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

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Heliophysics Seminar, PPPL
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Princeton, NJ

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

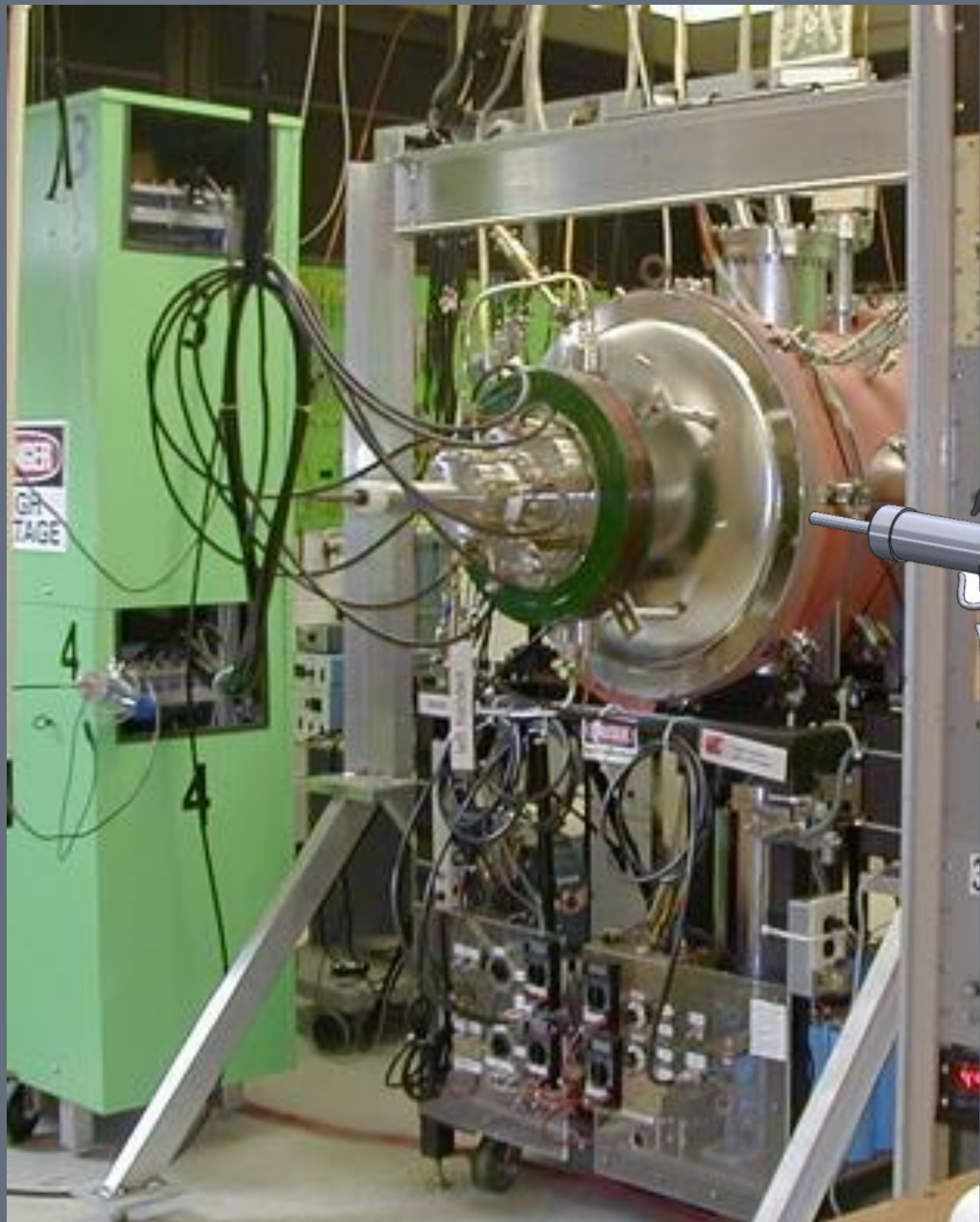
Describe general approach to generating and studying magnetic turbulence in a laboratory setting

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

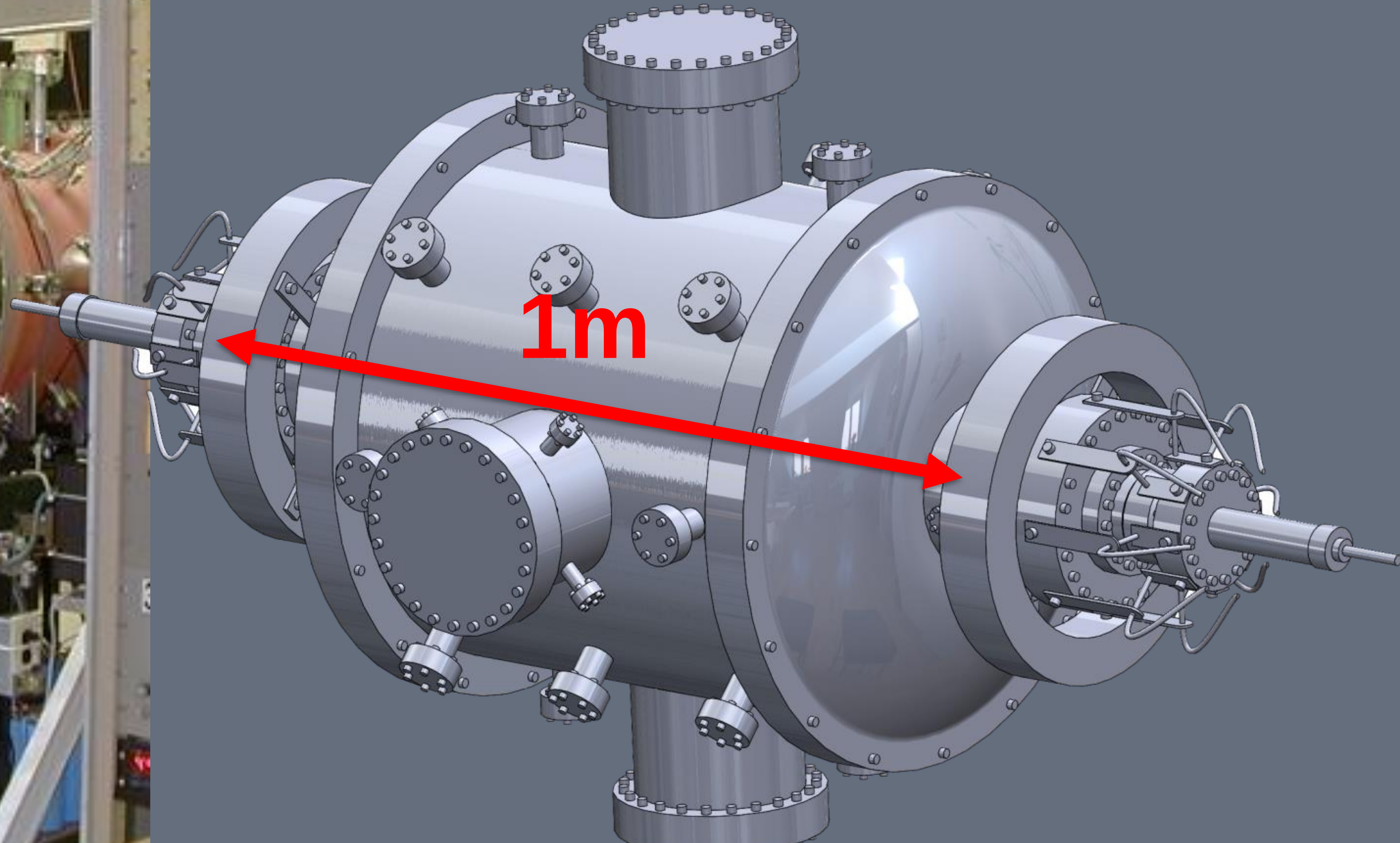
Discuss motivations, designs, advantages and plans of new experiment at Bryn Mawr, BMX

Present preliminary results from first runs on BMX

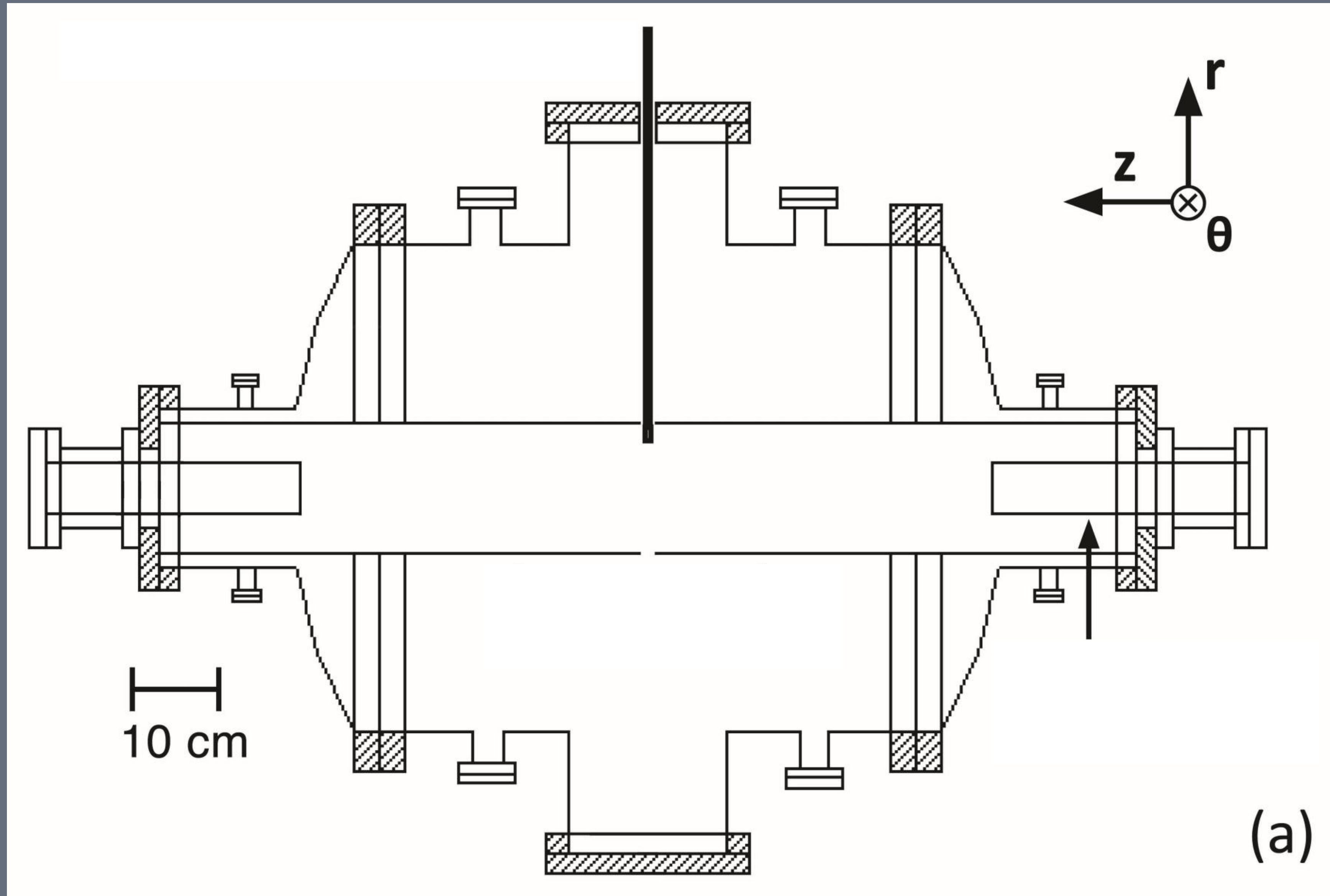
Generating magnetic turbulence in the laboratory



Swarthmore Spheromak Experiment, SSX



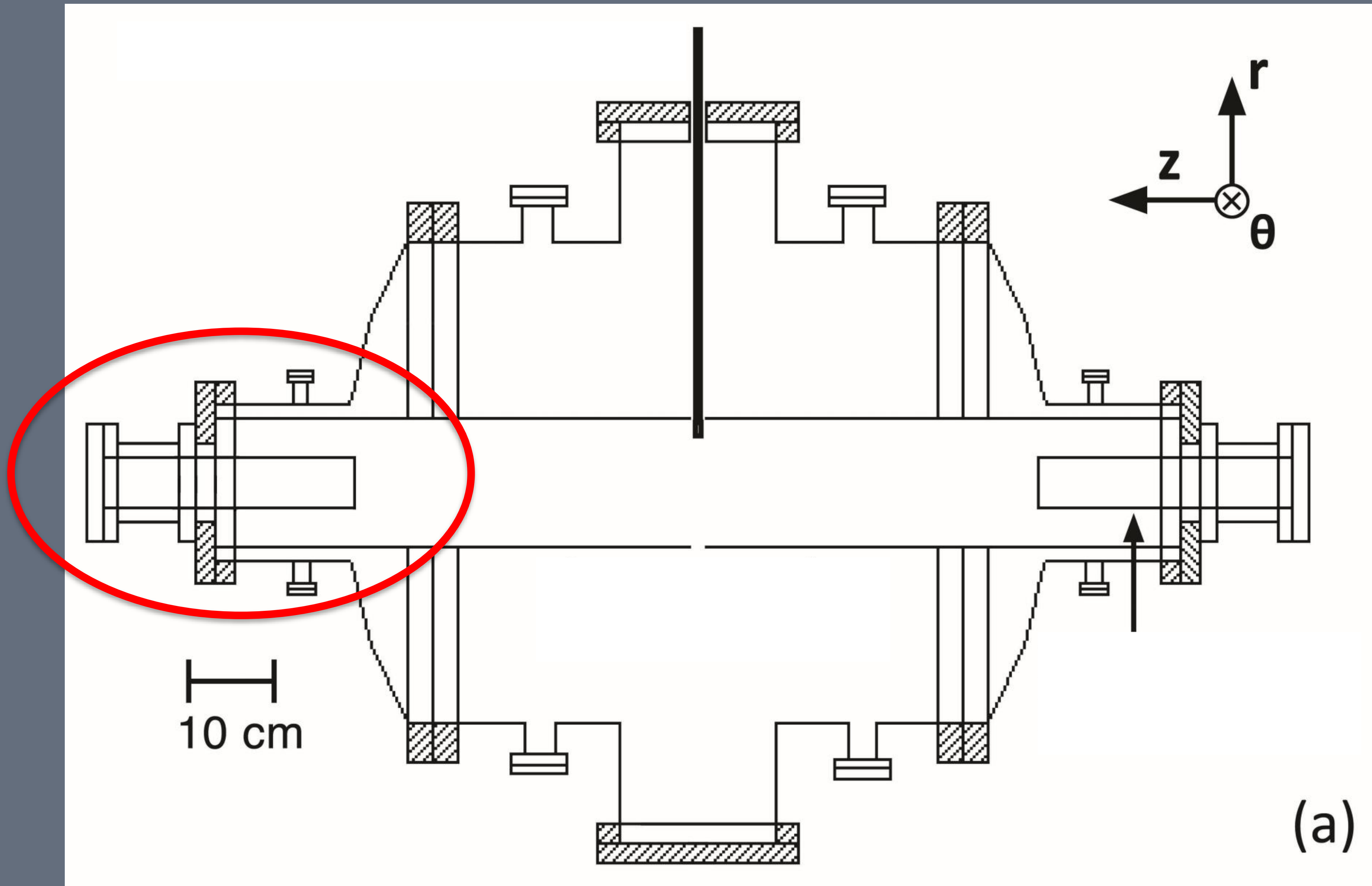
Generating magnetic turbulence in the laboratory



