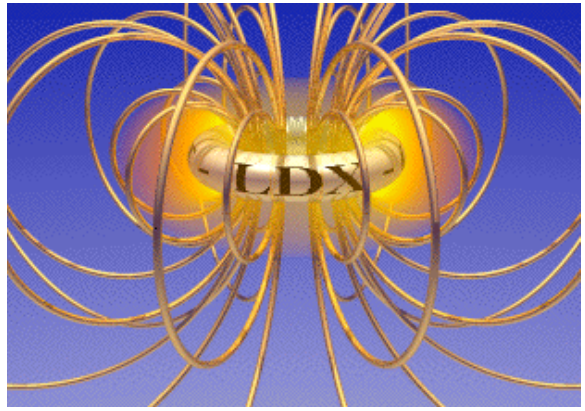



# The Levitated Dipole Experiment: Experiment and Theory

Jay Kesner, R.M. Bergmann, J.E. Ellsworth,
B. Kardon, P.P. Woskov,
*MIT*
M.S. Davis, D.T. Garnier, M.E. Mauel
*Columbia University*

**Columbia University**

*Poster UP8.00052*
*Presented at the DPP Meeting, Atlanta, November 5, 2009*

# ABSTRACT

A closed field line confinement system such as a levitated dipole is shear-free and the plasma compressibility provides stability. Theoretical considerations indicate the possibility of both MHD and electrostatic instability that can create turbulent driven transport. Importantly, the resulting transport is expected to create ``stationary", inwardly-peaked density and pressure profiles. In LDX, ECH is used to create a low density hot-electron species embedded in a background plasma which, during levitation is seen to contain approximately half of the stored energy. When the floating coil is levitated, competing along-the-field-line losses disappear (all losses become cross-field) and near-stationary density profiles are observed. For edge fueling this inwardly peaked density requires an inward pinch which is also observed. Low frequency kHz range fluctuations appear [Garnier et al., J. Pl. Phys. (2008)] that presumably maintain these profiles. The plasma edge is turbulent and for stationary profiles the edge parameters provide boundary conditions which determine the core parameters.

# Recent results - Turbulent pinch observed

- Transport drives plasma inwards resulting in inwardly peaked pressure and density
  - Stationary state has peaked p and $n_e$ determined by N=number/flux=nV and s=entropy density=pV$^{\gamma}$. $V = \oint d\ell / B$
  - Localized core heating drives instability. Turbulence will reduce pressure gradient to critical value while driving particles inwards.
    - Core turbulence determines strength of the pinch
  - Underlying physics: adiabatic mixing of flux tubes, I.e. conservation of $\mu$ and j.
- Edge transport will determine core parameters.
  - Edge turbulence drives plasma into scrape-off-layer (SOL)
  - SOL physics, i.e. divertor physics, will determine core parameters (N & s).

# Energetics of Pinch

- **LDX is a driven system**
- **MHD (collisional) plasma**

  Ref: Pastukhov et al, Pl Ph Rep, 27, (2001), 907, Kouznetsov et al, PoP 14 (2007).

  - **Local heating causes instability for $-\nabla p > (\nabla p)_{crit}$**
  - **Subsequent flux tube mixing reduces $|\nabla p|$ to $\nabla p_{crit}$ ⇨ ($p \propto 1/V^{\gamma}$) and also compresses flux tubes moving inward leading to $n_e \propto 1/V$.** $V = \oint d\ell / B$ **is the volume per unit flux, $\gamma$=5/3.**

- **Collisionlesss plasma**

  Ref: Hasegawa et al, NF 30 (1990) 2405.

  - **Drift resonant heating breaks flux (i.e. cononical angular momentum) invarient while conservating $\mu$ and J. Leads to $p \propto 1/V^{\gamma}$, $n_e \propto 1/V$**

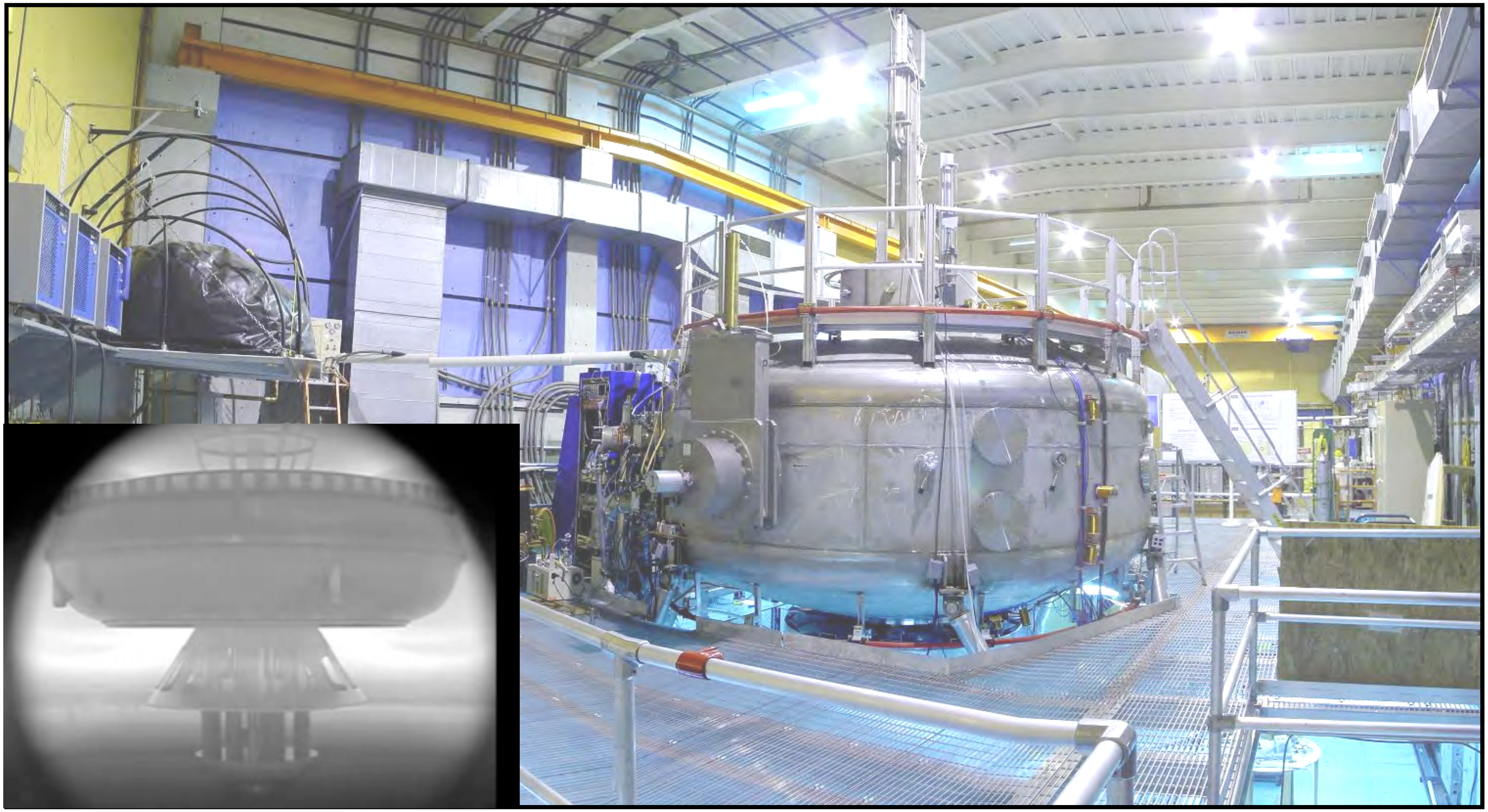
# Attractiveness of Dipole

- **Dipole research presents novel physics, challenging engineering and an attractive fusion confinement scheme**
  - Steady state
  - Disruption free
  - No current drive
  - High average beta
  - Low wall loading due to small plasma in large vacuum chamber
  - $\tau_E \gg \tau_p$ , as required for advanced fuels
- **LDX focus**
  - Evaluate $\tau_E$ and $\tau_p$
  - Stability and $\beta$ limits
  - Formation of "stationary" (peaked) density and pressure profiles
  - Issues relating to presence of hot species

# Summary of Results

- LDX routinely operates in levitated mode.
  - LDX can also operate supported for comparison.
- Levitation eliminates parallel particle losses and LDX exhibits a dramatic peaking of density (and pressure).
- Fluctuations of density and potential show large scale circulation that is the likely cause of the measured inward pinch.
  - Unlike most confinement schemes turbulence leads to inward transport and peaking of density.
- Increased stored energy consistent with adiabatic profiles.

