Levitated Dipole Experiment (LDX)

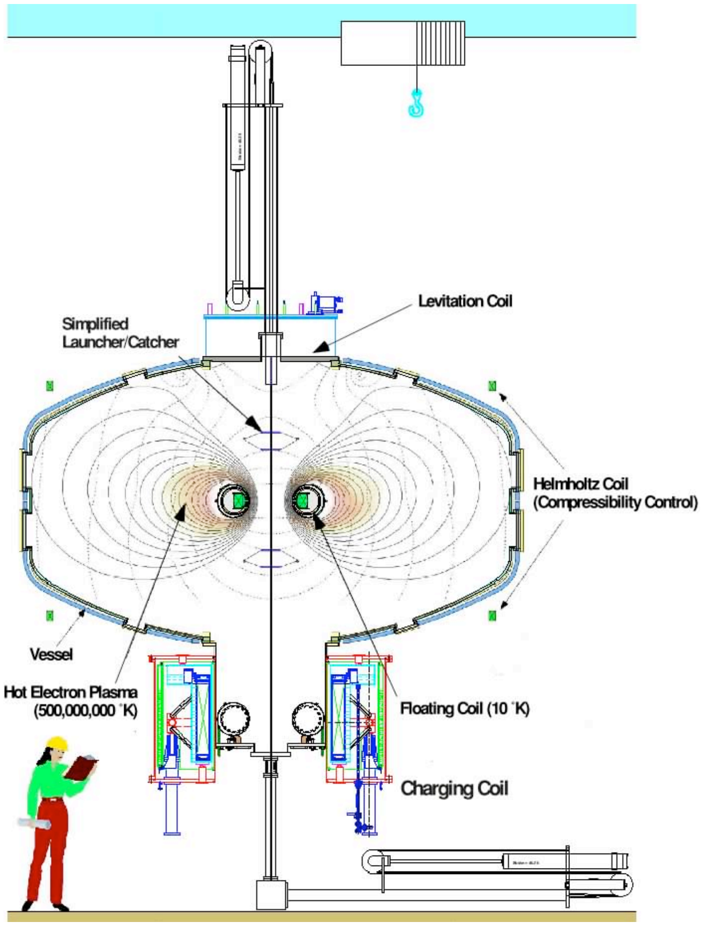
A fusion concept inspired by nature:

Can fusion benefit from unique features found in the planetary magnetospheres?

- Simplest magnetic field geometry
- Energetic plasma confined with □ > 1
- Rapid plasma circulation combined with strong adiabatic compression

A partnership between plasma physics and magnet technology:

- Floating Coil (Nb_3Sn / 1.5 MA)
- Charging Coil (NbTi / 4.2 MA)
- Levitation Coil (Bi-2223 / 300 kA)



First operation expected within months!

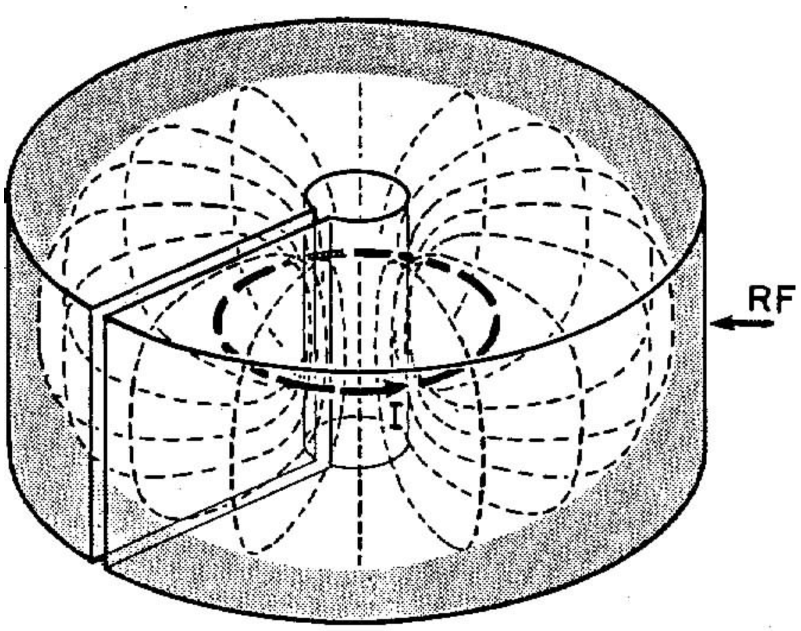
Dipole Fusion Concept and the LDX Experiment

Mike Mauel, representing the
LDX Physics and Engineering Team:
Darren Garnier, Alex Hansen, Jay Kesner, Mike Mauel,
Phil Michael, Joe Minervini, Alex Zhukovsky
Columbia University and MIT

Outline

- Physics Basis for High-□ Dipole Confinement
- Dipole Fusion Energy
- Description of LDX and Research Plan
- “Family photos” and Description of SC Magnets

Dipole Fusion Concept



- Originated by A. Hasegawa (1987)
- Motivated by observations of **planetary magnetospheres…**

  High-β, high-temperature plasma **with centrally-peaked profiles** result naturally from radial diffusion/circulation and adiabatic heating.

MHD Stabilization by Compressibility is Long Ago "Understood" (but with few laboratory tests)

- Dipole concept derives from the thermodynamic arguments of Rosenbluth and Longmire, *Ann. Phys.* (1957). The work required to exchange tubes of equal magnetic flux is

$$\Delta E_p = \delta V \left(\delta p + p\gamma \frac{\delta V}{V} \right) = \delta \left(p V^\gamma \right) \frac{\delta V}{V^\gamma}$$

  where $V \propto \oint dl/B = dV/d\psi$.

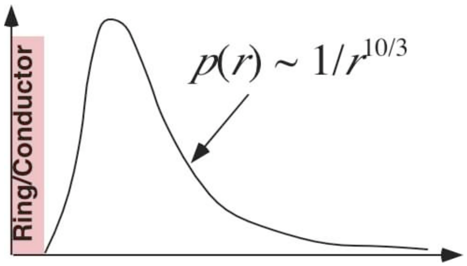
- For $\delta(pV^\gamma) < 0$, an exchange of flux tubes will *decrease* plasma energy and allow MHD instability.

- Stability by compressibility defines a critical pressure gradient. When $-\nabla p < (\nabla p)_{crit} = p\gamma\nabla \ln V$, MHD perturbations do not grow.

- For $\delta(pV^\gamma) > 0$, any exchange of flux tubes will increase plasma energy. Marginally stable profiles may still result from forced mixing.

- Compressibility is important when the volume of flux tubes changes significantly, like the dipole and maybe the low-aspect ratio tokamak with $R/a \leq \gamma = 1.7$.

The “Straight” Dipole (Hard-Core Pinch)



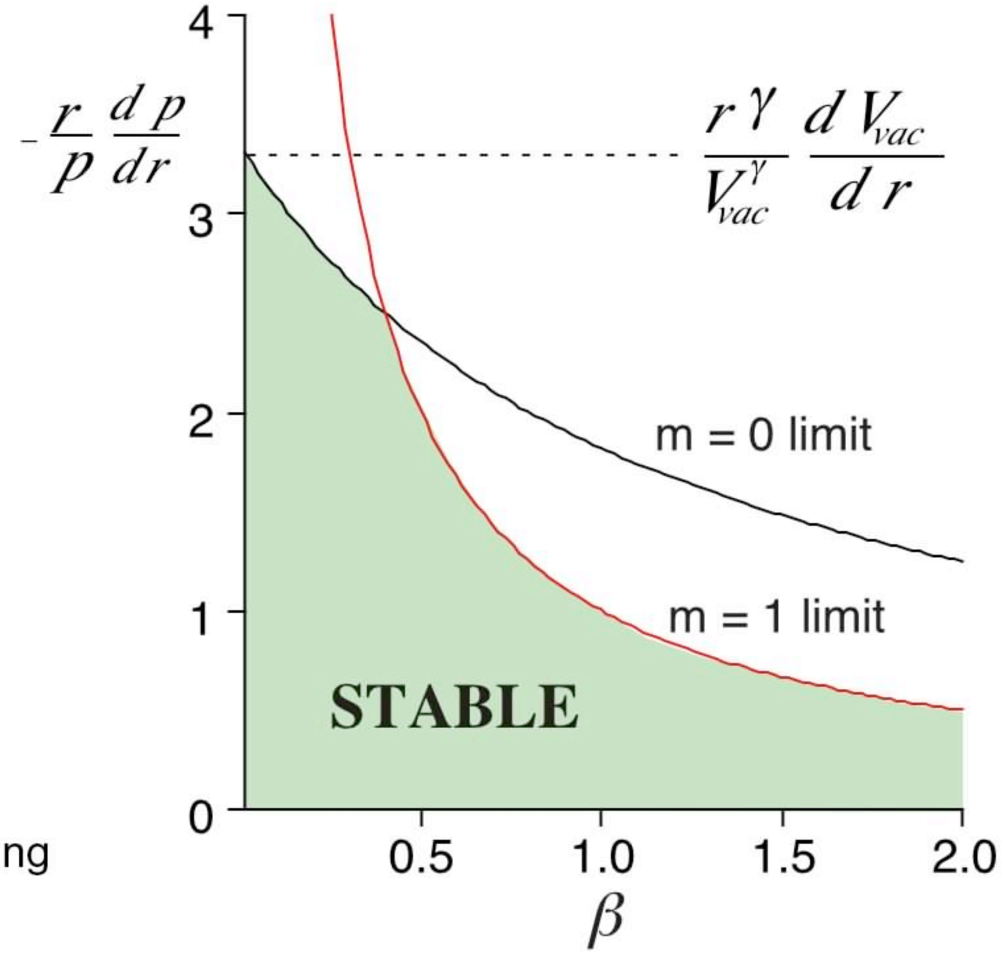
- Simple 1D equilibrium, solvable at finite β.
- At low β, $B \propto R^{-1}$ and

$$V(R) = \oint \frac{dl}{B} \propto R^2$$

- $m = 0$ interchange stability requires

$$-\nabla \ln p < 2\gamma = 10/3$$

- At higher β, $m = 1$ ballooning sets stability limit.
- Sufficiently gentle profiles are stable for $\beta > 1$.



From Freidberg, *Ideal MHD*, Plenum (1987).

Gold's "Motions in the Magnetosphere of the Earth"

- T. Gold, *J. Geophys. Res.* (1959) coined the word "magnetosphere" and described the critical pressure gradients for a dipole.
- With B ~ R^{-3}, tubes of equal magnetic flux have volumes

$$V \sim R^4$$

- The magnetosphere is "unstable against fast adiabatic convection" if the pressure gradients are steeper than

$$P \sim R^{-20/3}$$

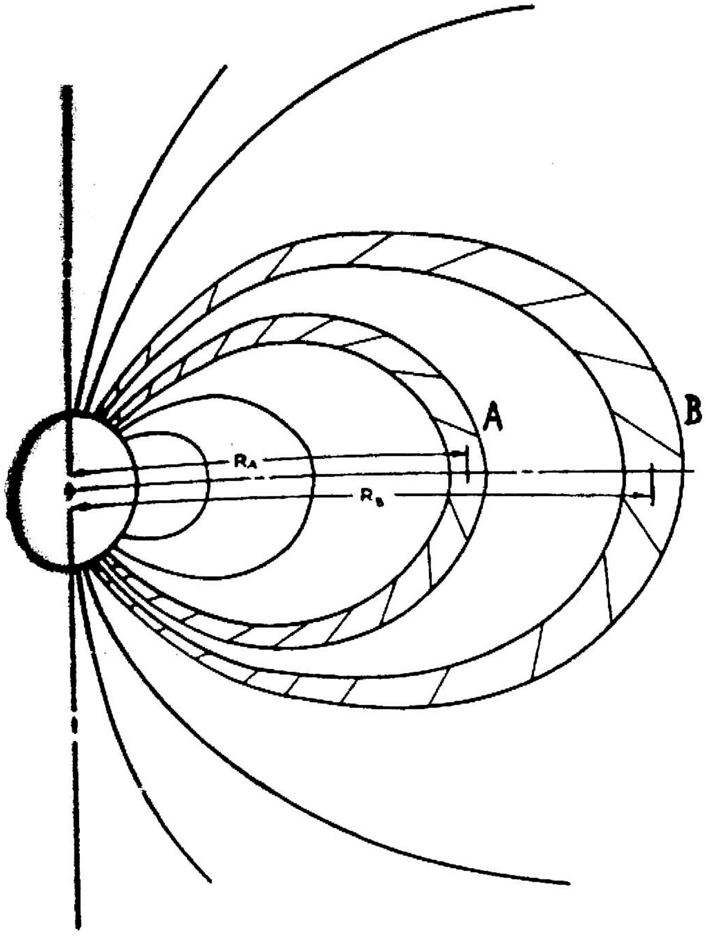
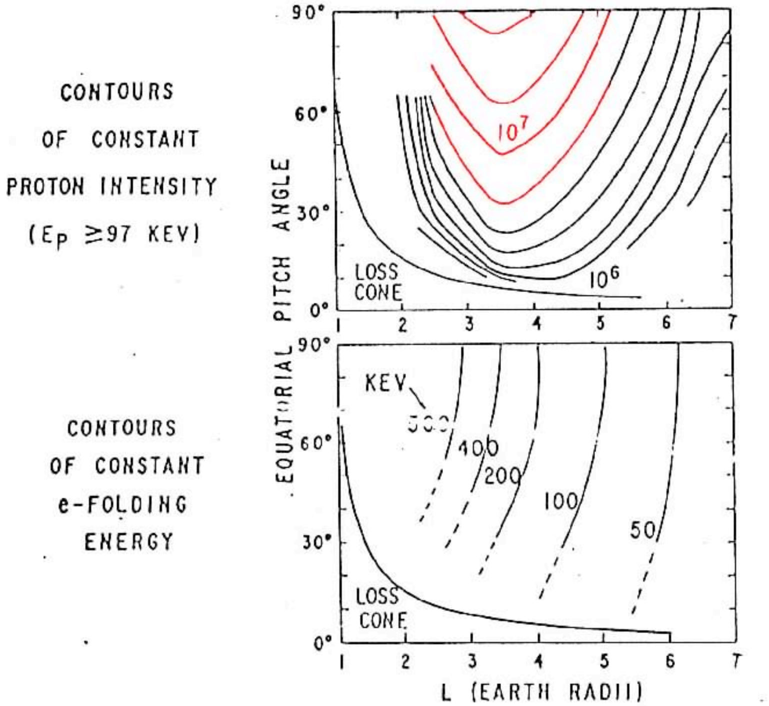
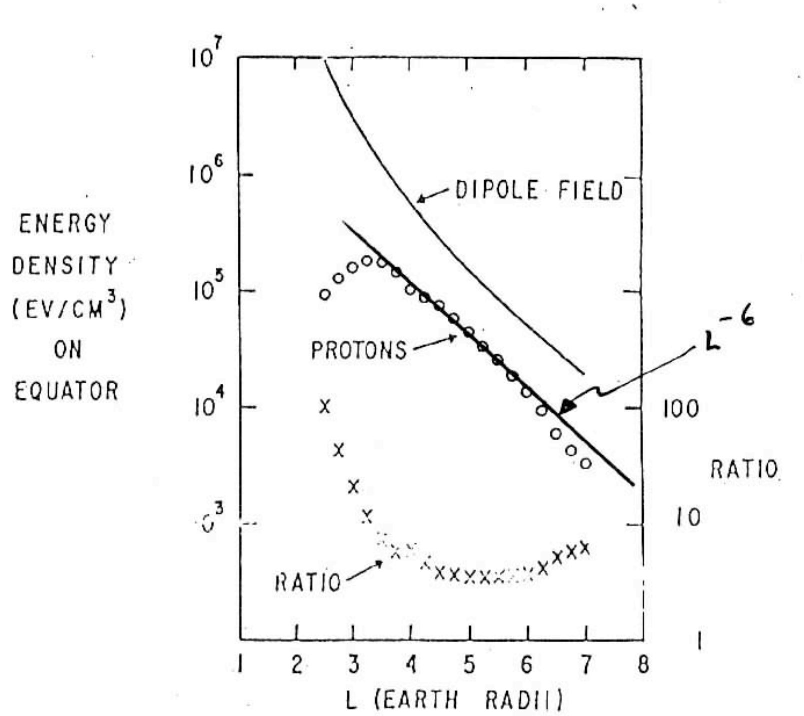


