

The LDX Experiment and the Levitated Dipole Approach to Plasma Confinement

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Dipole confinement avoids a toroidal field and the plasma obtains stability from compressibility without the need for shear or good magnetic well. The dipole coil is internal to the plasma and when it is supported, substantial plasma losses result from scrape-off on the supports. By levitating the dipole coil we have been able to evaluate the improvement in confinement and stability that derives from the removal of material supports. Experiments in LDX with a levitated dipole coil began in 2007. Experiments using up to 15 kW of ECRH heating were performed and the results were compared to experiments in which the internal dipole coil was supported. We observed a reduced fueling requirement which indicates improved confinement. ECRH is known to create a hot electron species and a clear improvement of the stability of the hot electron species with respect to the hot electron interchange mode was observed indicating a broadened radial profile of the hot electrons and a higher density of background plasma. We also observe changes in the behavior of low frequency fluctuations. The plasma pressure was power limited.

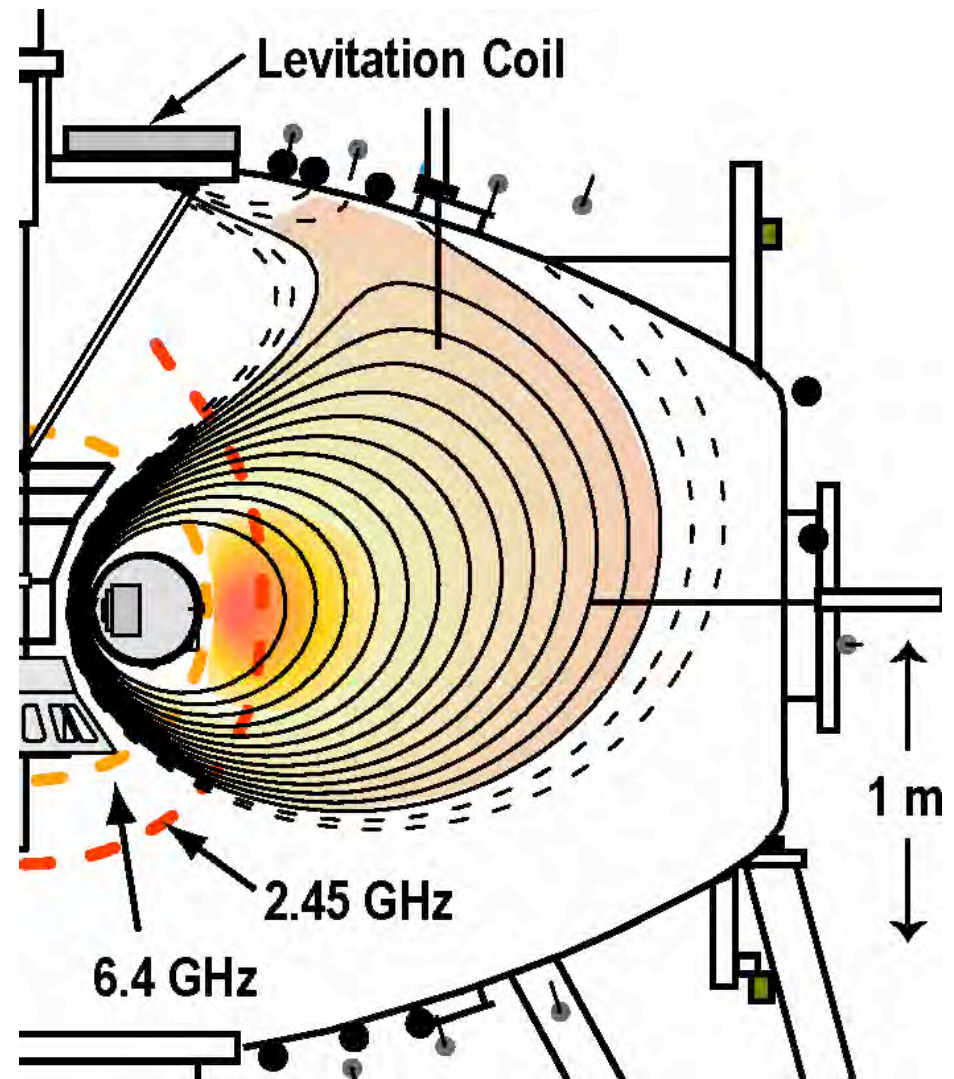
Summary - Dipole perspective

- **Dipole presents interesting 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**
 - **Evaluate stability and β limits**
 - **Investigate formation of peaked (density and pressure) profiles**
 - **Issues around presence of hot species**