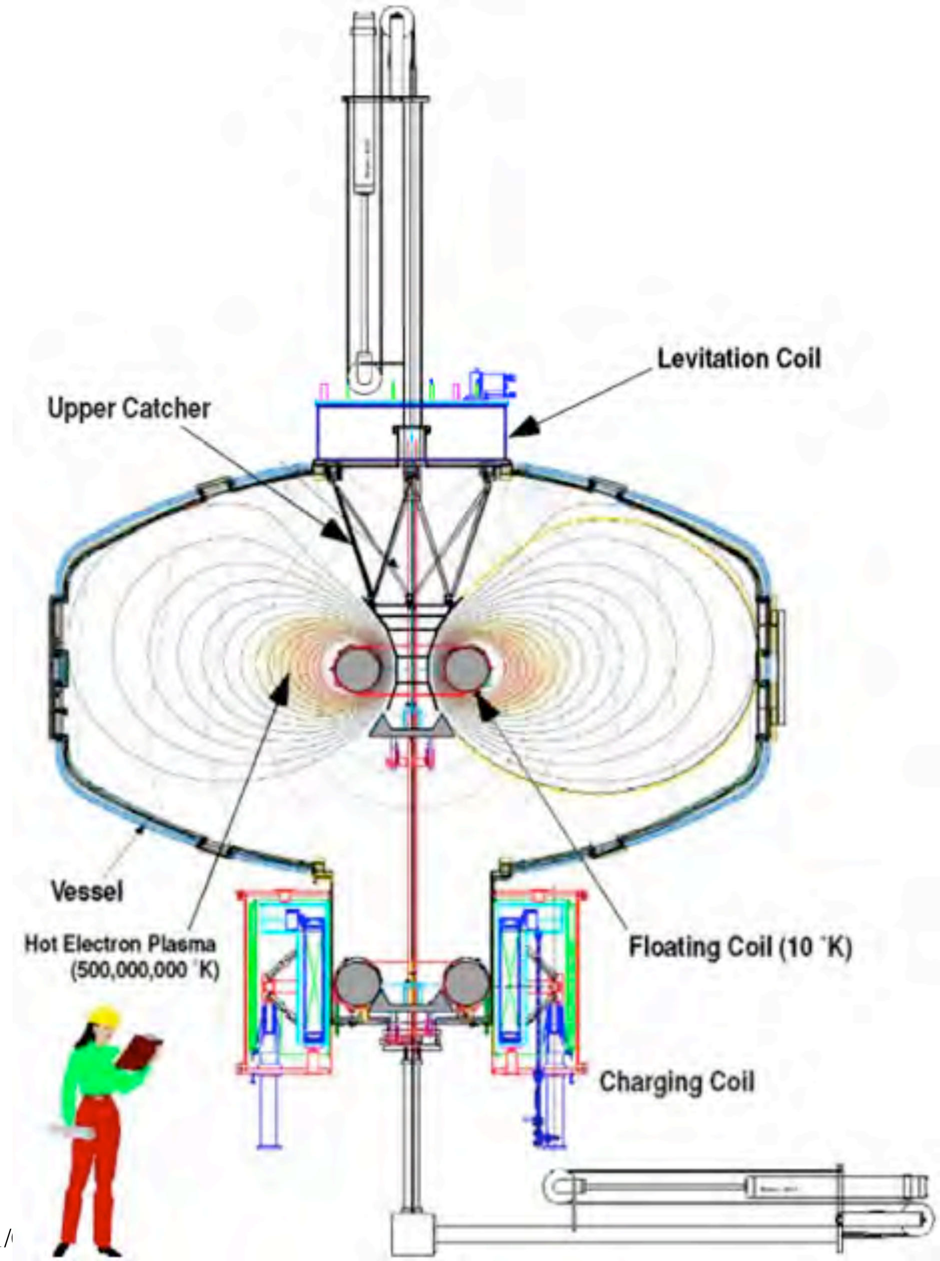
# The Levitated Dipole Experiment (LDX)



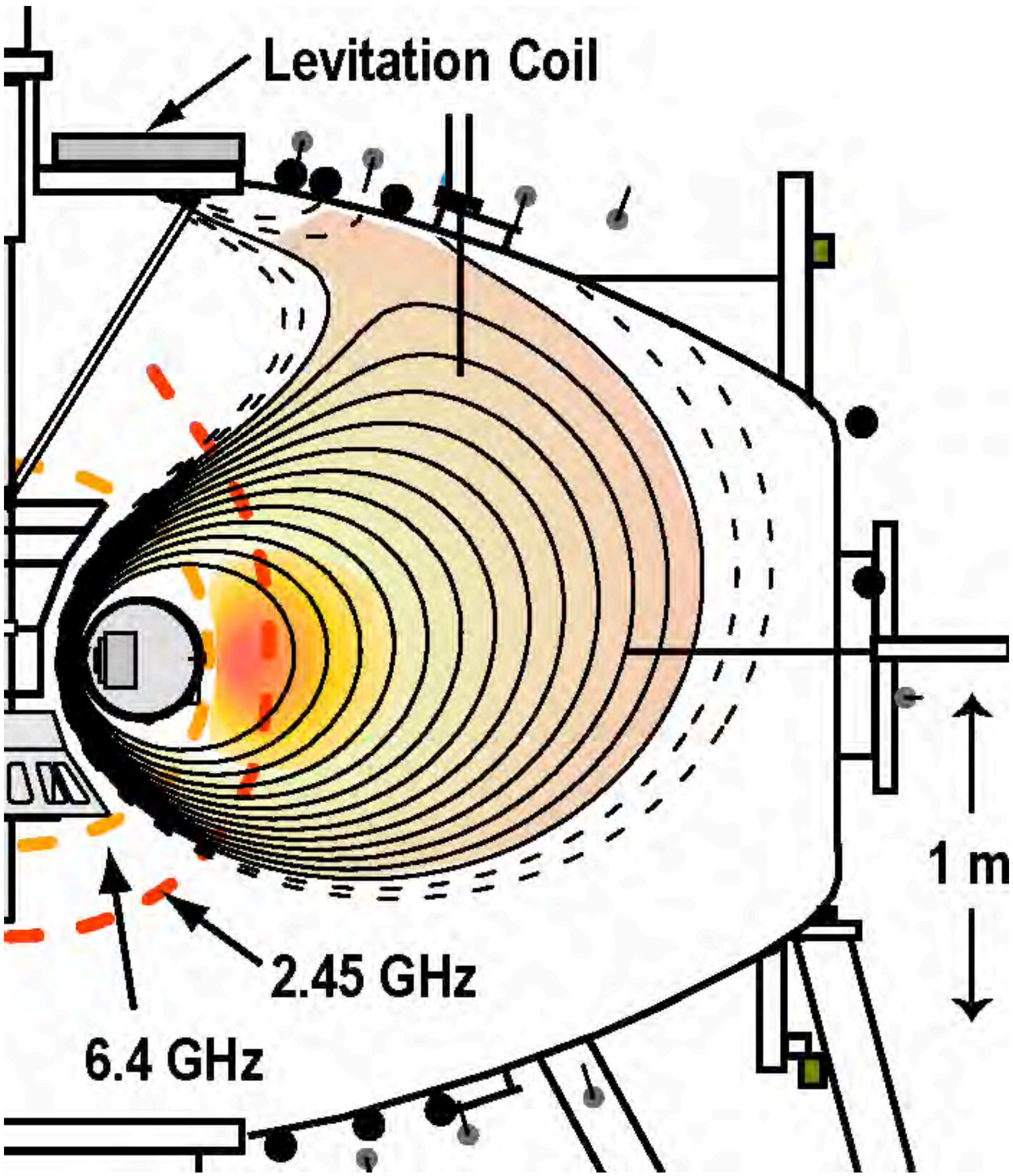
1200 lb floating coil is levitated within 5 m diameter vacuum vessel for up to 3 hours.

# LDX - Technical Capability

- Routine operation of superconducting dipole. Up to 3 hr float time
- ECRF heating: 17 kW at 2.45, 6.4 & 10.5 GHz
- 10 kW at 28 GHz being installed
- Excellent diagnostic access
- Diagnostic set includes magnetics, edge probes, interferometer array, visible light arrays ...



