The Laboratory Magnetosphere: Studying space physics in plasmas confined by a levitated dipole magnet

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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

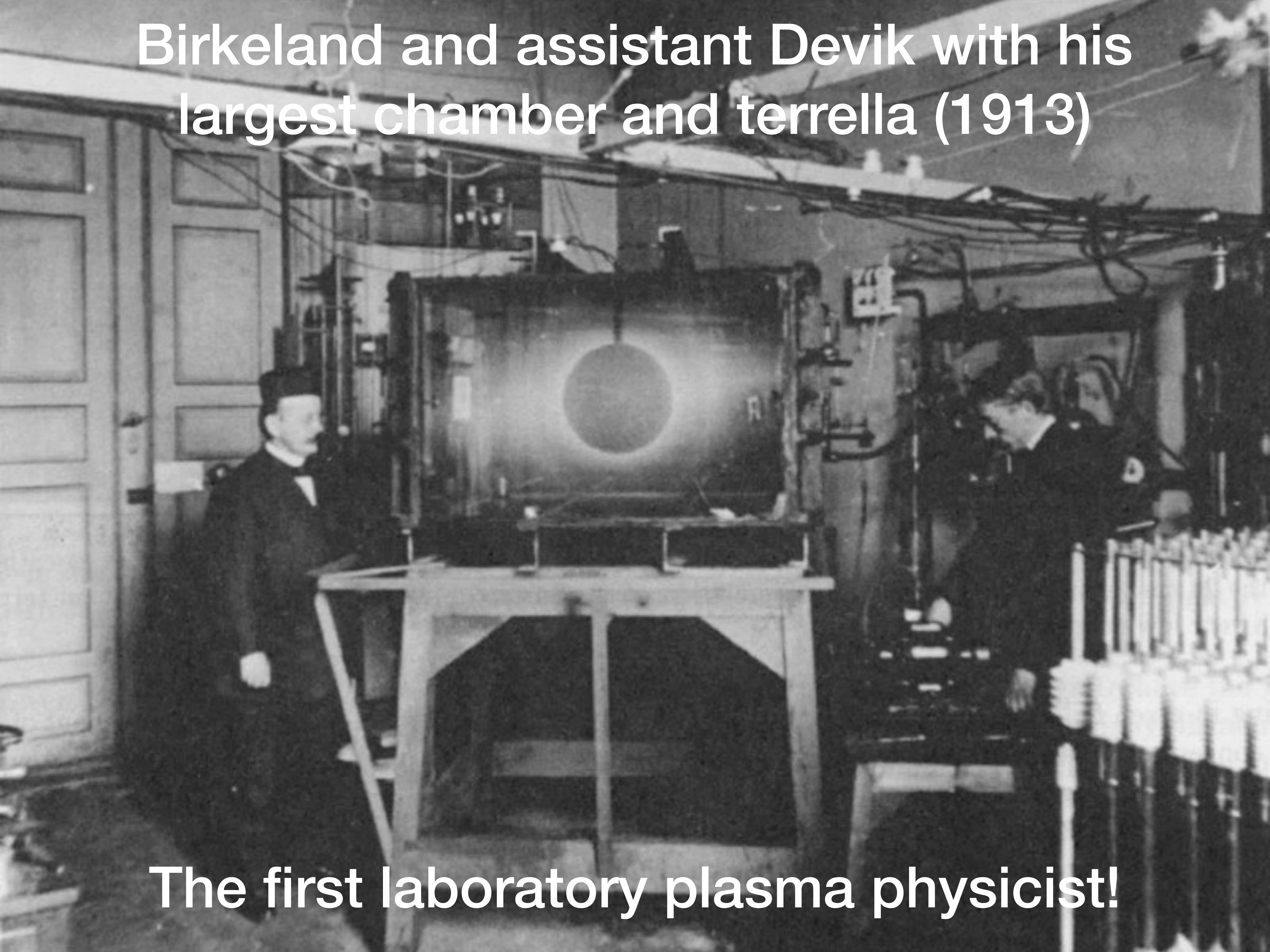
representing results of Jay Kesner, Masaki Nishiura, Barrett Rogers, Zensho Yoshida, and the students and scientists conducting research in support of the CTX, LDX, and RT-1

@MIT PSFC

Bring Space Down To Earth

University of California, Los Angeles, April 12, 2017

Birkeland and assistant Devik with his largest chamber and terrella (1913)



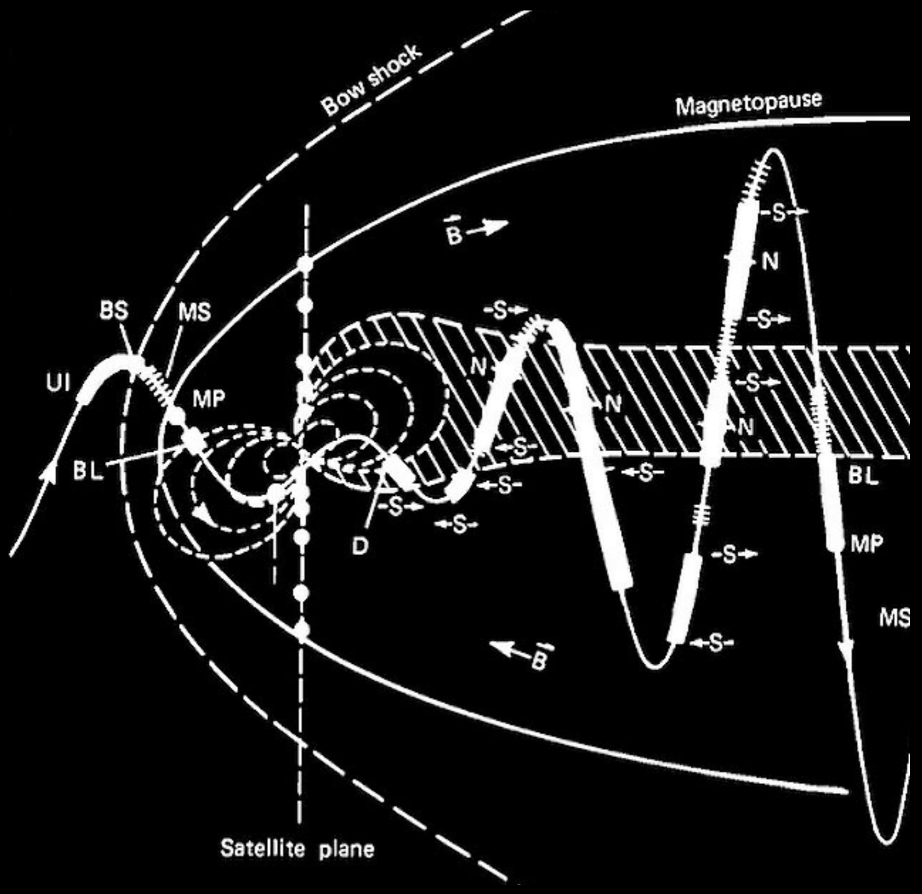
The first laboratory plasma physicist!

Laboratory Magnetospheres

- (Space) Plasma Physics started with the terrella
  - From Birkeland to the present, much has been studied in the dipole magnetic configuration
- "Laboratory Magnetospheres" have been built to study a particular process in magnetospheric physics
  - Hasegawa's question: Can fluctuations drive particles and energy to steep radial profiles in the laboratory as seen in space?
  - Spoiler: Yes.
- However, they are much more generic platforms, capable of studying other processes in laboratory
  - Reliable, steady state plasmas, with high beta, large size, lower collisionality
  - Opportunity to build a new facility with higher density and warm ions

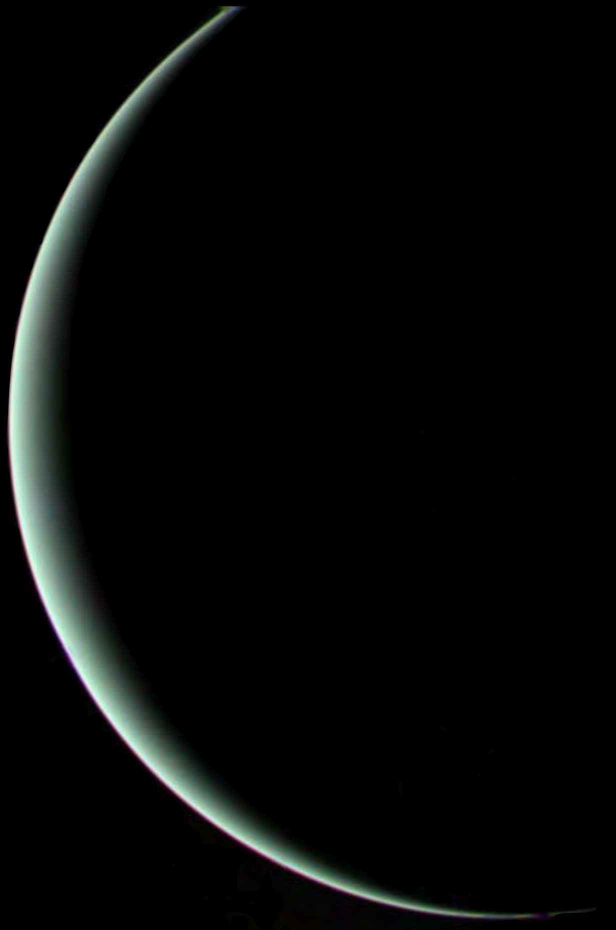
Akira Hasegawa invited to Voyager 2’s encounter with Uranus

January 24, 1986



12 Hour Flyby

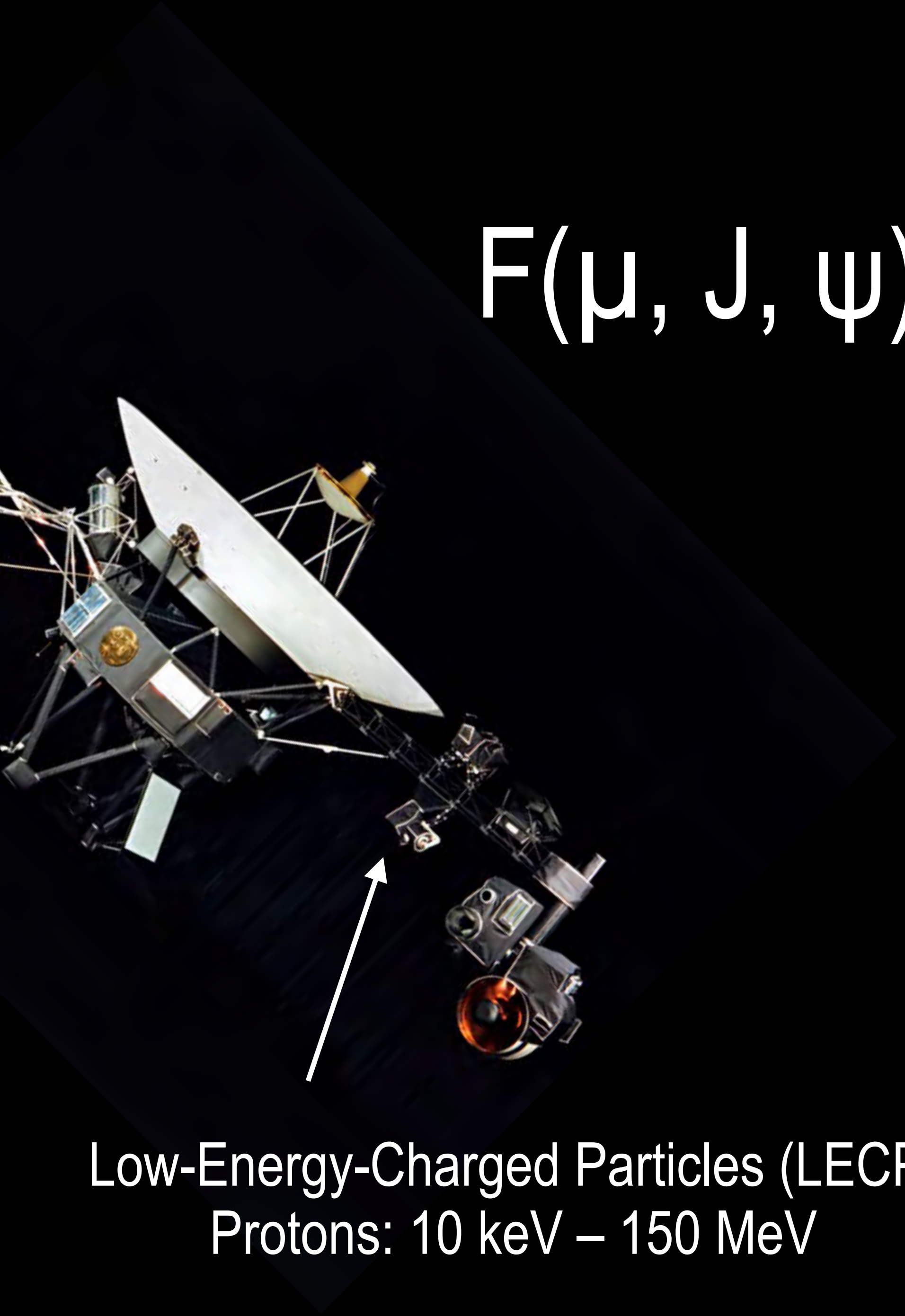
10 Newly Discovered Moons
Large, Tilted Magnetosphere
Long, Twisted Magnetotail
Substorm Injection
Inward diffusion and convection
Energetic Particles
Centrally-peaked Profiles
Plasma - Moon Interactions
…



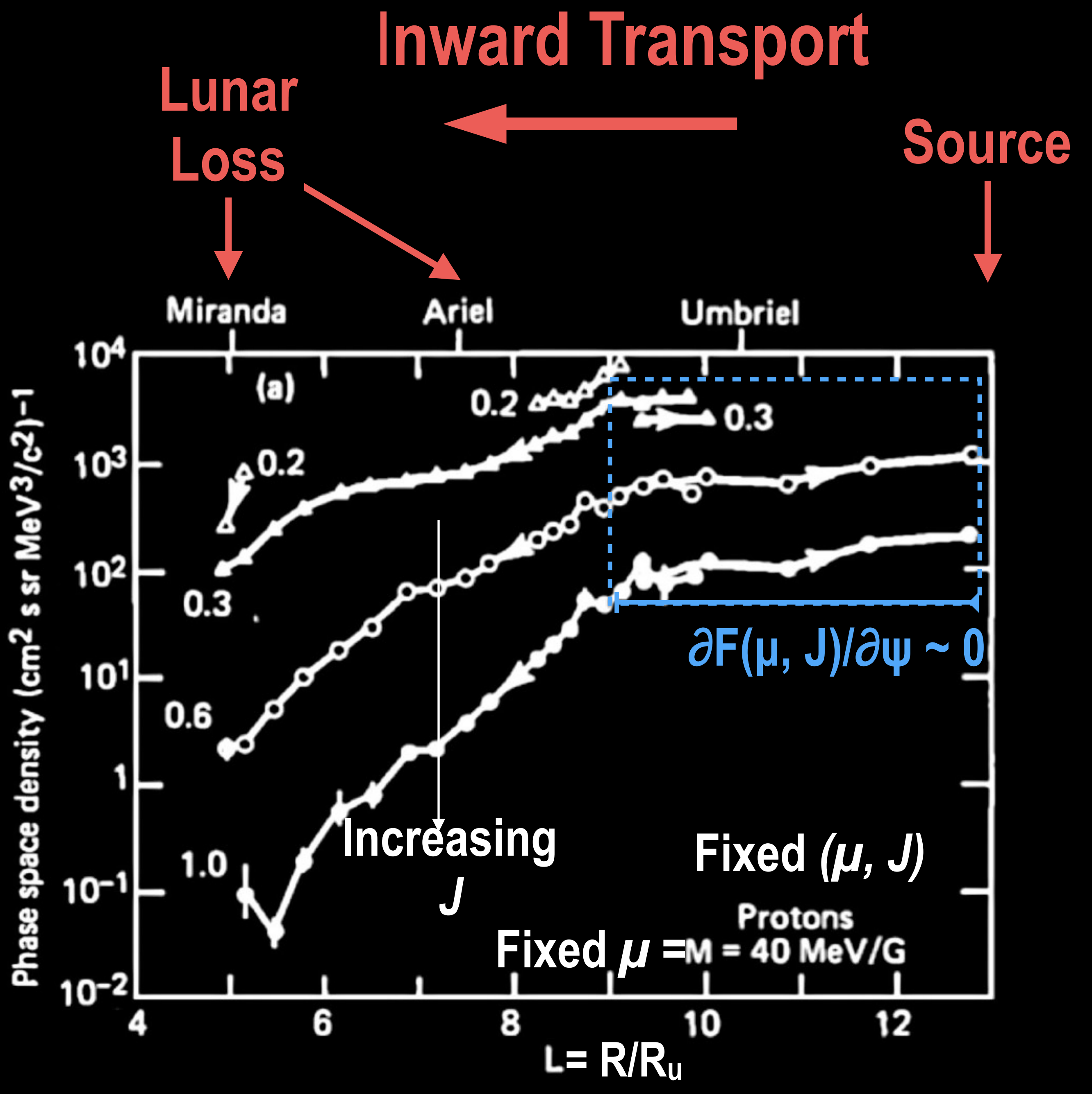
Ed Stone, *JGR* **92**, 14,873 (1987)