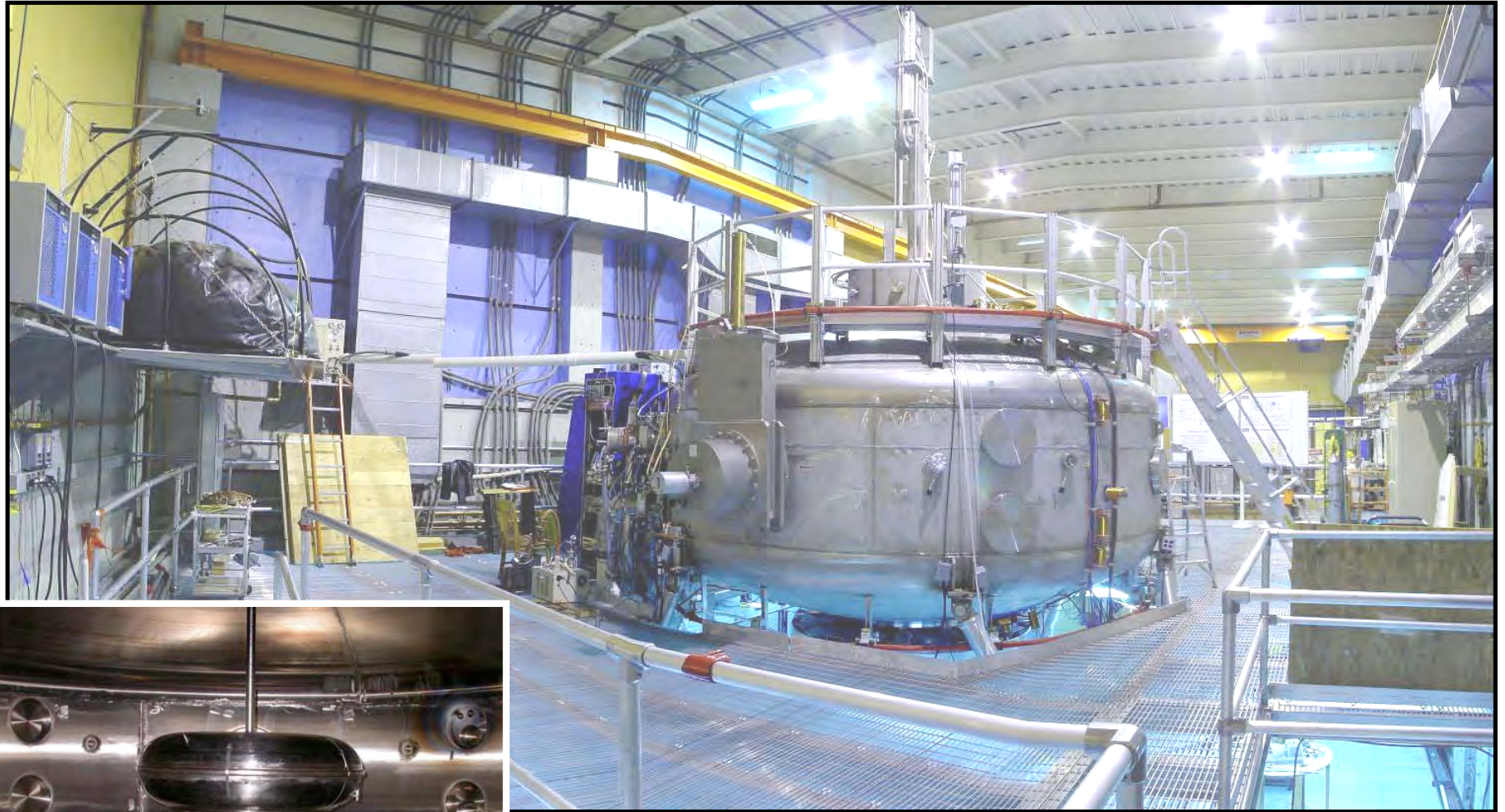
LDX operation

Floating (F-coil) can be supported or floating

- Charging coil excited inductively with F-coil in charging station
 - $I_F > 1.2$ MA
 - Liquid Helium cools F-coil
- F-coil lifted into midplane position
- For floating mode energize levitation coil and apply feedback
- Plasma heated by 15 KW of RF at 2.45, 6.4 & 10.5 GHz
- Run experiment for up to 2.5 hr
- May be re cooled or discharged

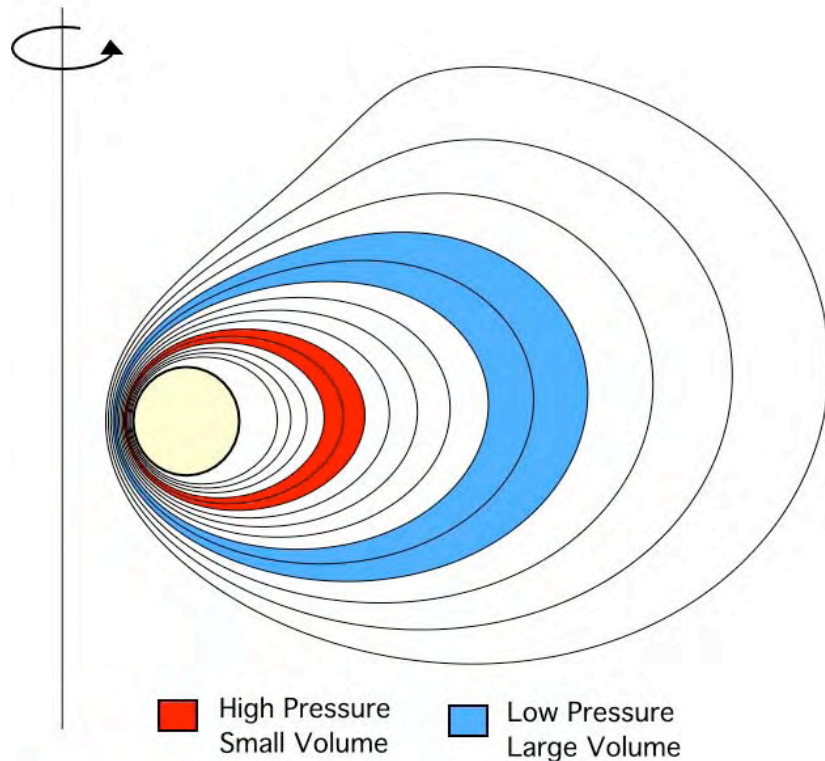


The Levitated Dipole Experiment (LDX)



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

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
 - $J_{\parallel} = 0 \Rightarrow$ no kink instability drive
 - No neoclassical effects
 - No TF or interlocking coils
 - ∇p constraint \Rightarrow small plasma in large vacuum vessel
 - Convective flows transport particles w/o energy transport

If $p_1 V_1^\gamma = p_2 V_2^\gamma$, then interchange does not change pressure profile.

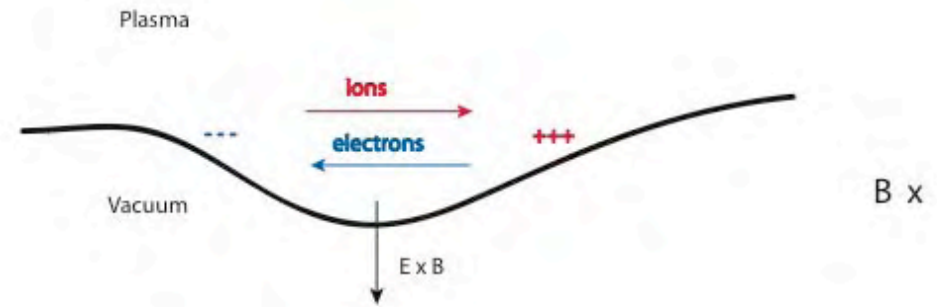
For $\eta = \frac{d \ln T}{d \ln n} = \frac{2}{3}$, density and temperature profiles are also stationary.

Dipole Stability Results from Compressibility

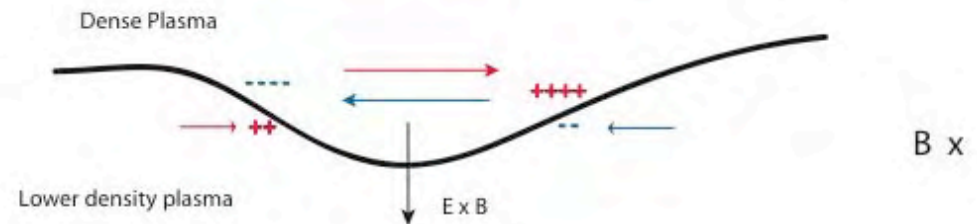
- **No compressibility:**
 “bad” κ & ∇B drifts cause charge separation \Leftrightarrow
 $V_{E \times B}$ increases perturbation
- **With compressibility:** as plasma moves downwards pressure decreases. For critical gradient there is no charge buildup

In bad curvature pressure gradient is limited to

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



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



Some theoretical results: Maxwellian Plasma

Bad Curvature region (between pressure peak & vacuum vessel)

- **MHD: stable to interchange when $\delta(pV^\gamma) > 0$,** $V = \oint dl / B$
 $p_{\text{core}}/p_{\text{edge}} < (V_{\text{edge}}/V_{\text{core}})^\gamma \sim 10^3$: therefore want large vacuum chamber
 - MHD equilibrium from field bending and not grad-B $\Rightarrow \beta \sim 1$
 - Unstable interchange modes evolve into convective cells
- **Ballooning modes are stable when interchange stable**
- **Weak resistive mode at high β ($\gamma \sim \gamma_{\text{res}}$ but no $\gamma \sim \gamma_{\text{res}}^{1/3} \gamma_A^{1/3}$ mode)**
- **Drift frequency modes: electrostatic “entropy” mode**
 - unstable when $\eta < 2/3$
- **Good curvature region (between floating coil and pressure peak)**
 - “entropy” mode can be unstable when $\text{grad}(n_e) < 0$

