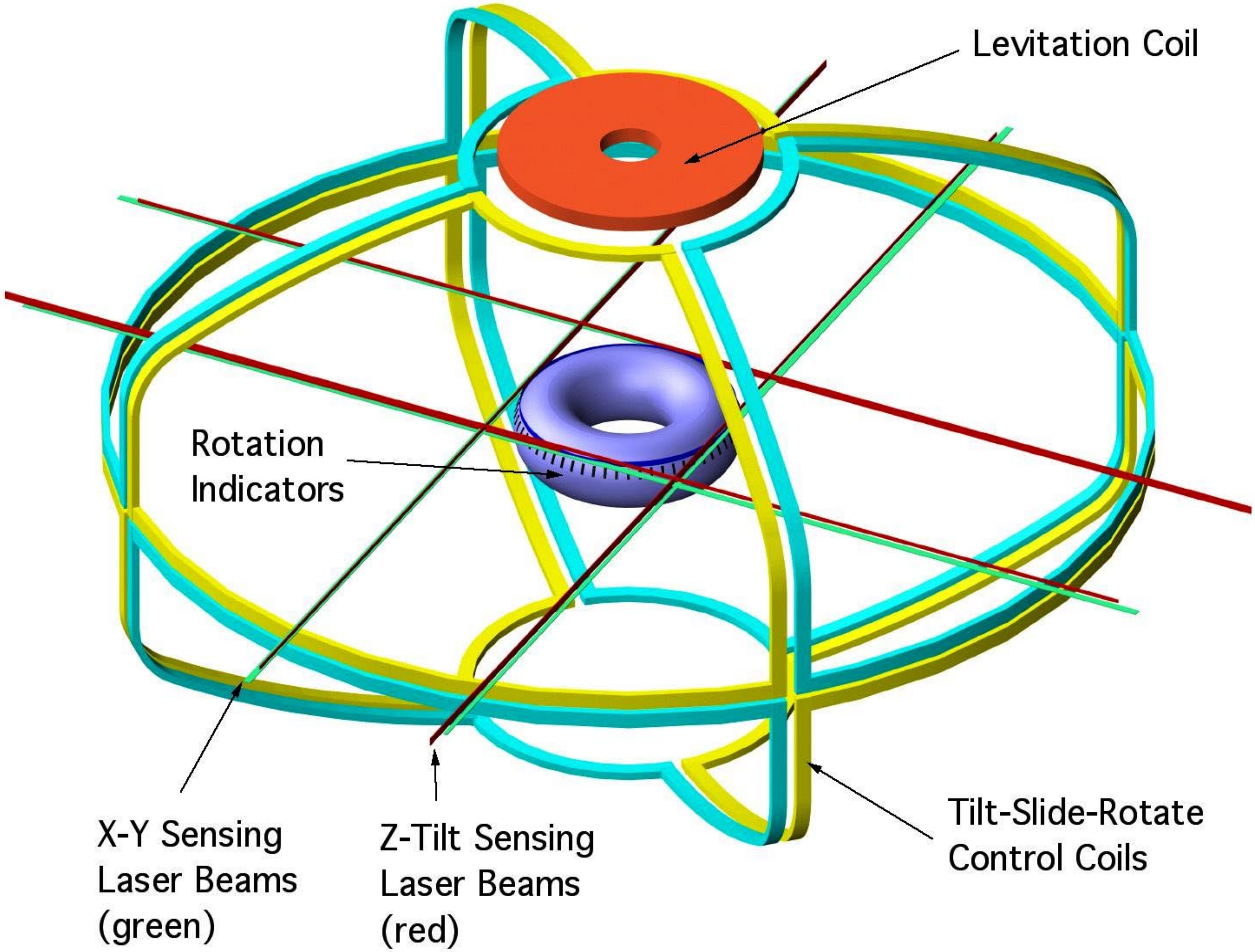


# Launcher/Catcher

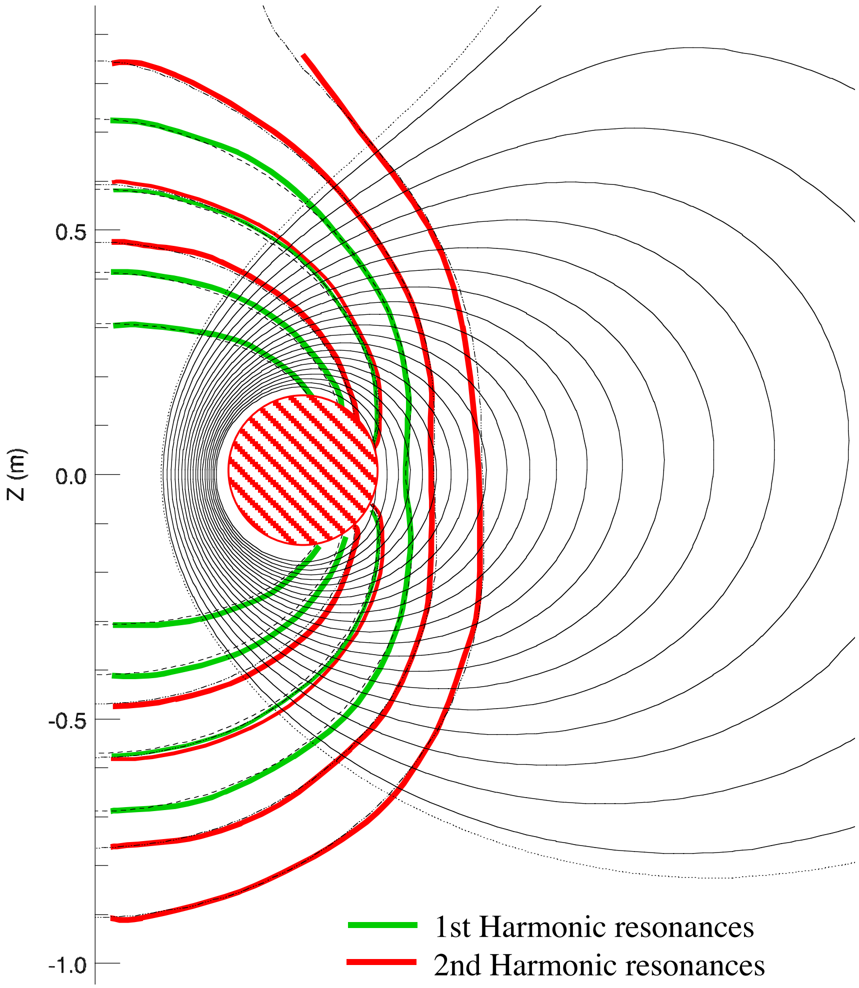
- "Simplified" Launcher/Catcher can be used in both supported and levitated operation
  - In supported operation "bicycle" wheels clamp floating coil in fixed position
  - In levitated operation, vertical spacing of wheels is increased
  - For upper levitation, all components are outside LCFS
- Currently being designed at PPPL
  - Dynamic testing to begin in late Spring 2000.



