Experimentally Driving the Inverse Energy Cascade in a Dipole Confined Plasma

Matthew Worstell

January 27, 2012

M.E. Mauel, T.M. Roberts

Columbia University
in the City of New York

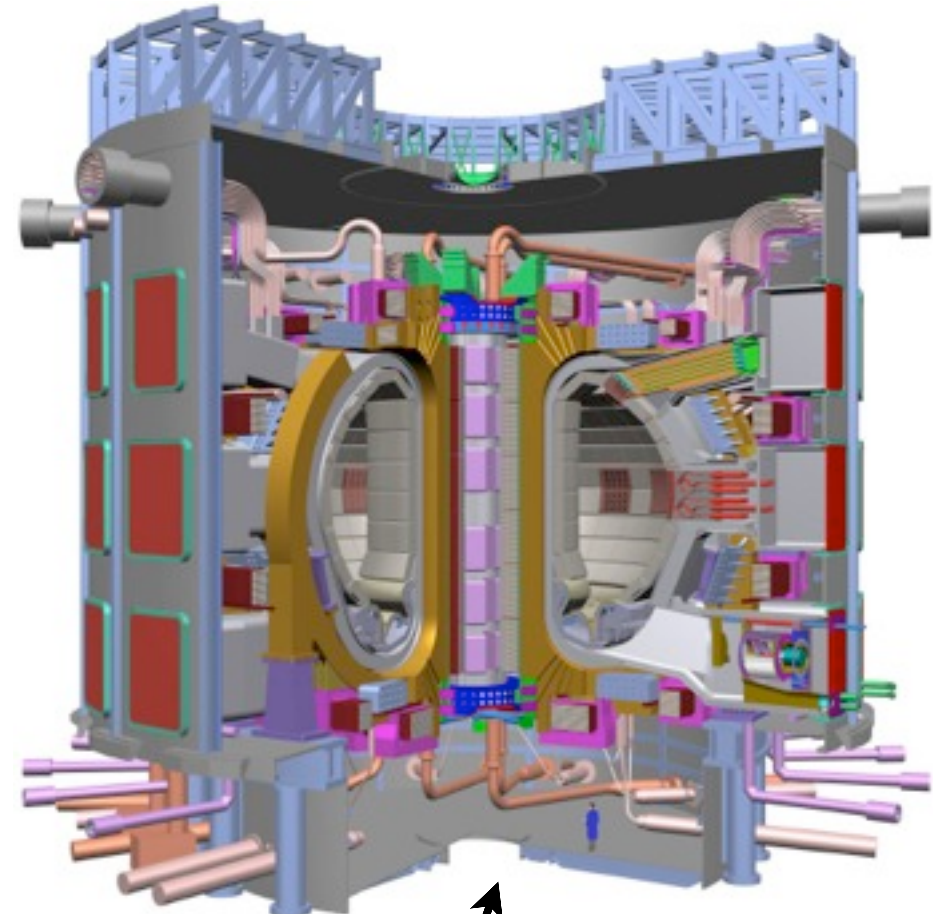
Outline

- Dipoles within the topological zoo
- The Collisionless Terella Experiment (CTX)
- Introduction of turbulence on CTX
- Turbulence, what is it? What does this mean?
- Modifying the turbulent spectrum

Columbia University
in the City of New York

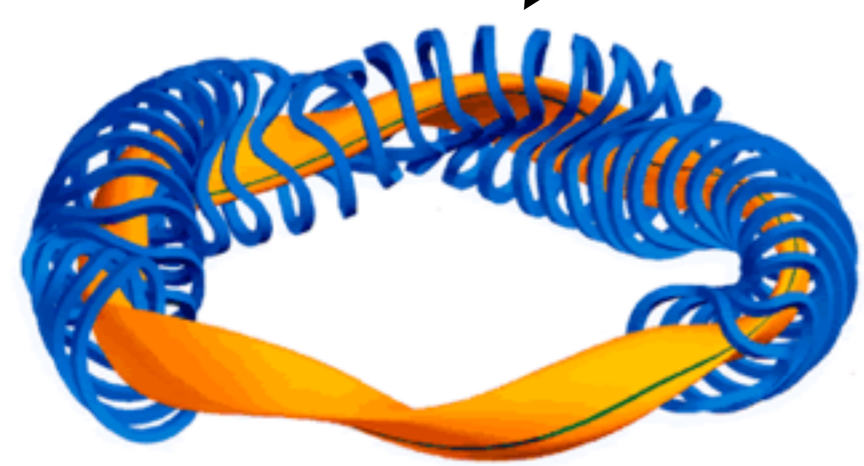
Magnetic Fusion Topology

- Most common magnetic geometries for plasma confinement employ magnetic surfaces
  - the Tokamak is the most common and relies on the plasma current to create magnetic surfaces
  - the Stellarator uses shaped magnetic coils to create magnetic surfaces, plasma current not necessary
  - other options like the Reverse Field Pinch (RFP) or Field Reverse Configuration (FRC) also exist



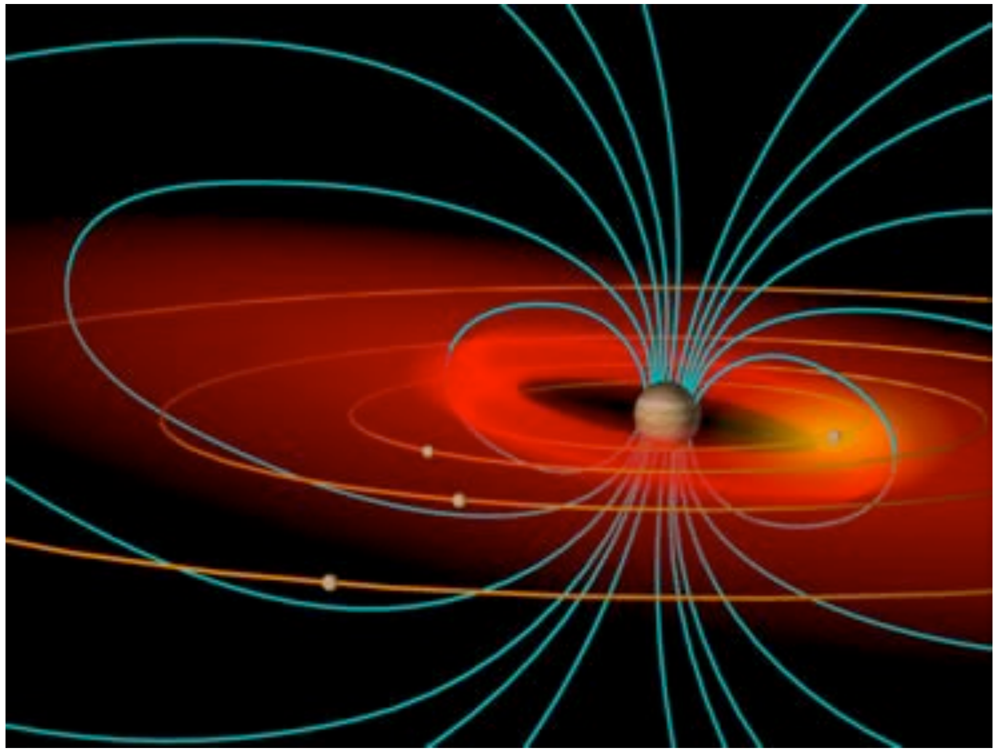
ITER

W7X

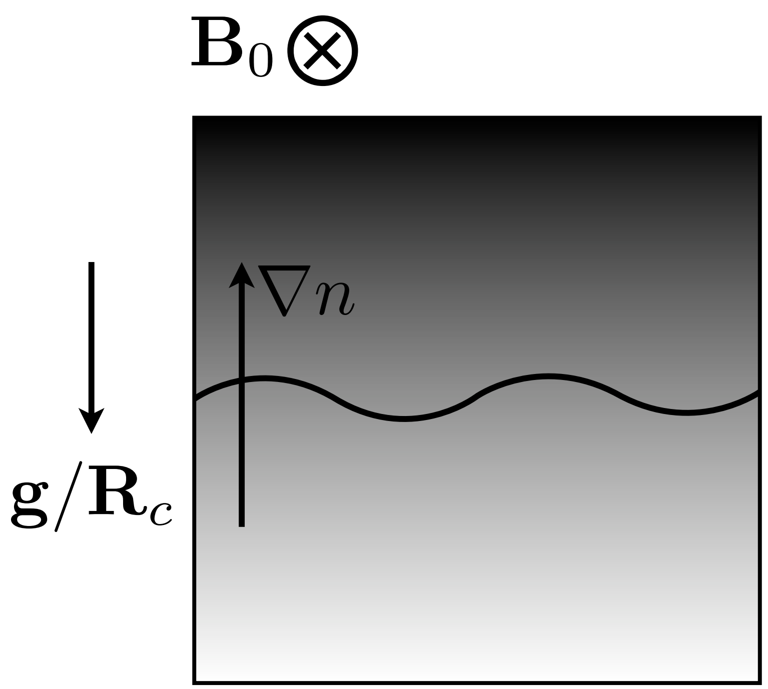


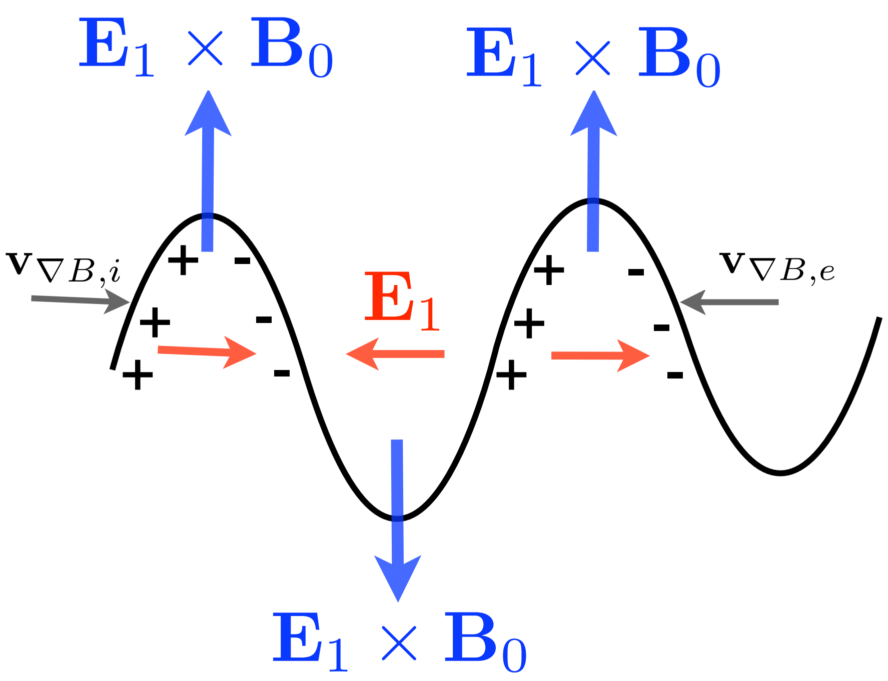
The Dipole Option

- Nature's choice for magnetic confinement.
- The field created by a magnetic dipole is a purely poloidal. All field lines close on themselves, creating "flux tubes" or "flux ropes" rather than magnetic surfaces.
- This experimental geometry has several advantages including: great diagnostic access, simple coil design, the possibility of advanced fuels, and bi-dimensional (2D) physics



