The Physics of the Laboratory Magnetosphere

Mike Mauel
Columbia University

with help from Darren Garnier, Jay Kesner, Masaki Nishiura, Barrett Rogers, Zensho Yoshida, and the students and scientists conducting research in support of the CTX, LDX, and RT-1 Laboratory Magnetospheres

57th Annual Meeting of the APS Division of Plasma Physics
November 16, 2015 • Savannah, GA
Akira Hasegawa invited to Voyager 2’s encounter with Uranus
January 24, 1986

12 Hour Flyby
10 Newly Discovered Moons
Large, Tilted Magnetosphere
Long, Twisted Magnetotail
Substorm Injection
Inward diffusion and convection
Energetic Particles
Centrally-peaked Profiles
Plasma - Moon Interactions

Ed Stone, *JGR* 92, 14,873 (1987)
Inward Transport of Energetic Particles

Low-Energy-Charged Particles (LECP)
Protons: 10 keV – 150 MeV

F(\mu, J, \psi)

Lunar Loss

Inward Transport

MP Source

\frac{\partial F(\mu, J)}{\partial \psi} \sim 0

Increasing J

Fixed (\mu, J)

Fixed \mu = M = 40 \text{ MeV/G}

Chen, et al., JGR 92, 15,315 (1987)
Inward Transport Creates Centrally-Peaked Pressure

\[
\frac{\partial F}{\partial \psi}(\mu, J) \approx 0
\]

\[P_\perp \propto \frac{B}{V} \sim \frac{1}{L^7}\]

\[P_\parallel \propto \frac{1}{L^2V} \sim \frac{1}{L^6}\]

Inward transport of magnetospheric plasma *compresses and heats*...


Low-Energy-Charged Particles (LECP)

Protons: 10 keV – 150 MeV

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\[\partial F(\mu, J)/\partial \psi \sim 0\]

Increasing $J$

Fixed $\mu = M = 40 \text{ MeV/G}$

Phase space density (cm$^2$ s$^{-1}$ sr MeV$/\text{c}^2$)-1

Miranda

Ariel

Umbriel

Fixed (\(\mu, J\))

$P_\perp$
Lower Energy (thermal) Plasma has Centrally-Peaked Temperature and Density

Plasma Science Experiment (PLS)
Ions and Electrons: 10 eV – 5.9 keV

Plasma and ions in the magnetosheath are heated by processes occurring downstream from the termination shock. Centrally peaked temperature and density are observed. Protons are observed with energies up to ~1 keV. The inbound and outbound regions are shown in the graph.

Selesnick and McNutt, *JGR* 92, 15,249 (1987)
Interchange Motion of Thermal Plasma Creates Regions with Constant Flux-Tube Content and Invariant Temperature

\[
\Delta (nV) \approx 0
\]
\[
\Delta (TV^{2/3}) \approx 0
\]

\[TV^{2/3} \approx \text{constant}\]
\[nV \approx \text{constant}\]

**Flux-tube Volume**

\[V = \int \frac{dl}{B} \propto L^4\]

Plasma Science Experiment (PLS)
Ions and Electrons: 10 eV – 5.9 keV

~ 1 keV Protons
Constant Invariant \((TV^{2/3})\)
Constant Flux-Tube \((nV)\)

Selesnick and McNutt, *JGR* 92, 15,249 (1987)
Magnetospheres are Nature’s Laboratories for Magnetic Confinement Physics

Observations of magnetospheric radial transport and stability…

- Inward transport of energetic particles preserve $(\mu, J)$ creating centrally-peaked pressure

- Interchange motion of thermal plasma preserves flux-tube content $(n V)$ and invariant temperature $(T V^{2/3})$ creating centrally peaked profiles

- Marginally stable profiles $\Delta(P V^{5/3}) \sim 0$ at high beta, $\beta \geq 1$

Stone and Lane, *Science*, 206, 925 (1979)
Stone, *JGR* 92, 14,873 (1987)
Does magnetospheric physics apply to magnetic confinement in the laboratory?

- **Levitate** a small, high-current superconducting current ring within a very large vacuum vessel

- **Inject** heating power and a source of plasma particles at outer edge (SOL)

- ** Somehow drive** low-frequency fluctuations that create radial transport, preserve \( \mu, J \), and sustain “centrally-peaked” profiles at marginal stability

- **Achieve** high beta, \( \beta \geq 1 \), steady-state, and link space and fusion studies

During the past decade, LDX and RT-1 have shown the physics of magnetospheric radial transport and stability does apply to the laboratory.

- **Levitation creates a large confinement volume with plasma regulated by turbulent radial transport.**

- **Density profiles are always centrally peaked**, and particle transport can be either inward or outward depending upon the location of the particle source.

