# Controlled Space Physics Experiments using Laboratory Magnetospheres

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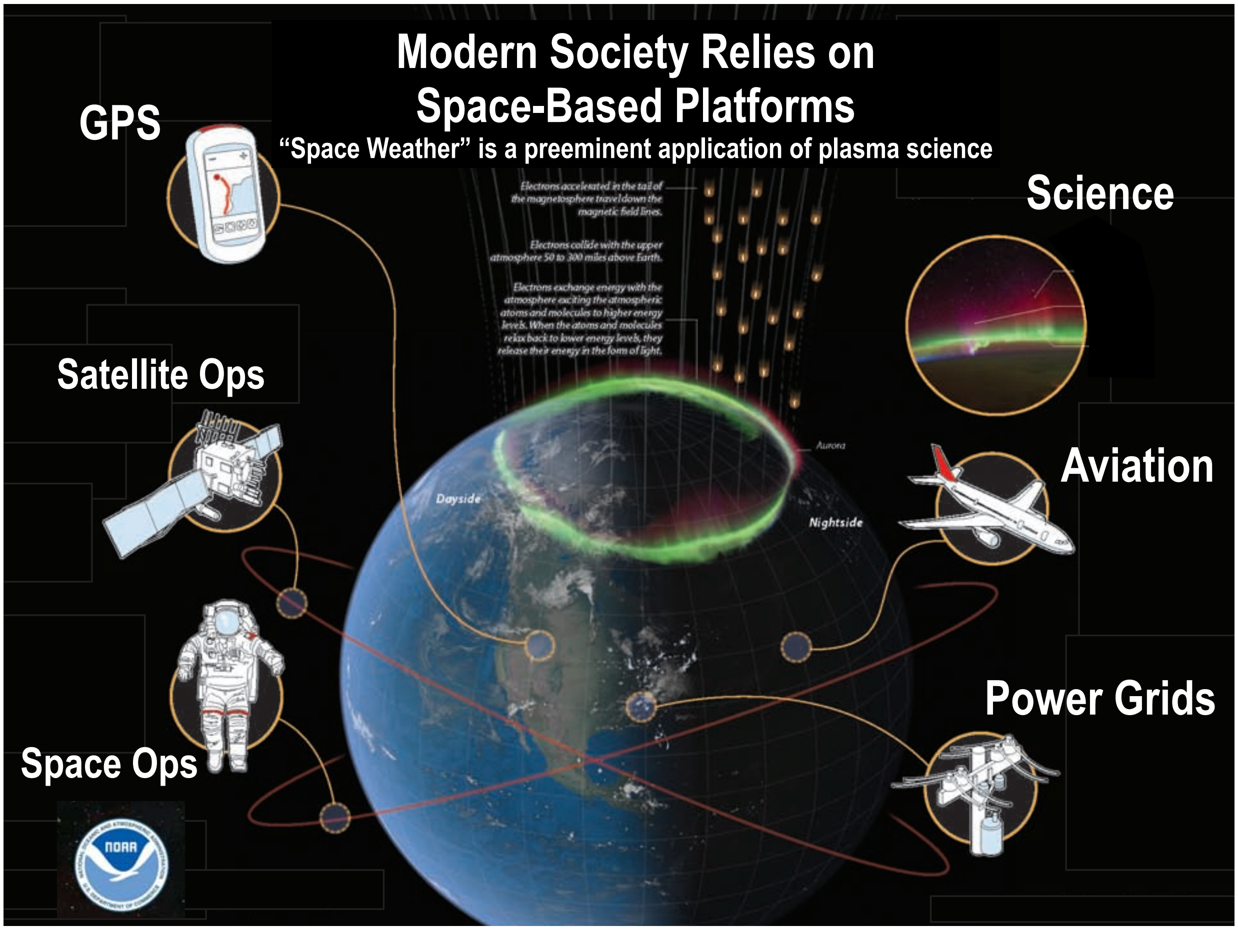
*June 2013*

## Modern Society Relies on Space-Based Platforms

"Space Weather" is a preeminent application of plasma science



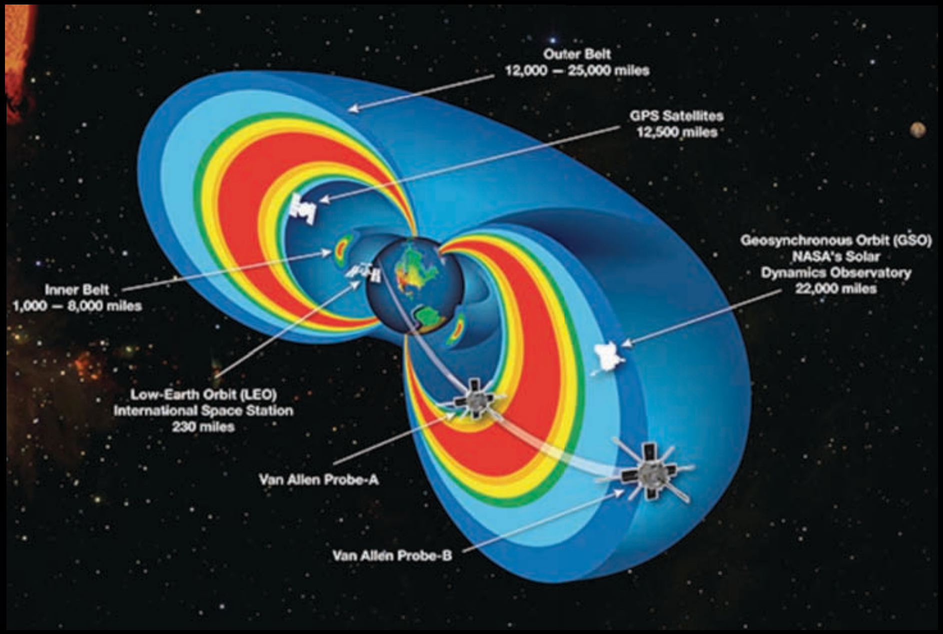
*Electrons accelerated in the tail of the magnetosphere travel down the magnetic field lines.*

*Electrons collide with the upper atmosphere 50 to 300 miles above Earth.*

*Electrons exchange energy with the atmosphere exciting the atmospheric atoms and molecules to higher energy levels. When the atoms and molecules relax back to lower energy levels, they release their energy in the form of light.*

