– 1 –
Turbulent Pinch & Laboratory Magnetospheres

– 2 –
“Economic Viability” is the 2nd Frontier of Fusion Research

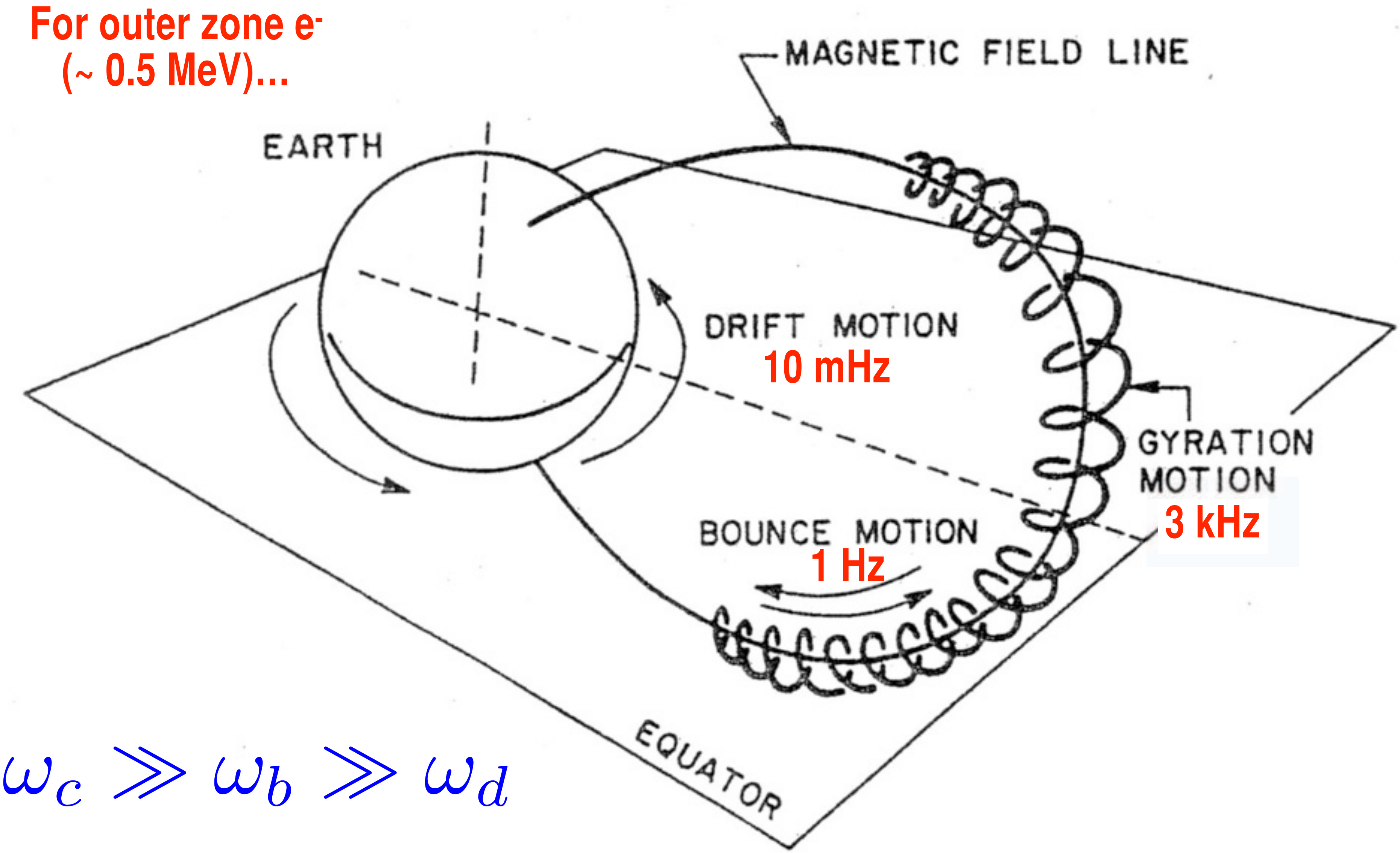
Mike Mauel
Columbia University
PPPL Theory Talk May 9, 2013

Turbulent Pinch

- Among the **most remarkable** phenomena of strongly magnetized plasma
- **Self-organization**: turbulent diffusion that is *counter to gradients* and creates highly peaked profiles
- First seen in **magnetospheres** (relatively *simple* to understand)
- Now, seen “*everywhere*” in high-temperature magnetically-confined plasma: like tokamaks & stellarators (relatively *difficult* to understand), gryokinetic codes, …
- Particles, momentum, heat (!)
- ***We do not yet understand*** self-consistent, non-local, off-diagonal turbulent transport flux in magnetized plasma

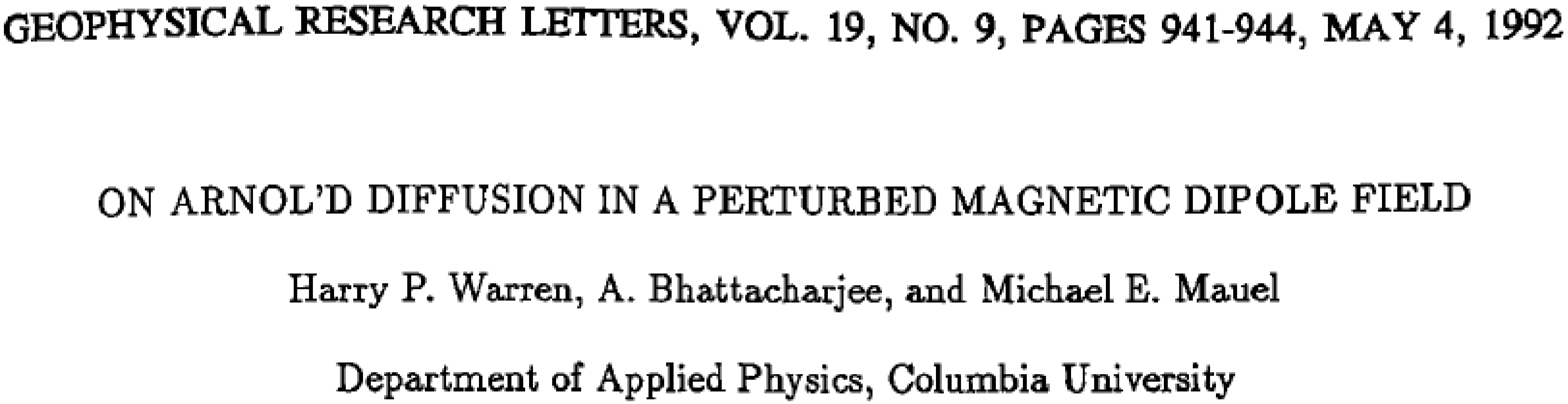
The First "Pinch":

Adiabatic Response of Trapped Radiation to Low-Frequency Fluctuations



$$\omega_c \gg \omega_b \gg \omega_d$$

An Important Paper …



GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 9, PAGES 941-944, MAY 4, 1992

ON ARNOL'D DIFFUSION IN A PERTURBED MAGNETIC DIPOLE FIELD

Harry P. Warren, A. Bhattacharjee, and Michael E. Mauel

Department of Applied Physics, Columbia University

Chaotic Transport Maintains Adiabaticity

Adiabatic $\longrightarrow (\dot{\mu},\ \dot{J}) \approx 0$

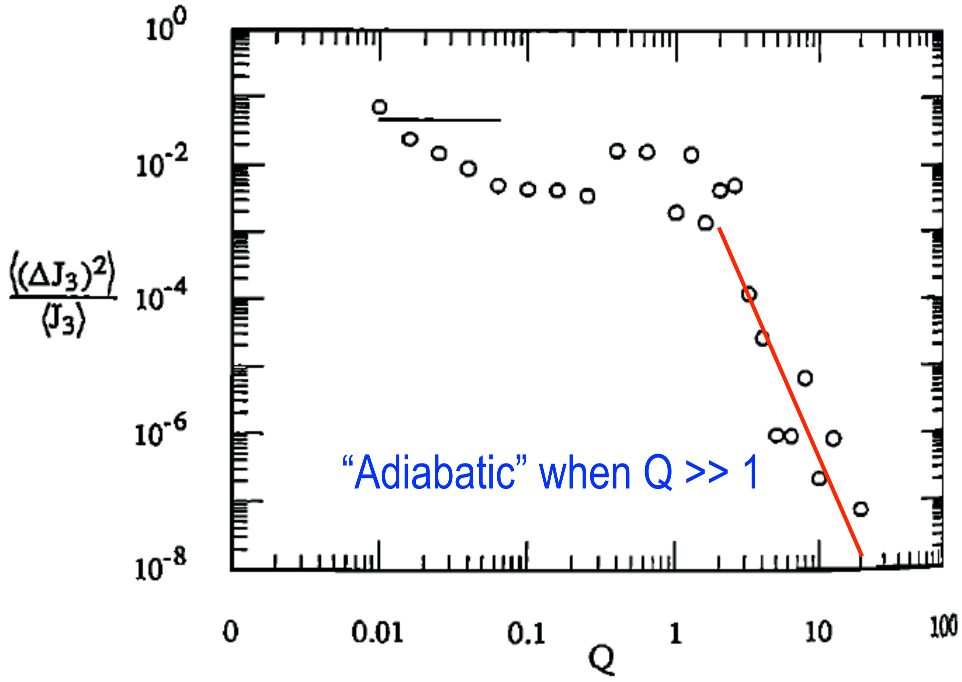


Fig. 2. Thick-Layer Arnol'd diffusion as a function of Q for $\epsilon = 0.01$ and $\eta = 1.1$. Each dot represents the value of $\langle(\Delta J_3)^2\rangle/\langle J_3\rangle$ at $t = 35,000$. The solid line represents the predictions of the stochastic pump model. Note the attenuation of diffusion at large values of Q.

Chaotic Radial Motion Due to Drift-Resonance

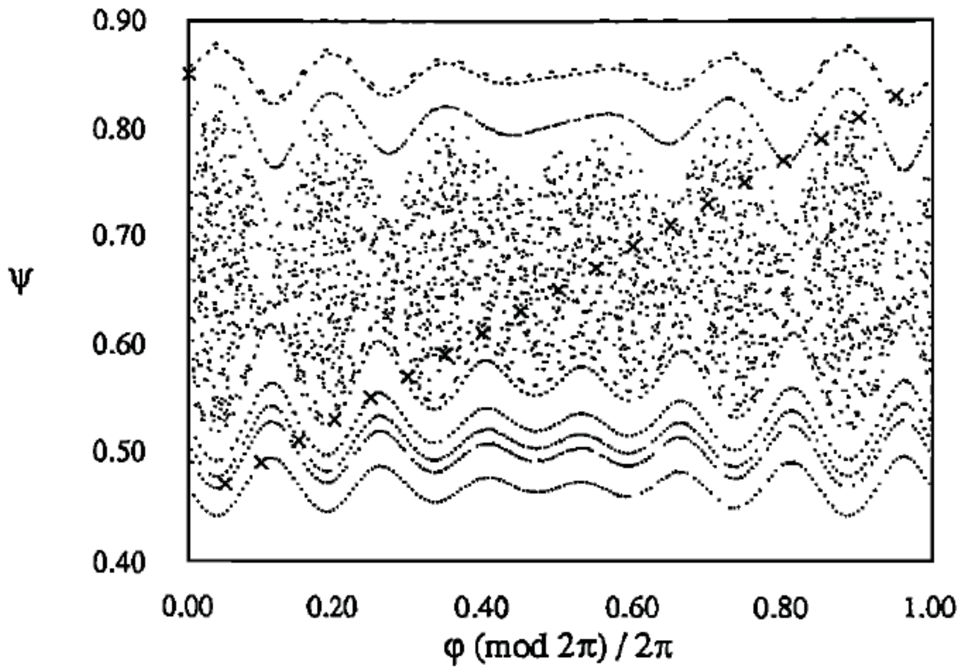


Fig. 3. Poincaré surface of section for energetic protons interacting with two waves. The integers $m_1 = 7$, $l_1 = 3$, $m_2 = 6$, and $l_2 = 3$ are chosen so that the primary resonances of the waves overlap.

$$Q \equiv \omega_b/\omega_d$$

$$\omega - m\omega_d(\mu, J) \approx 0$$

Low-Frequency Dynamics is **One-Dimensional**

(1D, $k_\perp \rho \ll 1$, Gyro/Bounce/Kinetics, with (μ, J) constant)

$$\mathcal{H} = \frac{m_e c}{2e}\rho_{\|}^2 B_0^2 + \mu\frac{c}{e}(B_0 + \delta B) - c\delta\Phi$$

$$B_0 \gg \delta B\,,\ \delta\mathbf{B} = \nabla\times\delta\mathbf{A}\,,\ \text{and}\ \delta\mathbf{E} = -\nabla\delta\Phi - \frac{1}{c}\frac{\partial\delta\mathbf{A}}{\partial t}$$

