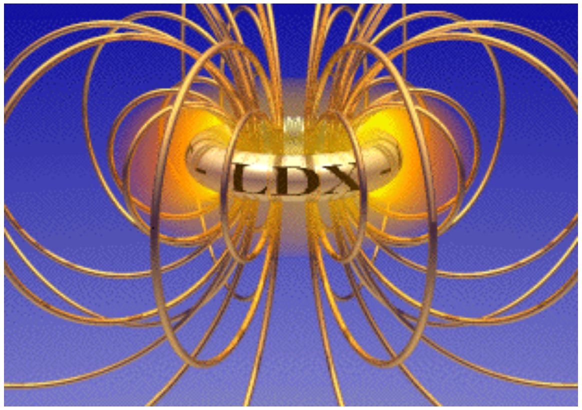

The Levitated Dipole Experiment: Towards Fusion Without Tritium

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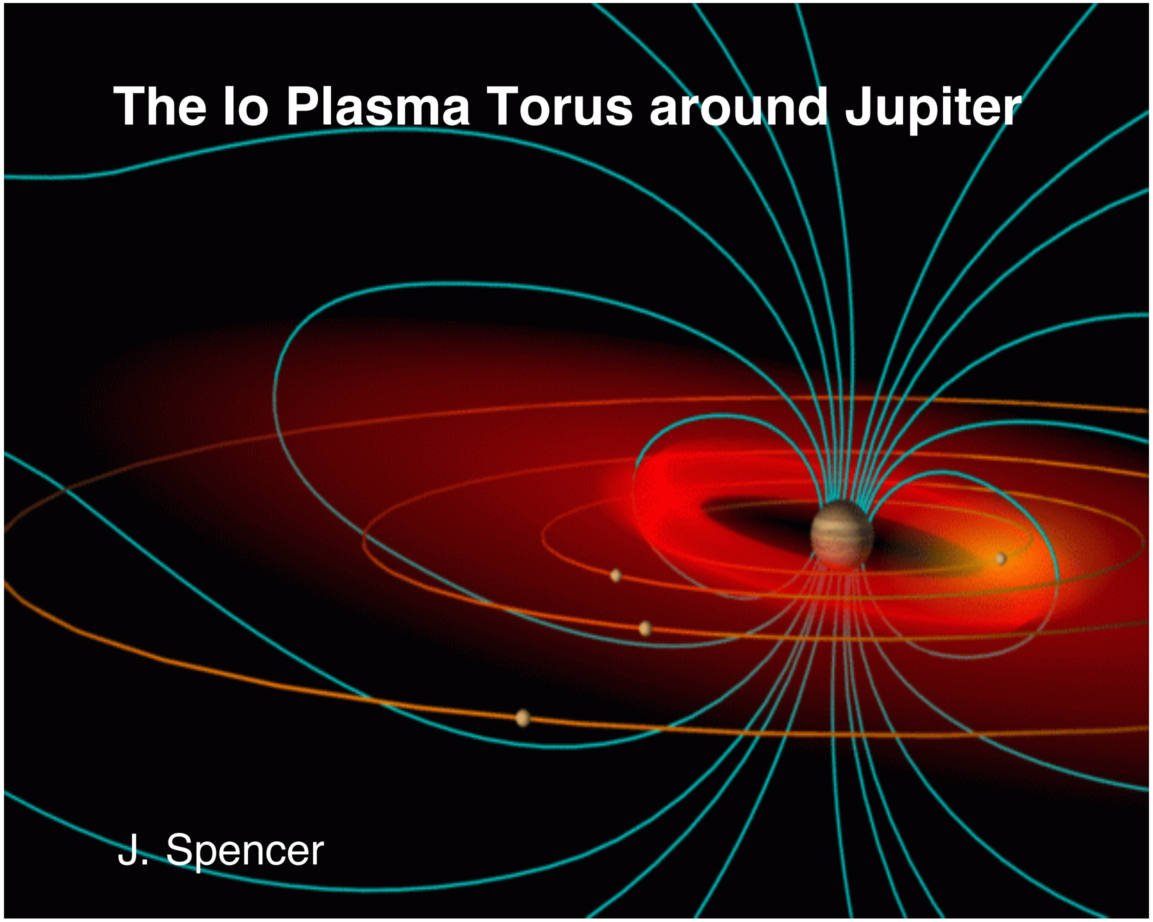
Dipole concept inspired by magnetospheric research