# Levitation Control System Schematic

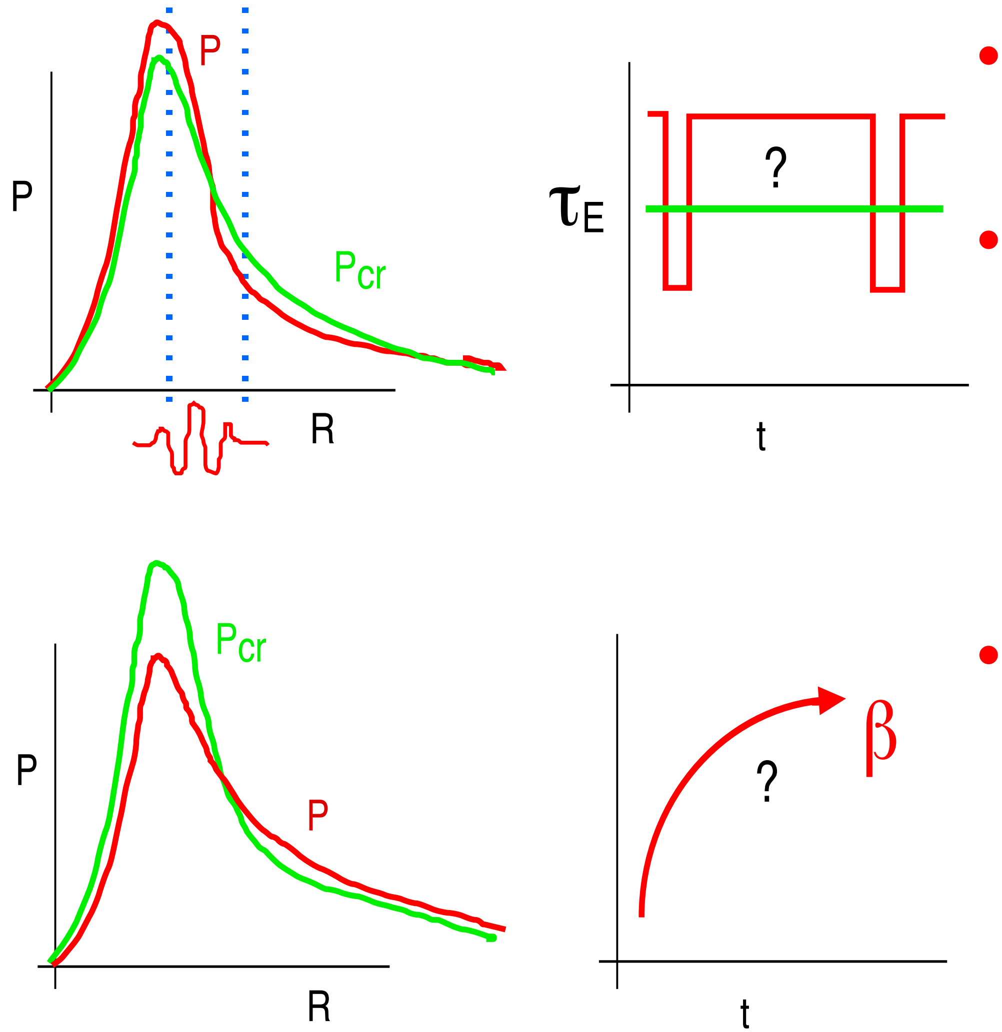


# Multi-frequency ECRH on LDX




- **Multi-frequency electron cyclotron resonant heating**
  - **Effective way to create high-$\beta$ hot electron population**
  - **Tailor multi-frequency heating power to produce ideal (stable) pressure profile with maximum peak $\beta$.**
  - **Profile control and improved ECRH efficiency seen in mirror program when using multiple frequencies.**

# Instabilities & Confinement




- Instability should exist when: $p' > p'_{critical}$
- Investigate nature of instability
  - How does it saturate?
  - How much transport is driven?
- Maximize $\beta$ when: $p' < p'_{critical}$ everywhere
  - What limits $\beta$ ?

# Multi-frequency ECRH in ST-1 Mirror

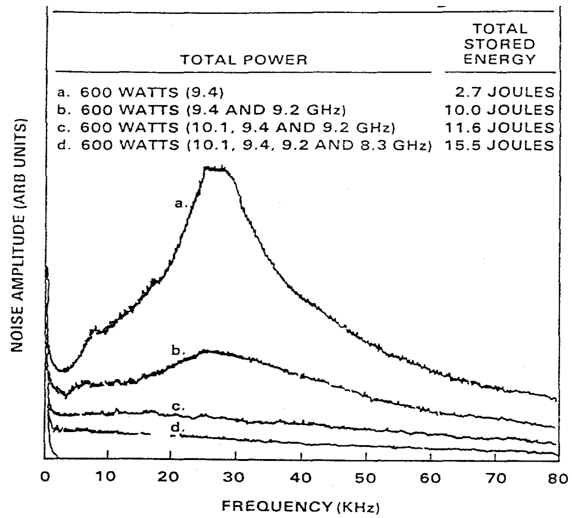



FIG. 11. Spectra of low-frequency fluctuations in the cold-electron end-loss current for four different heating configurations.

