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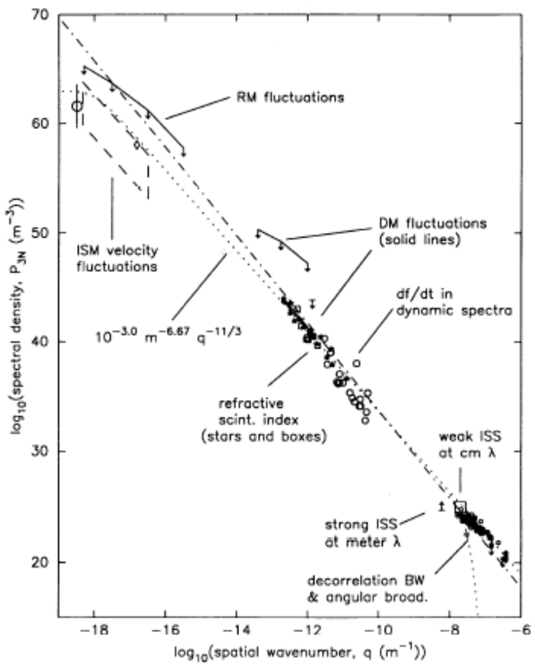
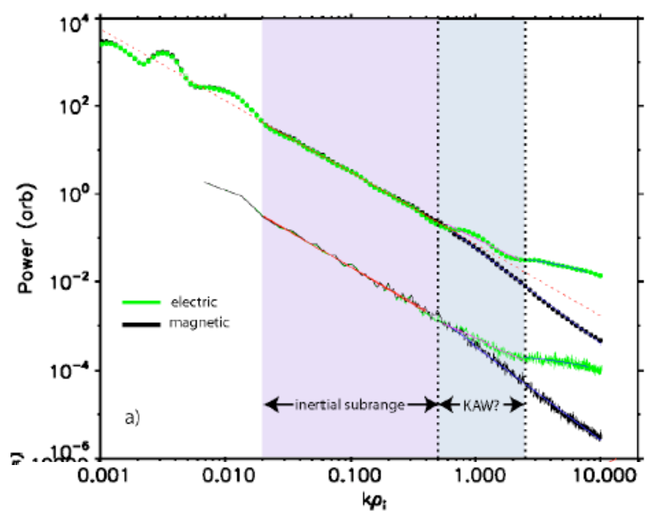


(Armstrong, Rickett, & Spangler, 1995)

(Fig. 3 from Bale et al. 2005)



Turbulence: Role of Observation/Experiment

- Observation (ISM, Solar Wind, Corona, etc) is driver for studies of MHD turbulence; excellent data on spectrum, particle heating, temperature anisotropy…
- Continuation/enhancement of observation is critical
- What role can laboratory experiments play:
  - Controlled experiments: scaling with parameters
  - Isolation of physical phenomena (e.g. basic physics of waves, instabilities)

Issues which could be addressed in laboratory experiment

- Basic physics of nonlinear wave interactions, wave damping (e.g. at high plasma β)
- Basic studies of important instabilities: e.g. mirror, firehose
- Drive turbulent cascade through stirring at large scale, either through driven flows or injected Alfvén waves. Study:
  - Spectrum, structure, anisotropy, intermittency.
  - Dissipation, heating
  - Identify role of instabilities (e.g. firehose/mirror in high beta plasma) in establishing spectrum, causing dissipation

Trade-offs in lab experiments

- "Basic plasma devices" (e.g. LAPD, MRX, ...)
  - Low temperature (10eV), probe diagnostics (very detailed, relatively easy measurements), simple geometry
  - But, typically high collisionality (except with low density, but then can't contain all important scales in expt)
- Confinement (fusion) devices
  - Low collisionality, high temperature, density, high S
  - Difficult to diagnose, complicated magnetic geometry
- No lab experiment will match space/astro parameters: have to carefully identify physical processes that are common to both, use theory/simulation to bridge the parameter gap

