White Paper for *Frontiers of Plasma Science Panel*

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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	P
• Turbulence and transport	P
• Interactions of plasmas and waves	
• Plasma self-organization	P
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

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Oral	
Poster	
Either Oral or Poster	

Title:	Determining the optimum magnetic configuration for confinement of a fusion plasma: perspective of the EPR workshop Executive Committee
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Introduction and political background: The work described in this white paper derives from projects in universities, national laboratories, and private industry that are regularly represented at the Exploratory Plasma Research (EPR) workshops. The authors of this white paper are members of the standing EPR Executive Committee. The EPR workshop began as the Innovative Confinement Concepts (ICC) workshop, which was dominated by work funded through OFES. The name of the workshop was recently changed in part to better reflect the broad scope of the work presented, ranging from fusion energy development to fundamental plasma science. OFES funding for work in this area has dropped substantially, such that some projects have been terminated, and opportunities for new projects are very limited. Hence, much high-quality fusion and plasma science research is being left on the table. New funding for projects in the EPR workshop portfolio has been added by ARPA-E and by private investors (e.g., Tri Alpha Energy). This is positive for fusion energy development, and advances in plasma science will no doubt result as well. But the advancement of plasma science, per se, is not a primary goal of ARPA-E or of private investors, and research results generated from private investment is sometimes proprietary. Hence, there remains a strong need for OFES, and NSF, to be stewards of a healthy plasma science research program.

The research frontier and importance of the scientific challenge: There is no single magnetic fusion plasma configuration that as yet represents *the* approach to the viable, reliable production of fusion energy. All present configurations, including the internationally dominant tokamak and stellarator, have their own outstanding challenges. And fusion science presently lacks the capability to predict what configuration, or combination of configurations, will be best suited for the production of fusion energy. This white paper focuses on magnetic confinement, but a similar statement can be made about laser-based inertial confinement fusion in the field of high-energy-density laboratory plasmas.

The approach to advancing the frontier and new research tools/capabilities required: Achieving true predictive capability for magnetic fusion science demands the exploration and understanding of a broad portfolio of magnetic configurations, for example, the field-reversed configuration (FRC), levitated dipole, reversed-field pinch (RFP), spheromak, stellarator, tokamak, and z-pinch. These configurations entail a broad range of fundamental variables, such as magnetic field geometry and applied magnetic field strength. The plasmas in these configurations must be well diagnosed, and measurements must be coupled to theory and validated computational models. And in the fusion energy development context, it is not only plasma-related quantities that are important, but also the material boundary, including its impact on the plasma and its ability to handle fusion-reactor-scale power and particle exhaust. This all entails support for an array of small-to-medium-scale facilities that will serve the synergistic goals of advancing fusion energy development and plasma science. We note in this context that projects funded by ARPA-E could in principle be leveraged by OFES and NSF.

Below we map onto three of the five panel-topical areas *a sampling* of frontier plasma science that underlies optimization of the magnetic configuration. Other examples, including contributions to Panel 3 (Interactions of plasmas and waves), appear in white papers submitted separately by other members of the EPR workshop community. And note that while the most logical entry point for this white paper in the Town Hall meeting is Exploratory Magnetic Confinement, other topical areas, e.g., Theory and Computation, High-Energy-Density Physics, and Astrophysical and Space Plasmas have strong connections to portions of the EPR portfolio as well.

Impact on plasma science and related disciplines and any potential for societal benefit: The work described herein will, of course, bring about advances in terrestrial plasma science, but it can, with dedicated effort, also help to advance the science of plasmas in space and astrophysical settings. Additionally, the work described herein provides excellent educational and training opportunities for undergraduate and graduate students, and postdocs. Typically, bright, hard-driving students and postdocs work on cutting-edge problems in experimental, theoretical, and computational plasma science.

Panel 1 -- Plasma atomic physics and the interface with chemistry and biology: How does the material surrounding a magnetically confined plasma affect the plasma, and how can this material be optimized for maximum fusion plasma performance? It is well established in tokamak plasmas that control of fuel-gas recycling and impurity influx can have a powerful impact on the plasma, e.g., leading to the production of H-mode [1]. Boundary control in the tokamak has entailed techniques such as divertors and wall coating, all with solid-state plasma-facing materials. And such techniques have been successfully applied in other configurations, contributing, for example to the recent production of world-record FRC plasmas [2]. These results are compelling, but the complicated mix of plasma and atomic physics in the plasma periphery, and the impact of this physics on the bulk plasma, is still not entirely understood. But of even greater importance is the uncertainty in the suitability of any solid-state plasma-facing material for a fusion reactor environment [3]. This uncertainty has motivated work on a liquid-metal plasma-facing boundary, in the tokamak. With partial coverage of a solid-state wall by (stationary) liquid lithium, the rate of energy loss is decreased ten-fold relative to plasmas surrounded by a solid-state lithium coating [4]. The next major goal in this work is to examine the feasibility of flowing liquid metal at the boundary, a very large challenge, but one with potentially large benefits. And, in principle, a liquid metal boundary