# 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

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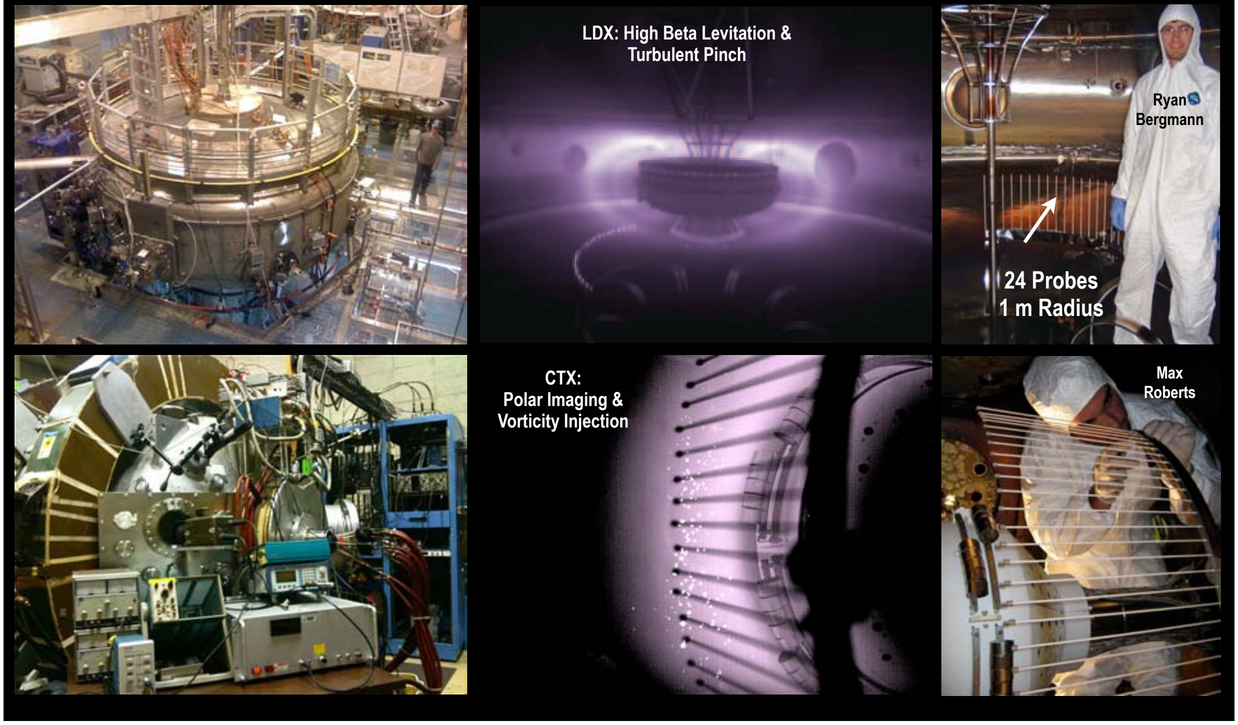
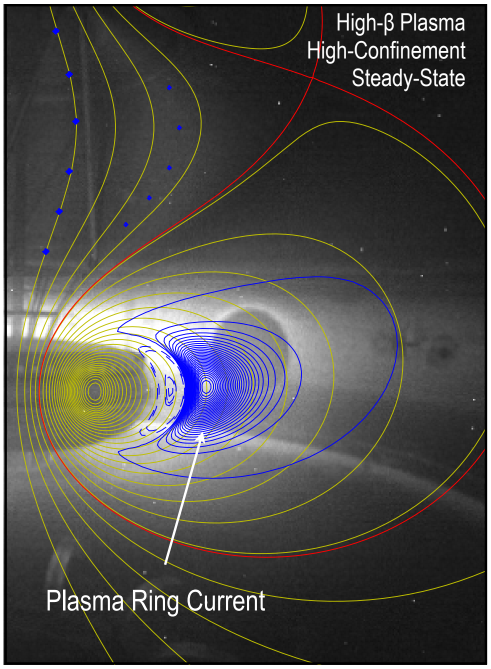
# Laboratory Magnetospheres: Facilities for Controlled Space Physics Experiments



# How do laboratory magnetospheres work?

- Very strong, but small, dipole magnet inside a very large vacuum chamber *making possible the largest plasmas "on Earth"*
- 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*
- Extreme plasma pressure and high density *when dipole is magnetically levitated*



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# Laboratory Magnetospheres are facilities to develop and test *integrated models in relevant magnetic geometry*

- Wave-particle interactions, particle acceleration and loss, wave excitations, resonances, …
- Radial transport, turbulent mixing, evolving density profiles, particle energization, PDF, …
- Disturbances, impulsive events, …
- Polar boundary sources, magnetopause boundary, …

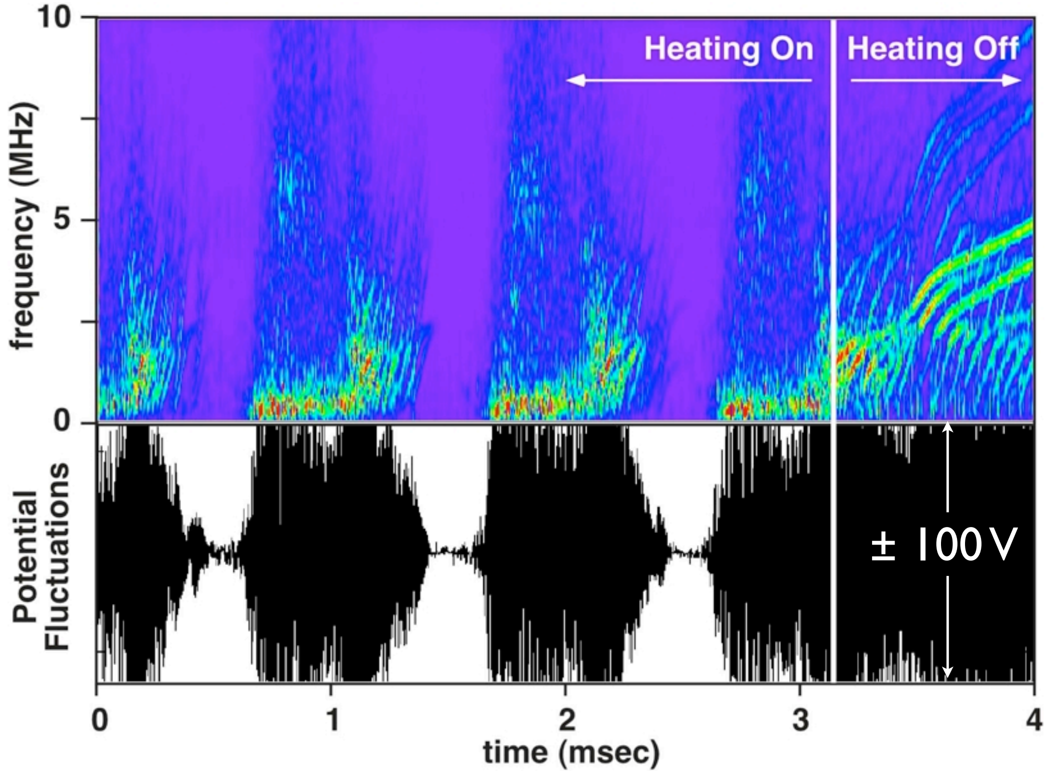
***Scientific goal***:

*__Test__ "whole plasma" models in relevant magnetic geometry and __Explore__ magnetospheric phenomena by controlling the injection of heat, particles, and perturbations*

# Examples of Controlled Experiments using Laboratory Magnetospheres…

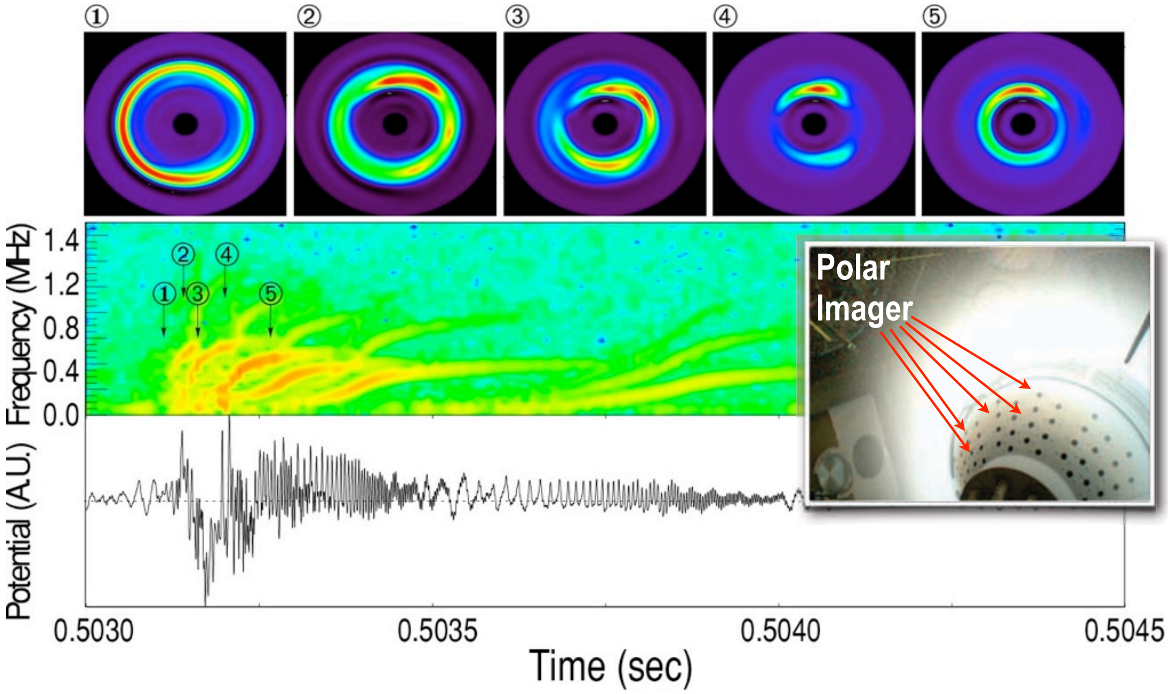
- “Artificial radiation belts” show drift-resonant and MHD turbulence are reproduced by bounce-averaged gyrokinetic simulations *and give quantitative verification of magnetospheric transport models*
- Low-frequency plasma dynamics is dominated by interchange turbulent convection *allowing study of 2D physics, inverse-cascade, global mixing, etc… in the laboratory*
- Levitated dipole can achieve > 50% peak beta with plasma profiles comparable to planetary magnetospheres *showing key connection between plasma dynamics in the lab and in space*
- (*New*) Exploring ULF and Alfvén wave interactions with trapped particles using controlled experiments at higher plasma density

# Drift-Resonant Transport of “Artificial Radiation Belt”



# Inward adiabatic transport and energization of “radiation belt” Observed with Polar Imager

*Evolving energetic electron precipitation during radial transport*



# Whole-Plasma Imaging of Magnetospheric Mixing

*Exploring the physics of low-frequency turbulent convection*

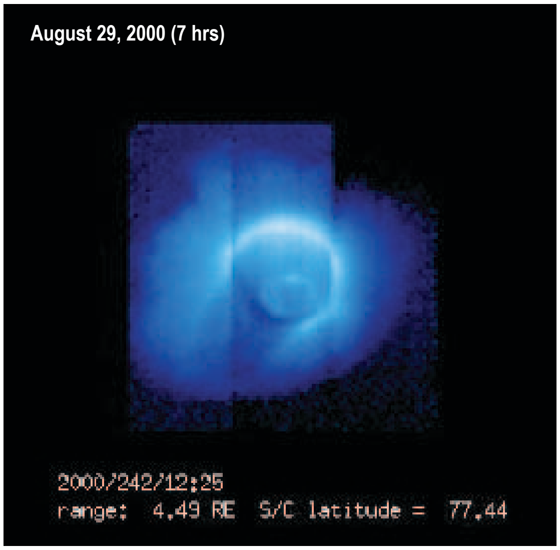
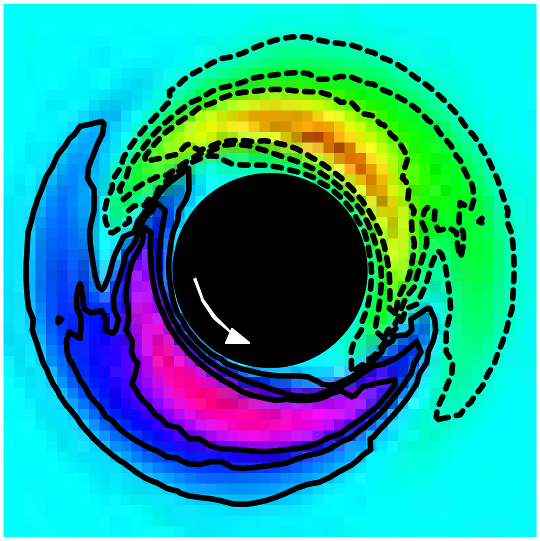