SSX Compact Wind Tunnel Configuration

Generating magnetic turbulence in the laboratory

Coaxial Electrode Plasma Gun Source

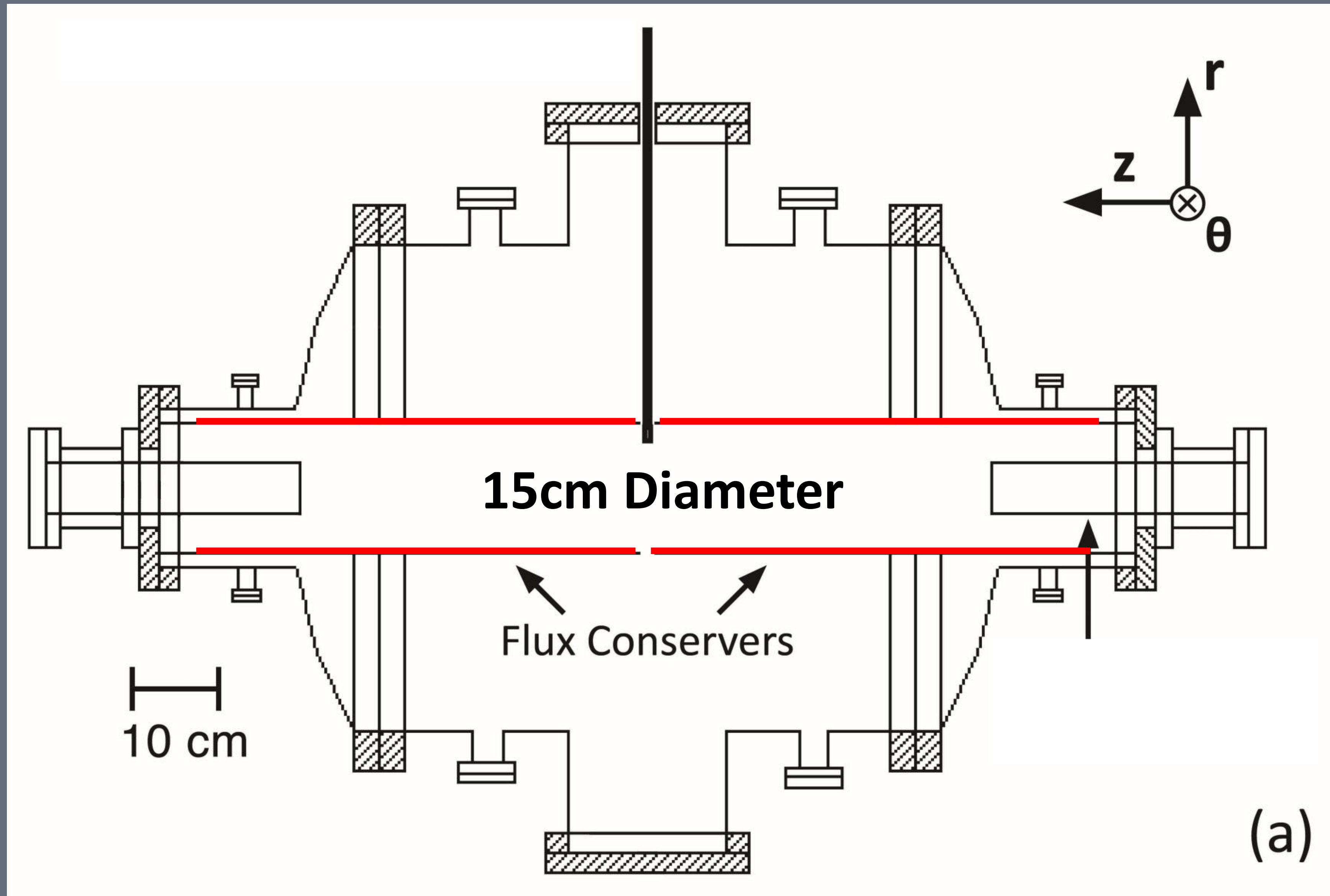


SSX Compact Wind Tunnel Configuration

Generating magnetic turbulence in the laboratory

Coaxial Electrode Plasma Gun Source

Flux conserving copper boundary



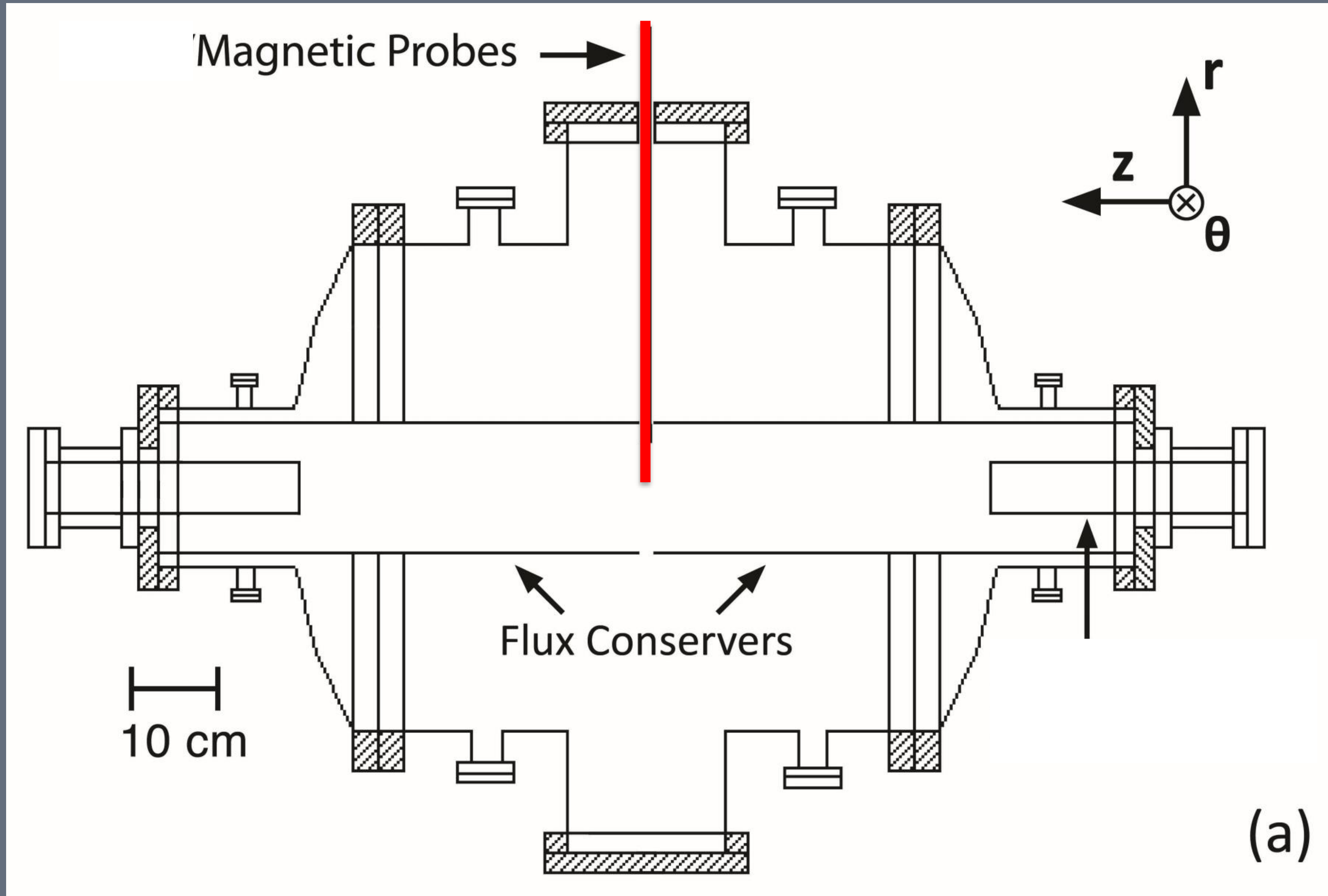
SSX Compact Wind Tunnel Configuration

Generating magnetic turbulence in the laboratory

Coaxial Electrode Plasma Gun Source

Flux conserving copper boundary

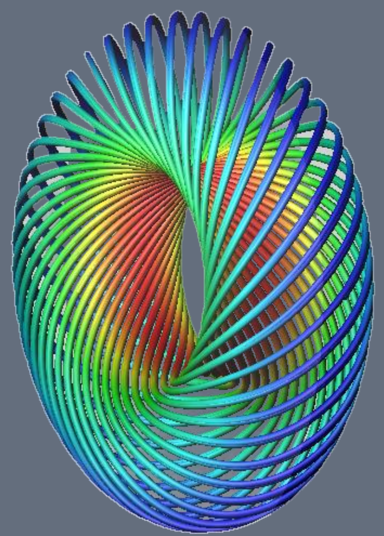
Pickup coils measure B-field fluctuations at midplane near central axis

