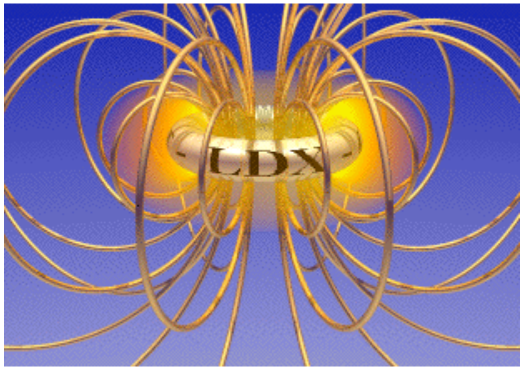

Low Frequency Fluctuations in the Levitated Dipole Experiment

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Poster PP8.00146
Presented at the DPP Meeting, Orlando
Novmber 14, 2007

Plasma that is heated by ECRH can be subject to instability that feeds on the free energy of either the hot component or the thermal plasma component. 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 and drift frequency (entropy mode) fluctuations. In experiments in LDX (in the supported mode of operation) we create a two-component plasma in which a thermal species contains most of the density and an energetic electron species contains most of the plasma stored energy. In addition to high frequency fluctuations reported elsewhere [Garnier et al, PoP (2006) 56001] we observe low frequency fluctuations in the kHz range that presumably are driven by the thermal species. The fluctuations become undetectable during strong edge fueling when the density profile broadens. During levitated operation lower fueling rates are required and we will compare the low frequency activity between the levitated and supported modes of operation.

Outline of Poster

- Introduction to LDX
- Observation of low frequency fluctuations
  - Indicative of background plasma. Transport?
  - Theory:
    - Entropy (drift frequency) mode
    - Rotating MHD driven convective cells
  - Compare supported (old) and floating (new)
- Influence of gas puffing
- Conclusions and future plans

Tokamak and Dipole

Tokamak

- "Hard" MHD limit set by ballooning and kink
  - Violation⇨disruption

- Turbulent transport
  - η_i for $(\eta > \eta_{crit})$ and TEM modes

η_i stable in reverse shear mode but ash/impurities accumulate.

Levitated Dipole

- "Soft" MHD limit set by interchange
  - Violation⇨Convective cells ⇨ stiff $p(\psi)$.

(Convective cells rapidly convect particles but not energy).

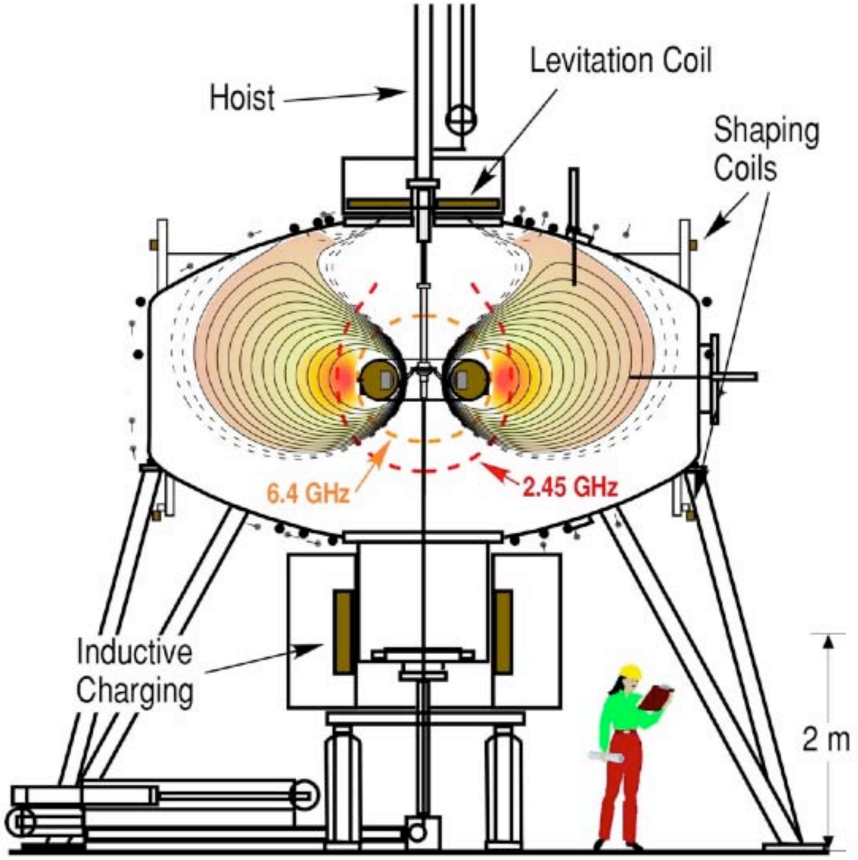
- Turbulent transport
  - Entropy mode for $\eta < \eta_{crit}$

We observe low frequency fluctuation in both supported and floating cofigurations