# Dipole Plasma Confinement




Toroidal confinement without toroidal field

- Stabilized by plasma compressibility
- Shear free

Poloidal field provided by internal coil

- Steady-state w/o current drive
- $J_{||} = 0$ ⇨ no kink instability drive
- No neoclassical effects
- No TF or interlocking coils
- $\nabla p$ constraint ⇨ small plasma in large vacuum vessel
- Convective flows transport particles w/o energy transport

# Some theoretical results - MHD

- **MHD equilibrium from field bending and not grad(B)**

  ⇨ $\beta \sim 1$ [1]

- **Ideal modes⇨arbitrary $\beta$:**
  - **Interchange modes unstable when -dlnp/dlnV> $\gamma$, i.e. $\delta(pV^{\gamma})<0$.** [1,2]
  - s= $pV^{\gamma}$, is the entropy density function. For s=const flux tube interchange does not change entropy density. $V = \oint d\ell / B$

- **Resistive MHD: Weak resistive mode at high $\beta$ [3]**
  - ($\gamma \sim \gamma_{res}$ but no $\gamma \sim \gamma_{res}^{1/3} \gamma_A^{1/3}$ mode)

- **Non-linear studies [4]:**
  - Cylindrical (hard core pinch approximation) - Interchange modes evolve into convective cells.
  - Can circulate particles w/o transporting energy

Ref:

1 Garnier et al., in PoP 13 (2006) 056111

2. Simakov et al.,PoP 9, 02,201

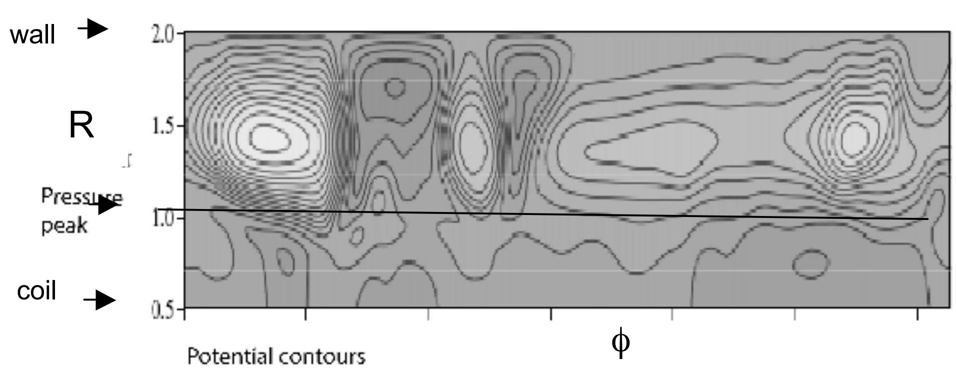
3. Simakov et al PoP 9, (02),4985

4. Pastukhov et al, Plas Phys Rep, 27, 01, 907

# Convective Cell Formation (Cylindrical z-pinch model)

- **Convective cells can form in closed-field-line topology.**
  - **Field lines charge up ⇨ $\psi - \phi$ convective flows (r-z in z-pinch)**
  - **2-D nonlinear inverse cascade leads to large scale vortices**
  - **Cells circulate particles between core and edge**
    - **No energy flow when $pV^{\gamma}$=constant, (i.e. $p' = p'_{crit}$).**
    - **When $p' > p'_{crit}$ cells lead to non-local energy transport.**

    **Stiff limit: only sufficient energy transport to maintain $p' \gtrsim p'_{crit}$.**
  - **Non-linear calculations use reduced MHD (Pastukhov et al) or PIC (Tonge, Dawson et al) in hard core z-pinch**



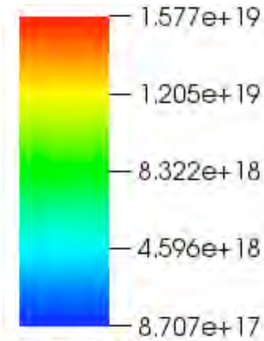

Reduced MHD: Pastukhov, Chudin, Pl Physics 27 (2001) 907.

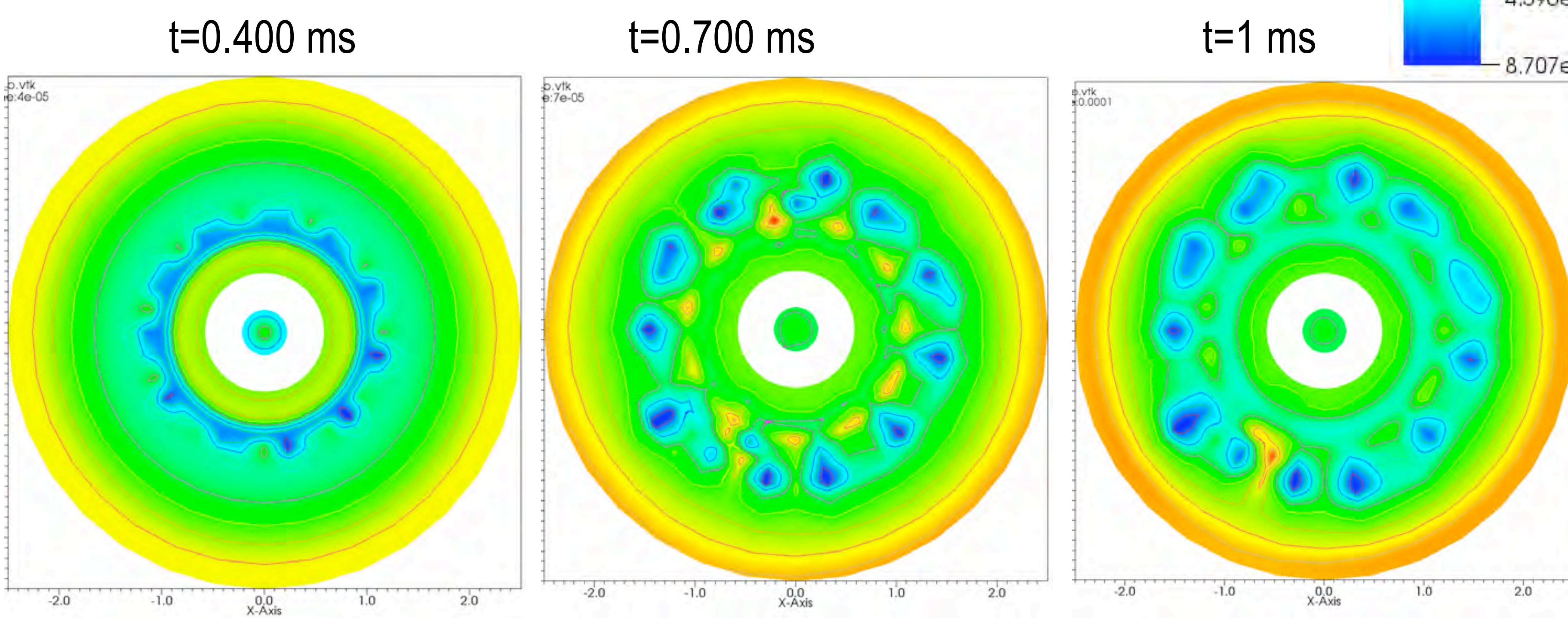
PIC: Tonge, Leboeuf, Huang, Dawson, 10 Phys Pl. (2003) 3475.

# NIMROD Resistive MHD: Dipole Geometry

- Strong local heating ar R=0.9 m.
- Internal heating, external fueling: Density initially peaks at outside. Instability leads to inwardly peaked profiles.
- Pressure driven interchange instability rearranges density(below) and pressure (not shown).
- Density profile becomes centrally peaked.

