Discovery Research in Magnetic Fusion Energy Science

A Public Comment to the
Fusion Energy Sciences Advisory Committee (FESAC)
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Thank you Dr. Martin Greenwald and members of FESAC for allowing me this opportunity to speak. Please note that my comments today are personal, and I am not representing the views of any organization or committee to which I belong.

I want to speak about our responsibility to maintain discovery research in magnetic fusion energy science. Discovery research is not the understanding and validating what we are already doing. It's making real discoveries, so that we can do things better.

Discovery research is vital to the health of any science. It has two parts: (1) it seeks deep understanding of fundamental phenomena, and (2) it uses broad exploration to find game-changing ideas. Discovery research can not be managed like technology development. Instead, discovery research must be nourished, encouraged, and promoted.

Fusion's history is filled with examples of discovery research. My favorite examples from small university experiments include: bootstrap current, stabilization of plasma turbulence with probe-driven flow-shear, helicity injection, lower hybrid current drive, resistive wall mode feedback control, reduced magnetic stochasticity through current profile control, and on-and-on. Each of these discoveries deepened our understanding of magnetic confinement, and each was a game-changing idea for fusion. In my opinion, as we look forward to ITER operation, we have a need and we have an obligation to keep discovery research alive in our field.

While I am certain that the Office of Science and the OFES are committed to discovery research in fusion science, the recent decision by the OFES to concentrate funding for experimental plasma research on tokamak and stellarator projects has had negative consequences: (1) the number of university-based plasma experiments has been sharply reduced, (2) the intellectual vitality at the scientific core of magnetic fusion research has been narrowed, and (3) some of the best researchers in our field have been alienated, in part, because of the sudden shut down of fully functioning and highly productive experiments.

At several universities, experimental plasma research have been significantly reduced or eliminated entirely. At my own university, Columbia University, experimental plasma research has been cut in half.

One of the projects being closed this year is the Levitated Dipole Experiment, called LDX, which is a joint research project of Columbia University and MIT.

LDX is also a good example of discovery research, because (1) it builds deep understanding of fundamental plasma confinement and stability, and (2) it explores what may be game-changing ideas for fusion. Because of this, and because LDX is being closed, I want to take a few moments to describe LDX and what we've lost by shutting down a working experiment.

LDX was dedicated in 2004. Its goal was to bring the physics of magnetospheres to the laboratory and partner with MIT's magnet engineers to launch the first study of steady-state toroidal confinement using the world's strongest levitated superconducting current ring.

The first LDX discharges were successful, achieving very high beta in steady state. Graduate students and scientists took two more years before they understood their discovery (while also understanding energetic particle instabilities, x-ray plasma imaging, microwave electron heating, and magnetic equilibrium reconstruction with anisotropic pressure, etc.), but, when these experiments were finally understood, they demonstrated that the high beta and outstanding trapped particle confinement seen in magnetospheres also occur in the laboratory.

The first magnetic levitation of the superconducting dipole occurred in 2007. Darren Garnier, the Chief Scientist for LDX, received the 2009 Fusion

Power Associates (FPA) Excellence in Fusion Engineering Award in recognition of this remarkable accomplishment. With LDX, steady-state plasma experiments are conducted for hours, over and over, all day long.

When dipole magnet is levitated, high-beta plasma is well confined by the superconducting current ring without any toroidal field. Most surprising, the density profile is always centrally peaked. When the density profile is transiently made less peaked, turbulence drives particles inward, and the central density rises again. LDX students and scientists directly measured the strongest inward turbulent particle pinch ever observed in the laboratory. Our colleagues at the University of Tokyo built a slightly smaller levitated dipole and made similar observations. When they applied even more heating power than used LDX, they reached even higher beta, in steady-state.

During the 2010 Annual Meeting of the APS-DPP, Dartmouth student, Kumire Kobayashi, presented nonlinear gyrokinetic simulations of the LDX observations. Her simulations were a “first principle” transport validation of LDX measurements. They also illustrated a relationship between particle and heat transport that can help interpret turbulent transport in tokamaks.

