What we've learned so far about the Stability of Plasma Confined by a Laboratory Dipole Magnet

M. E. Mauel and the CTX and LDX Experimental Teams

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Columbia University in the City of New York

PPPL Princeton Plasma Physics Laboratory

MIT Massachusetts Institute of Technology

Abstract

During the past decade, new experiments with collisionless plasma confined by magnetic dipoles have been built at Columbia University, MIT, and the University of Tokyo. These have resulted in detailed observations of interchange instability, convective mixing, and high-beta toroidal confinement without magnetic shear.

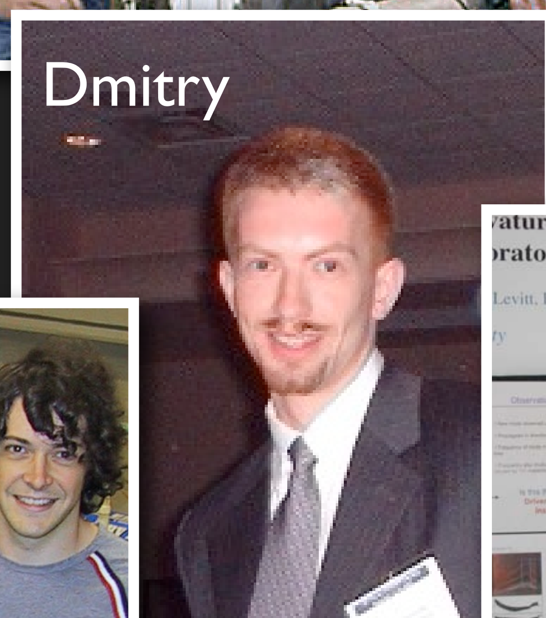
This poster discusses these new results with the aim of understanding linear, nonlinear, and turbulent plasma physics due to interchange dynamics.

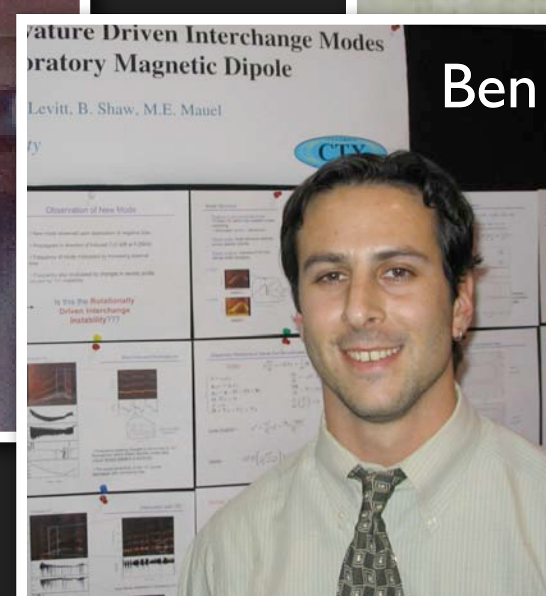
To date, observations show interchange modes to be **fixed-boundary modes with broad structures** that are easily measured and understood theoretically. Additionally, for a strong dipole magnet, **interchange modes create wave-particle kinetics that are essentially one-dimensional**. Hence, observations of linear and nonlinear MHD, fast-particle drift-resonances, transport in magnetospheric and fusion systems, and the effects of strong plasma flows are dominated by low-dimensional dynamics and show good agreement between observation, theory, and numerical simulation.

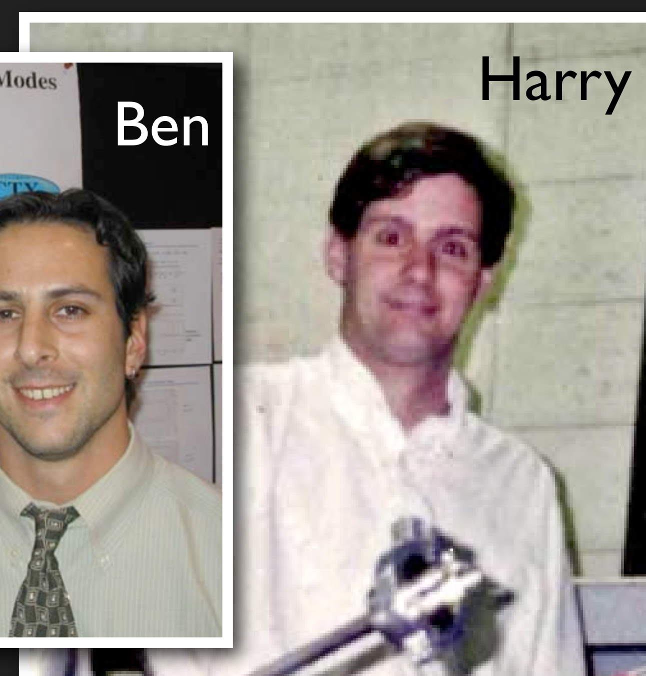
What We've Learned…

1. Robust ECRH start-up
2. Profile control with multiple-frequency ECRH
3. Gas programming yields high beta
4. Fluctuations have "Fixed-Boundary MHD" structures
5. Wave-particle dynamics are "One-Dimensional"
6. Turbulence spectrum dominated by machine size
7. Levitation causes "dramatic" confinement improvement

Acknowledgments



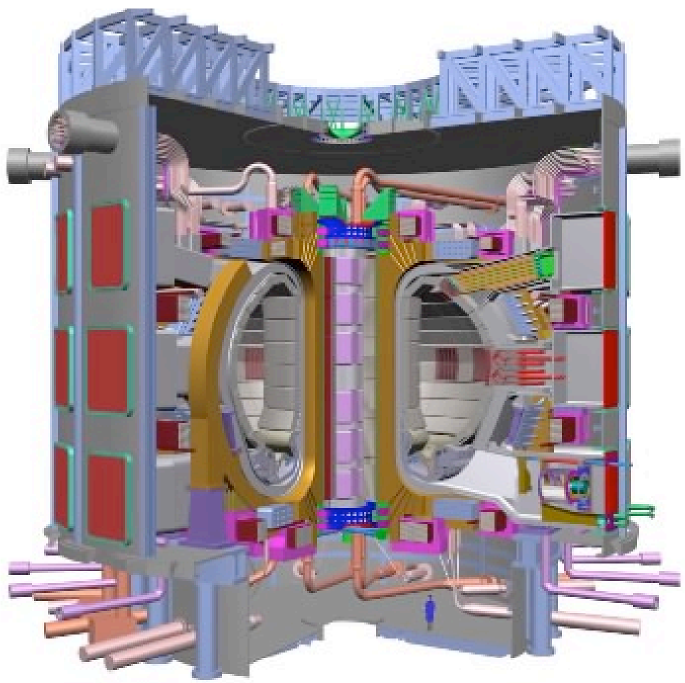




Acknowledgments

Dipole Fusion Concept

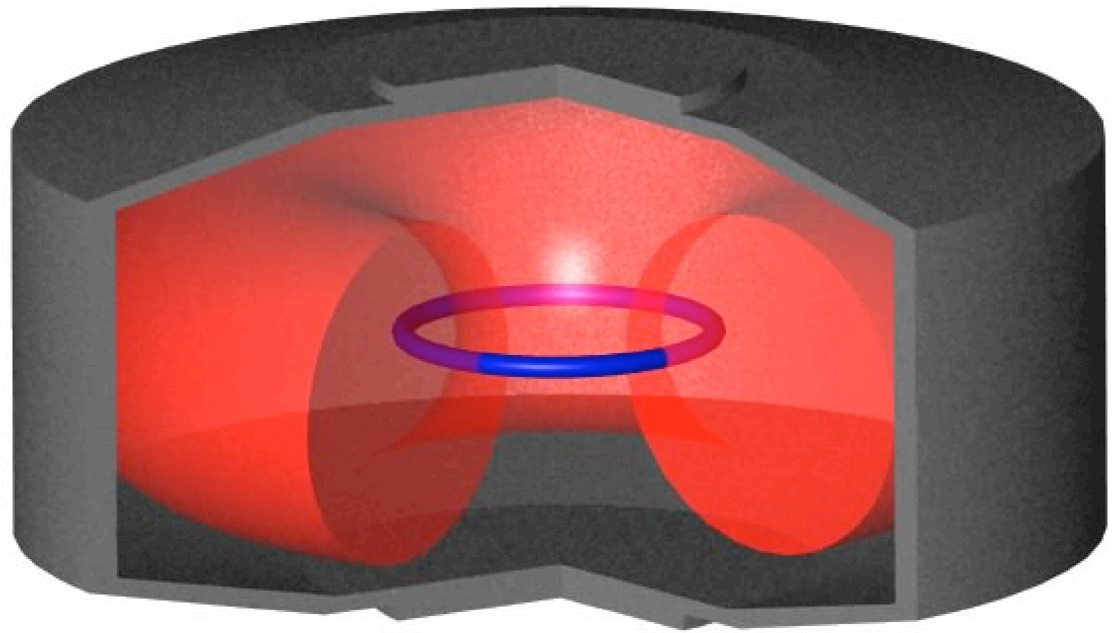
ITER



30 m

400-600 MW
DT Fusion

Levitated Dipole Reactor



60 m

500 MW
DD(He3) Fusion

Kesner, et. al. Nucl. Fus. 2002

Dipole Fusion Concept

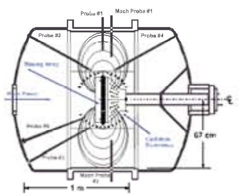
- Advanced fusion fuel…
  - D-D (^3He) with active triton removal
  - No tritium breeding; simplified fusion technology
- Requires…
  - High plasma beta
  - Good plasma energy confinement
  - Poor particle (*i.e.* triton) confinement
  - High-field, high-temperature superconductors

What We've Learned #1 to #3:

Dipole Plasmas Are Easy to Make and to Control

1. Robust microwave/ECRH plasma start-up
2. Pressure and density profile control is readily obtained using multi-frequency ECRH
3. Controlling the neutral fueling rate stabilizes hot electron interchange mode and produces high beta quasi-steady anisotropic plasma

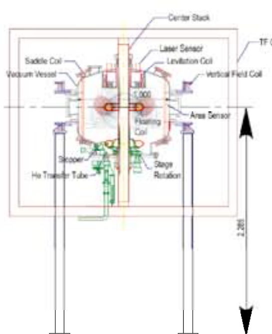
Today's Dipole Experiments

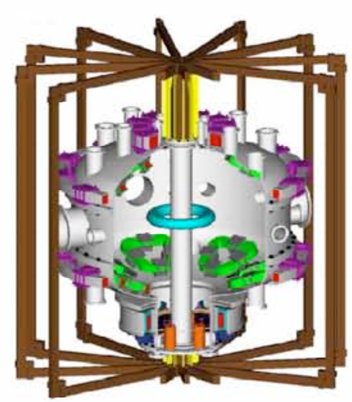


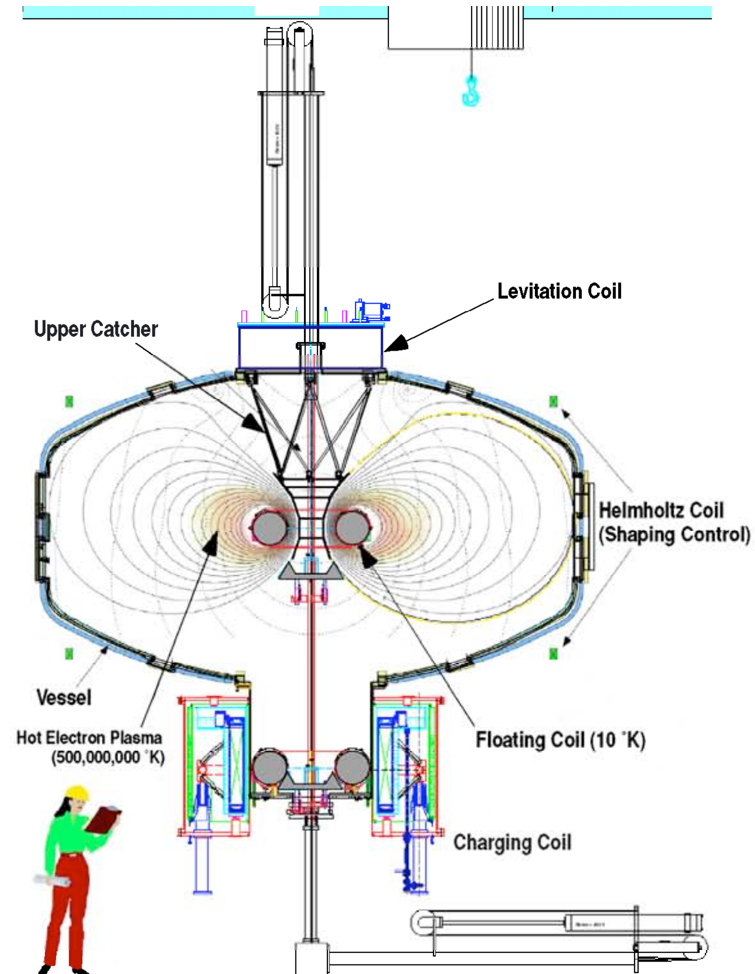
Investigate Instability- or Electrostatically-Driven Interchange Mixing