FIG. 1

Early Observations of Peaked Profiles

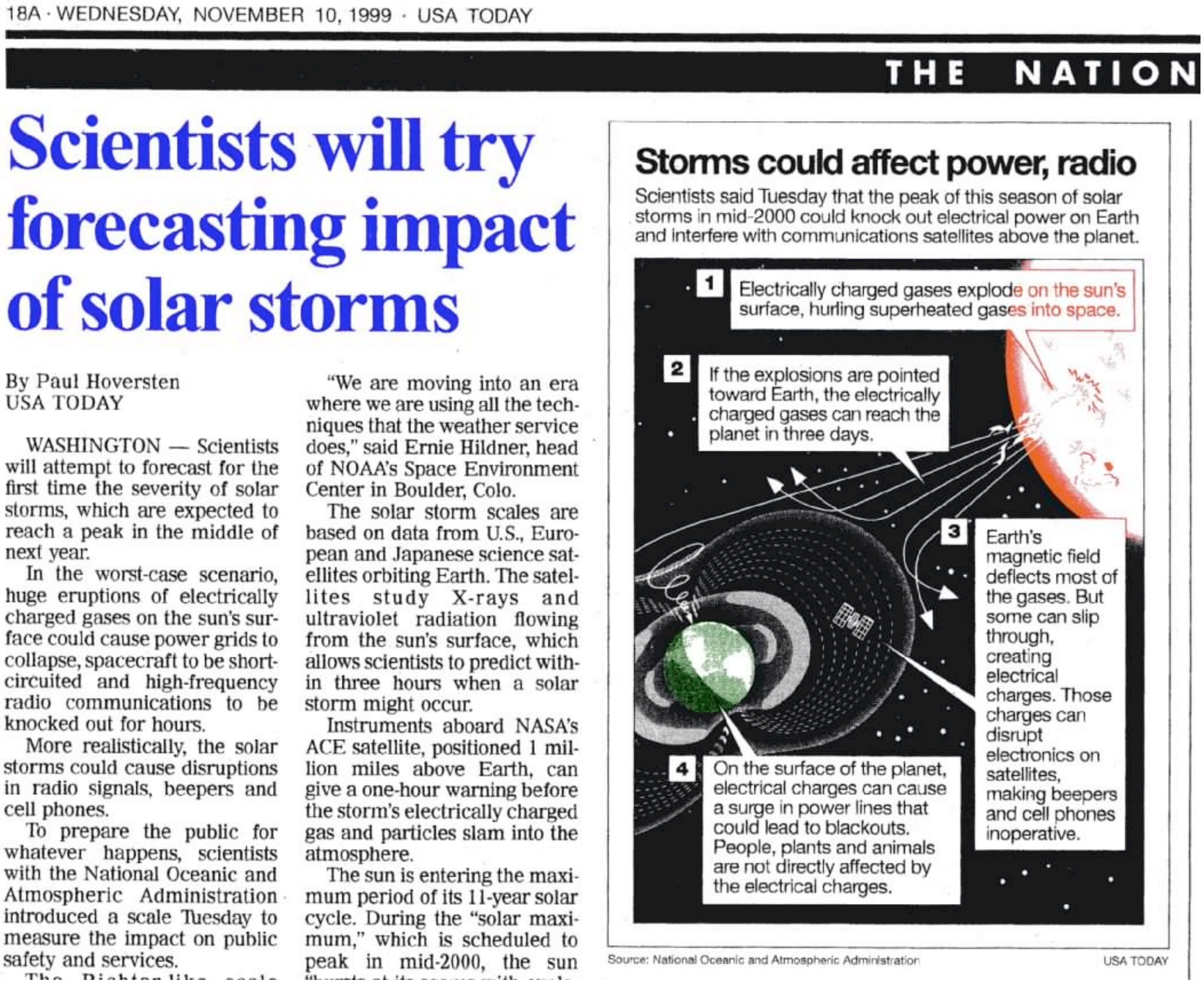
From Explorer XII, XIV, XV.
L. R. Davis, *Proceedings of the Plasma Space Science Symposium*,
Washington, D. C., 1963.





pV^{γ} called by D. Southwood the magnetosphere’s “Fourth Adiabatic Invariant”

Magnetic Storms: “Disruptions” in Space



18A · WEDNESDAY, NOVEMBER 10, 1999 · USA TODAY

THE NATION

Scientists will try forecasting impact of solar storms

By Paul Hoversten
USA TODAY

WASHINGTON — Scientists will attempt to forecast for the first time the severity of solar storms, which are expected to reach a peak in the middle of next year.

In the worst-case scenario, huge eruptions of electrically charged gases on the sun's surface could cause power grids to collapse, spacecraft to be short-circuited and high-frequency radio communications to be knocked out for hours.

More realistically, the solar storms could cause disruptions in radio signals, beepers and cell phones.

To prepare the public for whatever happens, scientists with the National Oceanic and Atmospheric Administration introduced a scale Tuesday to measure the impact on public safety and services.

“We are moving into an era where we are using all the techniques that the weather service does,” said Ernie Hildner, head of NOAA's Space Environment Center in Boulder, Colo.

The solar storm scales are based on data from U.S., European and Japanese science satellites orbiting Earth. The satellites study X-rays and ultraviolet radiation flowing from the sun's surface, which allows scientists to predict within three hours when a solar storm might occur.

Instruments aboard NASA's ACE satellite, positioned 1 million miles above Earth, can give a one-hour warning before the storm's electrically charged gas and particles slam into the atmosphere.

The sun is entering the maximum period of its 11-year solar cycle. During the “solar maximum,” which is scheduled to peak in mid-2000, the sun

Storms could affect power, radio

Scientists said Tuesday that the peak of this season of solar storms in mid-2000 could knock out electrical power on Earth and interfere with communications satellites above the planet.

1 Electrically charged gases explode on the sun's surface, hurling superheated gases into space.

2 If the explosions are pointed toward Earth, the electrically charged gases can reach the planet in three days.

3 Earth's magnetic field deflects most of the gases. But some can slip through, creating electrical charges. Those charges can disrupt electronics on satellites, making beepers and cell phones inoperative.

4 On the surface of the planet, electrical charges can cause a surge in power lines that could lead to blackouts. People, plants and animals are not directly affected by the electrical charges.

Source: National Oceanic and Atmospheric Administration

USA TODAY

“Inward Diffusion” of the Active Magnetosphere

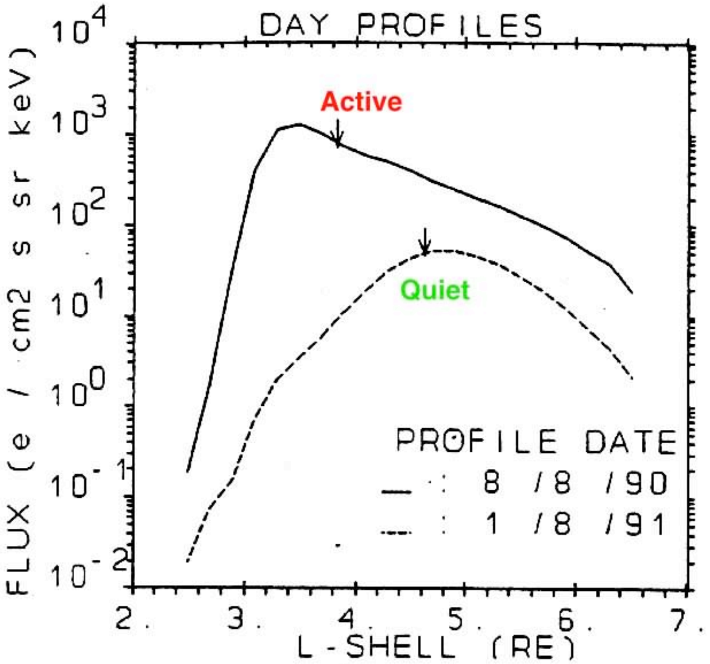


Figure 2. Electron flux intensity as a function of L-value, in Earth radii, for an intense outer zone (8 August 1990, solid line) and a weak outer zone (8 January 1991, dashed line). Arrows mark the centroid L of each profile (see text).

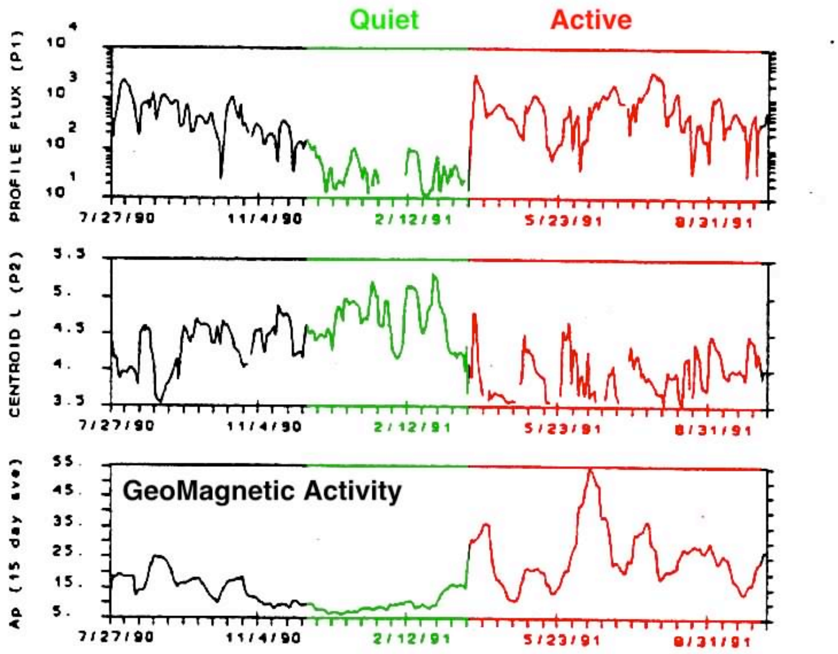


Figure 3. Profile flux (P_1; top panel) and centroid L (P_2; middle panel), as defined in the text, plotted versus time (in days). Both parameters were derived from daily 1.55 MeV fluxes. Fifteen day running average of Ap (Ap_{15}) versus time (in days) is plotted in bottom panel.

Solar wind fluctuations drive random, impulsive interchange motions and **“inward” diffusion and adiabatic heating**!

Ideal MHD Stability of Dipole Plasma at High β

3432 Phys. Plasmas, Vol. 6, No. 9, September 1999 Garnier, Kesner and Mauel

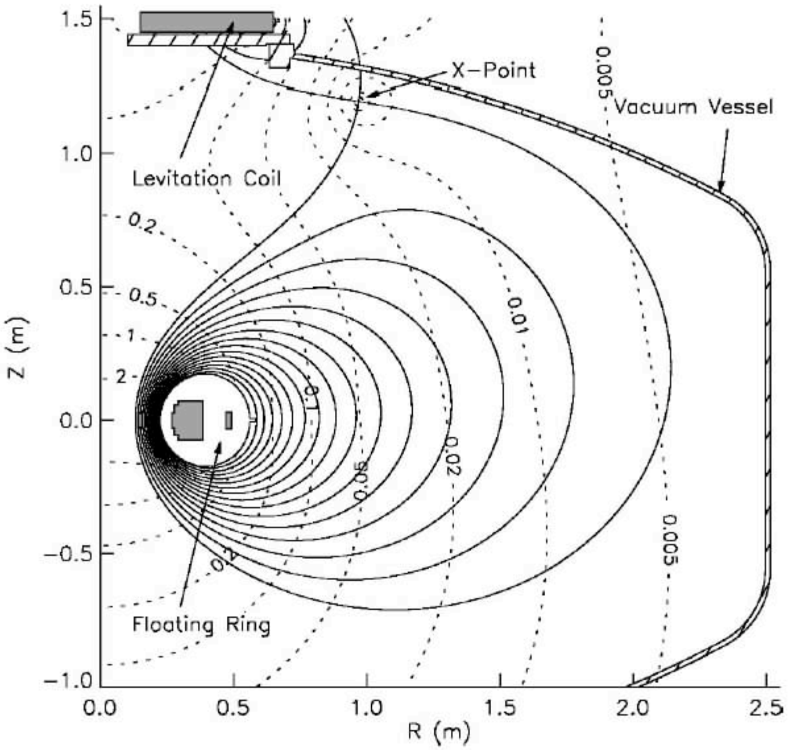


FIG. 1. Vacuum field in LDX.

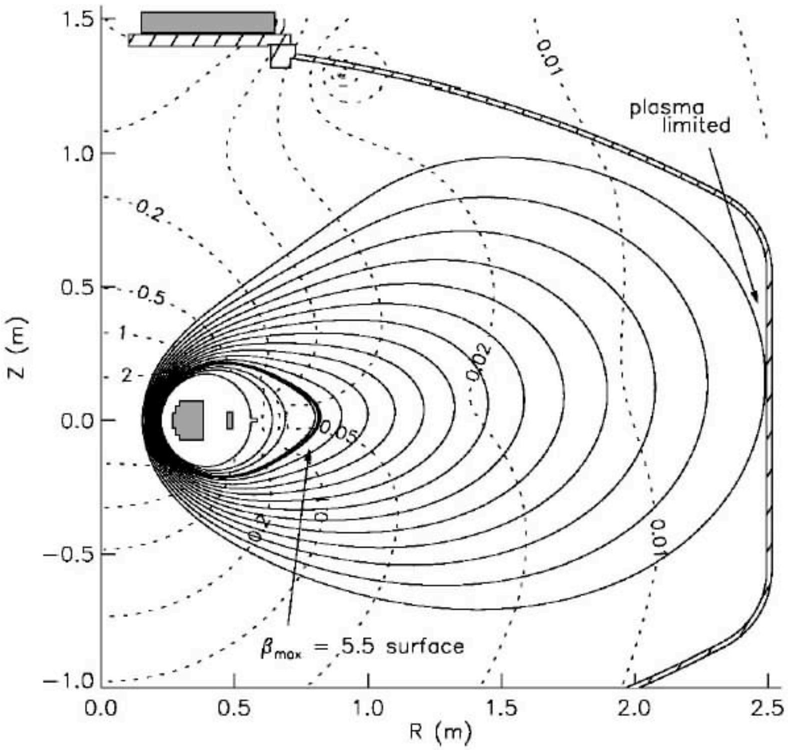


FIG. 2. High β equilibrium ($\beta_{max} = 10$) solution in the LDX geometry.

Peak local β = 10, Peak flux-averaged β = 4, Volume-averaged β = 0.5!

