Exploring Plasma Dynamics with Laboratory Magnetospheres

Mike Mauel and
LDX and CTX Experimental Teams
Columbia University and PSFC, MIT

Michigan Institute for Plasma Science and Engineering
February 2014
Laboratory Magnetospheres are facilities for study of steady-state and high-beta plasma transport and can test space physics and technology in relevant magnetic geometry

- Very high plasma pressure, $\beta > 50\%$, when dipole is magnetically levitated showing key connection between laboratory and planetary magnetospheres
- Very strong, but small, dipole magnet inside a very large vacuum chamber making possible very large plasma experiments at relatively low cost
- Electron cyclotron waves (“chorus”, ECH) and radio waves (Alfvén and ion-cyclotron waves) heat and maintain plasma and trapped particles giving variety and control over plasma properties
- Whole plasma access for unparalleled imaging and diagnostic measurement
- Polar boundary control and polar diagnostics when dipole is mechanically supported

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.
Laboratory Magnetospheres: Facilities for Controlled Space Physics Experiments

LDX: High Beta Levitation & Turbulent Pinch

CTX: Polar Imaging, Current Injection, Rotation

24 Probes 1 m Radius
• How does a laboratory magnetosphere work?

• Interchange disturbances and magnetic drift resonances
  
  ▸ Low frequency interchange turbulence: the remarkable “pinch” of magnetized plasma resulting in “canonical” profiles
  
  ▸ Fast kinetic interchange instabilities: “plasma storms” in the lab

• Examples: exploring plasma dynamics by injection of heat, particles, current, and magnetic perturbations by decreasing ion inertial lengths
LDX and CTX Team


The University of Tokyo

American Superconductor

Dynavac

D.V. Efremov Institute

Columbia University

AFOSR

Brookhaven National Laboratory

PPPL

MIT
Laboratory Dipole Experiments Around the World

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
Lifting, Launching, Levitation, Experiments, Catching
First Levitated Dipole Plasma Experiment

Floating
(Up to 3 Hours)
Diagnostics

CHAPTER 3. OVERVIEW OF THE LEVITATED DIPOLE EXPERIMENT

Figure 3.3: A cartoon overview of a subset of the LDX diagnostic set.
Example Plasma Experiment

- 20 kW injected electron cyclotron waves
- Hydrogen gas density $4 \times 10^{10}$ cm$^{-3}$
- Plasma energy 250 J (3 kA ring current)
- Peak $\beta \sim 40\%$ (70\% achieved in RT-1)
- Peak plasma density $10^{12}$ cm$^{-3}$
- Peak $\langle T \rangle > 1.4$ keV (electrons)
- Density proportional to injected power
- Sustained, dynamic, “steady state”

---

**Figure 5.1:** Overview of supported shot 100805045 and levitated shot 100805046. The top row shows that the heating power profile was the same in both shots. The second row shows that the vessel pressure was similar on both shots. The third row shows that during levitation the change in the magnetic flux measured by a flux loop at the outer mid-plane (diameter 5 m) is nearly a factor of two greater than during supported operation. The last row shows the phase measurement of the 4 chord interferometer: black (77 cm tangency radius), red (86 cm), green (96 cm), and blue (125 cm). The large phase change on the inner chords during levitation show that the electron density is much higher and centrally peaked during levitated operation. The light red and light blue vertical lines indicate the times used in the reconstructions described in the next sections. The vertical black lines mark times when the input power changes.
Measuring the Plasma Pressure from the Plasma Ring Current

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

What is the plasma ring current distribution that fits magnetic sensor arrays?

**Plasma Ring Current**

**Reconstruction Grid**

**Levitation Coil**

**Levitated Dipole Coil**

2.45 GHz

6.4 GHz
Measuring the Plasma Pressure from the Plasma Ring Current

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

Reconstruction Results in Very Good Accuracy of Pressure Profile

![Graph showing the plasma ring current and its reconstruction results.](image)