CTX (Columbia)

150 kA turns
(Not Levitated)
0.15 m







Mini-RT (Univ. Tokyo)

50 kA turns
17 kg
0.15 m

RT-1 (Univ. Tokyo)

250 kA turns
110 kg
0.25 m

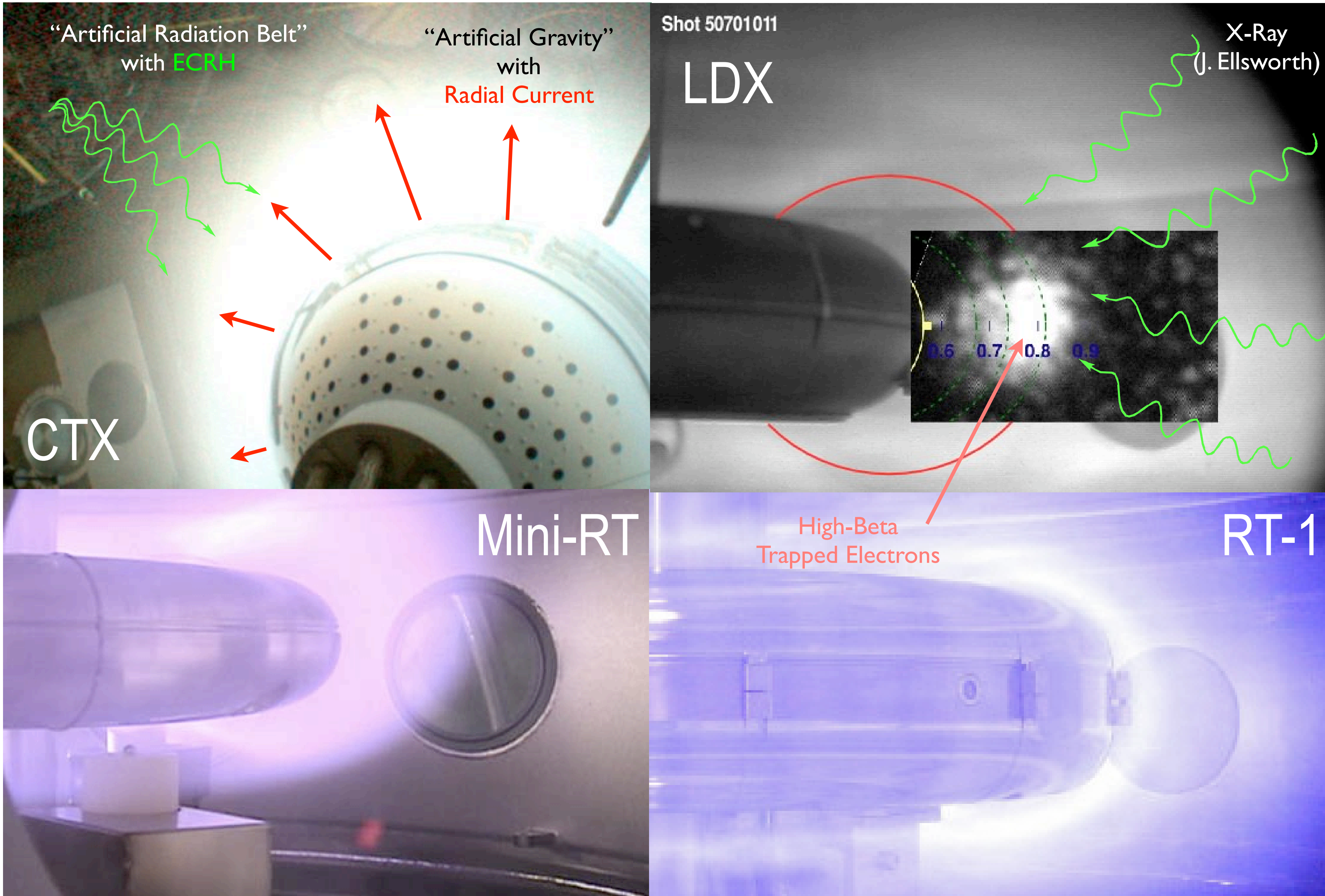
LDX (Columbia-MIT)

1200 kA turns
565 kg
0.34 m

Test Beltrami Physics

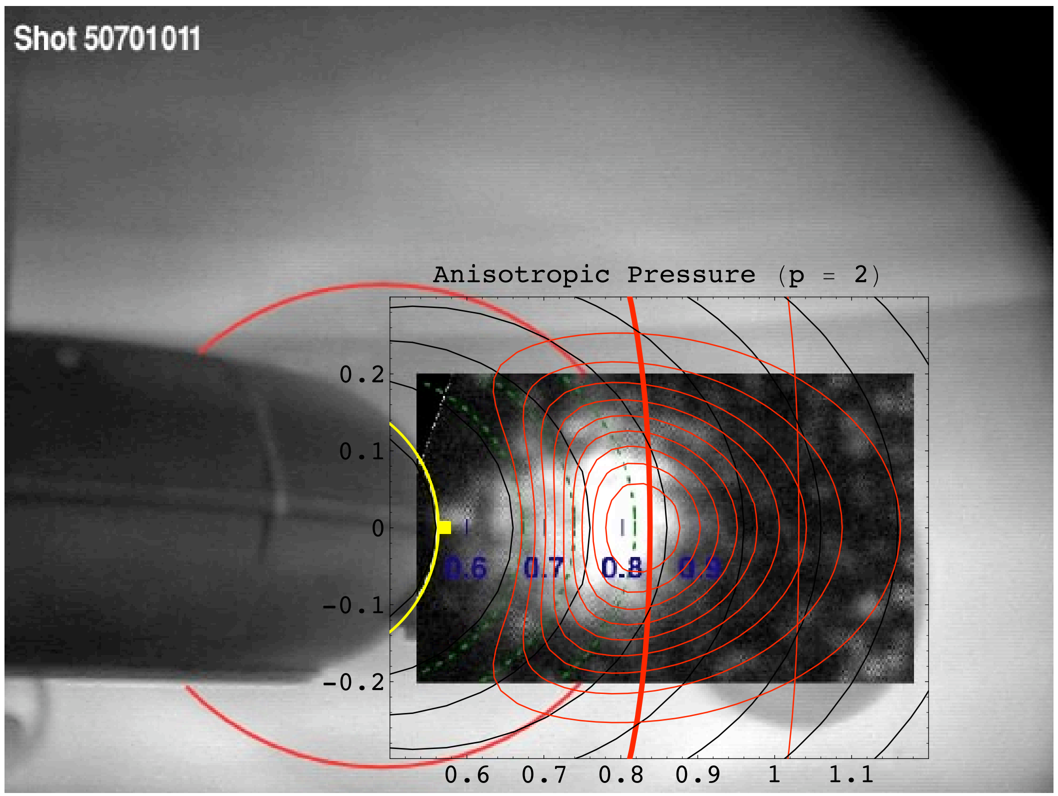
Test Fusion-Dipole Physics

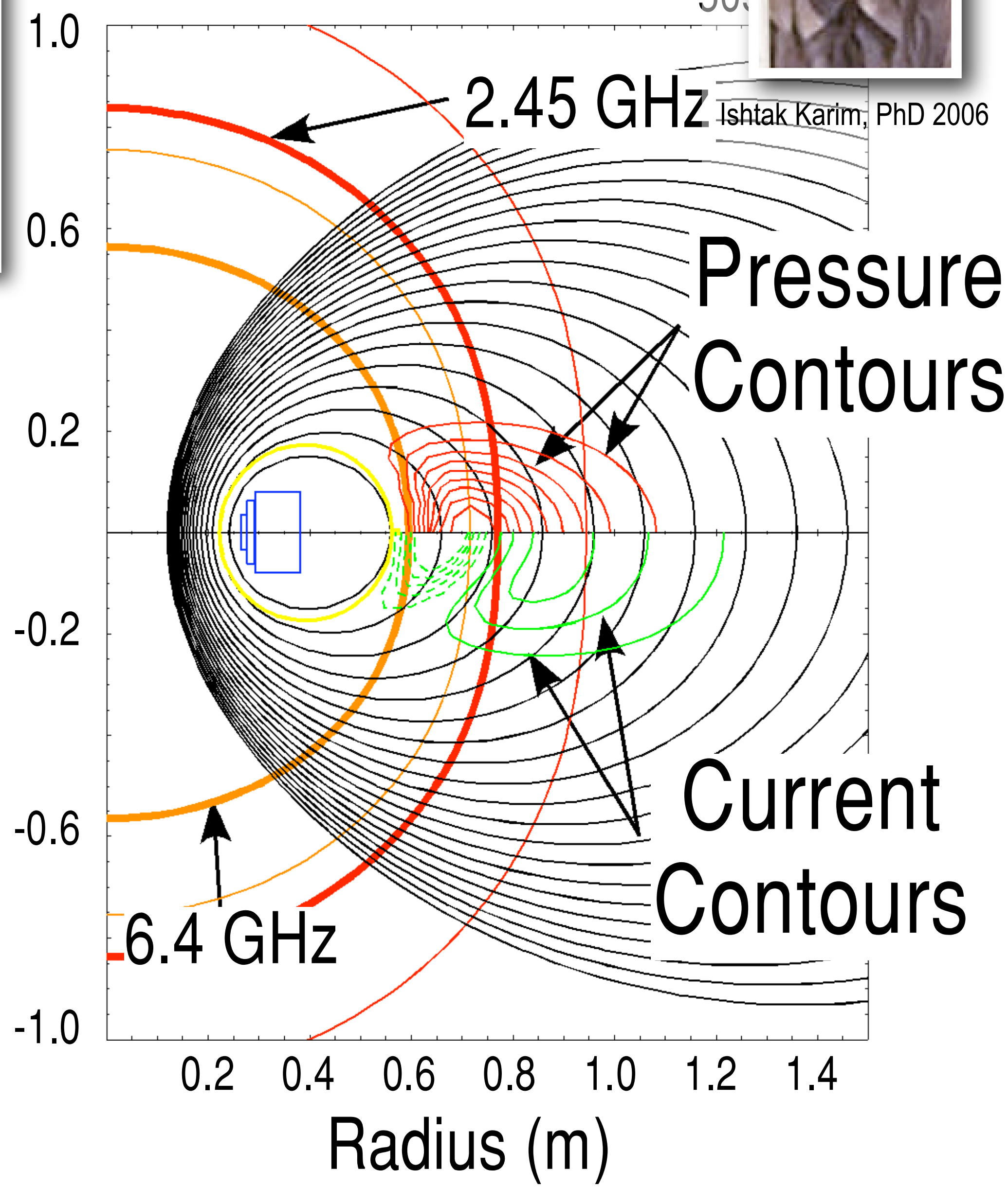
ECRH Sustained Dipole Plasmas



LDX: High Beta on First Shot!

Peak pressure "in-between" 2.45 and 6.4 resonance.