Collective Modes in a Dipole

- **Hot electron driven modes**
 - Hot electron interchange (HEI): $\omega \sim \omega_{dh}$, $f \sim 1-50$ MHz
Ref: Garnier et al., in PoP 13 (2006) 056111.
 - Whistler (loss cone) modes; $\omega \sim \omega_{ce}$, $f \sim 1-30$ GHz
- **Background plasma**
 - Entropy mode: $\omega \sim \omega_{*b}$, $\omega \sim \omega_{db}$, $f \sim 1-10$ KHz
 - Background MHD: $\gamma \sim \gamma_{MHD-b}$, $f \sim 50-100$ KHz
[Krasheninnikova, Catto, PoP 12 (2005) 32101].
 - ◆ Non-linear development can form convective cells
[Pastukhov and Chudin, Plasma Physics Reports 27 (2001) 907.]

Stability of background plasma is relevant to thermal plasma dipole confinement

In dipole natural 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 in process
- Pressure profile results with $pV^\gamma \sim \text{constant}$.
- Flux tube mixing will cause $n_e V \sim \text{constant}$.
 - Equal number of particles/flux tube
- Result 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 can 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 34, (85) 1, Hasegawa, Mima, PF 21,(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 $n_e V = \text{constant}$, $p V^\gamma = \text{constant}$, $V = \oint dl/B$

ECH creates two electron species

Properties of hot and thermal species in LDX

- **Hot electron species: $E_{eh} > 50 \text{ KeV}$**
 - **Hot electron interchange mode: $f \sim 1\text{-}100 \text{ MHz}$**
 - ◆ Free energy of hot electron density gradient
 - **Loss cone modes: unstable whistler modes: $f > 2 \text{ GHz}$**
 - ◆ Hot electron loss cone and anisotropy
- **Background plasma: $T_e(\text{edge}) \sim 25 \text{ eV}$**
 - **Drift frequency (entropy) modes: $f \sim 0.5\text{-}5 \text{ KHz}$**
 - ◆ Background plasma density and temperature gradients

ECRH sustains hot electron and thermal species

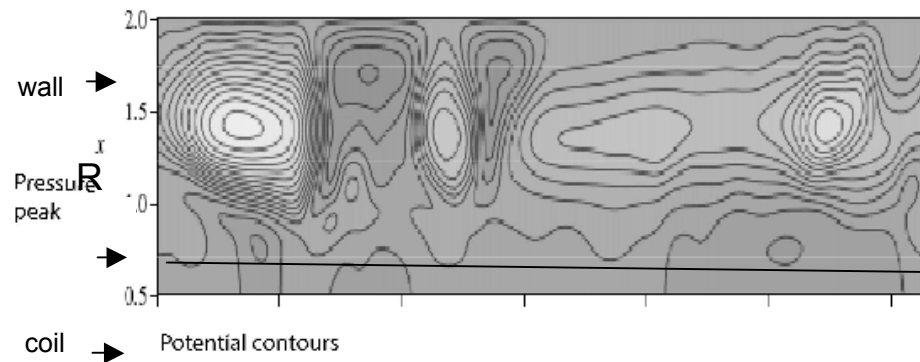
$$n_e = n_{eb} + n_{eh}, \quad n_{eb} \gg n_{eh}$$

- **Plasma density dominated by background thermal plasma**
 - Background can be unstable to low frequency modes: $\omega \sim \omega_d \sim \omega_*$
 - Background can be unstable to MHD
- $\beta \sim \beta_{eh}$: **Stored energy (β) is dominated by hot electrons**
 - Hots can be unstable to hot electron interchange: $\omega \sim \omega_{dh}$
 - Stability of hot electron species requires background density

As density increases more energy is stored in thermal species

Convective Cells in Dipole

- **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 $pV^\gamma=\text{constant}$, (i.e. $p'=p'_{\text{crit}}$).**
 - ◆ **When $p'>p'_{\text{crit}}$ cells get non-local energy transport. **Stiff limit: only sufficient energy transport to maintain $p' \gtrsim p'_{\text{crit}}$****
 - **Non-linear calculations use reduced MHD (Pastukhov et al) or PIC (Tonge, Dawson et al) in hard core z-pinch**



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

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

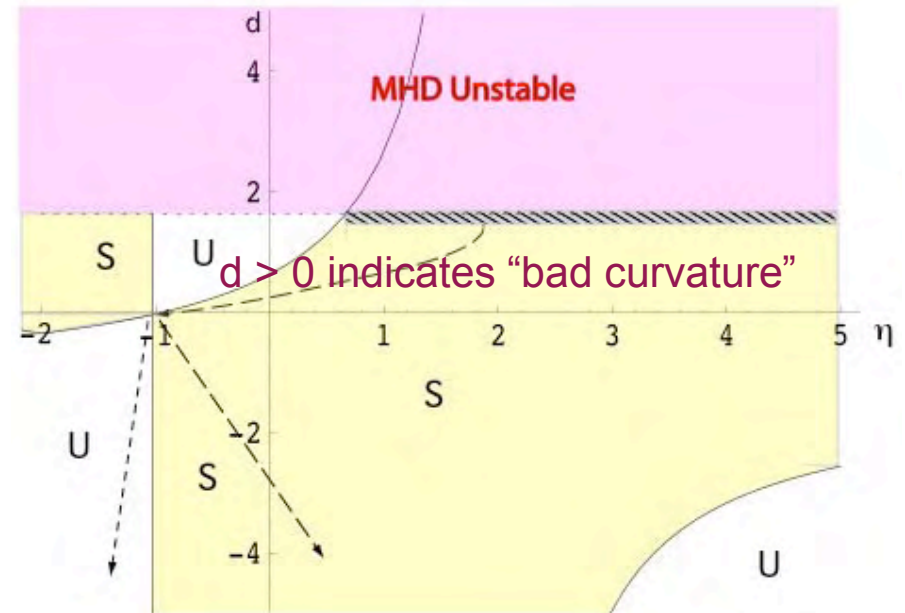
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Plasma can be stable to drift frequency modes

- 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]
- Linear theory not always relevant to real plasmas



