Magnetic turbulence in a plasma wind tunnel at the Bryn Mawr Plasma Laboratory

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Disclaimer: Placing these experiments in the proper frame and context

Cannot replicate space plasma exactly

Instead, we seek characteristics that CAN be replicated or modeled

Our target: better understand the dynamic, (mostly) unbounded magnetic field turbulence observed in space
Particularly, solar wind and magnetosphere

Our approach: generate and study turbulence of a laboratory plasma with both dynamic flows and fields
Goals for this talk

Describe general approach to generating and studying magnetic turbulence in a laboratory setting

Give overview of results to date from SSX (with some background on analysis techniques, some familiar, some maybe not)

Discuss motivations, designs, advantages and plans of new experiment at Bryn Mawr, BMX

Present preliminary results from first runs on BMX
Generating magnetic turbulence in the laboratory

Swarthmore Spheromak Experiment, SSX
Generating magnetic turbulence in the laboratory

SSX Compact Wind Tunnel Configuration
Generating magnetic turbulence in the laboratory

Coaxial Electrode
Plasma Gun Source

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Flux conserving copper boundary

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Pickup coils measure B-field fluctuations at midplane near central axis

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Coaxial Electrode Plasma Gun Source produces a compact toroidal plasma called a spheromak.

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The spheromak is launched into the flux conserving tube

Relaxes into a lower energy configuration called a Taylor State under the constraint of constant helicity.

SSX Compact Wind Tunnel Configuration
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Magnetic Turbulence

Plasma Parameters during Turbulence Phase

- $\bar{B} \sim 3$ to $5kG$
- $\bar{n} \sim 1 \times 10^{15} cm^{-3}$
- $\lambda_{ii-mfp} = 0.2cm$
- $\rho_i \sim 0.1cm$
- $c/\omega_{pi} = \lambda_i \sim 0.5cm$
- $T_i \sim 20eV, T_e \sim 10eV$
- $V_A > C_s > V_z$
- $200km/s > 50km/s > 30km/s$

Weakly Collisional

Sub-Alfvenic, Sub Mach Flows

Chamber 30-100x these scales
Broadband magnetic fluctuation spectra observed

Scaling is slightly steeper than Kolmogorov for lower frequencies.

Steepens at higher frequencies.

Inflection point at scales consistent with convected ion inertial length → Suggests potential onset of dissipation physics.
Comparison of spectra to solar wind, magnetosphere

*Cluster FGM and STAFF-SC Data: Sahraoui, PRL 2009

*Cluster Data: Yordanova, PRL 2008

*SSX PoP 2016
Experimental process for laboratory astrophysics

1) Generate dynamic flows and fields in laboratory
2) Conduct analysis techniques to find characteristics of turbulence
   - Some motivated by space: intermittency, structure functions
   - Some new techniques: Permutation Entropy/Statistical Complexity, Recurrence Quantification Analysis
3) Utilize advantages of lab
   - Can make simultaneous spatial measurements
   - Can scan conditions: primarily injected helicity
4) Generate full-system simulations of process for comparison
Work thus far stemming from SSX lab

Wide range of experiments and techniques studied thus far

Overview of analysis techniques: Schaffner, Brown, Wan PPCF 2014
Intermittency changes with helicity: Schaffner, Brown, Wan PRL 2014

SSX MHD Wind Tunnel Overview: Brown and Schaffner, JPP 2015
Possible Signatures of Dissipation: Schaffner, Brown, and Rock, PoP 2016

Three Case studies:
  Intermittency changes with helicity
  Variance anisotropy observation and comparison with simulation
  Evaluation and comparison using permutation entropy/statistical complexity
Expt 1: Effect on Intermittency with Injected Helicity

Examining intermittency is a common tool used in space physics and simulation communities for identification of current sheets and magnetic reconnection.

*Schaffner, Brown, Wan PRL 2014

*Schubert, Brown, Wan JGR 2014

*Dudok de Wit, Space Science Review 2013

*Servidio et al, JGR, 2011
Expt 1: Effect on Intermittency with Injected Helicity

Spheromaks can be generated with different values of toroidal and poloidal magnetic field → the ratio of field can be related to the magnetic helicity of the experiment

\[ K_B \equiv \int A \cdot B dV = 2 \int \Phi V_{gun} dt \]

Schaffner, Brown, Wan PRL 2014
Expt 1: Effect on Intermittency with Injected Helicity

Intermittency of magnetic fluctuations quantified by using a PDF of increments approach

Level of departure from non-Gaussian distribution is quantified using kurtosis or Flatness (4\textsuperscript{th} order moment)

Schaffner, Brown, Wan PRL 2014
Expt 1: Effect on Intermittency with Injected Helicity

**Main Result:** Average kurtosis (over a few time scales) increases with injected helicity

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**Potential Implications:** Increased frequency of magnetic reconnection sites (that is, twisting the plasma up more seems to produce more sites of reconnection)

Schaffner, Brown, Wan PRL 2014
The anisotropy of magnetic fluctuations has implications for understanding the turbulence cascade, dissipation mechanisms effects of MHD turbulence.

