

The Compact Levitated Dipole

Derek Baver

Outline

- Introduction
- Background
- Issues
- Solution
- Results
- Conclusions

Introduction

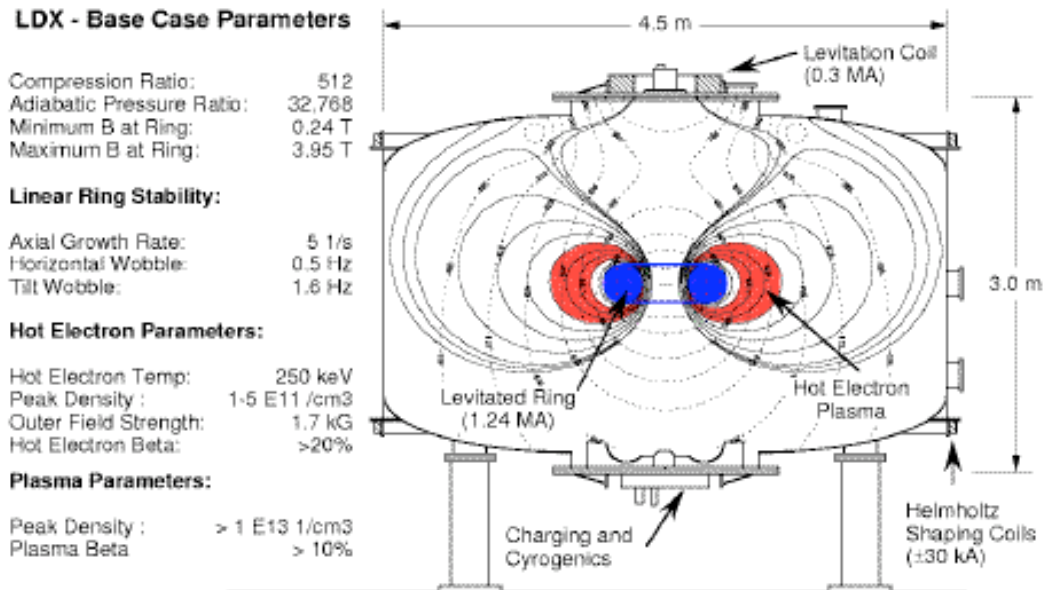
- The Compact Levitated Dipole (CLD) is a confinement concept based on the levitated dipole configuration.
- The CLD differs from the LD by adaptations intended to reduce space requirements.
- These adaptations also improve confinement-relevant statistics given a volume constraint.

Background

- The Levitated Dipole is a plasma confinement configuration inspired by planetary magnetic fields
- The LD consists of a levitated ring surrounded by plasma
- Dipole field confines plasma to vicinity of ring
- Examples in operation:
 - CTX: Compact Terrella Experiment (Columbia)
 - LDX: Levitated Dipole Experiment (MIT and Columbia)

Example: LDX

LDX Base Case Configuration



- Vacuum vessel much larger than levitated ring
- $1/r$ near field
- $1/r^3$ far field
- X-point separatrix
- Plasma confined in vicinity of levitated ring

Dipole physics

- Inward stability: good curvature
- Outward stability: plasma compressibility
 - Interchange modes compress plasma advecting in, expand plasma advecting out
 - Plasma heats up under compression
 - If pressure gradient is less than critical gradient, interchange mode results in net inward energy flux and is stable
 - Criterion for stability based on flux tube volume:

$$\frac{d \ln P}{d \ln U} \leq \gamma \text{ where } \gamma = \frac{5}{3}, U = \oint \frac{dl}{B}$$

- Pedestal: various stabilizing mechanisms
 - Neutral drag, FLR effects, good pedestal curvature, etc.

Issues

- Core/edge pressure and temperature ratios
 - Edge pedestal has characteristic stability limit
 - Core related to edge by critical gradient hence yields core limit
 - Edge temperature affects loss rates therefore confinement
- Size
 - Larger reactor relative to core volume is more expensive to build relative to power output
 - Larger experiment takes longer to build, may face practical constraints
- These are related: more core/edge ratio means larger size, smaller size means less core/edge ratio
- Can we get a better trade-off?

