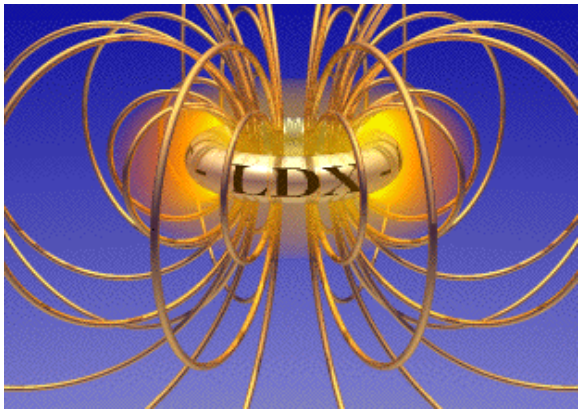


Status of the LDX Project

Darren Garnier

Columbia University

for the LDX Team

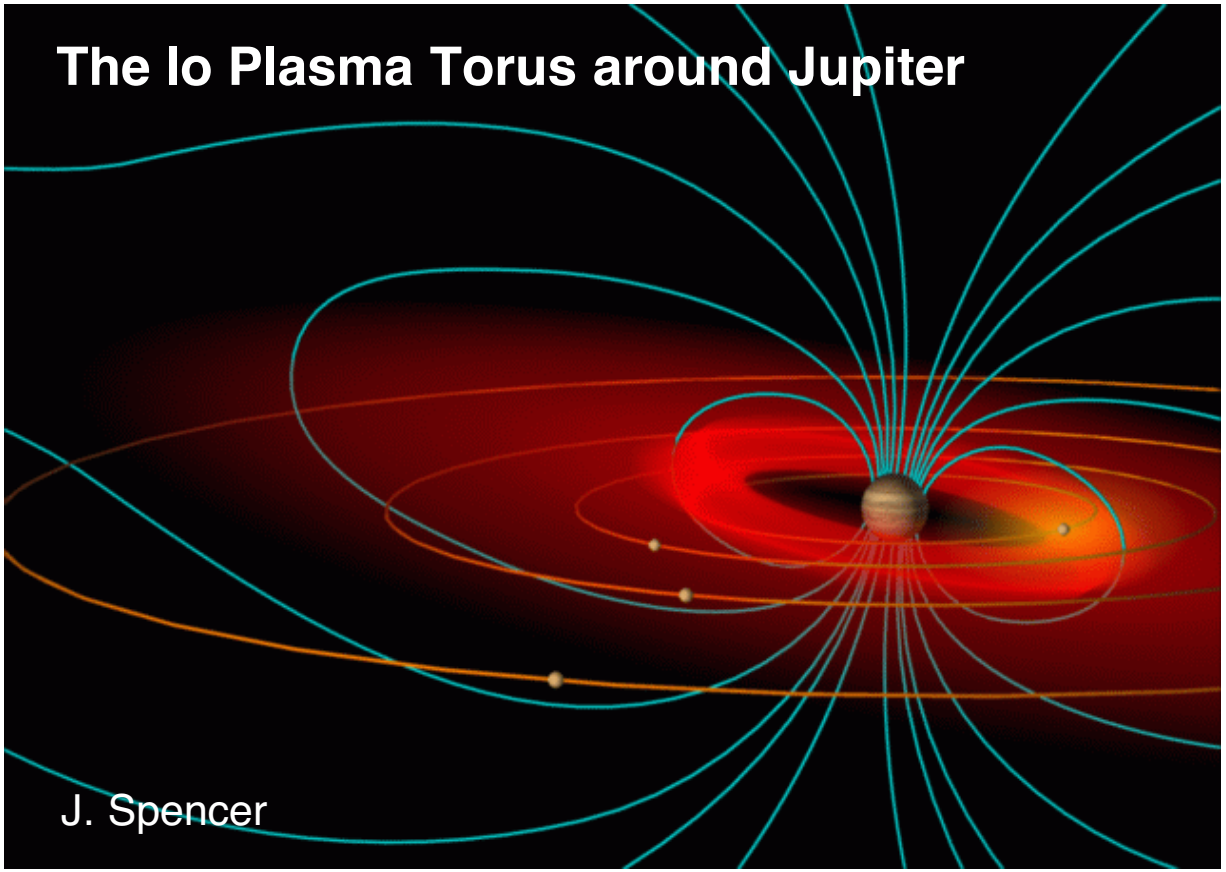
Columbia University

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

Outline

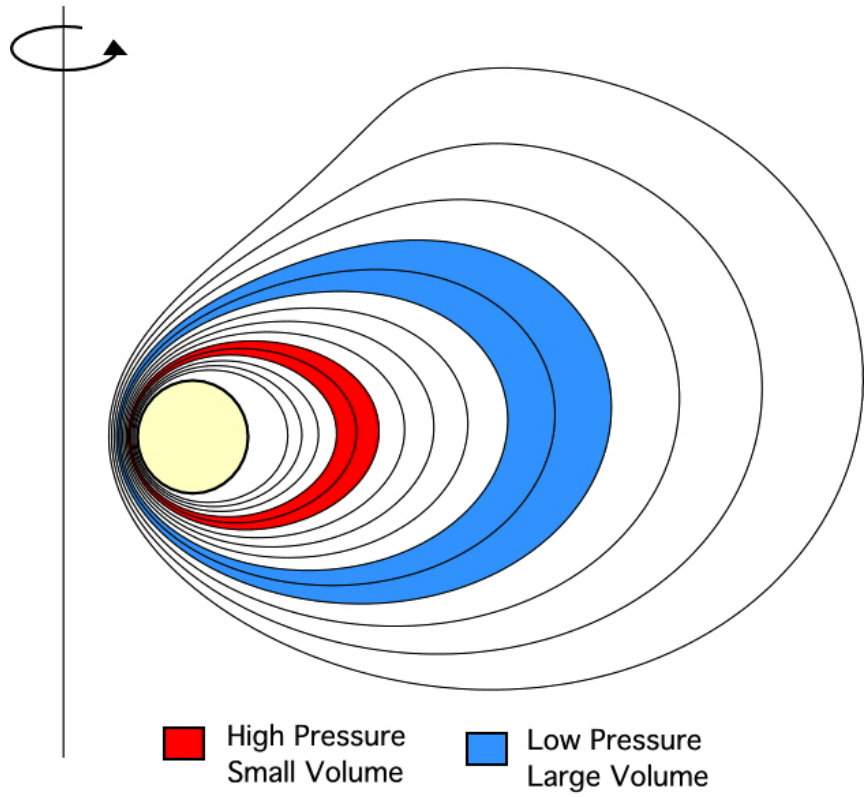
- Short introduction to LDX
  - Intro to Dipole physics
  - Goals of LDX program
- "A day in the life" of LDX
  - LDX Machine Design
  - Construction Progress of Major Components
- Experimental Plan and Schedule

Why is dipole confinement interesting?