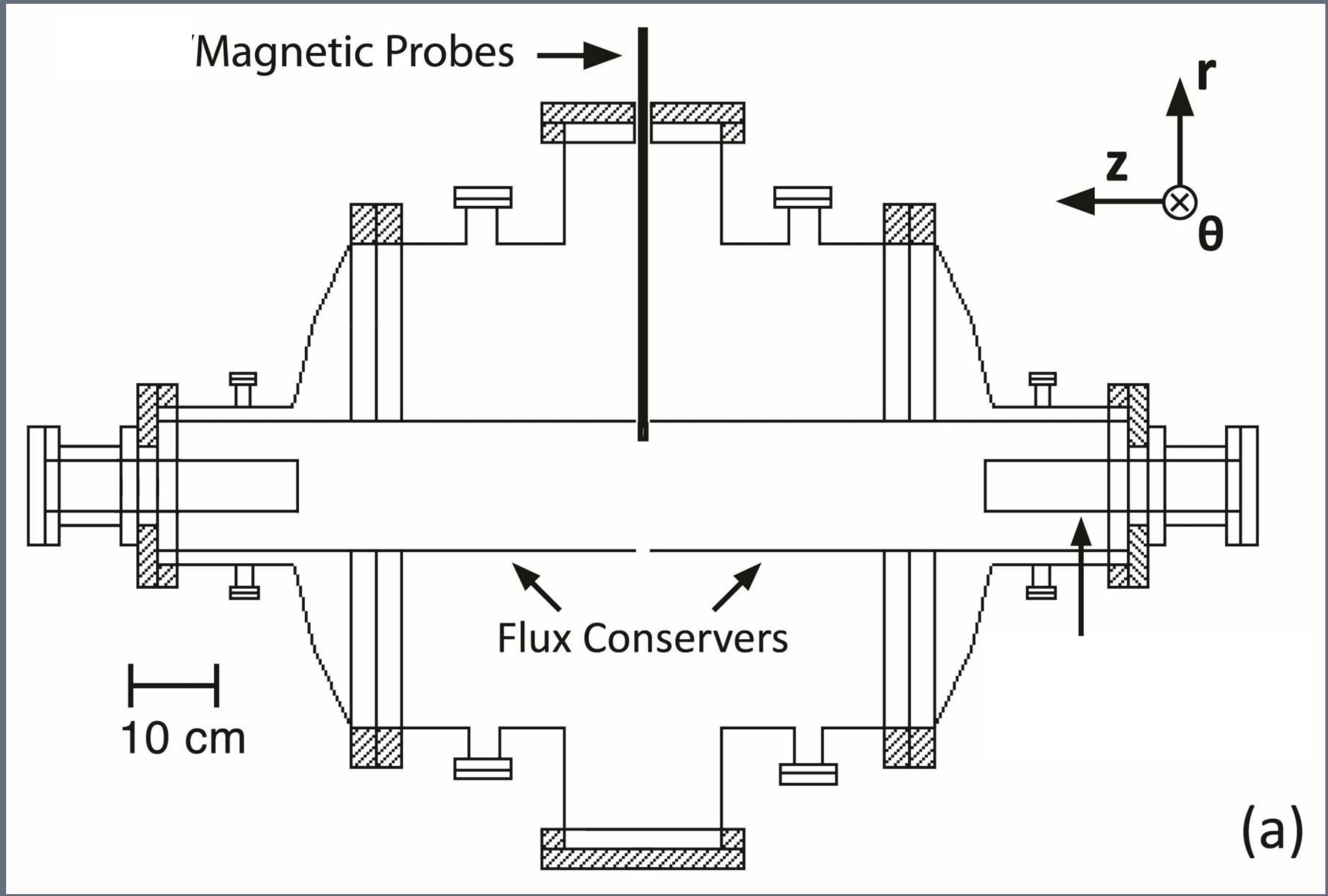


SSX Compact Wind Tunnel Configuration

Generating magnetic turbulence in the laboratory

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





SSX Compact Wind Tunnel Configuration

Generating magnetic turbulence in the laboratory

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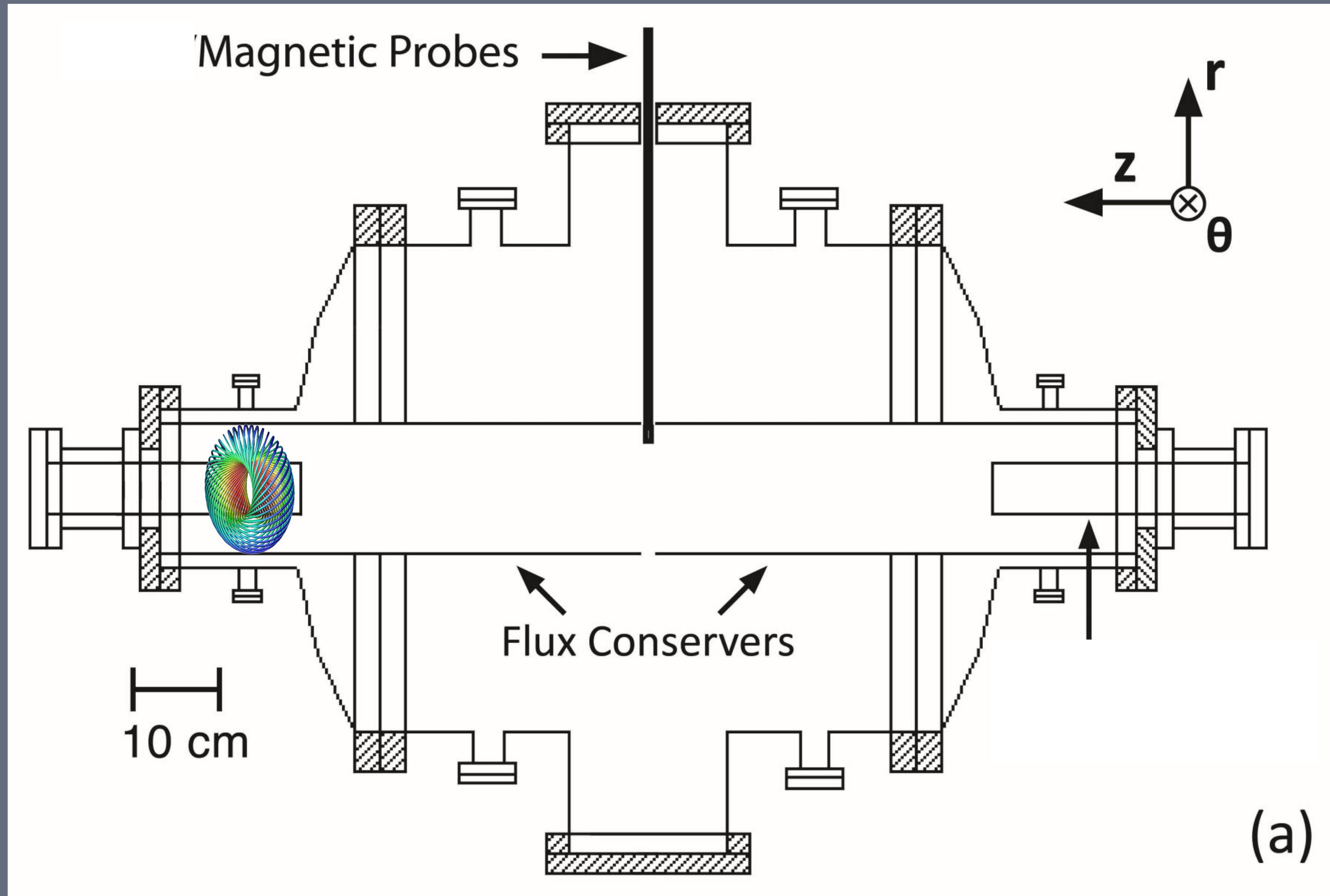
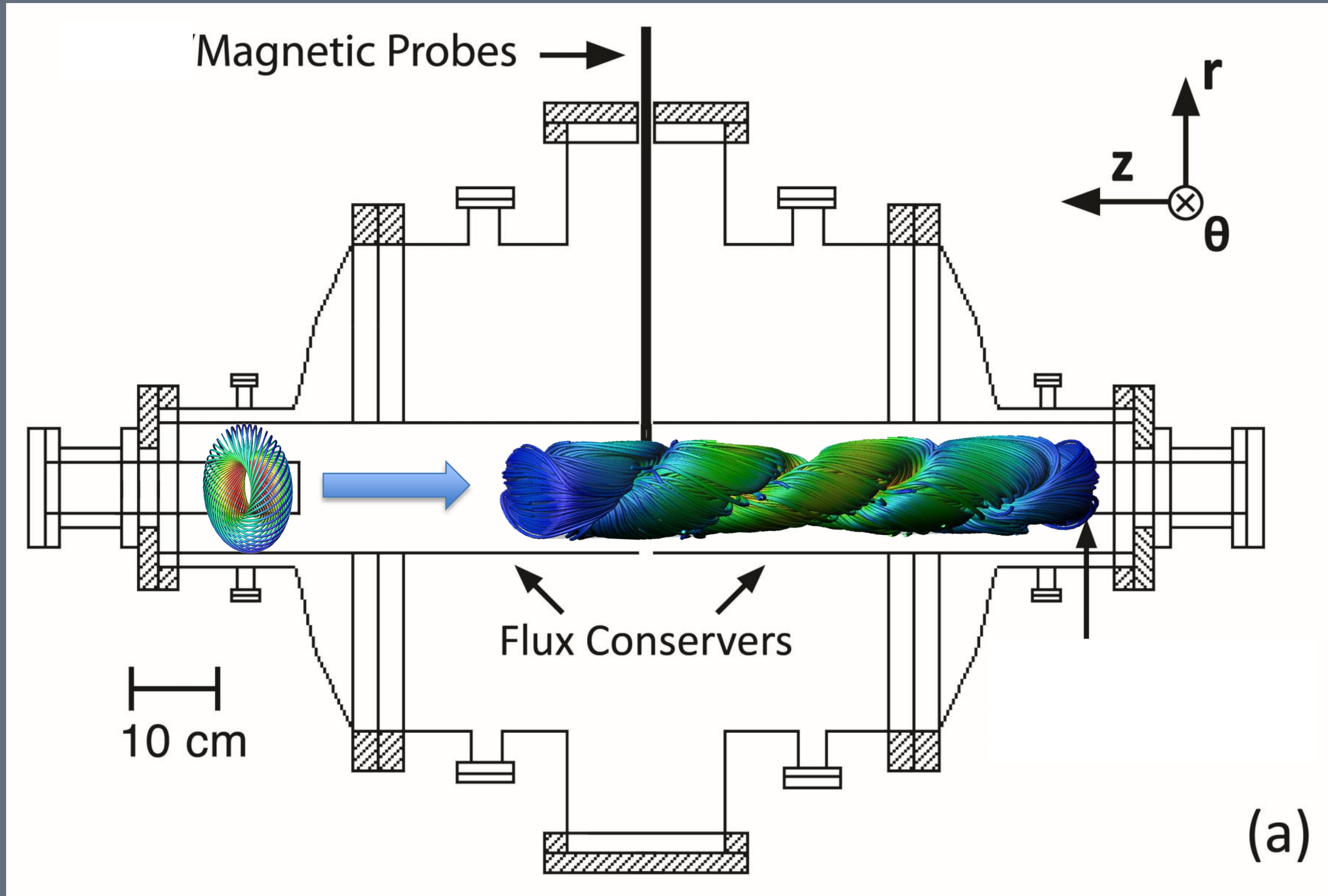


SSX Compact Wind Tunnel Configuration

Generating magnetic turbulence in the laboratory

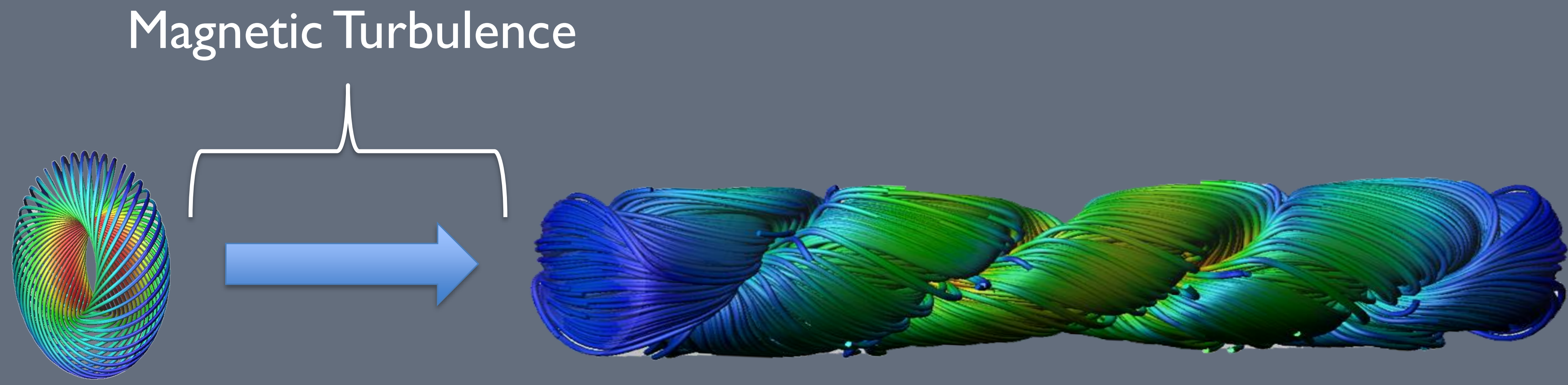
The spheromak is launched into the flux conserving tube

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



SSX Compact Wind Tunnel Configuration

Generating magnetic turbulence in the laboratory



Plasma Parameters during Turbulence Phase

$\bar{B} \sim 3\ to\ 5kG$

$\rho_i \sim 0.1cm$

Chamber 30-100x these scales

$\bar{n} \sim 1 \times 10^{15} cm^{-3}$

$c/\omega_{pi} = \lambda_i \sim 0.5cm$

Weakly Collisional

$\boxed{\lambda_{ii-mfp} = 0.2cm}$

$T_i \sim 20eV, T_e \sim 10eV$

Sub-Alfvenic, Sub Mach Flows

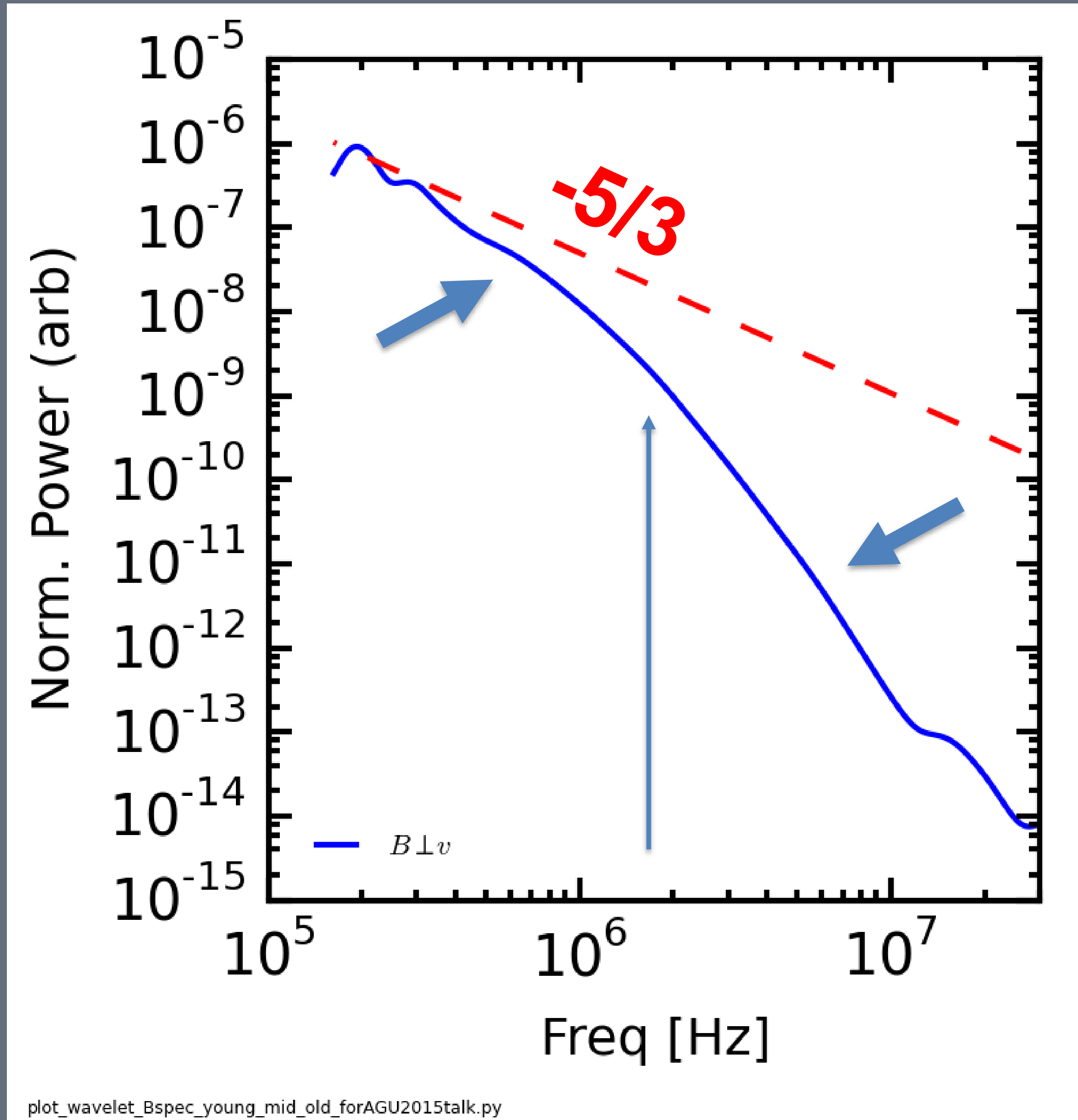
$V_A > C_s > V_z$

$\boxed{200km/s > 50km/s > 30km/s}$

Broadband magnetic fluctuation spectra observed

Scaling is slightly steeper than Kolmogorov for lower frequencies

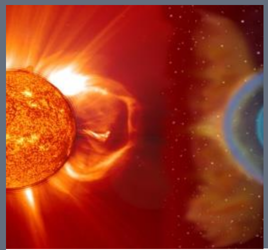
Steepens at higher frequencies



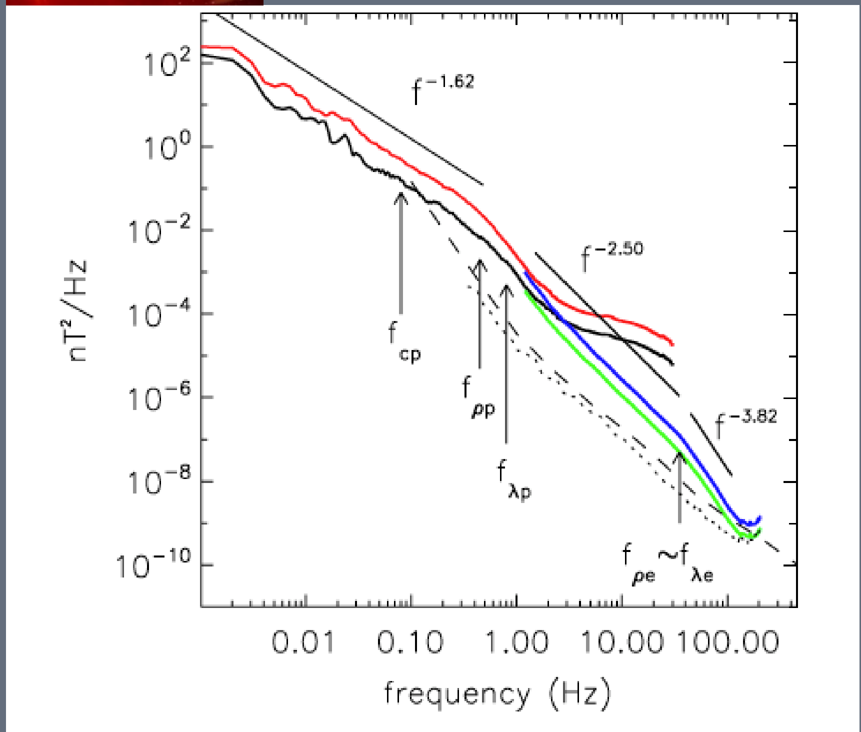
Inflection point at scales consistent with convected ion inertial length

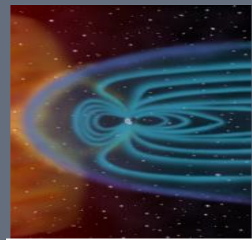
→ Suggests potential onset of dissipation physics

Comparison of spectra to solar wind, magnetosphere

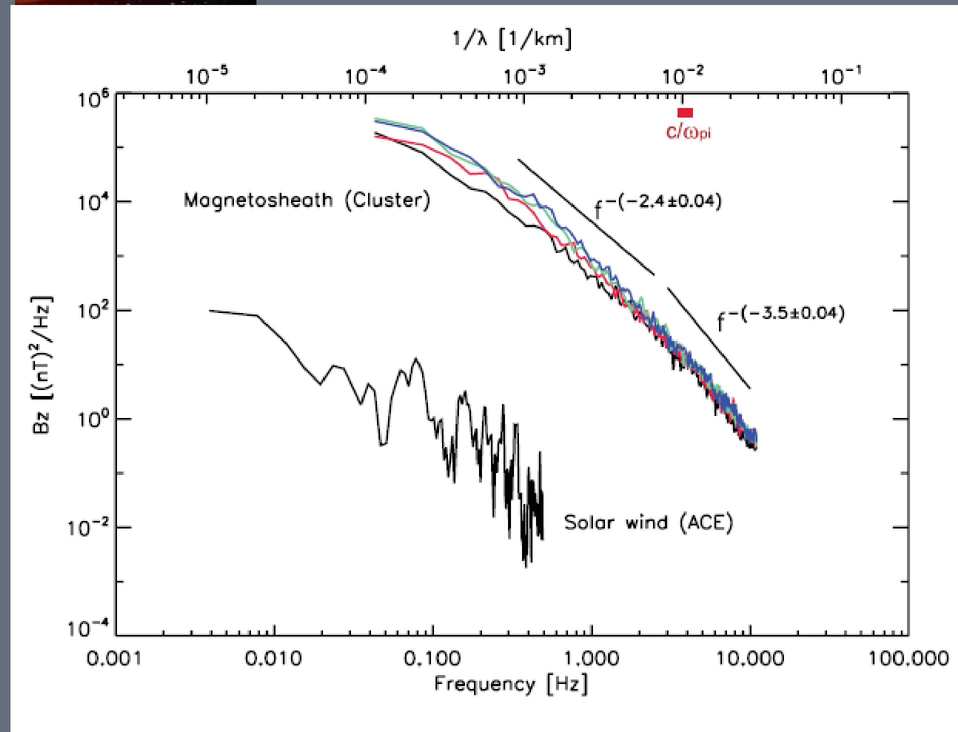


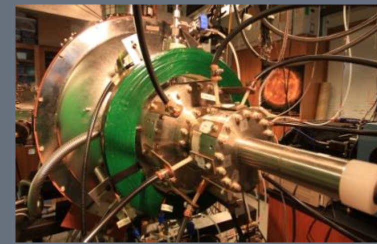
*Cluster FGM and STAFF-SC Data: *Sahraoui, PRL 2009*



