Progress in Levitated Dipole Research

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for the LDX Team

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Columbia University

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MIT PSFC

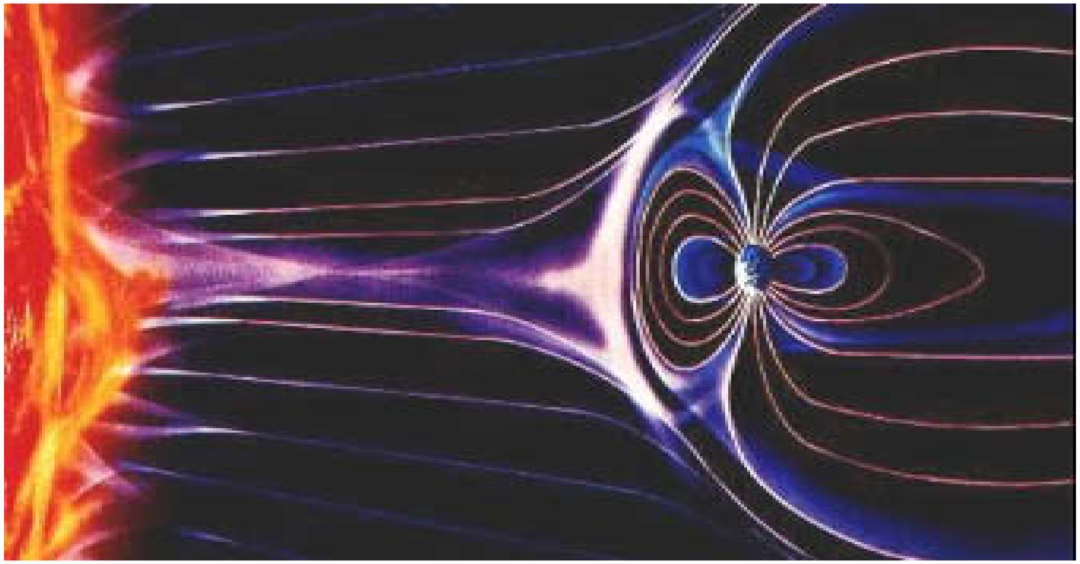
LDX Collaboration

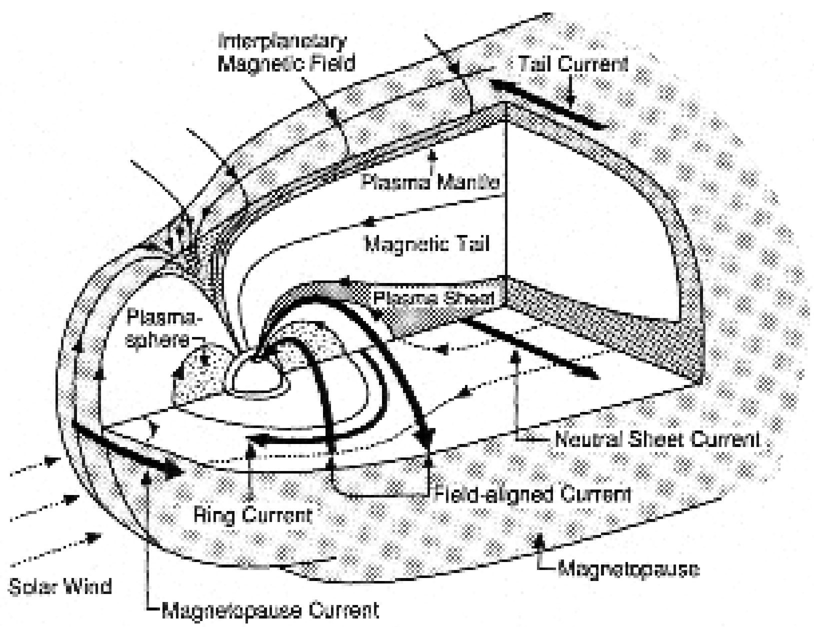
- Columbia University, Department of Applied Physics
  - Mike Mauel, Darren Garnier, Alex Hansen, Thomas Sunn Pedersen, Eugenio Ortiz
- MIT Plasma Science and Fusion Center
  - Jay Kesner, Joe Minervini, Chris Jones, Ishtak Karim, Phil Michael, Alexi Radovinsky, Joel Schultz, Brad Smith, Alex Zhukovsky, and many others
- Other Universities / Laboratories
  - PPPL, LBNL, BNL, Efremov Institute
- Industrial Partners
  - Ability Engineering Technology, Everson Electric, IGC-Advanced Superconductor, American Superconductor, DynaVac

Outline

- Introduction to the Levitated Dipole
  - Physics of dipole plasma confinement
  - MHD equilibrium and linear stability
- Recent Theoretical Work
  - Linear drift wave theory
  - Non linear theory
- The Levitated Dipole Experiment
  - LDX Machine Design
  - Current construction status
- Conclusion