Variance anisotropy (or magnetic compressibility) be measured in the laboratory MHD experiments.

Variance anisotropy on SSX is computed using a wavelet decomposition of magnetic field fluctuations from a three-axis pickup coil and projecting them onto a mean B-field to construct $B_{\parallel}(f)$ and $B_{\perp}(f)$.

$$Var.\ Ani. = \frac{B_{\perp}(f)}{B_{\parallel}(f)}$$

Expt 2: Variance Anisotropy and Comparison to Simulation

**Main Result:**
Variance Anisotropy increases (becomes more anisotropic) up to about 1 MHz, but then becomes more isotropic at higher frequencies.

**Main Implications:**
This effect is consistent with what has been observed in solar wind turbulence (Kiyani 2013). Effect is connected to dissipation scale.

We can compare to a Hall-MHD simulation in the HiFi framework (Lukin)

Simulations shows qualitatively similar behavior (increasing than decreasing variance anisotropy)

Expt 3: Evaluation and comparison using permutation entropy/statistical complexity

Very Brief overview of PESC

Main Idea: Decompose a signal into a distribution of ordinal patterns (rather than Fourier components, say) and construct metrics based on these distributions for comparison.

Weck PRE 2015
Expt 3: Evaluation and comparison using PESC

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\[ p_j = \frac{\text{(# }j - \text{Patterns)} \text{ }}{\text{total}} \quad j = 1, \ldots, n! \]

Permutation Entropy, S[P]

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

Weck PRE 2015
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\[ \text{disequilibrium} \times \text{PE} = \text{Complexity} \]

Statistical Complexity, \( C[P] \)

\[
C[P] = -2 \frac{S[P+P_e] - \frac{1}{2} S[P] - \frac{1}{2} S[P_e]}{\frac{N+1}{N} \log(N+1) - 2 \log(2N) + \log(N)}
\]

Weck PRE 2015
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**Laboratory Examples**
- Density fluctuations of from temperature gradients in LAPD – Maggs PPCF 2013
- Magnetic field of Flux Ropes in LAPD – Gekelman PPCF 2014
- Density Fluctuations in DIII-D L-mode plasmas – Maggs PPCF 2015

**Space Examples**
- Magnetic field fluctuations of the solar wind from WIND – Weck, Schaffner et al PRE 2015

CH Plane

**CH Plane**

Jensen-Shannon Complexity vs Entropy

**SSX Data**

Expt 3: Evaluation and comparison using PESC
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The shift to increasing complexity with decreasing scale correlates qualitatively with dissipation scale.

One speculative interpretation: dissipation regime correlates with enhanced mode activity that manifests as larger complexity.
Limitations of magnetic turbulence research on SSX

Short time duration of “turbulent” plasma

Few access points

Relatively small size
Magnetic turbulence research on the Bryn Mawr Magnetohydrodynamic Experiment (BMX)
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High spatial sampling – 36 access ports staggered to allow axial probe separation of 0.5cm

- High sampling allows for direct spatial spectral measurements
- Can make comparisons of spatial and temporal spectra
- Less reliance on Taylor Hypothesis

Ports at 60° separation

- Allows tetrahedral probe array which can mimic pattern used in Cluster/MMS for extraction of wavenumber information
- Fine axial sampling allows for fine variation in tetrahedral size
Magnetic turbulence research on the BMX

Longer current/injected helicity using a pulse forming network of 8 500uF capacitors (compared to SSX’s 2)

Threshold Current for Helicity injection about 3x that of SSX

Duration of Entire SSX Shot

2.2kV bank discharge yields a peak current of 58.4kA and an average of 47.4kA over ~180us.
Magnetic turbulence research on the BMX

Magnetic spectra consistent with that found on SSX, but sustained over ~8x the analysis period → More wind-tunnel-like
Magnetic turbulence research on the BMX

Bulk velocity determined using time-delay estimation of $|B|$ 180us-long timeseries from two nearby magnetic pickup coils

Velocities are between 50 and 80km/s with an average of 66km/s (only 10 shots taken so far)
Upcoming Experiments at Bryn Mawr

Short(er) term:
Correlation of Density and Magnetic Field fluctuations for mode identification, study of compressive turbulence (identical expts @ both SSX and BMPL)

Longer pulses (from ~100us to ~300us) for better statistical analyses (BMPL)
Effect of magnetic targets, terrella experiments, space weather (BMPL)

More simulation development:
- HIFI
- Kinetic

Long(er) term:
- Ion transport
- Comparisons

Suggestion for experiments/analyses from the Community are very welcome!