Ideal MHD Stability of Dipole Plasma at High β

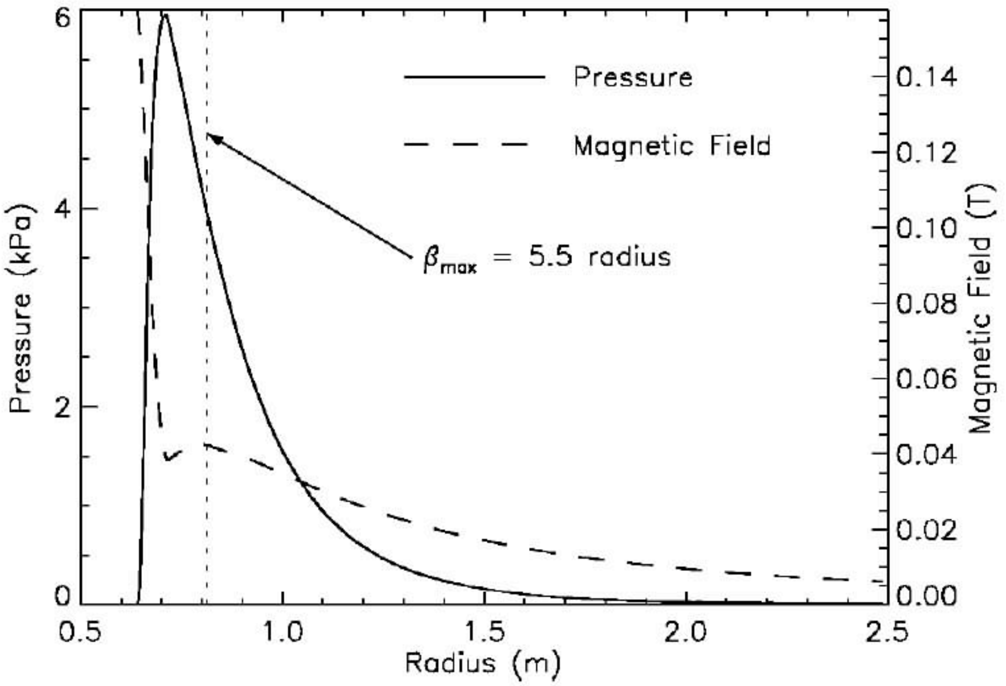
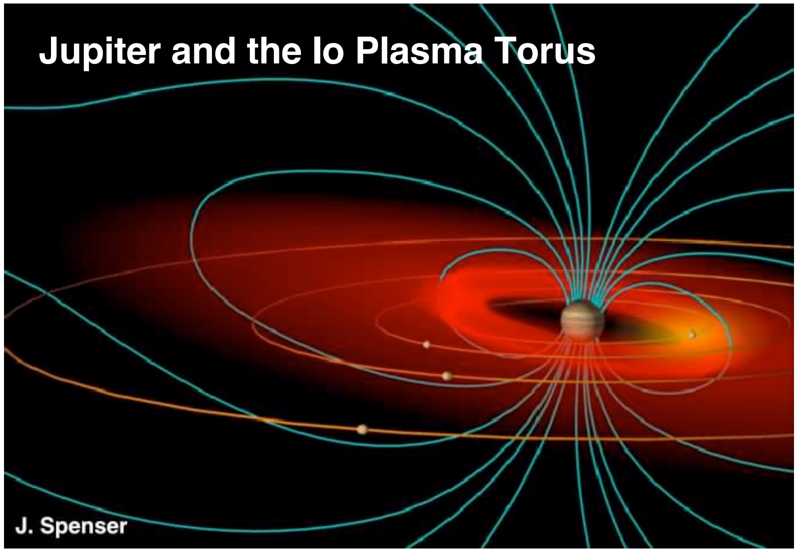
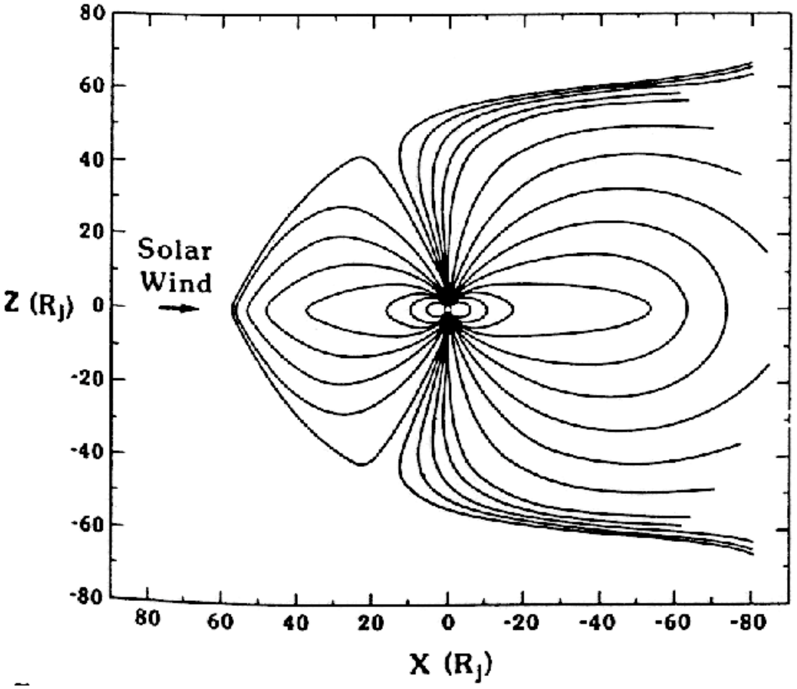


FIG. 3. Pressure profile and midplane magnetic field for an equilibrium with ($\beta_{\text{max}} = 10$) solution in the LDX geometry.

Peak local β = 10, Peak flux-averaged β = 4, Volume-averaged β = 0.5!

Nature’s Way to Confine High β Plasma



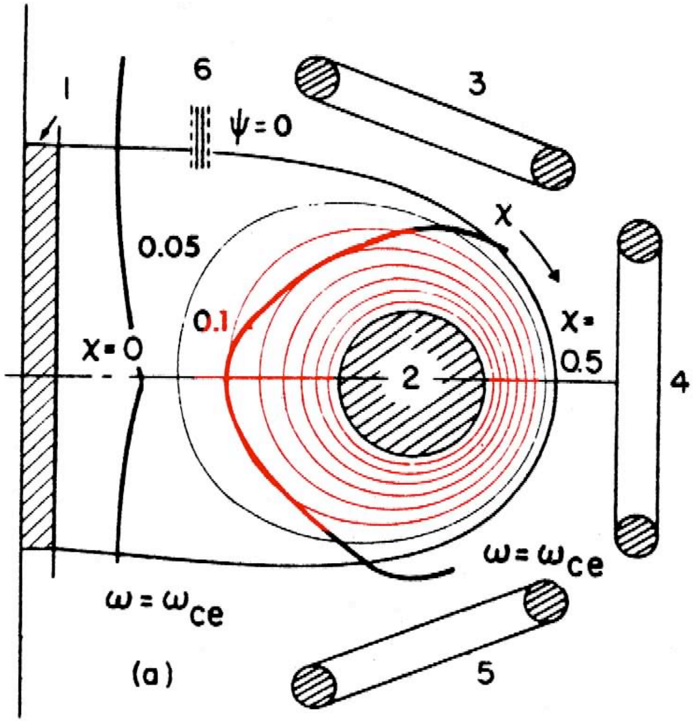


- Voyager and Galileo Missions to the outer planets show high β confinement occurs naturally (β > 2 in Jupiter)
- High-β equilibria become “disk like.”

  Plasma pressure is balanced by magnetic tension.
- Dipole-confined plasma can be **stable for all β**!

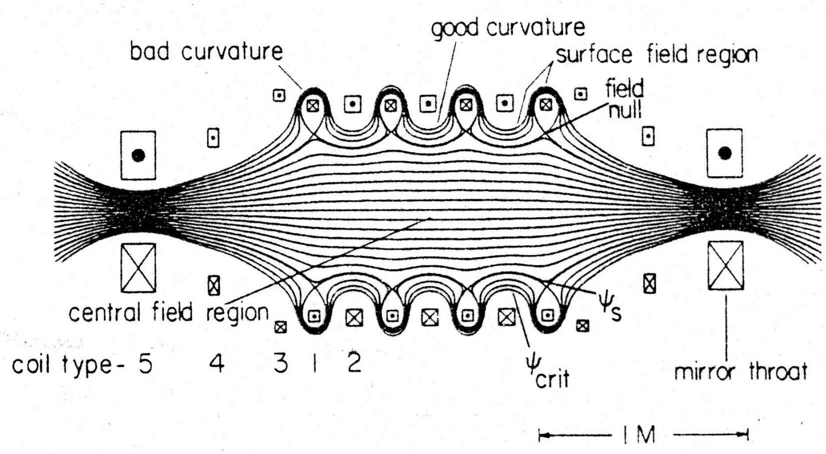
A Dipole is not a Spherator!

- Spherators have *much less* flux expansion. Levitrons add toroidal and vertical fields to produce *average* good curvature (and neoclassical effects).
- Dipole allows ▯ > 1; average well allows only ▯ < 0.1.
- In FM-1, separation between floating coil and edge ~ 6 cm.
- In LDX, R_{wall} ~ 2.5 m, and R_{wall}/R_{coil} ~ 5.
- In LDX, compressibility is very large: V_{out}/V_{in} ~ 600



FM-1

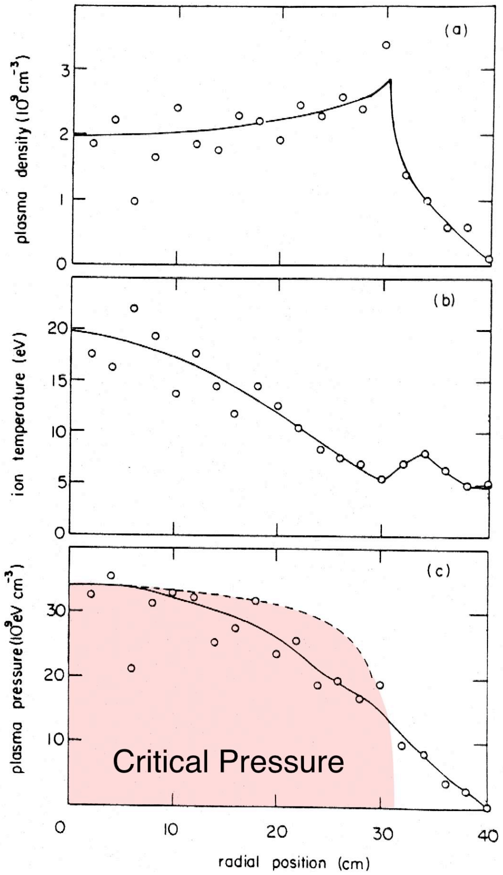
Effects of Compressibility Stabilization seen in Internal Ring Experiments



John Ferron, et al. Phys. Fluids (1983)

“Stability can be maintained… provided that the product of the pressure gradient and the specific flux volume gradient is positive.”

i.e. $\square(pV^{\square}) > 0$



Theory and Modeling

- Ideal MHD (Equilibria with > 1, Interchange & Ballooning stable; Weak res. mode)
  - Garnier,… Phys. Plasmas (1999)
  - Krasheninnikov, Catto, Hazeltine, PRL (1999)
  - Simakov, Catto, Krasheninnikov, Phys. Plasmas (2000)
  - Simakov,…, Phys. Plasmas (Dec 2002)
- Electrostatic & Electromagnetic Drift/Kinetic Stability
  - Kesner, Phys. Plasmas (2000) (stable to drift modes with ~ 2/3)
  - Simakov,…, Phys. Plasmas (2001)
  - Kesner and Hastie, Phys. Plasmas (2002)
  - Simakov, Hastie, Catto, Phys. Plasmas (2001) (inner drift modes)
- Nonlinear Convection (convection cells transport particles; may not energy!)
  - Tonge, Huang, Leboeuf, Dawson, 2001 APS DPP
  - Pastukhov and Chudin, Plasma Phys. Repts (2001)
  - Rey and Hassam, Phys. Plasmas (2001) (conv cell with nonuniform fueling)

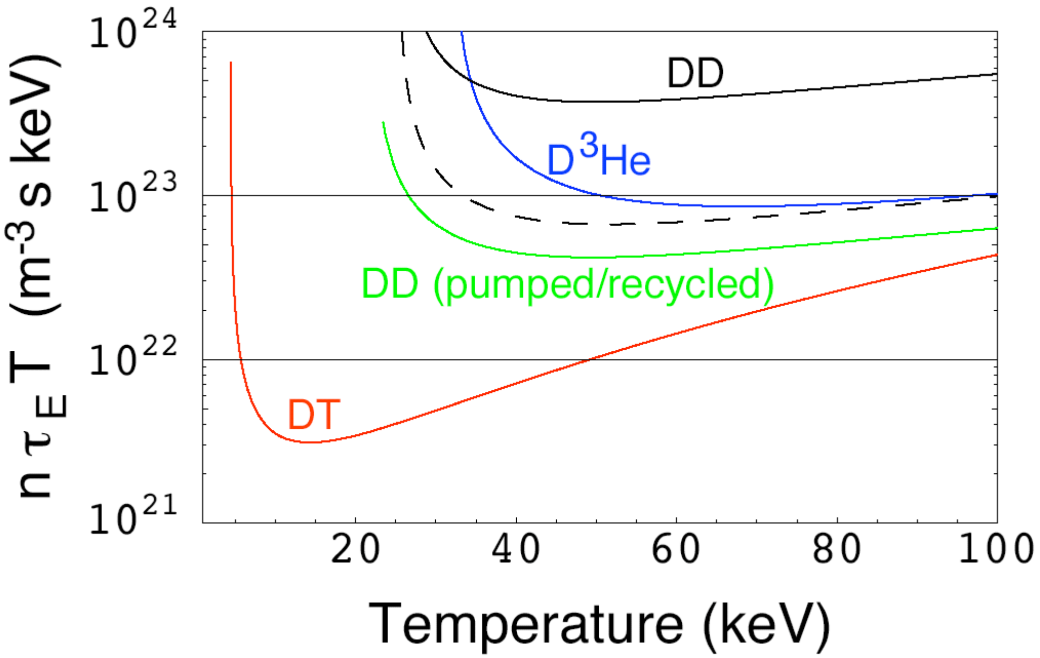
Dipole may be an attractive Fusion Power Source…

- MHD instability restores marginally-stable profiles (that are very peaked). No disruptions.
- Steady state operation
- Circular, non interlocking coils
- High β for economic field utilization and increased power density
- Low divertor heat load on outer wall
- Plasma surrounds coil (unlike other concepts where coils surround plasma). Plasma volume greatly exceeds magnet volume.
- Theory suggests MHD and drift wave stability.
  Can a dipole plasma achieve near "classical" confinement?
- **No toroidal field; No magnetic shear**:
  - No neo-classical effects
  - Large-scale convection may enable low τ_p and ash removal
- Advanced fuels (with component and technology advantages)
- Requires levitated internal ring technology (!) and high-field superconducting magnets

Fusion Fuels

- D-T offers our best chance for fusion, but…
- D-T fusion requires Li breeding blanket
- D-T fusion requires materials R&D program
- D-D and D-^{3}He fuels may **simplify component development** and improve lifetime…

…provided **good energy confinement** is achieved at high ▯with **rapid** ash removal and particle pumping/recycling.



