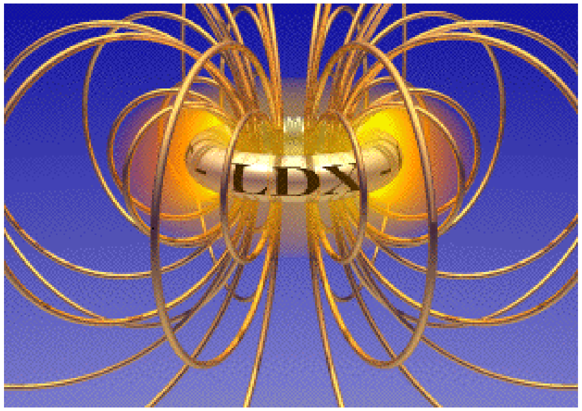


Overview of the Levitated Dipole Experiment (LDX)

D. Garnier, M. Mauel, *Columbia University*

J. Kesner, J. Minervini, P. Michael, A. Radovinsky,
J. Schultz, B. Smith, P. Thomas, A. Zhukovsky, *MIT PSFC*

R. Ellis, *PPPL*

Presented at

The 41st Annual Meeting of the Division of Plasma Physics

of the American Physical Society

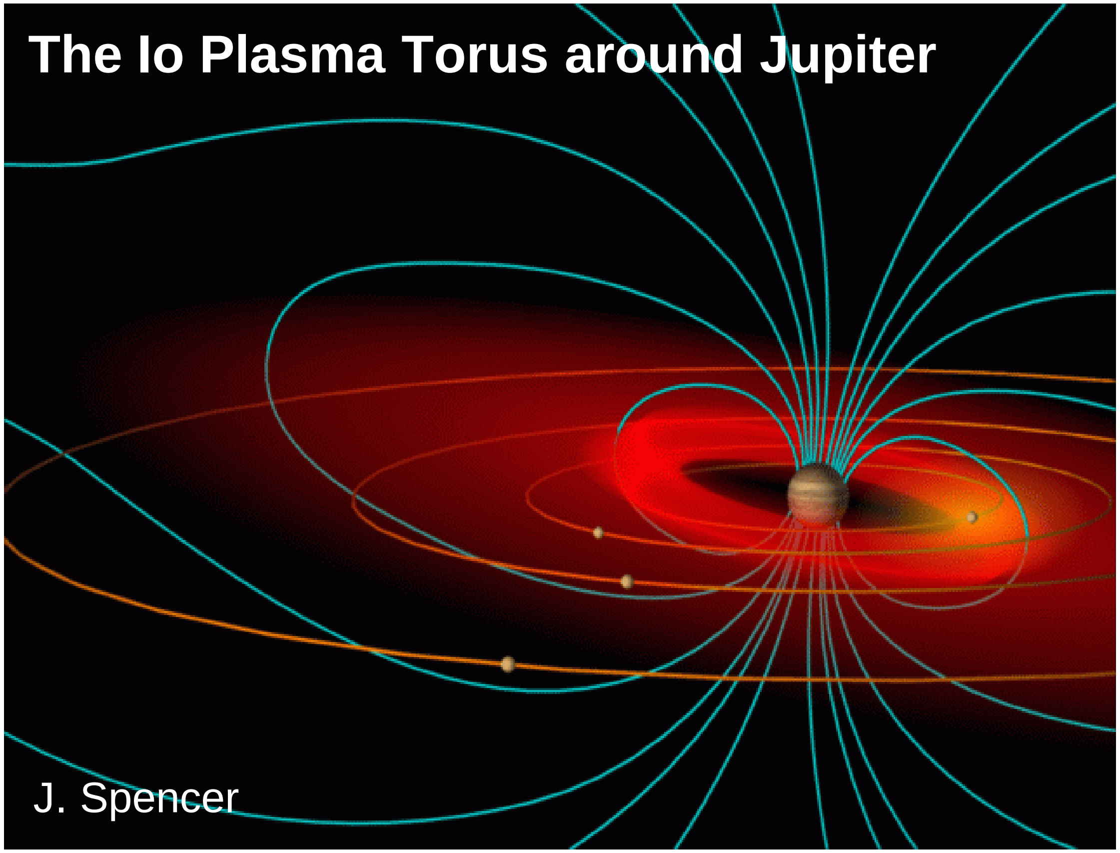
Seattle, Washington, November 15, 1999

Abstract

The Levitated Dipole Experiment (LDX) is designed to study high-β plasmas confined by a magnetic dipole with near-classical energy confinement. LDX is currently under construction at MIT. Current construction status, including results from the dipole magnet test program, is presented.

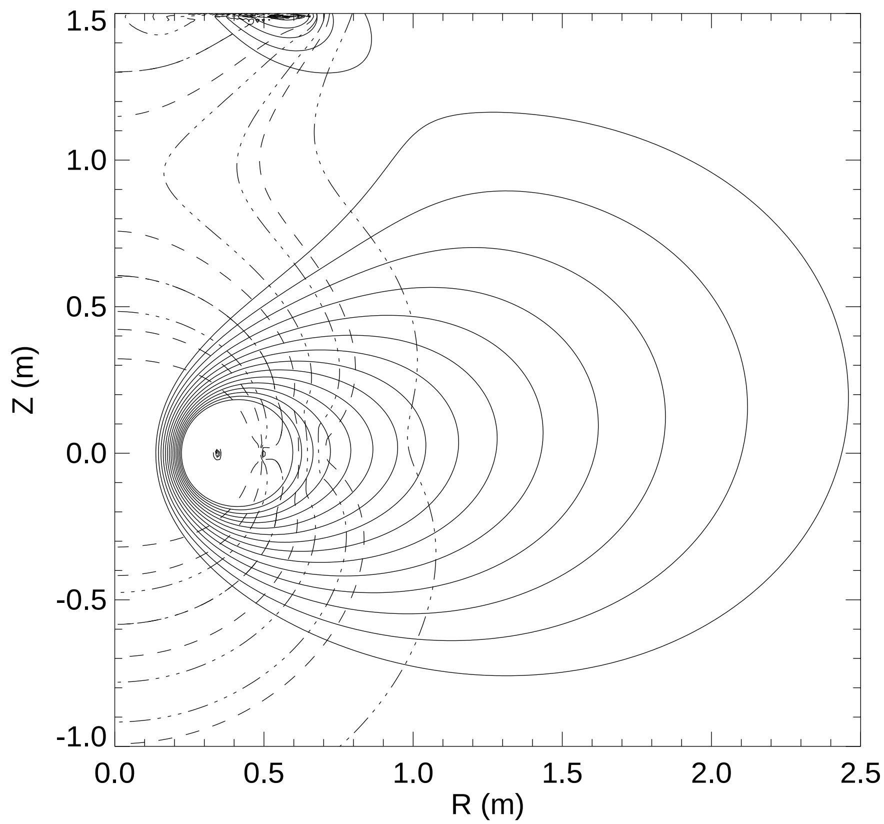
The primary goal of the initial phase of LDX operation is the study of plasma behavior near marginal stability for interchange modes at high β (β ~ 0.5). In these experiments, the dipole ring will be mechanically supported and hot-electron plasmas will be produced by multiple frequency electron cyclotron heating. Initial experiments will focus on plasma formation and density control with later experiments investigating pressure profile control and MHD stability. An overview of the LDX machine design, initial diagnostic set, and experimental plan for the first year of operations is presented.

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 Confinement



Computed LDX equilibrium showing plasma flux surfaces and electron cyclotron resonant surfaces. The Equilibrium has a peak local beta $\beta \sim 2$and a flux tube average beta $<\beta>\sim 1$

- **Toroidal confinement without toroidal field (no neoclassical effects)**
- **Stabilized by plasma compressibility**
- **Marginally stable profiles satisfy adiabaticity condition.**
  - **M.N. Rosenbluth and Longmire, *Ann. Phys.* 1 (1957) 120.**
- **Such plasmas are ideal ballooning stable**
  - **D. Garnier, J. Kesner and M. Mauel, submitted to *Phys. Plasmas* (1999)**
- **For $\eta \leq 2/3$ profiles, dipoles are also drift wave stable.**
  - **J. Kesner, *Phys. Plasmas*, 5 (1998).**