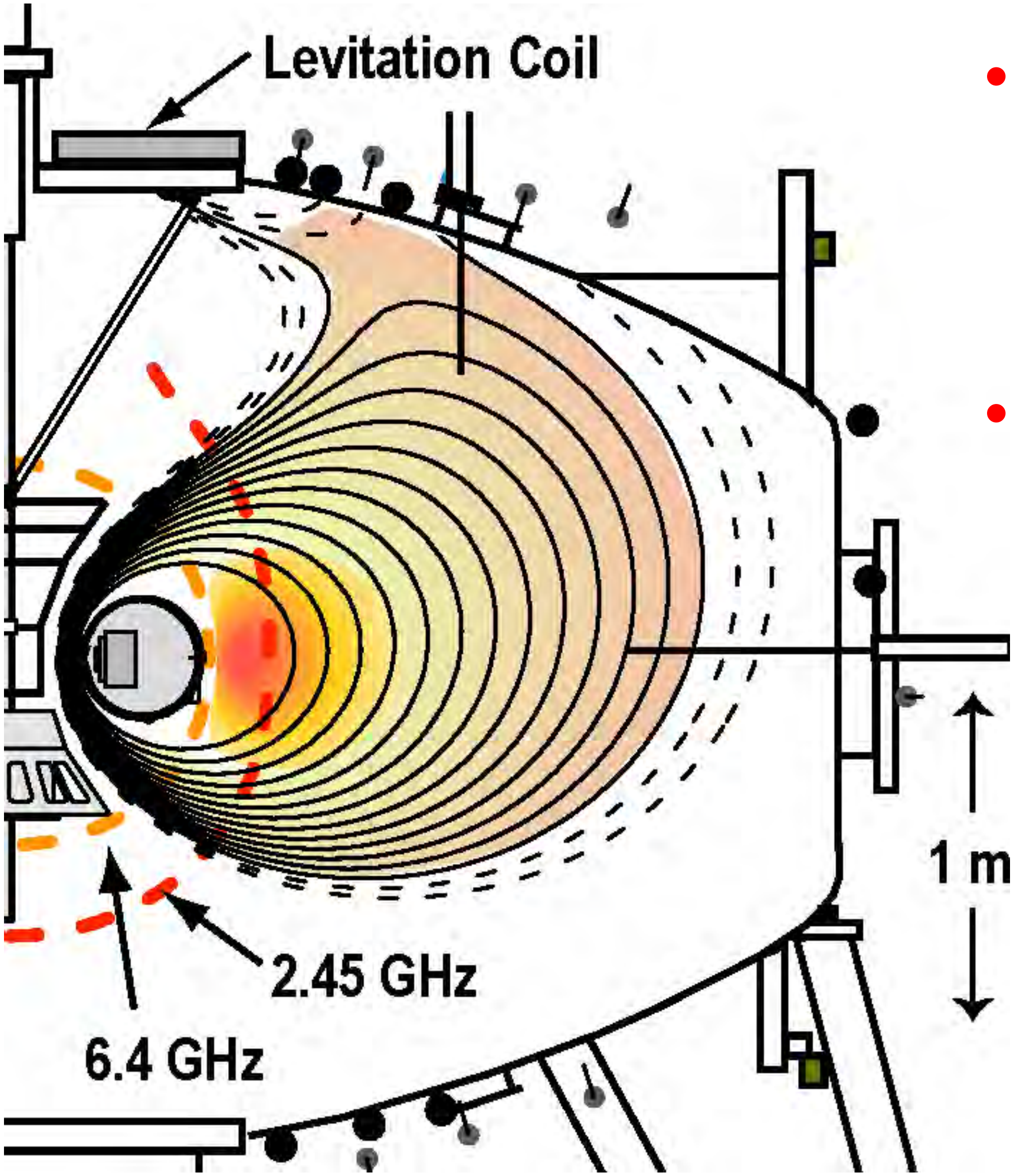


- **Dipole is simplest confinement field**
- **Naturally occurring high-β plasma (β ~ 2 in Jupiter)**
- **Opportunity to study new physics relevant to tokamak fusion and space science**
- **Can lead to advanced-fuel fusion power source** [Hasegawa, CPP&CF 1(1987)147]

Dipole can have particle transport without energy transport

- Plasma confined in bad curvature When $-d\ln p/d\ln V > \gamma$ will reduce pressure gradient to $pV^{\gamma} \approx const$ $\quad V = \oint d\ell/B \propto R^4$
  - When $pV^{\gamma} \approx constant$ flux tube mixing does not cause energy transport [Rosenbluth, Longmuir (1957)]
  - In tokamak $-d\ln p/d\ln V$ can exceed γ. Thus turbulence is accompanied by energy transport.
- Turbulence driven flux tube mixing will determine density profile with $N=n_eV=$constant.
  - Density profile independent of D and Source
  - Profiles characterized by constant particles/flux.
    - **Tokamak (L-mode): n_e~1/V~1/q** [Ref: Baker, PoP 6 (2002) 2675]
    - **Dipole: n_e~ 1 / V ~1 / R^4**

Dipole Plasma Confinement



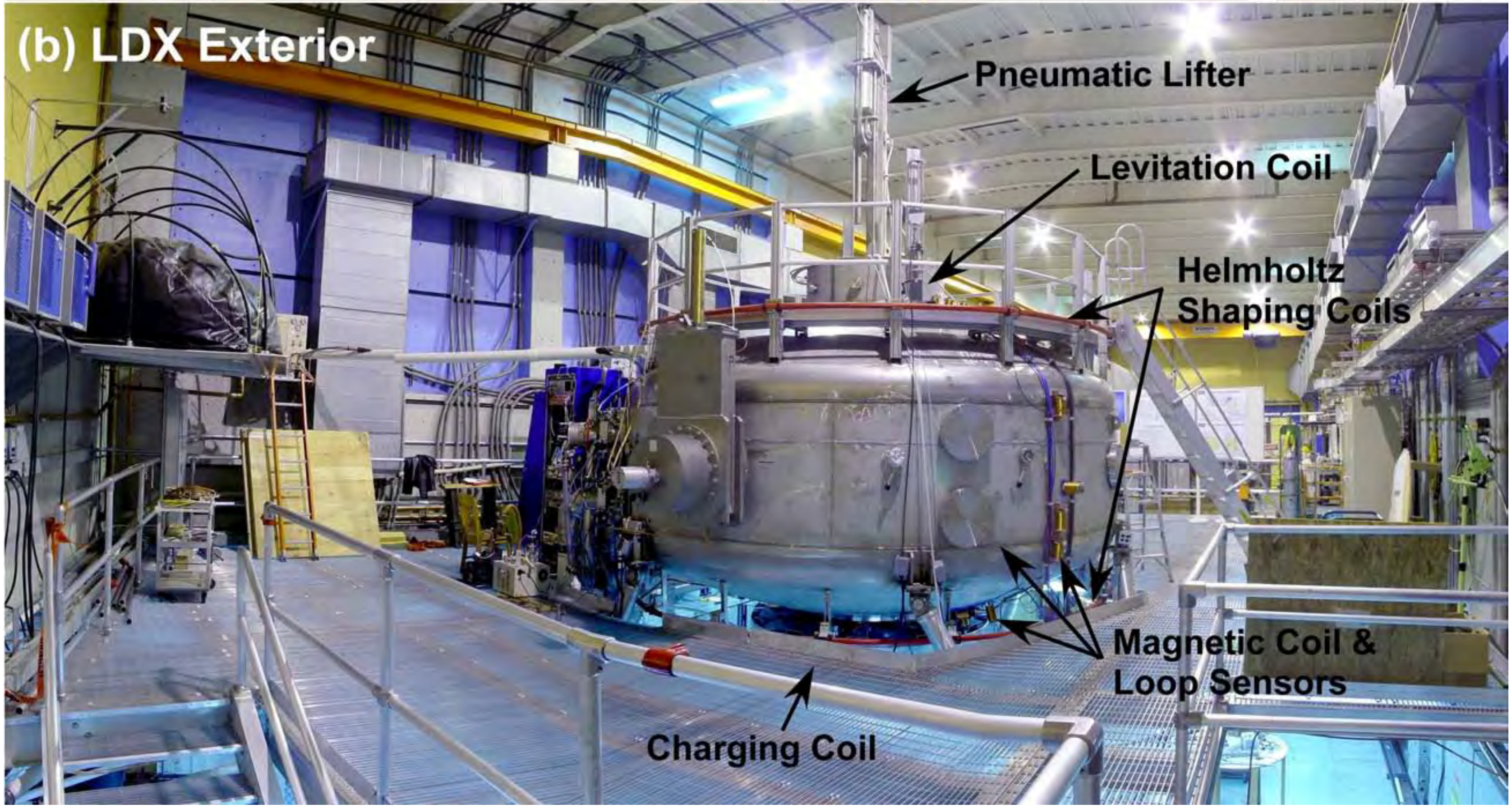
- Toroidal confinement without toroidal field
  - Closed field line topology
- Superconducting floating coil creates poloidal field
  - No loss to supports
  - Steady state
  - Natural separatrix