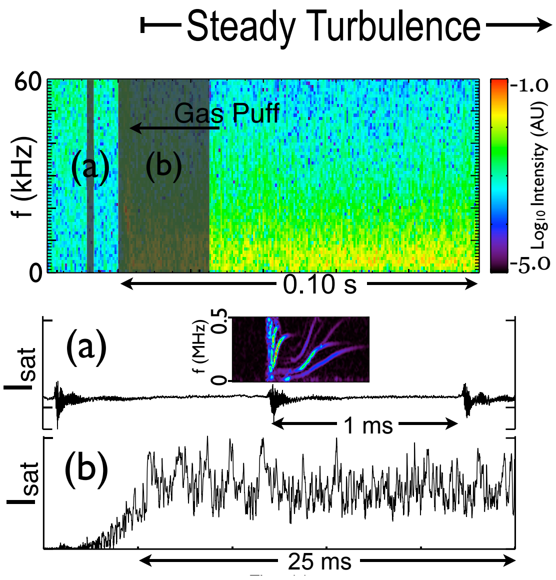
IMAGE: Sunlight reflected from $He^+$ showing interchange mixing of plasmasphere



Streamfunction during Mach ~ 1 rotation showing plasma mixing from saturated centrifugal mode

# Low-Frequency Turbulent Convection: Quantitative Verification of Particle Transport Models

- Gas injection controls turbulent dynamics: from fast energetic particle drive to slower MHD turbulent convection
- Mach ≥ 1 rotation drives centrifugal interchange ("Jupiter" mode)
- Chaotic dynamics of global convection structures
- High-speed imaging of "blobs" and "holes" during turbulent transport
- Inverse cascade in 2D turbulence
- Symmetry breaking
- Feedback



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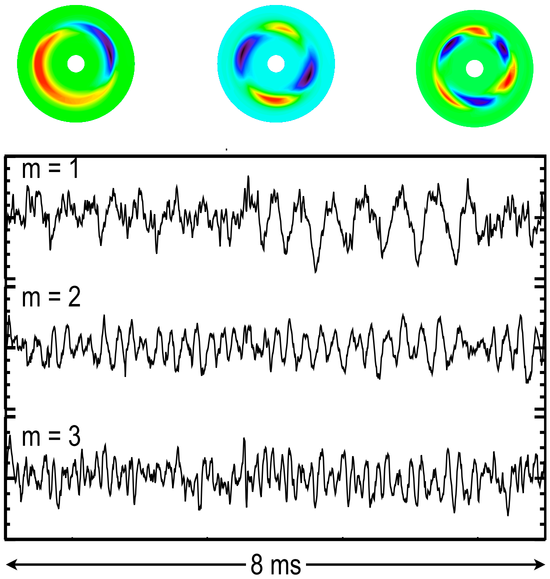
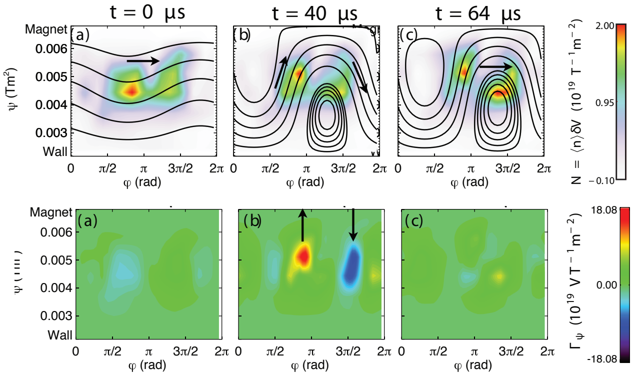
# Low-Frequency Turbulent Convection: Quantitative Verification of Particle Transport Models



Convective Structures Dynamics

Interchange Transport of "**Inward**" and "**Outward**" Moving Flux Tubes

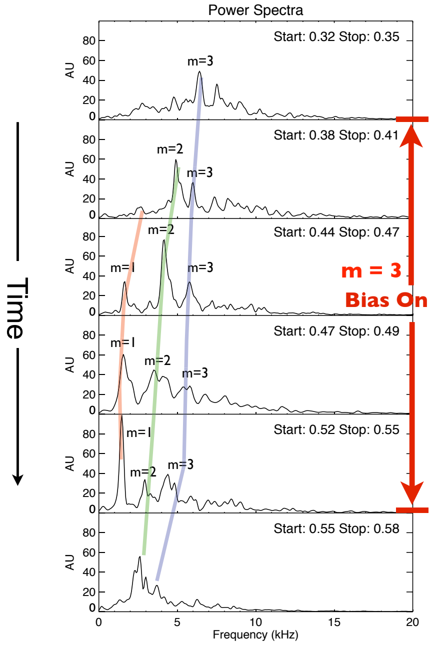


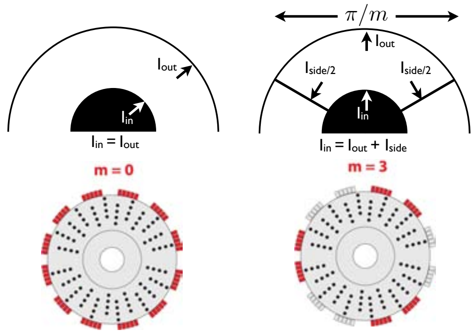
Chaotic Interaction between Convective E×B Streamlines and Plasma Density Perturbations

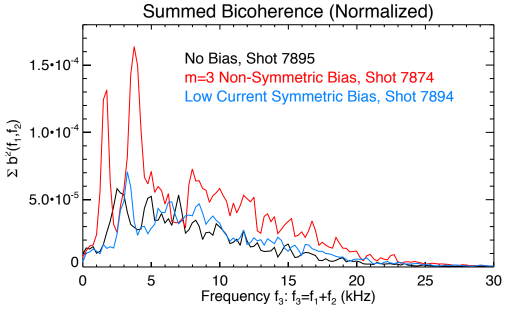
# Recent Advancements in Dipole Turbulence Control

*Symmetry Breaking Enhances Inverse Cascade and Coherence*

(Matt Worstell, PhD 2013)







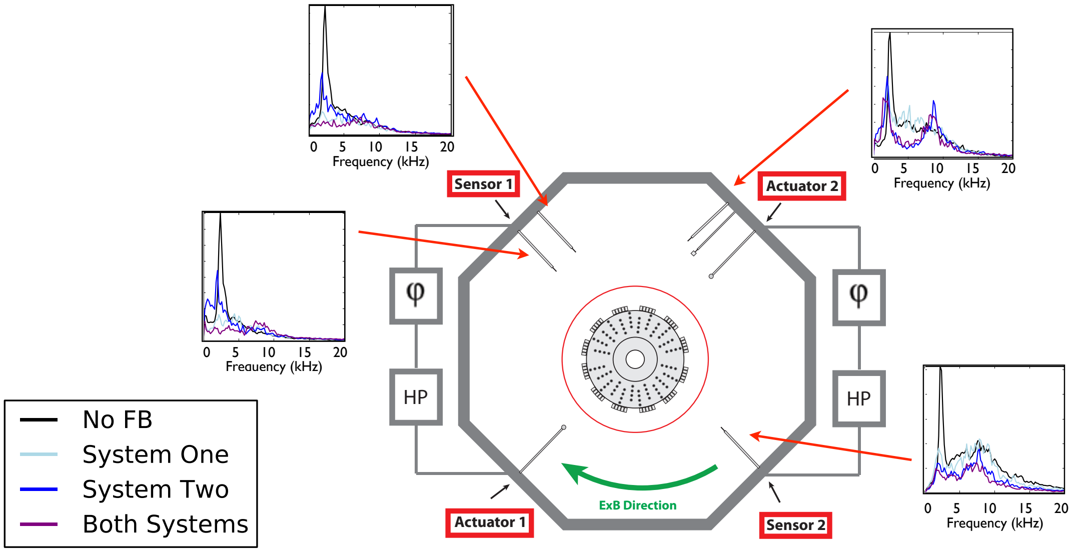
# Recent Advancements in Dipole Turbulence Control

