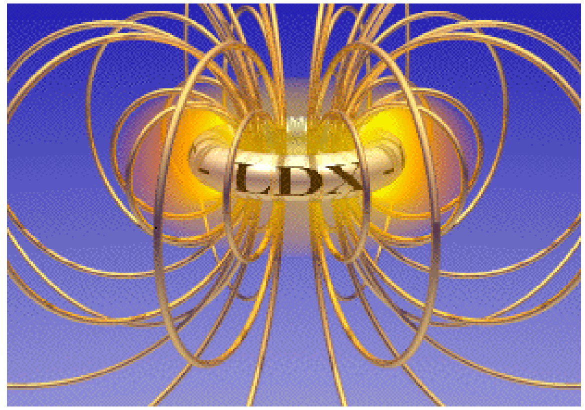

Physics and Operations Plan for LDX

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Abstract

Immediately after construction, the Levitated Dipole Experiment (LDX) will begin its plan to study the confinement and stability of high-temperature plasma in dipole geometry. The primary objective of this program is to investigate the possibility of steady state, high-beta dipole confinement with near classical energy confinement. The experimental program will also include new studies of basic and applied plasma science including:

(1) the study of high beta plasma stabilized by compressibility,

(2) the relationship between drift-stationary profiles having absolute interchange stability and the elimination of drift-wave turbulence,

(3) the induced flows and characteristics of low-frequency electrostatic potential structures, or convective cells,

(4) the coupling between the scrape-off-layer and the confinement and stability of a high-temperature core plasma,

(5) the stability and dynamics of high-beta, energetic particles in dipolar magnetic fields, and

(6) the long-time (near steady-state) evolution of high-temperature magnetically-confined plasma.

In order to achieve these goals, we have developed a staged physics and operation plan that both establishes the operation of LDX and minimizes risks to the superconducting coil systems. The initial experiments will feature the dipole field coil supported within the vacuum chamber, rather than levitated. This configuration has end losses for magnetic field lines that intersect the supports, and consequently provides benchmark plasmas for comparison with levitated coil operation.

Abstract (cont'd)

LDX plasmas will be formed and heated using ECRH. Initially, 3 kW will be applied at 6.4 GHz, because that source is currently operational. Eventually power will be applied at multiple frequencies, i.e. multiple resonance regions. We plan to use this multiple-frequency capability to control the heating (and pressure) profile by adjusting the input power from each frequency. Profiles adjusted to be near marginal stability should maximize <□>. We also plan experiments that adjust the axial symmetry of the heating and fueling in order to produce and/or suppress convective cells. Control of the pressure profile will also help reduce convective energy losses. When the pressure profile has gradients near critical, these so-called "stationary profiles" minimize thermal convective-cell transport associated with particle circulation.

Only base-case diagnostics will be employed for the first plasmas. The initial magnetic diagnostics set will include flux loops, Hall probes, and Mirnov coils. The edge magnetics will be employed for fluctuation measurements as well as for equilibrium reconstruction. X-ray and microwave diagnostics will be used to measure the energy of the energetic electrons and the total electron density profile. External coils will be switched on to change the magnetic topology and directly test high-beta plasma stability due to compressibility effects.