Unique dipole properties

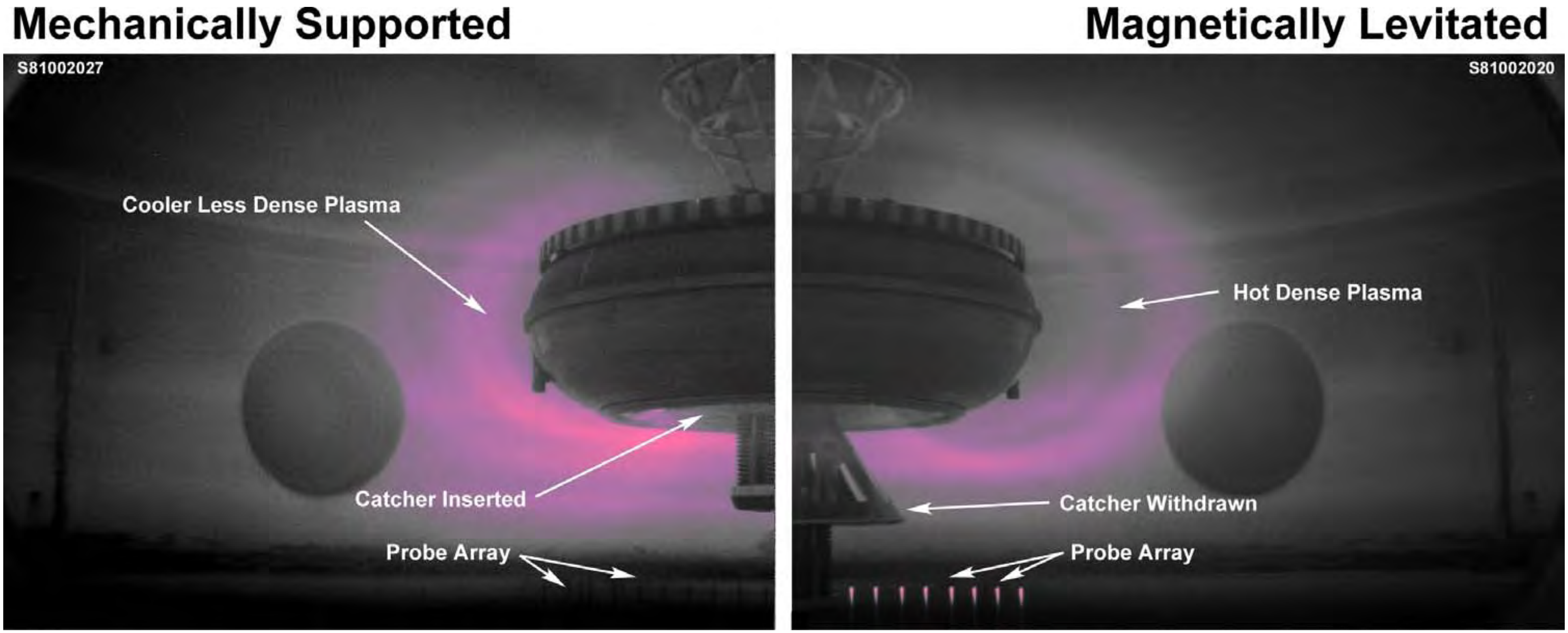
- **Coil inside of plasma**
  - Field falls dramatically: $B^2/4\pi \sim 1/R^6$
  - Field and plasma pressure fall off together leading to high average β
- Stability from plasma compressibility
  - Limit on pressure gradient ⇨ Small plasma in large vacuum chamber
- No shear ⇨ Large-scale adiabatic convection
- No toroidal field, no $j_{||}$ ⇨ No drift off field lines (i.e. NC), High β
- Strong density pinch observed, leading to stationary profiles

  Dipole illuminates physics of turbulent pinch
- Internal coil not compatible with 14 MeV (DT) neutrons which can penetrate and heat floating coil.
  - $\tau_E >> \tau_P$ makes dipole ideal for advanced fuels (D-D, D-^{3}He).

The Levitated Dipole Experiment (LDX)



LDX Floating coil can be supported or levitated



- Observe ionization glow move outwards with levitation as density rises due to pinch
- Supported mode: Losses to supports dominate X-field transport (mirror machine)

Physics of turbulent pinch

- Turbulence driven transport: MHD equations for N=number/flux=nV and s=entropy density=pV^γ.

$$\frac{\partial}{\partial t} n_e V = \frac{\partial}{\partial \psi} D \, \frac{\partial}{\partial \psi} n_e V \qquad D \sim \Sigma E_\phi^2 \, \tau_{corr} \qquad V = \oint d\ell / B$$

$$\frac{\partial}{\partial t} pV^\gamma = \frac{\partial}{\partial \psi} D \frac{\partial}{\partial \psi} pV^\gamma + \left\langle P_{in} \right\rangle$$

- Constant N=n_eV and s=pV^γ are stationary (invariant) states
- Turbulence driven diffusion will tend to flatten gradients in N and s

Operating scenario

- Central heating will drive instability ($-\partial \ln p / \partial \ln V > \gamma$). Creates pressure gradient with s~const (not disruptive).
- Turbulence will draw in density (pinch) leading to N=n_eV~constant.
- For p and n_e profiles ⇨ boundary conditions (I.e. edge physics) determine total stored energy and particle content.

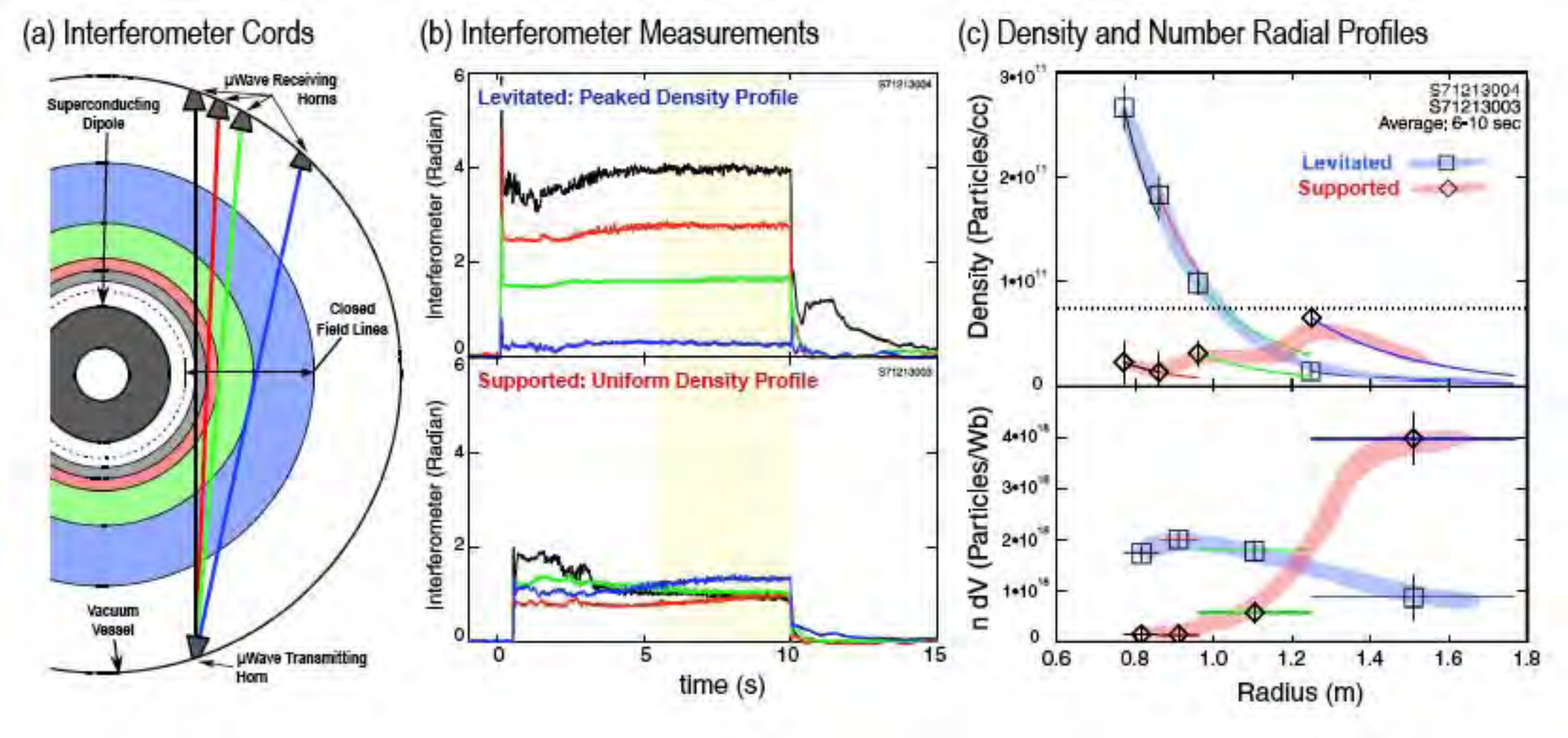
During levitated operation *stationary density profiles* are usually observed

