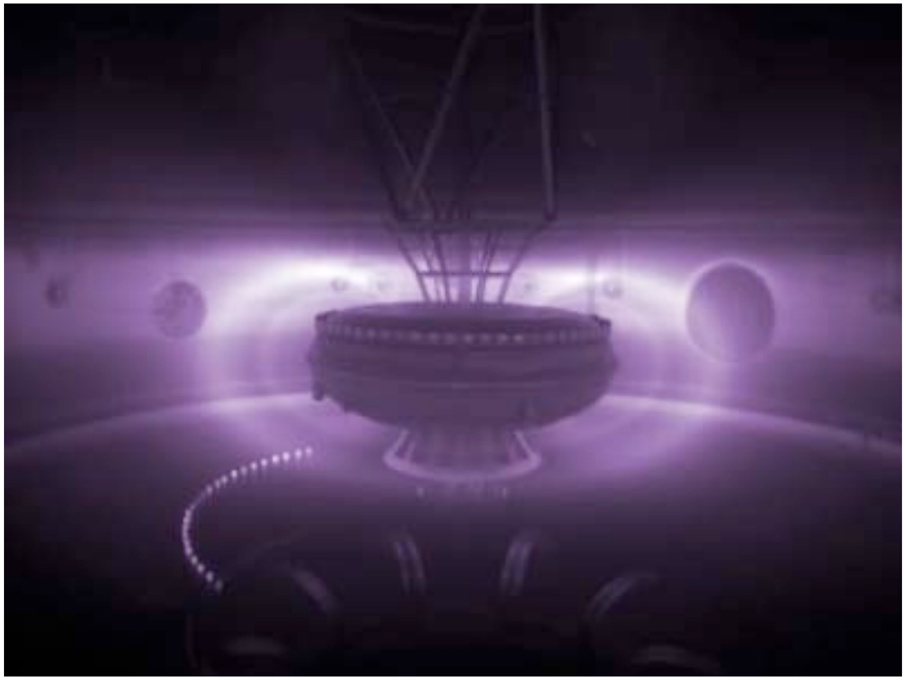

Laboratory Dipole Plasma Physics

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53th APS-DPP Conference on Plasma Physics

Salt Lake City, Utah

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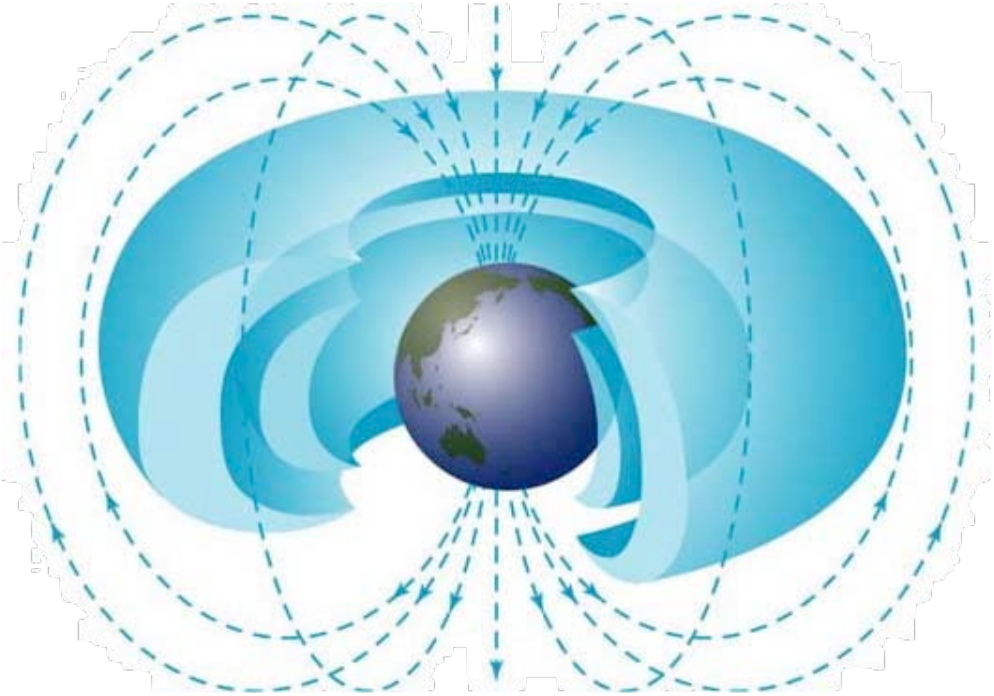
Dipole concept was inspired by over 50 years of magnetospheric research: earth, Jupiter…



- Gold (1959): Plasma pressure is centrally peaked with $p \sim 1/V^{\gamma} \sim R^{-20/3}$
- Melrose (1967): Plasma density is centrally peaked with $\langle n \rangle \sim 1/V \sim R^{-4}$
- Farley (1970): Turbulence causes strong inward particle pinch (radiation belts)

- Dipole is simplest confinement field
- Naturally occurring high-β plasma ($\beta \sim 2$ in Jupiter)
- p and n_e strongly peaked

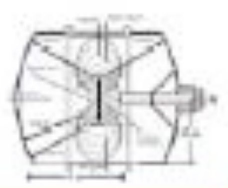
- Relevant to space science & fusion plasmas
- Hasegawa, [CPP&CF 1(1987)147]

  Can lead to advanced-fuel fusion power source

Magnetic topology determines equilibrium and stability

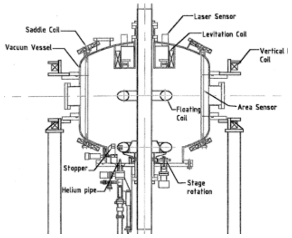
- Three magnetic topologies
  - Irrational flux surfaces, average well: tokamak, …
    - Equilibrium: plasma pressure ↔ field pressure ⇨ $\beta << 1$
    - Low frequency modes balloon
  - Open field lines: mirror … Equilibrium determined by $F = -\mu \nabla_{||} B$
  - Closed field lines: Dipole, ….
    - Equilibrium: plasma pressure ↔ field line tension ⇨ $\beta \sim 1$
    - Interchange-like modes $(k_{||} = 0)$
- Plasma – magnet arrangement
  - Plasma within coil set: tokamak, …
    - Easy access to coils, divertor difficult
  - Coil within plasma
    - Plasma easy to access, large flux expansion ⇨ easy divertor

Laboratory Dipole Experiments



CTX (Columbia)

150 kA turns
(Not Levitated)
0.15 m

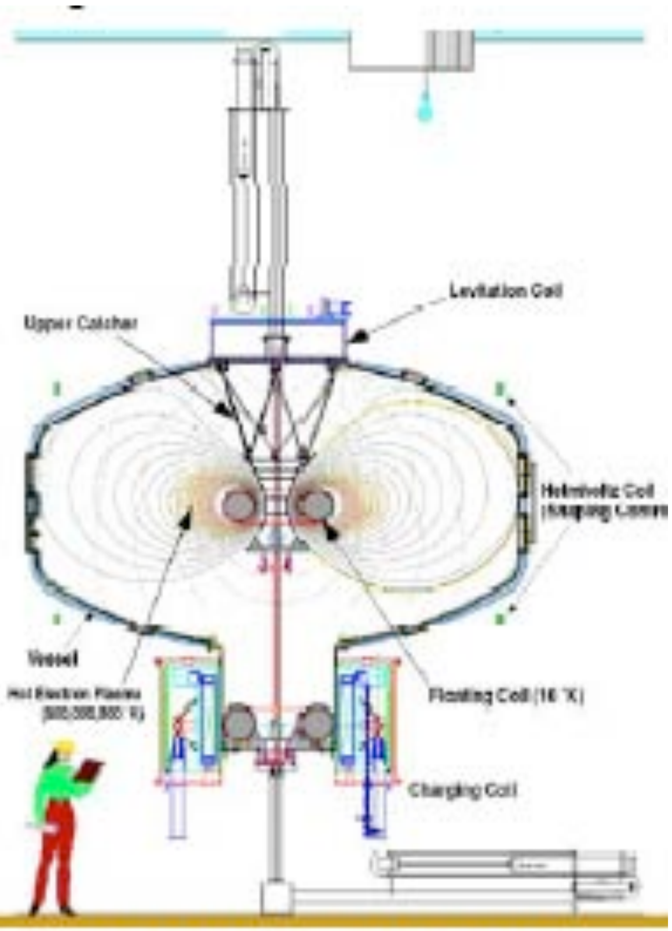


Mini-RT (Univ. Tokyo)