Dipole Geometry

- **Compressibility Condition**
  - **Stationary pressure profiles**

$$\delta\left(pV^{\gamma}\right)=0$$

$$V\equiv\oint\frac{d\ell}{B},\gamma=5/3$$

- **Dipole Geometry**

$$B\propto r^{-3}\Rightarrow V\propto r^{4}$$

$$\Rightarrow p\propto r^{-20/3}$$

$$\beta\propto\frac{p}{B^{2}}\propto r^{-2/3}$$

$$\eta\equiv\frac{L_n}{L_T}=2/3$$

- **Stationary *n* & *T* profiles**

$$n\propto r^{-4},\ T\propto r^{-8/3}$$

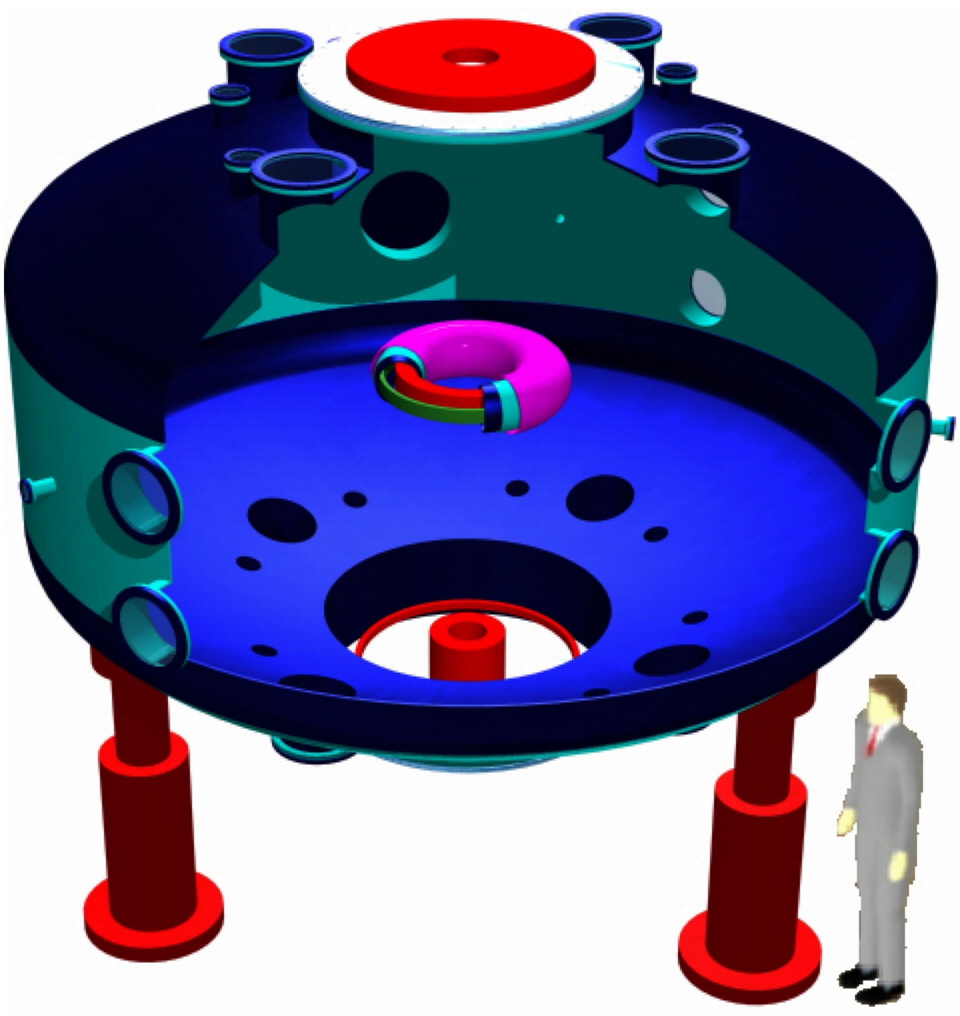
- **Scale Lengths**
  - **Dipole**
  - **Tokamak**

$$R_c\approx\frac{r}{2},\ L_n\approx\frac{r}{4}\Rightarrow\frac{R_c}{L_n}\approx 2$$

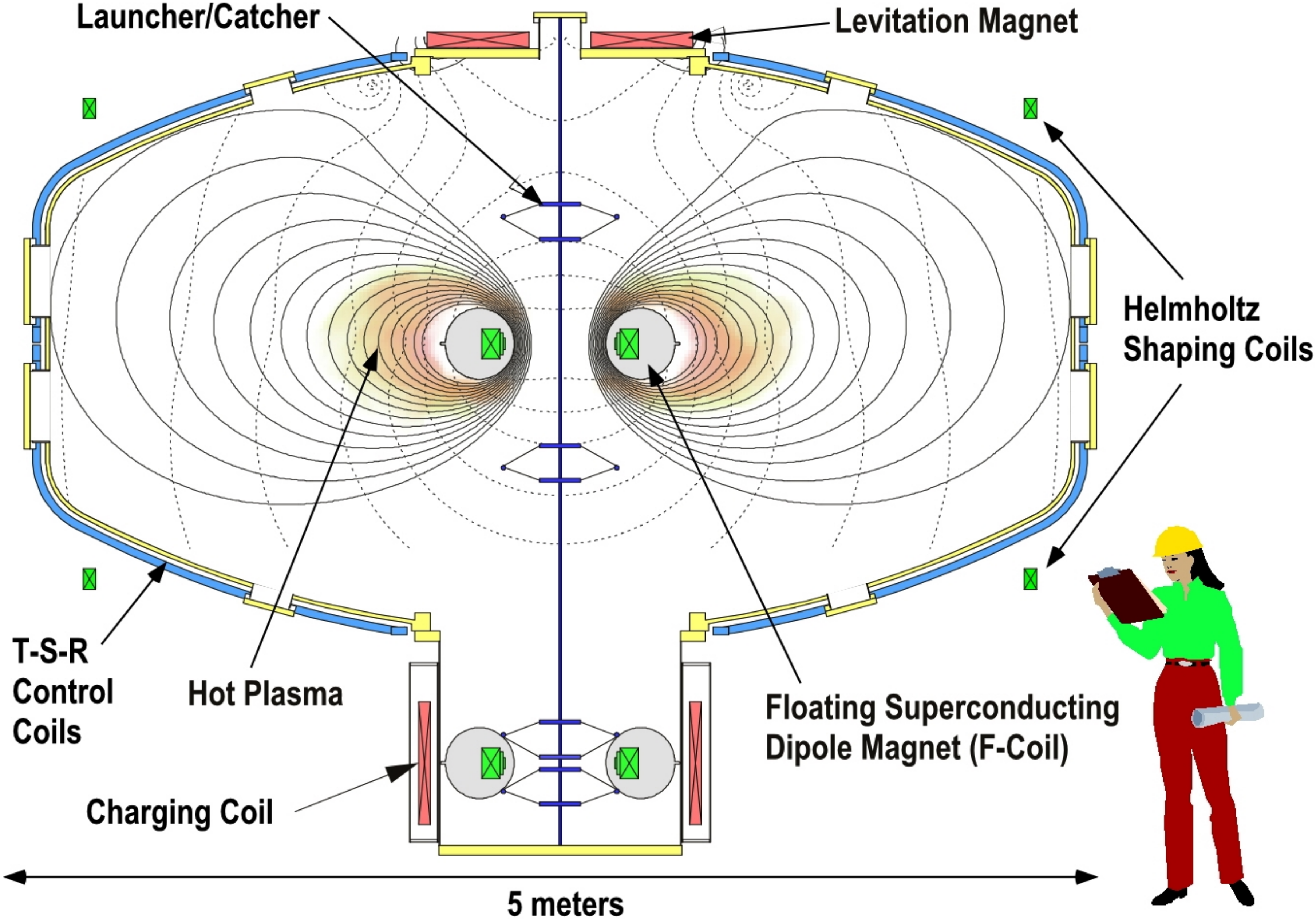
$$R_c\approx \mathrm{R},\ L_n\approx a\Rightarrow\frac{R_c}{L_n}\approx\frac{R}{a}\approx 3-4$$

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



LDX Experiment Cross-Section

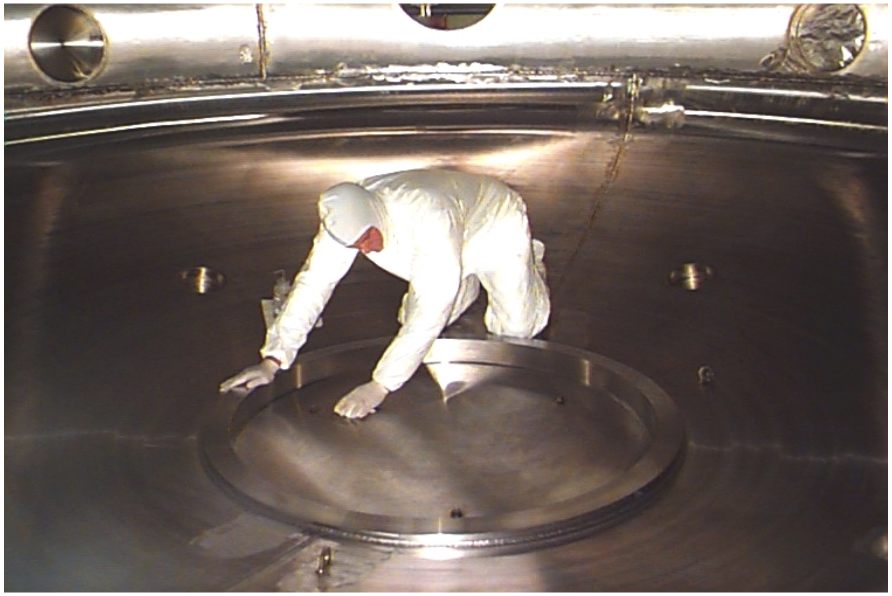


LDX Vacuum Vessel

- 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!

Initial Vessel Pumpdown !

