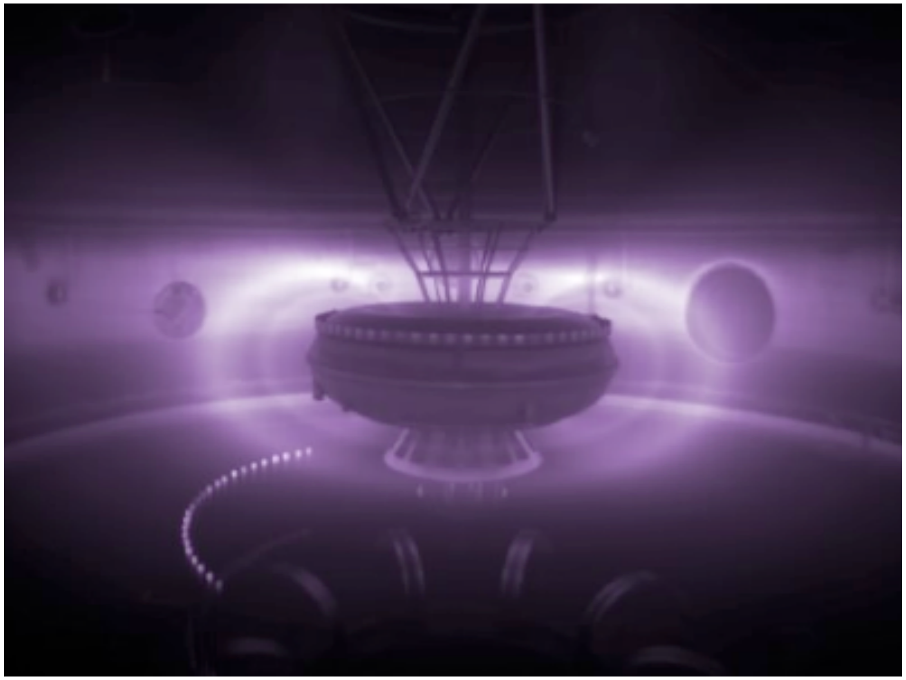

Results from the Levitated Dipole Experiment

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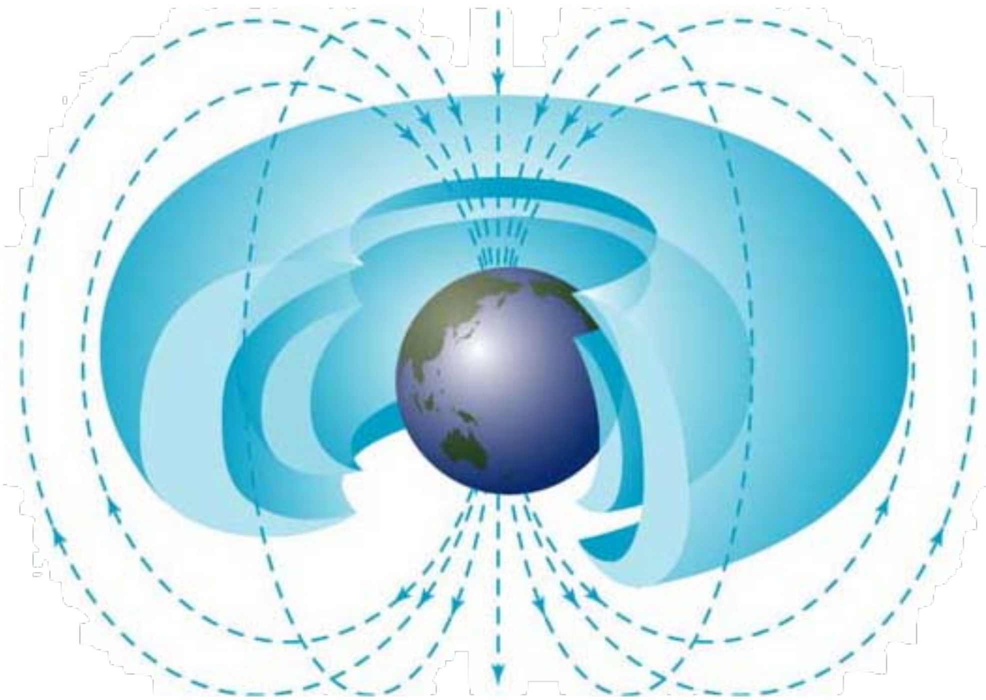
FES: Advance the fundamental science of magnetically confined plasmas

- Too early to narrow research to tokamaks (disruptions, steady state, …)
- Different pathways lead naturally to breadth in science and technology
- Example: Confinement in the field of a levitated dipole
  - Unique physics illuminated by closed field line systems
  - Unique technology challenges: superconducting magnet development

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



- Gold (1959): Plasma pressure is centrally peaked with $p \sim 1/\delta V^{\gamma} \sim R^{-20/3}$
- Melrose (1967): Plasma density is centrally peaked with $\langle n \rangle \sim 1/\delta V \sim R^{-4}$
- Farley et al. (1970): Turbulence causes strong inward particle pinch (radiation belts)
- Adriani et al. (2011): Discovery of geo-magnetically trapped cosmic-ray antiprotons

- 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]

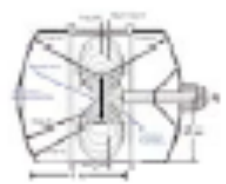
Can lead to advanced-fuel fusion power source

Magnetic topology determines equilibrium and stability

- Two basic toriodal magnetic topologies
  - Irrational flux surfaces, average well: tokamak, …
    - Equilibrium: plasma pressure ↔ field pressure ⇨ $\beta<0.1$
    - Low frequency drift modes balloon to outside
  - Closed field lines: Dipole, ….
    - Equilibrium: plasma pressure ↔ field line tension ⇨ $\beta\sim1$
    - Drift modes are Interchange-like