Laboratory experiments on Turbulence

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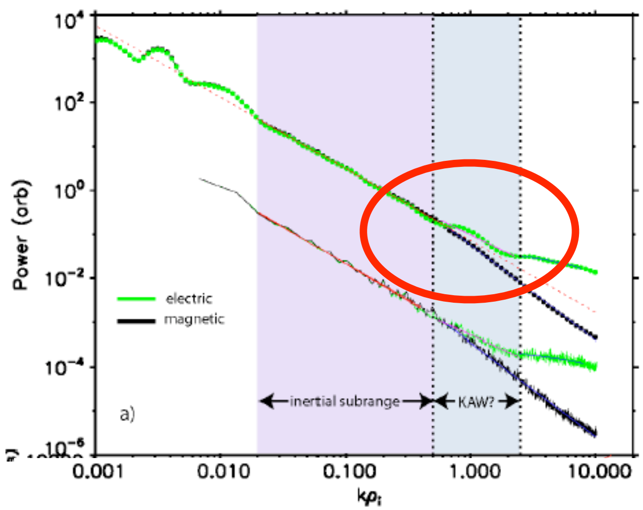
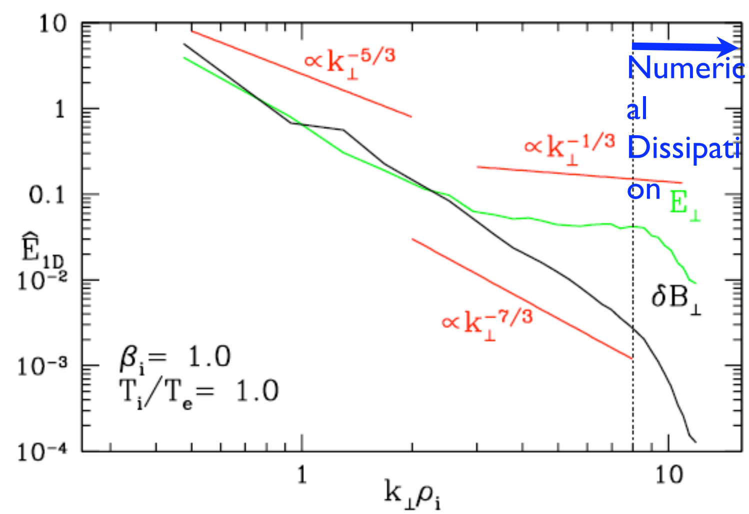
  - Astrophysical impact: gyrokinetic codes tested against lab measurements now used to simulate, e.g. solar wind, accretion disks, ISM

(Fig. 3 from Bale et al. 2005)



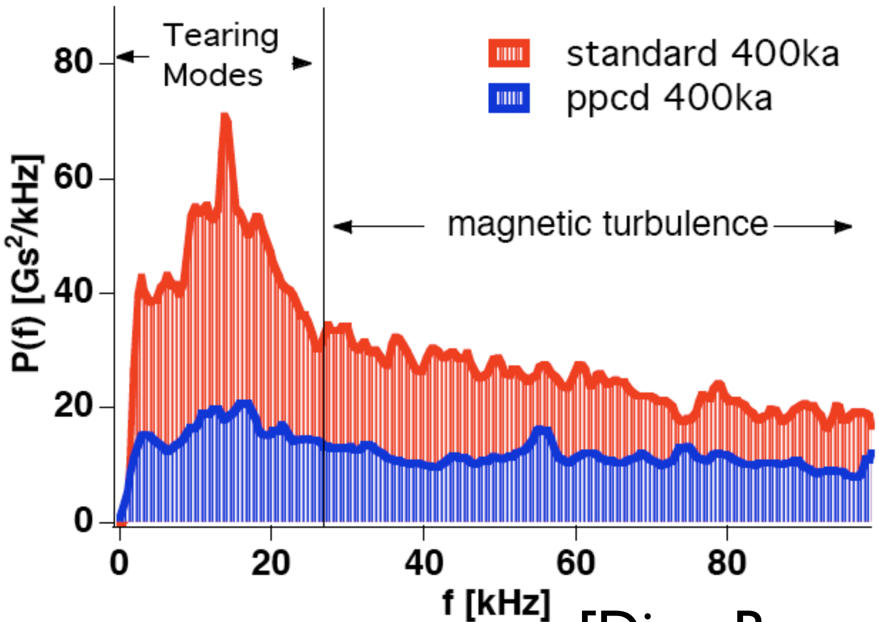
(Howes et al. 2008a)



