White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***7/20/2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
• Interactions of plasmas and waves	S
• Plasma self-organization	S
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	
Will not attend	

Title:	The need for high-beta, high-flow, low-collisionality fundamental laboratory plasma experiments (inspired by Town Hall talk by M. Kunz)
Corresponding Author:	Michael Brown
• Institution:	Swarthmore College
• email:	doc@swarthmore.edu
Co-Authors:	David Schaffner

**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

- ***Describe the research frontier* and importance of the scientific challenge.**

Many space and astrophysical plasmas are both collisionless and have $\beta>1$. Cosmic plasmas also typically operate at high velocities compared to their sources ($M>1$). In particular, the solar wind exhibits various phenomena directly connected to low collisionality and high beta. The research frontier is to explore this regime in the laboratory, and to compare with observations made in the solar wind. Typical plasma experiments operate at low beta, and low Mach number, and therefore don't exhibit the myriad of interesting phenomena observed in the solar wind. The regime of unity to high beta and low collisionality is particularly difficult to attain in the lab. Some ideas are suggested.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

State of the art:

Conventional laboratory plasma experiments employ a strong applied magnetic field for stability, confinement, and enabling low-density plasma production. This dominance of magnetic energy is particularly true of experiments designed for magnetic confinement fusion. The relative influence of

magnetic energy can be parameterized by β, the ratio of thermal to magnetic energy, and by M_A, the ratio of flow speed to Alfven speed. In figure 1, we plot the operating points of several laboratory and space plasmas in β-M_A space. We note that generally, laboratory plasmas occupy the low-beta, low-flow corner of the space. There is an opportunity for experiments to begin to fill the high-beta, high-flow part of this parameter space.

Another important consideration for connecting lab experiments to space plasmas is collisionality. Some laboratory experiments have low collisionality (high mean free path compared to system size) but they tend to be low-beta (Egedal). The MPDX experiment operates at high beta and high Mach number (Cooper), but as yet has not generated internal dynamical magnetic fields. The LDX experiment can operate at modest electron beta (20%), and low collisionality but ion beta remains low (Garnier). The SSX plasma wind tunnel (Brown) can operate at proton beta and Mach number about unity, but the collision frequency is high ($\omega_{ci}\tau_{coll}$ is about unity).

Examples of recent solar wind observations:

The solar wind is a well-studied, turbulent, collisionless (λ_{MFP} = 1 AU), high beta (β = 1) plasma with numerous features that have yet to be measured in terrestrial laboratories. A few recent examples are summarized here. Figure 2 is a plot from Bale, et al showing the distribution of proton temperature anisotropy measurements as a function of proton parallel beta. The plot is the result of over a million separate measurements from the Wind satellite over a ten-year period. The color represents the magnetic fluctuation level. There are enhanced fluctuation levels at the marginal stability boundaries for anisotropy-driven kinetic instabilities (mirror, cyclotron, fire-hose). In addition, there are essentially no observations beyond the boundaries, so evidently the action of anisotropy-driven instabilities in collisionless, high beta, high-flow plasmas tends to self-regulate a temperature anisotropy near unity.

Maruca et al studied the roles of heating and cooling in this parameter space. They found that scalar proton temperature is highest at the stability boundaries (about 3-4 times hotter than stable plasma). Since anisotropy-driven instabilities tend to equilibrate the component temperatures, rather than add energy, the authors suggest there must be heating mechanisms at play that dominate cooling mechanisms.

Osman et al considered the roles of intermittency and coherent structures in this parameter space. They found, like Maruca, that the scalar temperature of protons was higher at the marginal stability boundaries, but also found evidence for a preponderance of coherent structures at the boundaries. Their tool to identify regions of high magnetic stress and coherent structures is the increment of the magnetic field vector ΔB, and the so-called PVI (related to the variance of ΔB). They found a preponderance of magnetic discontinuities as evidenced by enhanced PVI at the stability boundaries, closely associated with the locations of higher temperature.

In other analyses related to conditional statistics, Kasper et al found that when solar wind data are sorted according to its "collisional age", the ratio of helium temperature to proton temperature is high (over 4) when the plasma is "young" ($A_C < 0.1$). Collisional age is the ratio of transit time to collision time, $A_C = R/V\tau$, where τ is the collision time, V is the solar wind speed, and R is the Sun-satellite distance. Chen et al (2014) found that when data are sorted according to beta, the shapes of the magnetic power spectra are different. The low-beta plasma (β = 0.01) has a break point in the spectrum associated with the ion inertial scale δ_i, while the high-beta plasma (β = 23) has a break point at ion gyro-scale ρ_i. In other words, the break point seems to occur at whatever scale is largest.