- Simplest confinement field
- High-β confinement occurs naturally in magnetospheres (β ~ 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**

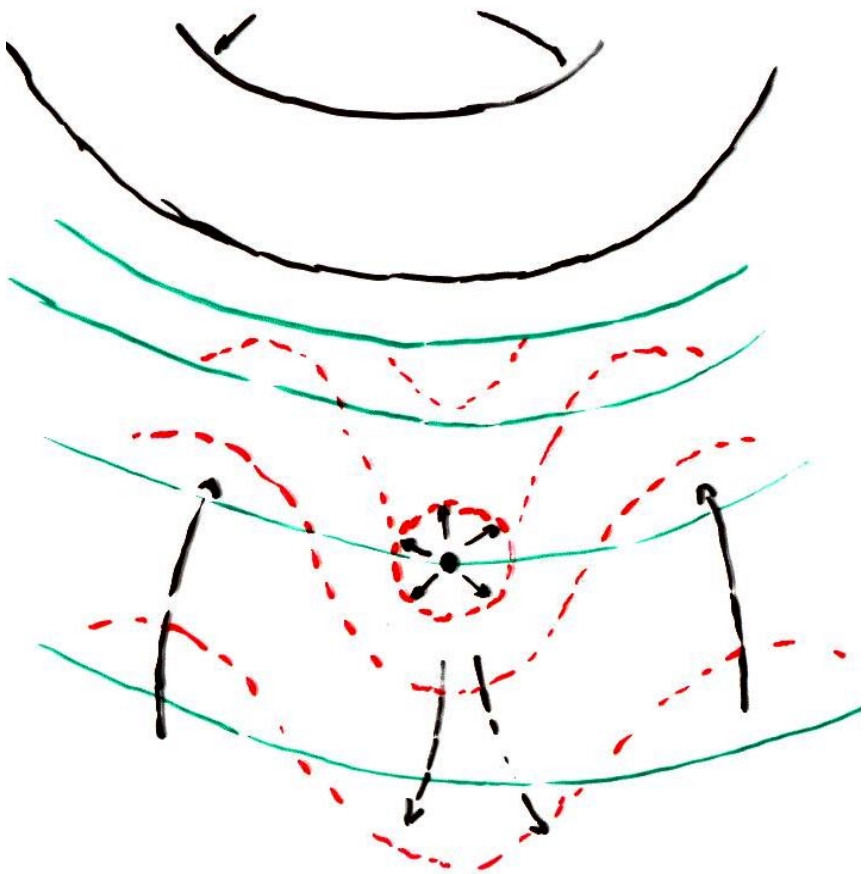
Dipole Confinement continued...

- **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 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 τ_p with high τ_E .
  - But, good curvature region near ring, convective cells can cause anomalous transport

Convective Cells



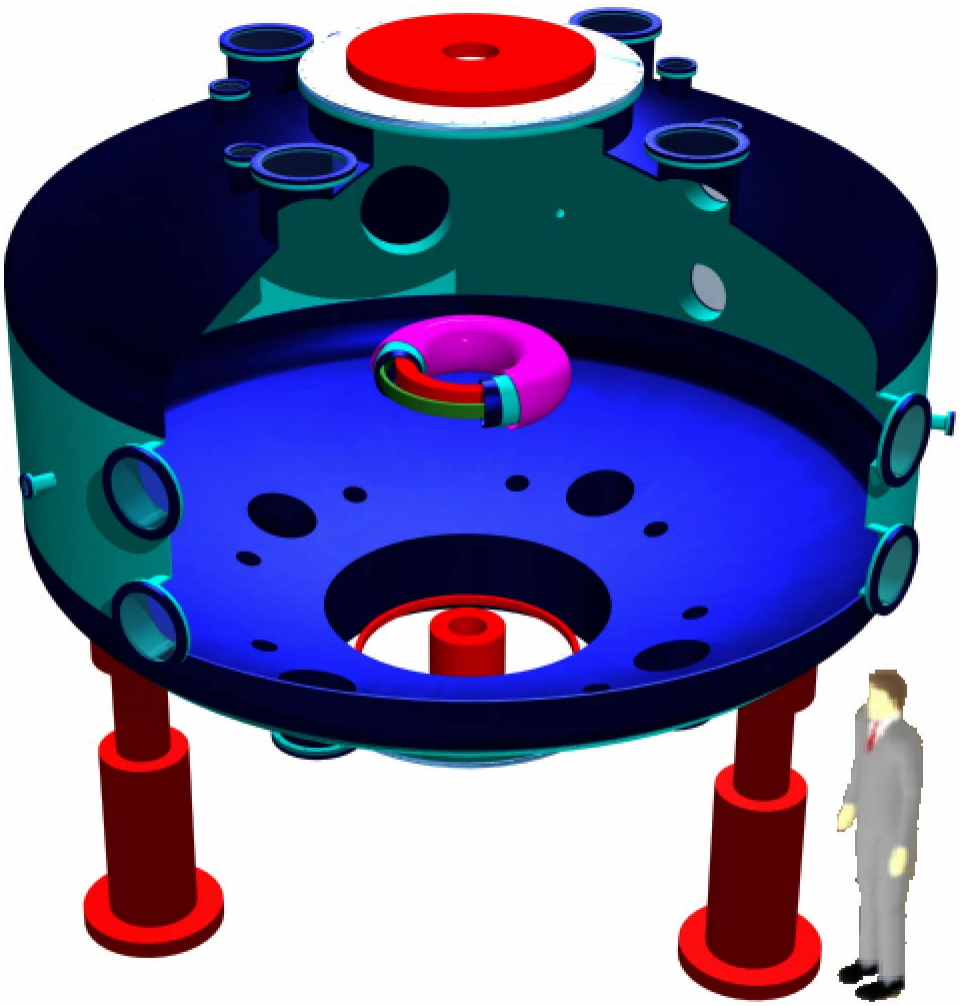
- **How are they formed?**
  - Are they the nonlinear saturation of interchange modes?
  - How asymmetric does the heating profile need to be to drive them?
- **Do they degrade energy confinement?**
  - Can we have high energy confinement with low particle confinement?
- **Explore methods for driving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