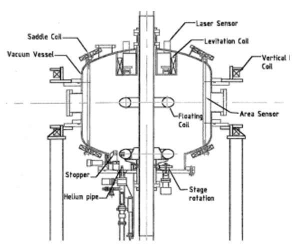
- Plasma – magnet arrangement
  - Plasma within coil set: tokamak, …
    - Easy access to coils but divertor, disruption difficulty
  - Coil within plasma
    - Plasma easy to access, large flux expansion, good field utilization

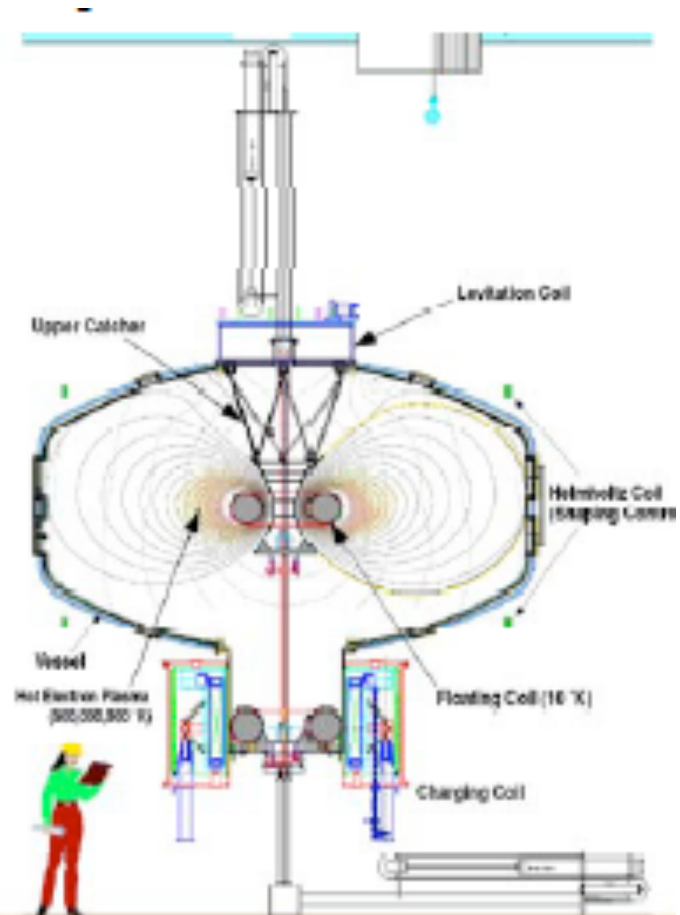
Laboratory Dipole Experiments



CTX (Columbia)

150 kA turns
(Not Levitated)
0.15 m





Mini-RT (Univ. Tokyo)

50 kA turns
17 kg
0.15 m

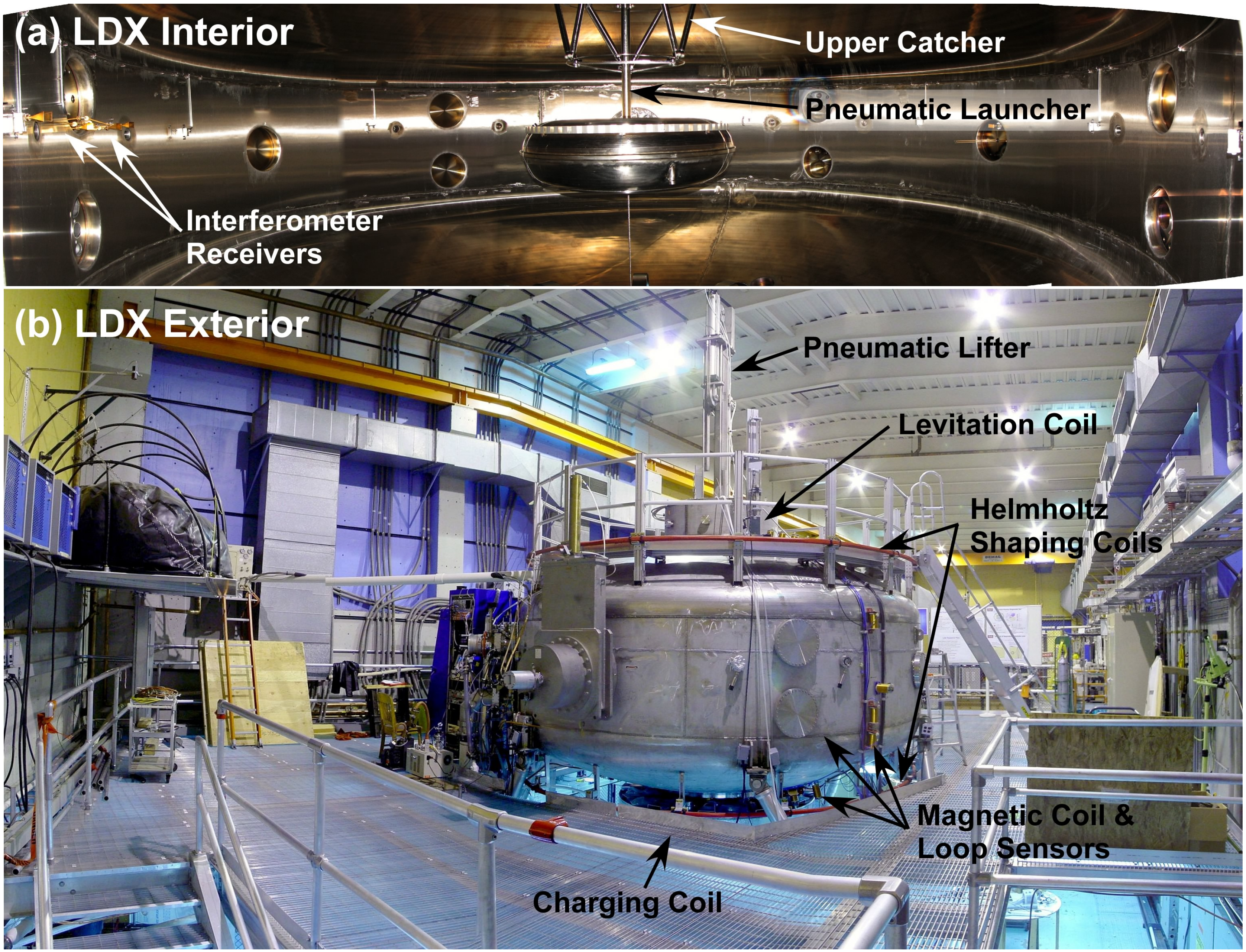
RT-1 (Univ. Tokyo)