- **Interchange and entropy instabilities cause low-frequency fluctuations**, and Turbulent “self-organization” creates regions of nearly uniform flux-tube content \((nV)\) and entropy density \((P V^{5/3})\).

- **High local beta, \(\beta \sim 1\), in steady state, can be achieved** provided drift-resonant fast particle instabilities are stabilized.
LDX and RT-1 have also shown the laboratory magnetosphere is a simple and versatile configuration for **fundamental study of toroidal magnetic confinement**

- **Levitation is robust and reliable**
  
  Very good **access** for diagnostics, plasma heating and fueling.

- **Simple, axisymmetric torus with no field-aligned currents**

  **Classical particle orbits** with comparable passing and trapped dynamics.

  “**Good**” **confinement** of heat, density, energetic particles.

- **Radial transport processes** relevant to space and to many toroidal confinement devices.

- **Nonlinear gyrokinetics is a good model for understanding**
  
  radial transport driven by interchange and entropy mode turbulence.
19 PhD Dissertations


Yoshihisa Yano, "Experimental analysis of the magnetic field structure on the high-beta plasmas in the magnetospheric plasma device," 2010, PhD, U. Tokyo


Alex Boxer, "Interchange Stationary Profiles in the Levitated Dipole Experiment (LDX)", Ph.D., MIT, (2008).

Alexie Kouznetsov, "Theoretical prediction of $\tau_E$ and $\beta$ in a large aspect ratio LDX", Ph.D., MIT (2007).


and 10 M.S. Dissertations
Two laboratory magnetospheres: LDX and RT-1, having large flux-tube expansion

Particle transport and turbulent relaxation to centrally-peaked profiles (LDX)
  - Matt Davis (PhD Columbia) and Alex Boxer (PhD MIT)

Understanding entropy mode turbulence near marginal stability (GS2)
  - Sumire Kobayashi (PhD Dartmouth/Rogers)

Achieving record high local $\beta$ by stabilizing fast electron interchange instability (RT-1)
  - Yoshihisa Yano (PhD Univ Tokyo/Yoshida)

Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement
Outline

• Two laboratory magnetospheres: LDX and RT-1, having large flux-tube expansion

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  • Matt Davis (PhD Columbia) and Alex Boxer (PhD MIT)

• Understanding entropy mode turbulence near marginal stability (GS2)
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• Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement
Two Laboratory Magnetospheres

Levitated Dipole Experiment (LDX)
(1.2 MA \cdot 0.41 \text{ MA m}^2 \cdot 550 \text{ kJ} \cdot 565 \text{ kg})
\text{Nb}_3\text{Sn} \cdot 3 \text{ Hours Float Time}
24 \text{ kW ECRH}

Ring Trap 1 (RT-1)
(0.25 MA \cdot 0.17 \text{ MA m}^2 \cdot 22 \text{ kJ} \cdot 112 \text{ kg})
\text{Bi-2223} \cdot 6 \text{ Hours Float Time}
50 \text{ kW ECRH}
Levitated Dipole Experiment (LDX)

Laboratory Magnetospheres: Designed for Maximum Flux Tube Expansion

Flux Tube Expansion:
$$\frac{\delta V(\text{out})}{\delta V(\text{in})} = 100$$

Compared to:

Ring Trap 1 (RT-1)

Flux Tube Expansion:
$$\frac{\delta V(\text{out})}{\delta V(\text{in})} = 40$$

The volume $V$ can be expressed as:
$$V = \int \frac{dl}{B} \propto L^4$$
Large Flux Tube Expansion Maximizes Plasma’s Stable Pressure Gradient

Ideal MHD interchange instability limits plasma pressure gradient relative to the rate of **flux-tube expansion**…

\[ \Delta W_p = \Delta \left( PV^{5/3} \right) \frac{\Delta V}{V^{5/3}} > 0 \]

and steep pressure gradients are MHD stable, **even as \( \beta >> 1 \)**. MHD stability **requires** finite plasma pressure at edge.

\[ \Delta W_p = \Delta P \Delta V + \frac{5}{3} \frac{P}{V} (\Delta V)^2 > 0 \]

**Magnetosphere:** Magnetopause plasma sustained by solar wind

**Laboratory:** Scraper-off-layer (SOL) maintained by escaping plasma

\[
\frac{P(\text{core})}{P(\text{edge})} \leq \left( \frac{V(\text{edge})}{V(\text{core})} \right)^{5/3} \sim 2000
\]
The Early Great Terrella Experiments Explored the Magnetospheric/Ionospheric Current Structure and the “Auroral Hypothesis”

Danielsson and Lindberg (1964)

Birkeland (1903)


Birkeland and his assistant Olav Devik with 36 cm terrella (1913)
The Laboratory Magnetosphere Explores Stability and Transport Without Field-Aligned Currents and Without the Magnetospheric Dynamo

