Role of Theory in Addressing RFP Physics Issues

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I. General Considerations

This paper is organized by the RFP physics issues called out in the recent Toroidal Alternates Panel (TAP) report. That report was focused the development path of the major toroidal alternates as stand-alone fusion concepts, including the RFP. In many ways this is an appropriate starting point for the considerations of this paper. However, the narrow programmatic focus does not do justice to the important contributions that the RFP can make to magnetic confinement understanding in a general way as a highly complementary approach to that of tokamaks and stellarators. As a relaxed state device, the RFP has complementary physical processes to those of tokamaks and stellarators, which have strong external constraints. At the same time, however, it has a magnetically confined plasma subject to the usual issues of confinement, discharge sustainment, boundary interactions, etc. The RFP can therefore provide a broader picture of governing physics, extending the physics of any key process like core density peaking or momentum transport from a situation dominated by localized electrostatic fluctuations to one dominated by global magnetic fluctuations. It also provides crucial information on performance relative to the question of where an ideal magnetic confinement configuration might position itself in a parameter space that ranges from highly constrained to unconstrained. Because these considerations span different experimental devices, theory is absolutely essential for making these connections. While this paper is organized along the topical lines of the TAP report, connections with broader magnetic confinement issues are called out where appropriate. Both analytic theory and computation are important for progress, as described below.

II. Physics Issues

TAP Tier 1

<u>A. Identify transport mechanisms and establish confinement scaling</u>

• How does stochastic transport decrease as a function of Lundquist number *S*?

Heat loss associated with particle streaming along stochastic fields dominates global transport in normal RFP discharges. Simple theoretical considerations predict a robust decrease in this transport as the Lundquist number *S* increases in hotter discharges. Experimentally, a decrease is observed, but it is much weaker than the prediction. The reasons for the discrepancy are not understood. A better understanding of stochastic regions in plasmas and the transport produced is required to address this issue. This includes a better theoretical description of the finite amplitude (finite island width) fluctuations in the turbulent spectrum, particularly as fluctuations change from global unstable tearing modes to stable, localized drift Alfvén fluctuations as the scale becomes smaller. The two-fluid effects associated with this transformation modify reconnection and lead to drifts, which in turn affect the macroscopic fluctuations spectrum and its scaling with *S*. Analytic theory can examine self-consistent transport associated with fluctuating magnetic fields. Wave particle resonances are important because the mean free path is long, and it is important to establish how they operate in situations with and without island overlap. It is crucial to consider both ion and electron behavior, the resulting self-consistent electric potential, and coupling to EXB rotation. This physics points to the need for developing kinetic computation capabilities that are compatible with the larger scale fluid physics of tearing modes. Recent observations point to the need to study transport in transient events such as sawtooth oscillations. Advances in understanding are also possible by addressing the statistical nature of the transport, i.e., sub-diffusive vs. super-diffusive transport. Axisymmetric shaping should be considered as it may help localized reconnection by pushing modes to *m* values greater than unity. This area is highly relevant to the physics of resonant magnetic perturbations in tokamaks.

• What is the nature of the single helicity state and its transport scalings?

A single helicity state with improved confinement characteristics may be possible in the RFP. Theory is required to characterize and understand observations pointing to this possibility. This includes understanding the role of dissipation (Hartman number) in transitions from multiple helicity to quasi single helicity spectra; understanding the mechanism that appears to decouple the single helicity perturbation from other fluctuations in the magnetic spectrum, and the temporal duration of single helicity and multiple helicity phases; and understanding the apparent current threshold condition. The possibility of an analog to the H mode transition involving magnetic field shear and refraction of Alfvénic fluctuations allows analytic theory approaches like those developed for tokamaks. Single helicity states can be calculated with the stellarator code VMEC and can probably be optimized to eliminate stochastic regions using CAS3D. In this calculation it is important to optimize non-axisymmetric neo-classical transport. Macroscopic simulation with codes will be very useful in determining when these states do and do not occur and how mode coupling changes during the transition.

• What is the residual transport and its scaling after reducing stochastic transport?

If stochastic transport is reduced sufficiently by profile control techniques other transport processes will likely emerge. How do these relate to the electrostatic drift wave fluctuations that govern transport in the tokamak? Gyrokinetic codes are currently being adapted to the RFP configuration to allow investigation of ion temperature gradient turbulence and related fluctuations. Analysis of computational and analytic results will show how key RFP features affect the transport. These include bad field line curvature everywhere, the shorter connection length and its enhancement of the role of $k_{\parallel}$, negative magnetic shear, q smaller than unity, and finite beta. Once the dominant residual transport mechanism is identified it may be possible to extend the kinds of theory developed for tokamaks to address potential control mechanisms like those present in the H mode and ITBs.

• What is the physics of rotation and momentum transport in the RFP?

