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.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	S
• Turbulence and transport	S
• Interactions of plasmas and waves	S
• Plasma self-organization	P
• Statistical mechanics of plasmas	

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	"X"
Oral	X
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Title:	Achieving an Ohmically Heated Plasma for Fusion Energy
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1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

- ***The research frontier, importance of the scientific challenge, and impact***

The opportunity for achieving an ohmically heated fusion reactor plasma is a frontier for plasma and fusion physics, with three important contexts:

1. *Heating a fusion plasma to burning conditions without rf or neutral beam power sources*
2. *Advancing the predictive understanding for magnetic confinement of hot plasmas*
3. *Advancing the physics and multi-scale modeling of self-organized plasmas for both basic and applied plasma science*

These contexts are closely associated with "exploratory magnetic confinement" elements of the FES portfolio, and the science opportunities are crosscutting for at least 4 of 5 of the Workshop Panels. They are also part of a more general frontier of multi-configuration magnetic confinement research.

Frontier Context 1: A tokamak-based fusion reactor plasma is anticipated to be heated and controlled to burn conditions using rf, likely a combination of cyclotron heating and lower-hybrid current drive [1]. While present-day experiments employ neutral beam injection, the 1-2 MeV neutral energy required for a large, dense fusion plasma plus unavoidable large holes in the wall and blanket make NBI extremely

challenging in a reactor. The rf antennas must be located close to the plasma for efficient coupling of ion cyclotron and lower hybrid waves, but the antenna boundary conditions are very different than for the majority of the plasma-material surface which must accommodate intense heat, particle, and neutron fluxes. If the antennas do not operate with high reliability and low maintenance, an energy source with high availability is not possible. Robust rf heating and control is a critical gap for fusion development [2].

Ohmic dissipation is a simpler and maximally efficient means of heating a current-carrying toroidal plasma. Furthermore, the material boundary is invisible to a low frequency inductive electric field, even metals with insulating breaks. Ohmic heating is small in a tokamak (or stellarator), since the plasma current is limited by safety factor $q(r)>1$, but it is the only alternative if rf and NBI prove too challenging. The reversed field pinch (RFP) and spheromak configurations have large plasma current and smaller toroidal field, with $q(r)<1$. Figure 1 illustrates the required energy confinement for an ohmically heated RFP with fusion parameters similar to the ARIES-AT [1] tokamak reactor design. Ohmic ignition and high fusion gain are possible without auxiliary heating if the confinement is similar to a same-size tokamak [3]. Hence the first-wall may be covered entirely by suitable fusion-relevant materials. While tokamak-like confinement is observed in present-day RFP experiments [4], key questions are what mechanism(s) govern transport and how do they scale? These can be resolved with larger, higher current experiments, which correspond to higher magnetic field in poloidal-field-dominated configurations [5,6].

Frontier Context 2: A combination of mature basic understanding, well-diagnosed experiments, and ever-increasing computational capabilities sets the stage for rapid progress in predictive fusion science. Arguably the highest priority issue for fusion energy is convincing the world its science foundations are predictive, so that successive development steps are trustworthy. By definition, "predictive" implies an understanding of the plasma's behavior when changing key variables. The various named configurations (tokamak, stellarator, RFP, etc.) are really one grand experiment in which the fundamental variables that govern magnetic confinement are set differently, because it is impractical to do this in a single laboratory setting. The frontier for predictive fusion science should embrace multiple configurations as close cousins, not just view them as competitors for fusion. The behavior of axisymmetric plasmas with large current and dominant poloidal field is synonymous with ohmic ignition in this context. For example, the RFP's set of variables simplifies some challenges, like heating and energetic particle confinement [7], but complicates others, like current-driven instability and stochastic transport [8]. Importantly, the base plasma models are the same for all configurations so that these physics and technological tradeoffs can be understood, even allowing the possibility for optimized configurations yet to be discovered.

Frontier Context 3: The self-organization of RFP and spheromak plasmas is both beautiful and practical. The basic science and astrophysical connections to such plasmas are elaborated in a separate white paper by M. Nornberg et al. and others on dynamo and magnetic reconnection. Here we emphasize the practical implication. While pulsed-current fusion scenarios are likely possible, the default on-off cycle for induction creates unwanted challenges. The magnetic self-organization behavior in the RFP and spheromak happens through nonlinear processes that enable rectification of an ac inductive electric field to create dc plasma current (a.k.a. helicity injection). Hence the plasma current could be sustained indefinitely by induction with ohmic efficiency. In the RFP this idea shows good promise in MHD computation [9] and experiments [10,11], but these studies also reveal that a larger, hotter, lower resistance plasma than any existing is necessary to reduce ac equilibrium modulation and validate the concept.

