Multi-University Research to Advance Discovery Fusion Energy Science using a Superconducting Laboratory Magnetosphere

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Presentation to FESAC Strategic Planning Panel
June 5, 2014

Outline

- Intermediate scale discovery fusion energy science needs support
- LDX example: a new laboratory facility built with new partnerships
- New regime discovered linking space science and toroidal confinement
- Opportunities at higher density and higher power

Support for Intermediate Scale Experiments should be a Key Strategic Element for Discovery Fusion Energy Science

- **Today, there is a strategic gap in DOE/FES programming because no formal mechanism exists for multi-year research and operation for intermediate scale discovery fusion energy science**.

- NRC *Plasma Science* (2007) recognized the need for intermediate scale facilities, but NRC *Fusion Energy Sciences Assessment* (2001) presented a plan, Recommendation #4:

  "Several new centers [each $1.5M to $7.0M/yr], selected through a competitive, peer-review process and devoted to exploring the frontiers of fusion science, are needed for both scientific and institutional reasons." (p. 4)

  "The center should enable links to various scientific disciplines ... have a plan for bringing practitioners of other disciplines from other institutions into the fusion community and should make the community's experimental resources more widely available." (p. 5)

- Like a center, **LDX is the first U.S. fusion science research facility built and operated as a multi-university collaborative research project**. LDX is an example, which…
  - Shows how a partnership of magnet technology experts and plasma physicists can successfully build our **only operating research facility with superconducting coils at relatively low cost**
  - Demonstrates a **new plasma regime can be discovered and explored at the intermediate scale**
  - Illustrates how **new laboratory experiments motivate new theory and simulation**, and
  - Proves intermediate scale can ***change the way we think about toroidal magnetic confinement***.

Multi-University Partnership for a New Laboratory Facility

Multi-University, National Lab,
International, Government, and Industry

National Science Foundation
WHERE DISCOVERIES BEGIN

Office of Fusion Energy Sciences
Excellent Science Attractive Energy

NSF

Columbia

MIT PSFC

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Efremov Institute

IGC ADVANCED SUPERCONDUCTORS
A DIVISION OF INTERMAGNETICS GENERAL CORPORATION

BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division

American Superconductor®

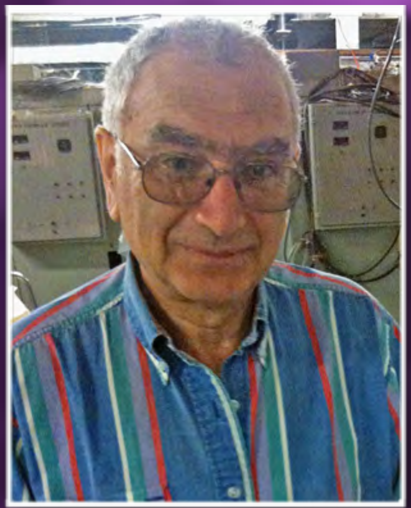
Ability Engineering Technology Inc.

Dynavac

Our Nation's Only Research Facility with Superconducting Magnets

Built by Award-Winning Plasma Science and Fusion Magnet Technology Experts

Levitation is *necessary* to study
Toroidal magnetic confinement
Steady state with β ~ 1





1.2 MA half-ton levitated magnet
Robust ± 1 mm levitation control
3 hrs float time

Alex Zhukovsky • Cryogenics
MIT Infinite Mile Award (2004)

Philip Michael and Rick Lations • Design, Installation, Operation, Maintenance of LDX
MIT Infinite Mile Award (2009)

Darren Garnier • Plasma Control and Experimentation
FPA Award for Excellence in Fusion Engineering (2009)

Joe Minervini • Superconducting Magnets
IEEE Award for Continuing and Significant Contributions to the Field of Applied Superconductivity (2013)

LDX Goal: Discover a New Regime

- ***<u>Leveraging space physics to discover a new regime</u>:*** axisymmetric, steady-state, compressibility ($\omega^* \sim \omega_d$), $\beta \sim 1$, no field-aligned currents, shear-free, bounce-averaged gyrokinetics, wave-particle dynamics, …

- Magnetospheric configuration but not a “miniature magnetosphere” (*high β stability but without polar losses and field-aligned currents*)