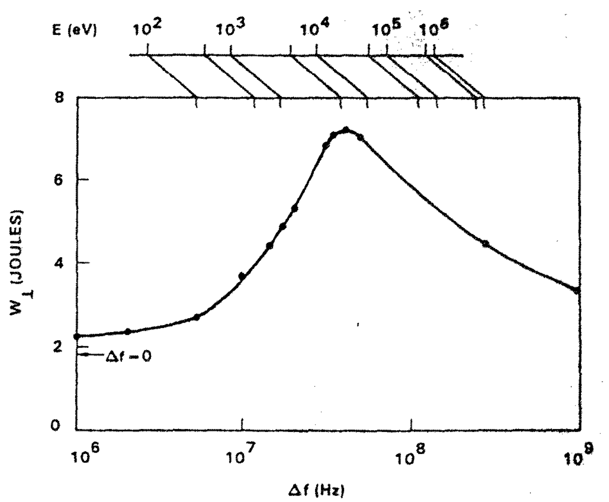



FIG. 9. Total stored energy as a function of frequency separation for two-frequency heating. The scale gives the electron energy for which the bounce frequency is equal to the applied frequency mismatch.

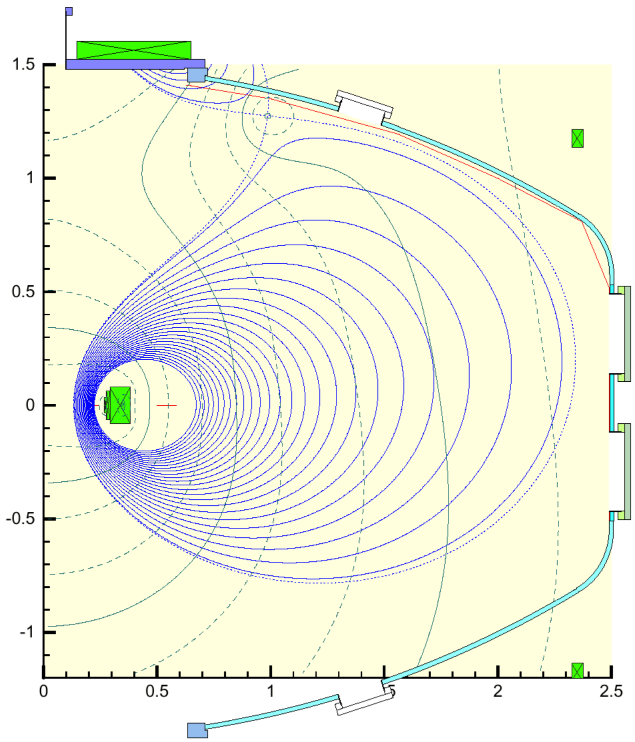
- **Widely spread ($\Delta f/f > 10\%$) multiple frequencies allowed stable operation**
  - **Low frequency fluctuations in cold electron end losses are reduced by order of magnitude**
  - **Large increase in stored energy in high-$\beta$ hot electrons**
- **Narrowly spread ($\Delta f \sim f_{bounce}$) frequencies improved efficiency of hot electron heating**
  - **Elimination of super-adiabatic effects that create phase-space barrier for further heating of hot electrons.**
- **B. Quon et al, *Phys. Fluids* 28, (1985) 1503.**