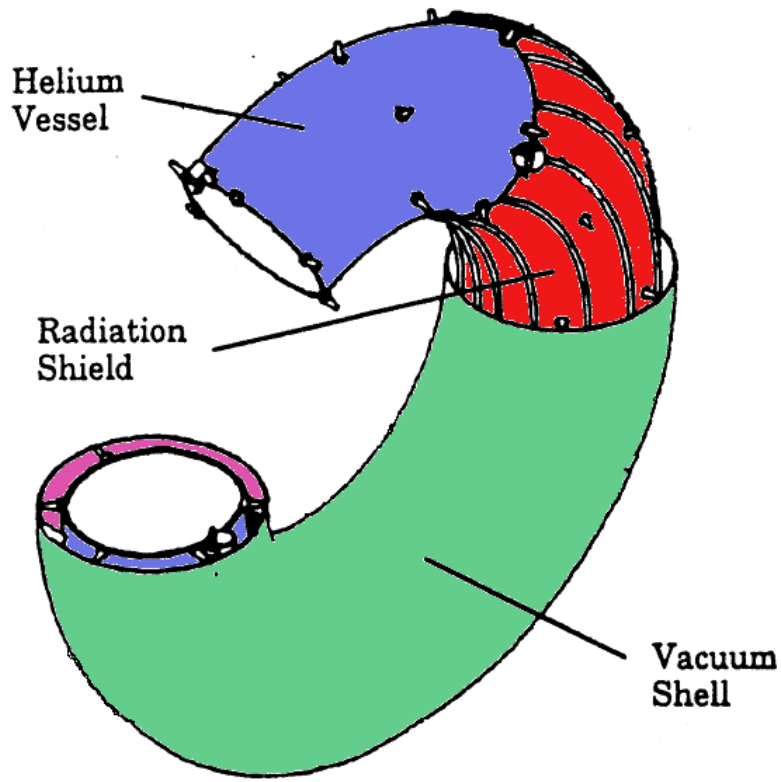


LDX Vacuum Vessel

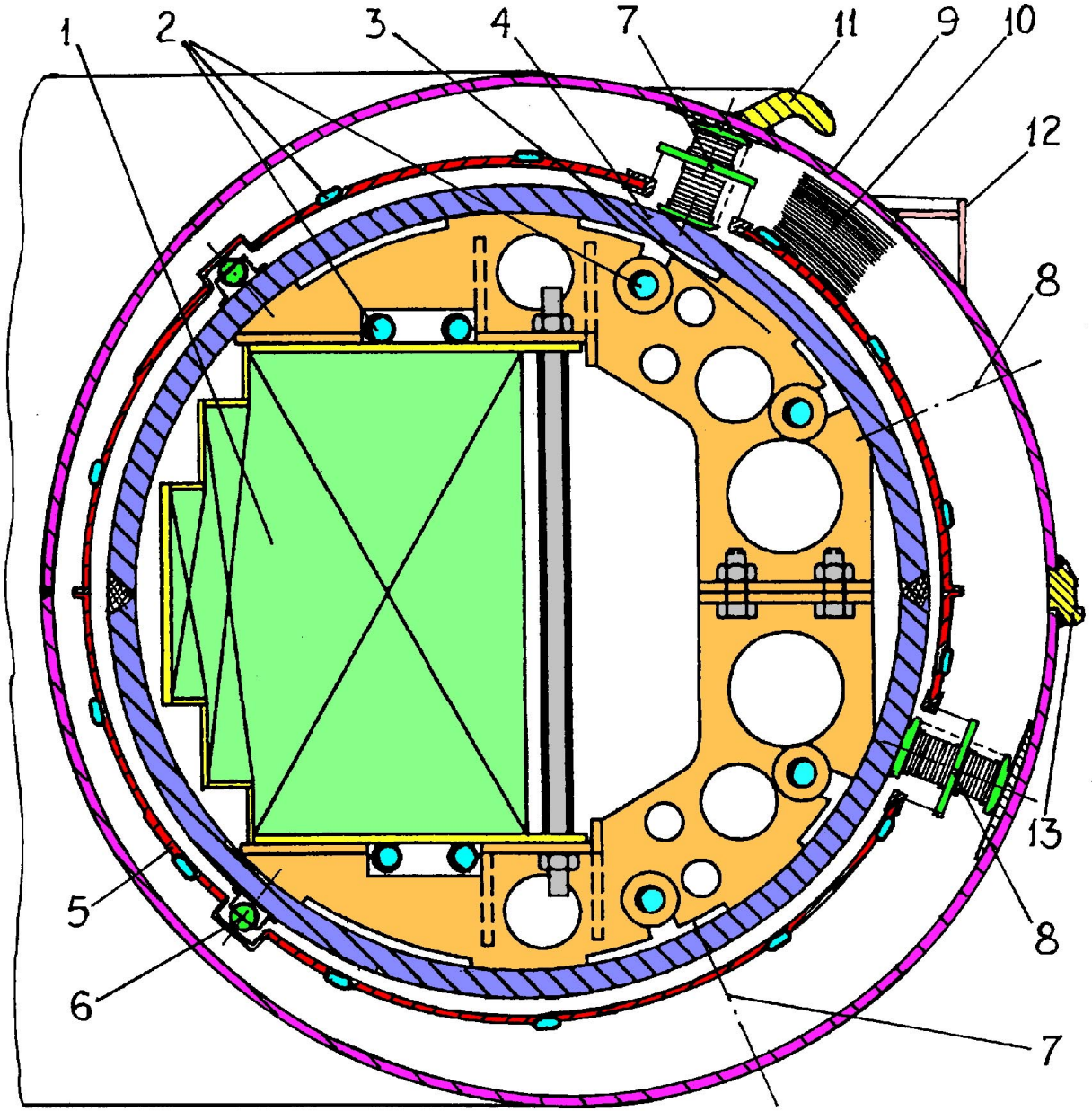
- Vacuum Vessel
  - Specifications
    - 5 meter (198”) diameter, 3 m high, elevated off chamber floor
    - 11.5 Ton weight
  - Manufactured by Vacuum Technology Associates / DynaVac
- Ports
  - 2 50” ports (for floating ring installation)
  - 2 24” ports for cryopumping
  - 10 16.5” horizontal diagnostic 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