LDX cross section/operation

F-coil can be supported or floating

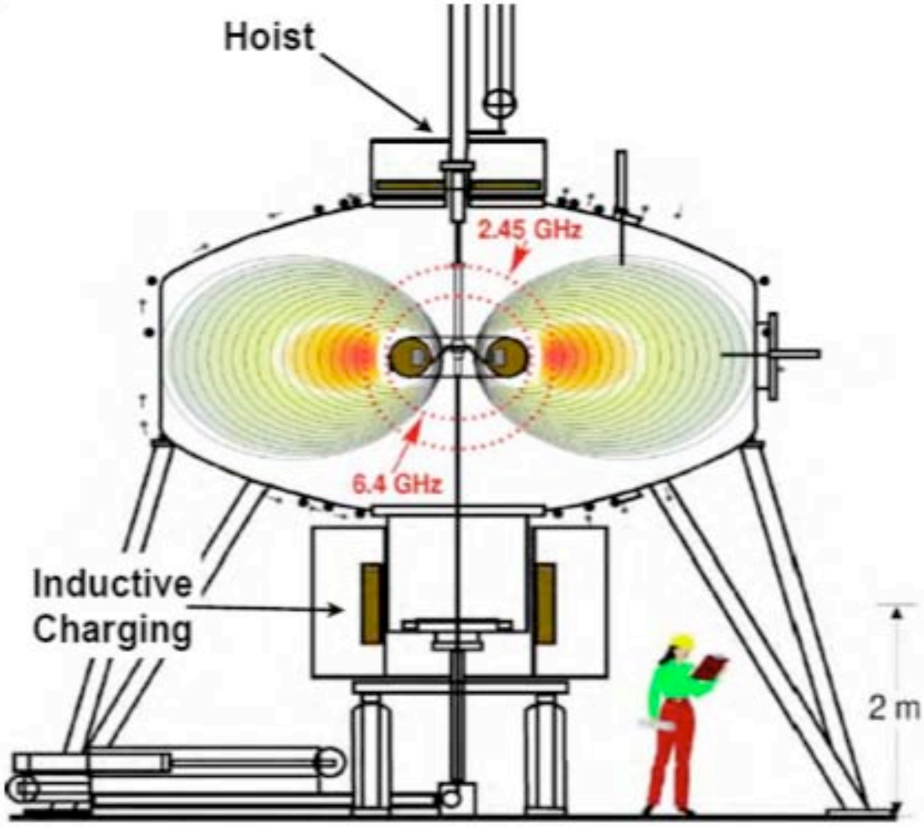
- Charging coil excited with f-coil in charging station
- Liquid He cools f-coil
- Lift f-coil into position
- For floating mode energize levitation coil and feedback
  - ➢ lower the launcher
- Add 5 KW of RF at 2.45 and 6.4 GHz
- Run experiment for 75 min
- Lower and discharge F-coil



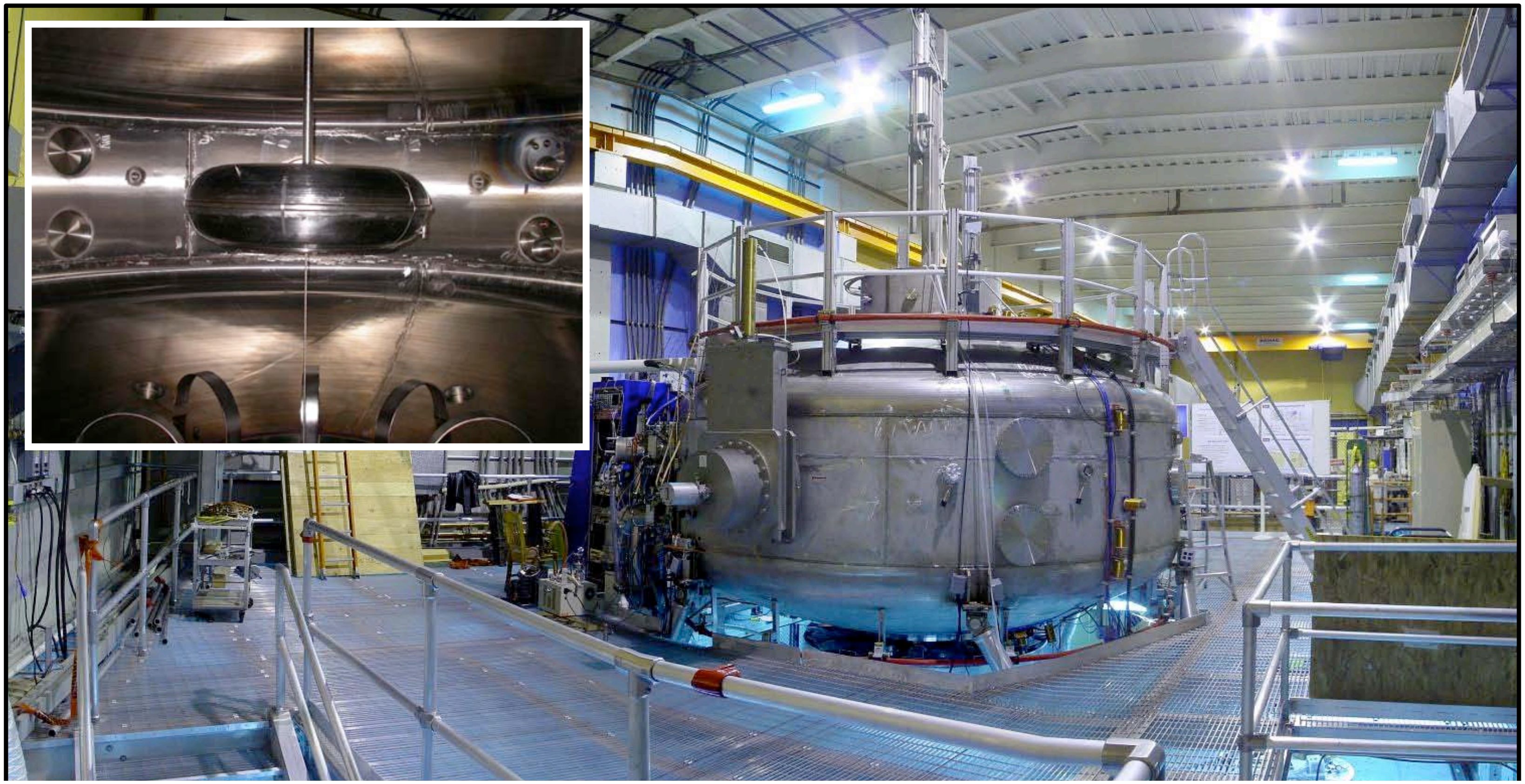
Flux geometry in supported Configuration