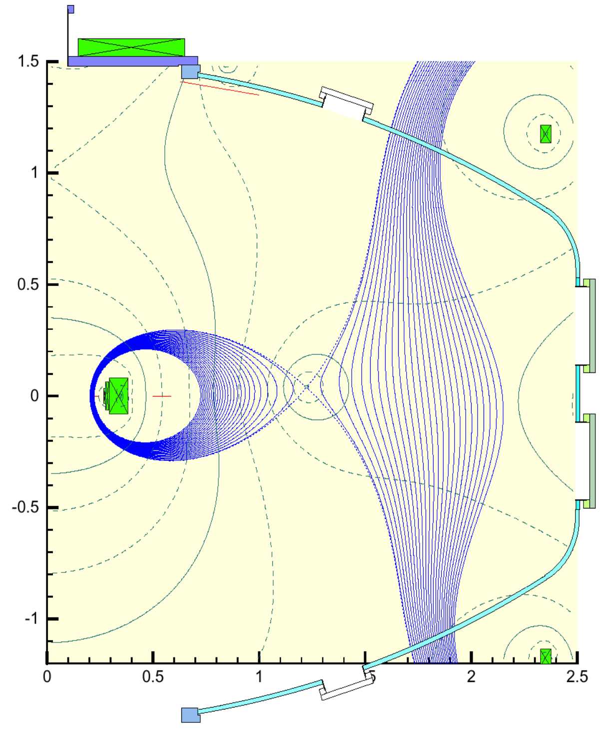
# Helmholtz Shaping Coils

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

| | |
|---|---|
| **Helmholtz Coil:** | **0 kA** |
| **Compression Ratio:** | **228** |
| **Adiabatic Pressure Ratio:** | **8500** |

| | |
|---|---|
| **Helmholtz Coil:** | **80 kA** |
| **Compression Ratio:** | **14** |
| **Adiabatic Pressure Ratio:** | **85** |




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

# LDX Experimental Plan

- Supported Dipole Hot Electron Plasmas
    - Spring 2001
  - High- $\beta$ Hot Electron plasmas with mirror losses
  - ECRH Plasma formation
  - Instabilities and Profile control
- Levitated Dipole Hot Electron Plasmas
    - Winter 2001
  - No end losses
  - $\beta$ enhancement
  - Confinement studies
- Thermal Plasmas
  - Convective cell studies
  - Concept Optimization / Evaluation

# Hot Electron Plasmas

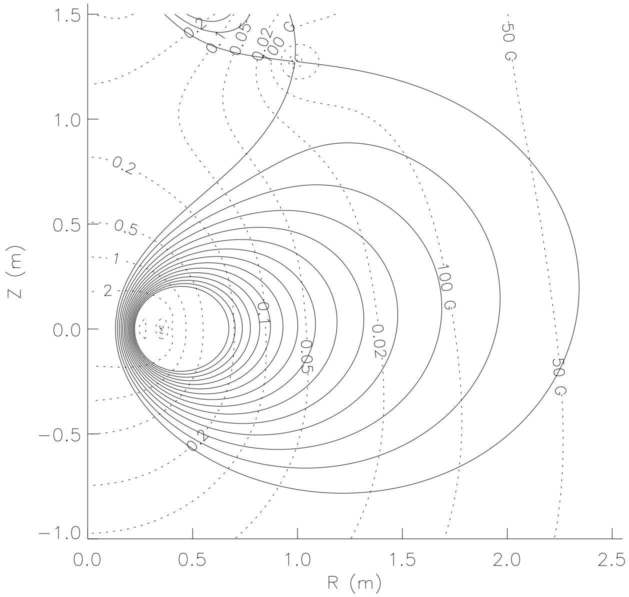
- Supported Dipole Campaign
  - Low density, quasi steady-state plasmas formed by multi-frequency ECRH with mirror losses
  - Areas of investigation
    - Plasma formation
    - Density control
    - Pressure profile control
    - Supercritical profiles & instability
    - Compressibility Scaling
    - ECRH and diagnostics development
- Levitated Dipole Campaign
  - No end losses
  - Areas of investigation
    - Global Confinement
    - $\beta$ enhancement and scaling