The arguments above support a more general frontier for multi-configuration research that can help resolve two key concerns for the future of fusion energy: (1) Due to the cost and complexity of steps toward a fusion reactor, extrapolation beyond those parameter ranges with experimental basis on any particular development path appears unavoidable. Maximizing understanding through research that adjusts the basic variables of magnetic confinement is much more likely to provide predictive fusion science than for research restricted to the narrow ranges that define the tokamak configuration. This is the case even if the ultimate fusion reactor configuration is similar to the present-day tokamak. (2) The large

technological gap between present-day experiments and a GW fusion power source implies the challenges have yet to be fully articulated. A fusion energy source must operate robustly for millions of seconds without major maintenance and repair to attain high availability required for an economically competitive power source. The unavoidable physics and technology tradeoffs required to address specific challenges and develop optimized magnetic configurations are more likely to succeed if they are based on predictive understanding that spans magnetic configuration space.

Following are example opportunities from the RFP mapped to the Workshop's crosscutting organization:

Plasma Self-Organization:
– Self-organization through several processes on multiple scales: reconnection, dynamo-like flux conversion, coupled ion-electron momentum transport, powerful particle energization, and turbulence
– Nonlinear extended (two-fluid) MHD physics [12] and a pressing need for multi-scale modeling
– Basic, astrophysical, and fusion contexts [13]
Turbulence and Transport:
– Heat, particle, and momentum transport from magnetic [8,14,15] and electrostatic [16] turbulence
– Micro-turbulence and gyro-kinetic modeling for B_p-dominated configurations [17]
– Tearing-driven turbulent cascade with Alfvenic and drift wave characteristics [18]
Interactions of Plasmas and Waves:
– Dynamics of multiple tearing modes with intense nonlinear interaction [12]
– Non-collisional particle energization [19,20] associated with reconnection and turbulent cascade [18]
– Complementary environment for energetic ion interactions and Alfvenic mode excitation [7,21-23]
Plasma Atomic Physics and the Interface with Chemistry and Biology
– Atomic-physics-based advanced diagnostic applications/development for basic and fusion plasmas
– Control of particles and heat in poloidal field dominated plasmas, possibly liquid metal surface

- ***Approach to advancing the frontier and the required new research tools and capabilities.***

A combination of experiment, theory, and computation is essential. Here we emphasize the RFP program, which consists of the MST experiment at UW-Madison plus four other RFP experiments worldwide. A summary of the RFP program is available in the white paper prepared for the 2014 FESAC strategic planning process [24]. The MST is a medium-scale user facility in the sense that about 20 groups and 60 scientists take advantage of the facility. It is well known for student and postdoc training. It is special not only as one of few RFP experiments but also in possessing a highly capable set of advanced plasma diagnostics. MST plasmas are hot, with Lundquist number $S \sim 10^{5\text{-}7}$, but the device design and scale of operation make it well suited for thorough diagnosis of critical parameters and processes. While a few additional diagnostics are needed, especially for studies of energetic particle interactions associated with MST's 1 MW NBI, the addition of a programmable power supply is the most important facility upgrade needed to maximize MST's current and inductive capabilities.

The RFP and spheromak plasmas have been major drivers for the development of theoretical and computational nonlinear visco-resistive MHD. These models are now being extended to include essential two-fluid physics [12]. An emerging area ripe for broad impact is gyrokinetic studies of the RFP [17]. This is motivated by improved-confinement regimes for which microturbulence likely plays a greater role in transport. Intriguingly it may also be important for the turbulent cascade in the "standard" RFP, which does not appear to be purely Alfvenic. A grand challenge shared by the RFP is modeling that encompasses the global tearing scale to the ion gyroradius scale, with capabilities to study physics likely to explain intense particle heating. How best to approach this is an intriguing frontier in plasma modeling, e.g., start from the global scale and work "down", or start with kinetic tools like PIC and work "up"?

While the existing set of RFP experiments are capable, including the new KTX facility at USTC in Hefei, China of comparable dimensions to MST and RFX-Mod (Italy), research over the past decade clearly points to the need for a future larger size and current experiment to resolve key science issues. This has been discussed in depth for the FESAC Toroidal Alternates Panel [5] and MFE ReNeW [6].