Magnetospheric Dynamo: 
100 TW Auroral Power
Regulates Interchange Motion

Internal Rings were used in Early Confinement Experiments to explore Stability and Transport with Good Curvature, Average Good Curvature, and Magnetic Shear

Yoshikawa, "Experiments on plasma confinement in internal-ring devices," *Nuc Fus* 13, 433 (1973)

Labatory Magnetospheres Explore Stability and Transport with the Large Flux-Tube Expansion Found in Space
Ring Trap 1 (RT-1)

Vacuum vessel

Cooling pipe (20 K Helium)

Coil case

Thermal shield (Copper)

Coil winding (Bi-2223)

Persistent Current Switch

Coil support

Cooling plate

Tech Note:
PCS (YBCO)

Bi-2223 · 6 Hours Float Time

0.63 T

(0.25 MA · 0.17 MA m² · 22 kJ · 112 kg)

8.2GHz microwave

Laser Z-Detector

Levitation coil

2.45GHz microwave

Levitated coil

Coil catcher

Transfer tube & power feeder structures

Coil lift

0 0.5 1 1.5

r (m)
Launching/Catching Superconducting Ring

Plasma Experiment on RT-1
Levitated Dipole Experiment (LDX)

- 20 Larger Magnet Energy
- 20 Larger Plasma Volume

(1.2 MA \cdot 0.41 \text{ MA} m^2 \cdot 550 \text{ kJ} \cdot 565 \text{ kg})

$\text{Nb}_3\text{Sn} \cdot 3 \text{ Hours Float Time}$
Tech Note:

**Routine and Reliable Levitation with Upper “Attractive” Levitation Coil**

**Excellent Control** (± 4mm) even with High β Plasma Ring Current

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Abstract

We report the first production of high beta plasma confined in a fully levitated laboratory dipole using neutral gas fueling and electron cyclotron resonance heating. The pressure results primarily from a population of energetic trapped electrons that is sustained for many seconds of microwave heating provided sufficient neutral gas is supplied to the plasma. As compared to previous studies in which the internal coil was supported, levitation results in improved particle confinement that allows higher-density, high-beta discharges to be maintained at significantly reduced gas fueling. Elimination of parallel losses coupled with reduced gas leads to improved energy confinement and a dramatic change in the density profile. Improved particle confinement assures stability of the hot electron component at reduced pressure. By eliminating supports used in previous studies, cross-field transport becomes the main loss channel for both the hot and the background species. Interchange stationary density profiles, corresponding to an equal number of particles per flux tube, are commonly observed in levitated plasmas.

1. Introduction

The dipole confinement concept [1, 2] was motivated by spacecraft observations of planetary magnetospheres that show centrally-peaked plasma pressure profiles forming naturally when the solar wind drives plasma circulation and heating. Unlike most other approaches to magnetic confinement in which stability requires average good curvature and magnetic shear, MHD stability in a dipole derives from plasma compressibility [3–5]. At marginal stability \((pV^{5/3}) = 0\) (with \(p\) the plasma pressure, \(V\) the differential flux tube volume, and \(\epsilon = 5/3\)), and an adiabatic exchange of flux tubes does not modify the pressure profile nor degrade energy confinement. Non-linear studies indicate that large-scale convective cells will form when the MHD stability limit is weakly violated, which results in the circulation of plasma between the hot core and the cooler edge region [6]. Studies have also predicted that the confined plasma can be stable to low frequency (drift wave) modes when \(\# \approx d\ln T_e/d \ln n_e > 2/3\) [7]. The marginally stable case to both drift waves and MHD modes, is thus where:

![Image of LDX device showing electron cyclotron resonance zones configuration.](image)

FIG. 1. Schematic of LDX device showing electron cyclotron resonance zones configuration.

2. Experimental Result

Figure 3.11: Response of the levitation system to a high beta plasma. The signal of the F-coil position is shown in the upper window and the signals of \(I_L\) and a diamagnetic current are shown in the lower window. A rise time of the diamagnetic signal is less than 50 ms in this discharge.

![Image of levitation and plasma diamagnetism interaction.](image)

Levitation coil current decreases under feedback control for high β plasma.
Earth’s Field nulled to 0.05 G

**Tech Note:**
Without a Toroidal Field, Suppression of Horizontal Magnetic Field-Errors Improves Confinement


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- **Understanding entropy mode turbulence** near marginal stability (GS2)
  - Sumire Kobayashi (PhD Dartmouth/Rogers)

- **Achieving record high local $\beta$** by stabilizing fast electron interchange instability (RT-1)
  - Yoshihisa Yano (PhD Univ Tokyo/Yoshida)

- **Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement**
Solar wind drives radial diffusion in planetary magnetospheres.