- Vacuum Vessel Pumpdown #1
  - Roughed down on 1st attempt
  - Achieved pressure of 7.5×10^{-8} Torr
    - After 7 days w/o baking
    - And with only a 1000 l/s turbo pump
    - Residual gas is primarily water
  - Calibrated leak check procedure found no discernable leak ($< 1 \times 10^{-9}$ std. cc. / sec)
- Performance exceeds requirements
- History
  - Columbia/MIT Design Complete 11/98
  - Contract Award 1/99
  - Vendor Design Review 3/99
  - On-site construction 6/99
  - "Big Lift" and large port welding 7/99
  - Vacuum pumping installation 8/99
  - Pump-down & Leak-check 9/99

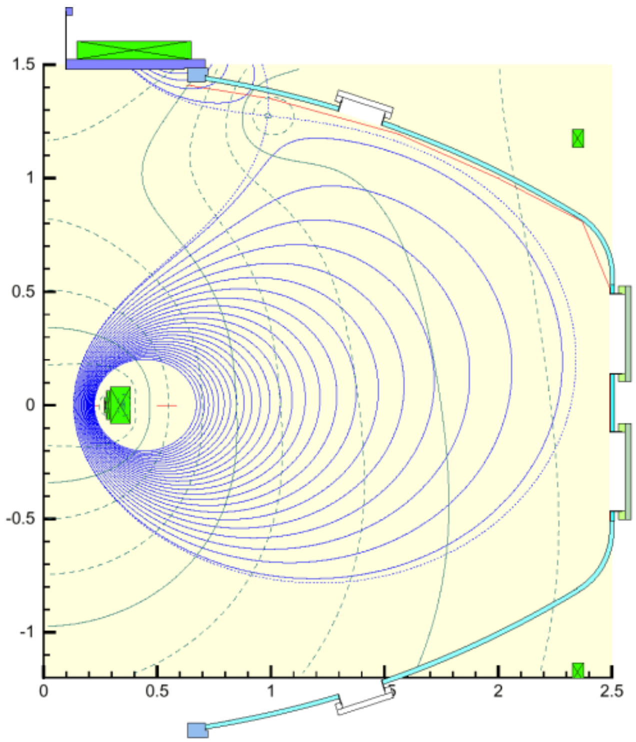


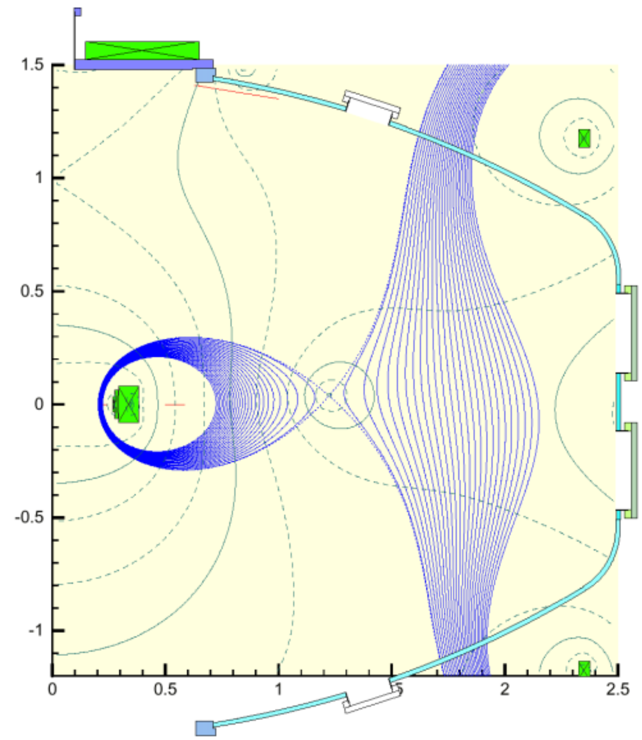
Helmholtz Shaping Coils

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

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

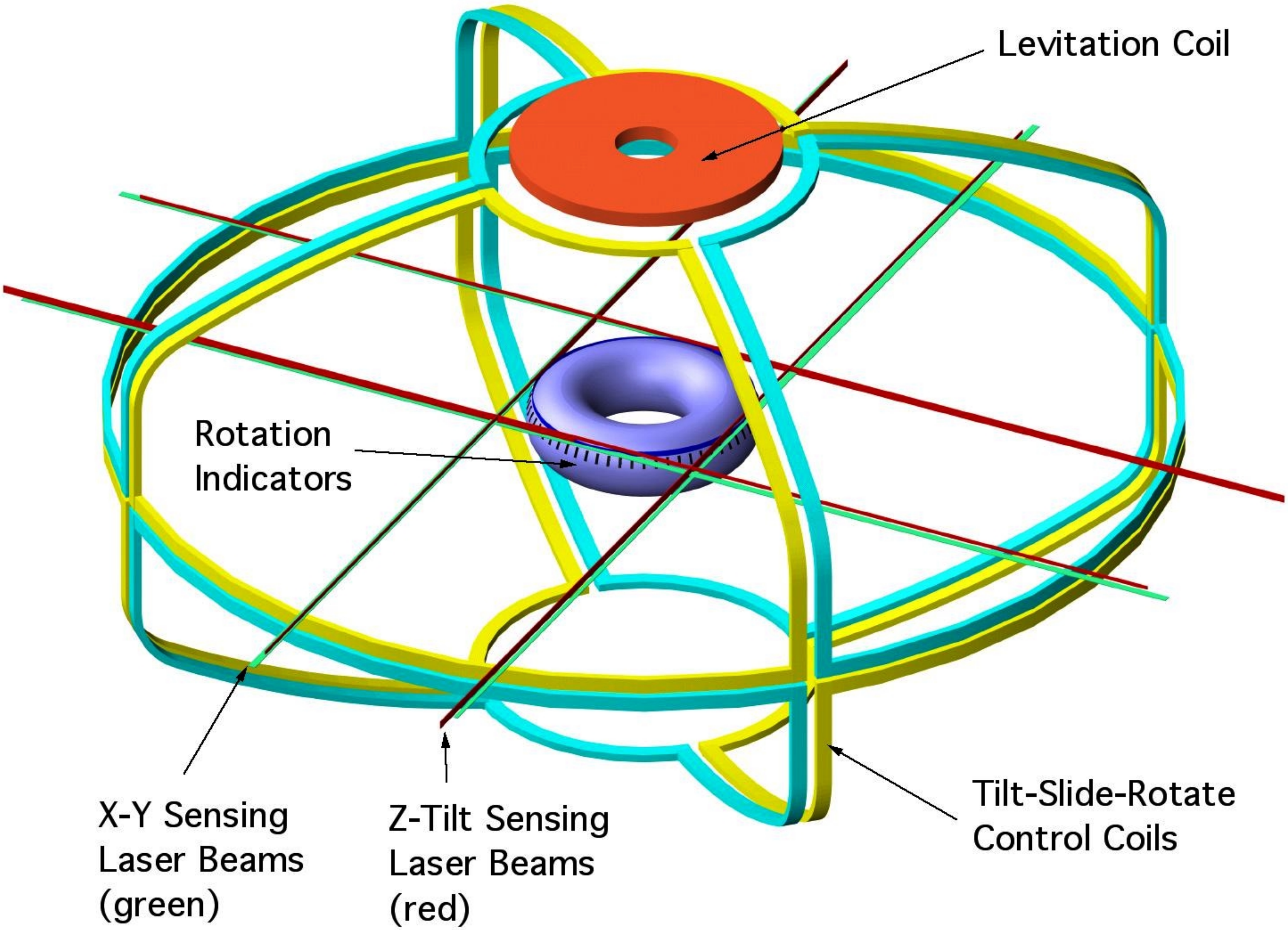
Helmholtz Coil:	**80 kA**
Compression Ratio:	**14**
Adiabatic Pressure Ratio:	**85**





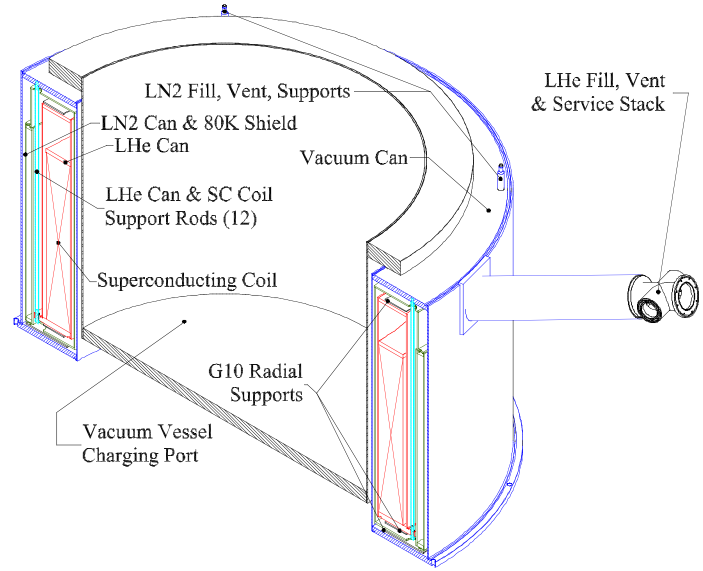
Compressibility can be adjusted to change marginal stable pressure by factor of 100!