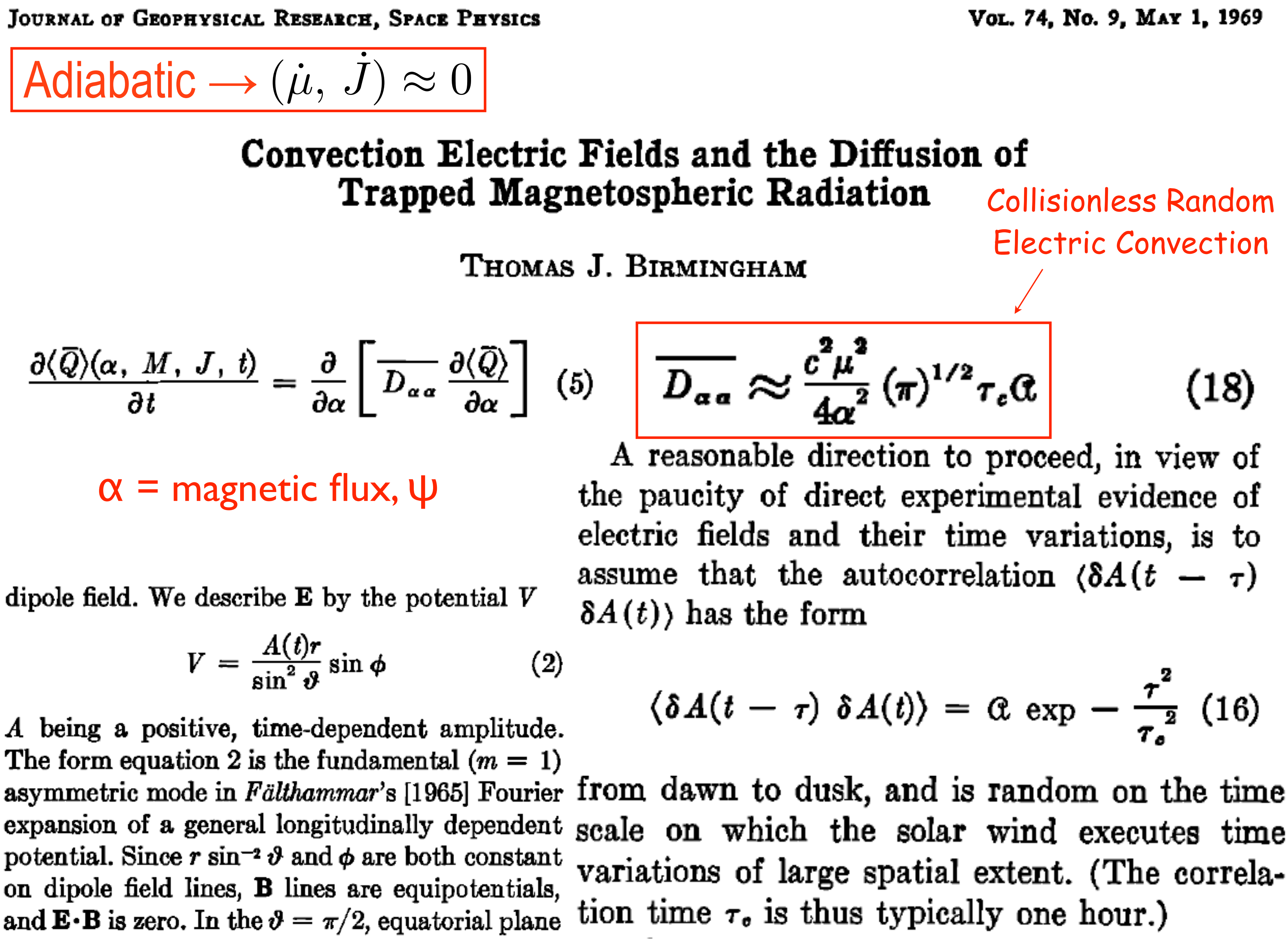
Adiabatic

$$\left\{\begin{array}{lcl}\dot{\mu} & = & 0\ (\omega \ll \omega_c)\\ \dot{J} & = & 0\ (\omega \ll \omega_b)\end{array}\right.$$

2D Phase Space

$$\left\{\begin{array}{lcl}\dot{\psi} & = & -\dfrac{\partial\mathcal{H}}{\partial\phi} = -c\dfrac{\partial\delta\Phi}{\partial\phi} + L\dfrac{\partial\delta A_\phi}{\partial t}\ (\propto \delta\mathbf{E}\times\mathbf{B})\\ \dot{\phi} & \approx & \mu\dfrac{c}{e}\dfrac{\partial B}{\partial\psi} - c\dfrac{\partial\delta\Phi}{\partial\psi} \approx \dfrac{3\mu}{eM^2}\psi^2 = \omega_d(\mu,\psi)\end{array}\right.$$

A. Chan, L. Chen, R. White, *GRL* (1989)
R. White and M. Chance, *Phys Fluids* (1984).



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

$$\boxed{\text{Adiabatic} \longrightarrow (\dot{\mu},\ \dot{J}) \approx 0}$$

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 ϕ 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

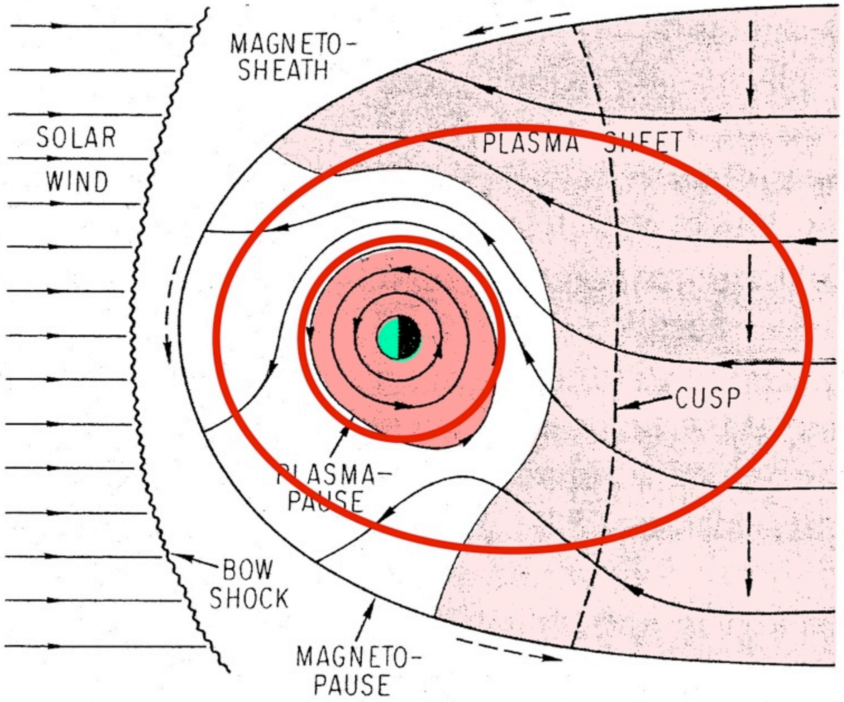
$$\boxed{\overline{D_{\alpha\alpha}} \approx \frac{c^2\mu^2}{4\alpha^2}(\pi)^{1/2}\tau_c\mathcal{A}} \quad (18)$$

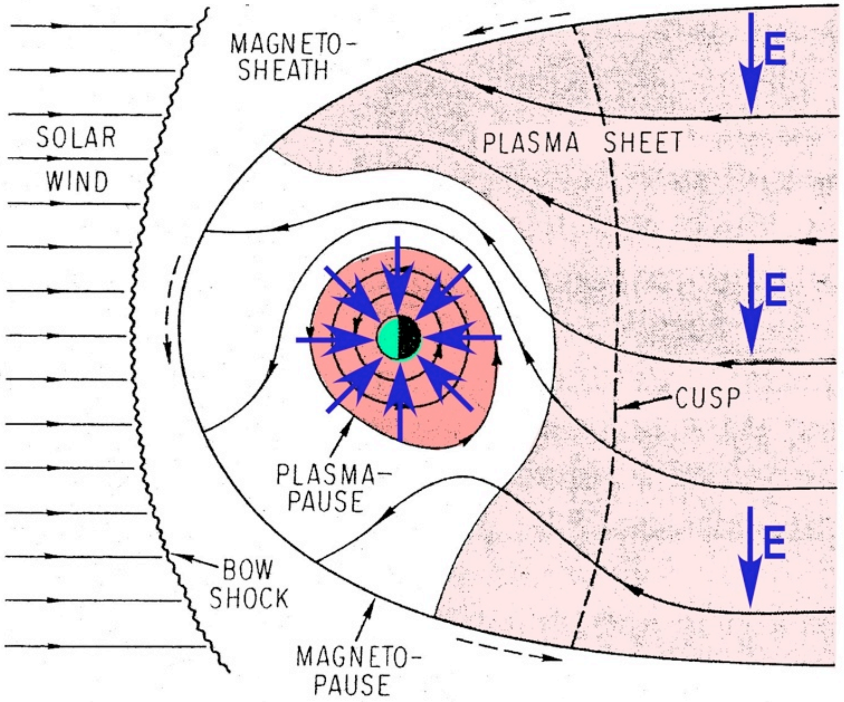
A reasonable direction to proceed, in view of the paucity of direct experimental evidence of electric fields and their time variations, is to assume that the autocorrelation $\langle\delta A(t-\tau)\,\delta A(t)\rangle$ has the form

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

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 τ_c is thus typically one hour.)

Measured Non-axisymmetric Perturbations of Geomagnetic Cavity Determine $D_{\psi\psi}$





$$\delta A_\phi \sim \overbrace{\frac{L}{4}\left(\frac{R_e}{R_m}\right)^3}^{\text{Axisymmetric}} - \underbrace{\frac{4}{30}\frac{L^2}{R_e}\left(\frac{R_e}{R_m}\right)^4 \cos\phi}_{m=\pm1} + \dots$$

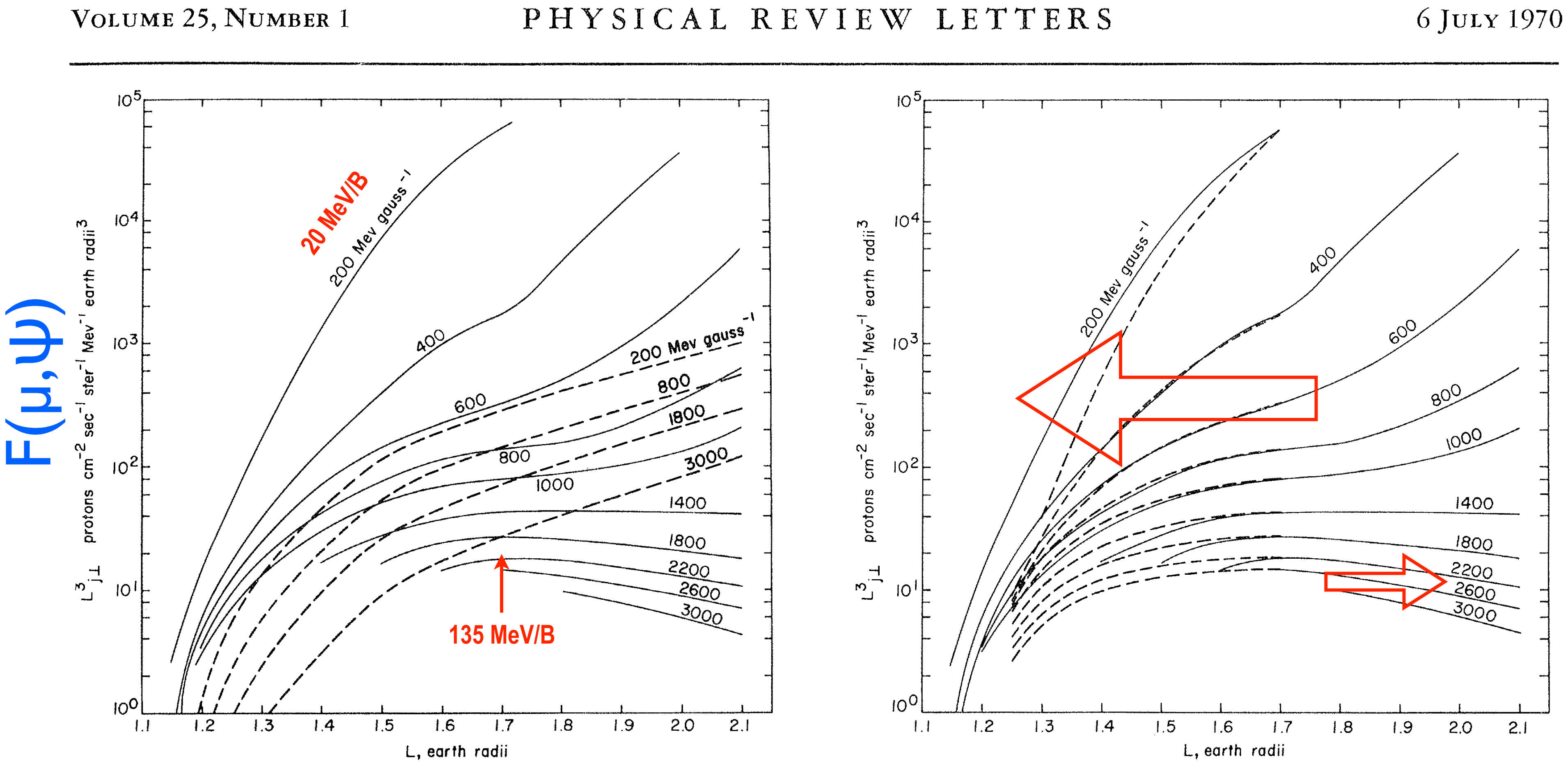
$$\delta\Phi \sim -\overbrace{E_c\left(\frac{R_e^2}{L}\right)}^{\text{Axisymmetric}} + \underbrace{E_c L \sin\phi}_{m=\pm1} + \dots$$

Nakada and Mead, *JGR* (1965)

T. Birmingham, *JGR* (1969)

First Report of Inward Particle Pinch

(Farley, Tomassian, Walt)