Stationary density: $n_e \propto 1/V,\ V = \oint d\ell/B \ \therefore\ n_e \propto 1/R^4$

- 4-chord interferometer measures density profile
  - ➢ Can extract density profile (e.g. Abel inversion)
  - ➢ Stationary profiles exhibit specific chord ratios; e.g. $P_{23} = nl_2 / nl_3 = 1.5$ for constant N, etc
- Stationary profiles form in 15-20 ms [1]
- Stationary density profiles are maintained during large changes in fueling and heating
- Supported operation: Losses to supports dominate X-field transport. Profiles not stationary, $P_{23} \sim 1$

[1] Boxer et al, Nature Physics **6** (2010) 207.

Density peaks up markedly when coil is levitated



(a) Interferometer Cords

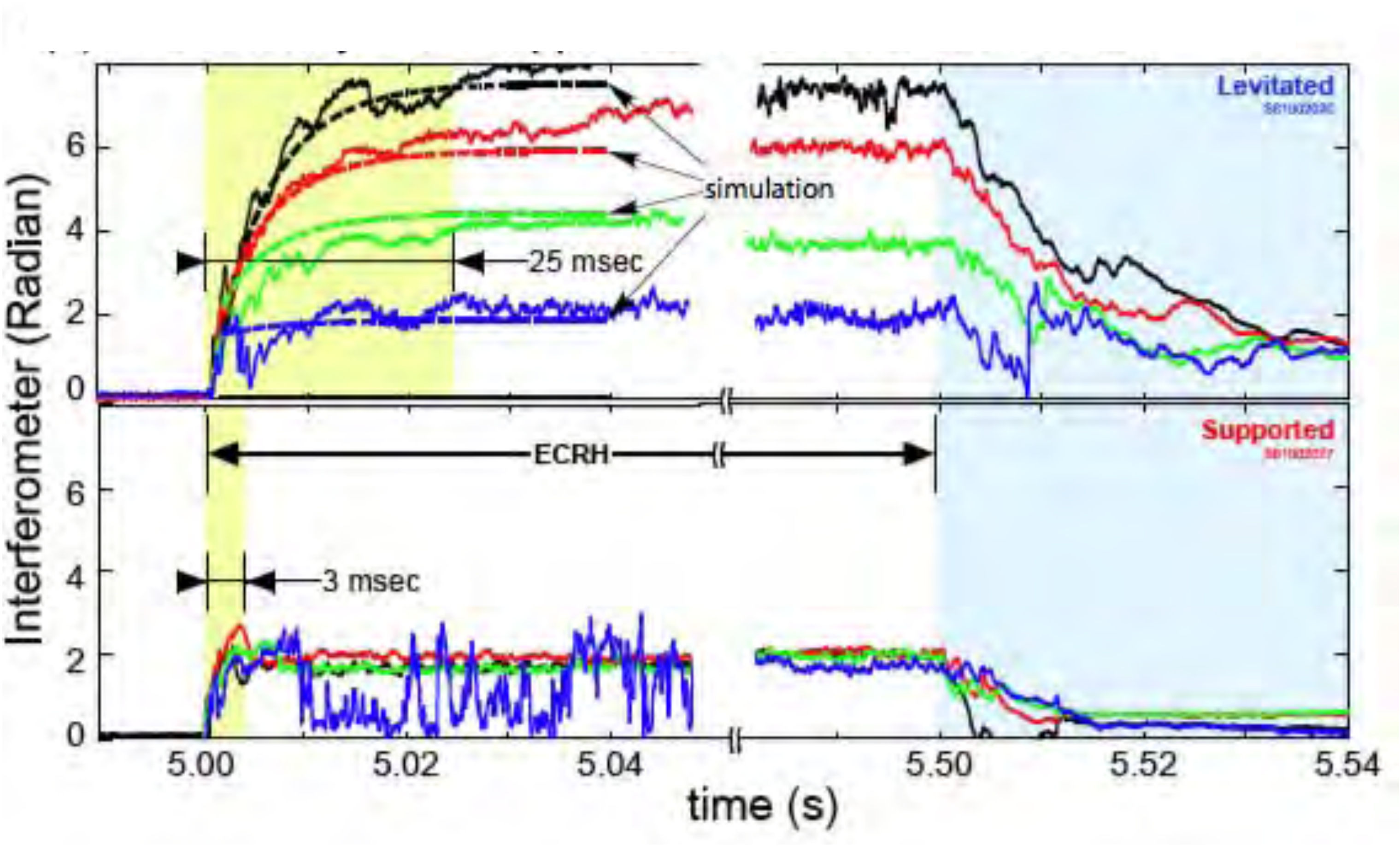
(b) Interferometer Measurements

(c) Density and Number Radial Profiles

- Supported plasmas show similar turbulence level. Losses along field mask pinch.