I believe the study of high-beta steady state confinement and the strong inward particle pinch seen with a levitated dipole is an example of discovery research that is important and cost-effective.

The observation of highly peaked plasma profiles through an inward turbulent pinch and the validation of nonlinear simulations of turbulent transport will support our efforts to understand transport in ITER.

The achievement of steady state, high-beta, high-confinement of plasma with a levitated dipole is also a game-changing idea for magnetic fusion. We now know that steady-state toroidal confinement of plasma does not require a toroidal field.

The next step for LDX was to be the exploration of higher-density plasma. General Atomics donated a 1 MW CW RF transmitter for ion cyclotron heating. Using techniques developed at ORNL, full-wave absorption calculations in real experimental geometry showed good antenna loading. LDX was also lucky to be located next to MIT’s Alcator C-MOD. C-MOD is home to leading experts in ICRF, and these experts offered RF antenna and engineering advice to the LDX Team.

Unfortunately, these next-step experiments were not supported.

Five months ago, as MIT engineers were directing the installation of the MW RF transmitter in the penthouse above the LDX device, Jay Kesner and I received letters from DOE informing us that the Levitated Dipole Experiment will be closed. It is my understanding that the decision to close LDX was a consequence of the new OFES policy to concentrate funding on tokamak and stellarator projects.

In my opinion, discovery research like LDX is important to the vitality of our field because it is *not* a tokamak or a stellarator.

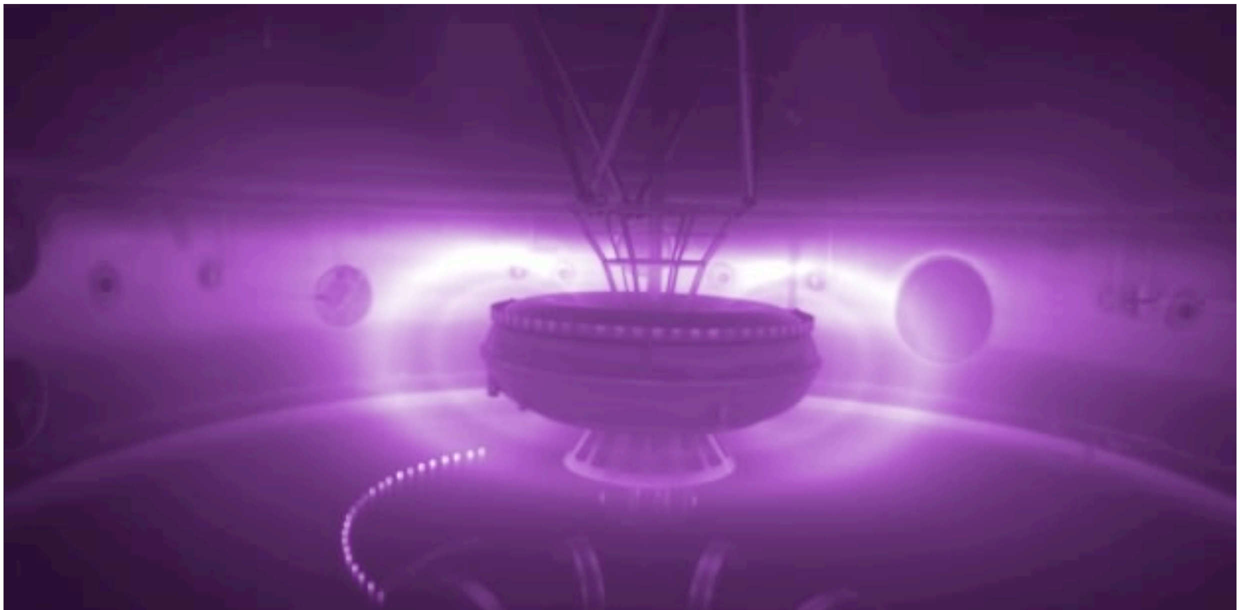
I also believe the abrupt shut-down of highly-productive and potentially game-changing research, like LDX, sends a discouraging message to the university plasma research community.

