Discovery Fusion Energy Science using a Superconducting Laboratory Magnetosphere

Columbia

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Outline

- Linking space science and laboratory toroidal confinement
- LDX: steady state, high temperature, low power (< 25 kW)
- Discovering a new regime: turbulent self-organization
- Opportunities at higher density, higher power, and larger size

Office of Fusion Energy Sciences
Excellent Science Attractive Energy
National Science Foundation
WHERE DISCOVERIES BEGIN

Tom Intrator:
Phaedrus-B -T ICRF and Alfvén Waves

NUCLEAR FUSION, Vol.29, No.3 (1989)

MEASUREMENTS OF ELECTROMAGNETIC WAVES IN PHAEDRUS-B: BENCH-MARK TEST OF ANTENA WAVE FIELD CALCULATIONS

T. INTRATOR, S. MEASSICK, J. BROWNING,
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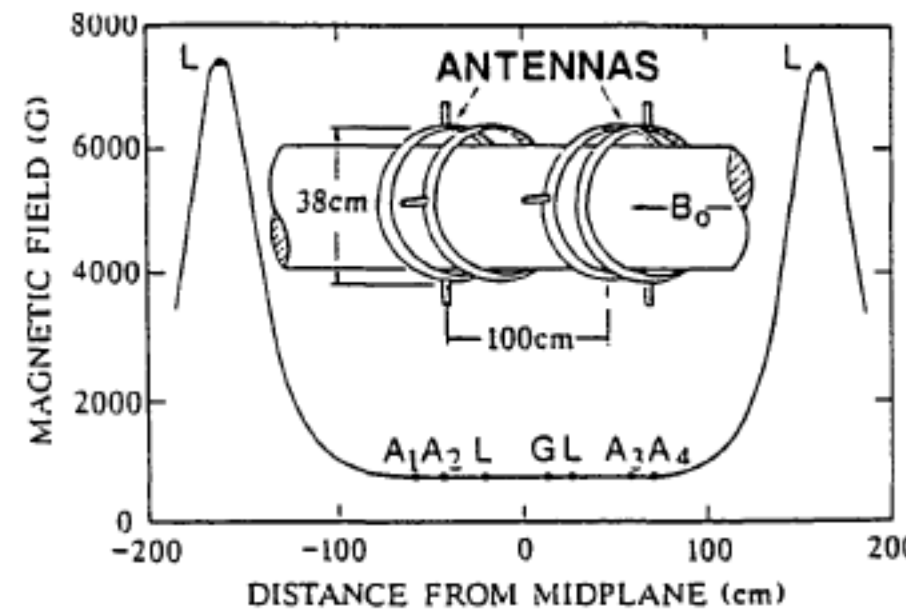
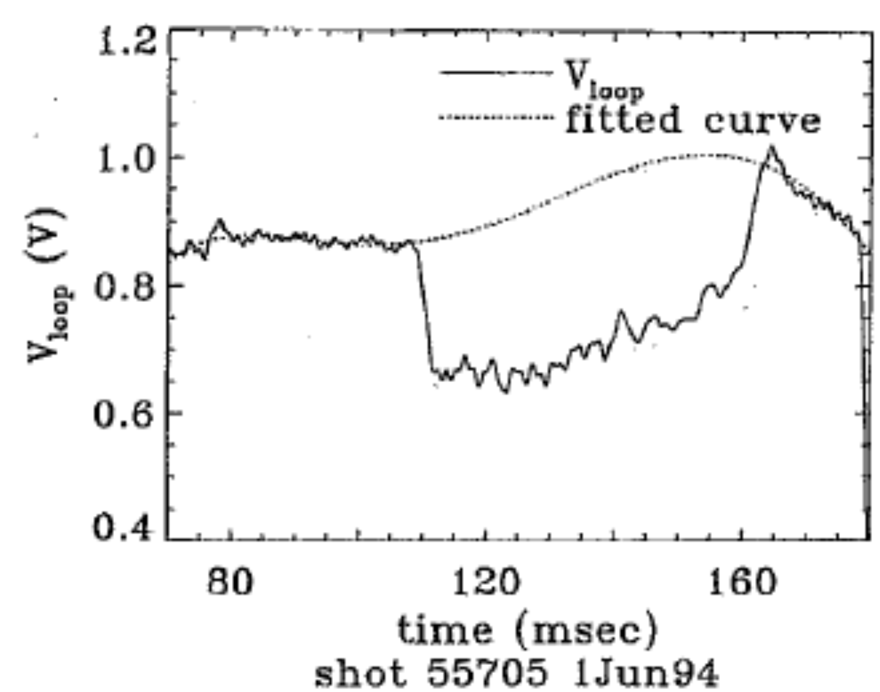
Department of Nuclear Engineering and Engineering Physics,
University of Wisconsin,
Madison, Wisconsin,
United States of America



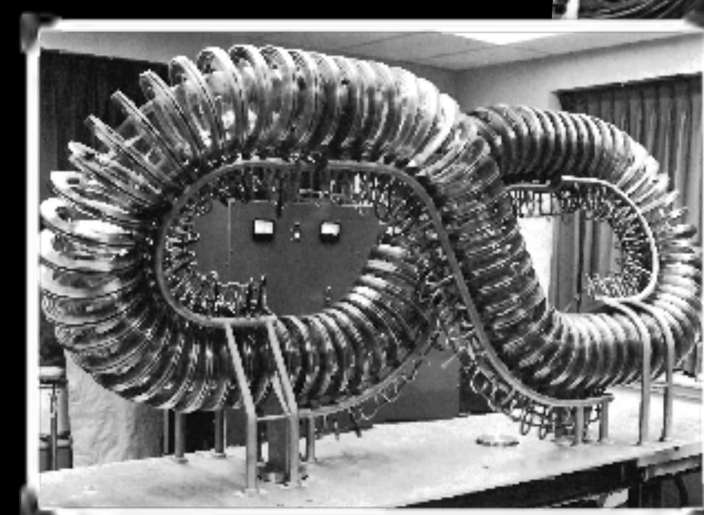
Phys. Plasmas **2** (6), June 1995

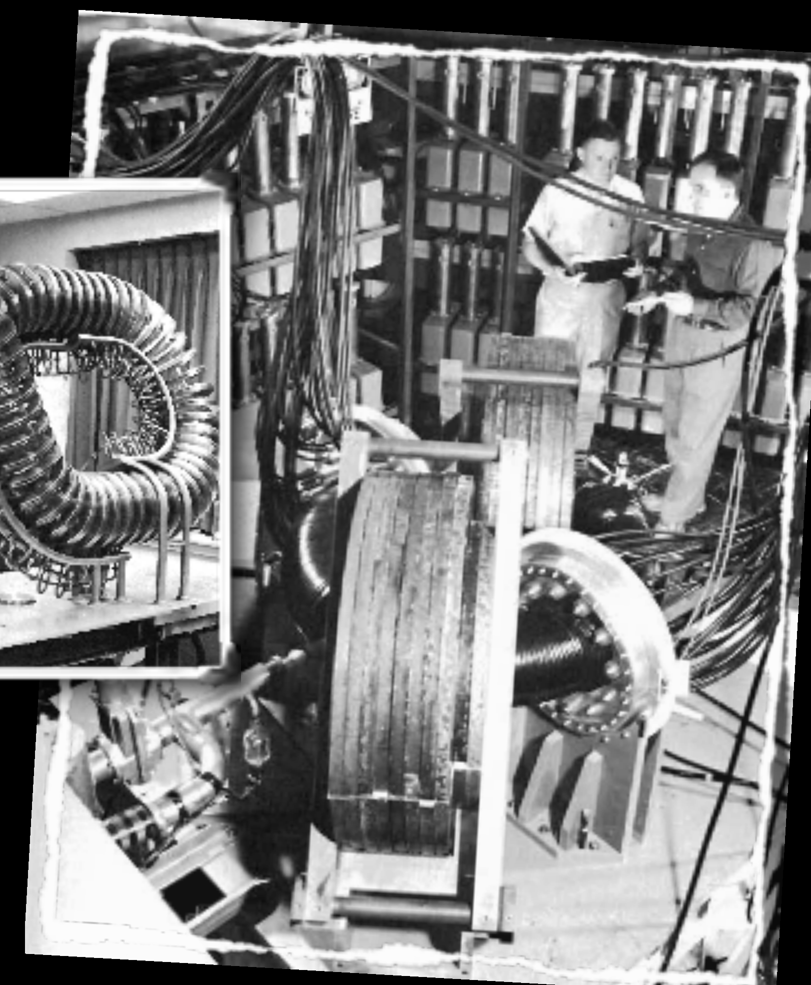
Alfvén wave current drive in the Phaedrus-T tokamak*

T. Intrator,[†] P. Probert, S. Wukitch, M. Vukovic, D. Brouchous, D. Diebold, R. Breun, M. Doczy, D. Edgell, A. Elfimov, N. Hershkowitz, M. Kishinevsky, C. Litwin, P. Moroz, P. Nonn, and G. Winz
Department of Nuclear Engineering and Engineering Physics, University of Wisconsin, Madison, Wisconsin 53706-1687



1958: Fusion and Space Research launch the rapid expansion of Plasma Physics





July 29, 1958
President Eisenhower signed the National Aeronautics and Space Act of 1958 which established the National Aeronautics and Space Administration.

(NASA: $6.6 B annual funding in 1958)

September 1-13, 1958
Second International Conference on Peaceful Uses of Atomic Energy (Geneva) marked declassification and was attended by 5,000 delegates with 2,150 papers.

(Fusion: $0.19 B annual funding in 1958)

Both Space and Lab Scientists study Magnetic Confinement…

- Strongly magnetized $\rho^* \sim 10^{-5}$
- Energetic particles
- Transport across boundary layers
- Fueling the plasma torus
- Multiple ions, H^+, He^+, O^+, …
- Magnetic reconnection
- …

… but dipole geometry is different from tokamaks

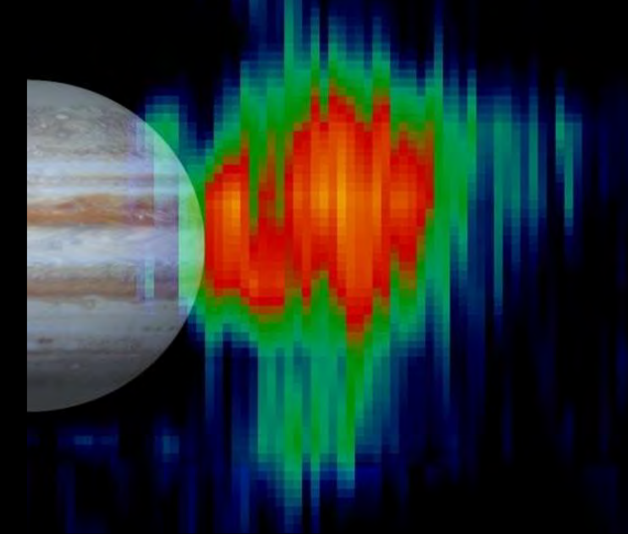
➡ Convection and flux-tube mixing drive profiles characterized by Lagrangian invariants

$$n \sim B/L \text{ and } T_\perp \sim B,\ T_{||} \sim 1/L^2, \text{ or } T \sim (B/L)^{2/3}$$

➡ Equilibria with invariant profiles are stable at $\beta \sim 1$

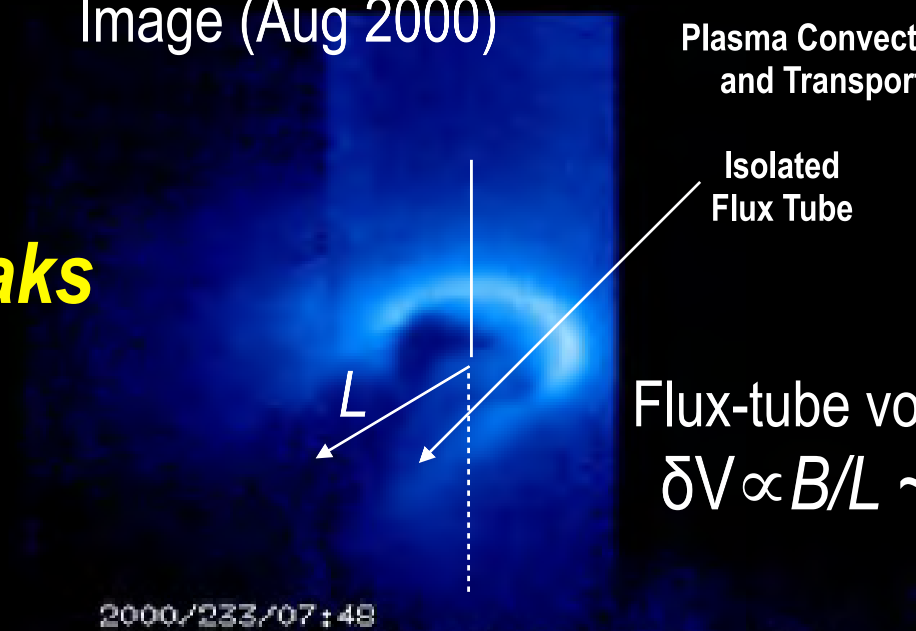
➡ Geometry strongly influences Alfvén waves, whistlers, and wave-particle resonances

Cassini (Jan 2001)



Hot Electron Radio Emission

Image (Aug 2000)



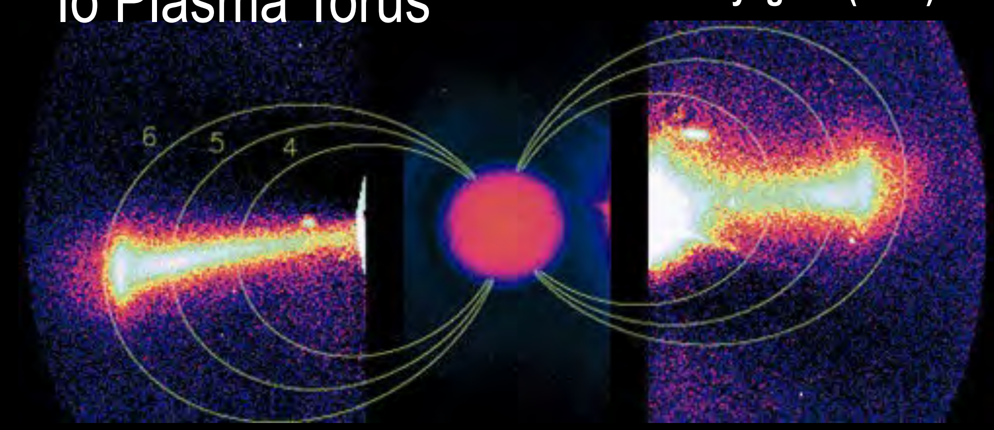
Plasma Convection and Transport

Isolated Flux Tube

Flux-tube volume:
$\delta V \propto B/L \sim L^{-4}$

Io Plasma Torus

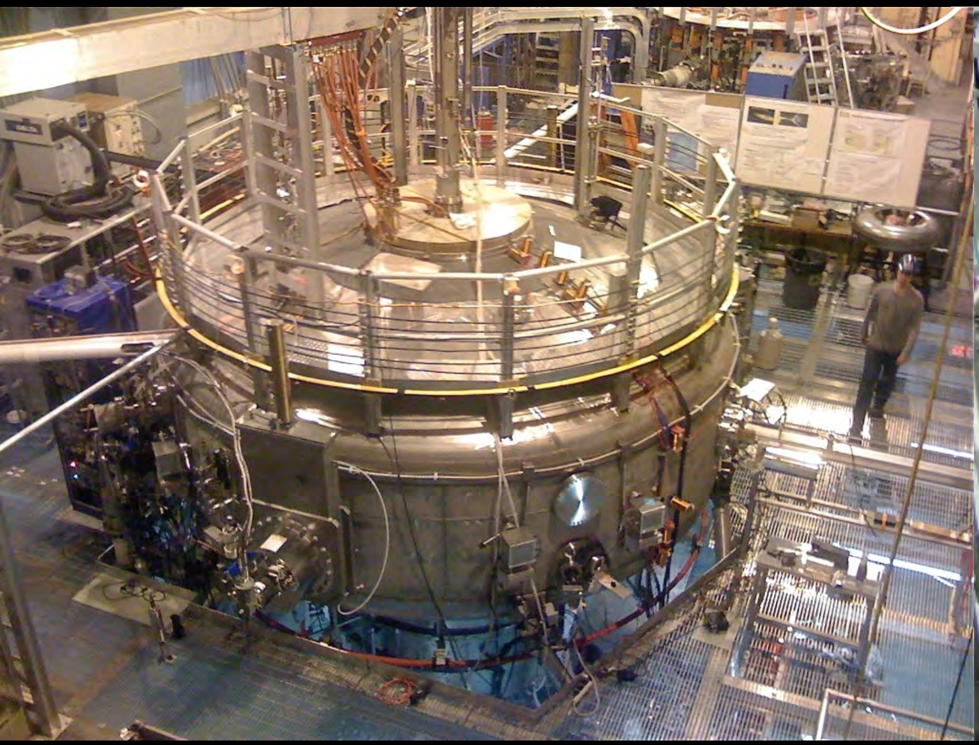
Voyager 1 (1979)

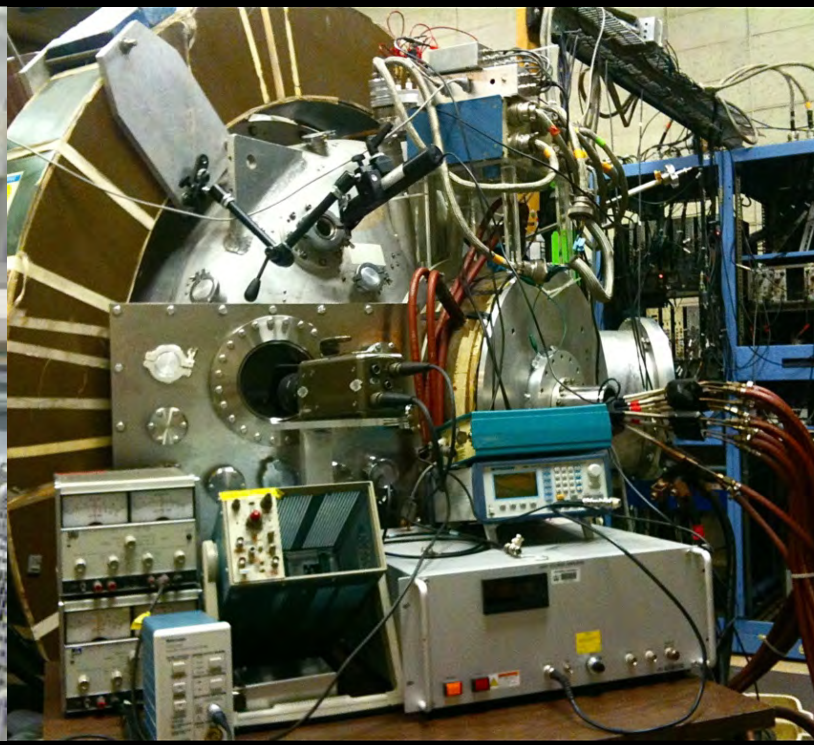


Research Goal of Laboratory Magnetosphere is to Link Space Physics ⇔ Laboratory Confinement Physics

- **Space geometry in lab helps test fundamental magnetic confinement physics**
  - Simple axisymmetric geometry, steady-state, with omnigeneous orbits
  - Very high plasma pressure, $\beta > 100\%$, no field-aligned currents (FAC), without toroidal field
  - Interchange and entropy modes ($\mathbf{E} \cdot \mathbf{B} \approx 0$, *not* kink, tearing, ballooning, or drift-gradient modes.)
  - Foundational tests of bounce-averaged gyrokinetics with similar trapped / passing dynamics
  - Turbulent self-organization, "canonical" profiles, inward pinch can cause plasma *energization*
- **Lab studies in space geometry helps test fundamental space science & technology**
  - Controlled experiments in relevant magnetic geometry
  - Injection of waves (ECH, "chorus", Alfvén, and ion-cyclotron waves), currents, and particles/ plasmoids gives control over plasma properties, transients, and behavior
  - "Whole plasma" access for unparalleled imaging and diagnostic measurement
  - Small dipole magnet within a large vacuum chamber → **very large plasma at low cost**