*Multiple Controllers Achieve Global Feedback Suppression*

(Max Roberts, Doctoral Student)

**Problem**: Turbulence decorrelates preventing global suppression

**Solution**: Apply multiple independent controllers



JOURNAL OF GEOPHYSICAL RESEARCH, SPACE PHYSICS VOL. 74, NO. 9, MAY 1, 1969

# Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation

THOMAS J. BIRMINGHAM

$$\frac{\partial\langle\bar{Q}\rangle(\alpha, M, J, t)}{\partial t} = \frac{\partial}{\partial\alpha}\left[\overline{D_{\alpha\alpha}}\,\frac{\partial\langle\bar{Q}\rangle}{\partial\alpha}\right] \quad (5)$$

α = magnetic flux, ψ

dipole field. We describe **E** by the potential $V$

$$V = \frac{A(t)r}{\sin^2\vartheta}\sin\phi \quad (2)$$

$A$ being a positive, time-dependent amplitude. The form equation 2 is the fundamental ($m = 1$) asymmetric mode in *Fälthammar*'s [1965] Fourier expansion of a general longitudinally dependent potential. Since $r\sin^{-2}\vartheta$ and $\phi$ are both constant on dipole field lines, **B** lines are equipotentials, and **E·B** is zero. In the $\vartheta = \pi/2$, equatorial plane

Collisionless Random Electric Convection

$$\boxed{\overline{D_{\alpha\alpha}} \approx \frac{c^2\mu^2}{4\alpha^2}(\pi)^{1/2}\tau_c\mathcal{A}} \quad (18)$$

A reasonable direction to proceed, in view of the paucity of direct experimental evidence of electric fields and their time variations, is to assume that the autocorrelation $\langle\delta A(t-\tau)\,\delta A(t)\rangle$ has the form

$$\langle\delta A(t-\tau)\,\delta A(t)\rangle = \mathcal{A}\exp -\frac{\tau^2}{\tau_c^2} \quad (16)$$

from dawn to dusk, and is random on the time scale on which the solar wind executes time variations of large spatial extent. (The correlation time $\tau_c$ is thus typically one hour.)

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E×B $\{$

$$\dot{\psi} = \nabla\psi\cdot\mathbf{V} = \frac{\partial\Phi}{\partial\varphi} = -RE_\varphi$$

Diffusion Coefficient $\{$

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

$$D = R^2\langle E_\varphi^2\rangle\tau_c$$

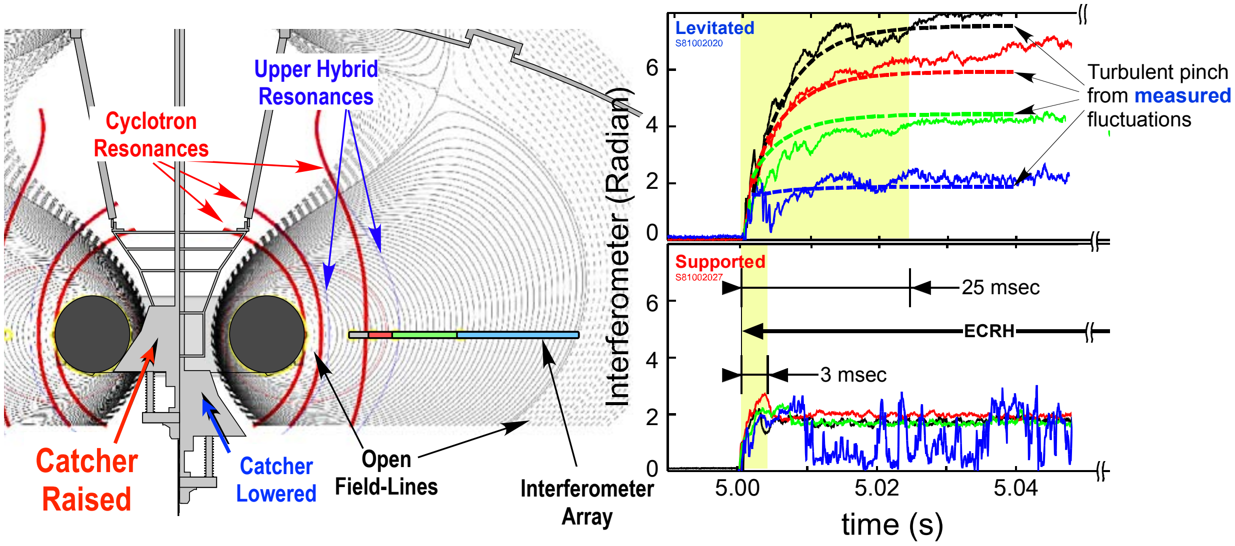
Transport of Plasma Flux-Tubes $\{$

$$\frac{\partial N}{\partial t} = \langle S\rangle + \frac{\partial}{\partial\psi}D\frac{\partial N}{\partial\psi}$$