Time for turbulent pinch determined by D

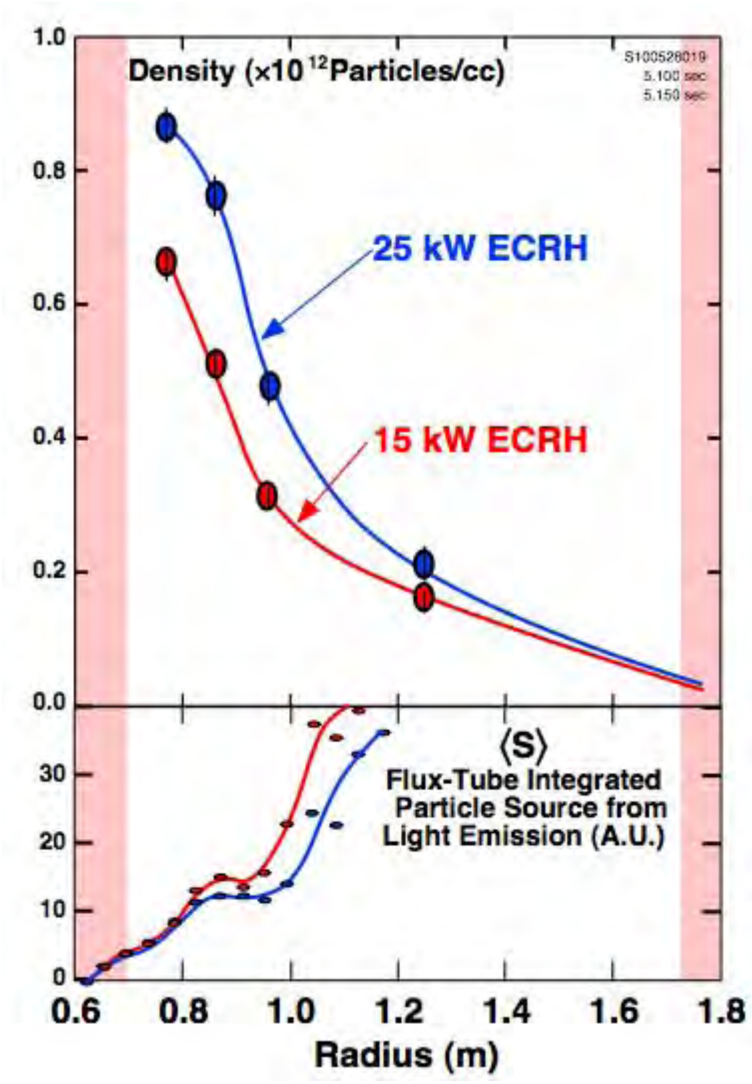
- Pinch takes ~20 ms to form $$\frac{d(nV)}{dt} = \langle S \rangle + \frac{d}{d\psi} D \frac{d(nV)}{d\psi} \qquad V = \oint dl/B$$
  - $D = R^2 \langle E_\phi^2 \rangle \tau_{corr} \approx 0.047\ V^2/s$ (Eϕ,τ_{corr} from edge probe)
  - Probe measurements match pinch time of ~20 ms.

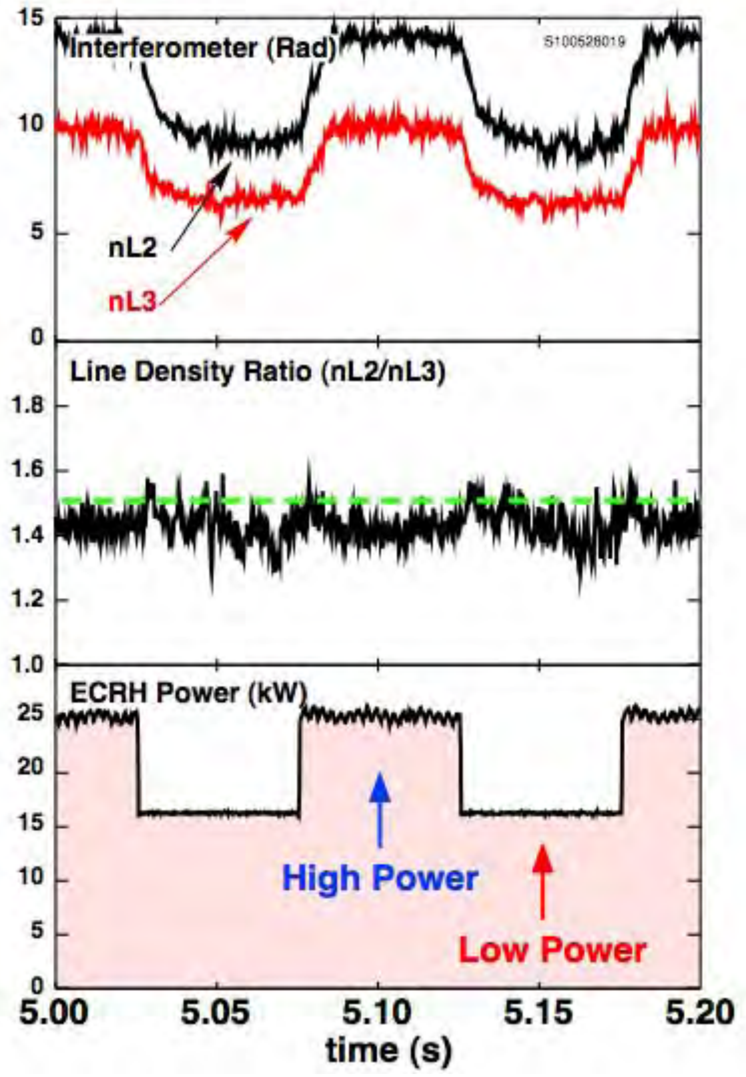


Profile is robust: heating power modulation experiment

10 Hz 10 kW (10.5 GHz) modulation

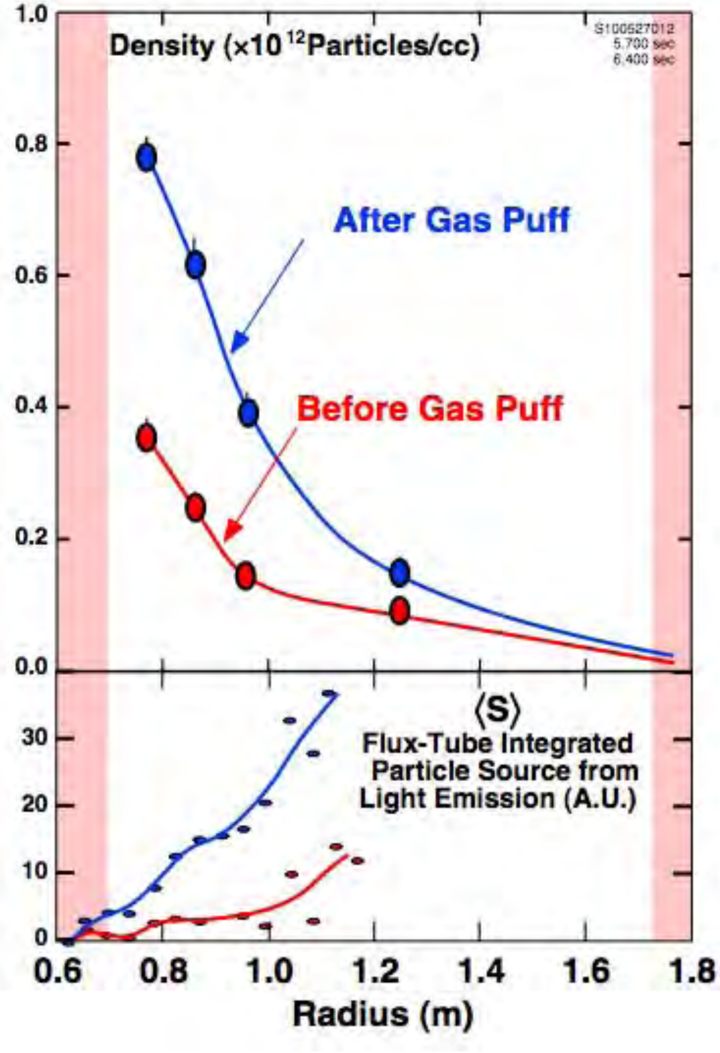
- Density modulation follows power: invariant profile remains unchanged