Like tokamaks, the RFP has spontaneous rotation. Global tearing modes are known to exert torques through the Lorentz force, but a complete picture of how the rotation profile is set is not available. This can be explored analytically through calculations of constrained relaxation including flows, diamagnetic effects in tearing modes, and calculations of Reynolds and Maxwell stresses with quasilinear and nonlinear theory. Rotation and momentum transport in smaller scale drift wave fluctuations can also be explored. The synergy of these calculations will answer questions like the following. What are the relative roles in rotation and momentum transport of electromagnetic versus electrostatic fluctuations, of global versus local fluctuations, of edge versus core physics? What is the connection between momentum transport and other transport channels? What happens to rotation in the RFP with current profile control?

• What physics governs the magnetic fluctuation spectrum?

The magnetic fluctuation spectrum is understood to result from unstable global tearing modes, and resistive MHD simulation has provided a reasonable understanding of many aspects of the long wavelength part of the spectrum. Questions, such as transport scaling with increasing S, and the role of two fluid and kinetic effects remain. Moreover many details of this process are not well understood, particularly with regard to the coupling to smaller wavelengths and the physics of that part of the spectrum. What is the saturation mechanism of unstable tearing modes in the experimental plasma? What is the relative role of current profile flattening (mostly a long wavelength process) versus wavenumber cascade (a short wavelength process)? How does this change during the sawtooth cycle? What sets the width of magnetic islands? What is the appropriate description for smaller scale fluctuations in the spectrum. How is energy dissipated? How does this relate to ion heating? Do smaller scale fluctuations have any effect on global transport scalings? Many of these questions can be addressed by analytic theory. It would also be highly valuable for a multiscale computational capability that could bridge the global tearing modes and smaller scale fluctuations, and possibly treat kinetic damping mechanisms.

• What is the mechanism for anomalous ion heating in the RFP?

Anomalous ion heating is a long-standing feature of RFP discharges. It is an alpha channeling mechanism because it takes electron-channel Ohmic energy and puts it in ions, preferentially heating minority impurity species. Because this mechanism is not understood, it is not known whether it could operate in reactor conditions. There are numerous theories for ion heating. A theoretical effort is needed to calculate predictable quantitative consequences for each theory, so that a determination can be made as to which theory is valid. Virtually all theories are analytical, hence, computation is needed to model the mechanisms.

<u>B. Understand the physics of current sustainment in the RFP</u>

• Can oscillating field current drive (OFCD) supply 100% of the plasma current?

Experimental tests of OFCD have demonstrated that a net mean current can be driven (to date, 10% of the total current). MHD computational studies with Lundquist number $\sim 10^5$ have been performed that demonstrate 100% current drive, bolstering the theoretical foundation. To keep the AC modulation of the magnetic equilibrium small, it is anticipated that the Lundquist number will need to be of order 10^7 or 10^8 for a 100% OFCD current drive experiment. In this regime effects beyond MHD could be important, and it is therefore important to extend computation to include two-fluid effects, even at lower Lundquist number. Computation can determine if it is possible to drive 100% of the current in this fashion, and if so, what are the nature and confinement properties of the discharge.

• Are there any other means for current sustainment

The possibility of RF wave injection in the RFP is being assessed for current profile control and current drive. Numerical computation has played an important role in developing antenna configurations and tracking wave propagation, absorption, and mode conversion. Although RF current drive is expected to be too inefficient to support a large fraction of the plasma current in a fusion reactor, it could be a useful tool for profile control to reduce the level of transport associated with tearing fluctuations. Even for this, the larger current in the RFP makes this challenging. A critical question, then, is to understand how much non-inductive current must be provided to reduce fluctuations to a level consistent with energy confinement requirements. Theory could be a cost effective way of exploring novel potential solutions to these obstacles. One recently recognized possibility to attain current profile control in an Ohmic RFP is to employ helical shaping. With toroidal induction, the helical field component causes the generation of poloidal current that broadens the current profile to improve its tearing stability. Codes such as VMEC can be used to investigate this possibility. Analysis of the stability and nonlinear evolution of tearing modes requires codes that do not exploit toroidal symmetry, including those used for most RFP research to date.

<u>C. Integration of current sustainment and improved confinement</u>

• Can good confinement be maintained during 100% current drive?

Current driven at the plasma surface requires a relaxation process to reach the magnetic axis, and will yield at best a flat $j_{||}/B$ profile. (OFCD does not drive a surface current, per se, although it does tend to drive current more in the outer region than for steady induction. Simulations show that OFCD works not too differently in the MHD model.) For penetration of a surface current, magnetic surfaces will be broken if the process is governed by low frequency fluid responses. Theory and computation can answer to what extent this process degrades heat and particle transport. It can also address whether non MHD fluctuations can relax the current, when such fluctuations might control the process, and how they affect heat and particle transport. It is also important to examine whether regions of relaxation near the edge can be sufficiently localized to prevent wall damage.