- Plasma Ring Current
- High-\(\beta\) Plasma
- High-Confinement
- Steady-State

81 ± 5 cm
2.1 ± 0.2
"Canonical" Profile: $\delta(PV^\gamma) \approx 0$

Levitated (100805046), $t = 8.2$ sec, $\gamma = 5/3$

Supported (100805045)
$t = 9.5$ sec
$\gamma = 5/3$

Figure 7.1: For levitated shot 100805046 with multiple ECRH sources on the entropy density factor is constant with radius outside the pressure peak (at radius 81 cm). This is consistent with a pressure profile that is marginally stable to the MHD interchange mode. For supported shot 100805045 with multiple ECRH sources on the entropy density factor decreases with radius outside of the pressure peak (at radius 80 cm) indicating a pressure profile that is steeper than the MHD limit.
Measurement of Density Profile with Interferometry
Measurement of Density Profile with Interferometry Show Equal Particle Number per Unit Magnetic Flux

(a) Interferometer Cords
(b) Interferometer Measurements
(c) Density and Number Radial Profiles

“Canonical” Profile: \( \delta(nV) \approx 0 \)
Remarkable “Pinch”: Dye Stirred in Glass
“Canonical” Profiles of Magnetized Plasma
\[ \delta(nV) \approx 0 \quad \& \quad \delta(PV^Y) \approx 0 \]

- Low frequency fluctuations in strongly magnetized plasma, \( \omega \ll \omega_b \ll \omega_c \), conserve constants of motion.

- **Turbulent mixing across flux tube volumes tries to “relax” to the canonical profiles**, which are Lagrangian invariants of the flow. Turbulence in strongly magnetized plasma tries to “self organize”.

- **Magnetic flux-tube geometry** relates turbulent diffusion in magnetic-flux-space to diffusive and pinch terms in coordinate-space.

- **Space (i.e. Dipole) geometry:**
  - Birmingham, *J. Geophysical Res.*, 1969

- **Tokamak geometry:**
Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation

THOMAS J. BIRMINGHAM

\[ E \times B \]

\[ \dot{\psi} = \nabla \psi \cdot \mathbf{V} = \frac{\partial \Phi}{\partial \varphi} = -R E_{\varphi} \]

Diffusion Coefficient

\[ D_{\psi} = \lim_{t \to \infty} \int_{0}^{t} dt \langle \dot{\psi}(t) \dot{\psi}(0) \rangle \equiv \langle \dot{\psi}^2 \rangle T_c \]

\[ = R^2 \langle E_{\varphi}^2 \rangle \tau_c \]

Adiabatic Radial Transport

\[ \frac{\partial F}{\partial t} = S + \frac{\partial}{\partial \psi} \left|_{\mu, J} \right. D_{\psi}(\mu, J) \frac{\partial F}{\partial \psi} \left|_{\mu, J} \right. \]

Turbulent Pinch in Toroidal Laboratory Plasmas

When the turbulent spectrum is sufficiently broad to interact with (nearly) all particles, independent of energy and pitch-angle, then ...

Flux-Tube Particle Number Transport:

\[
\frac{\partial (\bar{n} \delta V)}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D_\psi \frac{\partial (\bar{n} \delta V)}{\partial \psi} \\
= \langle S \rangle + \frac{\partial}{\partial \psi} \left[ D_\psi \delta V \frac{\partial \bar{n}}{\partial \psi} + \bar{n} D_\psi \frac{\partial \delta V}{\partial \psi} \right]
\]

Diffusion Pinch Velocity

Flux-Tube Plasma Energy/Entropy Transport:

\[
\frac{\partial (\bar{P} \delta V^\gamma)}{\partial t} = \langle H \rangle + \frac{\partial}{\partial \psi} D_\psi \frac{\partial (\bar{P} \delta V^\gamma)}{\partial \psi}
\]
Magnetic flux-tube geometry sets low frequency dynamics

- **Dipole...**
  - Interchange sets pressure and density gradient limits in dipole-plasma (*compressibility not average good curvature*) with $\beta \sim 100\%$
  - Flux-tubes can interchange globally without bending (*no magnetic shear*)
  - No toroidally circulating particles: all particles have similar response to low-frequencies
  - **Flux tube volume increases rapidly** with radius, $V \sim 1/L^4$, resulting in steep profiles

- **Tokamak...**
  - Ballooning and kinks set pressure limit with $\beta \sim \epsilon/q \approx 5\%$
  - Short radial scale of fluctuations, drift waves
  - Passing and trapped particle dynamics differ
  - **Flux tube volume nearly constant** with radius, $V \sim 1/q$, mixing creates flat profiles
Geometry of Magnetic Flux Tubes, $\delta V$, Determines Pinch