In the laboratory, Central heating excites instability, and Centrally-Peaked Pressure and Density are the Final State of Turbulent Self-Organization

Alexie Kouznetsov (PhD MIT/Freidberg), et al., “Quasilinear theory of interchange modes in a closed field line configuration,” Phys Plasmas, 14, 102501 (2007)

Entropy Modes have changed the way we think about Turbulent Self-Organization

The MHD interchange mode limits pressure gradients, but entropy modes drive turbulent "self-organization" even when MHD interchange is stable.

*Entropy Modes* regulate density and temperature gradients, driving $\eta \to 2/3$.

$$\Delta (nV) \sim 0 \quad \text{and} \quad \Delta \left( T V^{2/3} \right) \sim 0 \quad \text{and} \quad \eta = \frac{\Delta \ln T}{\Delta \ln n} = \frac{2}{3}$$

Entropy mode transport depends upon the relative gradients of density and temperature profiles, and $\eta$ determines the direction of particles flux…

- When $\eta > 2/3$ (a "warm core"), particles pinch inward & temperature outward.
- When $\eta < 2/3$ (a "cool core"), particles outward & temperature pinches inward.


CHAPTER 3. OVERVIEW OF THE LEVITATED DIPOLE EXPERIMENT

Probe array

Fast cameras

Visible light camera

Movable probes

L-coil

Magnetics

View tangency radii

Flux loop

Poloidal field coil

Interferometer

SDD X-ray

CZT X-ray

Photodiode array

4-Channel μWave Interferometer

Probe array

X-Ray Spectrometers

External Magnetic Sensors

plus Internal Flux Loops

Measurements of Pressure and Density Turbulent Self-Organization in LDX

Matt Davis (PhD Columbia) and Alex Boxer (PhD MIT)
Levitated
Good confinement
Some Energetic Electrons

Supported
Poor confinement
Energetic Trapped Electrons
Example Plasma Discharges: Supported vs. Levitated Coil

18 kW ECRH

Actively Controlled Neutral Pressure

Flux from Plasma Ring Current

Plasma Line Density

Internal Magnetic Flux Sensors

Accurate Reconstruction of the Plasma Pressure from the Plasma Ring Current Requires Internal Magnetic Sensors

\[ J_\perp = \frac{\mathbf{B} \times \nabla P_\perp}{B^2} + \frac{\mathbf{B} \times \kappa}{B^2} (P - P_\perp) \]

Reconstruction Results in Very Good Accuracy of Pressure Profile

\[ P_\perp \sim P_\parallel \]

Levitated Coil: Broad Isotropic Pressure Profile
Supported Coil: Narrow Anisotropic Pressure Profile

In the last set of levitated and supported shots (100805033-51) the upper mirror plasma was significant.

Upper mirror plasma is modeled as two currents, $I_{M1}$ and $I_{M2}$, that are evenly distributed across two sets of filaments.

Central mirror plasma, $I_{M1}$, can be several kA.

Outer mirror plasma is always less than a couple hundred amps.

Figure 4.11: A grayscale visible light image of a plasma shot with magnetic field lines overlaid in yellow, separatrix in red, and current density contours in blue. The upper mirror plasma current is modeled as 2 currents ($I_{M1}$ and $I_{M2}$) distributed over a finite set of points in the upper mirror.

The upper mirror plasma is separated by the mechanical upper catcher into an inner region (inside the catcher) and an outer region (outside the catcher). Figure 4.12 shows the electron cyclotron resonances zones for a typical magnetic configuration on LDX. The locations of the resonances indicate that the inner upper mirror plasma should only form when the 10.5 GHz and/or 6.4 GHz power sources are on (it should not form with just the 2.45 GHz power source). Figures 4.13(a) and 4.13(b) show that the inner plasma is seen on the visible light camera when all power sources are on but is not seen when only the 2.45 GHz source is on.

Instability, or some other unknown event, often causes the inner upper mirror plasma to be rapidly lost. When this loss occurs there is a rapid change in the flux measured by flux loop 11 that coincides with a simultaneous decrease in the visible light emitted from the plasma.

Figure 6. Pressure and current density contours for a supported (100805045) and a levitated (100805046) shot. In the top figures the pressure is shown with green contours indicating higher pressure and black contours indicating lower pressure (the same pressure contours levels are plotted for levitated and supported operation). The bottom figures show the current density with solid blue indicating high positive current density, solid black low positive current density, dotted black low negative current density, and dotted yellow high negative current density (the same current density contour levels are plotted in levitated and supported operation). The red contour marks the separatrix. During levitation the pressure and current density profiles are broader with lower maximum values.

Table 3 compares levitated shots with similar ECR heating power and neutral gas pressure. Discharge 100527002 permits upper mirror currents to form whereas in 130814045 the spider largely eliminates these currents. We have magnetically reconstructed the equilibrium for both of these shots. Table 3 shows the best fit parameters and calculated plasma parameters for the plasma with and without mirror plasma.