View looking down at plasma. Density contours: Top view

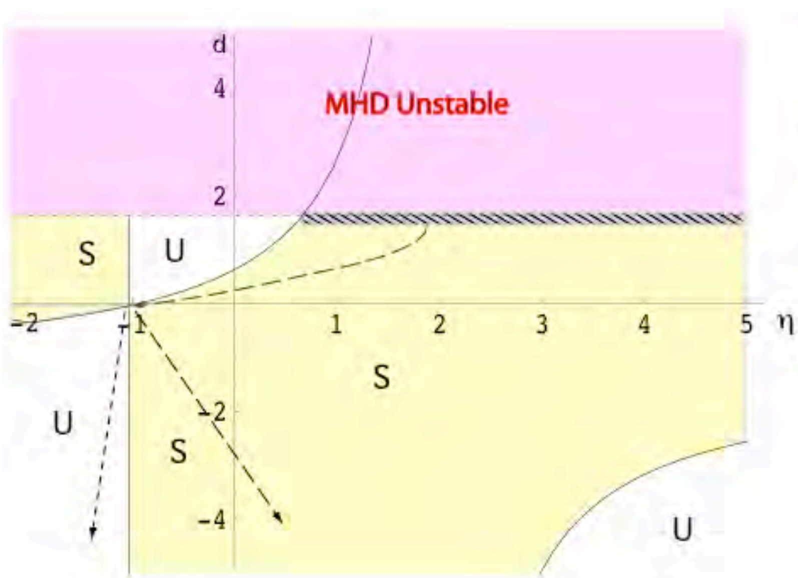


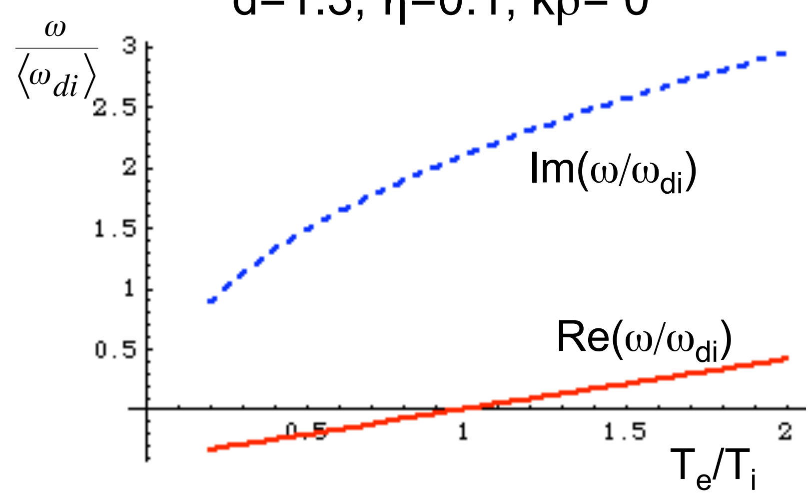



# Low frequency instability: Entropy Mode

- Entropy mode is a drift frequency, flute mode.
- Dispersion Relation $\hat{\omega}=\omega/\langle\omega_{di}\rangle$, $d=-\frac{d\ln p}{d\ln V}=(1+\eta)\frac{\omega_{*i}}{\langle\omega_{di}\rangle}$, $\eta=\frac{d\ln T}{d\ln n}$

$$\hat{\omega}^2\left(\frac{d\ln p}{d\ln V}+\frac{5}{3}\right)+\frac{5\hat{\omega}}{3}\left(\frac{T_e}{T_i}-1\right)\left(\frac{d\ln p/d\ln V}{1+\eta}+1\right)+\frac{5}{9}\frac{T_e}{T_i}\left(\frac{d\ln p}{d\ln V}\frac{3\eta-7}{\eta+1}-5\right)=0$$



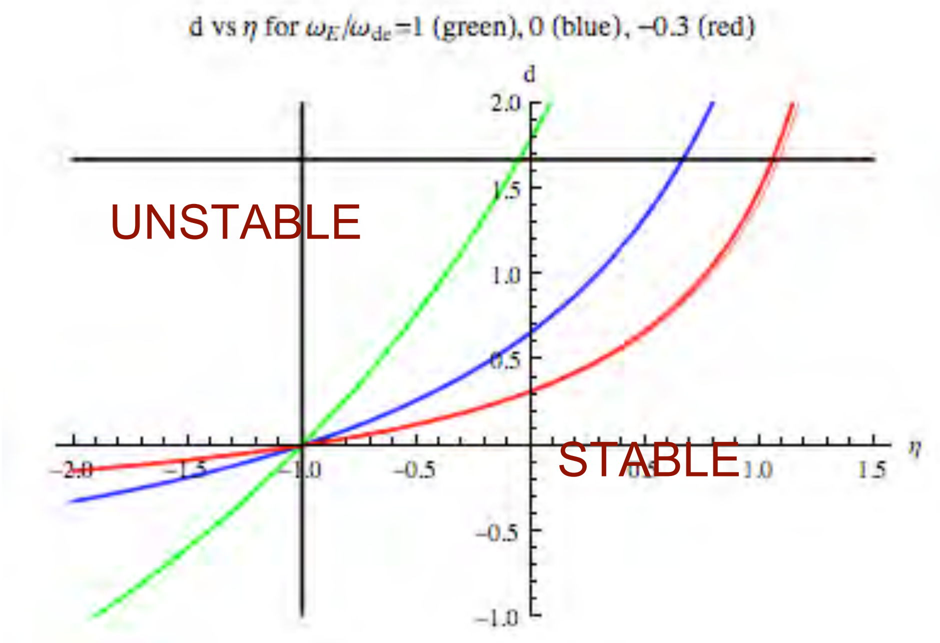

Real frequency is introduced for $T_e \neq T_i$

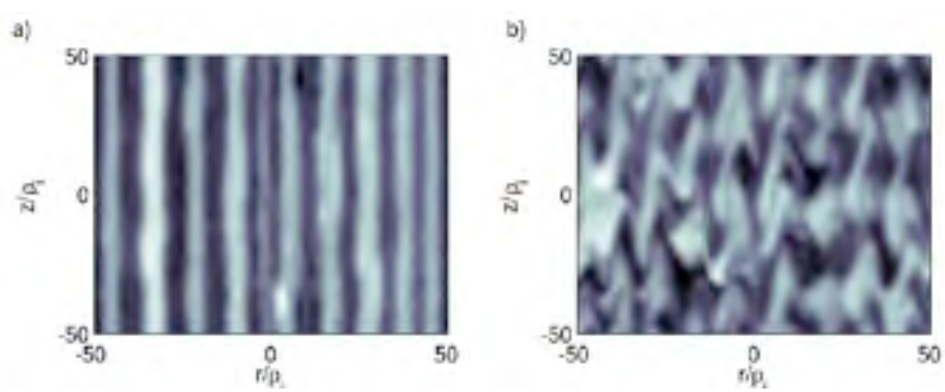
# Effect of rotation on entropy mode

- **LDX: Rotation in electron direction observed**
  - $\omega_{ExB}$ **in electron drift direction reduces unstable area**
  - **Ion direction increases unstable region**
- **Non-linear simulations:**

