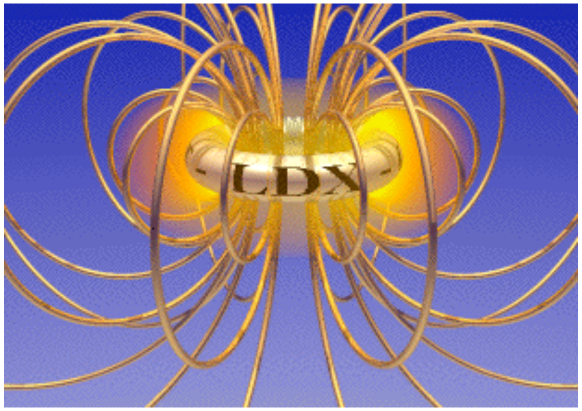


The Levitated Dipole Experiment: Experiment and Theory

Jay Kesner, R. Bergmann, A. Boxer,
J. Ellsworth, P. Woskov,
MIT
D.T. Garnier, M.E. Mauel
Columbia University

Columbia University

Poster CP6.00083
Presented at the DPP Meeting, Dallas, November 17, 2008

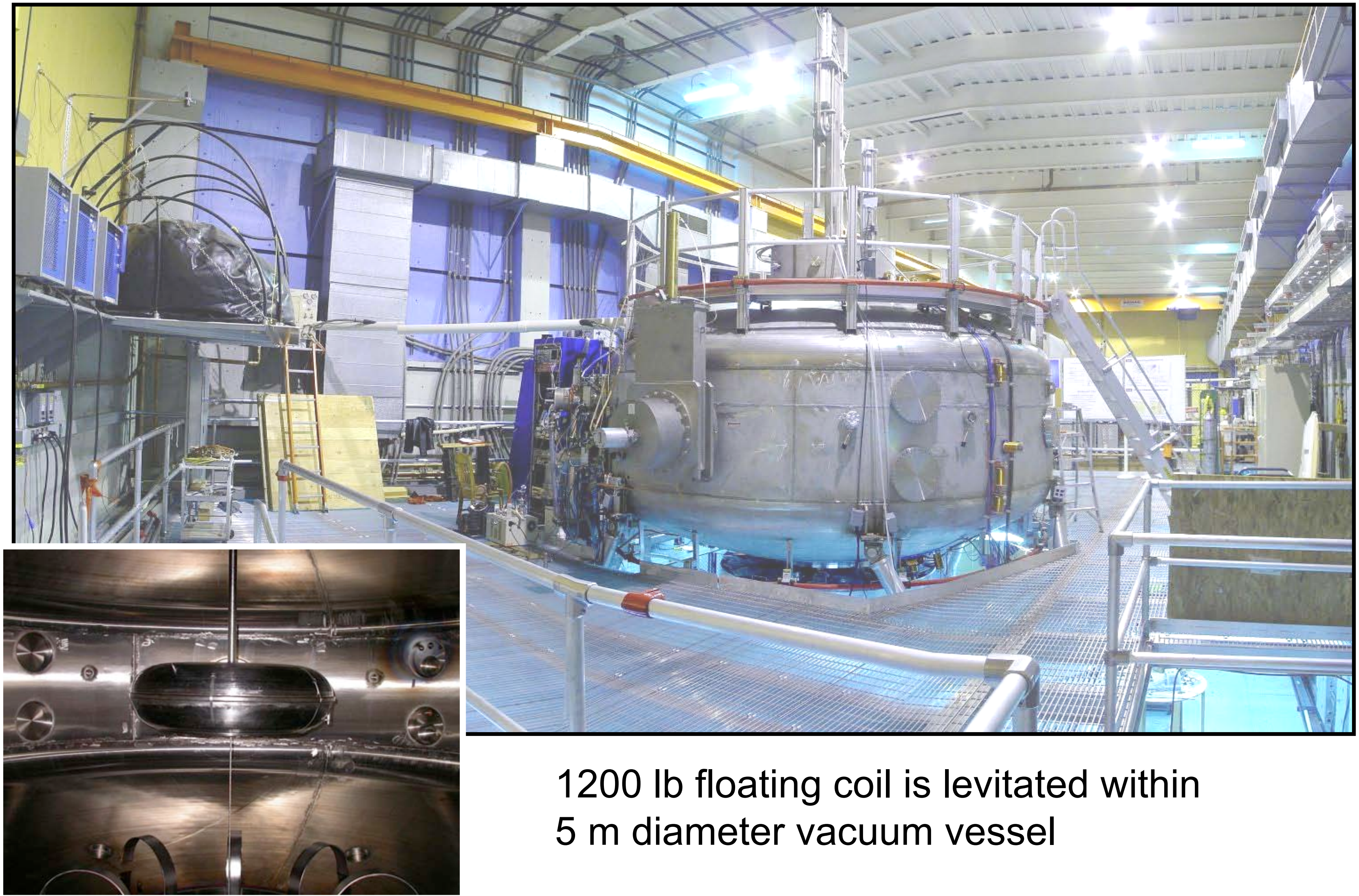
A closed field line confinement system such as a levitated dipole is shear-free and the plasma compressibility provides stability. Theoretical considerations of thermal plasma driven instability indicate the possibility of MHD-like behavior of the background plasma, including convective cell formation as well as drift frequency, interchange-like (entropy mode) fluctuations.

In recent experiments in LDX the floating coil was fully levitated and therefore all losses should be cross-field. During levitated operation lower fueling rates were required. We create a non-thermal plasma in which a substantial fraction of energy is contained in an energetic electron species that is embedded in a cooler background plasma. Under some circumstances we observe the density tending to a stationary profile with a constant number of particles per unit flux. We observe low frequency fluctuations (drift and MHD) in the kHz range that presumably are driven by the thermal species. The fluctuation amplitude is reduced in the stationary state, consistent with theoretical predictions.

