The Levitated Dipole Experiment: Towards Fusion Without Tritium

Jay Kesner
MIT
M.S. Davis, J.E. Ellsworth, D.T. Garnier, M.E. Mauel, P.C. Michael, P.P. Woskov
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Dipole concept inspired by magnetospheric research

- Dipole is simplest confinement field
- Naturally occurring high-$\beta$ plasma ($\beta \sim 2$ 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]

The Io Plasma Torus around Jupiter

J. Spencer
Dipole can have particle transport without energy transport

• Plasma confined in bad curvature. When

\[ -\frac{d\ln p}{d\ln V} > \gamma \]

will reduce pressure gradient to

\[ pV^\gamma \approx \text{const} \]

\[ V = \oint d\ell / B \propto R^4 \]

➤ When \( pV^\gamma \approx \text{constant} \) flux tube mixing does not cause energy transport [Rosenbluth, Longmuir (1957)]

➤ In tokamak \( -\frac{d\ln p}{d\ln V} \) can exceed \( \gamma \). Thus turbulence is accompanied by energy transport.

• Turbulence driven flux tube mixing will determine density profile with \( N = n_e V = \text{constant} \).

➤ Density profile independent of \( D \) and Source

➤ Profiles characterized by constant particles/flux.

★ Tokamak (L-mode): \( n_e \sim 1/V \sim 1/q \) [Ref: Baker, PoP 6 (2002) 2675]

★ Dipole: \( n_e \sim 1 / V \sim 1 / R^4 \)
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 $\beta$

- **Stability from plasma compressibility**
  - Limit on pressure gradient $\Rightarrow$ Small plasma in large vacuum chamber

- **No shear $\Rightarrow$ Large-scale adiabatic convection**

- **No toroidal field, no $j_\parallel$ $\Rightarrow$ No drift off field lines (i.e. NC), High $\beta$**

- **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 $= pV^\gamma$.

$$\frac{\partial}{\partial t} n_e V = \frac{\partial}{\partial \psi} D \frac{\partial}{\partial \psi} n_e V$$

$$D \sim \Sigma E \frac{2}{\phi} \tau_{corr} \quad V = \xi d \ell / B$$

$$\frac{\partial}{\partial t} p V^\gamma = \frac{\partial}{\partial \psi} D \frac{\partial}{\partial \psi} p V^\gamma + \langle P_{in} \rangle$$

- Constant $N=n_e V$ and $s=pV^\gamma$ 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 $s \sim$ const (not disruptive).
- Turbulence will draw in density (pinch) leading to $N=n_e V \sim$ constant.
- For $p$ and $n_e$ profiles $\Rightarrow$ boundary conditions (i.e. edge physics) determine total stored energy and particle content.
During levitated operation *stationary density profiles* are usually observed

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

- 4-chord interferometer measures density profile
  - Can extract density profile (e.g. Abel inversion)
  - Stationary profiles exhibit specific chord ratios;
    e.g. $P_{23} = n l_2 / n l_3 = 1.5$ 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, $P_{23} \sim 1$

Density peaks up markedly when coil is levitated

- Supported plasmas show similar turbulence level. Losses along field mask pinch.
Time for turbulent pinch determined by $D$

- Pinch takes $\sim 20$ ms to form
  \[
  \frac{d(nV)}{dt} = \langle S \rangle + \frac{d}{d\psi} D \frac{d(nV)}{d\psi}
  \]
  \[V = \oint dl/B\]

- $D = R^2 \langle E^2 \rangle \tau_{corr} \approx 0.047 \, V^2/s$ (\(E_\phi, \tau_{corr}\) from edge probe)

- Probe measurements match pinch time of $\sim 20$ 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 ($P_{23} \sim 1.5$)
- 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**
  \[ n_{\text{sol}} U_B (T_e) A_{\text{eff}} = \langle \sigma v \rangle n_{\text{sol}} n_0 \text{Vol} \rightarrow T_e \approx \text{constant}, \ T_e \approx 20 - 30 \ eV \]

- **SOL density determined by power balance**
  \[ P_{\text{tot}} - P_{\text{Rad}} = e n_e U_B A_{\text{eff}} \epsilon \text{ionize} \rightarrow n_e \propto P_{\text{tot}} \]
Some consequences of invariant profiles

- For $p \propto 1/V$, $V = \oint d\ell/B$ have $E_{\text{tot}} = \frac{3}{2} p_{\text{sol}} R_{\text{sol}}^3 (R_{\text{sol}}/R_0)^{11/3}$

  - Define $\tau_E = E_{\text{tot}} / P_{\text{tot}}$, noting $p_{\text{sol}} \propto n_{\text{sol}} \propto P_{\text{tot}}$ find $\tau_E$ independent heating power

- For $n_e \propto 1/V$, have $N_{\text{tot}} = n_{\text{sol}} R_{\text{sol}}^4 / R_0$

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

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

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

- Find $\tau_E / \tau_P$ 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.
- $D + D \rightarrow T + p \rightarrow He^3 + n$
- requires $\tau_p << \tau_E$ for T removal
- Similarly $\tau_p << \tau_E$ for ash removal
- Burn secondary $^3He$
  - $T$ decays to $^3He$
- T-suppressed power source would reduce DPA/He to fission levels
- Dipole study
  Kesner et al, Nuc Fus 44 (2004) 193

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
  - $\tau_E \gg \tau_p$, 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 $\beta$ limits
  - Evaluate $\tau_E$, $\tau_p$ and $\tau_E/\tau_p$
  - 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