Laboratory Magnetospheres: Facilities for Space-Relevant Physics Experiments

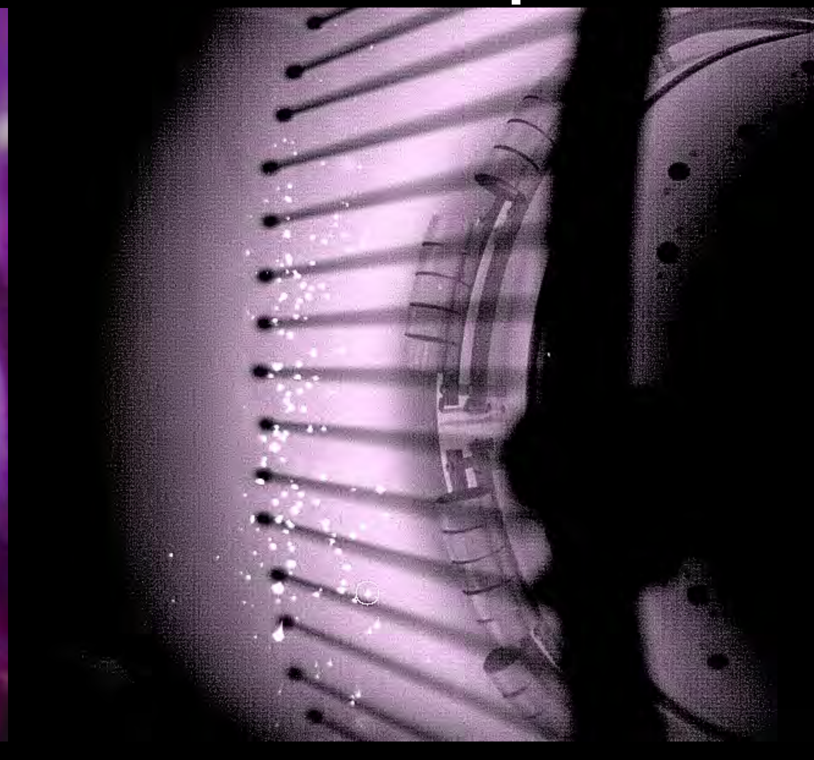


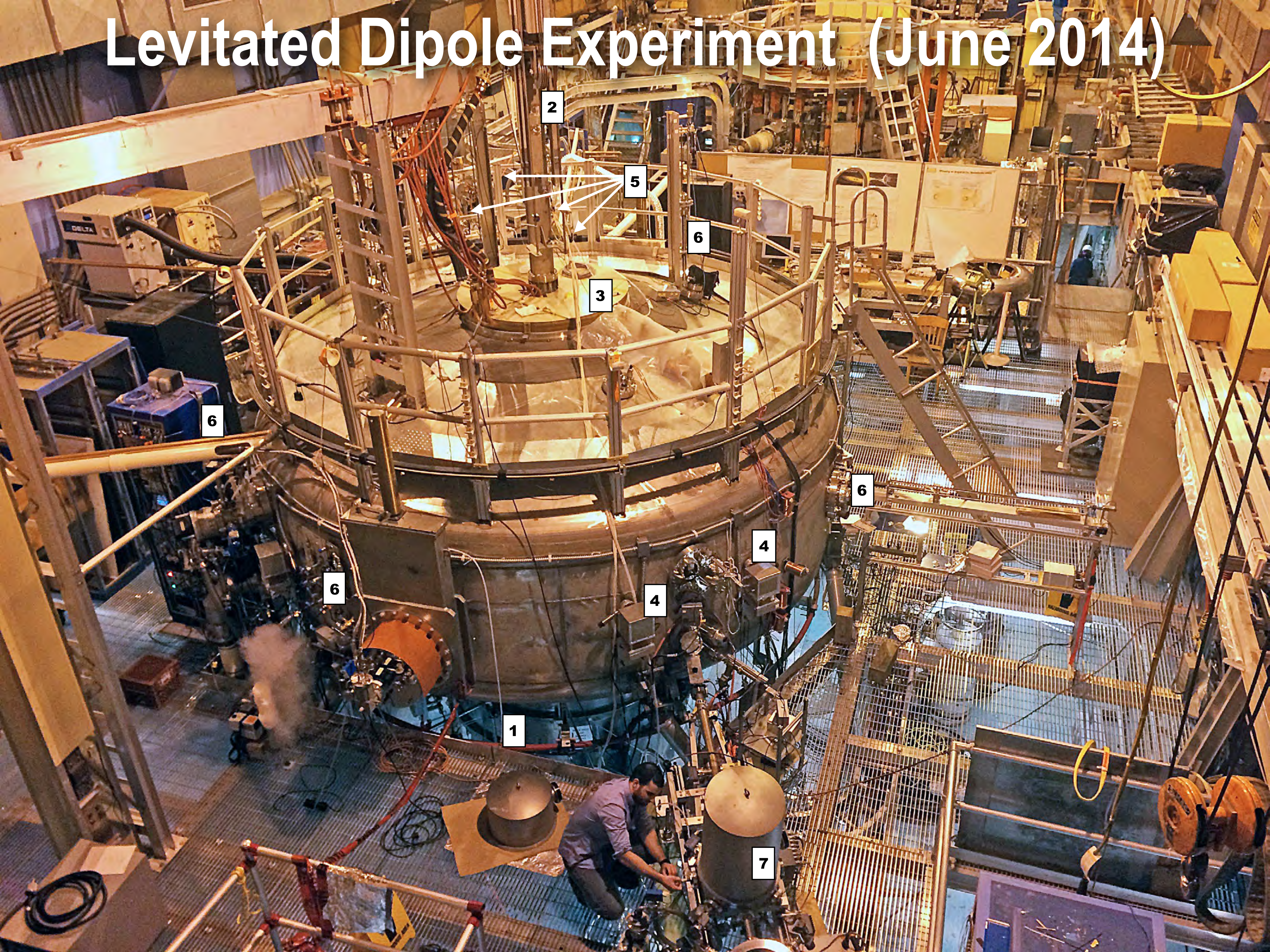


LDX (MIT)
Largest Size

RT-1 (U Tokyo)
Highest Power and β

CTX (Columbia)
Easiest to Operate




Levitated Dipole Experiment (June 2014)
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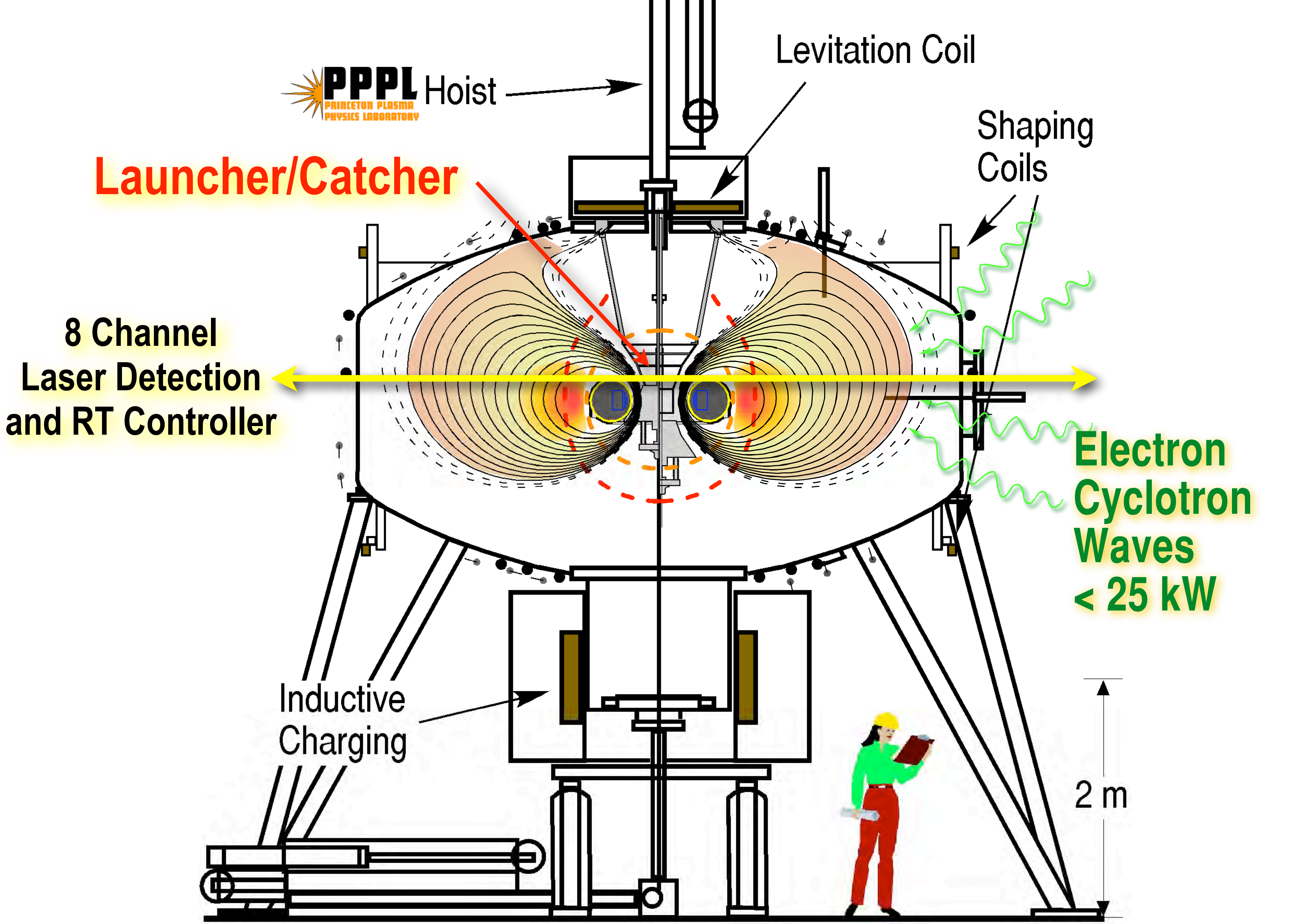
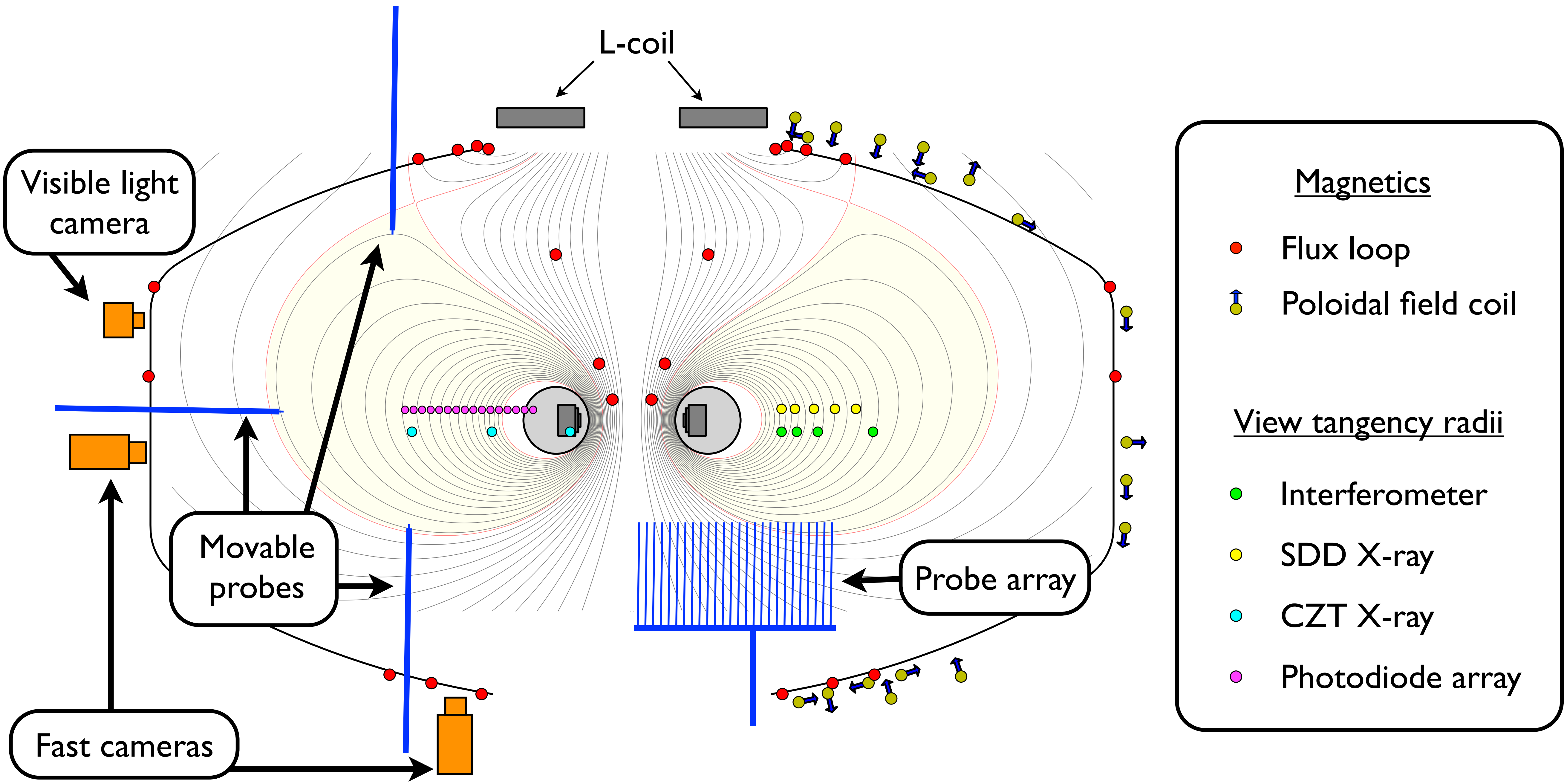


PPPL
PRINCETON PLASMA PHYSICS LABORATORY
Hoist
Levitation Coil
Shaping Coils
Launcher/Catcher
8 Channel Laser Detection and RT Controller
Electron Cyclotron Waves < 25 kW
Inductive Charging
2 m

LDX Diagnostics



Key Result: Discovery of a New Regime

- Turbulence self-organizes centrally-peaked profiles
  - ***Space weather***: *externally-driven* fluctuations drive plasma to "canonical" profiles
  - ***Lab plasmas***: *internally-driven* fluctuations drive plasma to "canonical" profiles
  - ➡ In a magnetospheric configuration, self-organization leads to centrally-peaked profiles

    Inward transport ⇒ ***heats and compresses*** plasma

    Outward transport ⇒ ***cools and expands*** plasma

    "Canonical" profiles are stationary, with $\eta \approx 2/3$, $\delta(PV^{\gamma}) \approx 0$

- Interchange and entropy modes, $\mathbf{E} \cdot \mathbf{B} \approx 0$, dominate low-frequency mixing
  - Plasma torus stable at $\beta \sim 1$, no magnetic shear, no FAC, closed field lines, similar trapped-passing particle dynamics, and strong compressibility $\omega^* \sim \omega_\kappa \sim \rho^{*2}\, \omega_{ci}$
  - Fast-particle interchange (*PRL* 1995, *POP* 2002, *PRL* 2005, *POP* 2006)
  - Centrifugal interchange (*PRL* 2005, *POP* 2005)
  - Pressure-driven interchange-entropy modes and inverse cascade (*POP* 2009, *PRL* 2010)

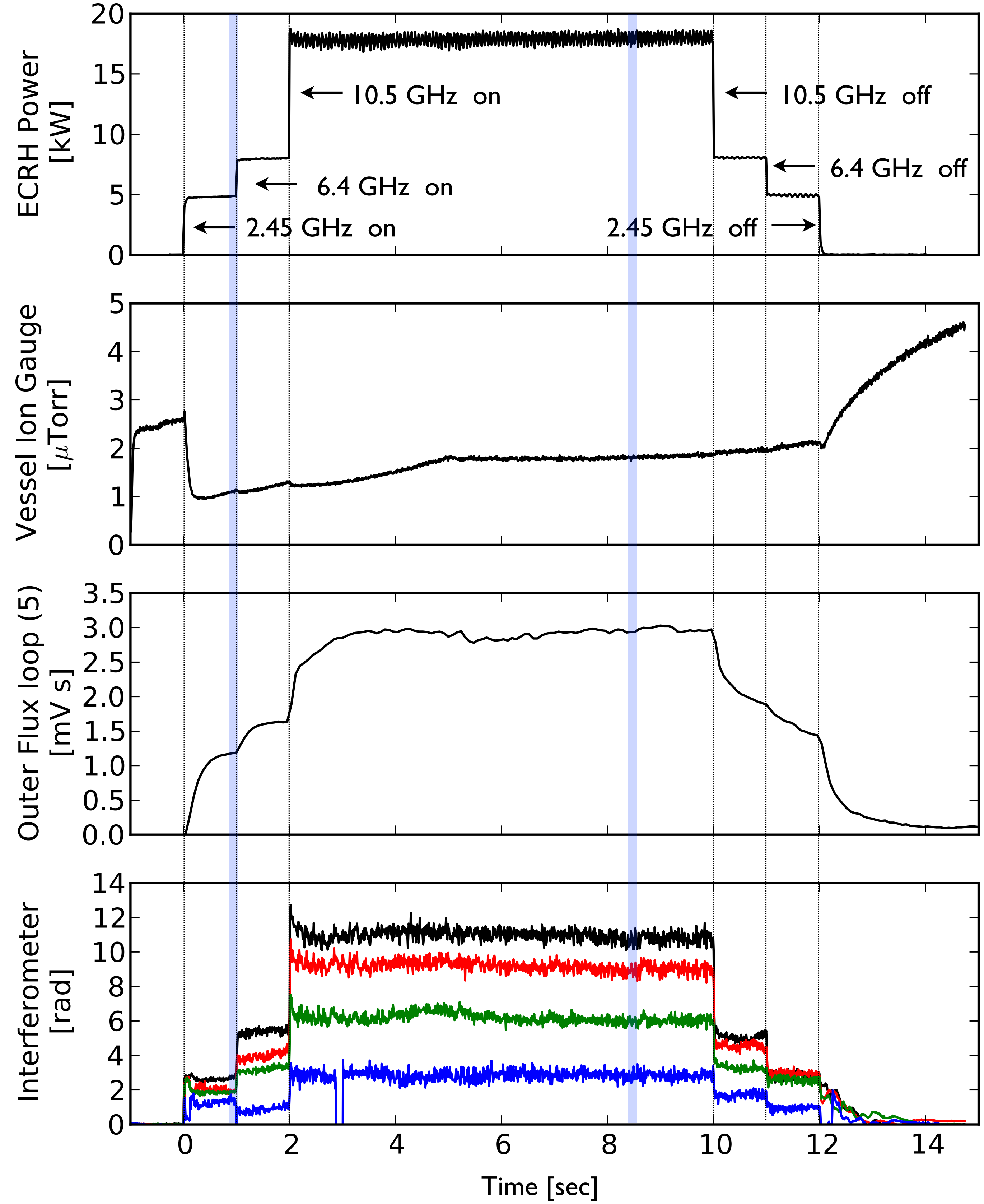
New Regime: High β, Turbulent Self-Organized, Steady-State

- 20 kW injected electron cyclotron waves
- Density proportional to injected power
- Plasma energy proportional to power
- Peak plasma density 10^{12} cm^{-3}
- Strong mass confinement effect: He ~ 2 × D
- Plasma energy 250 J (3 kA ring current)
- Peak β ~ 40% (100% achieved in RT-1)
- Classical fast particles $\langle E_h \rangle$ ~ 54 keV
- Peak $\langle T_e \rangle$ > 0.5 keV (thermal) but T_i ~ 0

Sustained, dynamic, steady state …

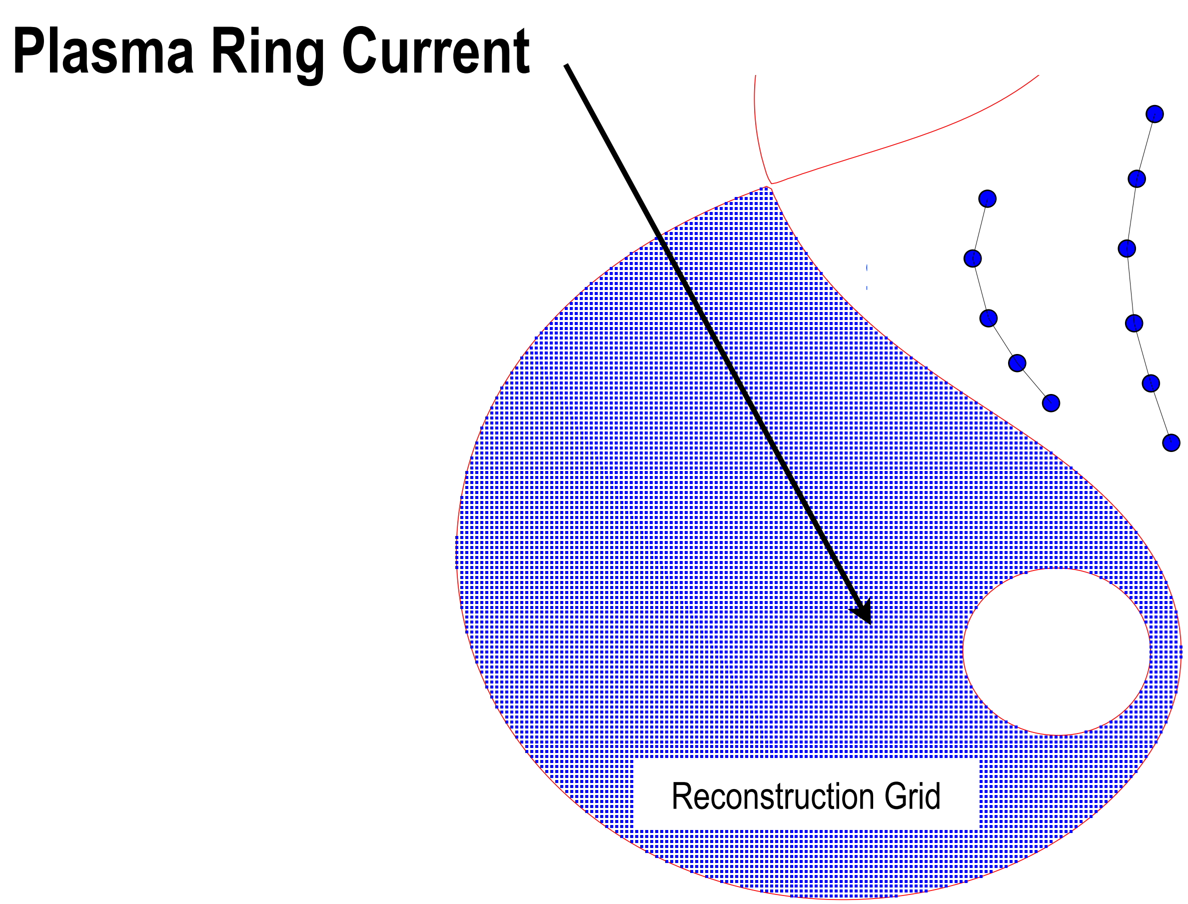
- ***Matt Davis (2014): Electron pressure naturally approach "canonical" profile shape determined magnetic flux-tube volume, δV.***
- ***Alex Boxer (2011): Density evolves at rates predicted by bounce-averaged gyrokinetic theory.***