Magnetic Dipole Confinement



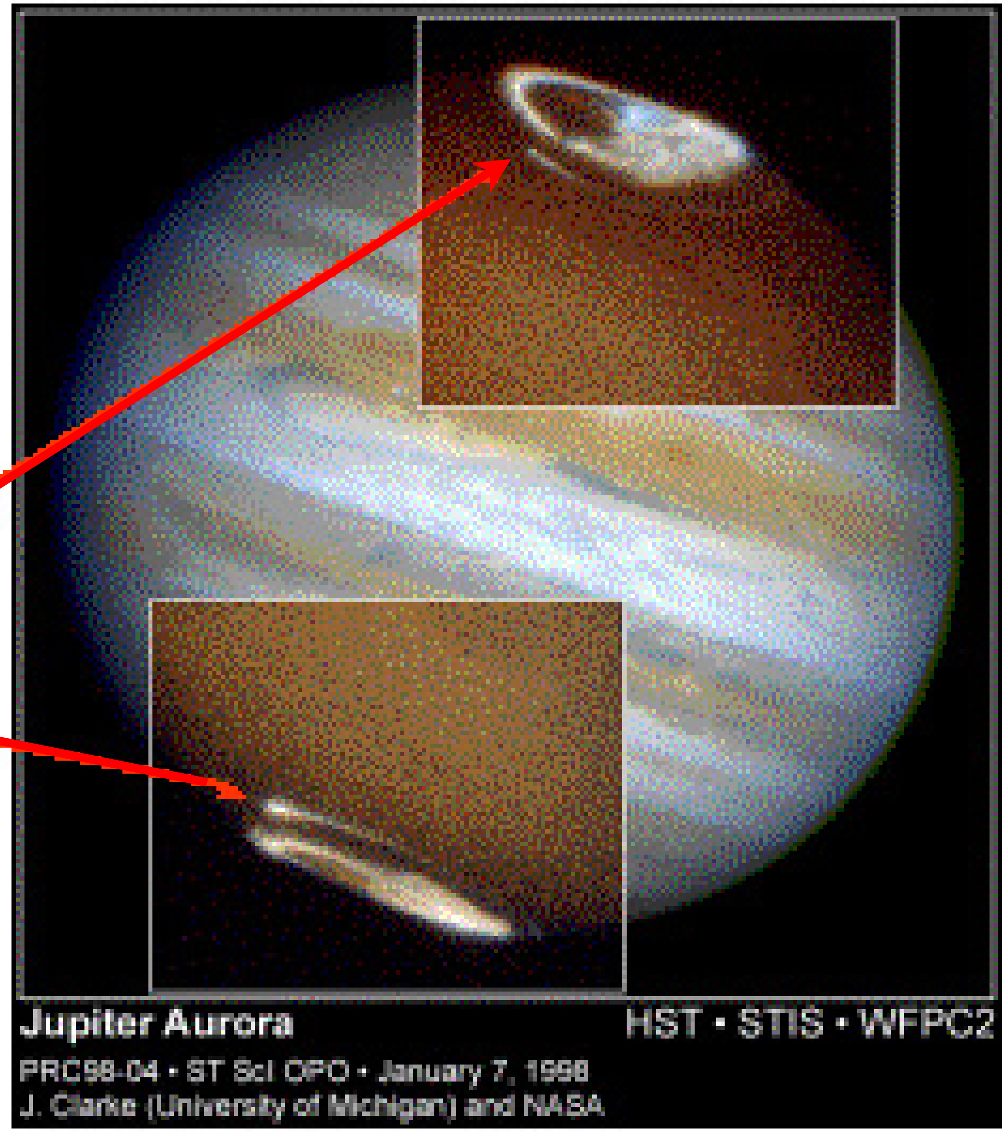


- Simplest magnetic field
- Nature's method of high-β magnetic confinement.
  - $\beta \sim 2$ in Jupiter
- Possibility of fusion power source with near-classical energy confinement
- Opportunity to study new physics relevant to fusion and space science

Oops! Aurora ⇒ Plasma Loss

- Plasma is mirror trapped with open field lines which end at planetary ionosphere

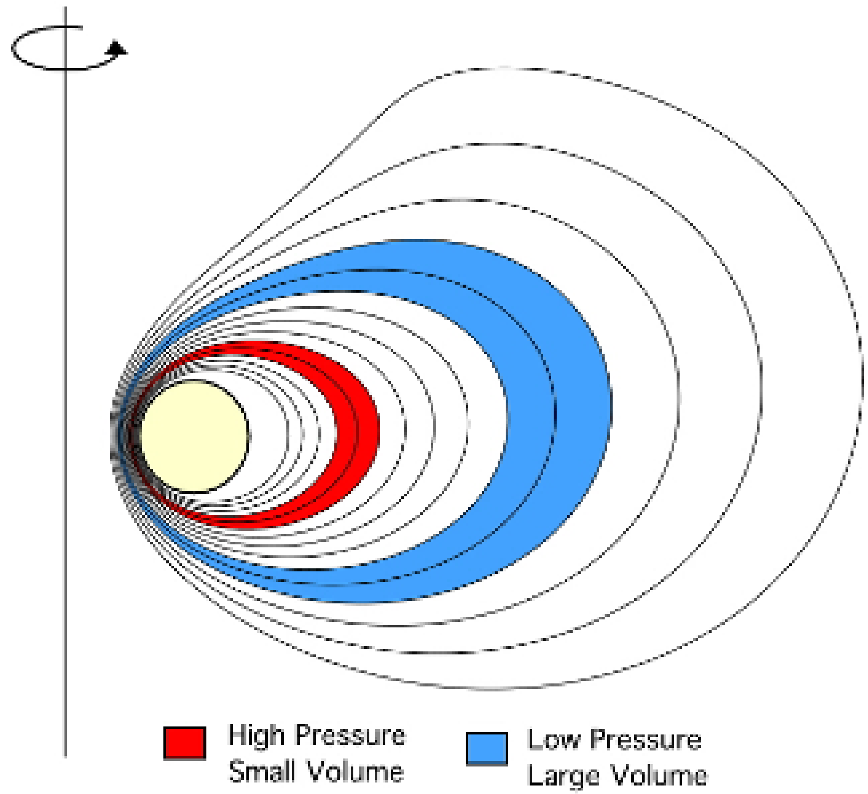
Bright spots at lower latitude from auroral ring are caused by untrapped plasma particles streaming from Io, a natural internal fuelling source.



- For fusion, get rid of poles!

⇒ Levitated superconducting dipole coil

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.

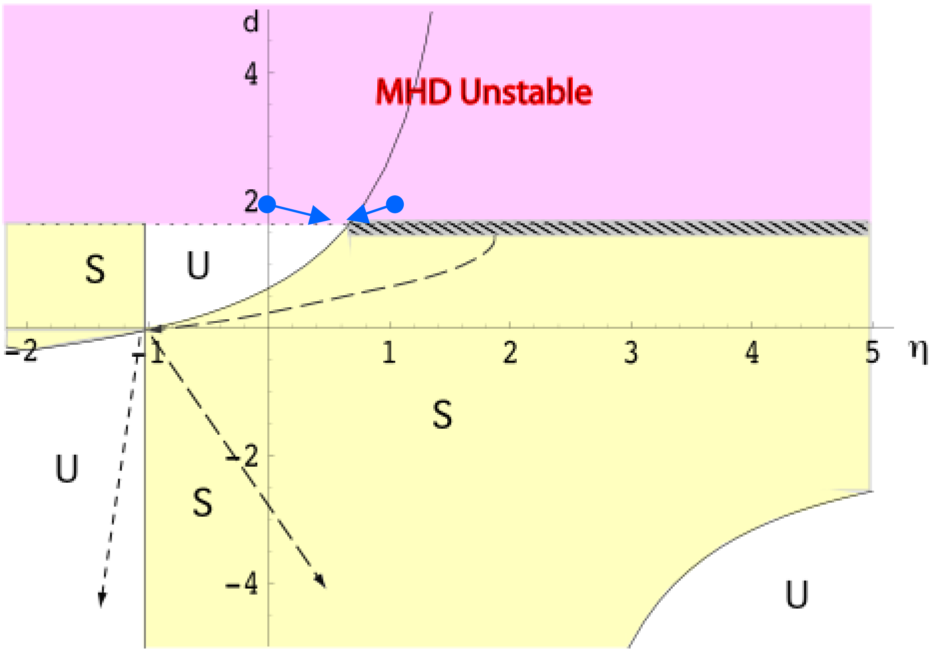
$$\delta(pV^{\gamma}) \equiv \delta(S) = 0, \text{ where } V \equiv \oint \frac{dl}{B}, \ \gamma = \frac{5}{3}$$

- **Equilibria exist at high-β that are interchange and ideal MHD ballooning stable**
- **For marginal profiles with $\eta = 2/3$, dipoles may also be drift wave stable**
  - Near-classical confinement ?
  - Theoretical work in this area has heated up in the last year…
- **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 .