Inward Transport of Energetic Particles

$F(\mu, J, \psi)$



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



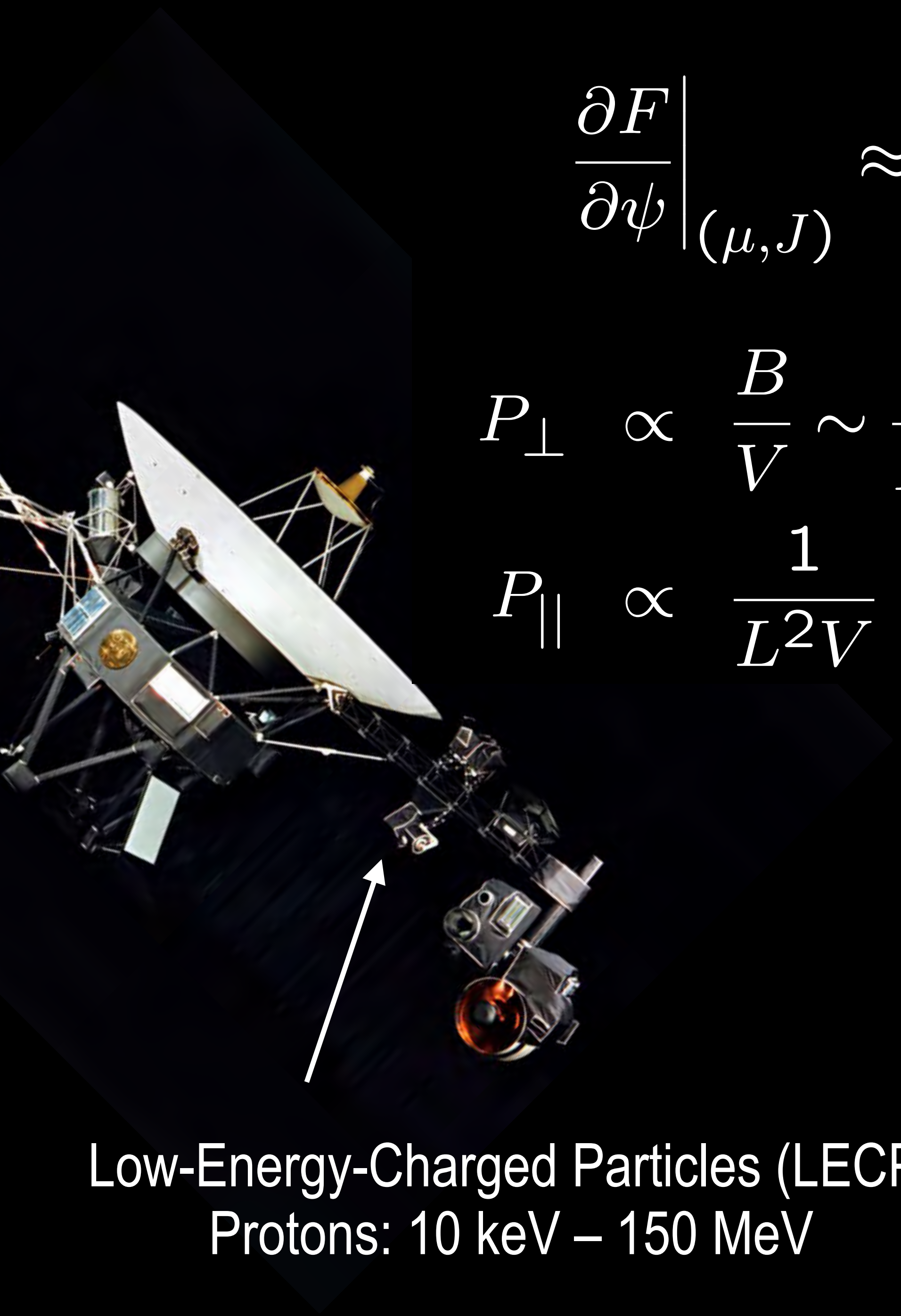
Chen, *et al.*, *JGR* **92**, 15,315 (1987)

Inward Transport Creates Centrally-Peaked Pressure

$$\left.\frac{\partial F}{\partial \psi}\right|_{(\mu,J)} \approx 0$$

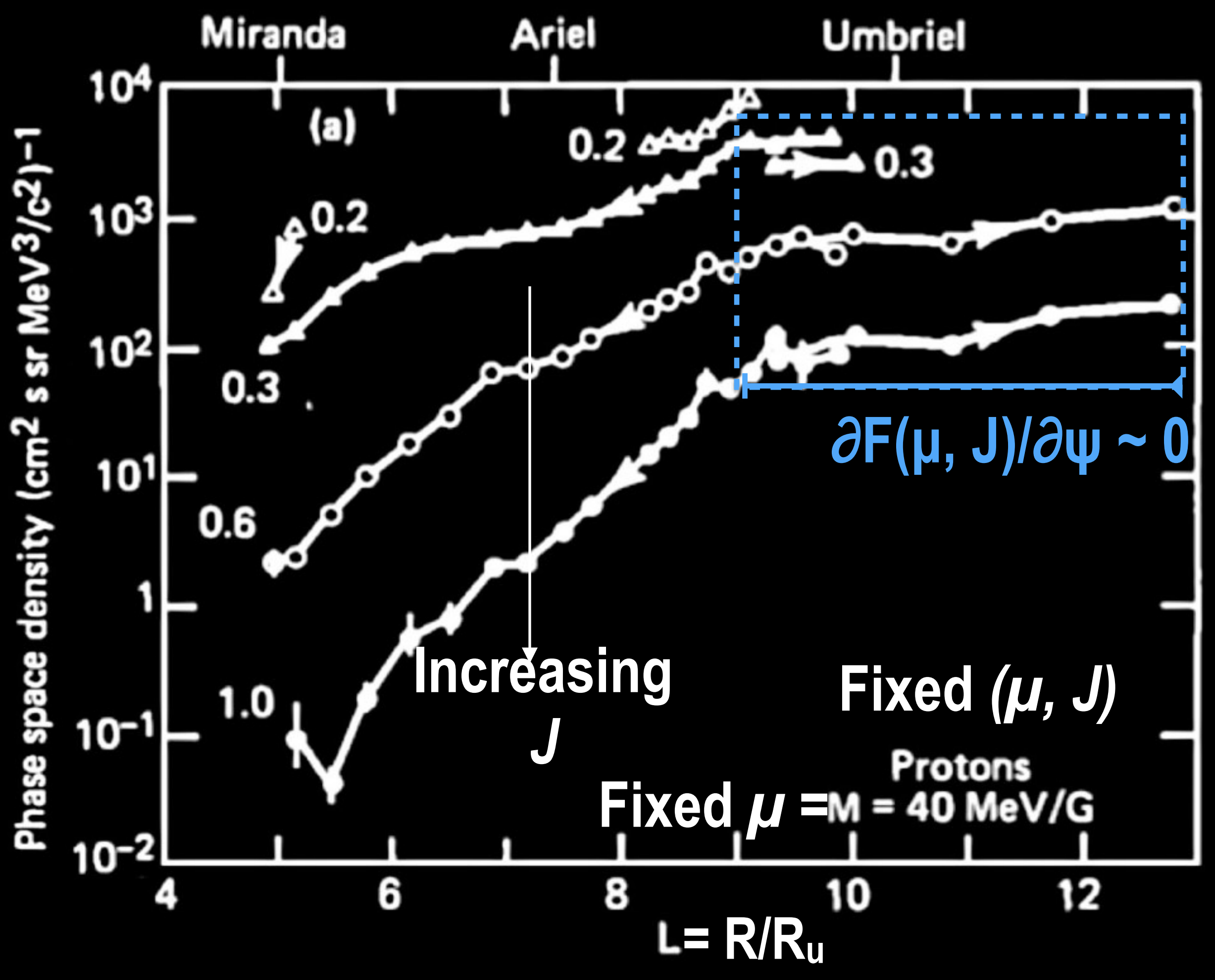
$$P_\perp \propto \frac{B}{V} \sim \frac{1}{L^7}$$

$$P_{||} \propto \frac{1}{L^2 V} \sim \frac{1}{L^6}$$



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

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



Chen, *et al.*, *JGR* **92**, 15,315 (1987)

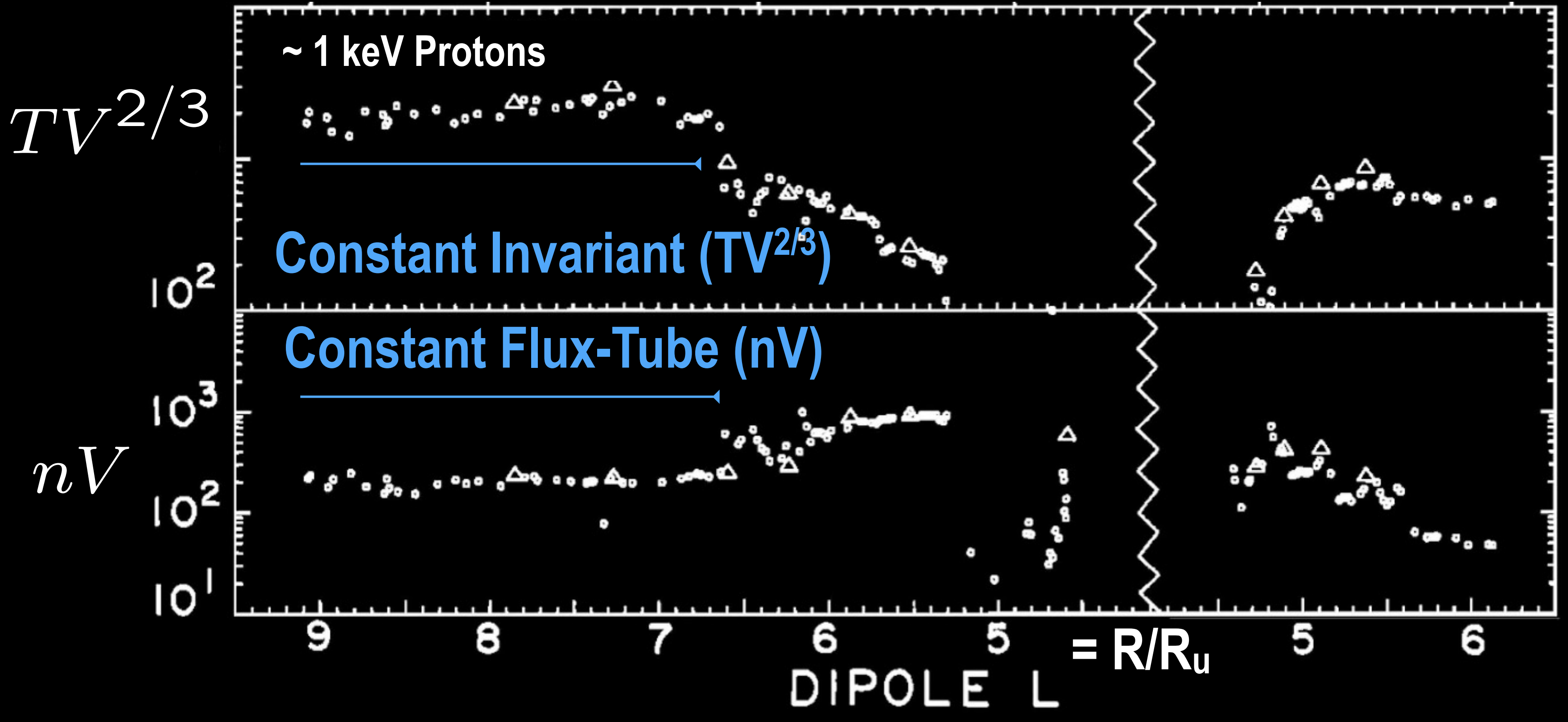
Flux-tube Volume = $V = \int \frac{dl}{B} \propto L^4$

Convection of Thermal Plasma Creates Regions with Constant Flux-Tube Content and Invariant Temperature

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

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

Flux-tube Volume = $V = \int \frac{dl}{B} \propto L^4$



Selesnick and McNutt, *JGR* **92**, 15,249 (1987)

$$P \propto \frac{1}{V^{5/3}} \sim \frac{1}{L^{20/3}}$$

Magnetospheres are Nature's Laboratories for Magnetic Confinement Physics

Voyager 2 Encounters: Jupiter (1979), Saturn (1981), Uranus (1986), Neptune (1989)