50 kA turns
17 kg
0.15 m

RT-1 (Univ. Tokyo)

250 kA turns
110 kg
0.25 m



LDX (Columbia-MIT)

1200 kA turns
565 kg
0.34 m

Unique properties of dipole field

- Coil inside of plasma
  - $B \sim 1/R^3$: Strong decay of field with radius
  - Field and plasma pressure fall off together leading to high average β
- Stability derives from plasma compressibility
  - Limit on pressure gradient ⇨ Small plasma in large vacuum chamber
- No shear ⇨ Large-scale adiabatic convection
- No toroidal field: $j_{||} = 0$ ⇨
  - No kink drive
  - No neoclassical transport

Superconducting Levitated Dipole Experiment (LDX)

Components of a Levitated Dipole Experiment:

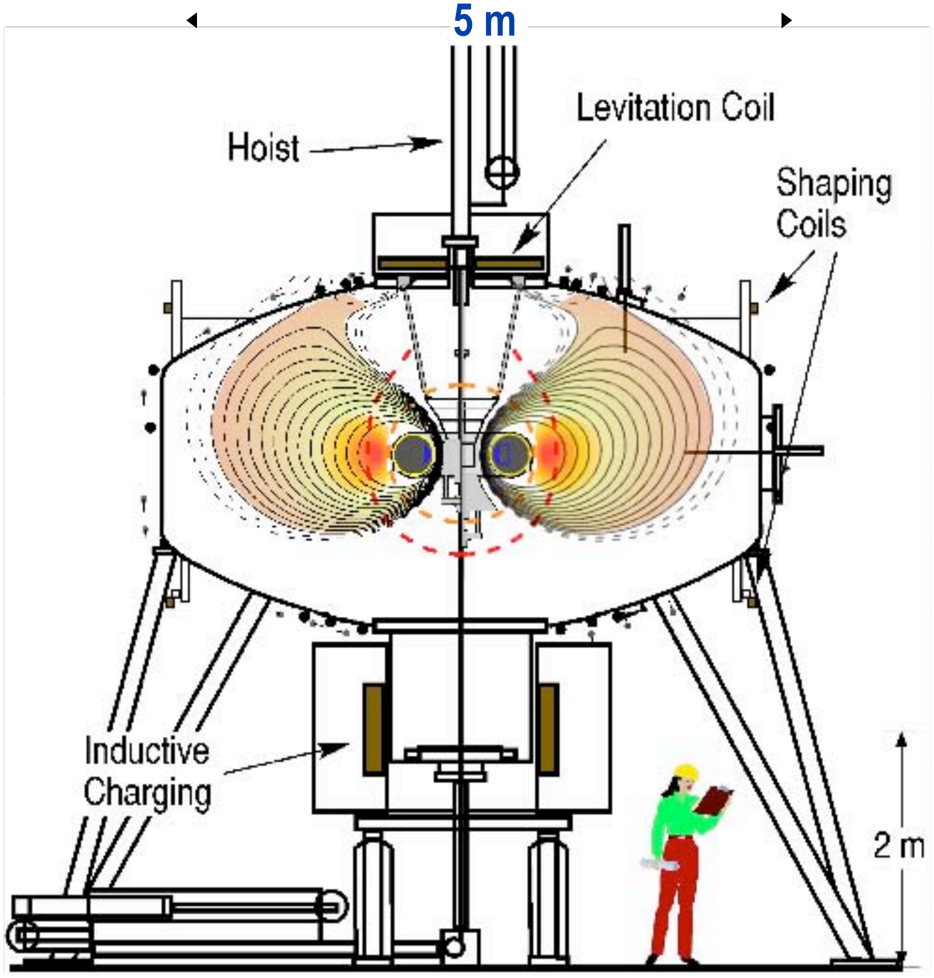
- **Strong superconducting dipole (B=3.5T) for long-pulse (3 hr), quasi-steady-state experiments**
- **Large vacuum chamber for excellent diagnostic access and large magnetic flux expansion**
- **Upper levitation coil for robust axisymmetric magnetic levitation**
- **Lifting/catching fixture for re-cooling, coil safety, and physics studies**
- **25 kW ECRH for high-temperature, high-beta plasmas**

LDX (MIT - CU)

