White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 24, 2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
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• Plasma Atomic physics and the interface with chemistry and biology	S
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Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	X
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Title:	Challenges for Spheromak Confinement at Fusion Relevant Temperatures
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**(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.**

The spheromak is a self-organized, magnetized plasma configuration with currents approximately aligned with the magnetic field (~ j || B) that has long been considered as a viable and economical candidate to confine fusion-grade plasmas. Its advantage over the more studied tokamaks and stellarators stems from its engineering simplicity since it does not require expensive superconducting coils, the plasma volume is simply connected, and a commercial reactor is expected to be at least an order of magnitude smaller than that of a tokamak. Spheromak experiments have in the past demonstrated[1] $T_e \sim 0.5$ keV, $B_{tor} > 1$ Tesla, $I_{plasma} \sim 1$MA, ne > $1\times10^{20}m^{-3}$, and a ratio of thermal to plasma pressure (ß) of > 5%. These parameters were achieved at the Sustained Spheromak Physics Experiment (SSPX)[2], which remains the hottest spheromak plasma with the longest confinement time demonstrated in an experiment. However encouraging, these results were achieved in a machine that was limited by the power driving system, as well as engineering considerations such as power loading and heat buildup by the plasma on the walls of the machine, which had a cylindrical shape of 0.5 m (radius) by ~0.5 m (height). The power driving system of SSPX could sustain hundreds of kiloamperes for about 5 milliseconds, but was configurable to

achieve a train of pulses of different amplitudes and durations[3]. Note that longer plasma sustainment has been achieved at HIT-SI using a current drive system different from coaxial helicity injection[4], but at much reduced temperatures compared to SSPX. The ***research frontier*** *is to demonstrate the viability of the spheromak to confine thermonuclear fusion plasmas for times that are long enough to test alpha heating, auxiliary heating, and engineering issues such as wall loading from plasma and neutrons, and dusty plasma generation and redeposition*. In the past, important engineering issues have been ignored. Even though the spheromak represents a significant reduction in engineering complexity and cost compared to tokamaks and stellarators, it is now accepted that engineering of any fusion device also represents a grand engineering challenge of our time[5].

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

Approach: Despite its promise as a compact and relatively simple fusion confinement concept, spheromaks have only been studied at the basic plasma science level (e.g. Caltech[6], SSX[7], etc.) and concept exploration (SSPX[2] and references within review by Yamada[8]). Support in theoretical, numerical, and experimental capabilities to study magnetized, self-organized fusion-relevant spheromak plasmas is required. Importantly, the numerical and theoretical efforts must be closely coupled to experimental ones. A major engineering advantage of the spheromak is that the vessel in which it is created is simply connected; the field at the walls is purely poloidal, and thus amenable to the use of liquid lithium, FLiBe, or other liquid metal first walls[9]. Liquid first walls may make a fusion reactor commercially viable, but also represent a challenge for plasma sustainment due to feedback to the main plasma from blanket evaporation. This and other challenges must be addressed as part of a program that can transition spheromak research from basic science and concept exploration, to proof of principle ($I_{plasma} \sim 1 - 10$ MA) and performance extension ($I_{plasma} \sim 10$ - 20 MA). Ultimately, the goal is to build a demonstration spheromak reactor that can lead to competitive commercialization of fusion energy.

The highest priority for spheromak viability is finding current drive systems that are compatible with good confinement[10]. Recent development[11] of the NIMROD code[12] has aided efforts at predictive and integrated modeling of spheromak plasmas. Interpretive analysis of computational results and validation against experimental SSPX diagnostic data has increased the confidence in the numerical model, which is being used to find an optimized current drive regime and flux conserver shape that can improve performance with pulsed coaxial helicity injection[1]. As the plasma dynamics and interactions span many orders of magnitude in spatial and temporal scales, any theoretical or computational model must contain simplifications in order to be tractable. Therefore, experimental validation is still required for numerical and theoretical predictions.

Resources: A path to spheromak fusion reactors can be segmented in five-year increments with at least two experimental facilities that can test scaling (i.e. flux conserver size), pulsed drivers (capacitor banks, high power switches, etc.), auxiliary heating (e.g. compact neutral beams), and liquid first walls. The first five years would concentrate on building a concept exploration experiment that will include multi-pulse Thomson scattering, auxiliary heating, and a power system that has flexibility for high rate of helicity injection (with low gun inductance). Concurrent to that effort and in a separate chamber, develop the technical capacity to safely handle liquid metal walls at the flow rate and field required for a proof of principle experiment. The following five years, the liquid metal walls are integrated with a plasma chamber to form a proof of principle experiment that can be sustained (in multi-pulse mode) for 100 ms or more (this allows time for fluid metal effects to equilibrate if jets flow at 50 – 100 m/s). Within this five years, a performance extension can be assessed the last two years of operation. A program that is

mainly managed by academic institutions but also contains collaboration with national laboratories and industry is ideal: the aim is to build scientific but also technical know-how for engineering issues such as pulsed power handling, reactive liquid metal handling, vacuum technology, and plasma-materials interactions. Based on previous innovative confinement concepts (ICCs) funding and achievements, a successful program with enough full time employees as well as academic summer salaries and graduate student support would require at least $10M in the first five years, and likely double that in following five years. An assessment can then follow on the accelerated path to a demonstration reactor.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

Achieving the goal of commercially viable controlled thermonuclear fusion with minimal engineering complexity would be the major impact of this research. This could lead to reactors for electrical generation that are competitive to build when compared to coal or gas-fired plants, but have a much smaller impact on the environment, and have the reliability not found in solar or wind power. A small footprint for a reactor is also important, as the sites and transmission infrastructure of existing nuclear and thermoelectric plants could be repurposed for spheromak reactors. Successful research results (i.e., those that show predictability and understanding of a spheromak reactor) will lower the risk for public and private investment in the concept, making it likely that the program would be picked up and accelerated by private parties. Magnetized, self-organized plasmas are also important in many areas of science, and particularly in astrophysics, where spheromak models can be applied to a wide range of phenomena, from solar prominences[13] and coronal mass ejections to astrophysical jets[14]; physics understanding of these issues could lead to better predictability of space weather near our planet, as well as better interpretation of observations that are used in testing cosmology theories.

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