Turbulent Transport in a Laboratory Magnetospheric Dipole

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Physics of dipole plasma confinement established by early space exploration

- More than 50 years of magnetospheric exploration: Earth, Jupiter, Saturn, Uranus, and Neptune
- Confinement and stability based on magnetic compressibility
- 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): Random solar-driven fluctuations cause strong inward pinch and adiabatic heating of radiation belts

\[
V = \int \frac{dl}{B} \propto R^4
\]
Observation of high $\beta$ in outer planets prompted study of laboratory magnetospheric dipole

- Two interesting properties of active magnetospheres:
  - Pressure and density profiles are strongly peaked
  - High beta: $\beta \sim 100\%$ in magnetosphere of Jupiter

- Akira Hasegawa, 1987
  - Can the physics of collisionless space plasmas be applied to collisional fusion plasma confinement?
MHD stability from plasma compressibility

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

Even as $\beta > 1$, interchange, not ballooning, limits pressure gradients (Garnier, PoP, 1999)

Including rotationally-driven centrifugal modes, MHD constrains density and temperature profiles, and

$$\eta = \frac{d \ln T}{d \ln n} \rightarrow \frac{2}{3}$$
Dipole drift-kinetic stability shows importance of interchange dynamics even for MHD-stable plasmas

- **Entropy mode** (*Kesner, Hastie, PoP 2002*) changed our thinking: not simply MHD, but drift-kinetic fluctuations depend upon $\eta$

- Entropy modes occur for MHD stable plasmas when either the density or temperature profiles are not “stationary”, with $\eta \sim 2/3$.

- Dipole fluctuations are interchange like $k_\perp \gg k_\parallel$

- Marginally stable profiles

\[ n \propto V^{-1} \text{ and } p \propto V^{-\gamma} \]

\[ \eta = \frac{d \ln T}{d \ln n} \rightarrow \gamma - 1 = \frac{2}{3} \]
Dipole profiles dynamics show strong pinch from turbulent mixing

- Natural or “Invariant” profiles are stationary solutions to adiabatic transport equations

\[
\frac{\partial (nV)}{\partial t} = \frac{\partial}{\partial \psi} D_\psi \psi \frac{\partial (nV)}{\partial \psi} + \langle S \rangle
\]

\[
\frac{\partial}{\partial \psi} \left( D_\psi \psi V \frac{\partial n}{\partial \psi} + n D_\psi \psi \frac{\partial V}{\partial \psi} \right)
\]

dipole geometry has large pinch term

\[
\frac{\partial (pV\gamma)}{\partial t} = \frac{\partial}{\partial \psi} D_\psi \psi \frac{\partial (pV\gamma)}{\partial \psi} + \langle H \rangle
\]


FIG. 5. The snapshots of the “self-organizations” process. Time \( t_1 \): before an instability is excited; \( t_2-t_4 \): different stages of self-organization.
Superconducting Levitated Dipole Experiments

LDX (MIT - USA)
Nb$_3$Sn Dipole  1.2 MA
Inductively Charged
3 Hour Float Time  25 kW CW ECRH

Components of a Levitated Dipole Experiment:

- Strong superconducting dipole for long-pulse, quasi-steady-state experiments
- Large vacuum chamber for unequalled diagnostic access and large magnetic compressibility
- Upper levitation coil for robust axisymmetric magnetic levitation
- Lifting/catching fixture for recooling, coil safety, and physics studies
- ECRH for high-temperature, high-beta plasmas
Superconducting Levitated Dipole Experiments

**LDX (MIT - USA)**

- **Nb$_3$Sn Dipole** 1.2 MA
- Inductively Charged
- 3 Hour Float Time
- 25 kW CW ECRH

**RT-1 (U. Tokyo - Japan)**

- **HTS Bi-2223 Dipole** 0.25 MA
- Electrically Charged w/SC Switch
- 6 Hour Float Time
- 45 kW CW ECRH
Levitated dipoles reproduce magnetospheric observations

- ECRH generates very high-beta plasmas consisting of centrally-peaked well-confined energetic electrons and warm collisional plasma...
  - Peak local beta observed ~ 50% (RT-1 reaches 70%)
  - Global energy confinement times up to 60 ms. LDX show levitated plasmas contain 40-70% of stored energy in collisional plasma.

- Plasma density profiles are centrally peaked caused by a strong inward turbulent particle pinch...
  - Near invariant density profiles measured with multi-chord interferometer
  - Rate of inward pinch (~ 25 ms) observed in LDX to be consistent with fluctuations measurements
Supported vs. Levitated

Mechanically **Supported**

- Removing catcher eliminates losses to supports
  - Source region moves outward, edge probes see plasma losses

**Magnetically Levitated**

- Radial transport determines profiles for levitated plasmas
Plasma Confined by a Supported Dipole

- 5 kW ECRH power
- Ip ~ 1.3 kA or 150 J
- Cyclotron emission (V-band) shows fast-electrons
- Long, low-density “afterglow” with fast electrons
Plasma Confined by a **Levitated** Dipole

- Reduced fast electron instability
- 2-3 x Diamagnetic flux
- Increased ratio of diamagnetism-to-cyclotron emission indicates **higher thermal pressure**.
- Long, higher-density “afterglow” shows improved confinement.
- 3-5 x line density
Energy confinement time and $\beta$ values

- Plasma pressure profile measured with magnetic reconstruction
  - Peak plasma beta $\sim 50\%$
- Energy confinement time estimated from stored energy and injected RF power
  - $\tau_E$ magnetics $\sim 60$ ms.
  - $\tau_E$ is shorter than that estimated from diamagnetic decay time of thermal component $\sim 150$ ms.
- Ratio of fast to slow decay gives estimate of bulk plasma energy content
  - 40-70% stored energy in bulk plasma
Plasma particle pinch illuminated by levitation

Launcher Inserted

Launcher Withdrawn

Density ($\times 10^{12}$ Particles/cc)

Levitated

Supported

$\langle S \rangle$ Flux-Tube Integrated Particle Source from Light Emission (A.U.)

