Next Generation Machine to Study Heliophysics in the Laboratory

Synopsis: How the solar wind is accelerated, heated, and driven turbulent is among the most persistent and important open questions in Heliophysics. The multi-scale, multi-dimensional nature of the problem makes it difficult to fully address these questions using spacecraft missions and numerical simulations alone. To complement these approaches, it is important to build a next generation laboratory facility to isolate, control, and diagnose plasma phenomena responsible for the complex solar wind behavior. This white paper discusses the motivation and example design parameters for such a Solar Wind Machine and outlines a planning process aimed at breaking ground within the next decade.

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How the solar wind is accelerated, heated, and driven turbulent is among the most persistent and important open questions in Heliophysics. The multi-scale, multi-dimensional nature of the problem makes it difficult to fully address these questions using spacecraft missions and numerical simulations alone. **Over the next ten years, it is important to break ground on a next generation laboratory facility to isolate, control, and diagnose plasma phenomena responsible for the complex solar wind behavior [1, 2].**

In order to best complement space observations, theory, and numerical simulations, the new Solar Wind Machine will need to operate in a regime where collisions are not physically important and cover a wider range of scales than existing laboratory experiments. The benefits of investing in such a facility are manyfold. A Solar Wind Machine can be constructed for a fraction of the cost of a modern space mission. The facility will engage research groups focused on laboratory space/astrophysics as well as groups focused on space observation, fostering new collaborations and broadening participation in both fields. Finally, such a venture would be a prime opportunity to coordinate among interested funding agencies, primarily NASA, NSF, and DOE, but also ONR and AFOSR. [1, 2].

This white paper is divided into five sections. Section 1 discusses important advantages of laboratory experiments including the ability to acquire volumetric data that spans multiple scales. Section 2 outlines the need for a new Solar Wind Machine to fully resolve the relevant scales in a regime where collisions are not physically important. Section 3 gives example design parameters for a study of solar wind turbulence, an important Heliophysics phenomenon that is notoriously difficult to produce in the laboratory. Section 4 describes the evolving community consensus on the need for a next generation machine. Finally, in Section 5 we propose a planning process necessary to pin down the details of the machine with the goal of breaking ground within the decade.

1. Advantages of Laboratory Experiments

Laboratory experiments are a key tool that can help understand the most important physical processes in Heliophysics [3]. Space measurements are limited by not only the number of spacecraft, but also the uncertainty in the timing of natural events, making it difficult to obtain a full spatio-temporal picture. Meanwhile, in even the most optimistic scenario for the growth of computing power over the next ten years, numerical simulations will still be unable to cover the range of scales in 3-dimensions necessary to resolve important open questions. By contrast, laboratory experiments yield improved spatio-temporal measurements and often feature copious diagnostics at a range of scales. As outlined in a companion white paper [4], these unique diagnostic capabilities mean that **laboratory experiments can play a range of useful and complementary roles from benchmarking theoretical predictions to investigating the reliability of spacecraft measurements.**

Most physical processes in the solar wind involve a wide range of spatial scales. Turbulence consists of a cascade of energy from large to small scales [5]. Magnetic reconnection often leads to dramatic changes in the macroscopic behavior due to field lines breaking in localized regions, requiring MHD and kinetic physics to adequately describe the dynamics [25]. Magnetospheric and interplanetary shocks are collisionless and dissipate their energy on scales much smaller than the collisional mean-free-path, but there remain many open questions as to how these shocks convert the kinetic energy of their large, supersonic bulk flows into electromagnetic energy, heating, and particle acceleration [26]. There are significant barriers to fully understanding these