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

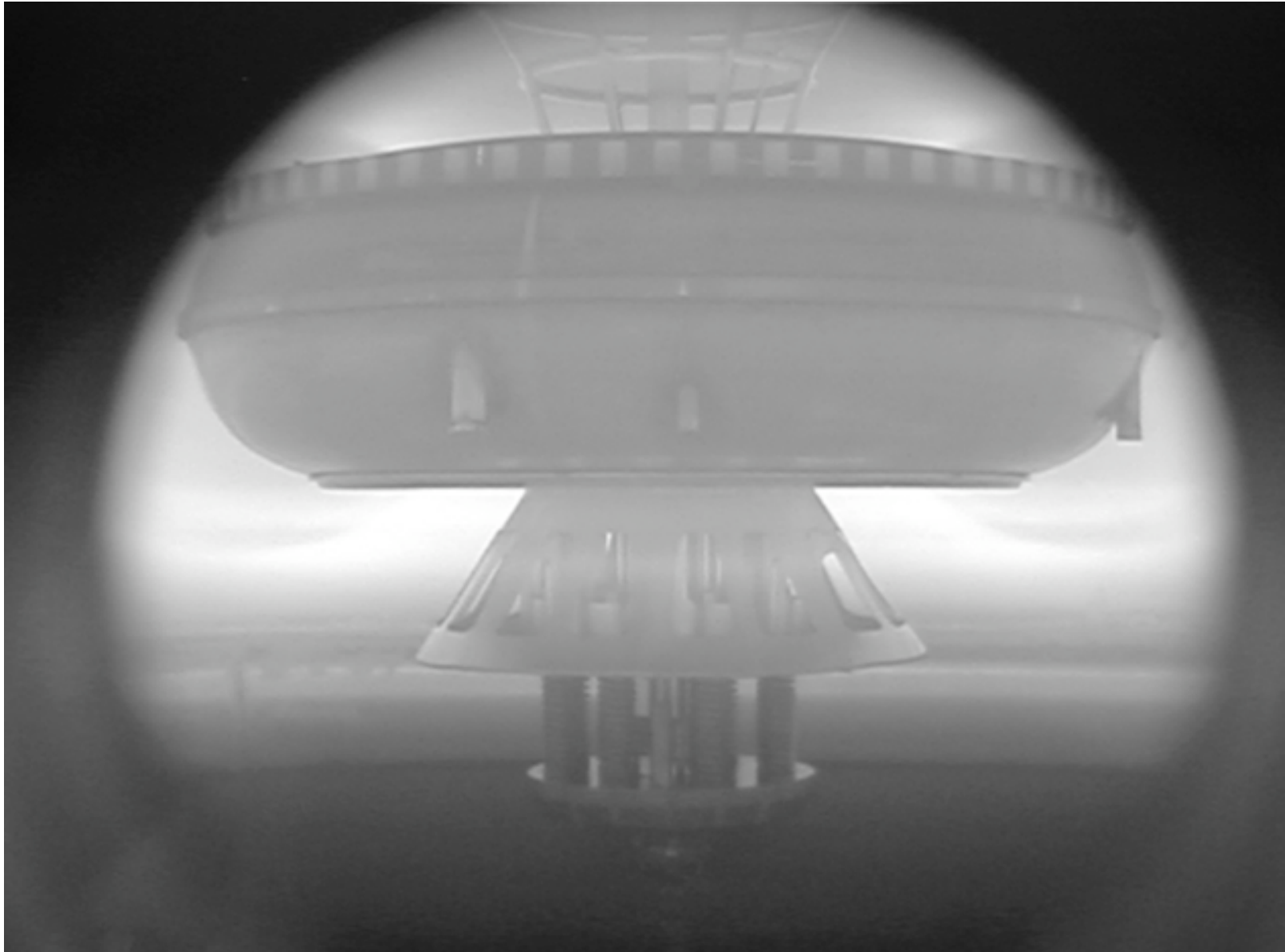
$$d = -d \ln p / d \ln V = \omega_{*i} (1 + \eta) / \overline{\omega_d}$$

$$V = \oint dl / B$$

Some references:

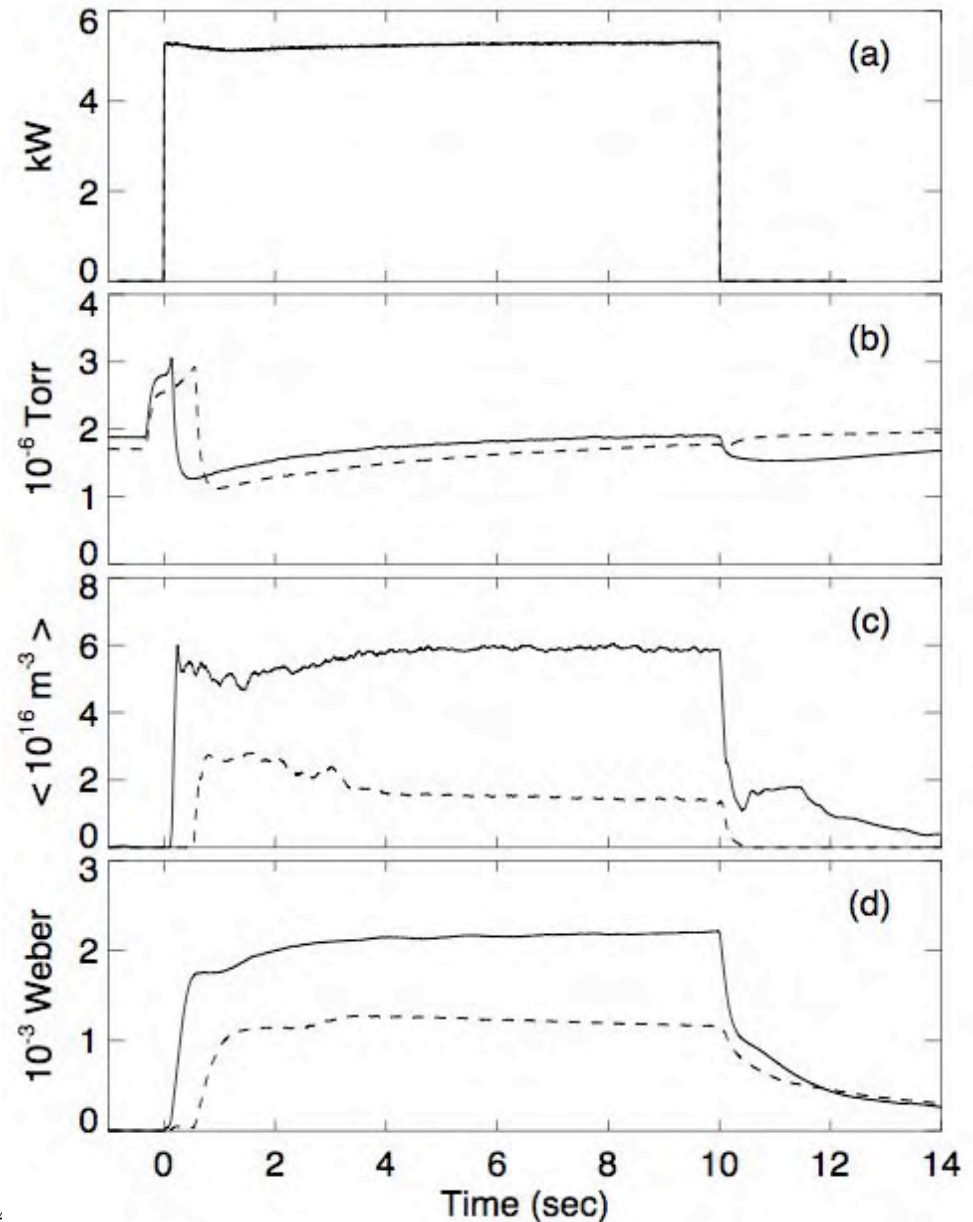
1. Kesner, PoP 7, (2000) 3837.
2. Kesner, Hastie, Phys Plasma 9, (2002), 4414
3. Simakov, Catto et al, PoP 9, (2002), 201
4. Ricci, Rogers et al., PRL 97, (2006) 245001.