Interchange Instability is the Primary Dipole Instability



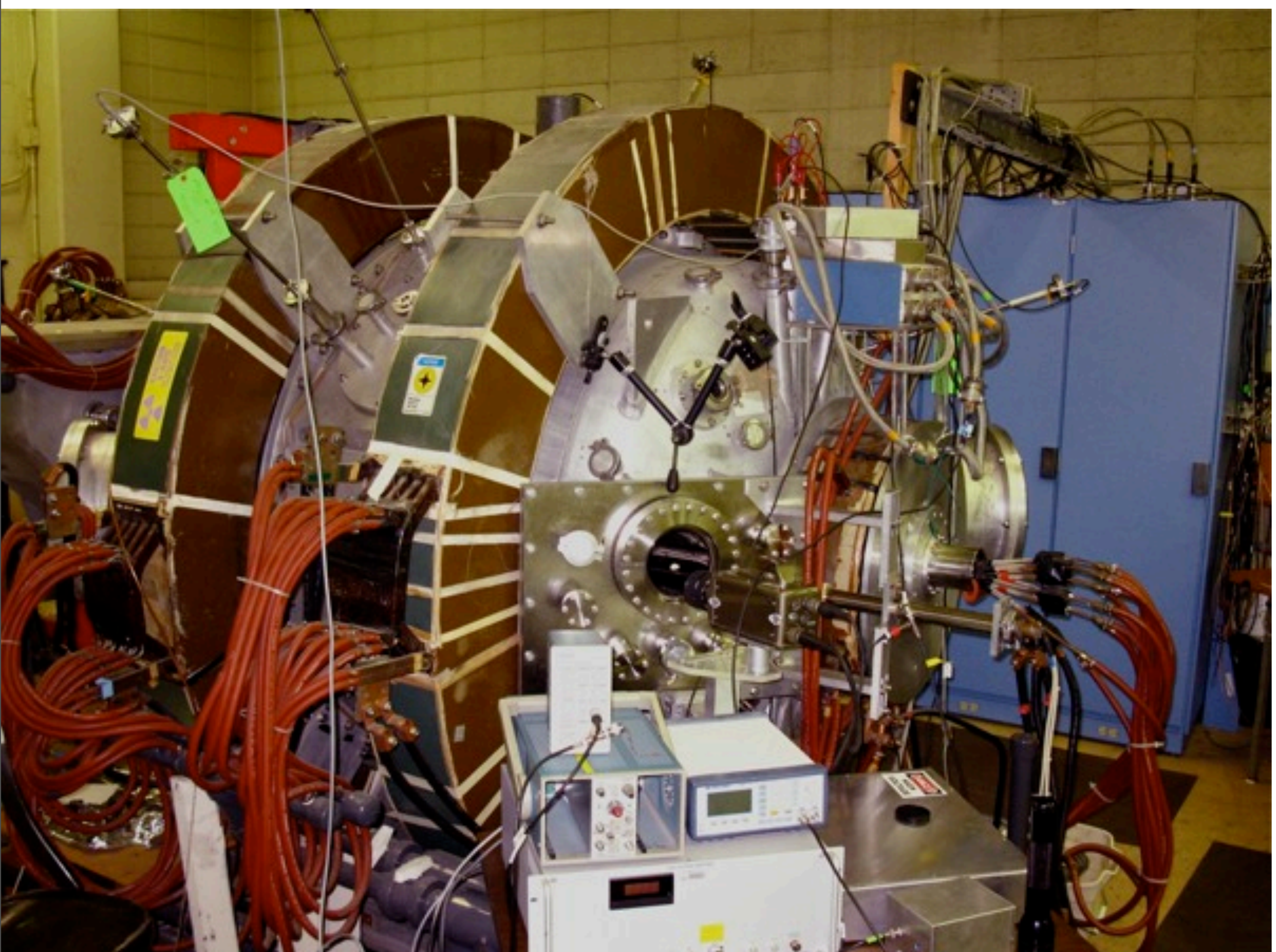


- Analogous to the gravitational Rayleigh-Taylor instability
- Similar to turning a cup of water upside down
- No field-aligned dynamics

Columbia University
In the City of New York

CTX

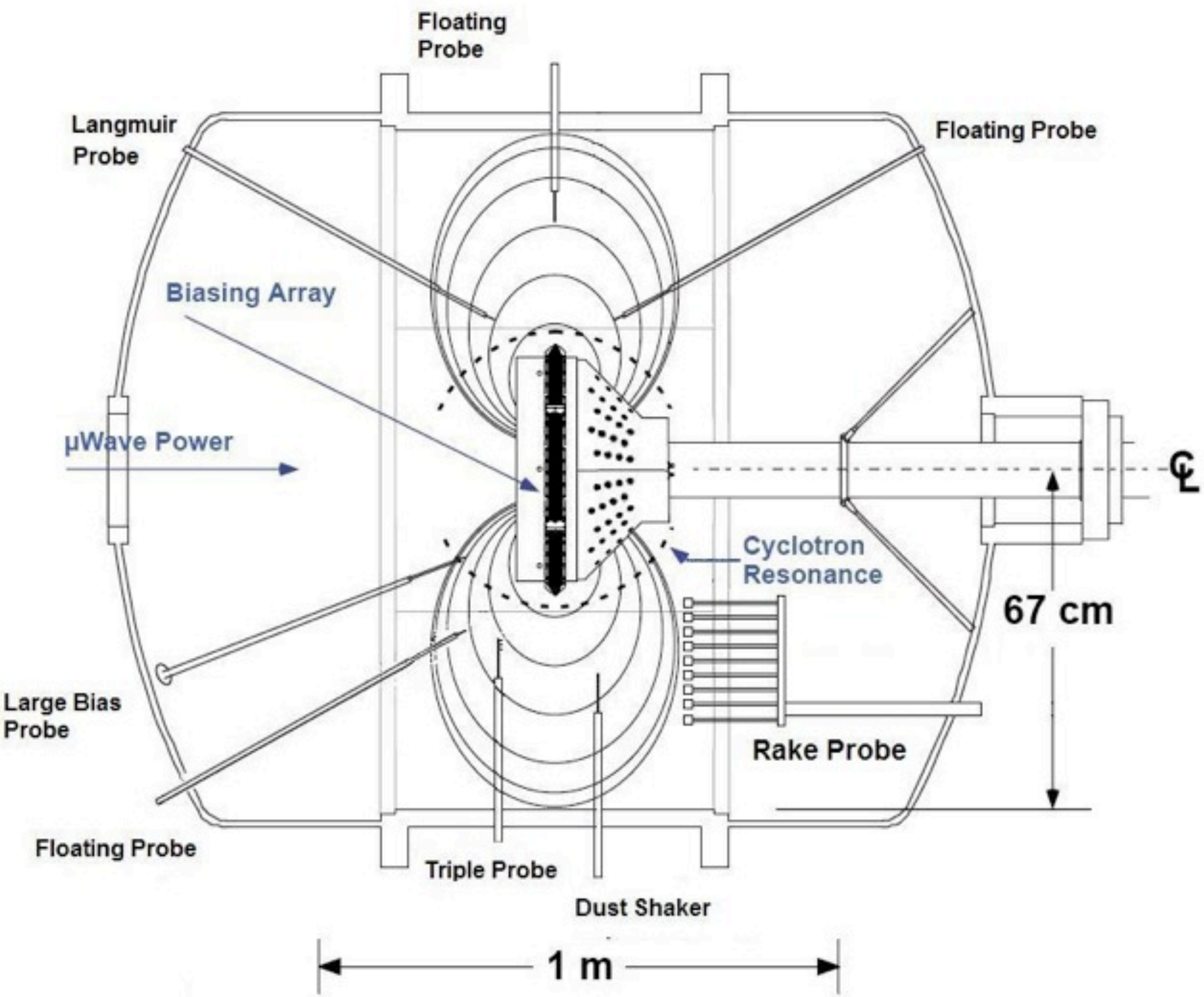
Creating Plasma on the Collisionless Terella Experiment



- Hydrogen plasma created with Electron Cyclotron Resonance Heating. (ECRH)
- 1.0kW of RF waves with f=2.45GHz injected.
- B_o=875G, resonance at L=27cm creates ring of deeply trapped, hot electrons.
- Base Vacuum Pressure ≈ 1-2*10^{-7} Torr

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

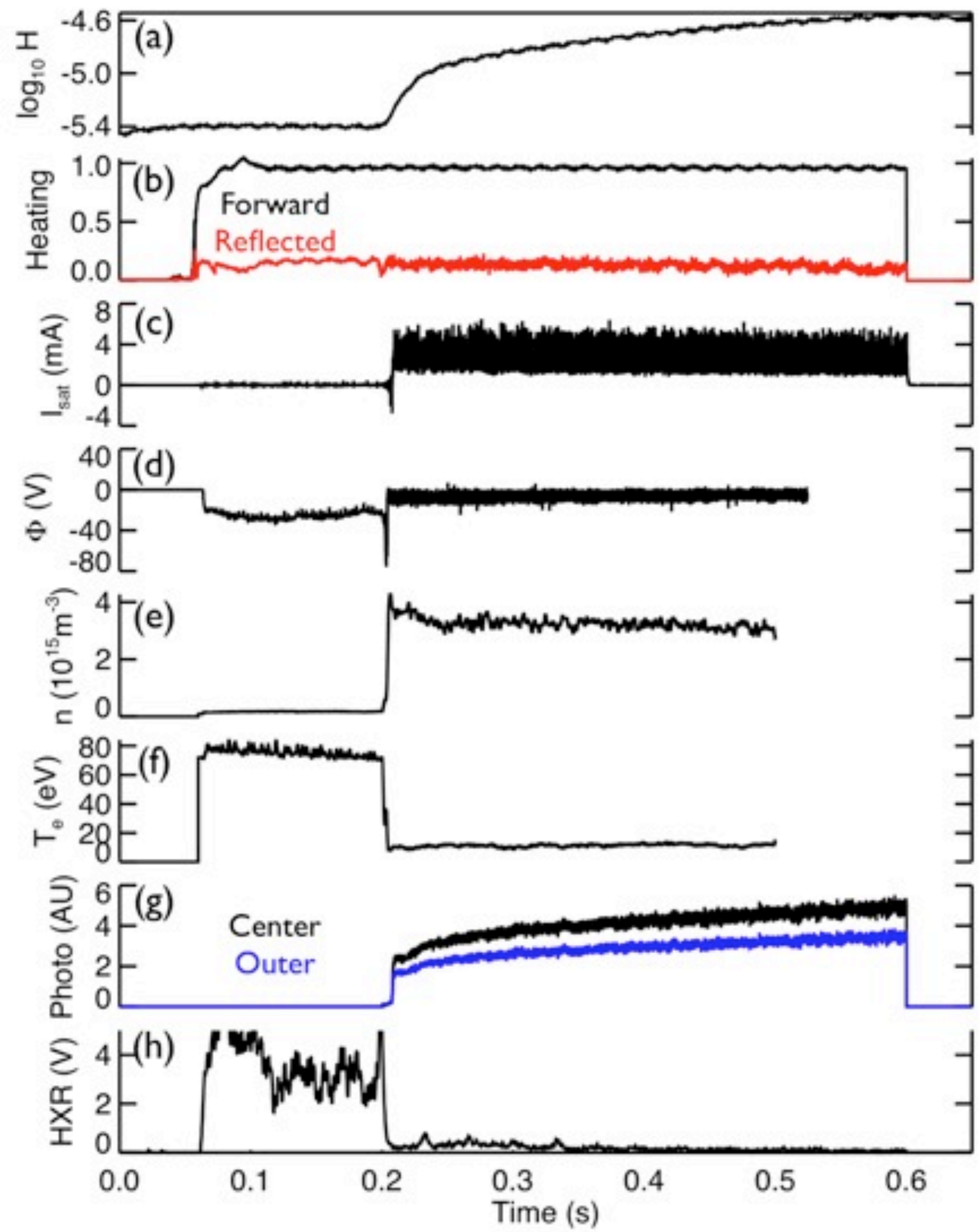
Diagnostics to Characterize Plasma Turbulence and Flow



- 3 Langmuir Probes
- Triple Probe Array
- I_{sat} Probe
- Bias Probe
- Equatorial Array
- 16 Point, 31 Tip Radial Transport Rake Probe Array
- Polar Imager (Array of 96 Gridded Energy Analyzers)

Plasma Discharge Enters Turbulent Regime with Sufficient Fueling*

- Transition to high density turbulent regime at t = 0.2 s.
- Temperature drops an order of magnitude.
- The edge density increases to $n \sim 3\text{-}4 \times 10^{15}\ m^{-3}$.
- Visible light increases dramatically and hard X-ray production decreases.