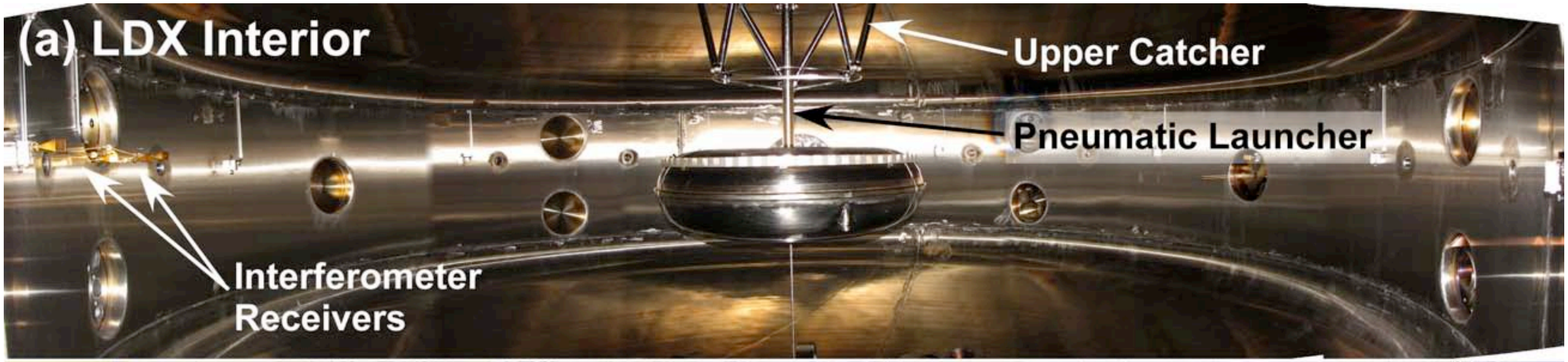
Nb_3Sn Dipole 1.2 MA

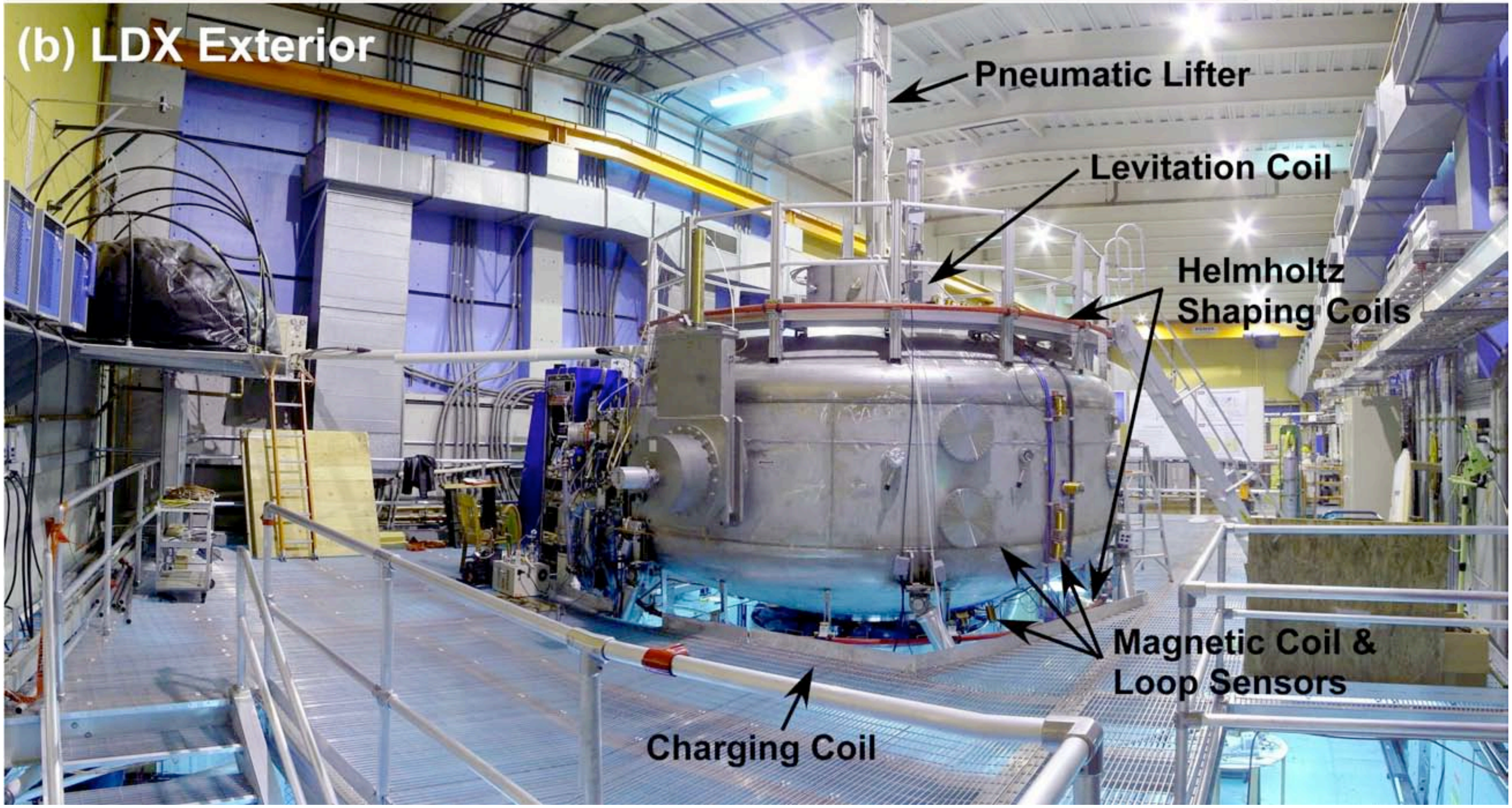
Inductively Charged

3 Hour Float Time 25 kW CW ECRH

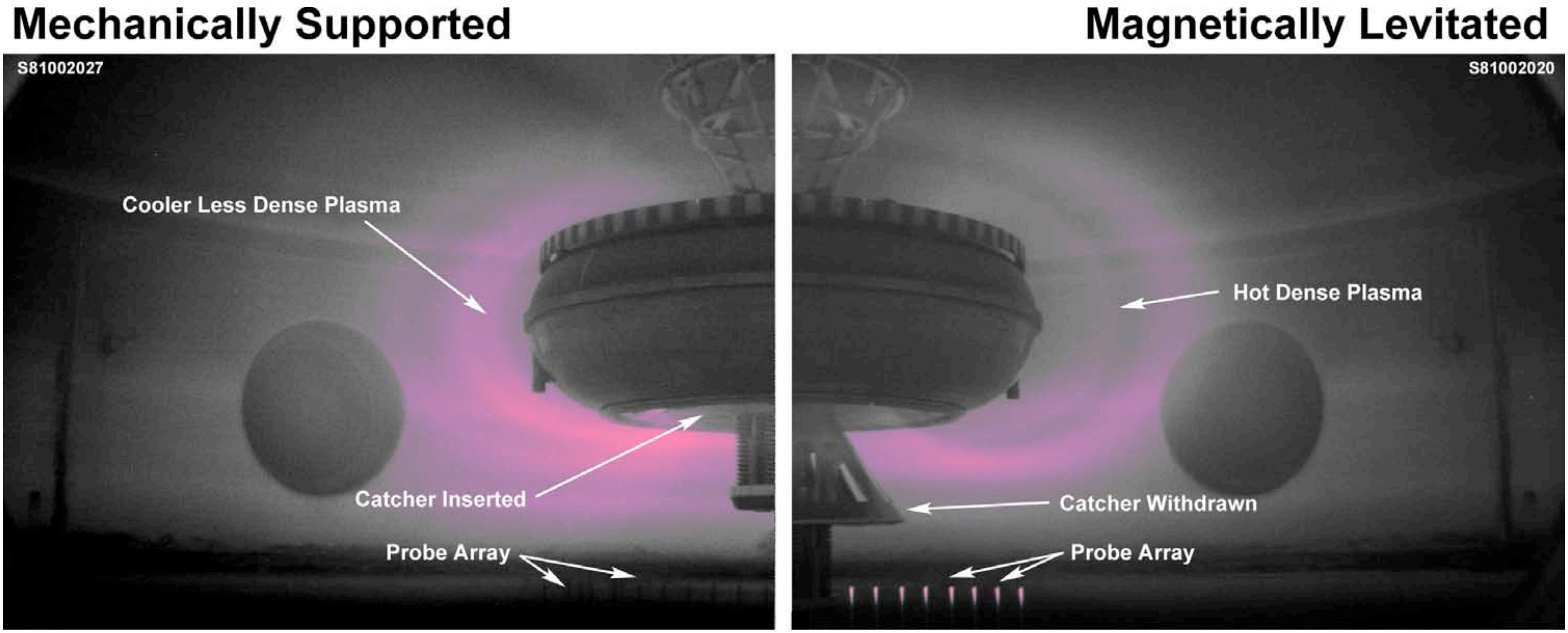


The Levitated Dipole Experiment (LDX)





LDX: Floating coil can be supported or levitated



- Observe ionization glow moves outwards with levitation.
  - ⇨ Profile determined by X-field transport.
- Supported mode: Losses to supports dominate X-field transport (mirror machine).

Main Experimental Results

- Low-frequency interchange instabilities dominate plasma dynamics
- Levitated dipole can achieve > 50% peak beta with levitation
- Turbulence drives plasma to very steep profiles and creates strong inward particle pinch