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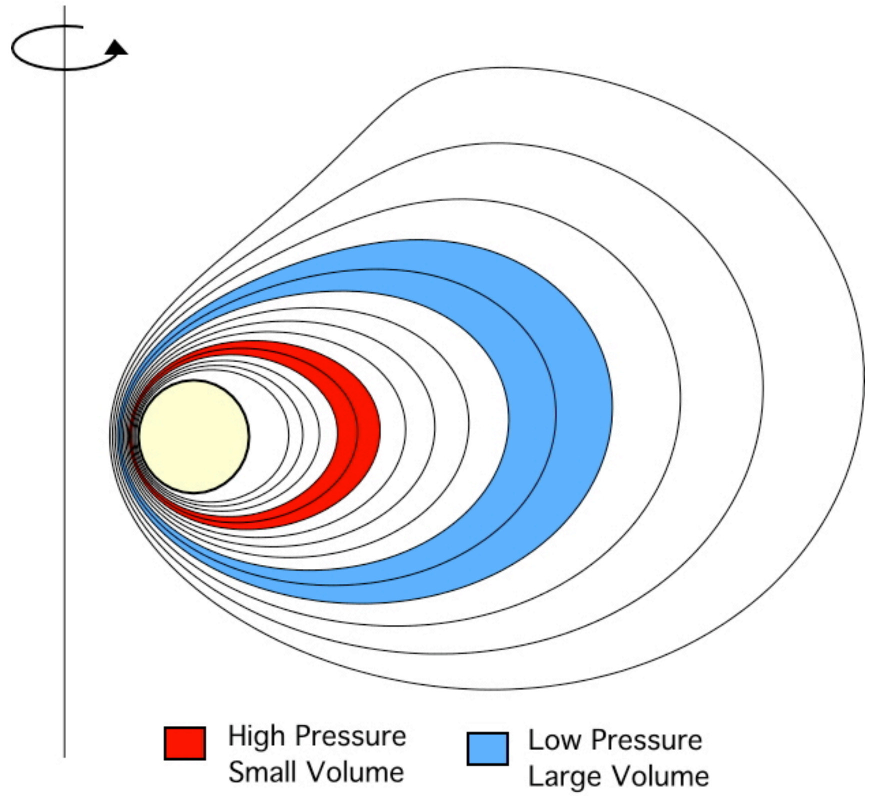
Outline

- Theoretical Expectations
- Experimental Plan
  - Supported dipole campaign
  - Levitated dipole campaign

A dipole can confine plasma.



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