Today is a critical time when we need to be strengthening discovery research and encouraging ever-greater university participation in fusion sciences.

FESAC has a responsibility to help maintain discovery research in fusion energy sciences. I ask you to send a clear message to the Office of Science and recommend a reinvigoration of discovery research in magnetic fusion energy. Your recommendation should ask that Alternate Confinement Experimental Research be focused on experiments that seek a deep understanding of fundamental phenomena and explore game-changing ideas. Of course, this means strong support for small tokamaks, stellarators, and STs, but not exclusively. In other words, Alternate Confinement Experimental Research should be selected for their contributions to discovery research and not for the shape of their magnetic topologies.

Additionally, because the recent reduction of university-based experimental plasma research discourages university participation in fusion research, I also ask that FESAC recommend that OFES immediately open a dialog with the university fusion research community and find ways to significantly increase the role of universities in today's experimental fusion science research program.

These remarks, references, and supporting materials are available online at www.apam.columbia.edu/mauel/mauel_pubs/FESAC_Public2011.pdf.



Levitated Dipole Experiment (LDX)

Accomplishments
Discoveries
Opportunities

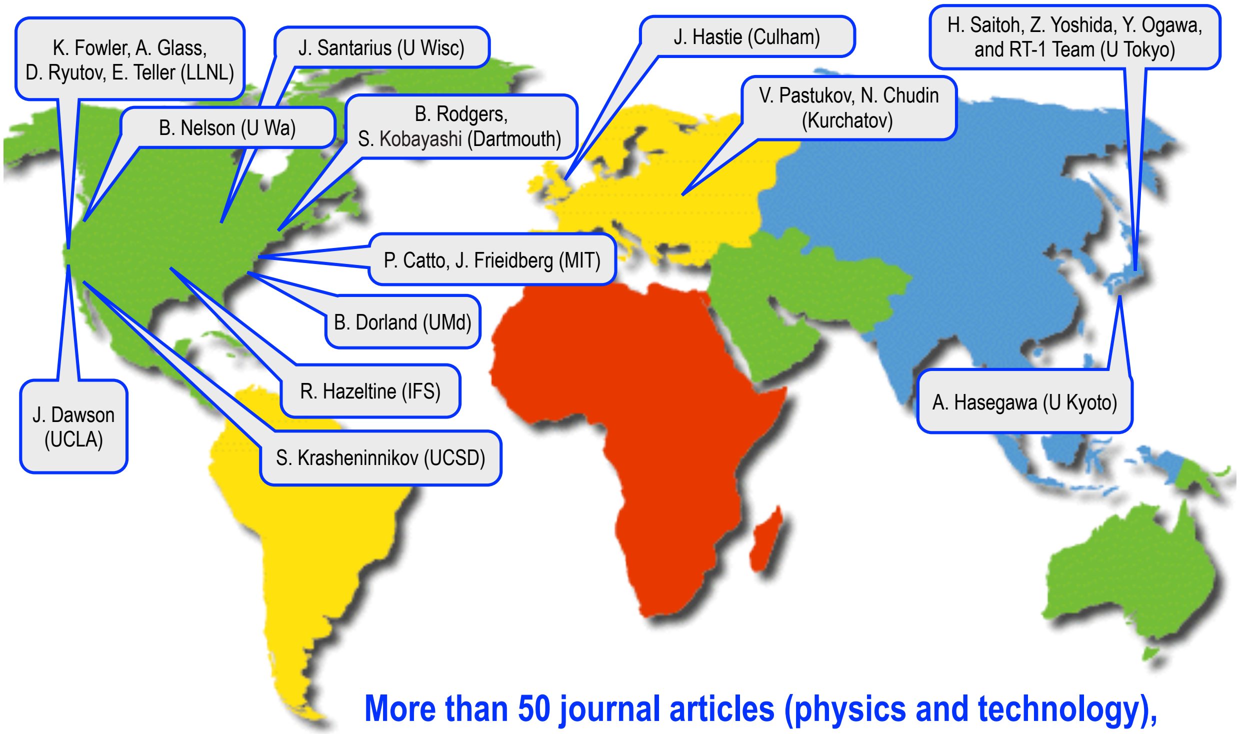
Presented to DOE/OFES January 29, 2011

Levitated Dipole Experimental Team

R. Bergmann, A. Boxer, D. Boyle, M. Davis, G. Driscoll, R. Ellis, J. Ellsworth, S. Egorov, D. Garnier, B. Grierson, O. Grulke, C. Gung, A. Hansen, K.P. Hwang, V. Ivkin, J. Kahn, B. Kardon, I. Karim, J. Kesner, S. Kochan, V. Korsunsky, R. Lations, S. Mahar, M. Mauel, P. Michael, E. Mimoun, J. Minervini, M. Morgan, R. Myatt, G. Naumovich, S. Nogami, E. Ortiz, M. Porkolab, S. Pourrahami, T. Pedersen, A. Radovinsky, A. Roach, A. Rodin, G. Snitchler, D. Strahan, J. Schmidt, J. Schultz, B. Smith, P. Thomas, P. Wang, B. Wilson, P. Woskov, B. Youngblood, A. Zhukovsky, S. Zweben

THE UNIVERSITY OF TOKYO
American Superconductor®
Dynavac
AET Ability Engineering Technology Inc.
Columbia University