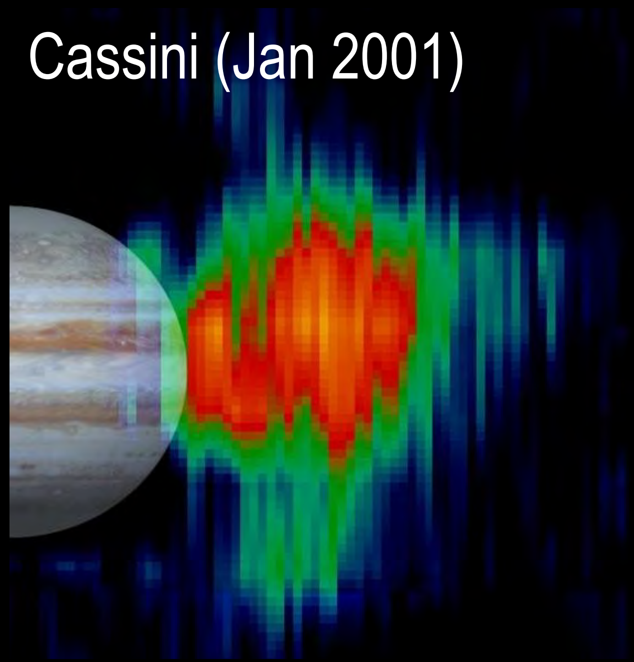
- Toroidal magnetic confinement, but not a “miniature fusion reactor” (*controlled tests of transport, stability, and self-organization)*

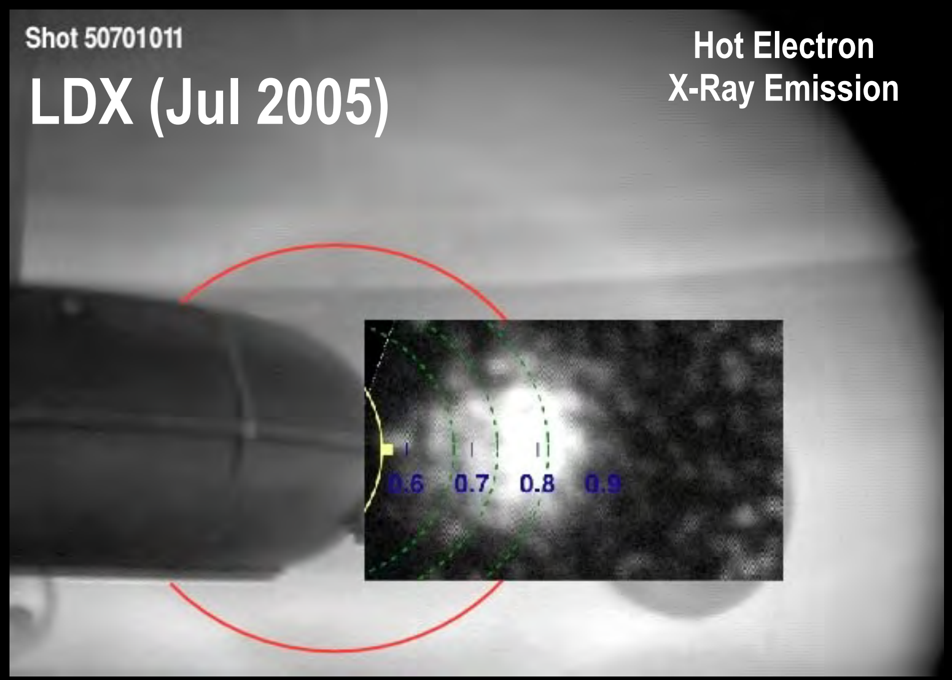
- NRC *Fusion Energy Sciences Assessment* (2001):

  “Scientific discoveries that a decade ago would have been unthinkable are the fundamental drivers of program direction at all levels. Scientific discovery is inherently coupled with progress toward fusion.” (p. 2)

  “With the development of new theoretical, computational, and experimental capabilities, a fundamental transition away from the empirically dominated approach is now taking place. ... creating new opportunities for achieving fundamental insight into the dynamics of plasma from the macroscale to the microscale.” (p. 42)