Levitated Coil: Broad Isotropic Pressure Profile
Supported Coil: Narrow Anisotropic Pressure Profile

- **Supported:**
  - High peak beta, $\beta \sim 40\%$
  - No thermal confinement
  - Ideal MHD *unstable*
- **Levitated:**
  - Peak beta, $\beta \sim 10\%$
  - Broad profile shows good thermal confinement
  - Marginally *stable* $\Delta(PV^{5/3}) \geq 0$

*Supported: No Thermal Confinement (only energetic trapped electrons)*

- $P_\perp \sim P_\parallel$
  - Levitated
- $P_\perp \sim 5P_\parallel$
  - Supported

![Pressure and current density contours for a supported (100805045) and a levitated (100805046) shot. In the top figures the pressure is shown with green contours indicating higher pressure and black contours indicating lower pressure (the same pressure contours levels are plotted for levitated and supported operation). The bottom figures show the current density with solid blue indicating high positive current density, solid black low positive current density, dotted black low negative current density, and dotted yellow high negative current density (the same current density contour levels are plotted in levitated and supported operation). The red contour marks the separatrix. During levitation the pressure and current density profiles are broader with lower maximum values.*

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Multichannel Microwave Interferometer

Levitated Coil creates Centrally-Peaked Density Profile

Supported Coil shows Poor Particle Confinement

Pressure and Density Profiles *During Levitation* Indicate *Marginally Stable Pressure* \((PV^{5/3})\) and *Flux-Tube Content* \((nV)\) *Decreasing Inward*

**Central Energy Source**

**Edge Particle Source**

**Entropy Density**

\[ 
\Delta (PV^{5/3}) \geq 0 
\]

\[ 
\Delta (nV) > 0 
\]

**Warm Core:** \(\Delta (nV) > 0\) and \(\Delta (TV^{2/3}) < 0\)

\[ 
\eta > \frac{2}{3} 
\]

\[ 
\eta = \frac{\Delta \ln T}{\Delta \ln n} 
\]


Edge fueling and central ECRH creates a “warm core” with $\eta > 2/3$

**Example thermal profile:** Short-pulse heating before appearance of energetic electrons...

- 11 kW ECRH creates thermal plasma energy: $W_{\text{th}} \approx 100$ J.
- Measured edge $T_e \approx 15$ eV, density profile, and stored energy, imply central $T_e \sim 500$ eV
- “Warm core” with $\eta > 2/3 \sim 1.2$
- $\rho^* \sim 0.02, \quad \omega_d/2\pi \approx 0.8$ kHz
- Semi-collisional thermal electrons: $2\pi \nu_e/\omega_b \sim 0.006$
  (Thermal electrons bounce > 100 times in a collision time.)

![Graph showing warm core conditions](https://via.placeholder.com/150)

**Legend:**
- $\langle T_e \rangle$
- $\langle n_e \rangle$
- $\eta = \Delta(\ln T) / \Delta(\ln n) \approx 1.2$

**Equations:**
- Levitation: $\eta = \Delta(\ln T) / \Delta(\ln n) \approx 1.2$
- Warm Core: $\Delta(nV) > 0$ and $\Delta(TV^{2/3}) < 0$

**Notes:**
The Radial Diffusion Coefficient is Measured by Ensemble Correlation of the Measured Radial $E \times B$ Velocity

$$E \cdot B = 0$$

$$\dot{\psi}(t) = RE_\varphi(t) = \nabla \psi \cdot E \times B$$

$$D_\psi = \lim_{t \to \infty} \int_0^t dt' \langle \dot{\psi}(t') \dot{\psi}(0) \rangle \equiv R^2 \langle E_\varphi^2 \rangle \tau_c$$

Radial Diffusion due to Interchange/Entropy Turbulence

Turbulent Fluctuations Propagate in Electron Drift Direction (during edge gas fueling)

|Eφ| ~ 55 V/m (RMS) \( \tau_c \sim 16 \mu \text{sec} 

Floating Potential (Φ > ± 100 V)

\[ \omega \approx m \omega_d \sim 2 \pi m \text{ 700 Hz} \]

m = 1, 2, 3, 4, 5, 6, …

Inverse mode structure cascade, chaotic mode dynamics, …


Rate of Inward Diffusion Agrees using Measured Interchange Diffusion Coefficient

With levitated dipole, inward turbulent transport sets profile evolution.