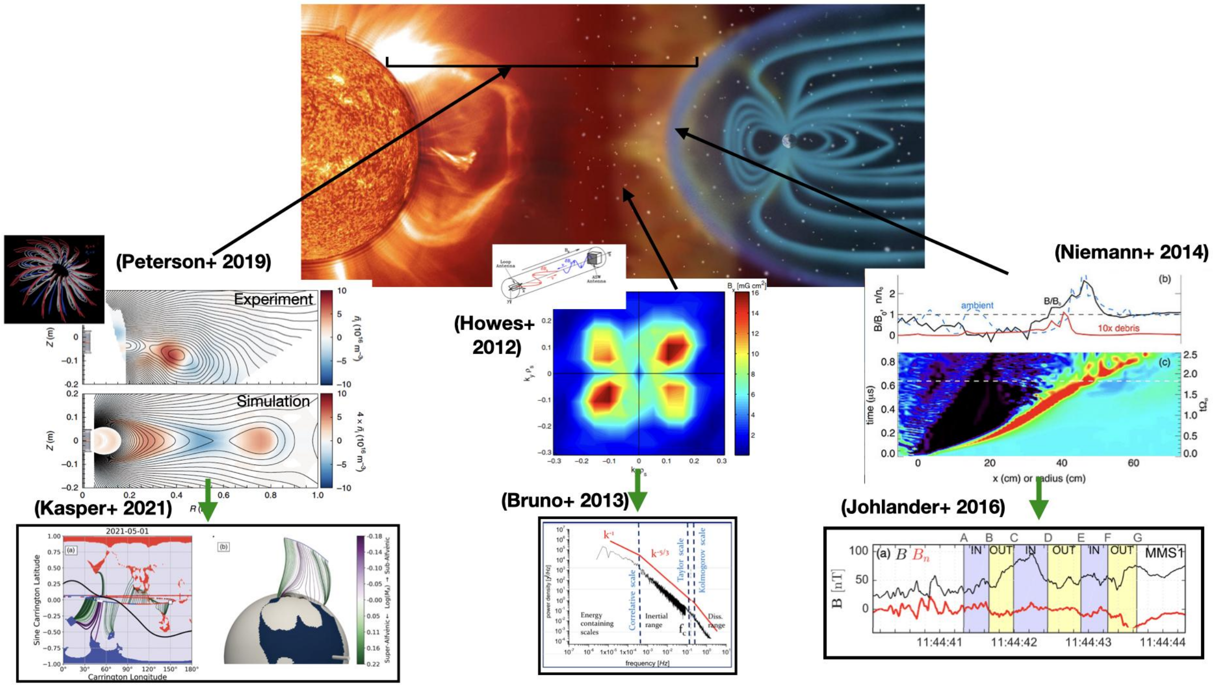

Figure 1. Illustration of solar-wind-relevant physical processes that both have been studied in the past by laboratory experiments (center row) and related observations that could be more fully investigated by a Solar Wind Machine. Peterson, et. al 2019 [14] produced the Parker Spiral in the lab for the first time; Howes, et. al. 2012 [16] produced the non-linear interaction at the heart of solar wind turbulence in the laboratory; Niemann, et. al. 2014 [18] measured the formation and structure of a magnetized collisionless shock in the laboratory.

processes through observations alone: the parameters in observational data are chosen by nature and the range of relevant scale sizes are enormous, making them difficult to fully diagnose in situ. In contrast, **laboratory experiments provide a controlled system with the ability to resolve the interplay between the macroscopic behavior and the microscopic dynamics.**

Similarly, the study of such complex solar wind processes will benefit from the many-point multi-dimensional coverage that laboratory experiments can provide. Turbulent structures are inherently 3D [5], but measurements of turbulence in the solar wind typically rely on single spacecraft where time series data is converted to spatial scales by assuming the evolution is much slower than the convection past the spacecraft. 3D instabilities and dynamics also impact the development of magnetic reconnection: rather than a current layer breaking up into many magnetic islands in 2D, the evolution is dominated by the interaction of flux ropes when allowed to develop fully in 3D [6]. Multiple studies have shown the relationship between solar energetic particles and changing 3D magnetic topology [7, 20, 21]. The large zoo of processes active in the solar wind along with the non-stationarity some processes display means that single-point spacecraft measurements can have difficulty reconstructing the particle dynamics and relating them back to the 3D, macroscopic behavior of the system. **Even if the number of *in situ* spacecraft were dramatically increased, it would still not be possible to get the 3D coverage that is easily achieved in laboratory experiments.**

2. The Need for a Next Generation Machine

While laboratory experiments have a demonstrated ability to investigate both the multi-scale and 3-D nature of heliospheric phenomena, the current generation of experiments can struggle to access relevant regimes. Some examples of recent successes in relating research on existing devices to heliospheric processes are provided in Fig. 1 and described in the figure caption. Despite these successes, current laboratory devices cannot adequately diagnose how the solar wind is accelerated, heated, and driven turbulent because they are either too collisional and/or too limited in the range of scales they can study. The physics at the largest scales of these devices can be heavily influenced by the presence of the device boundary, limiting the applicability of the results.