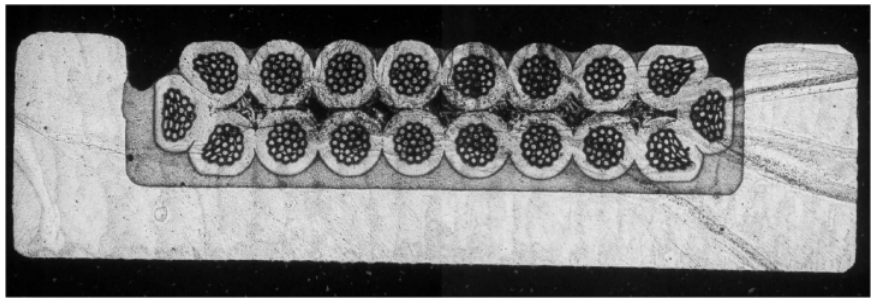
1. Magnet Winding Pack
2. Heat Exchanger tubing
3. Winding pack centering clamp
4. He Pressure Vessel (Inconel 625)
5. Thermal Shield (Lead/glass composite)
6. Shield supports (Pyrex)
7. He Vessel Vertical Supports/Bumpers
8. He Vessel Horizontal Bumpers
9. Vacuum Vessel (SST)
10. Multi-Layer Insulation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

F-Coil Superconductor

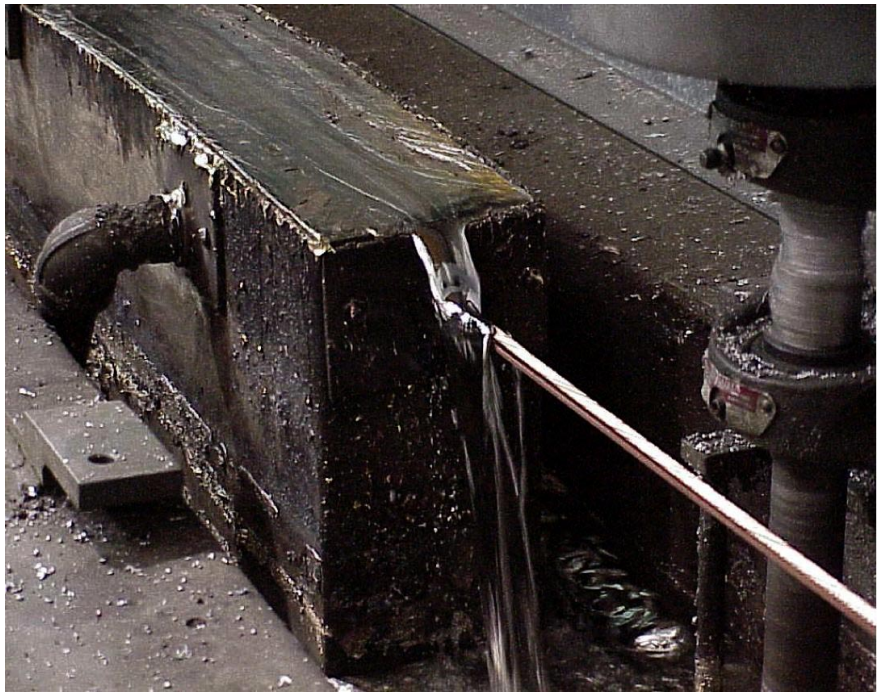
- Nb3Sn cable-in-channel superconductor manufactured in collaboration between industry, universities and national laboratories

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.