Inward pinch calculated from measured fluctuations.

| Eφ | ~ 55 V/m (RMS)  | τc ~ 16 μsec |
|-----------------|------------------|

Dψ ~ 0.047 (Wb²/s)

Dψ = R²⟨Eφ²⟩τc

Edge Transport is “Bursty”: Outward Warm Filaments and Inward Cool Filaments


Edge Transport is “Bursty”: Outward Warm Filaments and Inward Cool Filaments

Probe Array:
- Floating Potential, $E_\phi$
- Ion Saturation Current
- Radial $E \times B$ Flux

$$RE_\phi \sim \Delta \Phi / \Delta \phi$$

Radial Flux $\sim (E_\phi/B) \times I_{\text{sat}}$


High Speed Pellet Injection Cools Core & Creates Internal Fueling and Reverses the Direction of Particle Diffusion
Li Pellet Injection Provides Internal Particle Source and Cools Plasma Core

(a) Overview of Li Pellet Injection

(b) Close-up of Li Pellet Injection

- Li Pellet Injection
- Probe Array
- Interferometer

Graphs showing:
- Interferometer (Rad)
- Total Particles (E18)
- Outer Flux Loop (mV sec)
- ECRH Power (kW)

Time (s):
- 0 2 4 6 8 10 12

Energy:
- 300 J
- 100 J

3 Electrons ×3 Energy
Li-Pellet Injection Increases Central Density ($\times 5$), Cools Core Temperature, and Decreases $\eta < 2/3$

$\eta > 2/3$ ("warm core"/edge fueling) becomes $\eta < 2/3$ ("cool core"/pellet fueling)
"Cool Core"/Li Pellet Fueling Reverses Direction of Particle Flux

Average Radial Particle Flux from Edge Probe Array

\[
\langle \Gamma_{\psi} \rangle = \langle R E_{\phi} I_{sat} \rangle (\Delta \phi, \Delta t)
\]
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- **Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement**
Physics Tools Used to Understand Magnetic Confinement in Tokamaks can be Applied to the Laboratory Magnetosphere

(a) Dipole Interchange-Entropy Modes

- \( nV \sim 0 \)
- \( TV^{2/3} \sim 0 \)
- \( PV^{5/3} \sim 0 \)

Weak gradients: \( \omega_\rho^* \sim \omega_d \)

Stable by compressibility and field line tension


(b) Tokamak ITG-TEM Modes

Steep gradients: \( \omega_\rho^* \gg \omega_d \)

Stable by average good curvature and magnetic shear

X. Garbet, Comptes Rendus Physique 7, 573 (2006)
Gyrokinetic Simulations of Closed Field Line Systems
Sumire Kobayashi (PhD Dartmouth)

- 5D Gyrokinetic (GS2) simulations and quasilinear theory of entropy mode turbulence consistent with observations.
- **“Warm Core”,** $\eta > 2/3$, creates inward particle pinch and outward heat transport.
- **“Cool Core”,** $\eta < 2/3$, creates outward particle pinch and inward heat flux.
- **Furthermore:** Nonlinear simulations show zonal flows, with significant transport reduction, appear at low collisionality.

GS2 show Entropy Modes Drive Turbulent “Self-Organization” even when MHD Interchange is Stable

MHD unstable $\Delta(PV^{5/3}) > 0$

MHD stable $\Delta(PV^{5/3}) < 0$

$d \equiv -\frac{\Delta \ln P}{\Delta \ln V}$

- “Warm Core”, $\eta > 2/3$, creates inward particle pinch and outward heat transport.
- “Cool Core”, $\eta < 2/3$, creates outward particle pinch and inward heat flux.

When $T_e >> T_i$, Linear Theory Shows Entropy Mode \textbf{Reverses} Direction with $\eta$

$\Delta W_p \sim \Delta (PV^{5/3}) \sim 0$

\[ \eta < 2/3 \quad \text{Outward Particle Flux} \quad \eta > 2/3 \quad \text{Inward Particle Flux} \]

- Electron Drift
- Reversed Drift
- “Cool Core”
- “Warm Core”

When $T_e \gg T_i$, Linear Theory Shows Entropy Mode **Reverses** Direction with $\eta$

$\eta < 2/3$

```
"Cool Core"
```

$\Delta W_p \sim \Delta (PV^{5/3}) \sim 0$ Energy & Pressure **Unchanged** for Adiabatic Mixing

$\eta > 2/3$

```
"Warm Core"
```

When $T_e >> T_i$, Linear Theory Shows Entropy Mode Reverses Direction with $\eta$

$\eta < 2/3$

"Cool Core"

$\eta > 2/3$

"Warm Core"

Drift-Kinetic Heat moves toroidally from Warm to Cool Flux-Tubes

Entropy Mode Rotation

$\Delta W_p \sim \Delta (PV^{5/3}) \sim 0$

Outward Particle Flux

Inward Particle Flux

Dispersion Measurements during Pellet Injection agree with Linear Theory

Entropy Modes Reverse Direction with Reversal of Particle Flux

Ensemble-Averaged Entropy Mode Dispersion

Before Pellet Injection

During Pellet Injection

Potential Fluctuations Reverse Direction

Before Pellet Injection

During Pellet Injection

\[ \omega/2\pi \sim m \pm 700 \text{ Hz} \]

\[ \omega/2\pi \sim m (-500) \text{ Hz} \]

\[ \eta < 2/3 \]

\[ \eta > 2/3 \]
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  - Sumire Kobayashi (PhD *Dartmouth/Rogers*)