The many benefits of laboratory experiments and limitations of current devices clearly demonstrate the need for a new, advanced Solar Wind Machine to specifically target processes which occur throughout the solar wind. To capture the key physics responsible for complex solar wind behavior, **a next generation experiment will need to achieve a regime where collisions are not physically important, fully resolve all the relevant scales, and take full advantage of the multi-dimensional measurements and reproducible nature of laboratory experiments.** Such a facility will be extremely beneficial both for the interpretation of spacecraft measurements and for validation of fluid and kinetic numerical codes, leading to increased confidence in data interpretation and code predictions. **To design this next generation device, there are five important questions that we believe need to be answered:**

1) What physical processes should a Next Generation Solar Wind Machine target?
2) What parameters are needed to observe these physical processes?
3) What machine configurations are needed to achieve these parameters?
4) What new plasma diagnostics are needed to make the required measurements?
5) Which of the target physical processes can be explored using existing laboratory devices? To what extent?

A planning process to fully address these questions is outlined in Section 5. As an example of what might be required for a Solar Wind Machine, we discuss in Section 3 the parameters required to produce a turbulent Alfvén wave cascade in the laboratory.

3. Example Design Parameters

To resolve the necessary scales for the phenomena of interest in a collisionless environment, the required plasma parameters and machine size may be significantly different from what can be achieved in existing basic plasma science experiments. While some possible design parameters are outlined in this section, the ideas presented are not meant to constrain the range of facilities that could come out of the planning process proposed in Section 5.

For example, an Alfvén wave cascade has long been considered somewhat of a “holy grail” of laboratory Heliophysics, as this phenomena cannot be produced in existing experiments. Both forward and inverse cascades have been observed in the solar wind [8], but the turbulent cascale is difficult to achieve in the lab for three main reasons:

1) The machine must be collisionless to prevent the launched waves from quickly damping.
2) The parallel scales must be large enough for several Alfvén wavelengths to fit in the device.
3) The perpendicular scales must be large enough for the ion skin depth to be much smaller than a perpendicular wavelength. If this condition is not satisfied, then the Alfvén wave includes density fluctuations and non-linearities that are not present at large scales in solar wind inertial-range turbulence.

These criteria are expressed in terms of dimensionless parameters in Table 1.

Parameter	Range	Reason
Collisionality / Alfvén frequency	$\nu_{ei}/\omega < 1$	Minimize electron-ion collisions
Electron thermal speed / Alfvén speed	$v_{the}/V_A >> 1$	Minimize Landau damping of launched waves
Parallel wavenumber * Machine length	$k_{\|}*L >> 1$	Fit several parallel wavelengths in the machine
Perpendicular wavenumber * Ion skin depth	$k_{\perp}*di << 1$	Study MHD Alfvén waves

Table 1: Key dimensionless parameters required for an Alfvén wave cascade experiment to satisfy the three criteria outlined in the text.

Setup	n (/cm^3)	Te (eV)	B (G)	di (cm)	$\lambda_{\|}$ (m)	v_{the}/V_A	$k_{\|}*di$	ν_{ei}/ω	β_e	R_m
A	1e13	50	400	7.2	1.0	15.2	0.45	0.71	0.13	1.3e4
B	1e14	500	8000	2.3	1.0	7.6	0.14	0.038	0.032	2.4e6

Table 2: Example target parameters for a solar wind experiment using Hydrogen plasma. Parameters are plasma density, electron temperature, background magnetic field, ion skin depth, Alfvén parallel wavelength, ratio of electron thermal speed to Alfvén speed, parallel wavenumber times ion skin depth, ratio of collisionality to Alfvén frequency, electron β, and Magnetic Reynolds number respectively.

The launched Alfvén waves can be damped by a combination of electron Landau damping and electron-ion collisions [9]. In the Large Plasma Device (LAPD) at UCLA, the amplitude of the wave will typically decrease by a factor of ~2 over one wavelength, which is not acceptable when many Alfvén wave interactions are required. LAPD operates near $v_{the} \sim V_A$, which is the optimal regime for electron Landau damping; meanwhile, electron-ion collisions scale with density and are inversely proportional to $Te^{3/2}$.

The most straightforward way to reduce these sources of damping is to operate in a high electron temperature regime. This will both reduce electron-ion collisions and allow for a regime where $v_{the}>>V_A$, reducing electron Landau damping. Two sets of example parameters exemplifying this approach are shown in Table 2. Both sets use a parallel wavelength of one meter; this means that the machine must be several meters long in order to satisfy $k_{\|} L >> 1$. Setup A lists parameters similar to what is achievable in existing basic plasma science laboratory experiments, but with larger electron temperature. Meanwhile, Setup B contains densities, temperatures, and magnetic fields that are more typically found in magnetic confinement devices such as tokamaks. Note that even with use of Setup A, the high electron temperatures will require plasma confinement and heating methods borrowed from the magnetic fusion community.