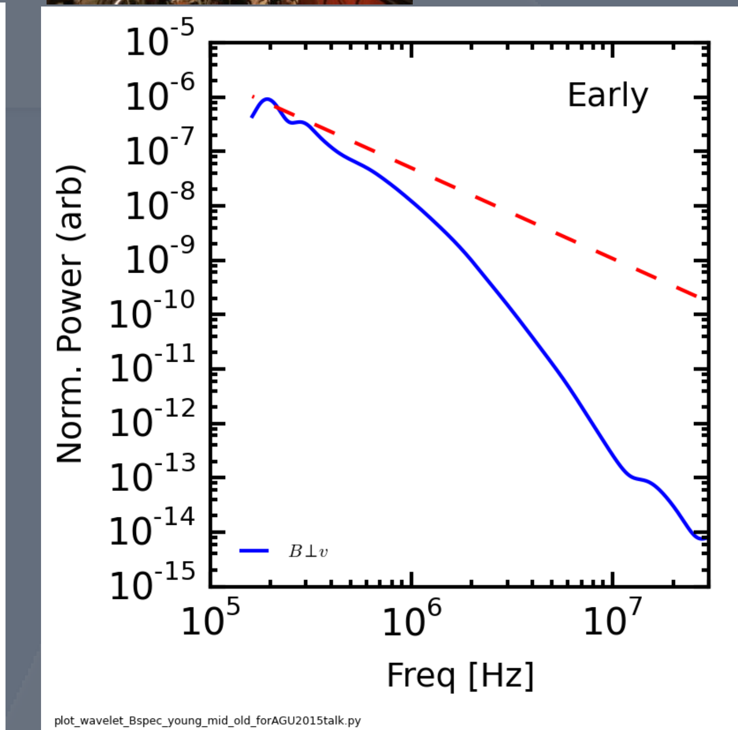


*Cluster Data: *Yordanova, PRL 2008*



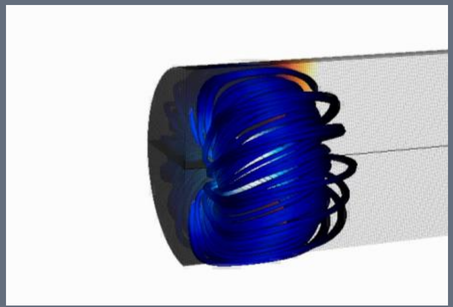


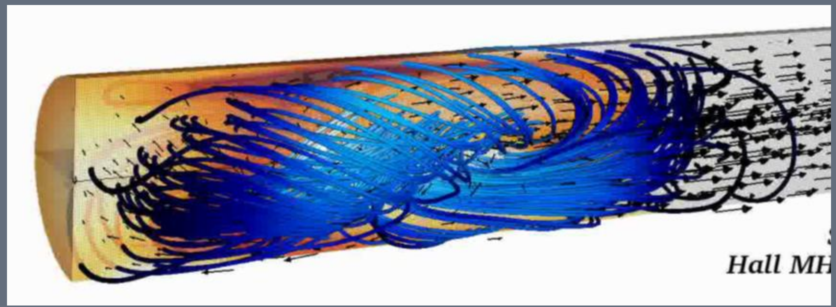
*SSX PoP 2016

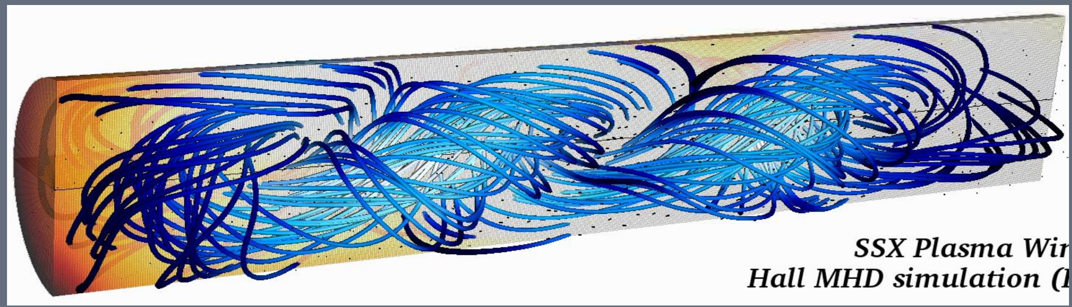


Experimental process for laboratory astrophysics

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

Temporal and Spatial Spectra, Variance Anisotropy: Schaffner, Brown, Lukin ApJ 2014

Permutation Entropy/Complexity of MHD Turbulence: Weck et al, PRE 2015

SSX MHD Wind Tunnel Overview: Brown and Schaffner, JPP 2015

Multifractal and Monofractal Scaling: Schaffner and Brown, ApJ 2015

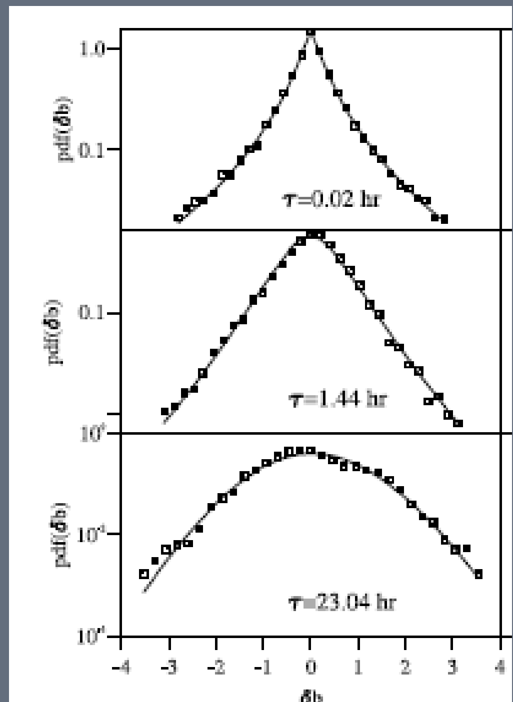
Possible Signatures of Dissipation: Schaffner, Brown, and Rock, PoP 2016

Three Case studies:

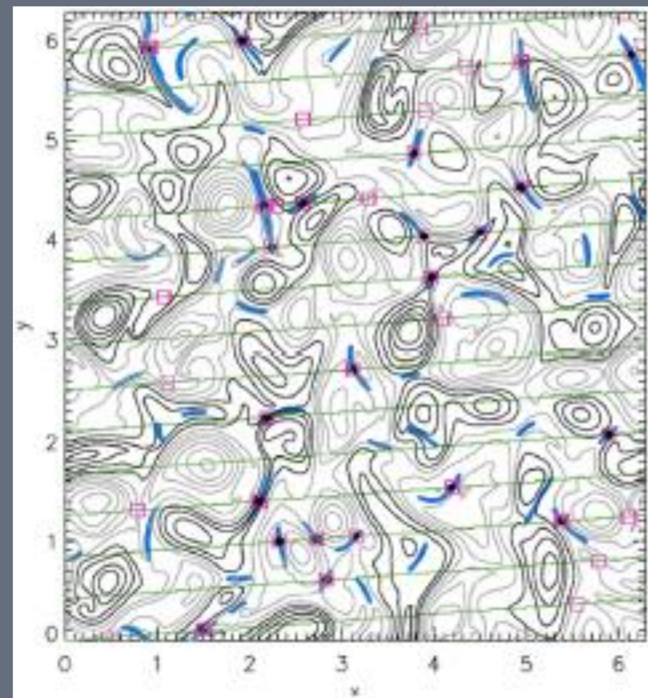
- Intermittency changes with helicity
- Variance anisotropy observation and comparison with simulation
- Evaluation and comparison using permutation entropy/statistical complexity

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.