D.V. Efremov Institute
Office of Fusion Energy Sciences
IGC ADVANCED SUPERCONDUCTORS
A DIVISION OF INTERMAGNETICS GENERAL CORPORATION
BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division
PPPL PRINCETON PLASMA PHYSICS LABORATORY
MIT PSFC

Levitated Dipole Physics: Key Collaborators



More than 50 journal articles (physics and technology), 8 PRLs, Nature-Physics, 12 invited talks at DPP, EPS, and IAEA

Technical Accomplishments

- Design, fabrication, assembly, and operation of the world's first levitated dipole experiment
- Superconducting fusion science facility: **reliable, steady-state experimentation for hours**
- High-beta; high-temperature; toroidally-confined plasma with confinement parameter ($n\ T_e\ \tau_E$) comparable to HSX
- With a major radius near 2 m, plasma volume of 10 m^3, built a research facility with **unprecedented diagnostic access**

Programmatic Accomplishments

- **First fusion experiment jointly-managed by two universities.** Built as a partnership between plasma scientists and magnet technology experts
- Strongly supported by university administrations; MIT invested heavily in the LDX facility (more than $0.5M plus in-kind equipment).
- Successfully coordinated manufacture of three superconducting magnets, including the large charging coil built in Russia.
- Following DOE/OFES schedule guidance, LDX achieves first high beta (20%) plasma with supported dipole. **LDX is dedicated in October, 2004**.
- Levitation experiments begin in October 2007.
- Major levitation results announced during 2008-10 APS, IAEA, EPS meetings. **LDX invited to speak at 2011 EPS (Strasbourg).**

Discoveries

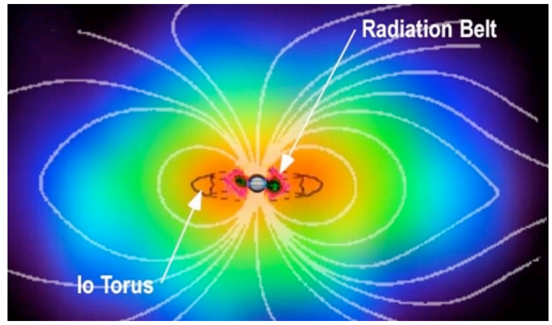
- Levitated dipole can achieve > 50% peak beta
  showing key connection between laboratory and planetary magnetospheres
- Low frequency fluctuations dominate plasma dynamics
  showing importance of kinetic effects beyond ∇P and ∇n interchange modes
- Turbulence drives plasma to very steep profiles and creates strong inward particle pinch in dipole geometry
  confirming "first principle" transport prediction based on measured fluctuations
- Fascinating plasma science and magnetospheric physics
  showing relevance to critical transport, modeling, and space physics goals