Progress in Dipole Theory

- Numerous Institutions - Columbia, MIT, IFS, UMd, UCLA, UCSD, others…
- MHD
  - Krasheninnikov, Catto, Hazeltine, PRL 82 (1999) 2689, and others.
  - Garnier, Kesner, Mauel, Phys Pl 6(1999) 3431.
  - Simakov, Catto, Krasheninnikov, Ramos, Phys Pl 7 (2000) 2526.
- Kinetic theory (Electrostatic)
  - Kesner, Phys Plasmas 7 (2000) 3837.
  - Simakov, Catto, Hastie Phys Plasmas 8, 4414 (2001)
  - Kesner and Hastie, to be published in Phys Pl (2002). P. 2.20
- Kinetic theory (Electromagnetic)
  - V. Pastukhov and A. Yu. Sokolov, Nuc. Fusion 32 (1992) 1725.
  - Wong, Horton, Van Dam, Crabtree, Phys Pl 8 (2001) 2415. P. 2.22
  - Simakov, Hastie, Catto, Phys Pl 9 (2002) 201. P. 2.21
  - Goswami, Dorland, Rogers, Garnier, 2001 APS DPP (LP1058)
- Non-linear (Convective Cells)
  - Tonge, Huang, Leboeuf, Dawson, 2001 APS DPP (LP1059).
  - Pastukhov and Chudin, Plasma Physics Report, 27, (2001) 963.
  - Rey and Hassam, Phys. Plasmas 8, 5151 (2001). P. 2.23

Electrostatic Kinetic Stability



$$d \equiv \frac{\omega_{*p}}{\omega_d} = \frac{d \ln p}{d \ln V} \quad \text{or} \quad p \propto V^{-d}$$

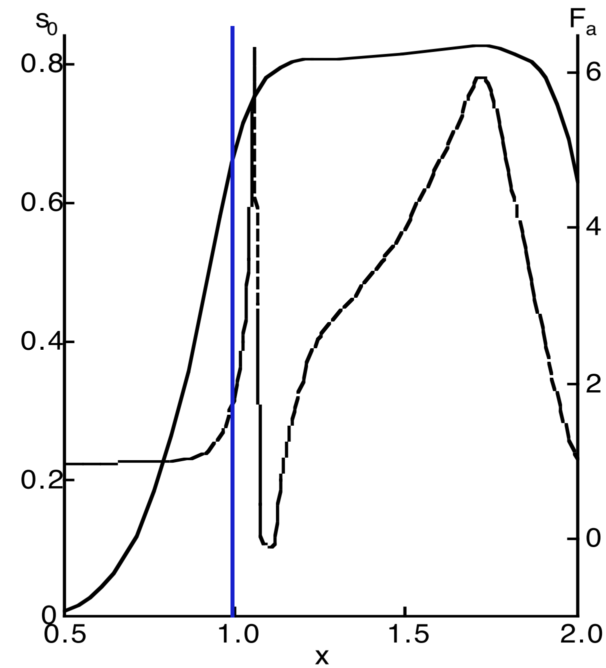
[after Kesner and Hastie, 2002]

- Linear electrostatic drift-wave stability boundaries shown
  - Plasma outside pressure peak (in bad curvature) can be drift wave stable
  - Experiment should be drift wave stable inside of pressure peak
    - Reactor may not be
- What happens when linear stability thresholds are exceeded?
  - Convective cells form
  - Tonge, Huang, Leboeuf and Dawson, [APS 2001] 3-D PIC code
    - shows evolution towards

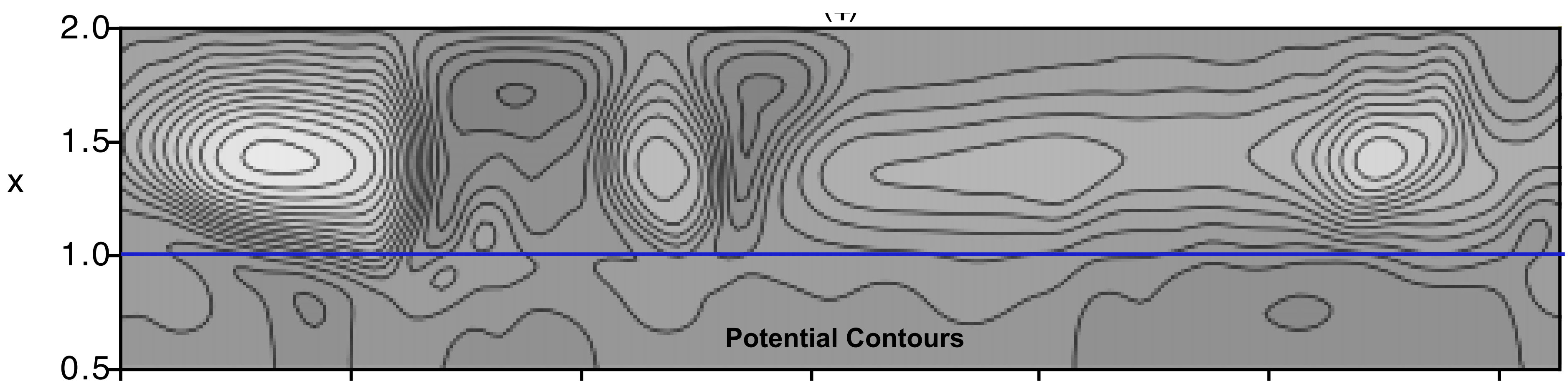
      d = 5/3 and η = 2/3

Super-critical non-linear evolution

- Pastukhov solved non-linear fluid equations for hard-core z-pinch in 2-D
  - Pastukhov, Chudin, Pl Phys Reports 27 (2001) 907
  - $\eta = 2/3$
  - Unstable S' < 0 edge constraint
- Equilibrium with flow found with large convective cells
  - $S_{core} > S_{edge}$
  - Transport is non-local in nature