Observations of magnetospheric radial transport and stability…

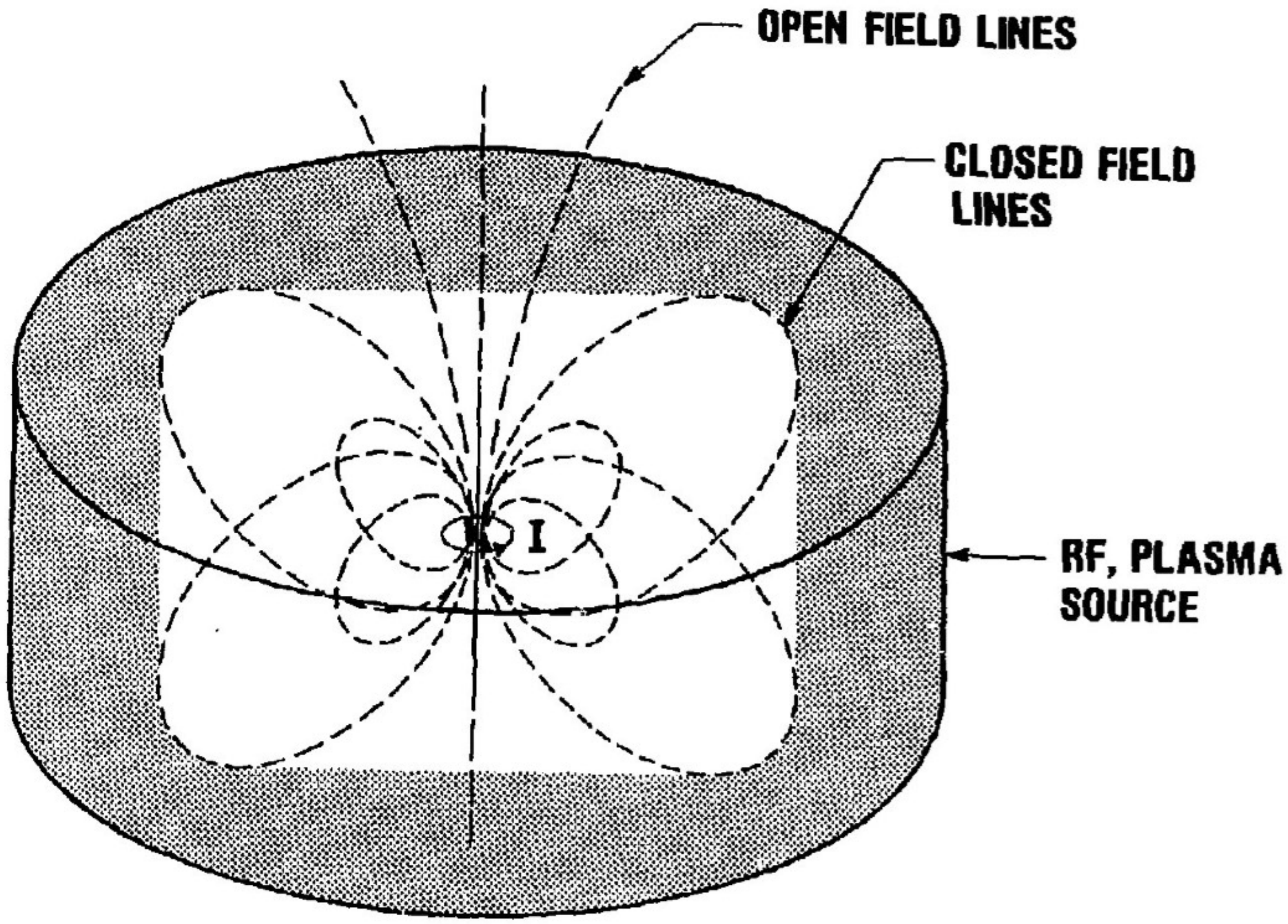
- ➡ Inward transport of energetic particles preserve (μ, J) creating ***centrally-peaked pressure***
- ➡ Interchange motion of thermal plasma preserves flux-tube content (**$n\ V$**) and invariant temperature (**$T\ V^{2/3}$**) creating ***centrally peaked profiles***
- ➡ Marginally stable profiles $\Delta(P\ V^{5/3}) \sim 0$ ***at high beta***, $\beta \geq 1$

Stone and Lane, *Science*, **206**, 925 (1979)
Stone, *JGR* **88**, 8639 (1983)

Stone, *JGR* **92**, 14,873 (1987)
Stone and Miner, *Science*, **246**, 1417 (1989)

Hasegawa: Does magnetospheric physics apply to magnetic confinement in the laboratory?

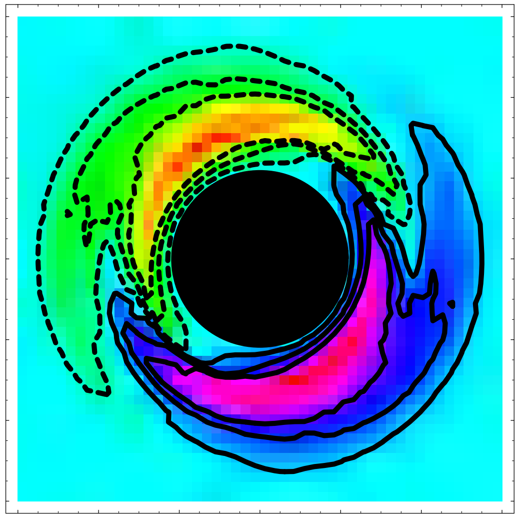
- **Levitate** a small, high-current superconducting current ring within a very large vacuum vessel
- **Inject** heating power and a source of plasma particles at outer edge
- **Somehow drive** low-frequency fluctuations that create radial transport, preserve (μ, J), and sustain "centrally-peaked" profiles at marginal stability
- **Achieve** high beta, β ≥ 1, steady-state, and link space and fusion studies

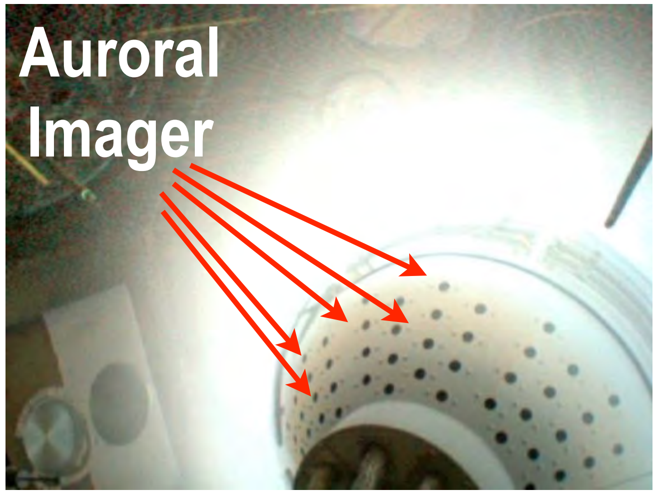


Akira Hasegawa, *Comments on Plasma Physics and Controlled Fusion* **11**, 147 (1987)

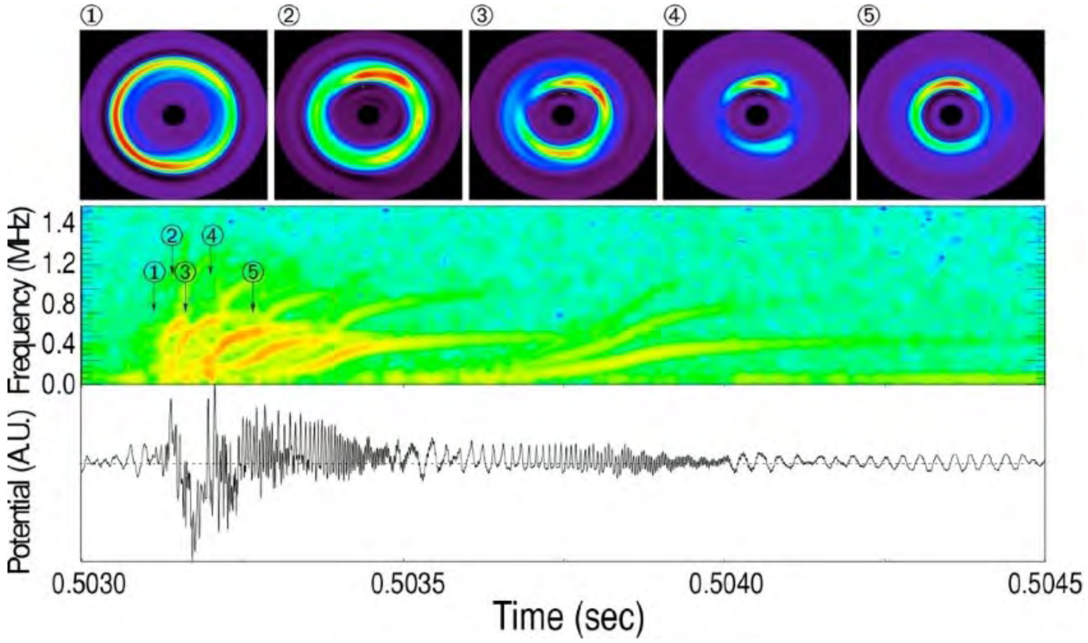
Much is already understood from non-levitated laboratory dipole experiments like CTX…

- ✓ Spatial structure and temporal dynamics of gradient and centrifugally-driven interchange and entropy mode turbulence

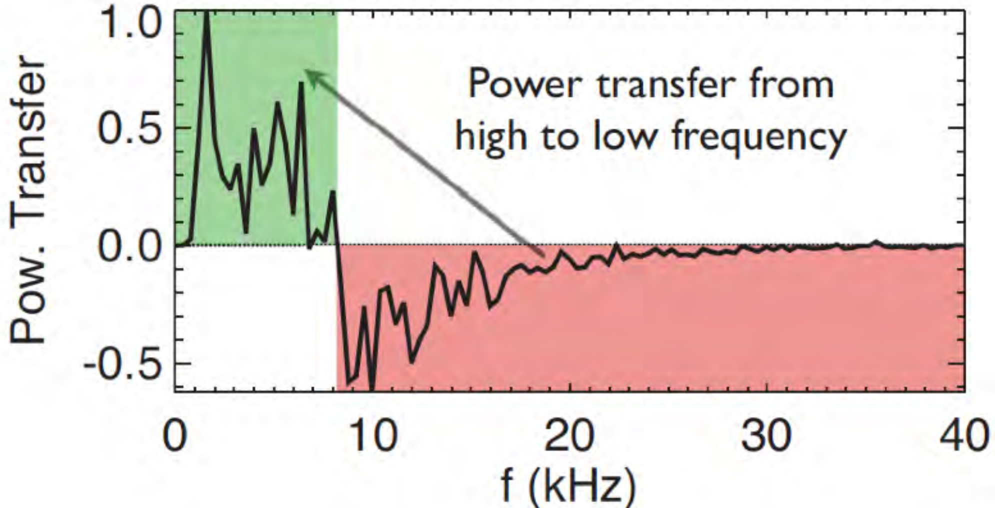




- ✓ “Artificial radiation belts” show complex nonlinear particle dynamics and drift-resonant transport understood without adjustable parameters

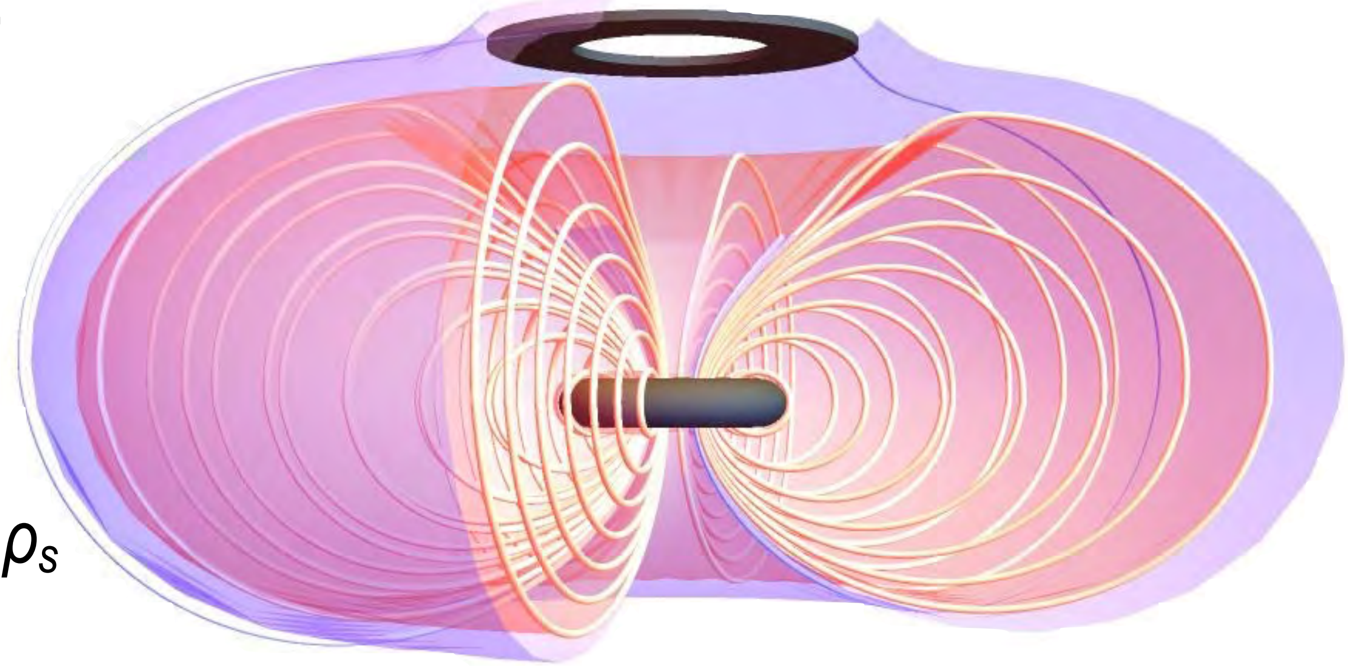


- ✓ Turbulent mixing is 2D (flute-like) with inverse cascade of scales



Turbulent Transport of Magnetized Plasma are at the Intersection of Laboratory and Space Physics

- Turbulence in magnetized plasma involves anisotropic fluctuations, which interact nonlinearly and couple energy, momentum, and particle number ***through spectral cascades spanning many length scales***:
  - The global plasma size, L
  - The ion inertial length, λ_i
  - The particle (sound) gyroradius, ρ_s
  - Dipole plasma ***must be large***: $L \gg \lambda_i \sim \rho_s$

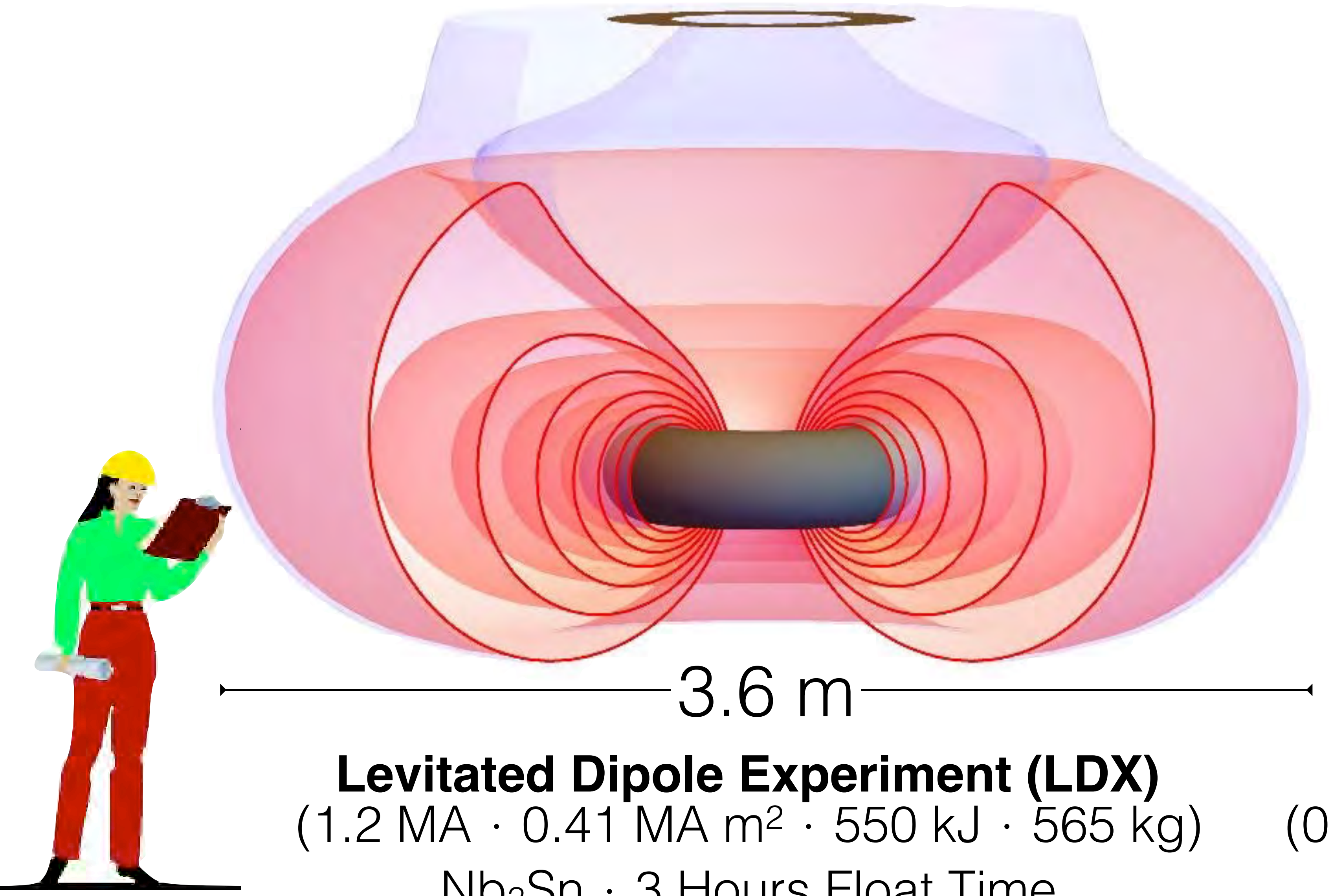


★***Technical challenges***:

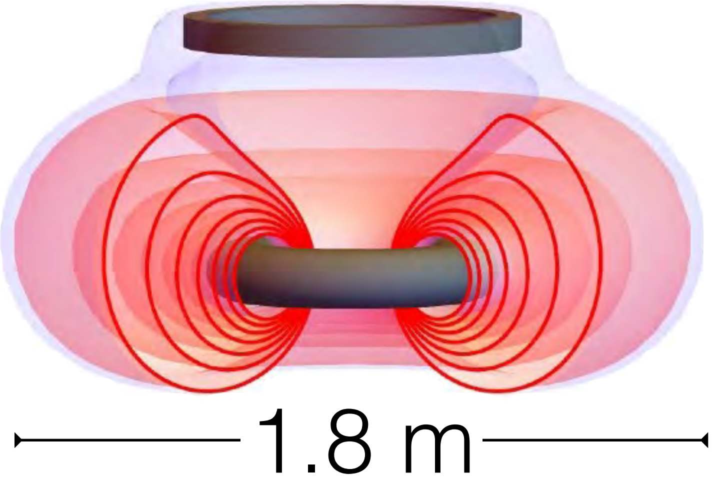
- Create conditions to study magnetized plasma turbulence across extreme range of scales ***while also at the very low collisionality*** *characteristic of space plasma*.
- Create and maintain plasma for ***the long time required*** to observe cross-field transport

➡ ***Technical solution***: **magnetically levitate** a high-field superconducting dipole magnet

Laboratory Magnetospheres



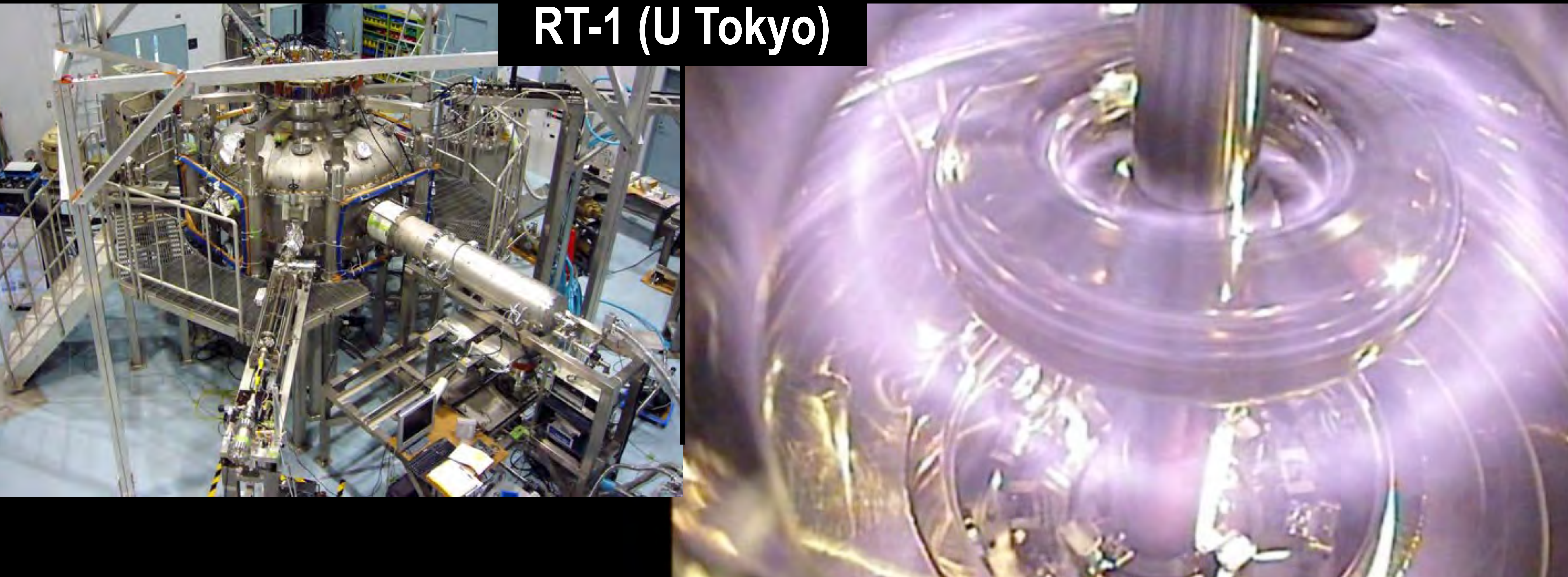
Levitated Dipole Experiment (LDX)
(1.2 MA · 0.41 MA m^2 · 550 kJ · 565 kg)
Nb$_3$Sn · 3 Hours Float Time
24 kW ECRH



Ring Trap 1 (RT-1)
(0.25 MA · 0.17 MA m^2 · 22 kJ · 112 k
Bi-2223 · 6 Hours Float Time
50 kW ECRH

LDX (MIT/Columbia)

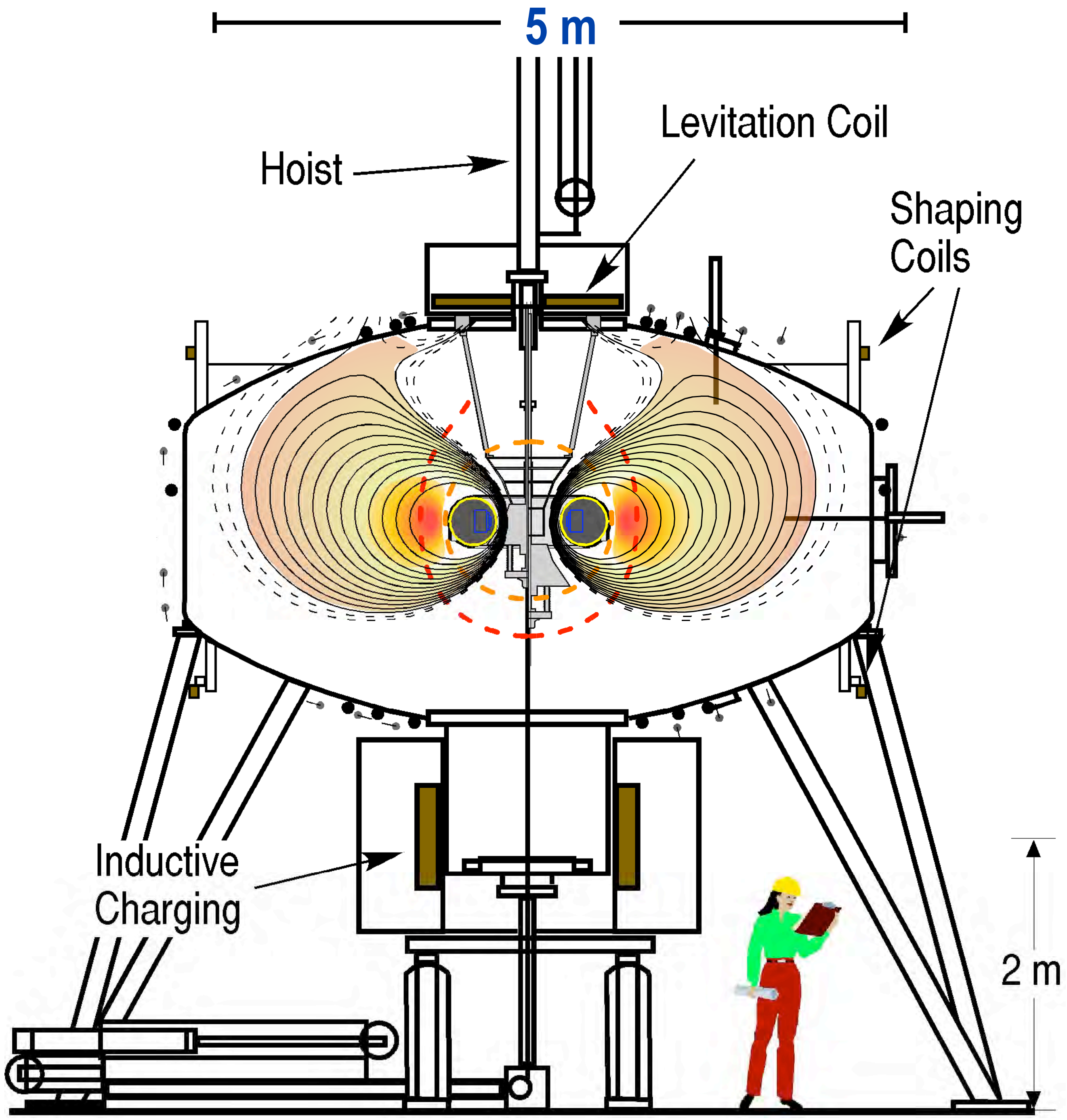
RT-1 (U Tokyo)



Laboratory Magnetospheric Devices

LDX (MIT - USA)

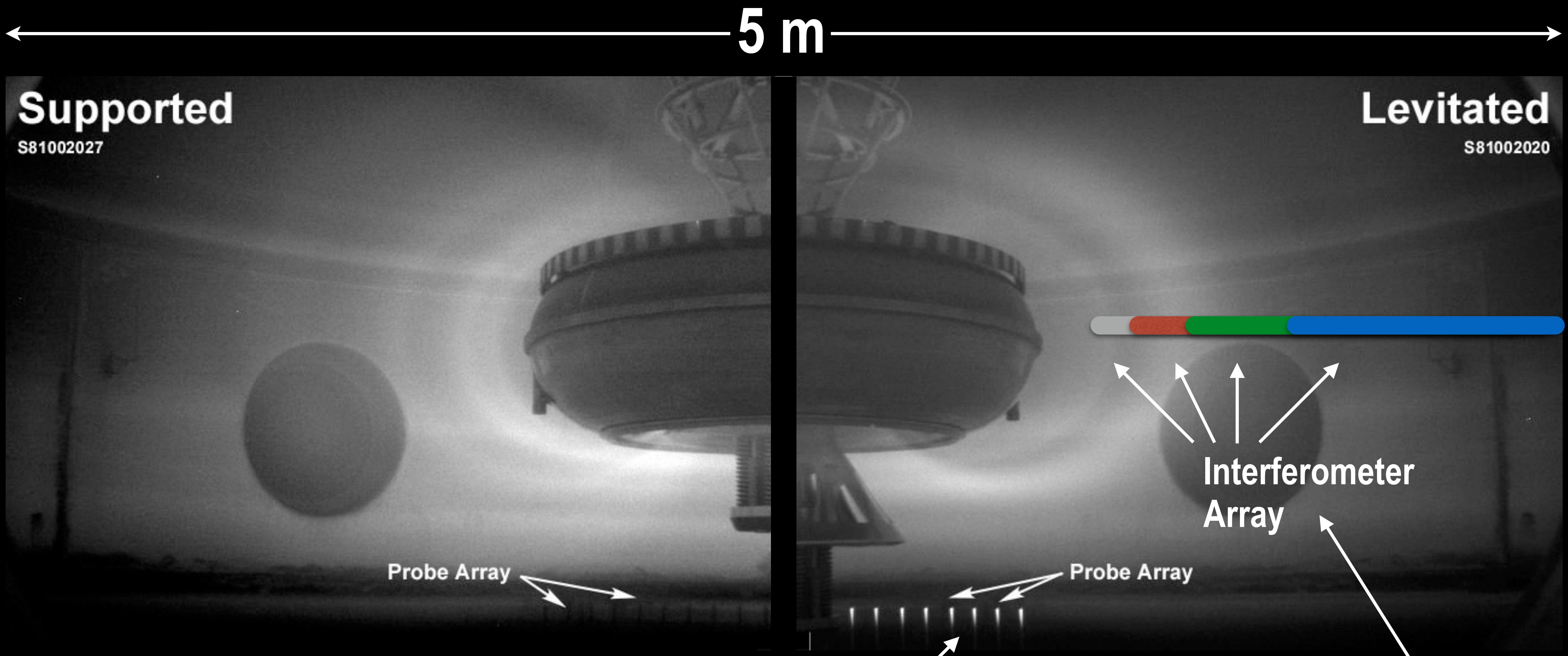
Nb_3Sn Dipole 1.2 MA
Inductively Charged
3 Hour Float Time 25 kW CW ECRH



Components of a Laboratory Magnetosphere

- **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 re-cooling, coil safety, and physics studies**
- **ECRH for high-temperature, high-beta plasmas**

Measurement of Density Profile and Turbulent Electric Field Gives Quantitative Verification of Bounce-Averaged Drift-kinetic Pinch