250 kA turns
110 kg
0.25 m

LDX (Columbia-MIT)

1200 kA turns
565 kg
0.34 m

The Levitated Dipole Experiment (LDX)

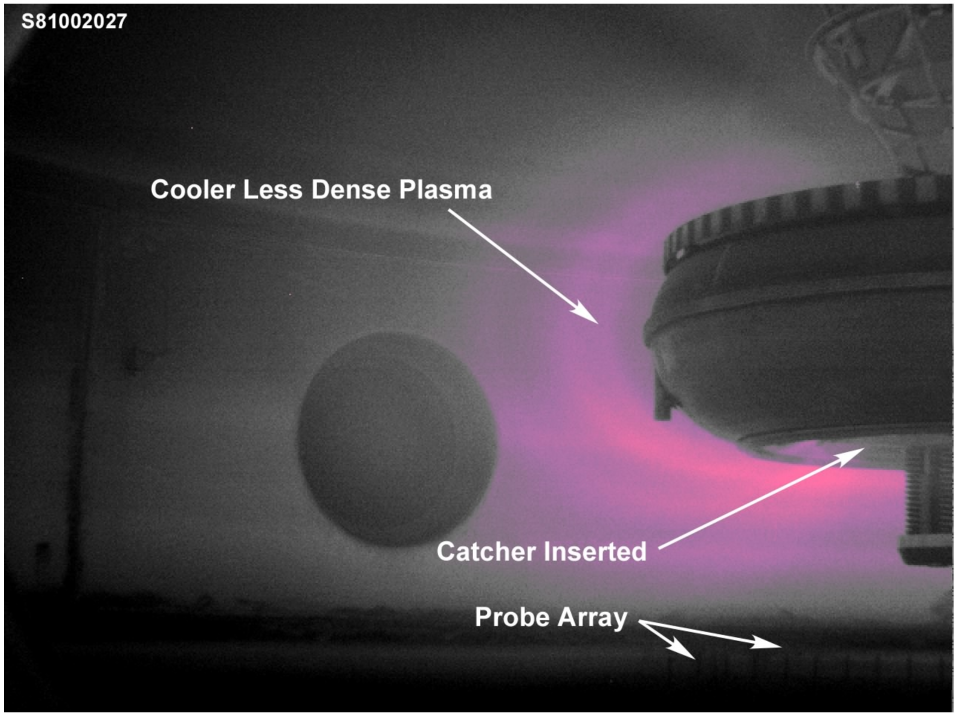


Unique properties of dipole field

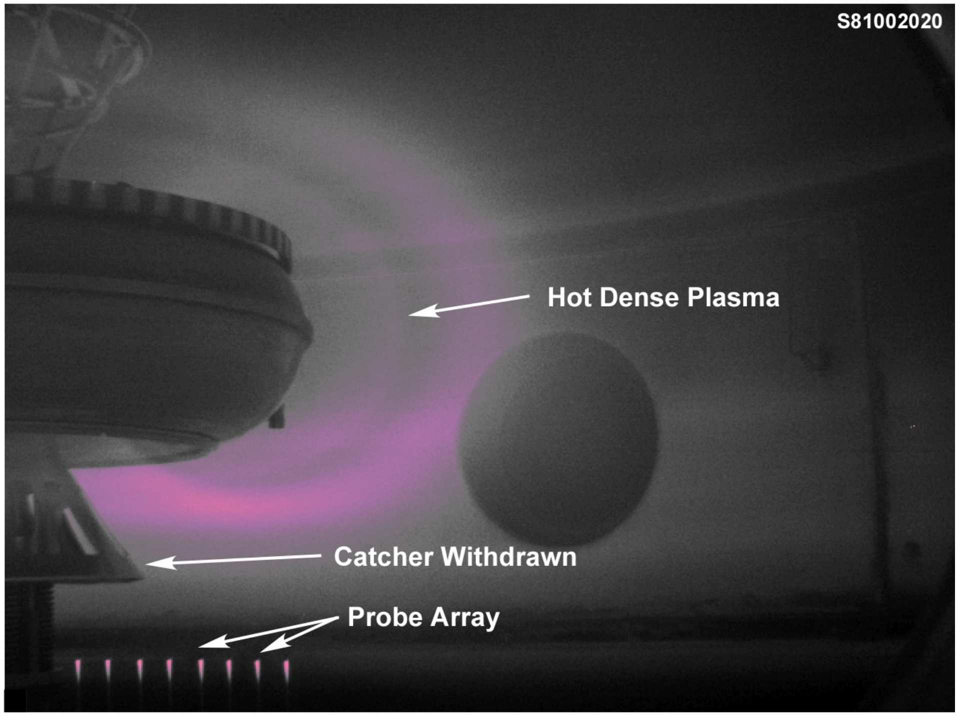
- Coil inside of plasma
  - $B \sim 1/R^3$: Strong decay of field with radius
  - Field and plasma pressure fall off together leading to high average β
- Stability derives from plasma compressibility
  - MHD stability limit on pressure gradient ⇨ Small plasma in large vacuum chamber
- No magnetic shear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