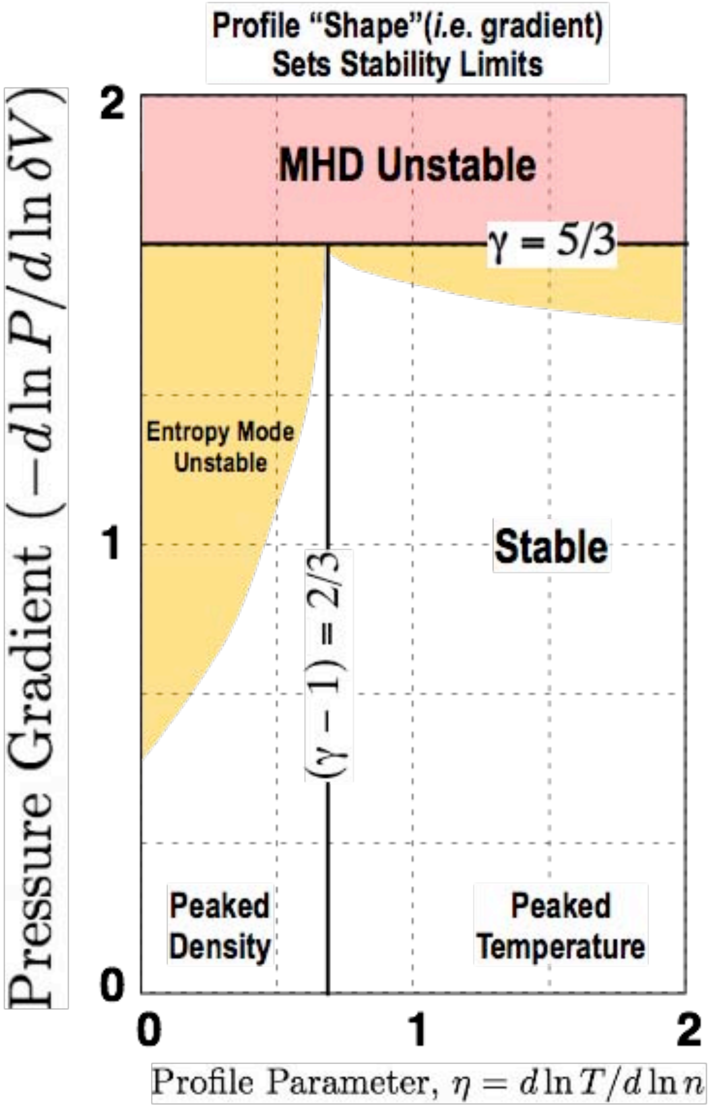
  - Pinch was first observed in the Magnetosphere
    [Farley et al. PRL (1970), Walt Space Sci. Rev. (1971)]

Stability: Dipoles exhibit both MHD and drift instability

- MHD unstable $\nabla p > (\nabla p)_{crit}$

$$-\frac{d\ln p}{d\ln V} \geq \gamma \quad V = \oint d\ell/B, \quad \gamma = 5/3$$

- Entropy mode drift-kinetic instability depends upon η.
- Entropy modes occur when either the density or temp profiles are not "stationary".
  - Stationary profiles at η=2/3
- Both MHD and entropy modes are flute-like.



Simple pinch derivation: Assume $\omega \ll \Omega_c, \omega_b$

- F-P eq. (turbulent equipartition) & conservation of μ and *j* :

$$\frac{\partial}{\partial t} f = \frac{\partial}{\partial \psi}\bigg|_{\mu,j} D^{\psi} \frac{\partial f}{\partial \psi}\bigg|_{\mu,j} \qquad \Rightarrow \qquad \Gamma(\mu,j) = -D^{\psi} \frac{\partial f}{\partial \psi}\bigg|_{\mu,j}$$

- Convert (μ, j) to (ε, j) and integrate. For $D(\mu,j) = D_0$

$$\Gamma = -D_0 \frac{\partial(nV)}{\partial \psi}, \quad \Gamma_s = -D_0 \frac{\partial(pV^{\gamma})}{\partial \psi} \qquad V = \oint d\ell / B, \quad \gamma = 5/3$$

D_0 results from MHD and/or drift (entropy) modes.

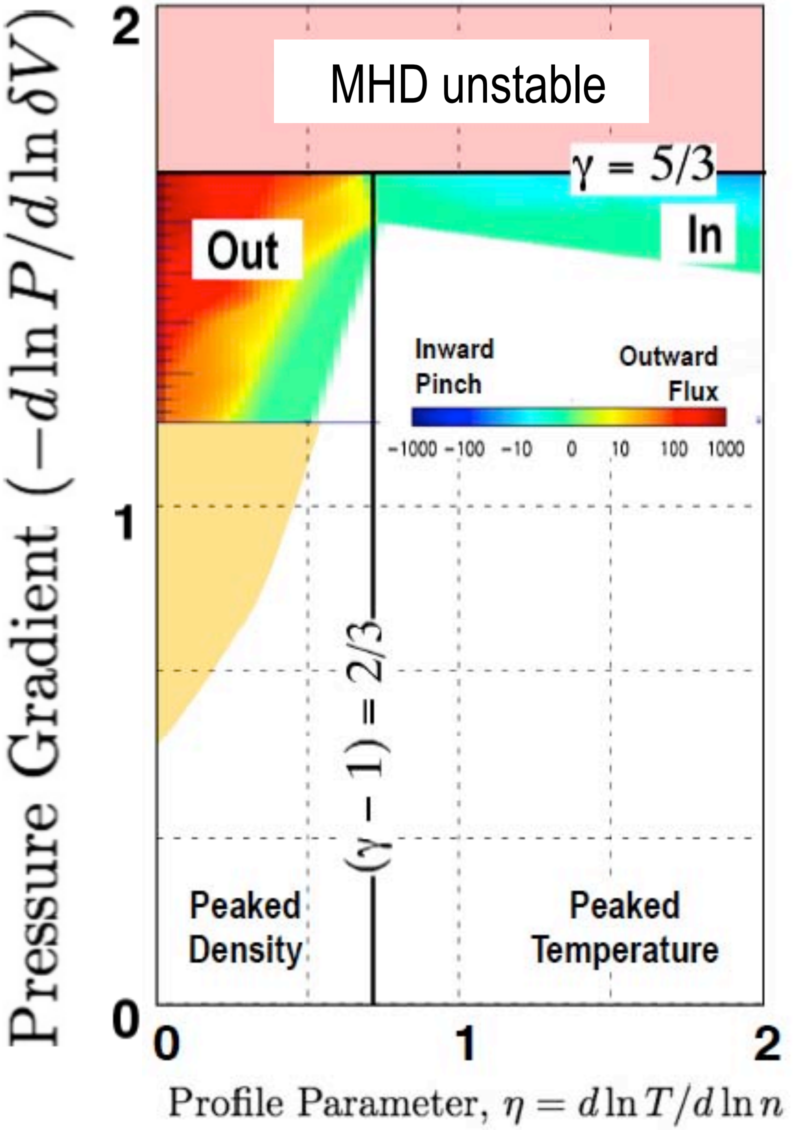
- Stationary states: $\Gamma, \Gamma_s \sim 0 \Rightarrow$ Constant $n_e V$ and pV^{γ} (MHD limit)

- ➢ Turbulence driven diffusion will tend to flatten gradients in N and s
- Combine Γ and set $\Gamma_s \sim 0$ $\Rightarrow$ $\Gamma \approx n_e D^{\psi} \frac{dV}{d\psi} \frac{(2/3 - \eta)}{(1 + \eta)}$
    - Pinch direction reverses sign at $\eta = 2/3$

Gyrokinetic simulations (GS2) corroborate turbulent pinch

- Entropy mode is unstable when MHD stable
- For η>2/3 pinch inwards;
    - i.e. for internal heating, edge fueling. Creates ``natural” profiles (η=2/3).
- Outwards energy flow accompanies inwards density pinch.
- MHD instability will similarly create pinch