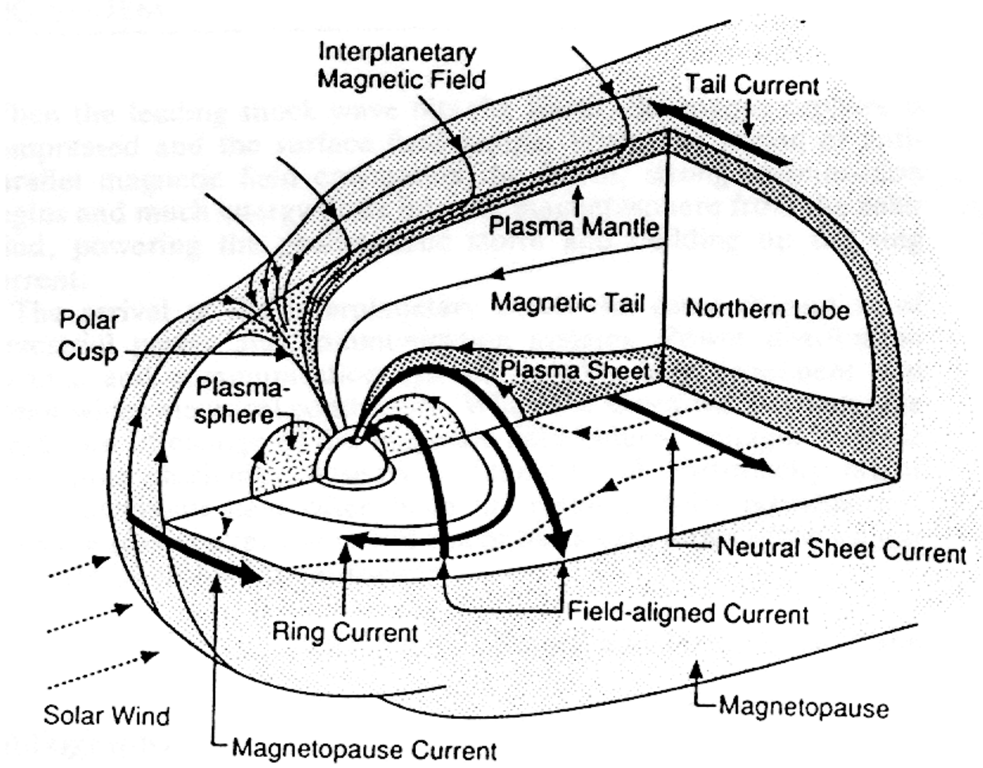
$$
\begin{array}{lll}
(1a) & D + D & \xrightarrow[50\%]{} T(1.01\,\mathrm{MeV}) + p(3.02\,\mathrm{MeV}) \\
(1b) & & \xrightarrow[50\%]{} He^3(0.82\,\mathrm{MeV}) + n(2.45\,\mathrm{MeV}) \\
(2) & D + T & \longrightarrow He^4(3.5\,\mathrm{MeV}) + n(14.1\,\mathrm{MeV}) \\
(3) & D + He^3 & \longrightarrow He^4(3.6\,\mathrm{MeV}) + p(14.7\,\mathrm{MeV})
\end{array}
$$

Rapid Plasma Circulation in Space

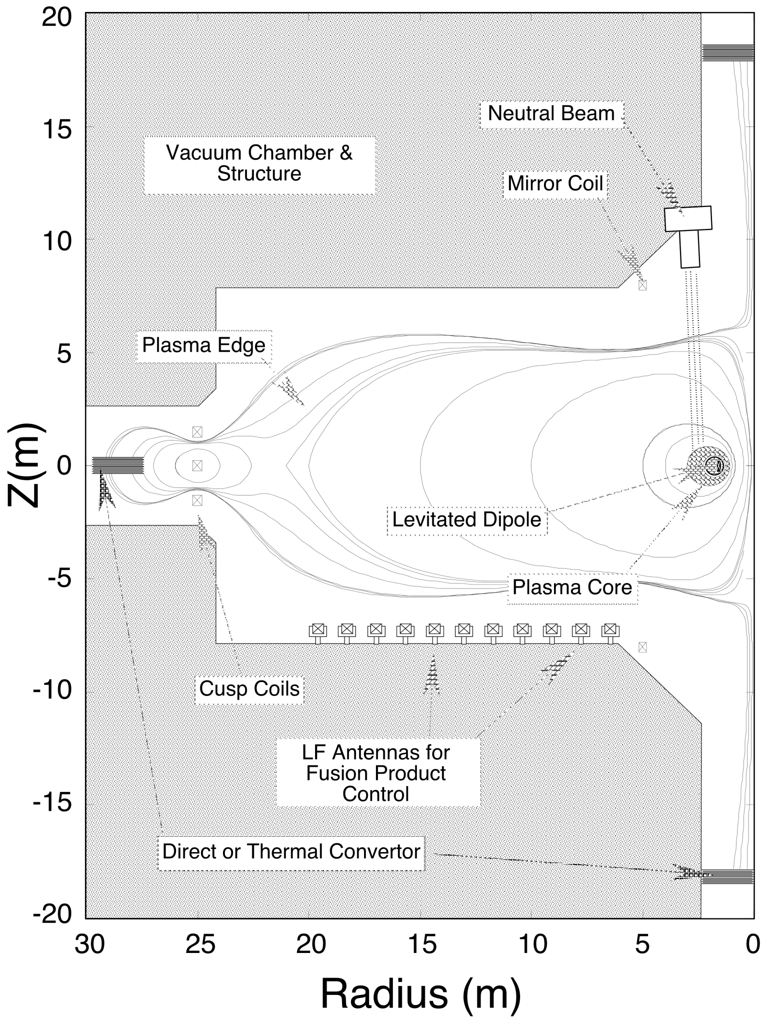
- Standing convection outside plasma sphere
- Co-rotation within plasmasphere

➔ Large scale plasma circulation is allowed in **shear-free** magnetic topology

- Dipole plasma may combine good energy confinement with poor particle confinement making **advanced fusion fuels feasible**.



D-^{3}He Reactor Cartoons



- Hasegawa, *et al. Fus Tech.* (1991) and Hasegawa, et al., *Fus. Tech.* (1992).
- Highest possible ring current (20 MA & 40 MA).
- $\beta \le 3$; large flux expansion
- Modest power (< 0.4 GW) and coil radius (~ 2 m)
- Everything in the kitchen…
    - Triton/Fusion product pumps
    - Direct convertors
    - Neutral beam fueling and heating

Teller's Dipole Rocket

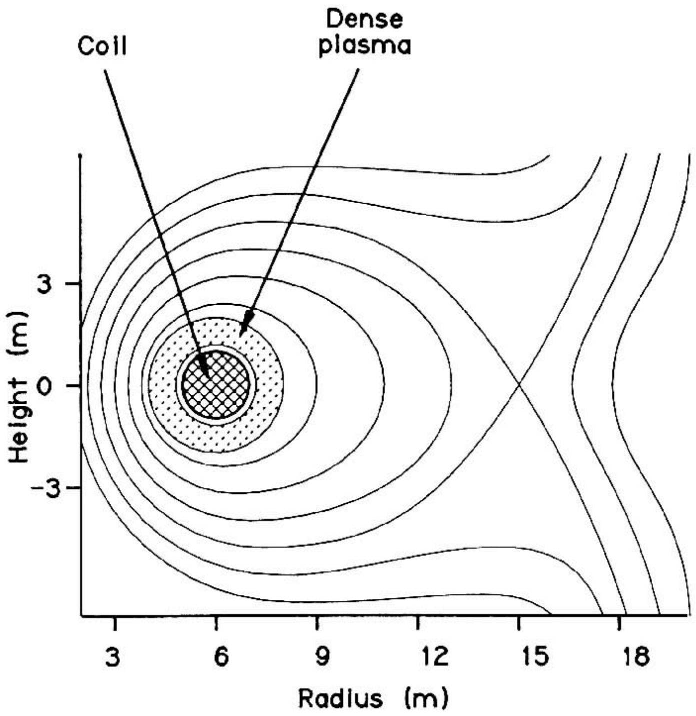
SPACE PROPULSION BY FUSION IN A MAGNETIC DIPOLE

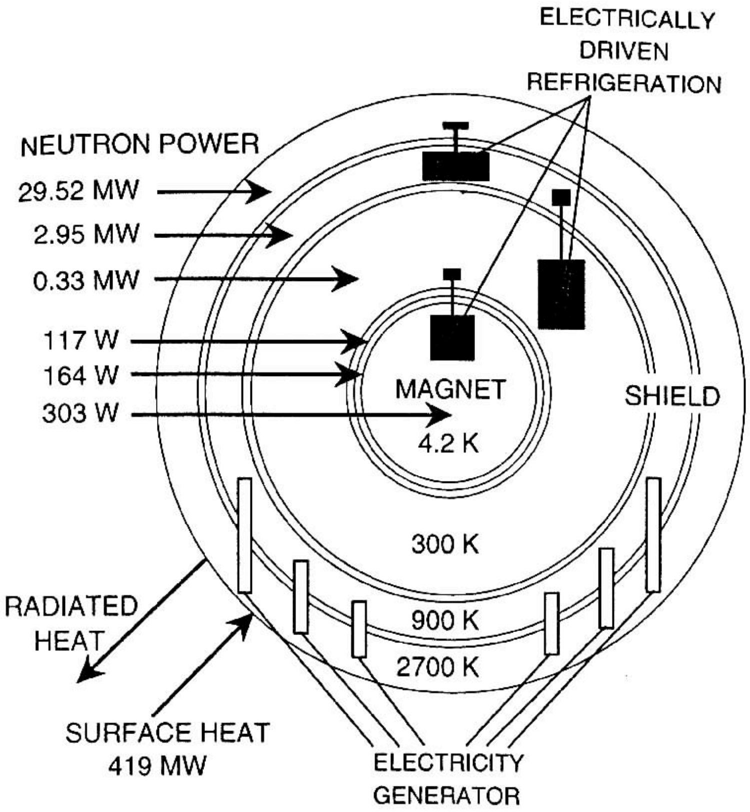
EDWARD TELLER, ALEXANDER J. GLASS, and
T. KENNETH FOWLER *Lawrence Livermore National Laboratory*
P.O. Box 808, L-640, Livermore, California 94551

AKIRA HASEGAWA* *AT&T Bell Laboratories, 600 Mountain Avenue*
Murray Hill, New Jersey 07974

JOHN F. SANTARIUS *University of Wisconsin-Madison*
Fusion Technology Institute, 1500 Johnson Drive, Madison, Wisconsin 53706-1687

1991

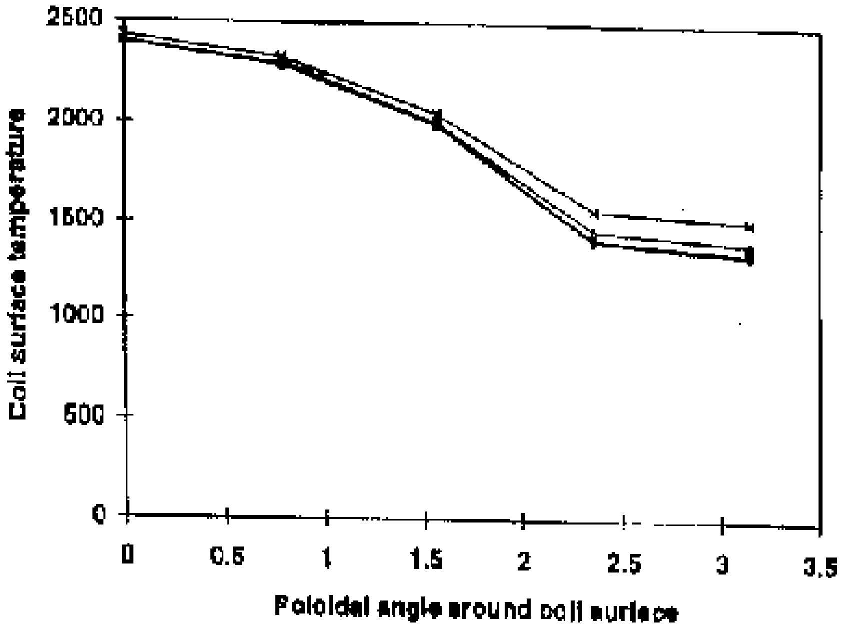




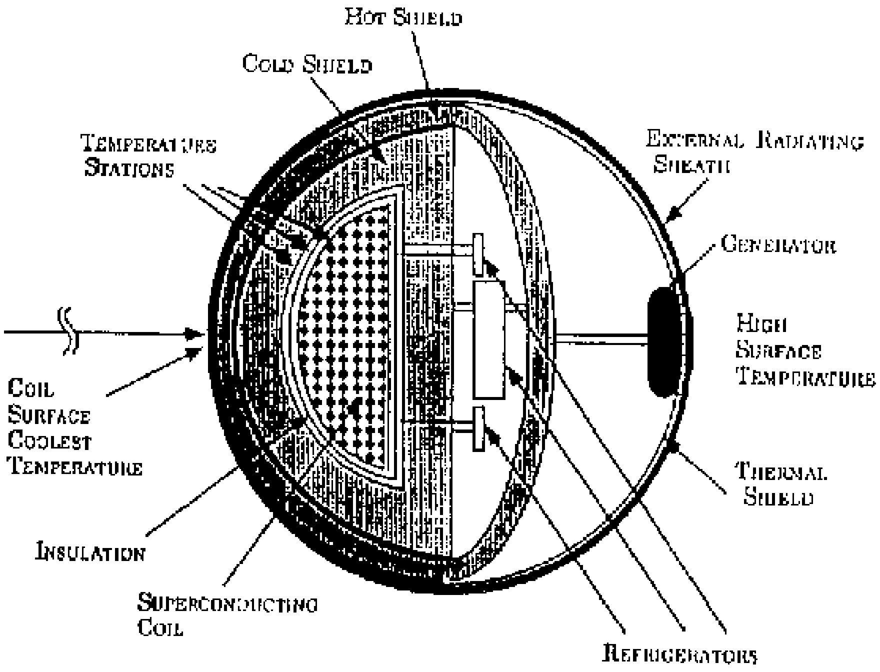
New Ideas for the Dipole Reactor

Examples…

- The impact of high-T_c superconductors
- Realistic onboard power sources (*e.g.* alkali metal thermal electric conversion**)** and refrigerators
- First wall issues and improvements in thermal power generation efficiency