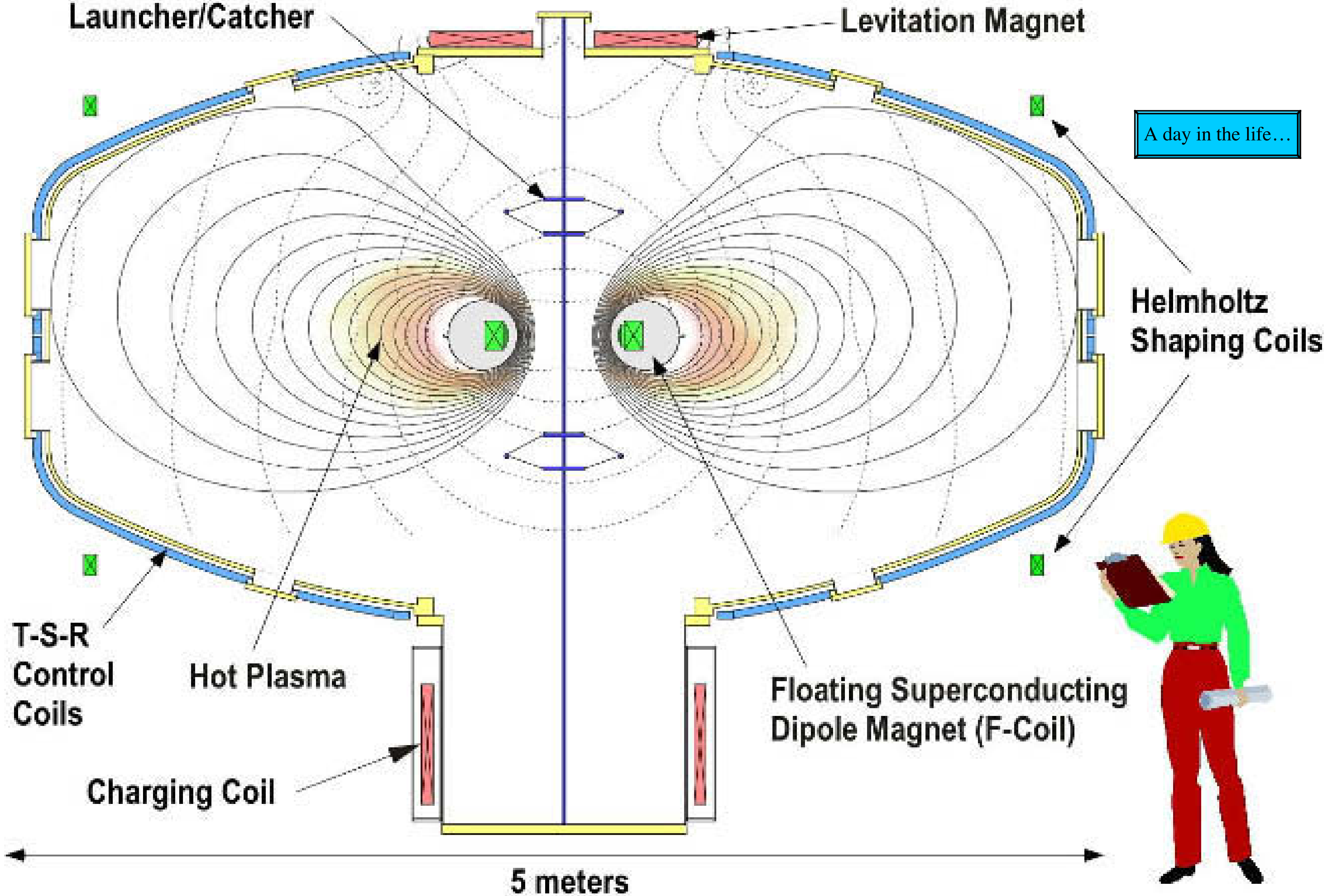
Average radial profiles of S and $\chi_{eff} / \chi_{classical}$



LDX Experimental Goals

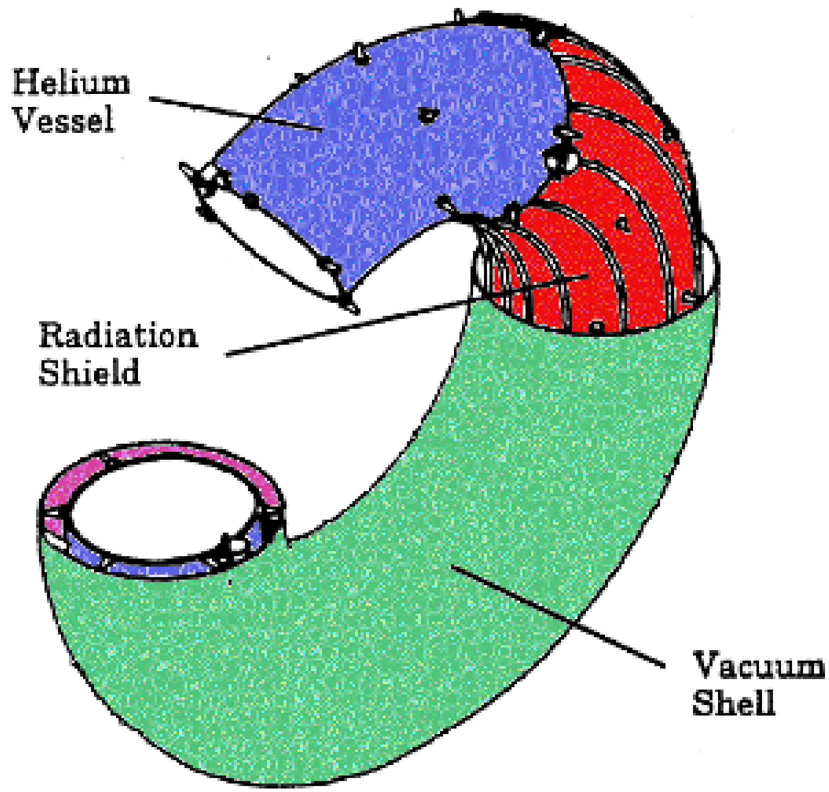
- **Investigate high-beta plasmas stabilized by compressibility**
  - Also the stability and dynamics of high-beta, energetic particles in dipolar magnetic fields
  - Examine the coupling between the scrape-off-layer and the confinement and stability of a high-temperature core plasma.
- **Study plasma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