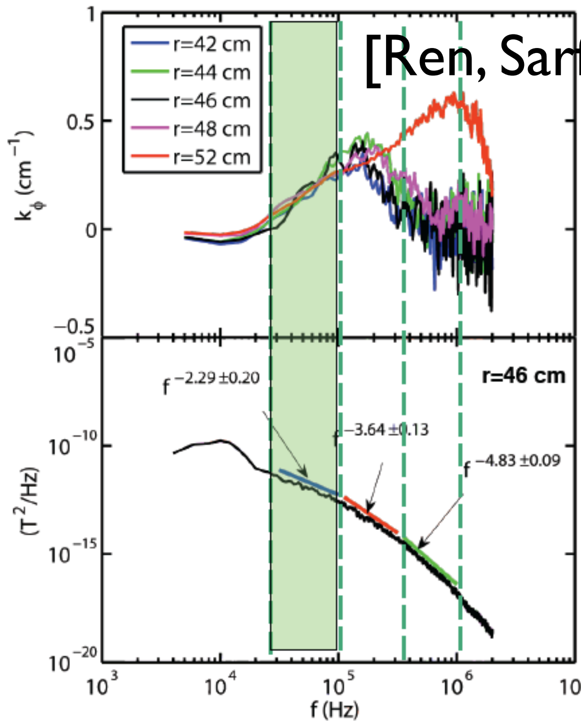
Laboratory experiments on Turbulence

- Turbulence is widely studied in laboratory plasmas; focus is on gradient-driven modes
  - Astrophysical impact: gyrokinetic codes tested against lab measurements now used to simulate, e.g. solar wind, accretion disks, ISM
- Fusion experiments have and can continue to contribute: tearing driven turbulence in MST, Alfvén Eigenmode cascade in ST/Tokamak (e.g. NSTX)

Turbulence studies in fusion plasmas (MST)



[Ding, Brower]



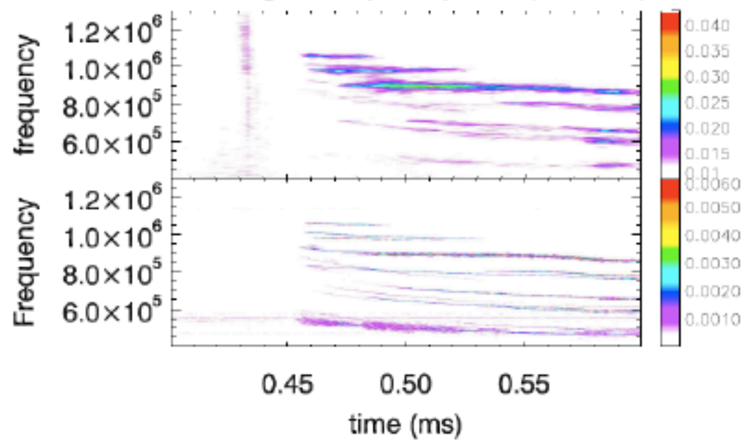
[Ren, Sarff, et al]