Levitation Control System Schematic



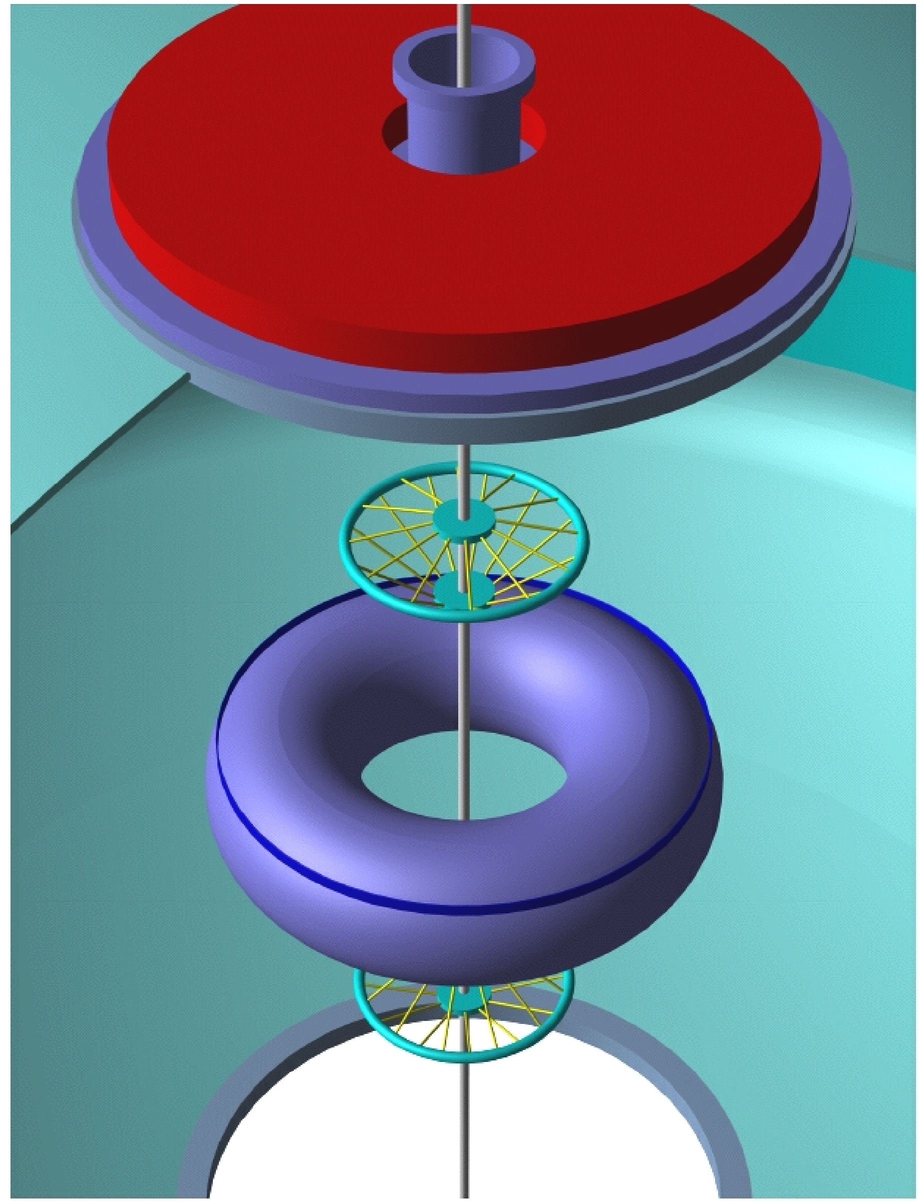
Superconducting Charging Coil

- Large superconducting coil
  - NbTi conductor
    - 4.5°K LHe pool-boiling cryostat with LN2 radiation sheild
  - 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.
- MIT design complete
  - Currently reviewing vendor bids
  - Expected delivery 12/00.
    - “Critical Path” item for project.



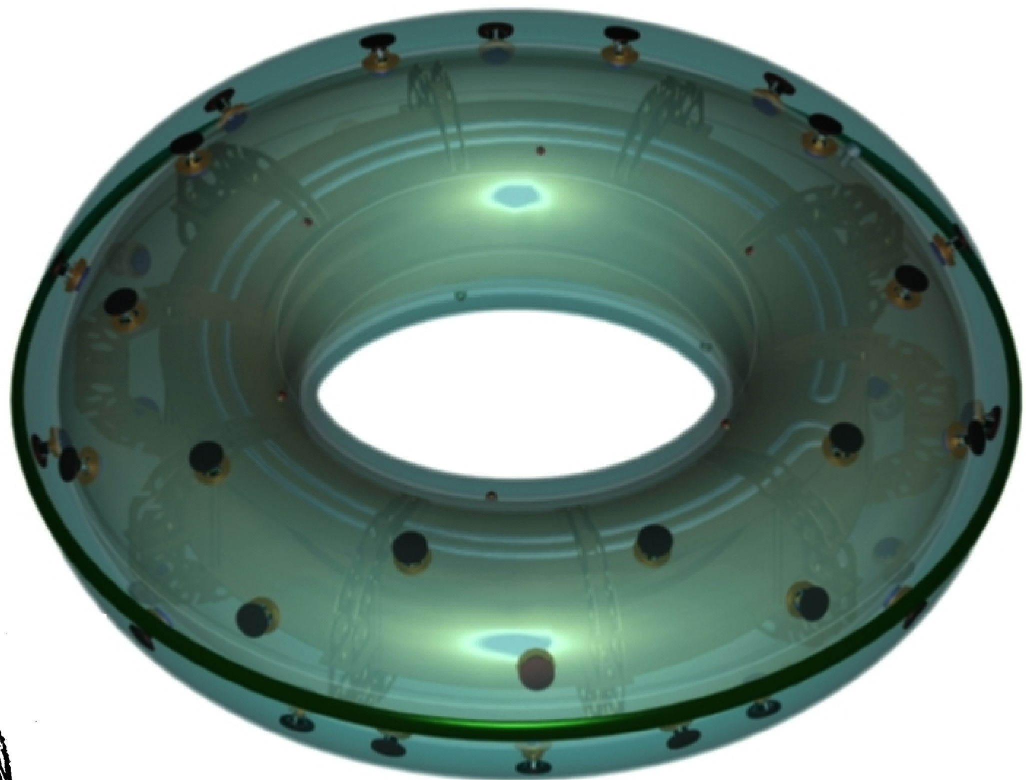
Launcher/Catcher

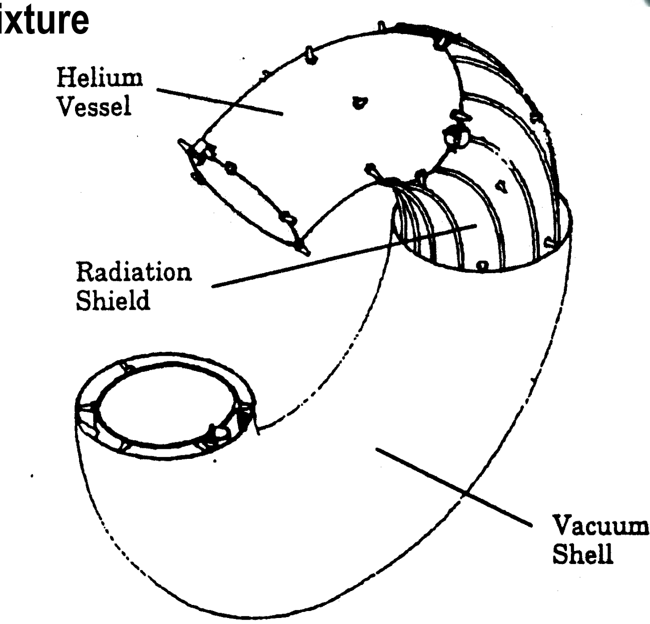
- "Simplified" Launcher/Catcher can be used in both supported and levitated operation
  - In supported operation "bicycle" wheels clamp floating coil in fixed position
  - In levitated operation, vertical spacing of wheels is increased
  - For upper levitation, all components are outside LCFS
- Currently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



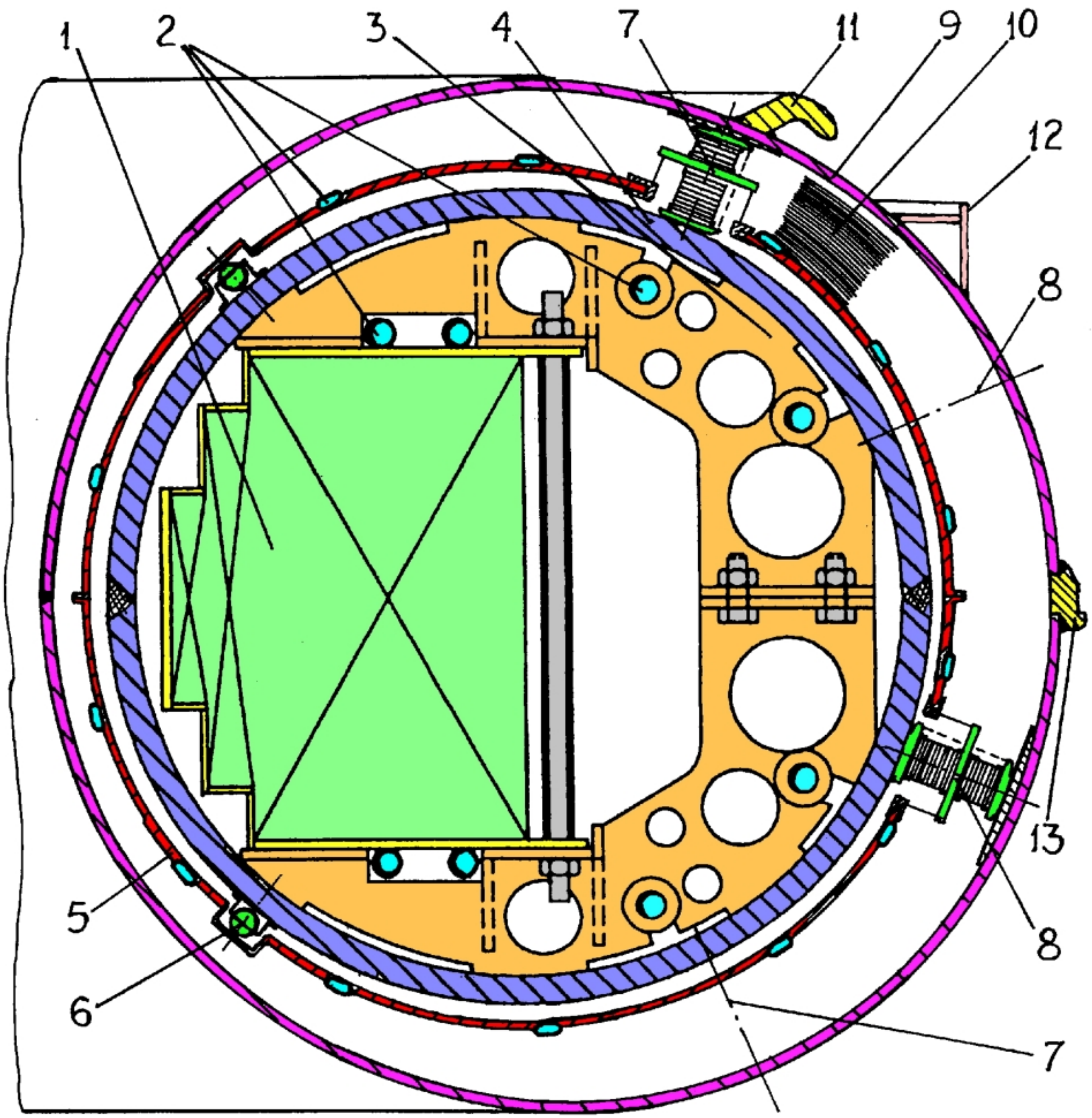
LDX Floating Coil Overview

- Helium Pressure Vessel
  - Coil Form
  - Superconducting Floating Coil
  - Heat-exchange/Cooling Tubes
- Lead Radiation Shield
  - Heat-exchange/Cooling Tubes
  - Supports & Bumpers
- Outer Vacuum Shell
  - Laser alignment surface
  - Lifting fixture
  - Limiter