- **Achieving record high local $\beta$** by stabilizing fast electron interchange instability *(RT-1)*
  - Yoshihisa Yano (PhD *Univ Tokyo/Yoshida*)

- Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement
Stable Toroidal Plasmas at Very High Local $\beta$ are Characteristics of the Giant Magnetospheres and Predicted for the Laboratory Magnetosphere


Measuring Record Peak $\beta \sim 1$ with Internal Hall Probe in RT-1
(Yoshihisa Yano, PhD Univ Tokyo)

$$J_\perp = \frac{B \times \nabla P_\perp}{B^2} + \frac{B \times \kappa}{B^2} (P - P_\perp)$$

Equilibrium Profile Reconstruction

Dessler-Parker-Sckopke Relationship:

- Earth’s Magnetosphere Energy = $0.54 \text{ GJ/A} \times I_{RC}$
- LDX’s Plasma Energy = $0.12 \text{ J/A} \times I_{RC}$

Plasma Ring Current ~ Energy ~ Peak Beta

**Figure 4.2**: Top view of the microwaves and interferometry system. The waveguide of the 2.45 GHz microwave is seeing the F-coil from midplane and the waveguide of the 8.2 GHz microwave is seeing it obliquely from above.

**Figure 4.3**: Drawing of the magnetic surfaces and the vertical position of the flux loops.

**Figure 6.18**: The arrangement of the new Hall probe system and the magnetic surfaces.

**Figure 6.19**: The photograph of the interior of the probe. Fourteen Hall elements are mounted. Hall elements are electrically shielded by stainless steel (SUS304).

**Figure 6.20**: The photograph of the exterior of the probe. The probe is thermally protected by a ceramic pipe.

**Figure 6.21**: The photograph of the Hall probe which is installed in the vacuum chamber.

Internal Hall Probe for Accurate Ring Current Profile Reconstruction
Measuring Record Peak $\beta \sim 1$ with Internal Hall Probe in RT-1
(Yoshihisa Yano, PhD Univ Tokyo)

$\beta \approx 0.18 \Delta \psi$ (mWb$^{-1}$, Peak-local)

80% Peak $\beta$
5 mWb

25 kW 8.2 GHz
19 kW 2.45 GHz


Hot Electron Interchange (HEI) Instability Must be Stabilized to Achieve High $\beta$

Transition

Low $\beta$ → High $\beta$

RT-1

Plots of:
- Pt/Pr (kW)
- Diamagnetism (m WB)
- Photodiode (au)
- Soft x-ray (au)

Transition

Low $\beta$ → High $\beta$

LDX

Graph showing:
- Edge Potential Fluctuations
- Frequency (MHz)
- Drift Resonant Energy (keV)
- Chaotic Radial Transport
- Intermittent Bursts

Fast Electron Instability Prevents High $\beta$ build-up...
Achieving High $\beta$ with ECRH Requires Stabilization of Hot Electron Interchange Mode and Creates a stable "Artificial Radiation Belt"

- ECRH *always* generates energetic electrons

- Hot Electron Interchange (HEI) modes appear with both supported and levitated magnets whenever the plasma density is too low.

- HEI instabilities are drift-resonant ($\omega \sim m\omega_{dh} \sim 1$ MHz), have global structures, with nonlinear frequency chirping.

- Transport preserves phase-space density $F(\mu, J)$.

- Can be stabilize with dense, colder plasma:

  \[ -\frac{d \ln n_{hot}}{d \ln V} > 1 + \frac{m^2}{24} \frac{\omega_{dh} n_{ion}}{\omega_{ci} n_{hot}} \]

  **Cold Density Stabilization**

(Six PhD Dissertations: Warren, Maslovsky, Levitt, Krasheninnikova, Grierson, Ortiz)
RT-1 Achieved Record Peak $\beta > 1$ with 50 kW ECRH 8.2 GHz Heating

Higher $\mu$Wave frequency makes higher density accessible. Higher $\mu$Wave power creates higher peak local $\beta$.

Higher Power and Higher Density
RT-1 has **Three Regimes** of High-\(\beta\) Operation depending upon Background Neutral Density and ECRH Power

\[ \mathbf{P}_\perp > \mathbf{P}_\parallel \]

\[ \mathbf{P}_\perp \approx \mathbf{P}_\parallel \]

\[ \mathbf{P}_\perp > \mathbf{P}_\parallel \]

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Outline

- **Two laboratory magnetospheres**: LDX and RT-1, having large flux-tube expansion

- **Particle transport and turbulent relaxation** to centrally-peaked profiles (*LDX*)
  - Matt Davis (PhD Columbia) and Alex Boxer (PhD MIT)

- **Understanding entropy mode turbulence** near marginal stability (*GS2*)
  - Sumire Kobayashi (PhD Dartmouth/Rogers)

- **Achieving record high local β** by stabilizing fast electron interchange instability (*RT-1*)
  - Yoshihisa Yano (PhD Univ Tokyo/Yoshida)

- **Opportunities and on-going research linking Space and Laboratory Magnetospheric Confinement**
Density profiles are always centrally peaked, and particle transport can be either inward or outward depending upon the location of the particle source.