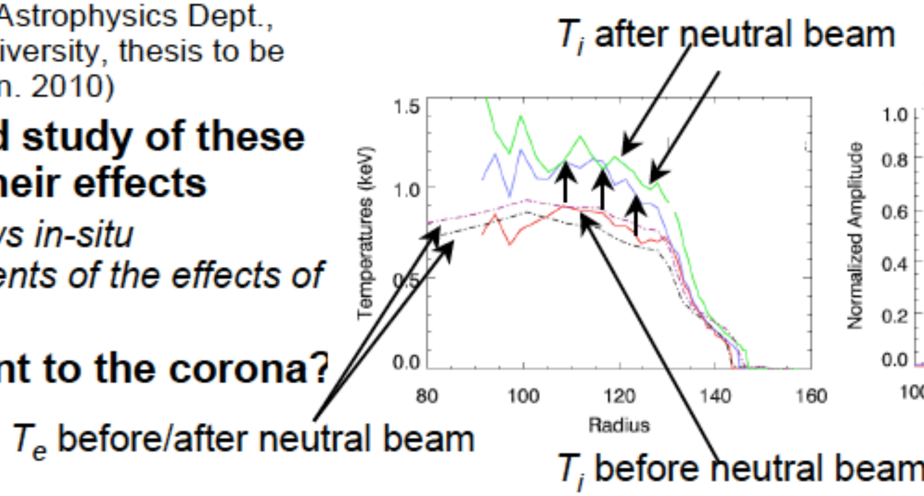
- Broadband magnetic fluctuation spectrum observed, with tearing modes acting as “stirring scale”. Ion heating observed (may be connected to cascade, especially for impurities [Tangrim, et al])
- Ongoing studies of spectrum (in some cases appears to be exponential, consistent with dominant dissipation?)

NSTX is an excellent laboratory for studying Alfvénic turbulence

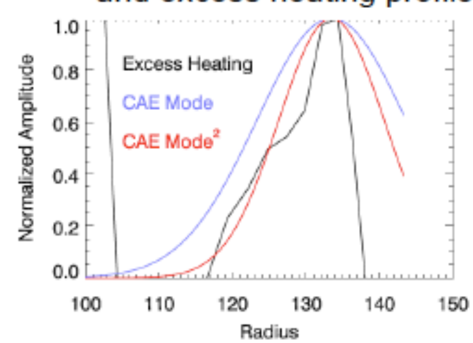
- High $v_{fast}/v_{Alfvén}$ drives many sub-harmonic Alfvén modes unstable
  - e.g., Fredrickson, et al., Phys. Plasmas **11** (2004) 3653
- Ion heating in excess of the heating due to beam-plasma collisions has been observed on NSTX
  - D. A. Gates, et al., Phys. Plasmas, **10** (2003) 1659
- Amplitudes of the observed modes are of the correct order to explain the observed heating
  - (P.W. Ross, Astrophysics Dept., Princeton University, thesis to be submitted Jan. 2010)
- **Need detailed study of these modes and their effects**
  - ***NSTX allows in-situ measurements of the effects of the waves***
- **Is this relevant to the corona?**

Spectrum from interferometer(top) and magnetic pickup coil (bottom)