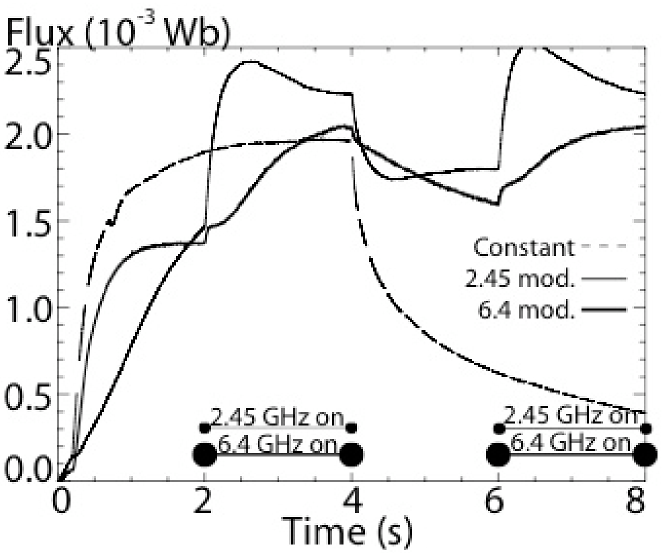




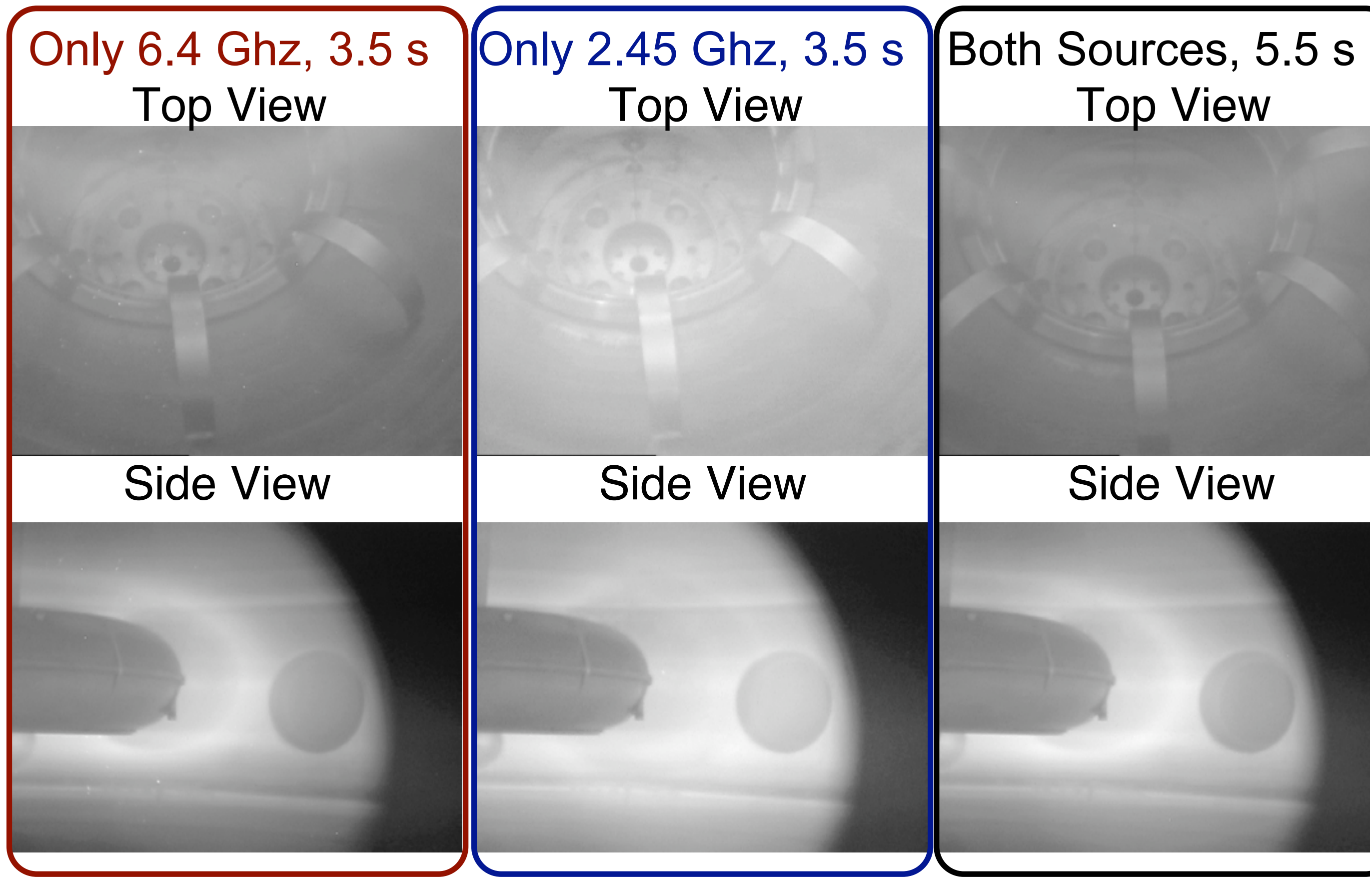
Ishtak Karim, PhD 2006

Multi-Frequency ECRH Profile Control…

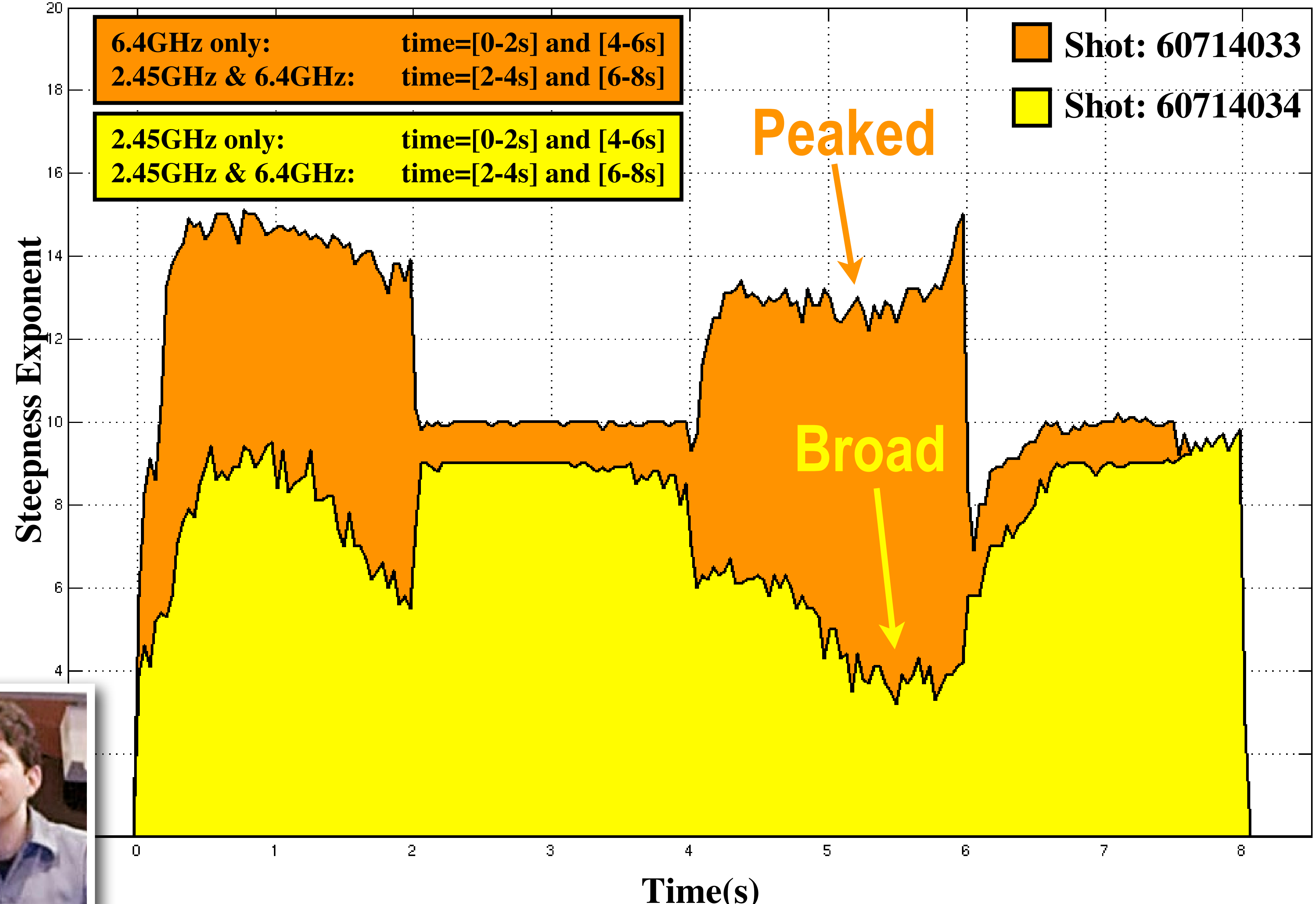
Alex Hansen



Plasma Photos



DENSITY PROFILE CONTROLLED BY ECRH



Alex Boxer

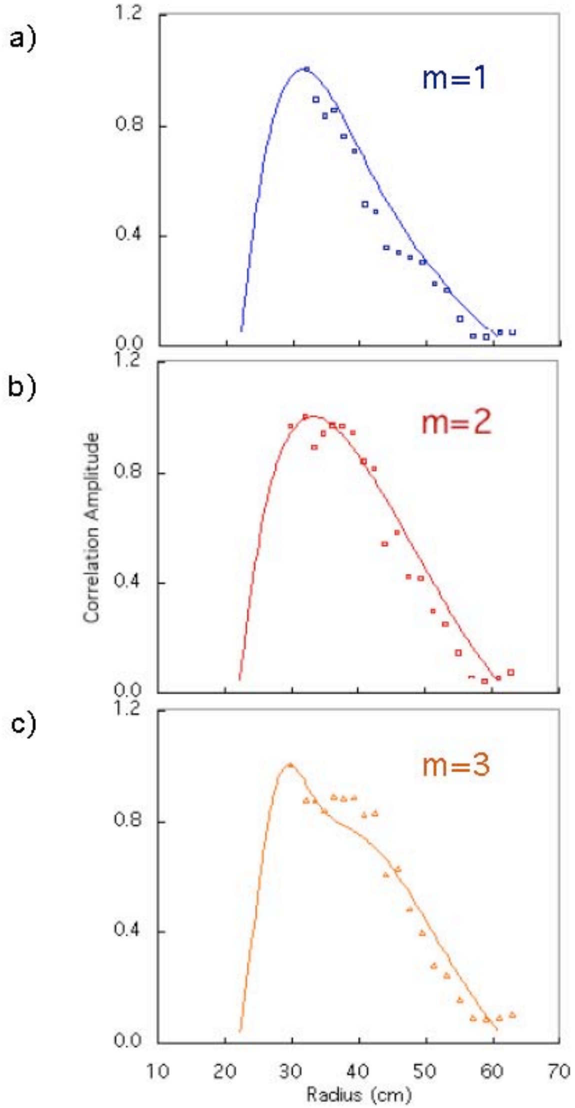
What We've Learned #4:

Dipole Plasma Dynamics Dominated by "MHD-Like" Interchange Modes

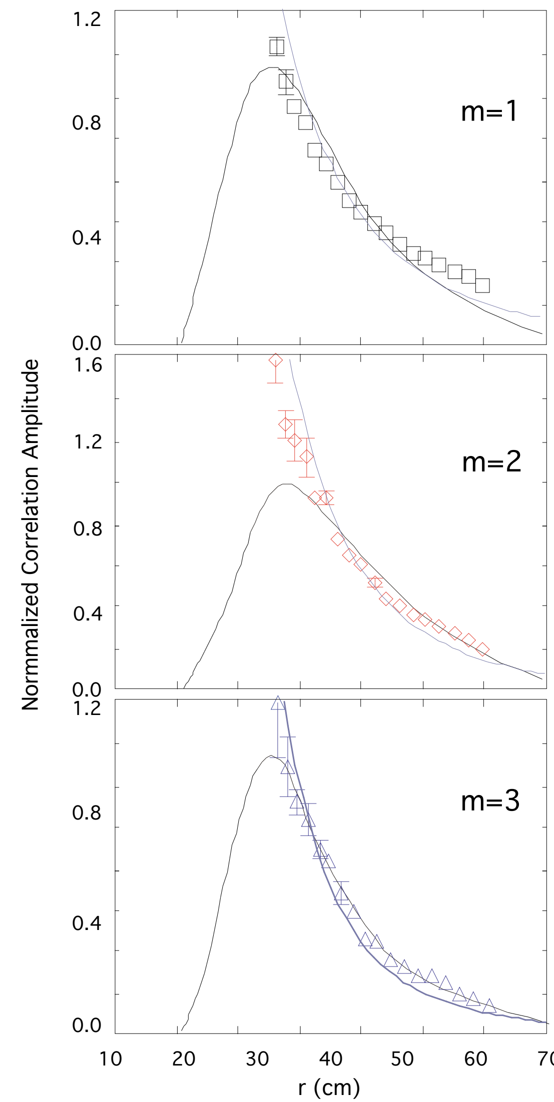
- Kinetic and centrifugal/gravity modes have broad radial structures just like "fixed-boundary" ideal MHD modes.
- Potential fluctuations constant along B
- Kinetic effects stabilize higher *m* modes near marginal stability. *m* = 1 usually dominates.