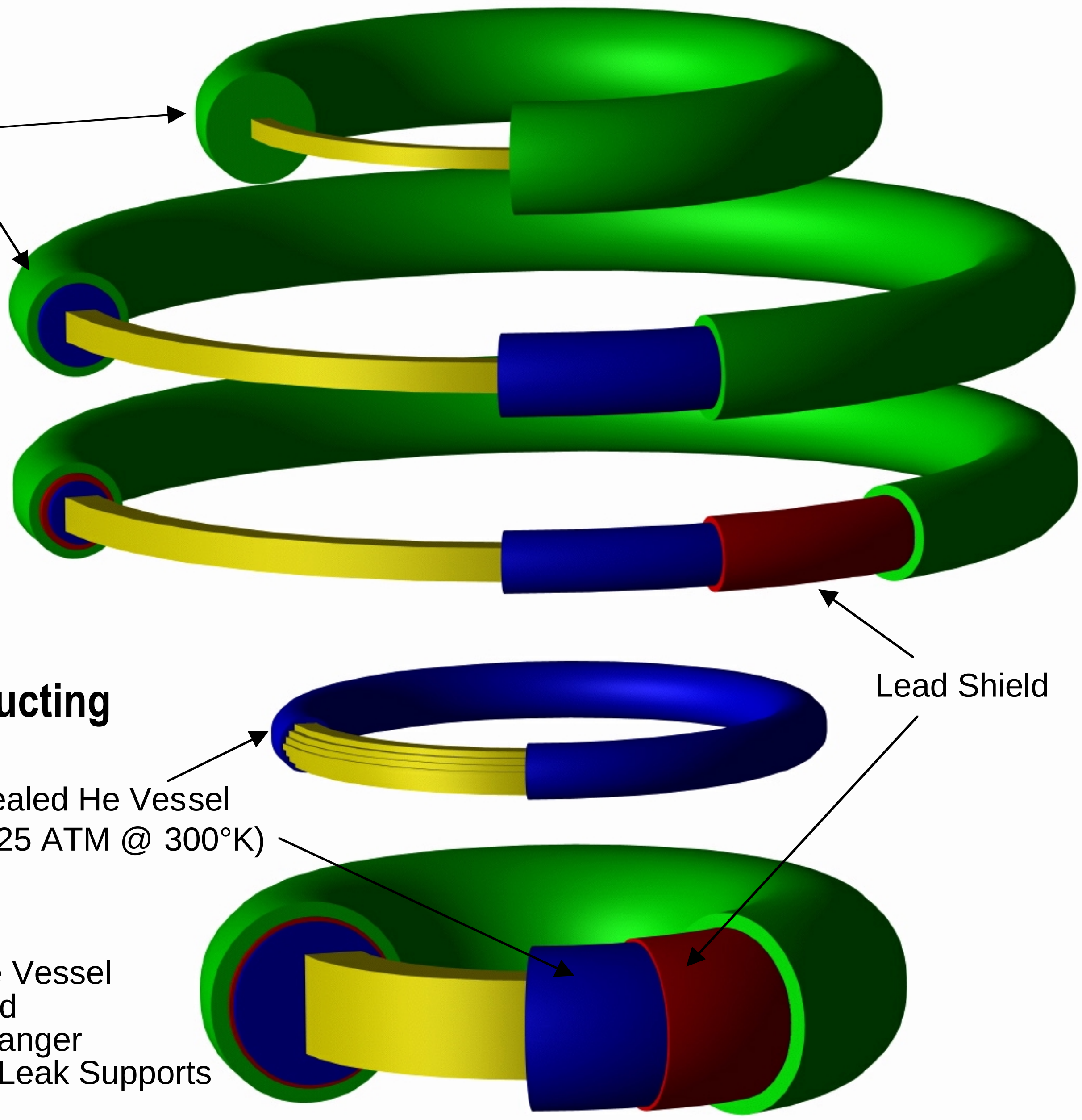


F-Coil Cross-Section



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

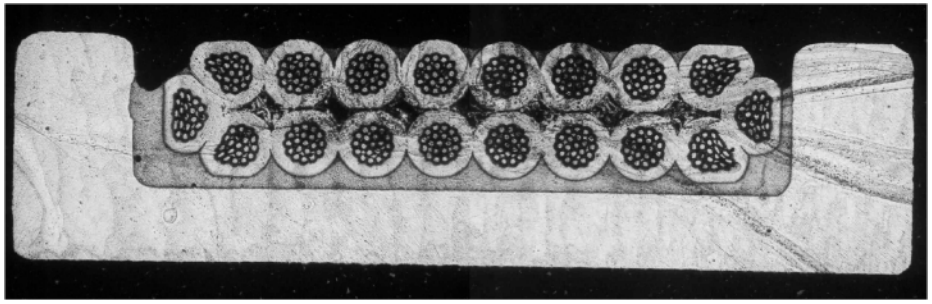
Nb_3Sn Floating Ring Experience Contributed to LDX Design



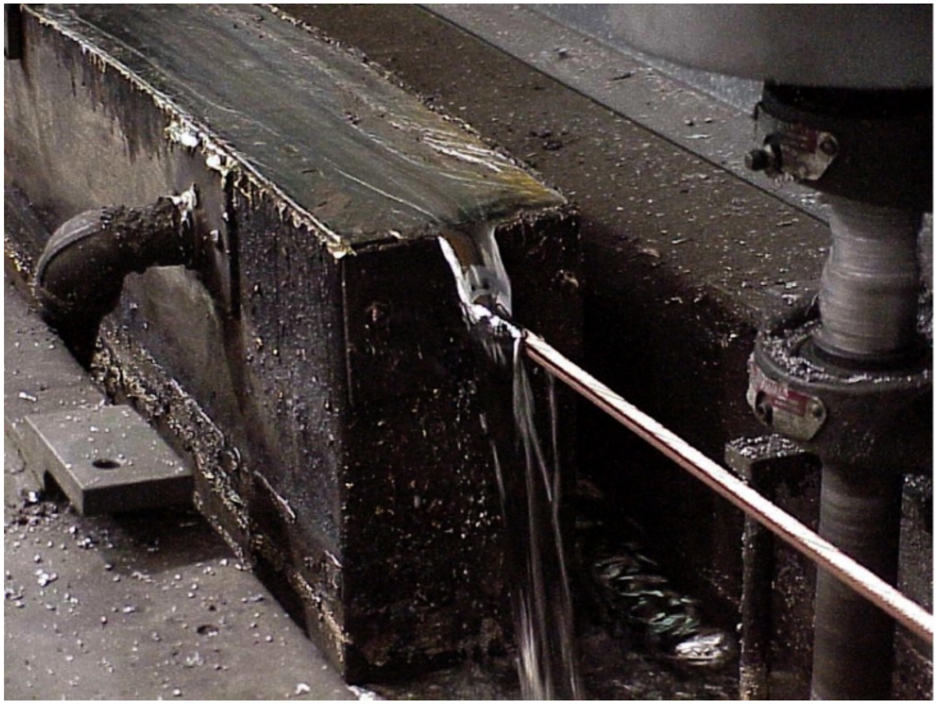
F-Coil Conductor Overview

- Nb3Sn cable-in-channel superconductor manufactured by IGC-Advanced Superconductor
  - 18 strand cable
  - soldered into copper channel
- History

Strand production (IGC)	6/98-5/99
Cabling (LBL)	5/99
Heat treatment (BNL)	7/99
Solder into Cu channel (IGC)	8/99
Conductor sample test (BNL)	9/99
Conductor repair	
Develop repair procedure	9/99
Test repaired sample (BNL)	9/29/99
Repair at Everson	11/99
Winding (Everson)	11/99