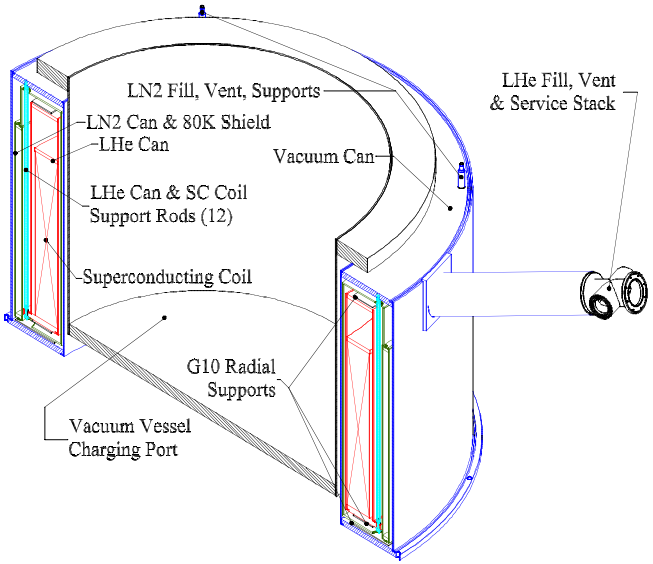


8 mm

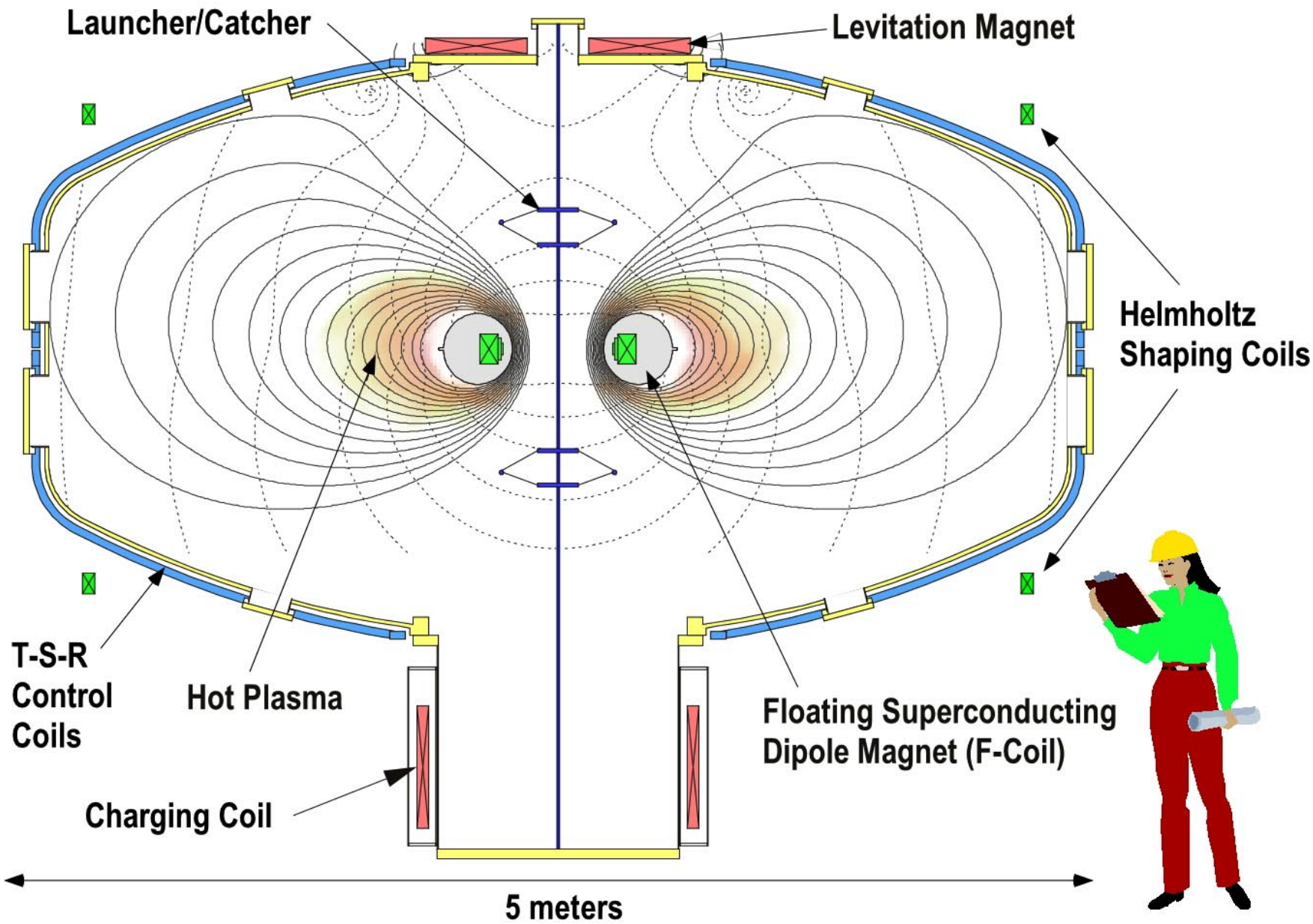


Superconducting Charging Coil

- 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.