Supported Mode

1) Liquid Helium cools F-coil in charging station
2) Inductively charge F-coil (1 MA), C-coil discharges
3) Lift F-coil into position
4) Use ECRH (5 kW); create plasma
5) Run experiments safely for two hours
6) Lower F-coil back to re-charge or discharge into charging station



The Levitated Dipole Experiment (LDX)

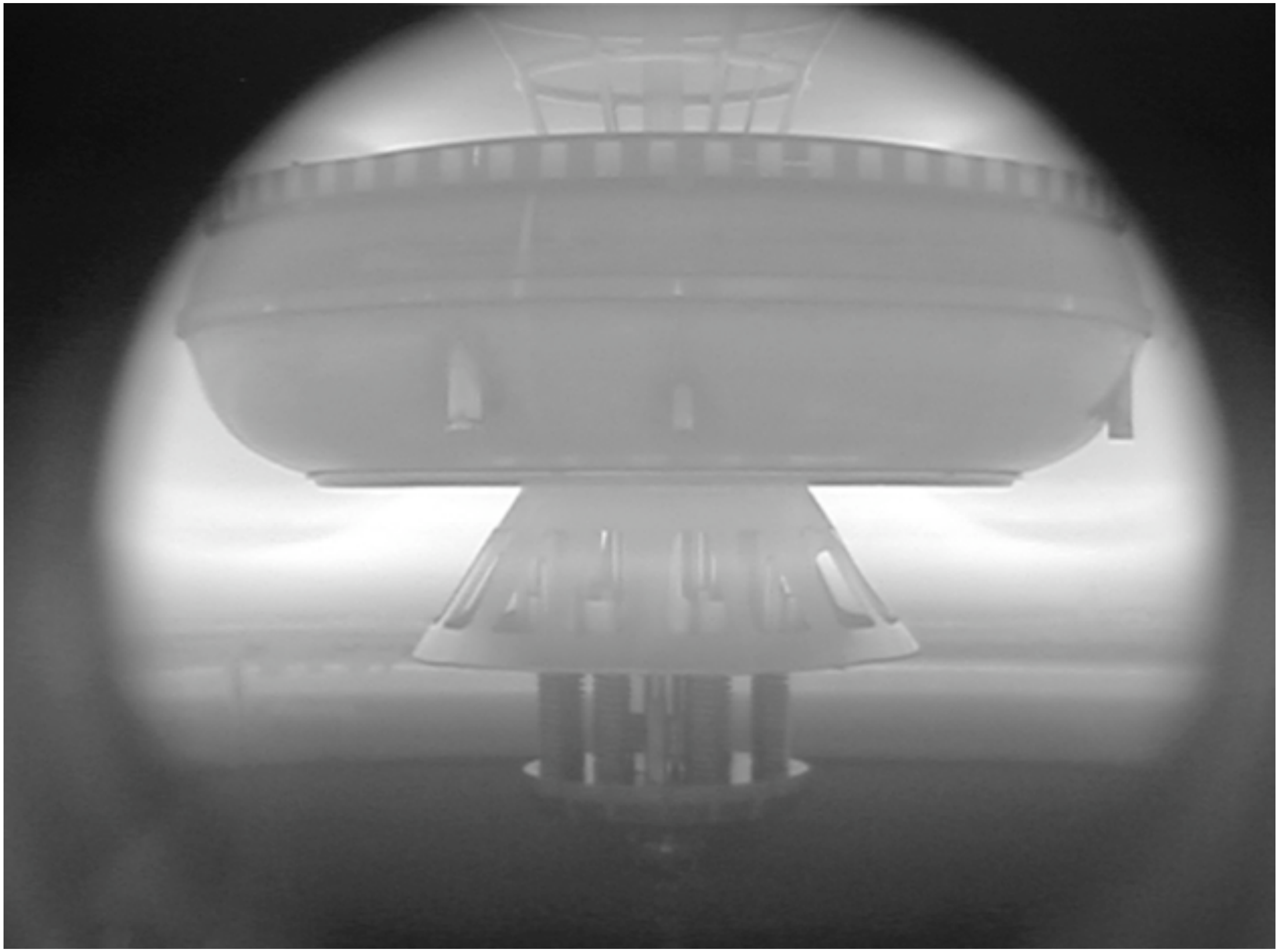


LDX utilizes 2 operating superconducting magnets

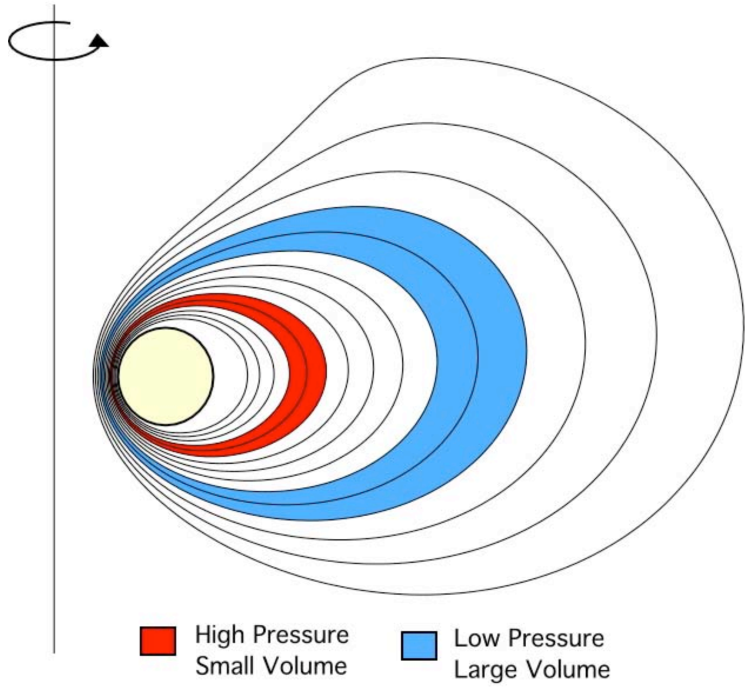
- ➢ Floating coil: (shown) Nb^3Sn (1-1.5 MA)
- ➢ Charging coil: NbTi (12 MJ, B_{max}=5.6T, 4.5K)
- ➢ Levitation coil: Cu coil

Ref: Garnier et al., in Fusion Engineering and Design **18** (2006), 2371.

First levitated data on 11/8/07



Dipole Plasma Confinement