LDX: Floating coil can be supported or levitated

Mechanically Supported



Magnetically 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
- **Very high peak beta** (> 50%) with levitation
- **Turbulence drives plasma to very steep profiles and creates strong inward particle pinch**
  - While Farley,Tomassian, Walt [*PRL* (1970)] were the first to observe the collisionless inward pinch in the magnetosphere
  - LDX was the first to clearly observe a strong inward turbulent pinch in a laboratory plasma

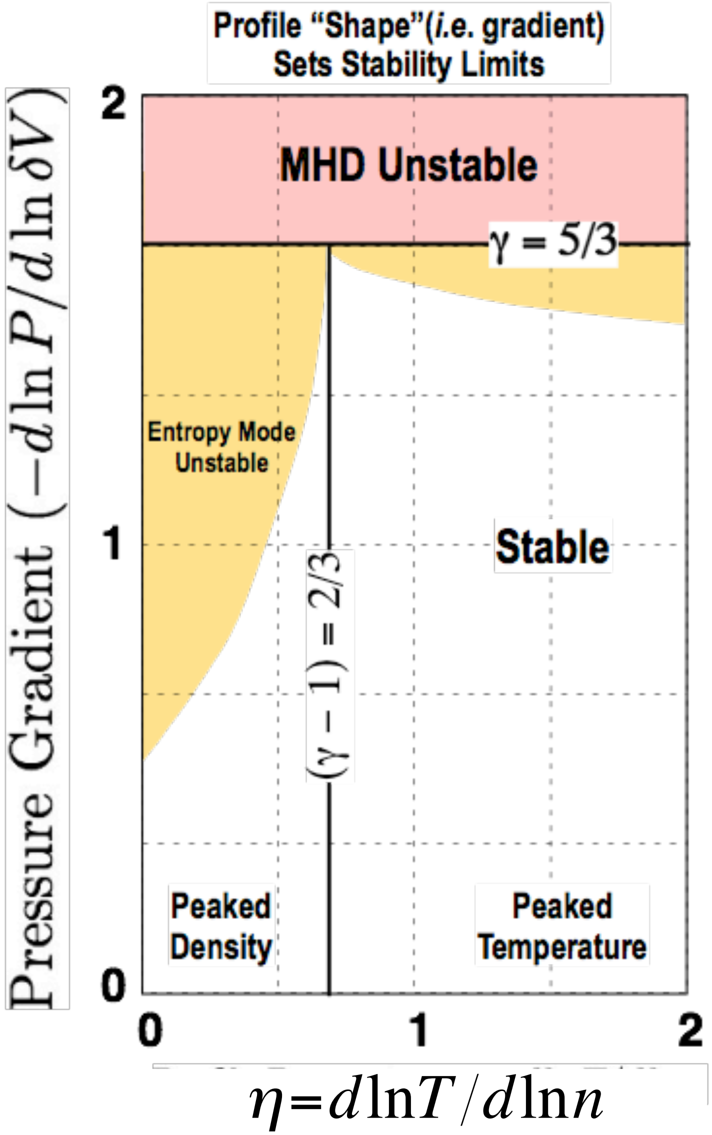
Stability: Dipoles exhibit both MHD and drift instability

- MHD stability $\nabla p < (\nabla p)_{crit}$

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

- Entropy mode drift-kinetic instability depends upon $\eta = \frac{n \nabla T}{T \nabla n}$

- Both MHD and entropy modes are flute-like.



Simple pinch derivation:

- Assume turbulence frequency<< bounce, cyclotron frequency
- F-P eq. (turbulent equipartition) & conservation of μ & $j(=\oint v_{||} ds)$

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

- Velocity space integration: For constant D_t

$$\Gamma = -D_{t0} \frac{\partial (n\delta V)}{\partial \psi} \quad \Gamma_s = -D_{t0} \frac{\partial (p\delta V^{\gamma})}{\partial \psi} \qquad \delta V = \oint d\ell / B, \quad \gamma = 5/3$$