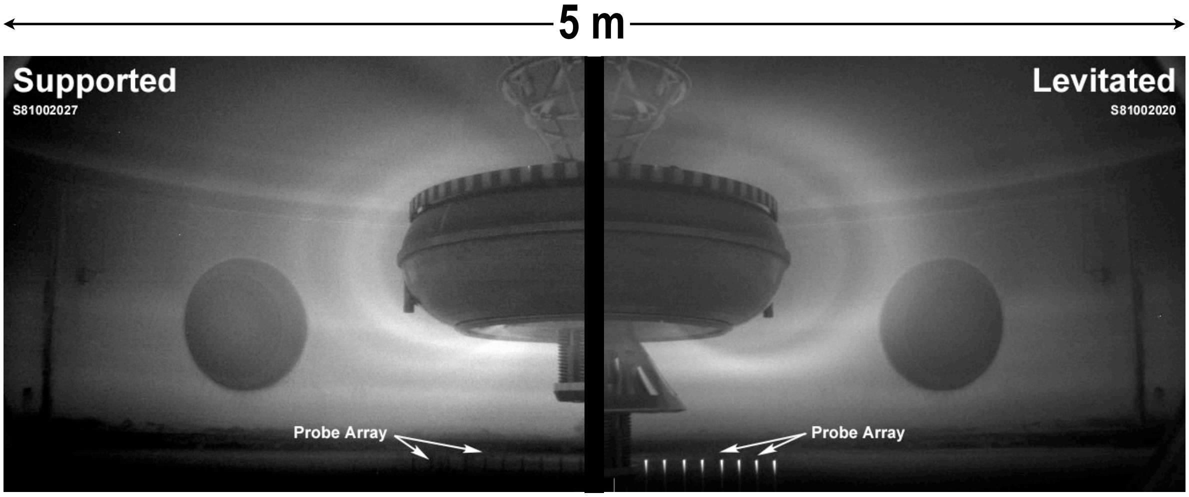
# Quantitative Verification of Inward Turbulent Convection

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

With levitated dipole, inward turbulent transport sets profile evolution

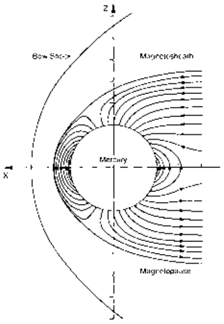


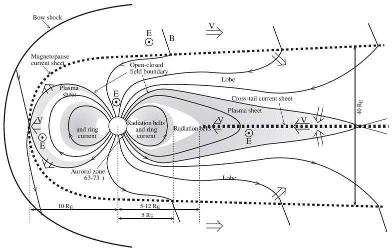
# World's Largest Lab Magnetosphere

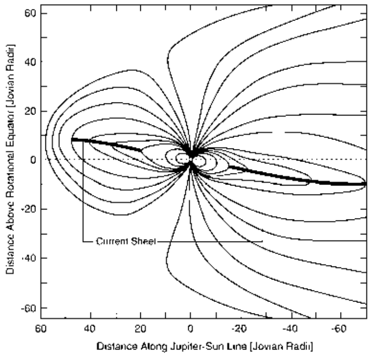


***Size matters***:
At larger size, trapped particle energy, intensity of "artificial radiation belt", and plasma density significantly increase

# High Density and Large Size are required for Controlled Investigations of Alfvén Wave Dynamics





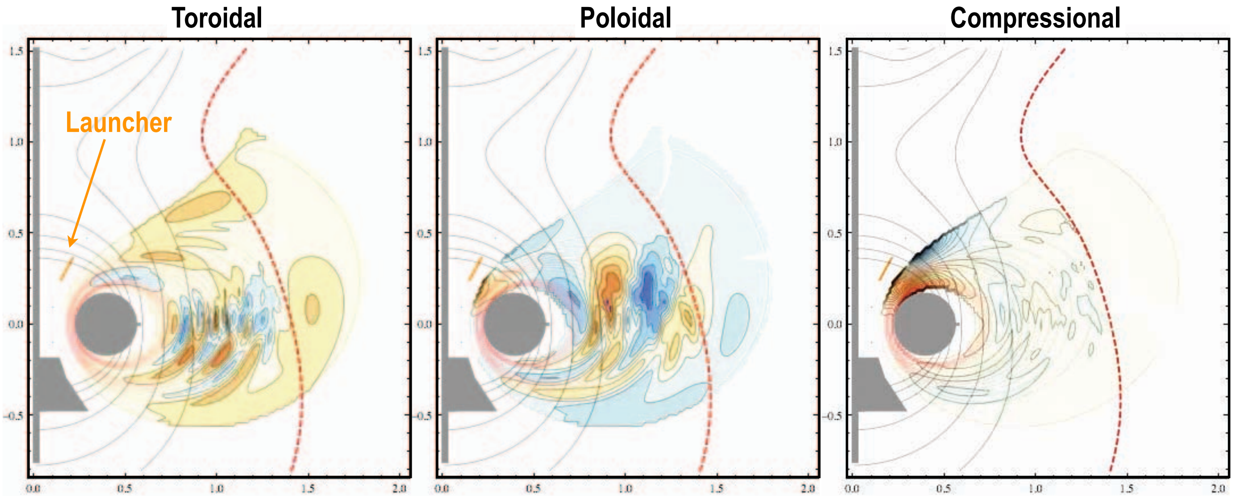


$$\boxed{\frac{V_A}{L} \sim f_A \ll f_{ci} \longrightarrow \frac{c/\omega_{pi}}{L} \ll 1}$$

| | **Mercury** | **Earth** | **Jupiter** |
|---|---|---|---|
| **Size** | 2 $R_H$ | 10 $R_E$ | 100 $R_J$ |
| **Density ($c$ / $\omega_{pi}$ $L$)** | 0.1 | 0.003 | 0.00001 |
| **Comments** | $V_a/L \sim f_{ci}$ | Alfvén Resonances | Propagating Alfvén |

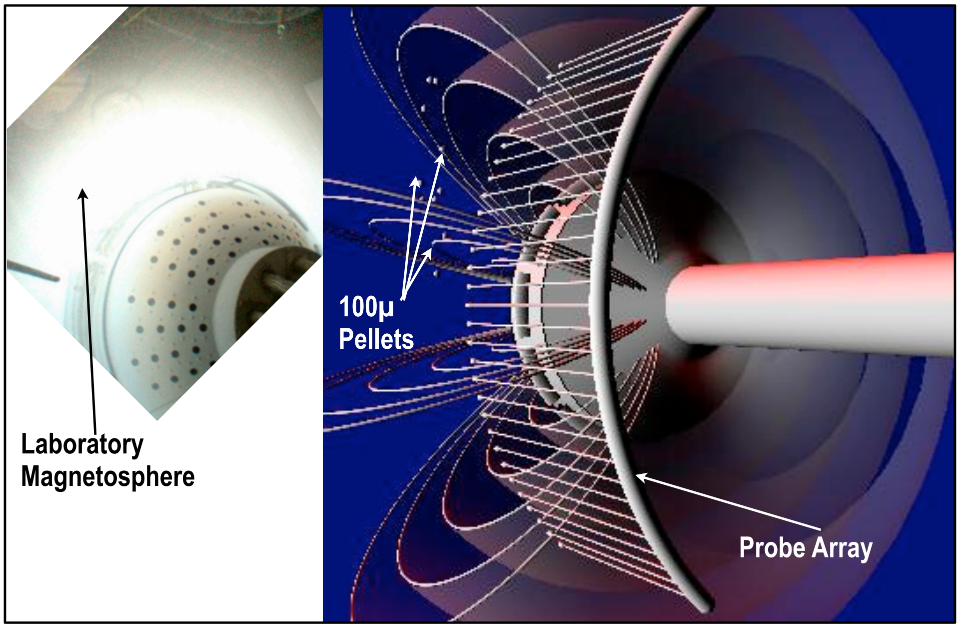
# Alfvén Wave Excitation in LDX: Opportunity for a Many Important Experiments

