Generating dynamic magnetic turbulence in a laboratory device using plasma guns and evolving spheromaks

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Bringing Space Down to Earth:
Exploring the Physics of Space Plasmas in the Laboratory
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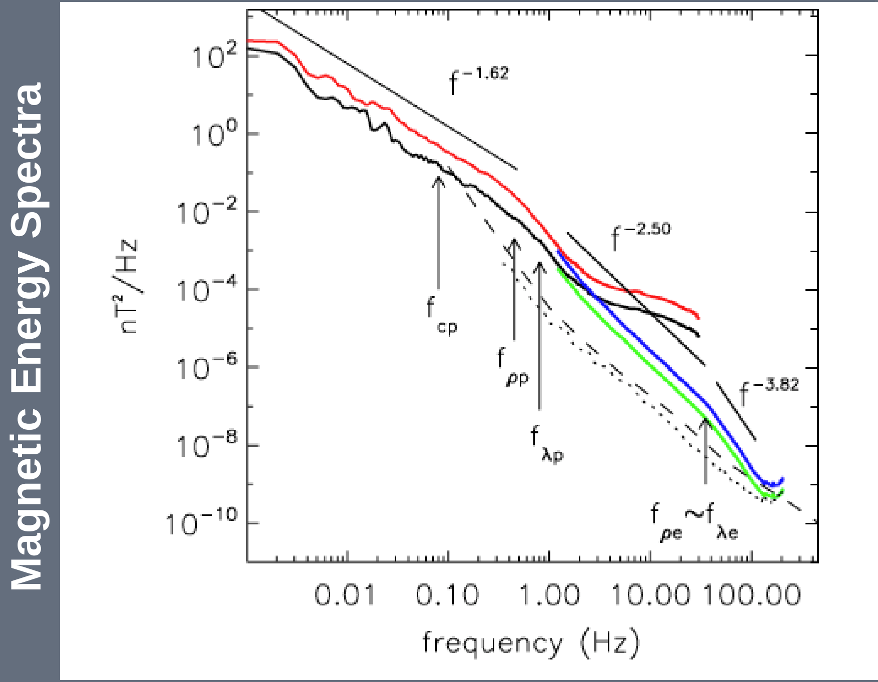
What kind of plasma turbulence are we talking about?

Space vs. Laboratory

What kind of plasma turbulence are we talking about?

Space – Solar Wind

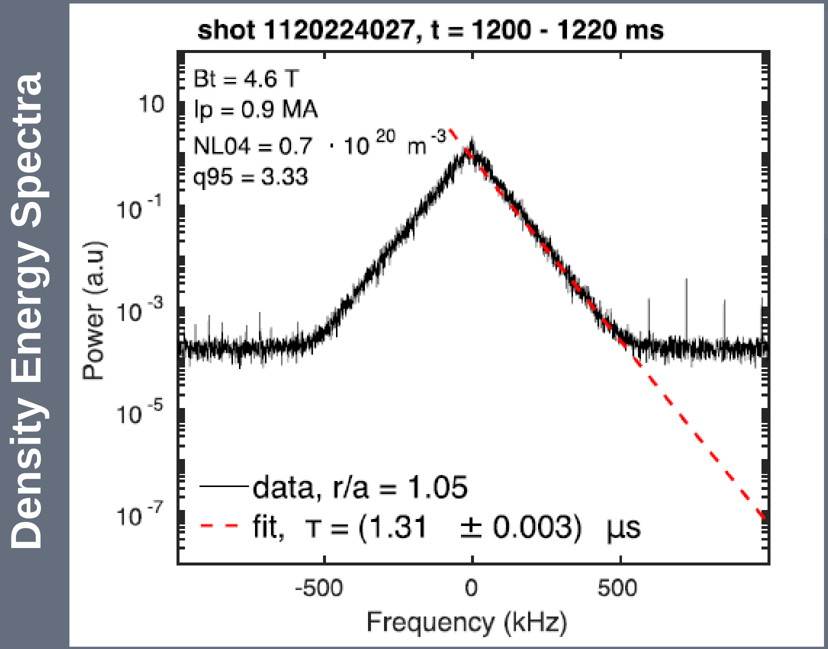


Cluster FGM and STAFF-SC Data:
Sahraoui, PRL 2009

- Dynamical flows ***and*** fields
- Power-law scaling (log-log) plots
- Large separation of scales
- Clearly transition from inertial to dissipation range
- Most "fluid-like"

What kind of plasma turbulence are we talking about?