Turbulent “self-organization” is characterized by nearly uniform flux-tube content, $\Delta(nV) \sim 0$, invariant temperature, $\Delta(TV^{2/3}) \sim 0$, and entropy density, $\Delta(PV^{5/3}) \sim 0$.

- **Space**: Turbulence driven by solar wind and planetary rotation
- **Lab**: Interchange and entropy instabilities drive fluctuations

High local beta, $\beta \sim 1$, “artificial radiation belt” in steady state
The Axisymmetric Plasma Torus is a *New Paradigm* for the Laboratory Study of Steady-State and High-Beta Plasma Transport

- **Levitation is robust and reliable** with very good access for diagnostics, plasma heating and fueling.

- **Simple, axisymmetric torus with no field-aligned currents** with classical particle orbits and good confinement of heat, density, and energetic particles.

- **Fascinating radial transport processes** relevant to space and to many toroidal confinement devices: *up-gradient pinch, zonal flows, bursty interchange filaments, avalanches …*

*Nonlinear gyrokinetics appears to provide a good model for predicting* radial transport driven by interchange and entropy instabilities
Physics of the Laboratory Magnetosphere: *Frontier Questions* …

- **Beyond ECRH and accessibility limits: high density and warm ions…**
  - What are the stability and transport properties of a high-density plasma torus with $T_i \sim T_e$?
  - How does Alfvén magnetic turbulence couple to interchange and entropy mode turbulence?
  - Whistler waves interactions with energetic particles, when $\omega_{pe} >> \omega_{ce}$

- **Develop and understand “whole plasma” predictive models of magnetized plasma transport with precision measurements of an axisymmetric high-$\beta$ torus…**
  - How do particle and heat sources influence the self-organized profiles? What are the roles of momentum input? Zonal flows? $T_i/T_e$ ratio? Ionic mass and impurities?
  - Are reduced dimension models effective to predict the saturated turbulence transport?
  - Can improved diagnostics give precision observation of plasma turbulent self-organization?
  - How do we understand core-edge connections, both boundary interfaces, and SOL flows?

- **Magnetospheric configuration toroidally confines non-neutral, single-component plasma…**
  - Can a levitated dipole be used to study exotic and electron-positron plasmas?

- **With a small superconducting magnetic, can we create and study very large confined plasma …**
First Successful Test of Wave Heating in Ion Cyclotron Range of Frequencies

- **Frontier opportunity:** reach high density with finite ion temperature allows $T_e \sim T_i$
- Whistler waves ($\omega_{pe} >> \omega_{ce}$) trapping
- Alfvén waves ($c/\omega_p L << 1$) resonances and dynamics at high beta
- FLR, ion drift-orbit bifurcation, ion mass/isotope
- Does high power drive zonal flows and create transport barriers in a dipole plasma torus?

JP12.00120 (Tue, Afternoon): Toshiba Mushiake, *et al.*, “Measurement of RF electric field ... using a Pockels detector in RT-1”


[Observed increase of $T_i$ with 10 kW of ICRF heating at 2MHz]
Laboratory Magnetospheres for Space Science and Astrophysics

- Harbin Institute of Technology
  - CO7.00014 (Mon, Afternoon): Wang Zhibin, et al., “Computational Design of the Plasma Sources in Harbin Dipole eXperiment (HDX)”

- Wisconsin Plasma Astrophysics Lab

- Collisionless Terrella Experiment (Columbia Univ)
Toroidal Confinement of Pure-Electron and Positron Plasmas


APEX/PAX (A Positron Electron Experiment/Positron Accumulation Experiment) aims to create and magnetically confine a laboratory electron-positron pair plasma for fundamental studies.
Hasegawa’s 1987 Question: Does magnetospheric physics apply to fusion magnetic confinement in the laboratory?

✓ LDX, RT-1, theory and simulation do not show any limitations preventing the scaling of stable high-β equilibria to larger size.

➡ However, the answer to Hasegawa’s question we need laboratory tests with high power heating and high plasma density. (We can do these experiments using existing facilities.)

➡ If turbulent self-organization and centrally-peaked profiles persist at large size, …

With only a small superconducting magnetic, we could create and study very large confined plasma for …

➡ Fundamental plasma physics

➡ Space science and technology

➡ Fusion energy confinement science