Summary - Dipole perspective

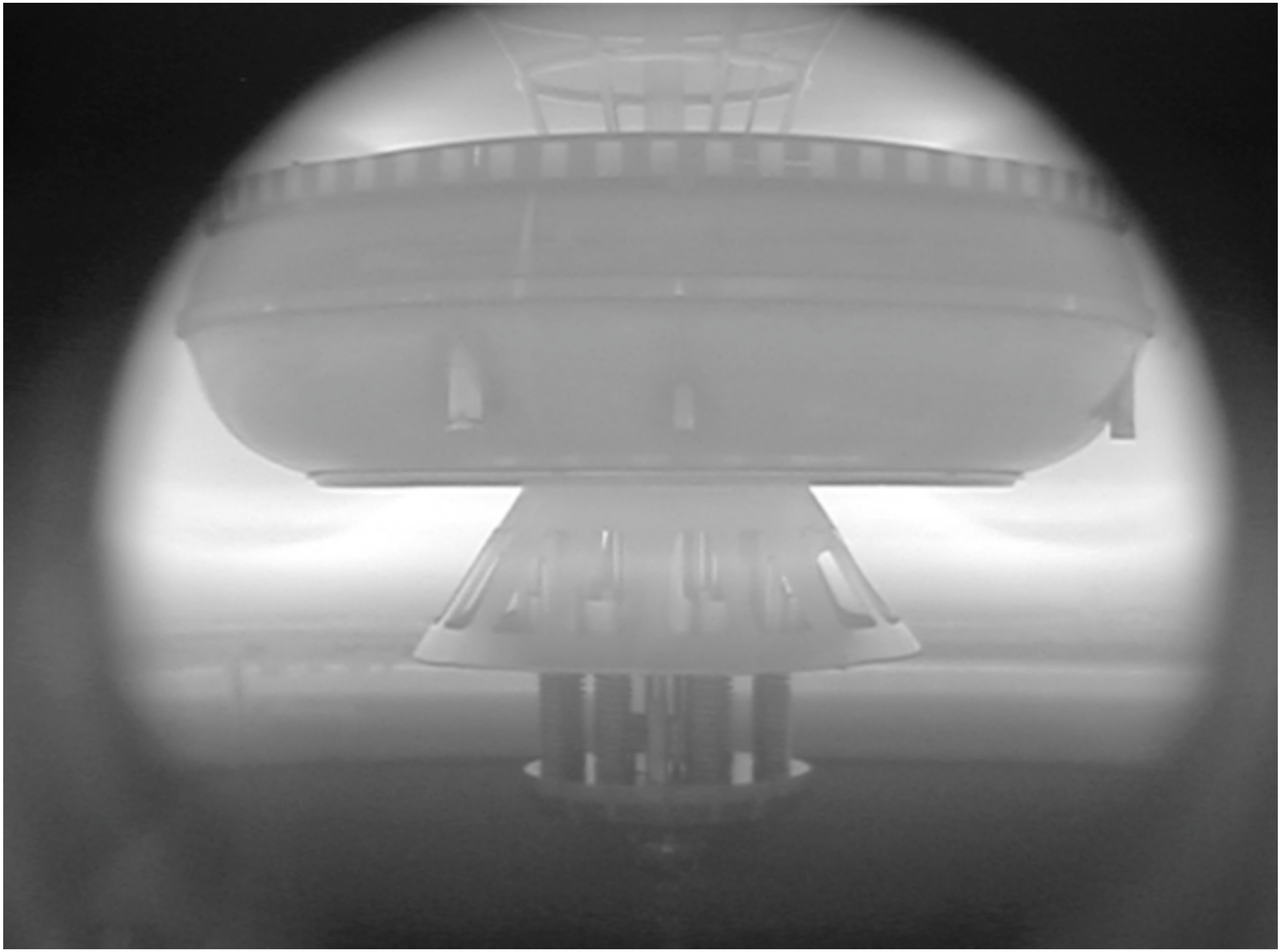
- Dipole research presents novel physics, challenging engineering and an attractive fusion confinement scheme
  - Steady state
  - Disruption free
  - no current drive
  - high average beta
  - low wall loading due to small plasma in large vacuum chamber
  - $\tau_E \gg \tau_p$ (as required for advanced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

The Levitated Dipole Experiment (LDX)

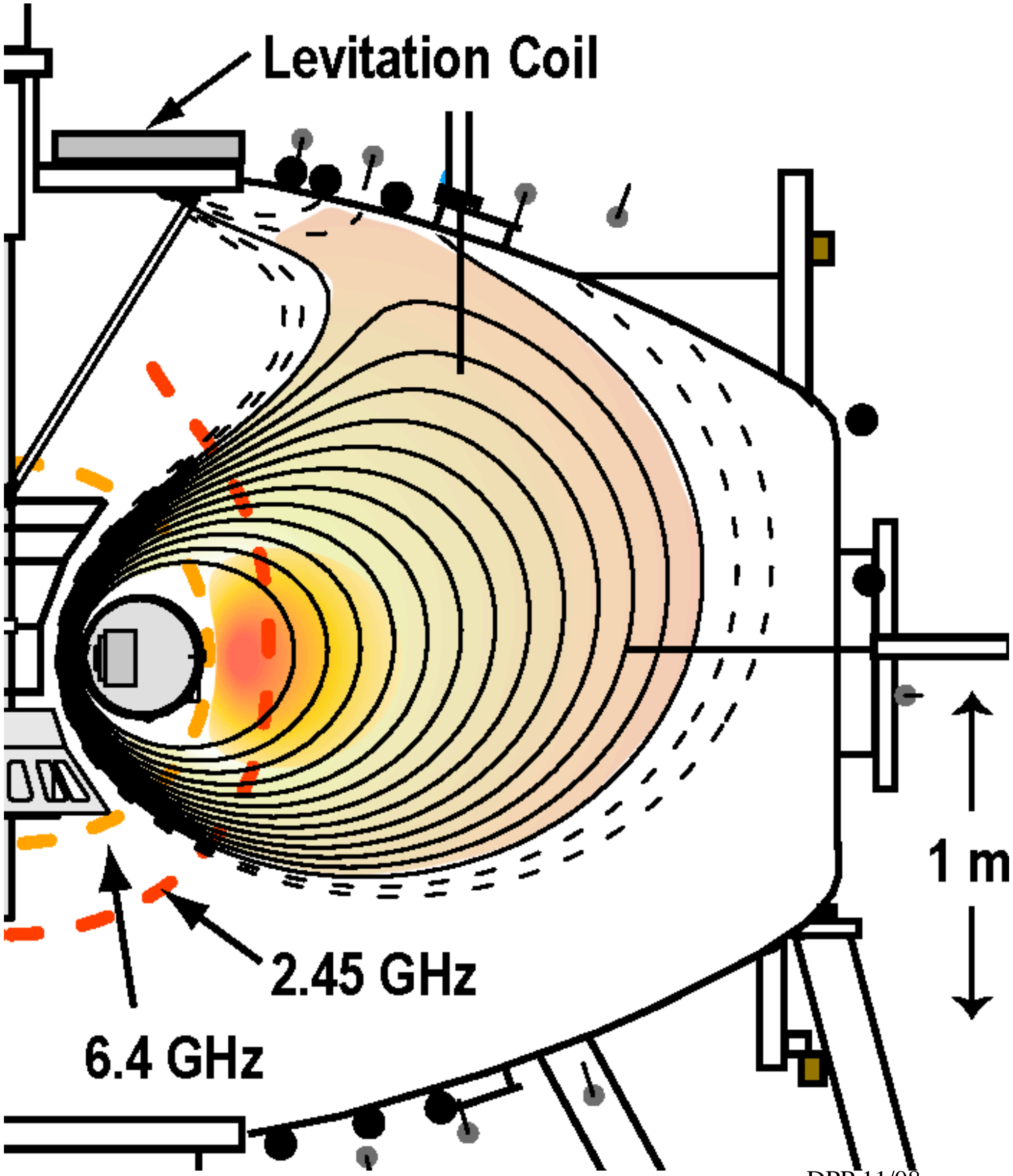


1200 lb floating coil is levitated within
5 m diameter vacuum vessel

First levitated experiments performed on 11/8/07



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
- ∇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 β: Interchange modes unstable when -dlnp/dlnV> γ, i.e. $\delta(pV^{\gamma})<0$.** [1,2]
  - $s = pV^{\gamma}$, the entropy density function. For s=const flux tube interchange does not change entropy density.
- **Resistive MHD: Weak resistive mode at high β** [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.
  - Circulate particles w/o transporting energy