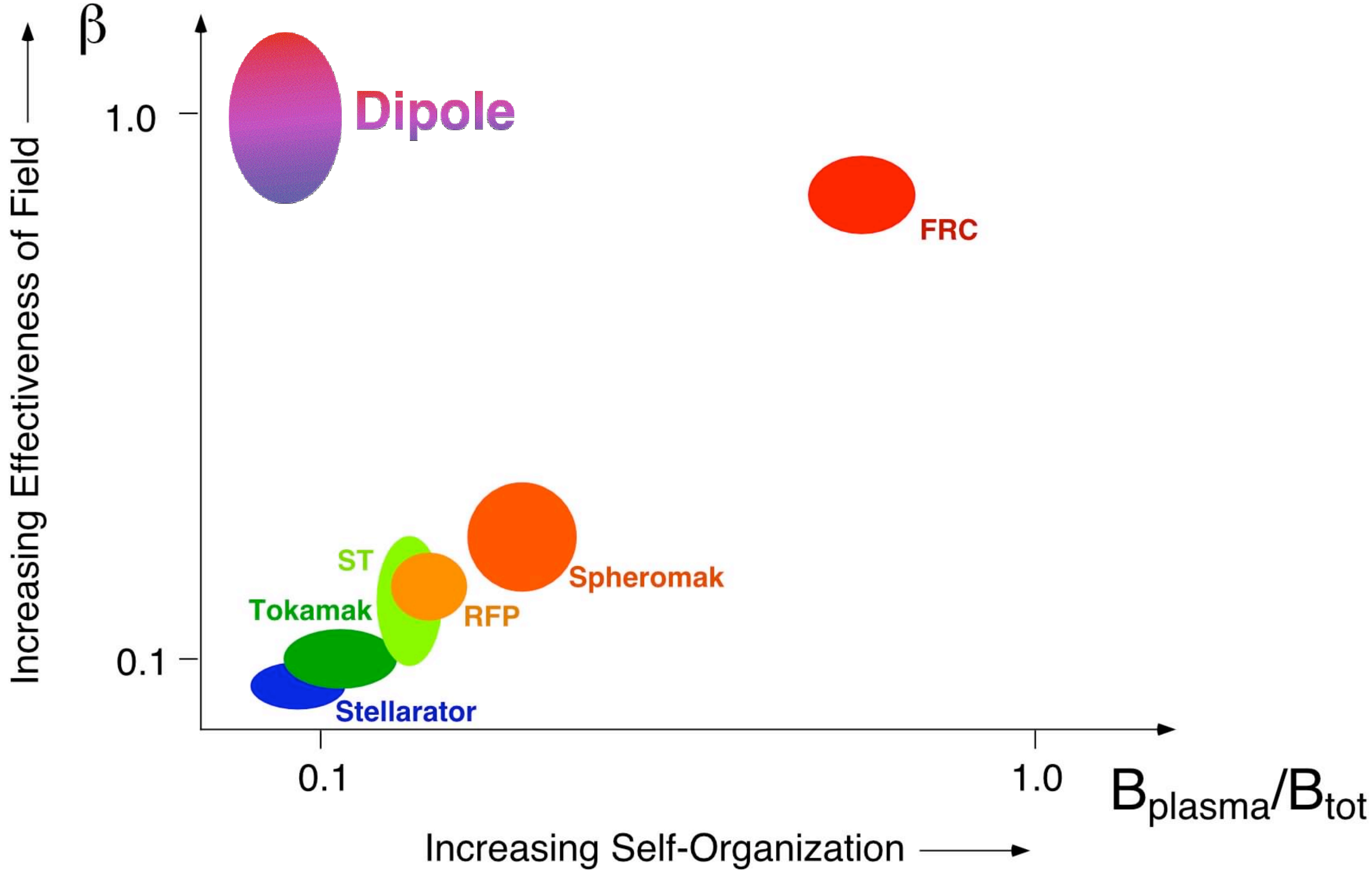


Peak heat ~ 2 MW/m2

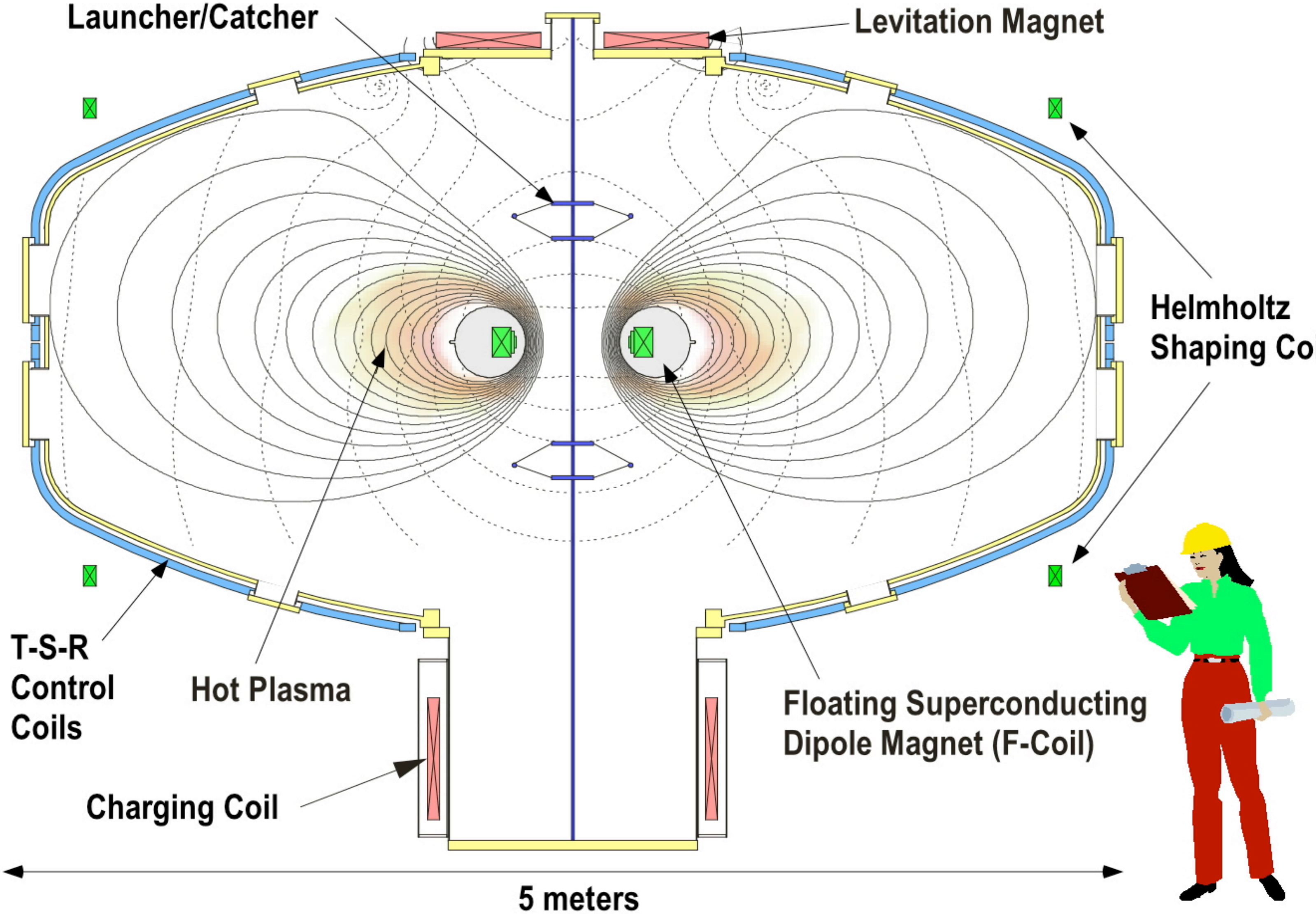


Schematic of coil elements

Dipole has a Unique Position in the Fusion Portfolio



Levitated Dipole Experiment (LDX)



Launcher/Catcher

Levitation Magnet

Helmholtz
Shaping Coils

T-S-R
Control
Coils

Hot Plasma

Floating Superconducting
Dipole Magnet (F-Coil)

Charging Coil

5 meters

http://www.psfc.mit.edu/ldx/

LDX

The Levitated Dipole eXperiment

Welcome to the Levitated Dipole eXperiment (LDX) web site. LDX is a novel experimental device designed to explore the physics of plasma confinement in a magnetic dipole field. What makes it unique? Besides levitating a 1/2 ton superconducting ring, we will conduct the first experimental test on the theory of plasma confinement by adiabatic compressibility. If this concept turns out to be correct, levitated dipoles may one day make an attractive magnetically confined fusion energy source. LDX is a collaboration between Columbia University's Dept. of Applied Physics and the MIT Plasma Science & Fusion Center and is funded by the Department of Energy's Office of Fusion Energy.

▸ LDX Project News

Look here for updates on the status of the LDX design and construction. Current construction status is here.

July 20, 2000: LDX dipole magnet test a success! Full current (1.57 mega-ampere) applied to superconducting coil. Read more...

▸LDX Overview

Explore a the workings of the Levitated Dipole Experiment through this presentation of the planned daily operation of the experiment. Macromedia Flash required. An older HTML overview is also available here. Further information about LDX experimental plans have been presented at various forums and are available here.

▸ Background & Theory

Explore the theoretical foundations of the LDX project, including tantalizing evidence from nature that the concept may be the answer to the fusion energy problem. Or check out our whitepaper. Recent theoretical publications supporting LDX are available here.

▸ Ask the Experts

Students and educators: ask a scientist any question about LDX, plasma physics or fusion energy. Links to other fusion energy sites. Check out the amazing Levitated Cheerio Experiment.

▸ Call for Collaborators

Physicists: as our initial diagnostic set will be limited, we invite collaborators to work with us on this unique high beta plasma.

▸ LDR: The Levitated Dipole Reactor

Learn the results from the MIT Dept. of Nuclear Engineering design course on the feasibility of a 1 GW levitated dipole commercial power plant.

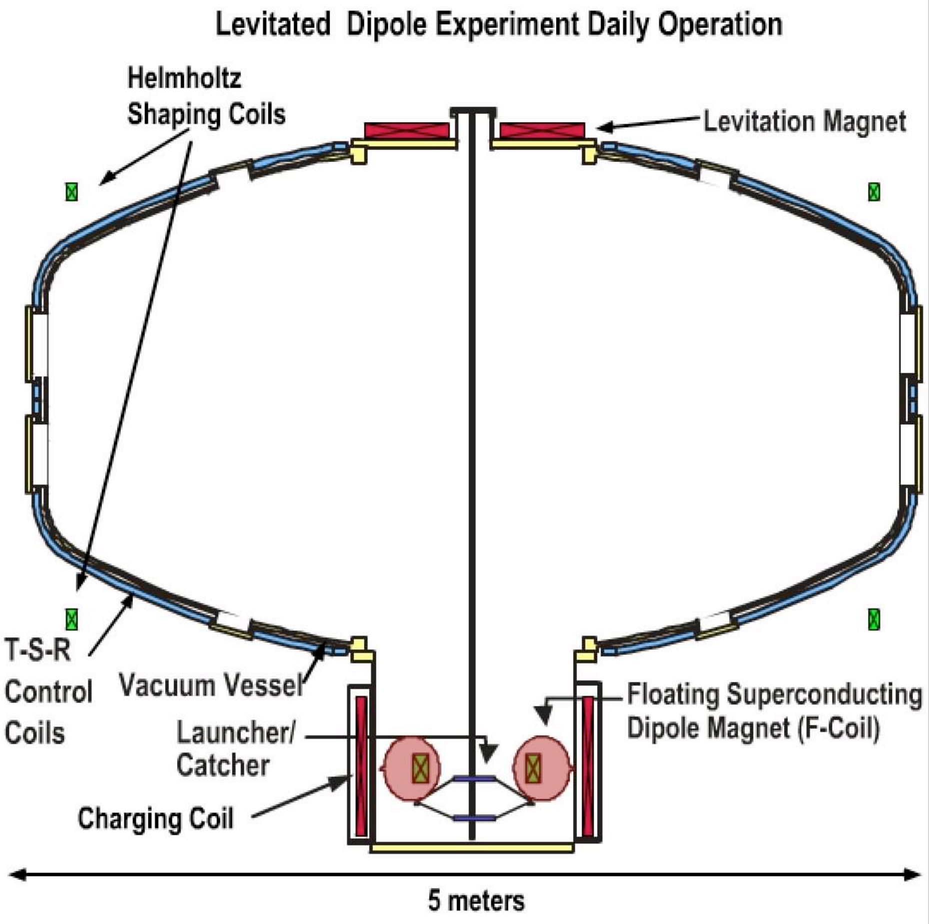
Image courtesy: John Spencer, Lowell Observatory

▸*Webmaster: D. Garnier*

▸ *Last updated: Mon, Nov 25, 2002*

Day in the Life of LDX…

5:00 am
5:30
8:00
8:30
9:00-3:00
3:00 pm
3:30
4:00
5:00



At 5:00, the charging coil is discharged, which concludes the day's operations.

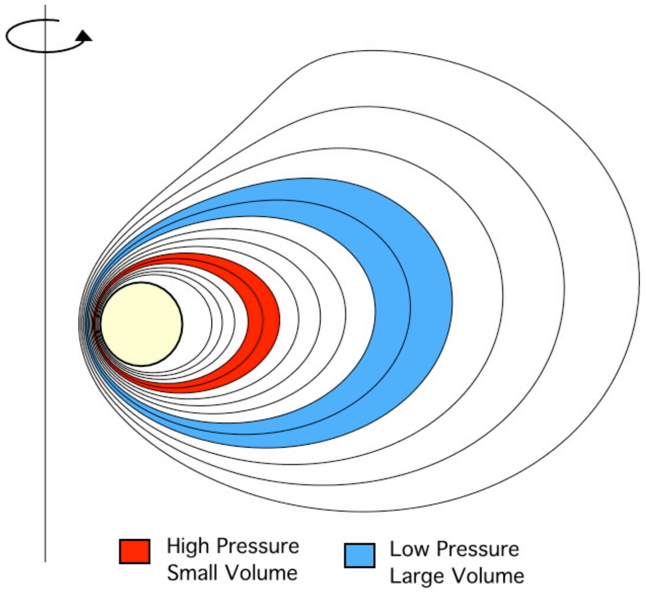
Field lines

Shockwave design
by Adam G. Unikowsky
aunikows@mit.edu

LDX Research Goals

- Study high-β plasma stabilized by compressibility.
  - Relationship between MHD stable profiles and the elimination of drift waves.
  - Influence of energetic particles on the stability of high-β plasma in dipole magnetic fields. Coupling between SOL and core plasmas.
  - Will quiescent plasma make “classical” energy confinement possible?
- Long time evolution of high beta dipole confined plasma.
  - Do convective cells form in plasma? Explore active control of convective cell circulation.
  - What is the relationship between particle and energy confinement?
- Demonstrate reliable levitation of a persistent superconducting ring using distant control coils.

SC magnets selected to reach LDX research goals



- Large flux expansion **requires high current with low weight**. Minimizes levitation field and moves x-point to outer vacuum wall.
- **Highest possible field** consistent with low-weight:
  - Use ECRH start-up to create high-beta plasma (□ ~ 30%) and benefit from earlier CTX experience
  - Reduce effects from field-errors and levitation control fields
- Use experience from previous levitrons and spherators to...
  - Maximize float time
  - Optimize cyrogenics to simplify maintenance and operations

LDX is a Partnership of Plasma Scientists and Magnet Technology Experts

- LDX is a relatively low cost, advanced technology facility
- **Incorporates innovative engineering and design:**
    - High-field persistent Nb_3Sn coil with **low mass and small size**
    - Innovative, light-weight cyrostat with distributed supports having low-thermal conductivity
    - Safe, relatively **easy-to-operate** cyrogenics
    - Large, inductive charging system designed for thousands of high-field cycling during daily charging and discharging
    - **Fusion's first high-temperature superconducting magnet**
    - Levitation and stabilization system with distant, upper levitation coil

LDX Research Plan

- Supported dipole hot electron experiments
  - High □ studies with hot electron (~ 200 keV) plasmas
  - Multi-frequency ECRH (28 GHz, 18 GHz, 10.5 GHz, 6.4 GHz, and 2.45 GHz) plasma formation and diagnostics
  - Experience with superconducting coils under safe conditions
- Levitated dipole experiments
  - Hot electron plasma in levitated configuration, □□50%
  - Confinement studies; profile effects; …
- Thermal, higher density plasma studies
  - Use gas puff or pellet injection to raise density
    - $n_e \sim 10^{19}$ m^{-3}, $T_e \sim T_i \sim 200$ eV
    - Obtain □ limits and confinement properties

LDX Design Parameters

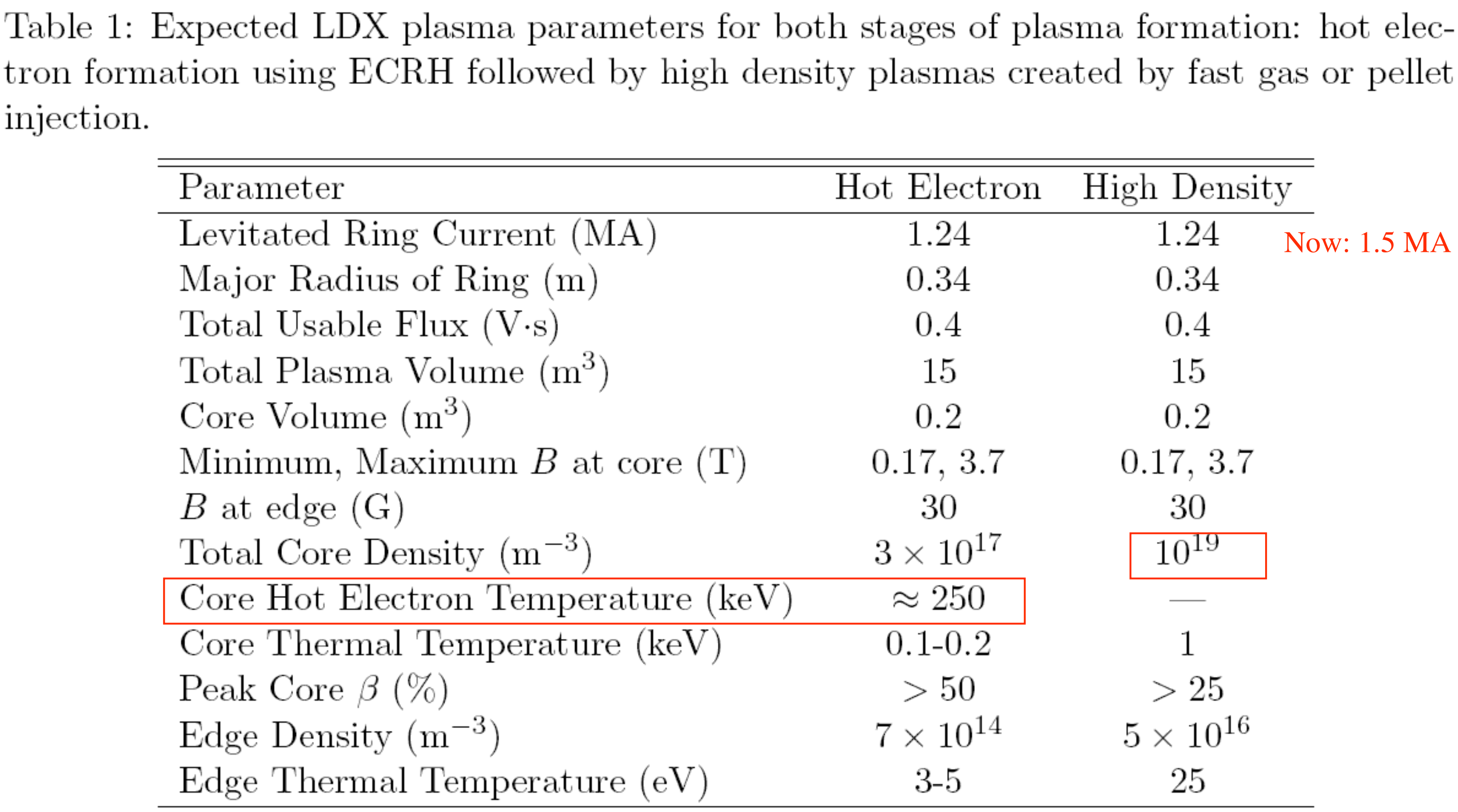


Table 1: Expected LDX plasma parameters for both stages of plasma formation: hot electron formation using ECRH followed by high density plasmas created by fast gas or pellet injection.