**Kobayashi, Rogers, Dorland, PRL 103, (2009) 055003**

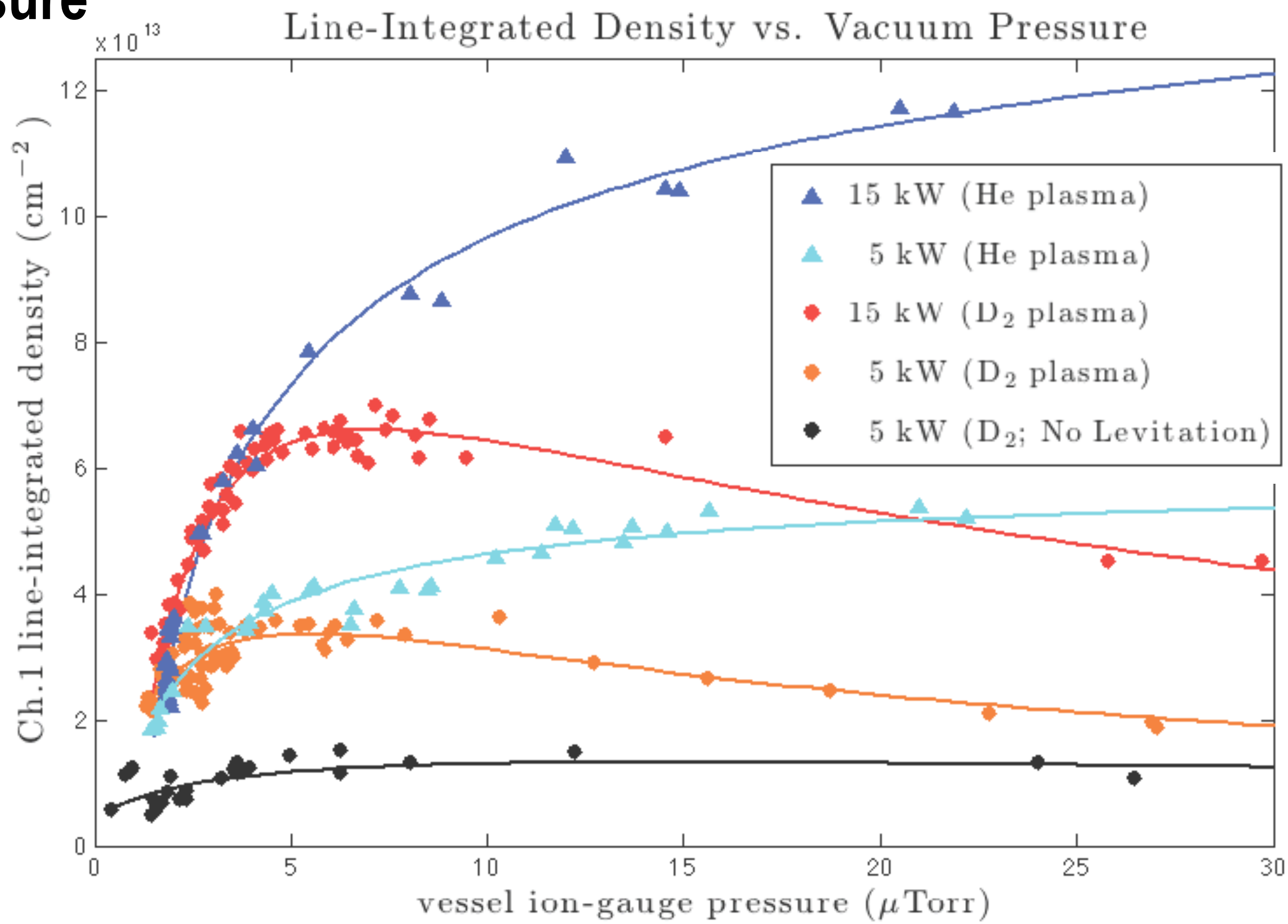
  - **Zonal flows limit transport**
  - **Increasing drive ($\nabla n_e$) limits zonal flows**
  - **Increasing collisionality limits zonal flows**



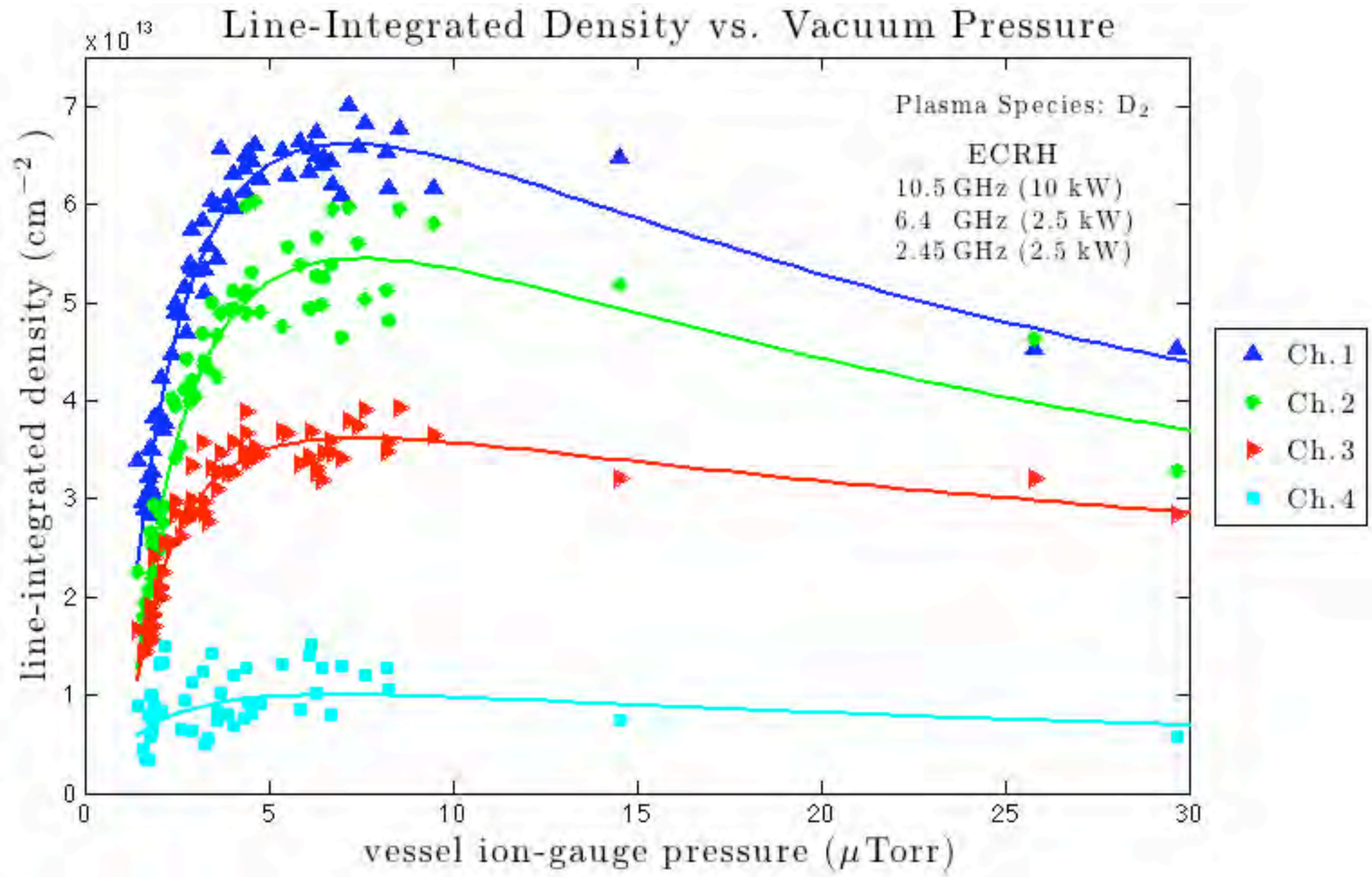
# LDX has 4 primary experimental "knobs"

- Levitation vs. supported
- Gas pressure
- RF Power
- Species



# Interferometer measurements confirm stationary profiles

- **Line-integrated density vs. vacuum pressure for $D_2$ plasmas heated by 3 frequencies (15 kW). The density initially, increases rapidly with $p_0$ (max at around 5-7 $\mu$Torr). Ref A.C. Boxer, Ph.D. thesis (2008). Submitted to PoP.**



# Dipole: Edge physics determine core parameters

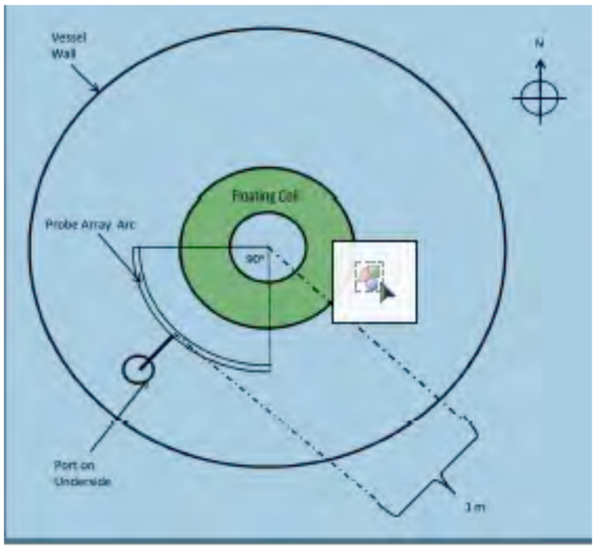
- **Scrape-off-layer (SOL) beyond separatrix has open field lines**
  - **Physics of the SOL determines core $n_e$ and $T_e$ (or p).**
- **The LDX approach is predicted to generate pinch leading to and** $pV^{\gamma}=const$ **, and** $nV=const,\ V=\oint d\ell/B$
- **Along open SOL field lines $T_e$ is determined by particle balance:**

$$n_e u_{bohm}(T_e)A_{eff} = \langle\sigma v\rangle_e(T_e)n_e n_0 Vol$$

- **We measure $T_e$ , $n_e$ and $n_0$ in SOL.**
  - **$n_0$ determined from neutral pressure (from Ion gauge)**
  - **$T_e$ & $n_e$ from swept Langmuir probe**
  - **Consistent with continuity $T_e$ is ~independent of $P_{RF}$**
- **From $T_e$ and $n_0$ we can solve for $A_{eff}$~0.17 $m^2$**