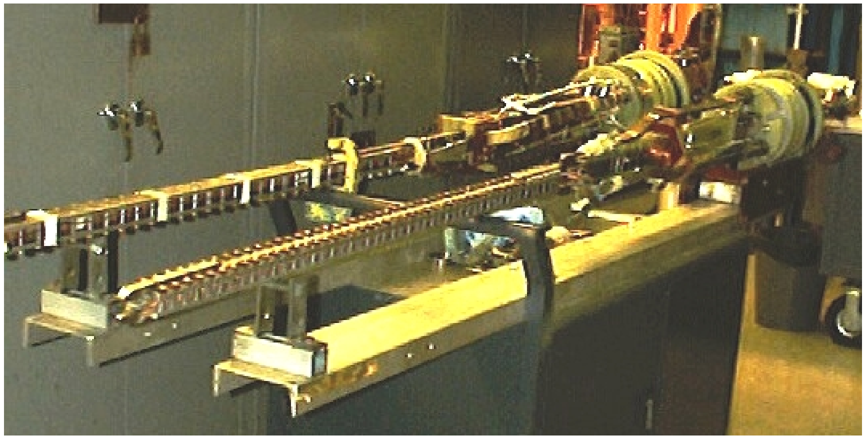


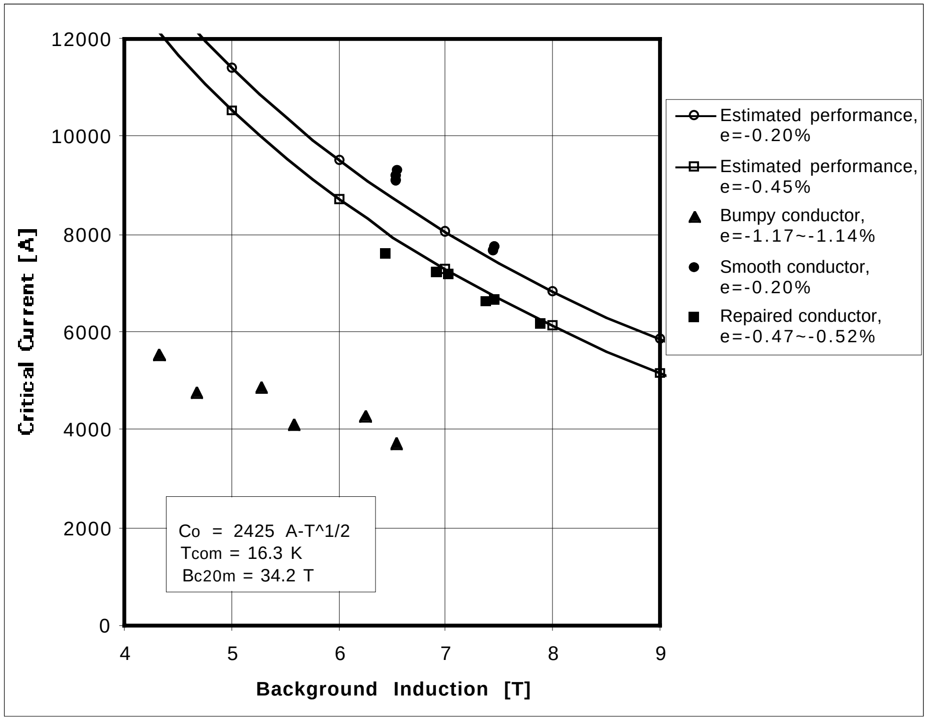
8 mm



F-Coil Conductor Testing

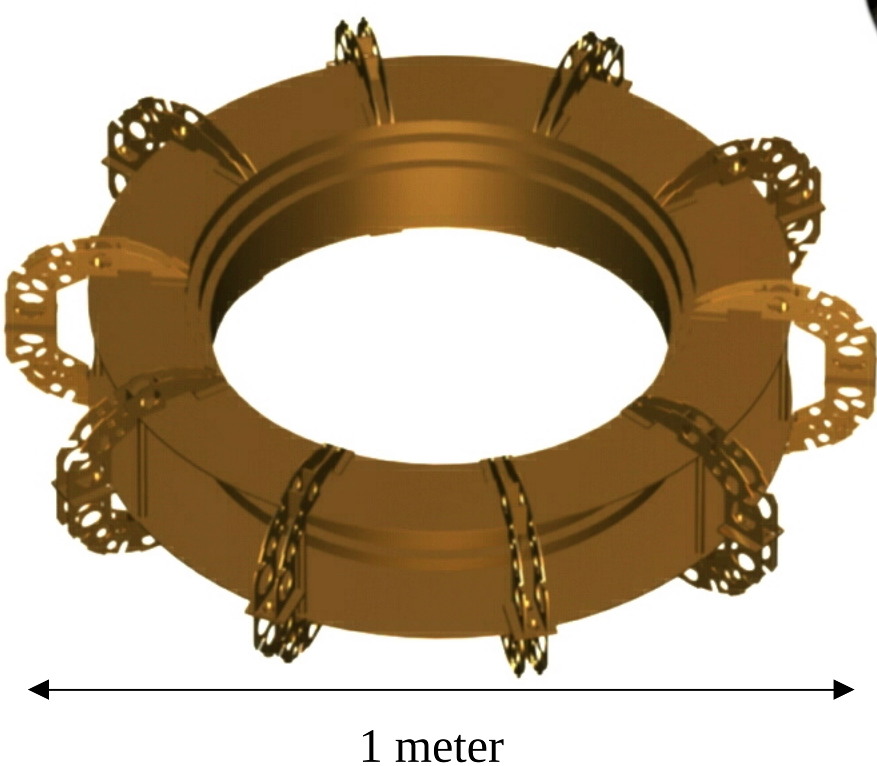
- “State-of-the-art” LDX conductor required performance testing
  - Multiple tests to ensure quality of conductor manufacturing techniques
  - Tests included
    - Dummy HP1 lower-performance conductor soldered into LDX form factor
    - Tests of individual strand performance
    - Tests of LDX final conductor
- 1st test of final conductor indicated damaged conductor!
  - Due to slight flaw in conductor
  - Flaw repair tested sucessfully
- Final conductor exceed performance expectations!
  - Many thanks to Brookhaven National Lab for providing many of these tests

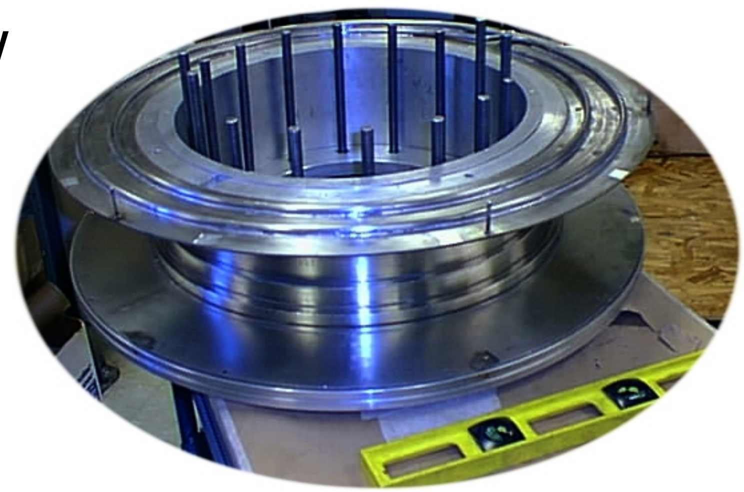




Floating Coil Form and Winding Mandrel

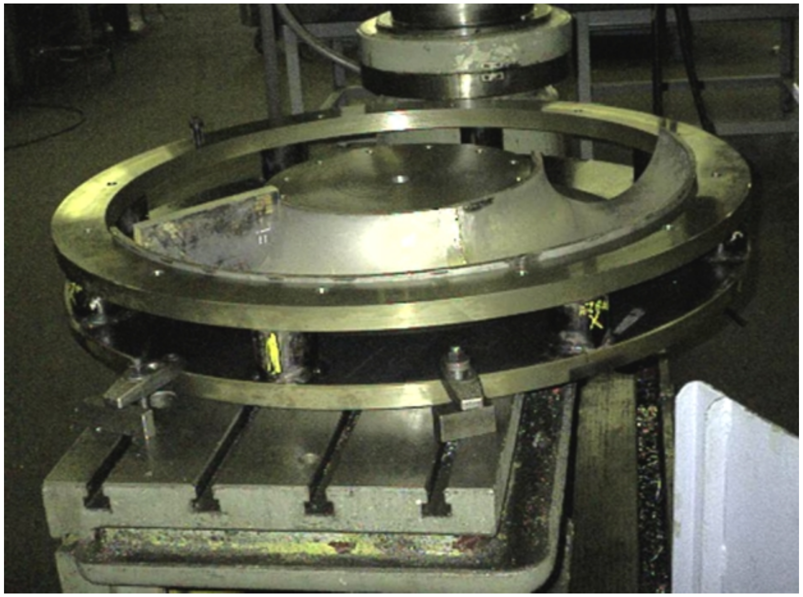
Floating coil form and mandrel completed by Ability Engineering and are now at Eversion Electric awaiting magnet winding.