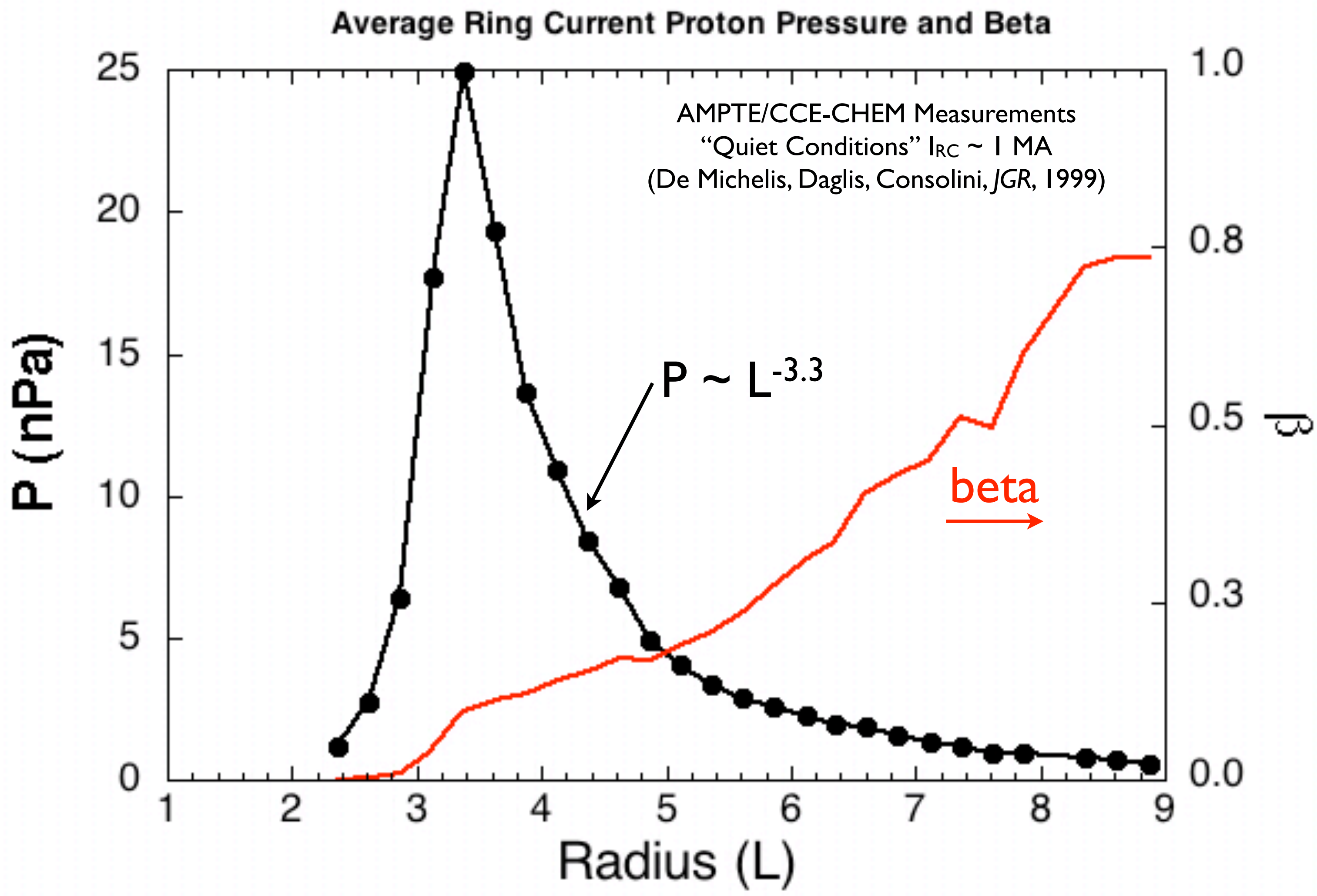

VOLUME 25, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JULY 1970

Cosmic Ray Source & Polar Losses

Driven Pinch with Adiabatic Diffusion

$$\boxed{\text{Adiabatic} \longrightarrow (\dot{\mu},\ \dot{J}) \approx 0}$$

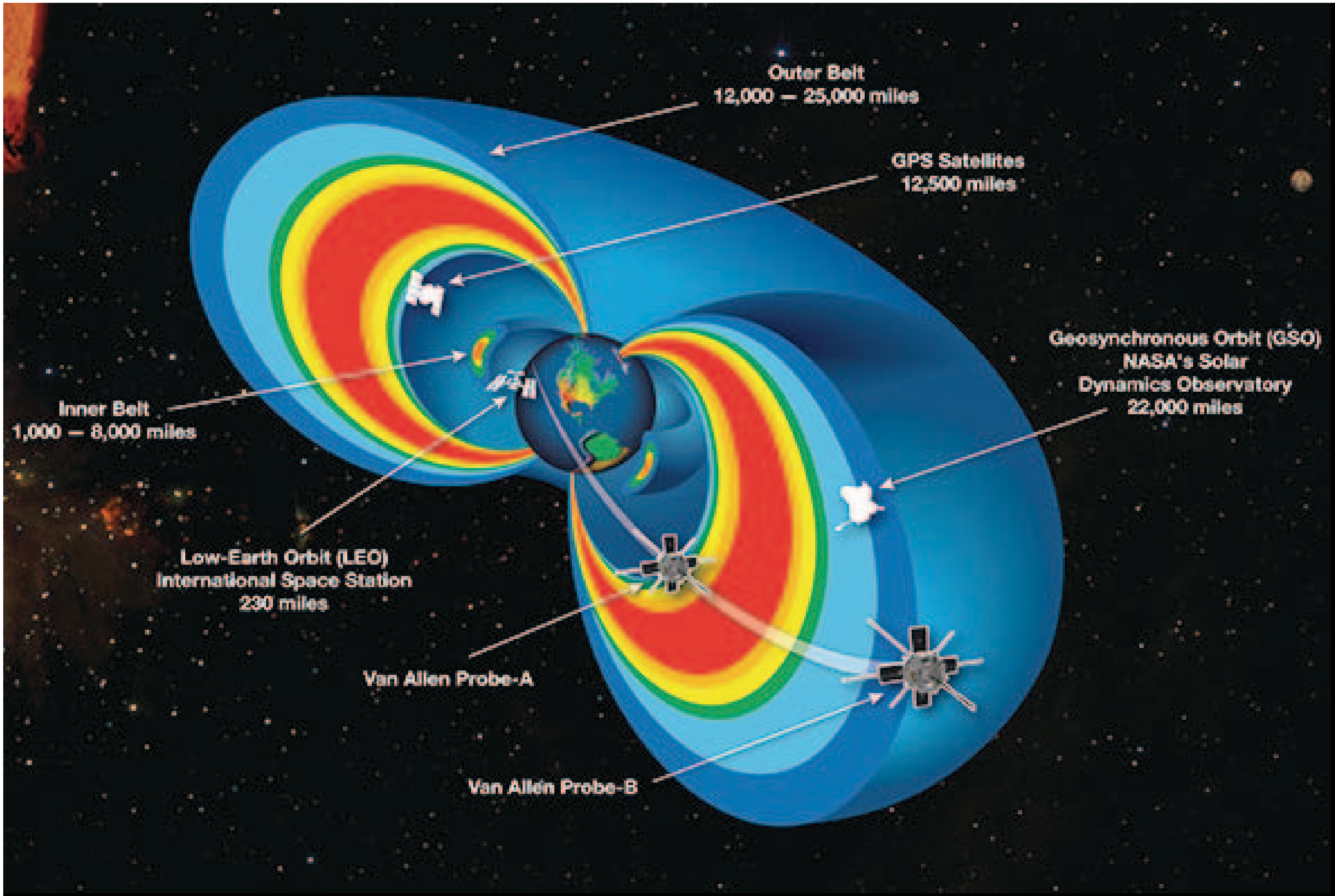
Naturally Peaked Pressure from Outer, Plasma Sheet Source illustrates “Self-Organization”



AMPTE/CCE-CHEM Measurements
“Quiet Conditions” I_{RC} ~ 1 MA
(De Michelis, Daglis, Consolini, *JGR*, 1999)

$P \sim L^{-3.3}$

beta →



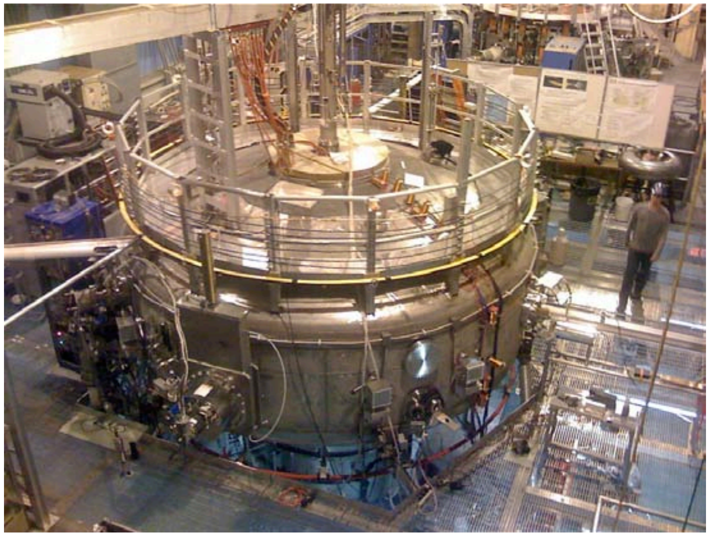
Van Allen Probes

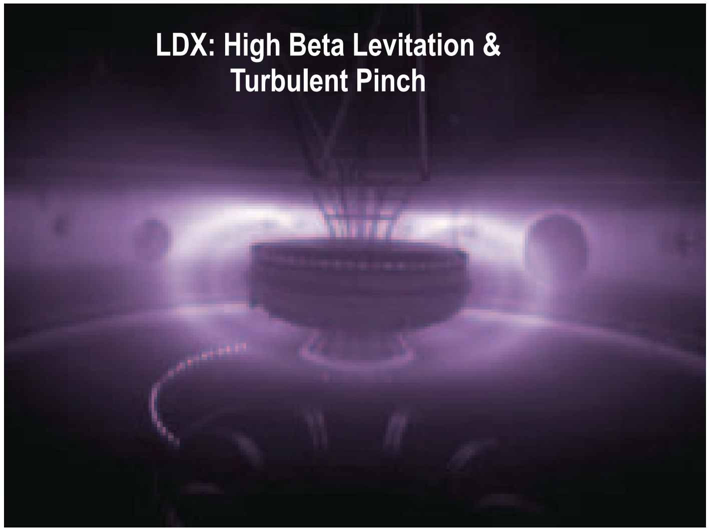
ScienceExpress, Baker, *et al.*, 28 Feb 2013

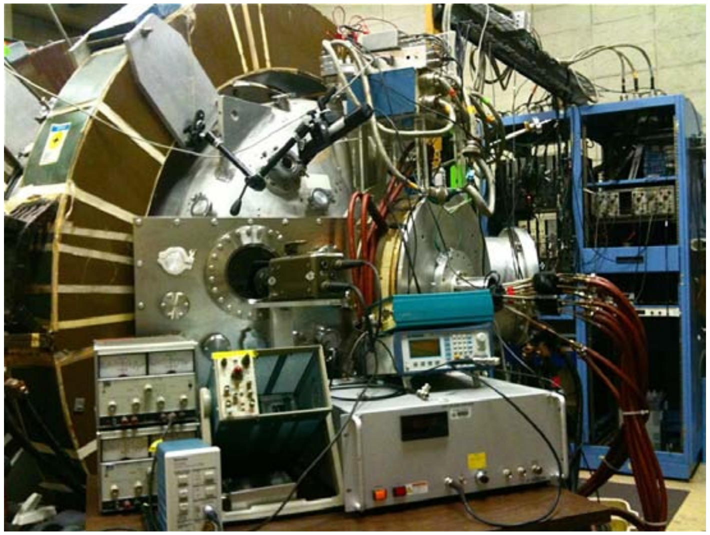
New 3rd Radiation Belt (2 MeV e^-) Discovered

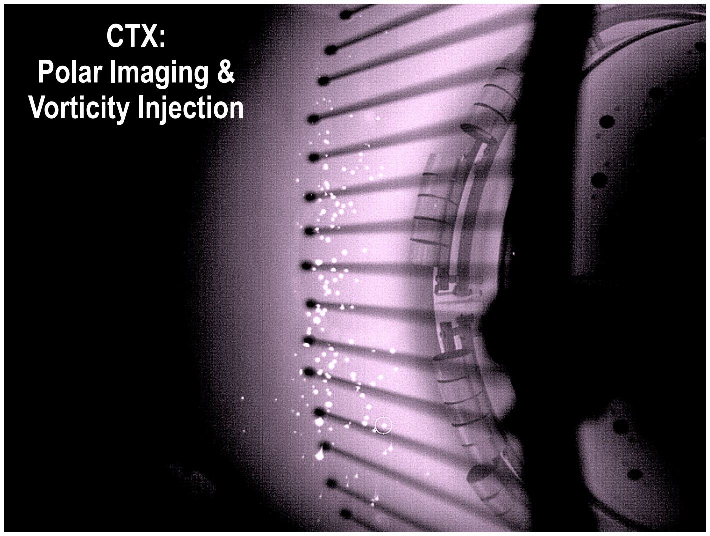
(then annihilated by passage of interplanetary shock)

The Physics of Laboratory Magnetospheres









Levitated Dipole Experiment (LDX)

Collisionless Terrella Experiment (CTX)

What Has Been Discovered…

(Over 15 years of research from four laboratory magnetospheres)

- Low-frequency interchange-like instabilities dominate plasma dynamics
  showing 2D physics, inverse-cascade, etc… in the laboratory magnetosphere

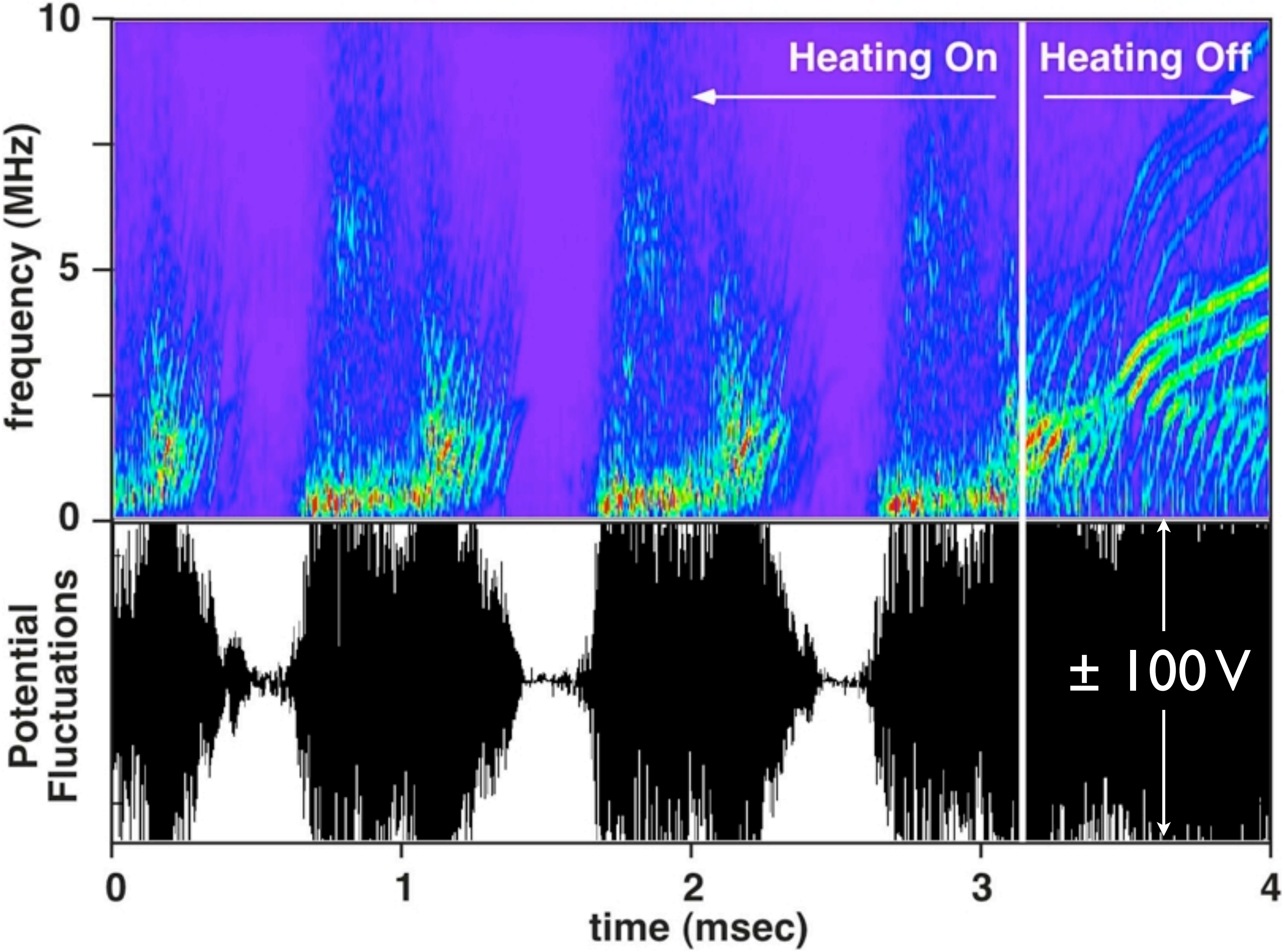
- The structure and dynamics of drift-resonant and MHD turbulence are well reproduced by bounce-averaged gyrokinetic simulations
  producing quantitative predictions of the laboratory magnetosphere