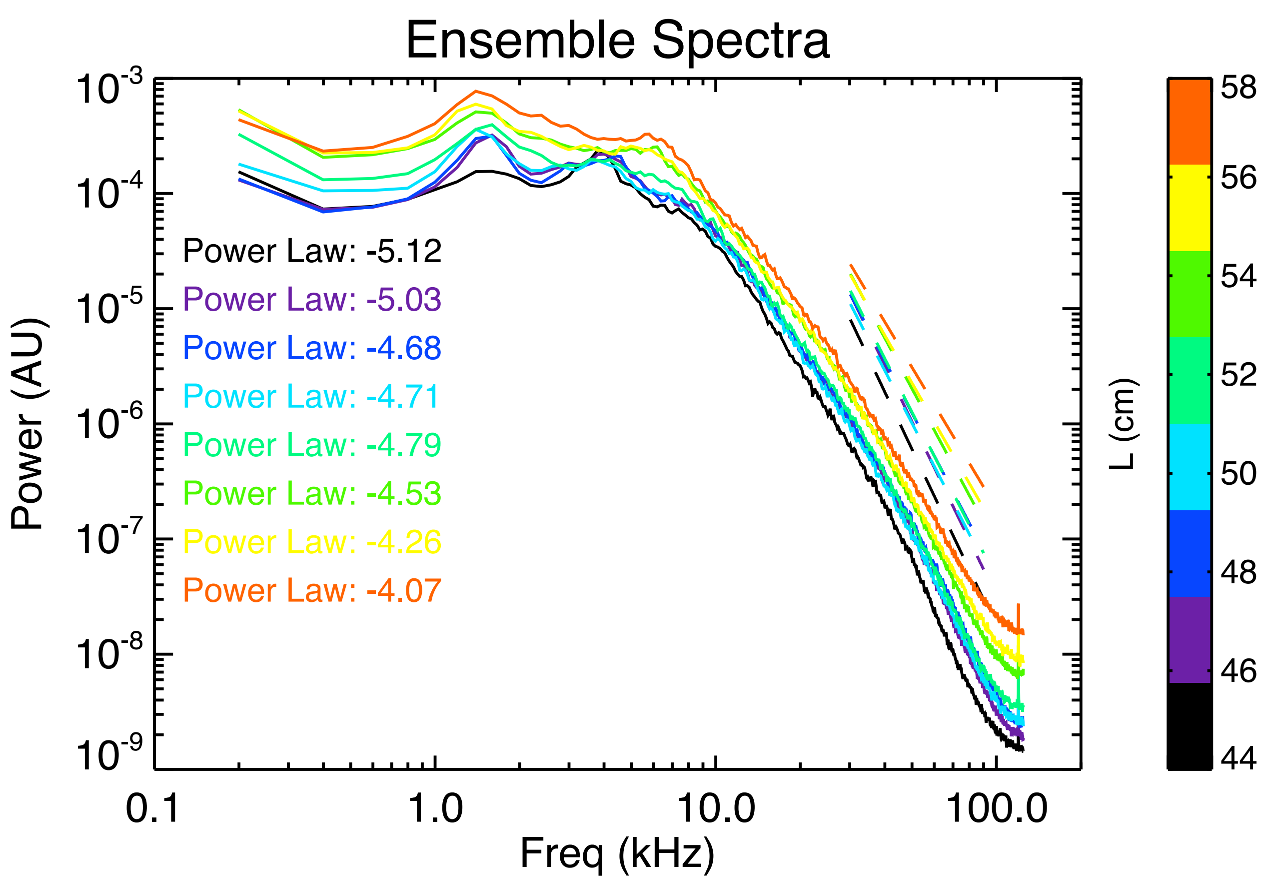


*N.A. Krall *Phys. Fluids* **9** (4)(1966)

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

High Density Single Point Measurements Look Turbulent

- After transition floating potential fluctuations exhibit broad power law spectrum.
- Two peaks observed at roughly 2 kHz and smaller peak at 4 kHz.



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

What Does Turbulence Mean?

- Turbulence implies highly stochastic, nonlinear, multi-scale dynamics
- Occurs in most flowing media: water, air, plasma
- A quote attributed to British physicist Horace Lamb is, "I am an old man now, and when I die and go to heaven there are two matters on which I hope for some enlightenment. One is quantum electrodynamics, and the the other is the turbulent motion of fluids. And about the former I am rather optimistic."

Enstrophy plays a large factor in differences between 3D and 2D

- Enstrophy is the mean square vorticity.
- Not a conserved quantity in 3D b/c of vortex stretching. (think of water draining through a funnel)
- Conserved in 2D in the incompressible, inviscid limit.
- In the Fourier representation we can see the relationship between energy and enstrophy.

$$\omega = \nabla \times \vec{v}$$

$$\epsilon = \langle \omega^2 \rangle$$

$$E = \int_0^\infty S(k)dk$$

$$\epsilon = \int_0^\infty k^2 S(k)dk$$

$$\epsilon = k^2 E$$

Columbia University
in the City of New York

Implications of Enstrophy Conservation

- Let's look at the effects this has with a simple example:

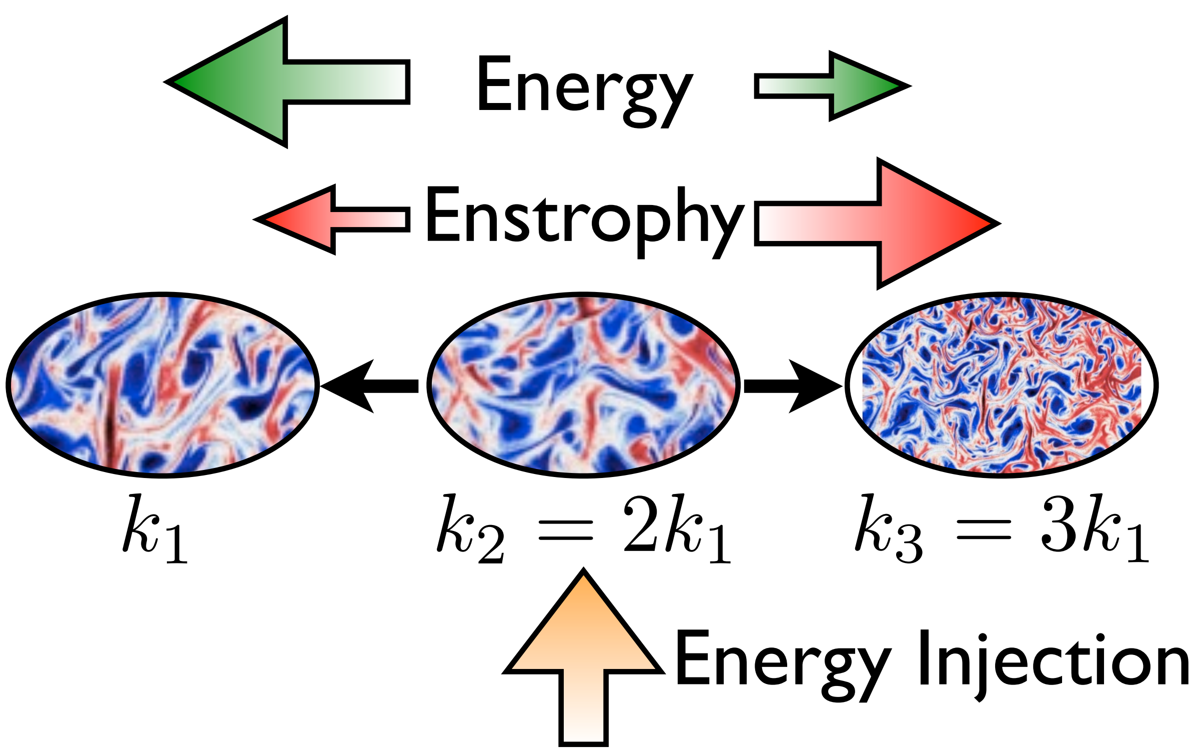
$$\vec{k_1} + \vec{k_2} = \vec{k_3} \ , |k_1| < |k_2| < |k_3|$$

$$\delta E_1 + \delta E_2 + \delta E_3 = 0$$

$$\delta \epsilon_1 + \delta \epsilon_2 + \delta \epsilon_3 = 0$$

$$||$$

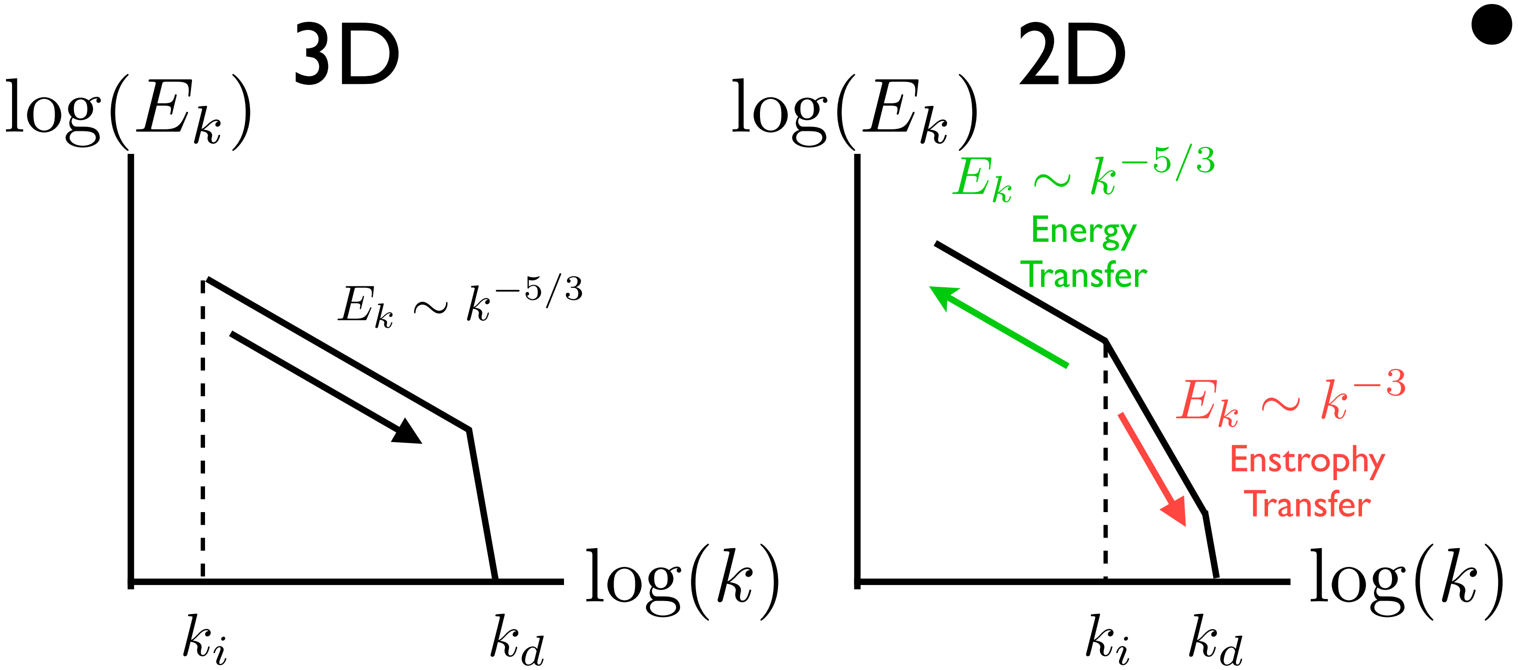
$$k_1^2 \delta E_1 + k_2^2 \delta E_2 + k_3^2 \delta E_3 = 0$$