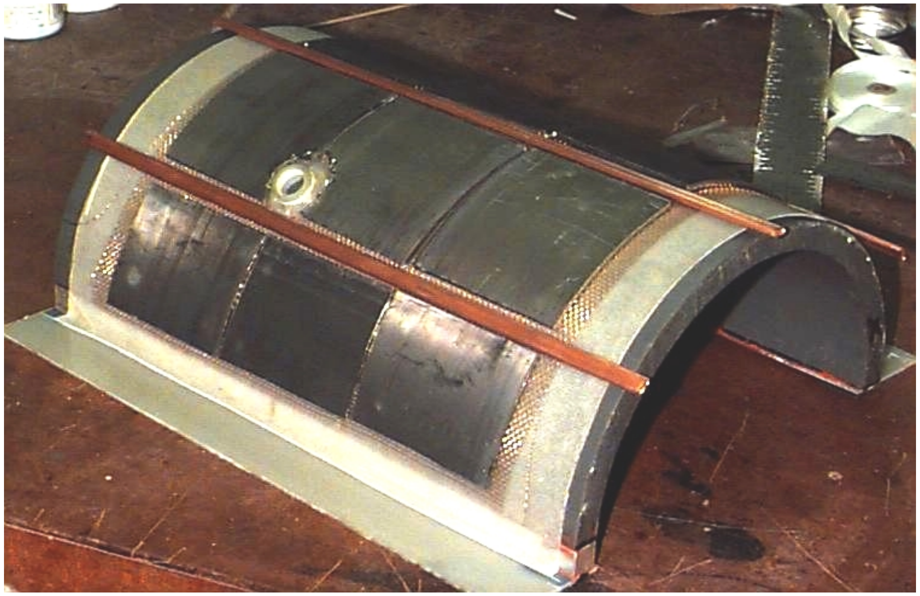
Helium Pressure Vessel

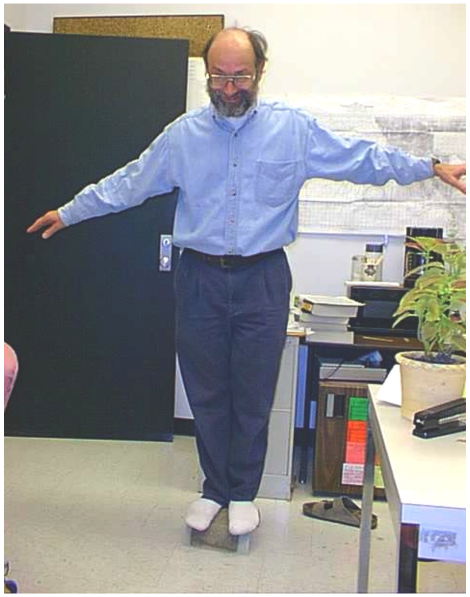
- Inconel 625 Pressure Vessel
  - 125 ATM at 300°K
  - 2-3 ATM cold
  - 1.5 kg He storage
- Created from 8 standard 10" pipe elbows
  - Elbow halves formed and then annealed
  - Butt welds complete, awaiting radiographic inspection
- Machining fixture for weld preps
  - also used for pressing of magnet support structure for final toroidal welds
- Final welds scheduled for Feb. 2000.



Thermal Radiation Shield

- Intercepts heat leak from warm (hot) vacuum vessel to cold He vessel
  - Operates from 10-80°K
- A "cored" fiberglass composite construction
  - 2 fiberglass skins, 0.5mm thick and separated by core provides strength
  - Lead panels provide thermal inertia
  - Copper screen for thermal conductivity
  - Copper heat exchange tubing
- Process prototypes built at MIT
  - Excellent strength properties!
- Final shield to be made on mold formed over He vessel





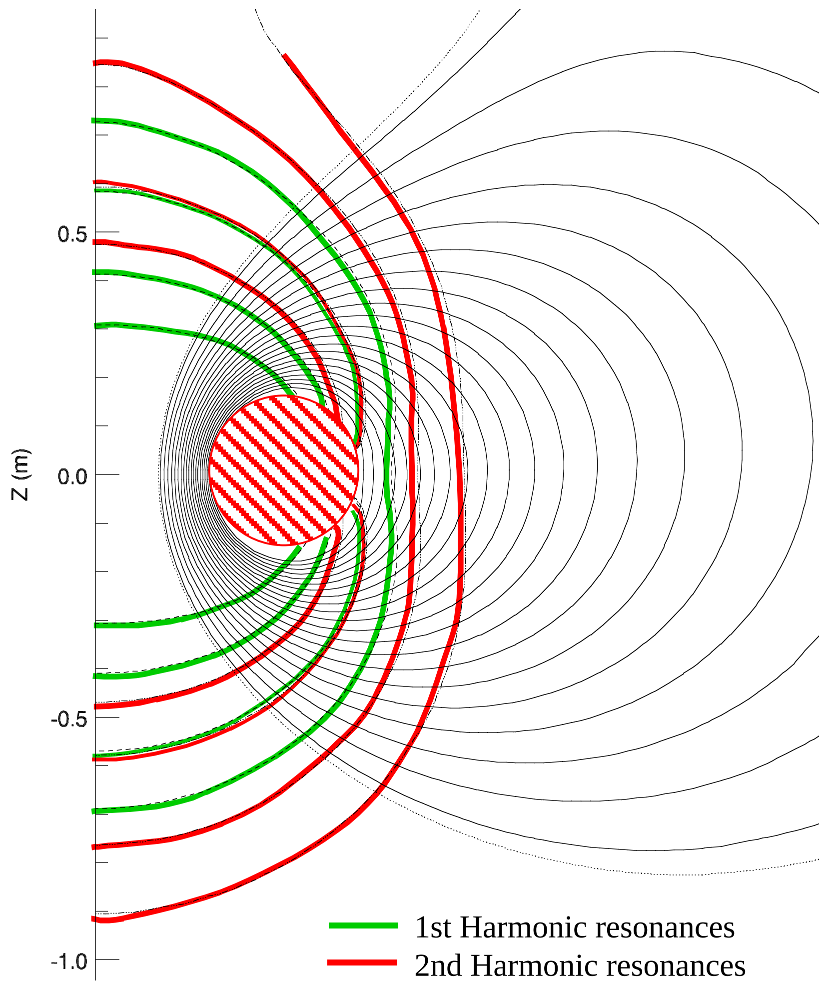
Experimental Goals

- Study of high beta plasma stabilized by compressibility.
- Explore relationship between drift-stationary profiles having absolute interchange stability and the elimination of drift-wave turbulence.
- Examine coupling between the scrape-off-layer and the confinement and stability of a high-temperature core plasma.
- The stability and dynamics of high-beta, energetic particles in dipolar magnetic fields.
- Explore convective cell formation and control and the roll 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

- 3 Major Campaigns
- Supported Dipole Hot Electron Plasmas
    - Winter 2000/2001
  - High- *b* Hot Electron plasmas with mirror losses
  - ECRH Plasma formation
  - Instabilities and Profile control
- Levitated Dipole Hot Electron Plasmas
    - Fall 2001
  - No end losses
  - *b* enhancement
  - Confinement studies
- Thermal Plasmas
  - Concept Optimization / Evaluation

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.
  - Improved ECRH efficiency seen in mirror program when using multiple frequencies.
    - B. Quon et al, *Phys. Fluids* 28, (1985) 1503.

Multi-frequency ECRH in ST-1 Mirror

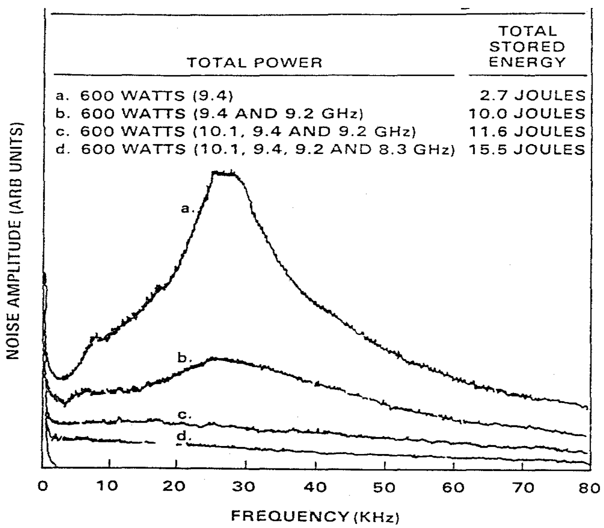


FIG. 11. Spectra of low-frequency fluctuations in the cold-electron end-loss current for four different heating configurations.

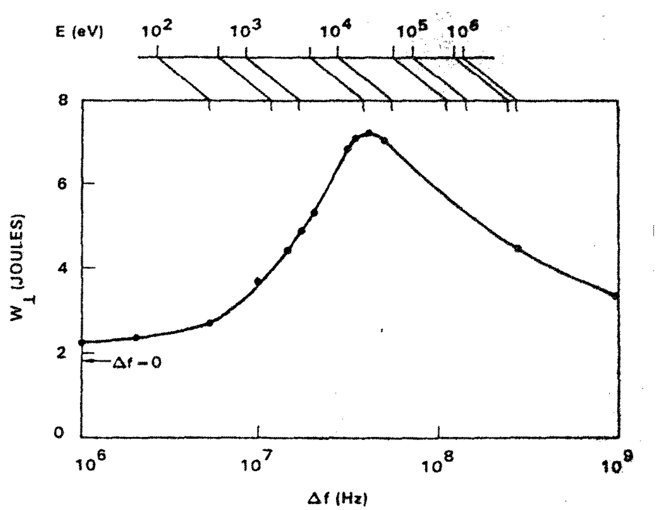


FIG. 9. Total stored energy as a function of frequency separation for two-frequency heating. The scale gives the electron energy for which the bounce frequency is equal to the applied frequency mismatch.

- 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-β 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.

