White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***May 19, 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	S
• 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 Grand Challenge of Fusion Power Cheaper than Coal**
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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.**

While the world fusion program is focused on achieving burning plasma, more effort is needed to make fusion power affordable. Coal fired power plants are being installed in China today because they have low capital cost. To have a large environmental impact fusion must beat fossil fuels economically. Fusion needs to be cheaper than coal, which is not the case for tokamak and stellarator based fusion.

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

The recent breakthrough of the efficient, inductive sustainment of a stable[1], high-beta[2] spheromak presents an opportunity to develop economically competitive fusion power. The spheromak reactor should be an order of magnitude cheaper than a tokamak reactor[3] and economically competitive with coal[4]. The surprising discovery is that relaxation (making j-parallel/B uniform) does not require instability or reconnection, but simply magnetic perturbations. Thus, by driving the edge and imposing perturbations, Imposed Dynamo Current Drive (IDCD) sustains stable equilibria. There are high beta

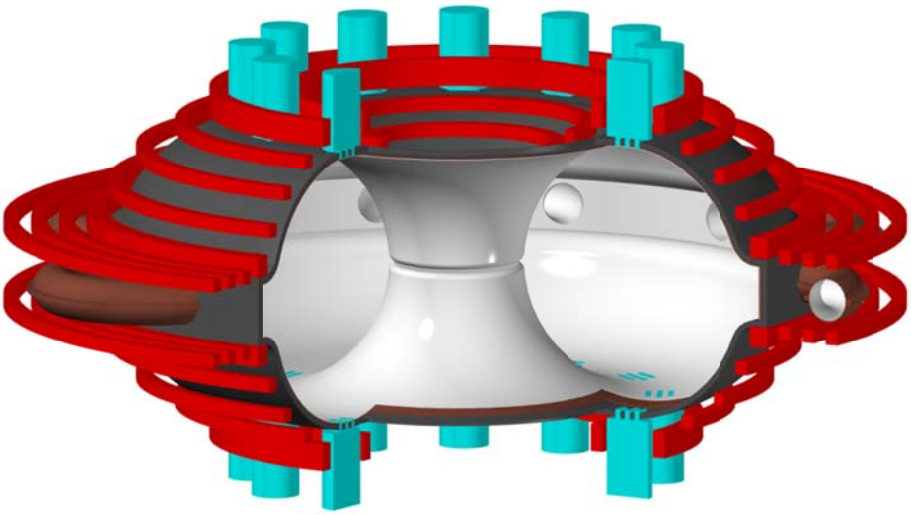
(16%) spheromak equilibria with uniform j-parallel/B that can be stably sustained with IDCD that should have good confinement and lead to a cost effective reactor.

The IDCD model provides an explanation for the level of field error ($\delta B/B = 10^{-4}$) that spoils tokamak performance, for the rate of poloidal flux loss in argon induced disruptions in DIII-D[5], and the change in plasma rotation direction with LHCD in the edge on C-Mod[6]. The toroidal current versus time, the injector impedance, and the current profile data of HIT-SI are predicted by the IDCD model[1].

Helicity injection current drive[7,8] is being pursued because it is orders of magnitude more efficient than RF or beams.[9,10,11] More efficient current drive improves the tokamak and enables the spheromak. If the spheromak can be efficiently sustained with sufficient confinement, economically competitive fusion power is possible[4]. Confinement is sufficient when the plasma heats to its MHD beta limit on current drive power alone. Unsustained, 150 eV-500 eV spheromaks have been produced[12,13] with sufficient confinement[14]. Recently, stable high pressure spheromaks have been sustained with sufficient confinement using imposed dynamo current drive (IDCD), but the density was so high that beta-limits may have prevented them from becoming hot.[1,2,15] Thus, high-temperature confinement was not tested. However, these experiments demonstrate high-beta sustainment with ideal MHD stability, a major breakthrough in spheromak sustainment.

Before HIT-SI, spheromak sustainment experiments used Coaxial Helicity Injection (CHI)[16]. Coaxial electrodes were used to inject helicity that formed and sustained the spheromak in an axisymmetric flux conserver. These experiments produced the necessary magnetic perturbations by driving the equilibria unstable. These sustained spheromaks had very poor confinement because of the instability. To sustain a stable equilibrium, the perturbations must be imposed rather than being generated by plasma instability. HIT-SI was the first experiment to sustain a stable equilibrium by imposing perturbations[1]. At high injector frequency (68.5 kHz), HIT-SI also showed stable sustainment of high-beta (20%)[2]. We have performed a detailed reactor study for this concept and it appears to be economically competitive with present conventional energy sources[4].

The spheromak program is now ready for the next experiment (consistent with Figure 2 on page 384 of the ReNeW report) to test high-temperature confinement with this current drive method. The proposed HIT-SIX experiment is shown below.



Conceptual drawing of the experiment. HIT-SIX has a minor radius of 0.55 m and a major radius 0.825 m. Design plasma current is 1.35 MA with peak temperature of 1 keV. (Equilibrium coils are shown in red, and pumping access locations are shown in cyan.) The fabrication cost of the experiment and power supplies is about $6M.

One issue of spheromak sustainment via CHI to date has been the necessity for closed-flux breaking instabilities for dynamo current drive. The necessity for non-axisymmetric magnetic fluctuations for dynamo current drive is predicated upon Cowling's theorem,[17] which suggests that a steady-state axisymmetric MHD dynamo is impossible. IDCD complies with Cowling's theorem since the magnetic axis is not axisymmetric due to the applied, non-axisymmetric perturbations. Since these non-axisymmetric perturbations are not generated via plasma instabilities, they may be compatible with sufficient confinement quality. Unlike in a tokamak where perturbations cause the profile to evolve toward poorer confinement, in an edge-driven spheromak the perturbations cause the profile to evolve towards better confinement.

The spheromak concept now has formation, sustainment, equilibrium, stability, confinement, (simultaneously demonstrated at low temperature) and economics in hand. No other concept can make this claim. The concept is ready for the next step and DOE should start a spheromak development program. By leveraging this breakthrough the U.S. can leap-frog to the lead in developing economical fusion power.

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

Understanding HIT-SI's achievement of the efficient, inductive sustainment of a stable, high-beta, spheromak will have an impact on plasma science. The societal benefit of replacing coal with fusion would be great.

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