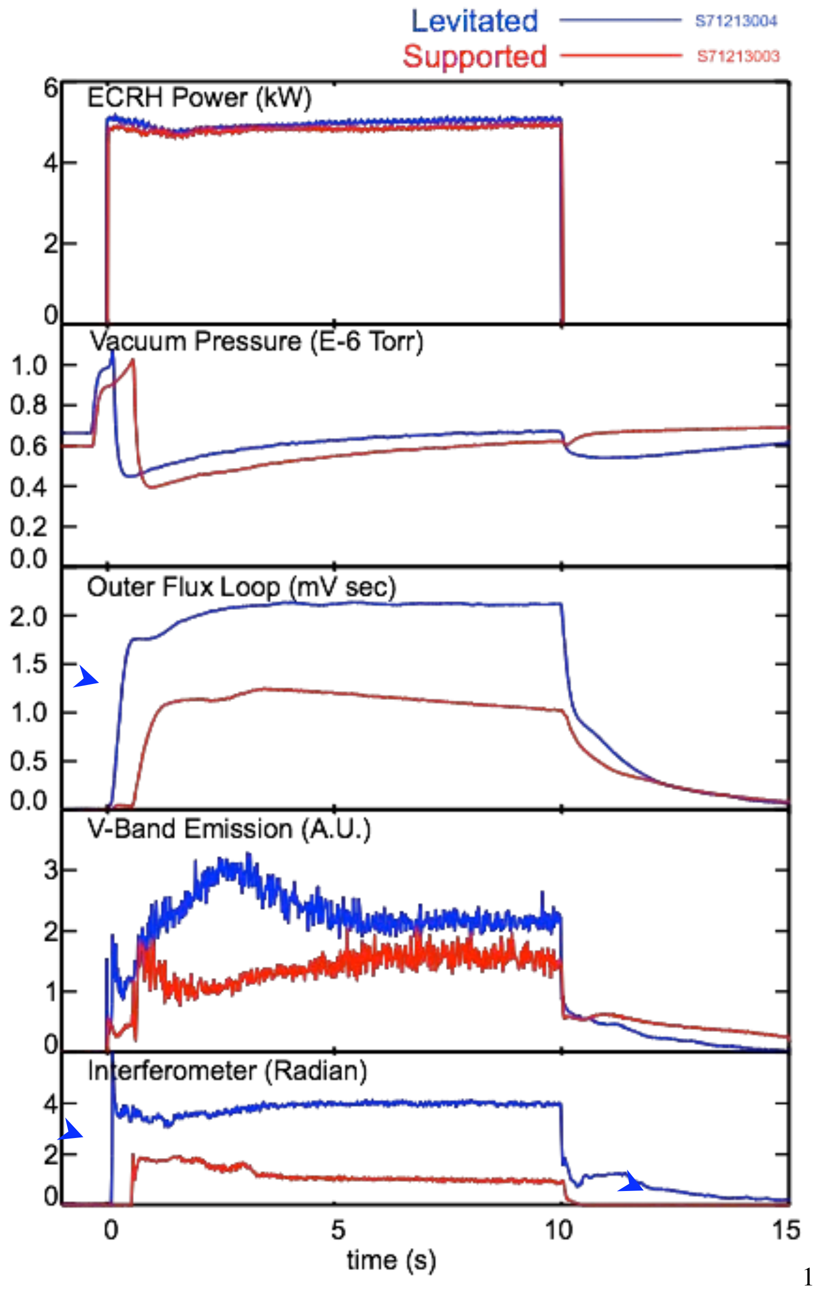
[Kouznetsov, Freidberg, Kesner, 2007].



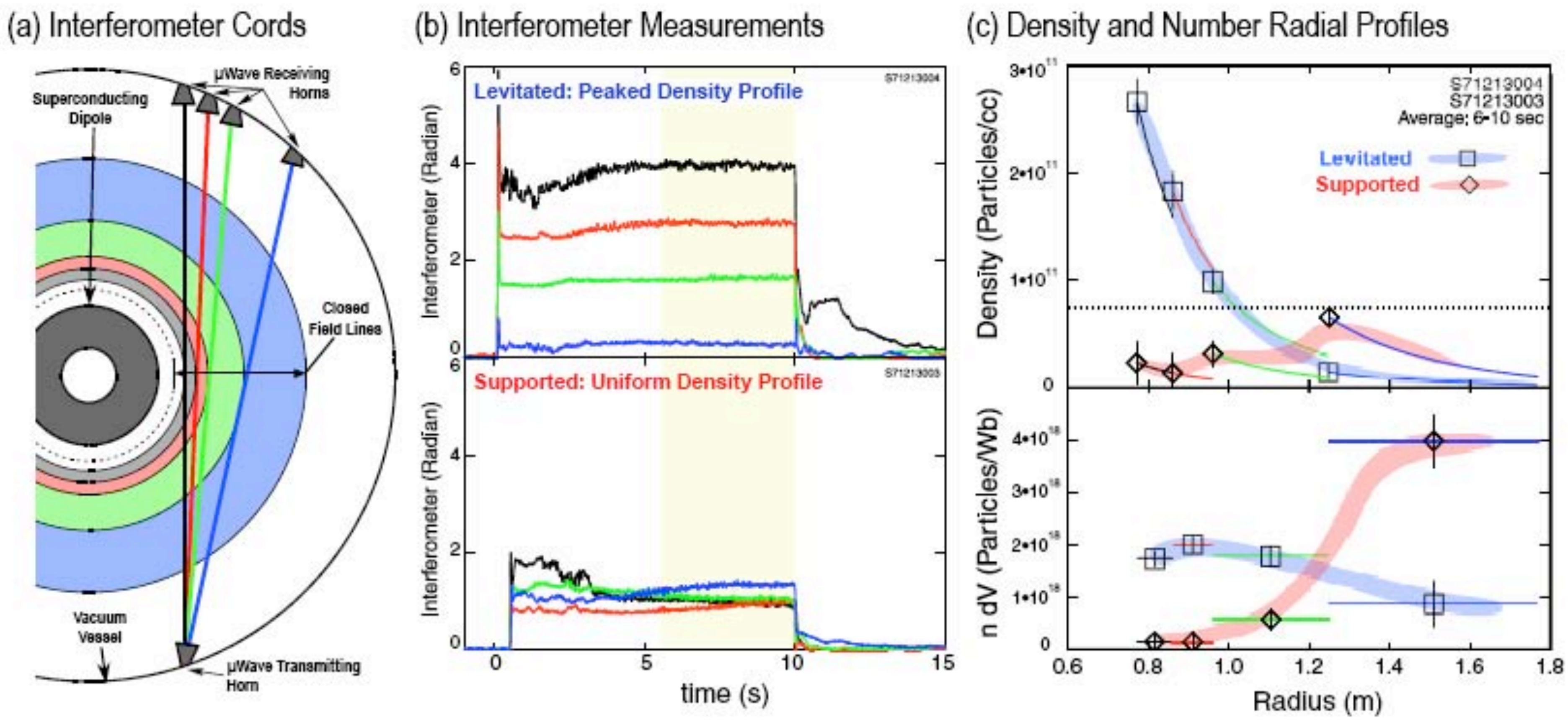
Kobayashi, Rogers, Dorland, PRL (2010)

Compare levitated and supported operation

- Levitation reduced fast electron instability
- Increased ratio of diamagnetism-to-cyclotron emission indicates higher thermal pressure.
- 2-3 x Diamagnetic flux
- Long, higher-density “afterglow” shows improved confinement.
- 3-5 x line density