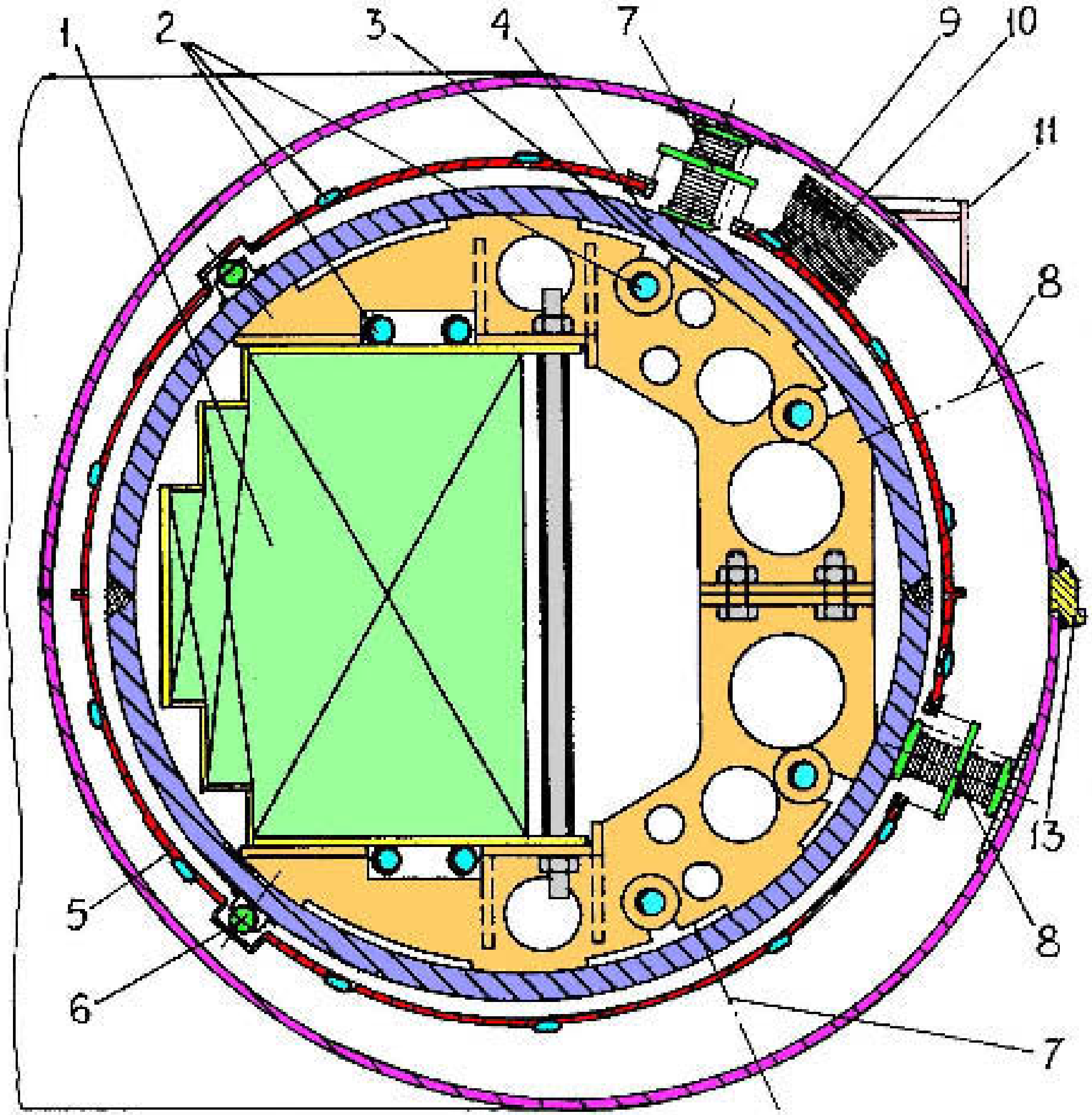


LDX Floating Coil Overview

- 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

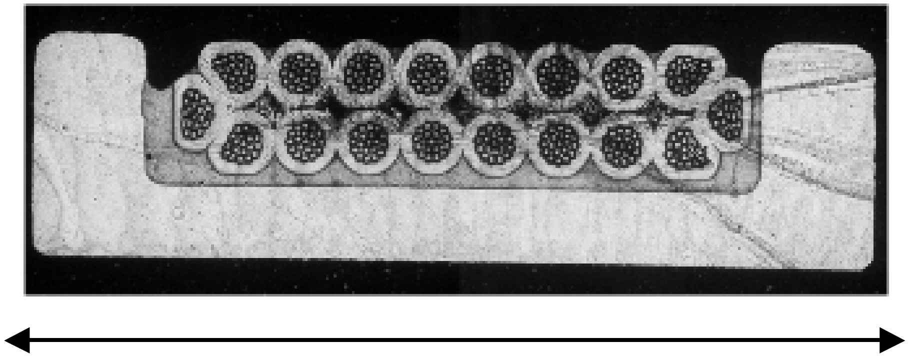


Floating Coil Cross-Section

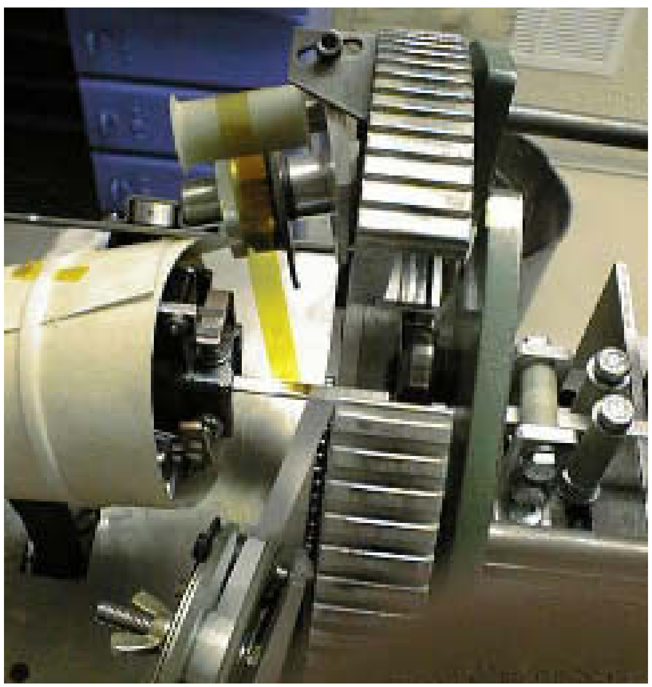


1. Magnet Winding Pack
2. Heat Exchanger tubing
3. Winding pack centering clamp
4. He Pressure Vessel (Inconel 625)
5. Thermal Shield (Lead/glass composite)
6. Shield supports (Pyrex)
7. He Vessel Vertical Supports/Bumpers
8. He Vessel Horizontal Bumpers
9. Vacuum Vessel (SST)
10. Multi-Layer Insulation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

Floating Coil Winding Pack Complete



Advanced Nb_3Sn react & wind conductor…

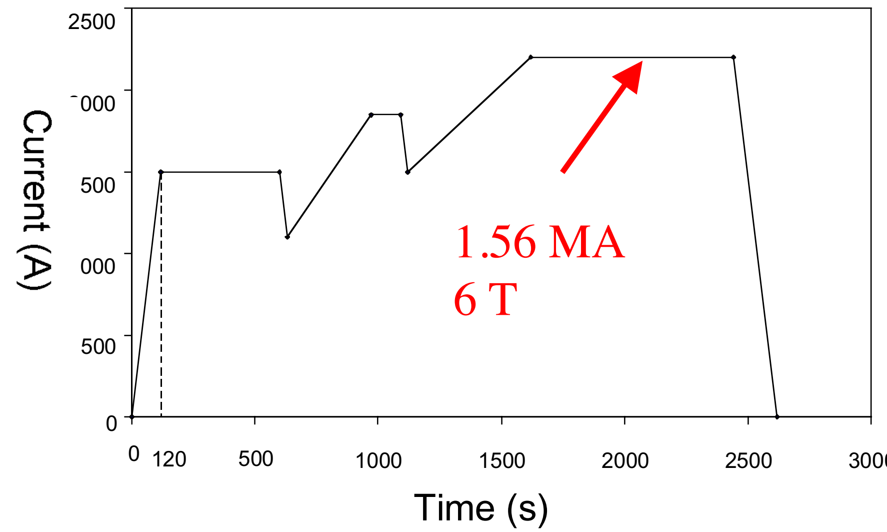


Conductor insulation taping head in operation

Winding 1/3 complete: pancake finished on right, layer winding continues…

Floating Coil Test is a Success!

