Turbulence Analysis of an MHD wind-tunnel

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Motivating Questions

Is the statistical character of MHD turbulence universal?

How can laboratory plasmas be used to study MHD turbulence?

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U.S. DEPARTMENT OF ENERGY | Office of Science | NSF | CMSO

References

REF 1: *Observation of turbulent intermittency scaling with magnetic helicity in an MHD plasma wind tunnel*, D.A. Schaffner, A. Wan and M.R. Brown. Physical Review Letters **112** 165001 (2014).

REF 2: *Turbulence analysis of an experimental flux rope plasma*, D.A. Schaffner, V.S. Lukin, A. Wan, M.R. Brown. Plasma Physics Controlled Fusion **56** 064003 (2014).

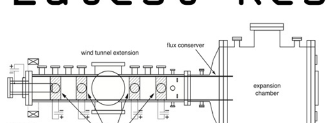
REF 3: *Temporal and Spatial Turbulent Spectra of MHD Plasma and an Observation of Variance Anisotropy*, D.A. Schaffner, V.S. Lukin, M.R. Brown. The Astrophysical Journal **790** 126 (2014).

REF 4: *Laboratory sources of turbulent plasma: a unique MHD plasma wind tunnel*, M.R. Brown and D.A. Schaffner, Plasma Sources and Science Technology. 23 063001 (2014).

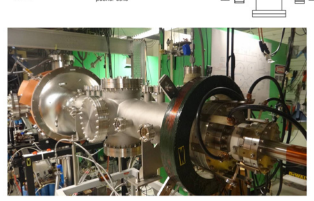
REF 5: *Spatial magnetic correlations functions and Taylor microscale in a turbulent MHD laboratory plasma*, A. Wan, D.A. Schaffner, V.S. Lukin, M.R. Brown, *in preparation for publication*

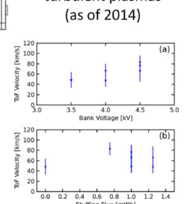
REF 6: Permutation Entropy and Statistical Complexity Analysis of Turbulence in Laboratory Plasmas and the Solar Wind. P.J. Weck, D.A. Schaffner, M.R. Brown and R.T. Wicks. Submitted to Physical Review E September 2014.

Latest Research



New configuration for exploring expanding turbulent plasmas (as of 2014)





Scan of plume velocity by varying bank voltage and stuffing flux

More Questions:

Is the Taylor Hypothesis Valid? We can test though will probes aligned with plasma flow.

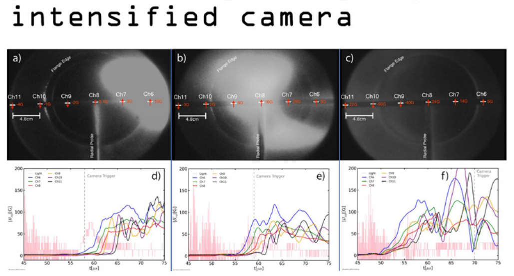
What kinds of modes are generated? We can explore this with measurements of simultaneous field and density measurements.

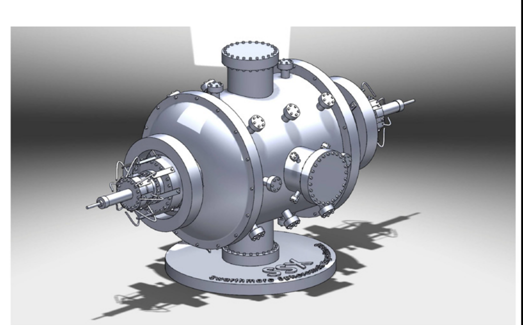
Does system size matter? We can use simulation and experiment comparisons to see if spectra, mode content change with system size.

What happens when more kinetic energy is added to the turbulence? Using accelerators in the tunnel extension, we can add to the flow energy

How can MHD turbulence be compared to turbulence in fusion devices? Exploration through the CH plan analysis can be conducted

Visualization of plasma plumes using a high-speed intensified camera

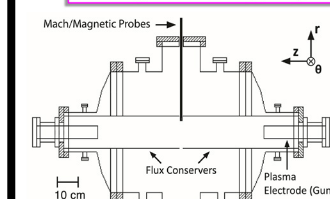


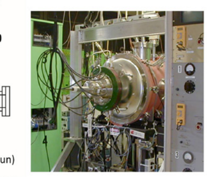


See more about SSX online at:
www.swarthmore.edu/ssx-lab

MHD Turbulence In the Lab: The SSX Wind-Tunnel

High field, high density Hydrogen plasma produced in a ~1m long, 15cm wide copper cylinder using plasma guns



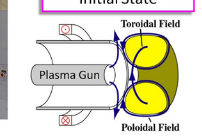


See REF 4

No Guide-field—magnetic fields completely dynamical!