# Hot Electron Plasma Diagnostics

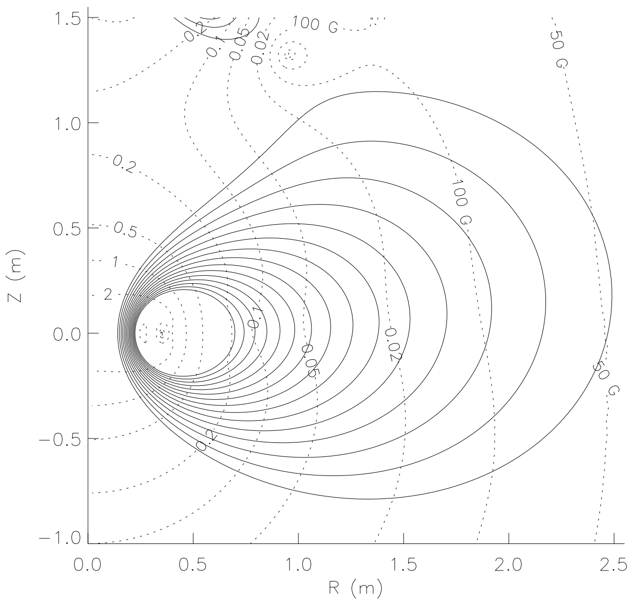
- Magnetics (flux loops, hall probes)
  - Plasma equilibrium shape
  - magnetic $\beta$ & stored energy
- Reflectometer
  - Density profile
- X-ray pulse height energy analyzer
  - Hot electron energy distribution / profile
- XUV arrays
  - Instabilities and 2-D profiles
- $D_a$ camera
- Edge probes

# LDX Magnetics Measurements

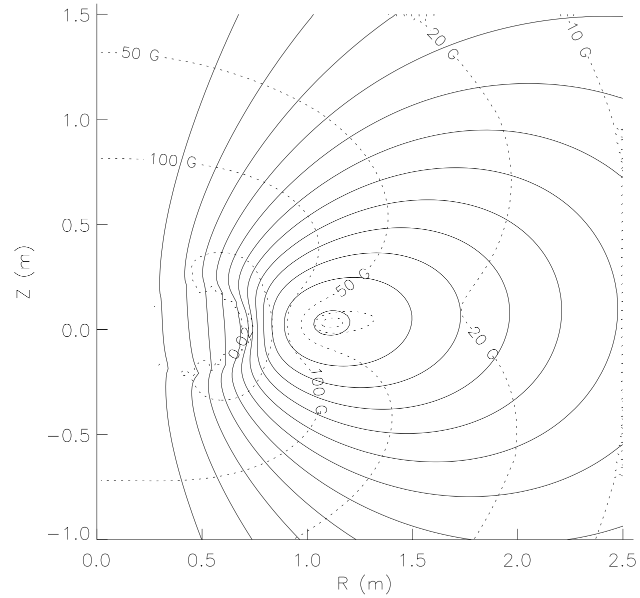
**Vacuum**




$\langle\beta\rangle_{max}$ = 50%




**Difference**




- **DC dipole field means standard integrator diagnostics can be used**
- **Superconductor dipole “freezes-in” flux giving an internal boundary condition for GS solver**

# Future LDX Project Milestones

- Floating Coil driven test
  - Full current test with leads in test cryostat
- F-Coil He pressure vessel sealed
- Floating Coil & Charging Station Delivery
- Integrated Systems Test
  - Small current induced in F-Coil with copper coil
- Charging Coil Delivery
- First Plasma
- First Levitation

# Conclusions

- Physics of the dipole is interesting and important for Fusion
- 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
- LDX is a “world class” superconducting fusion experiment
- All major parts are either finished or under construction
- Look out for us next year ! Watch http://www.psfc.mit.edu/ldx/