- Levitated dipole can achieve > 50% peak beta with levitation
  showing key connection between laboratory and planetary magnetospheres

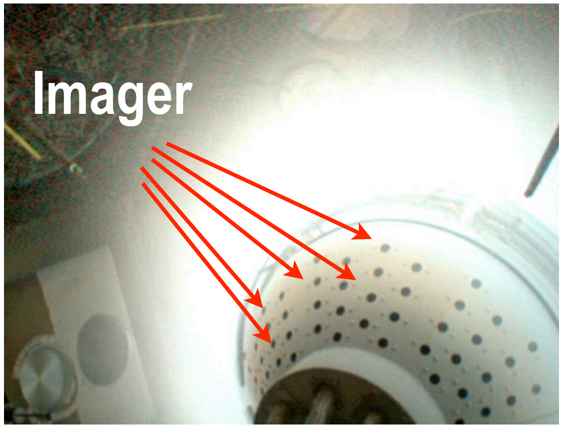
- Turbulence drives plasma to very steep profiles and creates strong inward pinch
  confirming "first principle" transport prediction based on measured fluctuations

- High-beta dipole confinement supports advanced fusion energy concepts
  showing space physics may have applications to fusion science development

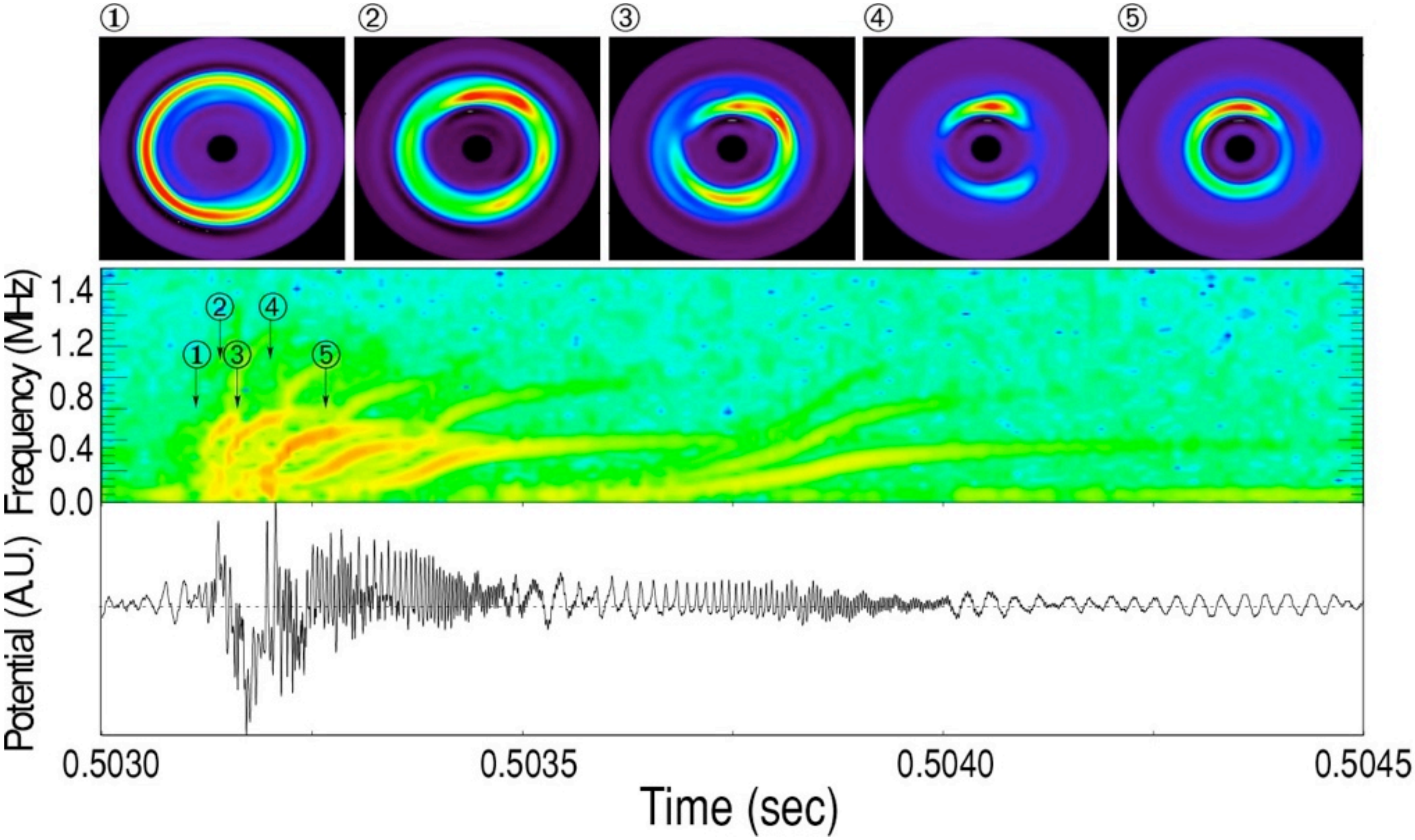
Drift-Resonant (Hot Electron) Interchange Instability



Polar Imager: Direct Measurement of Adiabatic Drift-Resonant Transport due to Energetic Particle Interchange Instability



$$\boxed{\text{Adiabatic} \longrightarrow (\dot{\mu},\ \dot{J}) \approx 0}$$



Turbulent E×B Diffusion from MHD Interchange Fluctuations

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

T. Birmingham, *JGR* (1969)

N = nδV = Flux tube particle number

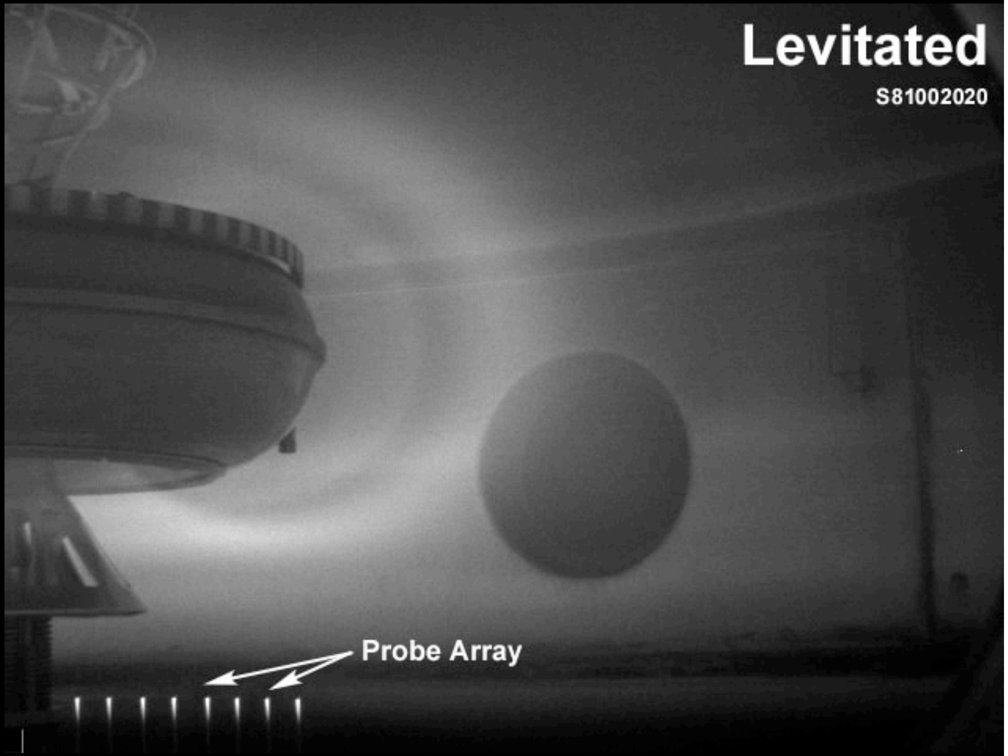
$$\frac{\partial N}{\partial t} = \langle S \rangle + \frac{\partial}{\partial \psi} D \frac{\partial N}{\partial \psi}$$

$P\delta V^\gamma$ ~ Entropy Density

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

QL equations low-frequency turbulence ExB transport:
Single "D" and geometry δV define particle and heat pinch

LDX: The World’s Largest Laboratory Magnetosphere

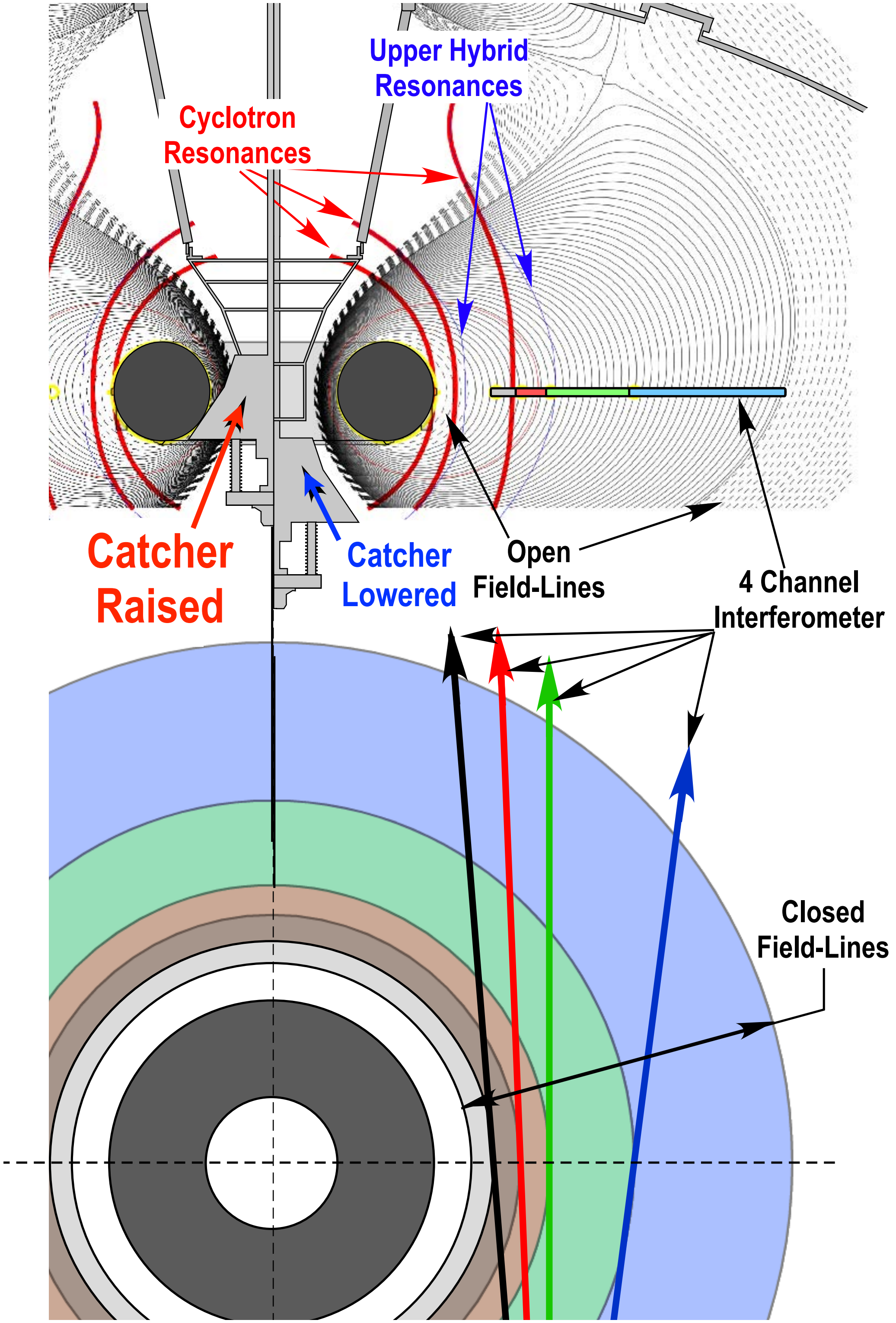


Steady-State, High-β, High-Temperature

Density Profile with/ without Levitation

- *Procedure*:
  - Adjust levitation coil to produce equivalent magnetic geometry
  - Investigate multiple-frequency ECRH heating
- *Observe*: Evolution of density profile with 4 channel interferometer
- *Compare*: Density profile evolution with supported and levitated dipole

Alex Boxer, MIT PhD, (2008)
Nature-Physics (2010)



Turbulence drives plasma to very steep profiles and creates strong inward particle pinch in dipole geometry

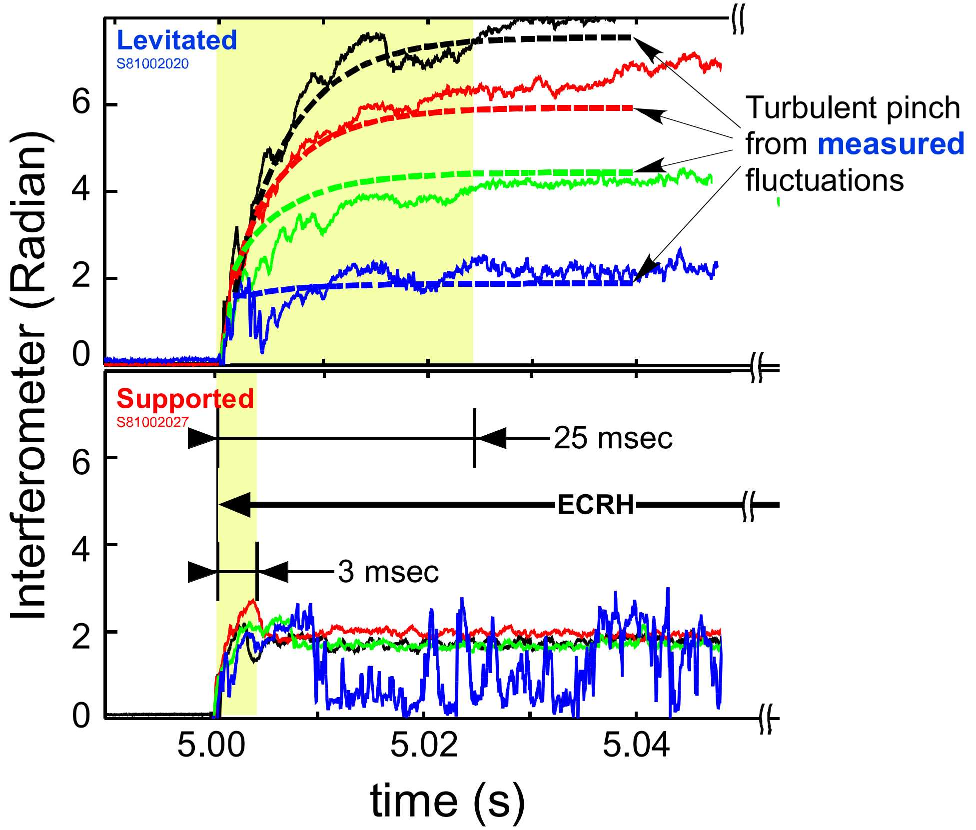
- **Dipole: δV ~ *R*^{4}**, creates strongly peaked profiles and **ideal conditions** for study of turbulent pinch effects: **particles, impurities, momentum, energy**