Turbulence produced during transition from initial spheromak state to final twisted Taylor State

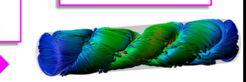
Initial State



Spheromak

Turbulence During Transition

Final State



Taylor State (Tilt and Twist) Double Helix Shape

Typical Average Plasma Parameters

Temps:	$T_i = 25ev, T_e = 10ev, \beta \approx 0.1$
Fields:	$B = 5kG \rightarrow \rho_i = 0.1cm$
Density:	$n \approx 1x10^{15}cm^{-3} \rightarrow \lambda_i = \delta_i = c/\omega_{pi} = 0.54cm$
Velocity:	$V_A > C_s >$ Axial Flow 256km/s > 31km/s > 20km/s

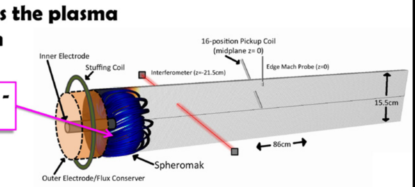
Collisional Plasma – MFP ~ 0.2-3cm

Magnetic Energy Minimized $E_B = \int \frac{B^2}{2\mu_0} dV$

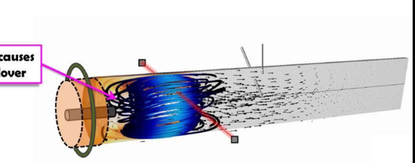
Under constraint of Conservation of Helicity $K_B = \int A \cdot B dV$

An MHD-Hall simulation using the HiFi Framework illustrates the plasma evolution

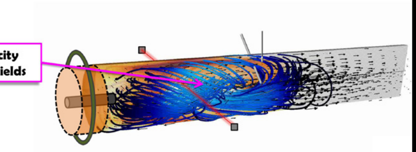
Initial State - Spheromak



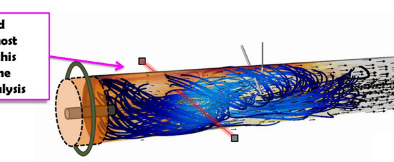
Tilt Instability causes spheromak rollover

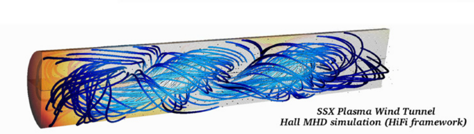


Conserved helicity forces twist in fields



Field lines and plasma are most turbulent at this stage—i.e. time frame for analysis

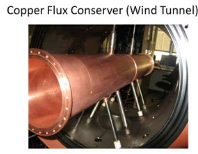




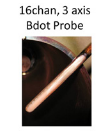
A final state called a Taylor State or Double-Helix is eventually reached when plasma (flow and magnetic) energy is minimized—*all turbulence analysis is performed before the structure reaches this state.*

SSX Measurements

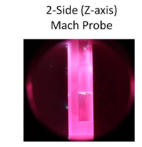
Copper Flux Conserver (Wind Tunnel)



16chan, 3 axis Bdot Probe

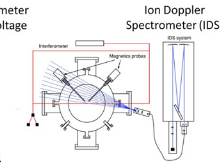


2-Side (Z-axis) Mach Probe



HeNe Interferometer
Gun Current/Voltage

Ion Doppler Spectrometer (IDS)



Al/Zr Metal Soft X-ray Photodiode

See REF 4

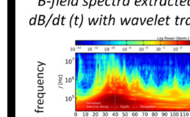
Time Series Analysis

Ensemble Average: x40+ shots

Analysis time range (from gun trigger)

See REF 2,4

B-field spectra extracted from dB/dt (t) with wavelet transform



Power spectrum

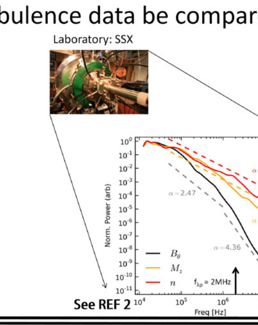
$$E_{B_i}(f) \simeq \frac{1}{f^2}\left(\int \dot{B}_i(t)e^{-ift}dt\right)^2$$

Turbulence Analyses

Can SSX turbulence data be compared to the solar wind or the magnetosheath?

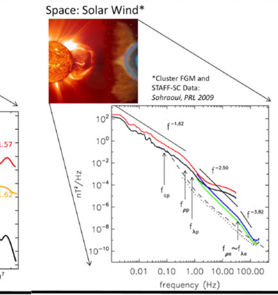
Many turbulence and statistical analyses performed on SSX data have been motivated by comparisons to the solar wind and the magnetosphere

Laboratory: SSX

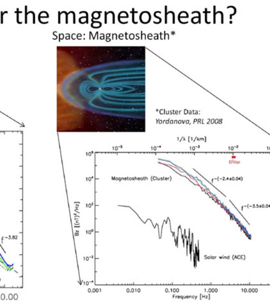


See REF 2

Space: Solar Wind*



Space: Magnetosheath*

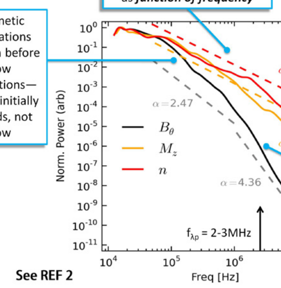


Spectra

Power-law scaling in B-field, density and flow as *function of frequency*

Magnetic spectra ***steeper*** than Kolmogorov

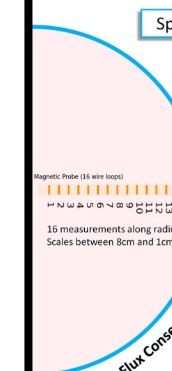
Magnetic fluctuations steepen before flow fluctuations—energy initially in fields, not flow