Dipole

$$D_\psi = R^2 \langle E_\varphi^2 \rangle \tau_c$$

Tokamak (Trapped Particles)

$$D_\psi = R^2 \langle E_\theta^2 \rangle \left( \frac{B_p^2}{B^2} \right) \tau_c$$

Flux-Tube Number Transport:

$$\frac{\partial (\bar{n} \delta V)}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D_\psi \frac{\partial (\bar{n} \delta V)}{\partial \psi} = 0$$

Steady-state without internal source, zero net flux condition:

$$\bar{n} \propto \frac{1}{\delta V} \sim \left\{ \begin{array}{ll}
1/R^4 & \text{Dipole} \\
1/q & \text{Tokamak (Trapped Particles)}
\end{array} \right.$$  

... and particles can move inward against a density gradient.
Quantitative Verification of Turbulent Particle Pinch

Using only measured electric field fluctuations, Thomas Birmingham’s diffusion model is verified with levitated dipole

Edge Probe Array:

\[ D = \lim_{{t \to \infty}} \int_0^t dt \langle \dot{\psi}(t) \psi(0) \rangle \equiv \langle \psi^2 \rangle \tau_c \]

\[ D_\psi = R^2 \langle E_{\varphi}^2 \rangle \tau_c \]
Quantitative Verification of Turbulent Particle Pinch

Using only *measured electric field* fluctuations, Thomas Birmingham’s diffusion model is verified with levitated dipole

Floating Potential ($\Phi > \pm 150$ V)

Edge Probe Array:

\[ D = \lim_{t \to \infty} \int_0^t dt \langle \dot{\psi}(t) \dot{\psi}(0) \rangle \equiv \langle \dot{\psi}^2 \rangle \tau_c \]

\[ D_{\psi} = R^2 \langle E_{\phi}^2 \rangle \tau_c \]
Quantitative Verification of Inward Turbulent Pinch

\[ \frac{\partial (\bar{n} \delta V)}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D_\psi \frac{\partial (\bar{n} \delta V)}{\partial \psi} \]

With levitated dipole, inward turbulent transport sets profile evolution

Heating modulation demonstrates robust inward pinch towards invariant profile

- Density increases with power ($T \sim \text{constant}$). Density profile shape is unchanged near $(n\delta V) \sim \text{constant}$.
- Gas source moves radially outward. **Inward pinch required** to increase central density.
Our Space Environment is Complex and Highly Variable
With Concurrent Plasma Processes and Important Questions to Answer

Van Allen Probes (A&B) Launched August 2012
Discovered New 3rd Radiation Belt (2 MeV e⁻) then annihilated by passage of interplanetary shock
ScienceExpress, Baker, et al., 28 Feb 2013
Levitated dipole can achieve > 50% beta

Garnier, POP (1999) shows equilibria with $\beta > 100\%$ possible

Garnier, POP (2006) reports peak beta 20% achieved

Garnier, NF (2009) reports peak beta doubles with levitation

Saitoh, JFE (2010) reports peak beta 70% achieved in RT-1

Cassini at Jupiter (Dec 30, 2000)

The natural high beta in planetary magnetospheres can be achieved in the laboratory. Steady-state.
Drift-Resonant (Hot Electron) Interchange Instability

± 100 V
Kinetic Interchange Drift Resonance with High-β “Artificial Radiation Belt”

Fast drift-resonant instability resonates with fast electrons causing **rapid** radial transport...

**Inward Transport**

**Outward Transport**

**Chaotic Radial Transport**

**Nonlinear Frequency Sweeping**

**Edge Potential Fluctuations**
Polar Imager: Measuring Inward Drift-Resonant Transport due to Gyrokinetic Interchange Instability
Drift Resonance \((\mu, J) \sim 1/L^2\)
“Chorus” Injection Fills-in Phase-Space Holes

ECR heating phase

RF pulse is applied

Frequency, MHz

Floating potential, A. U.