Fast Particles in Space and Lab





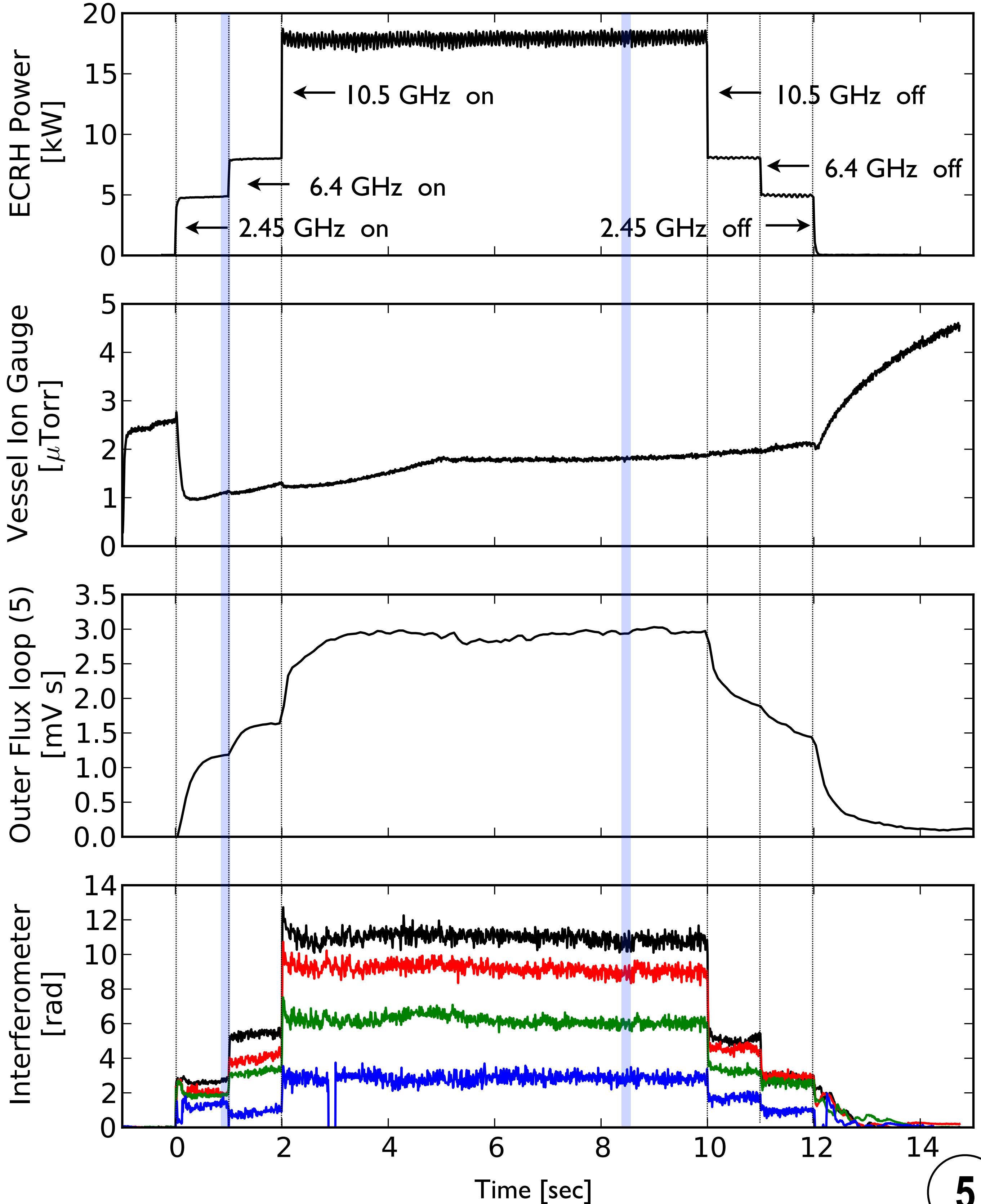
New Regime: High β, Turbulent Self-Organized, Steady-State

- 20 kW injected electron cyclotron waves
- Density proportional to injected power
- Plasma energy proportional to power
- Peak plasma density 10^{12} cm^{-3}
- Plasma energy 250 J (3 kA ring current)
- Peak β ~ 40% (100% achieved in RT-1)
- Classical fast particles 〈E_h〉 ~ 54 keV
- Peak 〈T_e〉 > 0.5 keV (thermal)

Sustained, dynamic, steady state …

- ***Plasma density and electron pressure naturally approach "canonical" profile shape determined magnetic flux-tube volume, δV.***
- ***Density evolves at rates described by bounce-averaged gyrokinetic theory.***

Self-Organized, Steady-State Profiles at High β



Measured "Canonical" Profiles: State of Minimum Entropy Production

① **Plasma density evolution shows turbulent self-organization:**

nature physics | ARTICLES
PUBLISHED ONLINE: 24 JANUARY 2010 | DOI: 10.1038/NPHYS1510