A dipole-confined plasma can be drift wave and MHD stable simultaneously.

- **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 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 advanced**

- **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 .**

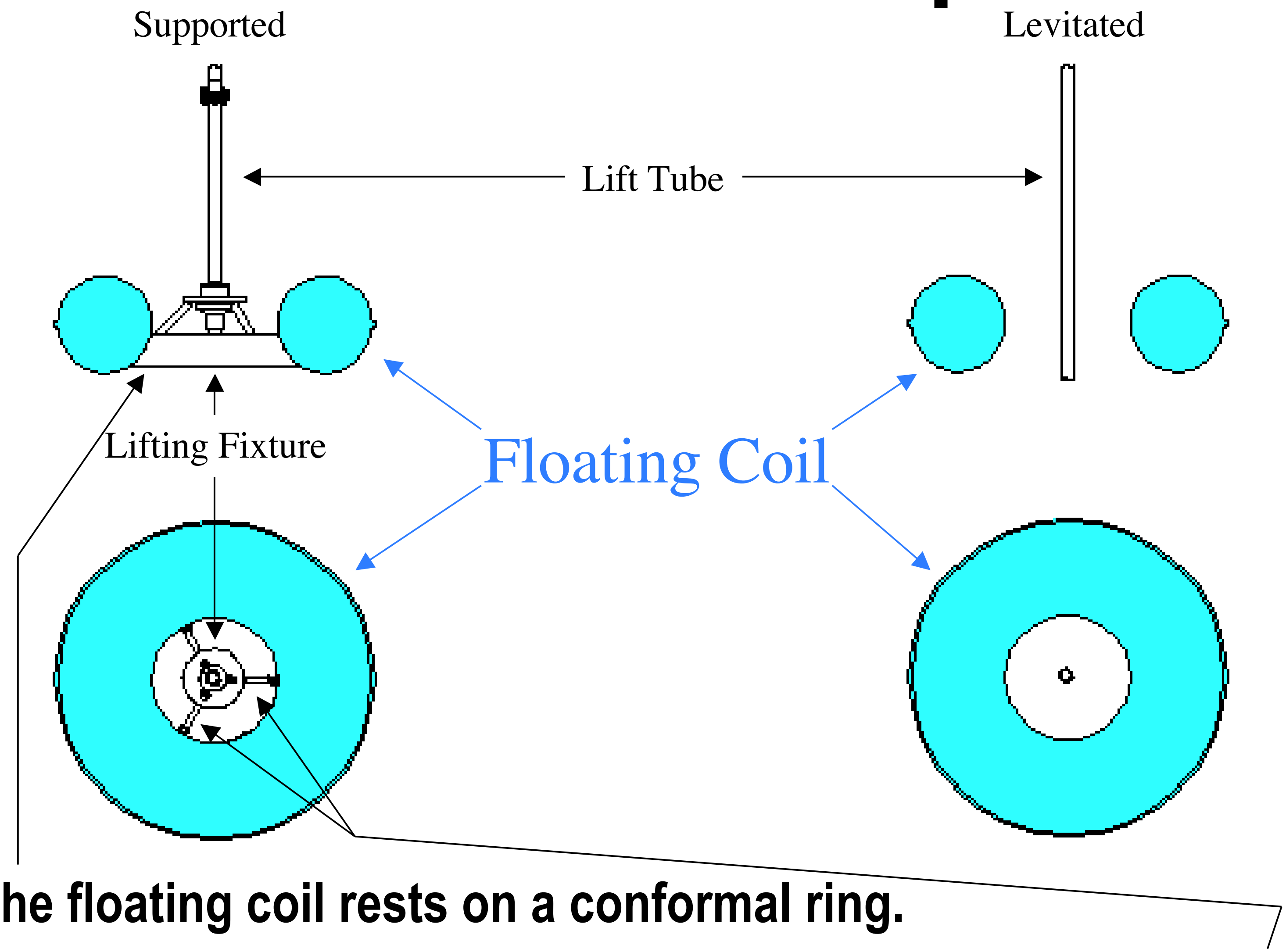
LDX will first operate with a supported internal coil.