Laboratory – Edge (Gradient Driven)



Alcator-CMOD Edge Reflectometry Data:
Zhu, White, Carter, Baek Terry, PoP 2017

- Fluctuating density, flow
- Strong background field
- Exponential scaling (log-linear) plots
- Possible mixing of scales—energy injection and dissipation simultaneously

What kind of plasma turbulence are we talking about?

Space vs. Laboratory

Exploring different plasma regimes

Speaking different turbulent languages

Can "space-like" magnetic turbulence be explored in the laboratory?

What are the important dissipation mechanisms (reconnection, wave damping, onset collisionality)?

What wave physics is present/important for energy injection, inertial range energy transport, and dissipation?

What role do coherent magnetic structures play in turbulence?

How does boundedness or confinement modify turbulent properties (say between solar wind vs magnetosphere turb)?

How are ions transported by magnetic turbulence?

Can "space-like" magnetic turbulence be explored in the laboratory?

Ideally, what do we need to recreate space plasma turbulence in the laboratory?

- Unbounded, dynamical magnetic fields
- High beta, low density (collisionless), uniform plasmas (no grad)

Solar Wind: n~10cm^{-3}, B~1uG, Beta~0.5-3, Mach~10

Magnetopause: n~30cm-3, B~10uG, Beta~0.1-10, Mach

- Large size for large separation of scales (Rm >10000)
- High spatial sampling (or ability to rely on Taylor Hypothesis)
- Ability to probe sub-gyroradii scales/distribution functions

Can "space-like" magnetic turbulence be explored in the laboratory?

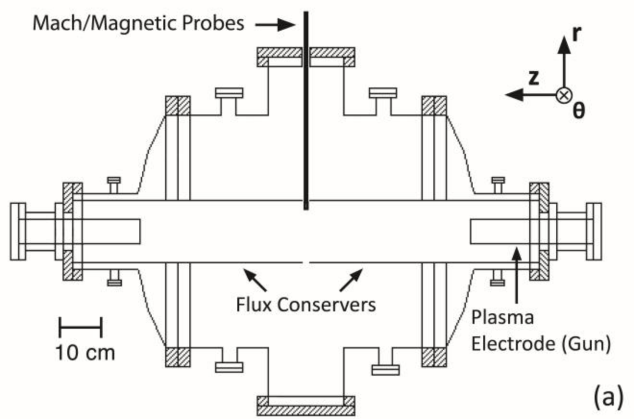
What can we ***currently hope to achieve*** to recreate space plasma turbulence in the laboratory?

- ~~Unbounded~~, *dynamical magnetic fields*
- *Highish beta*, low collisional, low gradient drive plasmas
- Large size? Maybe, but can be prohibitively expensive
- High spatial sampling (or ability to rely on Taylor Hypothesis)
- ~~Ability to probe sub-gyroradii scales →~~ maybe sub ion inertial scales, distribution function measurements difficult

A method for approaching space-like plasma turbulence: Evolving spheromaks from plasma guns

First developed at Swarthmore College on SSX

New experiment under construction at Bryn Mawr College



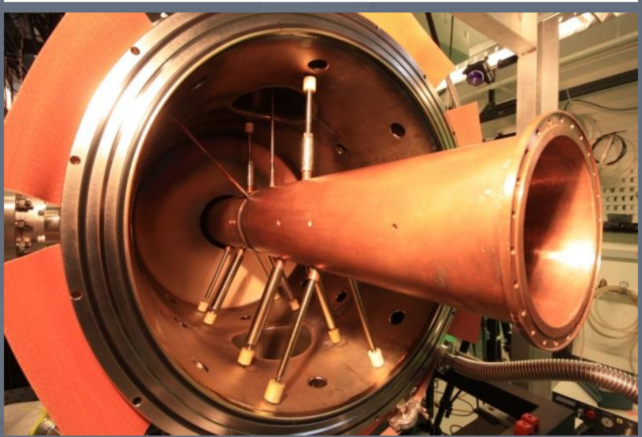
Method aims to:

-generate dynamical (turbulent) magnetic fields w/o background field

-achieve >*10% beta plasmas*, low collisional (λ_{mfp}~few ρ_i)

-short lifetime prevents strong gradients or gradient driven fluctuations to develop

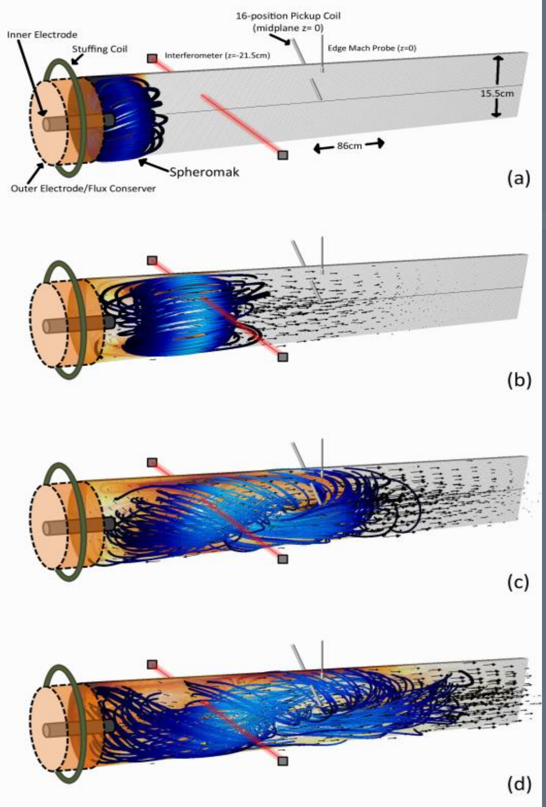
-system size ~100x ρ_i, ~$20\delta_i$



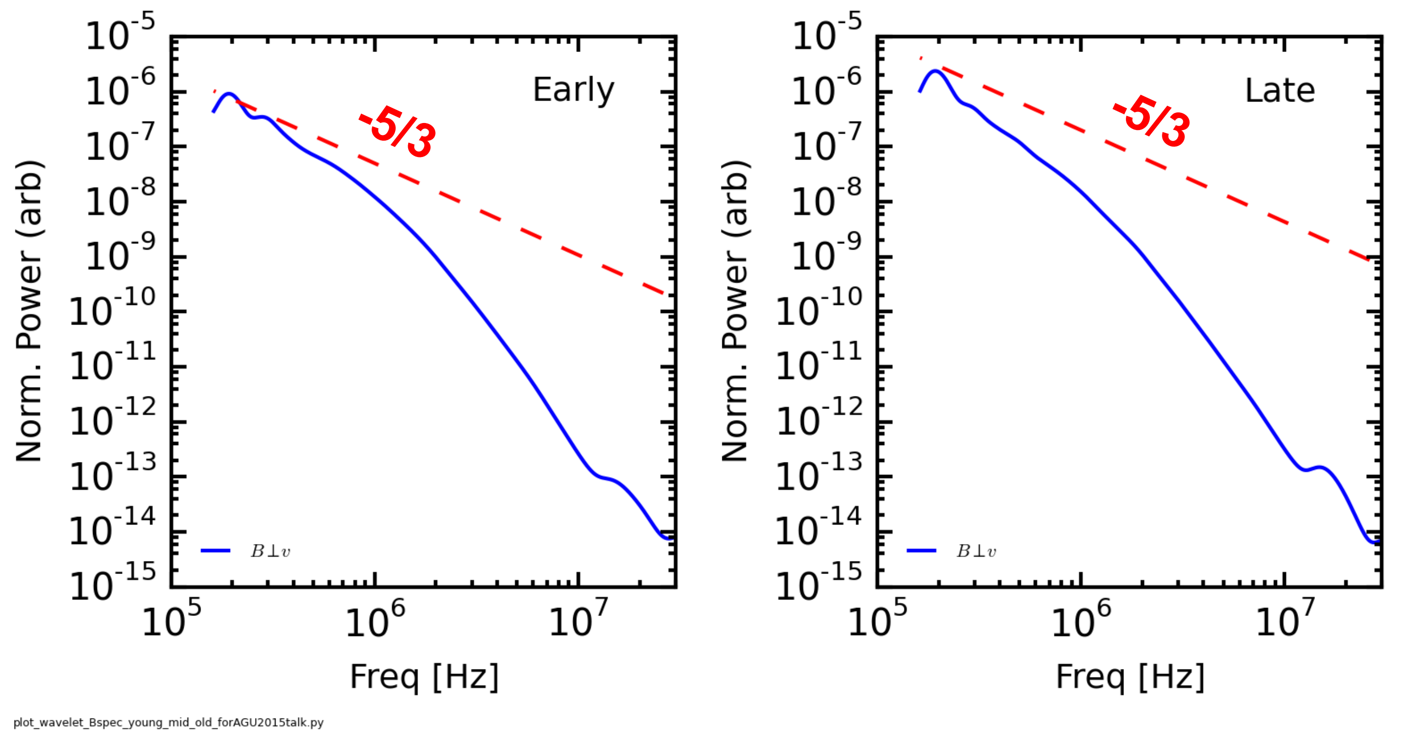
A method for approaching space-like plasma turbulence: Evolving spheromaks from plasma guns

Basic Idea:

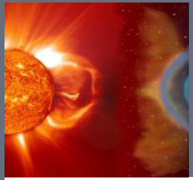