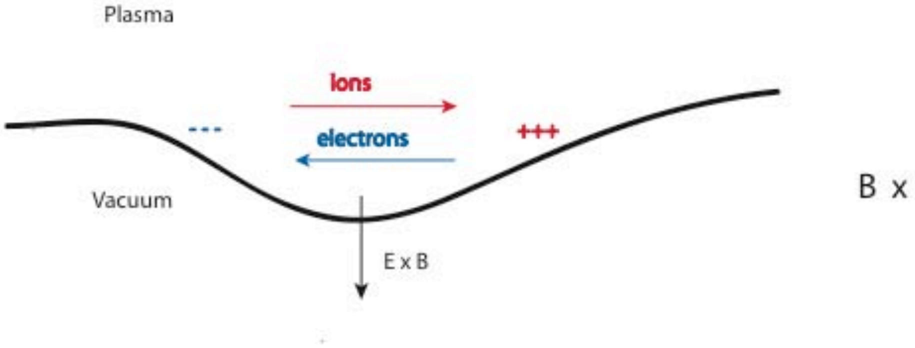
Ref:

1 Garnier et al., in PoP 13 (2006) 056111
2. Simakovet al.,PoP 9, 02,201
3. Simakov et al PoP 9, (02),4985
4. Pastukhov et al, Plas Phys Rep, 27, 01, 907

Dipole Stability Results from Compressibility

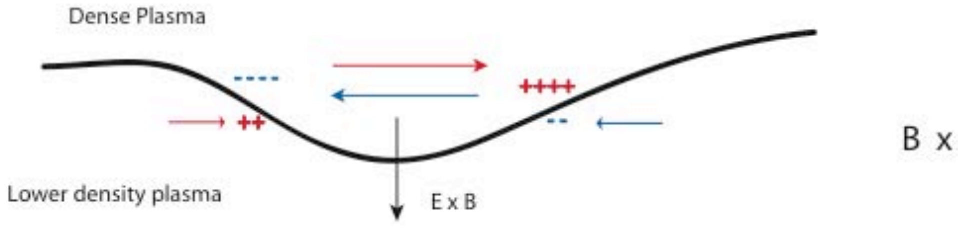
- **No compressibility:**

“bad” κ & ∇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**

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



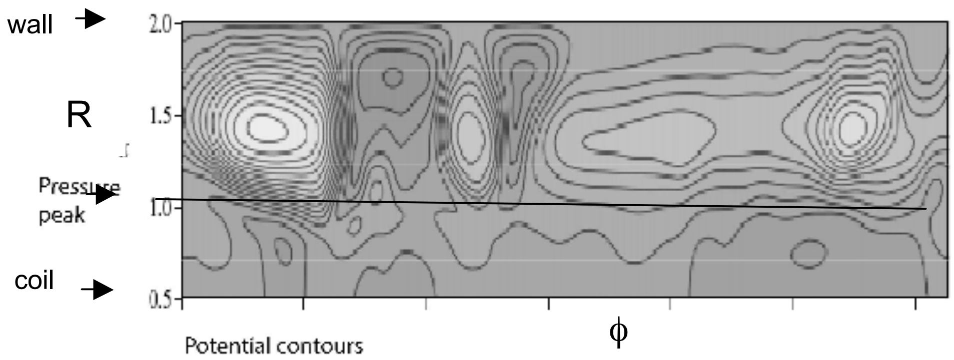
In bad curvature pressure gradient is limited to

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

Convective Cell Formation (Cylindrical 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^{γ}=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



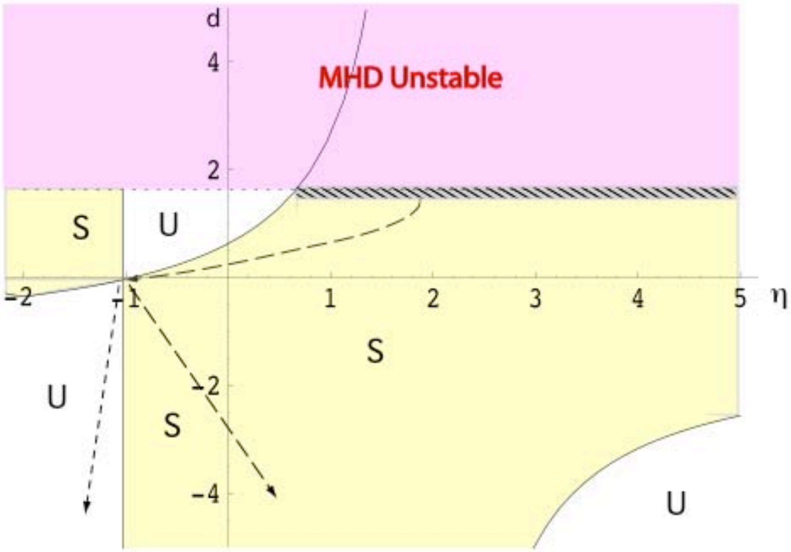
Reduced MHD: Pastukhov, Chudin, Pl Physics 27 (2001) 907.

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

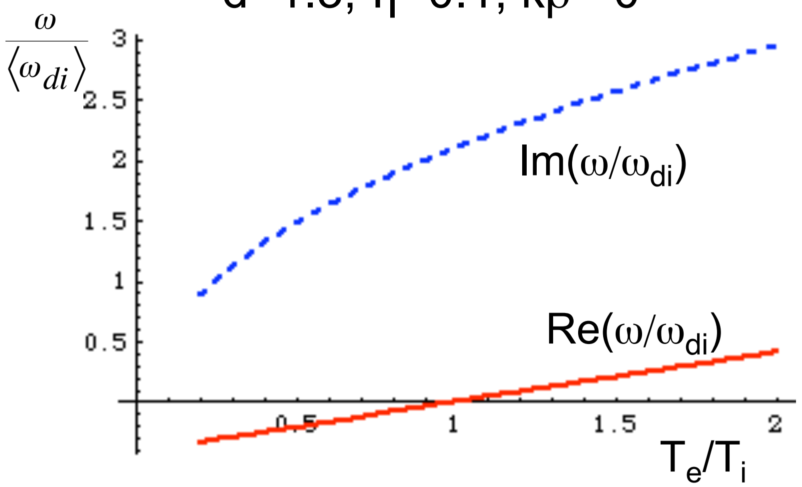
Entropy Mode

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

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



d=1.3, η=0.1, kρ= 0



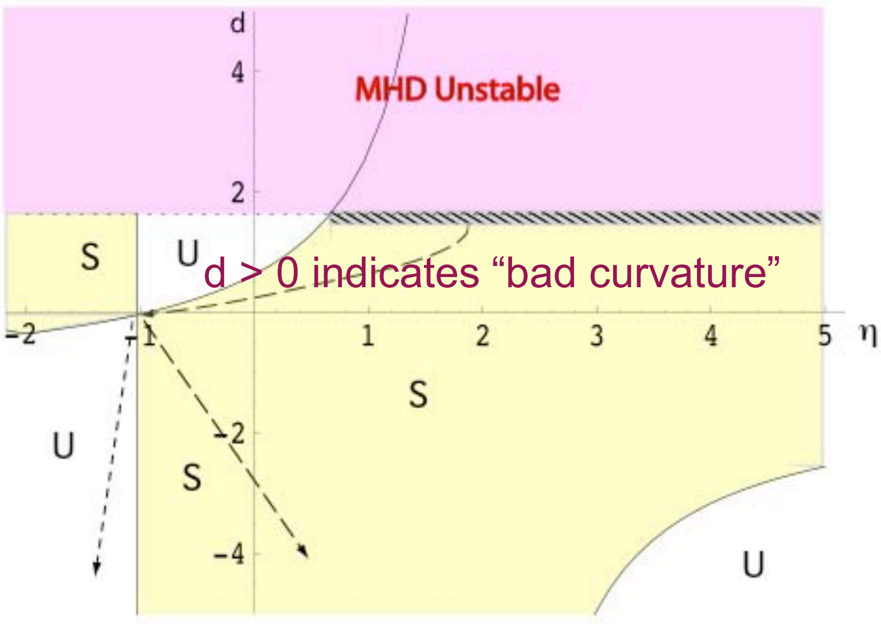
Real frequency is introduced for $T_e \neq T_i$