The exact format of the machine (tokamak, mirror machine, etc.) is left to the planning process proposed in Section 5, and each potential format comes with additional challenges that will need to be considered. For example, the periodic geometry of a tokamak leads to distinct Alfvén eigenmodes [22] while no such constraint exists in the solar wind. Nonetheless, **Setup B shows that it is feasible to achieve lower collisionality and resolve the relevant scales using**

parameters that are achievable in existing fusion devices. Setup A is more marginal in this regard; the ratio of collisionality to Alfvén frequency is significantly higher than Setup B in order to keep the waves far below the ion cyclotron resonance.

In both setups, depending on the obliquity of the Alfvén waves, we may be unable to satisfy the perpendicular scale criteria ($k_{\perp}$di<<1). However, even if $k_{\perp}$*di ~ 1, the machine will still be extremely useful since it can then be used to study kinetic range turbulence, which has also never before been produced in the laboratory.

Note that for this fundamental study of turbulence, the only real requirement on plasma β is vthe/VA >> 1; both sets of parameters choose β < 1 to make laboratory plasma confinement easier. The more realistic collisionality and better scale separation make these proposed parameters relevant to the inner heliosphere and solar corona. However, since turbulence is similar in the inner and outer heliosphere and not sensitive to plasma β [23], the **physical insights gained from the proposed Solar Wind Machine will be broadly applicable throughout the Heliosphere.**

A machine with these tokamak-like parameters will be useful for studying Heliophysics phenomena beyond the turbulent cascade. Each phenomena may require slightly different dimensionless design parameters. For example, while the ion temperature could be significantly lower than the electron temperature to study the inertial range turbulent cascade, a study of temperature anisotropy instabilities in the solar wind will work best at ion β of order unity. Several other areas of relevance to Heliophysics involve the interaction of two plasmas (both with similar dimensionless parameters to those in Table 1 interacting with a relative drift velocity several times the Alfvén speed. Examples include beam instabilities and shock formation in the solar wind and at planetary bow shocks. For the scenario in setup A, the Alfvén speed is ~300 km/s, which means beams could potentially be generated with laser produced plasmas or plasma guns, while the ~2000 km/s Alfvén speeds of setup B are compatible with beams generated by a high current ion accelerator. System lengths L/di >> 10 are desirable for many experiments of this type.

In existing laboratory experiments using fusion devices, various phenomena related to energetic particle acceleration in the solar wind plasma have been observed. For instance, studies at the MAST tokamak have suggested parallels between edge localized modes (ELMs) and solar flares in the way both types of events lead to electron acceleration via parallel electric fields [10]. While capable of producing interesting magnetic field topology and well-diagnosed energetic particles, tokamaks and other fusion devices typically have limited time available for fundamental plasma research (for example, the Frontiers Campaign in the DIII-D tokamak). Therefore, a machine with some similar parameters but fully dedicated to solar wind studies will greatly benefit the Heliophysics community.

A new Solar Wind experiment would offer another major upside: cost. Currently operating basic plasma science collaborative facilities cost under $2 million to construct and have annual operating budgets ranging from $0.6 - $2.5 million, depending on needs and capabilities of the various facilities. Given the necessary increase in size and magnetic field strength a next-generation solar wind machine would likely cost more to construct, on the order of tens of millions of dollars. This is still quite affordable when compared to the cost of spacecraft: MMS and PSP cost approximately $1 and $1.5 billion to construct and launch, respectively, and have annual operating budgets in the tens of millions. After the initial MMS investment, continuing support for the spacecraft has been funded at $26 million per year [11].