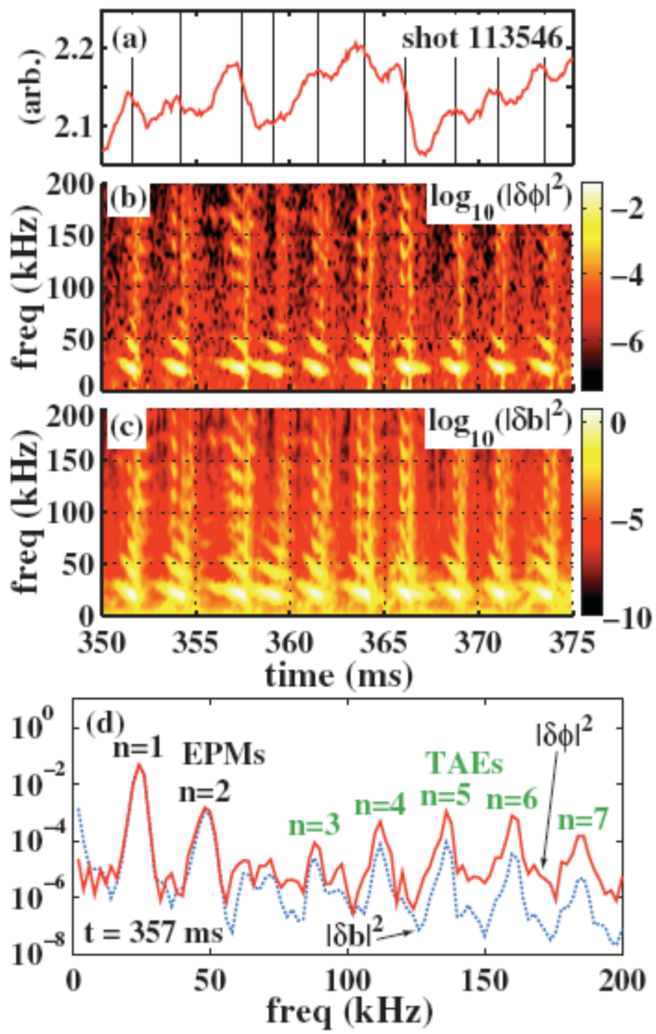




Mode radial eigenfunction and excess heating profile



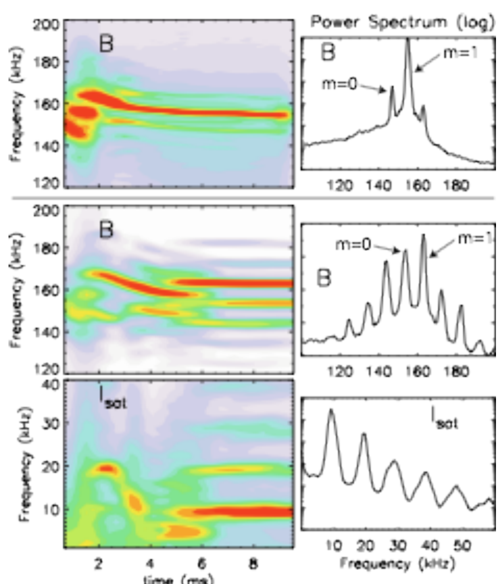
Nonlinear interactions among AEs in NSTX



- Fast particles (e.g. alphas) in fusion plasmas can destabilize Alfvén eigenmodes
- Multimode excitation can lead to nonlinear interactions (Crocker, PRL 2006)
- Possibly could have driven cascade through interaction of TAEs

Studies in LAPD

- Nonlinear interactions between co- and counter-propagating kinetic Alfvén waves
- Strong beat-wave interaction between co-propagating waves observed (below)



- Ongoing: Single wave collisions studied, development of turbulent spectrum hampered by damping ("outer scale" waves already have $k_\perp \rho_s \sim 0.5$)
- Low β (relevant in some astro contexts, e.g. corona)

[T.A. Carter, B. Brugman, et al., PRL 96, 155001 (2006)]

Desired characteristics of new experiment

- Desirable for new experiment have less dissipation, have access to higher β. Important characteristics:
- Low collisionality (high T or low n)
  - May be able to study inertial range with collisional damping, but would like to study kinetic damping processes, instabilities
  - Would like $\lambda_{mfp} >> \rho_i$, $\lambda_{mfp} > \lambda_{||,A}$ (preferably $\lambda_{mfp} \sim$ device size)
    - e.g. LAPD (5eV, 10^{12} cm^{-3}), λ_{ei}~20cm, $\lambda_{||,A}$~2m; need 25eV (hard to do without lots of power or better confinement)
  - But density can't be too low: causes problems in having Alfvén waves of low enough frequency fit in the device! Minimum wavelength $\sim v_A/\Omega_i \propto 1/\sqrt{n}$ (1.4m for 10^{12} cm^{-3})