Dudok de Wit, Space Science Review 2013



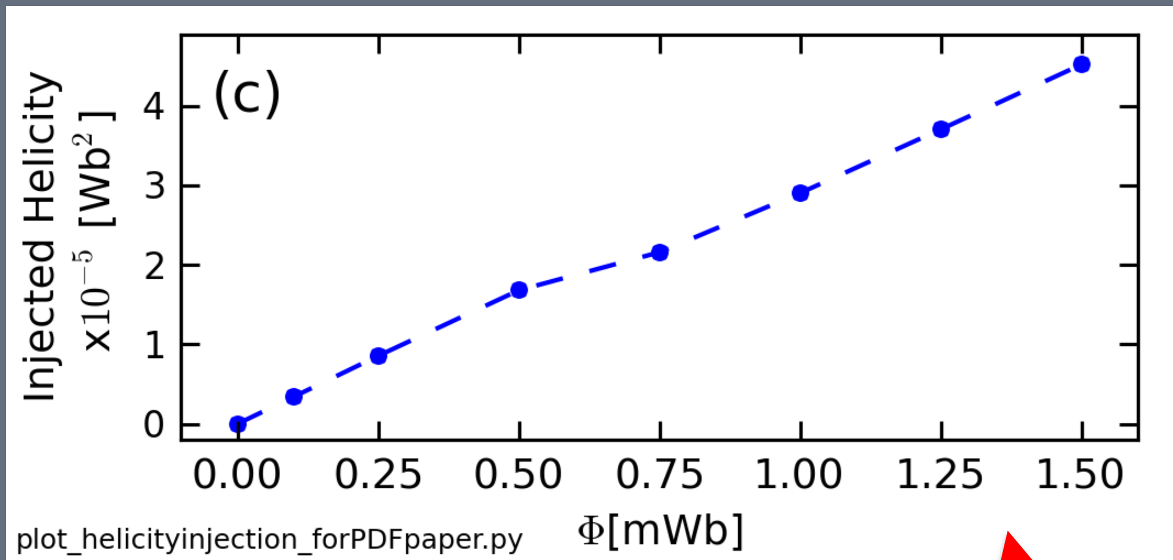
Servidio et al, JGR, 2011

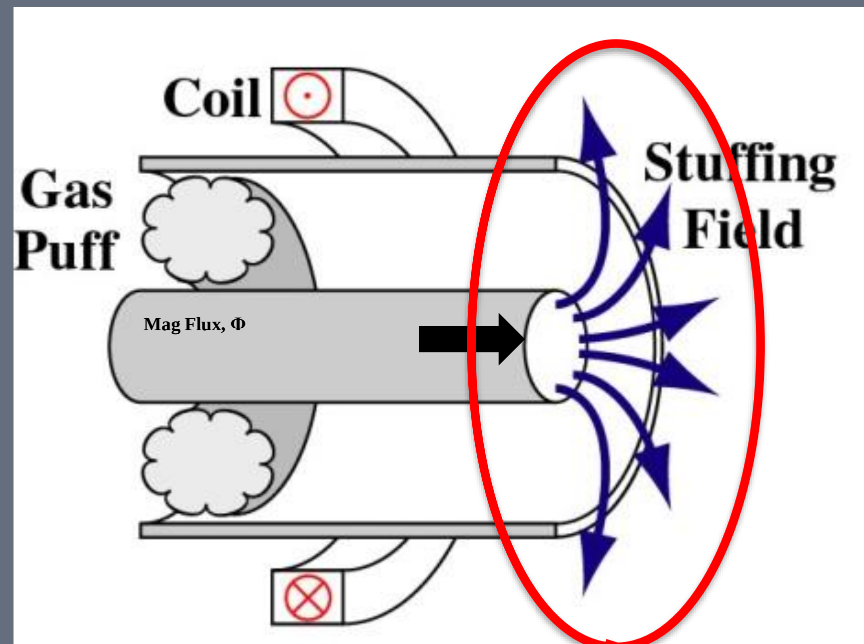
Schaffner, Brown, Wan PRL 2014

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

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

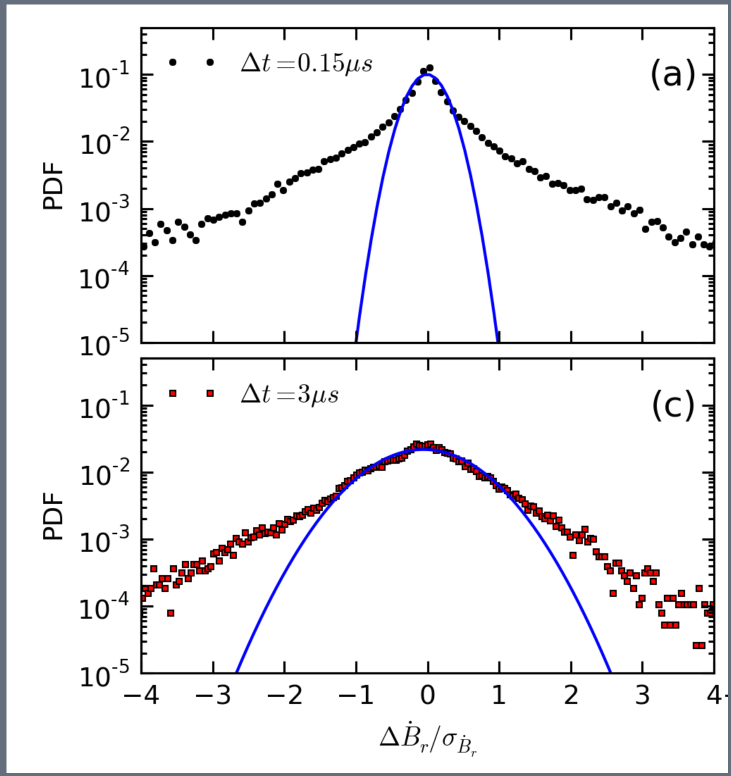


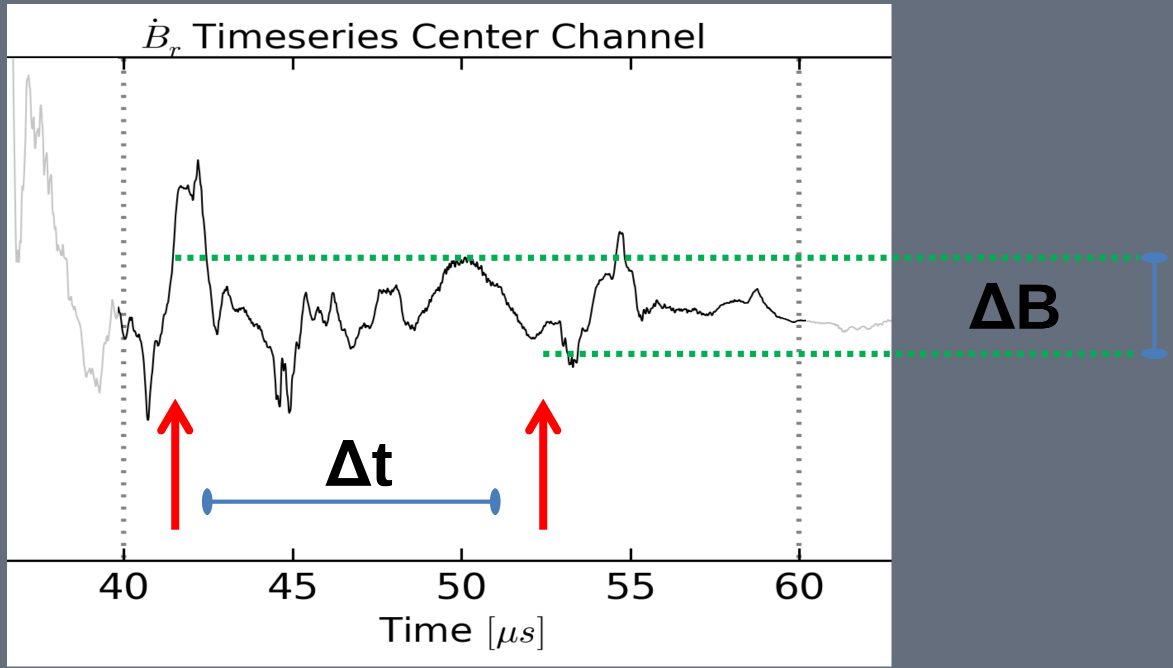


Schaffner, Brown, Wan PRL 2014

Expt 1: Effect on Intermittency with Injected Helicity

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



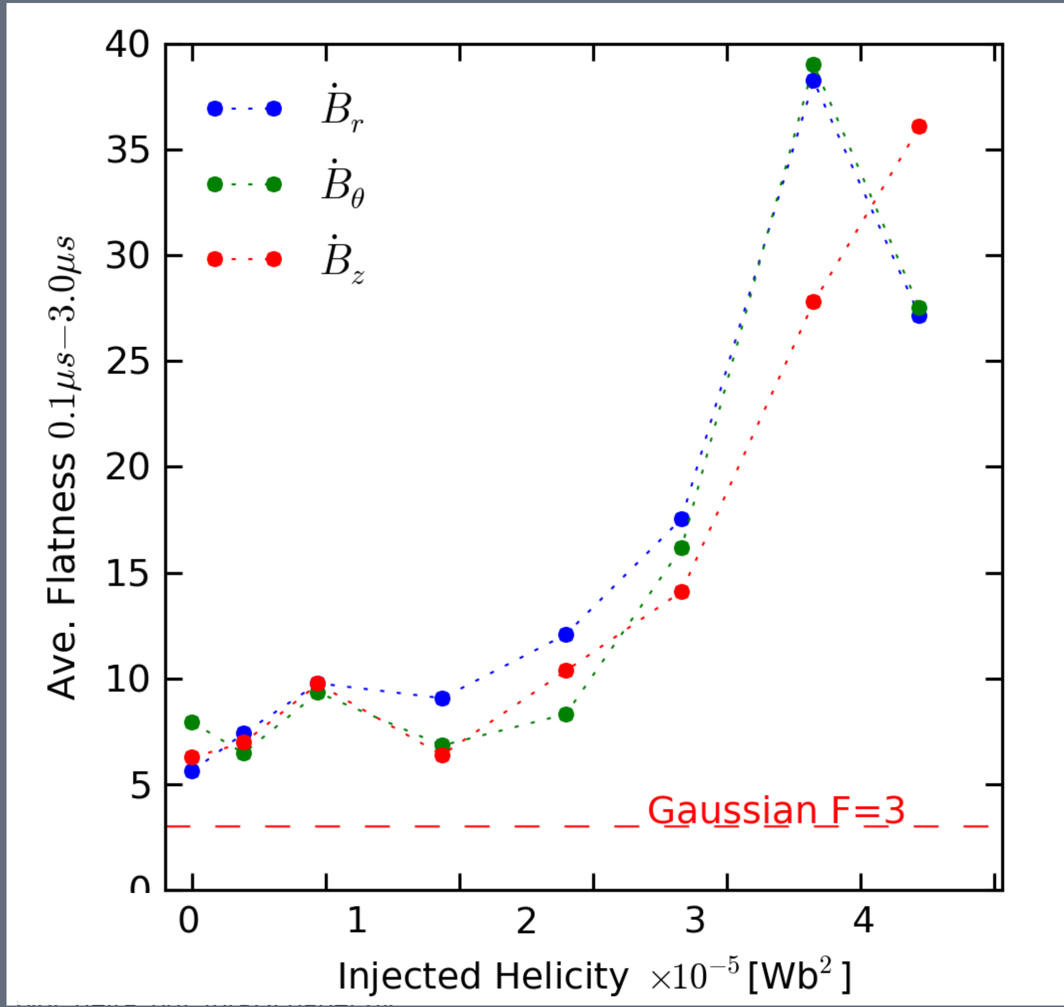


Level of departure from non-Gaussian distribution is quantified using kurtosis or Flatness (4th order moment)

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

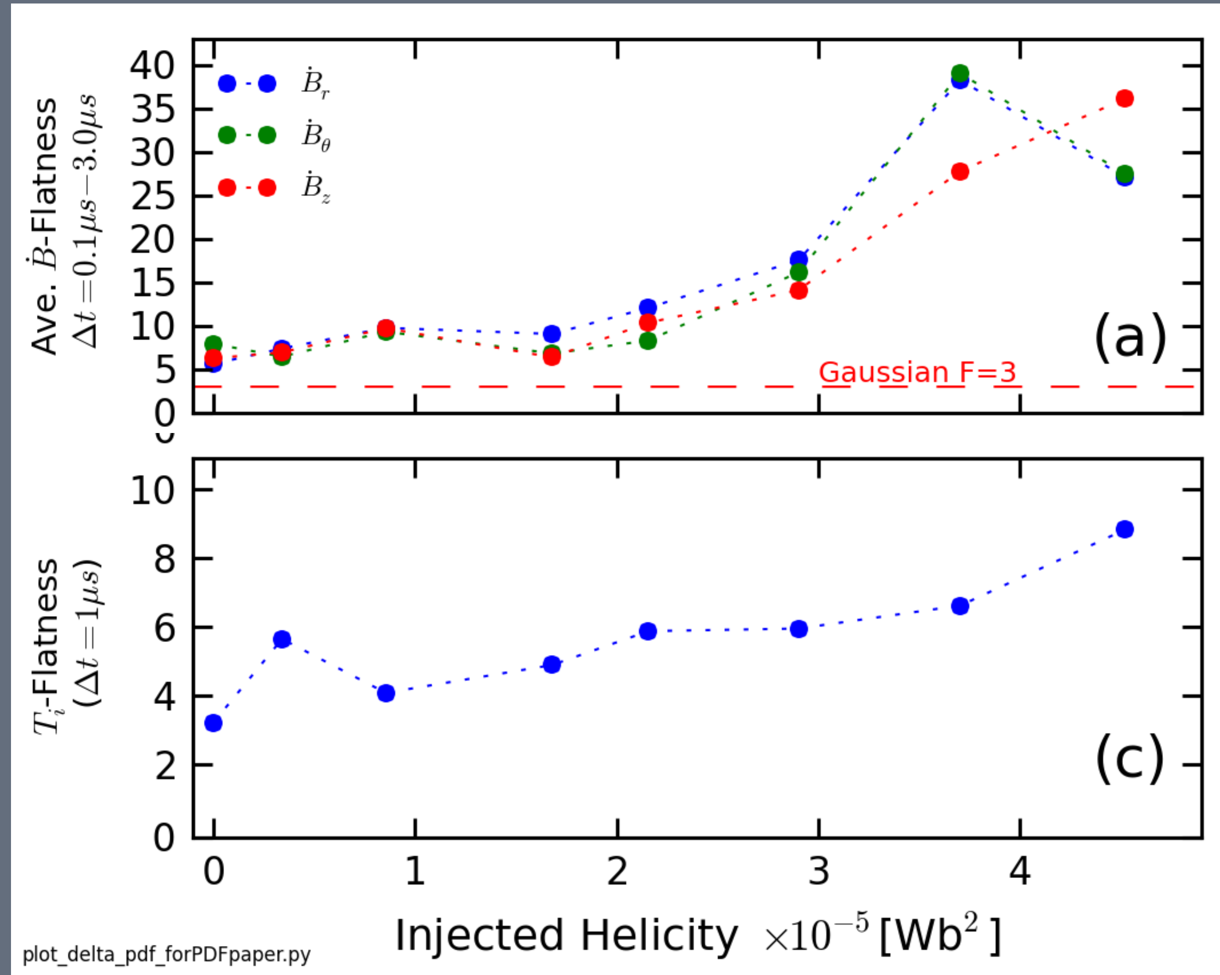


Schaffner, Brown, Wan PRL 2014

Expt 1: Effect on Intermittency with Injected Helicity

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

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

Expt 2:Variance Anisotropy and Comparison to Simulation

The anisotropy of magnetic fluctuations has implications for understanding the turbulence cascade, dissipation mechanisms effects of MHD turbulence

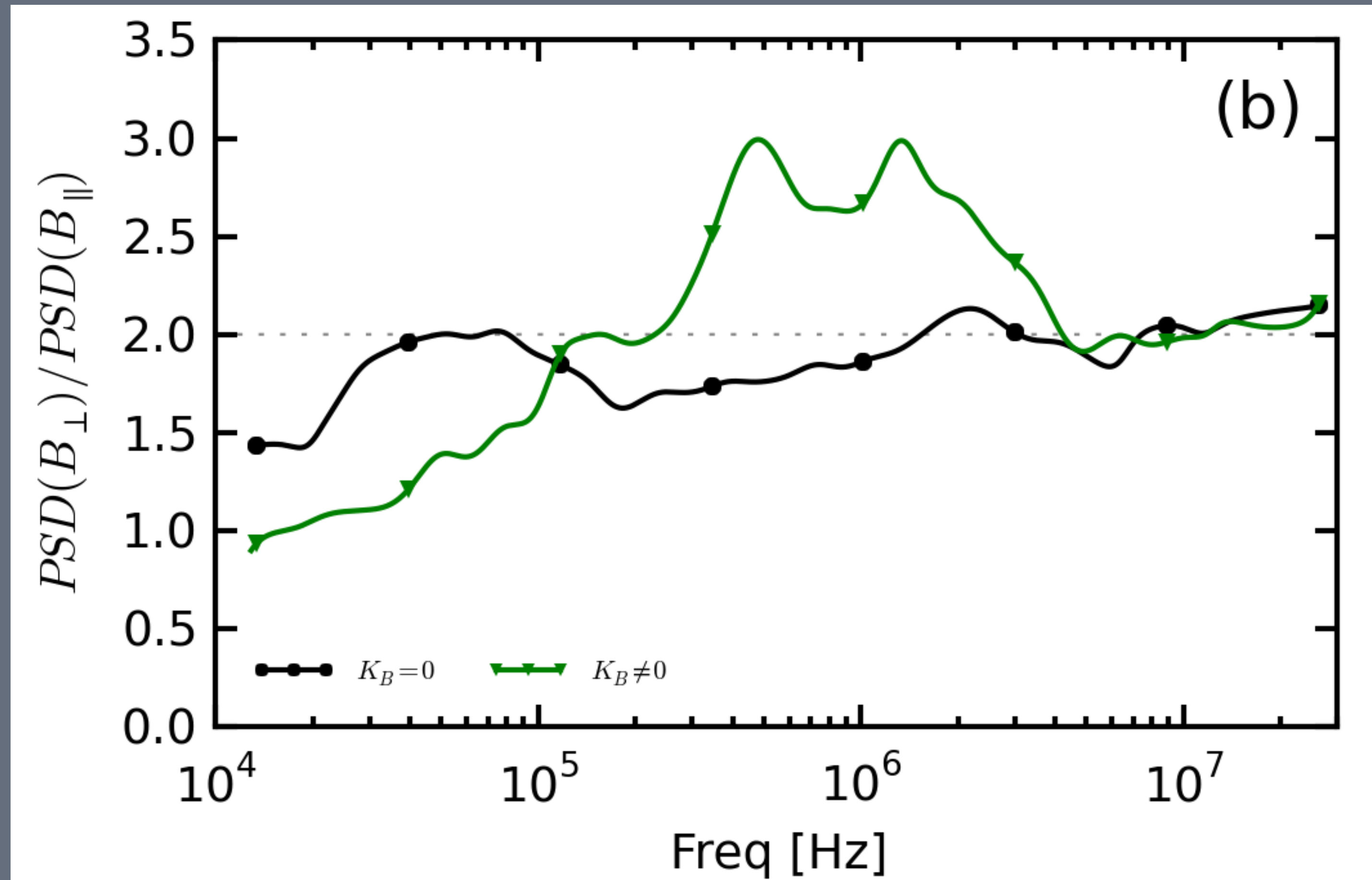
Variance anisotropy (or magnetic compressibility) be measured in the laboratory MHD experiments

Schaffner, Brown, Lukin ApJ 2014

Expt 2:Variance Anisotropy and Comparison to Simulation

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 $B_{||}(f)$ and $B_{\perp}(f)$.

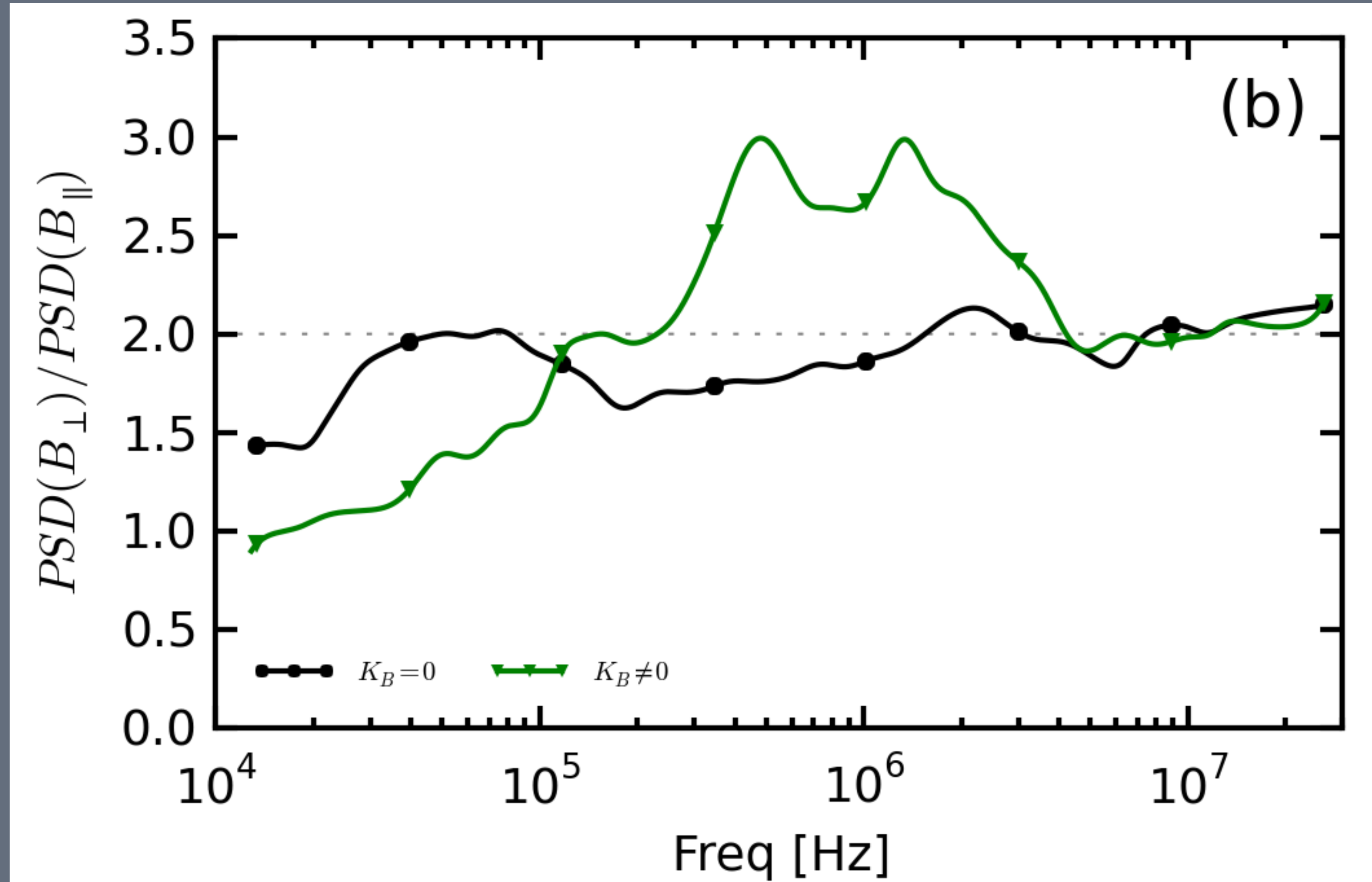
$$Var.Ani. = \frac{B_{\perp}(f)}{B_{||}(f)}$$