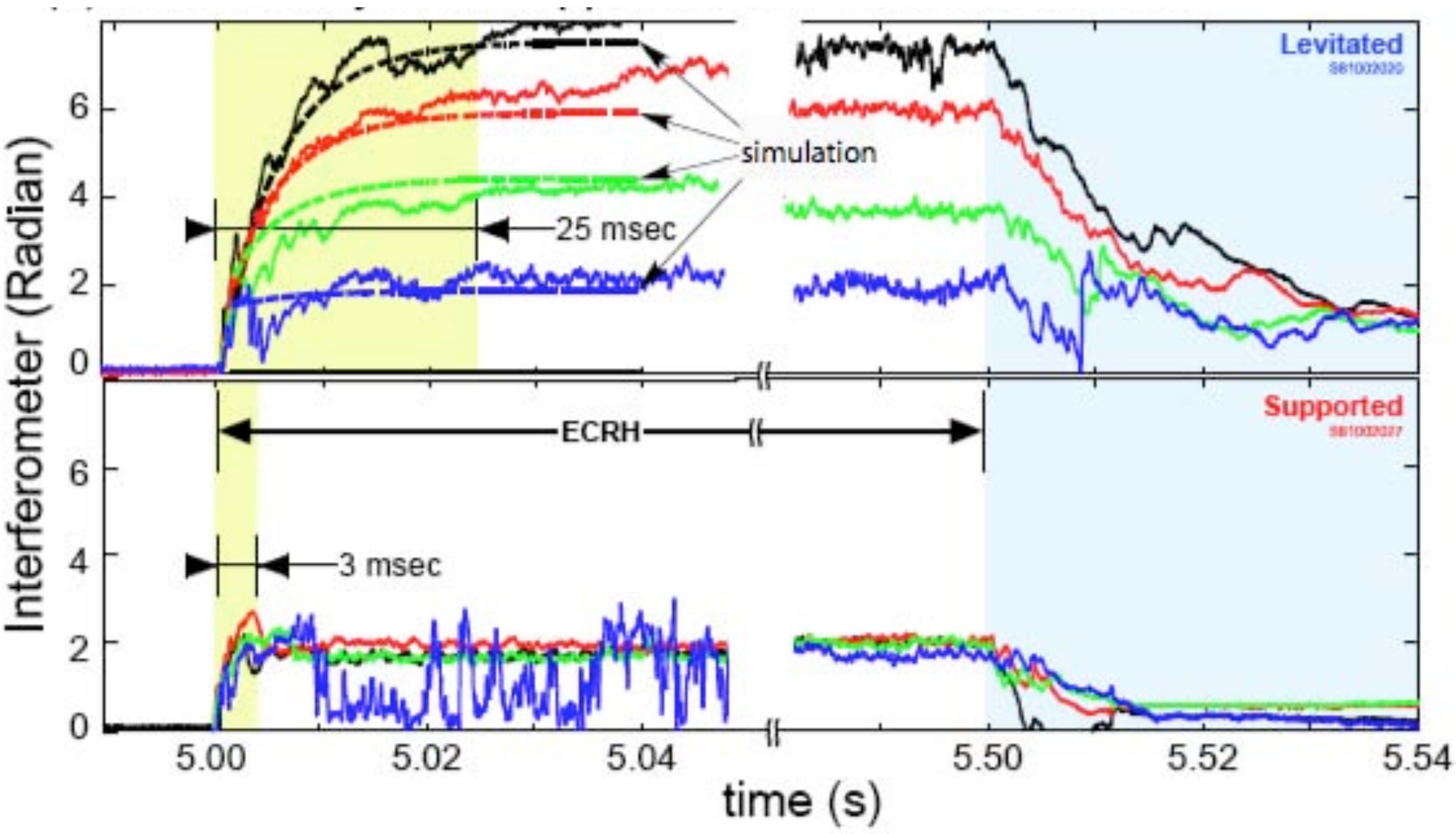
Multi-cord interferometer indicates strong density peaking during levitation



- Elimination of loss to supports ⇨ density pinch

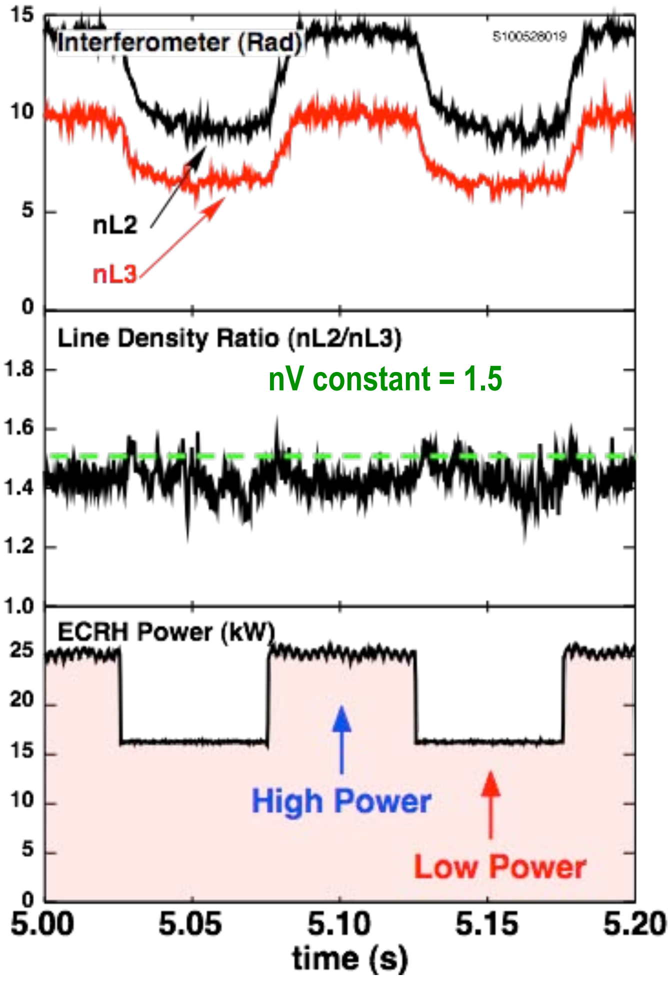
Higher turbulence level leads to a faster pinch

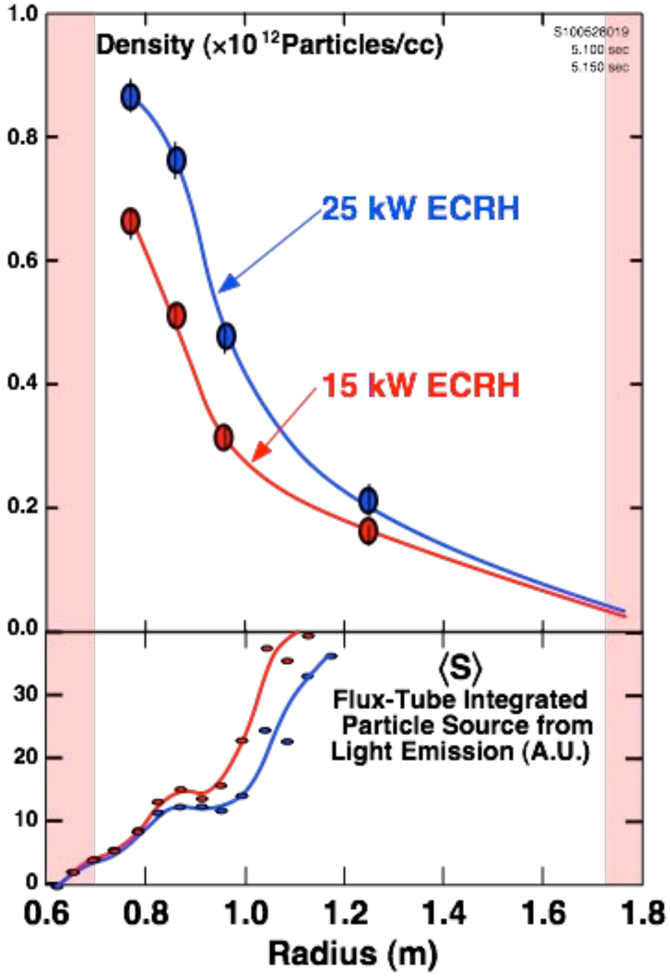
- D drives pinch $\Gamma = -D \frac{d(nV)}{d\psi} \quad V = \oint dl/B$
  - $D = R^2 \langle E_\phi^2 \rangle \tau_{corr} \approx 0.047\ V^2/s$ ($E\phi$, τ_{corr} from edge probes)
  - Probe measurements match pinch time of ~20 ms.