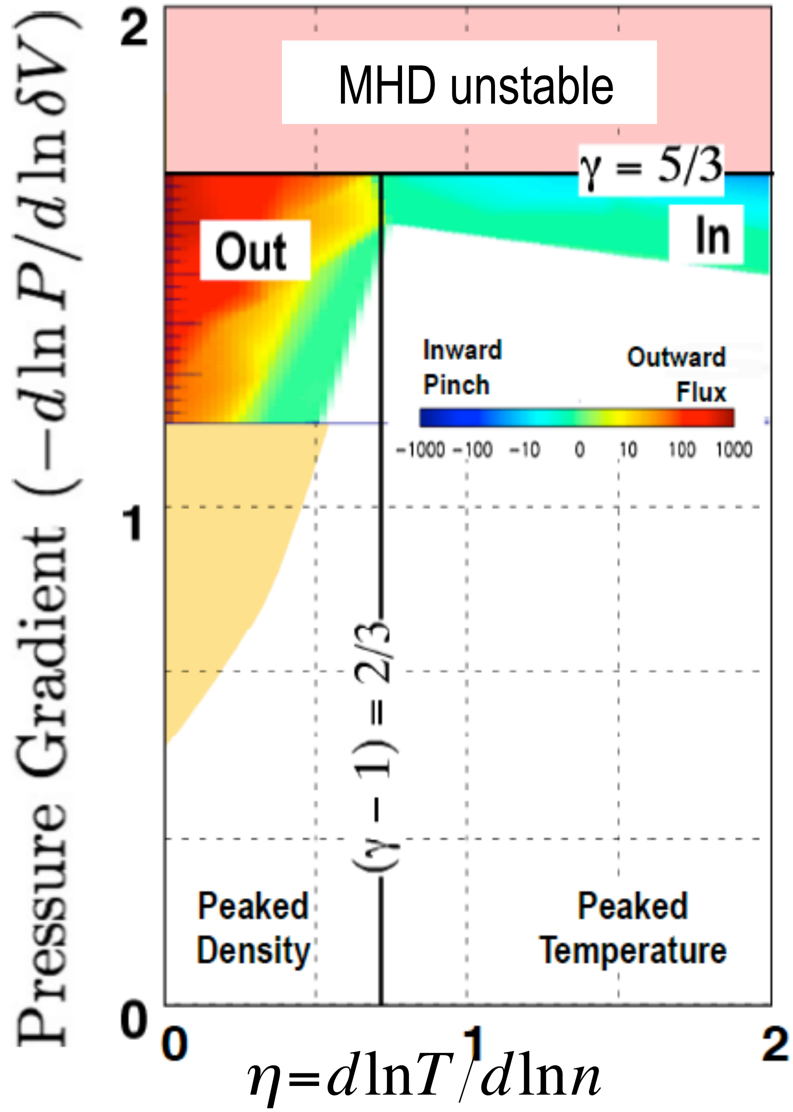
➤ Stationary states: $\Gamma, \Gamma_s \approx 0 \Rightarrow n_e \propto 1/\delta V, \quad p \propto 1/\delta V^{\gamma}$

➤ $\Gamma = -D_0 \frac{\partial (n\delta V)}{\partial \psi} = -\hat{D}\, \nabla n + n\hat{V}$

Gyrokinetic simulations (GS2) corroborate turbulent pinch

When MHD is stable & entropy mode is unstable:

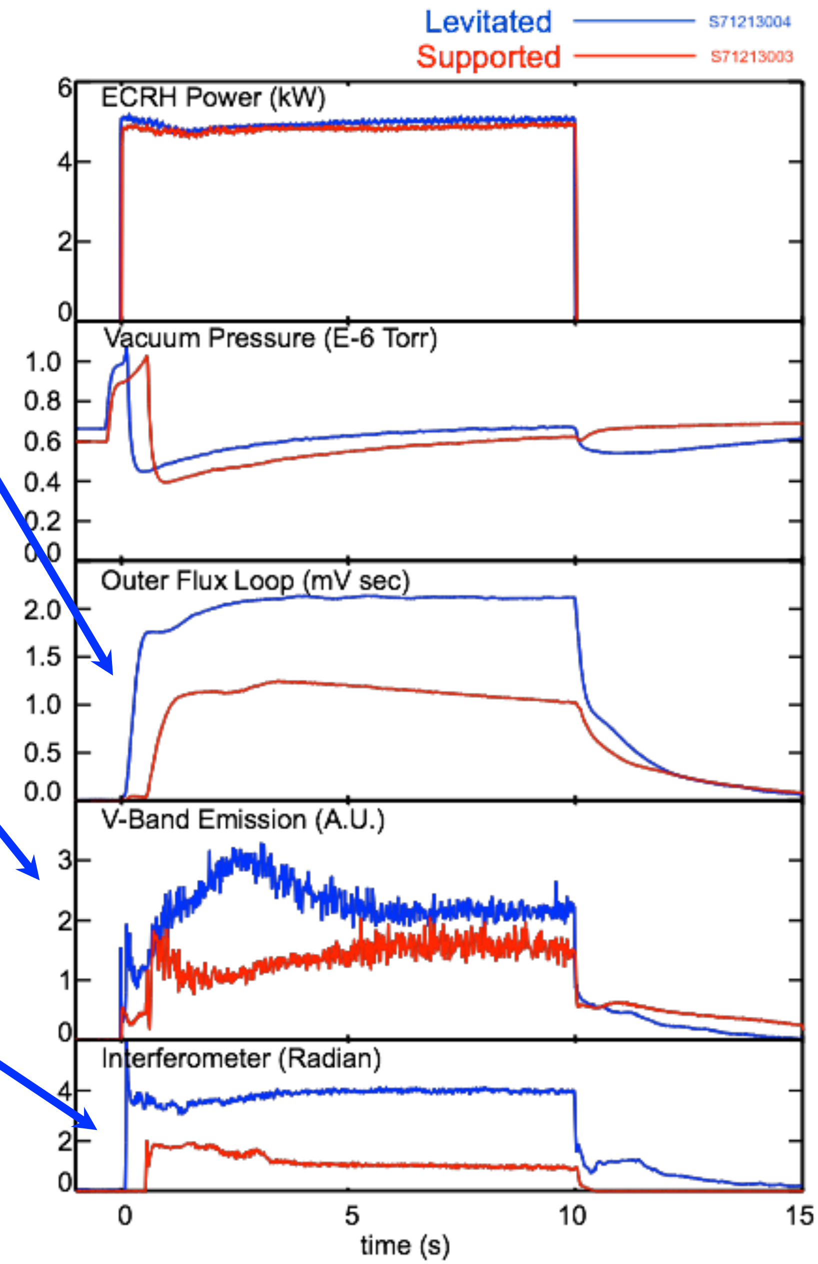
- For η>2/3 pinch inwards;
  - Outwards energy flow accompanies inwards density pinch & visa versa.
  - LDX: internal heating, edge fueling yields η>2/3.
- MHD instability will similarly create pinch [Kouznetsov, Freidberg, Kesner, 2007].