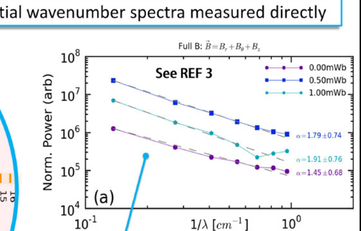


If average flow is used to invoke Taylor Hypothesis: ***Break in B-field spectra near Doppler-shifted ion inertial length***

See REF 2

Spatial wavenumber spectra measured directly

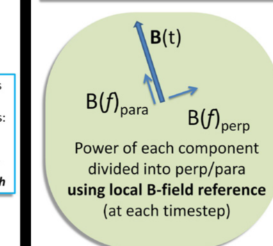




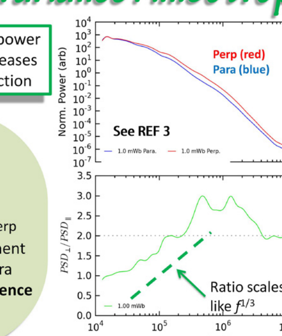
Lower resolution spectra, but slopes are closer to a Kolmogorov -5/3

Variance Anisotropy

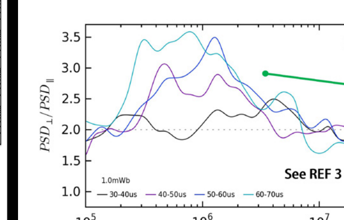
Variance analysis shows power in parallel direction decreases faster than parallel direction



Power of each component divided into perp/para **using local B-field reference** (at each timestep)



Anisotropy ratio increases with time

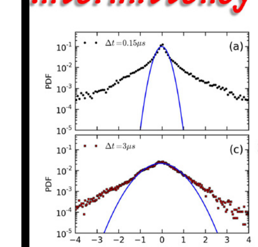


Anisotropy peaks around 1MHz, returns to isotropy at higher frequencies

Scaling increases from purple to blue to light blue

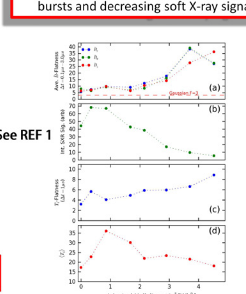
Intermittency

Flatness increases with increasing helicity; correlates with increasing ion temperature bursts and decreasing soft X-ray signal



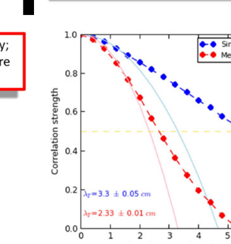
Flatness of PDFs of Increments increases with smaller time increments

See REF 1



Results possibly indicative of increasing number of reconnection sites with increased plume helicity

Radial Correlation



Radial correlation determined from cross-correlation of radial magnetic probe

Taylor Microscale found by fitting:

$$R(r) \simeq 1 - \frac{r^2}{2\lambda_T^2}$$

Best fits give λ_T = 3.3cm
$\rightarrow \lambda_T \approx 5\ \delta_i$

Effective Reynolds Number:

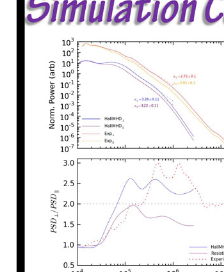
$$R_M^{eff} = \left(\frac{\lambda_C}{\lambda_T}\right)^2$$

λ_C can range 7.75cm to 42cm depending on definition measurement

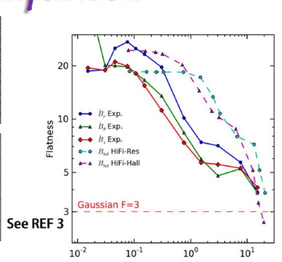
$$R_M^{eff} \simeq 6 - 160$$

See REF 5

Simulation Comparison



See REF 3



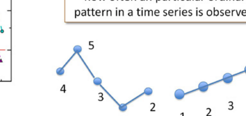
Variance anisotropy observed

Similar intermittency statistics observed

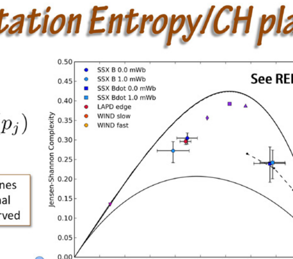
Permutation Entropy/CH plane

$$S[P] = -\sum_{j=1}^{N} p_j ln(p_j)$$

Permutation Entropy determines how often an particular ordinal pattern in a time series is observed



For n=5, n!=120 different ordinal patterns would be possible (two examples given above)



PE can be combined with a complexity measure—different time series will have different coordiantes on the CH plane. This can be used to distinguish between different "types" of turbulence