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.

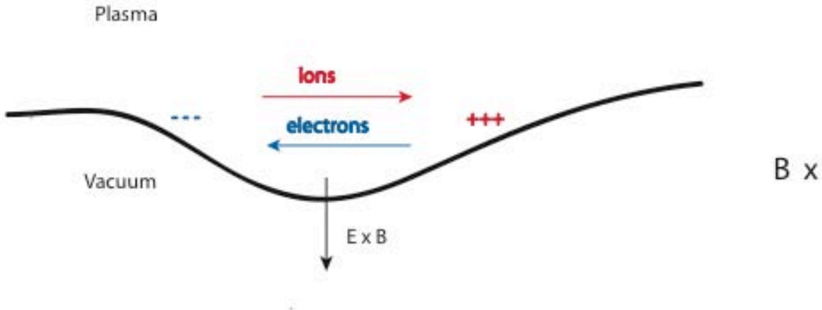
- Toroidal confinement without toroidal field
  - Stabilized by plasma compressibility
  - Shear free
- Poloidal field provided by internal coil
  - Steady-state w/o current drive
  - $J_{||} = 0$ ⇨no kink instability drive
  - No neoclassical effects
  - No TF or interlocking coils
  - ∇p constraint ⇨small plasma in large vacuum vessel
  - Convective flows transport particles w/o energy transport

Dipole Stability Results from Compressibility

- No compressibility:

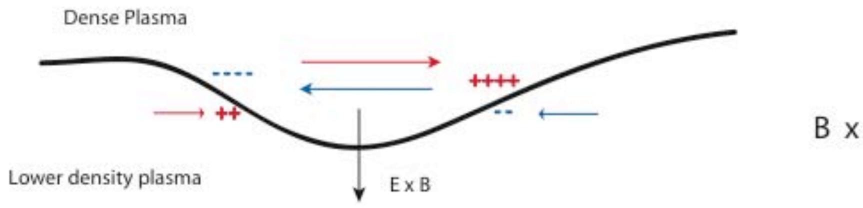
“bad” κ & ∇B drifts causes charge separation ➪

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.