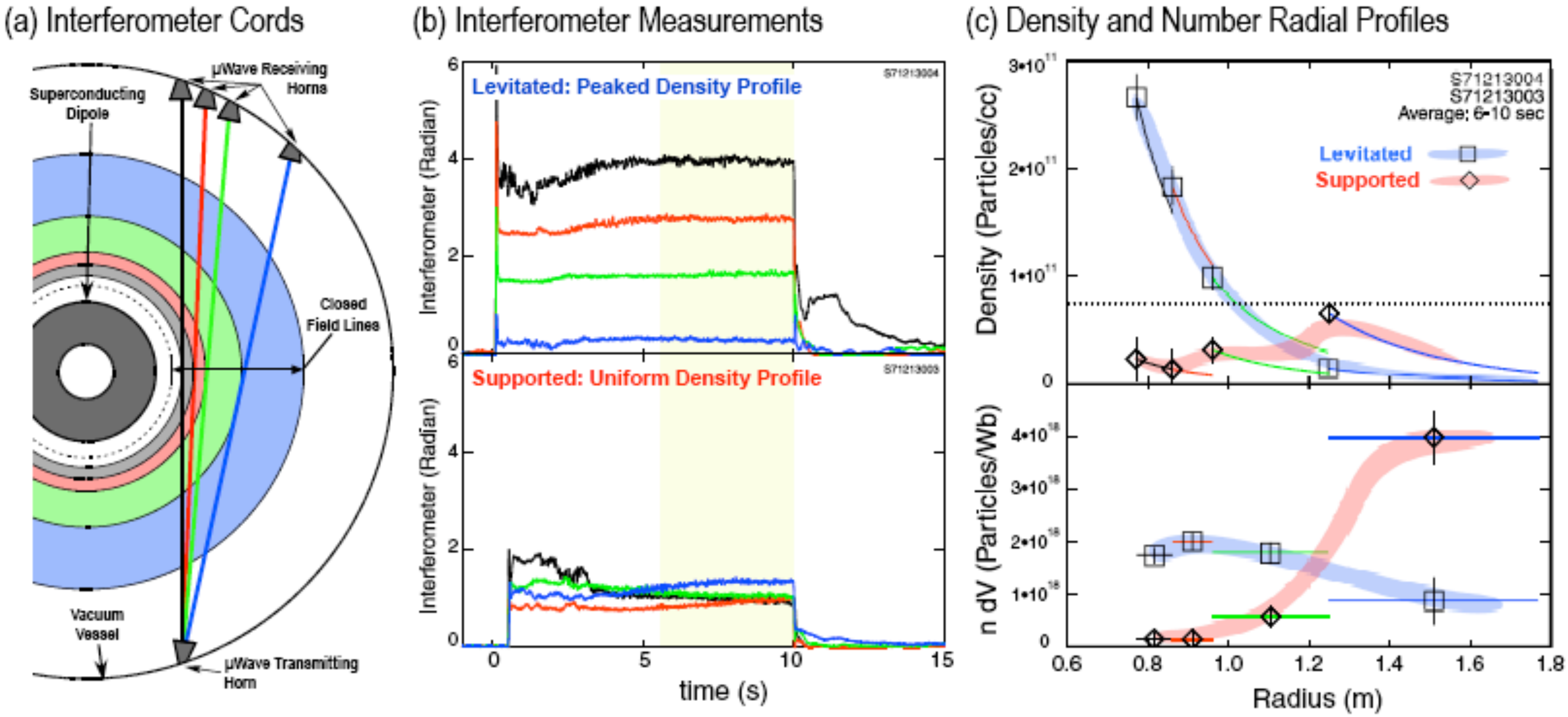
Kobayashi, Rogers, Dorland, PRL (2010)

Compare levitated and supported operation

- 2-3 x Diamagnetic flux
- Increased ratio of diamagnetism-to-cyclotron emission indicates higher thermal pressure
- 3-5 x line density