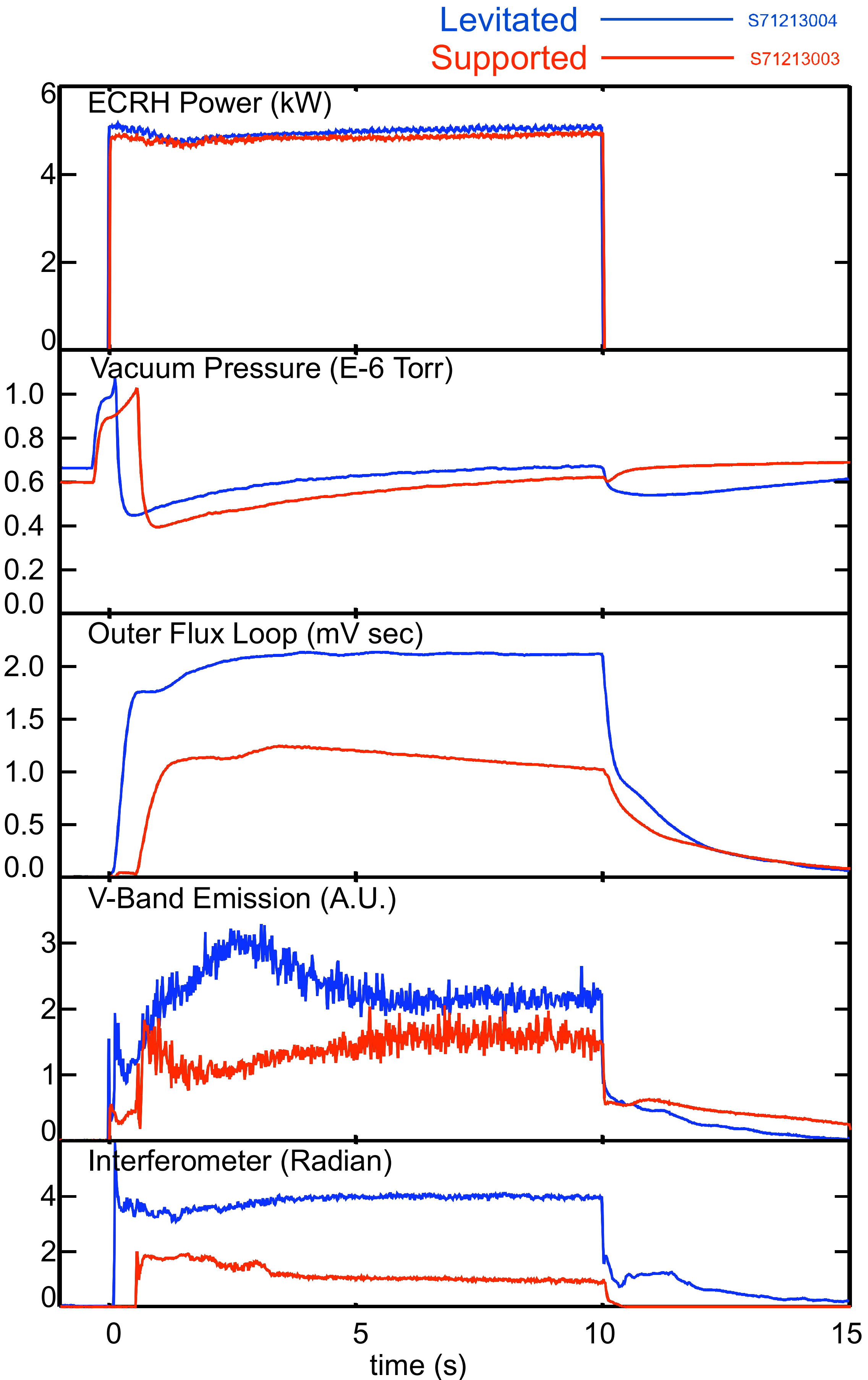


Measured Density Profile Evolution

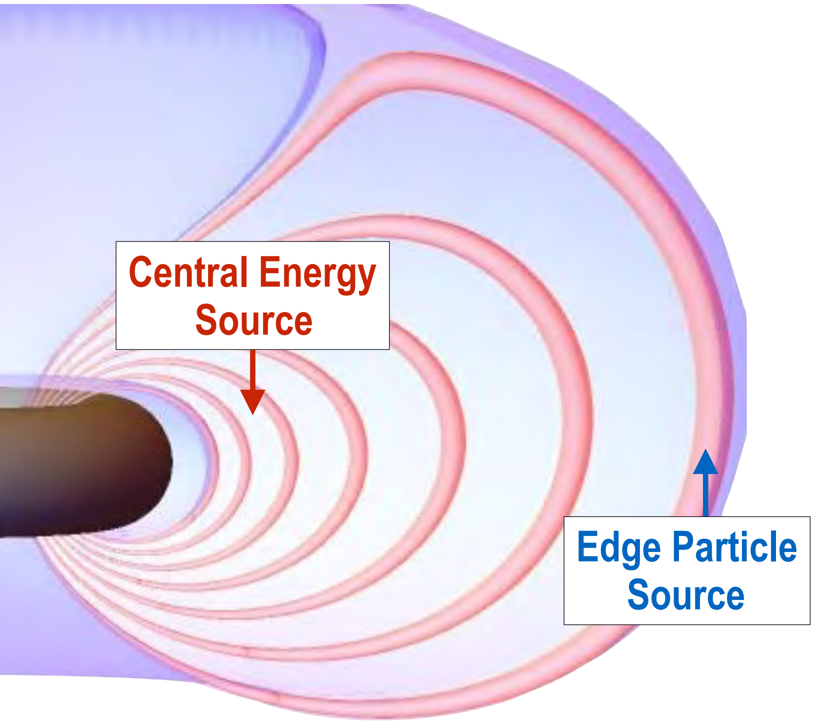
Measured Turbulent Electric Field

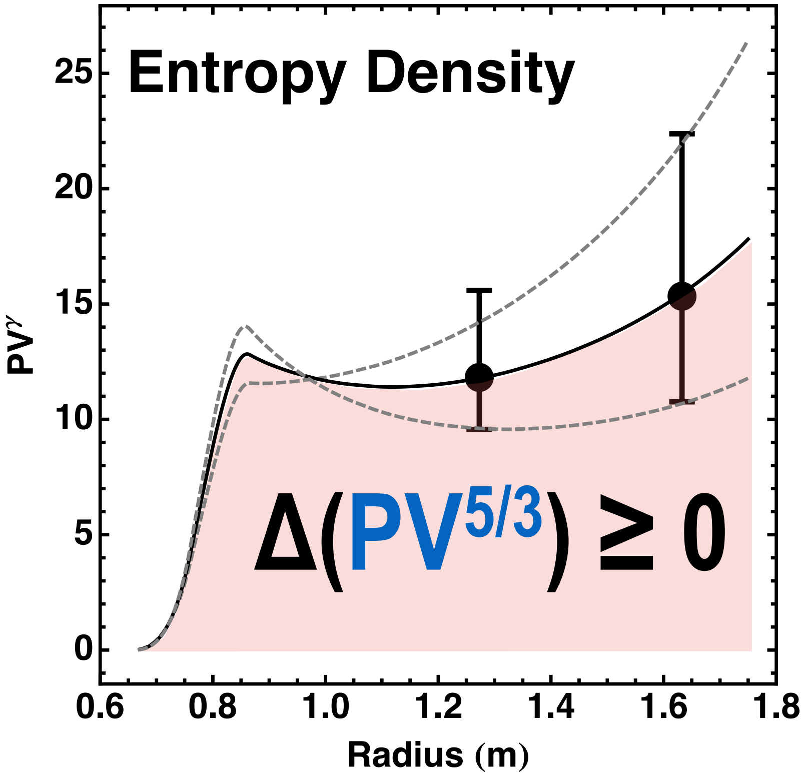
Plasma in Supported vs Levitated Dipole

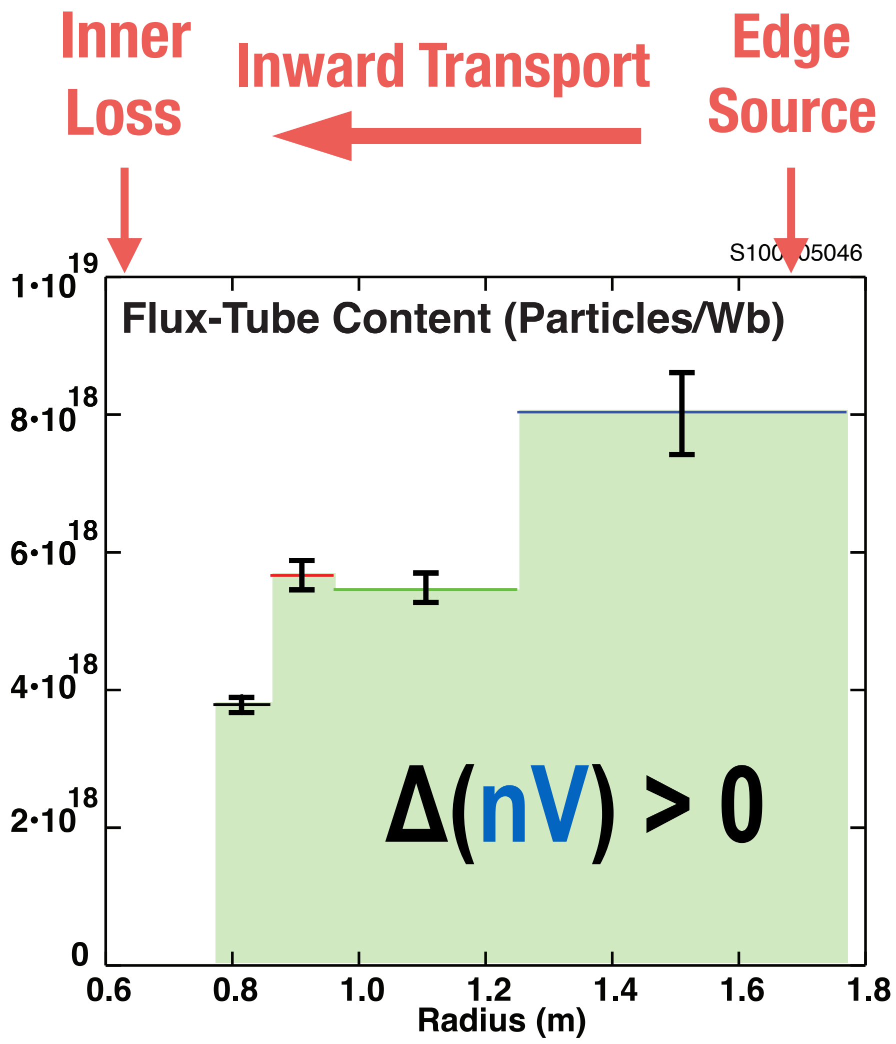
- 5 kW ECRH power and ~ 300 J stored energy (levitated)
- Peak local beta ~ 40%
- Supported plasma has stored energy in energetic electron population
- 2-3 x stored energy when levitated
- Levitation increases ratio of diamagnetism-to-cyclotron emission indicating higher thermal pressure.
- Supported long afterglow confinement indicative of energetic particle confinement
- Long, higher-density levitated afterglow shows improved bulk plasma confinement.



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







"warm core"
$\eta > 2/3$

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

$$\eta = \frac{\Delta \ln T}{\Delta \ln n}$$

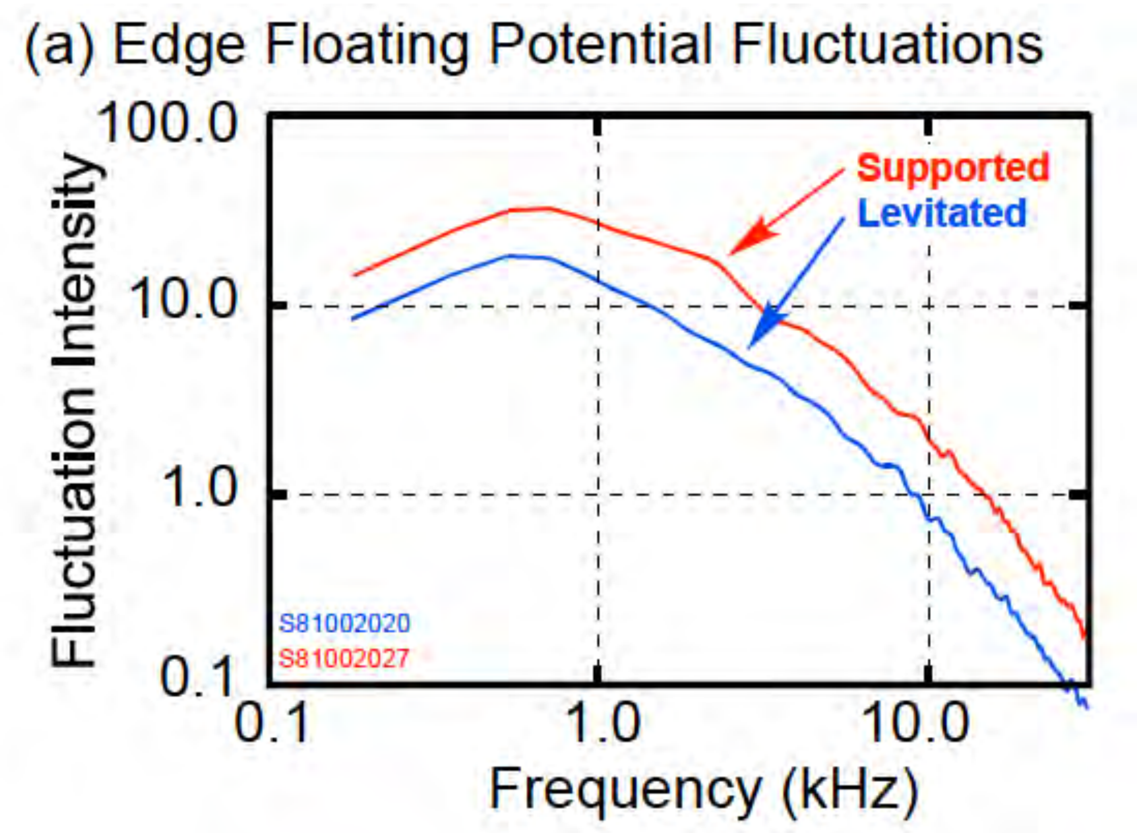
Alex Boxer, *et al.*, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nat Phys* **6**, 207 (2010).
Matt Davis, *et al.*, "Pressure profiles of plasmas confined in the field of a magnetic dipole," *PPCF* **56**, 095021 (2014).

Quantitative Verification of Inward Turbulent Pinch

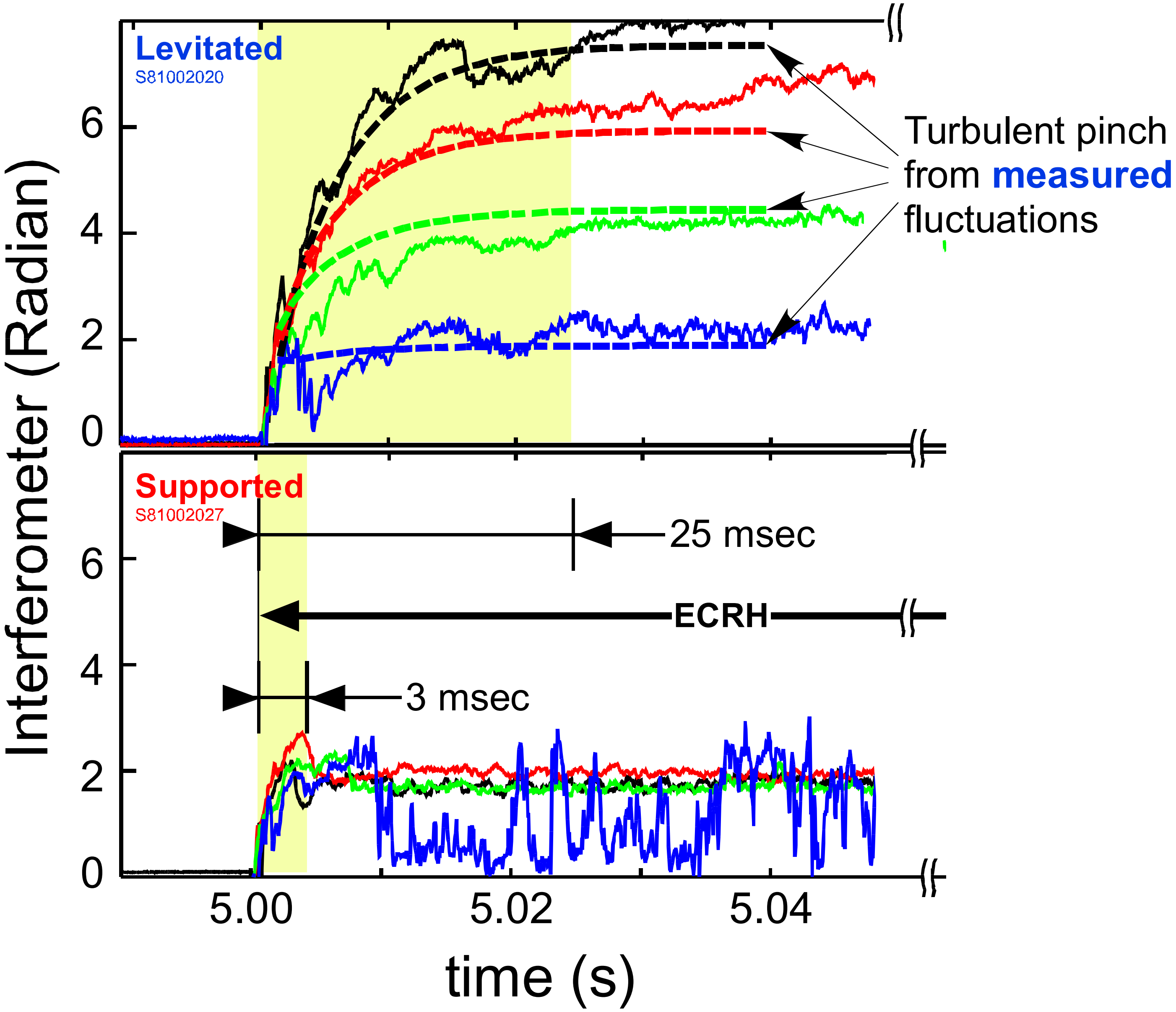
Thomas Birmingham, "Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation," *JGR*, 74, (1969).
Alex Boxer, *et al.*, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nature Phys* 6, (2010).