1) Plasma gun generates and launches a spheromak into large aspect ratio flux-conserving chamber
2) Break-off event + evolution from spheromak to Taylor State initiates magnetic turbulent cascade
3) Flux-conserving chamber confines plasma w/o restricting magnetic field dynamics
4) Turbulence measurements taken during window between birth and relaxation



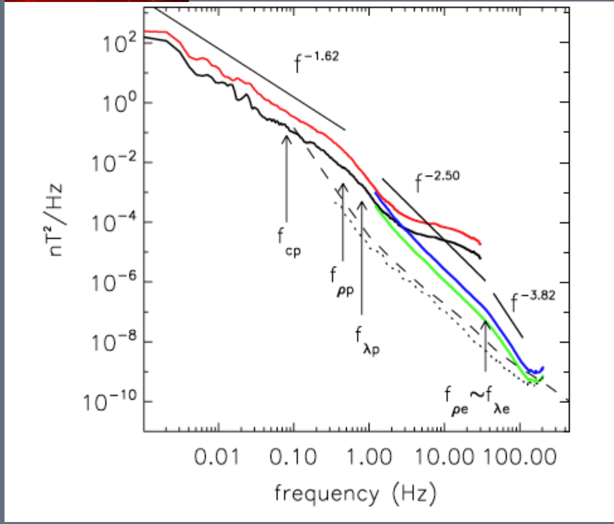
Initial Results: Broadband magnetic turbulence observed, observation of transition from inertial to dissipation range