Average Electron Current, A. U.

time, s
Relative Strength of Centrifugal and Curvature Drives Determine Nonlinear Mode Structure

Relative strength of centrifugal and curvature drives determine nonlinear mode structure. The diagrams illustrate the mode structure for different values of $m$: $m = 1$, $m = 2$, and $m = 4$. The relative strength is indicated by the color gradient, with darker colors representing higher strength. The figure also includes a graph showing the hot electron fraction, $\alpha$, against the ion centrifugal drift over energetic magnetic drift ratio, $\left( \frac{\omega_g}{\omega_{dh}} \sim \Omega^2 \right)$. The regions labeled 'HEI' and 'Stable' indicate the operational and stable conditions for the system.
High Speed Imaging of Interchange Turbulence at 0.5 Mfps

- Detectors biased to collect ion current
- Visualize turbulence
- Density fluctuations rotate in electron drift direction with random amplitude and phase modulations
- Compute turbulence cascade and compare with nonlinear simulations
Low-Frequency Turbulent Convection: Quantitative Verification of Particle Transport Models

Interchange Transport of “Inward” and “Outward” Moving Plasma-Filled Flux Tubes

Convective Structures Dynamics

Chaotic Interaction between Convective E×B Streamlines and Plasma Density Perturbations
**Symmetry Breaking and the 2D Inverse Energy Cascade.**

- **Power Spectra**
  - Frequency (kHz)
  - AU
  - Start: 0.32 Stop: 0.35
  - Start: 0.38 Stop: 0.41
  - Start: 0.44 Stop: 0.47
  - Start: 0.47 Stop: 0.49
  - Start: 0.52 Stop: 0.55
  - Start: 0.55 Stop: 0.58

- **Summed Bicoherence (Normalized)**
  - Frequency $f_3$: $f_3=f_1+f_2$ (kHz)
  - Start: 0.32 Stop: 0.35
  - Start: 0.38 Stop: 0.41
  - Start: 0.44 Stop: 0.47
  - Start: 0.47 Stop: 0.49
  - Start: 0.52 Stop: 0.55
  - Start: 0.55 Stop: 0.58

- **Results**
  - No Bias, Shot 7895
  - $m=3$ Non-Symmetric Bias, Shot 7874
  - Low Current Symmetric Bias, Shot 7894

---

**Matt Worstell**
Current Injection for Dipole Turbulence Control

**Problem:** Turbulence decorrelates preventing global suppression

**Solution:** Apply multiple independent controllers

![Diagram showing current injection for dipole turbulence control with sensor and actuator layouts, and power spectra for different conditions.](Image)

Max Roberts
High Speed Pellet Injection for Localized Density Transients
Flux Tube Dynamics Following Pellet Release Experiments in Laboratory Magnetospheres

Pellet Explosion

CH Pellet Ablation

Plasma Flux Tube Evolution
Low-cost “Smart-Probes” for Multiple-Point *in situ* Measurements

FRDM-KL05Z Development Board
With Arduino & USB Interfaces
3-axis accelerometer

KL05 MCU

32 MB Flash Memory

Smart Probe Enclosure

Battery Power

10 mm Dia
World’s Largest Lab Magnetosphere

Size matters:
At larger size, trapped particle energy, intensity of “artificial radiation belt”, and plasma density significantly increase.
High Density and Large Size are required for Controlled Investigations of Alfvén Wave Dynamics

\[ \frac{V_A}{L} \sim f_A \ll f_{ci} \rightarrow \frac{c}{\omega_{pi}} \ll 1 \]

<table>
<thead>
<tr>
<th></th>
<th>Mercury</th>
<th>Earth</th>
<th>Jupiter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>2 R</td>
<td>10 R</td>
<td>100 R</td>
</tr>
<tr>
<td>Density ((c/\omega))</td>
<td>0.1</td>
<td>0.003</td>
<td>0.00001</td>
</tr>
<tr>
<td>Comments</td>
<td>V</td>
<td>Alfvén Resonances</td>
<td>Propagating Alfvén</td>
</tr>
</tbody>
</table>
Alfvén Wave Excitation in LDX: Opportunity for a Many Important Experiments

- Alfvén Wave Spectroscopy and Resonances
- Toroidal-Poloidal Polarization Coupling
- Alfvén Wave interactions with Radiation Belt Particles
- Ion Cyclotron Resonance and FLR

Example: 200 kHz $m = 2$ Polar Launcher
NASA’s early effort in Laboratory Testing and Validation can be Significantly Advanced with Modern Modeling and Diagnostics

Earth, (2) electrical compatibility of the thruster system and the rest of the spacecraft, or (3) degradation by thruster exhaust products of the spacecraft solar cells, the thermal control surfaces, or the optical properties of various spacecraft surfaces (NASA 1970).