First levitated experiments performed on 11/8/07



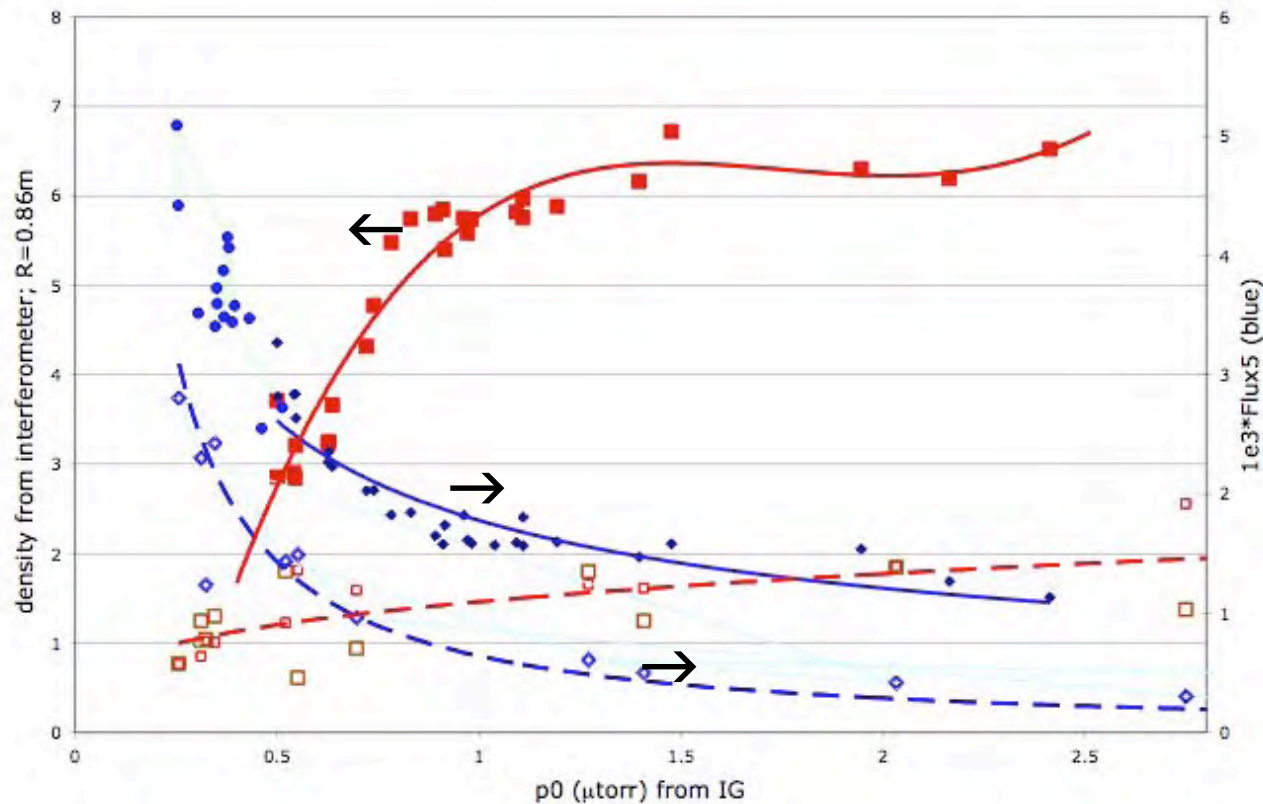
Compare supported and levitated shots

- 5 kW @ 2.45 and 6.4 GHz
- Similar vacuum pressure evolution
- Line density up by 3-5
 - (may be limited by wave accessibility)
- Diamagnetism (hot electron pressure) up by a factor ~2



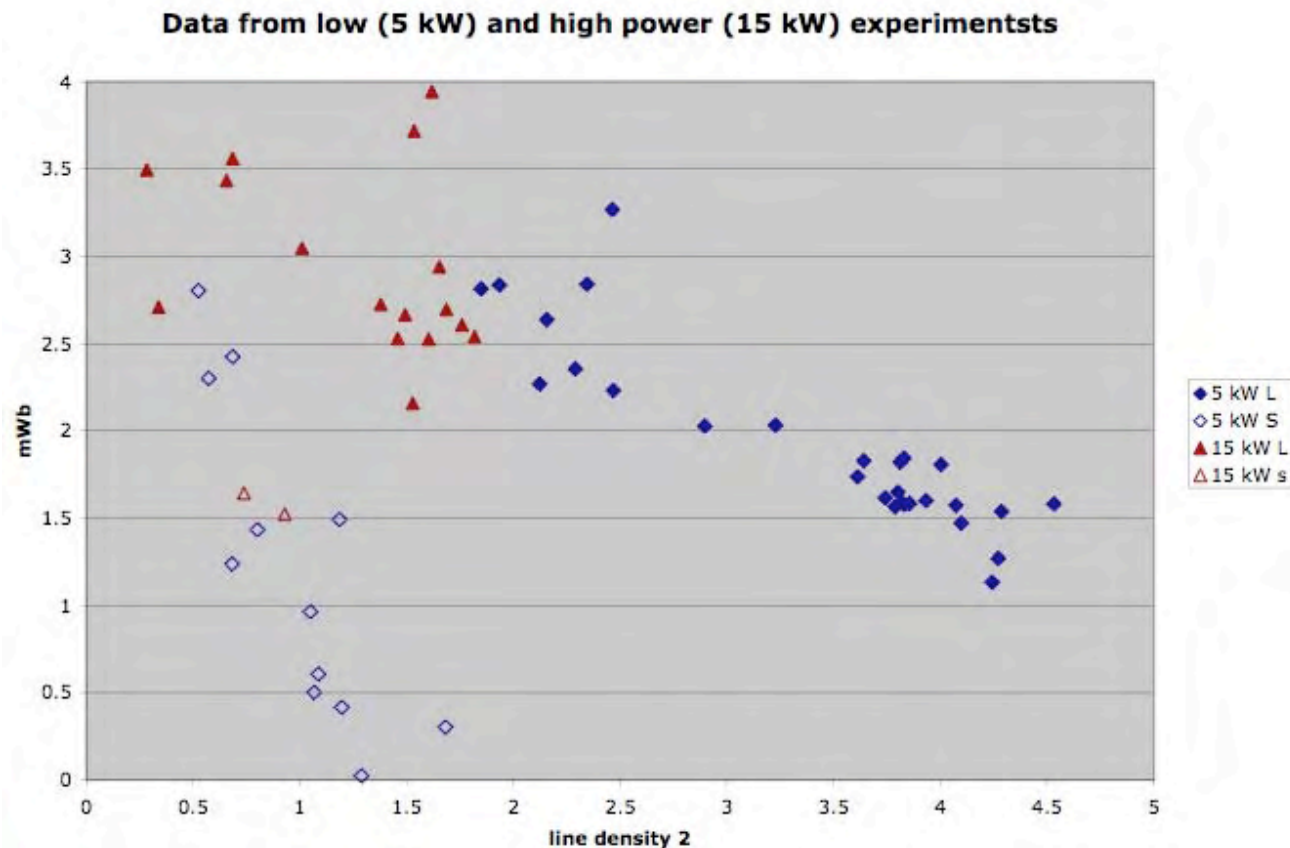
Vary background pressure

- 5 kW @ 2.45 & 6.4 GHz
- Density (red) increases and then flattens
 - During strong gas puffing density will fall (ionization rate drops).
- Diamagnetism falls as density rises indicating reduced power into hot electron species
- Density rises ($\sim 3x$) and pressure rises (2x) with levitation