Levitated

Supported
Heating modulation demonstrates robust inward pinch towards invariant profile

- **10 Hz 10 kW (10.5 GHz) ECH modulation**
  - Density modulation follows power: profile shape remains unchanged near nV=constant
  - Source moves radially outward, requiring pinch to create increased central density
Dipole plasmas are dominated by low frequency turbulence
Top-view visible fast camera fluctuations

- Low coherence large structures observed
Character of low frequency turbulence

- Observed turbulence in magnetospheric dipole experiments are:
  - Interchange like
  - Low frequency (0.1-10 kHz)
    - near zero in plasma frame
  - Broad k spectrum
    - peaked at lower modes
    - often with quasi-coherent low order modes
  - Bursty
    - distinctly non-gaussian PDFs
  - Exhibit inverse cascade of power from high frequency to low

- RT-1 low frequency density fluctuations
Observed turbulence consistent with simulations

- Non-linear evolution of MHD interchange instabilities lead to large scale convective cells

- Gyrokinetic studies of entropy mode also show broad spectrum
  \[ k_{\perp} \rho_s < 1 \]

Quasilinear MHD: Kuznetzov, Friedberg, Kesner PoP 2008
Edge probes used to estimate diffusion operator

- Instantaneous ExB radial flow of 35 km/s

\[
\frac{\partial (nV)}{\partial t} = \frac{\partial}{\partial \psi} D \frac{\partial (nV)}{\partial \psi} + \langle S \rangle
\]
With a levitated dipole, thermal plasma profiles are established quickly, well before energetic electrons.

Within 0.15 sec, thermal plasma energy reaches 100 J.

Density profile is established in the first 20 msec.

Turbulence is responsible for inward particle pinch with centrally-peeked density profiles.
Measured low frequency fluctuation intensity and spectrum reproduces observed turbulent pinch

\[
\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi},
\]

where \(\langle S \rangle\) is the net particle source within the flux-tube, and the diffusion coefficient is \(D = R^2 \langle E^2_\psi \rangle \tau_{cor}\) in units of \((V \cdot \text{sec})^2/\text{sec}\).
Within 0.15 sec, thermal plasma energy reaches 100 J with 11 kW of ECRH.

With measured edge temperature (14 eV), measured density profile, and measured thermal stored energy...

Stationary pressure and temperature profiles characterize the inward particle pinch.

\( - \frac{d \ln P}{d \ln \delta V} = \gamma = \frac{5}{3} \)

\[ \eta = \frac{d \ln T}{d \ln n} \approx 1.2 \]
Gyrokinetic (GS2) simulations show turbulence drives particles or heat to maintain uniform entropy density:


\[
\eta = \frac{d \ln T}{d \ln n} \rightarrow \frac{2}{3}
\]

\[- \frac{d \ln n}{d \ln \delta V} \rightarrow 1\]

\[- \frac{d \ln P}{d \ln \delta V} \rightarrow \frac{5}{3}\]
Tokamaks (with magnetic shear): \( n \sim V \sim 1/q \)

- DIII-D L-mode density profiles

Lagrangian Transport
Description with Preserved Adiabatic Invariants leads to profiles with equal number of particles per flux tube

\[
\frac{\partial f_M}{\partial t} = \frac{\partial}{\partial \psi} \left( D^{\psi \psi} \frac{\partial f_M}{\partial \psi} \right),
\]

\[
\Gamma = -D^{\psi \psi} \int d\mu dJ \frac{\partial f_M}{\partial \psi} \bigg|_{J, \mu}
\]

\[
\frac{1}{n} \frac{\partial n}{\partial \rho} \approx \xi \left\{ q \mathcal{H} \frac{\partial}{\partial \rho} \frac{1}{q \mathcal{H}} \right\},
\]

or \( n(\rho) \propto (q \mathcal{H})^{-\xi} \).
Controlling $pV^\gamma$ profile improves energy confinement

- Pastukhov and Chudin
  - Reduced MHD simulation of tokamak turbulence
- Improvement in confinement due to control of entropy profile
  - Case b has $S = pV^\gamma$ flat
- Consistent with experimental result of off-axis ECH heating experiments on T-10 and ASDEX

Summary

• The magnetospheric levitated dipole bridges space and laboratory magnetic confinement
  ▸ Large flux expansion allows steep profiles to be formed with turbulent transport

• Superconducting levitated dipoles achieve stable, high-beta, well-confined, plasmas
  ▸ Error field corrected, optimized RT-1 plasmas show peak local ~ 70%.
  ▸ Global energy confinement time ~ 60 ms. LDX shows 40-70% of stored energy in “warm” collisional electron population

• “Natural” invariant density profiles self-generate in a laboratory dipole confined plasmas
  ▸ LDX and RT-1 demonstrate peak profiles near \( nV = \) constant, driven by low-frequency fluctuations
  ▸ Stored energy is consistent with expectations, demonstrating good confinement and “stationary” profiles in LDX