Floating coil on test probe and being lowered into LHe cryostat for powered test at 4.2 K



- **Full current driven test in test cryostat.**
- **First current ramp sequence to 106% of normal operating current.**
  - **Maximum dI/dt = 12.5 A/s**
- ***The coil did not quench !***
  - **No observable degradation of conductor parameters**

LDX 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.
  - He vessel formed and machined
  - F-coil & supports fitted
  - Heat exchange tubing installed
  - 2 closure welds
  - Pressure tested & code stamped
  - Leak test to vacuum @ 125 atm. for both vessel and heat exchanger

Thermal Radiation Shield

- Intercepts heat leak from warm vacuum vessel to cold He vessel
  - Operates from 10-80°K
- "Cored" fiberglass composite construction (sailboat technology)
  - 2 fiberglass skins, 0.5mm thick and separated by core provides strength
  - Lead panels provide thermal inertia
  - Copper heat exchange tubing & conduction strips
- Process prototypes built and tested at MIT
- Major fabrication complete, undergoing acceptance testing.

Support Washer Stacks

- Specification
  - Hold heat leak to 5 K < 10 mW
  - Withstand 10g crash
- Solution
  - Stack of 400 4mil thick washers
- Status: Complete!
  - Prototype testing complete
  - 24 Stacks (~7000 coins) Assembled
  - Awaiting integration into F-coil cryostat

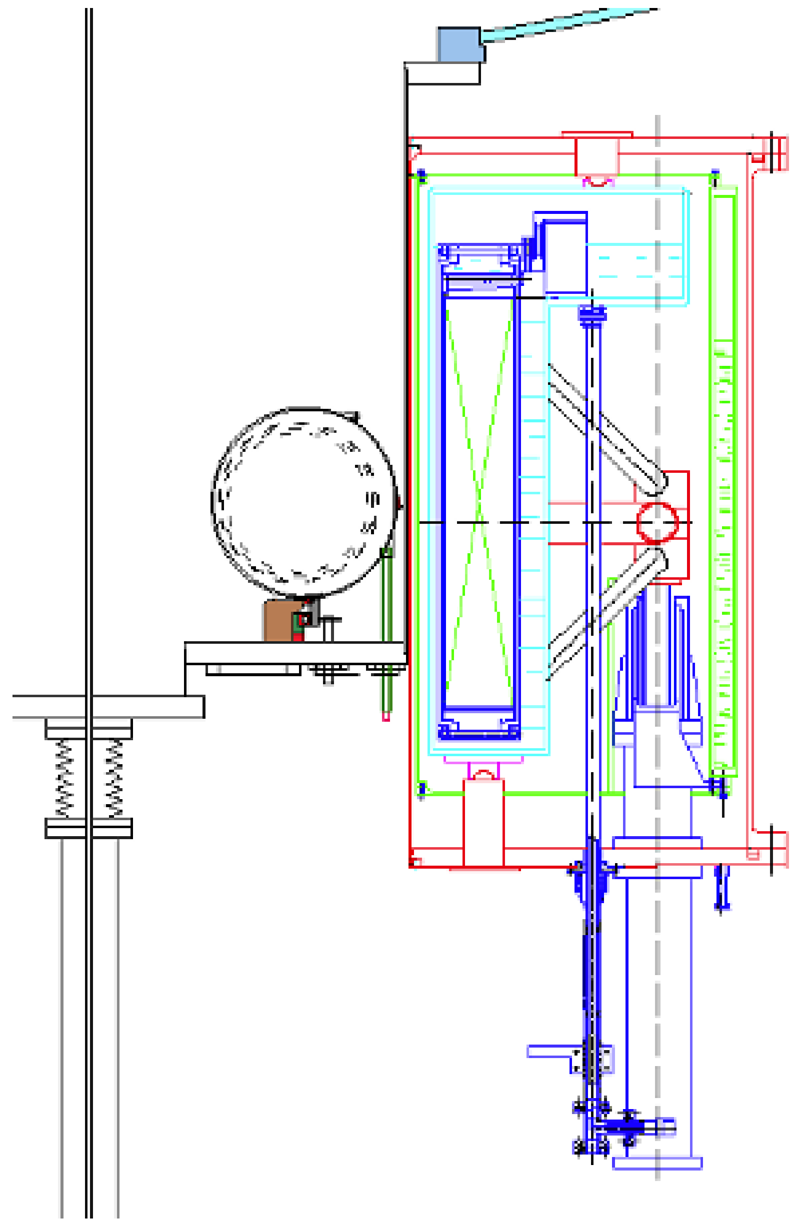
Floating Coil Cryostat & Charging Station

- Cryostat Assembly tooling complete
- Current work on cryostat vacuum vessel, support space frame and other details
- Charging station vacuum vessel under construction

Cryostat vacuum vessel and support space frame

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
  - Completed design and review
  - Scheduled delivery 8/02.
    - "Critical Path" item for project.