Do the algebra...

$$\frac{\delta E_1}{\delta E_3} = \frac{5}{3} \qquad \frac{\delta \epsilon_1}{\delta \epsilon_3} = \frac{5}{27}$$

This Creates a Dual Cascade



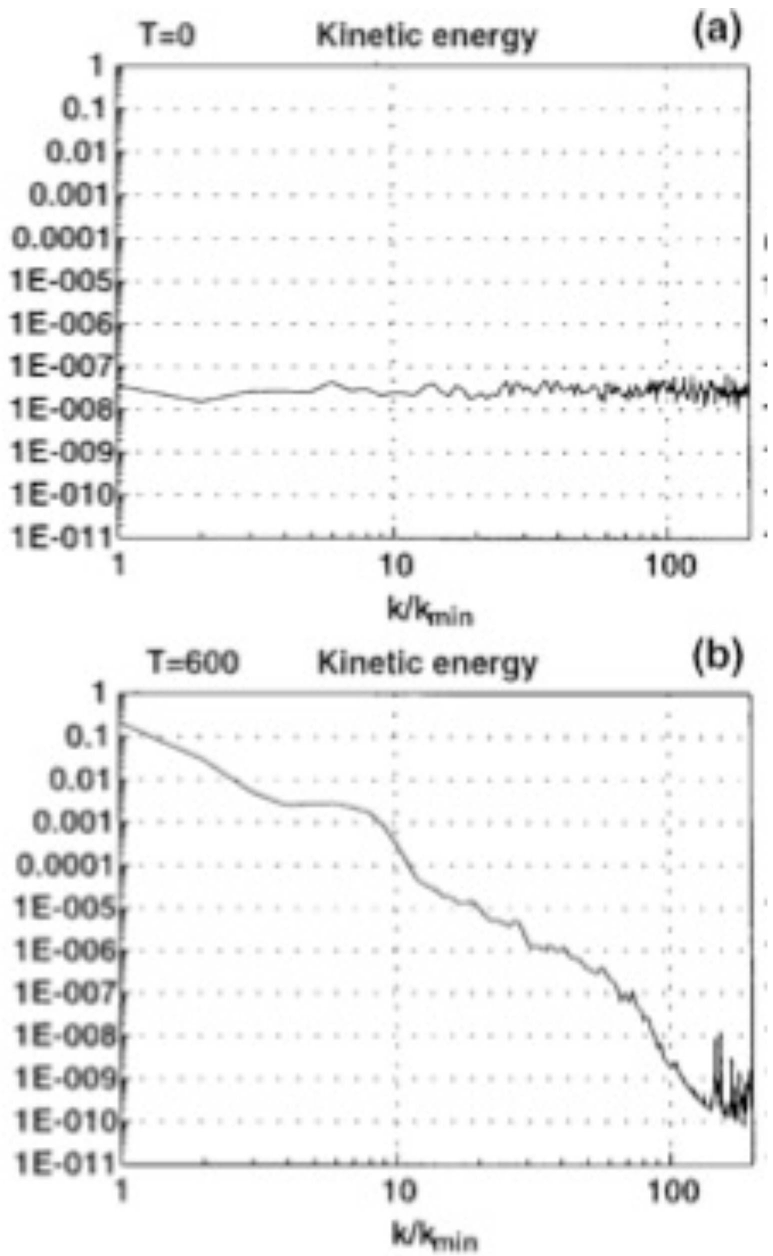
- So we see as a result of reducing the dimensionality, we have another conserved quantity (enstrophy), which in turn creates dual cascades.

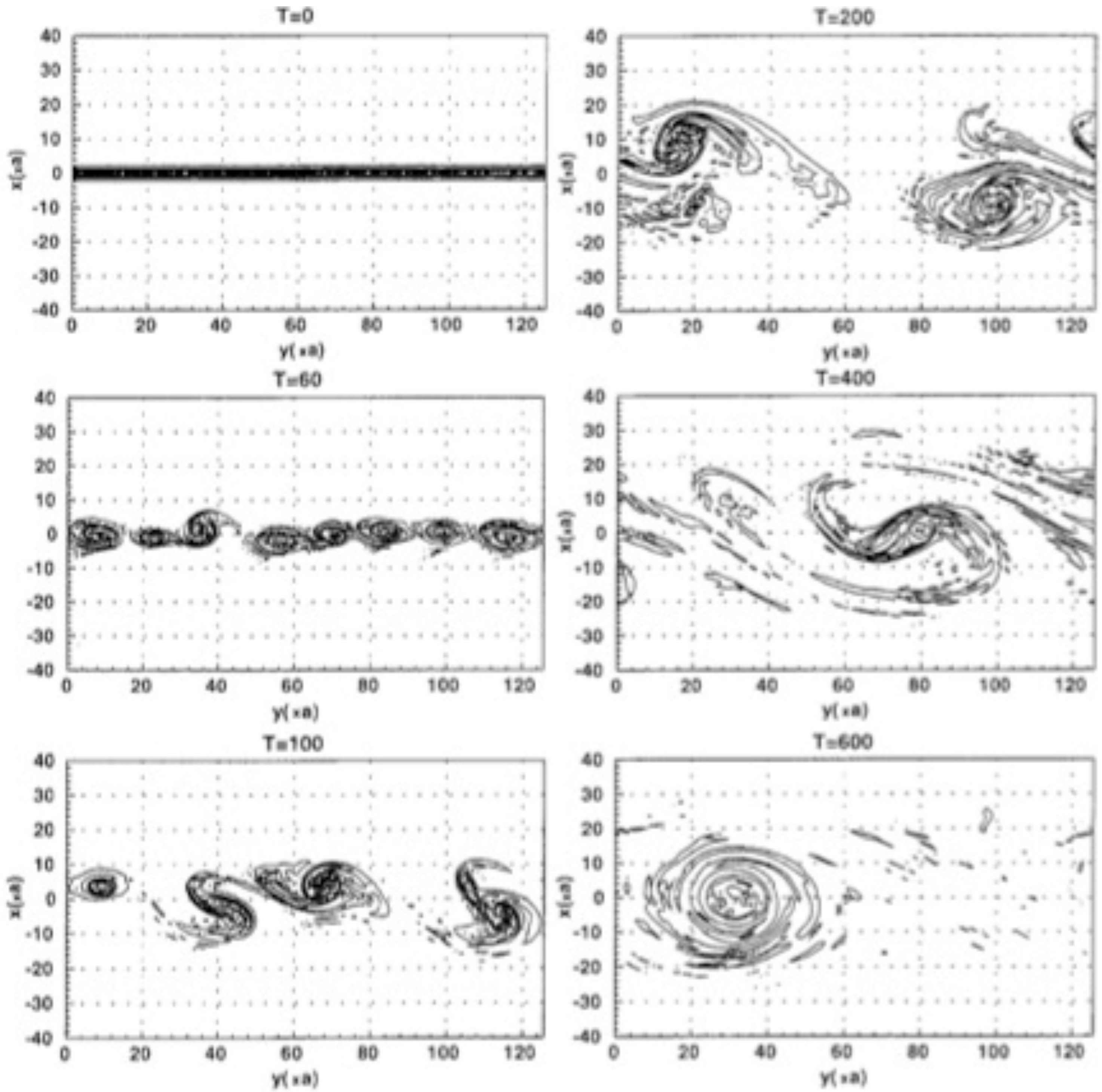
- Enstrophy exhibits a forward cascade from large to small spatial scales. (small to large k-values) k^{-3}

- Energy has a backward cascade, the so-called inverse energy cascade, from small spatial scales to larger ones. (large to small k-values) $k^{-5/3}$

An Inverse Cascade Example in a 2-D Kelvin-Helmholtz Simulation

*A. Miura, PRL **83**, 8 (1999)





Are We Observing the Inverse Energy Cascade?

- We have reported that in the high density turbulent regime the observed fluctuations can be recreated through spatially broad and temporally chaotic signals*
- This is consistent with an inverse energy cascade (pooling at large spatial scales), but we aim to inject energy at finer scales and watch the spectrum evolve
- The goal is to experimentally verify the inverse energy cascade through application of an electrostatic perturbation

*Grierson, et al. Phys. Plasmas **16,** 5 (2009)

Columbia University
IN THE CITY OF NEW YORK

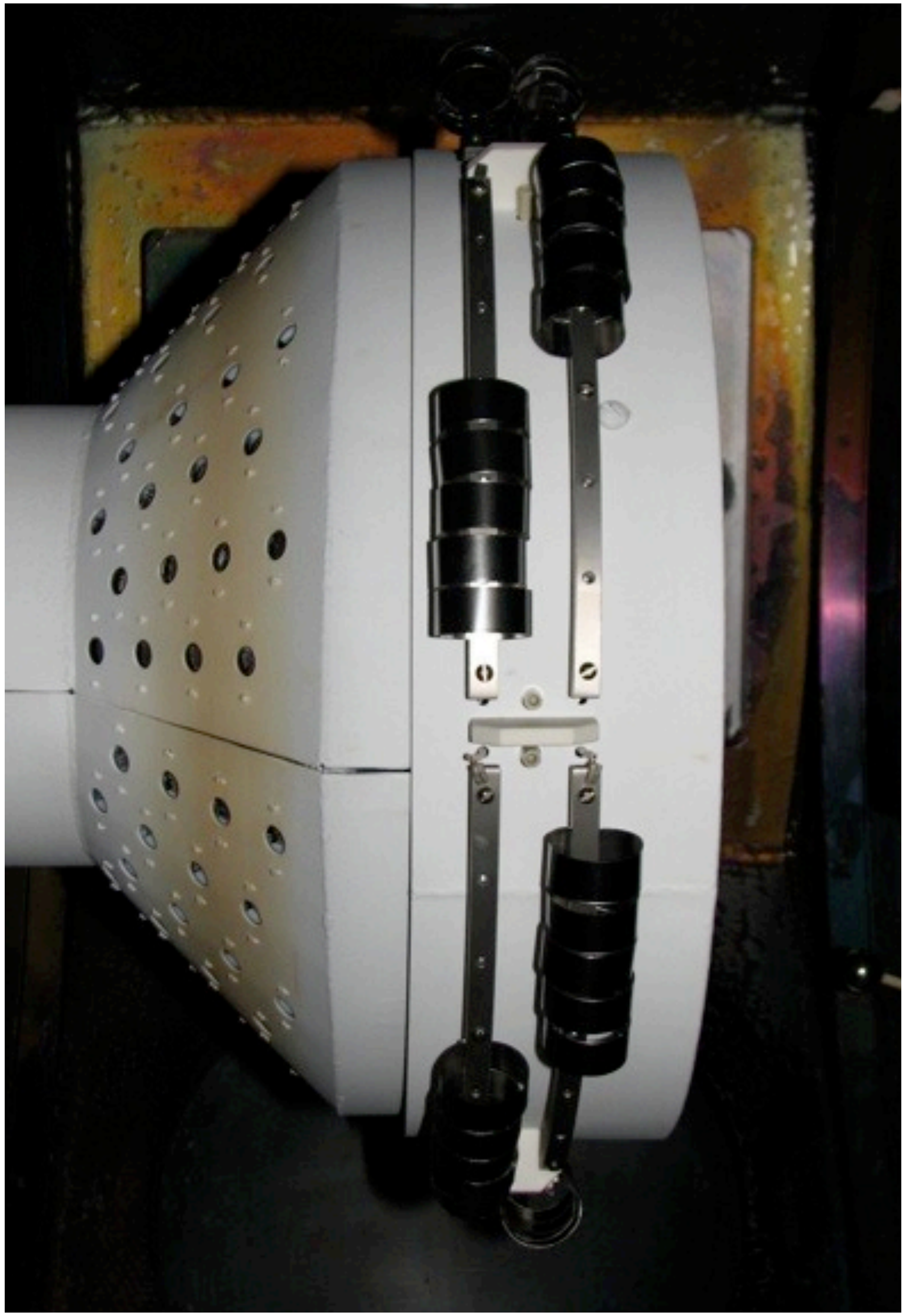
How can we most effectively couple to the plasma?