References

[1] *The ARIES-AT Advanced Tokamak, Advanced Technology Fusion Power Plant*, F. Najmabadi et al., Fusion Engineering and Design **80**, 3 (2006)

[2] *Priorities, Gaps and Opportunites: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy*, http://science.energy.gov/~/media/fes/fesac/pdf/2007/Fesac_planning_report.pdf

[3] J.P. Christiansen and K.V. Roberts, Nucl. Fusion **22**, 77 (1982)

[4] *Tokamak-like confinement at a high beta and low toroidal field in the MST Reversed Field Pinch*, J.S. Sarff et al., Nucl. Fusion **43**, 1684 (2003)

[5] *FESAC Toroidal Alternates Panel Final Report*, (2008) http://fusion.gat.com/tap/final_report.php

[6] *Magnetic Fusion Energy Sciences ReNeW Workshop Report*, (2009) http://science.energy.gov/fes/news-and-resources/workshop-reports

[7] *Fast ion confinement and stability in a neutral beam injected reversed field pinch*, J.K. Anderson et al., Phys. Plasmas **20**, 056102 (2013)

[8] *Experimental Evidence for a Reduction in Electron Thermal Diffusion due to Trapped Particles*, J.A. Reusch et al., Phys. Rev. Lett. **107**, 155002 (2011)

[9] *The three-dimensional magnetohydrodynamics of ac helicity injection in the reversed field pinch*, F. Ebrahimi et al., Phys. Plasmas **10**, 999 (2003)

[10] *Oscillating-Field Current-Drive Experiments in a Reversed Field Pinch*, K.J. McCollam et al., Phys. Rev. Lett. **96**, 035003 (2006)

[11] *Equilibrium evolution in oscillating-field current-drive experiments* , K.J. McCollam et al., Phys. Plasmas **17**, 082506 (2010)

[12] *First-order finite-Larmor-radius fluid modeling of tearing and relaxation in a plasma pinch*, J.R. King et al., Phys. Plasmas **19**, 055905 (2012)

[13] See, for example, http://cmso.uchicago.edu/overview.php

[14] *Magnetic-Fluctuation-Induced Particle Transport and Density Relaxation in a High-Temperature Plasma*, W.X. Ding et al., Phys. Rev. Lett. **103**, (2009)

[15] *Kinetic Stress and Intrinsic Flow in a Toroidal Plasma* , W.X. Ding et al., Phys. Rev. Lett. **110**, 065008 (2013)

[16] *Core Electrostatic Fluctuations and Particle Transport in a Reversed-Field Pinch*, J. Lei et al., Phys. Rev. Lett. **89**, 275001 (2002)

[17] *Microturbulence studies of pulsed poloidal current drive discharges in the reversed field pinch,* D. Carmody et al., Phys. Plasmas **22**, 012504 (2015)

[18] *Experimental Observation of Anisotropic Magnetic Turbulence in a Reversed Field Pinch Plasma*, Y. Ren et al., Phys. Rev. Lett **107**, 195002 (2011)

[19] *Anisotropic Ion Heating and Tail Generation during Tearing Mode Magnetic Reconnection in a High-Temperature Plasma*, R.M. Magee et al., Phys. Rev. Let **107**, 065005 (2011)

[20] *Charge-to-mass-ratio-dependent ion heating during magnetic reconnection in the MST RFP*, S.T.A. Kumar et al., Phys. Plasmas **20**, 056501 (2013)

[21] *Fast-Particle-Driven Alfvenic Modes in a Reversed Field Pinch*, J.J. Koliner et al., Phys. Rev. Lett. **109**, 115003 (2012)

[22] *Energetic-particle-driven instabilities and induced fast-ion transport in a reversed field pinch*, L. Lin et al., Phys. Plasmas **21**, 056104 (2015)

[23] *Runaway of energetic test ions in a toroidal plasma*, S. Eilerman et al., Phys. Plasmas **22**, 020702 (2015)

[24] *Opportunities and Context for Reversed Field Pinch Research*, (2014) http://plasma.physics.wisc.edu/uploadedfiles/misc_presentations/FESAC-SPpaper-Sarff-sm.pdf

[25] *The TITAN reversed-field pinch reactor study*, F. Najmabadi and R.W. Conn, UCLA-PPG-1200 (1990); also http://aries.ucsd.edu/ARIES/DOCS/TITAN/bib.shtml