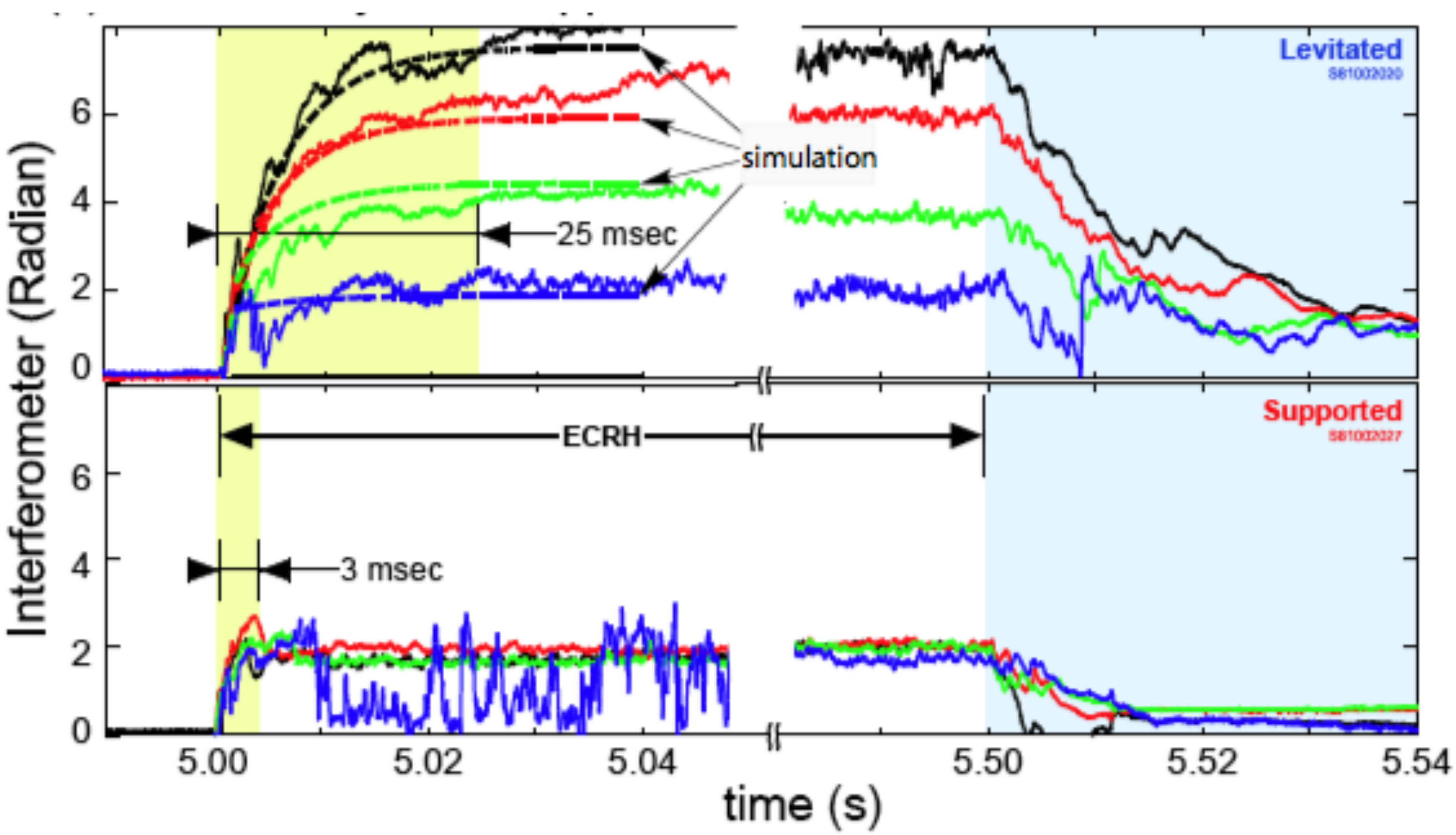
Multi-cord interferometer indicates strong density peaking during levitation



- Elimination of loss to supports ⇨ density pinch

Observed density evolution matches expectations

- D drives pinch $\Gamma = -D\frac{d(n\delta V)}{d\psi}$ $\delta V = \oint dl/B$
  - $D = R^2\langle E_\phi^2\rangle\,\tau_{corr} \approx 0.047\ V^2/s$ ($E\phi$, τ_{corr} from edge probes)
  - Probe measurements match pinch time of ~25 ms.



Pinch observed in tokamaks and stellarators

- Observations of a pinch
  - Stellarator LHD: Tanaka, *et al.*, [Fus. Sci. & Tech., **58** (2010) 70].
  - Tokamak DIII-D: L-mode: Baker and Rosenbluth, [PoP **5**, (1998) 2936], Baker [PoP **9**, 2002) 2675].
    - Stationary (pinched) density profiles have $n_{max}/n_{edge}>2$
  - Tore Supra: Hoang et al, [PRL **90**(2003) 155002].
  - Cmod: "I-mode" observes L-mode (inwardly peaked) density with h-mode temperature. [Whyte et al., Nucl. Fusion **50** (2010)].
- Will pinch be operative in ITER?
- Tokamak/stellarator pinch is weaker than in dipole and more difficult to observe and to formulate.

Why is pinch particularly strong in a dipole?

- Pinch drives stationary profiles: $n_e \propto 1/\delta V, \;\; p \propto 1/\delta V^{\gamma} \;\; \delta V = \oint dl/B$
  - Dipole : $B \propto 1/R^3 \Rightarrow n_e \propto 1/R^4$
  - Tokamak: $n_e \propto 1/q$
- Trapped particles drive pinch ** :
  - ⇨ All dipole 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 $\Gamma = -\iint d\mu dj \, D^{\psi} \left.\frac{\partial f}{\partial \psi}\right|_{\mu, j}$
- In dipole $p\delta V^{\gamma} \sim Const$ and particle pinch does not necessarily transport energy.
  - In tokamak with good curvature no MHD constraint on ∇p

    & a particle pinch is accompanied by an energy outflow.

** Isichenko, Gruzinov, Diamond, PRL (1995) 4436.

For invariant profiles τ_E & τ_P set by edge physics

- For $p \propto 1/\delta V^{\gamma}$, $E_{tot} = \frac{3}{2} p_{sol} R_{sol}^3 (R_{sol}/R_0)^{\gamma+2}$ $\tau_E = E_{tot}/P$
- For $n_e \propto 1/\delta V$ $N_{tot} = n_{sol} R_{sol}^3 (R_{sol}/R_0)$ $\tau_P = N_{tot}/S$