Drift frequency modes, Entropy mode

- **Entropy mode [1]**
  - **Plasma beyond pressure peak stable for** $\eta > 2/3$
  - **Frequency** $\omega \sim \omega_* \sim \omega_d$

  ω **increases with** ∇n_e **and** T_b
  - **Instability will move plasma towards** $d=5/3$, $\eta=2/3$.

  i.e. tends to steepen ∇n_e
- **Stability in good curvature region depends on sign of** ∇n_e
- **Mode appears at both high and low collisionality [2]**
- **Electrostatic "entropy" mode persists at high** β [3]
- **Non-Linear GS2 simulations [Ref. 4]**



d > 0 indicates "bad curvature"

$$\eta = d\ln T / d\ln n_e$$

$$d = -d\ln p / d\ln V = \omega_{*i}(1+\eta)/\overline{\omega_d}$$

$$V = \oint dl/B$$

Some references:

1. Kesner, PoP 7, (2000) 3837.
2. Kesner, Hastie, Phys Plasma 9, (2002), 4414
3. Simakov, Catto et al, PoP 9, (2002), 201
4. Ricci, Rogers et al., PRL 97, (2006) 245001.

Non-linear simulations of entropy mode (Ricci et al.[1])

- Zonal flows limit transport

- Increasing collisionality (a⇨ b) degrades zonal flows
- Increasing ∇n_e (a⇨c) degrades zonal flows.

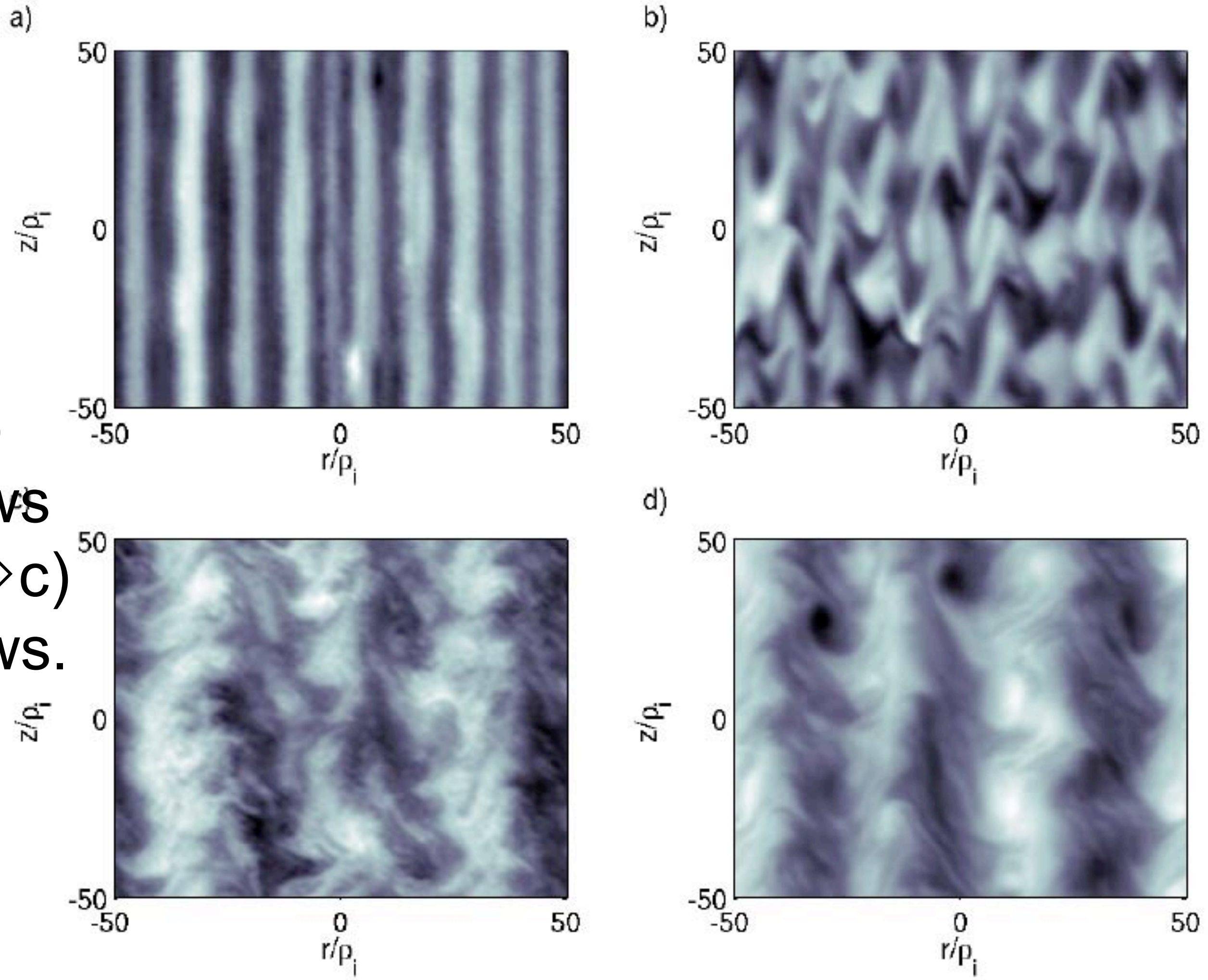


FIG. 4: ϕ at (a) $L_n/R = 1$, $\nu = 0$; (b) $L_n/R = 1$, $\nu = 0.01$; (c) $L_n/R = 0.5$, $\nu = 0$; (d) $L_n/R = 0.5$, $\nu = 0.01$.