Parameter	Hot Electron	High Density
Levitated Ring Current (MA)	1.24	1.24
Major Radius of Ring (m)	0.34	0.34
Total Usable Flux (V·s)	0.4	0.4
Total Plasma Volume (m^3)	15	15
Core Volume (m^3)	0.2	0.2
Minimum, Maximum B at core (T)	0.17, 3.7	0.17, 3.7
B at edge (G)	30	30
Total Core Density (m^{-3})	3×10^{17}	10^{19}
Core Hot Electron Temperature (keV)	≈ 250	—
Core Thermal Temperature (keV)	0.1-0.2	1
Peak Core β (%)	> 50	> 25
Edge Density (m^{-3})	7×10^{14}	5×10^{16}
Edge Thermal Temperature (eV)	3-5	25

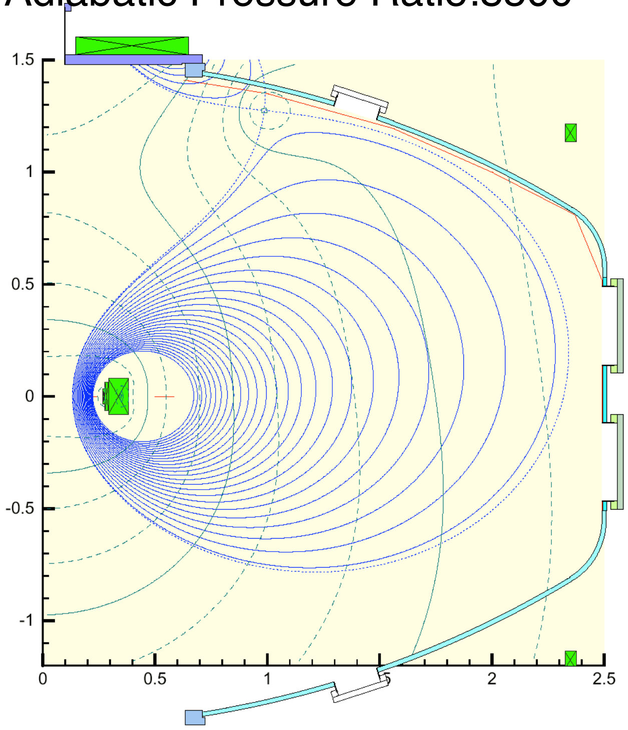
Now: 1.5 MA

(Original design parameters.)

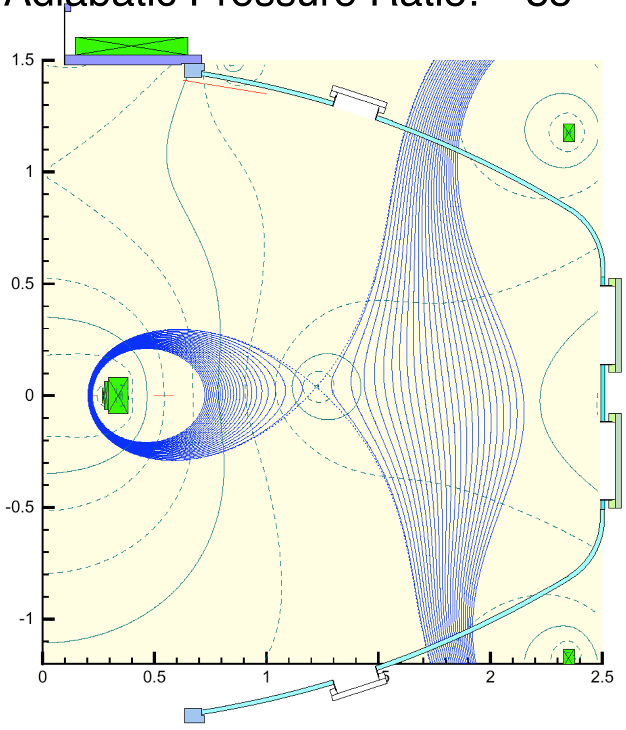
Helmholtz Coils Test Compressibility Stabilization

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

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



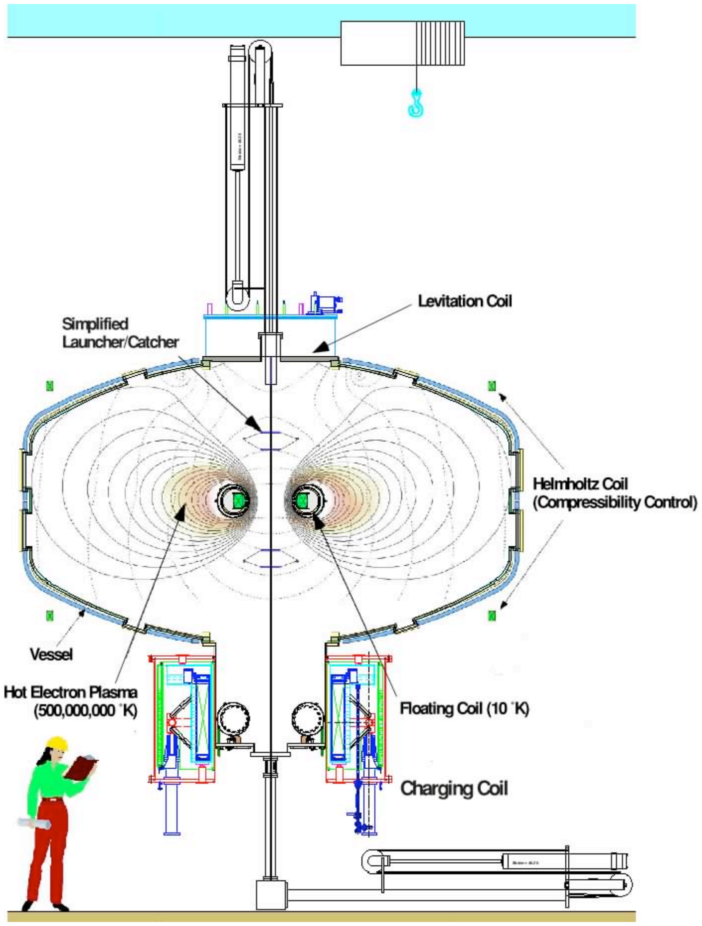
Helmholtz Coil: 80 kA
Compression Ratio: 14
Adiabatic Pressure Ratio: 85



Compressibility can change marginal stable pressure by factor of 100!

Three Superconducting Magnets

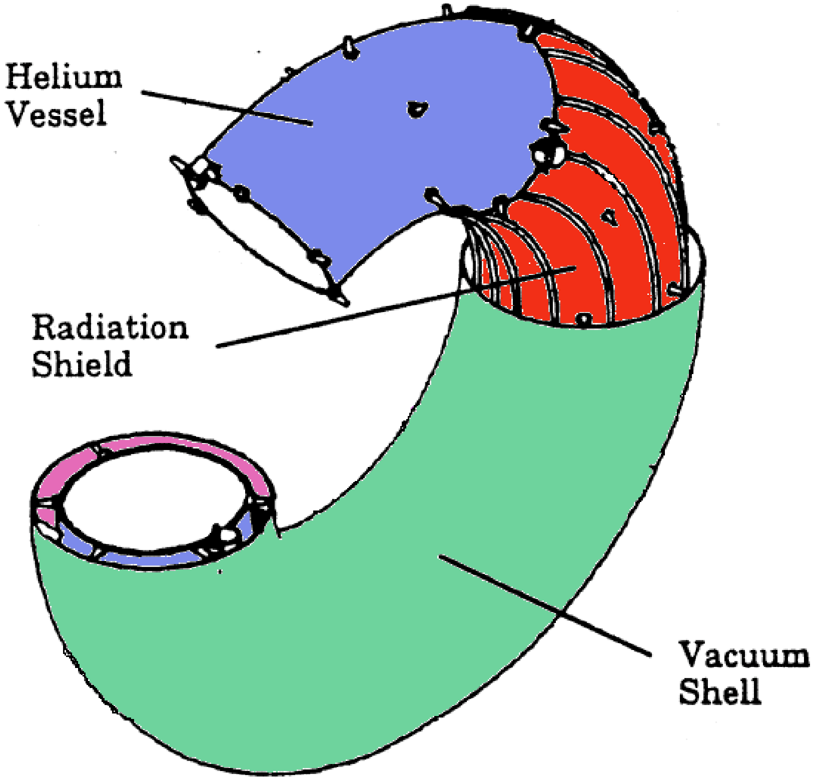
- **Floating Coil**
  - 714 Turns, Nb_3Sn, 5T, 1.3 MA turns
  - Ability Engineering (South Holland, IL)
  - Coil completed and tested at 1.56 MA (6 T)
  - Final assembly of outer cyrostat underway
- **Charging Coil**
  - 8000 turns/35 km, NbTi, 5T, 4.2 MA turns
  - SINTEZ/Science Technology Center (St. Petersburg, Russia)
  - Coil completed
  - Final assembly of cyrostat underway
- **Levitation Coil**
  - 1310 turns, Bi-2223, 0.275 MA turns
  - Everson Electric (Allentown, PA)
  - Coil completed
  - Manufacture of cyrostat underway



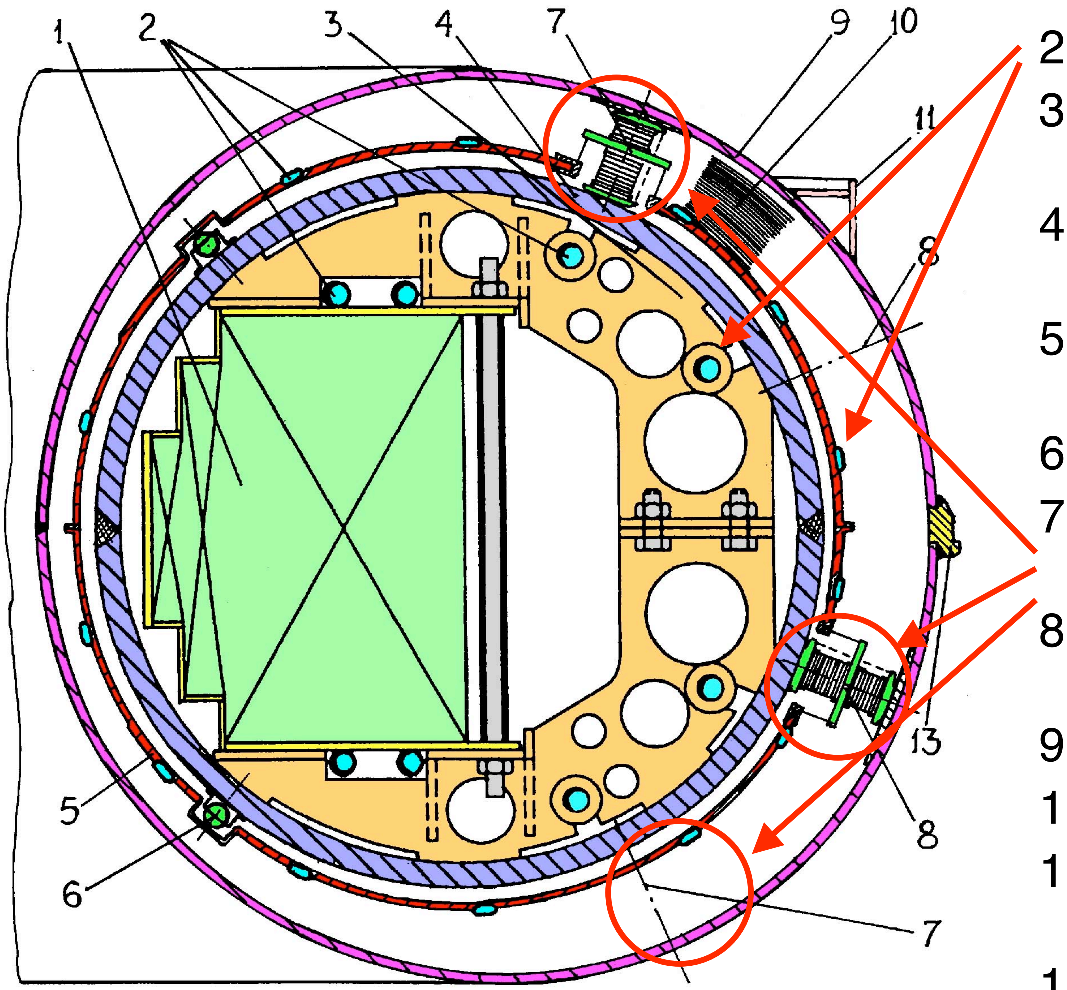
Today, our focus is to oversee completion of the magnet systems ***expected within months!***

Floating Coil

- High-performance Nb_3Sn coil
    - 150% of the ITER J_c
    - 1.5 MA, 800 kJ
    - 1300 lbs weight
    - 8 hr levitation
    - Inductively charged
- Cryostat: three concentric tori
    - Design < 1 W heat leak to Coil
    - Helium Pressure Vessel
    - Lead Radiation Shield
    - Outer Vacuum Shell