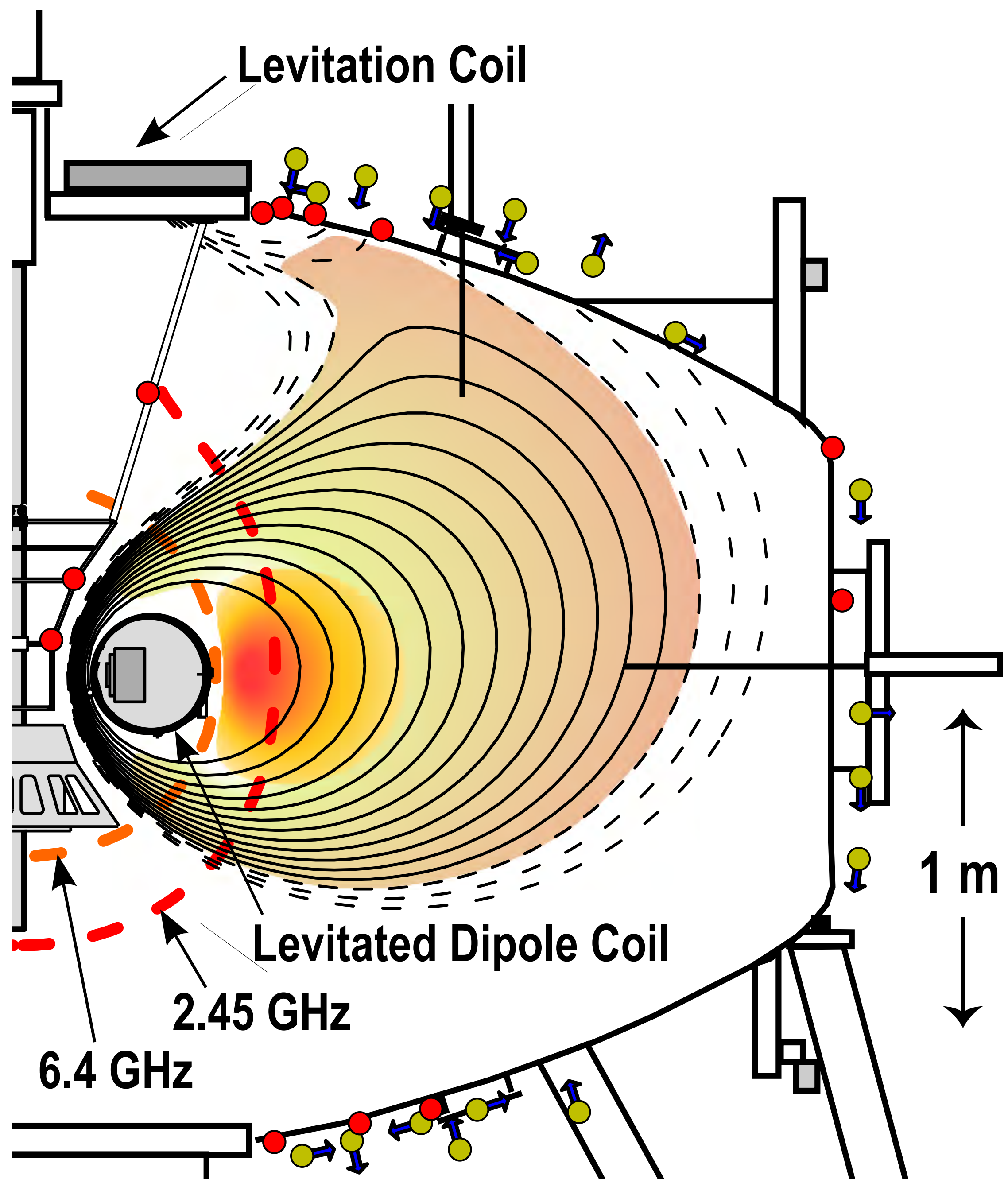
Self-Organized, Steady-State Profiles at High β



Measuring the Plasma Pressure from the Plasma Ring Current

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



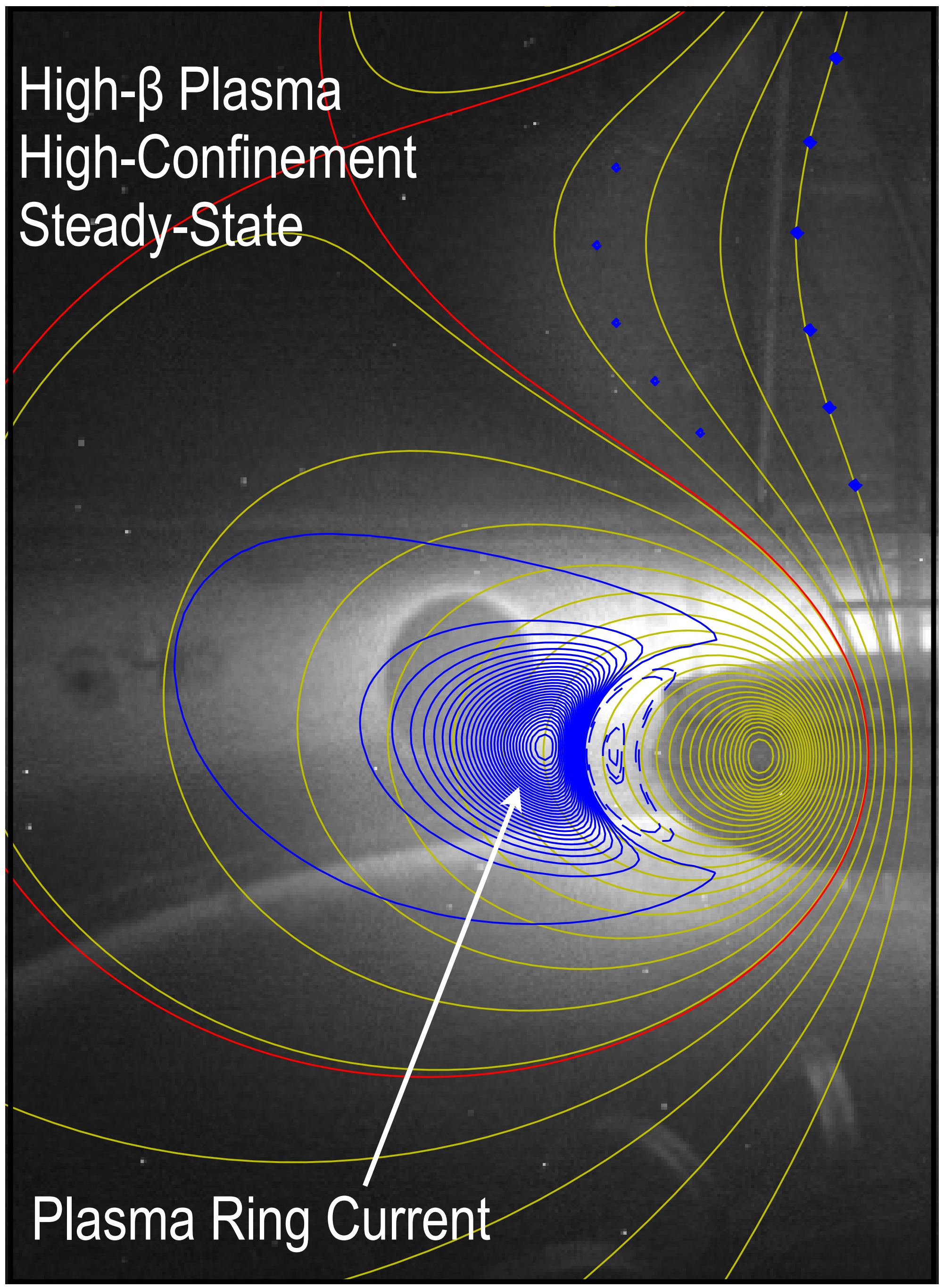


What is the plasma ring current distribution that fits magnetic sensor arrays?

Matt Davis, *et al.*, "Pressure profiles of plasma confined in the field of a magnetic dipole," to appear in *PPCF*, (2014).

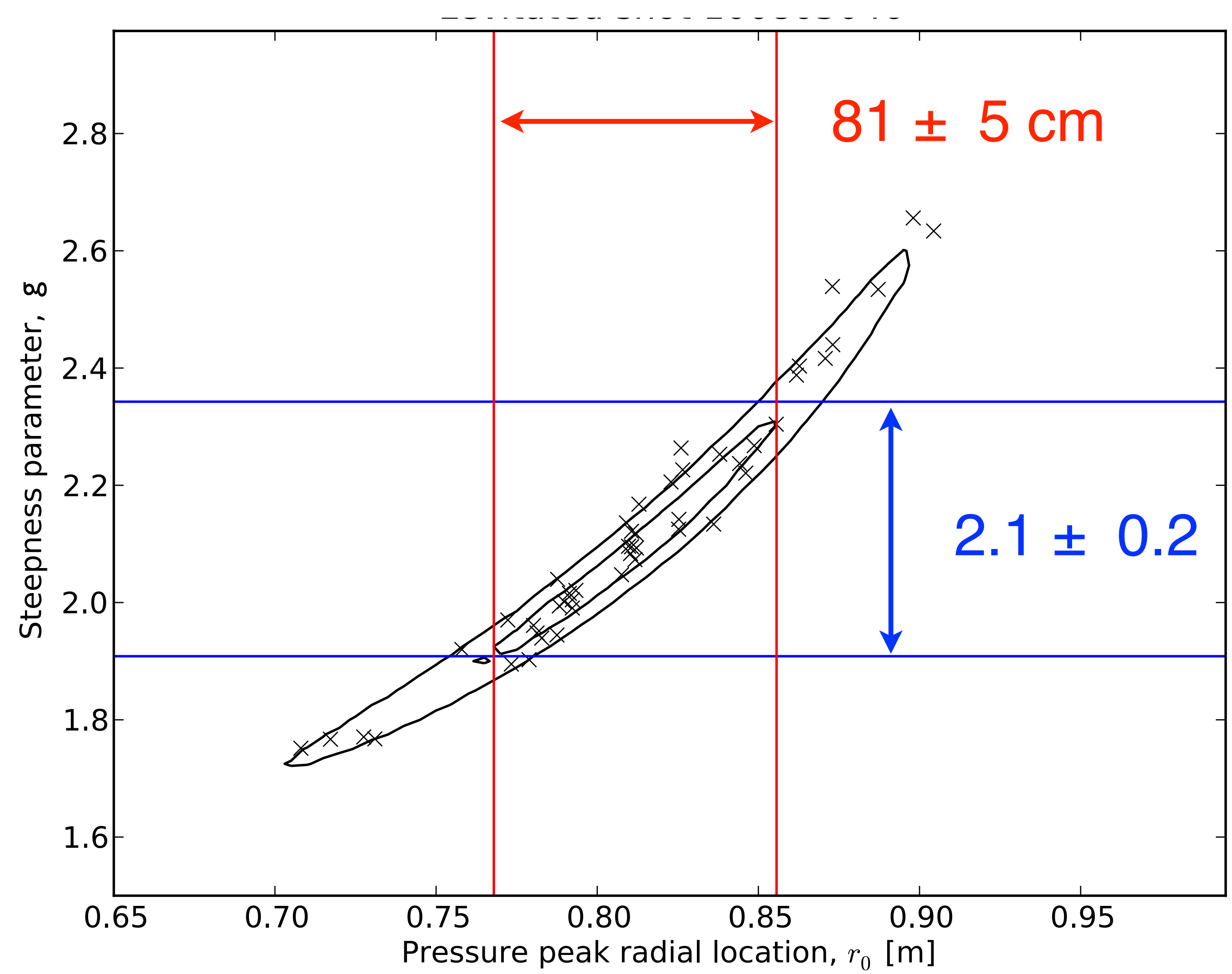
Measuring the Plasma Pressure from the Plasma Ring Current

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



3 kA

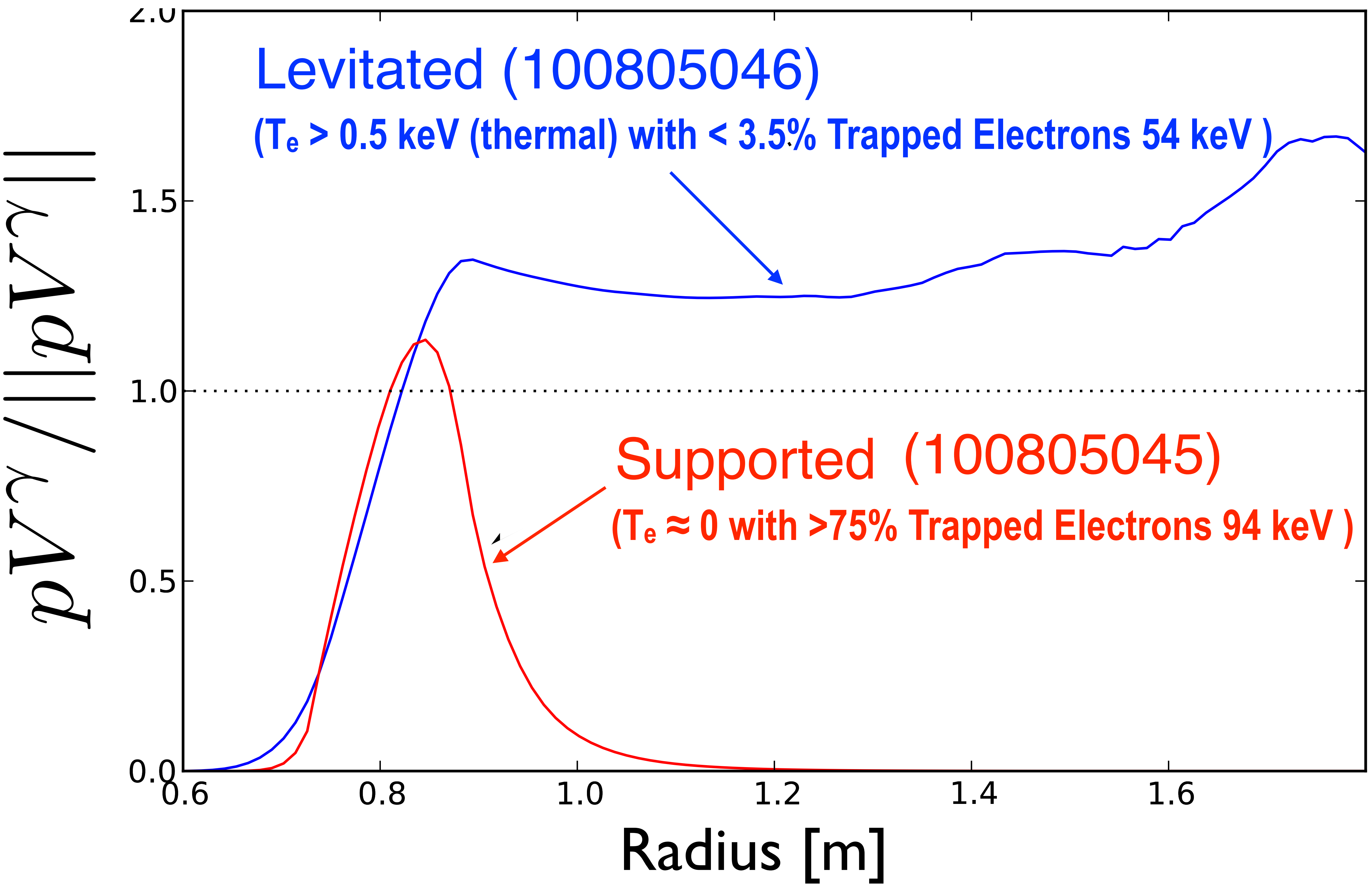
Reconstruction Results in Very Good Accuracy of Pressure Profile



$$P_{||} \approx P_\perp$$

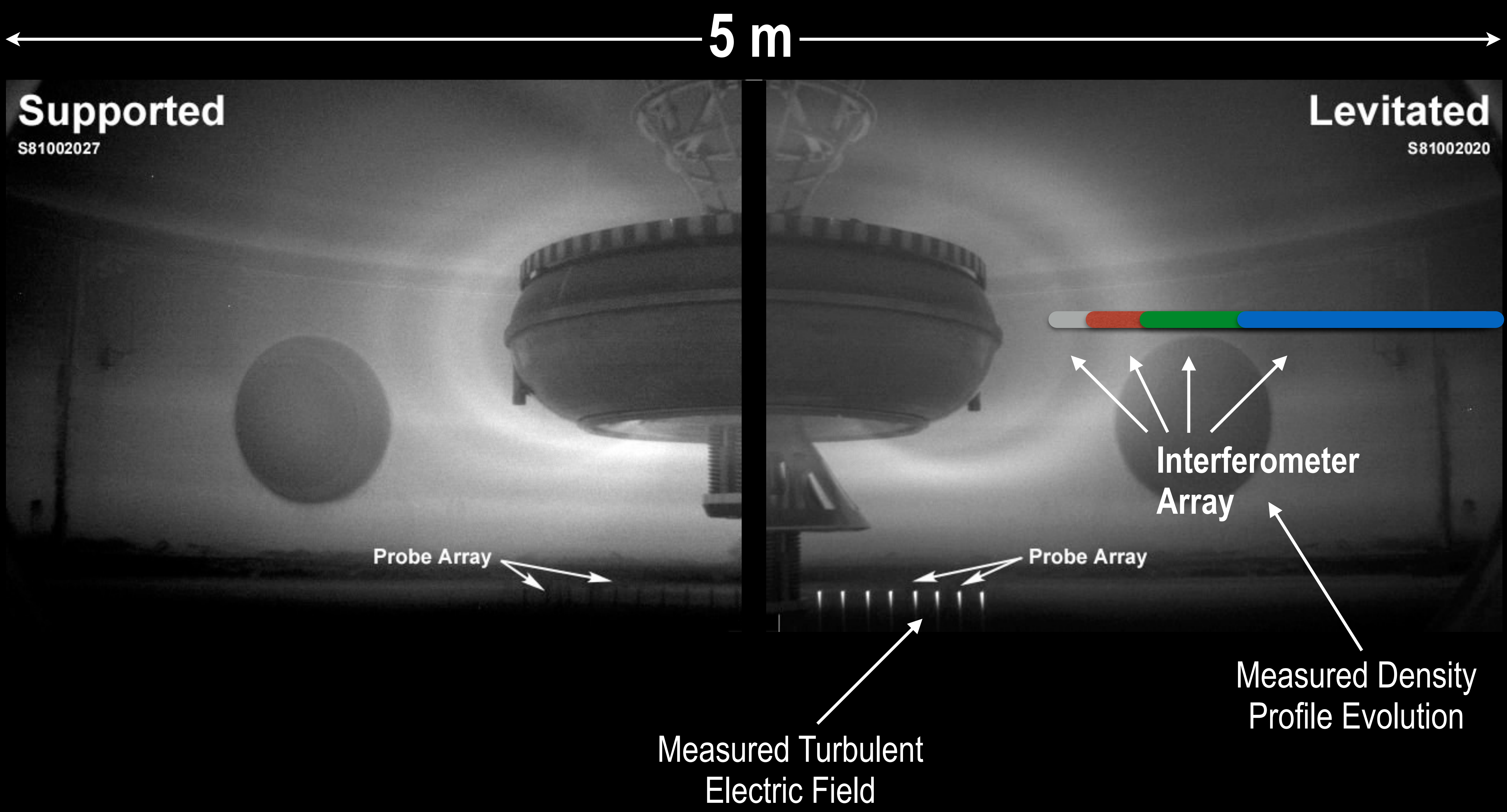
“Canonical” Profile: $\delta(PV^\gamma) \approx 0$

Reconstruction combining Magnetics and X-Ray Spectroscopy



Matt Davis, *et al.*, “Pressure profiles of plasma confined in the field of a magnetic dipole,” to appear in *PPCF*, (2014).