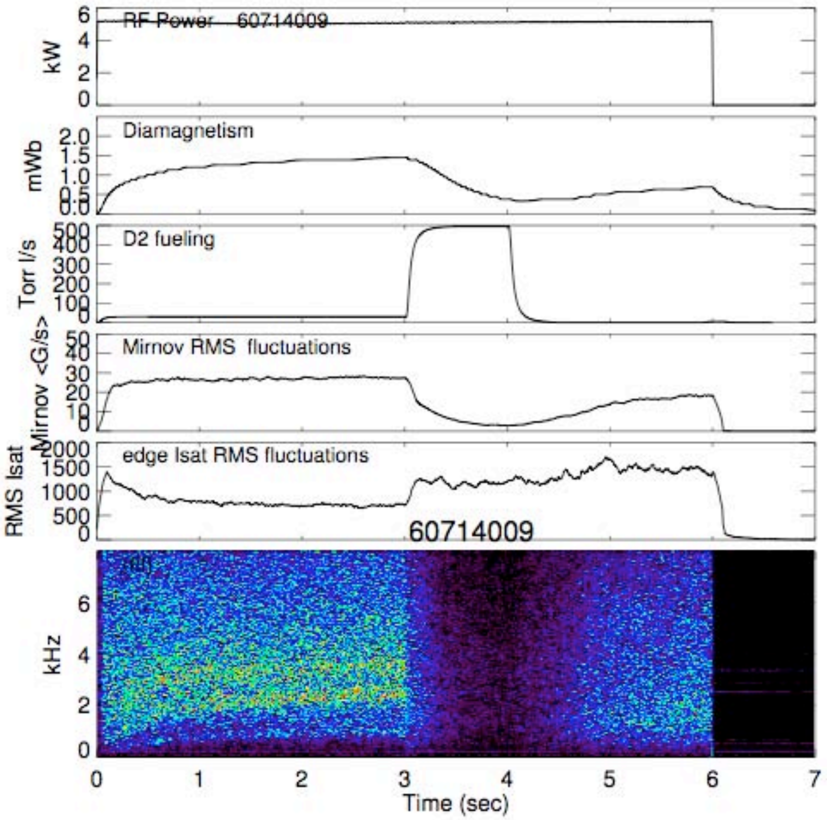


In bad curvature pressure gradient is limited to $-\frac{d\ln p}{d\ln V} < \gamma$ $\quad V = \oint dl/B$

11/9/07

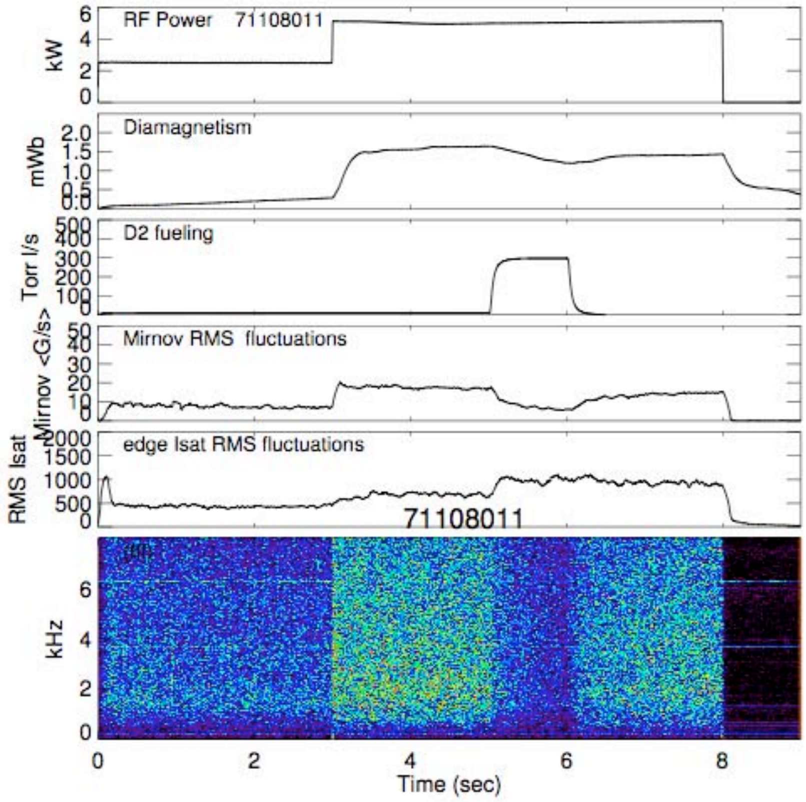
Supported mode, discharge with gas puff

- Plasma diagnostics include diamagnetic loops, Mirnov coils, probes
- Heating with 5 kW at 2.45 and 6.4 GHz.
- High β maintained in steady state
- Quasi coherent mode observed
- Gas puff:
  - Mirnov and visible signal falls
    - Core mode stabilized?
  - Edge fluctuations rise
    - Transports plasma inwards?



Floating mode, discharge with gas puff

- Plasma diagnostics include diamagnetic loops, Mirnov coils, probes
- Heating with 5 kW at 2.45 and 6.4 GHz.
- High β maintained in steady state
- Broadband turbulence develops. (No quasi coherent)
- Low gas fueling and smaller puff
- Gas puff:
  - Mirnov and visible signal falls
    - Core node stabilized?
  - Edge fluctuations rise
    - Density transported inwards?