4. Community Consensus on the need for a Solar Wind Machine

With the advent of community wide collaborative scale facilities in the basic plasma experimental community, including facilities such as BaPSF at UCLA, WiPPL at the University of Wisconsin, Madison, and MPRL at Auburn University, interest in potential laboratory Heliophysics studies has grown tremendously. Such collaborative facilities have enabled fruitful collaborations between Heliophysics researchers and colleagues from various other fields of plasma science and engineering. Coupled to this expanding research thrust has been the recognition that existing facilities do not meet the parameter space needs for making laboratory comparisons to many phenomena observed in the Solar Wind. While **the idea for constructing a solar wind plasma physics relevant laboratory device has been floating around the community for many years**, the most recent push was jump started during a 2019 NSF-led workshop with funding support from DOE FES, AFSOR, and ONR called *Workshop on Opportunities, Challenges, and Best Practices for Basic Plasma Science User Facilities* [12]. One of the topic focus groups discussing research needs for studying coherent structures and energy dissipation proposed a facility that could address both large scale fluid structures and small scale kinetic structures which would require a device that would be at least 100 ion inertial scales across, would be capable of producing high β plasmas, and large enough to approach collisionless conditions. The new Solar Wind Machine would be the practical realization of such a device.

These ideas were further elaborated on during the APS-DPP Community Planning Process that was also initiated in 2019 [13]. The CPP solicited community input on research interests and priorities in plasma physics including laboratory astrophysically relevant study. Community input was solicited through multiple town hall meetings, white paper submissions, culminating in a final community gathering in Houston in January 2020 to finalize details in advance of a final report. **The report itself included a programmatic recommendation to build a solar wind relevant laboratory, calling for the community to "Invest in an intermediate scale general plasma science facility to investigate the science of solar wind plasmas in the laboratory" [13]**. The final CPP Report was endorsed by 543 members of the plasma physics community.

This recommendation was reiterated in a prioritization and planning study called for by the Fusion Energy Sciences Advisory Committee (FESAC) [2]. This report was approved unanimously by FESAC in December 2020. It called for the construction of a solar wind facility if significant funding could be allocated to it. In addition, it recommended the formation of a network of experimental magnetized plasma facilities called MagNetUS which would coordinate the research community most interested in laboratory astrophysics, and would provide input for development of a future solar wind facility. The MagNetUS community has since been formally organized (www.magnetus.net) and the idea for this white paper came out of discussions at a recent meeting in Williamsburg, VA.

5. Planning Process Necessary to Break Ground within the next Decade

To break ground on such a facility within the next ten years, NASA and NSF, in collaboration with other interested federal agencies, should support a planning and proposal process as outlined in this white paper. To answer the five important questions identified in Section 3, the planning process should include brainstorming and discussion sessions at various conferences (AGU, GEM/SHINE, APS/DPP, NSF Eclipse, etc.) aimed at gathering ideas from the broader community as well as more focused work by a smaller working group to compile the ideas in a comprehensive report. A dedicated conference/workshop run by the working group may also be desirable. At the conclusion of the planning process, it is expected that we will have a community consensus on the possible forms a Solar Wind Machine might take as well as ideas for related experiments that can be conducted on existing laboratory devices. If there is one clear best idea, then NASA, NSF, and other interested funding agencies should work with the community to fund that project. However, if there are multiple competing ideas (probably the more likely outcome), then there should be a formal request for proposals from the funding agencies. Teams formed around each idea would then submit proposals for review and selection.

Because a Solar Wind Machine falls at the intersection between space physics and basic plasma science, successful funding of the machine will require collaboration between funding agencies, per a recommendation from the NAS Plasma 2020 Decadal Survey [1]:

> **Recommendation: Federal agencies and programs within federal agencies that are separately focused on fundamental plasma research, and those that are focused on science and technologies that utilize plasmas, should jointly coordinate and support initiatives with new funding opportunities.**

There are various ways funding agencies may get involved, including funding initial construction of the machine, funding operations/equipment/staff salaries, and/or funding user projects. Part of the planning process will include conversations with funding agencies regarding the best way for agencies to collaborate and discussions on what type of funding aligns best with the mission of each agency. For example, one possibility would be to leverage existing funding calls: the NSF mid-scale research infrastructure opportunity is a possible path for machine construction. NASA may contribute funding for a staff scientist whose portfolio includes connecting the lab results and current space missions. Meanwhile, related experiments on existing machines identified in the report could be funded as part of the facility call, as part of a separate call, or could be given higher priority in existing calls such as NASA HTIDeS or a successor to the NSF/DOE plasma partnership.

The proposed Solar Wind Machine is intended to operate as a collaborative facility, similar to existing basic plasma science experiments. This means that the facility will solicit white papers from scientists interested in conducting experiments on the device – such white papers will be solicited once per year with the opportunity advertised widely to the community. A local group consisting of several staff scientists and engineers will maintain the facility, assist with user projects, and conduct their own research on the facility.

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