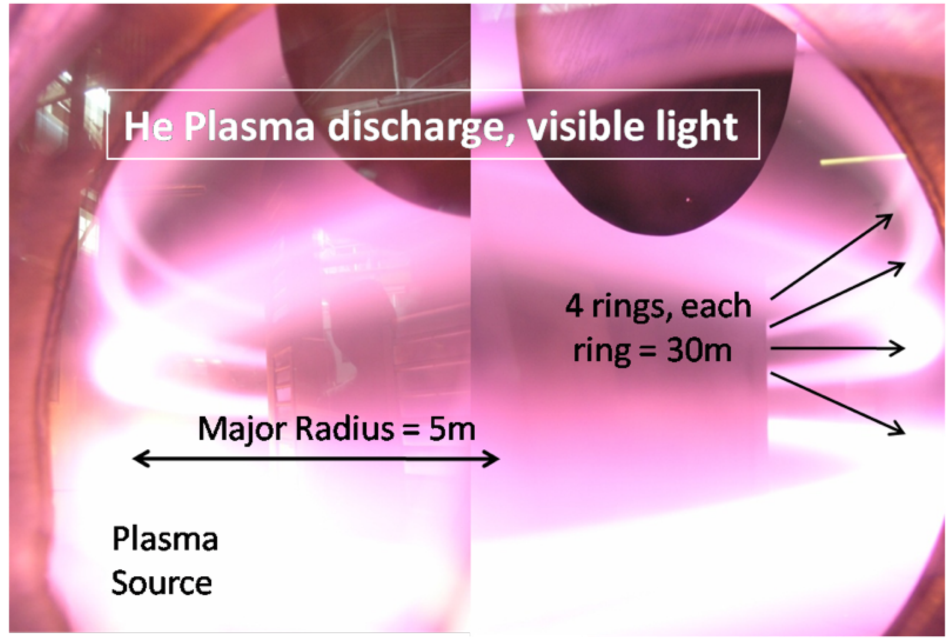
Desired characteristics, cont.

- Large enough magnetic field
  - Would like to have room between outerscale (machine size) and ion gyroradius to allow a turbulent spectrum to develop
    - Could be relaxed for firehose/mirror studies?
    - But, want to be able to access larger β
- Need reasonable mechanism for injecting energy at "stirring" scale: driving flows, exciting Alfvén waves of sufficient amplitude (directly, or through instability)

Next steps

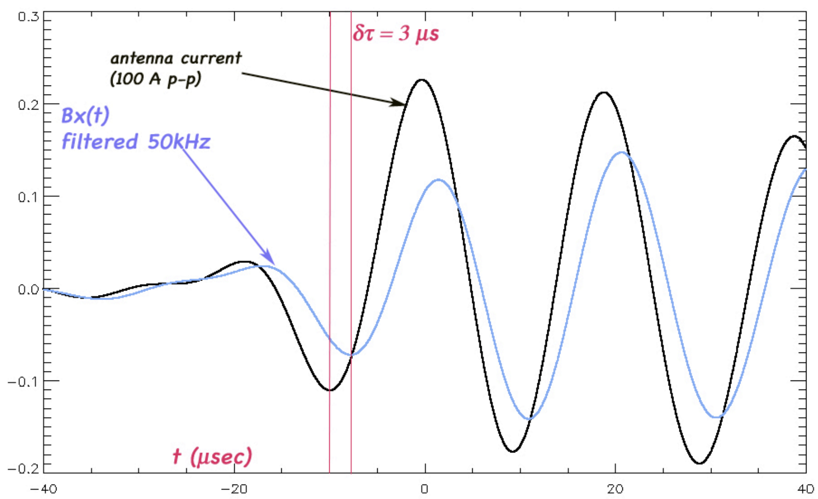
- Strong case for dedicated experiment(s) on turbulence and instabilities in collisionless plasma, with access to high beta
  - Coupled to theory and simulation, can make significant progress on understanding of basic physics of turbulence relevant to astrophysical plasmas
- To indicate what might be possible, briefly discuss new experimental facilities that might produce suitable plasmas for these studies