Pressure in levitated and supported plasmas

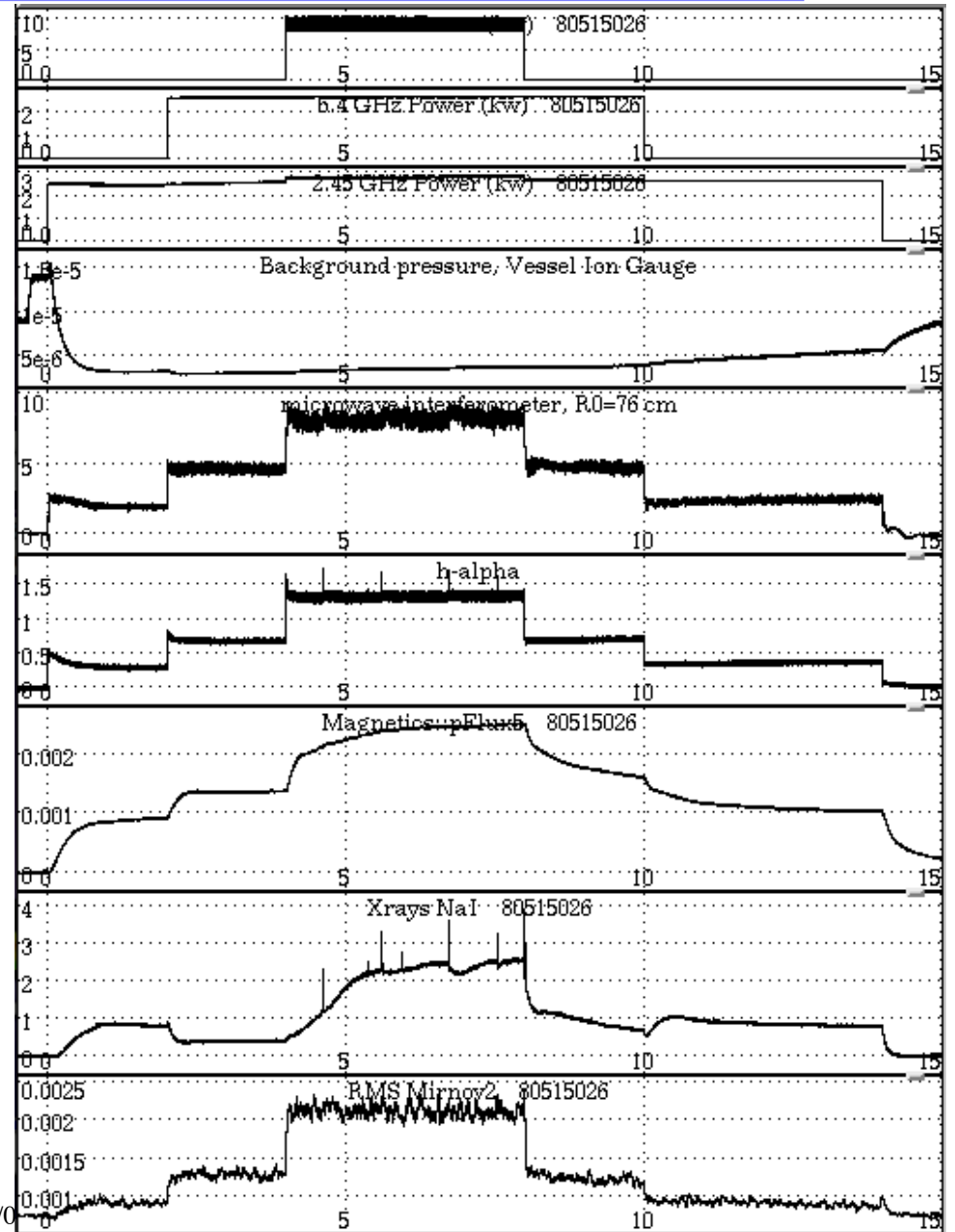
- 5 kW ECRH power.
- Diamagnetism falls as background plasma density rises
 - Hollow points for supported operation
 - High power: 15 kW (red) and low power: 5 kW (blue)