- Allows for plasma operation while levitation and feedback systems are made ready.
- There will be enhanced losses on field lines that intersect the supports.
  - The support is designed to minimize interactions, however.
- The supported mode provides a benchmark with which confinement by a levitated coil may be directly compared.
  - Note: there is an X-point when the coil is levitated, which is absent in supported operation.
    - This is only the case when the coil is levitated from the top.

The supported dipole campaign will provide the physics baseline for LDX.

- Low density, quasi steady-state plasmas formed by multi-frequency ECRH with mirror losses.
- Areas of investigation:
  - Plasma formation
  - Density control
  - Pressure profile control
  - Characterization of equilibrium
  - Supercritical profiles & instability
  - Compressibility scaling
  - ECRH and diagnostics development

The support is designed to have minimal interaction with the plasma.

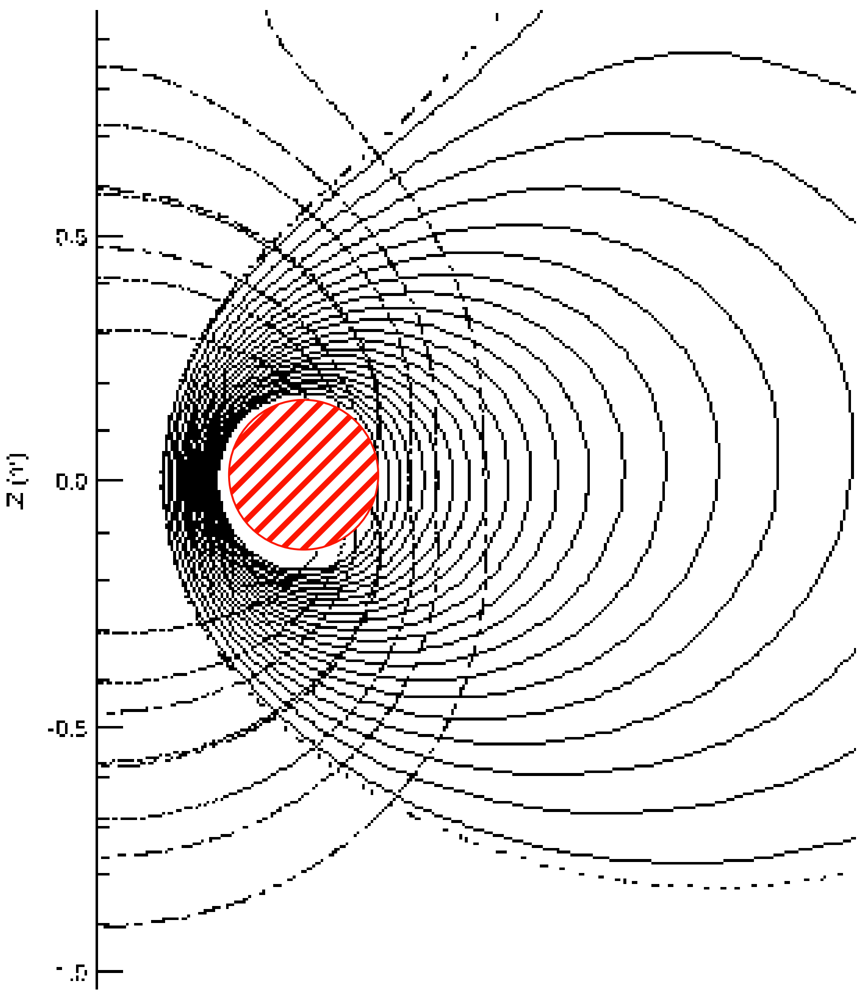


- The floating coil rests on a conformal ring.
- Field lines close to the coil intercept the lifting fixture only at the struts.

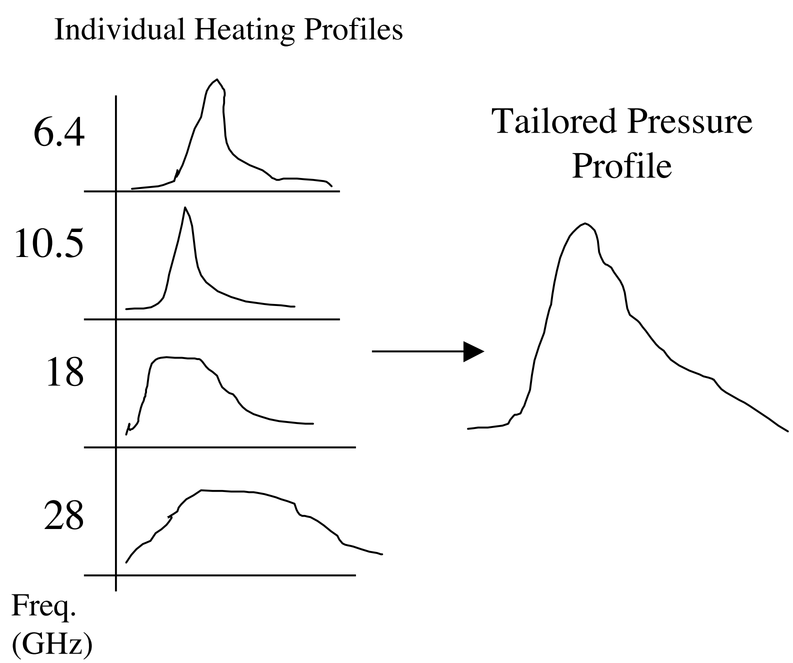
Using multiple frequencies of ECH (MFECH) provides a mechanism for pressure profile control.

- Use multiple sources with different resonant zones to tailor the pressure profile to marginal stability.
- Results from the SM-1 symmetric mirror:
  - Multiple frequency electron cyclotron heating (MFECH) with large frequency separation.
  - Elimination of low frequency fluctuations in cold electron population with multiple sources.
  - Order of magnitude increase in stored energy in hot electrons.
    - B. H. Quon, R.A. Dandl, W. DiVergilio, G. E. Guest, L.L. Lao, N.H. Lazar, T.K. Samec and R.F. Wuerker, *Physics of Fluids* **28**, 1503 (1985).
- Results from CTX supported dipole:
  - Hot electron interchange mode “bursts” with only one source.