Levitation modifies plasma profiles and affects stability

- During levitation:
  - Hot electrons fill out flux tube (pitch-angle scatter) and diffuse radially
  - Background plasma will spread radially
- Levitated plasmas tend to have flat background $n_e(\psi)$ as seen in interferometer array [PP8.00147, Boxer et al.]
- The pressure profile (hot electrons) remains peaked near heating resonance (seen in diamagnetic loops)
- Therefore $\eta_e = \nabla \ln T_e / \nabla \ln n_e$ gets large
- This will tend to stabilize entropy mode (stable for $\eta_e > 2/3$)

Theory of Entropy Mode

Linear properties

- Drift frequency: $\omega \sim \omega_* \sim \omega_d$
  - Real frequency for $T_e \neq T_i$
  - Flute-like along field
  - Max growth rate for $k_\perp \rho_i \approx 1$
  - Weakly effected by β
  - Present at all collisionalities
- Unstable when $\eta < \eta_{crit}(\nabla p)$

Non-linear properties

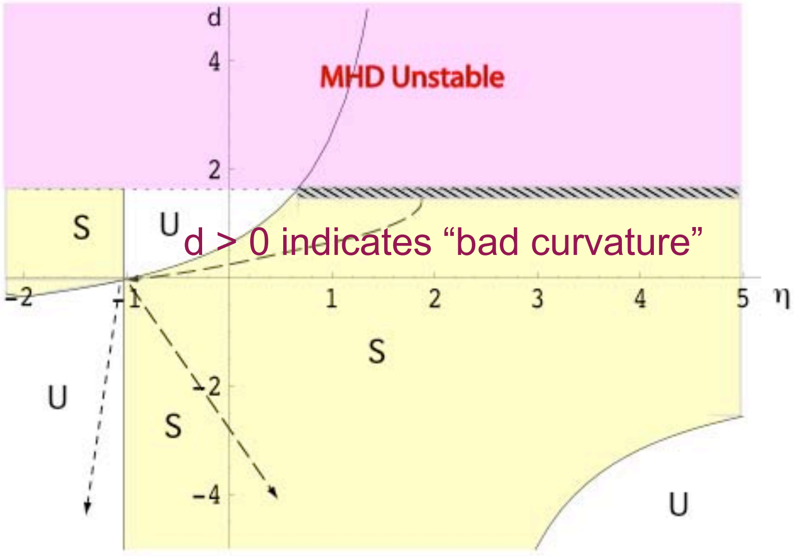
- Turbulence requires primary (linear) instability
- Transport limited by zonal flows
  - Zonal flows limited by Kelvin-Helmholtz (KH)
  - Compressibility limits onset of KH
  - Collisionality damps zonal flows
- Becomes MHD-like near MHD marginality
  - Non-linear MHD ⇨large scale convection

Plasma can be unstable to drift frequency mode

- Entropy mode properties [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 relax plasma towards d=5/3, η=2/3.

  i.e. it 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].
- Linear theory not always relevant to real plasmas



d > 0 indicates "bad curvature"

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

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

$$V = \oint dl / B$$

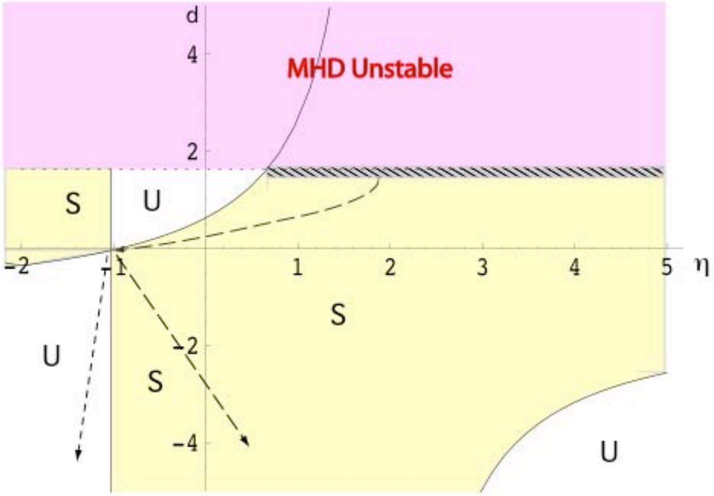
Some references on linear properties:

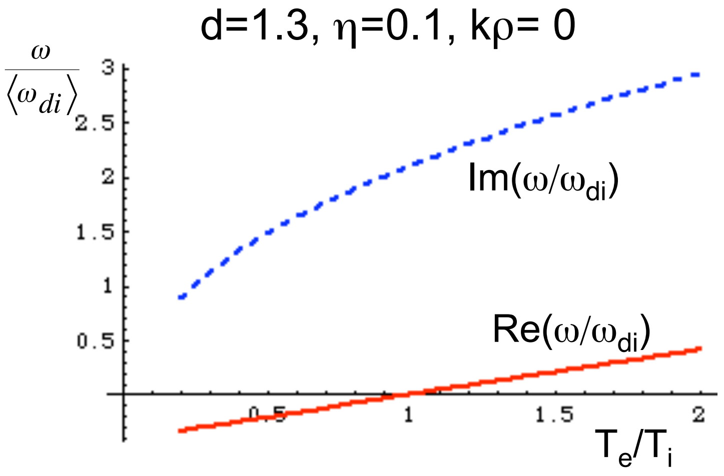
1. Kesner, PoP **7**, (2000) 3837.
2. Kesner, Hastie, Phys Plasma **9**, (2002), 4414
3. Simakov, Catto et al, PoP **9**, (2002), 201