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

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

D measured from edge fluctuations

Line Density Shows Strong Pinch Only with a Levitated Dipole



Turbulent pinch from **measured** fluctuations

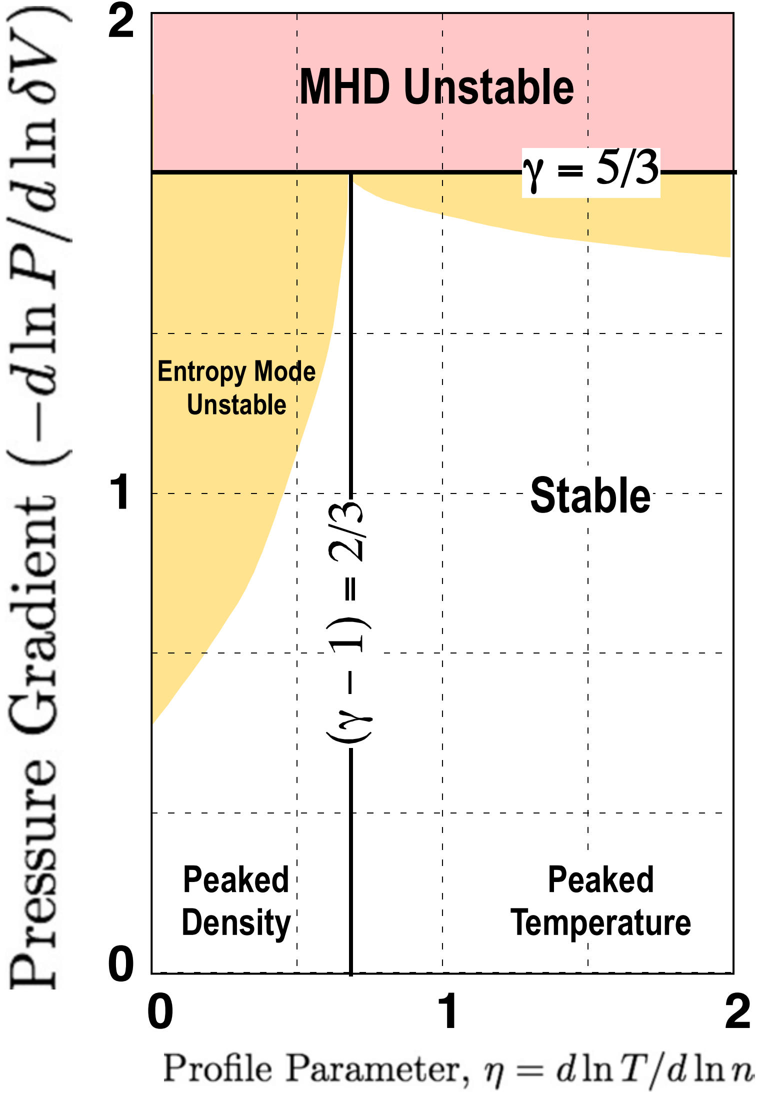
Boxer, *Nature-Physics* (2010)

Low frequency fluctuations dominate plasma dynamics: interchange & entropy modes

- MHD interchange modes set pressure and density gradient limits in dipole-plasma (*not ballooning*)
- Entropy mode (Kesner, Hastie, *POP*, 2002) **changed our thinking**: not just pressure and density gradients, but also η = d(ln*T*)/d(ln*n*)
- Entropy modes generate zonal flows and **nonlinearly self-regulate transport levels** (Ricci, Rogers, Dorland, *PRL*, 2006)
- **Fluctuations disappear** with flat density profiles (Garnier, *JPP*, 2008; and Kobayashi, Rogers, Dorland, *PRL*, 2009)
- Measurements show fluctuations throughout plasma (*Nature-Physics*, 2010); inverse energy cascade (*POP*, 2009); intermittency (*PRL*, 2010)

$k_\perp \gg k_{||}$

Profile "Shape"(*i.e.* gradient) Sets Stability Limits



Turbulence drives plasma to very steep profiles and creates *either* particle *or* heat pinch in dipole geometry

Gyrokinetic (GS2) simulations show turbulence drives particles or heat to maintain uniform entropy density:

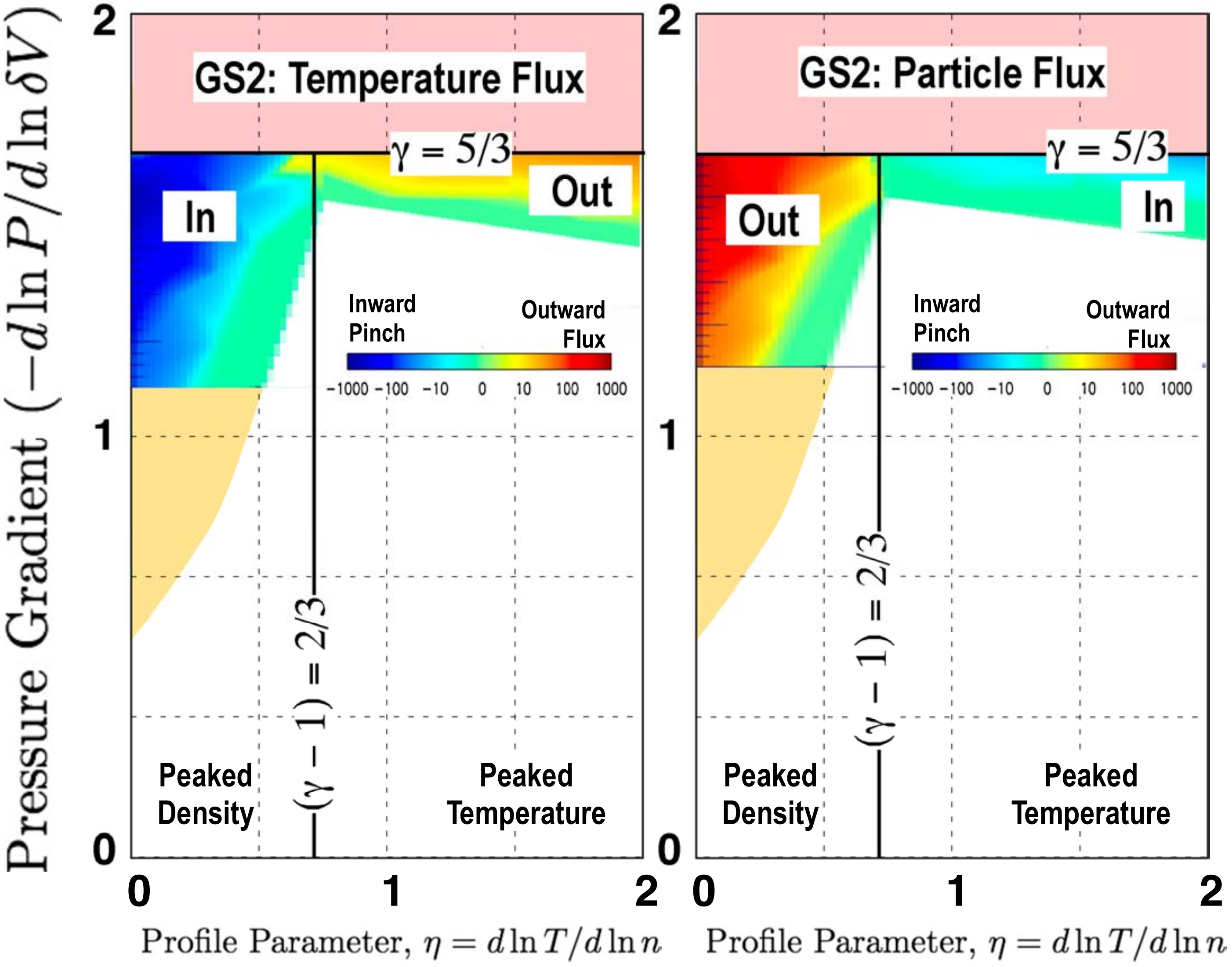
Kobayashi, Rogers, Dorland, *PRL* (2010)

(1) Turbulent self-organization
(2) Independent (n,T) flux

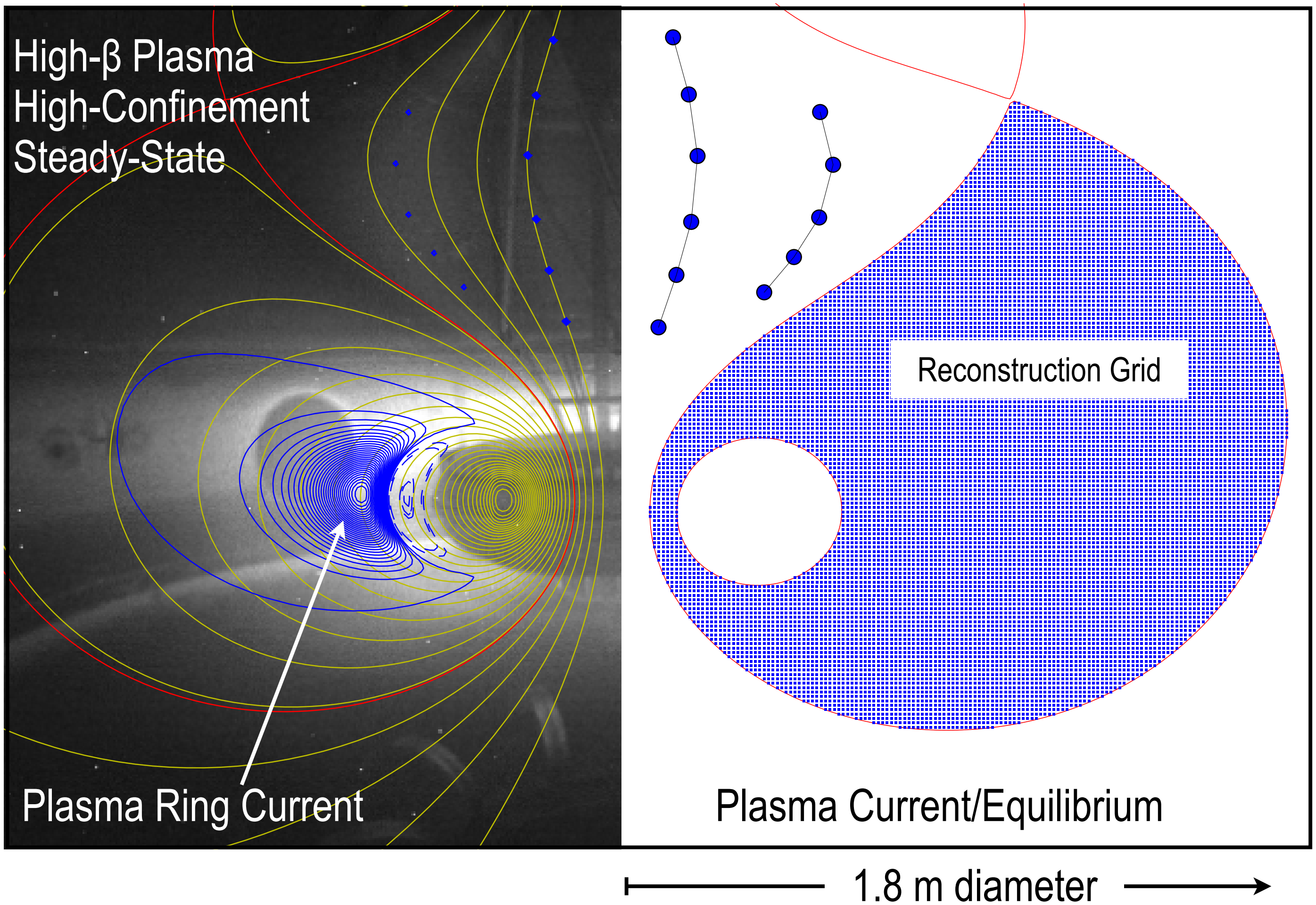
$$\eta = \frac{d\ln T}{d\ln n} \to \frac{2}{3}$$