Turbulent inward pinch of plasma confined by a levitated dipole magnet

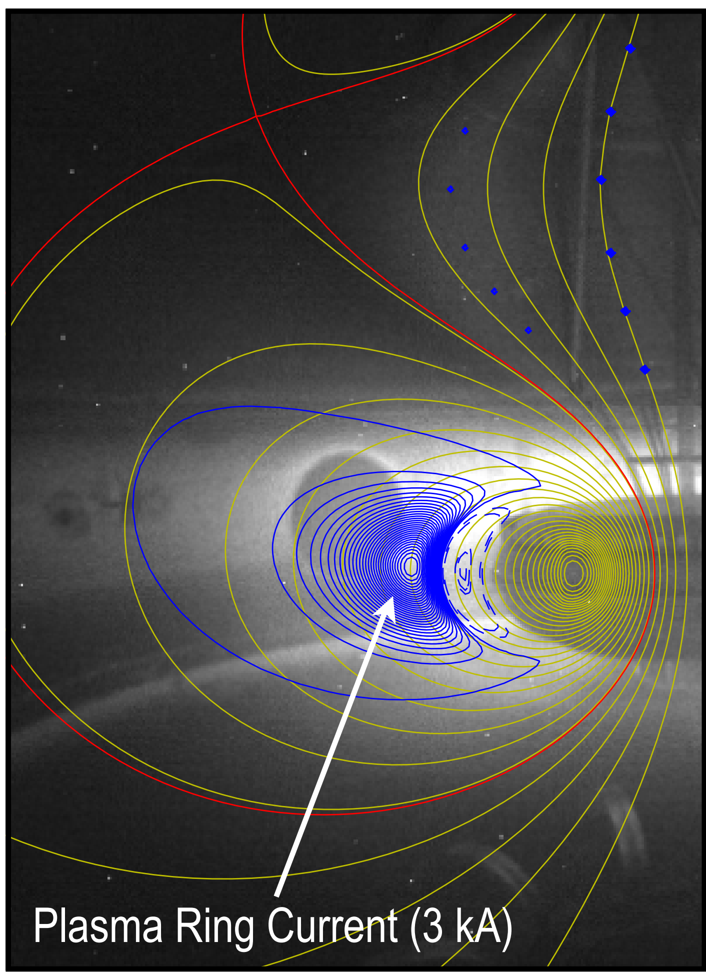
A. C. Boxer[1], R. Bergmann[1], J. L. Ellsworth[1], D. T. Garnier[2], J. Kesner[1], M. E. Mauel[2]* and P. Woskov[1]

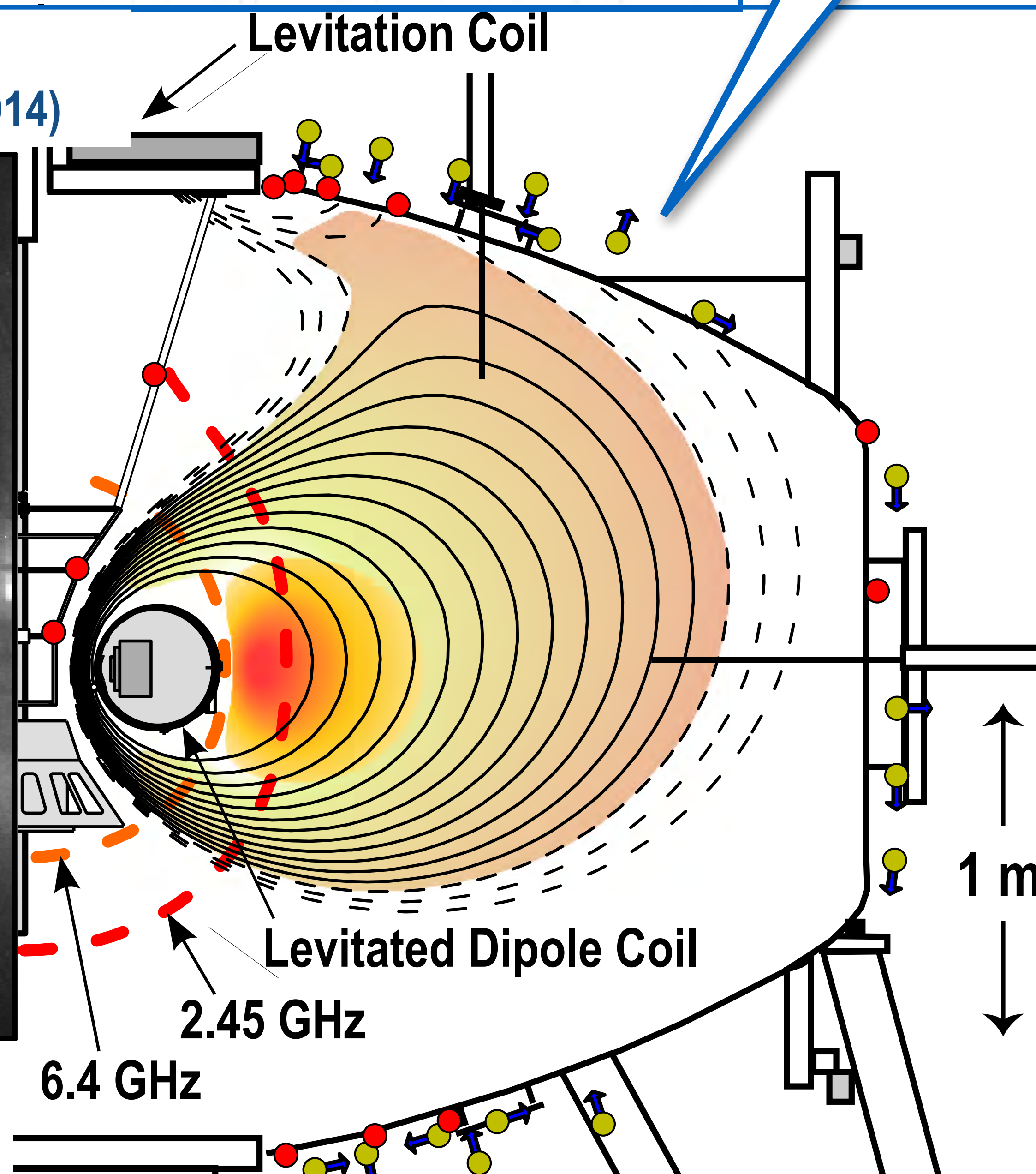
① $$-\frac{d\ln n}{d\ln \delta V} \rightarrow 1$$