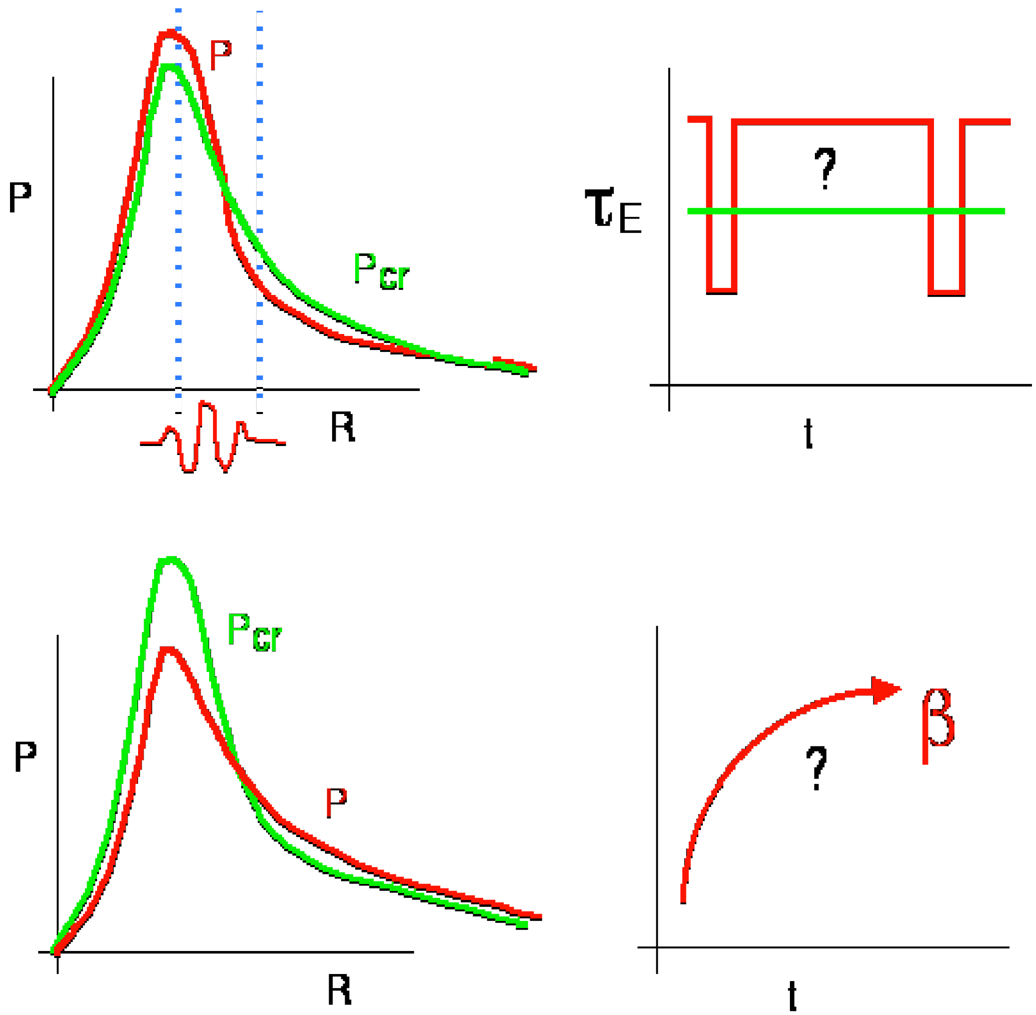
The pressure profile can be controlled via the multiple resonances.



- Multi-frequency electron cyclotron resonant heating
  - Effective way to create high-β hot electron population.
  - Measure single frequency response.
  - Tailor multi-frequency heating power to produce ideal (stable) pressure profile with maximum peak β.