$$-\frac{d\ln n}{d\ln \delta V} \to 1$$

$$-\frac{d\ln P}{d\ln \delta V} \to \frac{5}{3}$$

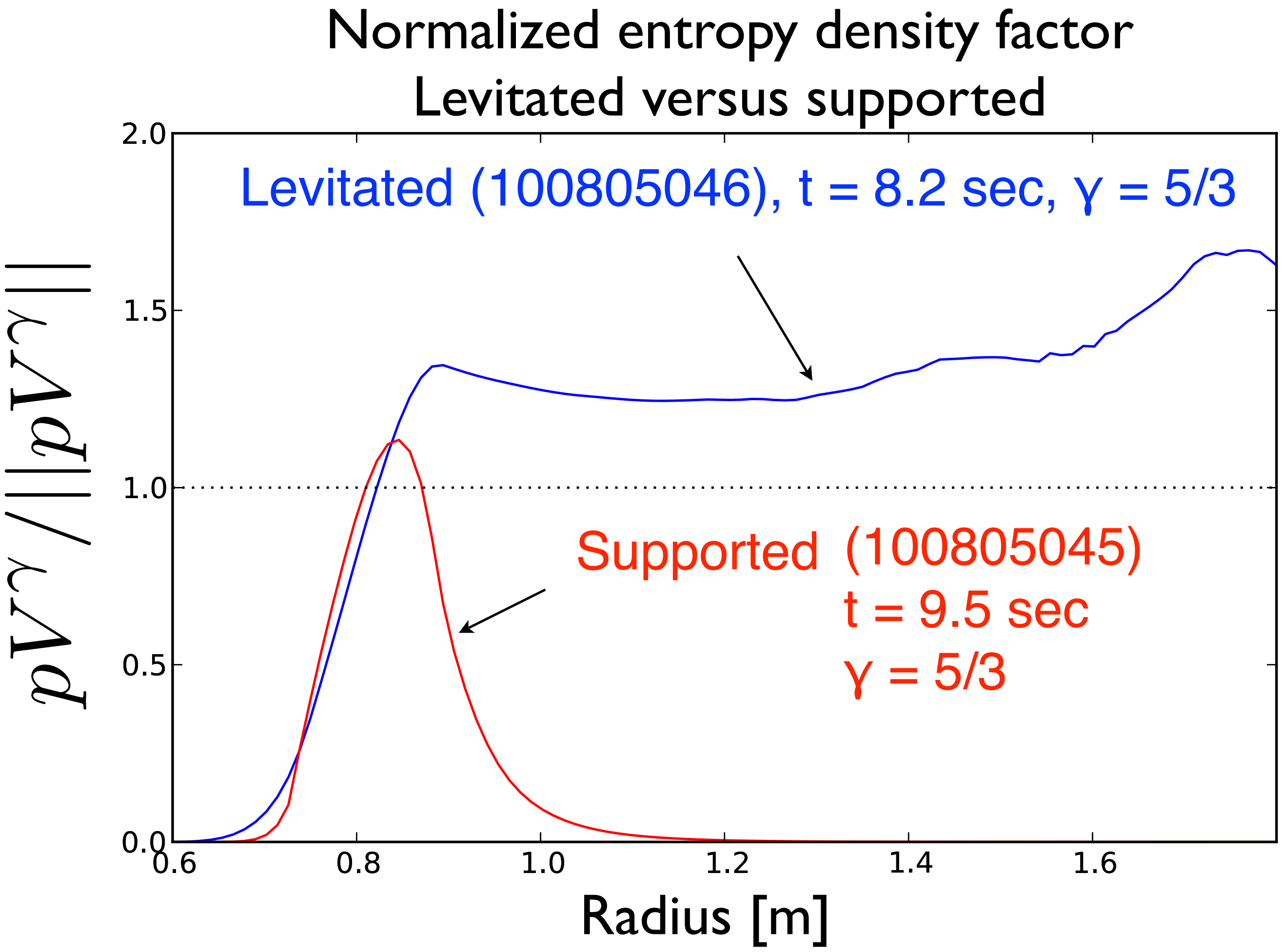


Accurate Pressure Profile Reconstruction Show Expected "Invariant" Pressure Profile



Last week:
Matt Davis, *Measurements the electron pressure profile in the Levitated Dipole Experiment (LDX)*, Columbia Dissertation, 2013

Accurate Pressure Profile Reconstruction Show Expected “Invariant” Pressure Profile



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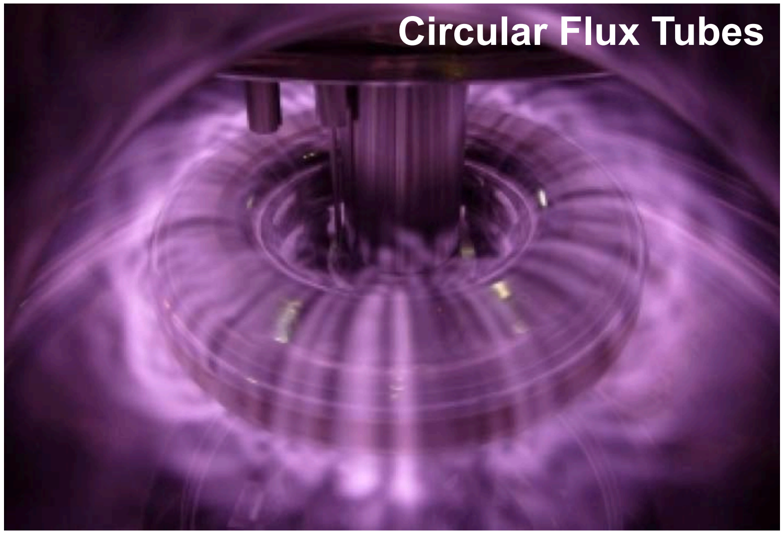
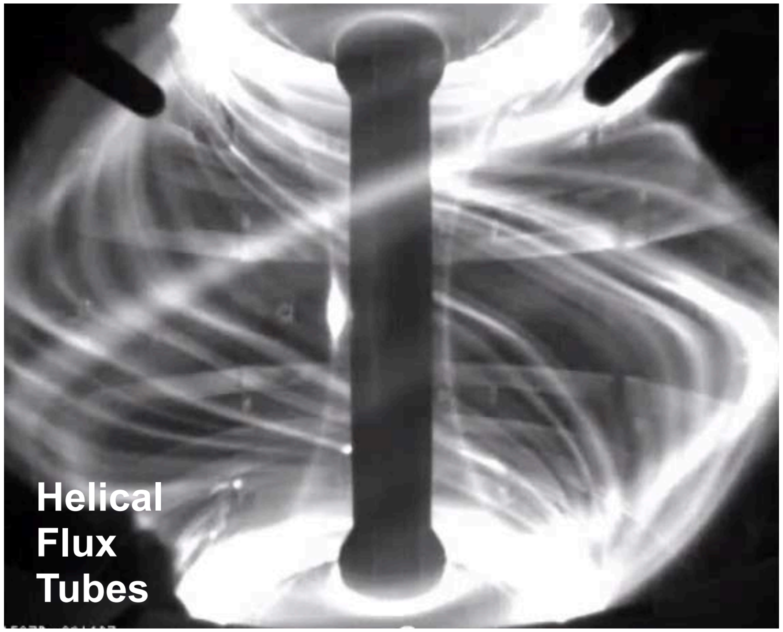
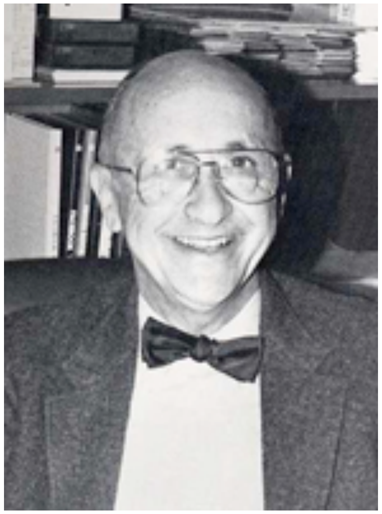
Dipole is Toroidal Confinement without Toroidal Field

- **Dipole…**
  - Interchange (***not ballooning***) 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-frequency turbulence
  - Flux tube volume increases rapidly with radius, **$\delta V \sim 1/L^4$**, allowing steep profiles
- **Tokamak…**
  - Ballooning and kinks set pressure limit with $\beta \sim \varepsilon/q \approx 5\%$ (shear stabilizes interchange)
  - Short radial scale of fluctuations, drift waves
  - Passing and trapped particles different
  - Flux tube volume nearly constant with radius, **$\delta V \sim q$**, mixing creates flat profiles







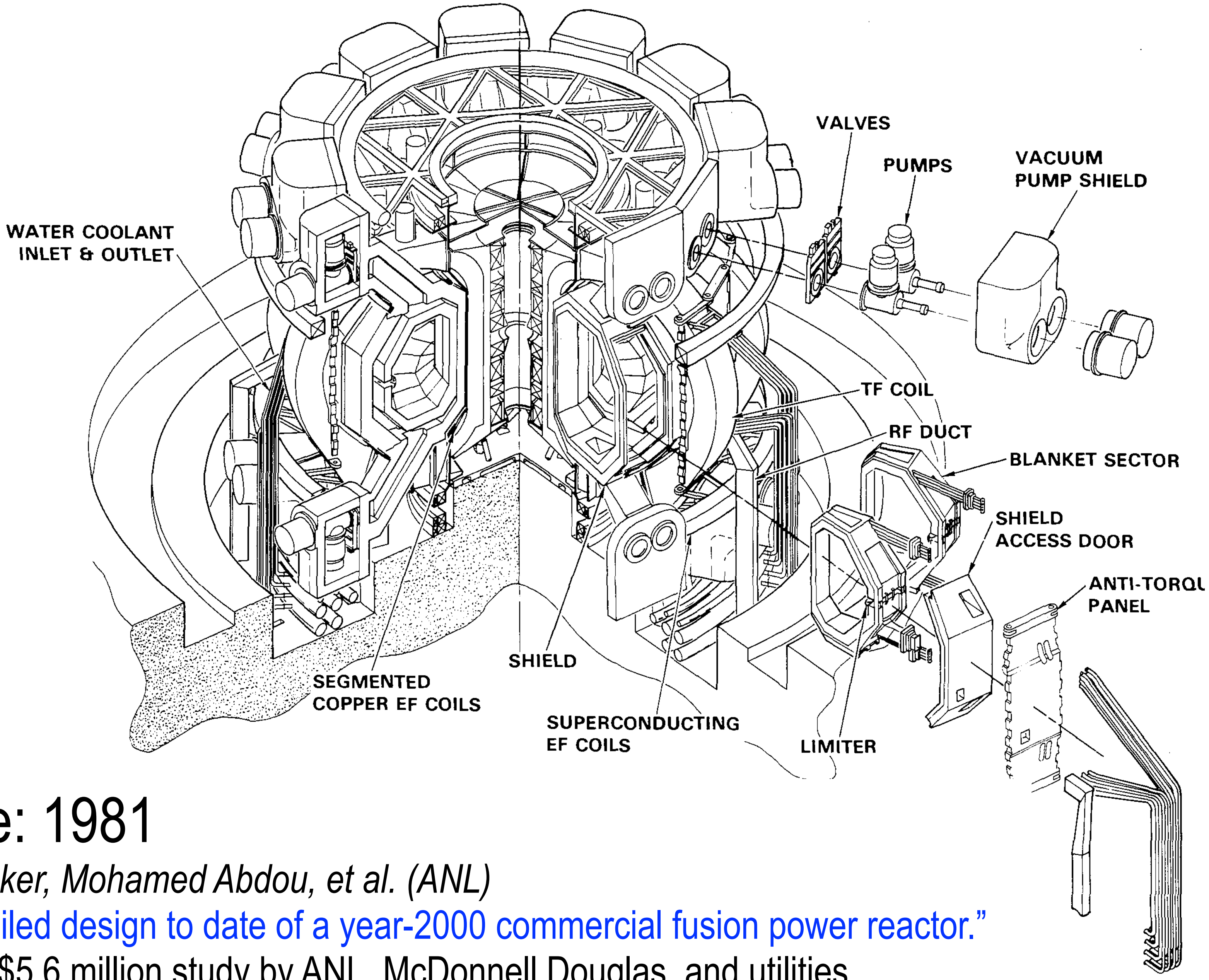
Robert Gross
Columbia
Fusion Energy
(1984)

"Fusion has proved to be a very difficult challenge.

The early question was—Can fusion be done, and, if so how? …

Now, the challenge lies in whether fusion can be done in a reliable, an economical, and socially acceptable way…"

Starfire Represented Optimism of early 1980’s

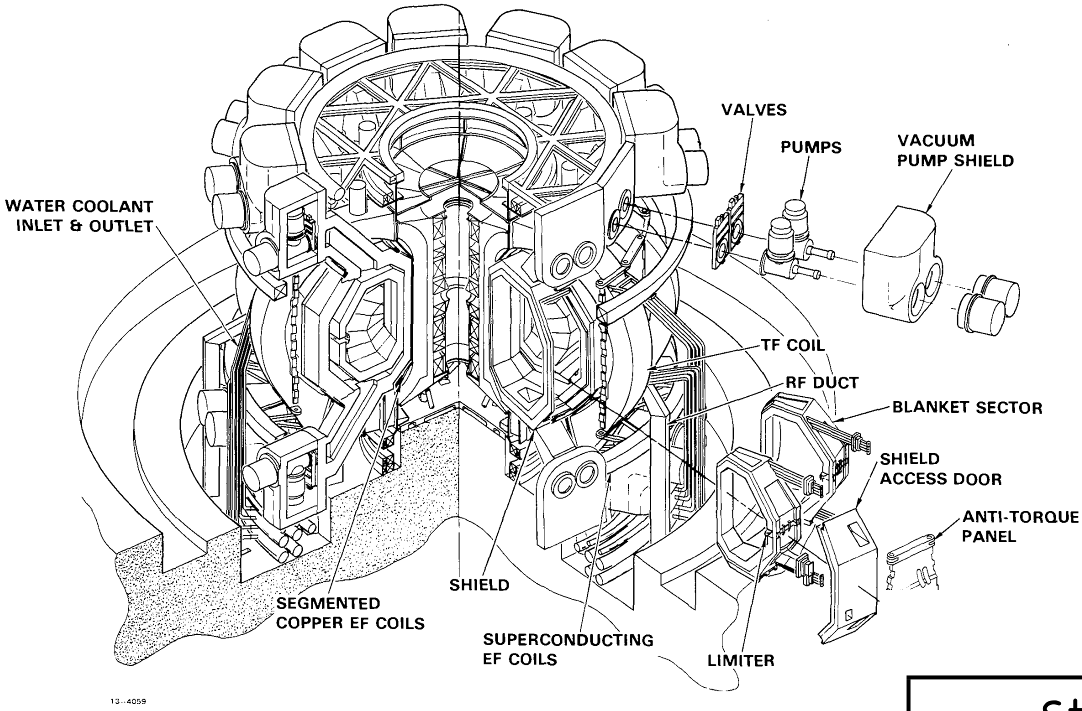


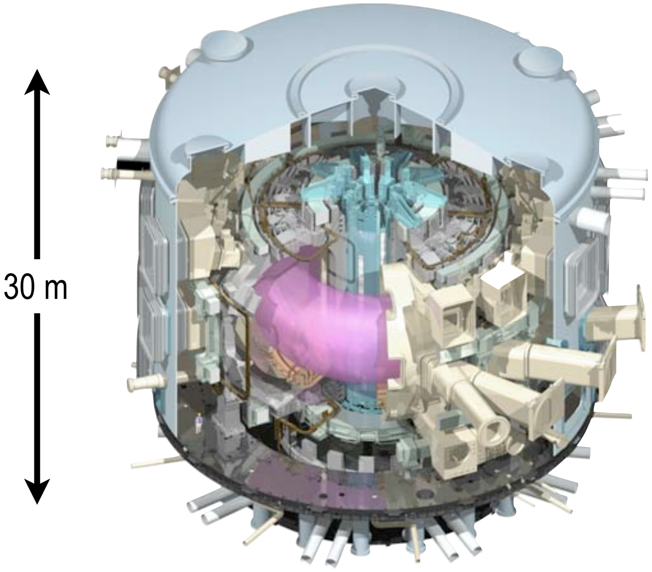
Starfire: 1981

Charlie Baker, Mohamed Abdou, et al. (ANL)

“Most detailed design to date of a year-2000 commercial fusion power reactor.”