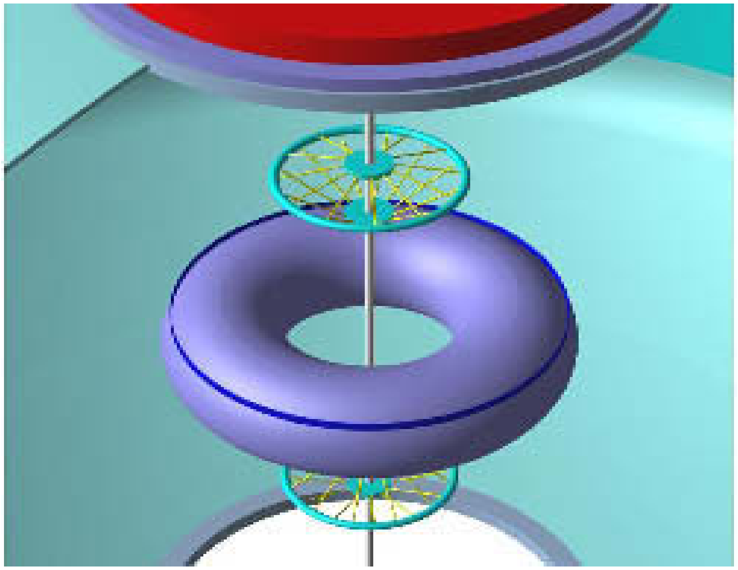


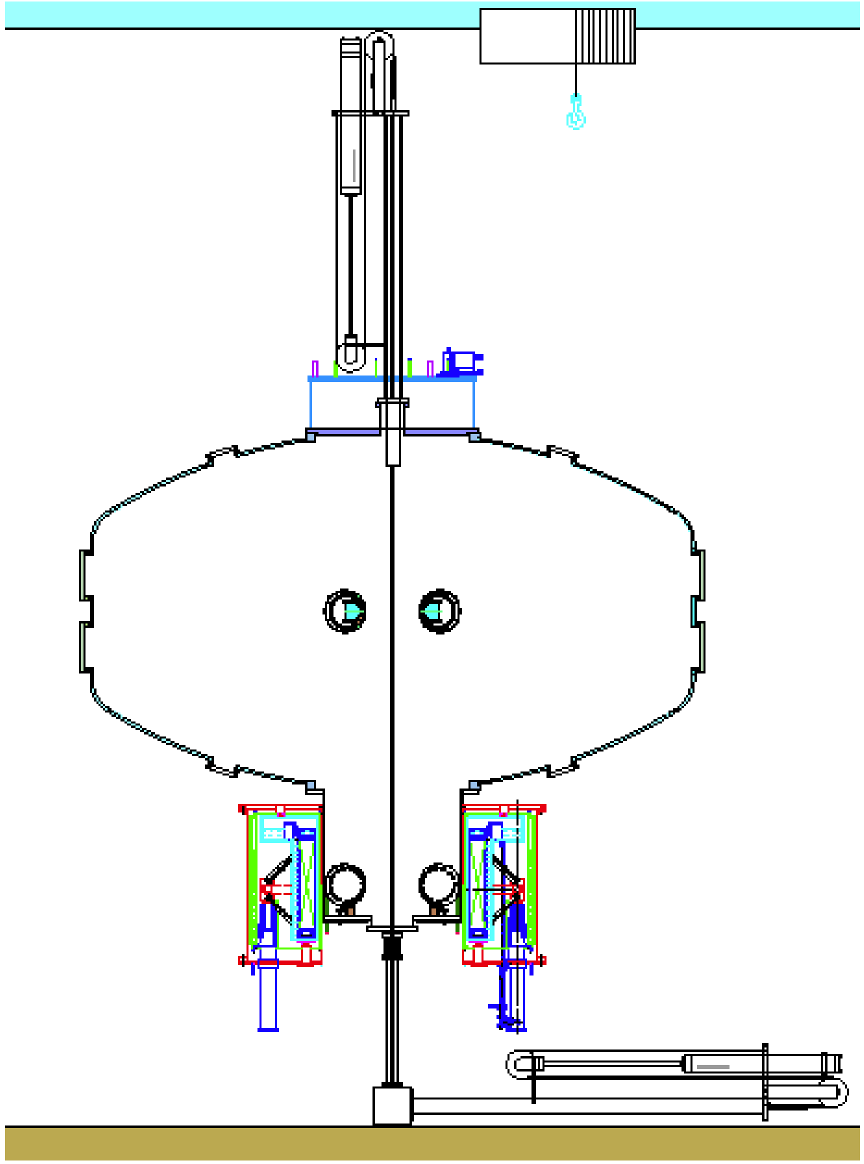
Charging Coil Construction Progress

- Winding pack status
  - Winding completed
  - Joints made
  - Awaiting warm weather for epoxy impregnation
- Quench protection equipment complete awaiting final testing
- Cryostat under production

Launcher/Catcher

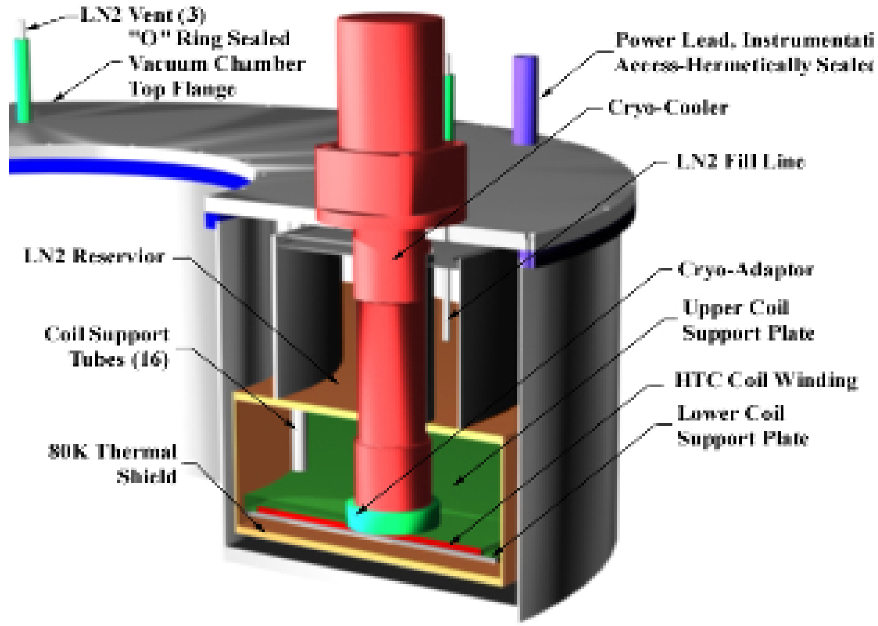
- Launcher/Catcher can be used in both supported and levitated operation
  - Central rod limits fault motion of floating coil without interrupting plasma.
  - Designed at PPPL
  - Installation and Testing imminent