② $$-\frac{d\ln P}{d\ln \delta V} \rightarrow \frac{5}{3}$$

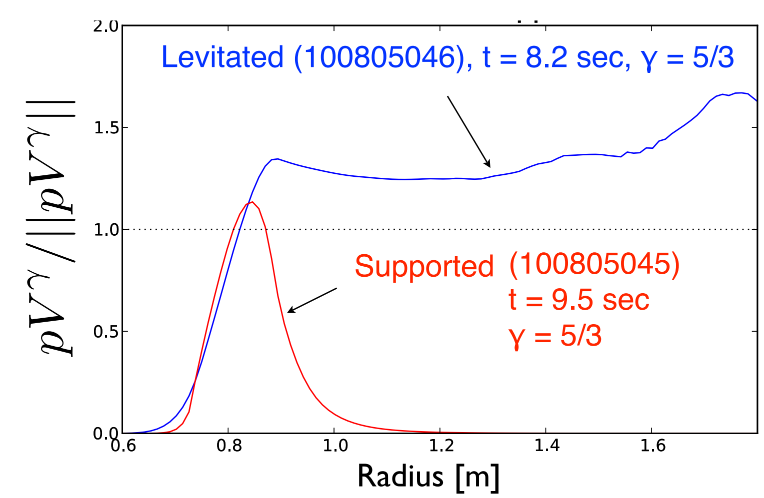
$$\eta = \frac{d\ln T}{d\ln n} \rightarrow \frac{2}{3}$$

② **Electron pressure profiles:**
M. Davis, *et al.*, to appear PPCF (2014)

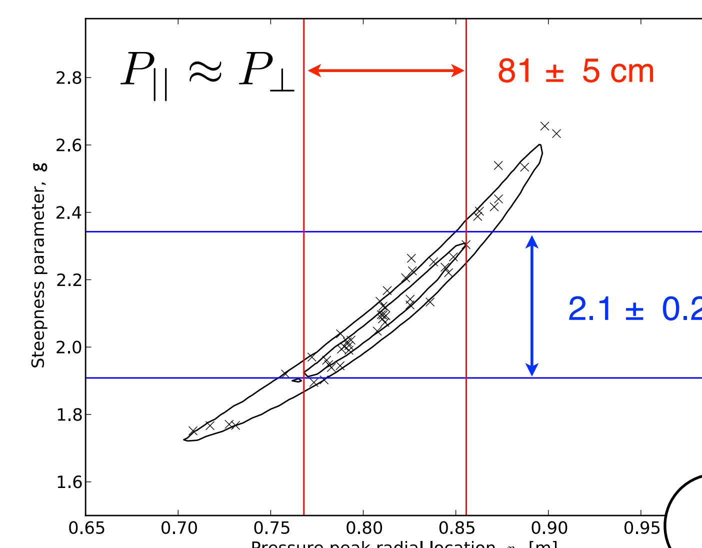




$$\mathbf{J}_\perp = \frac{\mathbf{B}\times\nabla P_\perp}{B^2} + \frac{\mathbf{B}\times\kappa}{B^2}(P_{||} - P_\perp)$$



Reconstruction Results in Very Good Accuracy of Pressure Profile



New Regime: New Experiments Motivate New Theory and Simulation

The combination of laboratory measurements, theory and simulation have
changed the way we think about toroidal confinement