SERT II comprised a spacecraft section and a spacecraft support unit. The spacecraft section included two identical 15-cm-diameter mercury electron-bombardment ion thrusters (each producing 28 mN of thrust and 4,200-s spec impulse at 850-W input power) and auxiliary experiments. The spacecraft support unit included power conditioning, switching, command and telemetry, and attitude control. The support unit (Fig.6) was attached to the forward end of a 7.2-m-long, 1.53-m-diameter Agena vehicle. Two solar arrays extended from the aft end of the Agena vehicle to provide power for the EP system. At the time, the arrays were the largest ever owned by NASA—each nominally 5.8-m long by 1.5-m wide—and provided a beginning-of-life power of 1,425 W. The SERT II spacecraft and Agena vehicle were to be launched from Vandenberg atop a Thorad launch vehicle into a 1,000-km-high, 99.1° inclination orbit.

GRC was responsible for (1) management of the Thorad-Agena launch vehicle; (2) staffing and operations of the mission control center, which was housed at GRC; (3) management of the primary mission experiments; (4) design and fabrication of the spacecraft and ion thrusters; (5) management of other spacecraft subsystem and solar array contracts; and (6) assembly and acceptance testing of the spacecraft (at Vacuum Facility #5 in GRC) (Kerslake and Ignaczak 1993) (Figs.7 and 8).

In what would become prophetic words—Channing Conger, GRC’s Chief of the Spacecraft Technology Division, stated at the time of the SERT II launching: "The earliest application of the ion engine might be to keep a large satellite correctly positioned in orbit for many years. Next, a cluster of such engines might be used as early as 1975 to propel an unmanned probe to the asteroids orbiting the sun between Mars and Jupiter. Asteroids are the hundreds of tiny 'planets' which may help explain the creation of the solar system." (The Plain Dealer 1970). His predictions were finally realized, 25 and 37 years later, with the launch of the Hughes (nee Boeing) HS–601 spacecraft with ion propulsion for stationkeeping in 1995 and the NASA Jet Propulsion Laboratory's (JPL) Dawn mission in 2007, respectively.

The SERT II spacecraft and Agena vehicle were successfully launched into a near-polar 1000-km-altitude orbit on February 3, 1970, and put into a gravity-gradient stabilized orientation (Figs.9 and 10). After a brief checkout of the spacecraft systems, IPS operations were initiated with the startup of thruster 2 on February 10, followed by the startup of thruster 1 on February 14. Thruster 1 was operated in a near-uninterrupted fashion for 5.25 months until July 22, when an unclearable grid short resulted in the termination of operation after 3,781 h. Ion thruster 2 was started on July 24, 1970, and operated for 2,011 h, nearly 3 months (until October 17, 1970), before a permanent high-voltage grid short occurred on this thruster as well. The permanent grid shorts on both thrusters precluded further operation with beam extraction until 1974, when thruster 2's grids were cleared by mechanically spinning the spacecraft.

Although the mission was of officially labeled a failure because the primary thruster operated for only 5 months (instead of the 6-month goal), many of the IPS elements functioned successfully for more than a decade—21 years in the case of the power electronics. The failure mode of the thrusters was successfully concluded, and design...
A Large Space Chamber Could be Filled with a Laboratory Magnetosphere
Laboratory Magnetospheres are Unique Opportunities for Controlled Space Physics Experiments

- Laboratory magnetospheres are facilities for conducting controlled tests of space-weather models in relevant magnetic geometry and for exploring magnetospheric phenomena by controlling the injection of heat, particles, and perturbations.

- Very large plasmas can be produced in the laboratory, continuously, with low power and great flexibility. Verification and discovery of critical plasma science.

- “Artificial radiation belt” dynamics and transport can be studied. Preliminary tests of radiation belt remediation underway.

- Larger laboratory magnetospheres significantly increase trapped particle energy, intensity of “artificial radiation belt”, and plasma density. Allowing controlled tests of complex Alfvén wave interactions in the magnetosphere.

- Outlook: We can build/operate the largest laboratory plasma on Earth.