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

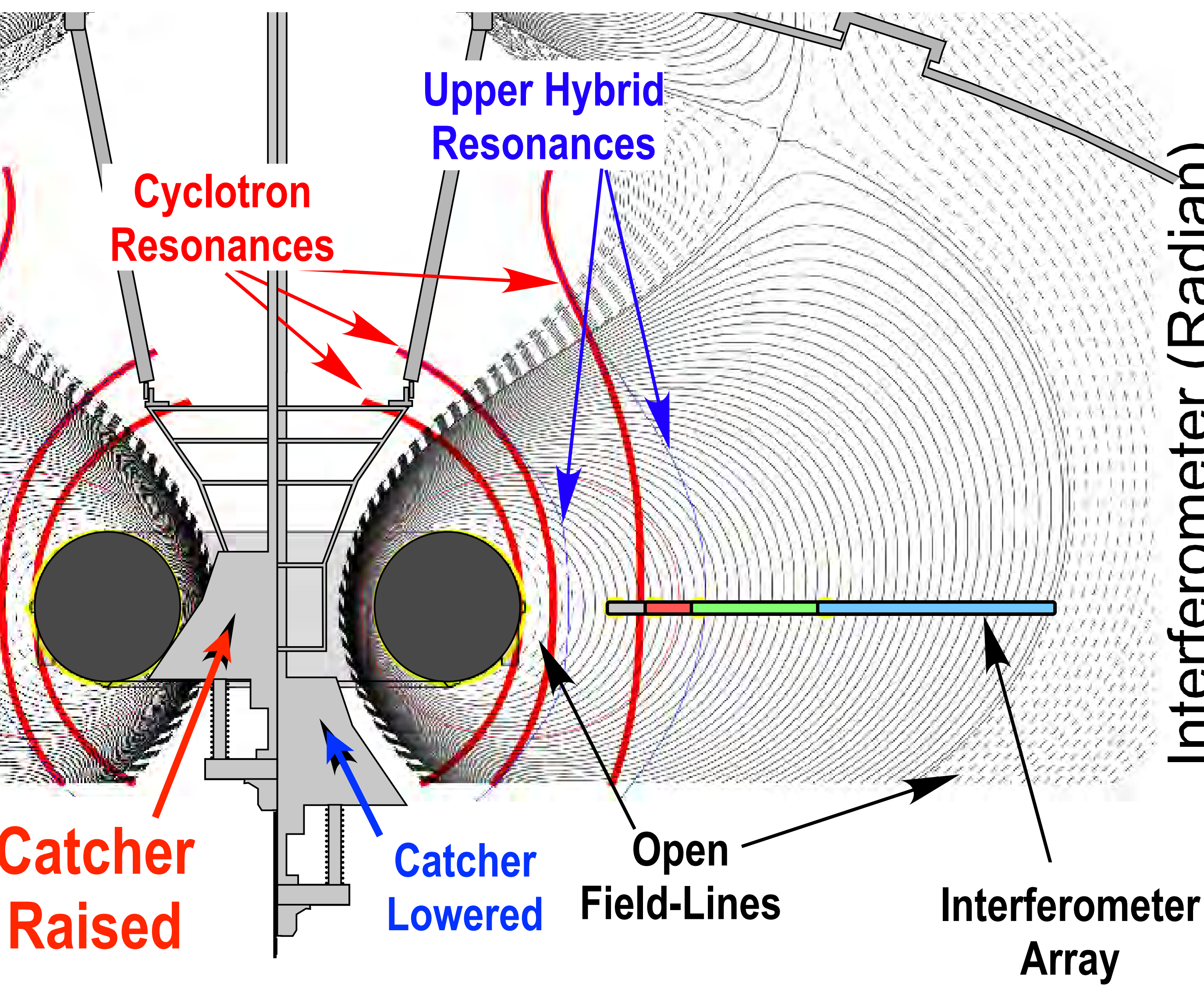


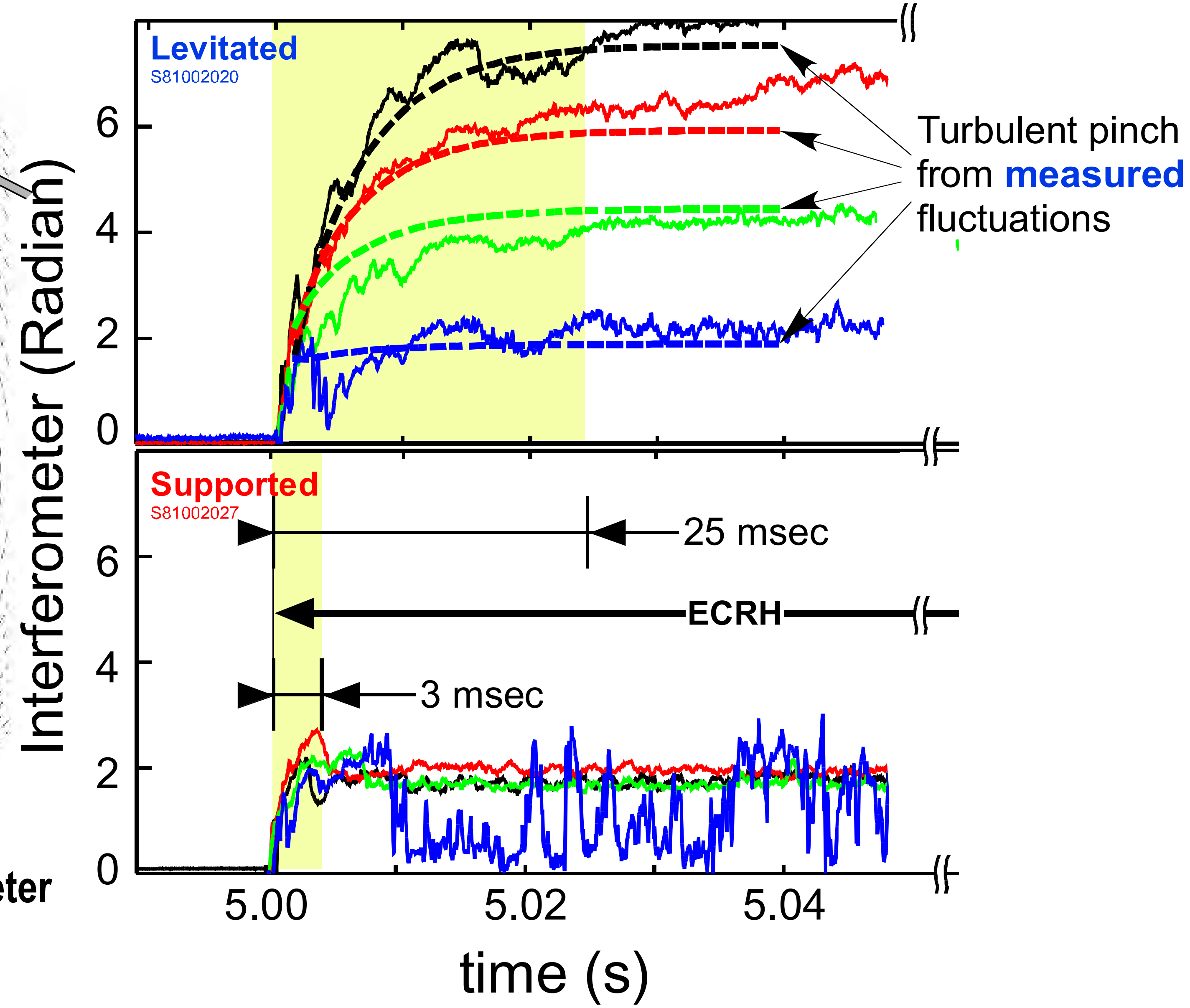
Quantitative Verification of Inward Turbulent Pinch

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).

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

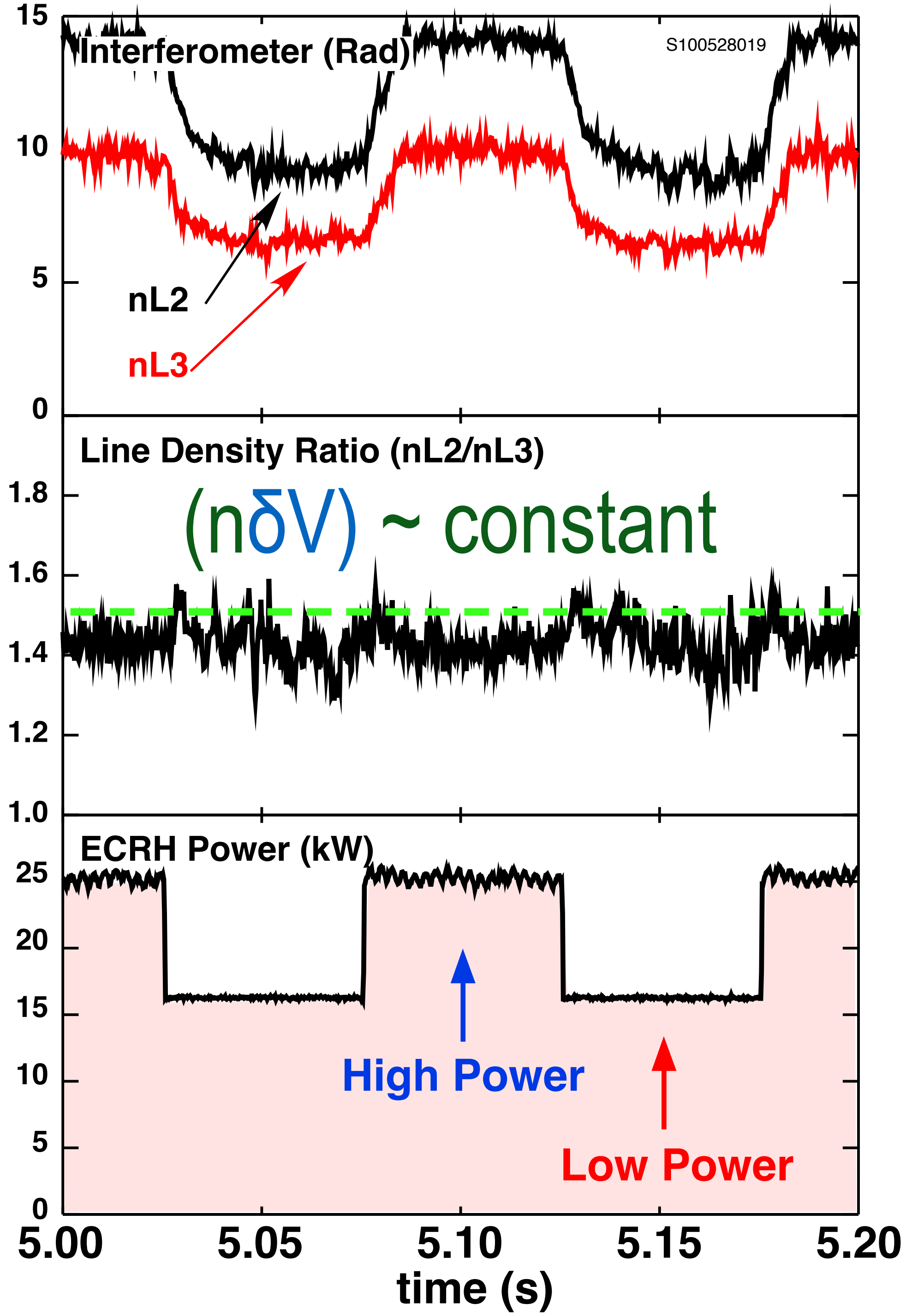
With levitated dipole, inward turbulent transport sets profile evolution

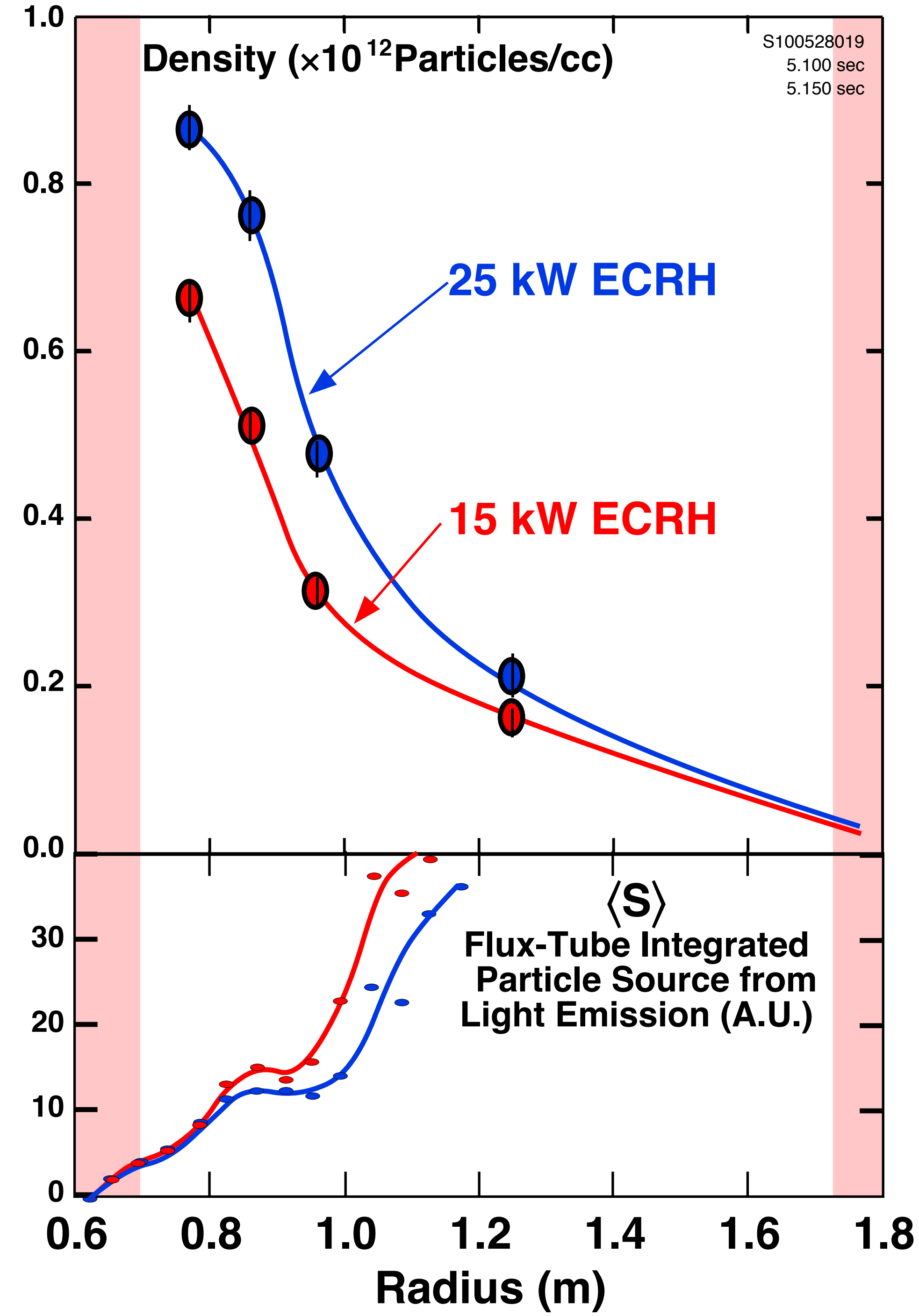




Heating or Gas Modulation Demonstrates **Robust** Inward Pinch & **Natural** "Canonical" Profile

- **Density increases with power** (*T* ~ constant). Density **profile shape is unchanged** near ($n\delta V$) ~ constant.
- Gas source moves radially outward while central density increases.





Kesner, *et al.*, "Stationary density profiles in the Levitated Dipole Experiment: Toward Fusion without Tritium Fuel," *PPCF*, (2010).

*Laboratory measurements, **explained with theory and simulation,** have* *<u>Changed the way we think about toroidal confinement</u>*

- **Sustained plasma pressure equal to the local magnetic pressure (β ~ 1)**

  Garnier, POP (1999); Krasheninnikov, Catto, Hazeltine, PRL (1999); Simakov, Catto, Hastie, POP (2000a,b); Catto, POP (2001); Kesner, NF (2001); Guazzotto, Freidberg, POP (2007)

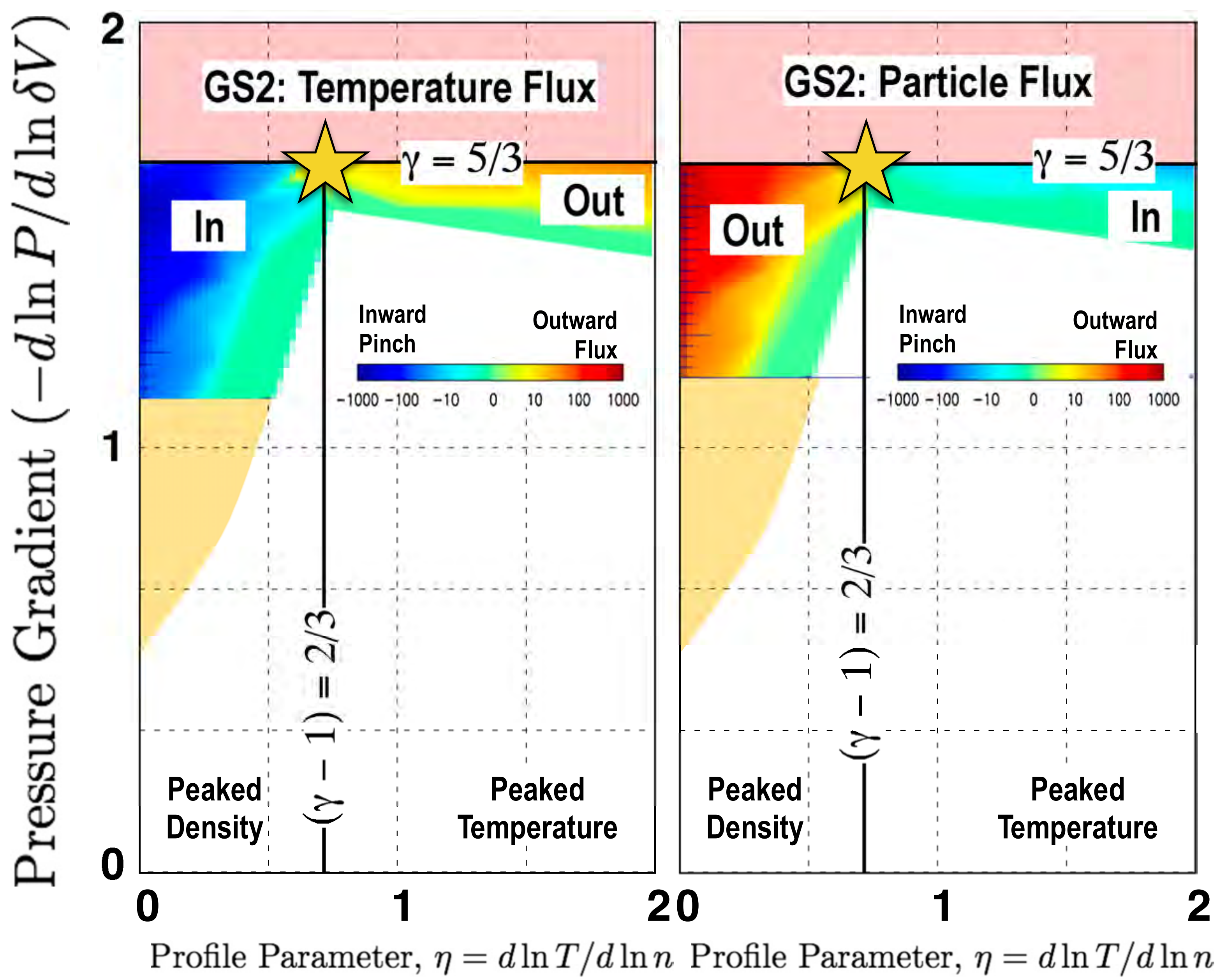
- **Interchange and entropy modes dominate plasma dynamics**

  Kesner, POP (2000); Kesner, Hastie, POP (2002); Ricci, Rogers, Dorland, PRL (2006); Ricci, POP (2006); Kouznetsov, Friedberg POP (2007a)

- **Turbulent self-organization maintains steep plasma profiles and approach state of minimum entropy production**

  Tonge, Dawson, POP (2003); Pastukov, JETP Lett (2005); Pastukov, Plasma Phys Rep (2005); Garbet, POP (2005); Kouznetsov, POP (2007b); Kobayashi, PRL (2009); Kobayashi, Rogers, Dorland, PRL (2010); Kesner, POP (2011)

Kobayashi, Rogers, Dorland, PRL (2010)
Gyrokinetic (GS2) simulations show turbulence drives particles or heat to maintain uniform entropy density



More Discoveries at Higher Density and Ion Temperature

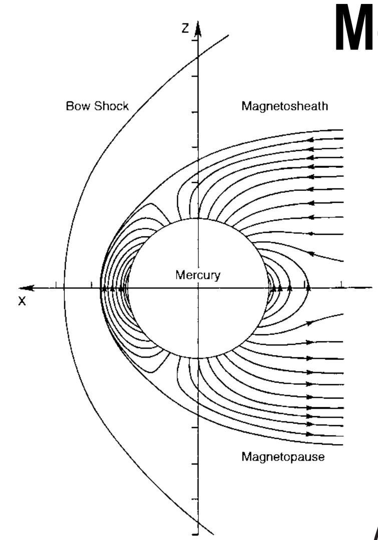
- ***Space science:*** high density, hot ions, and very large size
  - High density ($\omega_{pe} >> \omega_{ce}$) trapping of whistler waves: "killer electrons" created by inward transport of particles and waves. *What is the character of trapped whistlers in a laboratory magnetosphere?*
  - High density ($c/L\omega_{pi} << 1$) Alfvén waves, resonances, and dynamics at high beta. *How does Alfvén wave dynamics change turbulent mixing and energetic particle confinement?*
  - Ring current $T_e \sim T_i \sim 10$ - 200 keV give FLR and ion drift-orbit bifurcation. *How does interchange/ flux-tube mixing change with space-relevant finite ion temperature?*
- ***Fusion science:*** high density and hot ions
  - Does a thermal, $T_i \sim T_e$, plasma self-organize?
  - How does FLR, ion mass/isotope, and ion pressure modify the turbulent spectrum?
  - Do electromagnetic and Alfvén wave effects change stability at $\beta \sim 1$?
  - Does high power drive zonal flows and create transport barriers in a dipole plasma torus?
  - Does bounce-averaged gryokinetics correctly predict particle and energy confinement times?