Heating modulation demonstrates robust inward pinch creating invariant profile

- 10 Hz 10 kW (10.5 GHz) ECH modulation
  - Density modulation follows power: invariant profile remains unchanged
  - Source moves radially outward at high power





Why is pinch particularly strong in a dipole?

- Pinch drives stationary profiles: $n_e \propto 1/V, \;\; p \propto 1/V^{\gamma} \qquad V = \oint dl/B$
  - Dipole : $B_{dipole} \propto 1/R^3 \Rightarrow V \propto R^4$
  - Tokamak: $V_{tok} \propto q$
- Trapped particles drive pinch:
  - ⇨ All particles effectively “trapped” (no toroidal streaming)
- Both MHD and drift frequency instabilities are flute-like
  - ⇨ All particles equally effected
  - ⇨ When $D = D(\lambda)$ must include D in integral $\Gamma = -\iint d\mu dj \; D^{\psi} \left. \frac{\partial f}{\partial \psi} \right|_{\mu, j}$
- For $pV^{\gamma} \approx constant$ no substantial outwards energy flux
  - In tokamak with average well the MHD (bad curvature) pressure limit does not apply:

$$-\frac{d \ln p}{d \ln V} > \gamma$$

For invariant profiles τ_E/τ_P set by edge physics

- For $p \propto 1/V^{\gamma}$, $E_{tot} = p_{sol}(\frac{3}{2}R_{sol}^{3}(R_{sol}/R_0)^{11/3})$ $V = \oint d\ell/B$
  - Define $\tau_E = E_{tot}/P_{tot}$. Note 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: $\frac{\tau_E}{\tau_P} = \frac{3}{2}(R_{sol}/R_0)^{8/3}(ST_{sol}/P_{tot}) \approx 10-50$

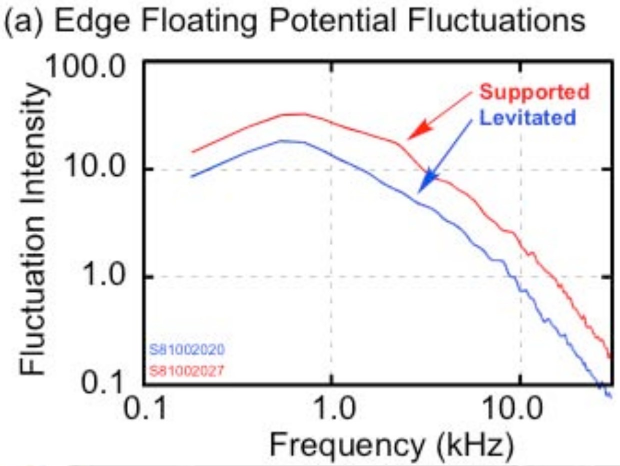
⇨ Energy and particle confinement set by SOL flows. Turbulence level will rise to create sufficient outflows.

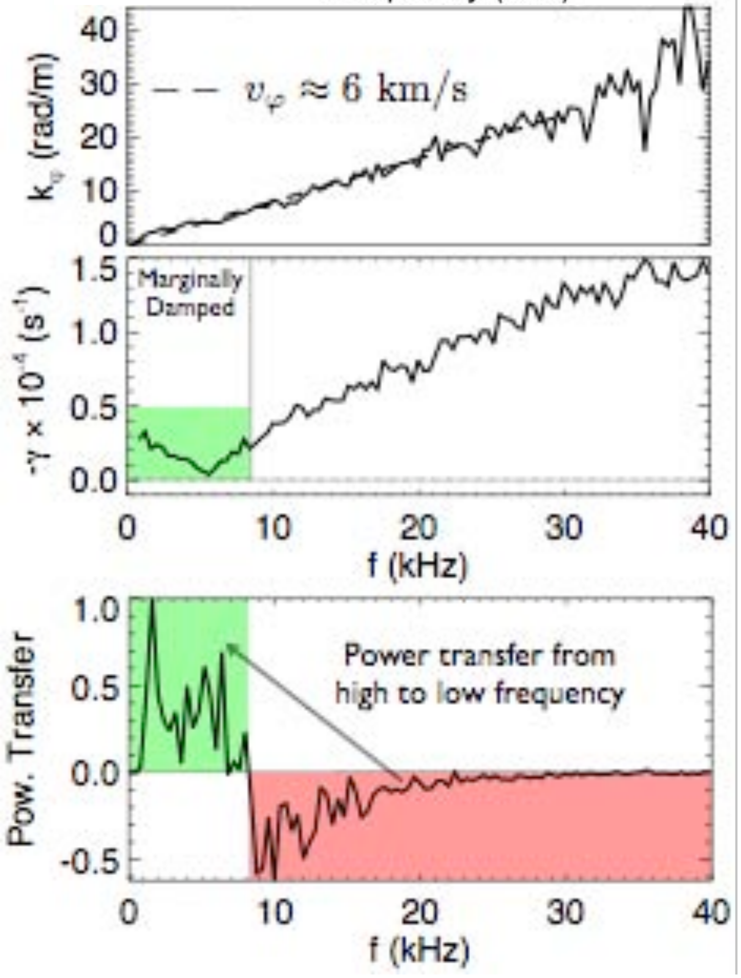
⇨ τ_E/τ_P is large and depends only on geometric factors (flux expansion)

Turbulence is similar in levitated and supported plasmas:

- 2D turbulence conserves energy and enstrophy* (vorticity)^2 leading to inverse cascade.
- CTX (Columbia): measured linear growth and quadratic coupling coefficients.
- Observe inverse cascade.
- Levitation eliminates end losses leading to dominant X-field transport

* R. Kraichnan, *Phys. Fluids* **10** (7) 1967

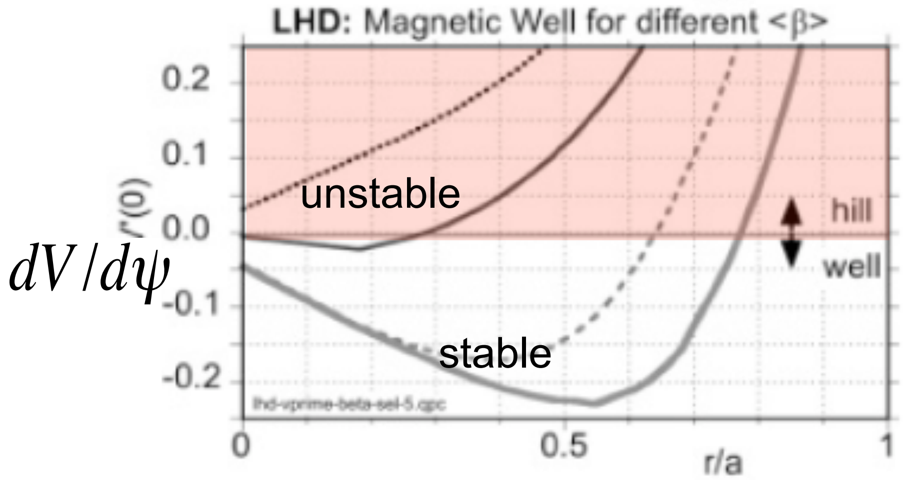

(a) Edge Floating Potential Fluctuations



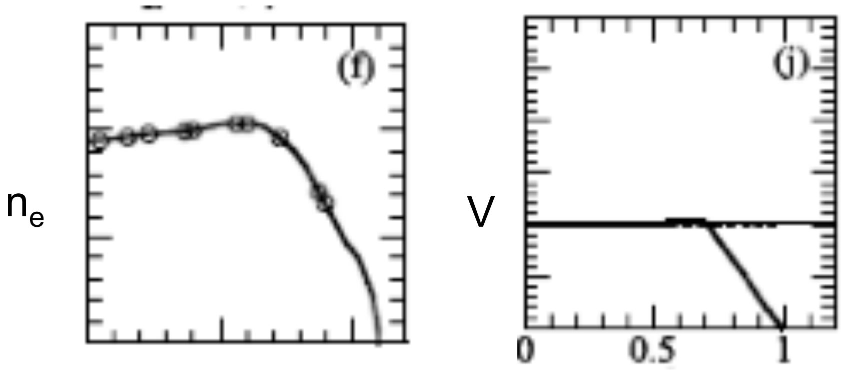
Stellarator pinch (LHD)

