White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 17, 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	
• Interactions of plasmas and waves	
• Plasma self-organization	P
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

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

Title:	The Importance of Compact Toroidal Plasma Research for Economical Fusion Power
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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 current pathway to net gain fusion power production through the construction of ITER is the primary focus of the fusion community, and will likely continue to be throughout the 2020s. The tokamak concept is currently poised as the most viable candidate for a successful burning plasma; however, it is unclear whether the tokamak will lead to an economically tractable energy source. As a result, it is important to continue research on compact tori (CT) that could prove to be more economical than tokamaks (or stellarators) due to the heavier reliance on plasma currents rather than superconducting coil sets for the generation of magnetic fields. Namely, the elimination of the toroidal field coil set leads to considerable cost reductions due to less superconducting material, but more importantly, the lower neutron shielding requirements on the inboard side that result in a substantially more compact reactor unit.[1] Also, in pursuit of high fusion power densities via high-field, compact tokamaks exhibit considerable $\vec{j} \times \vec{B}$ stresses on the inboard section of the TF coil that must be buttressed with additional structural supports; eliminating the toroidal field coil through the use of a CT plasma configuration ameliorates this issue.[1,2] Additionally, the lower shielding requirements allows for an easily attainable sufficient tritium breeding ratio (TBR) for a closed deuterium-tritium (DT) fuel cycle.[1] All of these strengths of compact toroidal plasma configurations serve as justification for continued research.

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

In order to rely more heavily on plasma currents, which allows for more compact fusion reactor units, it is necessary to employ highly efficient means of current drive that will allow for a sufficiently low recirculating power fraction. Imposed-dynamo current drive (IDCD) is one such promising method that is estimated to be over two orders of magnitude more efficient than RF or NBI-driven current drive.[1,3] IDCD has been used on the HIT-SI device at the University of Washington to sustain kink-stable, high-β spheromak configurations, seemingly overcoming the discouraging sustainment results obtained in the SSPX experiment.[4,5] SSPX required plasma instabilities to generate the necessary non-axisymmetric motion for dynamo current drive during the sustainment phase of the pulse.[5] Instead, non-axisymmetric magnetic fluctuations are externally imposed for IDCD in HIT-SI, and are able to sustain plasma current in steady-state without gross plasma instabilities. The confinement prospects for sustained spheromaks are now more hopeful by overcoming the requirement for plasma instabilities for dynamo current drive.[3,4,6] A reactor vision based on the IDCD mechanism sustaining a stable, high-β spheromak configuration, called the dynomak shown in Figure 1, is estimated to be cost competitive with conventional energy sources.[1] This reactor concept is designed to output 1000 MWe with a toroidal plasma current of 41.7 MA. The total estimated coupled current drive power for IDCD is 58.5 MW, which is a testament to the efficiency of IDCD. A molten-salt blanket made of FLiBe is used for neutron moderation, tritium breeding, and first-wall cooling in a unified, liquid immersion blanket design. Due to the absence of toroidal field coils, the full inboard neutron flux is utilized for tritium breeding; a TBR of 1.125 is obtained without Li-6 enrichment or additional neutron multipliers. The only required superconductors are the equilibrium coils, which are located a considerable distance away from the fusion neutron source, allowing for adequate shielding to enable a 30 full-power-year (FPY) lifetime. Though this reactor is at the conceptual stage and considerable development is required, this is but a single reactor design concept that highlights the benefits of using a CT as the core of a magnetic fusion reactor.

A renewed effort toward the development of compact toroidal plasmas for fusion applications is proposed. Research into low/no externally applied toroidal magnetic field configurations, such as reversed-field pinches (RFPs), spheromaks, and field-reversed configurations (FRCs) are critical for the development of economical fusion energy. Additionally, current drive advancements that are necessary for the success of these devices could be beneficial to the tokamak configuration as well. With more efficient current drive methods, tokamaks could rely on substantially lower bootstrap current fractions than in recent designs[7] while maintaining an acceptable recirculating power fraction, which would allow for considerable control of the current profile. Additionally, it should be noted that entities in the private and/or other public sectors have invested considerable sums of money into spheromaks (General Fusion Inc.), and field-reserved configurations (Helion, Tri-Alpha Energy) because their development costs are lower than tokamaks or stellarators, and they are projected to lead to economical attractive fusion reactors, if successful. There should be a renewed effort into developing alternative confinement schemes by the U.S. DoE OFES as well.