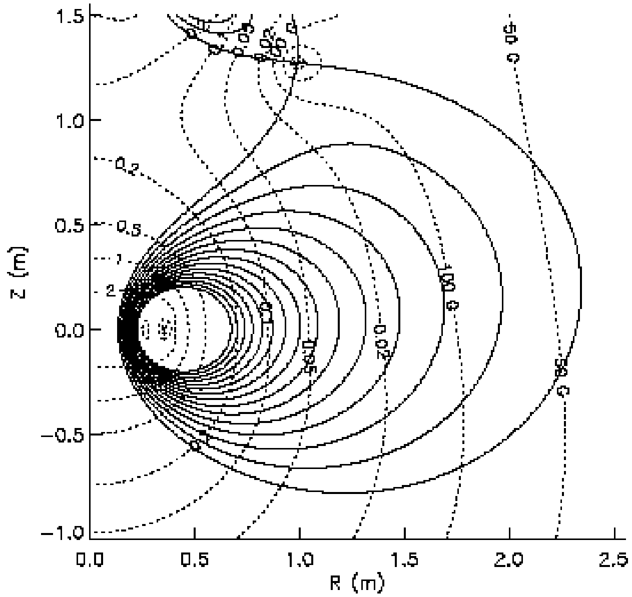
Instabilities and confinement can be investigated with ECH.



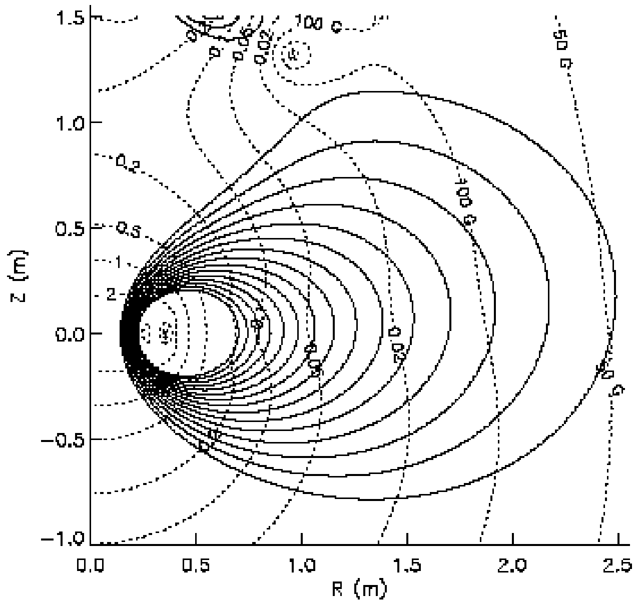
- Instability should exist when: $p' > p'_{critical}$.
- Investigate nature of instability.
  - How does it saturate?
  - How much transport is driven?
- Maximize β when: $p' < p'_{critical}$ everywhere
- What is maximum attainable β and what is limit?

Magnetics measurements on LDX will be used to calulate magnetic equilibria.