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 $T_e \neq T_i$

Non-linear entropy mode simulations

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

- Hard core z-pinch geometry:
  - Low β, vary density gradient and collisionality.
  - No shear, but compressibility is stabilizing
  - Observe formation of zonal flows that damp transport
  - Zonal flows reduced by collisionality and can become unstable to kelvin-Helmholtz
  - As density gradient increases to approach MHD critical pressure gradient, can get large transport.
  - Stable when primary (entropy) mode stable.
- At low collisionality zonal flows can limit transport.
- After gas puff reduced density gradient (high η) can stabilize primary instability

As we approach MHD limit (L_n/R~0.5) zonal flows are damped, for all collisionality (from Ricci, Rogers, Dorland)

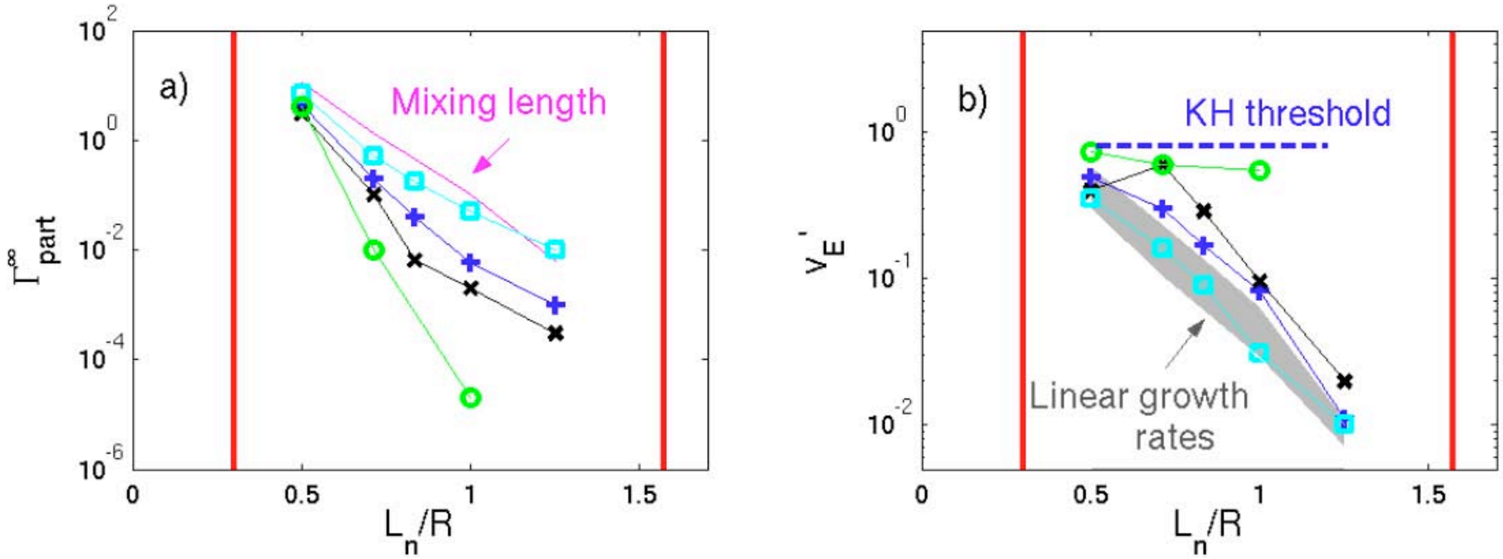


FIG. 3: (a) Γ^{∞}_{part} vs L_n/R; (b) zonal flow shearing rates V'. Light-blue squares are $\nu = 0.01$, dark blue '+' are $\nu = 0.01$, black 'x' are $\nu = 0.001$, green 'o' are $\nu = 0$. The vertical lines delimit the entropy mode instability region.

- Note: Rogers formulates particle and not energy transport.
- In MHD limit, in the absence of zonal flows, expect convective cells.

Increasing collisionality (a->b) or increasing gradient (a->c) degrades zonal flows (from Ricci, Rogers, Dorland)