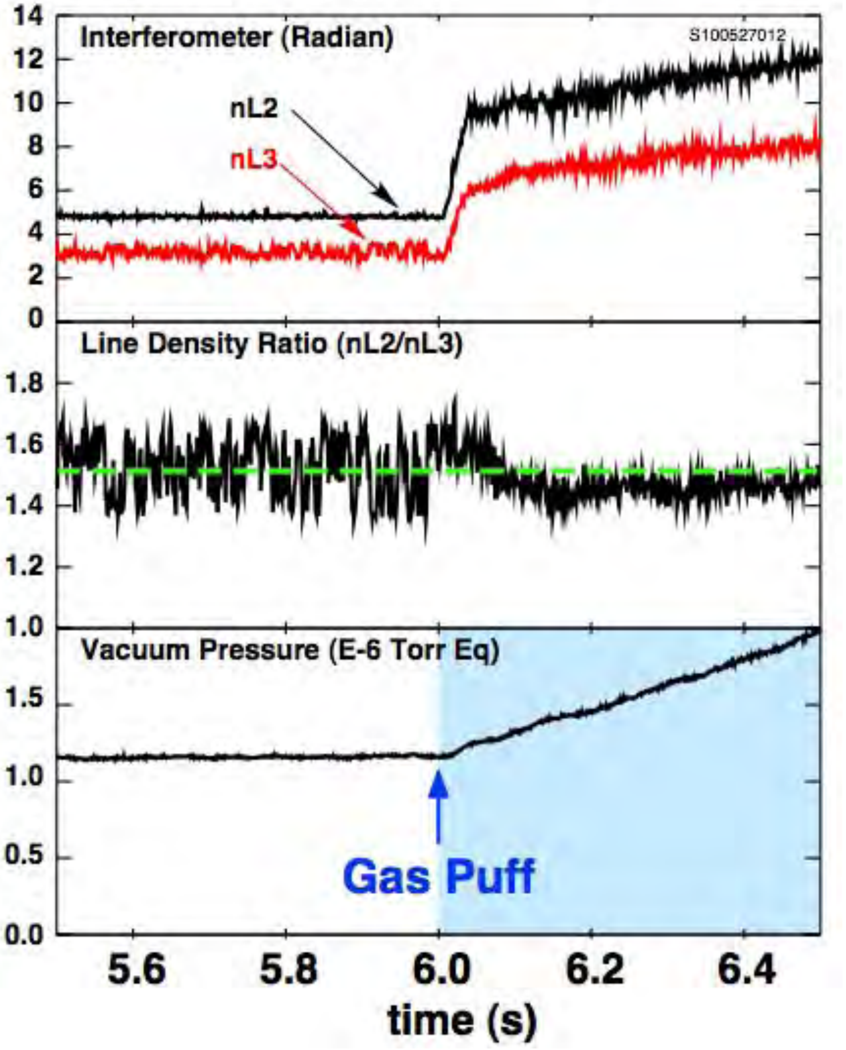




Gas puff experiment

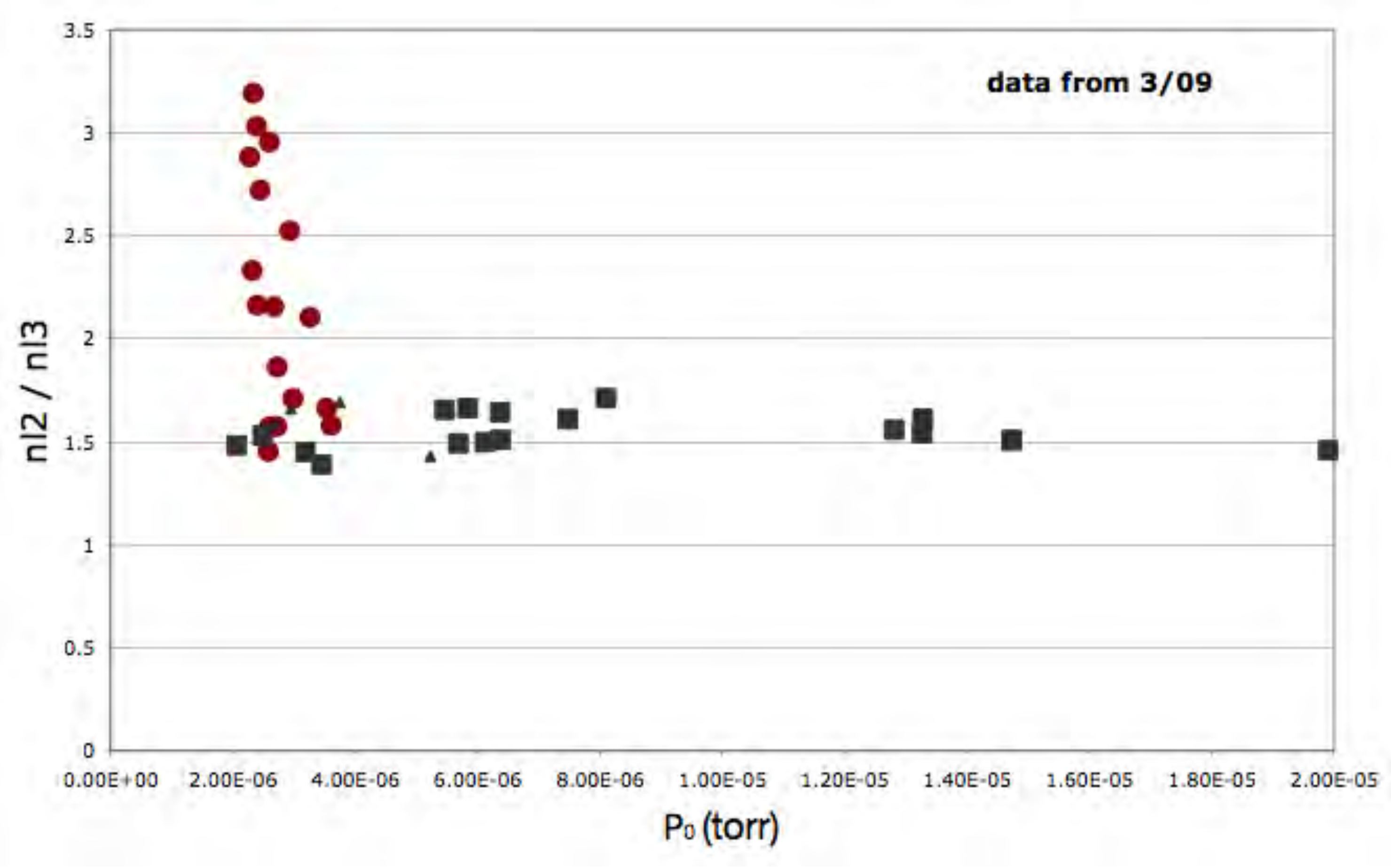
- Fueling experiment: Gas puff at t=6 s
  - Source (particles/flux) from PDA array peaks to the outside
- Core density doubles