- 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

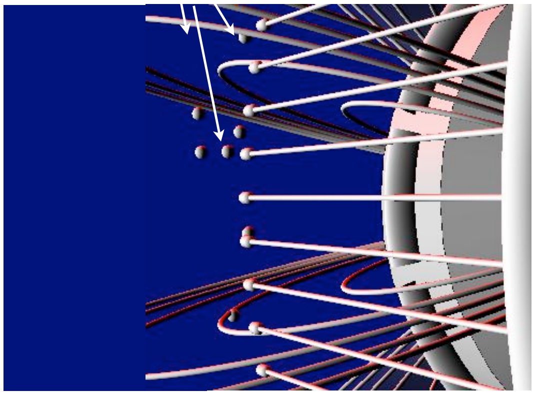
# “Exploding Pellet” Experiments: Transient High Density and Plasmaspheric Mixing



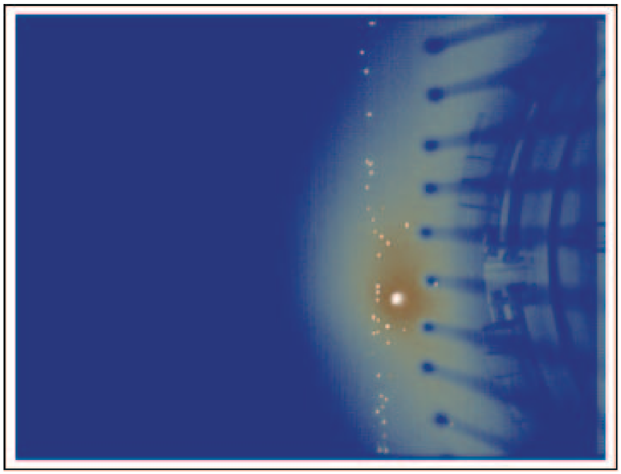
# First “Exploding Pellet” Experiments

**Next-step:** “Exploding Pellet” Experiments scheduled August in larger MIT device with **×100 more energy** with faster dynamics expected

200 micron Polystyrene



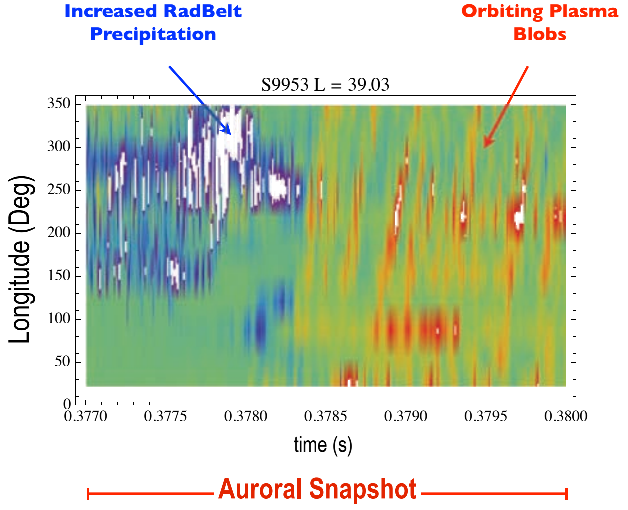
Fast Camera View

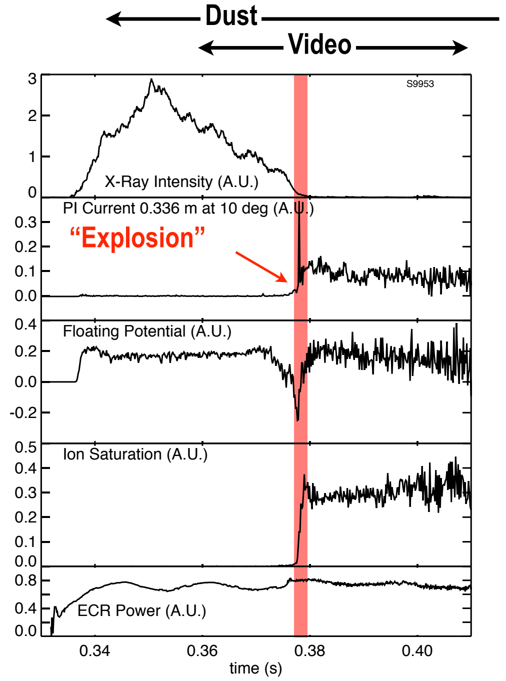


250 μsec/frame

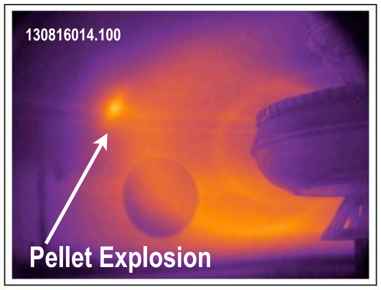
# First "Exploding Pellet" Experiments

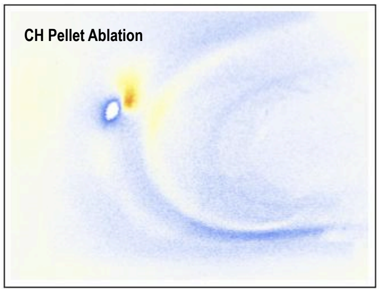
High-Speed record of "Auroral Current" at the moment of "**Explosion**"

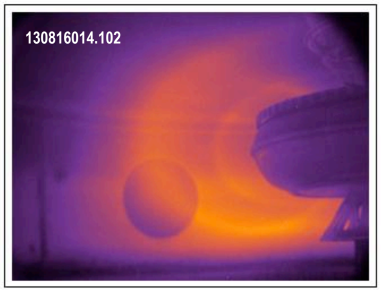


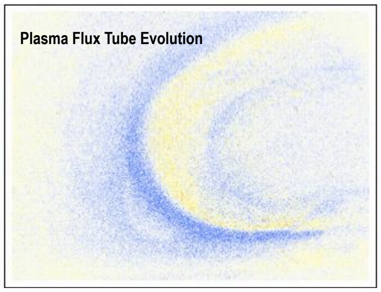


# Pellet Injection Allows Direct Measurement of Flux-Tube Mixing Dynamics









# Near-Term Follow-on Experiments: Fast Injection & Pico-Pico-Satellites

- 2.5 mm Pellet Injector (500 - 1000 m/sec) for deep fast penetration

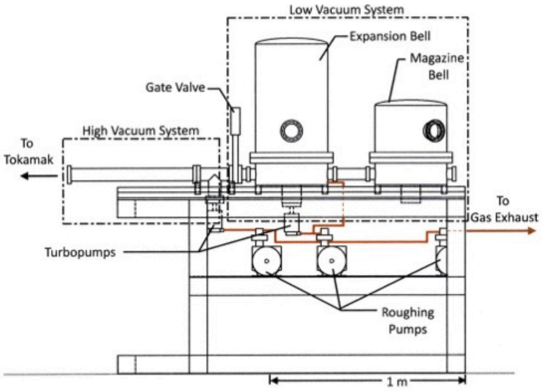
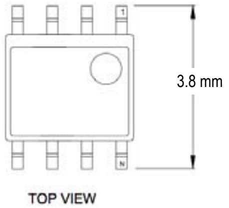