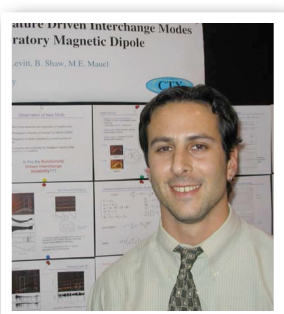
Dipole Interchange Modes have **Broad** Radial Structures

Centrifugal Interchange



Hot Electron Interchange

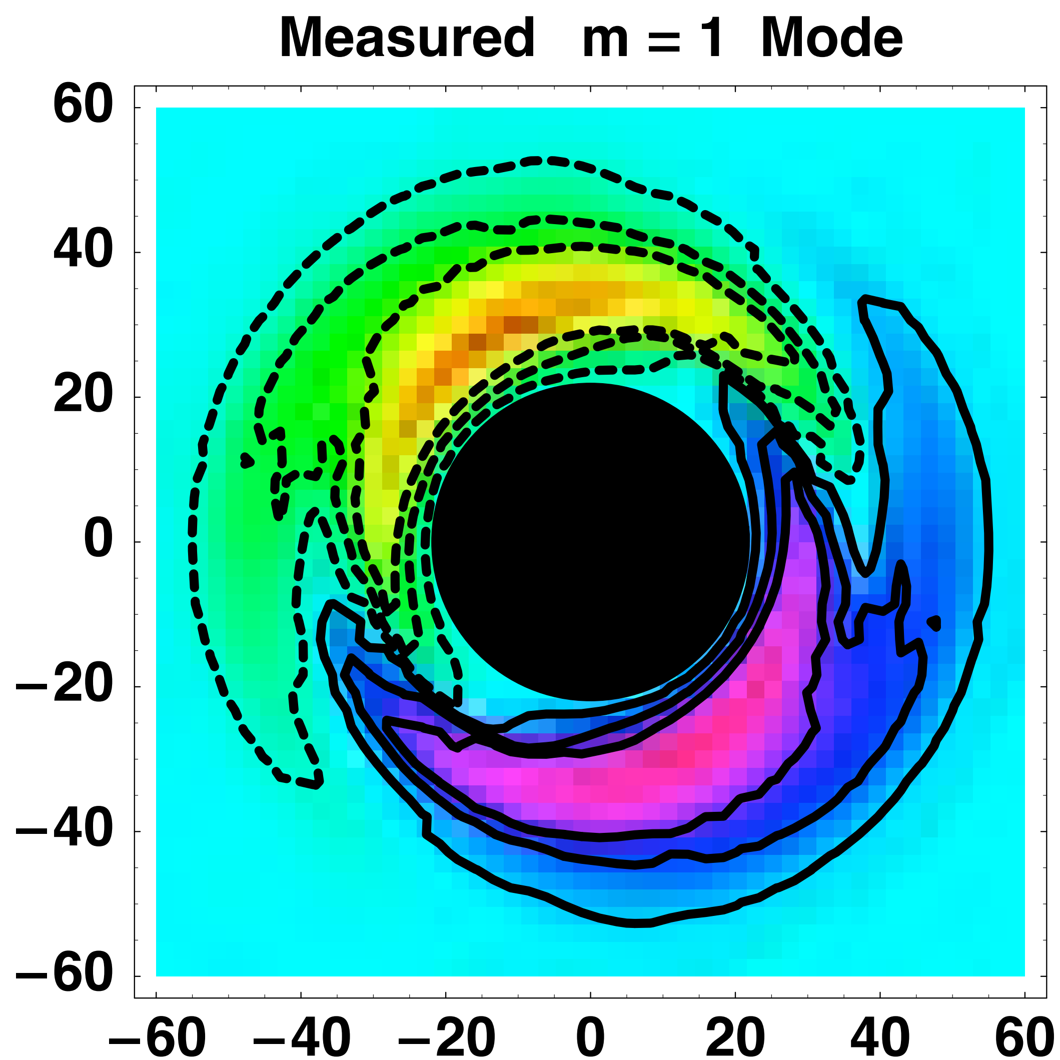




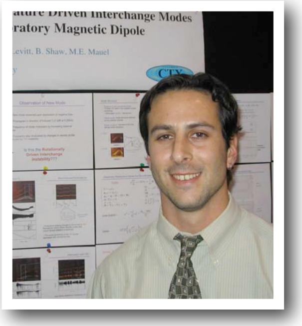
Ben Levitt, PhD 04

(Computed, self-consistent, mode structures shown with solid lines.)

Measured Centrifugal Mode Structure
(A "Fixed Boundary" MHD Mode)



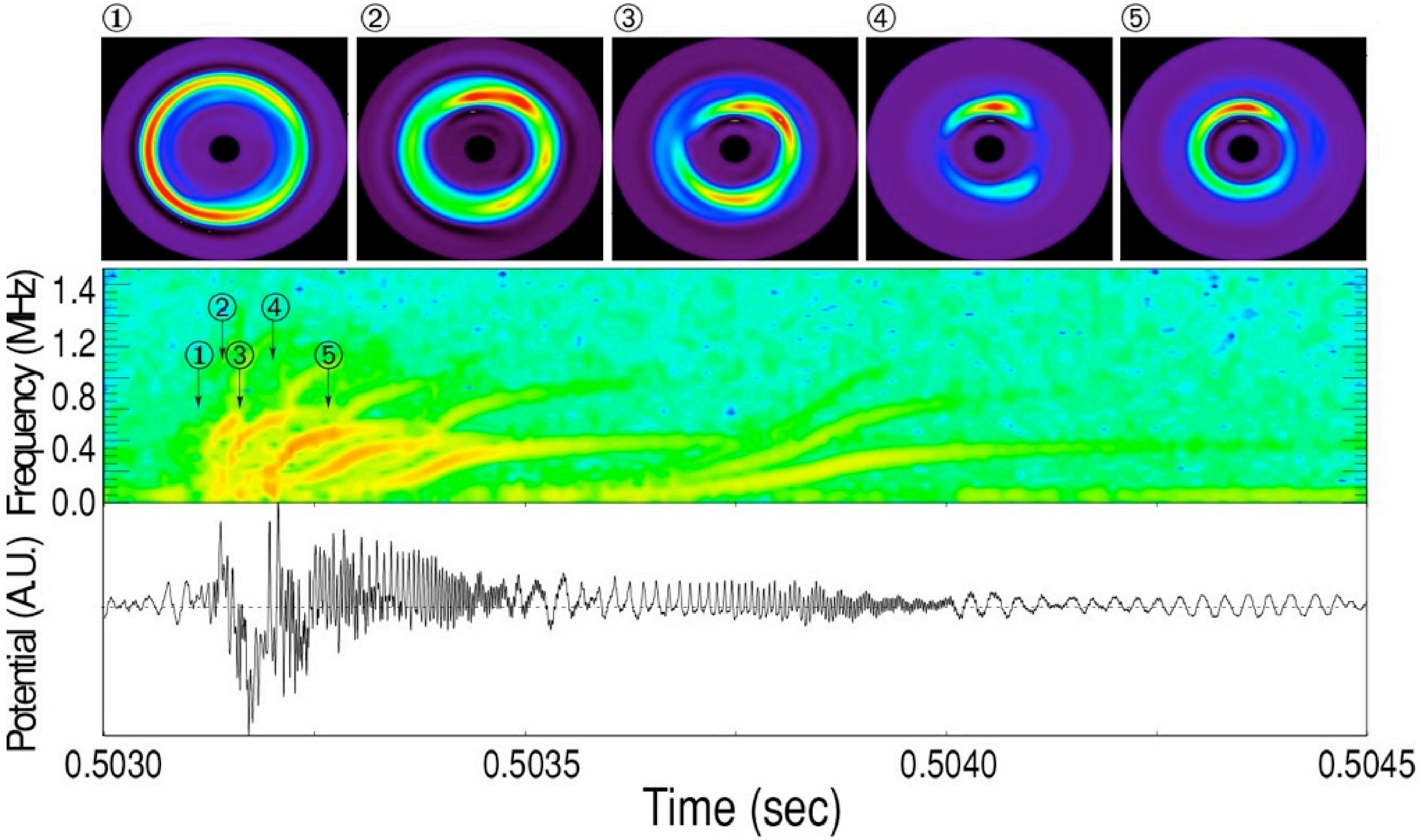
(ϕ ~ Stream function)



Ben Levitt, PhD 04

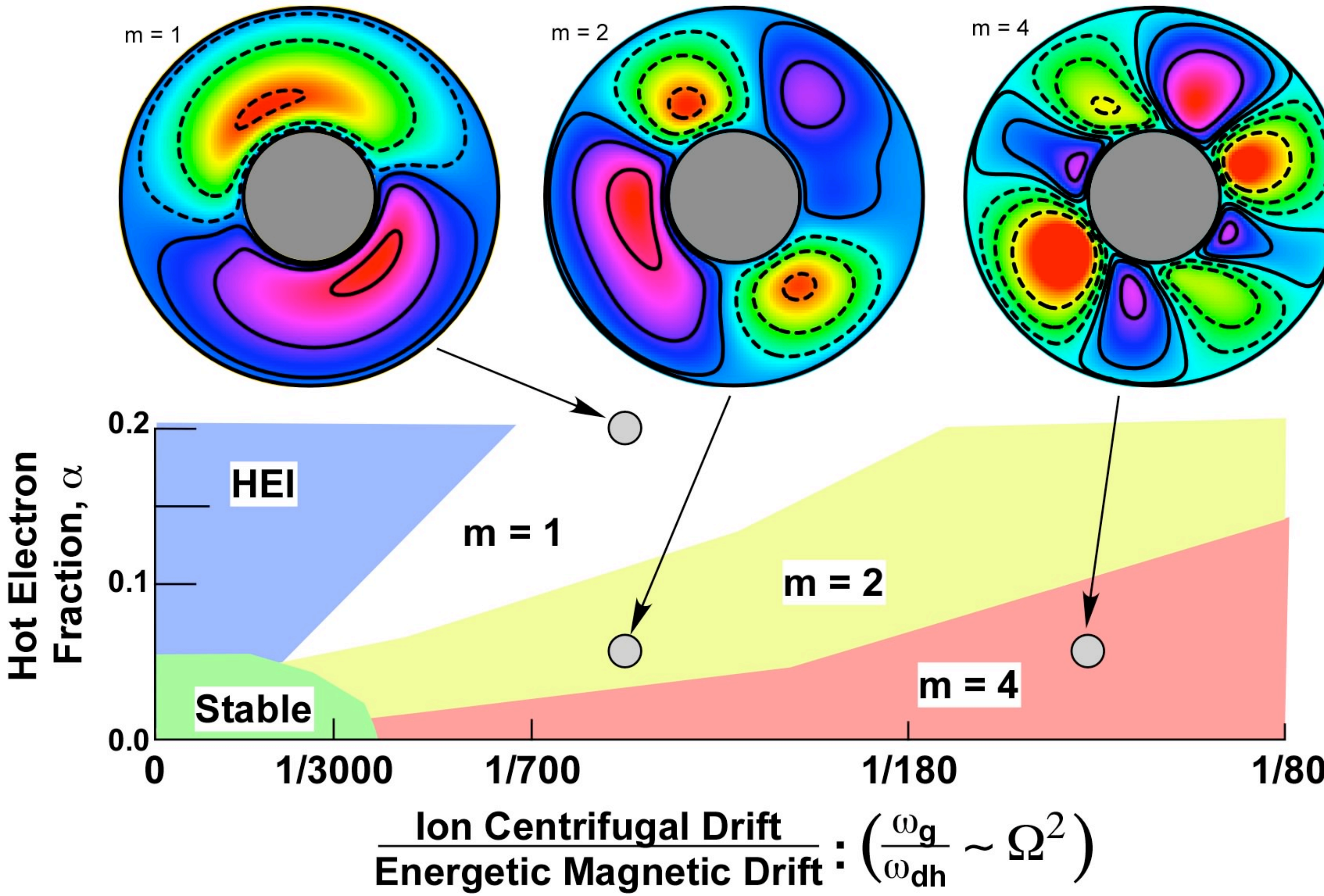
Measured Kinetic Interchange Mode: Structure of Driven Polar Losses