Finally, there have been a number of statistical observations of small-scale phenomena (between ion and electron scales) in the solar wind. Kiyani et al noted that anisotropy in fluctuations perpendicular versus

parallel to the local magnetic field were reduced to isotropy at scales approaching the electron gyro orbit. Chen et al (2010) used structure functions to demonstrate anisotropy in perpendicular fluctuations at scales between ion and electron gyro orbits. Chen et al (2012) also found a steeper than expected spectral index for density fluctuations at small scales.

New research tools:

The results presented above could be and should be studied in a terrestrial plasma physics lab. Laboratory measurements can be made with multiple (even 100's) of probes, rather than single spacecraft, and can be repeated multiple times under similar conditions. The problem is that the combination of high beta, low collisionality, and high flow speed is particularly difficult to attain in the lab.

Higher beta is achieved by increasing density and temperature, while lowering magnetic field, however lower collisionality suggests dropping density while increasing temperature. One possibility is to provide auxiliary heating to existing experiments to both increase beta and lower collisionality. The SSX plasma wind tunnel has about 200 J of thermal energy at T_i = 20 eV (Brown). Heating to 100 eV (say with pulsed coils to launch Alfven waves) would entail adding 1 kJ of thermal energy in a few microseconds. This would increase beta to over unity, while increasing the collision time by a factor of 10. The LDX dipole plasma could be heated with ICRF to increase the ion beta. These are both possible, but involve non-trivial infrastructure improvements.

Another possibility is to operate existing toroidal confinement devices (eg MST or NSTX) at substantially reduced toroidal field. It is difficult to establish a toroidal discharge at low toroidal field, and in any case β=1 is challenging in a toroidal system. It might also be possible to add parcels of turbulent magnetofluid to MPDX or LDX to induce magnetic turbulence at low collisionality.

Finally, there is the issue of how to measure temperature anisotropy in the lab, particularly when gyro orbits are smaller than the sizes of typical probes. In the solar wind, the spacecraft are always small compared to gyro orbits, so measurement of particle flux from different directions with respect to the mean magnetic field can construct the entire particle distribution function. In the lab, one option is to use a hybrid magnetostatic-electrostatic probe to map out the perpendicular and parallel distribution function (see Brown 1991).

References (Maximum 1 page)

Bale, S. D., et al. "Magnetic fluctuation power near proton temperature anisotropy instability thresholds in the solar wind." *Physical review letters* 103.21 (2009): 211101.

Brown, M. R., and D. A. Schaffner. "Laboratory sources of turbulent plasma: a unique MHD plasma wind tunnel." *Plasma Sources Science and Technology* 23.6 (2014): 063001.

Brown, Michael R., and David A. Schaffner. "SSX MHD plasma wind tunnel." *Journal of Plasma Physics* 81.03 (2015): 345810302.

Brown, M. R., et al, "Temporal evolution of the electron distribution function in an electron cyclotron resonant discharge," *Journal of Applied Physics*, 70, 5306-5313 (1991).

Chen, C. H. K., et al. "Anisotropy of solar wind turbulence between ion and electron scales." *Physical review letters* 104.25 (2010): 255002.

Chen, C. H. K., et al. "Density fluctuation spectrum of solar wind turbulence between ion and electron scales." *Physical review letters* 109.3 (2012): 035001.

Chen, C. H. K., et al. "Ion-scale spectral break of solar wind turbulence at high and low beta." *Geophysical Research Letters* 41.22 (2014): 8081-8088.

Cooper, C. M., et al. "The Madison plasma dynamo experiment: A facility for studying laboratory plasma astrophysics." *Physics of Plasmas (1994-present)* 21.1 (2014): 013505.

Egedal, Jan, et al. "Laboratory observations of spontaneous magnetic reconnection." *Physical review letters* 98.1 (2007): 015003.

Garnier, D. T., et al. "Production and study of high-beta plasma confined by a superconducting dipole magnet." *Physics of Plasmas (1994-present)* 13.5 (2006): 056111.

Kasper, J. C., A. J. Lazarus, and S. P. Gary. "Hot solar-wind helium: Direct evidence for local heating by Alfvén-cyclotron dissipation." *Physical review letters* 101.26 (2008): 261103.

Kiyani, Khurom H., et al. "Enhanced magnetic compressibility and isotropic scale invariance at sub-ion Larmor scales in solar wind turbulence." *The Astrophysical Journal* 763.1 (2013): 10.

Maruca, B. A., J. C. Kasper, and S. D. Bale. "What are the relative roles of heating and cooling in generating solar wind temperature anisotropies?." *Physical review letters* 107.20 (2011): 201101.