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

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



With levitated dipole, inward turbulent transport sets profile evolution



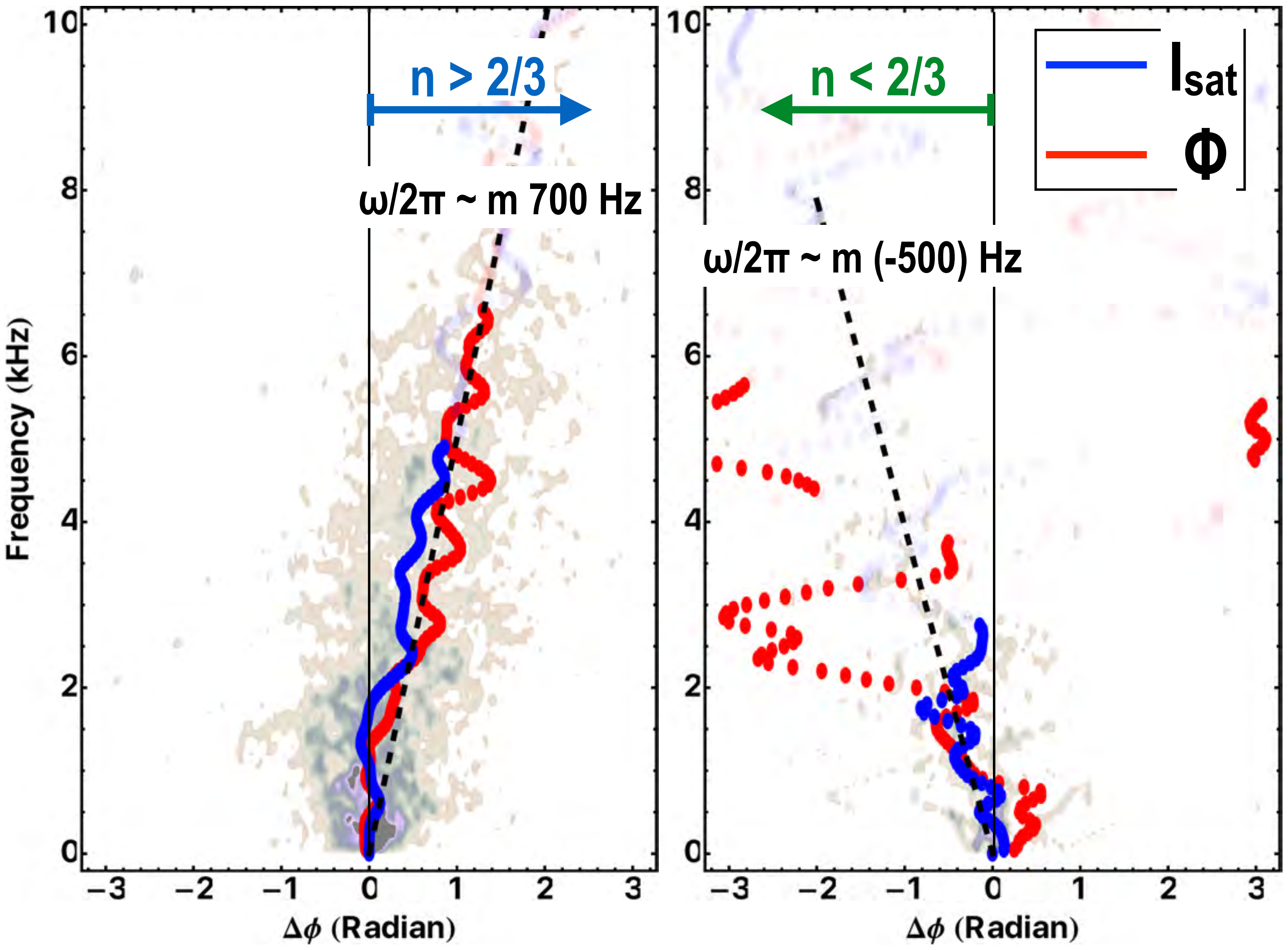
Turbulent pinch from **measured** fluctuations

Dispersion Measurements during Pellet Injection consistent with Linear Theory

Entropy Modes ***Reverse*** Direction with ***Reversal*** of Particle Flux

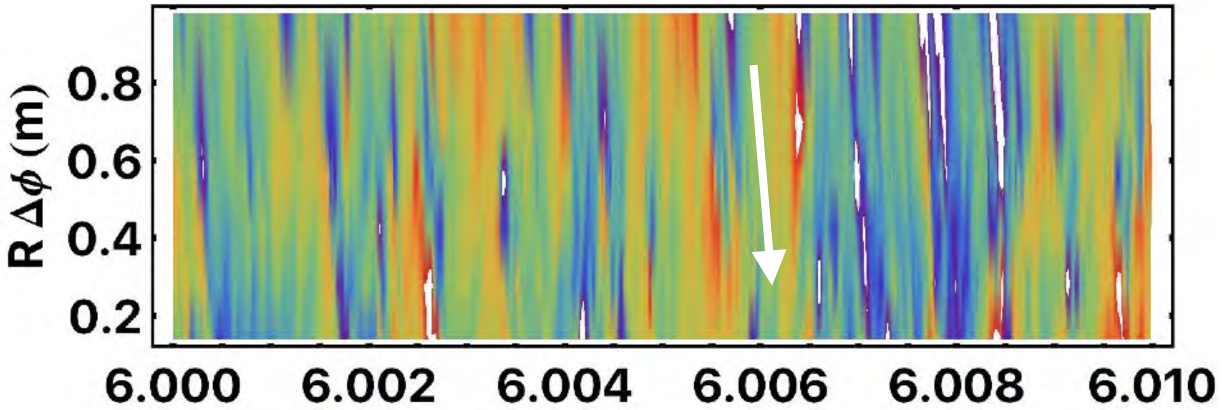
Ensemble-Averaged Entropy Mode Dispersion

Before Pellet Injection **During Pellet Injection**

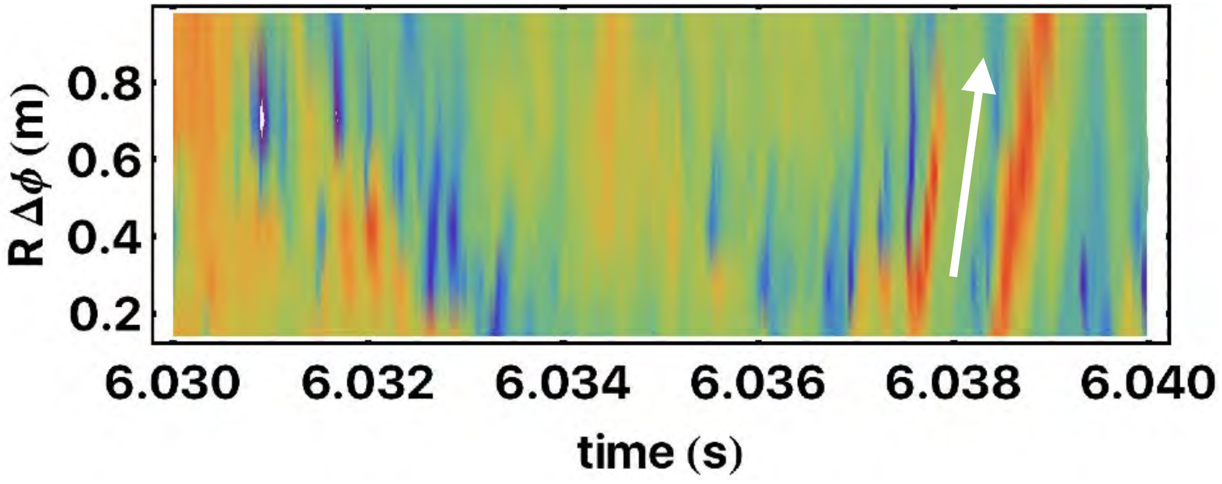


Potential Fluctuations Reverse Direction

Before Pellet Injection



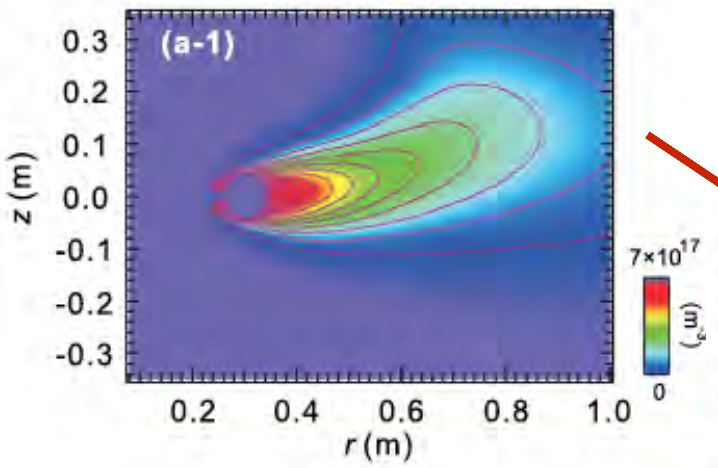
During Pellet Injection

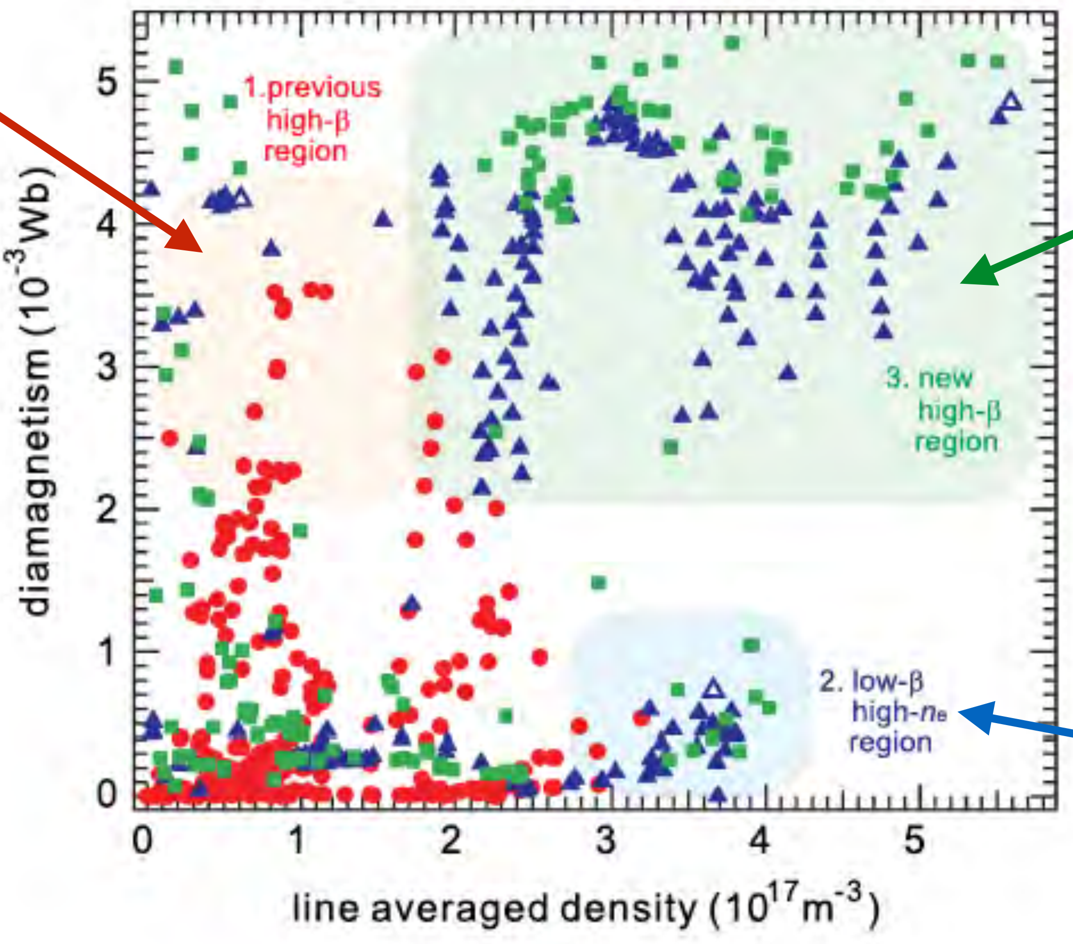


DT Garnier,et. al. Turbulent fluctuations during pellet injection into a dipole confined plasma torus. Physics of Plasmas, 24(1), 012506 (2017)

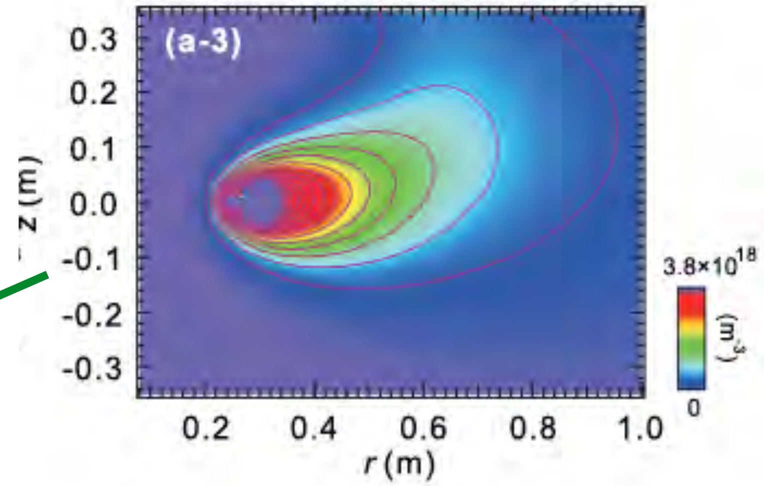
RT-1 has ***Three Regimes*** of High-β Operation depending upon Background Neutral Density and ECRH Power

$P_\perp \gg P_\parallel$

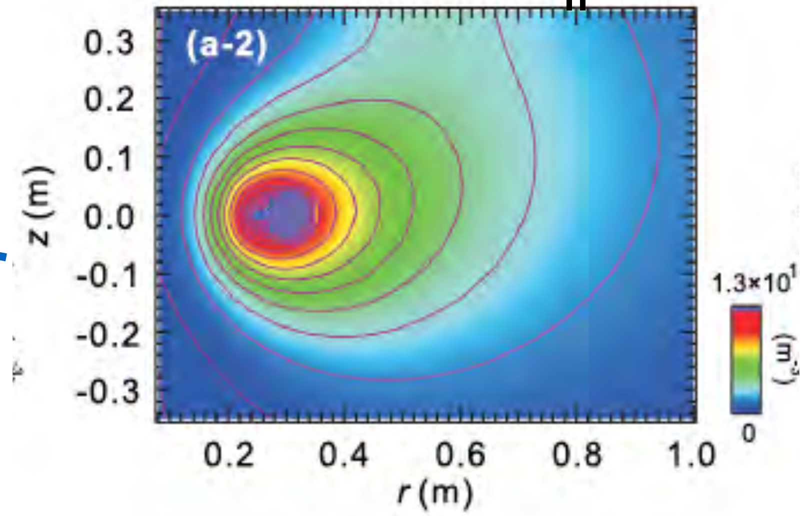


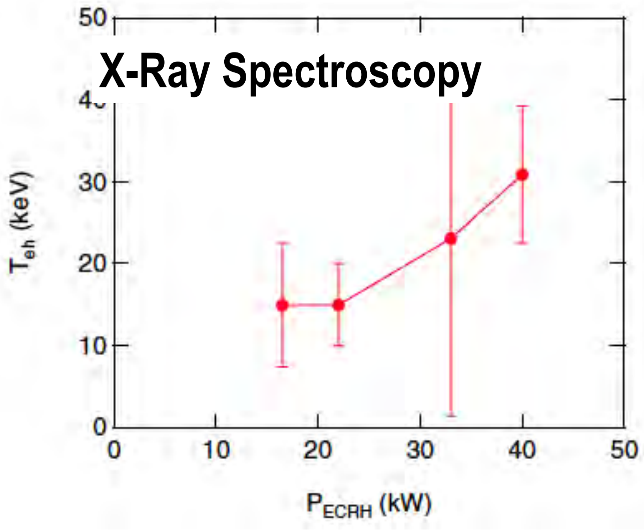


$P_\perp \gtrsim P_\parallel$



$P_\perp \sim P_\parallel$





Nishiura, et al., "Improved beta (local beta >1) and density in electron cyclotron resonance heating on the RT-1 magnetosphere plasma," Nuc Fus 55, 053019 (2015).
Saitoh, et al., "Observation of a new high-β and high-density state of a magnetospheric plasma in RT-1," Phys Plasmas 21, 082511 (2014).