Figures

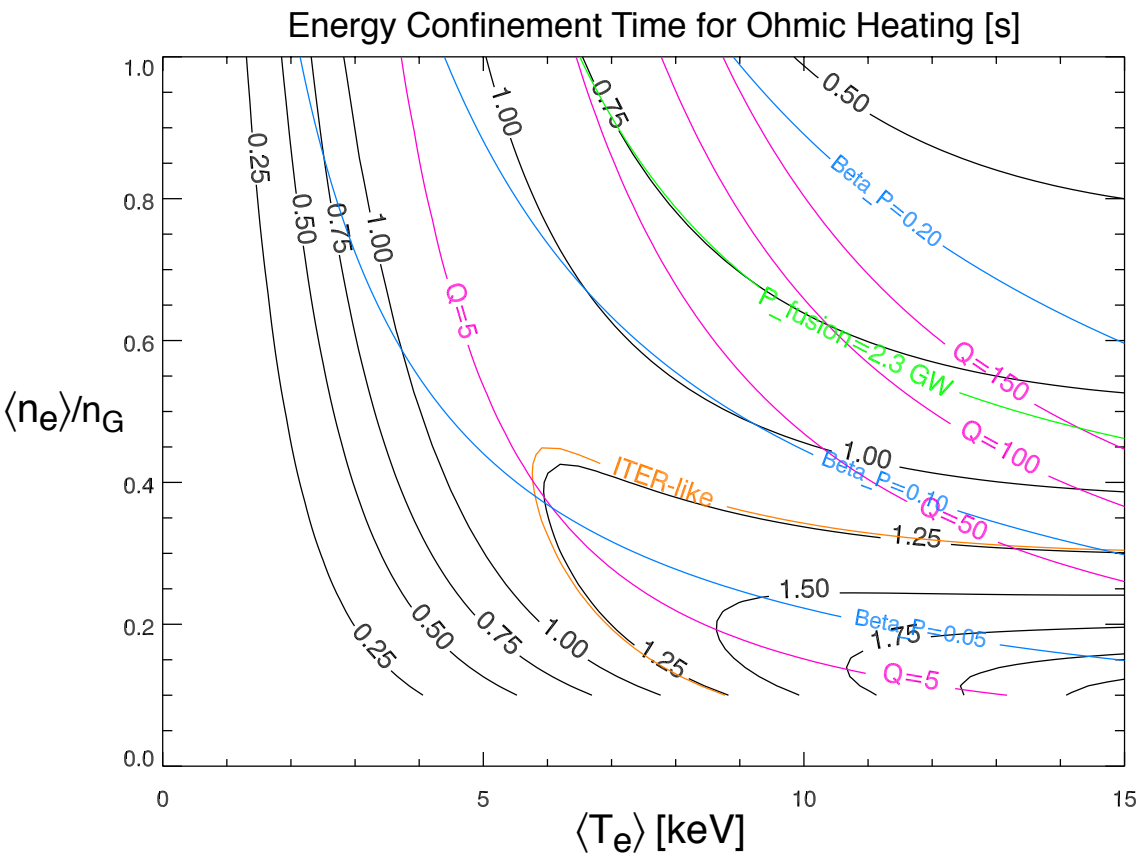

Fig. 1: Contour plot of the global energy confinement time, τ_E [s], required to achieve a given temperature and density for an ohmically heated RFP plasma. Density is normalized to the empirical limit, $n_G=I_p/\pi a^2$. A Lawson-like power balance similar to the analysis in reference [3] is employed but with parameters and plasma profiles informed by present-day RFP experiments and modeling (listed below). The plasma size and current are chosen to yield a neutron flux of P_n/A=5 MW/m^2 for P_f = 2.3 GW, similar to ARIES studies [1]. (The most recent RFP system study is TITAN, also with P_f = 2.3 GW [25].) The minimum $\tau_E \approx 1.2$ s for ohmic ignition is at the saddle point $\langle T_e \rangle \approx 5$ keV where $P_\Omega \approx 70$ MW for the parameters below. For reference, the value of τ_E labeled "ITER-like" is an estimate for confinement in a same-size tokamak plasma implied by scaling $\langle \chi \rangle \approx 4\kappa a^2/\tau_E$, where κ is the elongation. Contours for the fusion gain, $Q=P_f/P_\Omega$, and poloidal beta, $\beta_P = 2\mu_0\langle p \rangle/B_P^2(a)$, are also shown. Parameters and profiles for the power balance calculation: a=1.53 m, R/a=4, I_p=30 MA, $J_\parallel/B \sim 1-(r/a)^{3.5}$, $\langle B \rangle$=5.6 T, $B(a)$=3.9 T, $B_{coil} \approx 3$ T, $n(r) = n_0\{0.98[1-(r/a)^8]+0.02\}$, $T_{e,i} = T_0[1-(r/a)^2]+0.3$ keV, Z_{eff}=2, and collisionality-dependent trapped-electron resistivity enhancement (~1.7X).