(A Kinetic MHD Mode)



Brian Grierson

Relative Strength of Centrifugal and Curvature Drives Determine Nonlinear Mode Structure



Ideal MHD

The ideal MHD equations are

$$\begin{aligned}
nM_i\frac{d\mathbf{V}}{dt} &= -\nabla P + \mathbf{J}\times\mathbf{B} \\
\frac{\partial n}{\partial t} + \nabla\cdot n\mathbf{V} &= 0 \\
\mathbf{E} + \mathbf{V}\times\mathbf{B} &= 0 \\
\nabla\cdot\mathbf{J} &= 0 \\
\frac{\partial P}{\partial t} + \nabla\cdot(P\mathbf{V}) &= -(\gamma-1)P\nabla\cdot\mathbf{V}
\end{aligned}$$

where $\gamma = 5/3$.

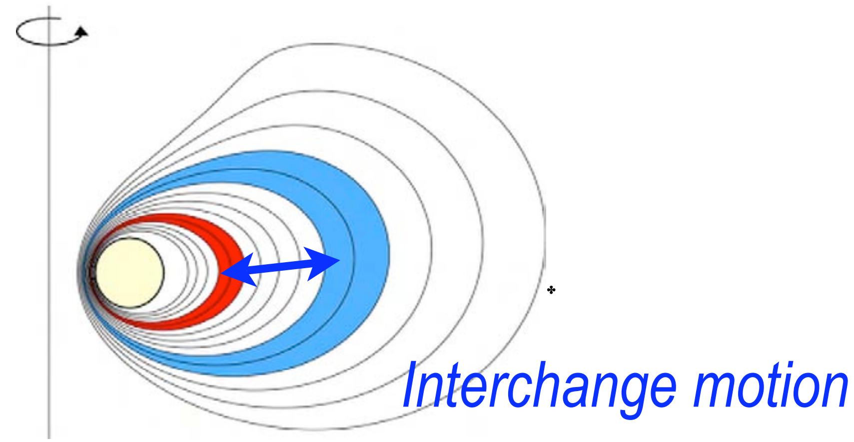
Rosenbluth and Langmuir, 1957

$\mathbf{E}\cdot\mathbf{B} = 0$, $\mathbf{E} = -\nabla\Phi$, axial symmetry, $\mathbf{B} = \nabla\varphi \times \nabla\psi$, and the electric potential, $\Phi(\psi, \varphi)$, is constant along a field line.

The plasma flow is **two-dimensional**,

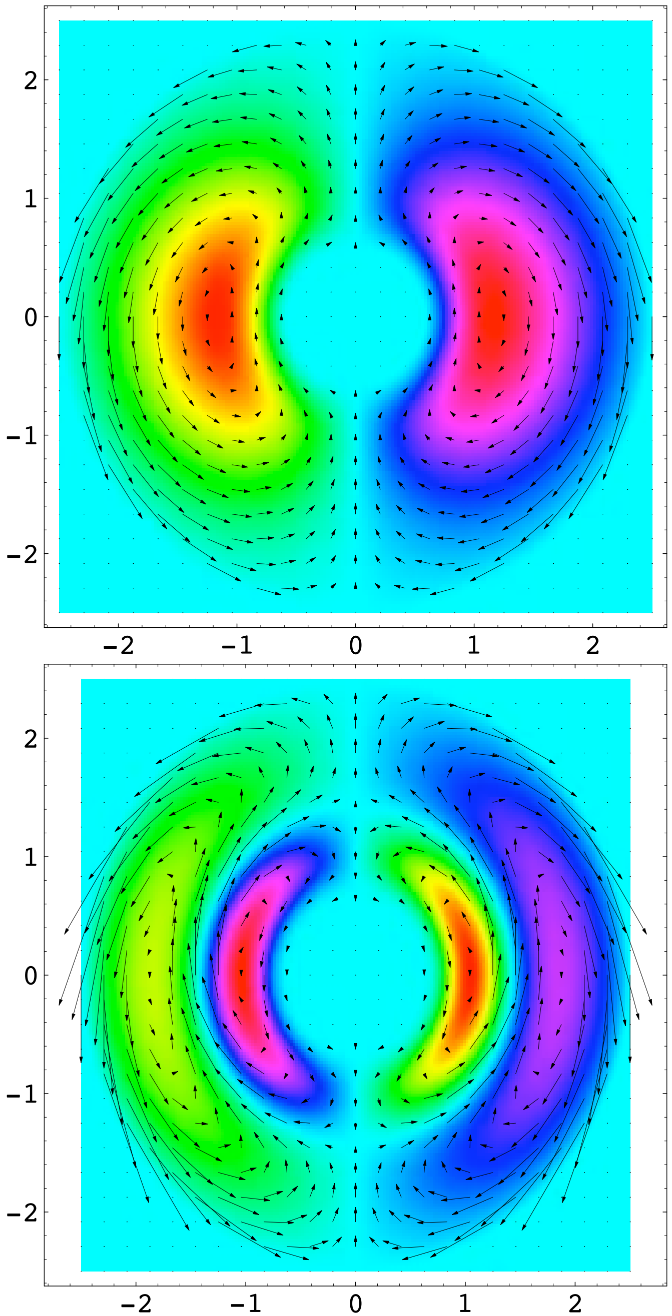
$$\mathbf{V} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = -\hat{\varphi} R \frac{\partial\Phi}{\partial\psi} + \frac{\hat{\psi}}{RB}\frac{\partial\Phi}{\partial\varphi}$$

Low-frequency ($\omega < \omega_B$) plasma dynamics is well described by **flux-tube averaged** motion!

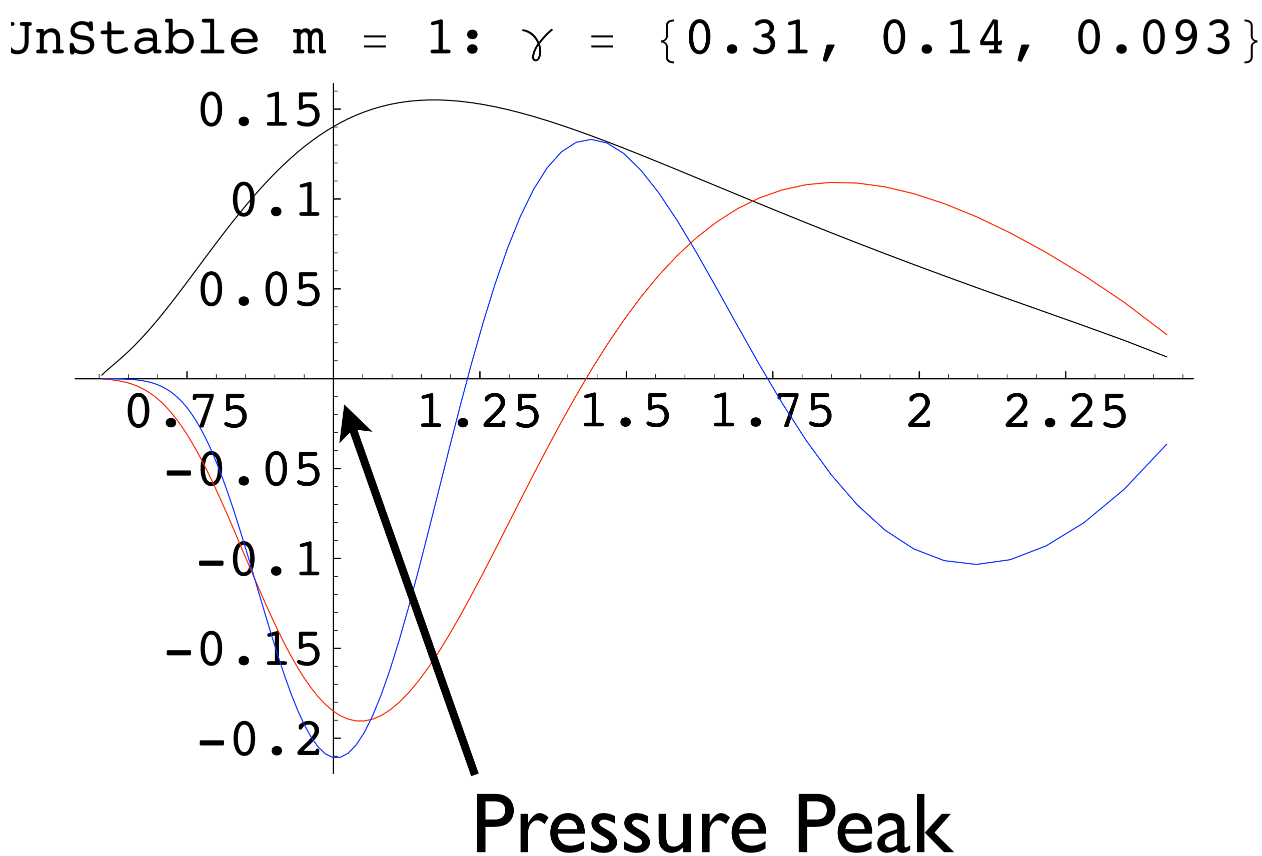


(…ballooning more stable than interchange.)

Typical Ideal Interchange Eigenmodes



Unstable "LDX"



(Radial structure variation always slows mode.)

What We've Learned #5:

Wave-Particle Dynamics in a Laboratory Dipole is **One-Dimensional**

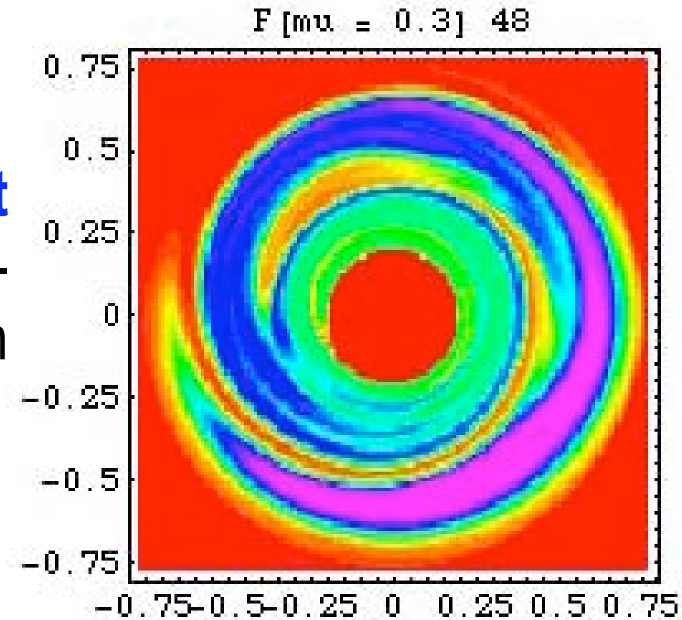
(at least for kinetic-interchange modes)

- (μ, J) remains invariant even during chaotic radial transport.
- Phase-space "holes" have long lifetimes during frequency sweeping.
- "Holes" can be destroyed with low-power RF scattering.
- High beta electron transport can be *very small* or *rapid and disruptive*.