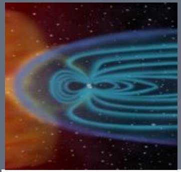


Comparison of spectra to solar wind, magnetosphere

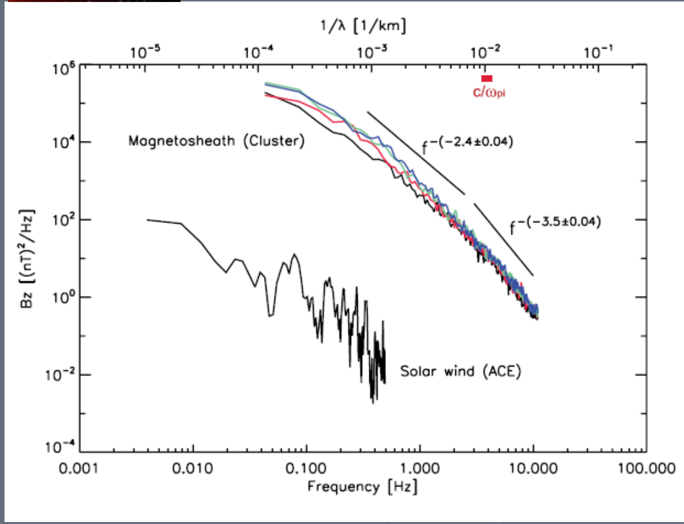


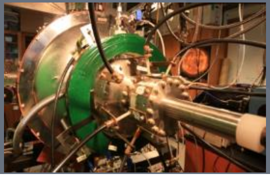
Cluster FGM and STAFF-SC Data:** ***Sahraoui, PRL 2009



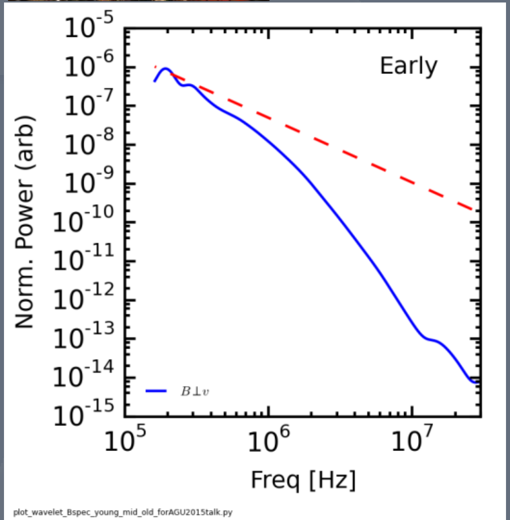


Cluster Data:** ***Yordanova, PRL 2008





***SSX PoP 2016**



Many other metrics explored, compared to solar wind and magnetospheric turbulence

Temporal and Spatial Spectra – Schaffner ApJ, 2015

Intermittency – Schaffner PPCF 2014, Schaffner PRL 2014

Structure Functions – Schaffner ApJ, 2016

Permutation Entropy/Statistical Complexity – Weck PRE 2015, Schaffner PoP 2016

-PE/SC analysis (and other information theory like metrics) in particular might have utility in developing a Turbulence Unification Theory (TUT) which could help generate a common language for describing "fluid-like" space turbulence and edge/gradient driven turbulence in magnetic confined laboratory experiments

Where do we fall short?

Scale separation – we're excited at Magnetic Reynolds numbers of ~100 compare to the values of 100k+ seen in space turbulence