- Using a bias probe the data indicate the perturbation does modify the plasma. However, limited by a single probe and the amount of power that can be applied
- Increasing the probe area would allow more power to be applied
- Desire ability to control the shape of the perturbation through broader spatial coverage

Columbia University
in the City of New York

Equatorial Biasing Array

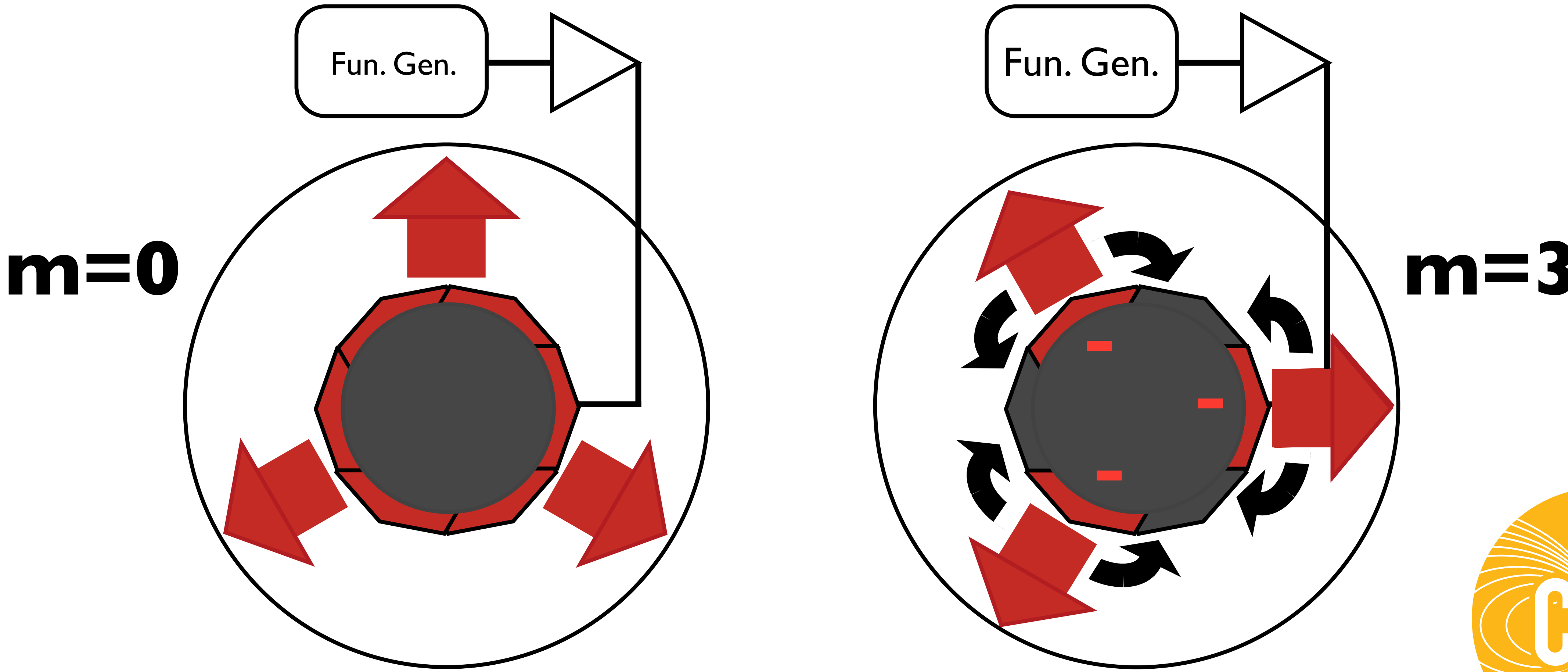
- Upgrade existing array and begin experiments
- Increase number of segments to twelve
- See symmetry breaking effect, m=0 has ~3x the current with 2x the number of meshes biased



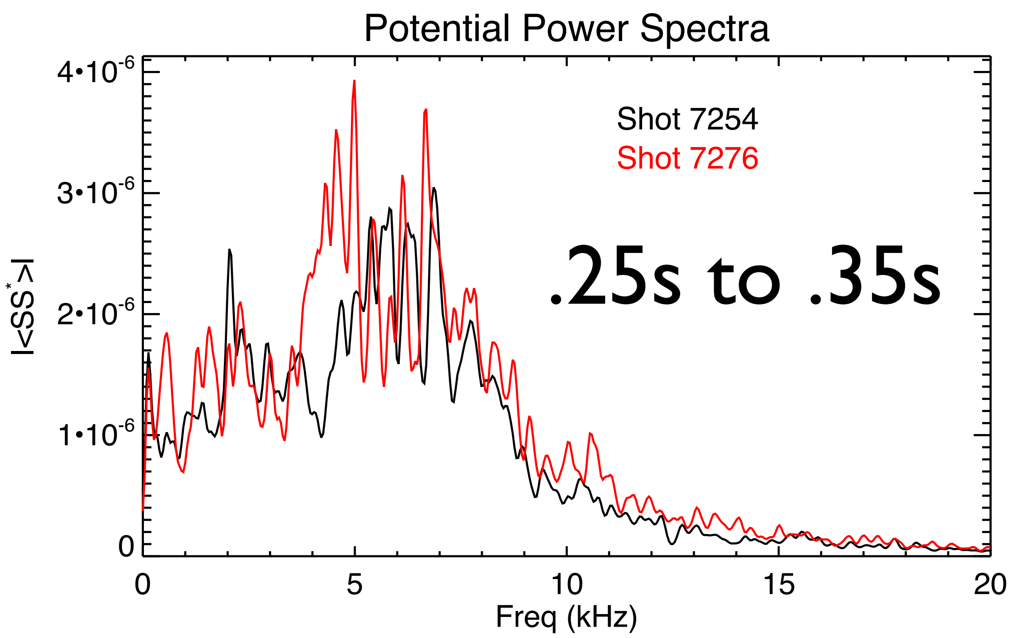
Columbia University
in the City of New York

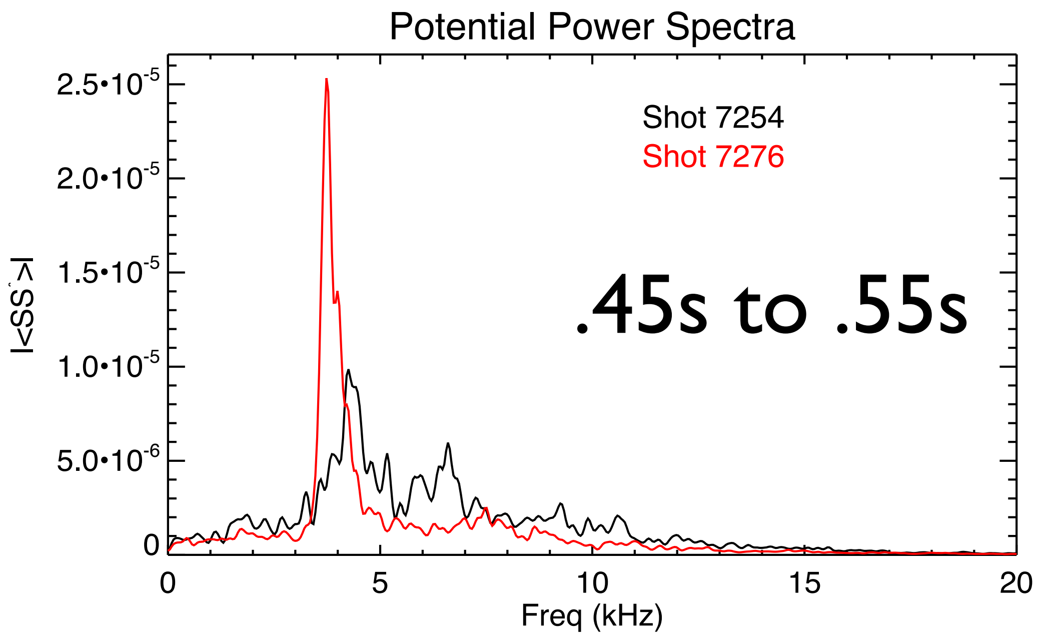
Driving Azimuthal vs. Radial Currents through Varied Mode Numbers

- When axisymmetry is broken currents can flow azimuthally in additional to radially
- Equatorial bias array designed to test mode numbers=0,1,2,3,6