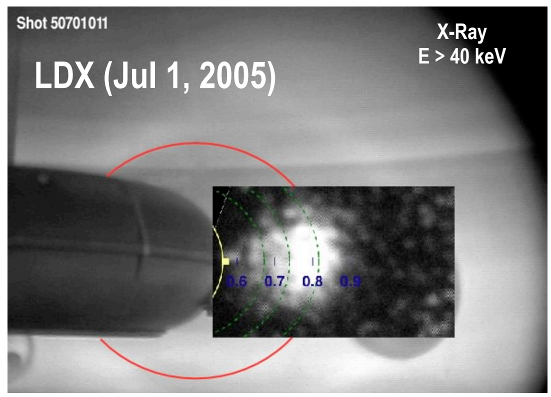
Levitated dipole can achieve > 50% beta

The natural high beta in planetary magnetospheres can be achieved in the laboratory. Steady-state.

- Garnier, POP (1999) shows equilibria with $\beta > 100\%$ possible
- Garnier, POP (2006) reports peak beta 20% achieved
- Garnier, NF (2009) reports peak beta doubles with levitation
- Saitoh, JFE (2010) reports peak beta 70% achieved in RT-1

Cassini at Jupiter (Dec 30, 2000)



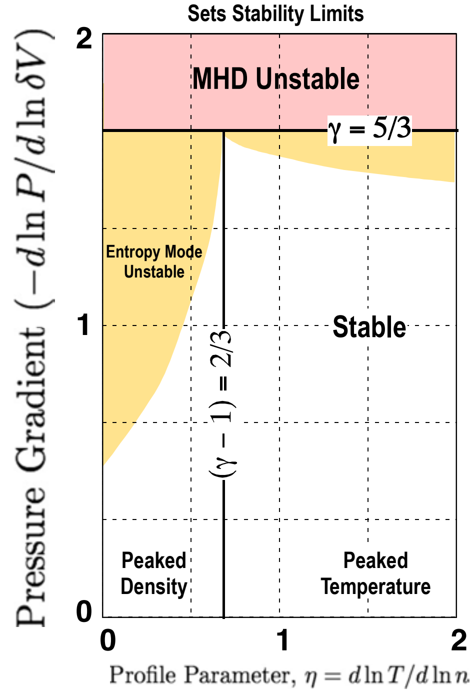


Low frequency fluctuations dominate plasma dynamics: interchange & entropy modes

- 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 $\eta = d(\ln T)/d(\ln n)$
- 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 strong inward particle pinch in dipole geometry

- Turbulence relaxes gradients and creates profiles that depend upon **flux-tube geometry, δV**:

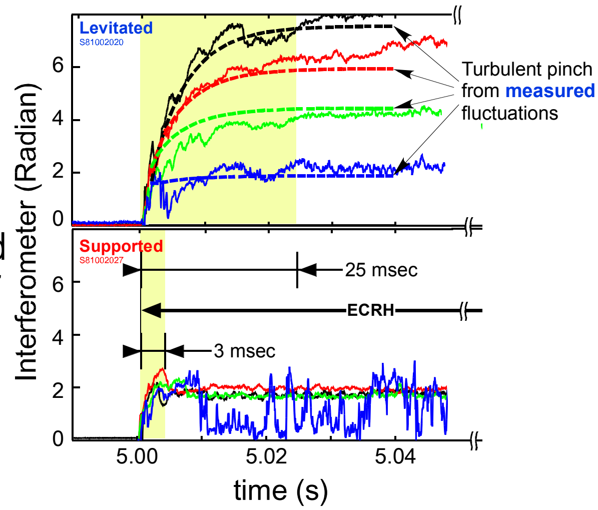
$$-\frac{d\ln P}{d\ln \delta V} = \gamma = \frac{5}{3} \qquad -\frac{d\ln n}{d\ln \delta V} = 1$$