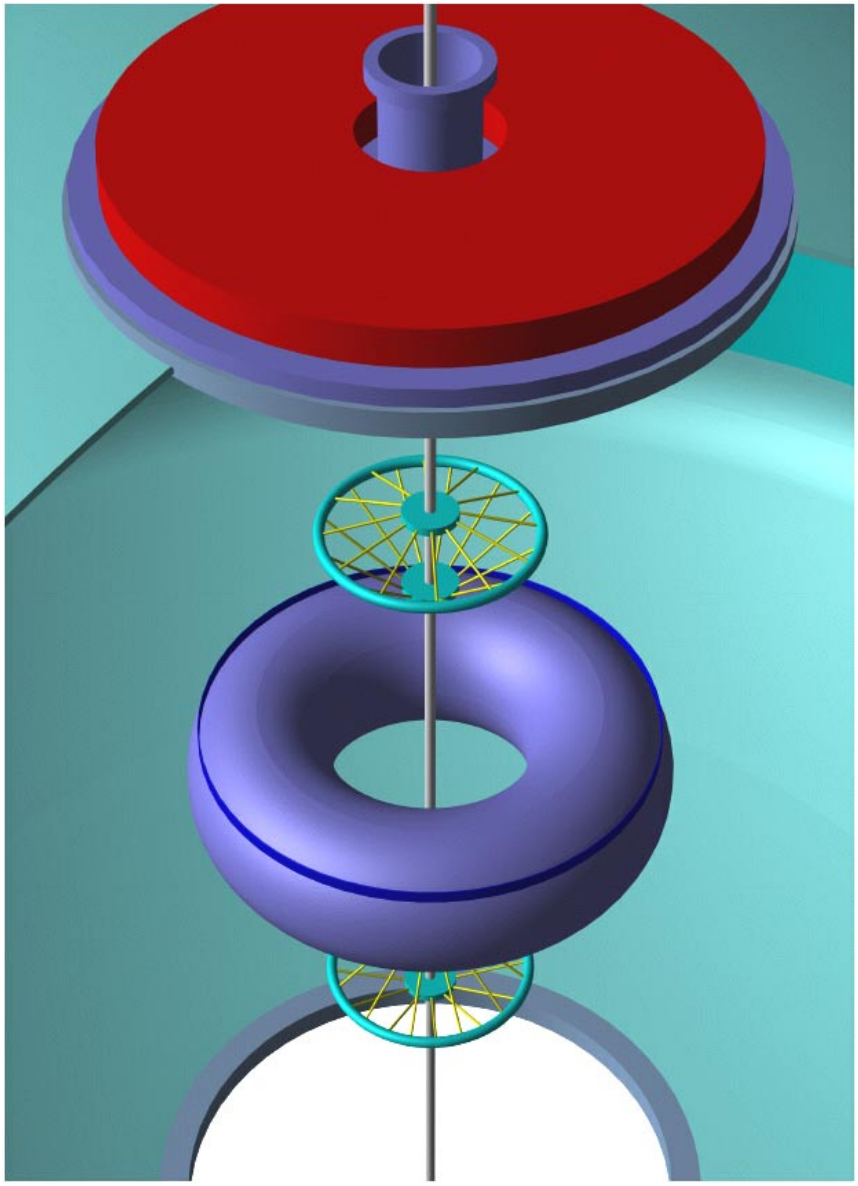


LDX Experiment Cross-Section

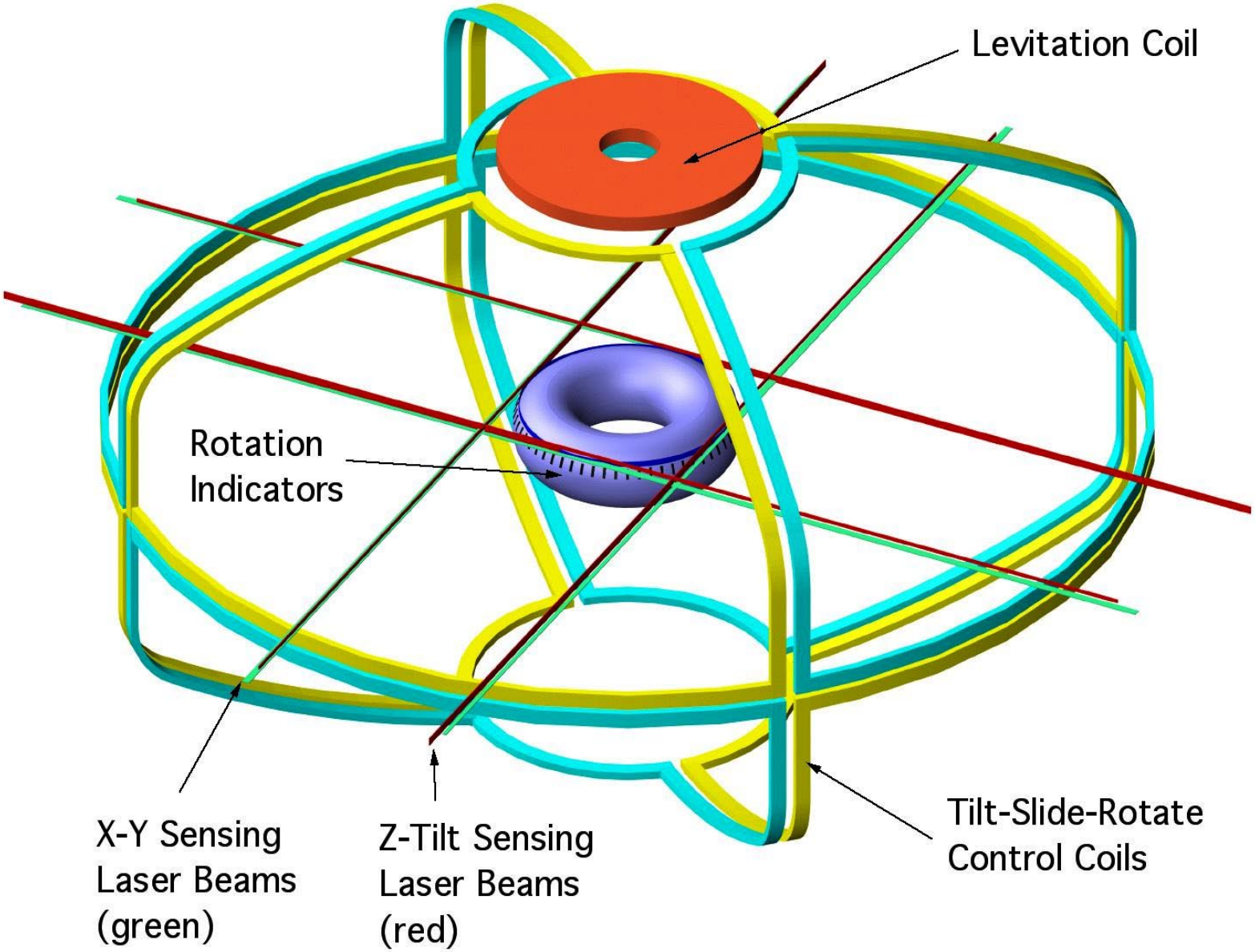


Launcher/Catcher

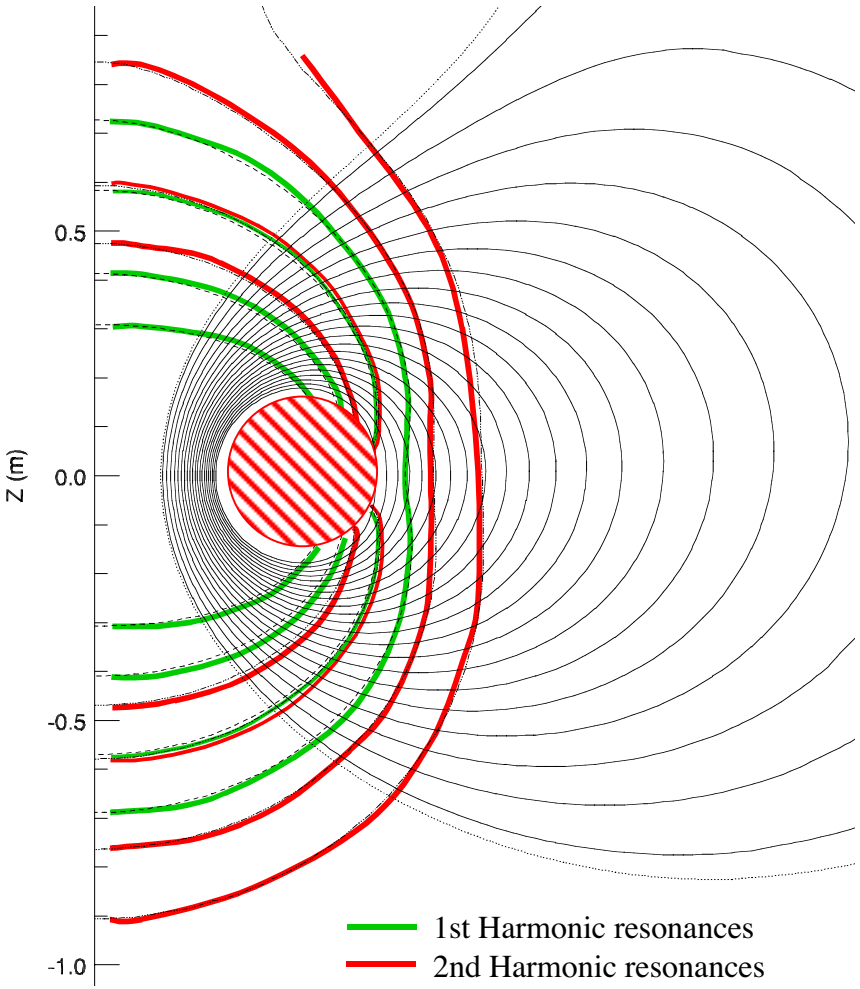
- "Simplified" Launcher/Catcher can be used in both supported and levitated operation
  - In supported operation "bicycle" wheels clamp floating coil in fixed position
  - In levitated operation, vertical spacing of wheels is increased
  - For upper levitation, all components are outside LCFS
- Currently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