Equatorial Bias Excites Quasi-Coherent Mode



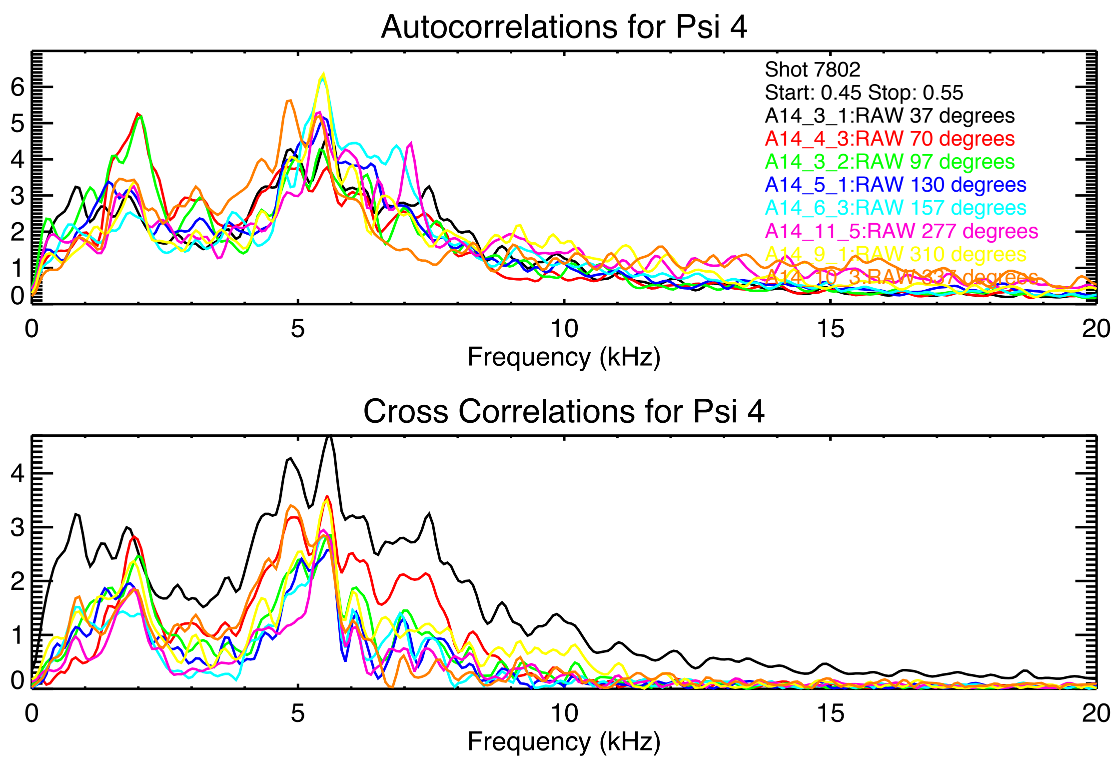


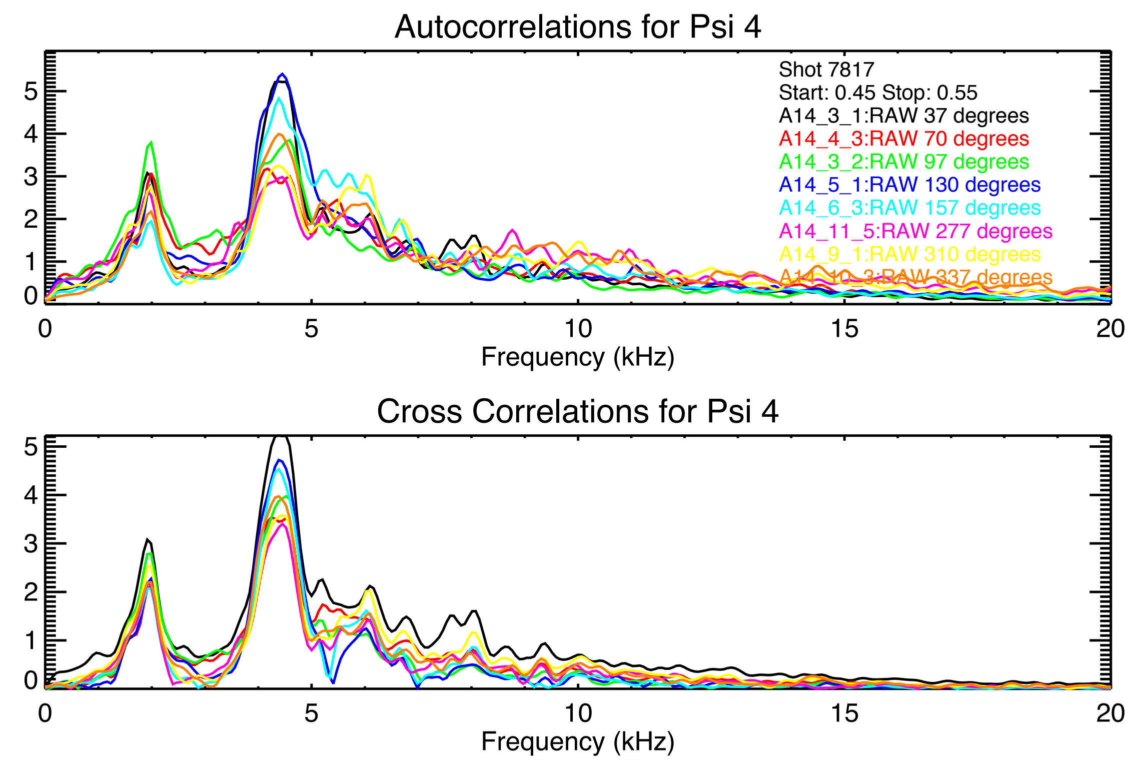
- Shots similar before bias, but see the quasi-coherent mode when bias is applied
- 7254:High Density
- 7276: -500V m=6 bias triggered from .35 to .55s, full bias around .45s

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

CTX

Mode Seen in Polar Imager Correlations





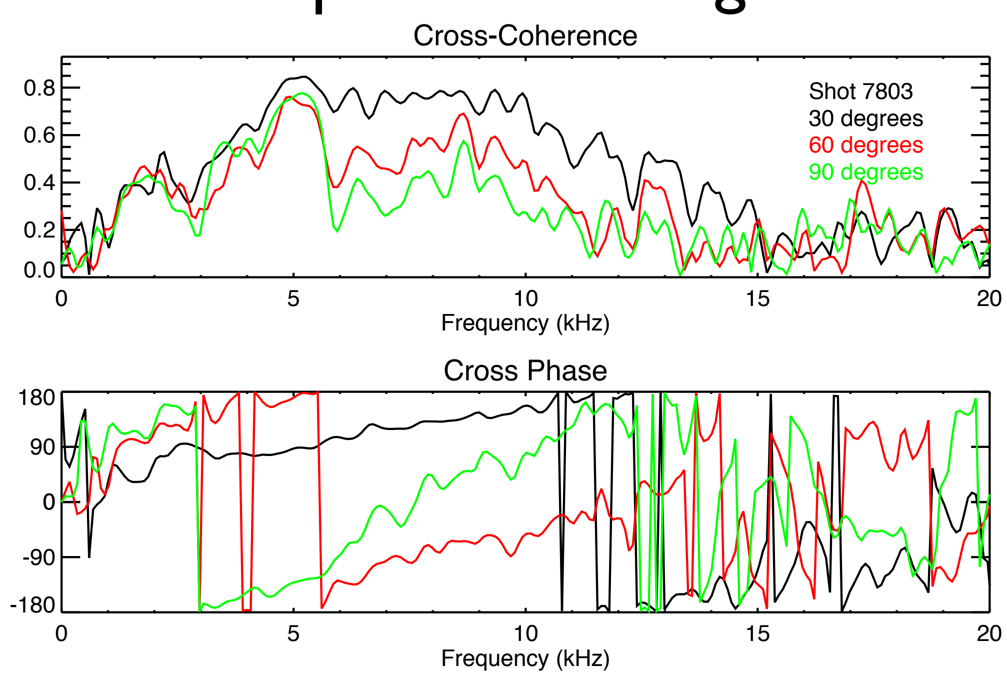
Unbiased

m=6 Bias -400V

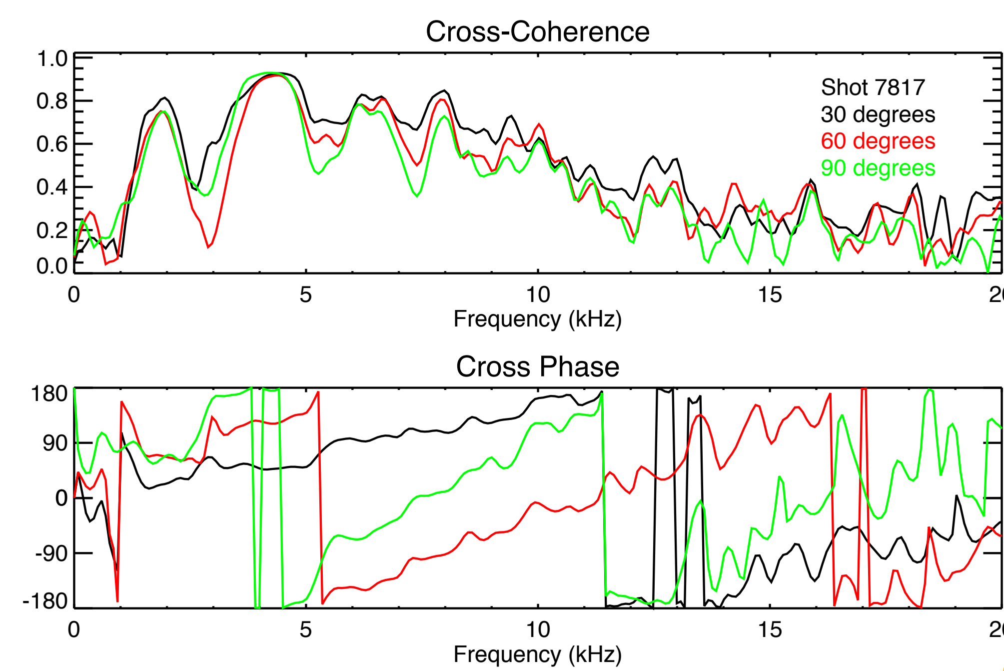
Columbia University
In the City of New York

Bias Increases Coherence in Potential Probes

- Unbiased shot displays decreased coherence length beyond dominant mode.
- Multiple modes present in shot with nonaxisymmetric bias.
- Increased coherence length evident through broad range of frequencies during bias.