1. Ricci, Rogers, Dorland, PRL 97 (2005) 245001.

Stationary density and pressure profiles can form

- MHD driven by high pressure gradients leads non-linearly to large scale convection and flux tube mixing
  - Cylindrical plasma simulations of Pastukhov
  - NIMROD simulations are in progress
- Pressure profile results in pV^{γ}~constant.
- Flux tube mixing will cause n_eV~constant (equal number of particles/flux tube)
  - Non-linear stationary state ref: Kouznetsov, Freidberg,

"Natural" (peaked) profiles are ideal for power source

- Steep, centrally peaked pressure and density profiles
- High energy confinement with low particle confinement

- This relaxation represents self organization with a conservation of energy and generalized enstrophy

Electrostatic self-organization

- **Self-organization requires 2 conserved quantities**
  - **i.e. RFP self-organization conserves energy and helicity**
- **For interchanges with closed field lines conserve energy and enstrophy**
- **With closed field lines define a generalized enstrophy,** Ω^2 **with** $\Omega = \nabla \times v + eB/m_i$

  Ref: Hasegawa, Adv in Phys <u>34</u>, (85) 1, Hasegawa, Mima, PF <u>21</u>,(78) 87.
- **Obtain inverse cascade for one quantity (that appears to reduce entropy) and forward cascade on second quantity**
- **For dipole, inverse cascade leads to large scale convective cells which redistribute pressure and density.**
  - **Leads to n_eV=*constant*, pV^γ=*constant*,** $\mathbf{V} = \oint \mathbf{dl/B}$

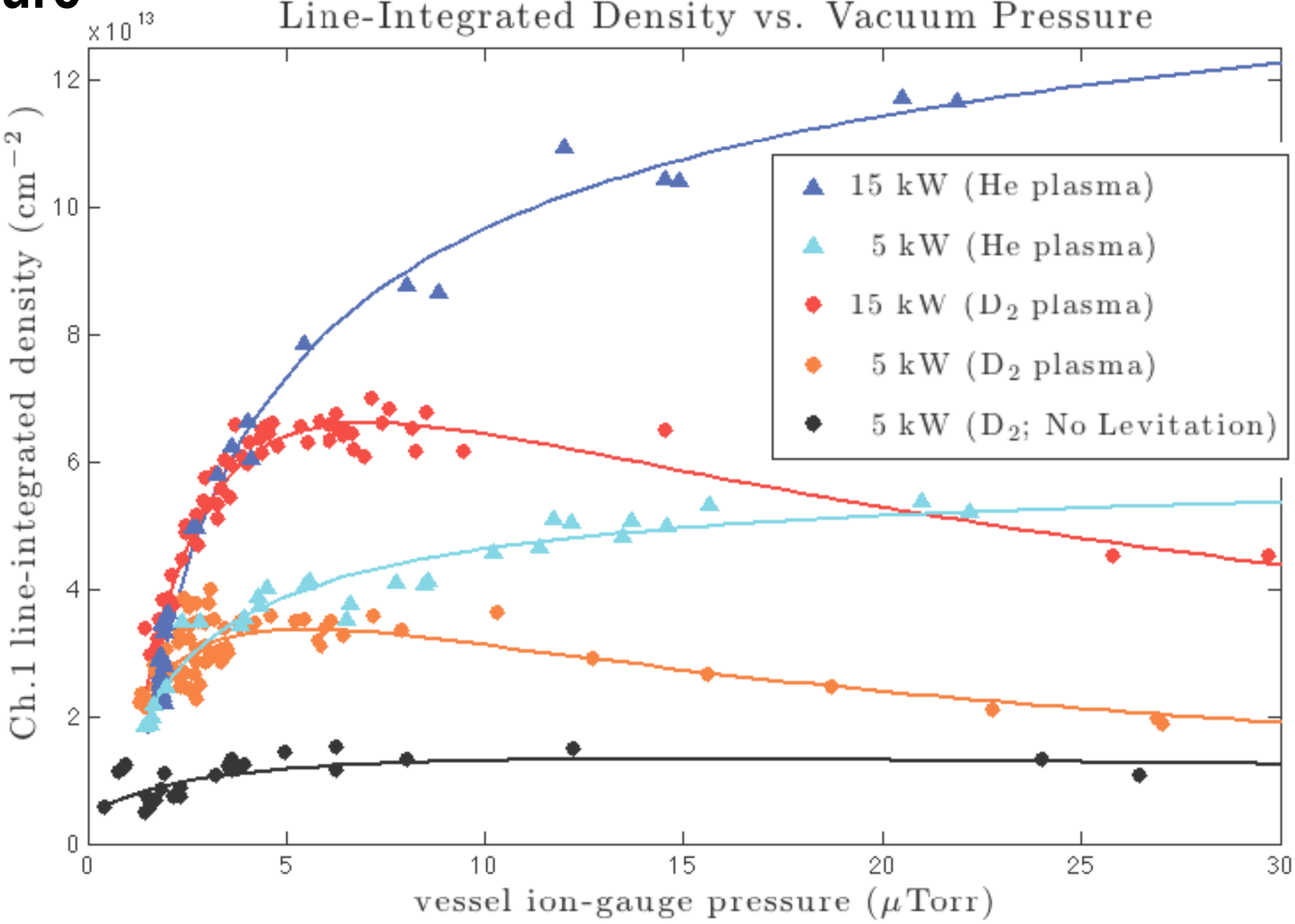
In LDX ECH creates two electron species

$n_e = n_{eb} + n_{eh}, \; n_{eb} >> n_{eh}$

- Hot electron species: E_{eh}> 50KeV
  - Hot electron interchange mode: f ~ 1-100 MHz
    - Free energy of hot electron density gradient
  - Loss cone modes: unstable whistler modes: f >2 GHz
    - Hot electron loss cone and anisotropy
- Background plasma: Te(edge)~20 eV
  - Drift frequency (entropy) modes: f~0.5-5 KHz
    - Background plasma density and temperature gradients
- Can modify MHD leading to hot electron interchange (HEI) instability

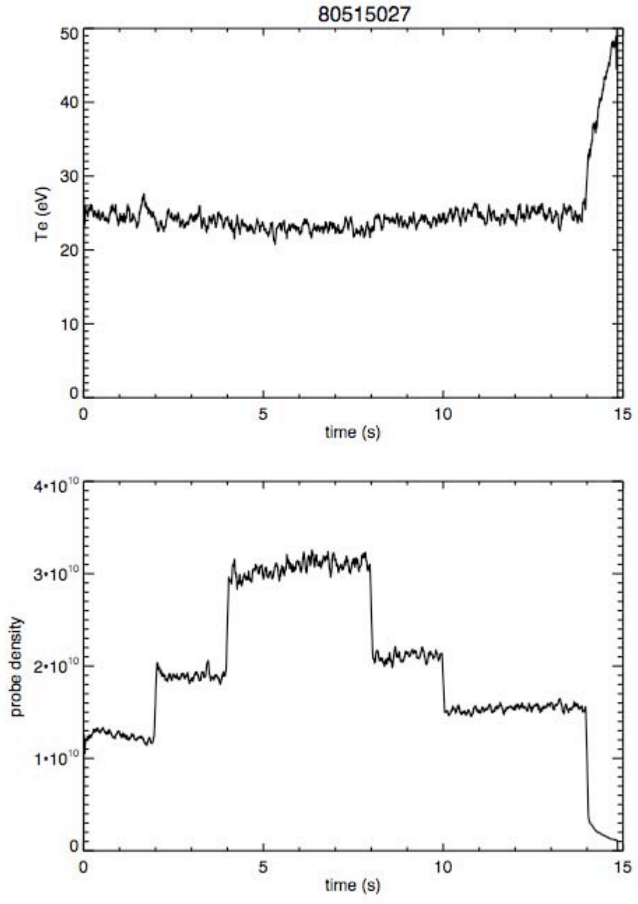
LDX has four primary experimental "knobs"