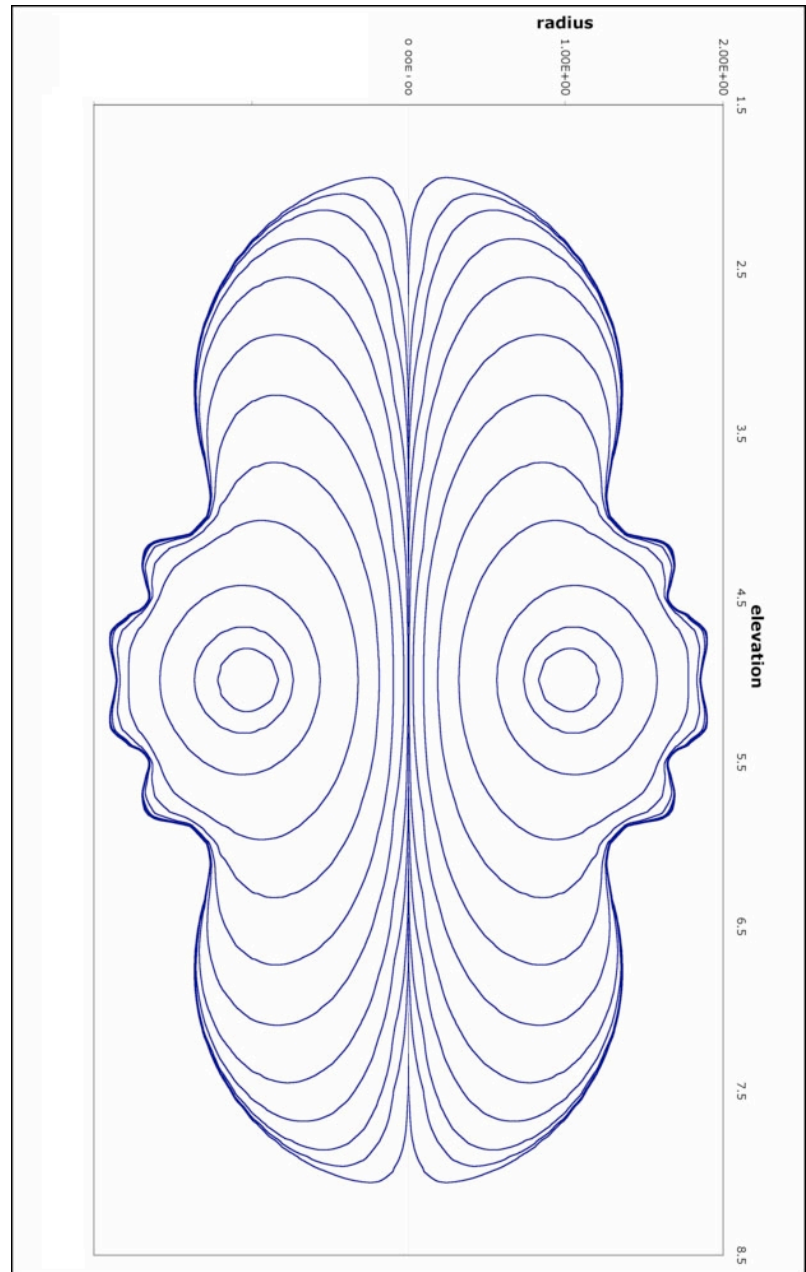
Solution

- Basic concept:
 - Far field region increases flux tube volume mainly through magnetic field gradients
 - Far field region accounts for most of device volume
 - Reduce volume of far field region by using different geometry to get more intense magnetic field gradient
- Basic structure:
 - Near field region is as conventional dipole
 - Magnetic field falls off as $1/r$
 - Far field is constrained to cylinder
 - Magnetic field falls off as exponential instead of $1/r^3$
 - Separatrix forms pair of cusp mirrors
 - High beta limit but poor confinement
 - Losses acceptable because fraction of total energy is tiny

- **Justification:**
 - Minimize volume ratio for given ratio of flux tube length
 - As field line length increases, pressure goes down as $l^{-5/3}$ with no change in field strength
 - As field strength decreases, pressure goes down as $B^{-5/3}$ yielding net $B^{1/3}$ beta increase
 - If edge and core beta are comparable, limit on flux tube volume ratio is l^6
 - Most compact design achieved by relying entirely on near field region for field line length increase
- **Implementation**
 - Construct code to solve vacuum fields for ring currents
 - Trial-and-error placement of ring currents gives approximation to desired geometry