More Discoveries at Higher Density and Ion Temperature

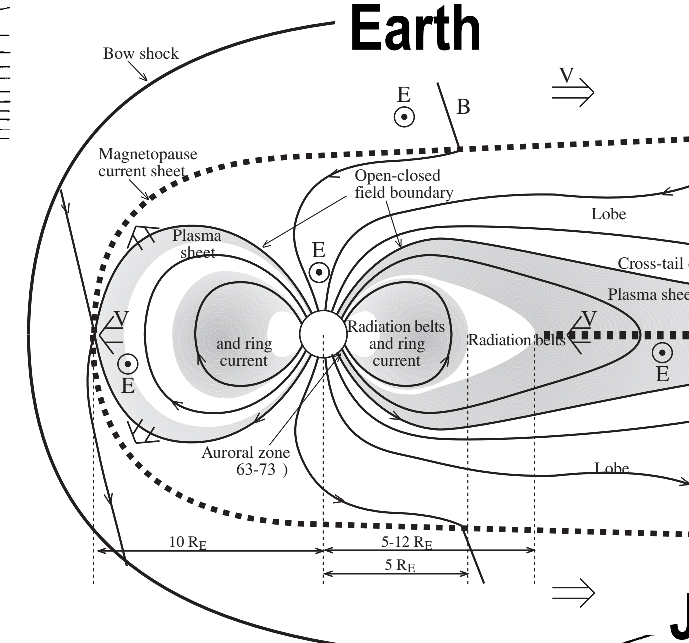
Next-step discoveries are significant…

- 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

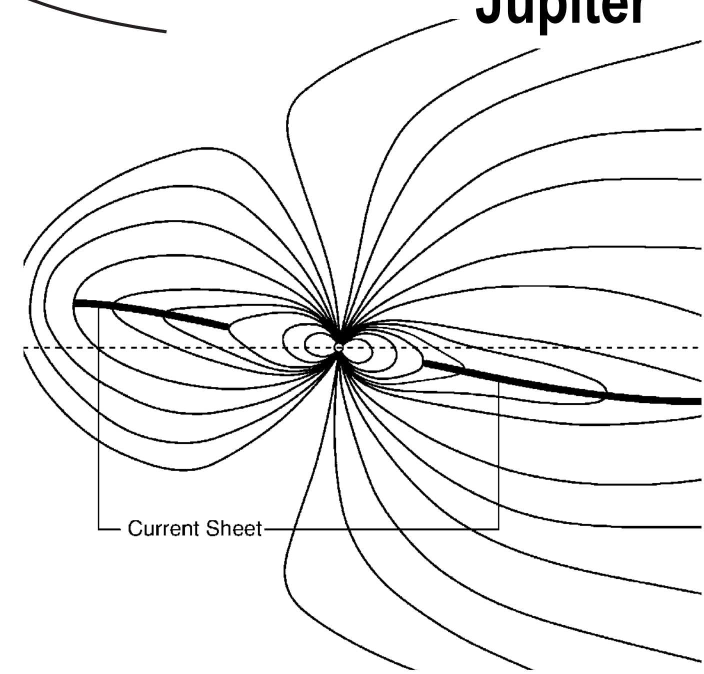
Mercury **(10th Anniversary of MESSENGER)**



Earth



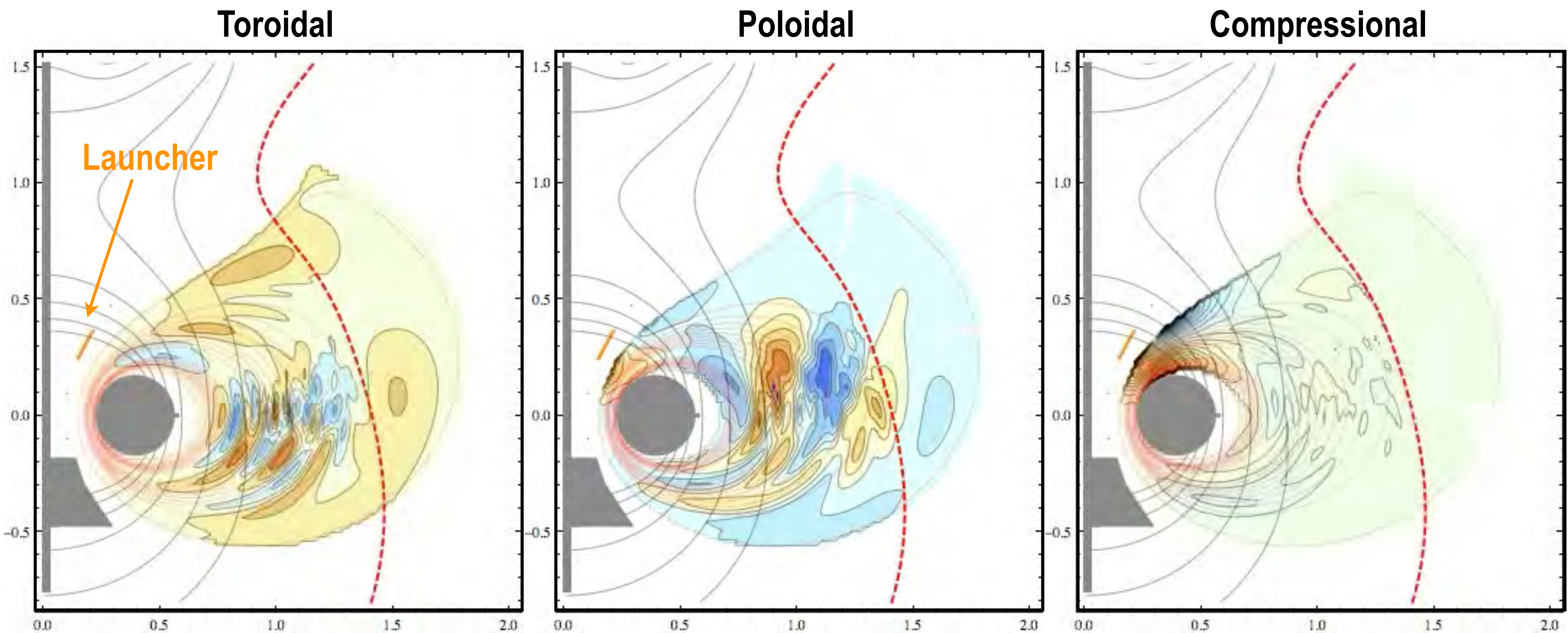
Jupiter



	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

Alfvén Wave Excitation and Spectroscopy will be Possible in LDX 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

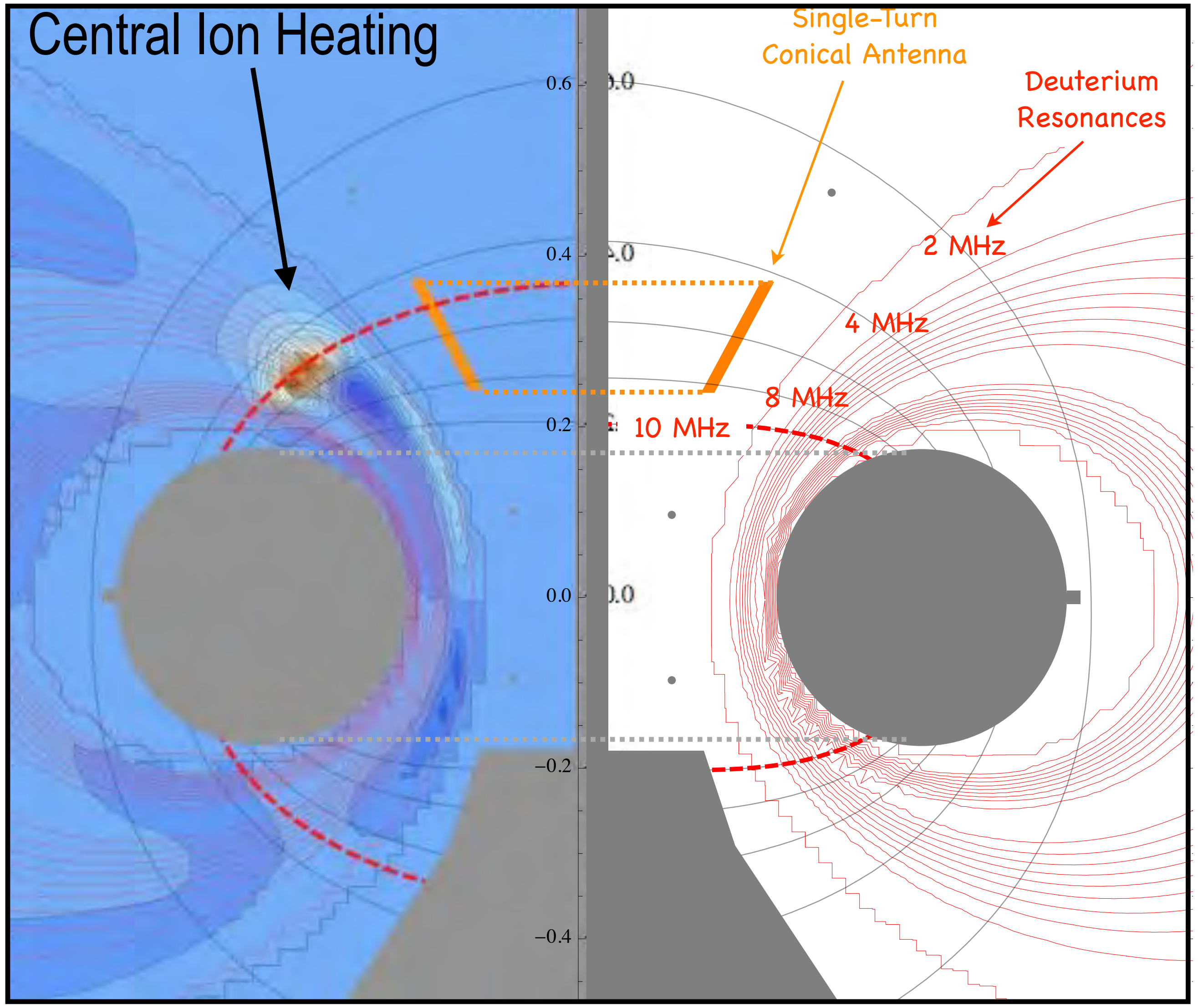
25 kW → 1 MW with RF Power Already Installed for LDX

Next step LDX experiments will increase plasma density (×10) for Alfvén wave studies and produce peak T_i ~ 0.5 keV for turbulent transport studies.

(Nov 2010) MIT-PSFC set into place a modern Thales TSW2500 short-wave transmitter and transmission line components received from General Atomics.

1 MW HF: 3.9 MHz – 26.1 MHz

Axisymmetric Heating
5 MHz Deuterium ICRF (1 Ω Loading)



Jaeger, et al., *Comp Phys Comm*, **40**, 33-64, (1986)

Beyond LDX → Larger Size

- With 250 kW of absorbed power, LDX is expected to demonstrate steady-state toroidal confinement at

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

- If turbulent self-organization persists and confinement is *maintained at large size*, …

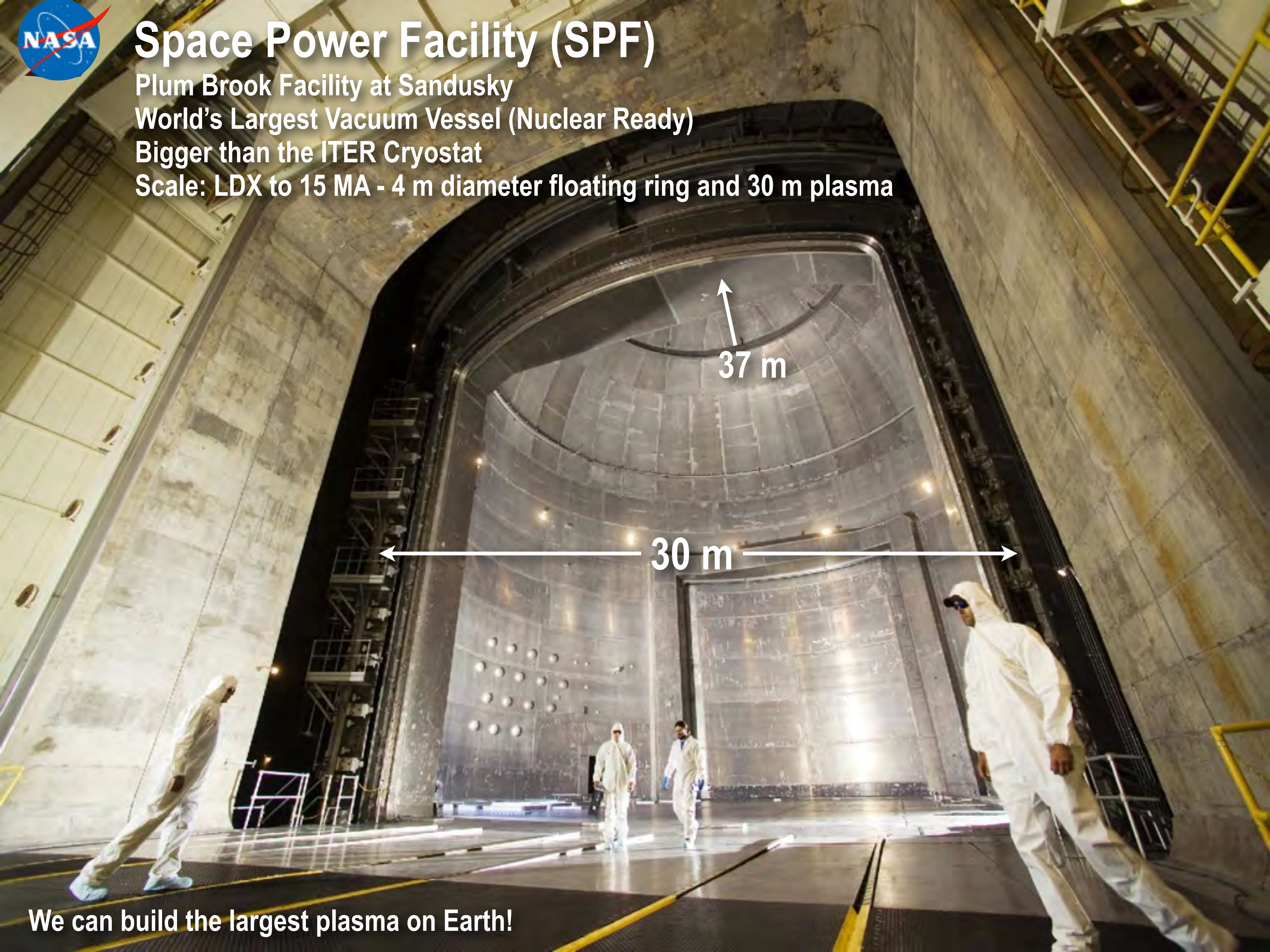
We could build the world’s largest magnetically-confined plasma at NASA’s Space Power Facility (SPF) at Sandusky, OH

Fundamental plasma physics and space technology

Exploration of burning plasma physics in 30 minute Q > 1 pulses

Space Power Facility (SPF)

Plum Brook Facility at Sandusky
World's Largest Vacuum Vessel (Nuclear Ready)
Bigger than the ITER Cryostat
Scale: LDX to 15 MA - 4 m diameter floating ring and 30 m plasma



We can build the largest plasma on Earth!

2014 Experiments:
Transient Injection and Harnessing the Turbulent Dynamo

- ***Darren Garnier:***

  Transient flux-tube dynamics with Li injection: ***×3 density rise***, plasma torus evolution, …

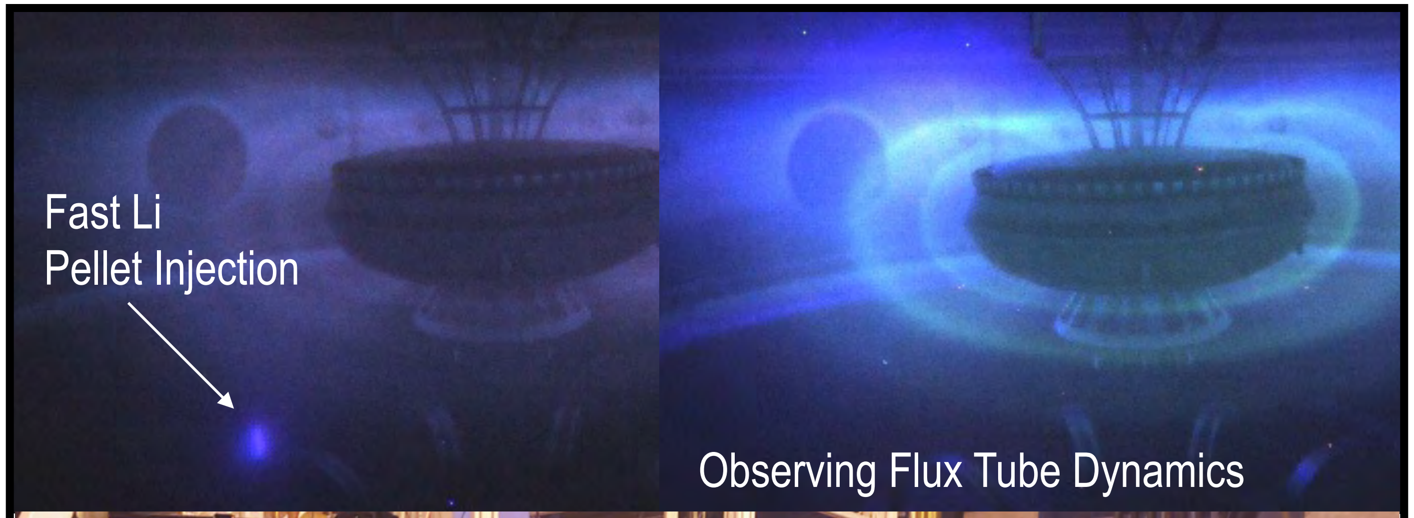
  Interest from new partners from space physics community: radiation belt physics (HANE, space weather), multi-point diagnostic "swarms", …

- ***Max Roberts: (APS-DPP 2014 Invited Talk)***

  Turbulence regulation with controlled current extraction

  The first laboratory observation of magnetospheric "dynamo"…

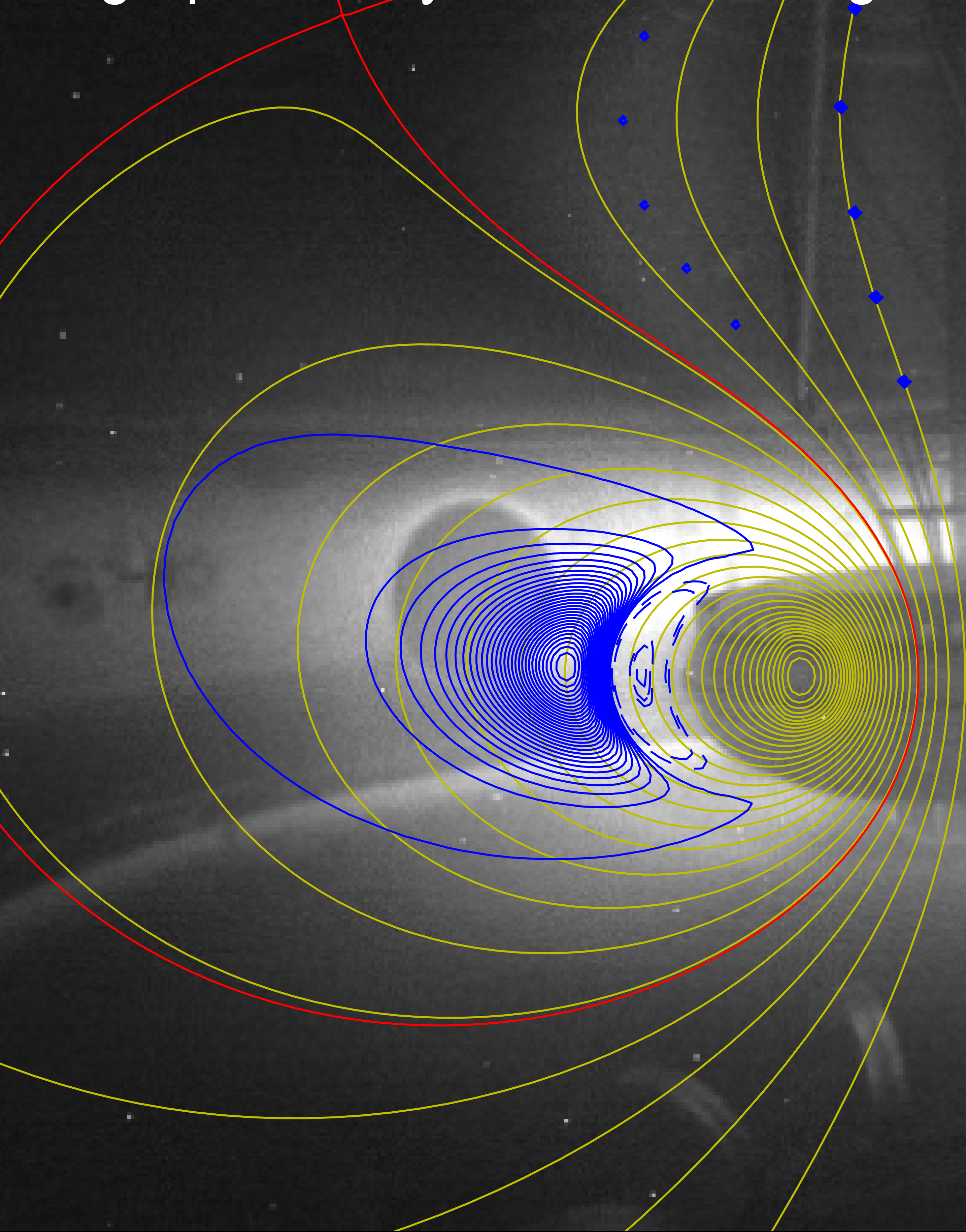
  About 20 mW extracted from the CTX Laboratory Magnetosphere!