- **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**

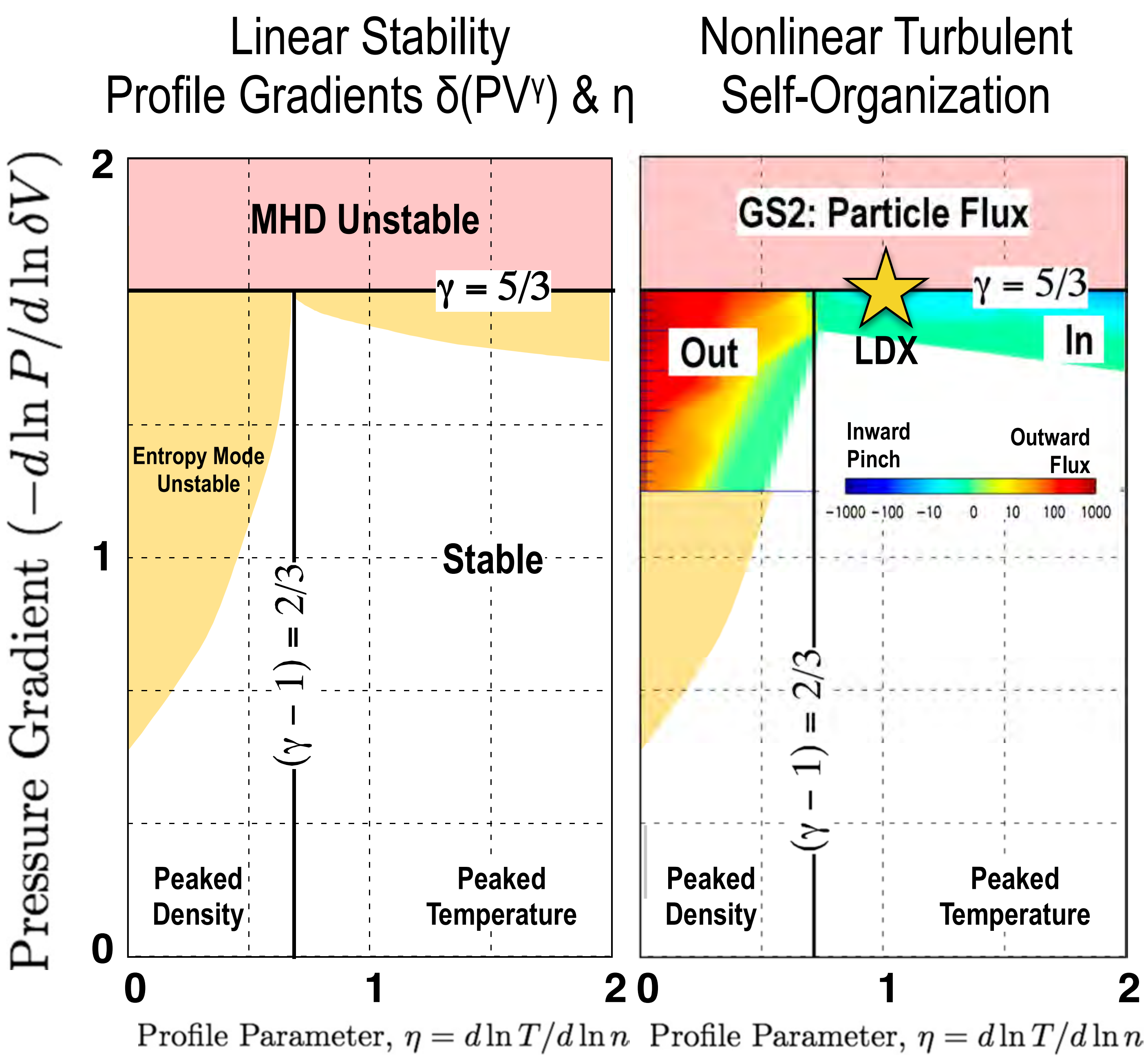
Kesner, POP (2000); Kesner, Hastie, POP (2002); Ricci, Rogers, Dorland, PRL (2006); Ricci, POP (2006); Kouznetsov, Friedberg POP (2007a)

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

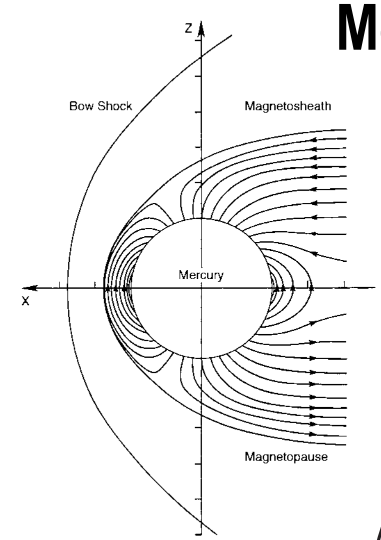
Tonge, Dawson, POP (2003); Pastukov, JETP Lett (2005); Pastukov, Plasma Phys Rep (2005); Garbet, POP (2005); Kouznetsov, POP (2007b); Kobayashi, PRL (2009); Kobayashi, Rogers, Dorland, PRL (2010); Kesner, POP (2011)

Kesner, *POP* (2000)