Two-year, $5.6 million study by ANL, McDonnell Douglas, and utilities





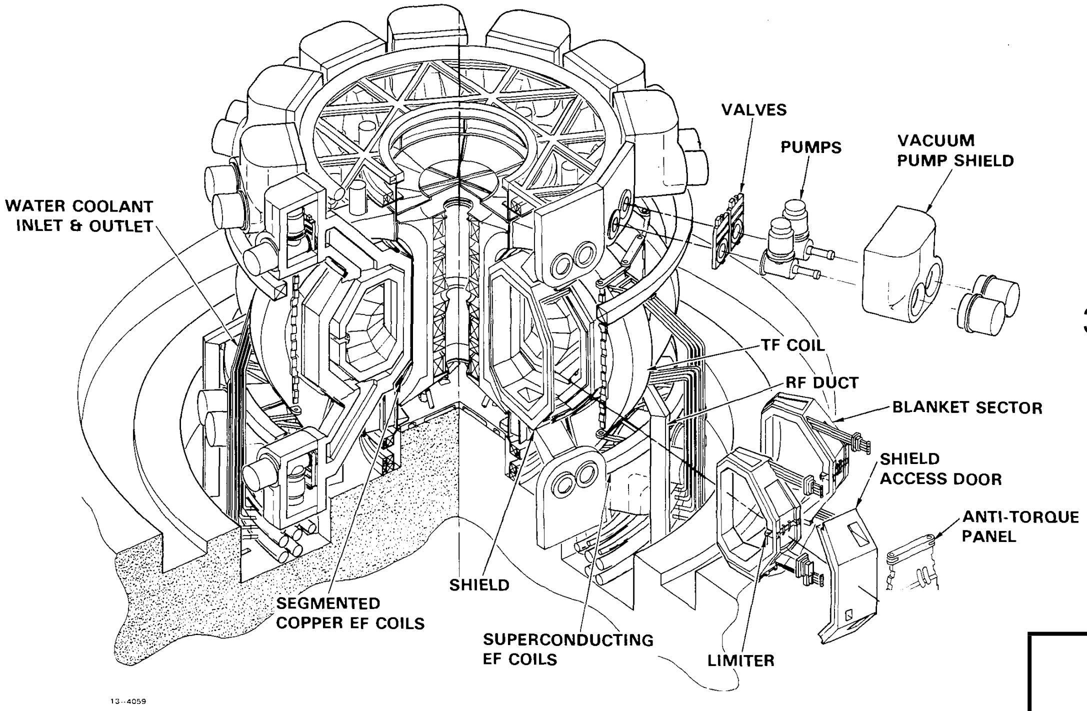
	Starfire (1981)	ITER (2027)
R, a (m)	7.0, 1.9	6.2, 2.0
I_p (MA)	10.1	15.0
B (T)	5.8	5.3
Duration	continuous	6000 x 7 min
P_{fusion} (MW)	3510	410
P_e (MW)	1200	−250
W_{mag} (GJ)	55	51
Tokamak (tonne)	24,000	23,000
Cost (\$M)	6,800	> 27,000

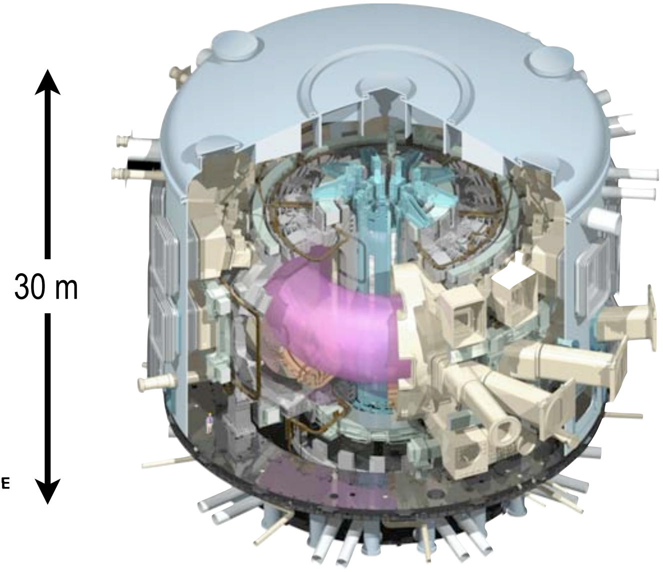
Starfire = $\$5.7/W_e$

ITER ≥ 34 × Starfire

1984: A great year for tokamak physics and
Turning-point for understanding tokamak limits

- P. H. Rebut, “Status and Programme of JET,” *Plasma Phys Contr F,* **26**, 1 (1984).
- R.J. Goldston, “Energy confinement scaling in tokamaks: some implications of recent experiments with ohmic and strong auxiliary heating,” *Plasma Phys Contr F,* **26**, 87 (1984).
- F. Troyon, *et al.*, “MHD Limits to Plasma Confinement,” *Plasma Phys Contr F,* **26**, 209 (1984).
- B. Kadomtsev, “Behavior of disruptions in tokamaks,” *Plasma Phys Contr F*, **26**, 217 (1984).
- M. Greenwald, *et al.*, “Energy Confinement of High-Density Pellet-Fueled Plasmas in the Alcator C Tokamak,” *Phys Rev Lett*, **53**, 352 (1984).
- F. Wagner, *et al.*, “Development of an edge transport barrier at the H-mode transition of ASDEX,” *Phys Rev Lett*, **53**, 1453 (1984). (and Wagner, *et al., PRL*, **49**, 1408 (1982).)





Today's 1st frontier for fusion…

"to demonstrate the scientific and technological **feasibility** of fusion energy for peaceful purposes"

should not supersede Gross's 1984 challenge…

"the challenge is whether fusion can be done in a reliable, an economical, and socially acceptable way"

	Starfire (1981)	ITER (2027)
β (%), β_N	6.7, 7.3	2.5, 1.8
τ_E (s), H	3.6, 5.5	3.7, 1.0
n (10^{20}m^{-3}), nG	1.0, 1.1	1.0, 0.85
T (keV)	24	9.0
λsol (mm)	100	~ 1
Max Flux (MW/m^2)	4	> 20
Neutrons (MW/m^2)	3.6	0.6
Material	Low-Activation SS	B-doped 316L

ITER and advances in Alternate Energy Technology have made the issue of fusion's cost unavoidable

- EIA (April 2013) Utility-scale Cost and Generation:

	Capital Cost	1984	2013
Fission:	\$5.5/W_e	37 GWy (96 units)	88 GWy (104 units)
Solar PV:	\$3.9/W_e	0	2.5 GWy
Solar Thermal:	\$5.1/W_e		
Onshore Wind:	\$2.2/W_e	0	16 GWy
Offshore Wind:	\$6.2/W_e		

- Fusion research must address "economic viability" and show cost competitiveness
- Holdren (*Science,* 1978): "Fusion, like solar energy, is not one possibility but many… The most attractive forms of fusion may require greater investment of time and money, but they are real reasons for wanting fusion at all."

Carbon capture may be a ways off, but ARPA–E is working on it

Several technologies are aimed at minimizing the cost of removing CO_2 during coal burning. But their deployment will require subsidies or a price on carbon emissions.

The goal of ARPA–E’s $40 million, three-year Innovative Materials and Processes for Advanced Carbon Capture Technologies (IMPACCT) program is to **dramatically reduce the cost of extracting CO_2 from flue gases so it can be sequestered from the atmosphere.** All carbon capture technologies consume energy; the current benchmark technology, an absorber–desorber process that uses a monoethanol amine (MEA) solvent, costs around $90 per ton of CO_2 captured—which would add as much as 50% to the cost of producing electricity from coal.

According to ATK claims, the company’s process would cost $48 per ton of CO_2. Other grantees claim similar costs. But Karma Sawyer, IMPACCT program manager, cautions that extrapolating cost-per-ton figures from bench-scale demonstrations—the current status of most CO_2 capture projects—“is not a trivial calculation to make.” **Her program adopted a goal set by DOE’s Office of Fossil Energy in 2008: to limit the cost increase for electricity generated with coal to 35%.** “I can say that our technologies have compelling arguments to make” on reducing the costs, she says.

- Alliant Techsystems (ATK)
- LLNL
- GE Global Research
- University of Notre Dame
- Texas A&M
- Columbia University

A Strategy for Fusion’s 2nd Frontier: “Economic Viability”

How to reduce fusion’s cost per Watt by more than an order of magnitude?

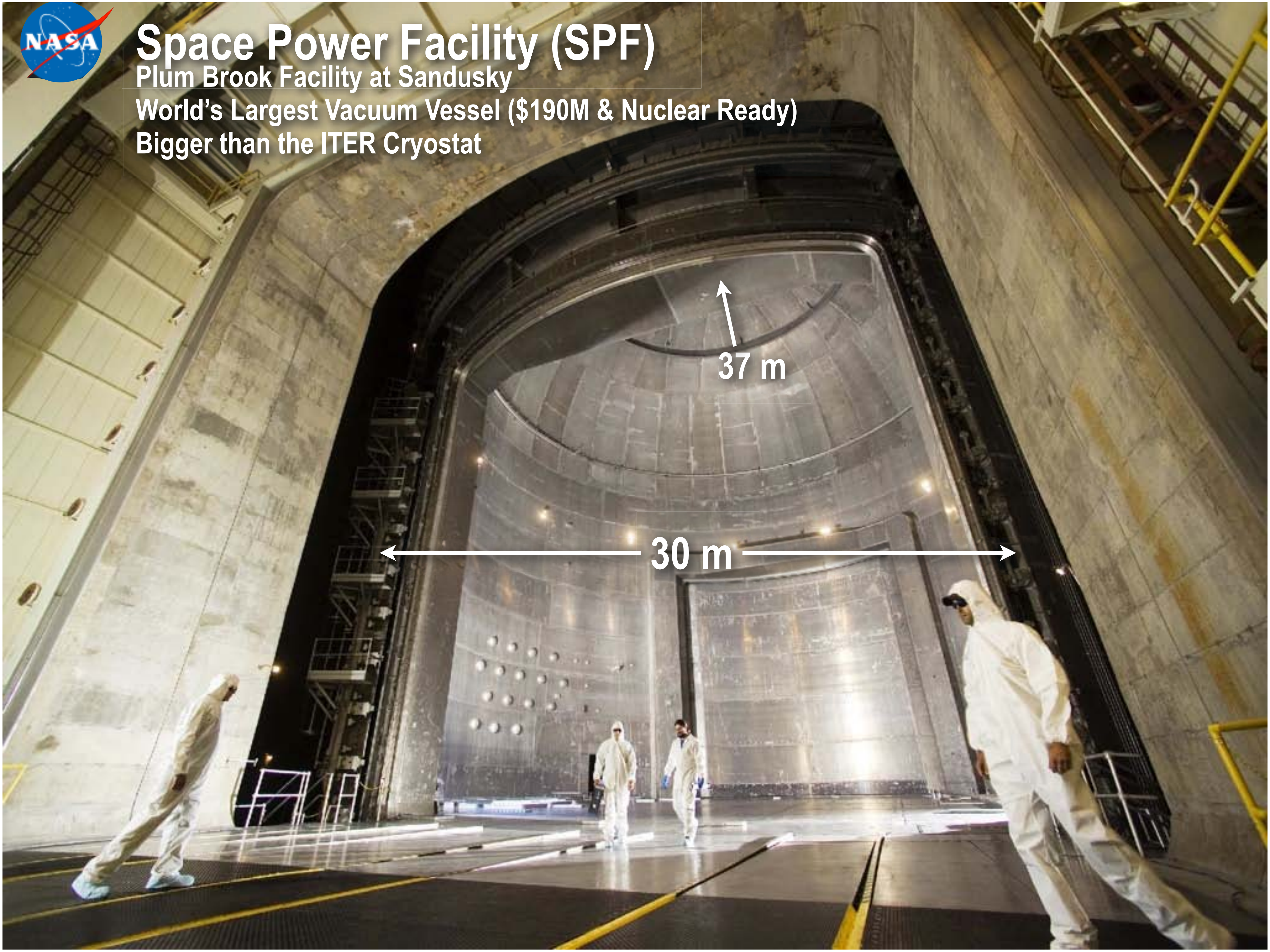
- Fusion research must resolve it’s “science rich” feasibility issues, *but the costs of this research should be commensurate with our target*
- Strengthen efforts to improve performance of the baseline, *e.g. the advanced tokamak, Li walls, novel divertors, stellarators,* …
- Broaden study to include new fusion concepts *that promise* ***significant*** *cost reductions and system simplifications*
- “Economically viable” fusion faces many simultaneous challenges, and ***wise policy will move research forward on multiple pathways***

Space Power Facility (SPF)

Plum Brook Facility at Sandusky

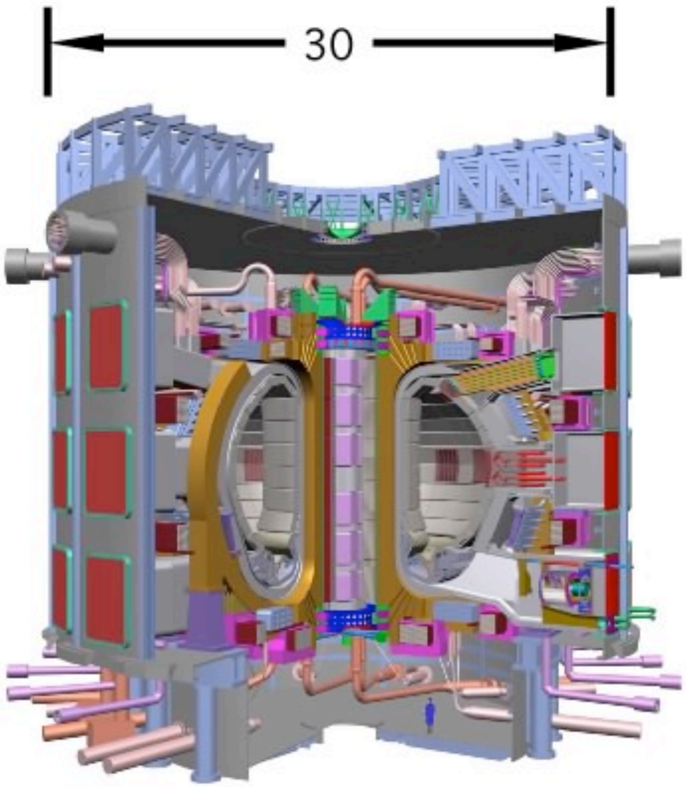
World’s Largest Vacuum Vessel ($190M & Nuclear Ready)