Compact dipole field structure

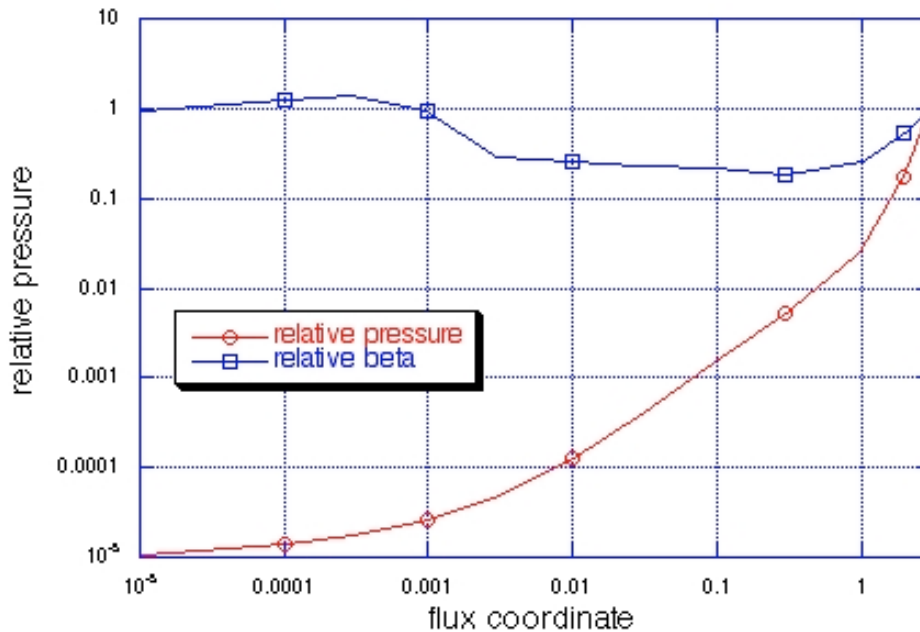
- Conventional dipole near core
- Edge ripple due to discrete coil set
- Flare at ends accompanied by vast drop in field strength
- Magnetic cusp at each end supports pedestal pressure at high beta



Results

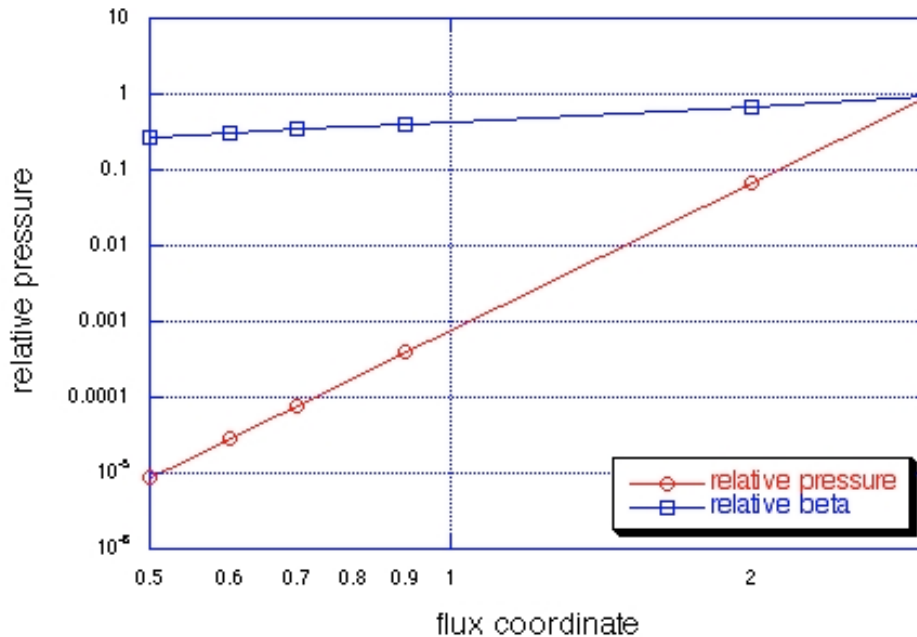
- How do we test the new configuration?
 - Solve for vacuum fields
 - Cylindrical coordinates
 - Adequate approximation at low beta
 - Allows tests of basic claims
 - Calculate flux surfaces
 - Vacuum fields solved in terms of flux coordinate
 - Equipotentials of flux coordinate gives surfaces
 - Integrate flux tube volume along flux surfaces
 - Flux tube volume can then be used to find core/edge pressure ratio at critical gradient
 - Compare resulting pressure to minimum magnetic field
 - Allows diagnosis of potential “beta explosion”

Results from Compact Dipole:



- Outermost flux surface encloses ~ 54 times volume of innermost flux surface
- Pressure drops by five orders of magnitude at critical gradient
- Beta remains close to core value at edge

Results from Conventional Dipole



- Outermost flux surface encloses ~ 298 times volume of innermost flux surface
- Pressure drops by five orders of magnitude at critical gradient
- Nearly six times as much volume needed for comparable performance

Conclusions

- CLD gets better results for a given volume than a conventional dipole
 - More economical as a reactor
 - Easier to scale experiments to fusion temperatures
- Advantage comes at a price
 - More coils, more complexity
 - Higher pedestal beta
- Compact dipole has probable advantage at high core-edge temperature ratio scaling