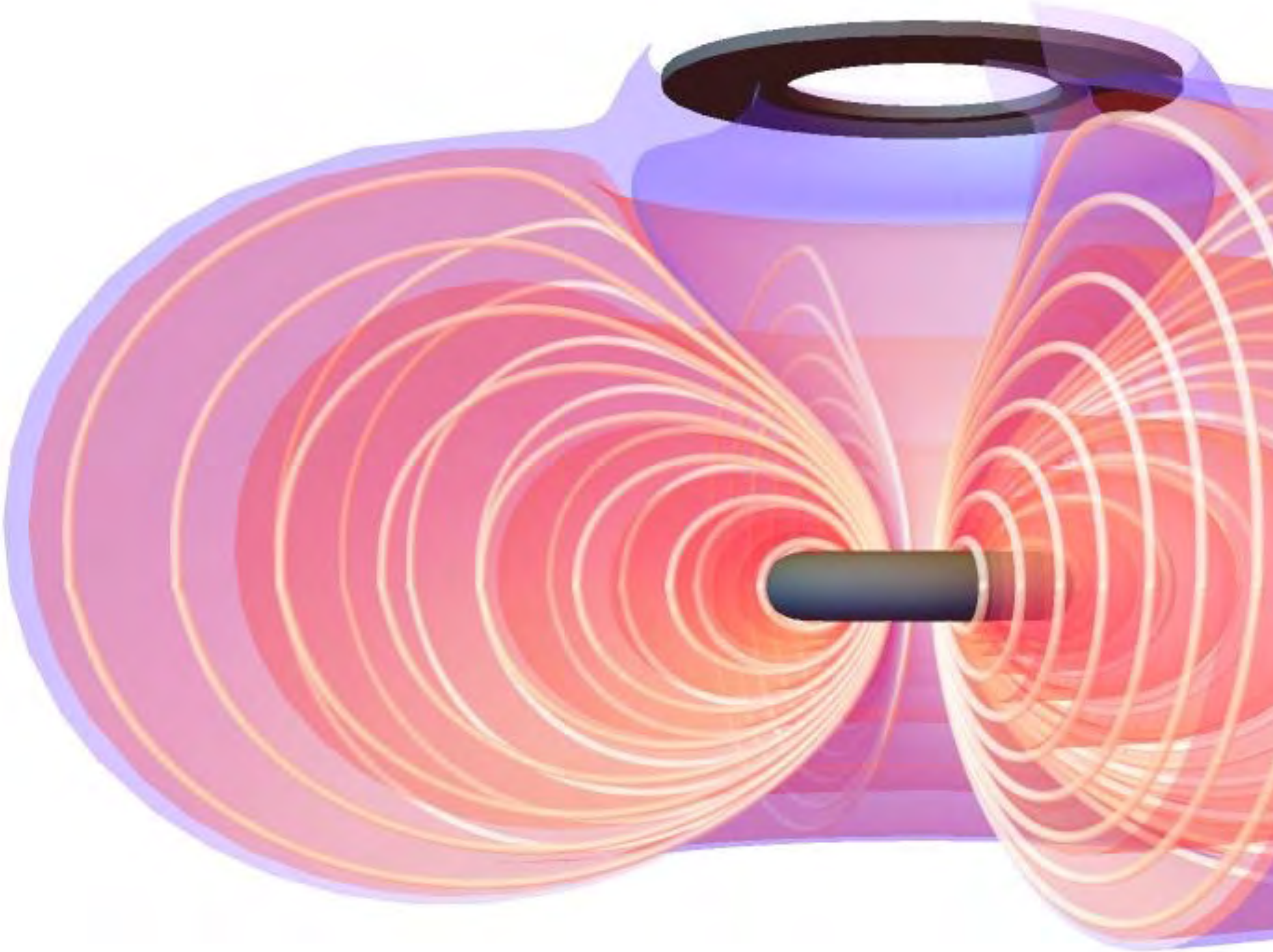
Hasegawa: Does magnetospheric physics apply to magnetic confinement in the laboratory?

- 30 years of further work in analytic and computational theory, and numerous experiments in the laboratory we can say…
  - YES!
  - We replicate the observation of flat particle and entropy density in flux space giving highly peaked profiles with high beta plasmas as seen by in space
  - And for thermal plasmas, we can show that this is a robust profile consistent with being driven by flute-like drift-entropy modes that give an inverse cascade of energy from small to large scale self-organization
- But! There are many more questions to answer besides the one posed by Hasegawa.

The Laboratory Magnetosphere is a robust platform for investigating physics relevant to space and laboratory plasmas

- ***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, APEX/PAX, …
- ***Unique radial transport processes*** relevant to space and to many toroidal confinement devices: *up-gradient pinch, inverse cascade, bursty interchange filaments, minimum entropy production* …

  Nonlinear drift/gyrokinetics appears to provide a good model for predicting radial transport driven by interchange/entropy instabilities



Investigations of Turbulent Transport of Magnetized Plasma in Laboratory and Space Physics Span “Extreme Scales”

Strongly Magnetized

$$\rho^* = \rho/L \ll 1$$

Dense and Big

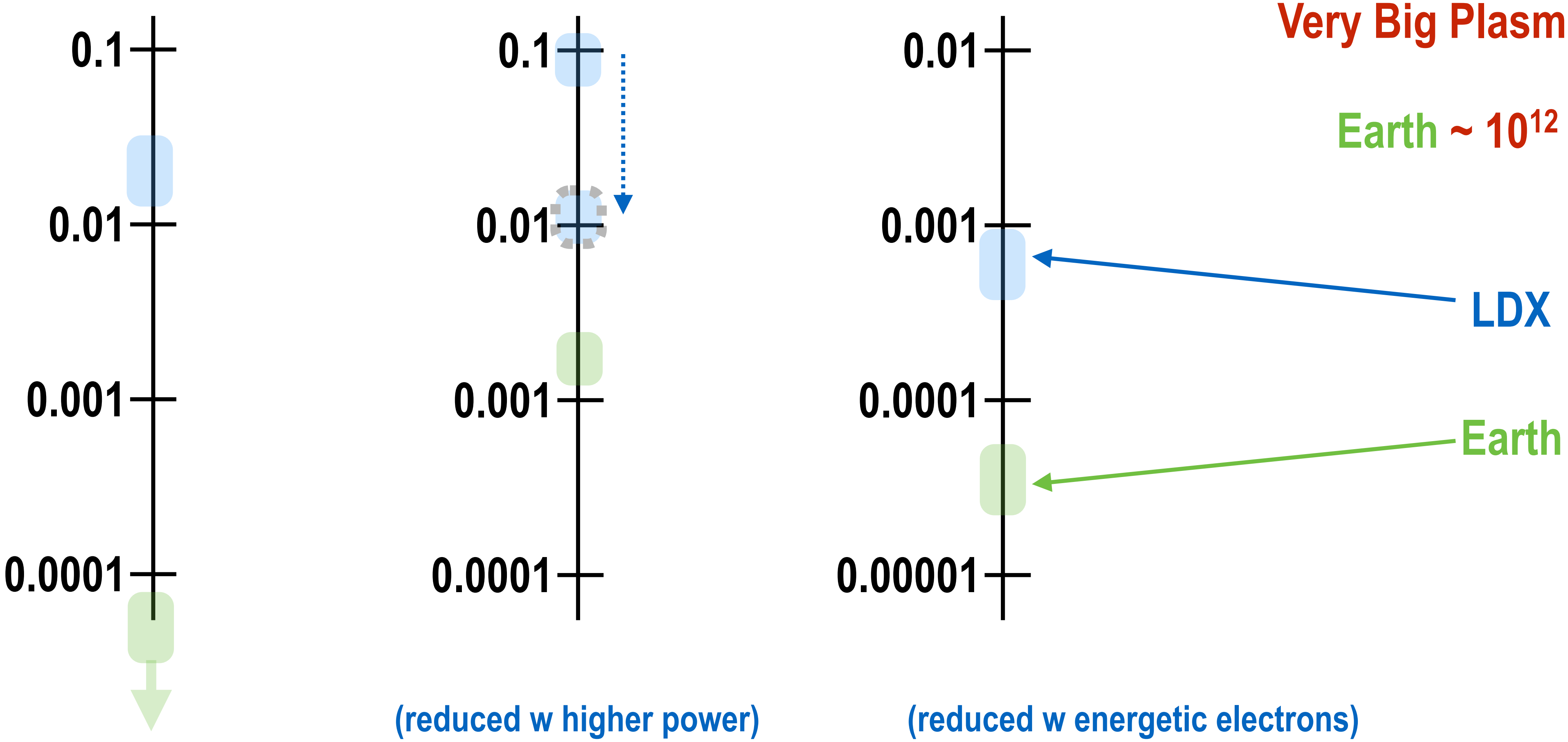
$$\begin{aligned}\lambda^* &= \lambda_i/L \\ &= \rho^*/\sqrt{\beta/2} \ll 1\end{aligned}$$

Collisionless

$$\begin{aligned}\nu^* &= \nu/\omega_b = L/\lambda_{mfp} \\ &= \frac{16}{\lambda^{*2}S} = \frac{2\beta}{\rho^{*6}} \times \left(\frac{2}{B_G^4 L_{cm}^5}\right) \ll 1\end{aligned}$$

Very Big Plasma Needed

Earth ~ 10^{12} × LDX



(reduced w higher power)

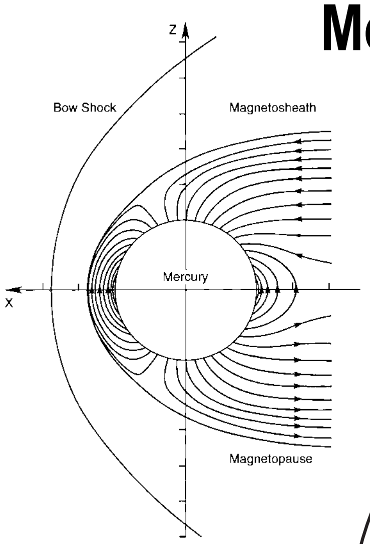
(reduced w energetic electrons)

More Discoveries at Higher Density and Ion Temperature

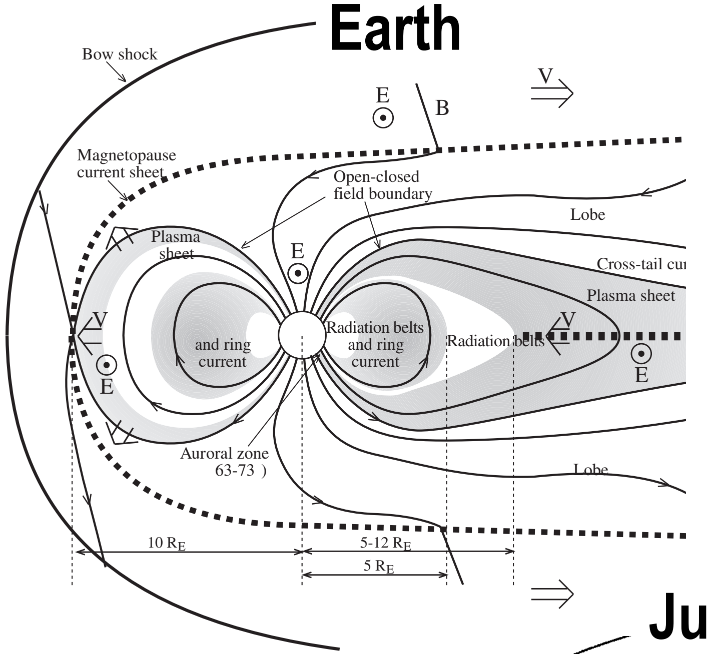
Next-step discoveries are significant…

- Magnetospheric Alfvén wave dynamics at high plasma β, *requiring shorter ion skin depth*
- FLR and isotope effects in bounce-averaged gyrokinetics and turbulent self-organization, *requiring ion heating*
- Critical plasma physics linking space science and toroidal confinement

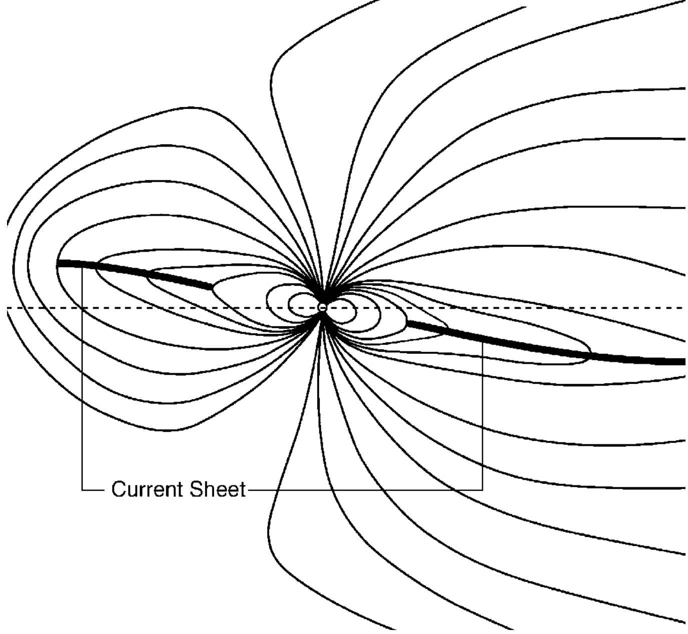
Mercury



Earth



Jupiter



	Mercury	**Earth**	**Jupiter**
Size	$2R_H$	$10R_E$	$100R_J$
Density $(c/\omega_{pi}L)$	0.1	0.003	0.00001
New Physics	$(V_A/L) \sim \omega_{ci}$	Alfvén Resonances	Propagating Alfvén Waves

Beyond LDX

- ➡ With an upgrade of up to 250 kW of absorbed ICRF power, LDX would have been expected to demonstrate steady-state toroidal confinement at

$$\beta \sim 1, \;\; T_i \sim T_e \sim 0.5 \text{ keV}, \;\; n \sim 10^{19} \text{ m}^{-3}$$

- ➡ And allowed investigation of ion physics, and Alfven wave turbulence

Magnetospheric Plasma Turbulence Facility (MTPF)

- A proposal by MIT to build next generation Laboratory Magnetosphere
- Utilize the unique capabilities of the MIT PSFC
    - Experience from building and operating LDX
    - Expertise with next-generation high temperature superconductors and persistent current switches
    - Availability of Alcator C-mod experimentalists, heating systems, and diagnostics that may be repurposed for MTPF

Features of Proposed Magnetospheric Plasma Turbulence Facility

- **REBCO current ring with PCS.** A superconducting current ring wound with second-generation rare-earth-barium-copper-oxide (REBCO) high-temperature superconductor (HTS) and built with a superconducting persistent current switch (PCS). The new HTS coil will have the highest magnetic field of any and also have a higher critical temperature resulting in a longer levitation time between re-cooling. In addition, an outboard plasma facing limiter will be utilized for long pulse high power operation

- **High-power RF and microwave heating systems.** At least a 40-fold increase of heating power is available using (i) the 4.6 GHz CPI klystrons (previously used for the LHCD system at CMOD.)(ii) the Thales TSW2500 1 MW short-wave transmitter and transmission line components (previously used for the Archimedes project). Additionally, the CMOD diagnostic neutral beam, up to 4 A neutralized protons at 20 – 55 keV (80-200 kW), can provide significant plasma heating at high plasma density for 3 s periods, including pulsed modulation studies.