$$\eta = \frac{d\ln T}{d\ln n} = \gamma - 1 = \frac{2}{3}$$

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

- **Tokamak: δV ~ q**, creates less peaked profiles, but **turbulent pinch effects are essential to predicting fusion transport**

Line Density Shows Strong Pinch Only with a Levitated Dipole

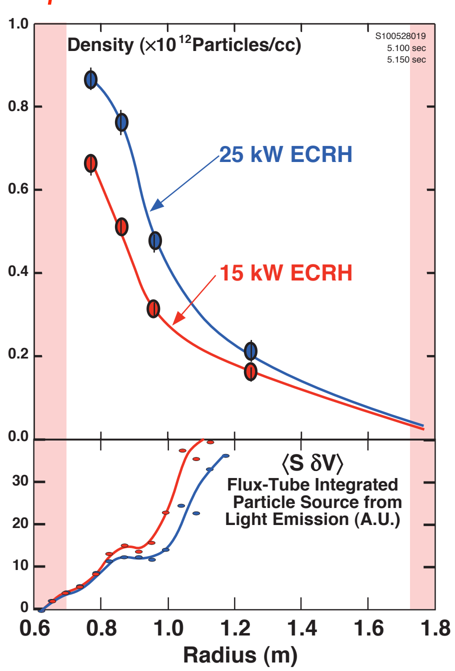


Boxer, *Nature-Physics* (2010)

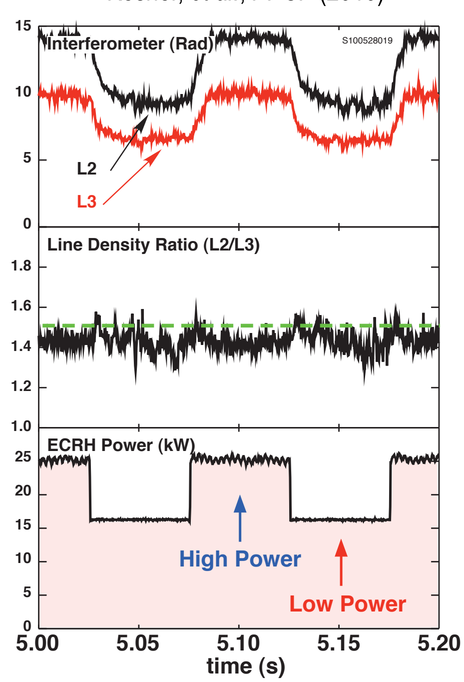
Turbulence drives plasma to very steep profiles and creates strong inward particle pinch in dipole geometry

Power and gas modulations show density always centrally peaked even as particle source moves outward

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



Kesner, *et al.*, *PPCF* (2010)