- Strong pinch is observed in outer LHD region
- Pinch in bad curvature region indicates MHD drive
- Off-axis density peaking observed

$$\Gamma \propto -n_e \frac{dV}{d\psi}, \quad V \equiv \oint \frac{dl}{B} = \oint \frac{dl}{rB^2 R_c}$$

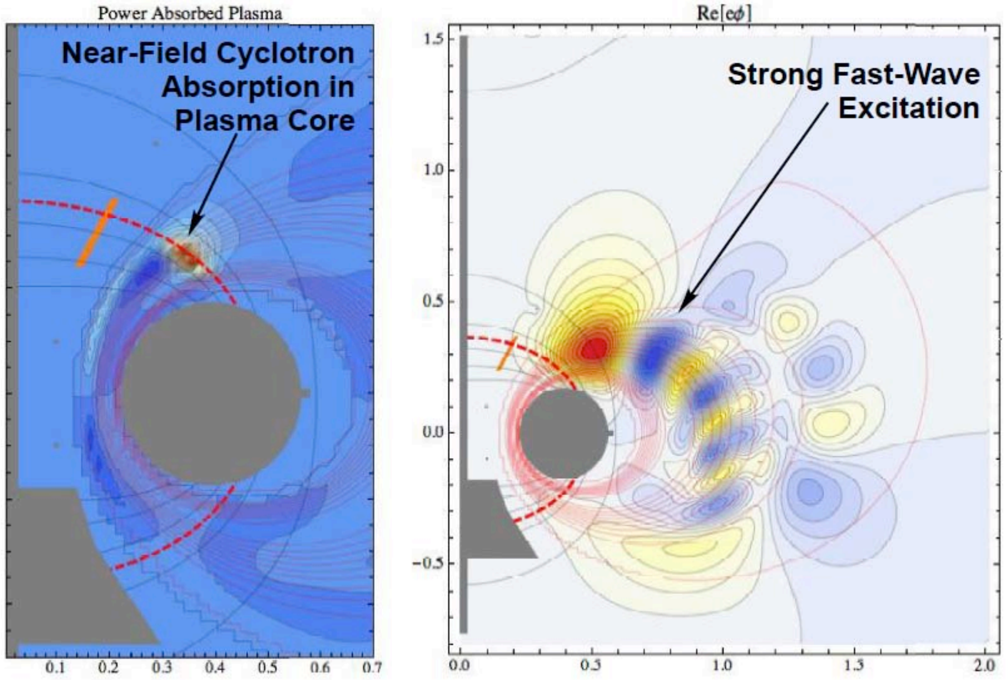


Weller et al, F.S. & T, (2006)



Tanaka et al, P. S. &T, (2010)

The next step for LDX was an ICRF upgrade


Power Absorbed Plasma

Near-Field Cyclotron Absorption in Plasma Core

Re[eϕ]

Strong Fast-Wave Excitation

- Obtain fusion relevant plasma densities with thermal ions

  $\beta \sim 1$, $n_e > 10^{19}$ m^{-3}, 500 eV ion thermal plasmas

  - 1 MW HF transmitter is on-site will allow 200 kW absorbed power.

    Heating scenario has been developed: m=0 high field antenna heats with near field and fast & slow waves

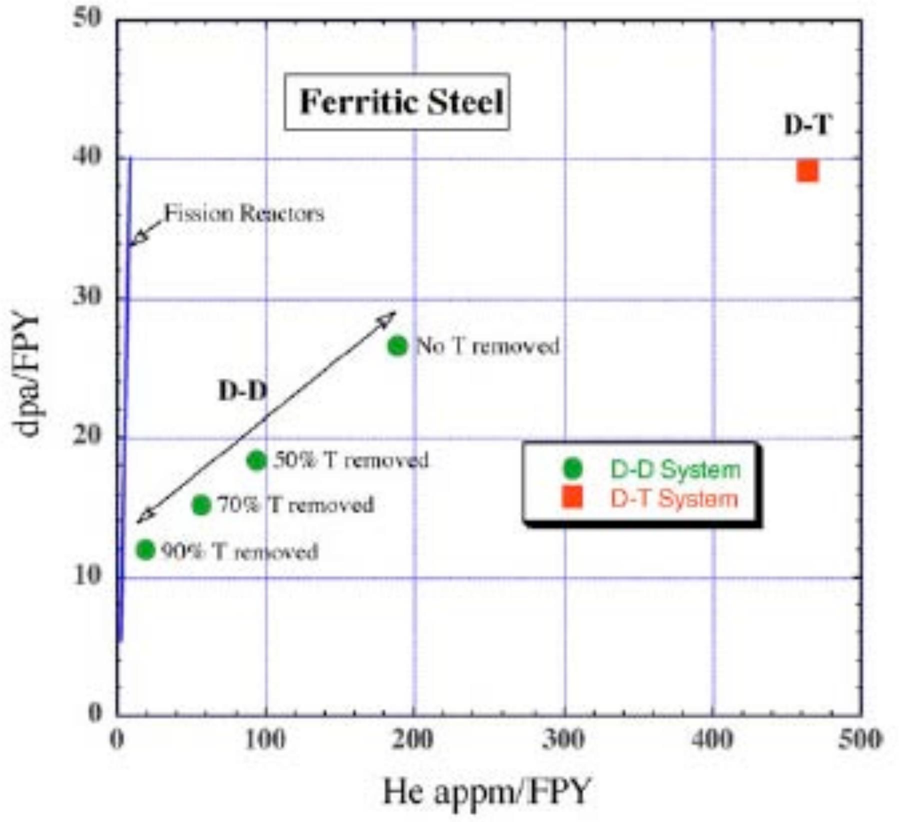
Dipole is ideal for tritium-suppressed fusion

- DT has difficult issues relating to materials damage (swelling and DPA) from 14 MeV neutrons and to tritium breeding.
- DD cycle, removing secondary T, would ameliorate problem.

$$D+D \quad \begin{array}{l} \rightarrow He^{3}+n \\ \rightarrow T+p \end{array}$$

- requires $\tau_P \ll \tau_E$ for T removal
- Similarly $\tau_P \ll \tau_E$ for ash removal
- Burn secondary ^{3}He
  - T decays to ^{3}He
- T-suppressed power source would reduce DPA/He to fission levels
- Dipole has $\tau_P \ll \tau_E$, high β, no interlocking coils.

Kesner et al, Nuc Fus 44 (2004) 193



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

Summary: Attractiveness of Dipole

- Dipole research presents novel physics, challenging engineering and an attractive fusion confinement scheme
  - Steady state
    - No current drive needed (need internal refrigerator)
  - Disruption free
  - High β
  - Low wall loading
  - $\tau_E >> \tau_p$
- LDX focus has been:
  - Formation of "stationary" (peaked) density and pressure profiles
  - Stability and β limits
  - Evaluation of τ_E , τ_p and τ_E/τ_p
  - Physics of energetic minority species

Prudent approach for fusion energy should include different confinement schemes and advanced (non D-T) fuel cycles

- Dipole avoids:
  - Disruptions
  - Current drive
  - Over-constrained equilibrium
  - Interlocking magnets
- Tritium suppressed D-D avoids:
  - 14 MeV neutron damage
  - tritium breeding