Drift-Resonances: Phase-Space "Holes"

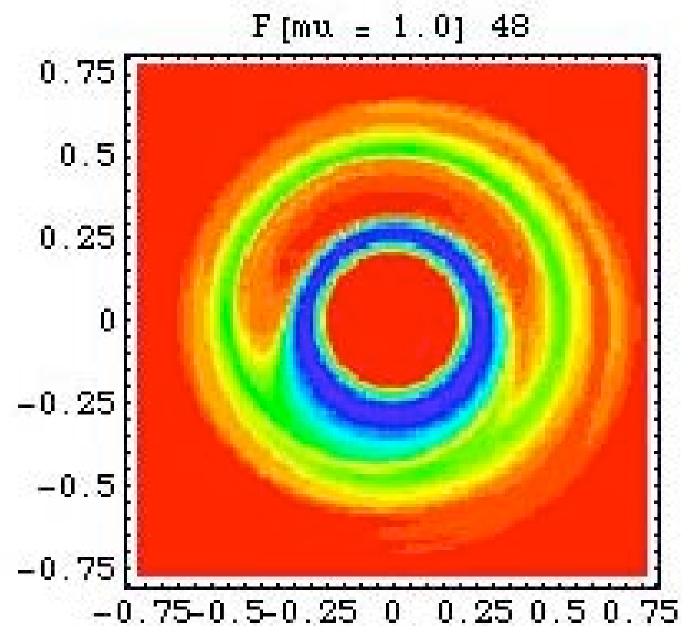
Harry Warren, PhD 1994

Chaotic, drift-resonant transport induced by a "beautiful chorus" of fast-electron interchange instabilities with frequency sweeping
(Warren, PRL, 1995)

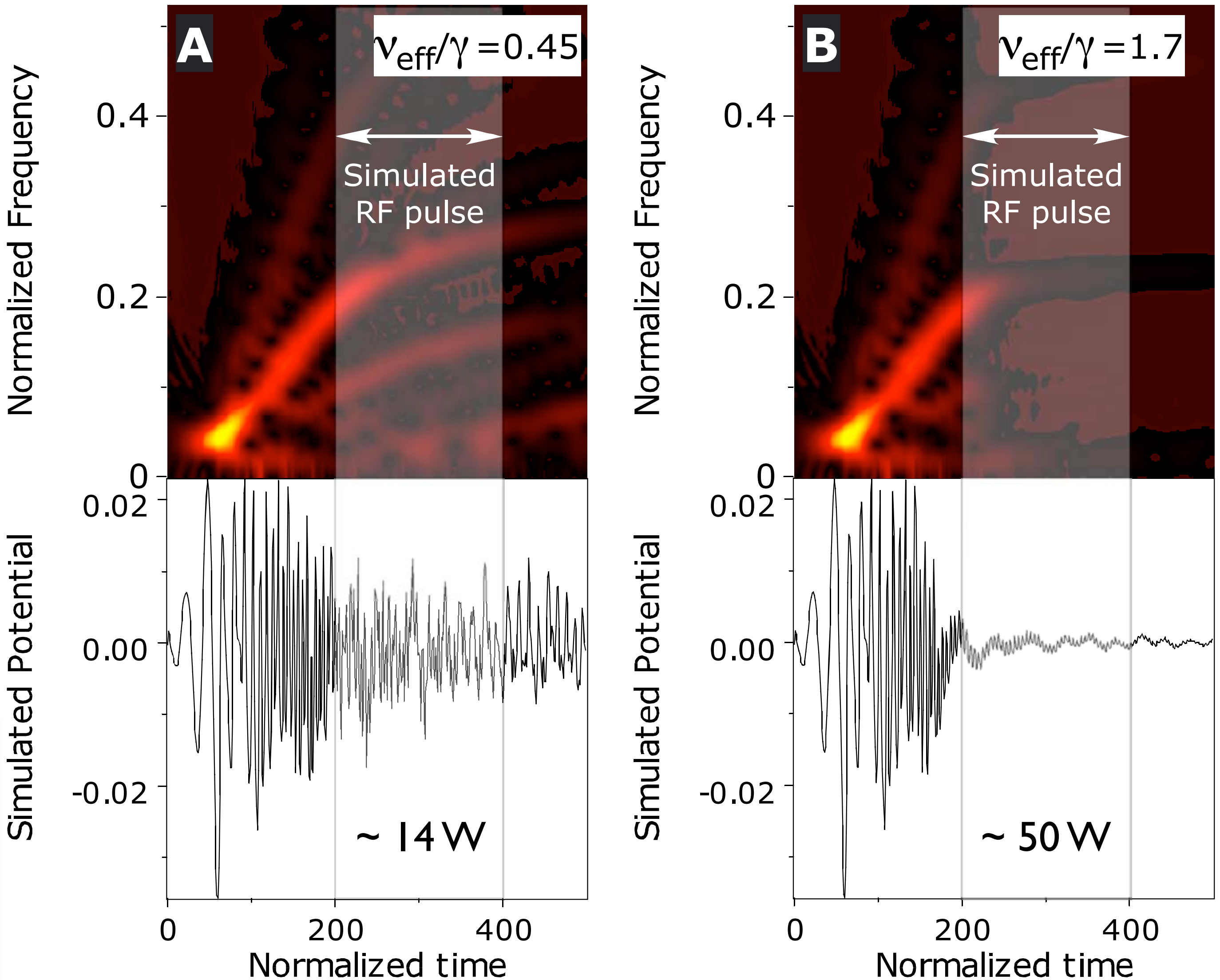


Dmitry Maslovsky, PhD 2003

Fast-electron, gyrokinetic interchange instability creates inward-propagating "**phase-space holes**" (bubbles) and a chorus of rising tones.
(Maslovsky, PRL, 2003)



Nonlinear Simulation Reproduces Measured Frequency Sweeping Suppression



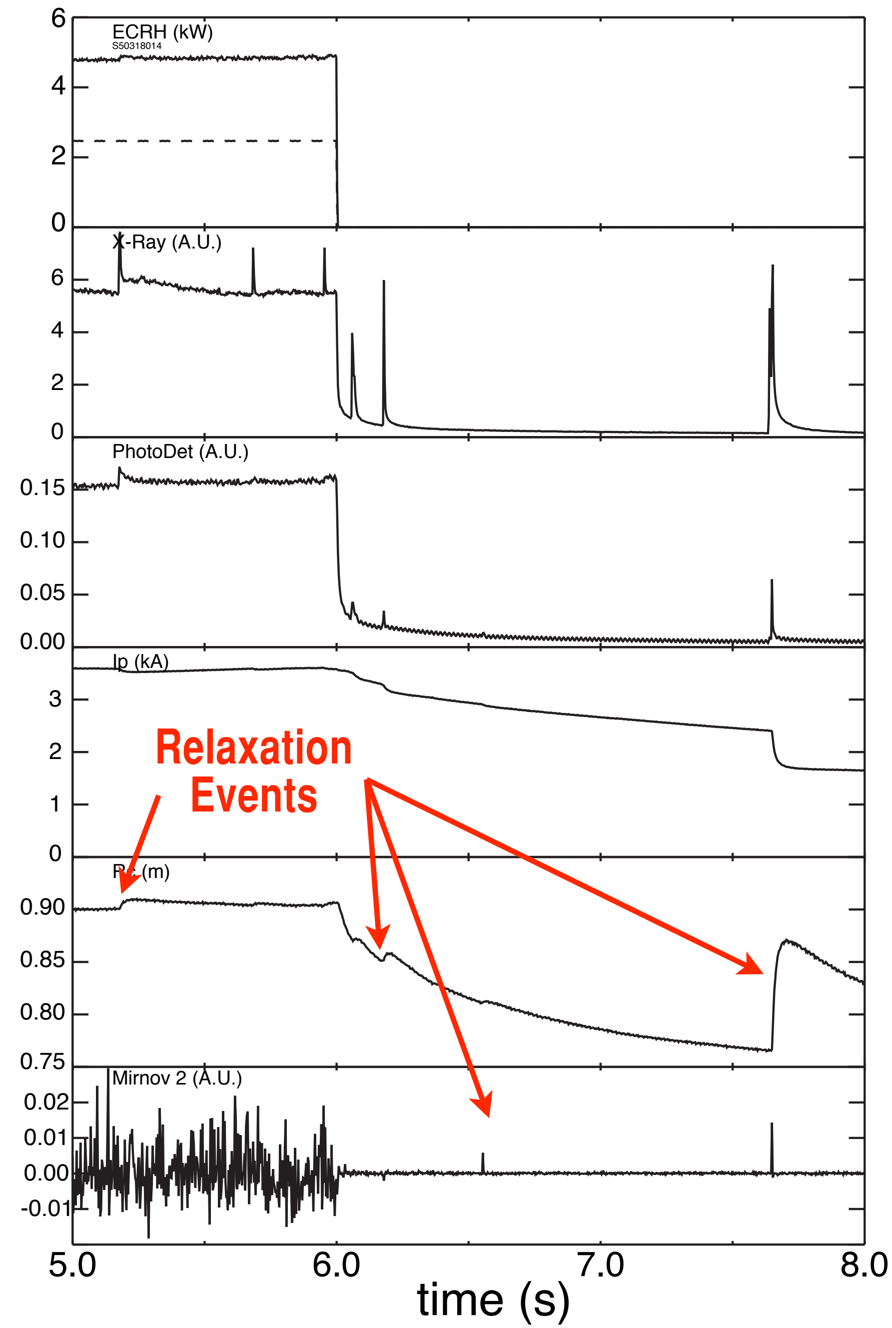
Dmitry Maslovsky, PhD 2003

$$\frac{\partial}{\partial t} F(\mu, \psi, \varphi, t) = D(\psi, t) \frac{\partial^2}{\partial \mu^2} (F - F^*)$$