# SOL diagnosed with several Langmuir probes [1]

- **2 fixed probes, 4 movable probes, 24-probe (90°) probe array**




- **Toroidal rotation 2-16 km/s in e-direction.**
- **$\tau_{correlation}$~150 $\mu$s < $\tau_{rotate}$, $L_{correlation}$~50 cm**
  - **Turbulent edge, structures de correlate in less than rotation period**
- **Similar level of edge turbulence in supported and levitated plasmas**

1. R. M. Bergmann, M.S. Thesis, May, 2009.

# Probe SOL measurements

- **Power in low n modes:**

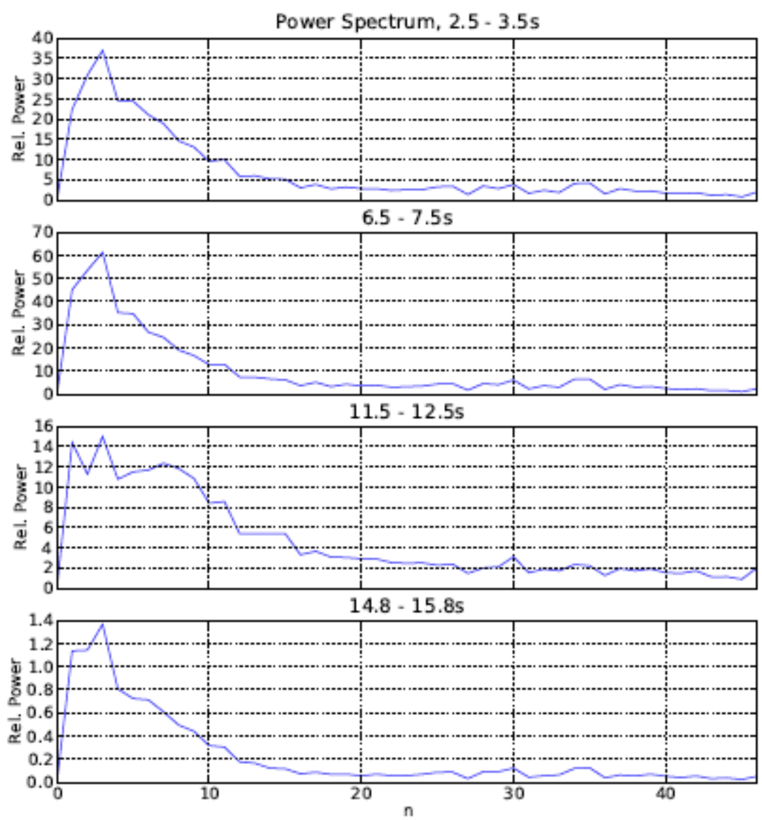



FIG. 4: Spatial time-averaged power spectra from shot 81003019. 5kW of heating power was being applied during 2.5-3.5 seconds, 15kW during 6.5-7.5 seconds, 2.5kW during 11.5-12.5 seconds, and 14.8-15.8 seconds was during the "afterglow" where no power was being provided.|

- **Plasma rotation**

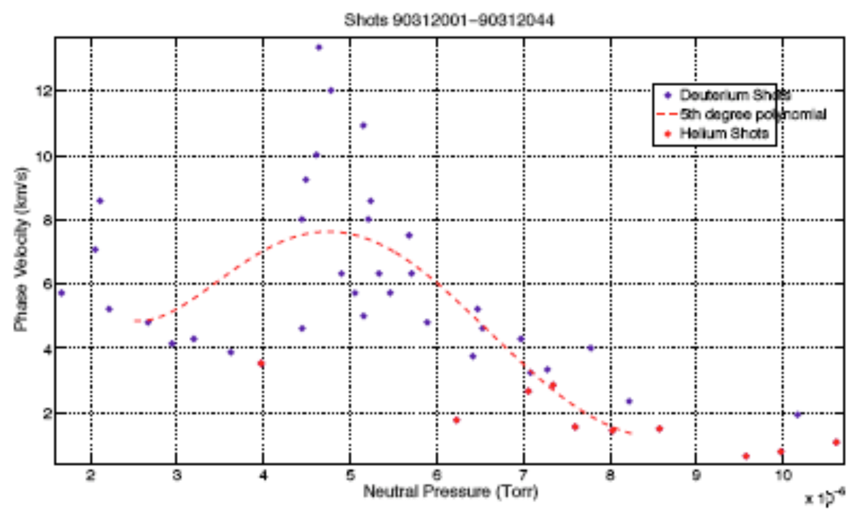
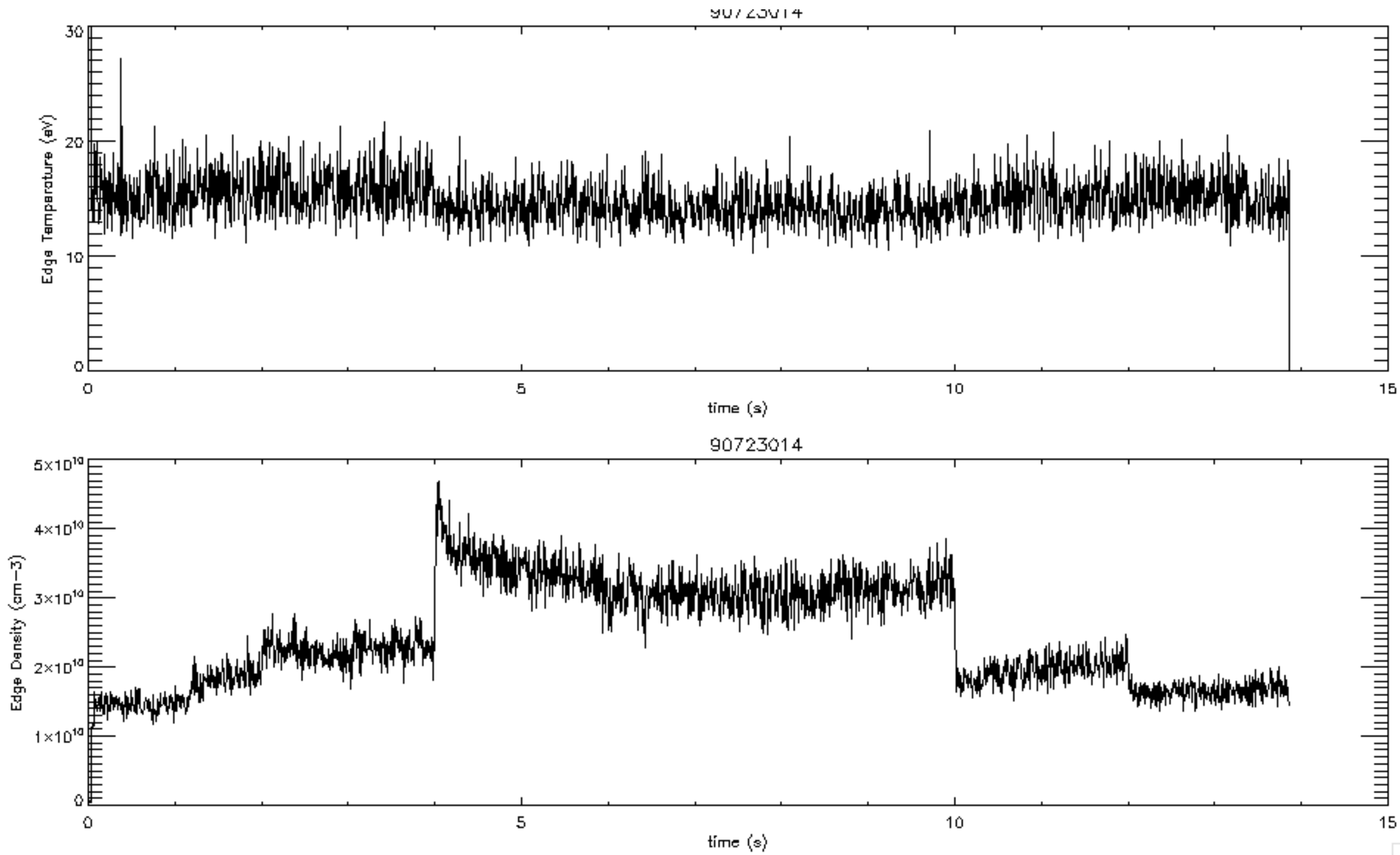



FIG. 5: The plasma rotational velocity plotted against the vessel neutral pressure. There is a maximum at $5\mu$Torr where the plasma density is greatest. Phase velocity decreases with neutral pressure when the plasma density is constant ( $> 5\mu$Torr). Below $5\mu$Torr, the plasma density is not constant with neutral pressure, and the velocity/pressure relationship is unclear.