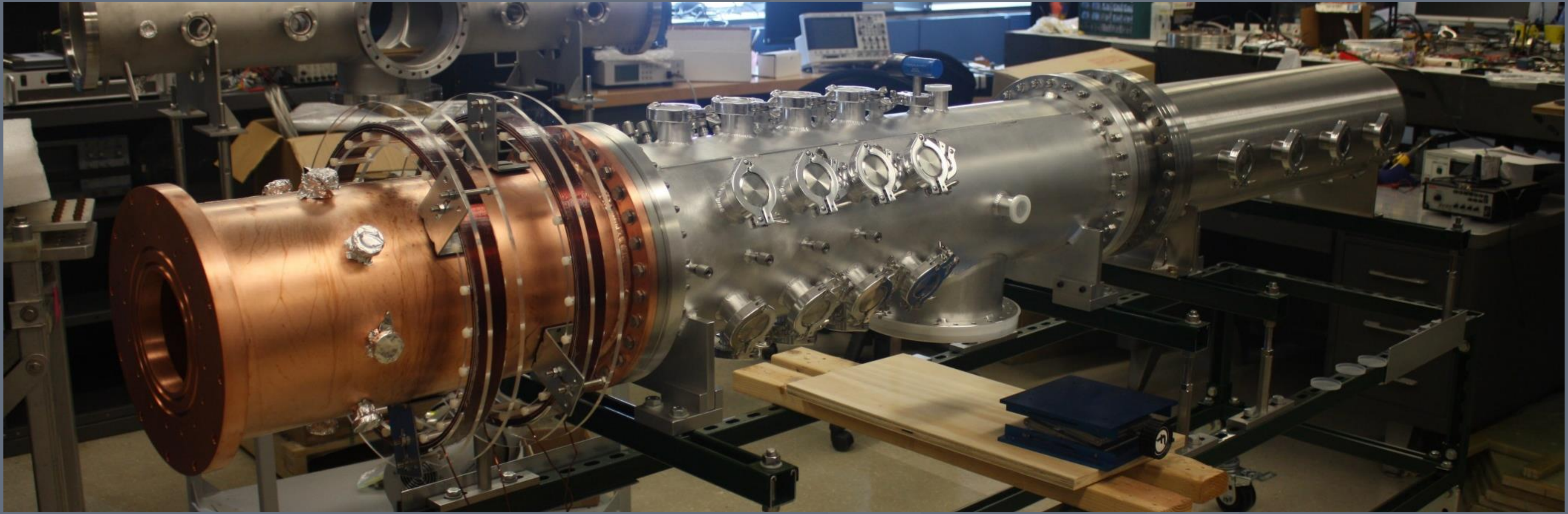
Sub-Alfvenic, Sub-Mach speeds – interpreting fluctuation data at these low speeds makes separation of spatial versus temporal evolution of the turbulence difficult

Limited probe scale – Our best current magnetic probe capabilities place us at scales just under the ion inertial length

Limited shot length – Given the nature of our turbulent system, we are limited in how much data we can collect which limits the ability to run certain analyzes to their fullest.

Limited spatial sampling of data

Where can we improve—a new experiment at BMC



Where can we improve—a new experiment at BMC

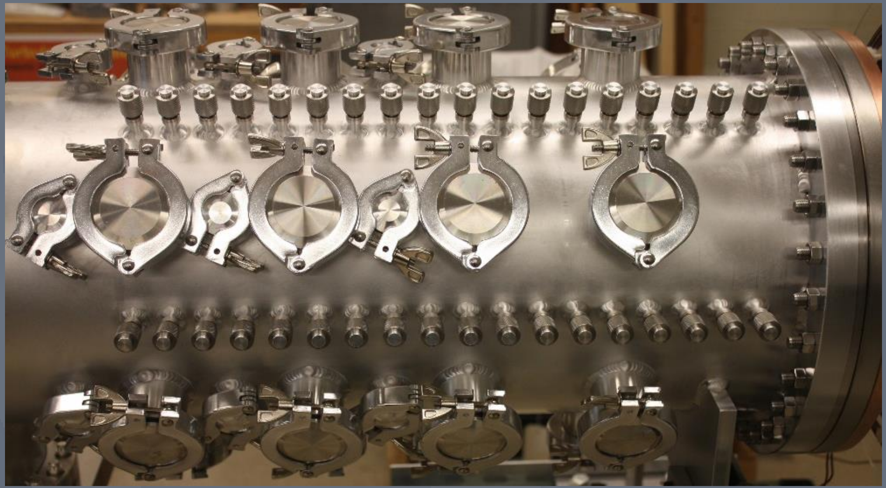
High spatial sampling – 36 access ports staggered to allow axial probe separation of 0.5cm

- 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 for extraction of wavenumber information