Isolated Relaxation Events and Rapid Beta "Collapse" at High Beta

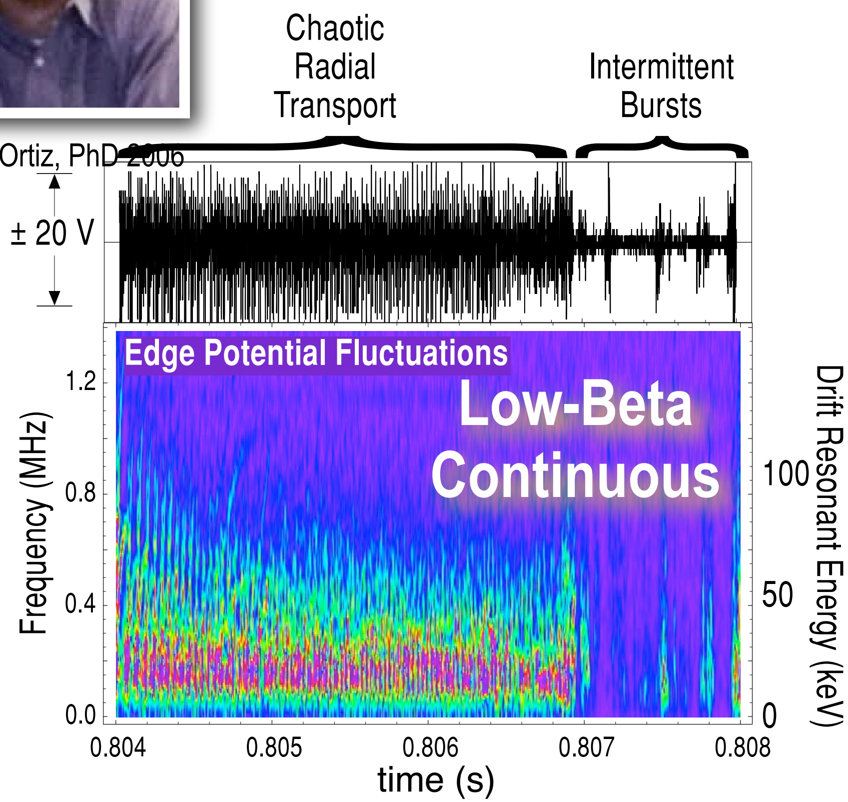
Eugenio Ortiz, PhD 2006

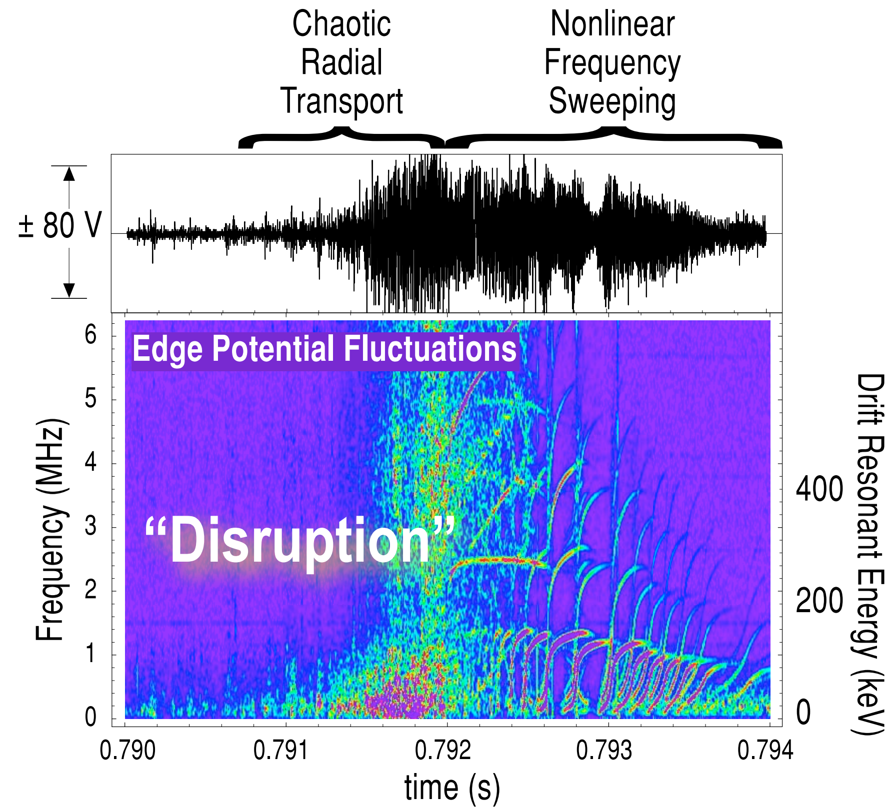
- At high β, periodic "relaxation" events occur a few times per second. **Outward motion of ring currrent.** (Also, x-ray and μwave bursts !)
- Depending upon neutral fueling and heating power, relaxation events can be ***small*** or ***fully disrupt*** high-beta regime.
- HEI can appear in (nearly?) all cases
- LDX is the first to observe the HEI in a ***high-beta*** dipole plasma!



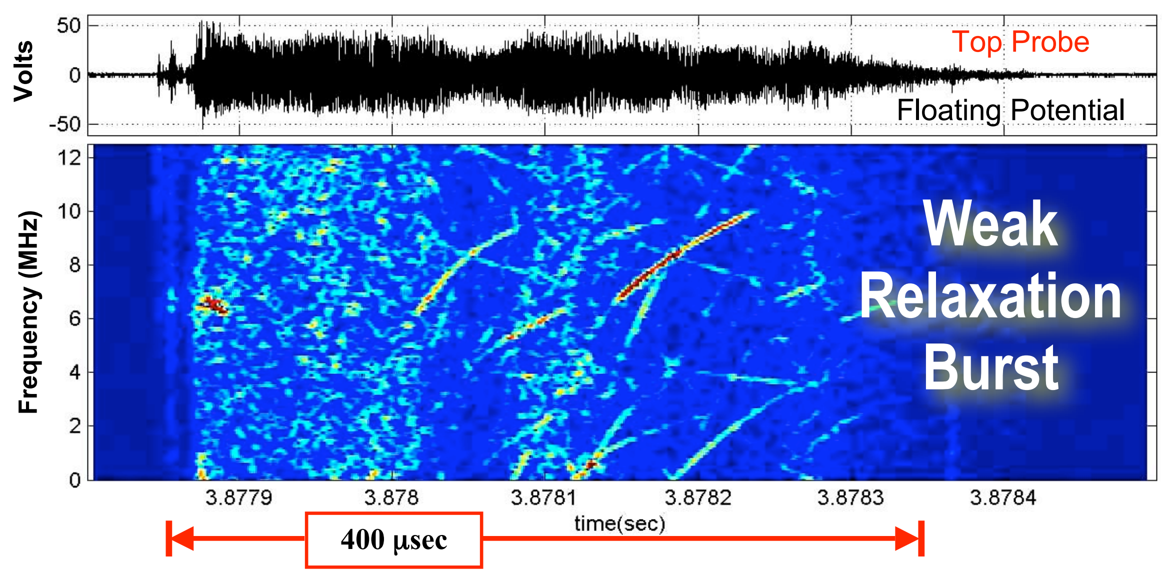
Three Types of Fast Electron Interchange Spectra

Eugenio Ortiz, PhD 2006





Instability behavior determined by beta and by gas fueling history! (Hysteresis)



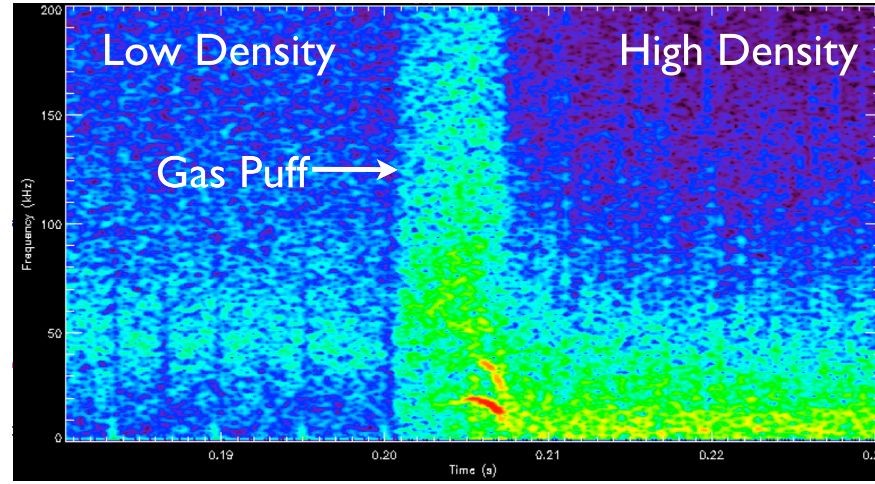
What We've Learned #6:

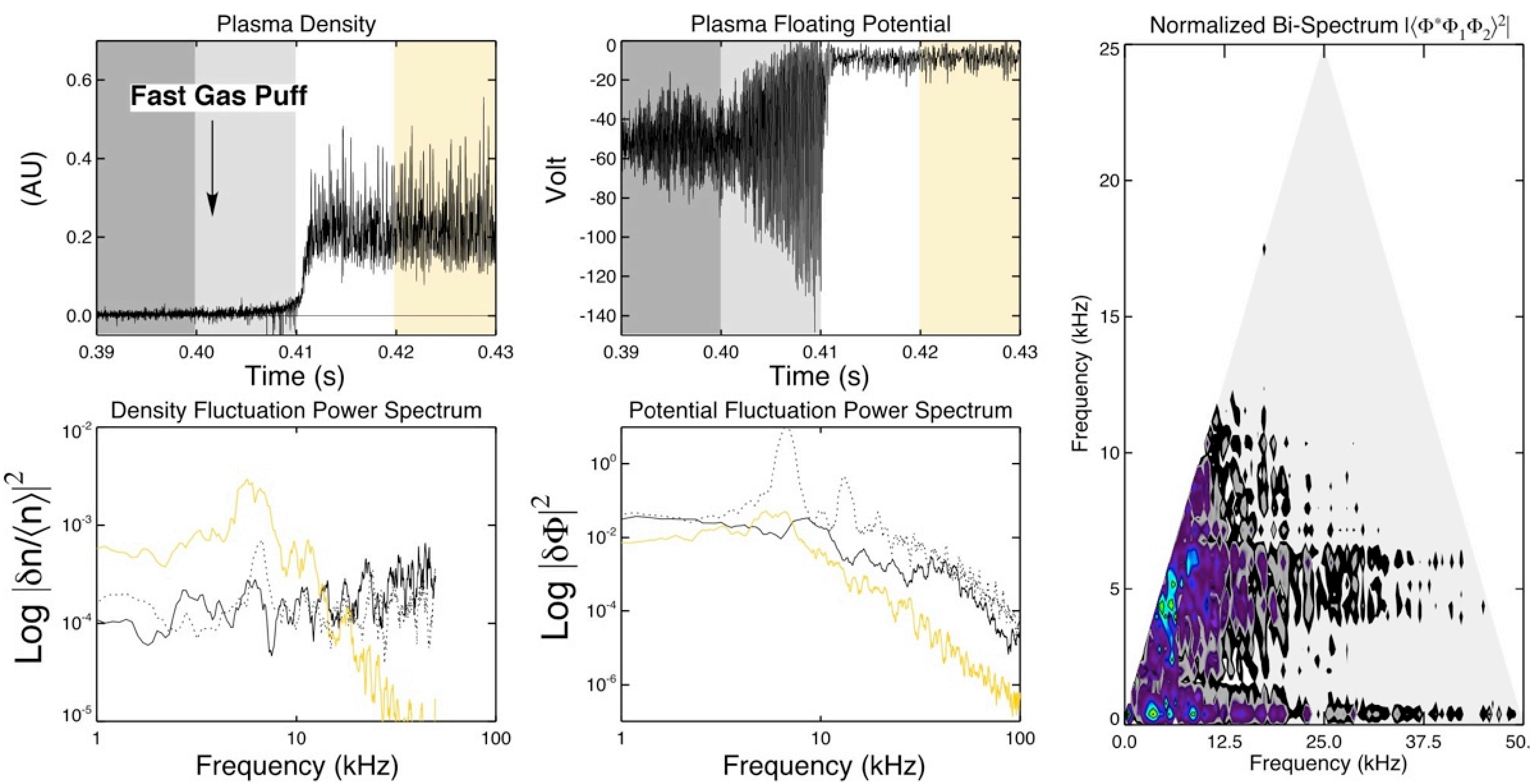
Turbulence in a Laboratory Dipole has **Length Scales Dominated by the System Size**

- Power-law spectrum for convective turbulence.
- Low-frequencies (in the rotating plasma frame) characterize the dominant long wavelengths.
- Transients and phase-transitions mediated by large $m = 1$ rotating perturbations.