• Is a hybrid scenario of OFCD and current ramp-down required and possible?

This scenario may compensate for drawbacks associated with OFCD in the steady state. This question is amenable to computation and should be pursued.

• Can the current profile be controlled efficiently in steady state?

Current profile control is more likely to be achieved than 100% current drive. However the issues mentioned above still apply and will need to be investigated as described above.

TAP Tier 2

D. Plasma boundary interactions

• To what extent is RFP boundary physics like that of the tokamak?

The RFP boundary has not been carefully studied. However, fluctuation measurements suggest the possibility that, like the tokamak, the boundary region is governed by different physics and processes than those of the core. A key question looking forward is whether RFP boundary physics is compatible with divertors. The boundary is accessible to probes and offers the possibility of more detailed comparison with theory. Theory must determine what mechanism dominates transport in the boundary region. Is the transport bursty as it is in a tokamak? Is this related to core transport, or is there an edge mechanism responsible for the intermittent production of blob-like fluctuations? What is the role of the edge shear layer on different fluctuations that are present in the edge, or linearly unstable in absence of shear? What happens to the shear layer if there is a divertor? How far can conducting walls and active feedback coils be from the plasma? Can a high central to edge temperature be sustained? How does the island overlap, but small magnetic fluctuation level associated with the edge q profile, affect edge properties? Can this provide useful information on the physics of resonant magnetic perturbations for ELM control in tokamaks? Some of these questions can be addressed with simple edge relevant models and analytic theory. Codes with flexible geometry and two fluid physics like NIMROD could also be adapted to the RFP edge configuration. To study divertor questions it may be advantageous to develop special purpose codes.

• Does the short connection length make significant differences?

It can be anticipated that the short connection length will make divertor detachment more difficult. More generally, this type of consideration suggests that the distance between reversal point and divertor x-point could have an important effect on divertor operation, and through the value f of the reversal parameter, an effect on core performance. Because divertor operation would likely require a new RFP device, this is an area in which theory could make a significant contribution to future planning.

E. Energetic particle effects

• What aspects of energetic particle effects are relevant in the RFP?

With neutral beam injection at a non negligible energy level, the RFP must now confront theoretical issues familiar to the tokamak. What is the spectrum of toroidal Alfvén eigenmodes in the RFP? Can it be driven by global tearing modes? What are anticipated experimental signatures? How is the stability of these modes affected by fast ions? What is the role of the high RFP beta? How does this factor into the strong energetic particle beta scaling for reactors of $T^{5/2}$, and the need to keep T high if Ohmic dissipation is to be minimized? One advantage of the RFP is the potential for high density operation, because the empirical density limit is high for the RFP (large current density). A more rapid alpha slowing down time at high density will help to limit the energetic particle population. The spectrum of toroidal Alfvén eigenmodes should be calculated analytically and its properties analyzed in reference to the magnetic spectrum of MST. Tokamak codes should be able to calculate energetic particle instability in the RFP core.

• What aspects of RFP energetic particle effects are different from the tokamak?

Energetic particles are expected to have an effect on tearing mode stability on the basis of approximate calculations. These calculations need to be improved to better account self consistently for the coupling between the energetic particle distribution and the bulk plasma collective excitation.

F. Determine and understand beta limiting mechanism

• What are the mechanisms to limit beta, and their dependence on geometry and profiles?

The RFP has yet to encounter clear evidence of having reached a beta limit. For many years power limitations kept discharges at lower beta values, but recently MST pellet injection studies reached beta values of 26% without disruption. Profile reconstruction suggests that those discharges exceeded the Suydam limit. Hence there is a need to comprehensively study RFP stability at finite beta, including pressure gradient effects and drifts to determine the beta limit in the RFP and the type of instability that produces it. Other important questions include the effect of helical equilibria and whether axisymmetric shaping has benefits by increasing local shear.

• How do beta limiting mechanisms affect the plasma?

Is the beta limit hard, resulting in disruption, or soft, leading to strong increases in transport? This question requires understanding of the nonlinear evolution of instability at finite pressure, finite pressure gradient, etc., and couples to confinement issues discussed above.

TAP Tier 3

G. Optimization of RWM control for fusion environment

• What are the minimum requirements for effective control of RWM?

General considerations indicate that RWM control requires that nearby wall conductivity be sufficiently high to allow time for the fields from the coils to penetrate. The fields required for controlling the RWM with m=1 and n of order the aspect ratio can be produced far back if the only shielding is the vacuum reduction with distance. Theoretical analysis is needed to quantify these trends.

H. Self-consistent reactor scenarios

• Are controls for plasma/wall interaction and RWM compatible with good confinement and efficient current sustainment?

This question requires the integration of confinement and sustainment understanding not yet available with the possible effect of external control perturbations, and can only be addressed on the long term.