Recent experiments tripled ECRH heating

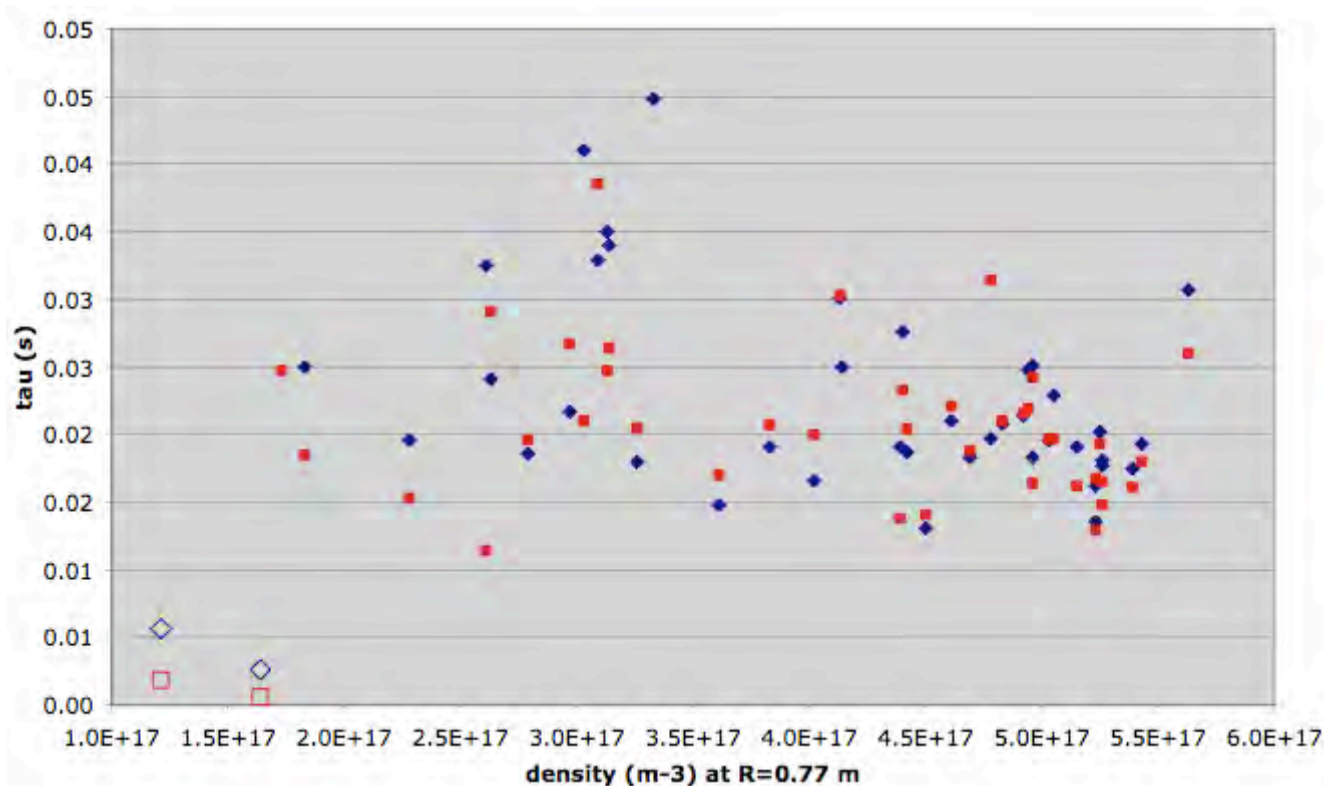
Typical discharge

- $P_{\text{ECH}}(2.45+6.4+10.5) \sim 15 \text{ kW}$
- Peak density $8 \times 10^{17} \text{ m}^{-3}$
 - Most density produced by 10.5 GHz heating
 - Find $\tau_p \sim 20 \text{ ms}$ from decay
- At high β ($\sim 20\%$) hot electron interchange instability can be excited
- Fluctuations are observed



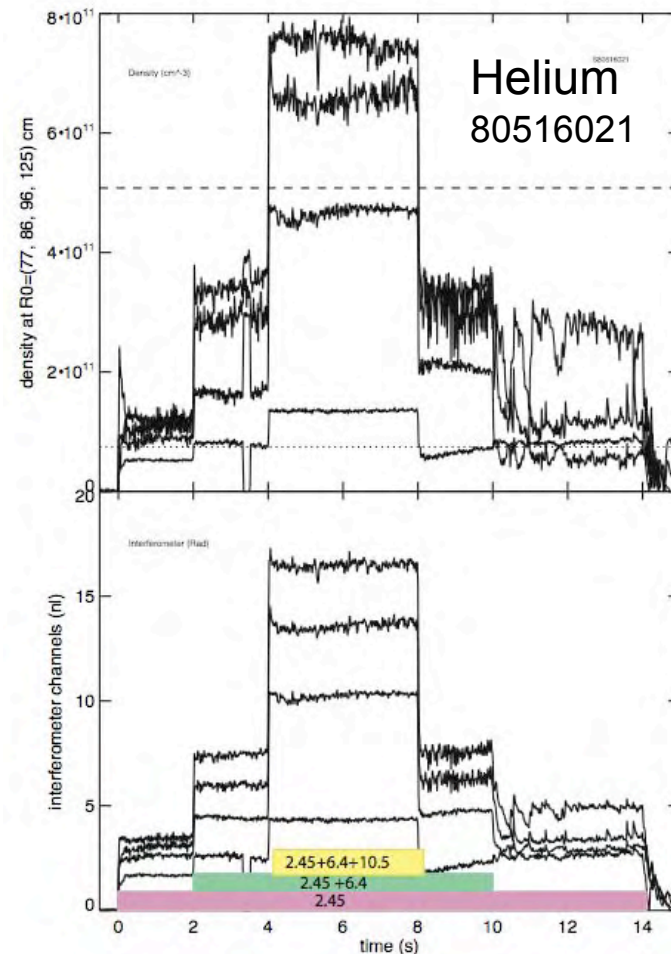
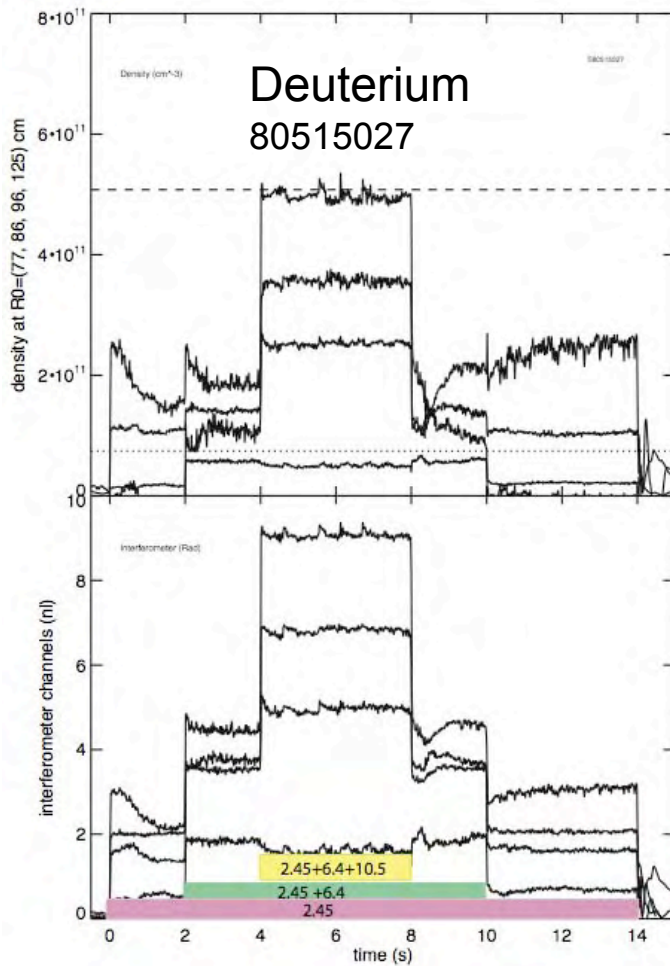
Confinement time from density decay

- Experiments with 15 kW ECH at 2.45, 6.4 & 10.5 GHz
- Evaluate exponential decay time at 10.5 GHz ECH turn-off
 - Interferometer array: $n_{l_{R0=77}}$ blue, $n_{l_{R0=86}}$ red
- $\tau_p \sim 20$ ms during levitated operation
- $\tau_p \sim 1-5$ ms during supported operation (hollow symbols).