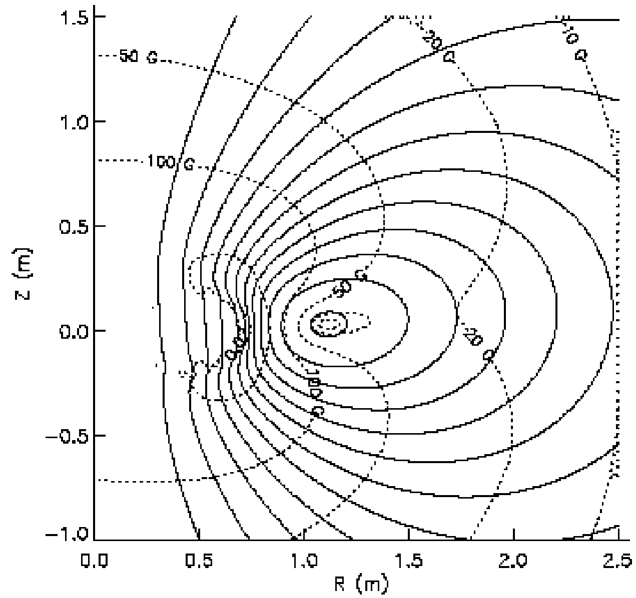
Vacuum



β/β_{max} = 50%



Difference

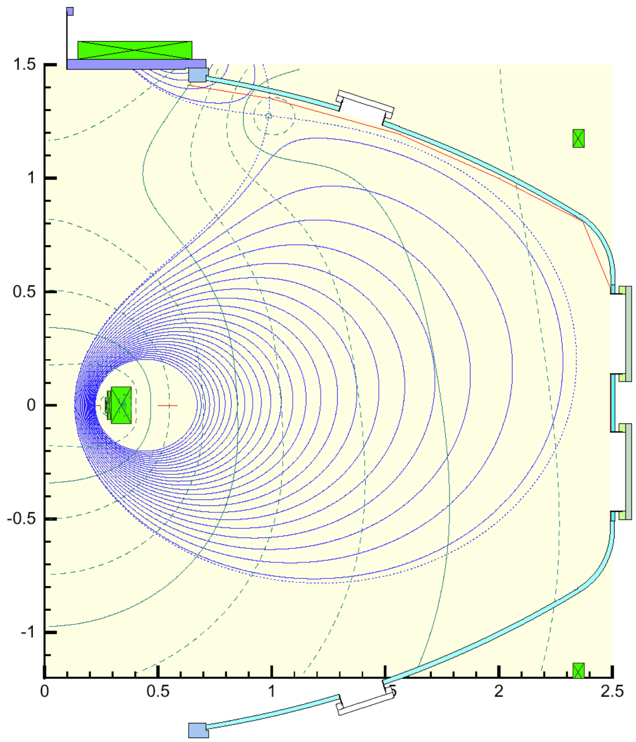


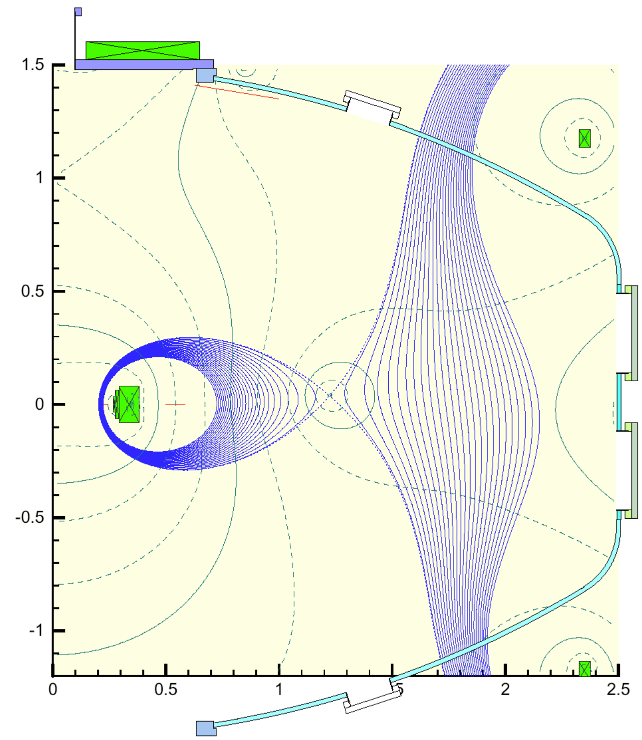
- DC dipole field means standard integrator diagnostics can be used
- Superconductor dipole “freezes-in” flux giving an internal boundary condition for GS solver
- Diagnostics include flux loops, Mirnov coils, and Hall probes

A Helmholz coil pair can change the compressibility ratio.