Schaffner, Brown, Lukin ApJ 2014

Expt 2:Variance Anisotropy and Comparison to Simulation

Main Result:
Variance Anisotropy increases (becomes more anisotropic) up to about 1MHz, 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

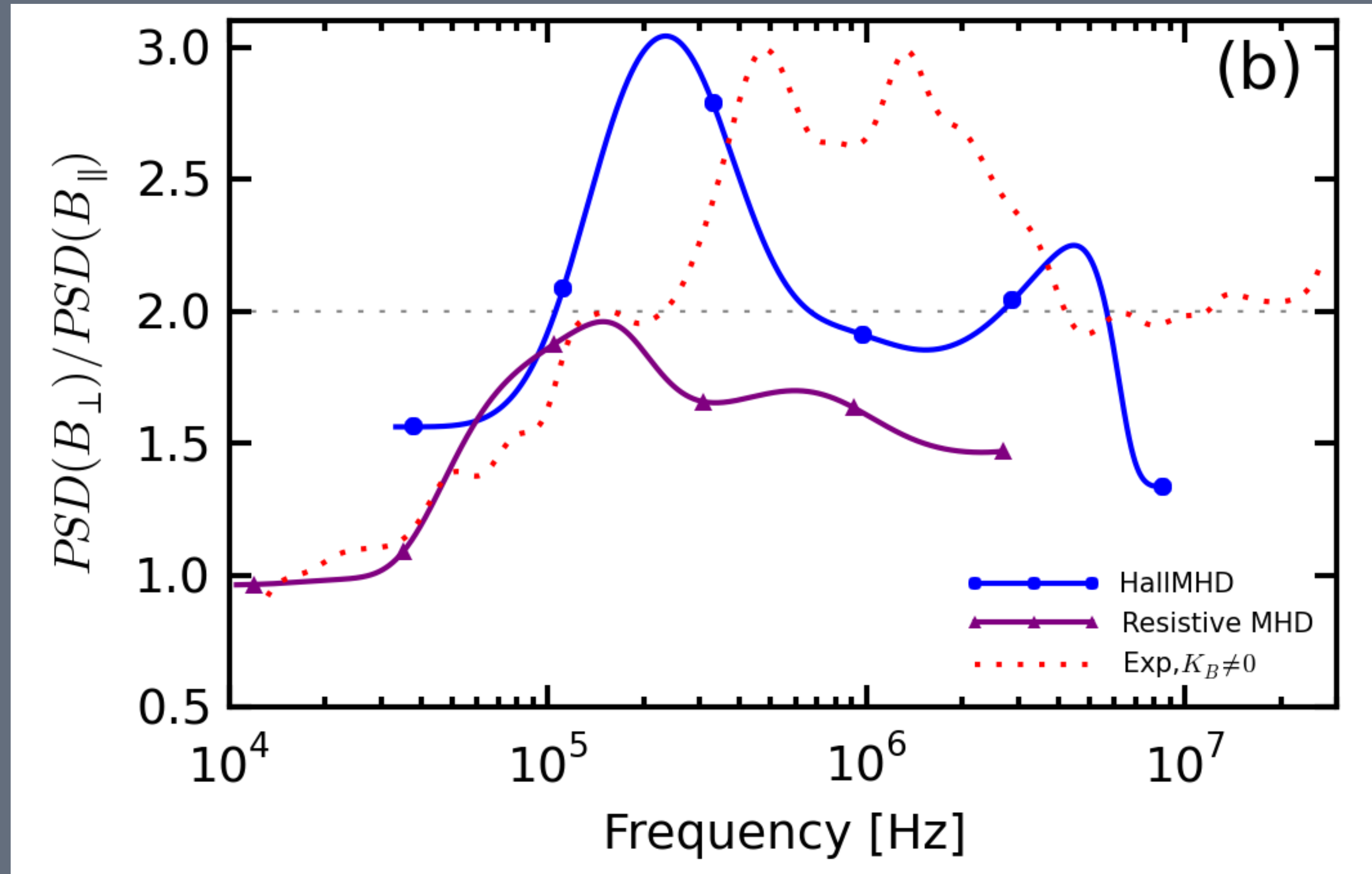


Schaffner, Brown, Lukin ApJ 2014

Expt 2:Variance Anisotropy and Comparison to Simulation

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

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

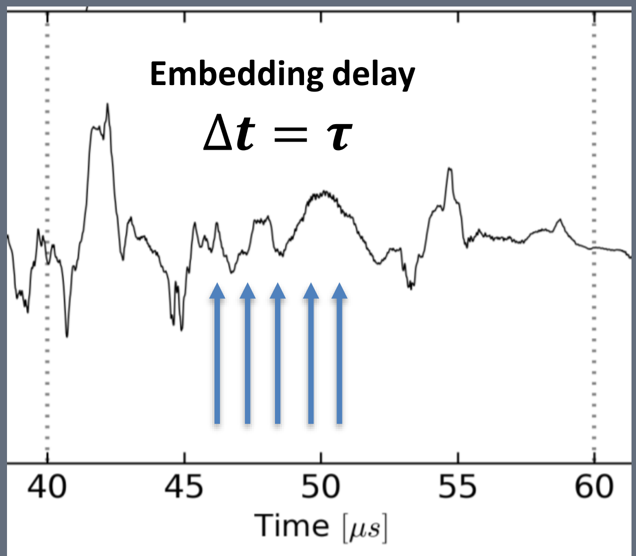


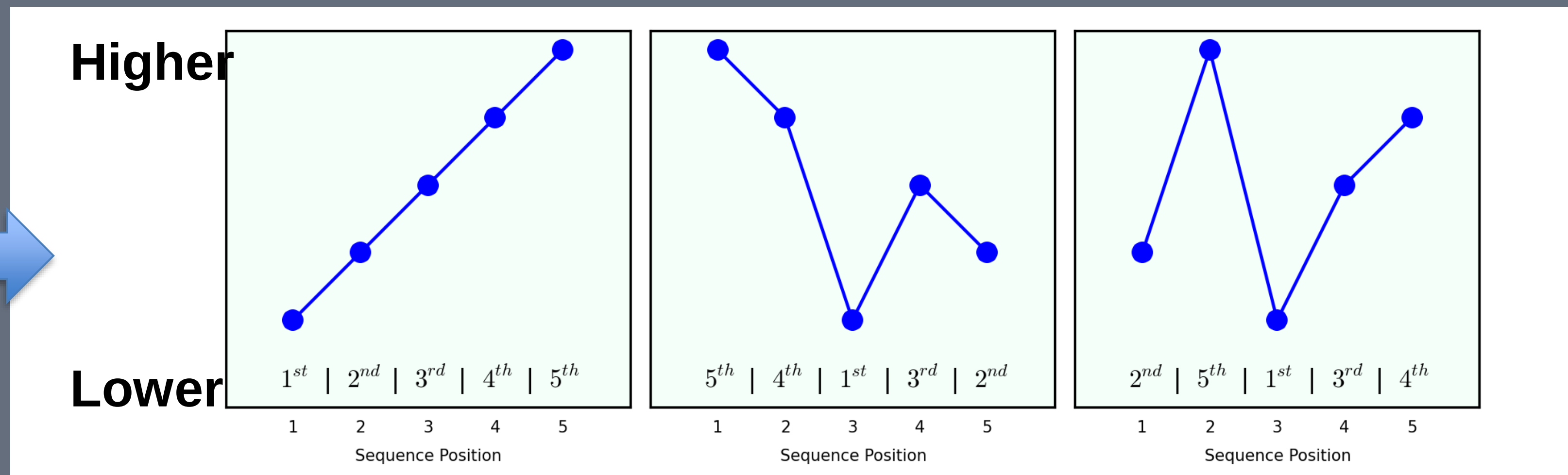
Schaffner, Brown, Lukin ApJ 2014

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



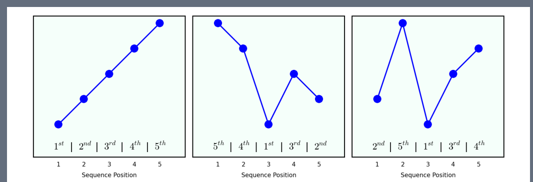


Weck PRE 2015

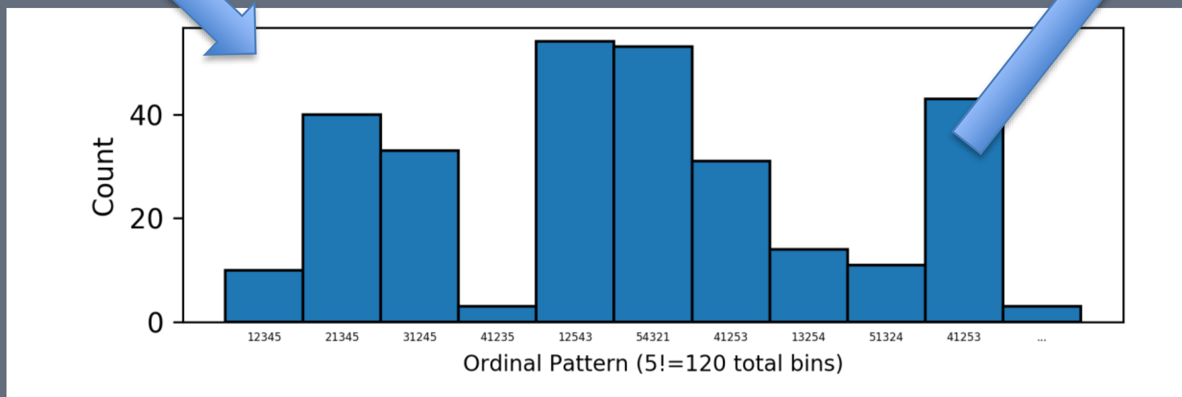
Expt 3: Evaluation and comparison using PESC

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



$$p_j = \frac{(\# j - Patterns)}{total} \quad j = 1, \dots n!$$



Permutation Entropy, S[P]

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

Weck PRE 2015

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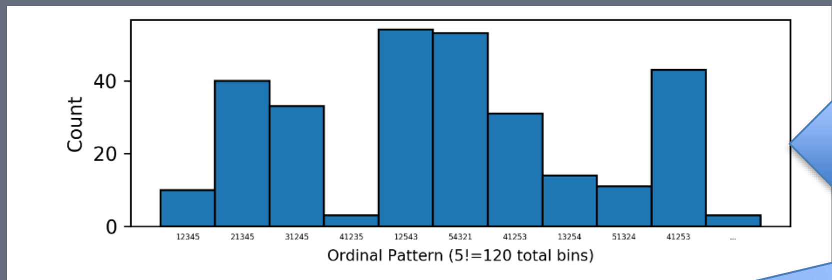
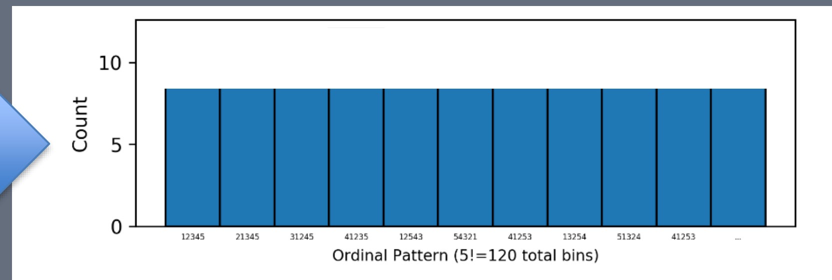




disequilibrium x PE = Complexity

Statistical Complexity, C[P]

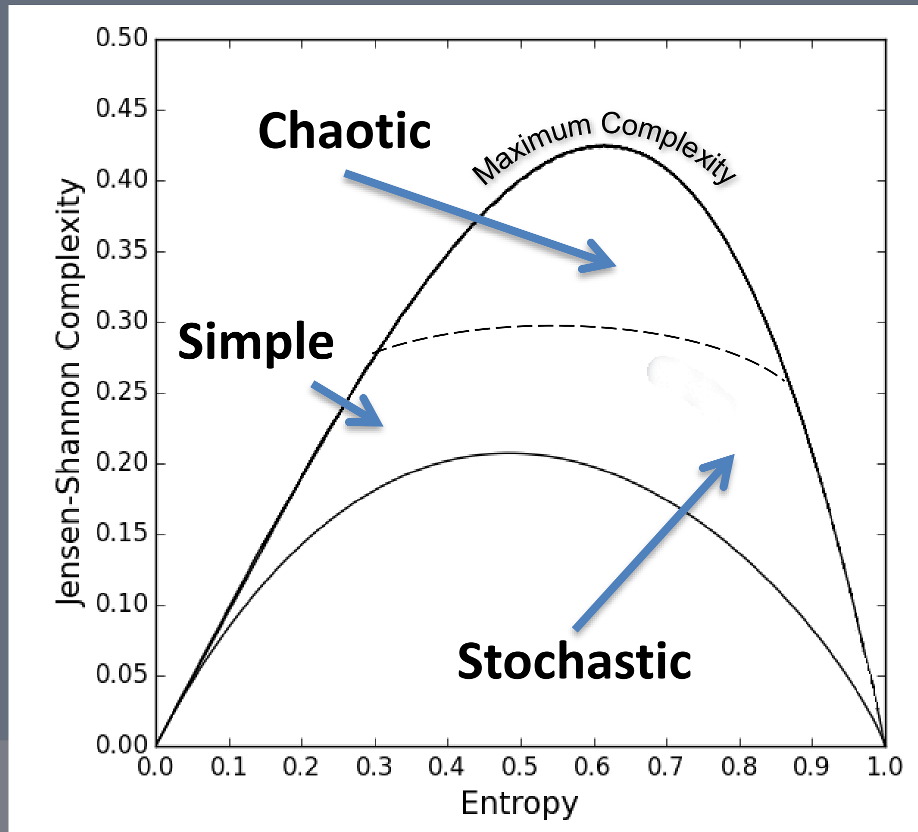
$$C[P] = -2\frac{S[\frac{P+P_e}{2}] - \frac{1}{2}S[P] - \frac{1}{2}S[P_e]}{\frac{N+1}{N}log(N+1) - 2log(2N) + log(N)}$$