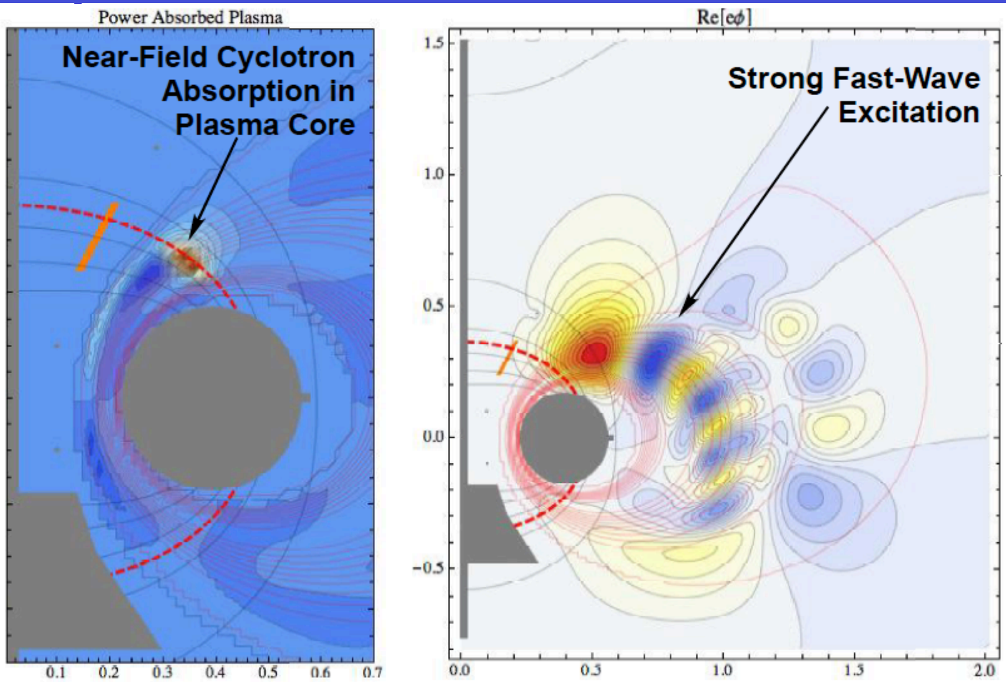
Dipole amplifies SOL density and pressure much like gas flow from a large volume through a small hole

- Confinement time ratio: $\frac{\tau_E}{\tau_P} \propto \frac{3}{2}(R_{sol}/R_0)^{\gamma+1} \approx 10-50$

⇨ For invariant profiles energy and particle confinement set by SOL physics.

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

The next step for LDX was an ICRF upgrade



- 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.

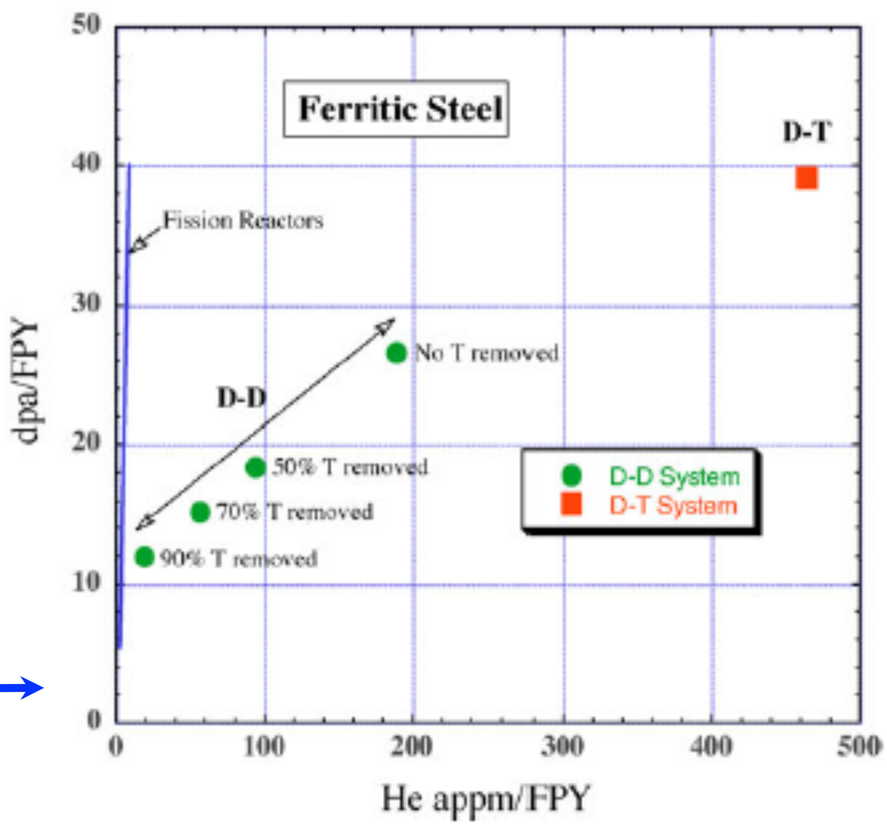
  Heating scenario has been developed including full wave simulation: m=0 high field antenna heats with near field and fast & slow waves

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

  DD cycle, removing secondary T, would ameliorate problem.
- Burn secondary ^{3}He
  - T decays to ^{3}He
- Requires $\tau_P \ll \tau_E$ for T removal
- Similarly $\tau_P \ll \tau_E$ for ash removal
- T-suppressed power source would reduce wall damage to fission levels
- Dipole has $\tau_P \ll \tau_E$, high β…

Kesner et al, Nuc Fus 44 (2004) 193



Sawan, Zinkle, Sheffield FED **61-62** (2002)

Laboratory Dipole Research

- Four laboratory dipole devices intensively studied during the past decade: Columbia University, MIT, University of Tokyo
- Demonstrated **the plasma physics of the magnetosphere appears in the laboratory**
  - Very high beta (>50%)
  - 2D dynamics
  - large-scale interchange turbulence
- **Directly observed the turbulent inward pinch**, which drives centrally-peaked density and temperature profiles
- Important consequence of the stationary profiles:
  Energy and particle confinement is set by SOL physics.
- **Energy confinement is longer than particle confinement**, making possible advanced fusion fuel cycles.