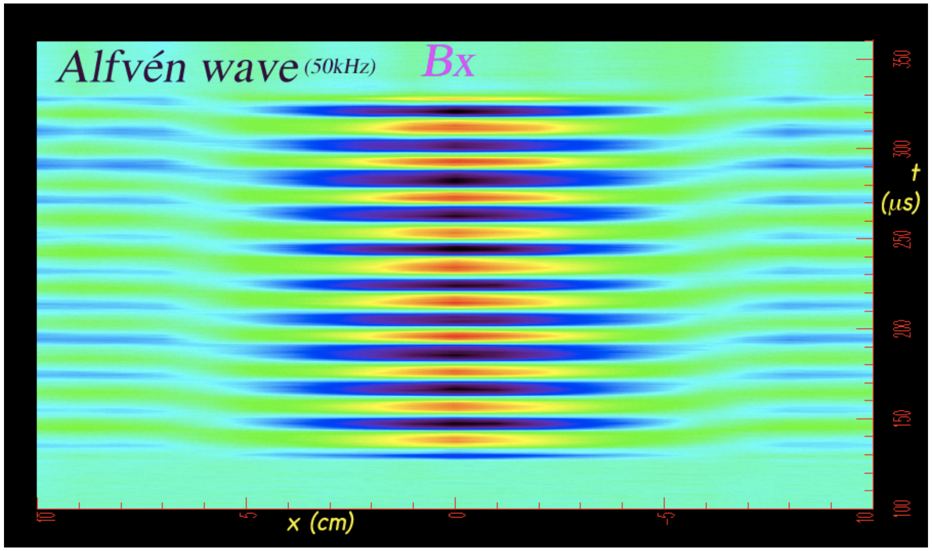
Enormous Toroidal Plasma Device at UCLA



- Former Electric Tokamak, (5m major radius, 1m minor radius) operating now with LaB_6 cathode discharge into toroidal+vertical field
- Produces ~100m long, magnetized, unity beta plasma (up to ~5×10^{13} cm^{-3}, Te, Ti ~ 20-50eV, B~200G, $\beta \sim 1$). Small (20cm) source operating presently, developing large area source (60cm wide plasma column planned).

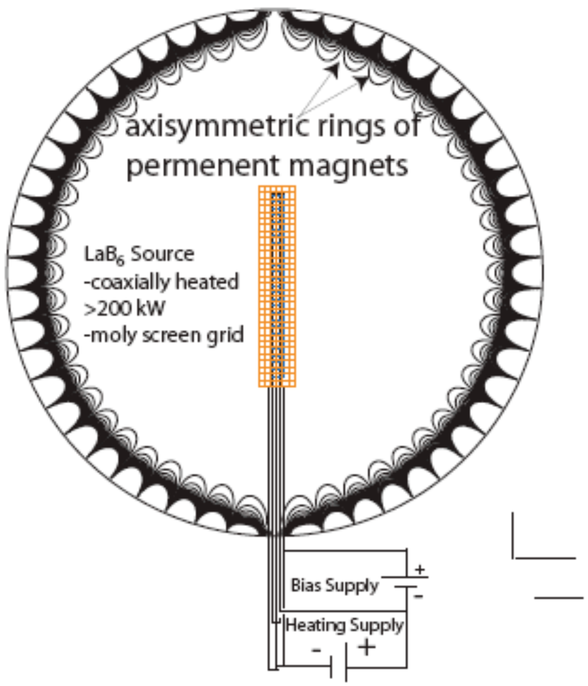
Possible turbulence studies in ETPD





- Alfvén waves, damping at β~1 (underway, data above), many (~100) Alfvén parallel wavelengths in device
- Wave-wave interactions, driven Alfvénic cascade at β~1 (collisional damping reduced over LAPD through higher temperatures)
- Gradient-driven/interchange turbulence at high β
- Mirror/firehose: Drive anisotropy, higher beta through expansion (drive plasma into low field region)

Madison Plasma Dynamo Experiment



plasma radius	a	1.5	m
density	n	10^{17}—10^{19}	m^{-3}
electron temperature	T_e	2—10	eV
ion temperature	T_i	0.5—2	eV
peak flow speed	U_{max}	0—20	km/s
ion species	H, He, Ar	1, 4, 40	amu
	τ_σ	50	msec
pulse length	$\tau_{\rm pulse}$	5	sec
	Rm_{max}	1400	
	Re	24—3.8×10^6	
	Pm	3×10^{-4}—56	
	β	10^4	

- Very high β, large volume plasma; experiment under construction
- Focus is dynamo, but can contribute to turbulence studies (EMHD regime at lower density, Alfvénic regime accessible at high density)
- In particular, has very high-β, easy access to anisotropy driven instabilities (stirring/dynamo process could excite)