Laboratory Magnetospheres are Unique Opportunities for Controlled Plasma Science 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***
- Laboratory magnetospheres are also facilities for ***conducting controlled tests*** of fusion-confinement models in a steady-state plasma torus by ***controlling the injection of heat, particles, and perturbations***
- Higher-power and larger laboratory magnetospheres will increase plasma density, particle energy, and intensity of “artificial radiation belt”, and allow new controlled tests of ***complex Alfvén wave interactions*** in the magnetosphere.
- ***Very large plasmas*** can be produced in the laboratory, continuously, with low power and great flexibility.
- ***Outlook***: We can build/operate the ***largest laboratory plasma on Earth***

High β, Steady State, Self-Organized, Very-Large Plasma Torus



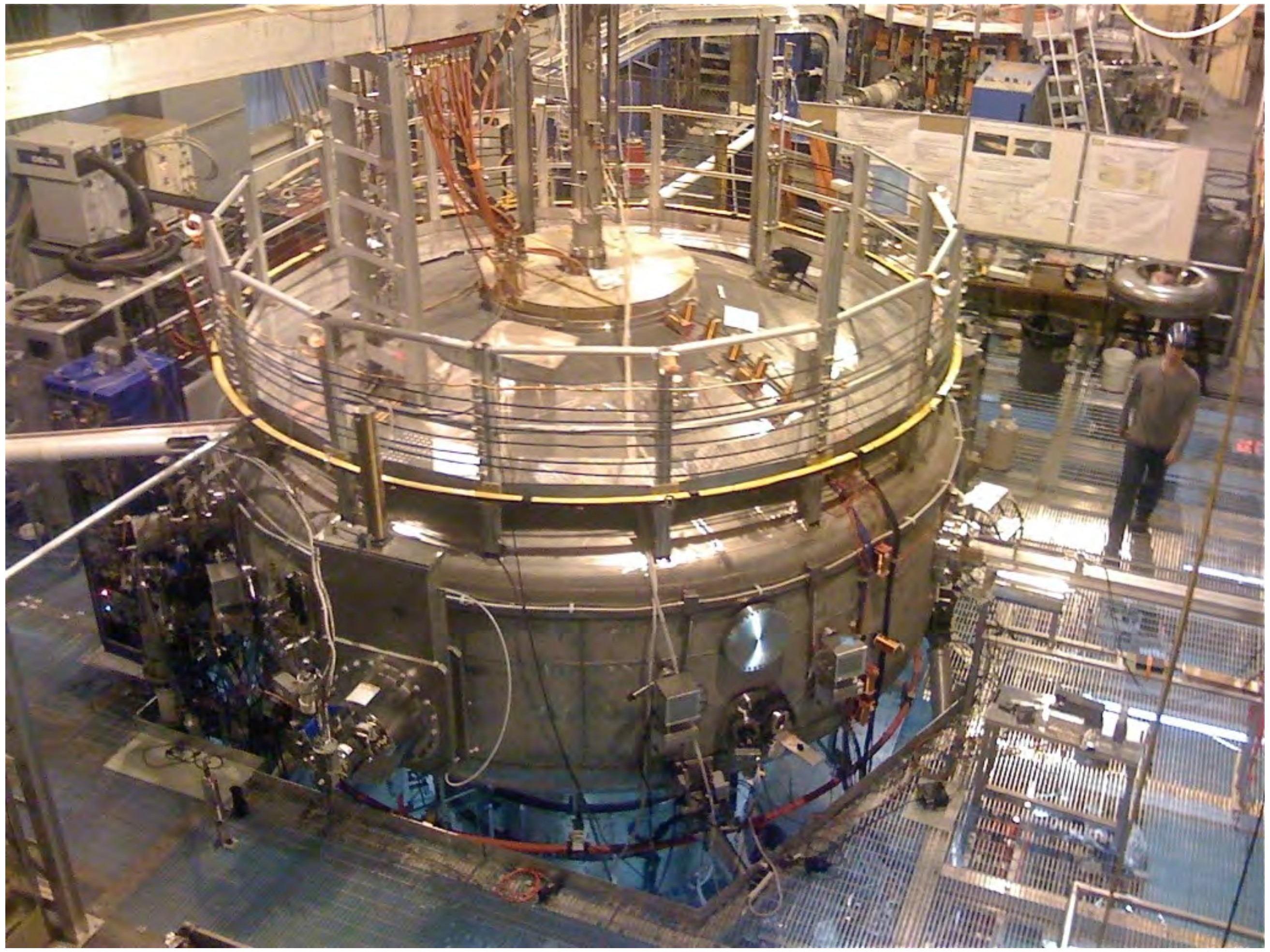
Back-Up Slides

- Inward particle pinch was first observed in the laboratory by Jim Strachan and colleagues at the PLT device. *<u>But, in tokamaks, the inward pinch is accompanied with enhanced plasma energy loss.</u>*

- Plasma confined in a dipole is described with space-weather codes, but a levitated dipole has no FAC/ionospheric coupling. Mixing occurs on the drift time, $\rho^{*2}\ \omega_{ci}$, *<u>regulated by ion inertial currents.</u>*

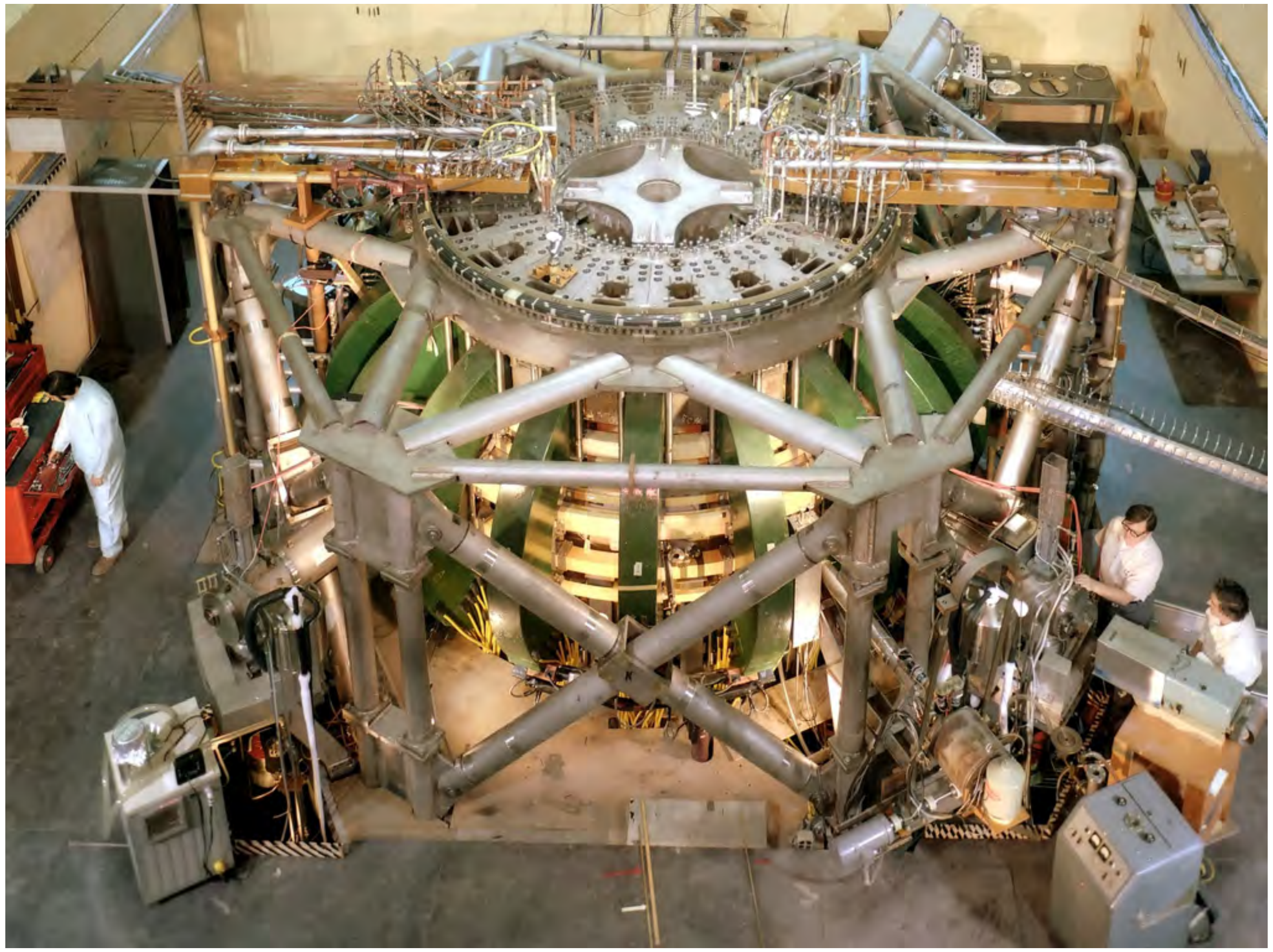
- Double-catalyzed ("tritium suppressed") D-D(^{3}He) fusion *<u>requires particle confinement less than energy confinement.</u>* This may be possible with a levitated dipole, allowing a transformational change in availability, safety, and cost of fusion energy.

Turbulent Pinch is a Fundamental Process found in Toroidal Magnetic Systems Including Tokamaks and Planetary Magnetospheres (but, different…)



Levitated Dipole Experiment (LDX)

1.2 MA Superconducting Ring
Steady-State
25 kW ECRH
1 MW ICRF (unused)



Princeton Large Torus (PLT)

17 MA Copper Toroid
1 sec pulses
750 kW Ohmic
75 kW LHCD
2.5 MW NBI & 5 MW ICRF

A (*Historic*) Density Rise Experiment on PLT

Jim Strachan, et al., Nuc. Fusion (1982)

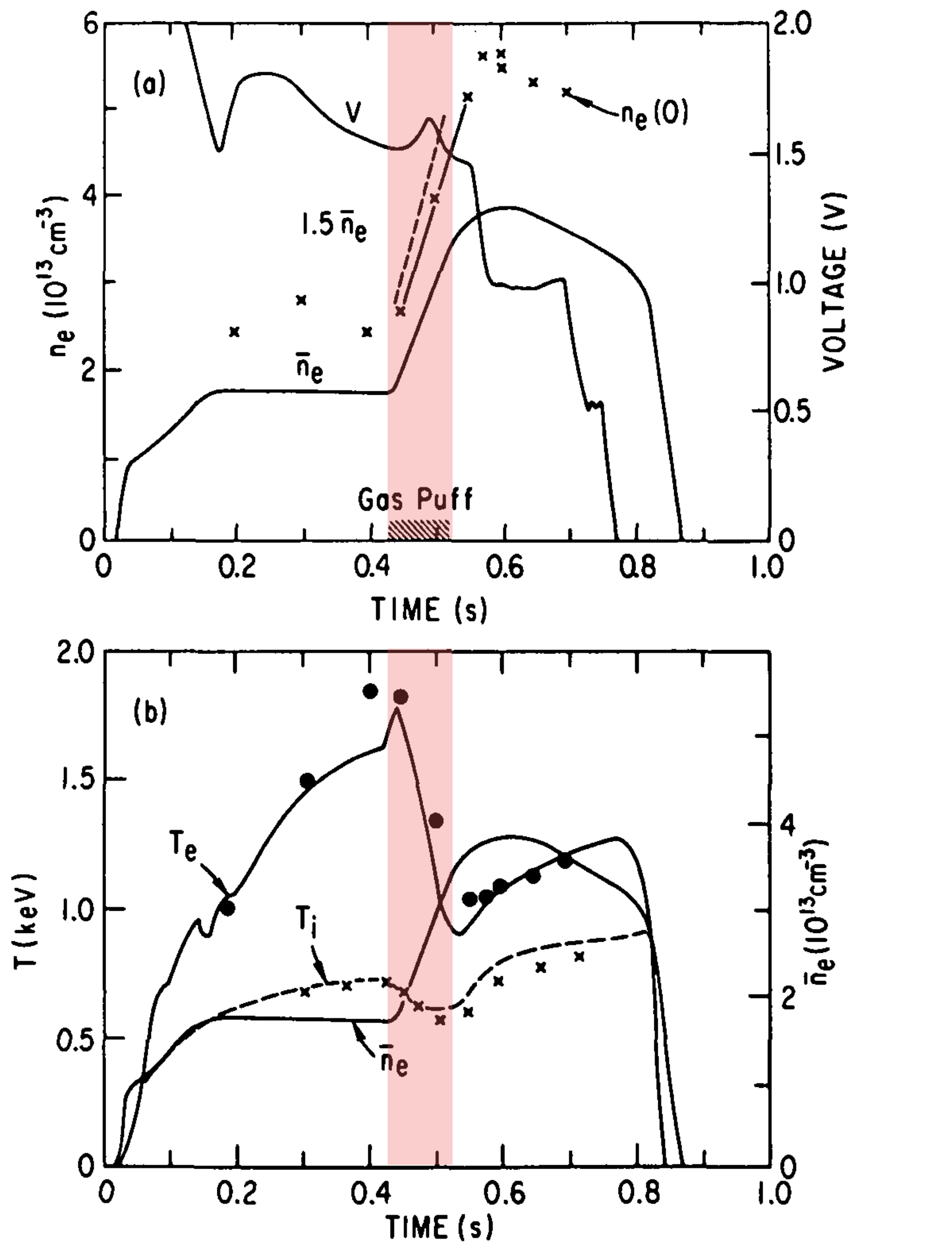
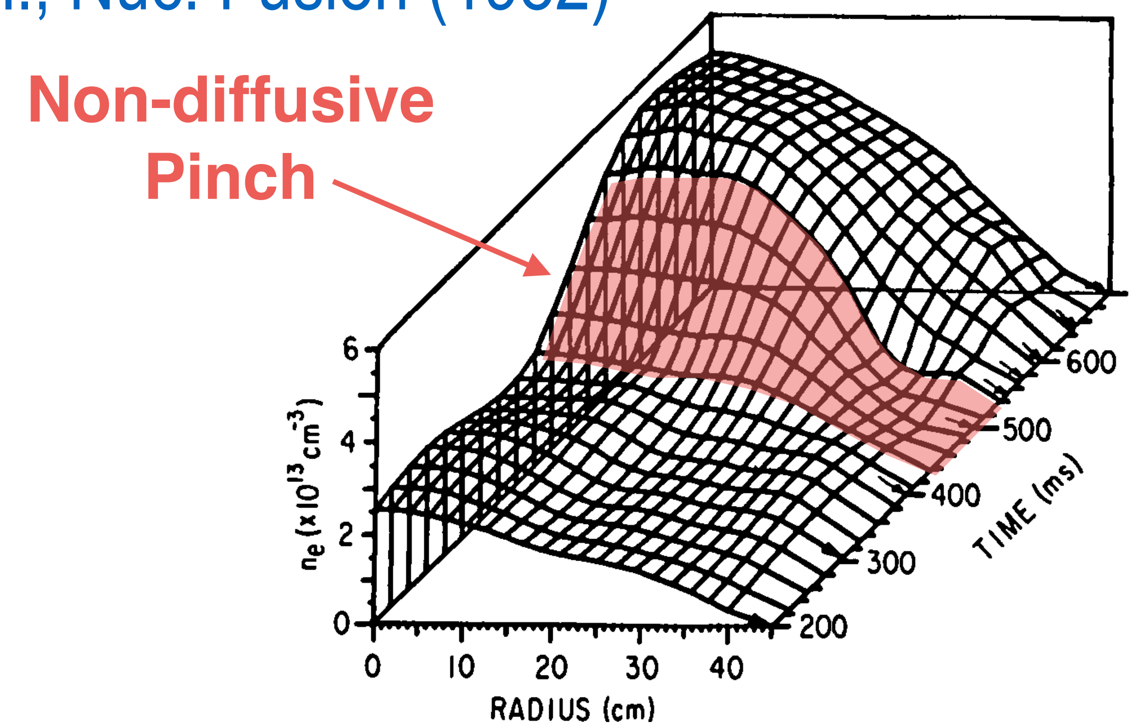
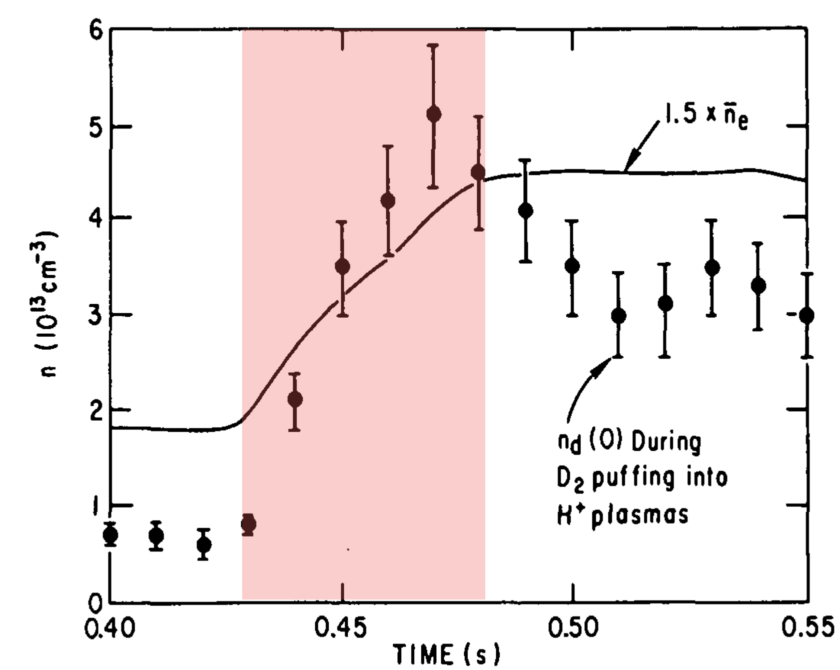


FIG. 2. (a) Time evolution of the loop voltage, V, the line-average density $\bar{n}_e$, and the central electron density, $n_e(0)$ during the density rise. (b) Time evolution of the central electron temperature from $2\omega_{ce}$ (——), and from TVTS (●), with the time evolution of the central ion temperature from neutrons (- -), and from charge exchange (X) during the density rise.