Bigger than the ITER Cryostat

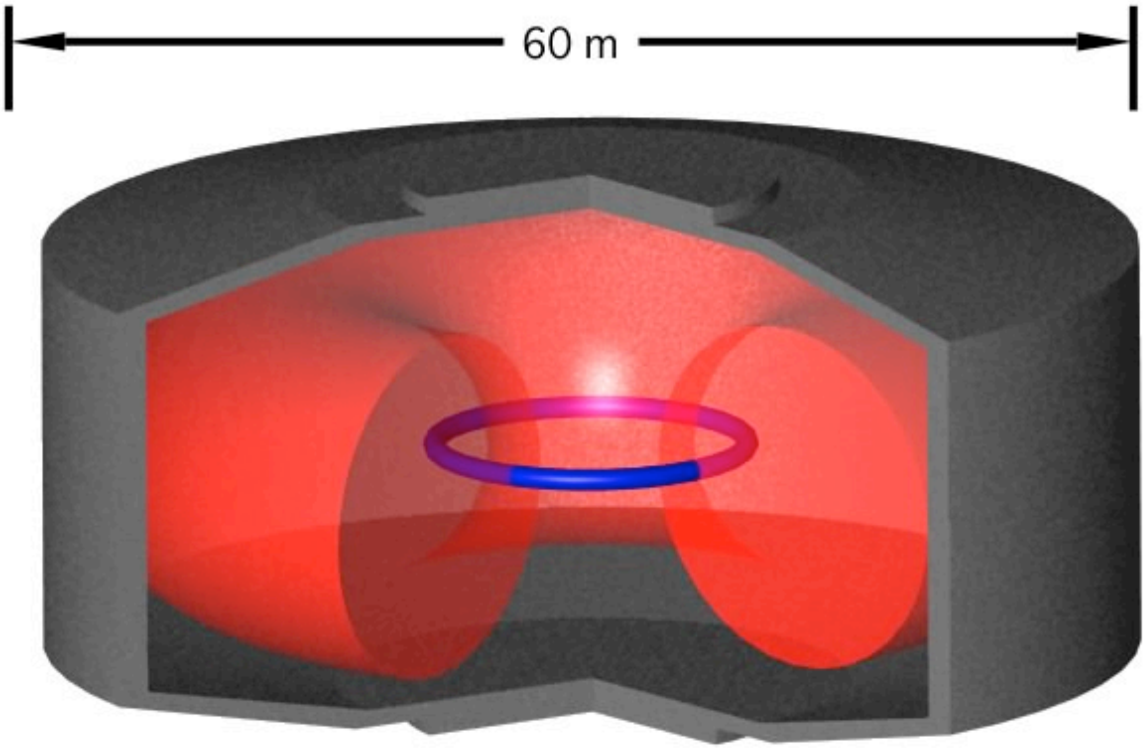


Levitated Dipole may Make Possible Tritium Suppressed Fusion

Dipole T-suppressed fusion is an **alternate technology pathway** that avoids the need to develop **breeding blankets** and **structural materials compatible with 14 MeV neutrons**.



ITER
500-700 MW
D-T Fusion



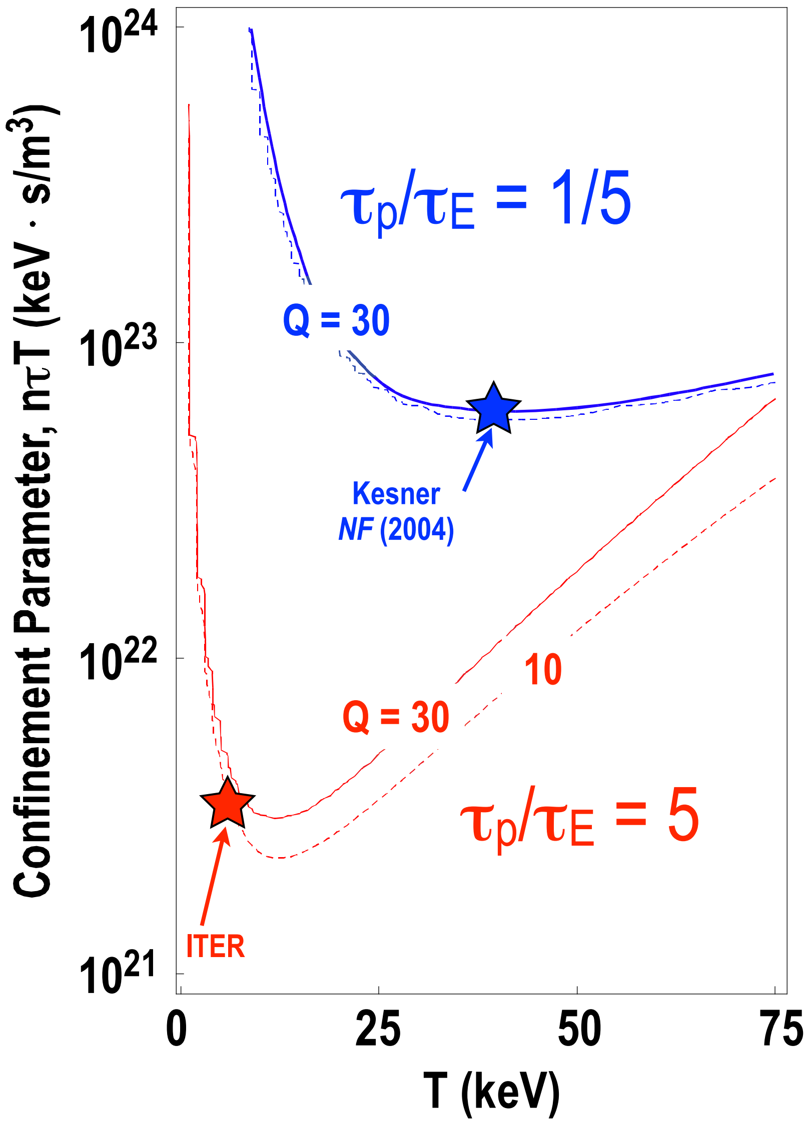
Levitated Dipole
600 MW
D-D(^{3}He) Fusion

51 GJ	W_B	**31 GJ**
0.3GJ	W_p	**3 GJ**
>400 MW	**14 MeV Power**	**14 MW**

Kesner, et al., NF (2004)

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



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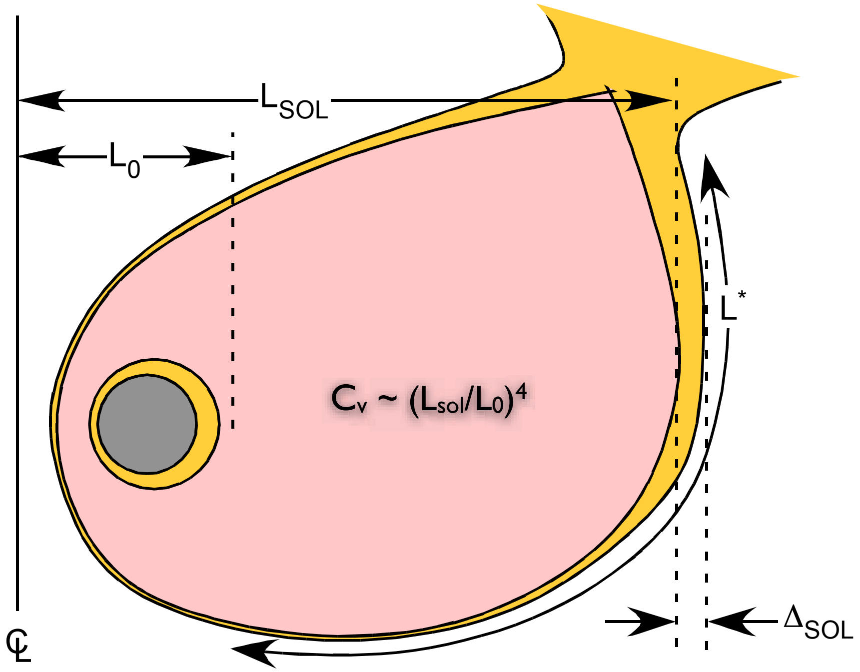
$(N, P\delta V^{\gamma})$ ~ constant implies peaked density and pressure profiles (**if $\gamma > 1$**)

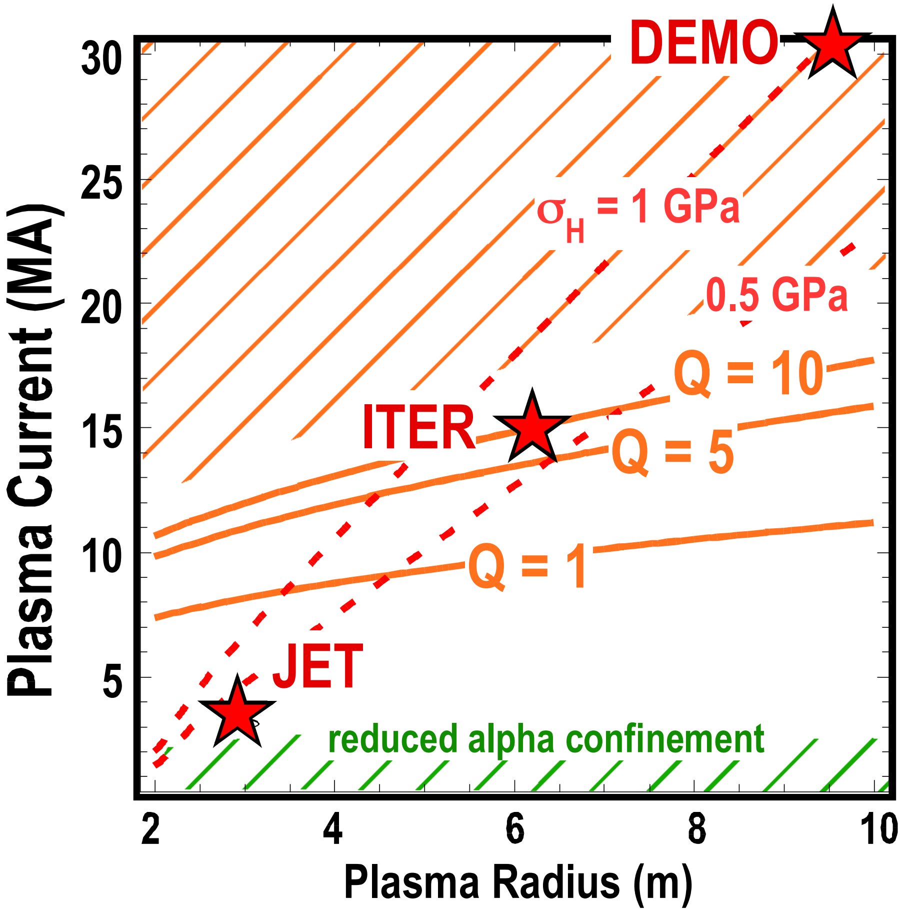


Adiabatic mixing implies
core parameters determined by edge & compressibility:

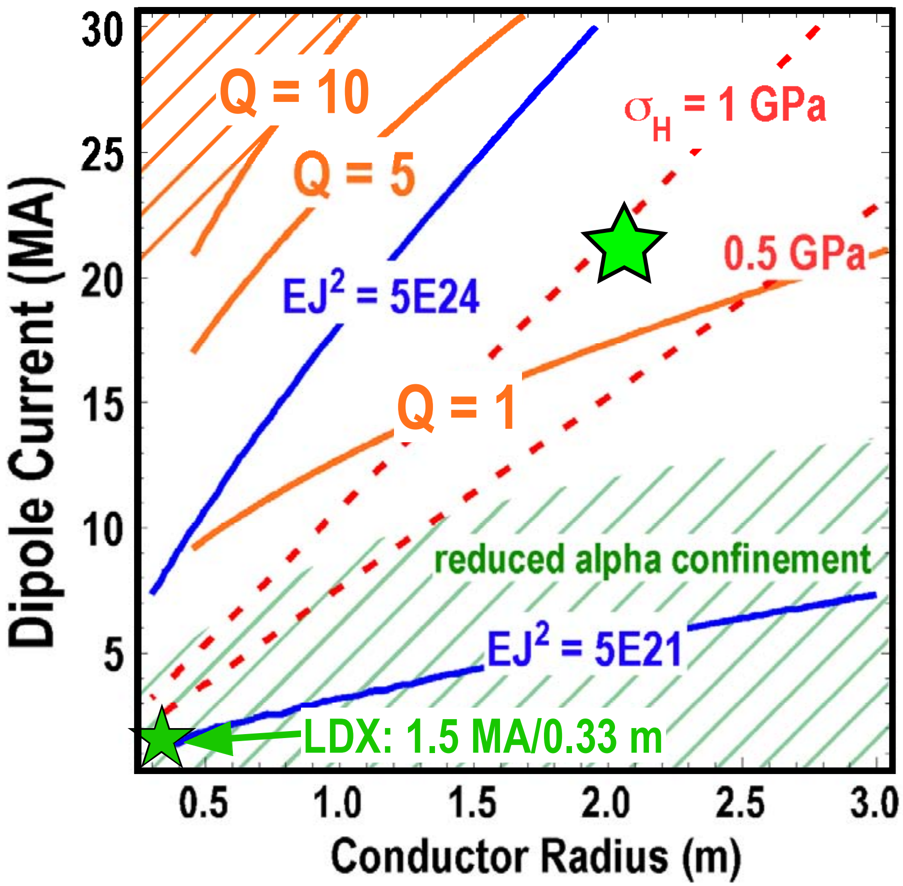
$$\tau_e/\tau_p \sim (4\gamma-3)C_v^{\gamma-1} > 50$$

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

(a) ITER-Like D-T Tokamak Scaling



(b) LDX-Like D-T Dipole Scaling



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

CNN Opinion

Nuclear fusion is the 'perfect energy source'

By **Steven Cowley**, Special to CNN
updated 9:40 AM EDT, Tue March 12, 2013

But what about our second objective of economic viability? ITER isn't meant to achieve that goal. In addition to clearing our last remaining scientific hurdle, we need to advance a parallel engineering agenda into key reactor technologies that will enable commercial fusion power plants to reliably deliver electricity in a highly competitive market.

This means technological advances in areas such as structural and functional materials, power conversion, and reliability.

Mike Mauel:

*"**Economic viability**" is the second frontier of fusion science and engineering.*

*This means integrating technology advances with **advancements in fusion plasma physics** to engineer and test fusion confinement concepts that **significantly simplify, reduce capital costs, and improve maintainability.***