Low gas pressure profile invariance can be violated

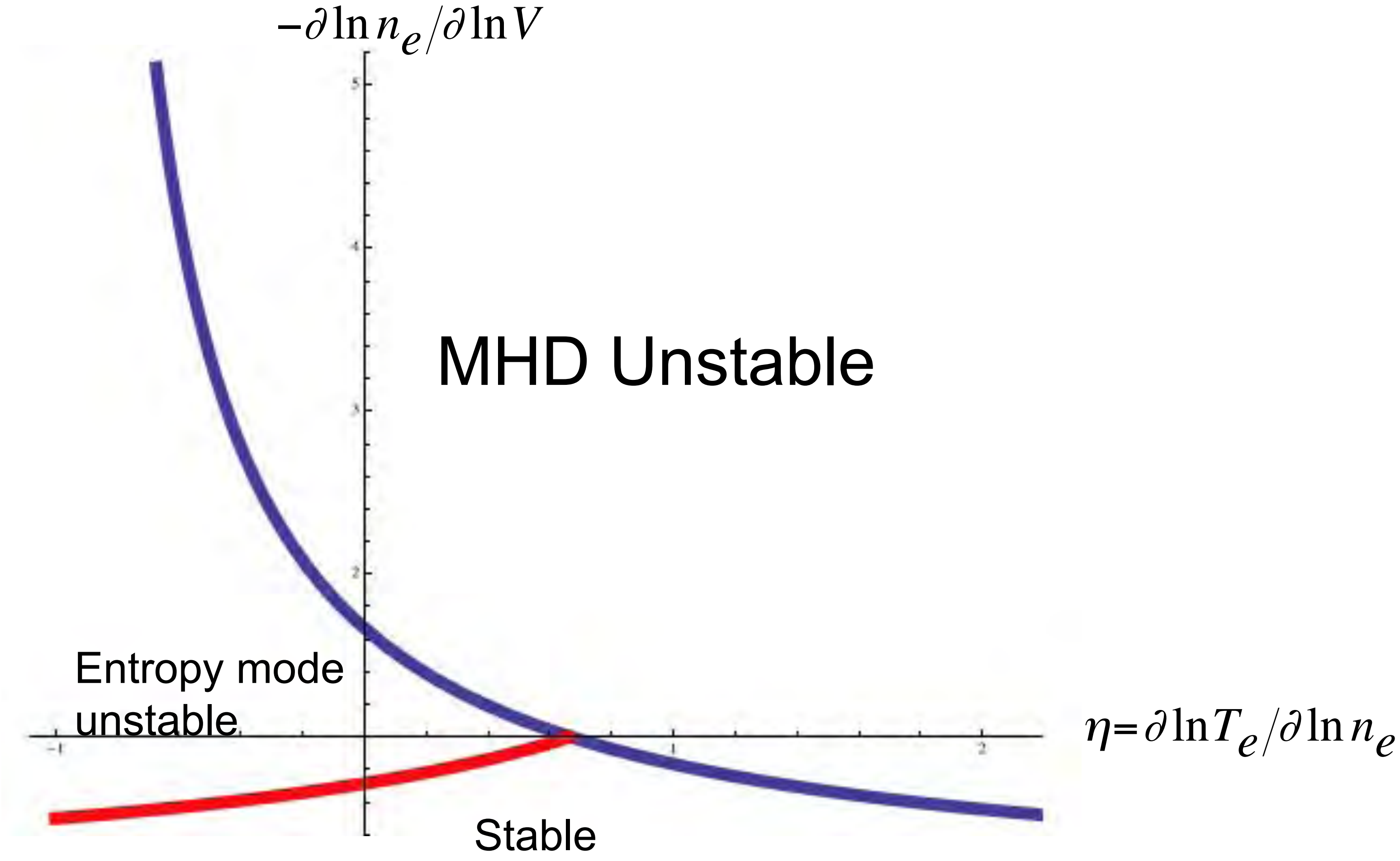
- For sufficient neutral pressure stationary density (P_{23}~1.5)
- Low neutral pressure p_0<3.5 mtorr, profile not stationary
  - ➢ Fluctuations become quasi-coherent.



MHD &/or drift modes unstable when $-\partial \ln n_e / \partial \ln V > 1$

- Pressure gradient driven MHD interchange (blue): $-\partial \ln p / \partial \ln V > \gamma$
- Entropy mode (red): $-\partial \ln n_e / \partial \ln V > 5/(7-3\eta)$ (collisional)

  or $-\partial \ln n_e / \partial \ln V > 1/(3(1-\eta))$ (collisionless)



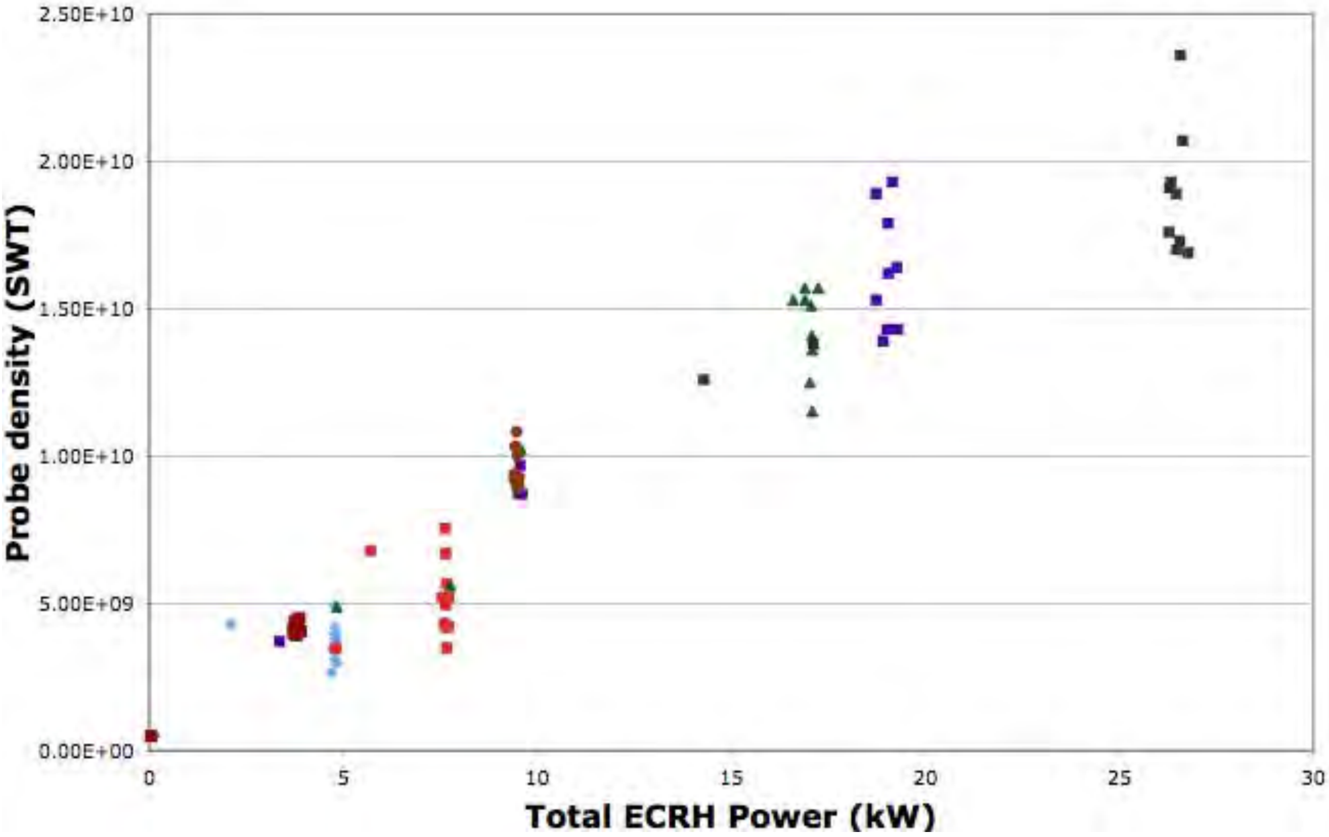
Scrape-off-layer physics provides boundary conditions