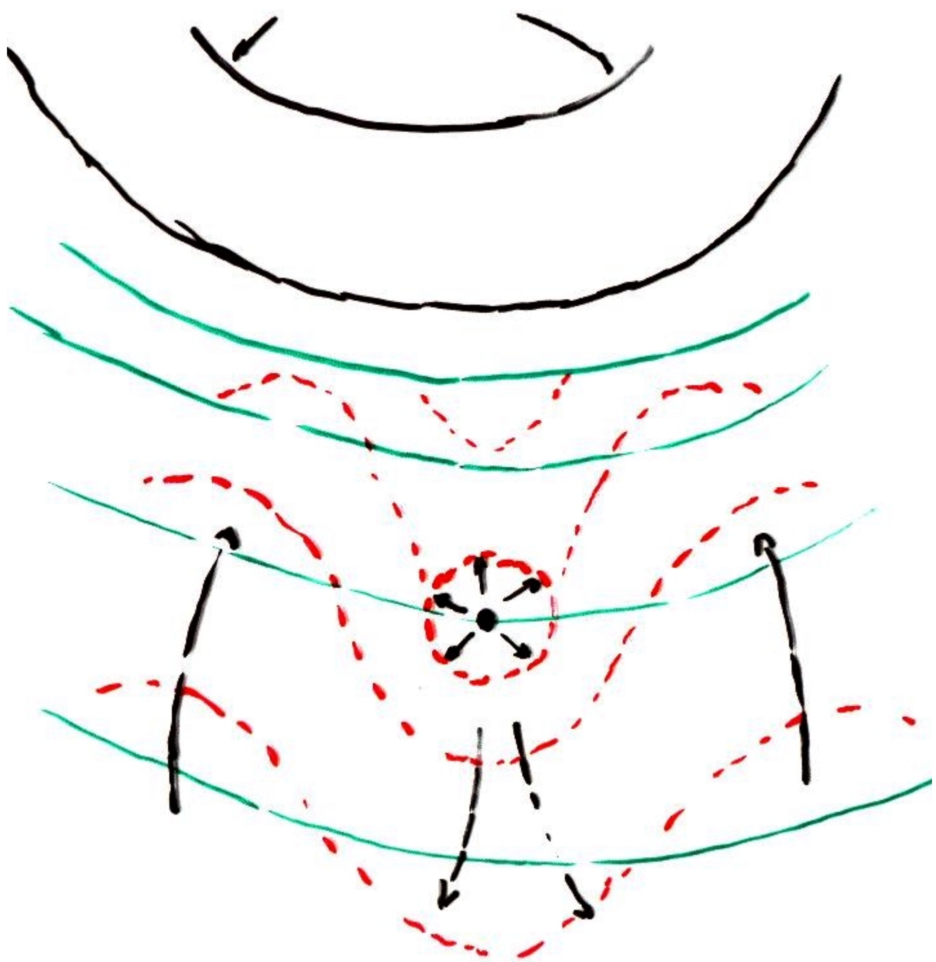
Hot Electron Plasmas

- **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**
    - β **enhancement and scaling**

Hot Electron Plasma Diagnostics

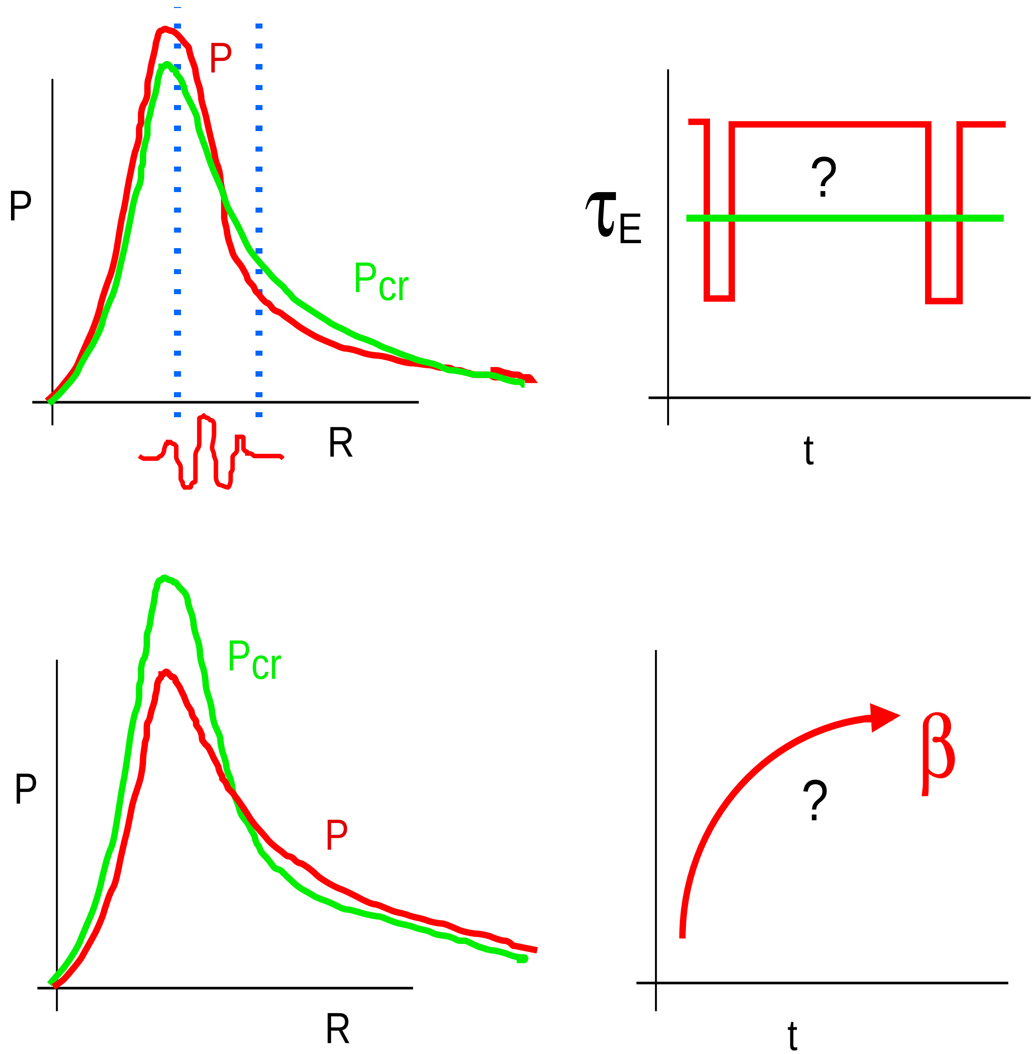
- **Magnetics (flux loops, hall probes)**
  - **Plasma equilibrium shape**
  - **magnetic β & stored energy**
- **Reflectometer**
  - **Density profile**
- **X-ray pulse height energy analyzer**
  - **Hot electron energy distribution / profile**
- **XUV arrays**
  - **Instabilities and 2-D profiles**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

Convective Cells



- Do they exist?
  - Are they the nonlinear saturation of interchange modes?
- Do they degrade energy confinement?
  - Can we have high energy confinement with low particle confinement?
- Explore methods for driving and limiting.

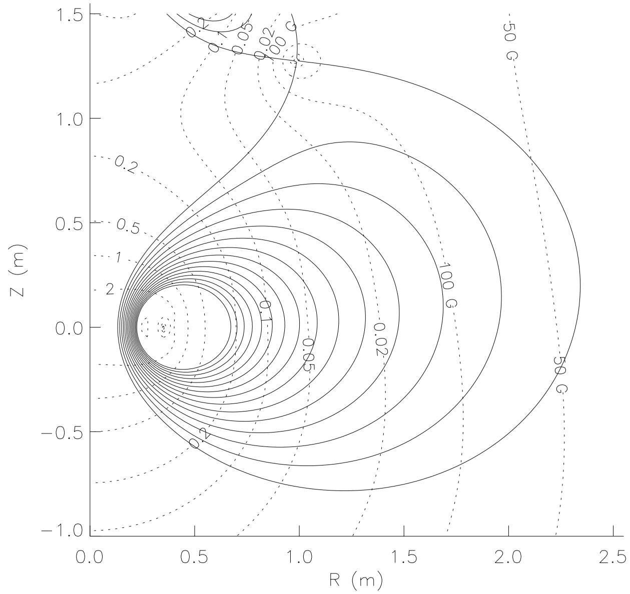
Instabilities & Confinement



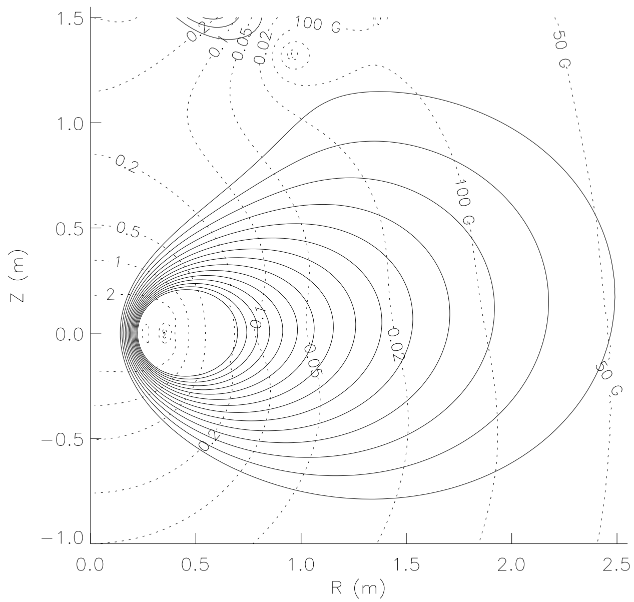
- Instability should exist when: $p' > p'_{critical}$
- Investigate nature of instability
  - How does it saturate?
  - How much transport is driven?
- Maximize β when: $p' < p'_{critical}$ everywhere
- What is maximum attainable β and what is limit?

LDX Magnetics Measurements

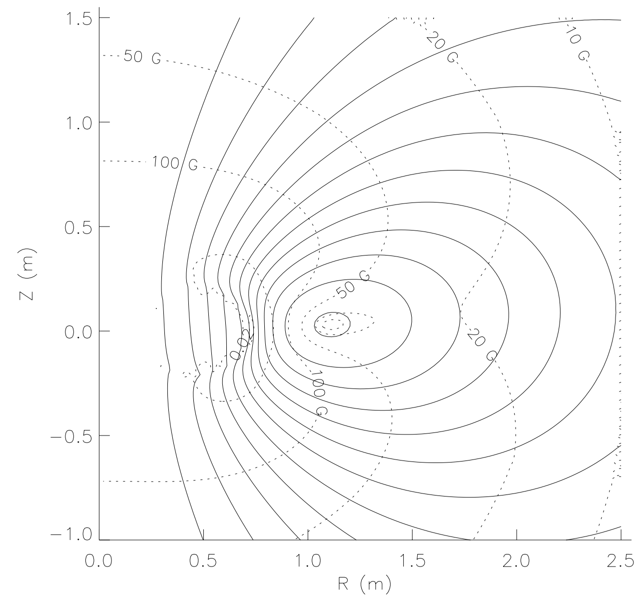
Vacuum



$\langle\beta\rangle_{max}$ = 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**