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

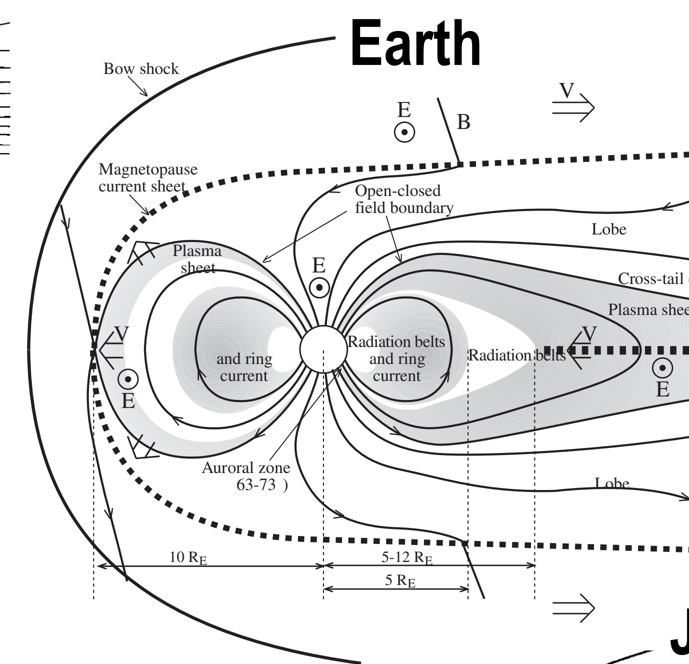


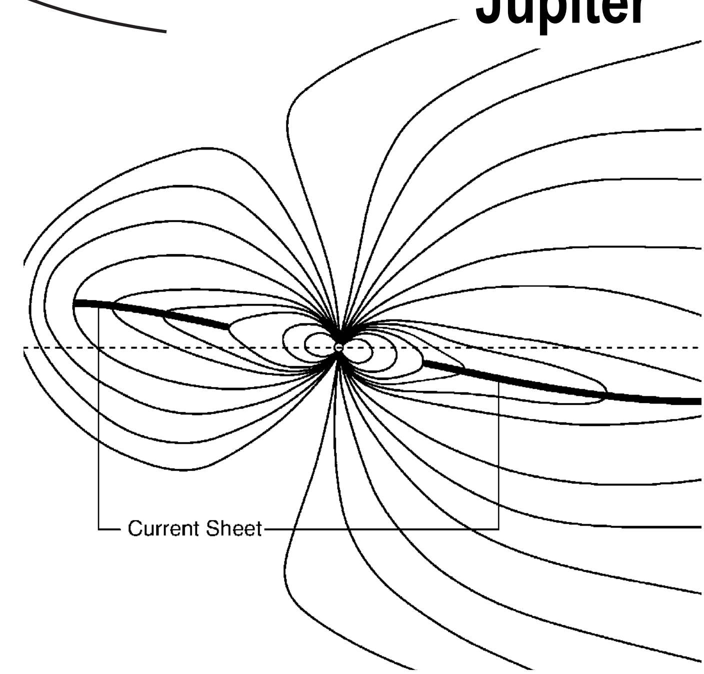
Priorities: Discoveries at Higher Density and Ion Heating



Next-step discoveries are significant…

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





	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

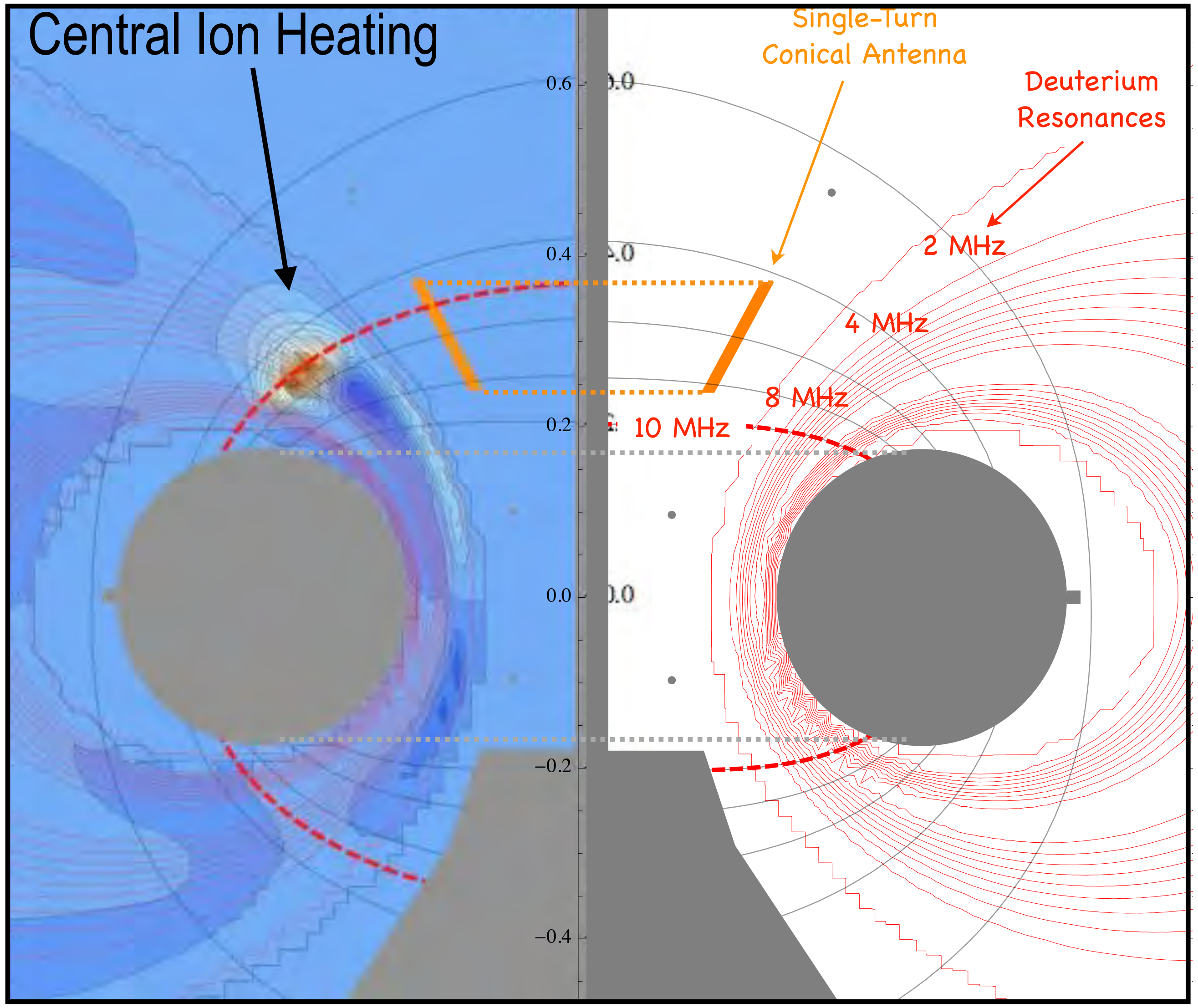
Priorities: 25 kW → 1 MW with RF Power Already Installed for LDX