could benefit other configurations as well, including those in magneto-inertial fusion. In many EPR devices, the plasma-facing boundary is rather primitive, and particularly in the case of some self-organized configurations, in which turbulence and transport are governed by the shape of the plasma current and resistivity profiles, a liquid metal boundary could have a profound impact. Furthermore, implementation of a low-recycling lithium boundary (liquid, or even just solid) should enable tests of novel confinement concepts on a smaller scale than would otherwise be feasible. With a standard boundary, recycled neutrals are plentiful and readily penetrate the core of lower-density, smaller-scale plasmas, causing charge-exchange loss to be substantial throughout the plasma. Such loss occurs only in the periphery of larger-scale plasmas.

Panel 2 -- Turbulence and transport: What is the character and impact on the plasma of micro-scale instabilities in magnetic configurations substantially different from the tokamak? Micro-instability on the gyro-orbit spatial scale has been studied, with gyro-kinetic models, for decades in the tokamak, which is a 2D axisymmetric configuration with a large applied toroidal magnetic field. But these instabilities are now being studied in other magnetic geometries, including the stellarator, which entails a strong, externally applied 3D magnetic field, and the RFP, another 2D configuration characterized by a small applied toroidal field but large magnetic shear. This ongoing work contributes in a powerful way to the predictive capability of fusion science. There are a number of variations of the stellarator geometry worldwide, including quasi-helical symmetry. In this particular configuration, turbulent transport is dominant throughout the plasma, and this transport turns out to be driven, at least in part, by a tokamak-like micro-instability resulting from the gradient in the electron temperature, but this is subject to further nonlinear modeling [5]. In the RFP, when current-gradient-driven global magnetic tearing instabilities are suppressed, local micro-instabilities becomes important, driven either by the local density gradient or ion temperature gradient, depending on the details of the equilibrium [6]. These instabilities once again are grossly similar to what is observed in the tokamak, but the critical gradients for the onset of these instabilities are found to be greater by roughly a factor of the toroidal aspect ratio. Transport in these plasmas is not yet well understood, however, with small-amplitude, localized residual magnetic fluctuations suspected of playing an important role. Work on this problem continues.

Panel 5 -- Plasma self-organization: How can magnetically-self-organized plasmas contribute to the predictive capability of fusion science? One important means is through the validation of 3D, nonlinear visco-resistive MHD codes. All magnetic fusion plasma configurations are self-organized to some extent, with various gradient-driven instabilities altering profiles of, e.g., plasma current, magnetic field, or kinetic quantities. But some configurations owe their existence to self organization, e.g., the spheromak and RFP. This magnetic self organization is reasonably well modeled by 3D, nonlinear, visco-resistive MHD, and these configurations have in fact been key drivers in the development of MHD codes. Validation in the context described here is rigorous and demanding, entailing detailed quantitative comparisons of experiment to computation, with metrics defined to quantitatively characterize a code's ability or inability to model experimental data. This also requires one to stretch the experimental-modeled parameter space as far as one can. Only thus can one attempt to determine the predictive capability of a given code in a parameter space occupied only by future devices. In a limited sense, validation of MHD codes has been occurring for decades with numerous, but often qualitative, comparisons of code results to experimental data. Validation in the sense described here is an emerging area of plasma science. Validation in the spheromak has entailed comparison of experimental and MHD model data in a case where the spheromak is driven inductively by two oscillating helicity injectors [7]. In the RFP, data has thus far been compared at a particular value of the Lundquist number, including effects like impulsive magnetic reconnection, magnetic stochasticity, and strong nonlinearity [8]. In both cases, there are data that agree well between code and experiment, but there are some data that disagree. Work is ongoing to quantify and understand the areas of disagreement. Work such as this is only a small step in the right direction. Much greater effort is required over as broad a configuration and parameter space as possible.

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[7] C. Hansen *et al*., Phys. Plasmas **22**, 056105 (2015).
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