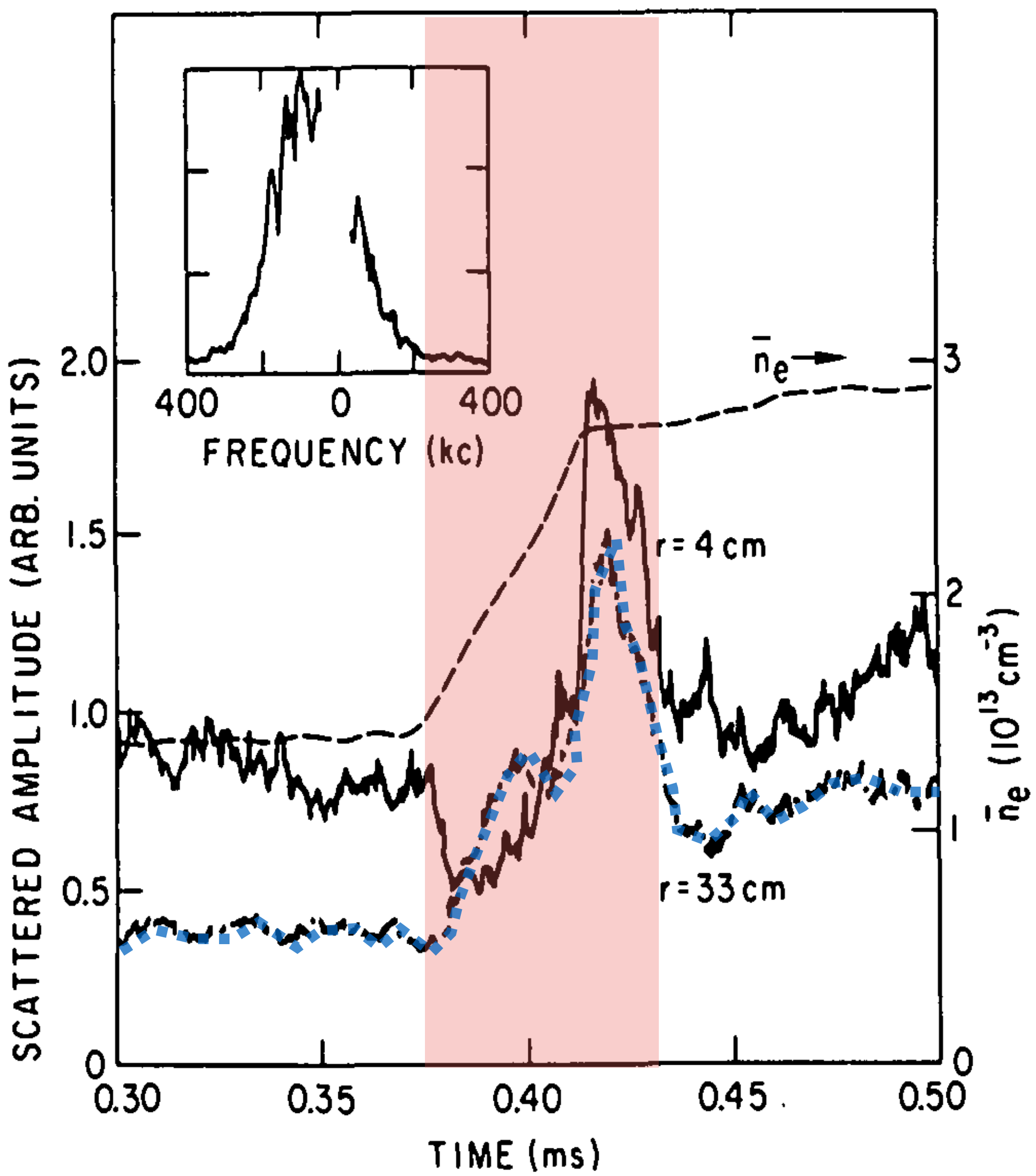


Inward Turbulent Pinch "*is necessary to model the experimental results*" of peaked density from edge gas source

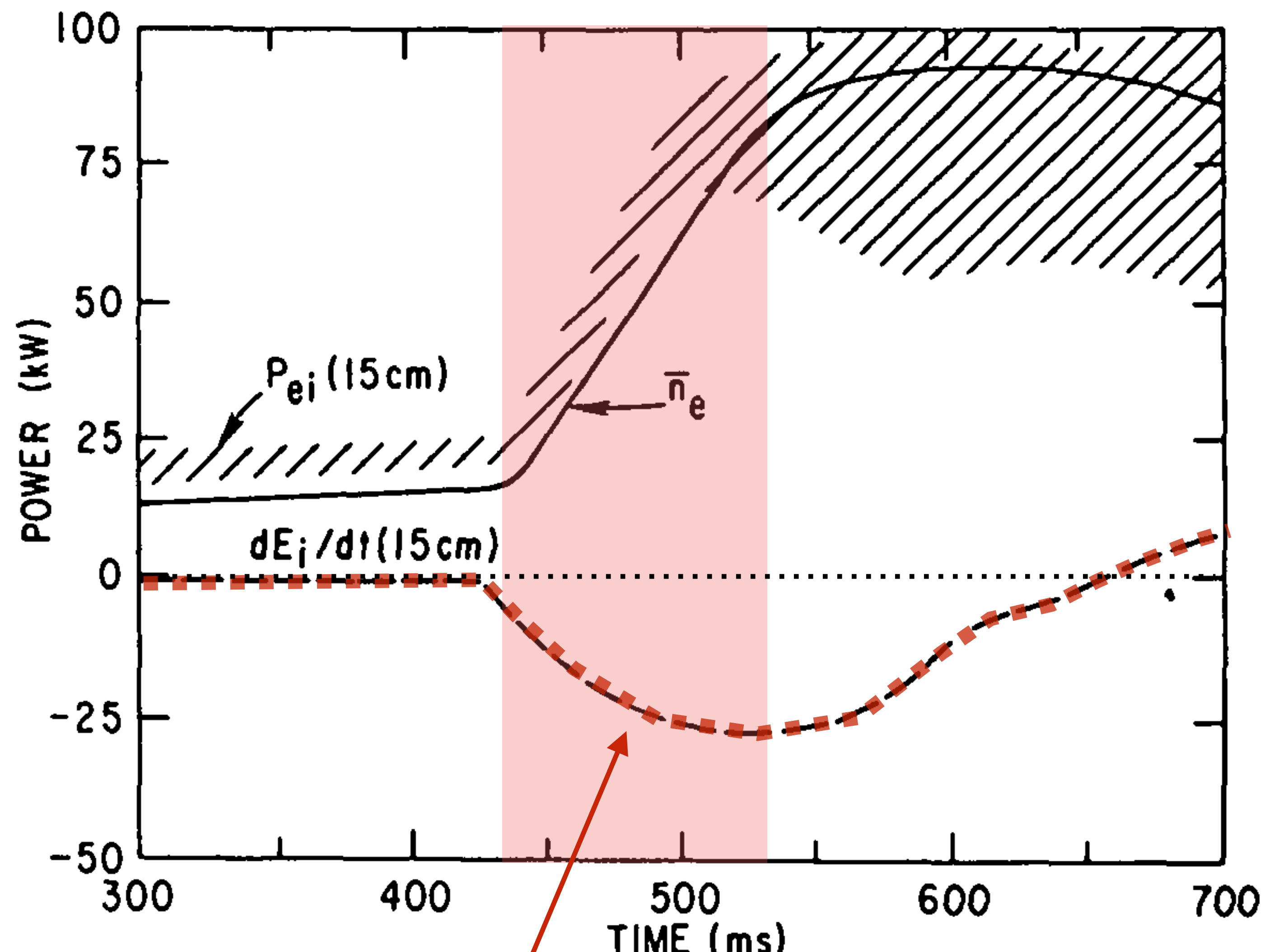
A (*Historic*) Density Rise Experiment on PLT

Jim Strachan, et al., Nuc. Fusion (1982)

Enhanced Turbulent Fluctuation Intensity…



… Causing Central Ion Cooling



but gas puff intensifies turbulence and Outward Ion Energy Flux accompanies Inward Turbulent Particle Pinch

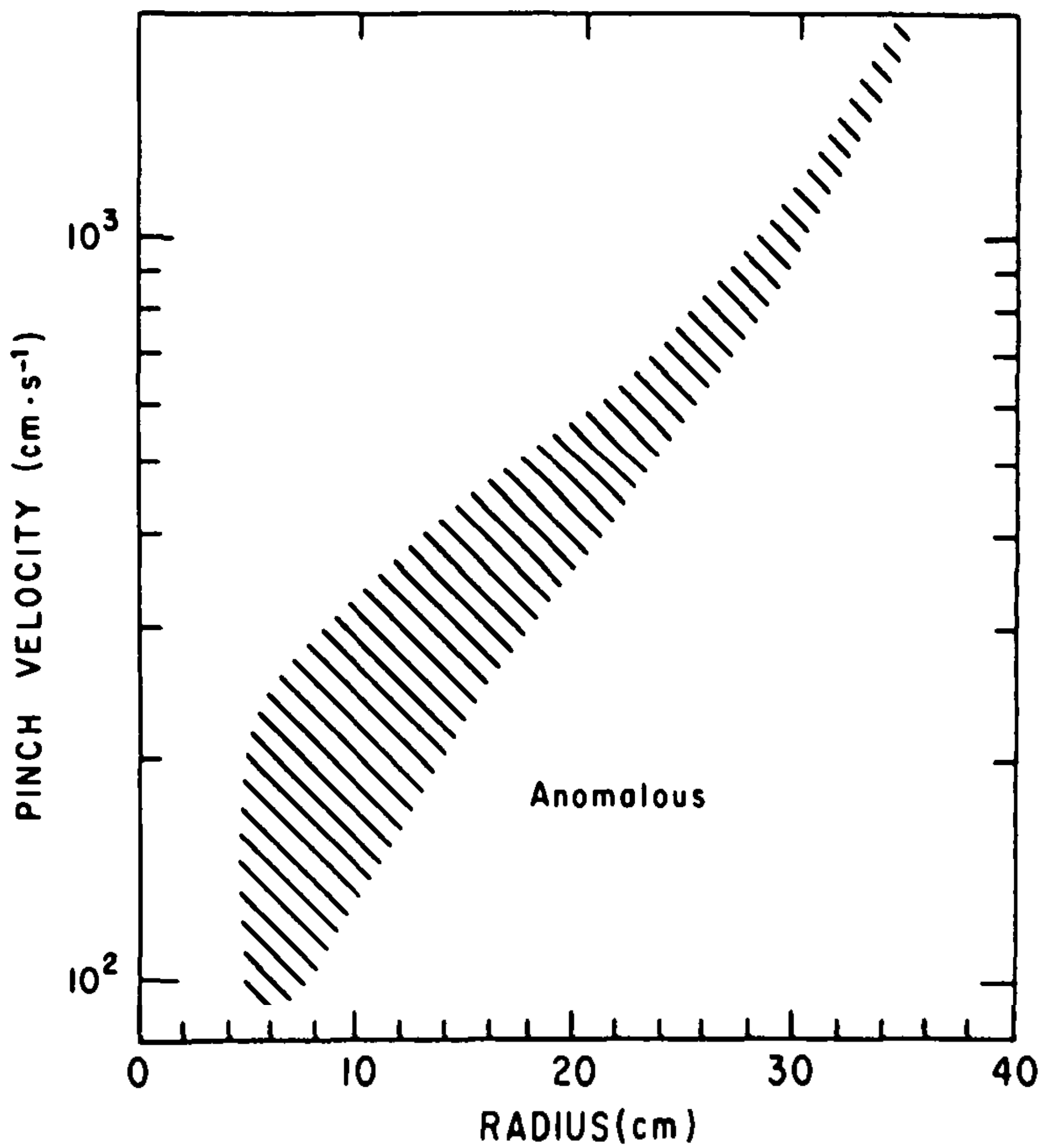
Comparing Inward Pinch Velocities on PLT and LDX

Strachen, et al., Nuc. Fusion (1982)

Boxer, et al., Nature-Physics (2010)

Princeton Large Torus (PLT)

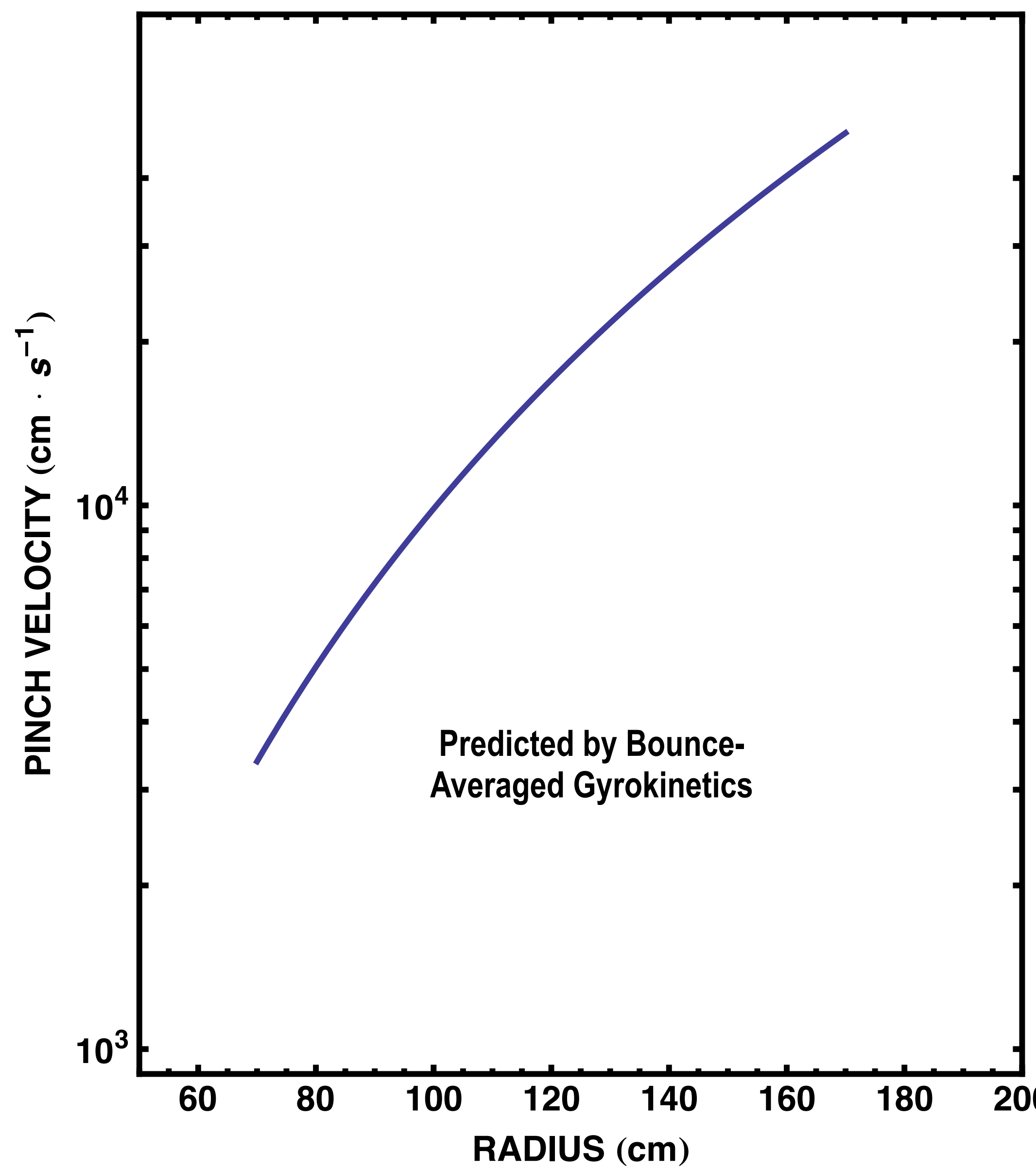
Inward Pinch is 10-100 × Neoclassical



but inward particle pinch causes central ion cooling in tokamaks

Levitated Dipole Experiment (LDX)

Inward Pinch is 10 × Larger in LDX than PLT



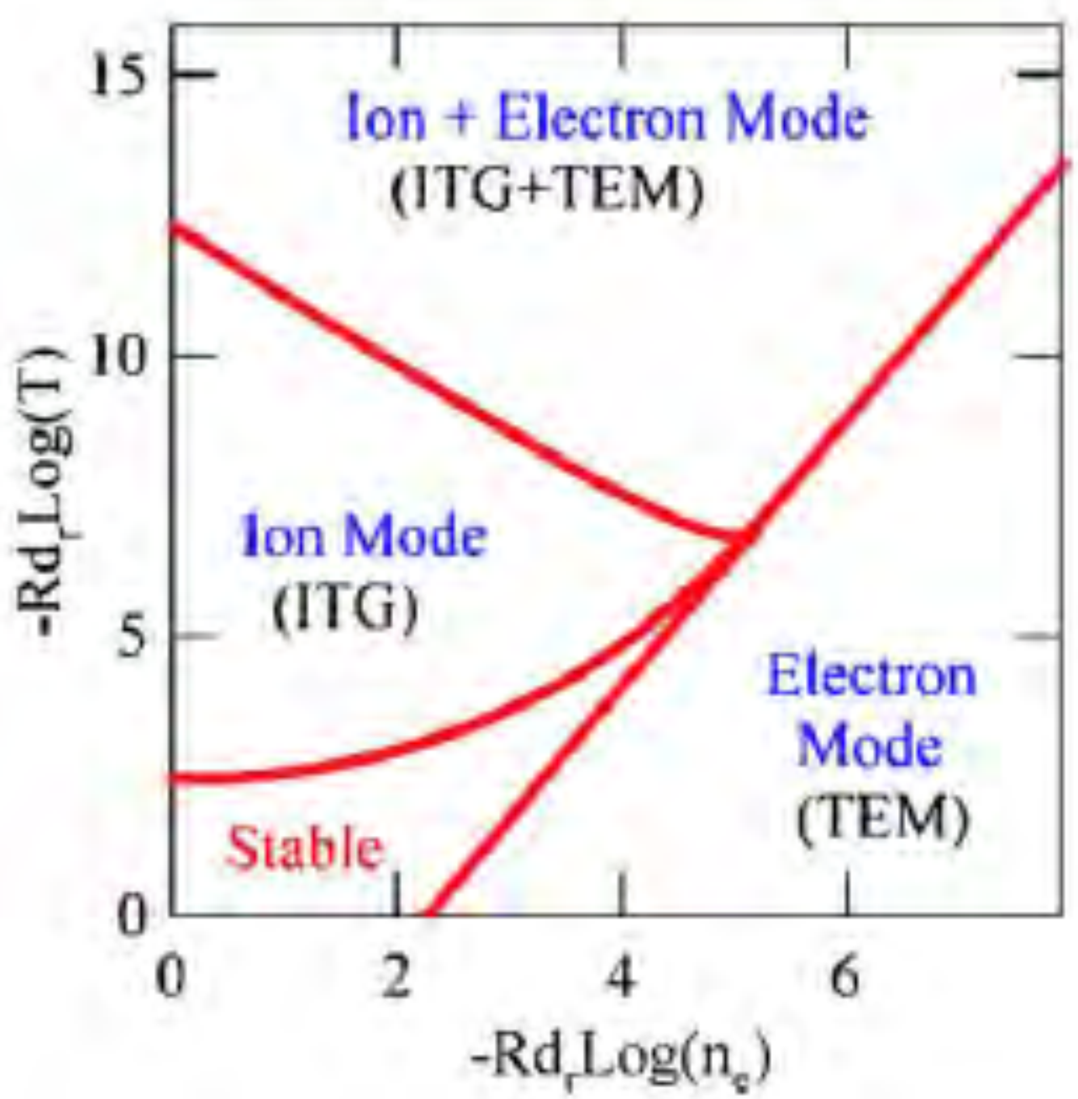
and inward particle pinch associated with central heating

Comparing Low-Frequency Interchange-Drift Stability

$k_{||} \neq 0$

Tokamak Stability

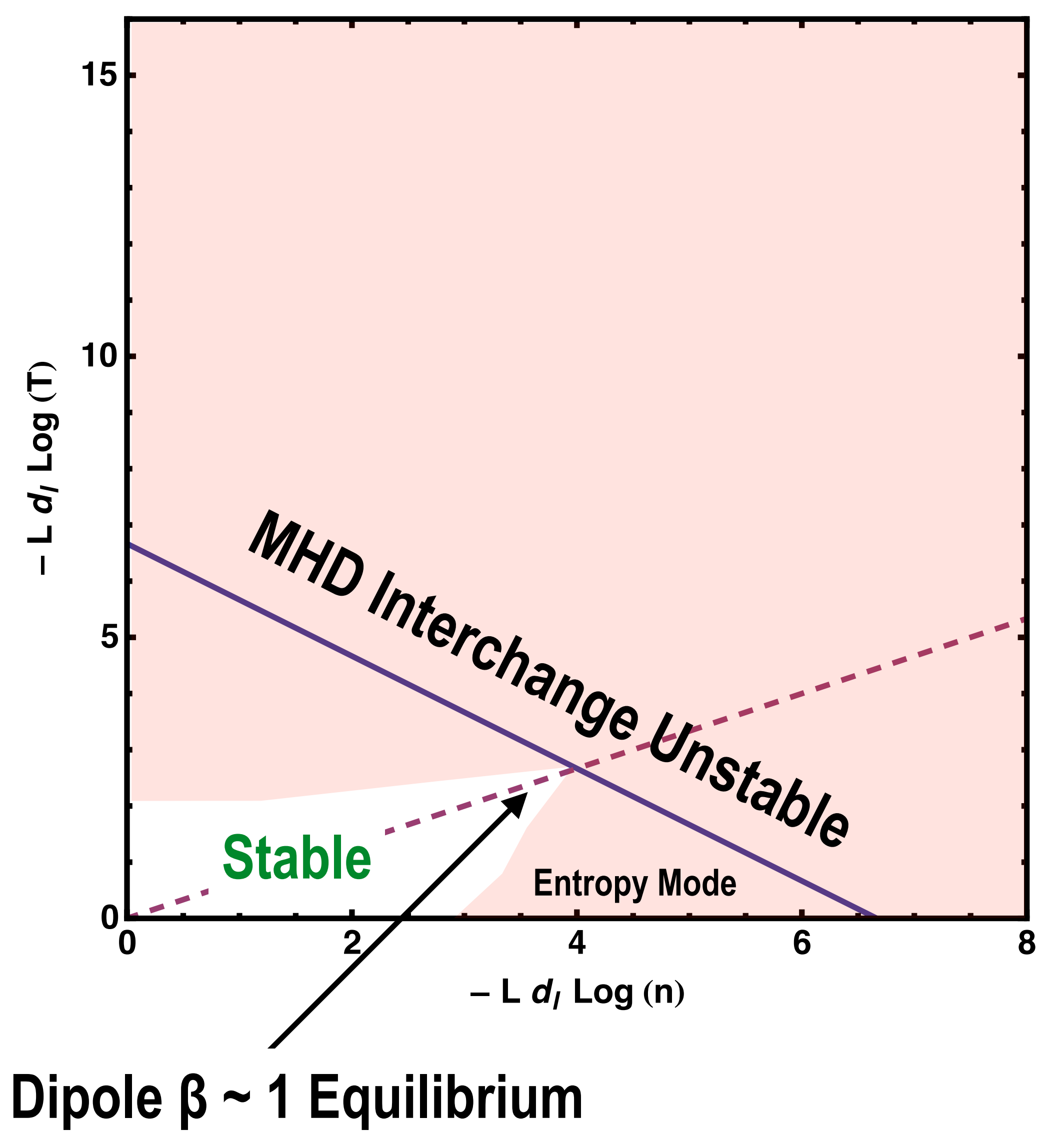
X. Garbet / C. R. Physique 7 (2006) 573–583



$k_{||} = 0$

Dipole Stability

J. Kesner, Phys Plasmas 7, 3837 (2000)



INNER MAGNETOSPHERIC MODELING WITH THE RICE CONVECTION MODEL

FRANK TOFFOLETTO, STANISLAV SAZYKIN, ROBERT SPIRO and RICHARD WOLF
Department of Physics and Astronomy, Rice University, Houston, TX 77005, U.S.A.