**Edge rotation permits convective cells to extend out to plasma edge**

# SOL Probe measurements

- Shot 90723014: $P_{2.45}$ (0-14s), $P_{6.4}$(2-12s), $P_{10.5}$(4-8s)
- $T_e$~15 eV remains constant. $n_e$ varies with power

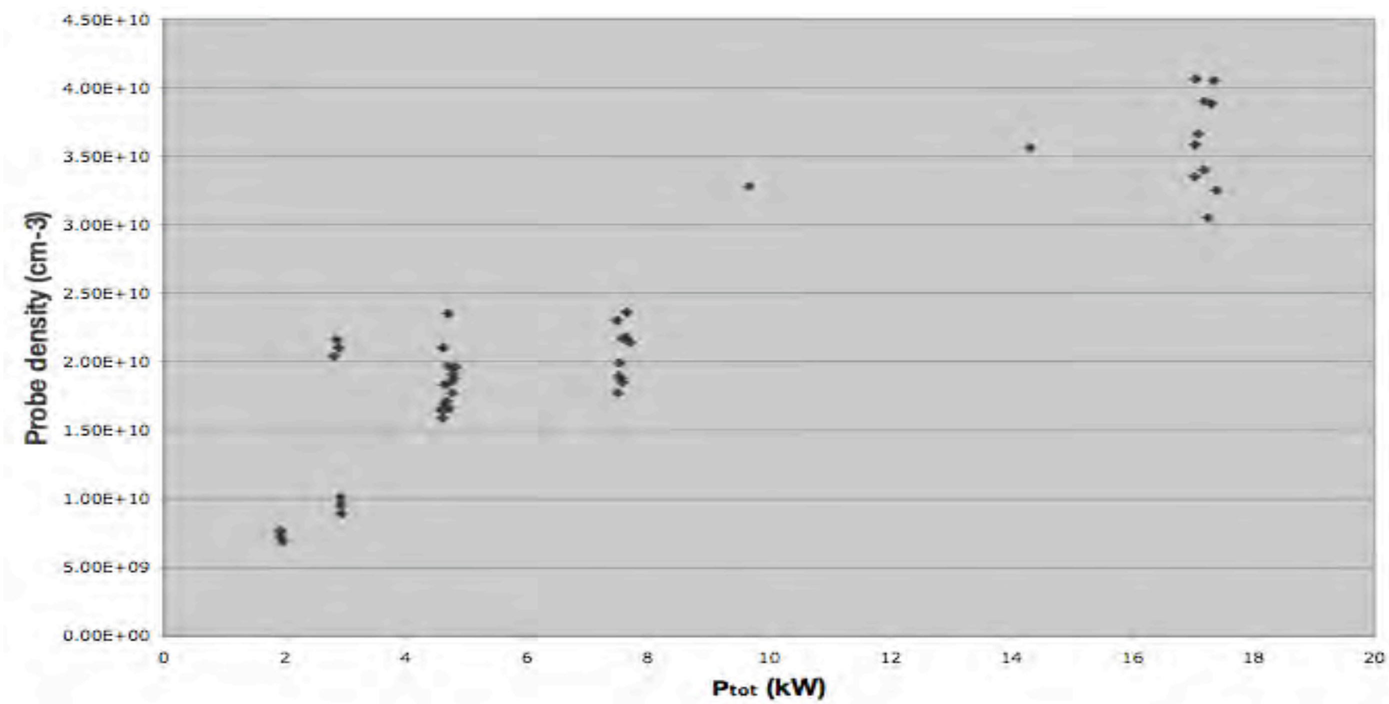


# Continue: SOL physics

- $n_e$ in SOL determined from power balance

$$\alpha P_{ECH} = e n_e u_B A_{eff} \varepsilon_T$$

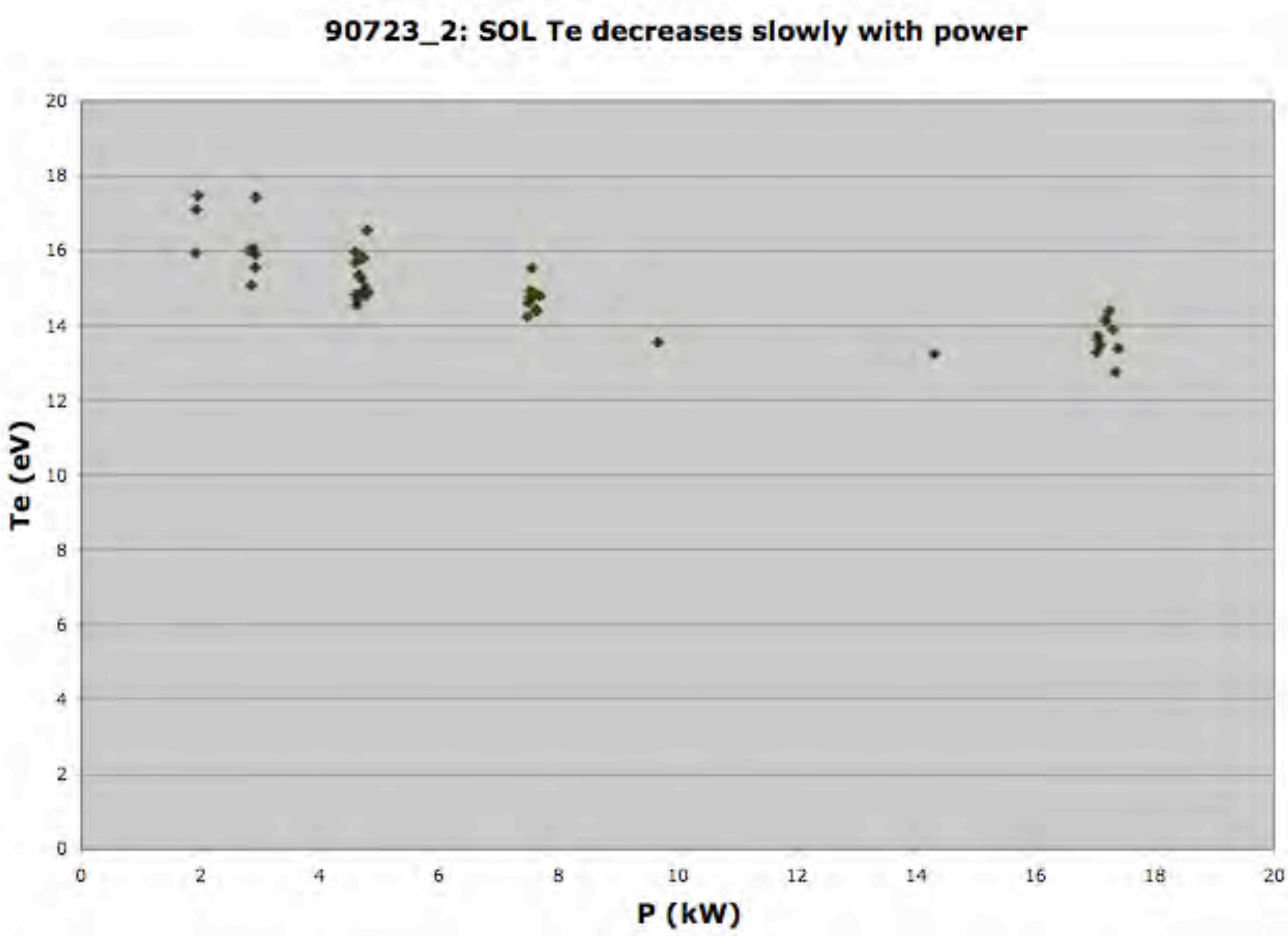
- $\therefore\ n_e \propto P_{RF}$ for fixed $A_{eff}$
- Swept probe at separatrix measures $T_e$ and $n_e$
- Also can measure SOL fluctuations of $V_{float}$