Levitation Control System Schematic

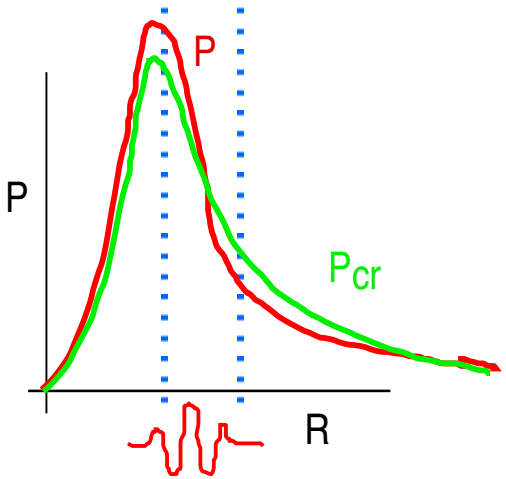


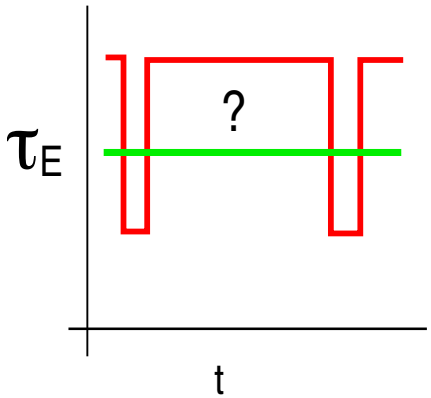
Multi-frequency ECRH on LDX

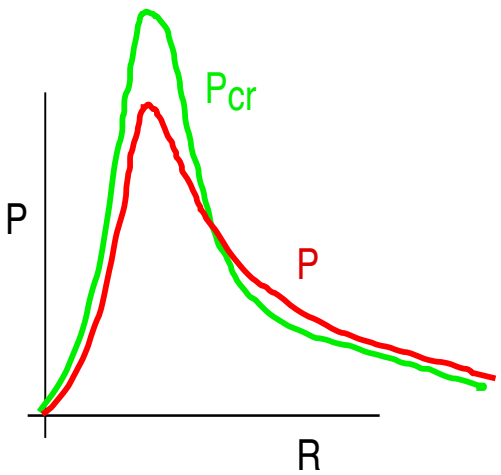


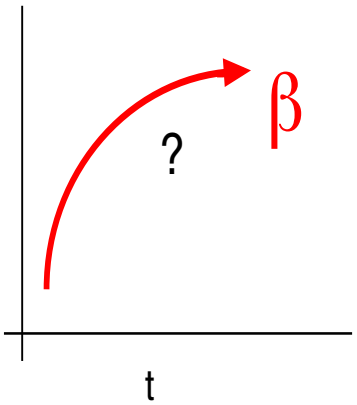
- **Multi-frequency electron cyclotron resonant heating**
  - **Effective way to create high-β hot electron population**
  - **Tailor multi-frequency heating power to produce ideal (stable) pressure profile with maximum peak β.**
  - **Profile control and improved ECRH efficiency seen in mirror program 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 β when: $p' < p'_{critical}$ everywhere**
  - **What limits β ?**

Multi-frequency ECRH in ST-1 Mirror

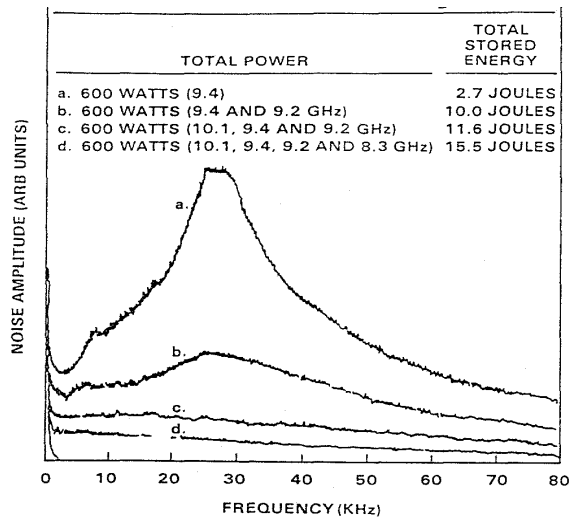


FIG. 11. Spectra of low-frequency fluctuations in the cold-electron end-loss current for four different heating configurations.

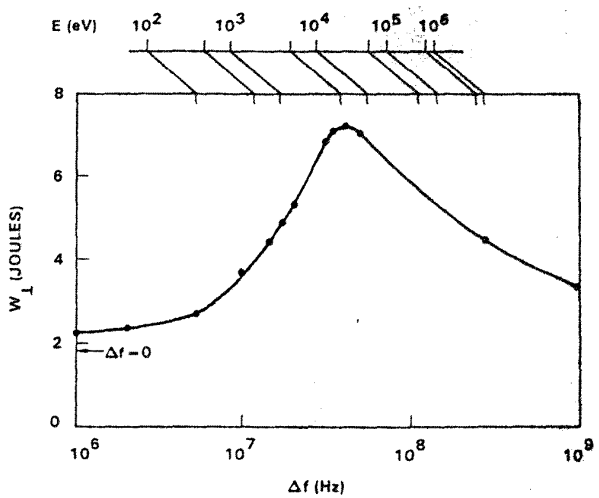


FIG. 9. Total stored energy as a function of frequency separation for two-frequency heating. The scale gives the electron energy for which the bounce frequency is equal to the applied frequency mismatch.

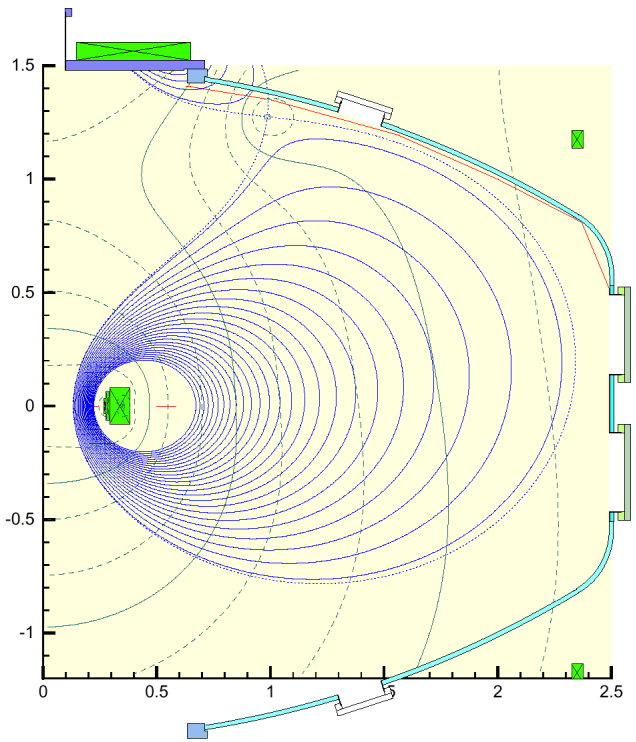
- **Widely spread ($\Delta f/f > 10\%$) multiple frequencies allowed stable operation**
  - **Low frequency fluctuations in cold electron end losses are reduced by order of magnitude**
  - **Large increase in stored energy in high-β hot electrons**
- **Narrowly spread ($\Delta f \sim f_{bounce}$) frequencies 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.**