Semi-collisional Plasmasphere and Ring Current

TABLE I

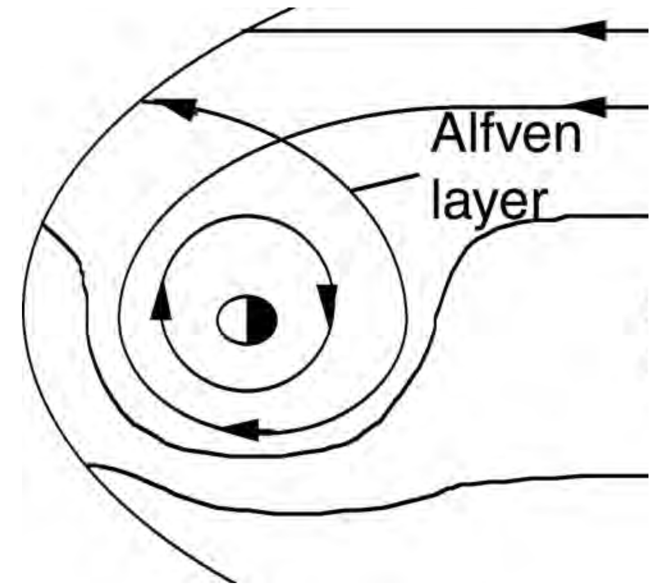
Comparison of equations of ideal MHD with those used in the RCM

Ideal MHD	RCM
$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$	$(\frac{\partial}{\partial t} + \vec{v}_k(\lambda_k, \vec{x}, t) \cdot \nabla)\eta_k = S(\eta_k) - L(\eta_k)$
$(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla)(\rho \vec{v}) = \vec{j} \times \vec{B} - \nabla P$	$\vec{j}_k \times \vec{B} = \nabla P_k$
$(\frac{\partial}{\partial t} + \vec{v} \cdot \nabla)(P\rho^{-5/3}) = 0$	$P = \frac{2}{3} \sum_k \eta_k \lvert\lambda_k\rvert V^{-5/3}$, $\lambda_k = constant$
$\nabla \cdot \vec{B} = 0$	Part of the magnetic field model.
$\nabla \times \vec{B} = \mu_0 \vec{j}$	Included in magnetic field, but $\vec{j} \neq \sum_k \vec{j}_k$.
$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	Included implicitly in mapping.
$\vec{E} + \vec{v} \times \vec{B} = 0$	$\vec{E} \cdot \vec{B} = 0$ and $\vec{E}_\perp + \vec{v}_k \times \vec{B} = \frac{\nabla W(\lambda k, \vec{x}, t)}{q_k}$

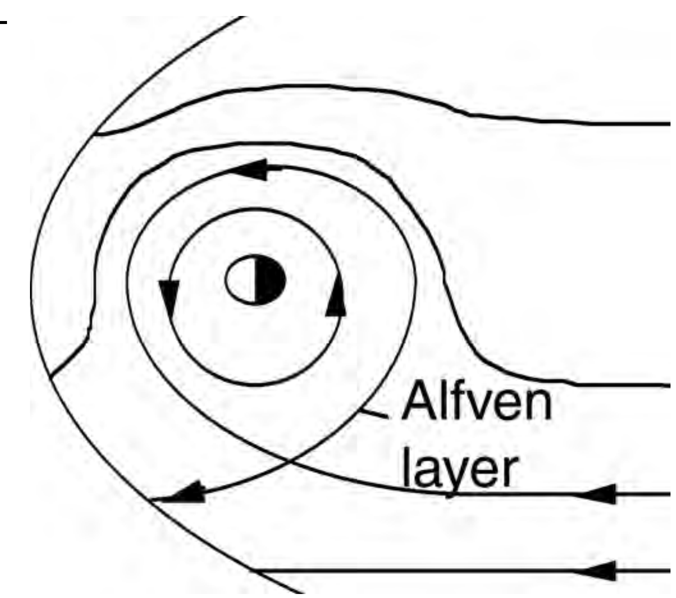
For each species and invariant energy λ, η is conserved along a drift path.
Specific Entropy

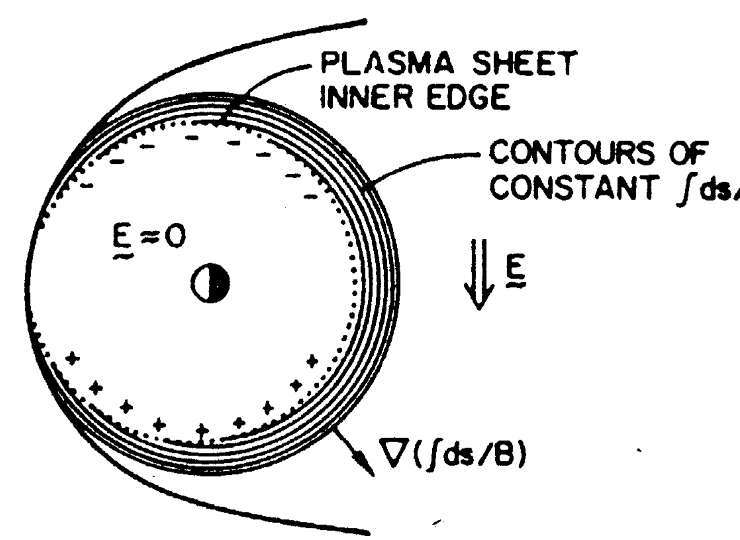
$$pV^\gamma = \frac{2}{3} \sum_s \lvert\lambda_s\rvert \eta_s$$

Ions



Electrons





Space Science Reviews **107:** 175–196, 2003.

“Canonical” Profiles of Magnetized Plasma

- Low frequency fluctuations in strongly magnetized plasma, $\omega_d \sim \omega << \omega_b << \omega_c$, conserve *energy* or *Lagrangian invariants* of the flow.

- **Turbulent mixing across flux tube volumes “self organizes”** magnetized plasma to **canonical profiles**, which are stationary when $\delta(nV) \approx 0$ and $\delta(PV^{\gamma}) \approx 0$.

- **Space (*i.e.* Dipole) geometry**:
  - ➡ Birmingham, *J. Geophysical Res.*, 1969
  - ➡ Harel, Wolf, *et al., J. Geophys. Res.*, 1981
  - ‣ Kobayashi, Rogers, and Dorland, *Phys. Rev. Lett.*, 2010
  - ‣ Kesner, *et al., Plasma Phys. Control. Fusion*, 2010; Kesner, *et al.*, *Phys. Plasmas*, 2011.

- **Tokamak geometry**:
  - ➡ Coppi, *Comments Plasma Phys. Controll. Fus.,* 1980
  - ‣ Yankov, *JETP Lett.*, 1994 and Isichenko, *et al.*, *Phys. Rev. Lett., 1995*
  - ‣ Baker and Rosenbluth*, Phys. Plasmas*, 1998; Baker, *Phys. Plasmas*, 2002
  - ‣ Garbet, *et al., Phys. Plasmas,* 2005

Bounce-Averaged Turbulent Mixing in Laboratory Magnetosphere

For isentropic mixing and when the ***low-frequency turbulent spectrum*** is sufficiently broad to drift-resonate ($\omega \sim m\omega_d$) with all particles, independent of energy and pitch-angle, then

Diffusion of flux-tube particle number, ***$n\delta V$***, …

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

$$= \langle S \rangle + \frac{\partial}{\partial \psi} \left[\underbrace{D_\psi \delta V}_{\text{Diffusion}} \frac{\partial \bar{n}}{\partial \psi} + \bar{n} \underbrace{D_\psi \frac{\partial \delta V}{\partial \psi}}_{\text{Pinch Velocity}} \right]$$

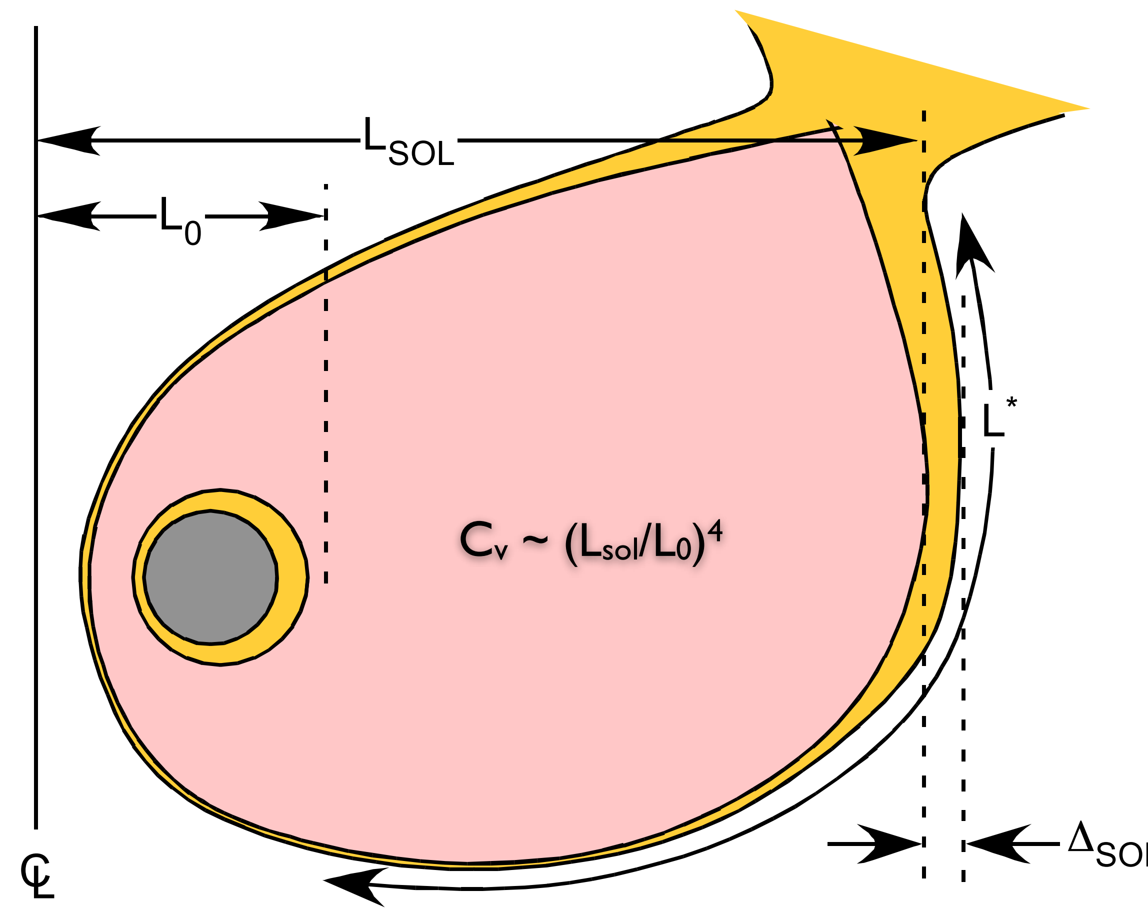
Diffusion of Energy/Entropy, $P\delta V^\gamma$, …

$$\frac{\partial(\bar{P}\delta V^\gamma)}{\partial t} = \langle H \rangle + \frac{\partial}{\partial \psi} D_\psi \frac{\partial(\bar{P}\delta V^\gamma)}{\partial \psi}$$

Turbulent Pinch in a Levitated Dipole may Make Possible Tritium Suppressed Fusion

- Sheffield, Zinkle, Sawan (2002-06)
- No tritium breeding blankets
- No 14 MeV neutrons
- No structural materials problem
- Requires $\tau_p/\tau_E < 1$
- Requires 35 keV
- Requires 10 fold confinement improvement
- Requires stronger, higher-field superconducting magnets

(N, $P\delta V^\gamma$) ~ constant implies peaked density and pressure profiles (**if γ > 1**)



Adiabatic mixing implies core parameters determined by edge & compressibility:

$$\tau_e/\tau_p \sim (4\gamma-3)C_v^{\gamma-1} > 50$$

Turbulent Pinch in a Levitated Dipole may Make Possible Tritium Suppressed Fusion

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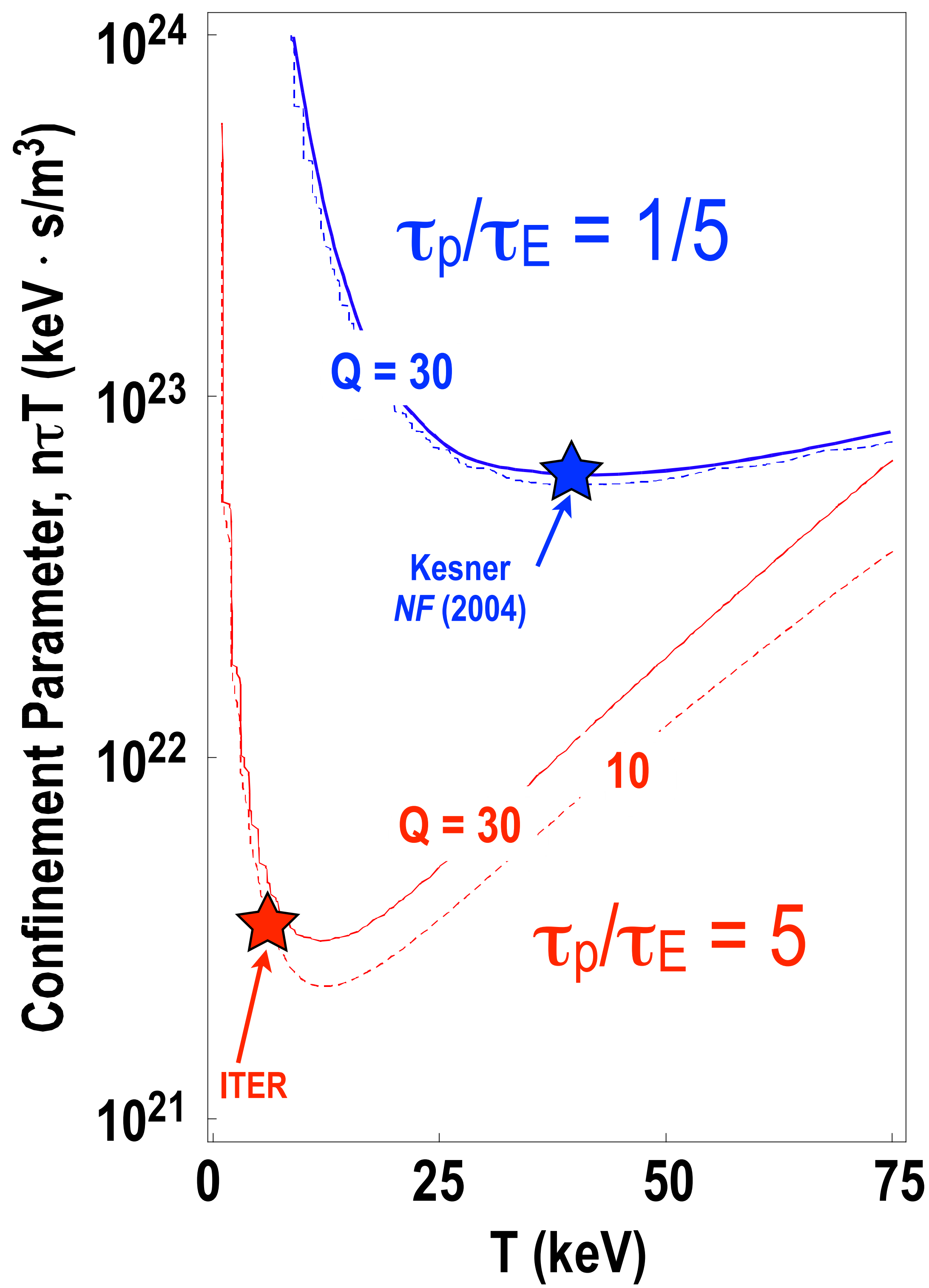
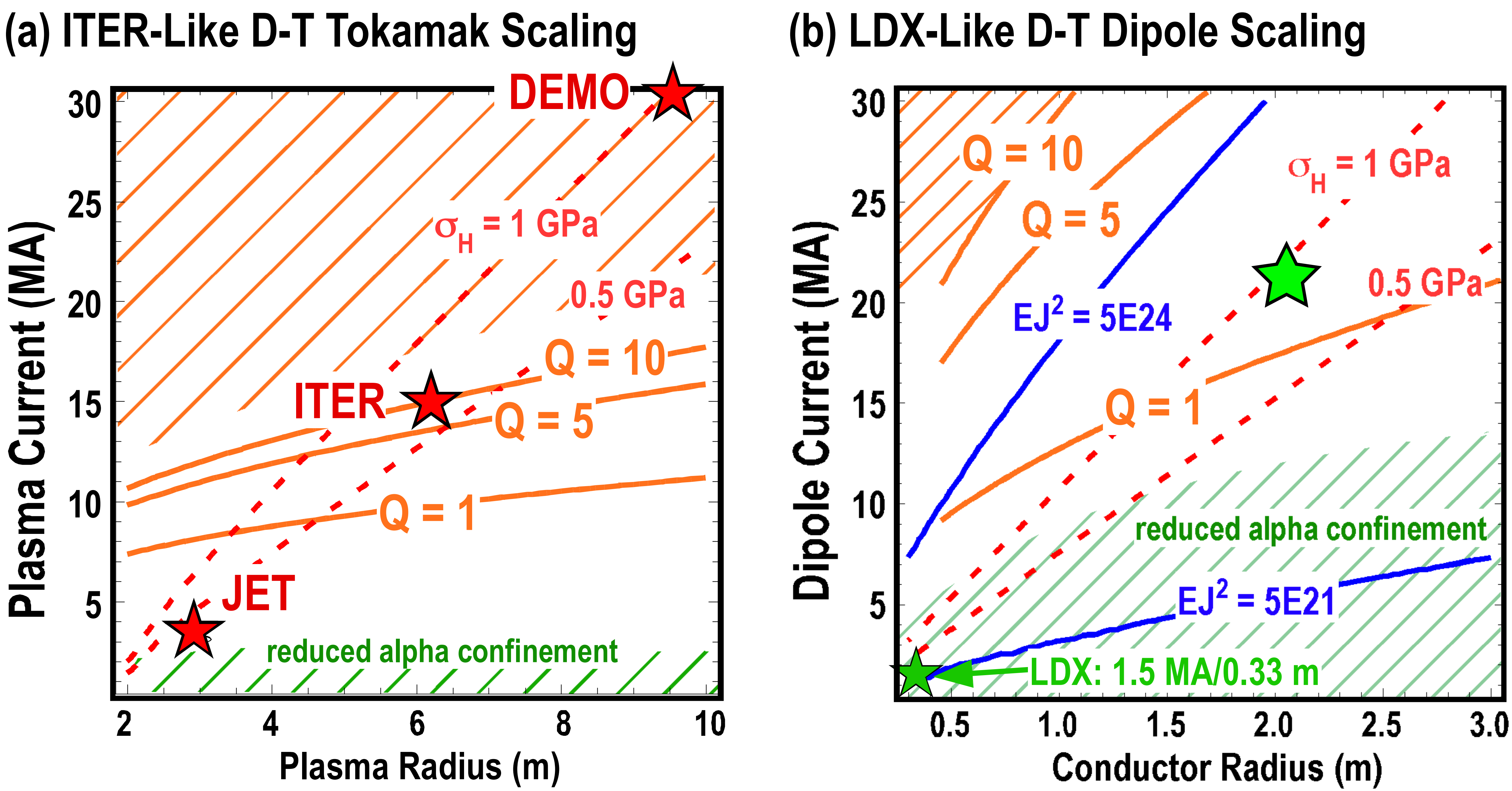


Dipole Proof of Performance Scaled from LDX to fit in NASA's SPF



Fusion Gain - Magnet Stress - Quench Safety Parameter - Alpha Confinement