Neutral pressure
Varies in data set

# $T_e$ is approximately independent of $P_{rf}$

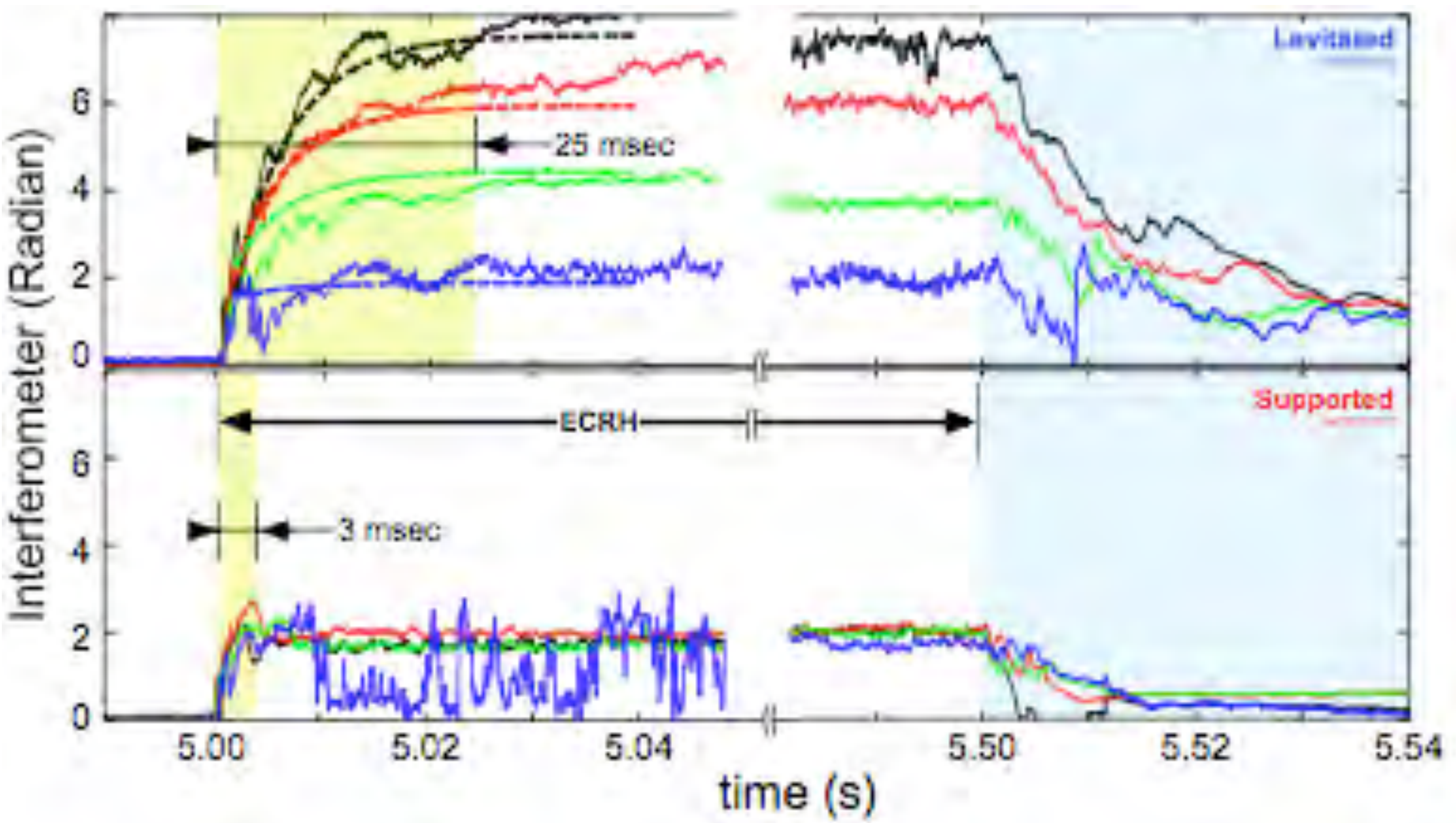
$T_e$ determined from particle balance: $n_e u_{bohm}(T_e) A_{eff} = \langle \sigma v \rangle_e (T_e) n_e n_0 Vol$



# Profiles established by turbulence driven diffusion

- **When levitated observe rapid peaking (t<25 ms).**
- **Transport in flux space** $\frac{\partial N}{dt} = \frac{\partial}{\partial \psi} D \frac{\partial N}{d\psi}$

**See Mauel UP8.00051**



# Implication of SOL Physics

- **Thermal plasma energy**

$$E_T = \int n_e(\psi)\, T_e(\psi) d\psi \propto P_{ecr}\, T_{sol} \int dV \left( {}^{Vsol}\!/_{V} \right)^{\gamma} \qquad V = \oint d\ell / B$$

- **Energy confinement** $\tau_E = E_T / P_{ecr} = T_{sol} \int (\ldots) \approx 100\ ms$
  - **Notice: $\tau_E$ is independent of $P_{RF}$**
    **(Compare: for tokamak $\tau_E \propto I / P^{1/2}$ )**
- **For sufficient $P_{RF}$ expect $T_e$ to rise**
  - **Power no longer balanced by ionization**
  - **Cmod SOL, Tara: $T_e$~50-100 eV**

# Dipole meets requirements for advanced power source

- MHD does not destroy confinement (no disruptions)
- Intrinsically Steady State
- High $\beta$ for economic field utilization
- High $\tau_E$ necessary for ignition
  - Ignition in small device
  - Advanced fuels (D-D, D-$^3$He)
- Low $\tau_P$ for ash removal
- Low divertor heat load - want plasma outside of coils for flux expansion
- Circular, non-interlocking coils

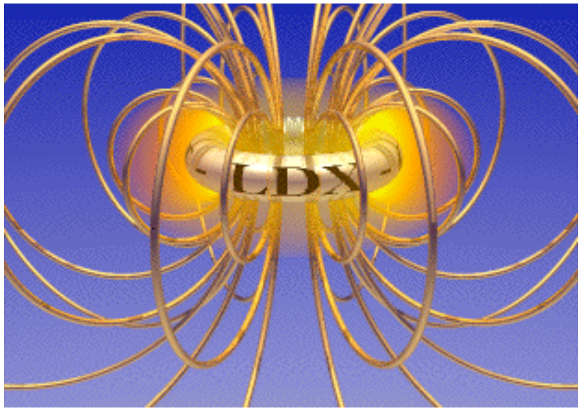
**Need to minimize 14 MeV flux to floating coil. We have evaluated dipole as an advanced fuel DD based power source .**

Ref: Kesner et al, Nuc Fus 44 (2004) 193.

# Conclusions

- The mechanics of levitation has proven reliable
- LDX has demonstrated the formation of "natural" profiles in a laboratory plasma and has demonstrated the applicability of space plasma physics to fusion science

- Fluctuations of density and potential show large scale circulation that is the likely cause of the measured inward pinch. Turbulent transport is inward (and desirable).
- Increased stored energy consistent with adiabatic profiles: a necessary condition for dipole fusion.
- See: http://www.psfc.mit.edu/ldx/




# EXTRA SLIDES

# Dipole Stability Results from Compressibility

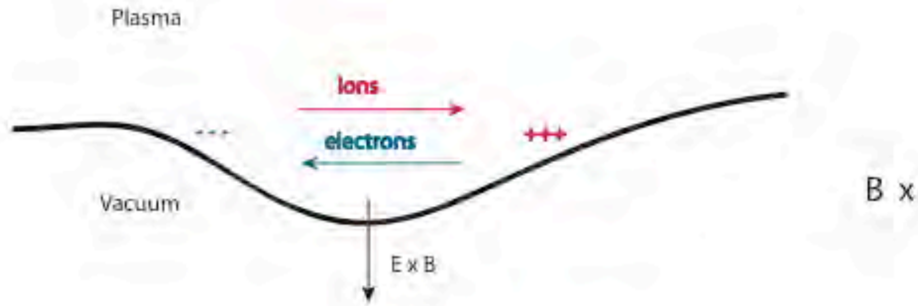
- **No compressibility:**

**"bad" $\kappa$ & $\nabla B$ drifts cause charge separation ⇨ $V_{ExB}$ increases perturbation**

- **With compressibility: as plasma moves downwards pressure decreases. For critical gradient there is no charge buildup**

**In bad curvature pressure gradient is limited to**

$$-\frac{d \ln p}{d \ln V} < \gamma \qquad V = \oint dl / B$$




Density gradient.
Compressibility: Density decreases as plasma moved downward.