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

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

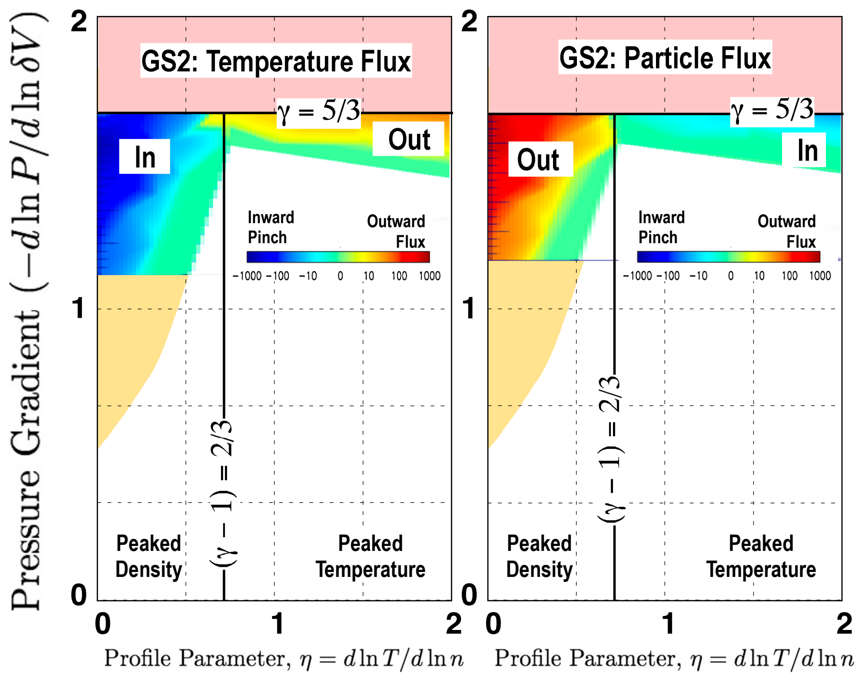
Kobayashi, Rogers, Dorland, *PRL* (2010)

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

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

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

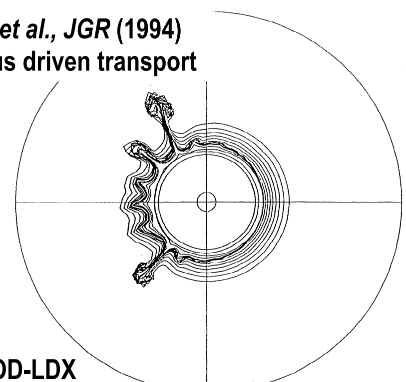
$$-\frac{d \ln P}{d \ln \delta V} \rightarrow \frac{5}{3}$$



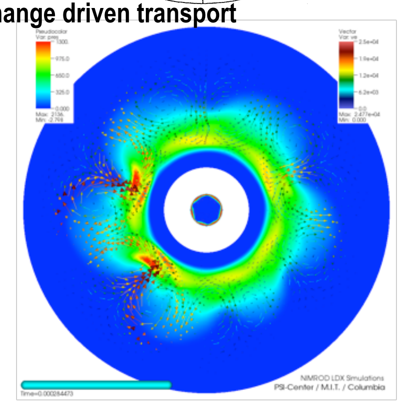
Fascinating plasma science and magnetospheric physics

- Plasma convection and nonlinear mixing corresponding to space weather
- Energetic electron energization and injection at high-beta
- Relativistic wave-particle interactions and trapped-radiation dynamics
- Nonlinear frequency sweeping and phase-space holes (like Alfvén eigenmodes)
- Centrifugal flux-tube buoyancy

Yang, *et al., JGR* (1994)
Io-torus driven transport



NIMROD-LDX
Interchange driven transport



Opportunities:
Advancing plasma science using a "laboratory magnetosphere"

- LDX is the world's leading facility for steady-state, high-beta, investigations of turbulent transport and laboratory magnetospheric physics
- Fundamental plasma science
  - Detailed measurement of turbulent self-organization
  - Measure the "adiabatic constant", γ, of low-frequency mixing of magnetized plasma pressure
  - Extend pinch understanding to energy, momentum, and impurities: critical questions for fusion and for space
  - Energetic particle physics: wave-particle and trapped radiation
- Validate predictive models: GS2, NIMROD, Space Weather, …

Combining Laboratory and Space Plasma Science Promotes the Field through Positive Outreach

- LDX brings high visibility to OFES plasma science efforts
- LDX provides opportunities to advance both space and laboratory research goals through partnership and shared physics goals:
  - Plasma transport
  - Energetic particles
  - Modeling and code validation

LDX Display at Boston Museum of Science

http://www.psfc.mit.edu/ldx/