Figure 4-1: Schematic of Lithium Pellet Injector, designed and constructed by Darren Garnier [77]

- ~ 5.0 mm Pico-Pico-Sats for laboratory validation of tiny satellite probes for swarm measurement in magnetosphere



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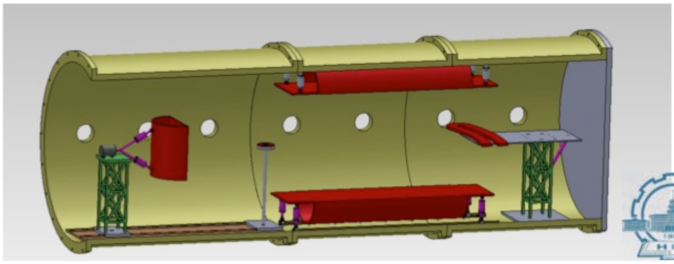
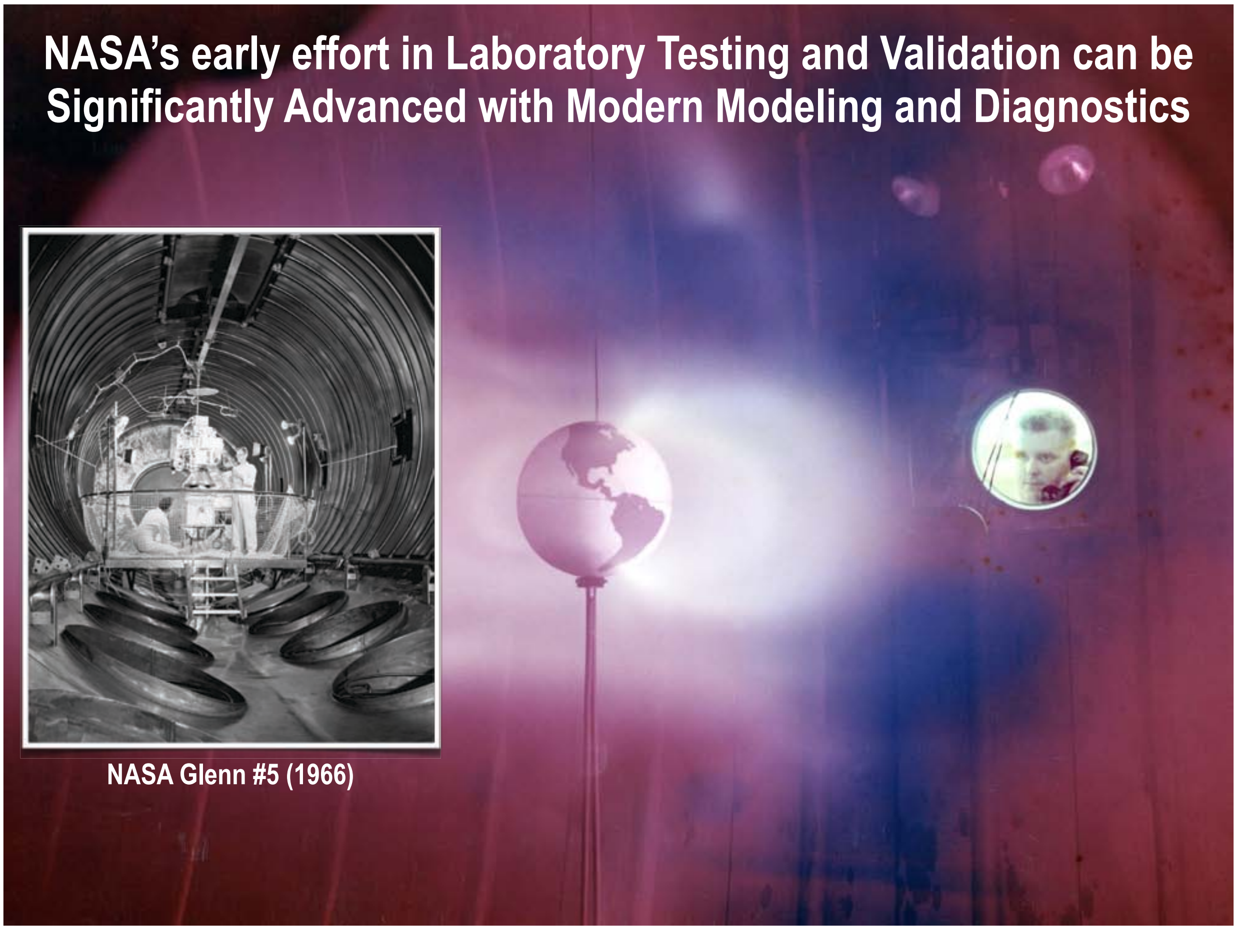
## Laboratory Magnetospheres:

# Very Large Plasma Experiments World-Wide

- **Columbia University**: 1.7 m dia; 1.5 kW heating power
  Turbulence studies, radiation belt dynamics and transport
- **MIT**: 5.0 m dia; 25 kW heating power; ***Levitated***
  World's largest, highest energy, most capability (1 MW available)
- **Univ. Tokyo**: 2.0 m dia; 40 kW heating power; ***Levitated***
  $e^-/e^+$ plasmas, supersonic flow, highest power and near "perfect" confinement
- **HIT (Harbin, China)**: 3.5 m x 10 m (*under construction*)
  Solar wind,
  magnetotail distortion,
  space weather





## NASA's early effort in Laboratory Testing and Validation can be Significantly Advanced with Modern Modeling and Diagnostics

NASA Glenn #5 (1966)

## Opportunity Exists to Explore a Large Scale Laboratory Magnetosphere

Space Power Facility (SPF)

Plum Brook Facility at Sandusky
World's Largest Vacuum Vessel

# 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 magnetosphere on Earth

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LDX Dedicated October 2004

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