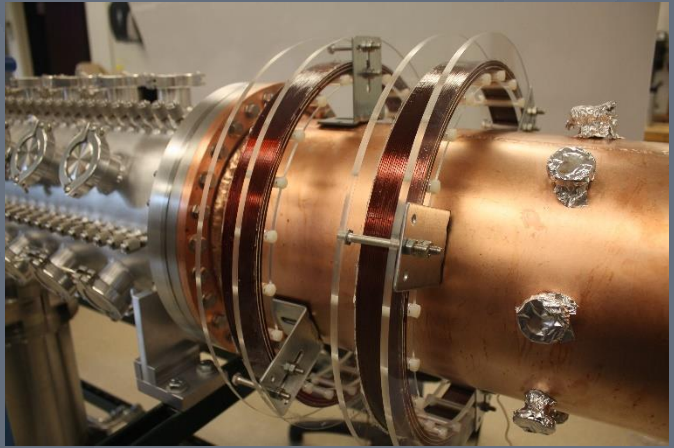
-Fine axial sampling allows for fine variation in tetrahedral size



Where can we improve—a new experiment at BMC

Long pulses – PFN designed to drive current of plasma gun for ~200-300us rather than the <100us currently feasible on SSX.

- Rather than generating distinct magnetic structures, the new gun parameters are designed to inject magnetized plasma continuously—more like a conventional fluid wind tunnel



Other avenues of exploration at Bryn Mawr

-Terrella experiments – study of turbulent interaction between magnetized plasma plumes and magnetospheric fields

- could also be relevant to CME physics if plumes can be accelerated

-Ion transport in magnetized turbulence – ion beam injectors being explored

-Comparison to solar plasma from SPP – while reaching solar-wind-like plasmas difficult in the lab, plasmas closer to the sun might be more comparable to the fields and density achieved in SSX, Bryn Mawr plasmas

-A system for detailed fluid, kinetic modeling – HiFi (Lukin), NIMROD (Woodruff), Gkeyll (TenBarge)

Next generation magnetic turbulence laboratory

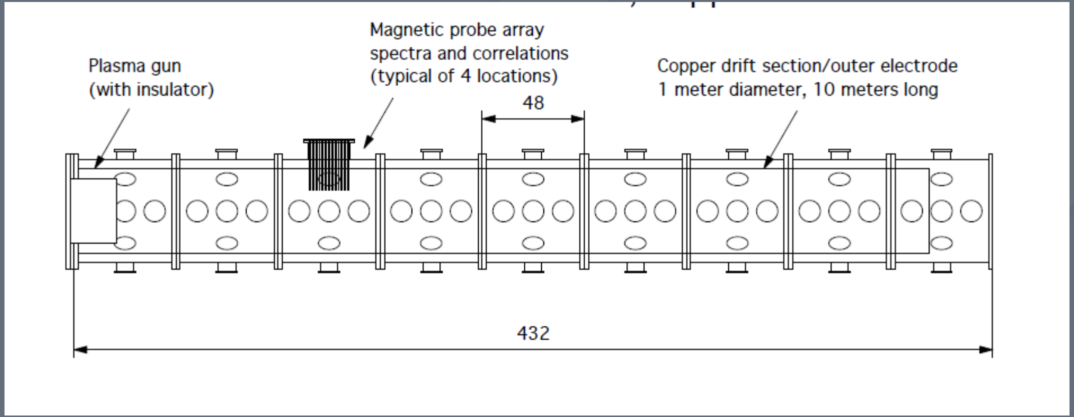
New Bryn Mawr experiment still lacks large scale separation, low density

Perhaps these things can be achievable on a larger scale device

What would it take to develop an LAPD sized plasma wind-tunnel?

-Meter wide plasma guns have been developed (SSPX, FAMU)

-Need a LAPD sized flux-conserving chamber (maybe Aluminum rather than copper?)



Next generation magnetic turbulence laboratory

Laboratory probe size limited

What are the prospects of next-generation probes?

-Growing micro, even nano Langmuir Probes, B-dot probes?

-Ability to probe sub gyroscale plasma which is easier to do in the sparse, expansive space plasmas

-Particle counting for distribution functions

-Larger size experiments make this less an issue.

For more info, visit:

www.swarthmore.edu/ssx-lab

www.brynmawr.edu/physics/plasma

Thank you for your attention