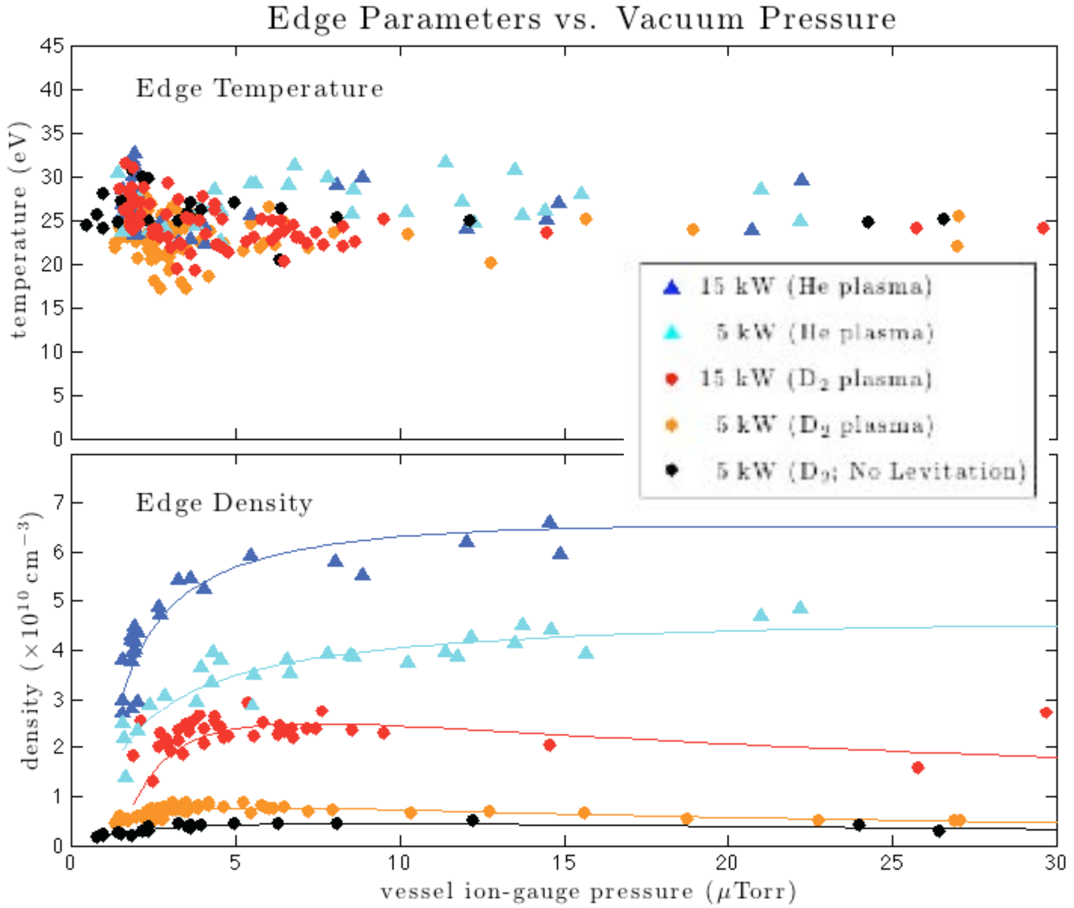
- **Levitation vs supported**
- **Gas pressure**
- **RF Power**
- **Species**



Langmuir probe can diagnose the plasma edge

- **Edge is typically T_e~20-30eV**
- **n_{edge}/n_{max}<<1**
- **Edge temperature is not dependent on heating power**
- **In probe scans of outer 20 cm T_e~constant and n_e rises moving inwards.**





Dipole edge operates as a low-pressure plasma source coupled to amplifier with “natural” profiles

- Outside the separatrix plasma flows into wall. From the power balance $n_e \approx \frac{P_{tot}}{n_e c_s A_{eff} \varepsilon}$ with ε the energy lost per ion lost.

  P_{tot} is total power entering SOL. SOL width is unknown

  ➢ T_e is obtained from continuity ⇨ $\frac{K_{iZ}(T_e)}{c_s(T_e)} = \frac{1}{n_0 D}$

  K_{iz} is electron-neutral ionization rate

  ➢ Edge density increases with heating power
- Within core flux-mixing region $n_e V = constant$

  and $pV^{\gamma} = constant$, i.e $(\therefore\ n_e \propto R^{-4.5})$ $(Te \propto R^{-8/3})$
- Thus we expect peaked density and temperature
- Core determined by edge plasma and size of

  Region in which flux-tube-mixing is dominant

Plasma Source model

- Data indicates increasing core and edge density with increasing power
  - Higher-Z (He) has decreased sonic speed ⇨ increased core and edge density
  - However increase in density > Sqrt[m_{He}/m_D]
- Extent of mixing region increases with RF power
  - Extent can be estimated from density measurements
- We do not (yet) measure pressure or temperature.
  - Can estimate T_e from stationary pressure assumption
- Unknowns:
  - SOL width comes A_{eff} in power balance

Extent of mixing region increases with power

- Mixing region defined by high ∇n
- More power ⇨ expanded mixing region
- Density higher for Helium than for D_2