Weck PRE 2015

Expt 3: Evaluation and comparison using PESC

Very Brief overview of PESC

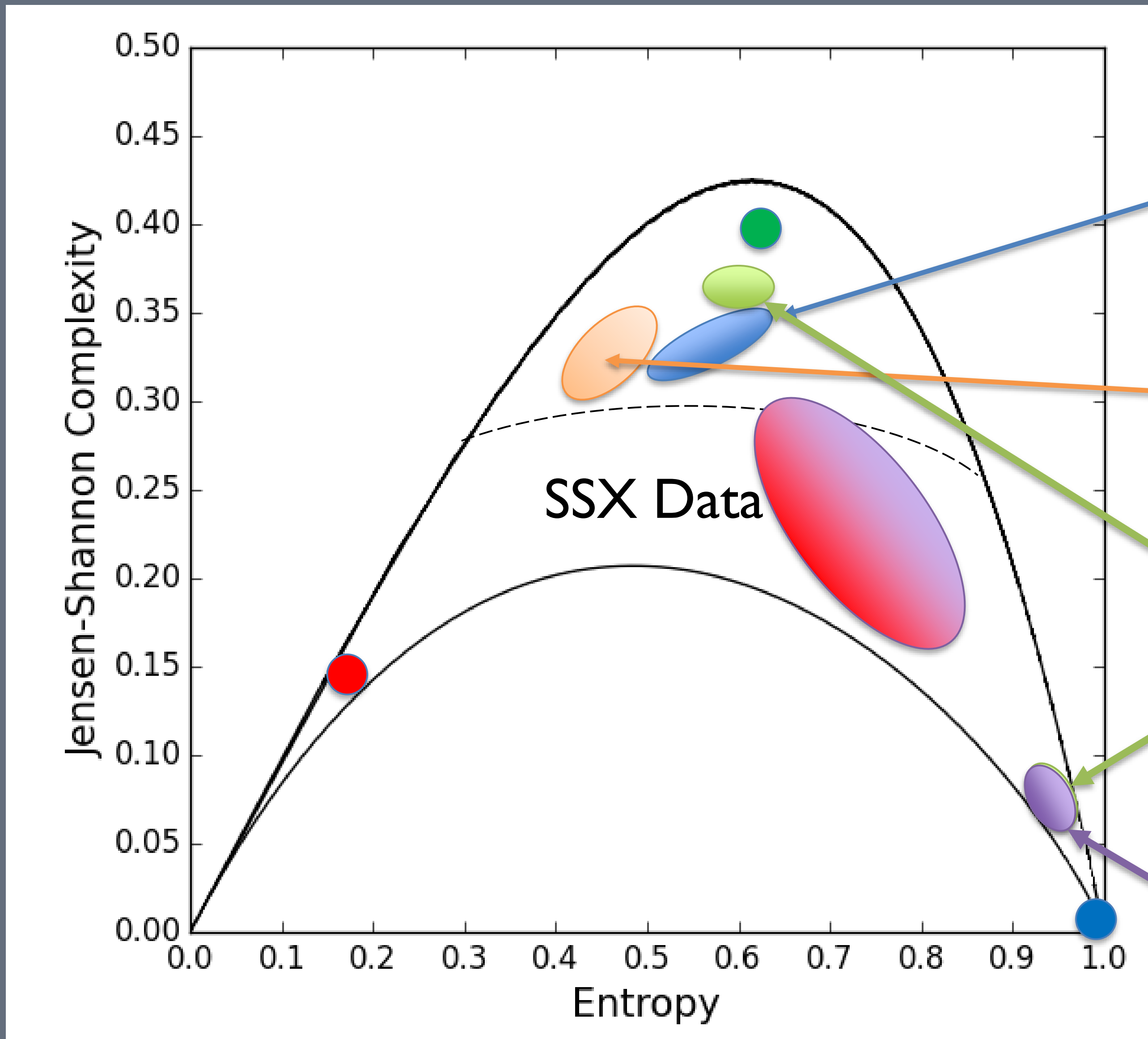
Main Idea: Decompose a signal into a distribution of ordinal patterns (rather than Fourier components, say) and construct metrics based on these distributions for comparison



Weck PRE 2015

CH Plane

Expt 3: Evaluation and comparison using PESC



CH Plane

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

Edge

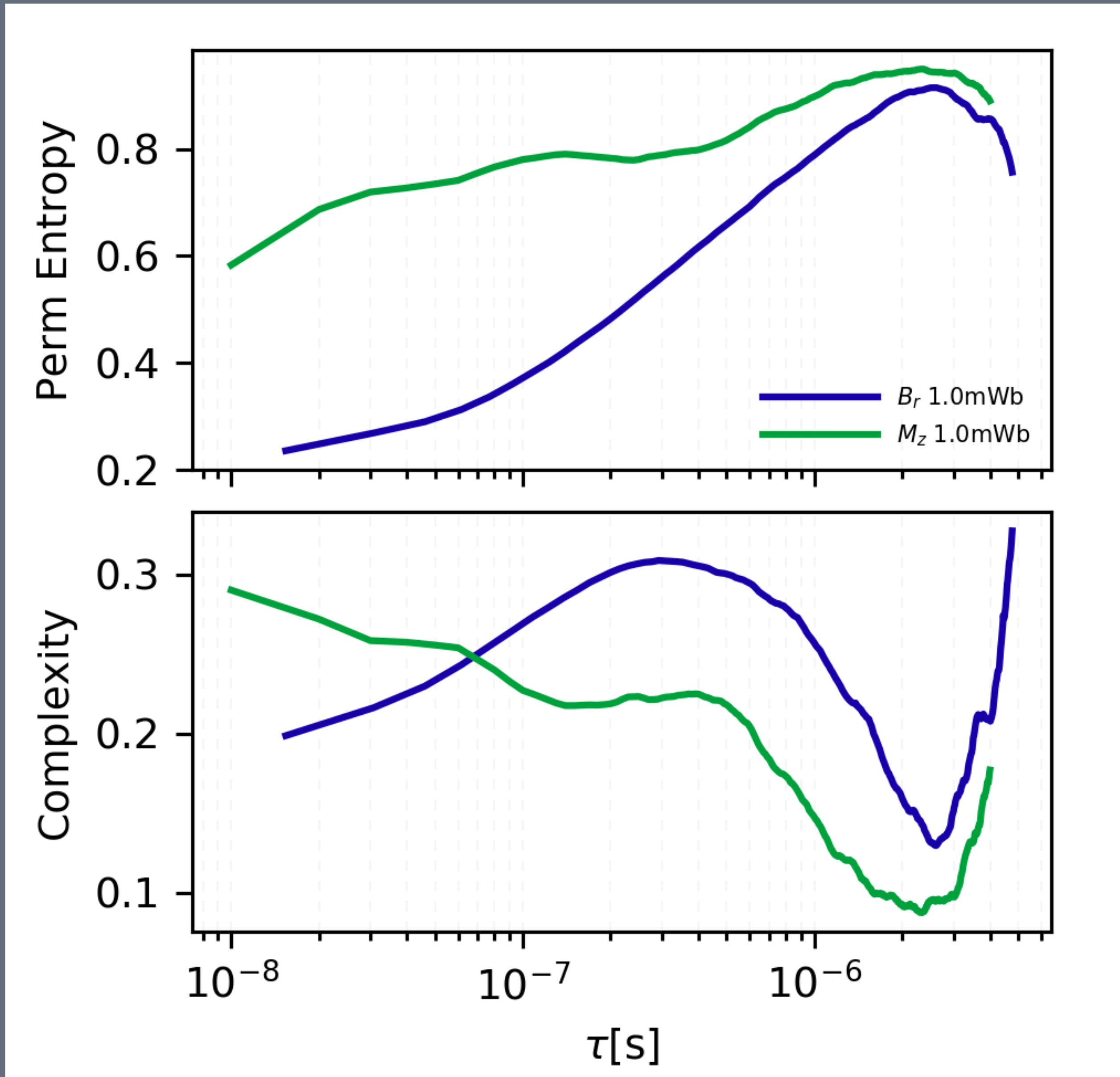
Interior

Space Examples

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

Jensen–Shannon Complexity Measurements in Solar Wind Magnetic Field Fluctuations – Weygand and Kivelson ApJ 2019

Expt 3: Evaluation and comparison using PESC



The shift to increasing complexity with decreasing scale correlates qualitatively with dissipation scale

<u>One speculative interpretation</u>: dissipation regime correlates with enhanced mode activity that manifests as larger complexity

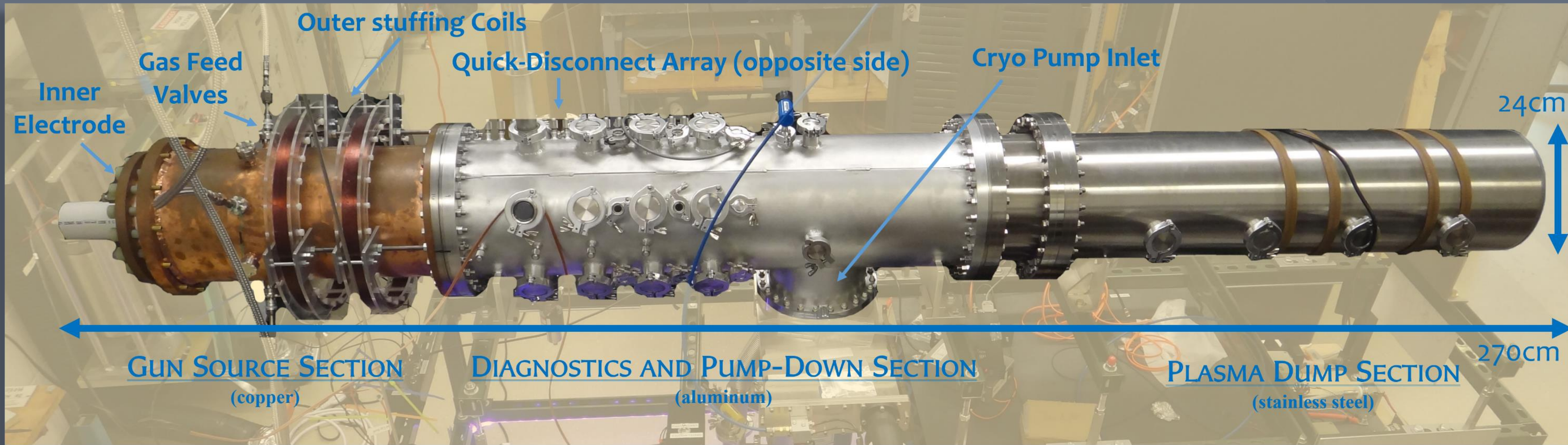
Limitations of magnetic turbulence research on SSX

Short time duration of “turbulent” plasma

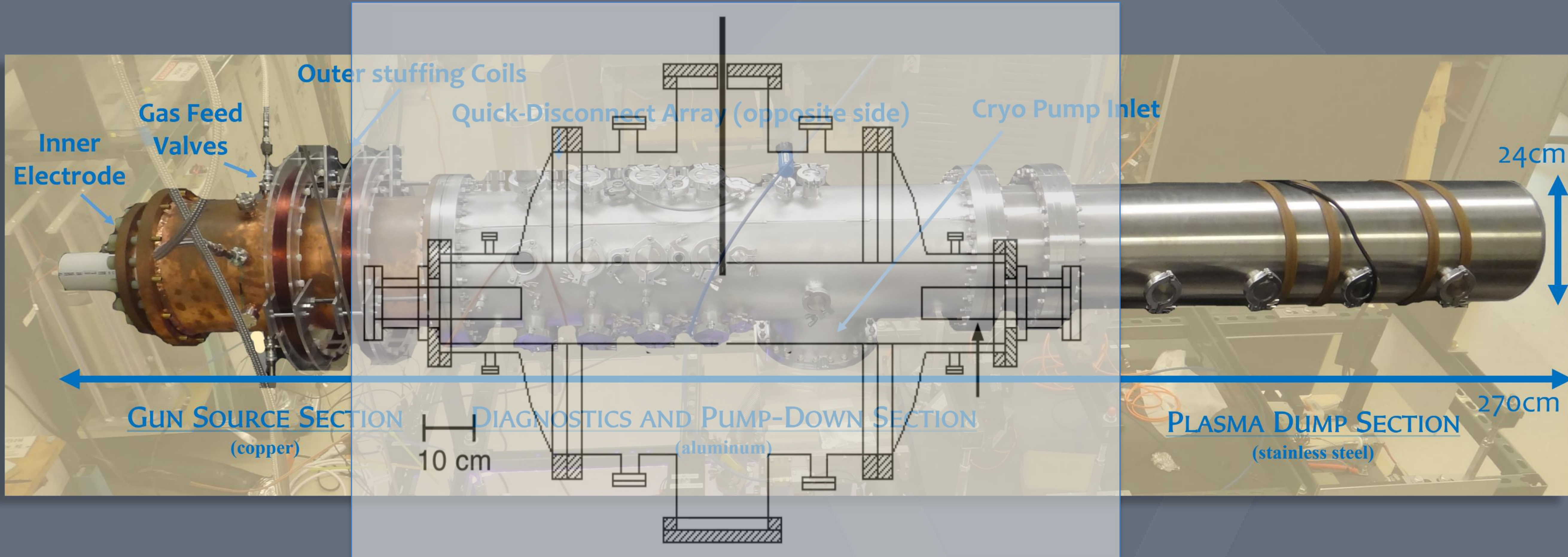
Few access points

Relatively small size

Magnetic turbulence research on the Bryn Mawr Magnetohydrodynamic Experiment (BMX)



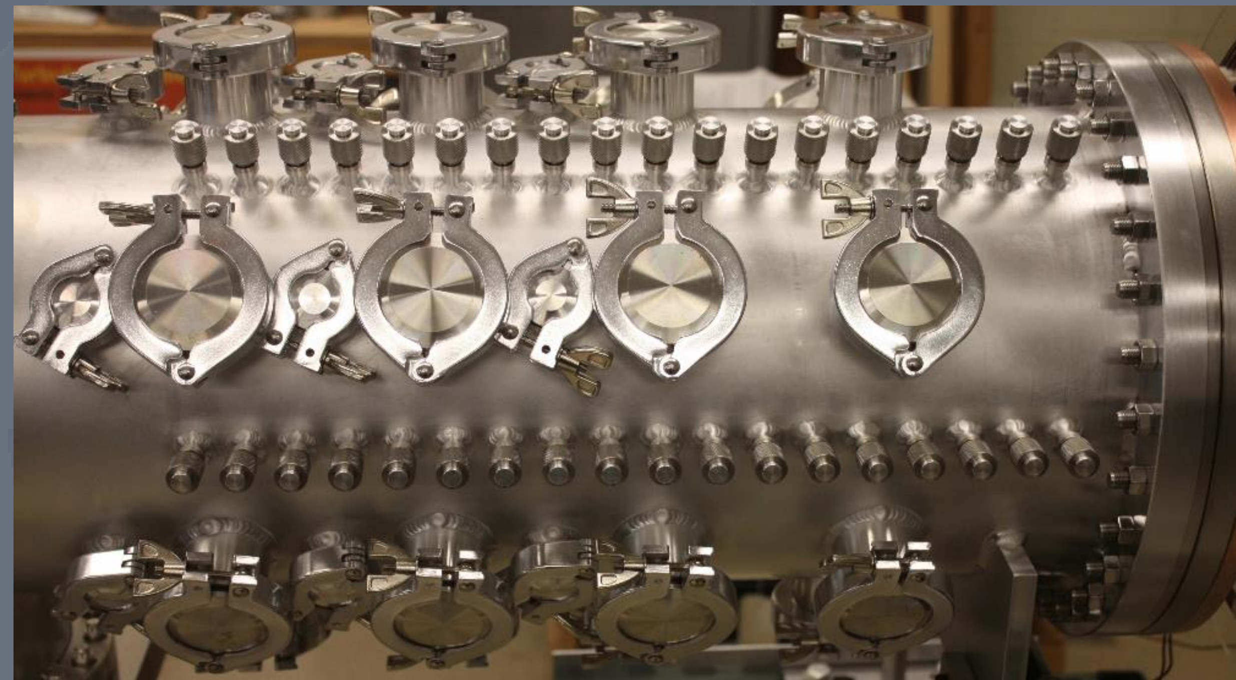
Magnetic turbulence research on the Bryn Mawr Magnetohydrodynamic Experiment (BMX)



Magnetic turbulence research on the BMX

High spatial sampling – 36 access ports staggered to allow axial probe separation of 0.5cm