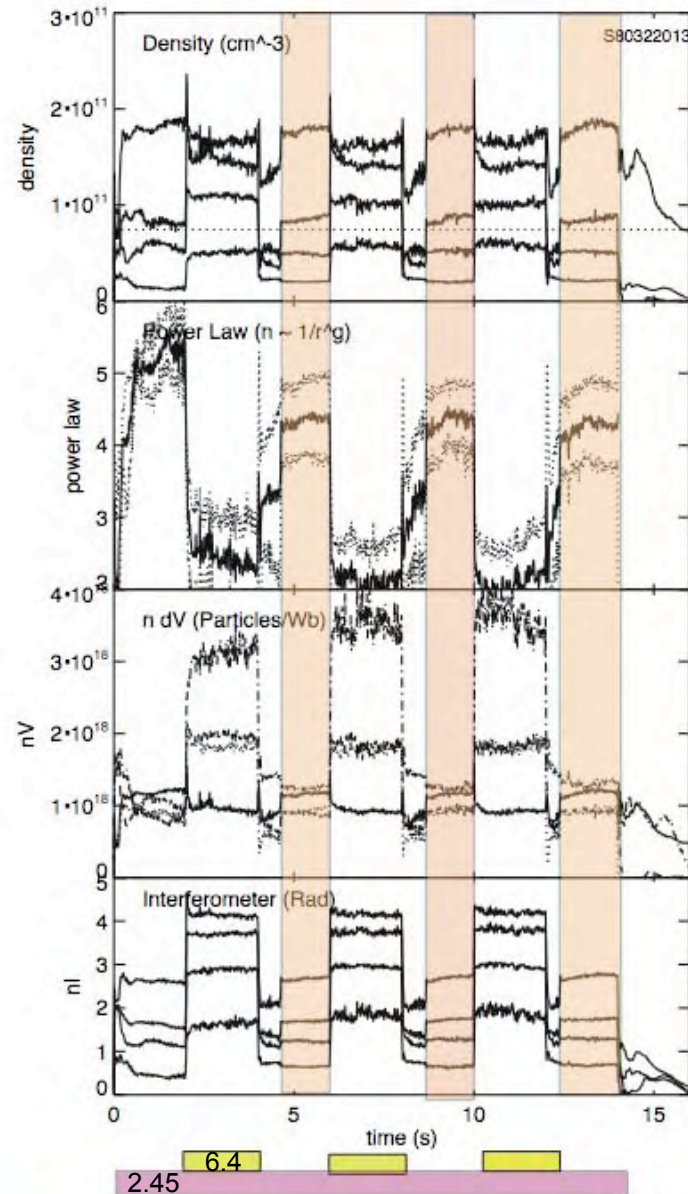
Density measurements (see Boxer IP.039)

- Density appears to be power limited
- Density obtained from 4 chord interferometer & edge Langmuir probe
- With 10.5 GHz heating lower frequencies appear to drive tails (at higher harmonics)
- On some discharges spontaneous rearrangement of density is observed



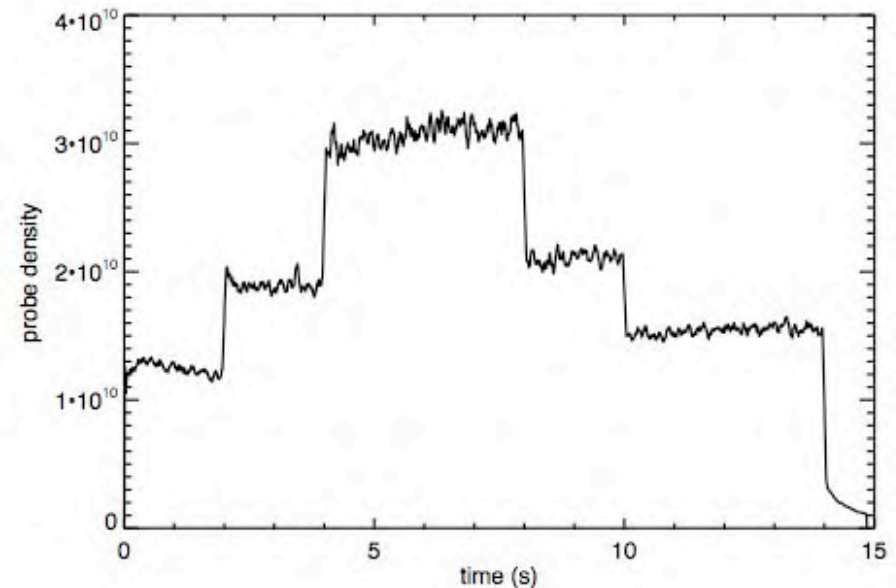
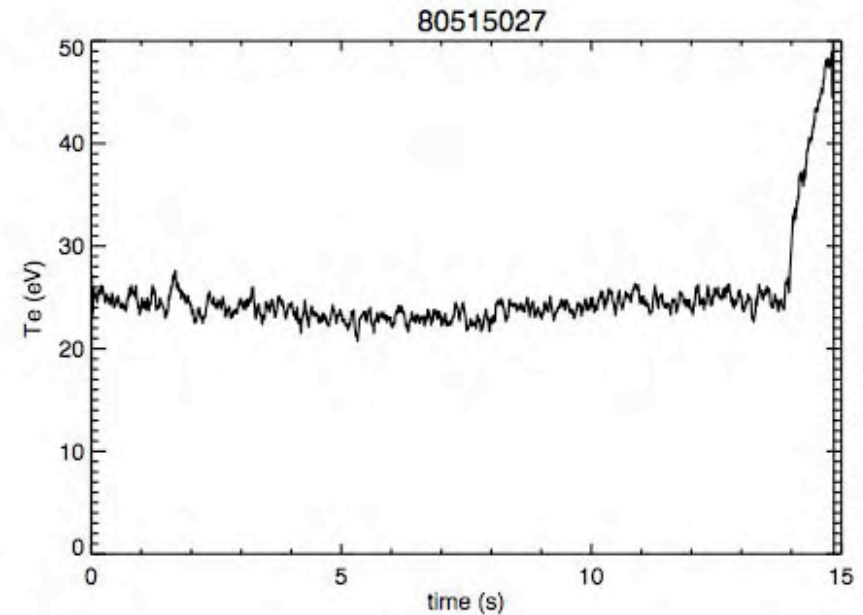
On some discharges spontaneous density reorganization is observed

- **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)**
- **Density assumes $nV \sim \text{constant}$ profile**
 - **Power law $n \sim R^{4.5}$ close to ideal $R^{4.7}$**
- **Density relaxation implies pressure relaxation**



Langmuir probe can diagnose the plasma edge

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



Summary

- Levitated operation now achieved regularly - Cryostat operates better with levitation (2 1/2 hr float).
- Substantial improvement in particle confinement: 3-5 times the density & 5-10 times τ_p
- Doubling of stored energy
- Substantial improvement in stability of hot species: No HEI at 5 kW heating level. Some HEI @ 15 kW level (with 10.5 GHz).
- Quasi coherent mode sometimes present
- Spontaneous density relaxation, i.e. self-organization sometimes observed. Leads to peaked n_e profile with constant # of particles/flux tube
- For 2.45 GHz heating density observed to exceed cutoff

Future directions

- **Additional diagnostics:**
 - High speed photodiode array and high speed camera
 - Measure background T_e
 - Reflectometer for peak density and fluctuations
- **Density is power limited**
 - Additional power to raise density which will increase thermalization of hot species and ease difficulty of measuring core parameters.
 - Will add power at either at 2.45, 18 or 28 GHz
- **Field error correction coils**