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

Helmholtz Coil:	**0 kA**	**Helmholtz Coil:**	**80 kA**
Compression Ratio:	**228**	**Compression Ratio:**	**14**
Adiabatic Pressure Ratio:	**8500**	**Adiabatic Pressure Ratio:**	**85**





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

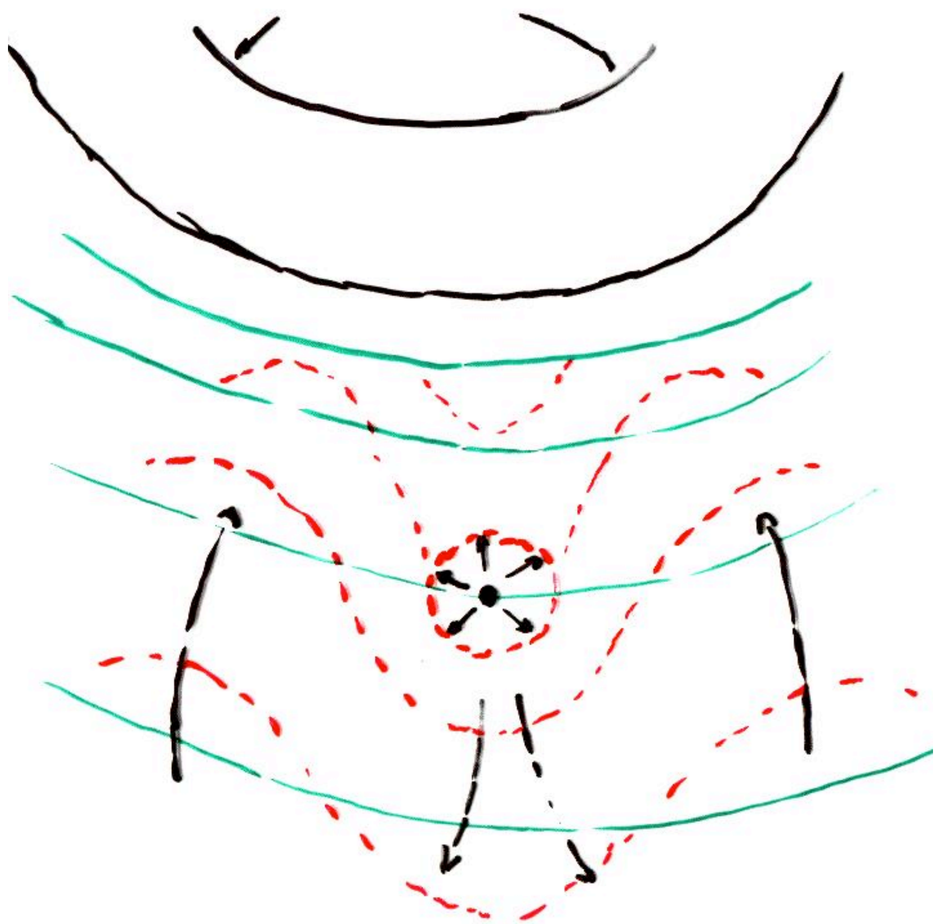
We plan a small set of diagnostics for initial operation.

- 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_{α} camera
- Edge probes
  - Emissive probe
- Note: some of these may be deferred until the levitated operation phase

Levitated Dipole Campaign

- No end losses
- Areas of investigation:
  - Global confinement
    - Referenced to supported operation
  - □ enhancement and scaling
  - Convective cells

Convective cells present their own challenges.



- What is their nature?
  - 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.
  - Asymmetric vs. symmetric
    - Fueling
    - Heating
- Measurements
  - Potential
    - Probes at edge
    - Low operation allows probes near core
    - HIBP for core?

Thermal plasmas are the ultimate goal.

- Transient thermal plasmas can be produced by gas puff or lithium pellet injection into hot-electron plasma.
- Areas of investigation
  - Thermalization of hot-electron □
  - Transient transport
    - Instability driven transport during profile relaxation
  - Convective cells
    - Investigate possibility of $\square_p << \square_E$
  - Heating of over-dense plasmas
    - With 28 GHz gyrotron, can heat to densities n □ 10^{19} m^{-3} before ECRF is cut off.
    - Methods for heating over-dense plasmas to be explored:
      - ICRF
      - Mode conversion of ECRF into electron-Bernstein waves
      - Launching of whistler waves from the high field region
      - Modest-sized neutral beam
        - Good beam penetration possible in a reactor to inside of ring
  - Confinement of thermal plasmas
  - Concept evaluation