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

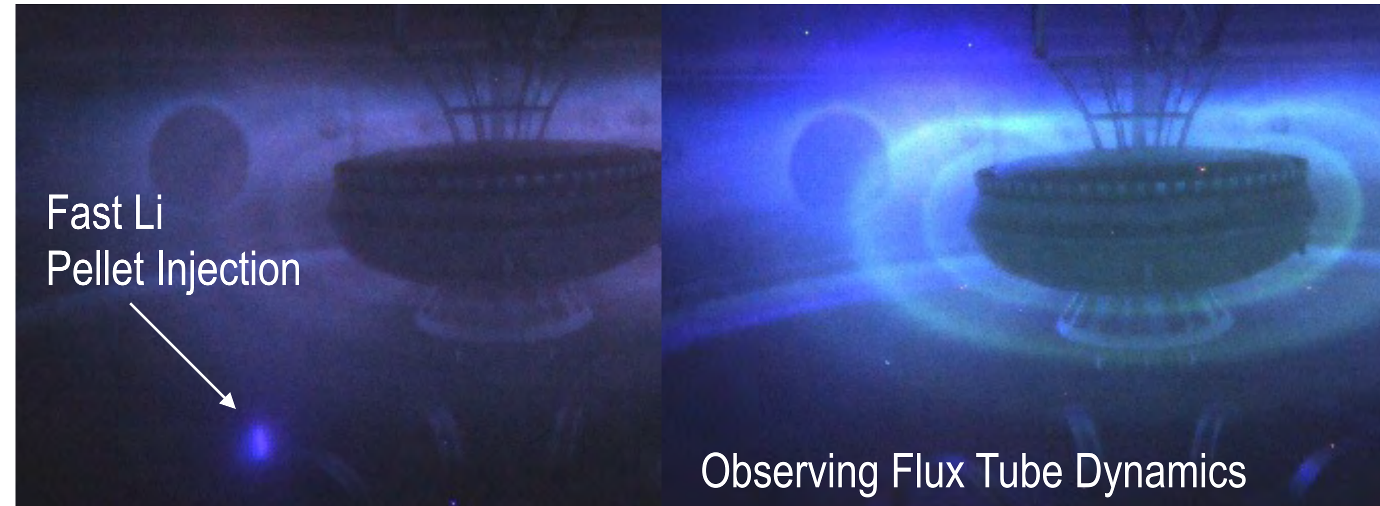
Axisymmetric Heating
5 MHz Deuterium ICRF (1 Ω Loading)



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

Status: Under-utilized but still Creatively Advancing Science

- NSF/DOE Partnership in Plasma Science: *Collaborative Research: Understanding Turbulent Mixing in Laboratory Magnetospheres*
- Two experiments (LDX and CTX) $0.4M/year
  - Turbulence regulation with controlled current extraction (first laboratory observation of magnetospheric "dynamo")
  - Transient flux-tube dynamics with Li injection: ***×3 density rise***, plasma torus evolution, …
- New partners from space physics community: radiation belt physics (HANE, space weather), multi-point diagnostic "swarms", …
- Seeking additional $1.5M to $2.0M/year for operation and exploration of dynamics at higher density with ion heating already on-site



Multi-university, intermediate-scale discovery fusion energy science needs support