- **Diagnostic systems for core plasma measurements.** In addition to the LDX diagnostic systems, new and repurposed C-mod diagnostics will be required to diagnose the hotter denser plasma. New diagnostic systems will measure the thermal ion and electron temperature profiles. High-speed videography is used for whole plasma imaging, and line-integrated visible light and interferometry provides estimates of the internal fluctuation levels. Local fluctuations are only possible at the plasma edge, which is inadequate for studies of multiscale turbulence. A critical goal is to install new diagnostic systems for local, internal density and temperature fluctuations.

MPTF Device Parameters

Parameter	LDX (prior experience)	MPTF (New)
Current Ring	1.2 MA Nb_3Sn	~ 2.2 MA (Superpower REBCO)
Ring Current Centroid	0.35 m	0.35 m
Ring Charging	NbTi Inductive Charging	Direct charging w/HTS PCS
Max Operating Temp	15 K	30 K
Levitation time before re-cool	3 hour	>5 hour
Microwave Heating Power	24 kW ECRH	1000 kW 4.6 GHz ECRH
RF Heating Power	–	1000 kW (4 – 26 MHz)
Plasma Size	3.5 m diameter	4.5 m diameter
Plasma ring current	4.0 kA (max)	(est.) 12 kA

MPTF Plasma Parameters

Parameter	LDX	MPTF-High T	MPTF-High n
Peak density (no pellet)	0.6 ($\times 10^{18}$ m^{-3})	2.0 ($\times 10^{18}$ m^{-3})	20 ($\times 10^{18}$ m^{-3})
Peak density (pellet)	3.0 ($\times 10^{18}$ m^{-3})	12 ($\times 10^{18}$ m^{-3})	100 ($\times 10^{18}$ m^{-3})
Peak T_e (thermal)	> 0.5 keV (est)	1.5 keV	0.6 keV
Ion temperature, T_i	n.a.	n.a.	0.6 keV
Energetic electron energy (†)	75 keV	250 keV	n.a.
Available power	25 kW (ECRH)	500 kW (ECRH)	> 500 kW
Peak plasma energy	0.4 kJ	8 kJ	16 kJ
Peak β (typical) (‡)	20%	50%	40%
Gyroradius, $\rho^* = \rho_s/L$	0.02	0.02	0.01
Ion skin depth (§), $\lambda^* = \lambda_i/L$	0.3	0.16	0.04
Alfvén frequency, $\omega_A/2\pi \propto V_A/L$	400 kHz	450 kHz	150 kHz
Thermal drift freq, $\omega^*/2\pi$	3 kHz	5 kHz	2 kHz
Energetic drift freq, $\omega_{dh}/2\pi$	450 kHz	750 kHz	n.a.
Electron collision freq	2 kHz	1.4 kHz	55 kHz
Ion collision freq	n.a.	n.a.	0.8 kHz

(†) Typical density fraction of energetic electrons ~2%.
(‡) Peak β ~ 100% achieved on RT-1.
(§) Shorter ion skin depth and lower Alfvén frequency during pellet injection.

Center for Laboratory Study of Multiscale Turbulence

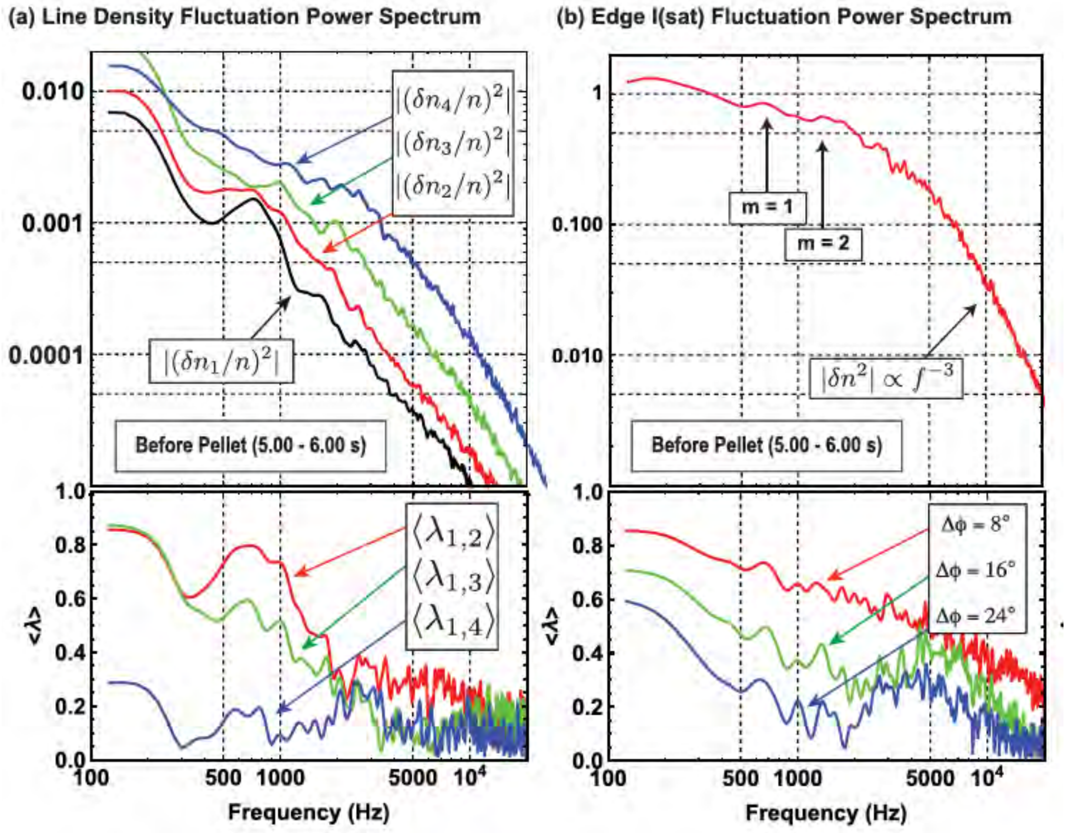
- MTFP would be awesome
  - To exploit it properly, we'll need a large group of external users where eventually half of operational plans will come from
- This new Center will:
  - Be capable of addressing multiple frontier plasma science questions at the intermediate-scale by supporting a wide range of diagnostic capabilities.
  - Facilitate an open, broad-based external user program in which the facility resources are allocated by merit review of the proposed work.

- Understand energy transfer mechanisms from large-scale flows and fluctuations to small-scale flows and magnetic fields;
- Understand inverse & forward energy cascade mechanisms (energy transfer from injection scale to both small- and large-scales) in magnetized plasmas;
- Identify the physical mechanisms that lead to loss of particles and energy in laboratory plasmas and that lead to heating (such as coronal heating or energization of the Van Allen belts in space plasmas)
- Developing the capability to predict the evolution of magnetized turbulent plasma system

Turbulence in Laboratory Magnetospheres

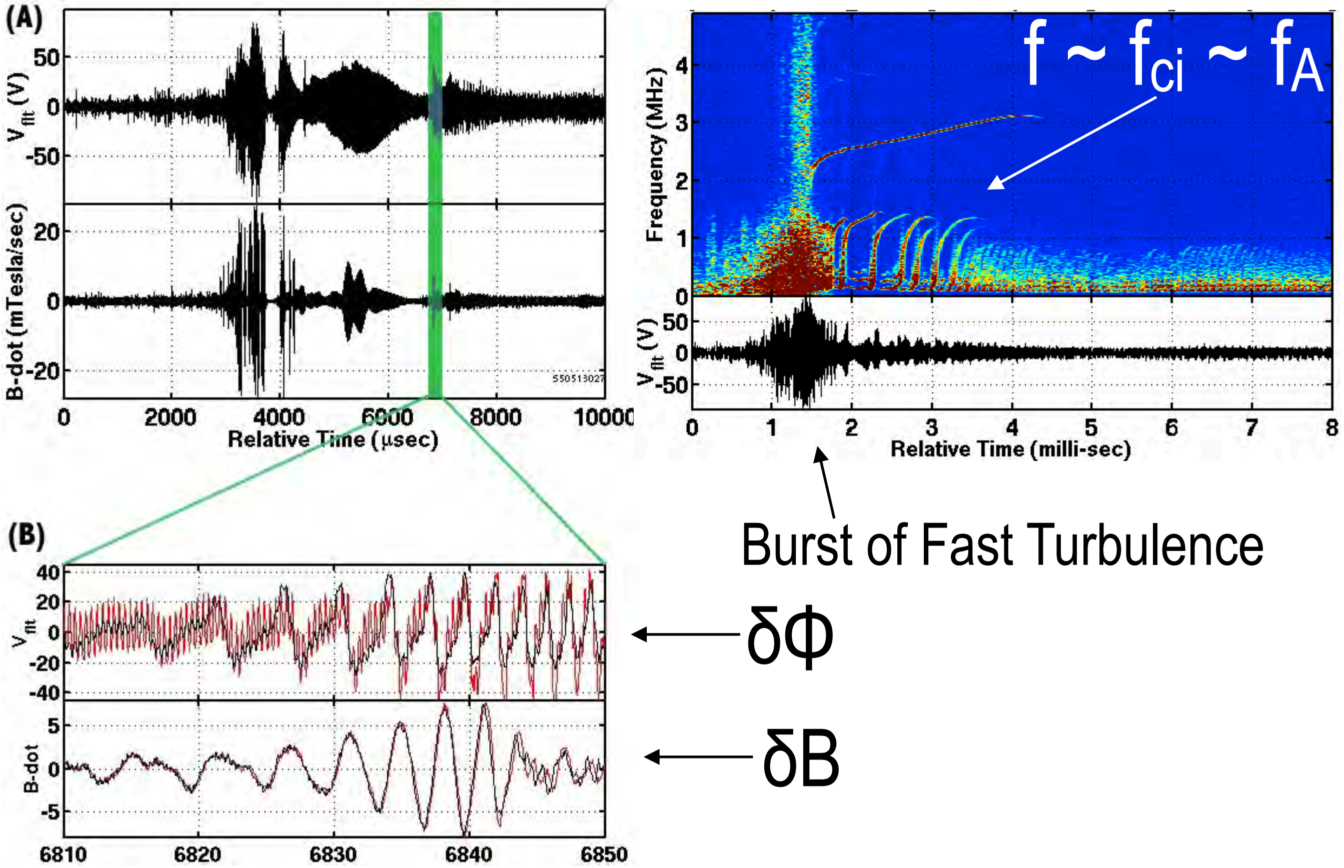
(with analogies to tokamaks and magnetospheres)

Interchange/Entropy Modes



Electrostatic, Inverse Cascade, Bursty, Pinch
“Good” comparison with theory/simulation

Fast Energetic Particle Modes



$f \sim f_{ci} \sim f_A$

Burst of Fast Turbulence

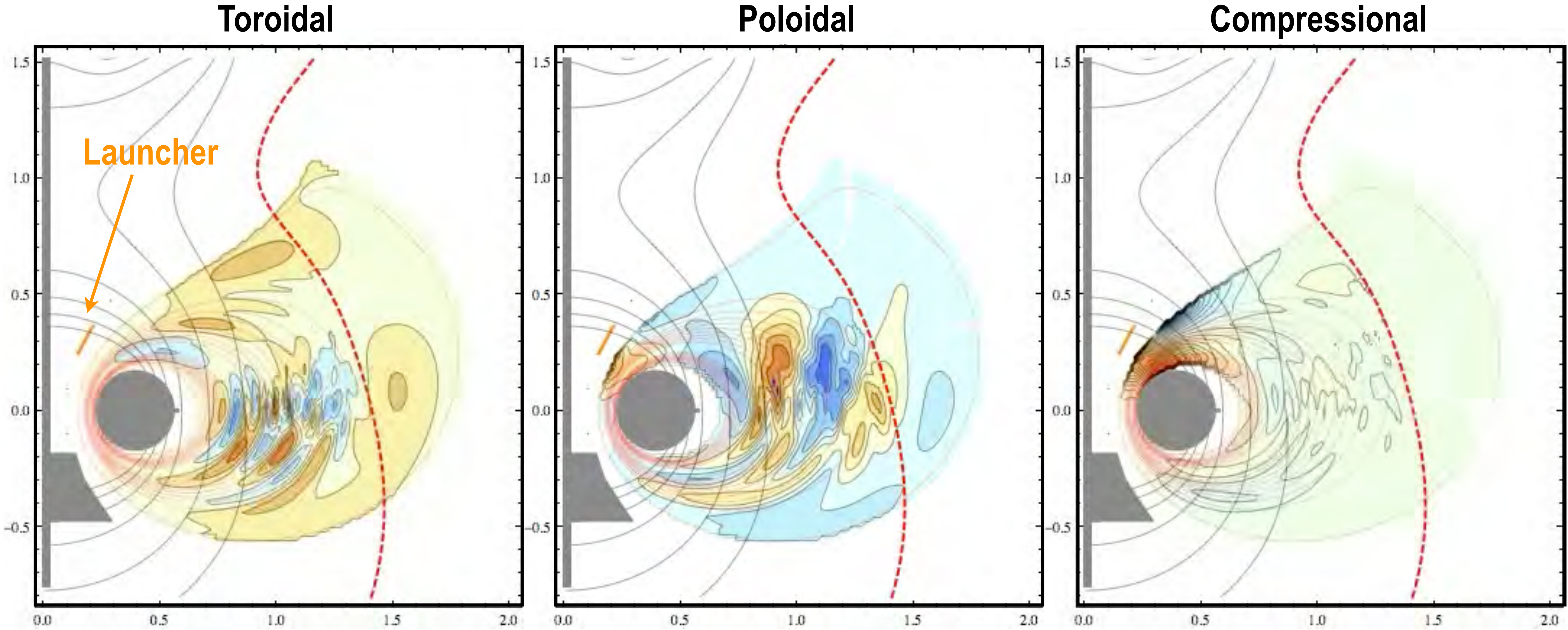
δΦ

δB

Electromagnetic, Drift-Resonant, Chirping
“Good” comparison with theory/simulation

Alfvén Wave Excitation and Spectroscopy will be Possible at Higher Density

- 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

Laboratory Magnetospheres are Unique Opportunities for Controlled Plasma Science Experiments

- Laboratory magnetospheres are facilities for ***conducting controlled tests*** of turbulent transport and 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 reasonable power and great flexibility.

- The only plasma torus capable of operating at state of minimum entropy production and providing ***verification and discovery*** of critical plasma science.

- Laboratory magnetospheres are ready to operated at much high power levels for new controlled tests of ***complex Alfvén wave interactions*** in the magnetosphere.