Unbiased



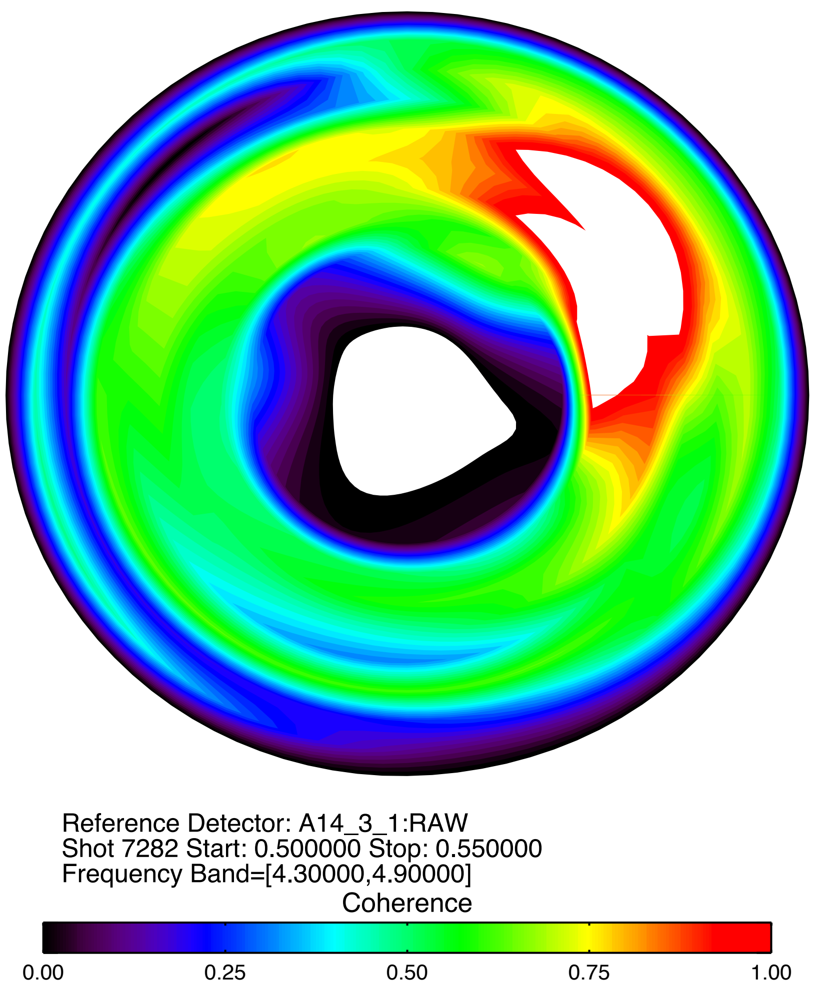
m=6 Bias -400V

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

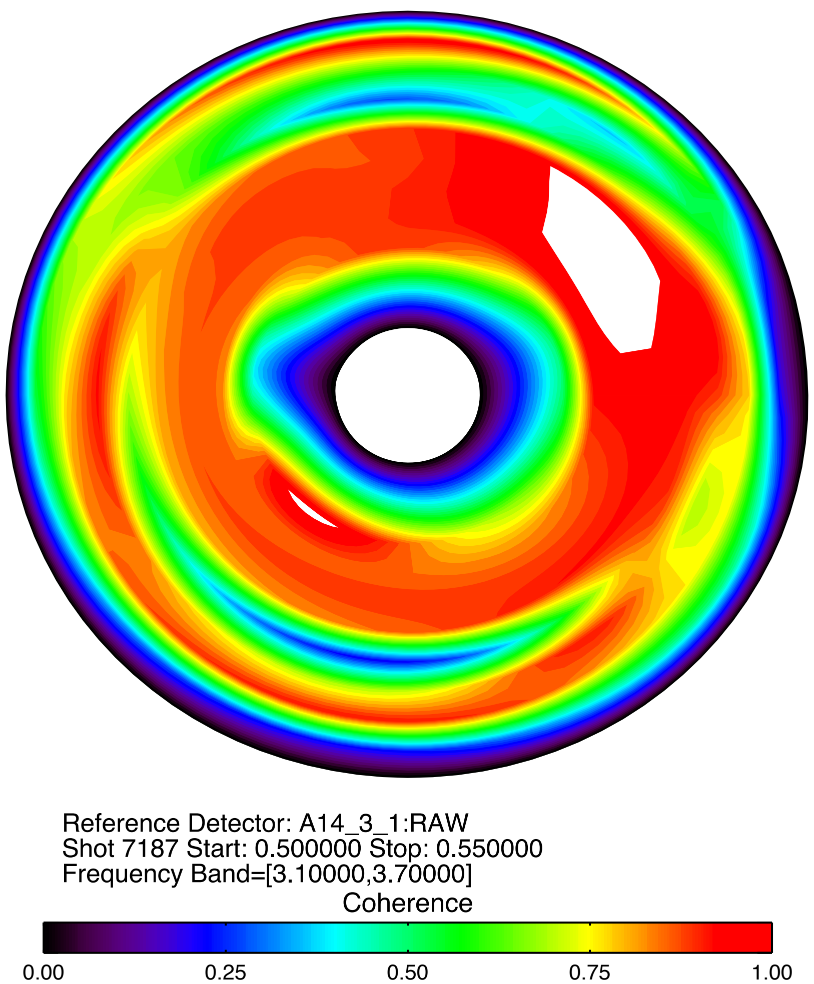
CTX

Coherence of Primary Mode Increases During Bias

Unbiased



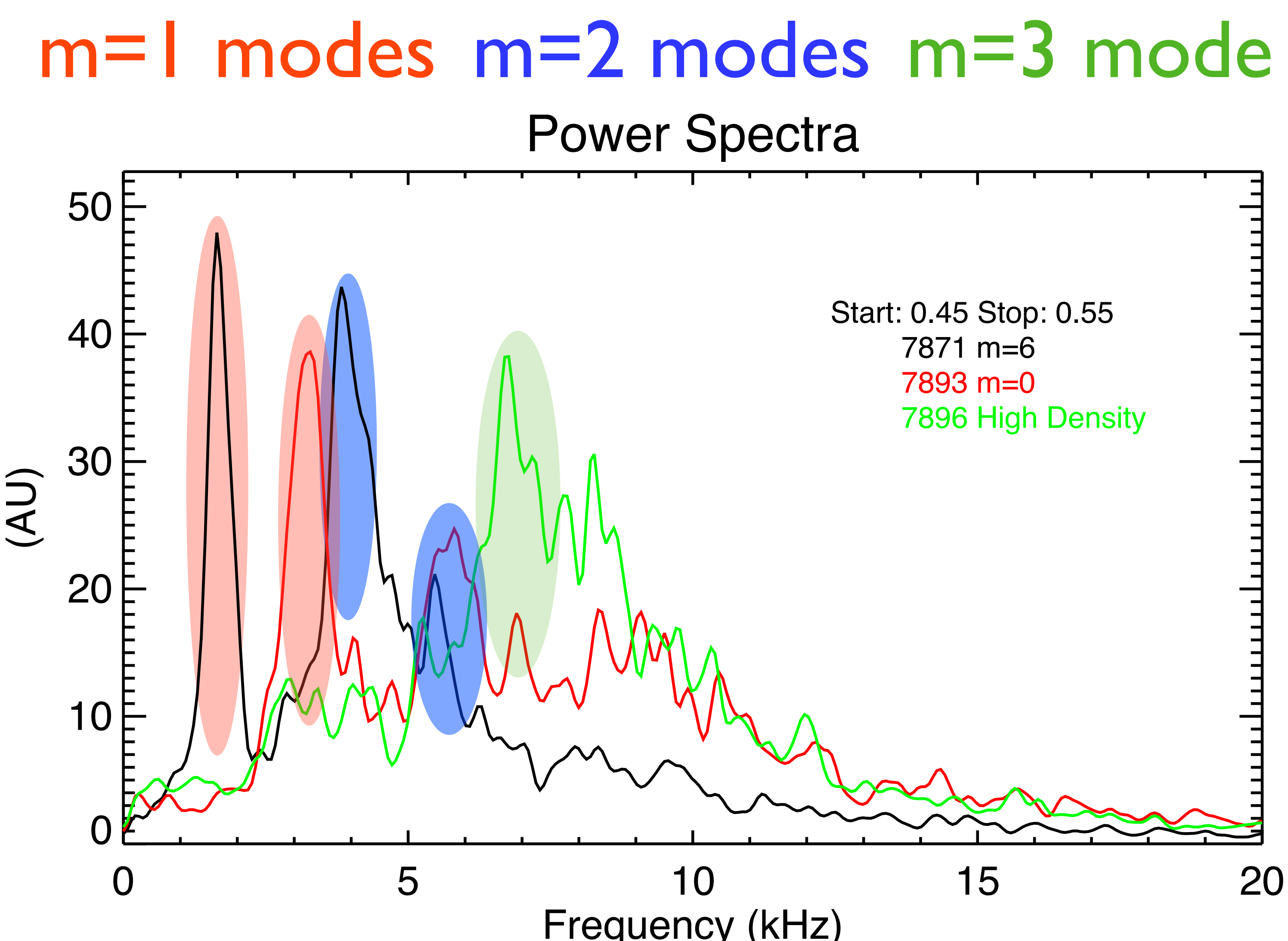
m=3 Bias -400V



- Strong azimuthal increase in coherence
- Coherence length also broadens radially

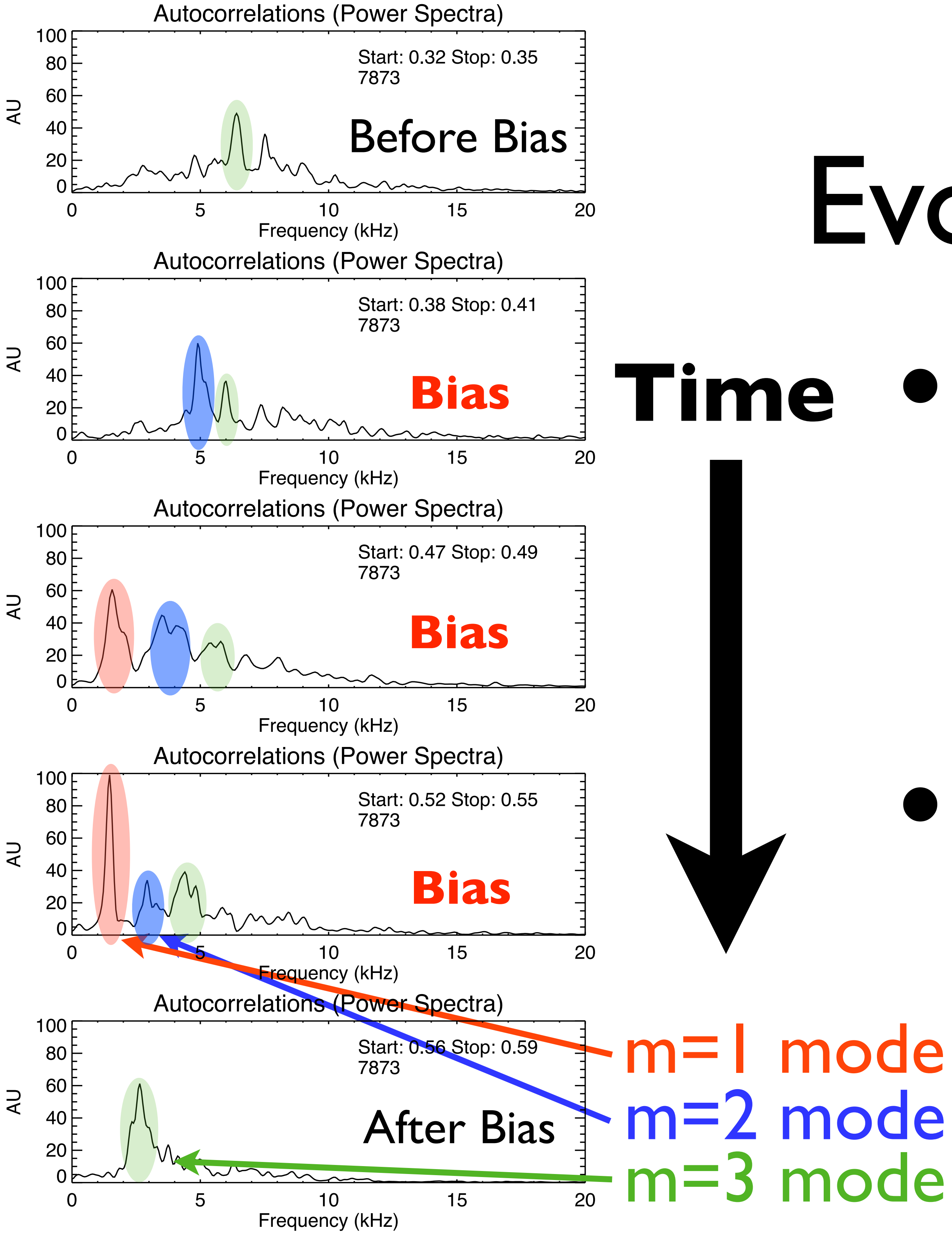
CTX

Nonaxisymmetric Bias Excites Inverse Energy Cascade



- Floating potential spectra
- Structure of unbiased dominant mode m=3 (not very coherent)
- Axisymmetric mode shows frequency upshift
- Nonaxisymmetric bias displays clear excitation of lower mode numbers
- RMS unchanged by bias

Potential Time Evolution During Bias



- We see frequency shift and mode amplitude jump after bias is triggered, and then decay once bias is removed
- Unbiased shots display a growing amplitude until saturates with slowing of principal mode (neutral drag)

Columbia University
in the City of New York

CTX

Spectral Analysis Can Reveal Nonlinear Coupling of Scales

- Standard FFTs and Spectrograms employed.
- Bicoherence also useful in quantifying three-wave coupling within a signal.