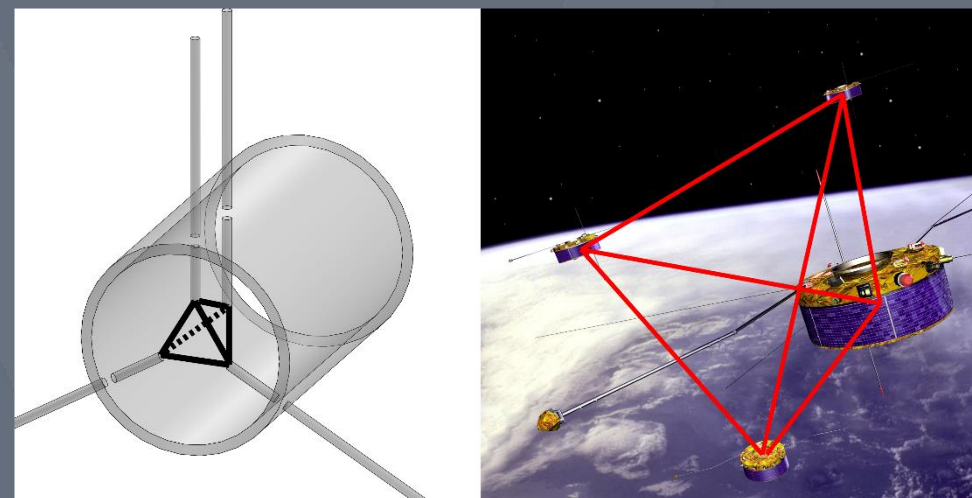
- High sampling allows for direct spatial spectral measurements
- Can make comparisons of spatial and temporal spectra
- Less reliance on Taylor Hypothesis



Ports at 60° separation

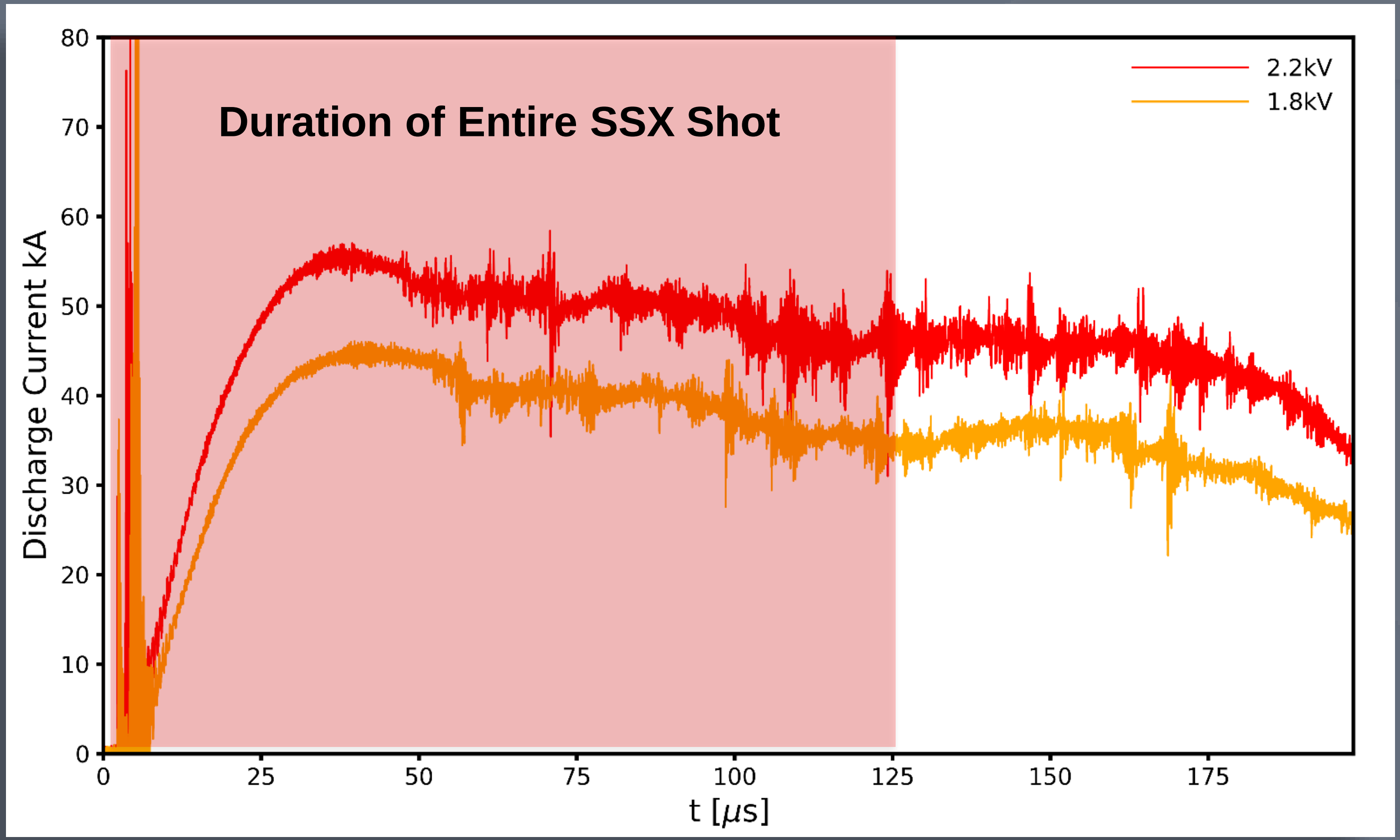
-Allows tetrahedral probe array which can mimic pattern used in Cluster/MMS for extraction of wavenumber information

-Fine axial sampling allows for fine variation in tetrahedral size



Magnetic turbulence research on the BMX

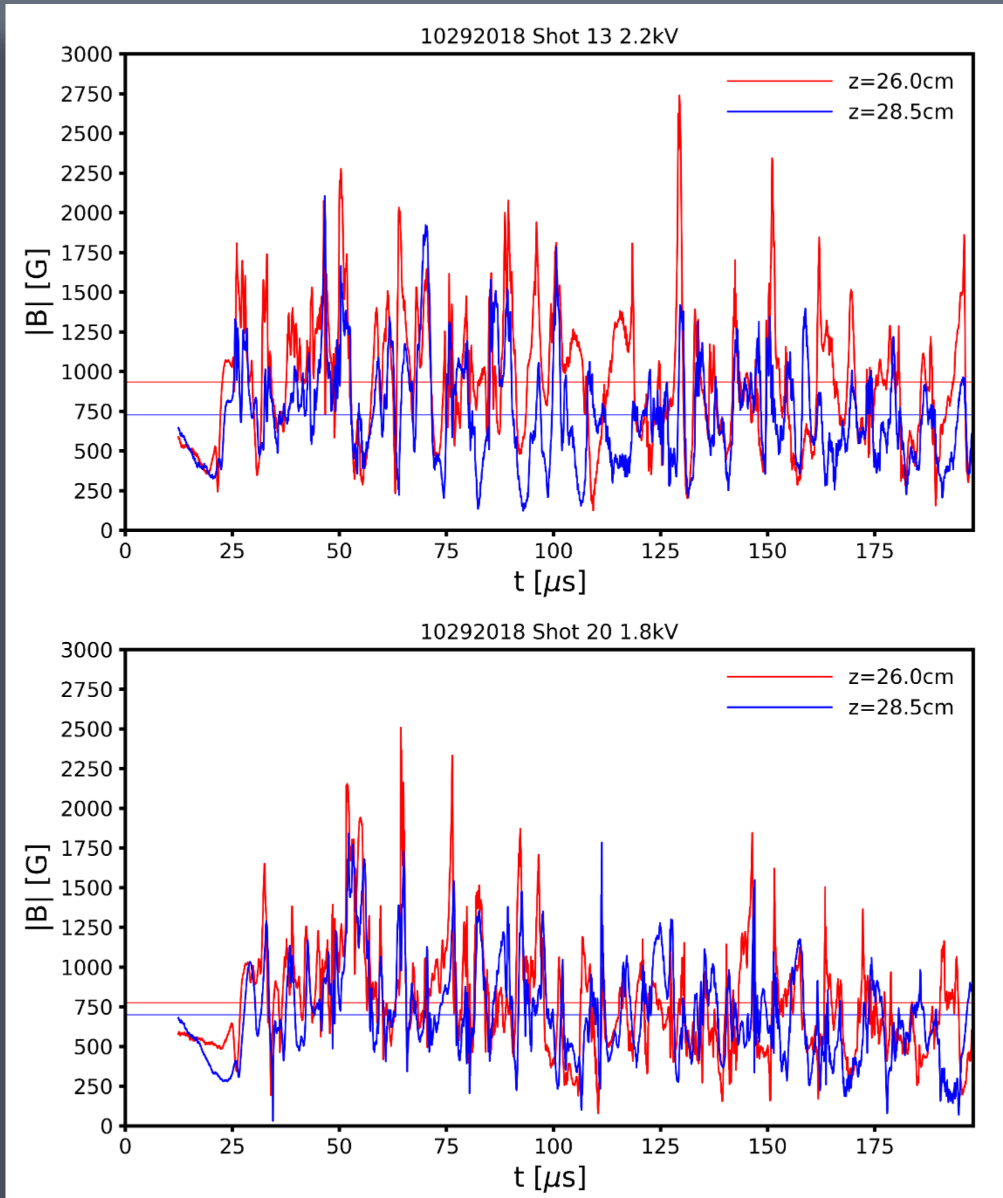
Longer current/injected helicity using a pulse forming network of 8 500uF capacitors (compared to SSX's 2)

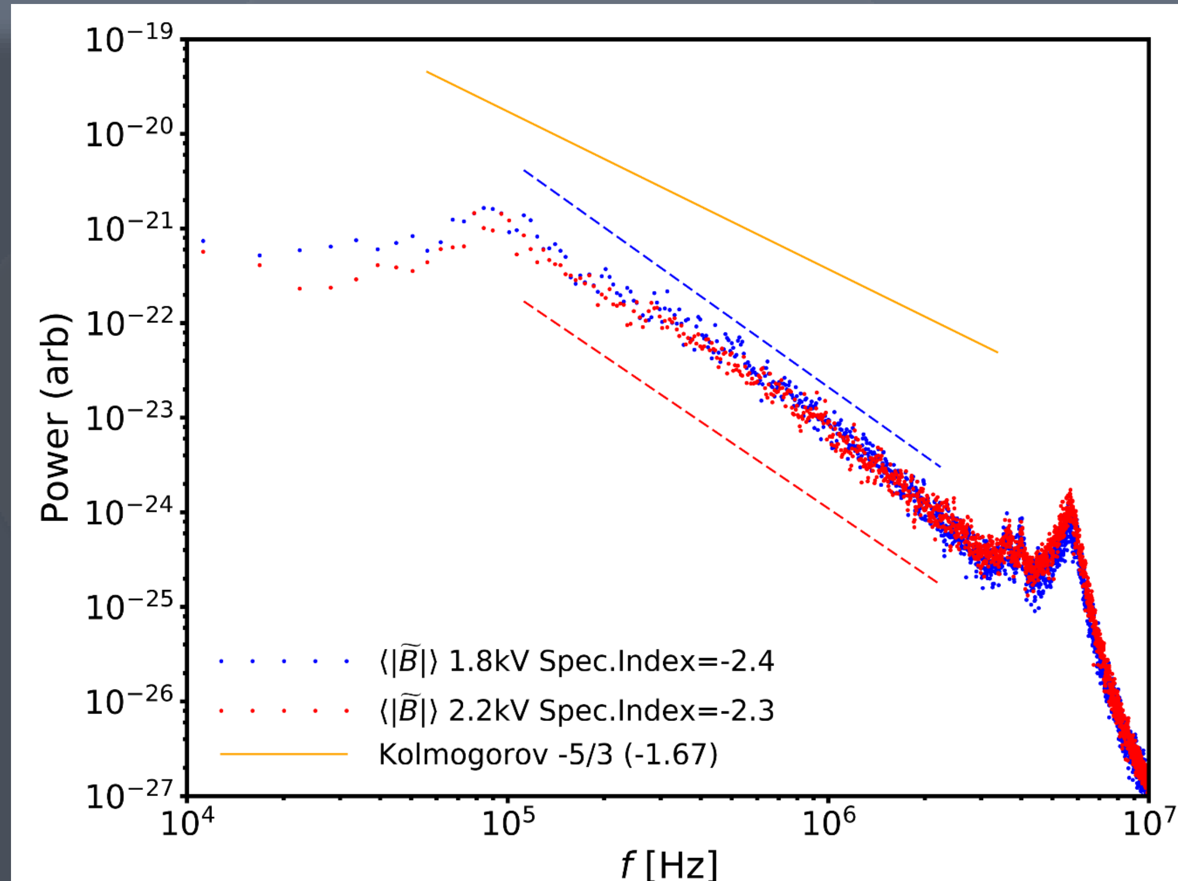


2.2kV bank discharge yields a peak current of 58.4kA and an average of 47.4kA over ~180us.

Threshold Current for Helicity injection about 3x that of SSX

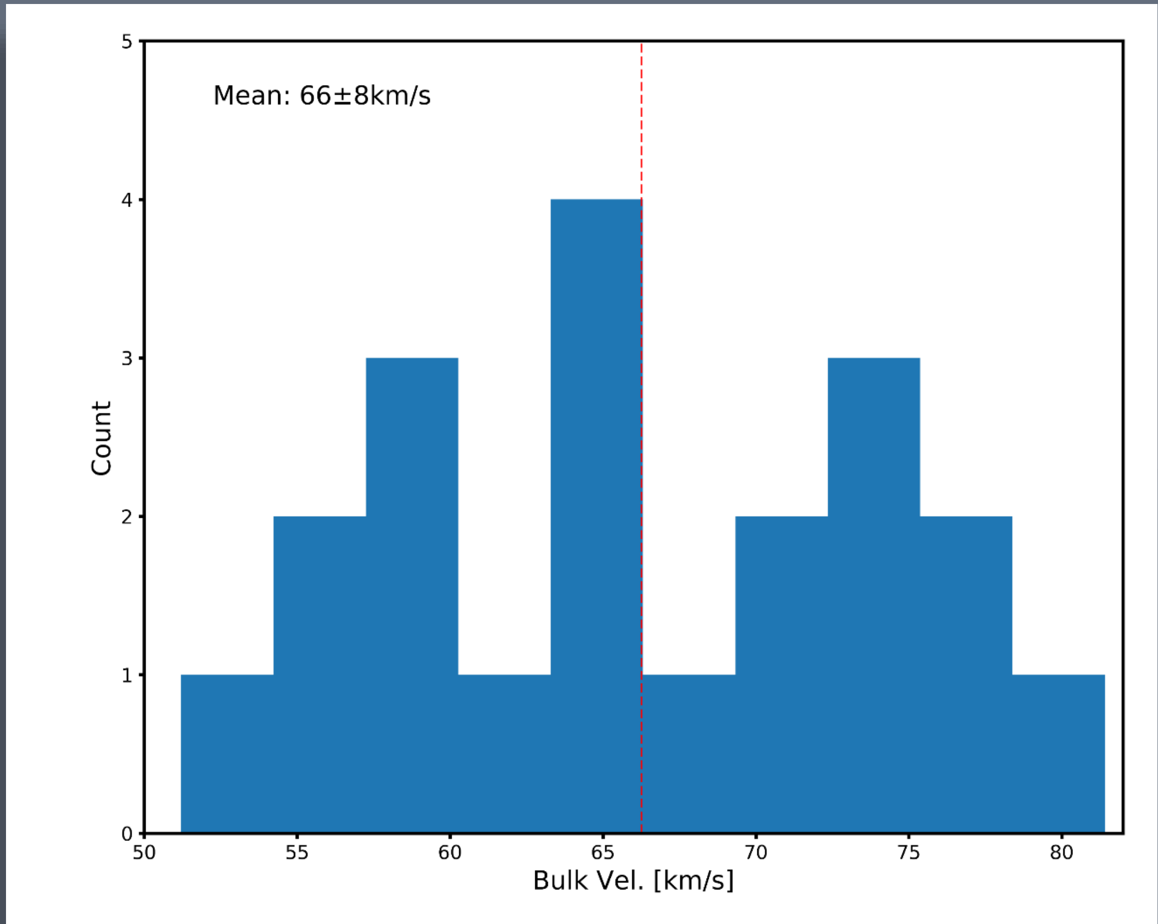
Magnetic turbulence research on the BMX





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) t

Ion transport

Comparisons

Suggestion for

elcome!