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

The goal of fusion energy research is to bring zero-carbon emitting, clean, and safe energy to the grid to displace conventional energy sources such as coal, natural gas, and fission. The former two energy sources are the hardest to displace because they are the most economical base-load energy sources[8] and have lower barriers to public acceptance than fission. In order to displace them without assuming substantial future carbon taxes or governmental subsidies, fusion must be economically competitive with them. CT plasma configurations provide a possible avenue towards achieving this economical goal, with the dynomak reactor concept as one example. The private sector has also began to realize the benefits of CTs for use in economical fusion development. If we, the fusion community, want to have an impact on slowing or halting anthropogenic climate change in this century, we need to put forth more effort in developing **economical** fusion energy while we construct and participate in the ITER tokamak project.

References (Maximum 1 page)

[1]D.A. Sutherland, et al., The dynomak: An advanced spheromak reactor concept with imposed-dynamo current drive and next-generation nuclear power technologies, *Fus. Eng. Design* **89** (2014) 4, 412-425.

[2]B.N. Sorbom, et al., ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets, *submitted for publication.*

[3]T.R. Jarboe, et al., Imposed-dynamo current drive, *Nucl. Fusion* **52** (2012) 8, 083017.

[4]B.S. Victor, et al., Sustained spheromaks with ideal n = 1 kink stability and pressure confinement, *Phys. Plasmas* 21 (2014) 082504.

[5]B. Hudson, et al., Energy confinement and magnetic field generation in the SSPX spheromak[a)], *Phys. Plasmas* **15** (2008) 056112.

[6]T.R. Jarboe, B.A. Nelson, D.A. Sutherland, A mechanism for the dynamo terms to sustain closed-flux current, including helicity balance, by driving current which crosses the magnetic field, *reviewed favorably and recommended for publication.*

[7]C.E. Kessel, et al., The ARIES Advanced and Conservative Tokamak Power Plant Study, Fus. Sci. Tech. **67** (2015) 1, 1-21.

[8]Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants*, U.S. Energy Information Administration: Independent Statistics and Analysis*, U.S. DoE, April 2013.

Figures (maximum 1 page)

Parameter	Value
R_o [m]	3.75
A [R_o/a]	1.5
I_p [MA]	41.7
n [10^{20} m^{-3}]	1.5
β_{wall} [%]	16.6
$T_{e,o}$ [keV]	20.0
<W_n> [MWm^{-2}]	4.2
TBR	1.125
P_{CD} [MW]	58.5
P_{th} [MW]	2486
P_e [MW]	1000
Q_e – engineering gain	9.5

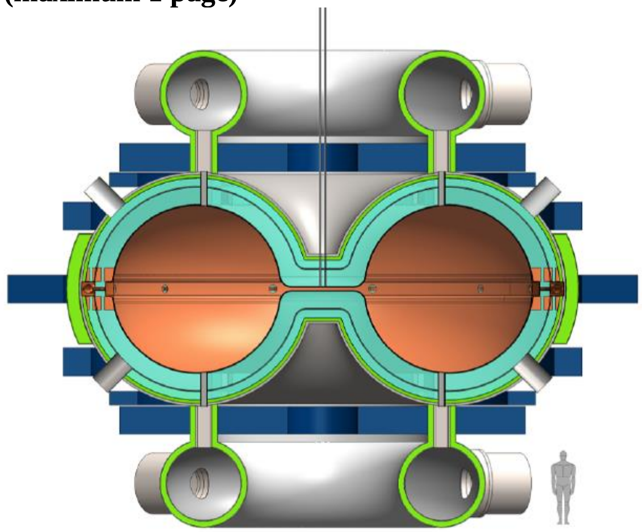

Figure 1: The dynomak fusion reactor concept and corresponding design point. Helicity injectors used for IDCD are located on outboard mid-plane. The use of FLiBe (turquoise) in a liquid immersion blanket system allows for a unified, single working fluid design. Additional neutron shielding (ZrH_2 or TiH_2 in green) is used to protect the superconducting coil set (blue) from fast neutron fluxes to allow for 30 FPY operation; high or low temperature superconductors can be used. ITER-developed cryopumps are connected to toroidal pumping manifolds that have 24 blanket penetrating ducts to remove helium ash. A supercritical CO_2 cycle (not depicted) couples to the primary FLiBe cycle for power generation.