$$S(t) \rightarrow_{FFT} \rightarrow \hat{S}(\omega)$$

$$< A >= \frac{1}{M} \sum_{i=1}^{M} A_i$$

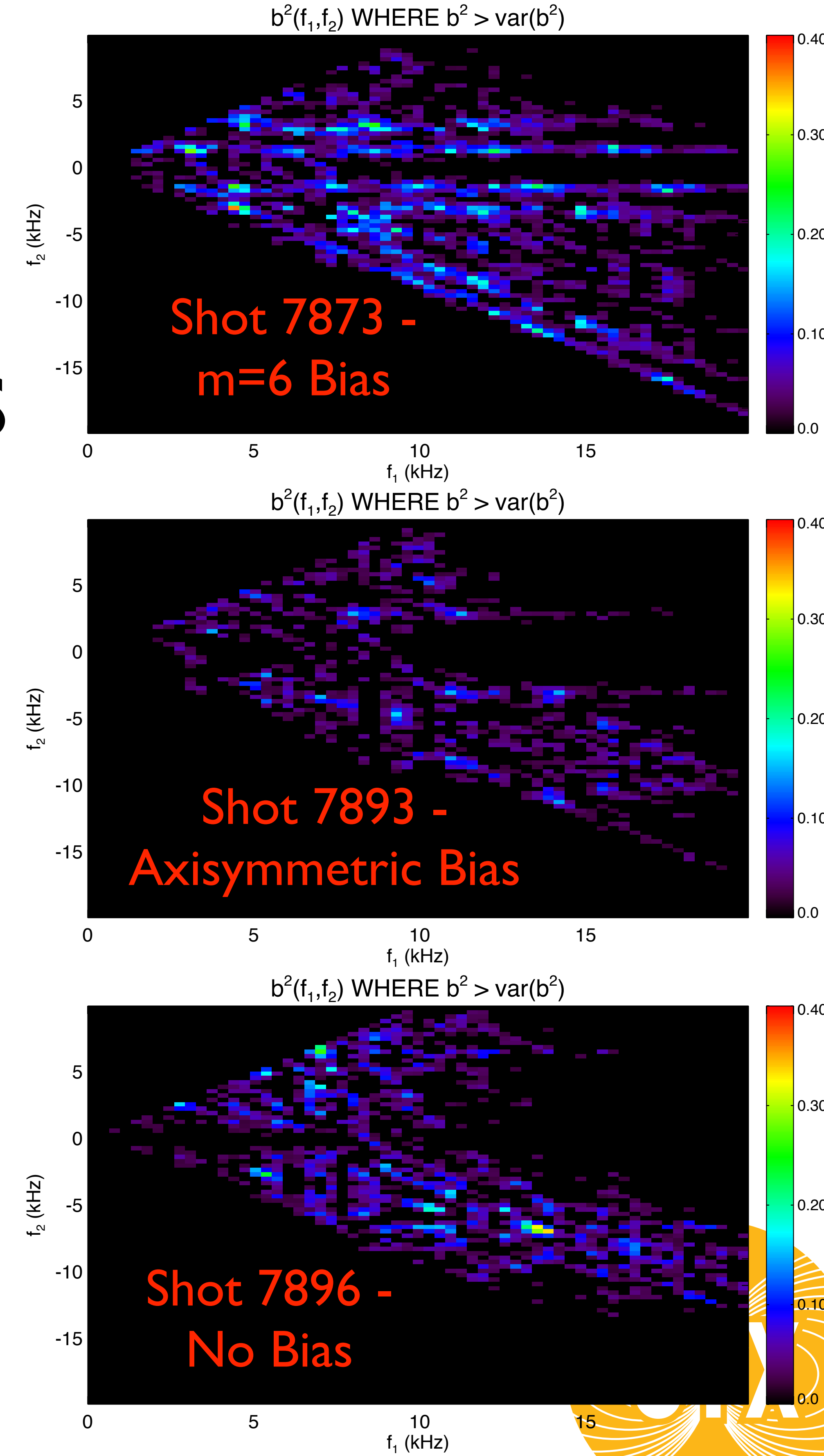
$$\hat{B}(\omega_1, \omega_2) =< \hat{S}(\omega_1)\hat{S}(\omega_2)\hat{S}^*(\omega_1 + \omega_2) >$$

$$\hat{b}^2(\omega_1, \omega_2) = \frac{|\hat{B}(\omega_1, \omega_2)|^2}{| < \hat{S}(\omega_1)\hat{S}(\omega_2) > |^2| < \hat{S}(\omega_1 + \omega_2) > |^2}$$

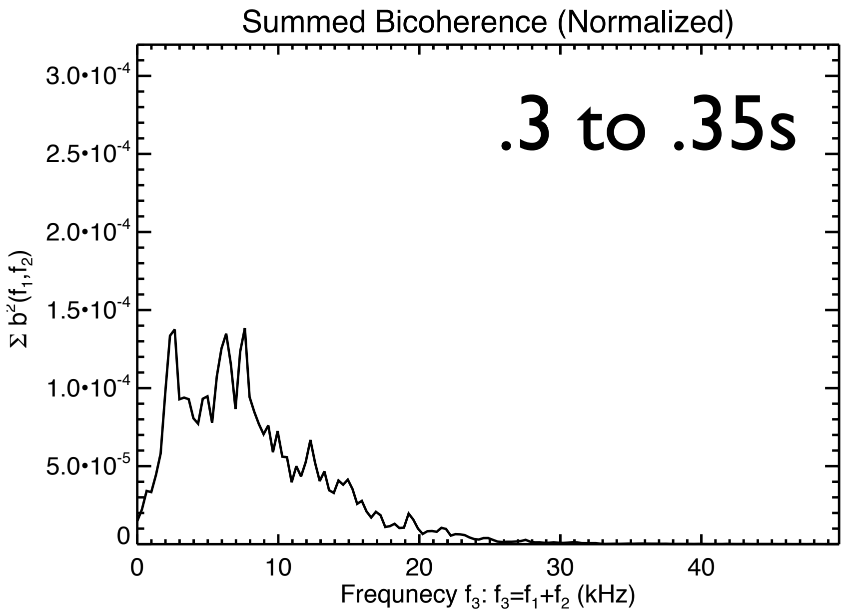
Columbia University in the City of New York

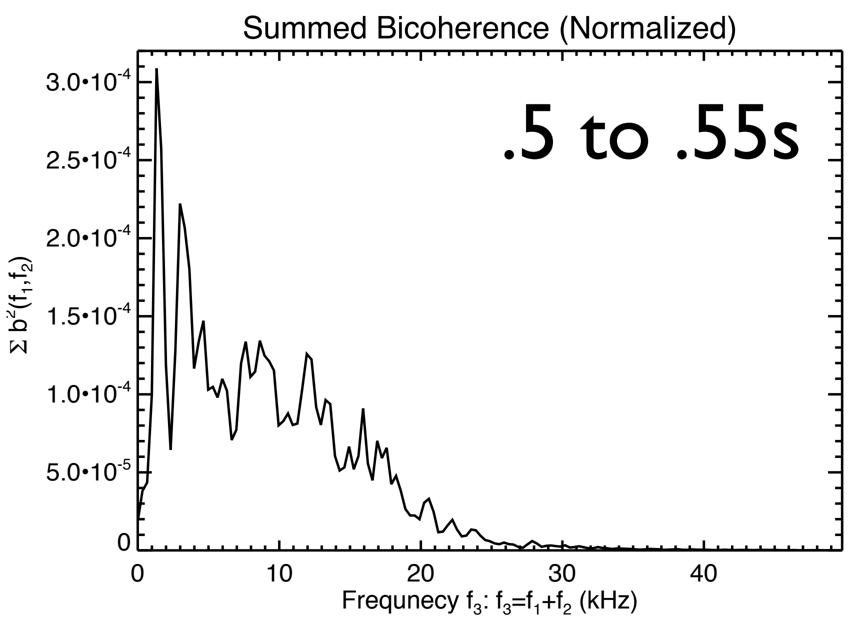
High Levels of Nonlinear Coupling in Nonaxisymmetric Bias

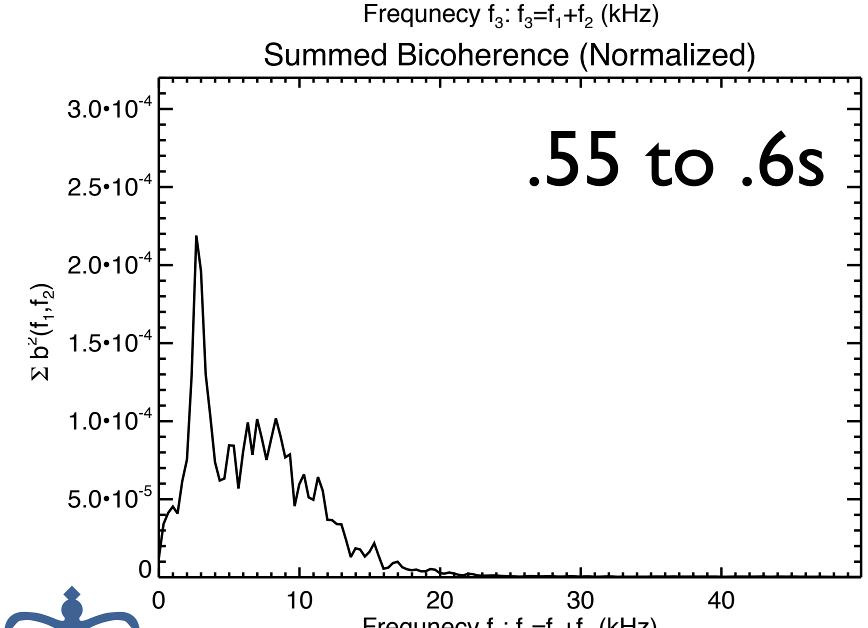
- Highest level of quadratic coupling see in m=6 bias shot
- See the coupling is very broadband across the spectrum
- Axisymmetric bias displays much lower coupling



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK







Nonlinear Coupling Increases During Bias

- Summed bicoherence shows the total amount of coupling at a specific frequency
- Shot 7873, m=6 bias
- See a large peak develop through bias and then relax to lower amplitude and higher frequency after bias removed
- Not seen in during axisymmetric bias or unbiased cases

Columbia University
In the City of New York

CTX

Conclusions

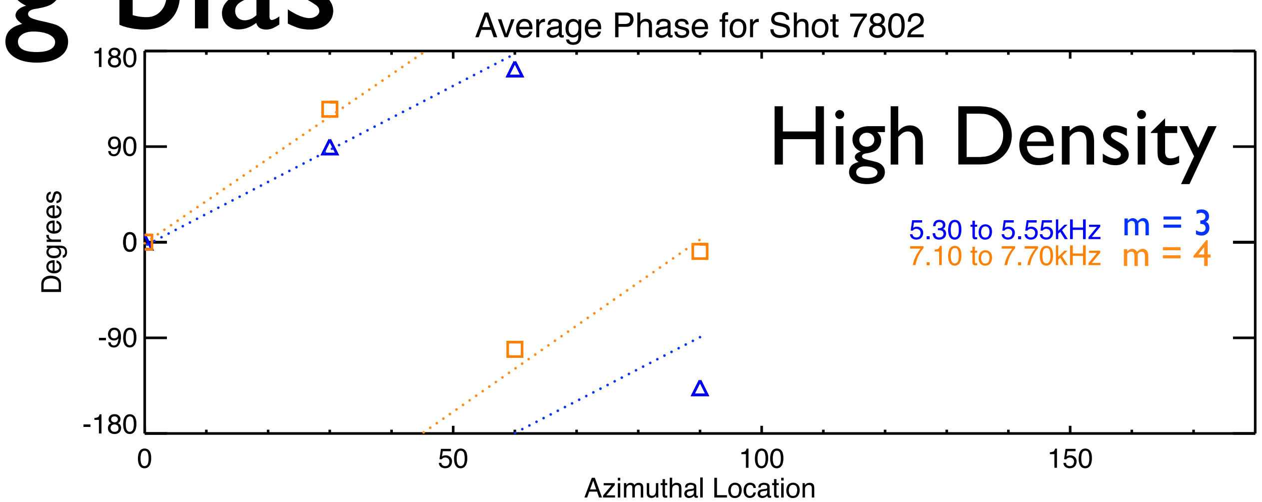
- Axisymmetric biasing drives the centrifugal interchange mode, even in a turbulent plasma.
- Electrostatic biasing increases coherence length and decreases broadband turbulent fluctuations.
- When nonaxisymmetric bias is applied, the evolution of the turbulent spectrum directly demonstrates the inverse energy cascade. This is the first demonstration of active bi-dimensional turbulence drive in a magnetized plasma.

Columbia University
in the City of New York

Thank You

Columbia University
in the City of New York

Clear identification of mode numbers during bias



- Averaging the phases during the peaks in the coherence identified we can easily trace mode numbers.

- High density phase is less clear (corresponding to lower coherence), but see m=3 and m=4. The phase evolution of at these frequencies produces clear modes, unlike lower frequencies that are presumably m=1 and m=2 modes.

- In bias we can pick out modes m=1,2,3,4,5 with maybe a hint of 6