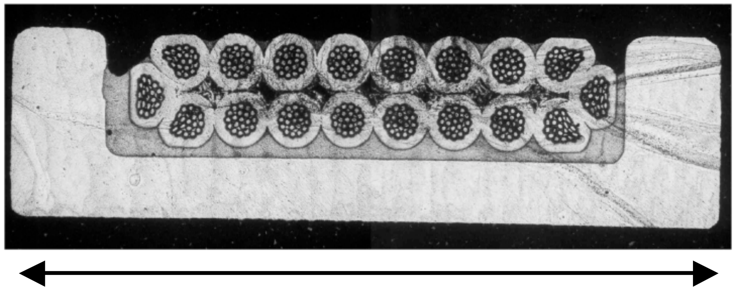
Floating Coil Cross Section



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

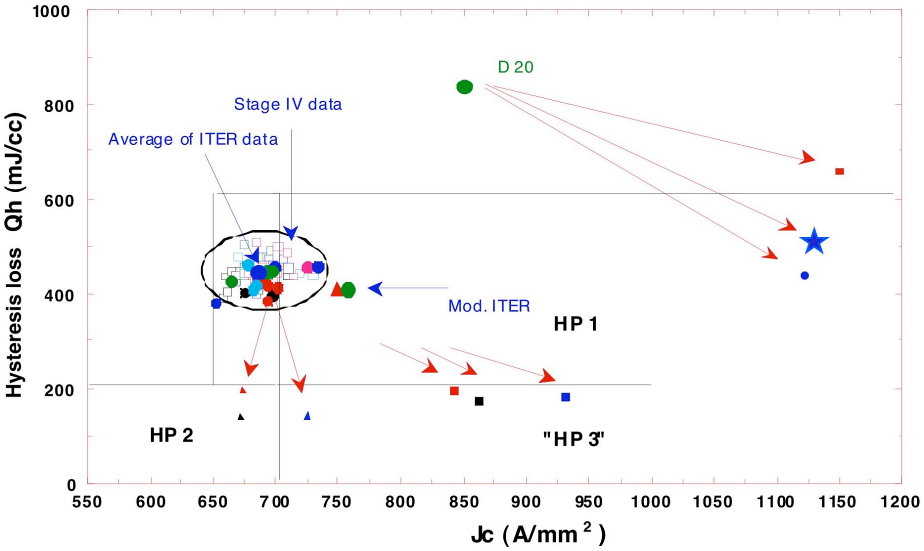
Floating Coil Gallery

Nb_3Sn Cable in Channel (react & wind)

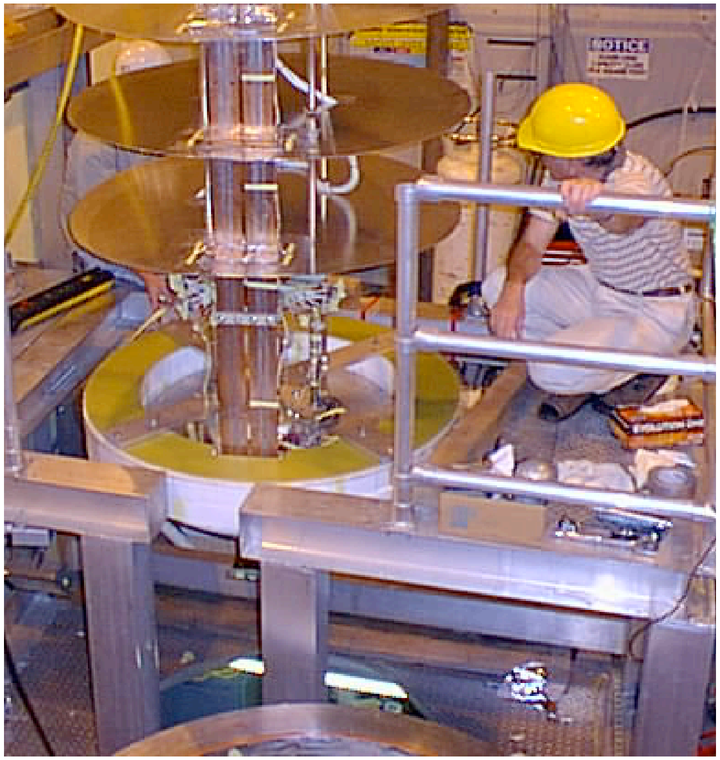


8 mm

Comparing LDX Conductor to ITER



Floating Coil Gallery



Tested to 1.56 MA at 6 T in 4.2 °K LHe bath

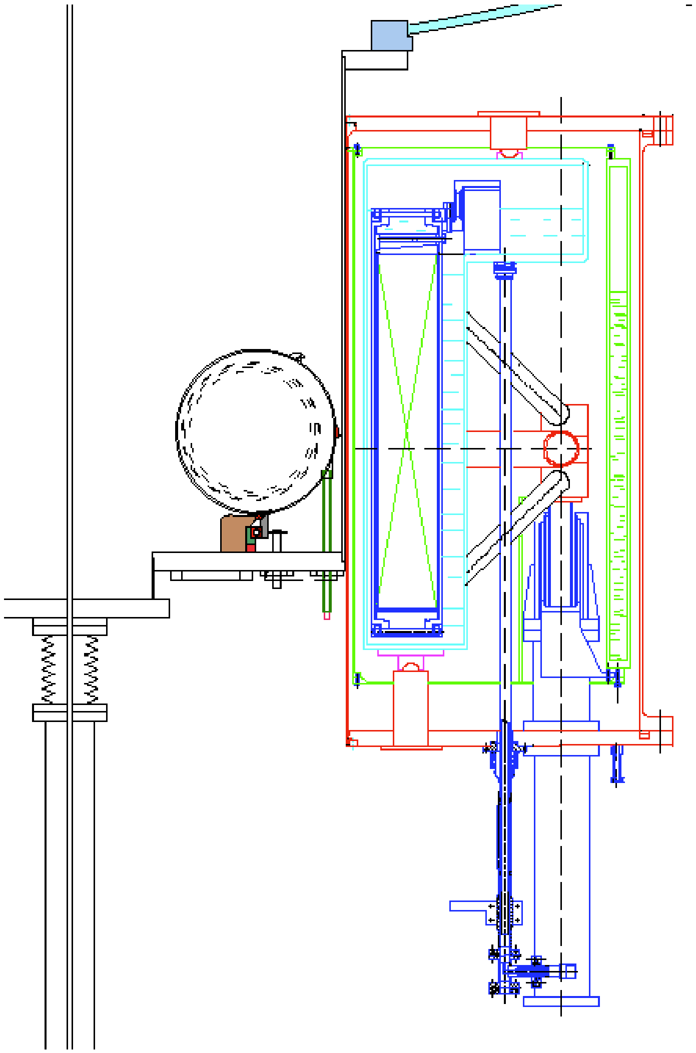
Floating Coil Gallery

Floating Coil Gallery

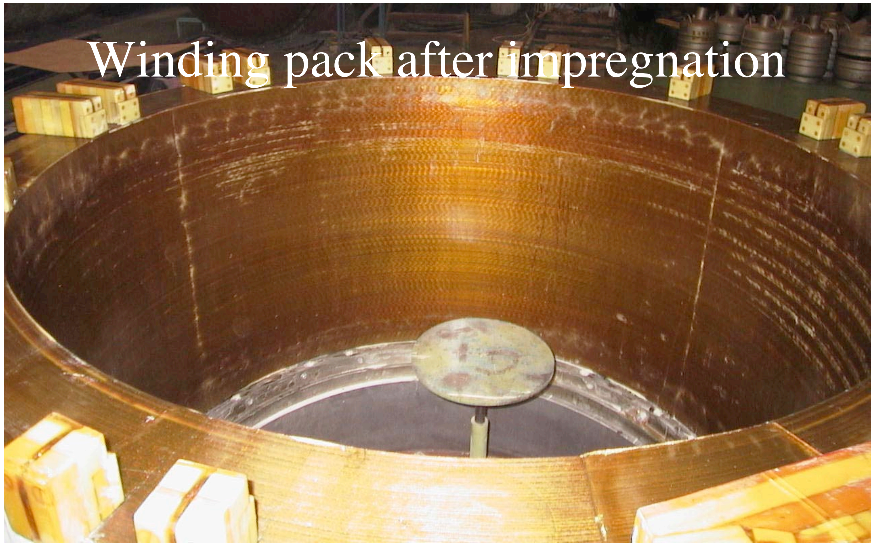
Floating Coil Gallery

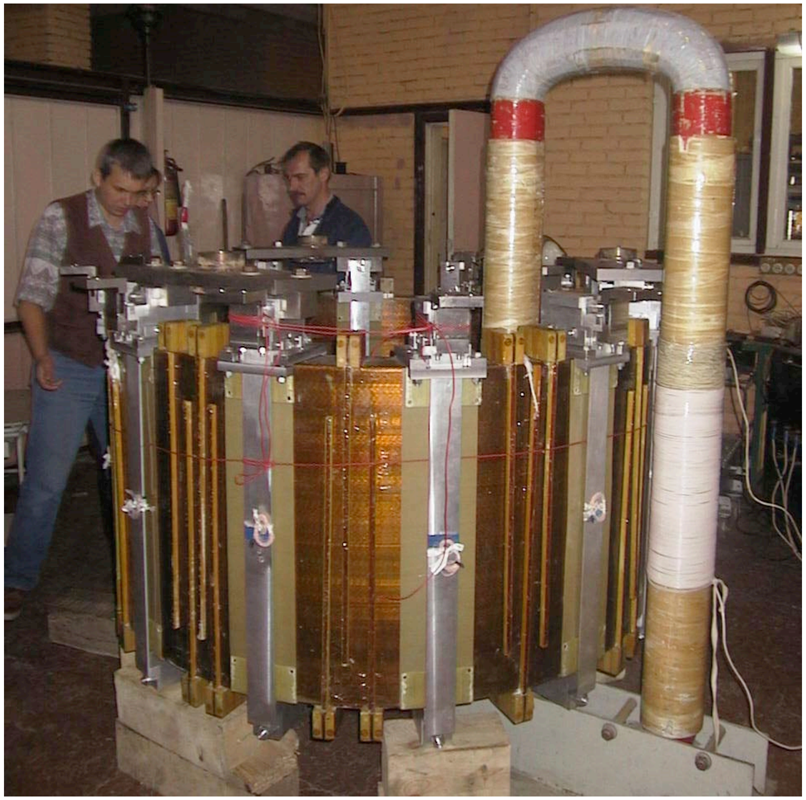
Charging Coil

- 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.
- SINTEZ/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