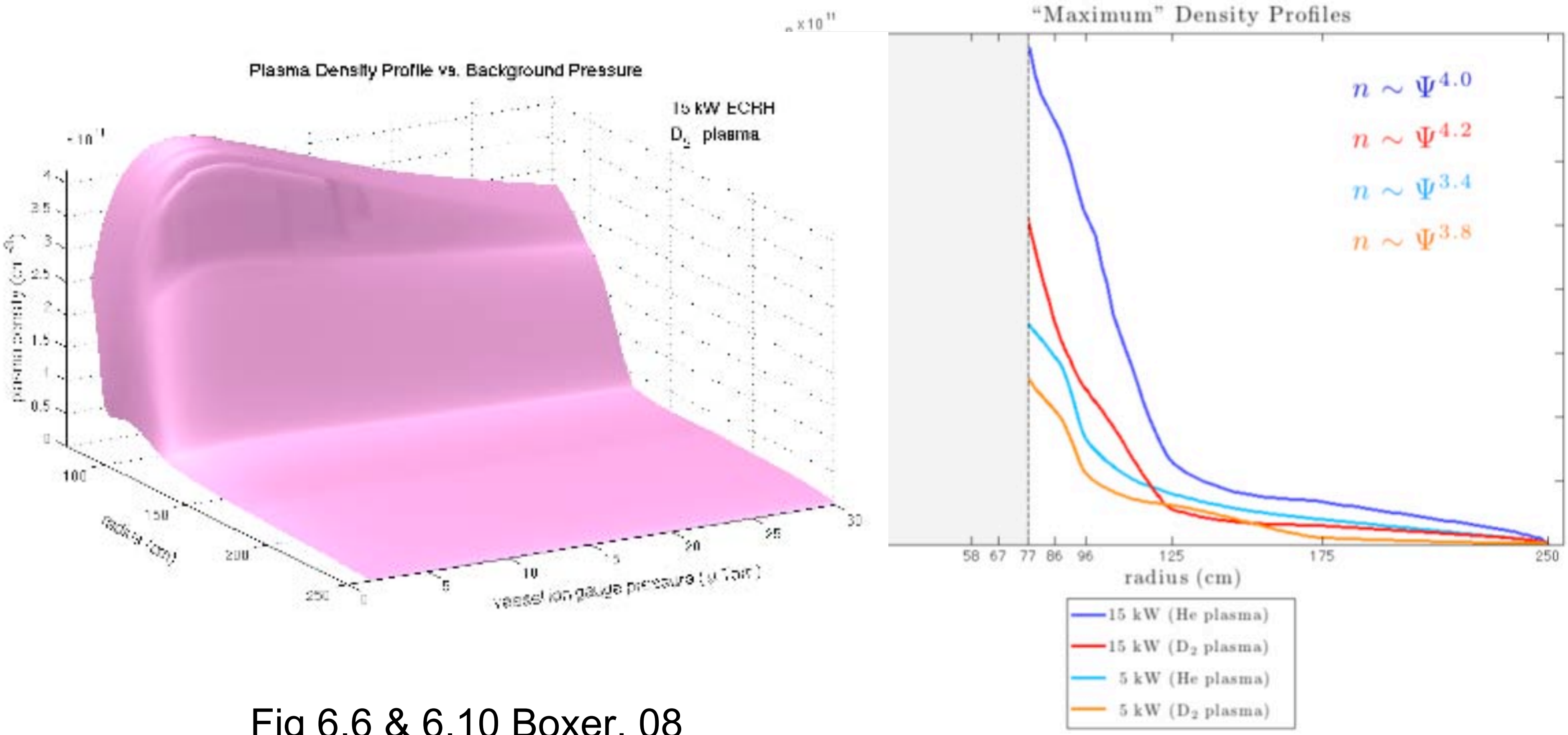


Fig 6.6 & 6.10 Boxer, 08

Energy confinement

- **Typically with P_{RF}=15 kW, n_{emax}(R=0.78m)~5e17 m^{-3} and T_{e_edge}~20 eV.**
- **Flux-tube mixing region extends out to R~1.25 m.**
  - **V(1.25)/V(.78)~8.5 with** $V = \oint dl/B$
  - **For constant pV^{γ}, T_{max}~ $(V(1.25)/V(.78))^{2/3}$~90 eV & p_{max}~7 Pa**
  - **Stored energy W~110 J ⇨ τ_E~7 ms**
- **Flux-tube mixing region extends out to separatrix.**
  - **V(1.75)/V(.78)~59**
  - **T_{max}~301 eV & p_{max}~7 Pa**
  - **W~407 J ⇨ τ_E~27 ms**
- **As heating power increases the mixing region expands and stored energy will increase.**

Quantify “natural” profiles

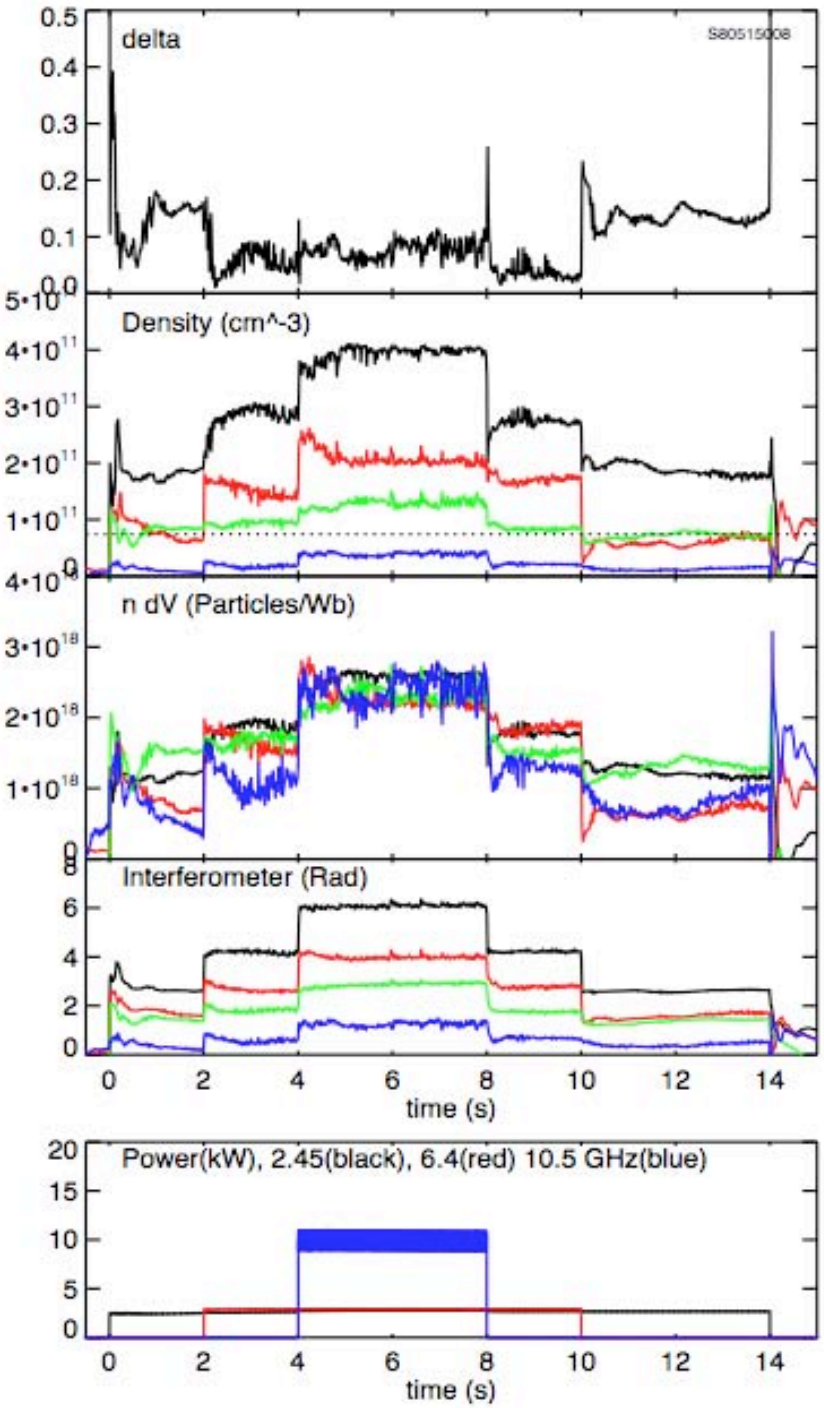
For levitation radial transport creates stationary density profile

- Compare ratio of measured chords with ideal ratio for ndV $(n_e V = constant)$ profiles

$$\Delta \equiv (1/3)\sum_{i=2}^{4}\left(\frac{\langle nl\rangle_i}{\langle nl\rangle_1} - \frac{\langle nl\rangle_i^{ndV}}{\langle nl\rangle_1} \right)^2$$