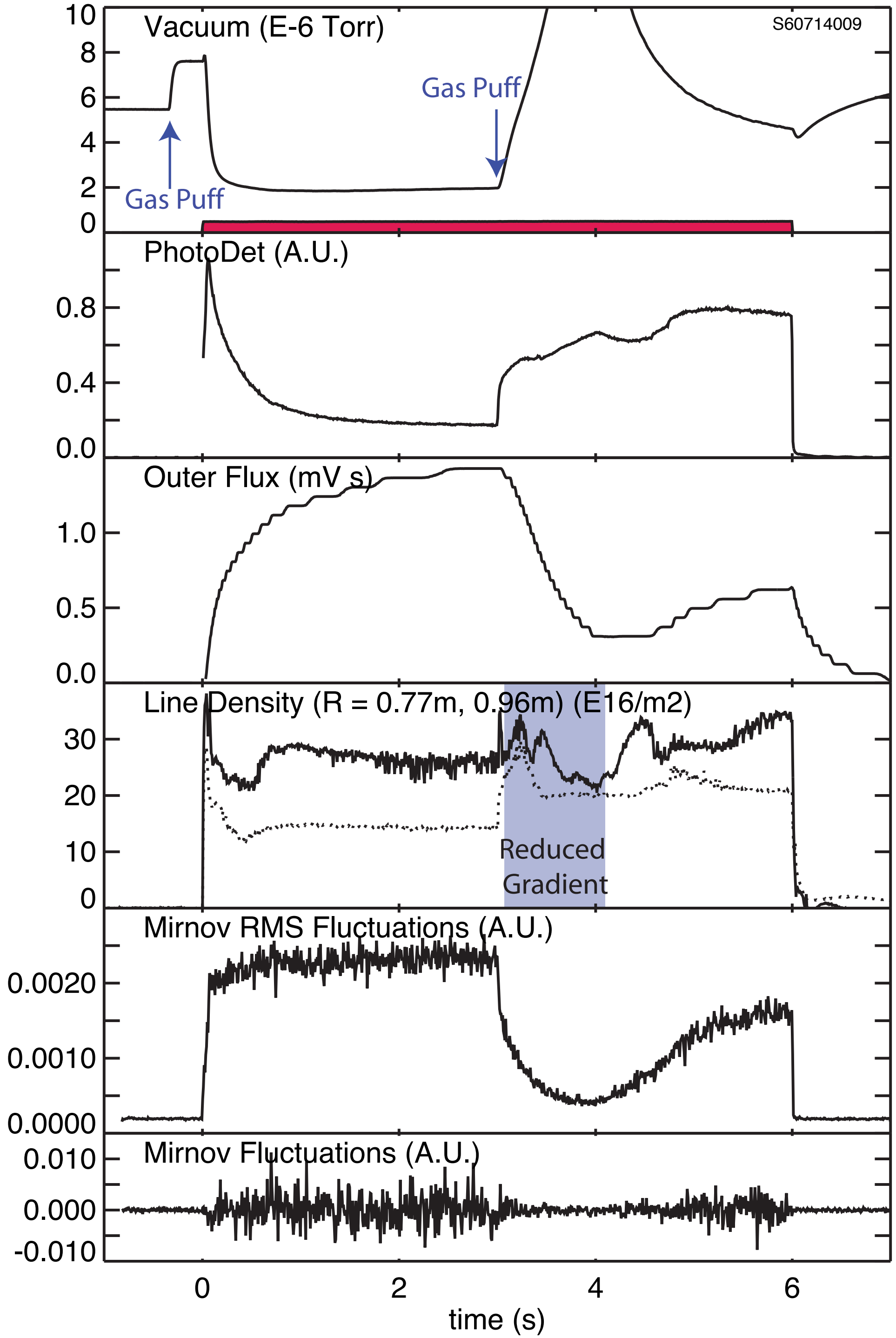
Evolution of Spectrum with Gas Fueling Rate Change

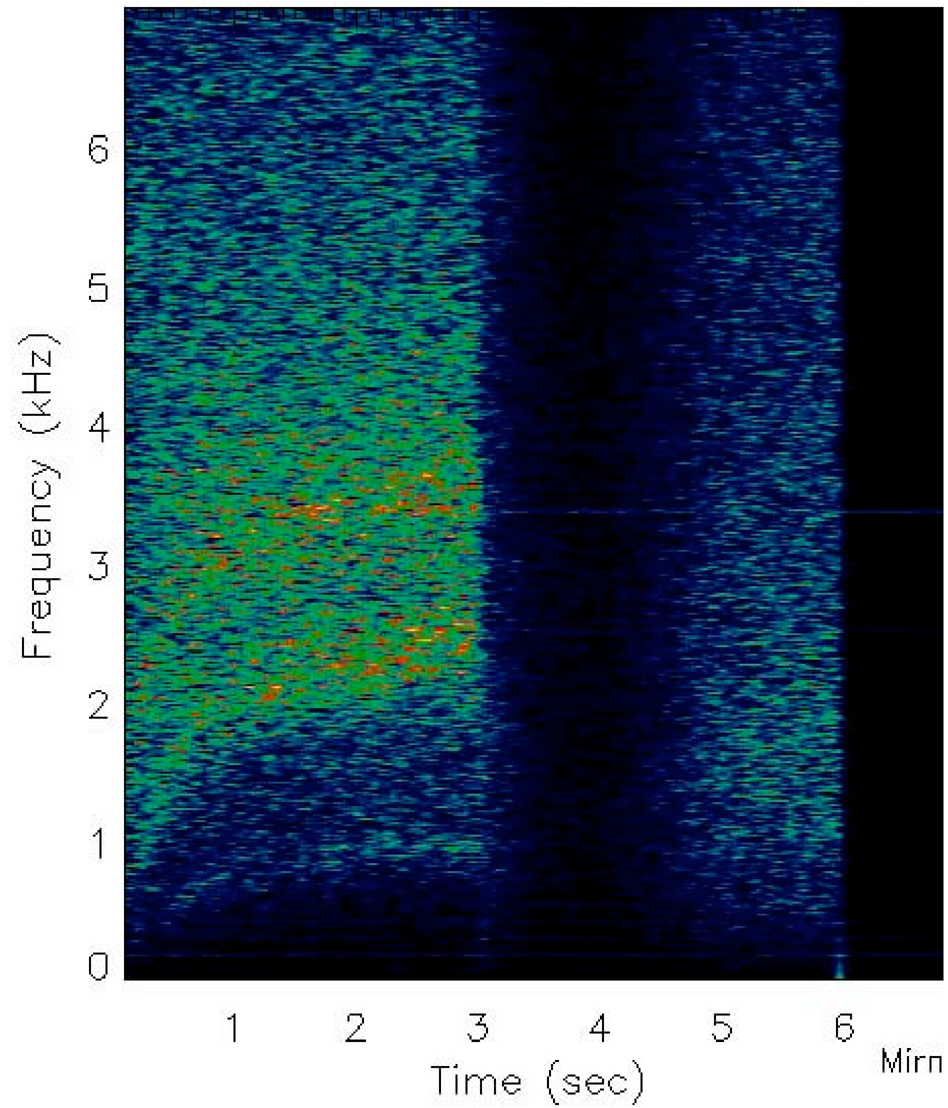
Brian Grierson
Matt Worstell





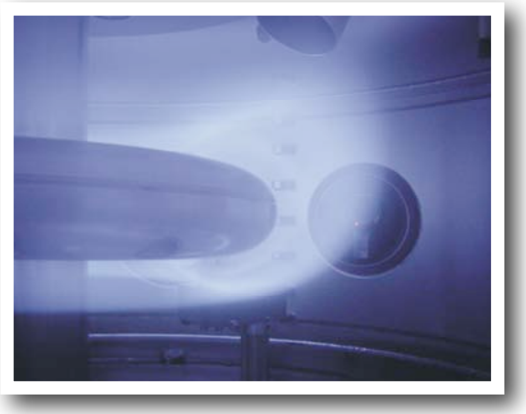
Coherent Fluctuations Suppressed with Flatter Gradient





What We've Learned #7:

Levitation Causes "Dramatic" Confinement Improvement



Mini-RT

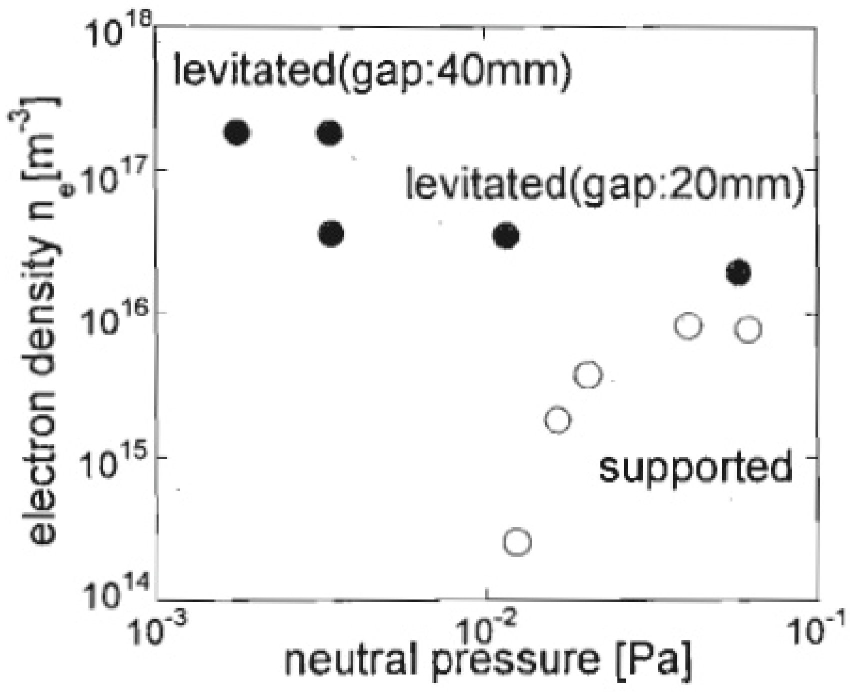


Fig. 5 Dependence of electron density on filling neutral gas pressure.

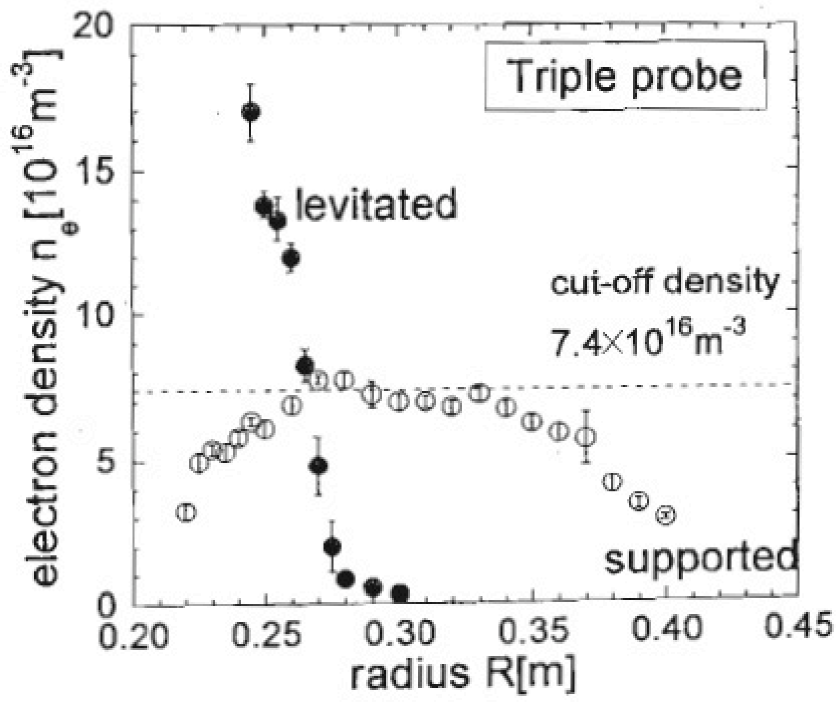


Fig. 7 Electron density profile with levitated internal coil measured by the electrostatic probe.

Still Many Unanswered Questions…

- What (and why) are the particle and energy transport rates?
- How do these rates depend upon the convective turbulence?
- What are the characteristics of the convective/ turbulent transport as profiles are adjusted? Why?
- Is thermal transport adiabatic in a dipole plasma?

Summary

- Dipoles provide magnetic confinement for hot plasma in nature and in the laboratory (*and dipole physics may help fusion energy!*)
- The dipole has a unique field structure for study of confined plasma: unmatched diagnostic access, well-characterized magnetic geometry, and fascinating (and musical) wave-particle interactions.
- Two types of global interchange instabilities excited/modeled:
  - Hot electron interchange (fast) modes illustrate collisionless dynamics with "phase-space" mixing and "bubbles".
  - Centrifugal interchange (slow) modes illustrate MHD mass flows and convective mixing.
- The world's first **high-beta (β > 20%)** dipole-confined plasma has been created in LDX by stabilization of the fast-electron interchange instability with programmed gas fueling.