Osman, K. T., et al. "Kinetic signatures and intermittent turbulence in the solar wind plasma." *Physical review letters* 108.26 (2012): 261103.

Schekochihin, A. A., et al. "Magnetofluid dynamics of magnetized cosmic plasma: firehose and gyrothermal instabilities." *Monthly Notices of the Royal Astronomical Society* 405.1 (2010): 291-300.

See white papers by Kunz, Bellan, Forest, Egedal, Amatucci, Schaffner, Howes, Ji, Mauel, Nornberg

Figures (maximum 1 page)

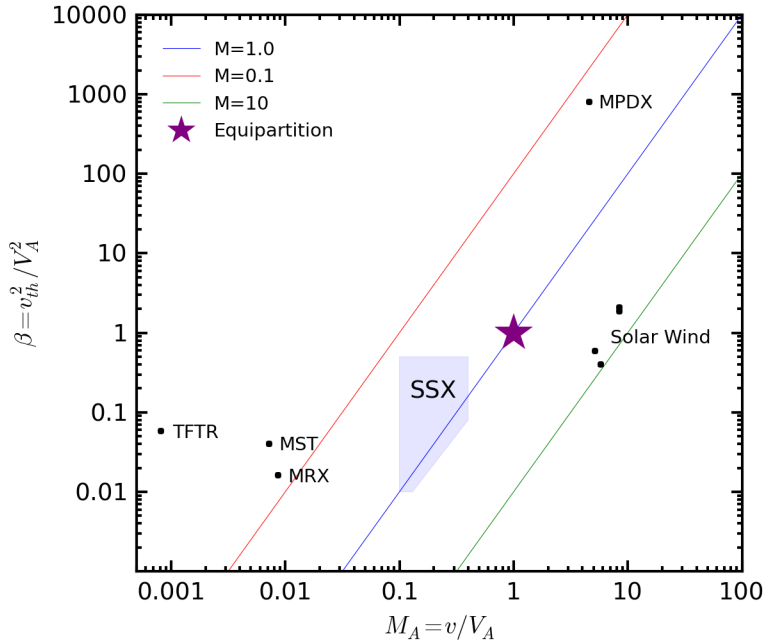

Figure 1: A parameter plot in β/Mach Alfven space showing operating points for laboratory and space plasmas. The star at center is equipartition among thermal, flow, and magnetic energies. Diagonal lines are constant sonic Mach number. Space and astrophysical plasmas tend to occupy the upper-right quadrant (high beta, high flow), while laboratory plasmas tend to occupy the lower-left (low beta, low flow) [ref: Brown, JPP, 2014]

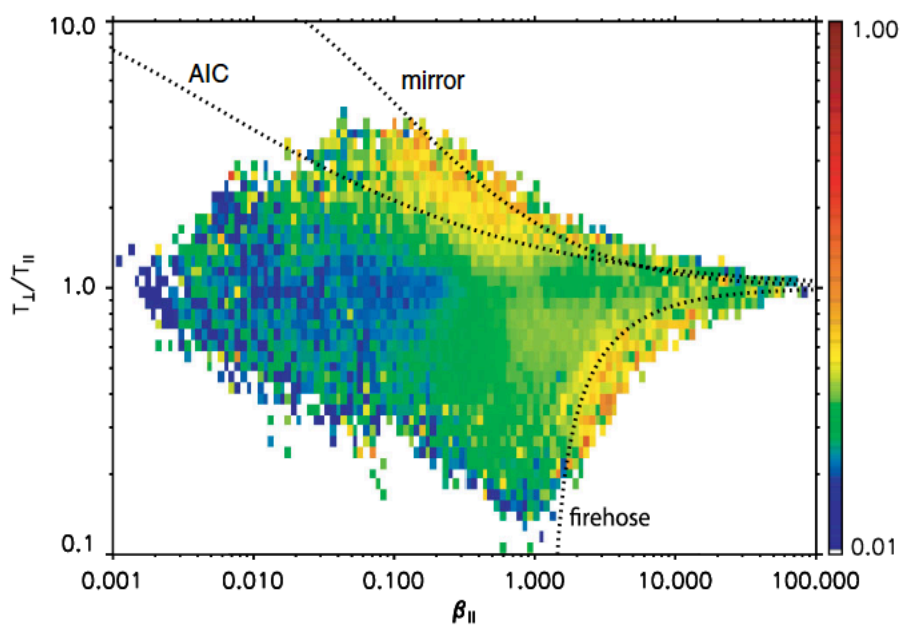

Figure 2: Plot of temperature anisotropy of protons in the solar wind as a function of parallel beta. The highest magnetic fluctuations exist at marginal stability boundaries [ref: Bale, PRL, 2009].