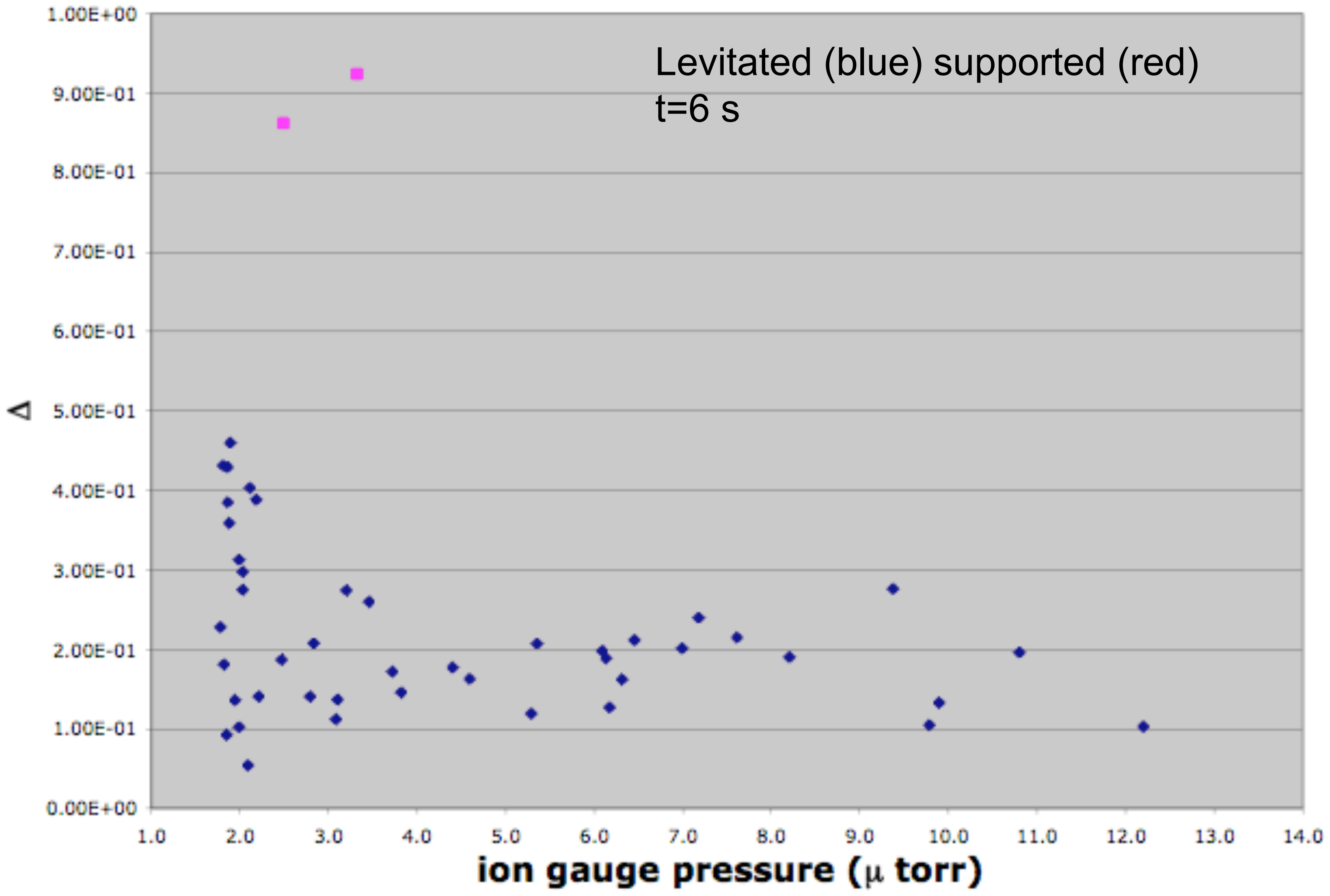
Δ=0 for stationary state

- Power turned on sequentially
- density & ndV shown at interferometer tangency points, R=77, 86, 96, 125 m
- For sufficient power Δ < 0.1



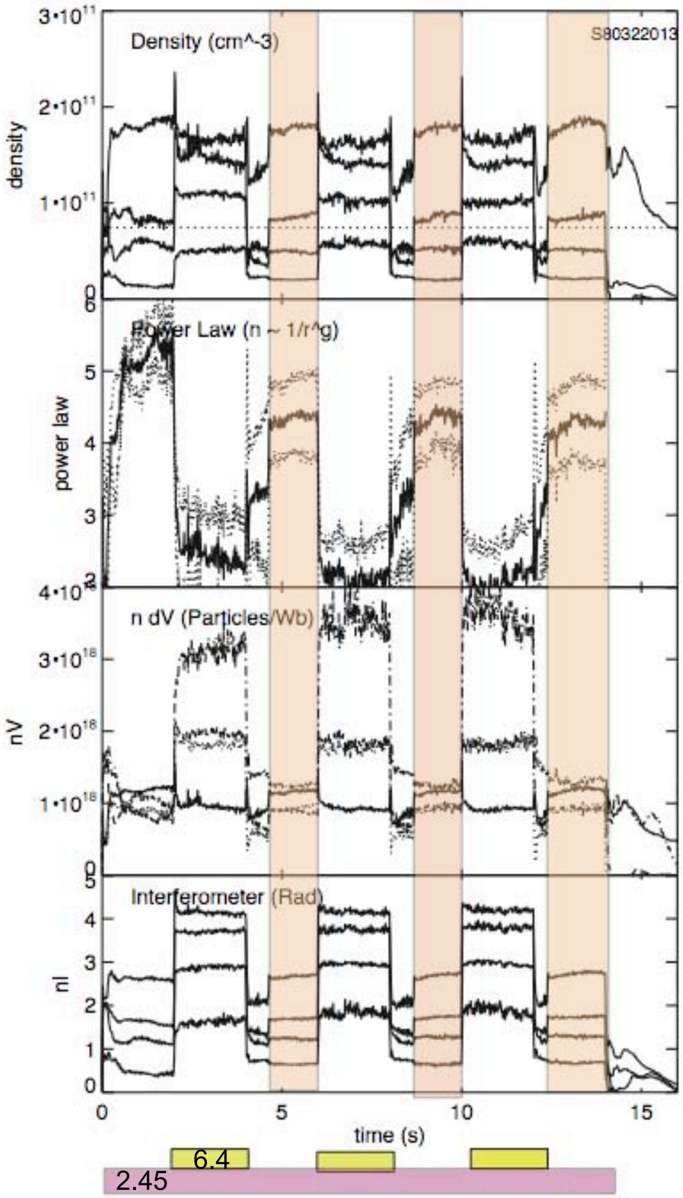
Pressure scan of profile factor, Δ from 5/08

- Tendency to stationary profiles seen in levitated discharges



A fast density re organization sometimes observed

- **80322013: Heat with 2.45 GHz (red) and pulse 6.4 (yellow).**
- Interferometer: density drops after 6.4 turn-off and then spontaneously peaks (pink)
  - Relaxation may reflect stabilization of hot electron interchange mode
- Density assumes nV~constant profile
  - Power law $n \sim R^{4.5}$ close to ideal $R^{4.7}$
- Density relaxation implies pressure relaxation



Summary - Levitated Plasma Results

- Levitated operation achieved regularly - Cryostat operates better with levitation (>2 hr float time).
- Substantial improvement in particle confinement: 3-5 times the density & 5-10 times τ_p
- Doubling of stored energy observed
- Substantial improvement in stability of hot species: No HEI at 5 kW heating level. Some HEI @ 15 kW level (with 10.5 GHz heating).
- Levitation observed to lead to “natural” profiles in density and presumably in pressure

- When non-natural profiles are set up a fast relaxation is observed, (similar to self-organization).
- For 2.45 GHz heating density is observed to exceed the cutoff which may reflect inward convection.