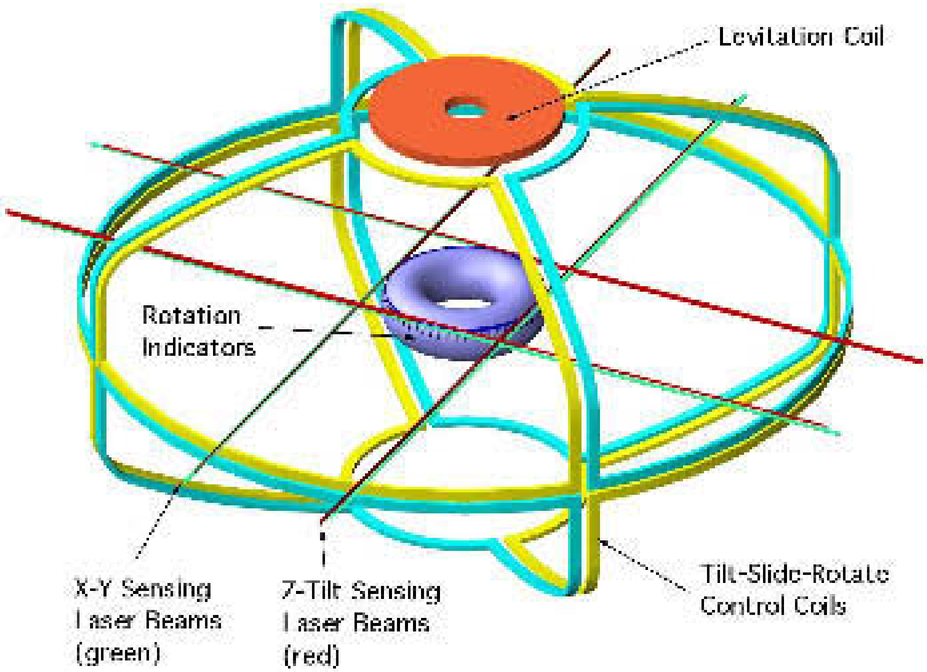


High T_c Superconducting Levitation Coil

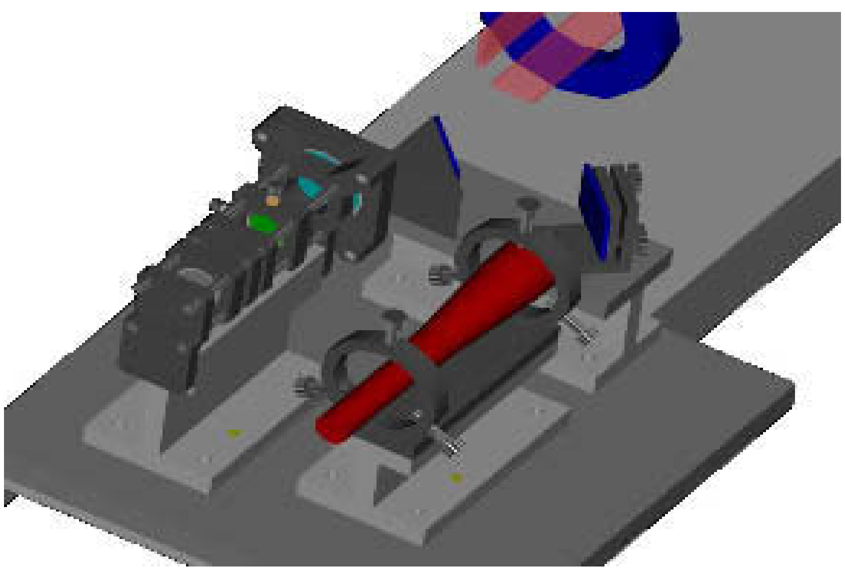
- SBIR collaboration with American Superconductor to build first HTS coil in the fusion community
- Uses available BSSCO-2223 conductor
- Operational temp 20-25° K
- Feedback gain selected for 5 Hz frequency
- 20 kJ stored energy can be dumped in < 1 second.
- Under construction
- Delivery this Spring!



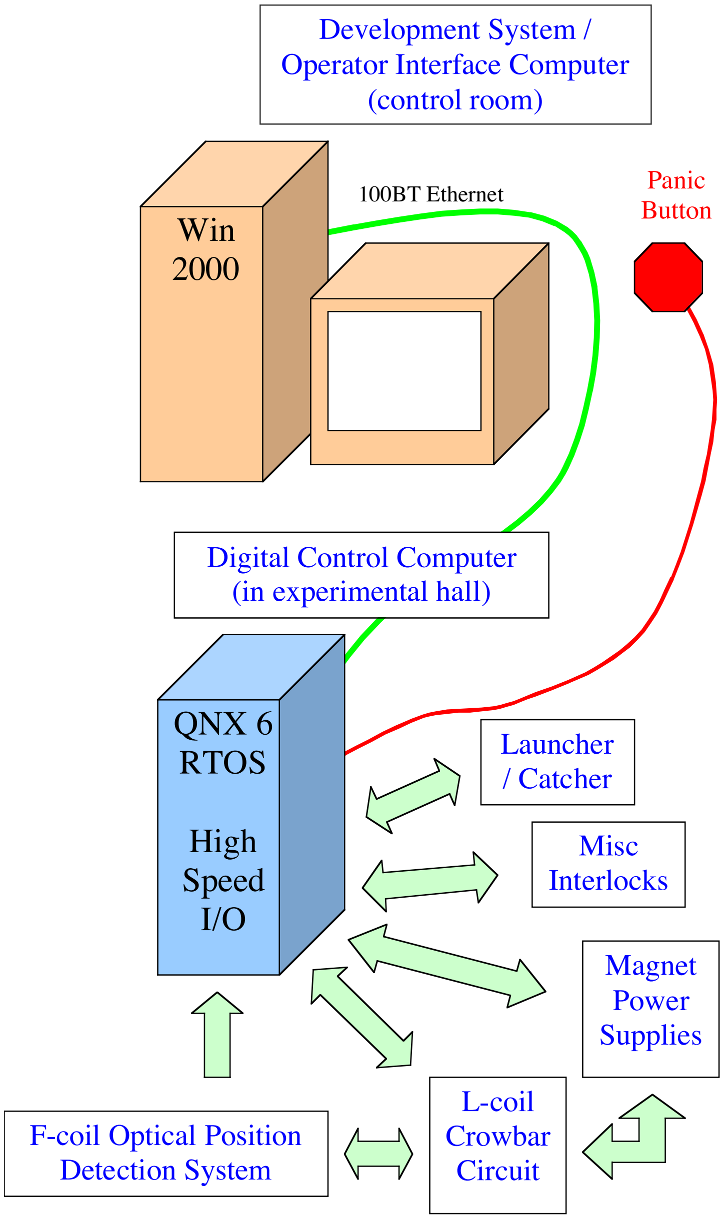
Levitation Control System



- 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

Conclusions

- Physics of the dipole plasma confinement is interesting and important for fusion
  - Also is a fascinating natural phenomenon
- 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
- 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
- All major parts are either finished or under construction
- Check www.psfc.mit.edu/ldx/ for updates on progress

Levitated Dipole Related Posters

- Dipole Theory
  - Kinetic Stability
    - Kesner, J. — *Theory of Plasma Confinement in a Levitated Dipole*
    - Simakov, A. N. — *Stability of Axisymmetric Plasmas in Closed Field Line Magnetic Fields*
    - Wong, H. V. — *High beta stability of magnetic dipole configurations*
  - Convective Cells
    - Goswami, P. — *Convective Cell Formation in a Magnetic Dipole Configuration*
- Dipole Experiments
  - LDX
    - Mauel, M. E. — *Status of LDX Fabrication*
    - Hansen, A. K. — *Physics and Operation Plan for LDX*
  - DISCUS
    - Tynan, G. R. — *DISCUS: A very high beta dipole disk-like equilibria physics experimental concept*