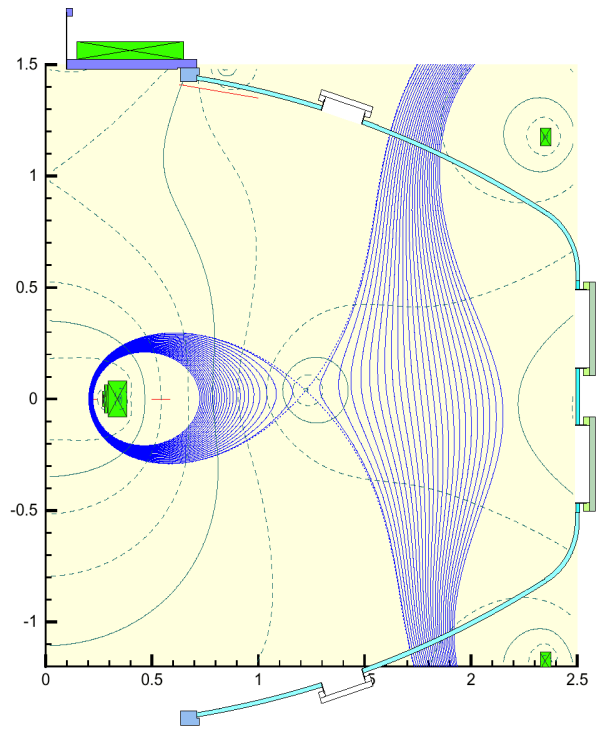
Helmholtz Shaping Coils

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

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- β Hot Electron plasmas with mirror losses
  - ECRH Plasma formation
  - Instabilities and Profile control
- **Levitated Dipole Hot Electron Plasmas**
  - Winter 2001
  - No end losses
  - β enhancement
  - Confinement studies
- **Thermal Plasmas**
  - Convective cell studies
  - Concept Optimization / Evaluation

Hot Electron Plasmas

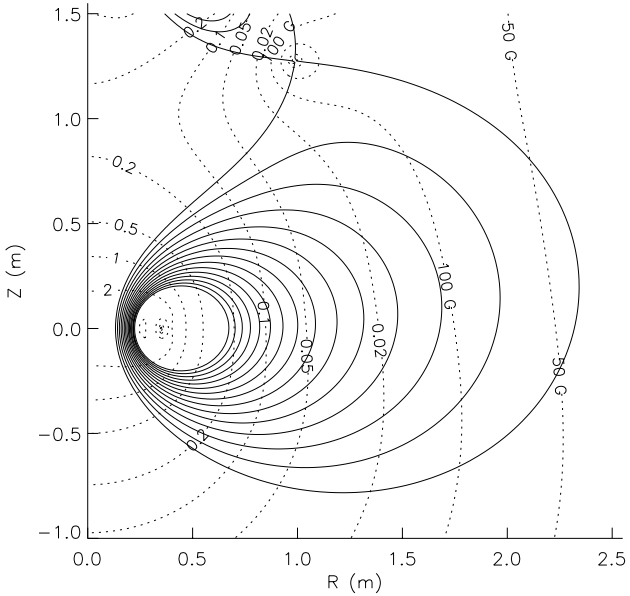
- **Supported Dipole Campaign**
  - Low density, quasi steady-state plasmas formed by multi-frequency ECRH with mirror losses
  - Areas of investigation
    - Plasma formation
    - Density control
    - Pressure profile control
    - Supercritical profiles & instability
    - Compressibility Scaling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

Hot Electron Plasma Diagnostics

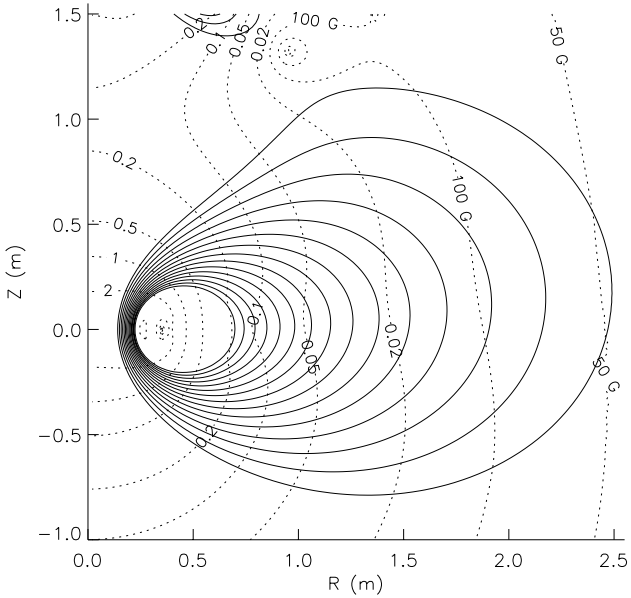
- **Magnetics (flux loops, hall probes)**
  - **Plasma equilibrium shape**
  - **magnetic β & stored energy**
- **Reflectometer**
  - **Density profile**
- **X-ray pulse height energy analyzer**
  - **Hot electron energy distribution / profile**
- **XUV arrays**
  - **Instabilities and 2-D profiles**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

LDX Magnetics Measurements

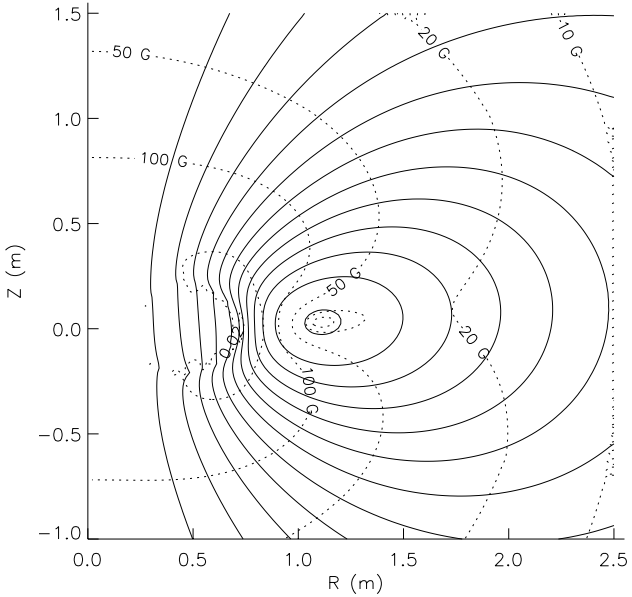
Vacuum



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