- **SOL temperature determined by particle balance**

$$n_{sol} U_B(T_e) A_{eff} = \langle \sigma v \rangle n_{sol} n_0 Vol \longrightarrow T_e \approx constant, \quad T_e \approx 20-30 \quad eV$$

- **SOL density determined by power balance**

$$P_{tot} - P_{Rad} = e n_e U_B A_{eff} \varepsilon_{ionize} \longrightarrow n_e \propto P_{tot}$$



Some consequences of invariant profiles

- For $p \propto 1/V^{\gamma}$, $V = \oint d\ell/B$ have $E_{tot} = \frac{3}{2} p_{sol} R_{sol}^{3} (R_{sol}/R_0)^{11/3}$
    - Define $\tau_E = E_{tot}/P_{tot}$, noting $p_{sol} \propto n_{sol} \propto P_{tot}$ find τ_E independent heating power
- For $n_e \propto 1/V$, have $N_{tot} = n_{sol} R_{sol}^{4} / R_0$

  Dipole amplifies SOL density and pressure much like gas flow from a large volume through a small hole

- Defining $\tau_P = N_{tot}/S$ find:

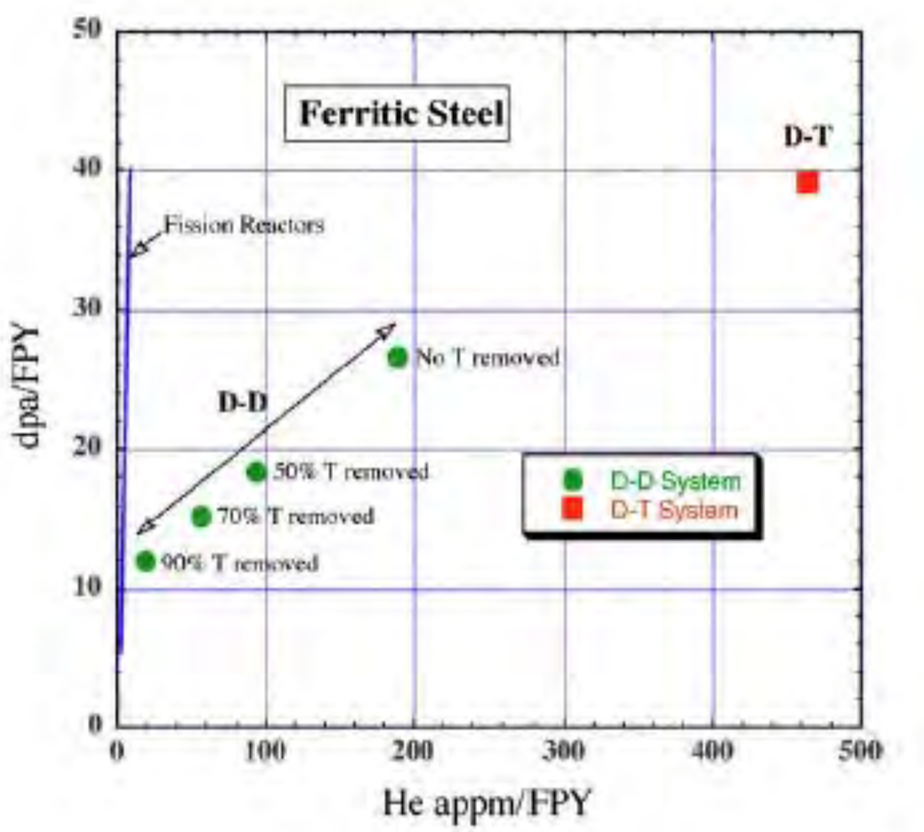
$$\frac{\tau_E}{\tau_P} = \frac{3}{2} (R_{sol}/R_0)^{8/3} (S T_{sol}/P_{tot}) \approx 10-50$$

- Find τ_E/τ_P is large and depends only on geometric factors (flux expansion)

Dipole energy source:Tritium suppressed fusion

- **DT has difficult issues relating to tritium breeding and materials damage (swelling and DPA) from 14 MeV neutrons.**
- **DD cycle, removing secondary T, would ameliorate problem.**
- $D + D \quad \begin{array}{l} \rightarrow T + p \\ \rightarrow He^{3} + n \end{array}$
- **requires $\tau_P << \tau_E$ for T removal**
- **Similarly $\tau_P << \tau_E$ for ash removal**
- **Burn secondary ^{3}He**
  - **T decays to ^{3}He**
- **T-suppressed power source would reduce DPA/He to fission levels**
- **Dipole study**

Kesner et al, Nuc Fus 44 (2004) 193



Sheffield, Sawan, FST **53** (2008) 780.

Attractiveness of Dipole

- Dipole research presents novel physics, challenging engineering and an attractive fusion confinement scheme
  - Steady state
  - Disruption free - (Plasma is pulled, not pushed)
  - High average beta
  - Low wall loading due to small plasma in large vacuum chamber
  - $\tau_E >> \tau_p$, as required for advanced fuels
  - No current drive needed but need internal refrigerator
- LDX focus
  - Formation of "stationary" (peaked) density and pressure profiles
  - Stability and β limits
  - Evaluate τ_E , τ_p and τ_E/τ_p
  - Issues relating to presence of hot species

Summary

- LDX routinely operates in levitated mode.
  - ➢ LDX can also operate supported for comparison.
- Stationary s & N observed during levitation
  - ➢ Levitation eliminates parallel particle losses and LDX exhibits a dramatic density pinch.
- Observe broadband fluctuations of density and potential that is likely cause of the observed pinch.
  - ➢ Unlike most confinement schemes, in a dipole turbulence leads to strong inward transport and peaking of density.
  - ➢ Density pinch without large energy transport
- Turbulent pinch is observed in tokamaks, but particularly strong with strong field gradient & w/o shear