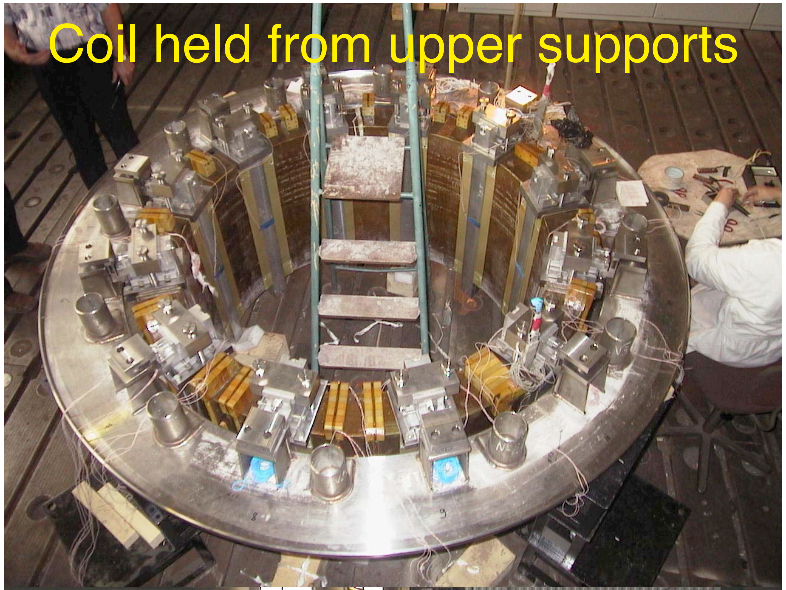


Charging Coil Gallery

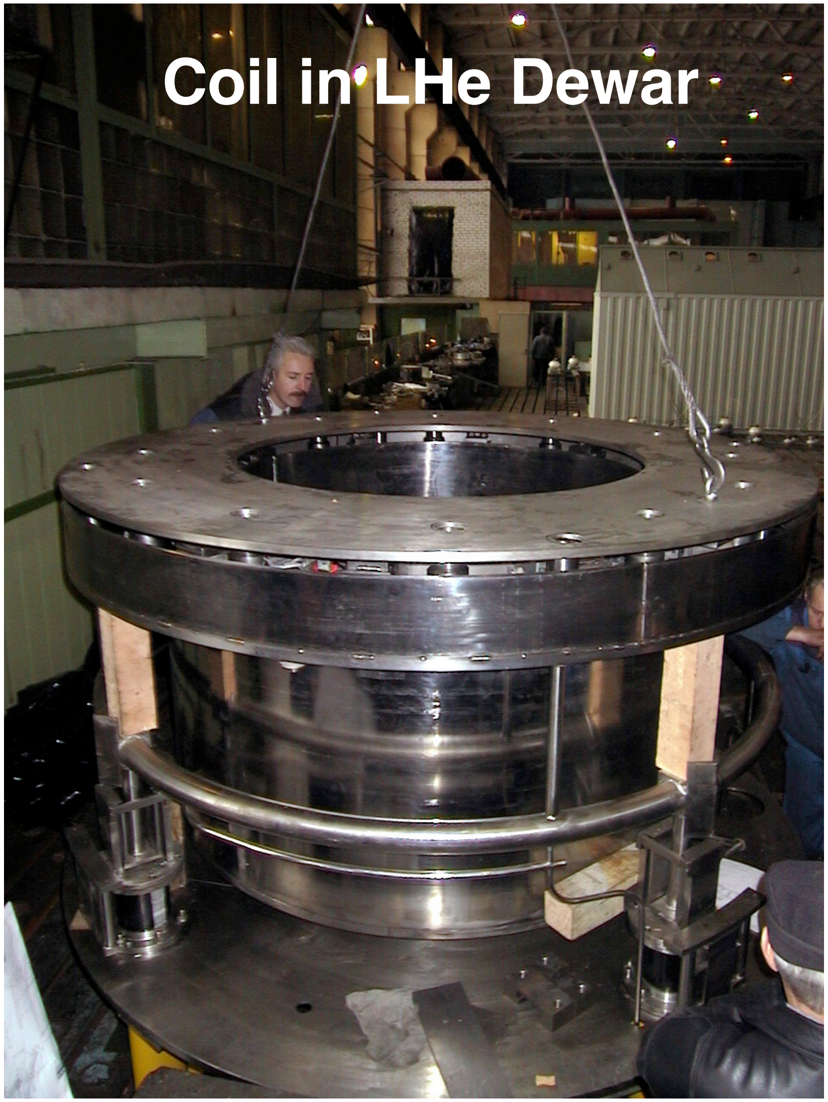

Winding pack after impregnation


Electrical tests complete

Charging Coil Gallery

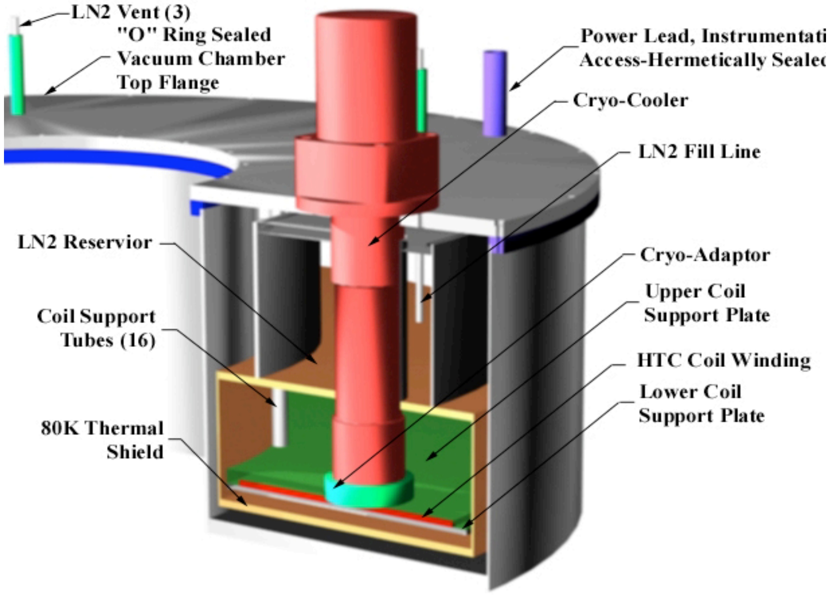

Coil held from upper supports

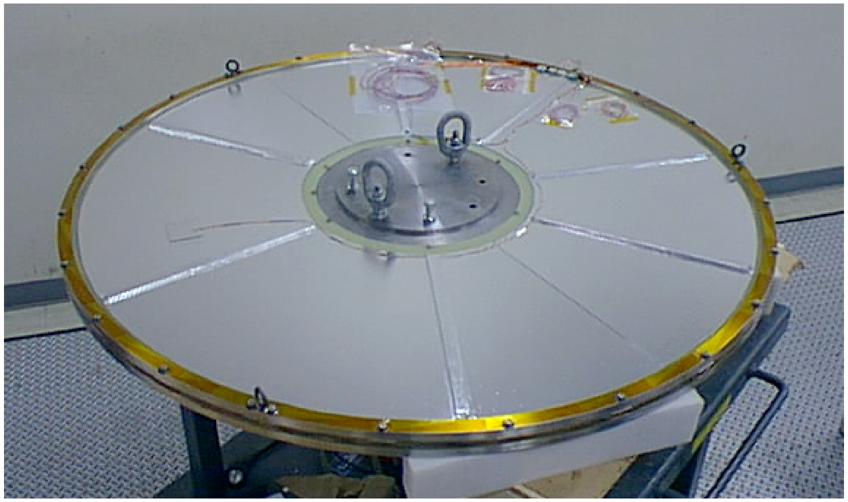

LN2 cooled copper shield ready


Coil in LHe Dewar

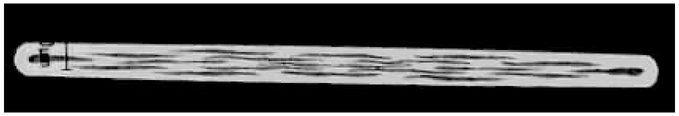
Levitation Coil

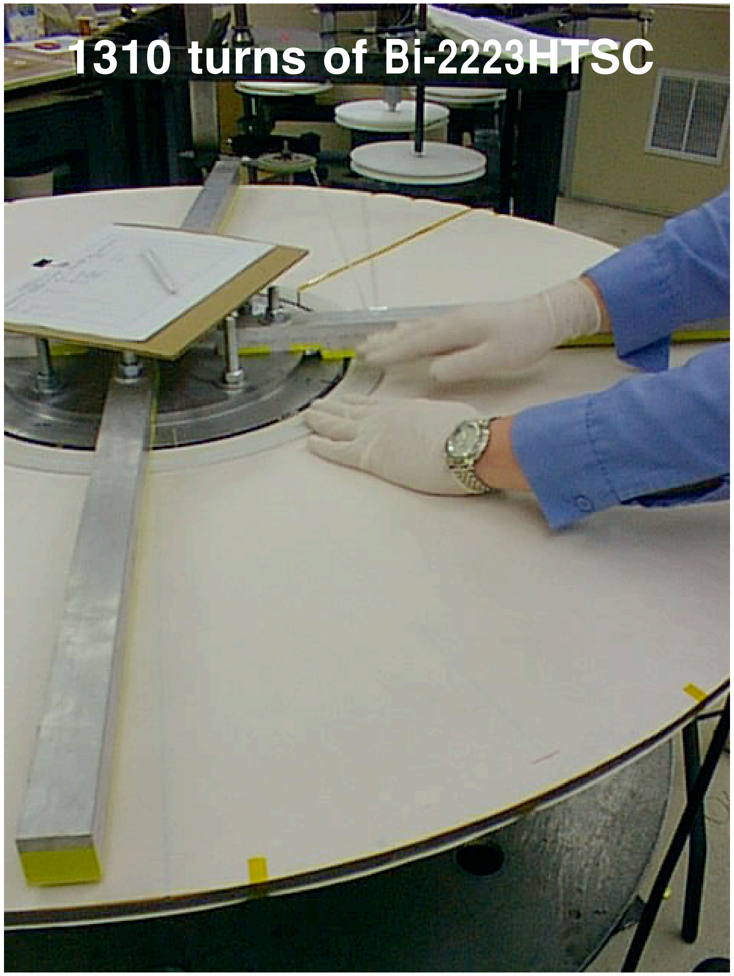
- First HTS coil in the fusion community. High strength BSSCO-2223 conductor.
- Operational temp 20-25° K
- Feedback for 5Hz mode frequency produces < 20 W
- 20 kJ stored energy
    - Emergency dump in less than one second
- Winding pack complete
    - 77° K superconducting tests successful
    - Cryostat currently under construction at Everson Electric

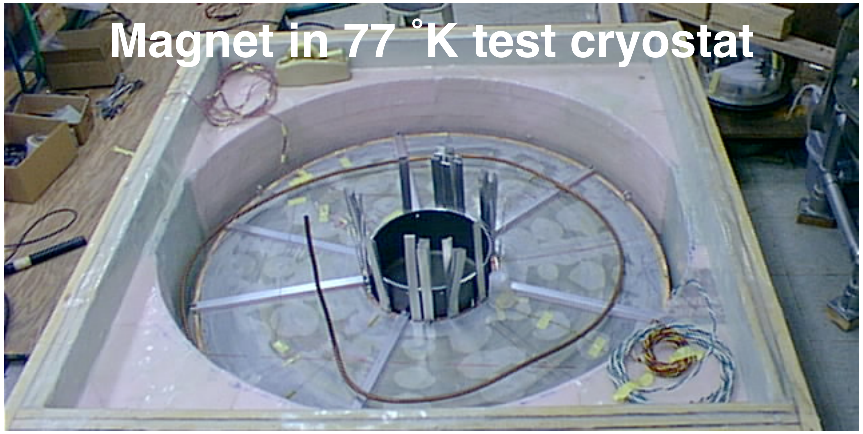


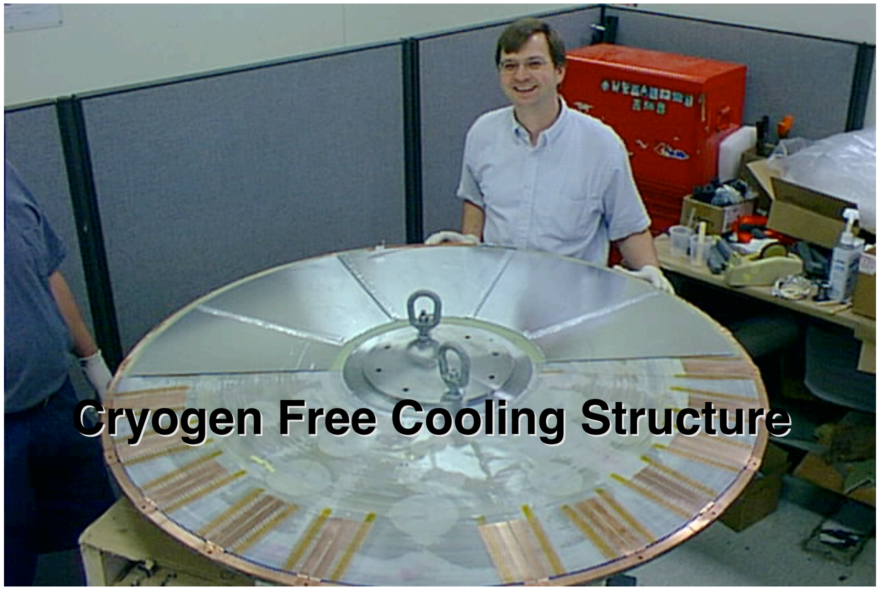


Levitation Coil Gallery

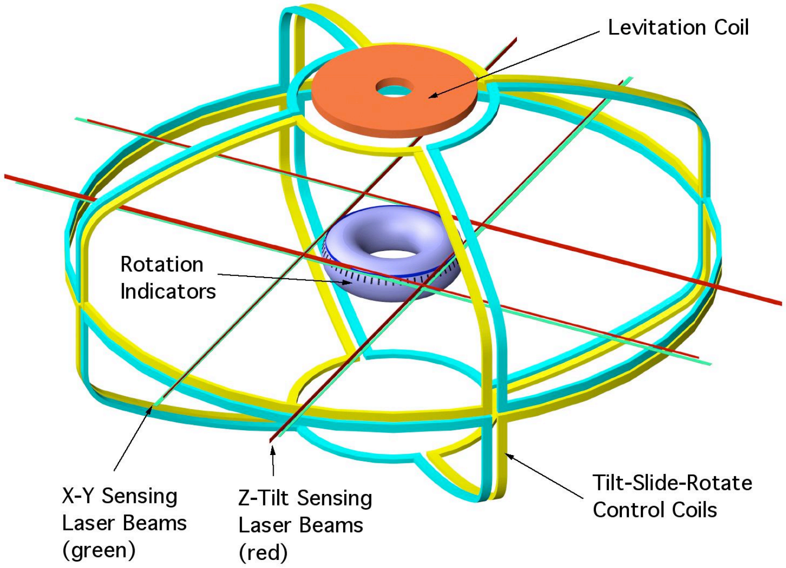



1310 turns of Bi-2223HTSC

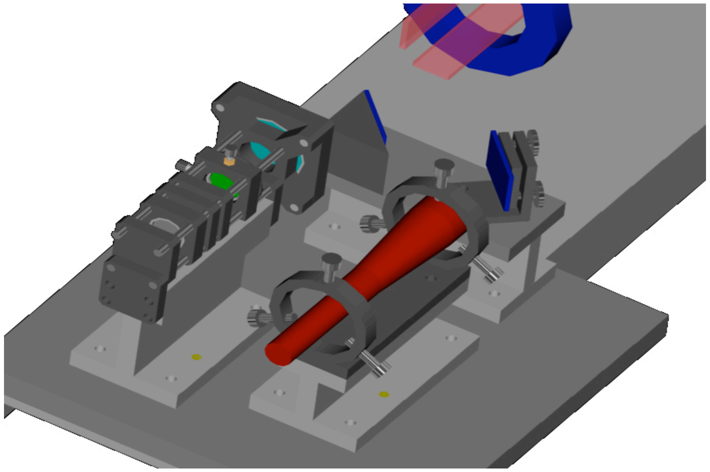

Magnet in 77 °K test cryostat


Cryogen Free Cooling Structure

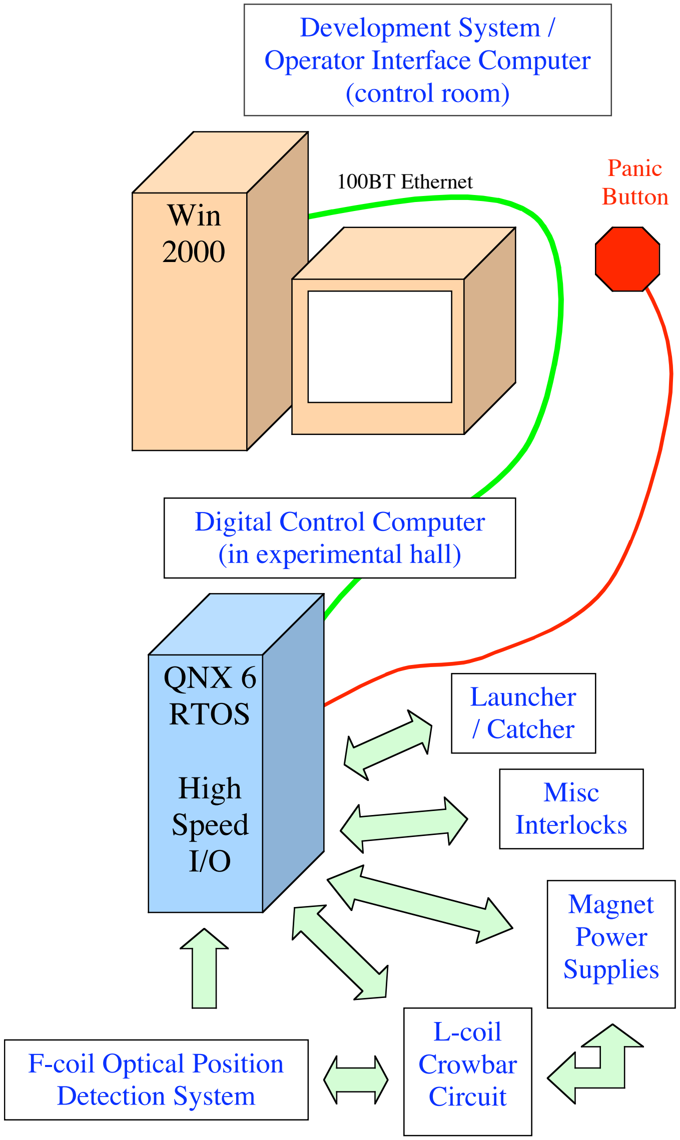
Levitation Control System



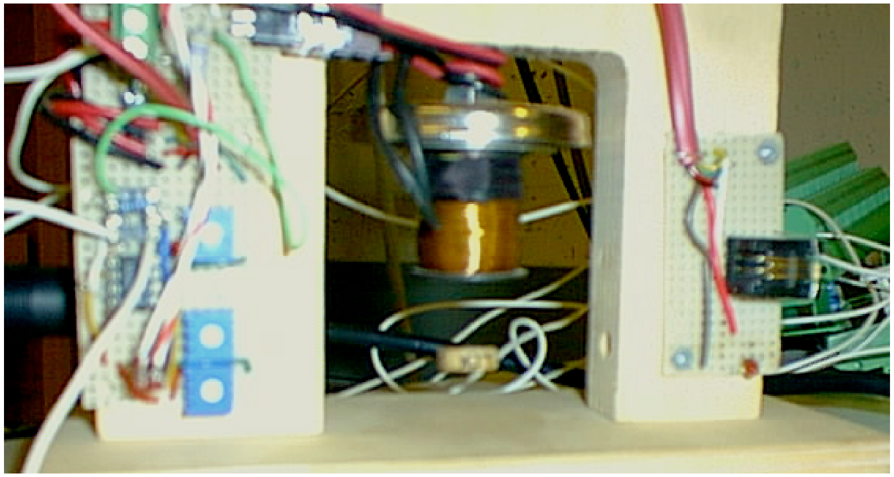
- Levitation from above
  - Requires stabilization of vertical motion by feedback
  - Other motions are stable
- Levitation control system
  - Optical detection system measures position and attitude of floating coil with 10 μm resolution
  - Digital control system



RT Digital Control System



- All digital process control; Process control on hard real-time operating system based computer
  - Easy to use commerical software tools (Mathworks Matlab/Simulink and visualization software)
- Modular (Opal-RT / QNX Neutrino Real-Time) system implemented and tested on “LCX”.



Summary

- Physics basis for Dipole concept has been developed through the study of magnetospheres, multipoles, mirrors and levitrons
- Theory predicts high □, good stability, and possible stability of drift waves. ***Can the dipole achieve "classical" confinement?***
- The dipole represents a new approach to fusion:
  - Closed field lines, no toroidal field, no shear
  - Stability derives from compressibility, not average well
  - No plasma current: no current drive, no disruptions
  - Large volume plasma outside of coil: simple divertor
- **Dipole presents *different* challenges for fusion technology**
  - Different engineering/technical issues than tokamak-like device
  - **D-D and D-^{3}He fuels:** alters neutronics, fusion components, breeding…
  - Floating coil requires advanced superconductor and cryostat
  - Significantly benefits from advancements in HTCSC
  - Internal refrigerator and power, hot outer shell, …
- LDX will be the first experiment of its kind.