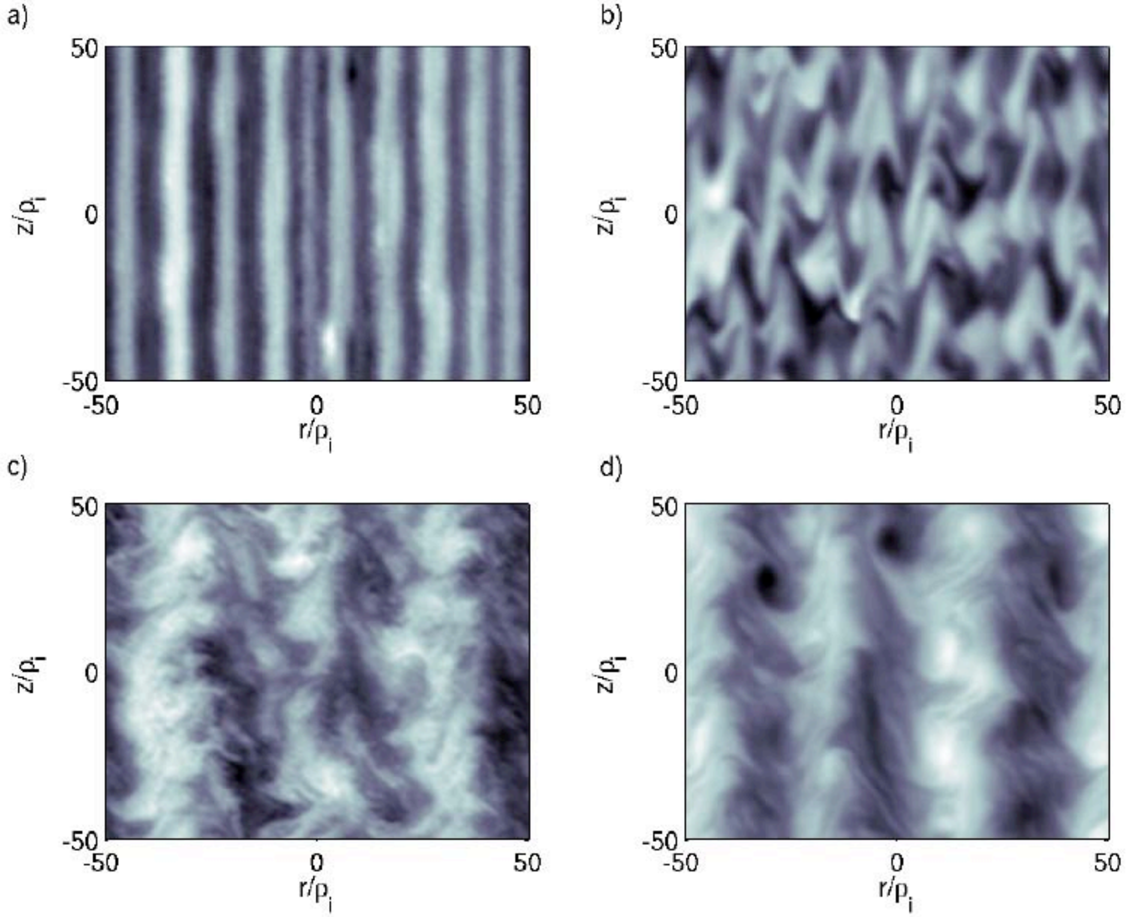
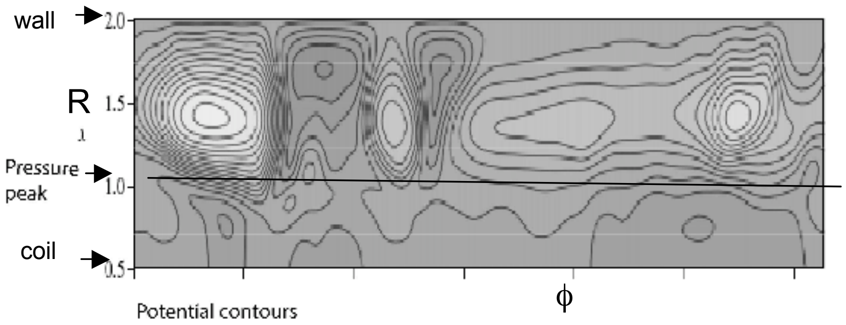


FIG. 4: ϕ at (a) $L_n/R = 1$, $\nu = 0$; (b) $L_n/R = 1$, $\nu = 0.01$; (c) $L_n/R = 0.5$, $\nu = 0$; (d) $L_n/R = 0.5$, $\nu = 0.01$.

Convective cells in dipole ⇨ to stiff $p(\psi)$

- 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 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 get 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, Phys Pl. **10** (2003) 3475.

Observation of quasi-coherent mode (in supported operation)

- Under good vacuum conditions $p_0 < 10^{-6}$, quasi-coherent low frequency activity observed: $f < 10$ kHz
- Mode seen on Mirnov, photodiodes, interferometer.
- Gas fueling can change frequency or stabilize mode
  - Cutoff fueling ⇨mode frequency rises
  - Sufficient fueling ⇨quasi-coherent mode disappears
    - Gas fueling tends to flatten the density gradient as seen in 60 GHz μ–wave interferometer array.
- Toroidal mode # m=1 (from Mirnov coil array)
- Large radial mode structure (from visible light array)
- In floating operation lower gas level and only broadband turbulence observed

Observations from first levitated plasmas

- Broadband turbulence observed during ECRH heating.
  - No quasi-coherent mode seen.
- Low frequency fluctuations
  - may evolve from entropy mode
  - may indicate rotation of MHD generated convective cells
- Stabilization observed with gas injection
  - Flattening of density gradient can stabilize entropy mode
- In levitated configuration smaller gas puff gives rise to larger density changes and cross field transport is observable.
  - Hope to back out transport coefficients from data
  - Are observed low frequency modes responsible for energy transport?

Conclusions

- Dipole is promising confinement concept: may be steady state, disruption free, high β, low divertor heat load, no interlocking coils.
  - Ideal for advanced fuel fusion.
- ECRF heated plasmas
  - Background plasma provides data for confinement of thermal plasmas. Hot electrons provide “minority heating”.
- Supported experimental campaign began in 2004
  - Plasma loss to supports gives compressibility stabilized mirror machine
- Levitated operation began recently.
  - Quasi-coherent mode not seen