Outstanding Theoretical Issues for Reversed Field Pinch Research

Derived from
RFP Theory Workshop
Madison, Wisconsin
January, 13 – 14, 2000

A workshop held in January, 2000 on theory and computation related to the reversed field pinch (RFP) led to the articulation of outstanding issues. These issues (and activities) are briefly described here. There is a substantial set of challenging topics, as well as a group of committed theorists and computationalists. However, it is evident that the magnitude of the challenge exceeds the quantity of physicists presently at work on the problems. This report serves as a reference for those already involved in RFP theory, as well as those with potential interest. It will be updated in time, and there was a consensus at the meeting (see attached attendance list) to hold similar workshops in the future

Below we present, in random order, the issues as a list of fourteen topics, which are strongly coupled. The understanding and control of transport are arguably the most important scientific challenges within RFP physics. This is reflected in the present document in that nearly all of the issues discussed are related to confinement. Within each topic we focus on next steps and challenges; we are not intending this to be a synopsis of the status of each topic. Following the itemization of topics, we discuss separately the connection of the outstanding research on plasma physics (and physics) in general.

1. NONLINEAR MHD DYNAMICS

In the RFP there are several dominant Fourier modes in the magnetic energy spectrum. These modes couple nonlinearly, with significant effect on a wide range of phenomena. Outstanding activities include

- Evaluate effect of magnetic stochasticity on magnetic-island based theories (torques, dynamo etc).
- Test analytic theory of torques and mode locking against full 3D MHD computation.
- Include more appropriate viscosity (both neoclassical and anomalous, as appropriate).
- Examine the stability, robustness, and accessibility of single helicity states. Evaluate the effect of boundary conditions , Lundquist number, aspect ratio etc.
- Examine relationship between single helicity states and stellarator configurations. Relate to stellarators at high values of rotational transform.
- Determine the mechanisms which govern the frequency of the modes.

2. RESISTIVE WALL INSTABILITIES

Instabilities which arise when a conducting boundary is replaced by a resistive shell can be critical to the behavior of a long-duration RFP plasma. Extensive linear and nonlinear (computational) study of this problem has been completed. This topic awaits experimental determination of the resistive wall instabilities and mechanisms for their control. However, two important computational tasks are to

- Investigate resistive wall instabilities with flow and nonlinear effects.
- Test feedback schemes in 3D MHD computation.

3. TWO-FLUID EFFECTS

Over the past decade and more, analytic and computational studies of linear and nonlinear single fluid MHD have reaped enormous insight into RFP behavior. A key next step is to extend these studies to a two-fluid description - both analytic and computational. This will constitute a major new arena with many ramifications. The NIMROD code is poised to attack the RFP configuration. Complete contact with experiment, in which the individual electron and ion fluid quantities are measured, ultimately requires at least a two-fluid description. Among the two-fluid theoretical and computational activities are

- Identify and understand the relative roles of different dynamo mechanisms (MHD, Hall, diamagnetic….) under a variety of physical conditions.
- Understand two-fluid effects on plasma and mode rotation.
- Incorporate an appropriate model for the viscosity
- Understand the relevance of collisionless reconnection to the RFP. What are the relevant dimensionless parameters in the collisionless regime? Is the Lundquist number still relevant?

4. MHD OPTIMIZATION OF THE RFP

The majority of experimental and theoretical study of the RFP has focused on circular cross-section, moderate aspect ratio RFP plasmas with naturally occurring profiles. A well-posed task is to

- Optimize the RFP (minimize fluctuations, optimize beta) with respect to its geometric properties (shape, aspect ratio, external transform) and profiles (current density, pressure, flow). This can be first studied with MHD, examining linear stability analytically and with the DCON code, and progressing to nonlinear behavior using the NIMROD code.

5. PRESSURE GRADIENT EFFECTS

Theoretical work has emphasized current-driven fluctuations, since at the beta values of present experiment, the energy source for the core fluctuations is evaluated to be the current density. However, edge fluctuations and transport may be influenced by pressure-gradient driven fluctuations, and pressure will become an important drive for core fluctuations at higher beta values (particularly as the current-driven fluctuations are suppressed by current profile control). Hence, an important activity is to

- Investigate the effect of pressure gradients on small-scale and large-scale fluctuations, and on transport, using MHD computation and other approaches.

6. KINETIC EFFECTS

An array of kinetic effects is important to RFP behavior, requiring a variety of kinetic approaches. The following are some of the activities required.

- Adapt electromagnetic gyrokinetic code to the RFP, for investigation of turbulence in the RFP edge, of pressure-driven fluctuations, and potentially for comprehensive treatment of the kink-tearing fluctuations.

- Investigate influence of RF waves on the RFP. The CQL-3D Fokker-Planck code has been used to evaluate RF wave-driven currents and heating (particularly lower hybrid fast wave, and electron Bernstein wave). Computation is needed to evaluate coupling between the antenna and plasma.

- Evaluate the kinetic dynamo effect (discussed below).

- Examine the effect of energetic particles on plasma stability.

7. MHD COMPUTATION AT HIGH LUNDQUIST NUMBER

The extensive nonlinear MHD computation performed for the RFP has been constrained by the difficulty of computation at Lundquist number values characteristic of present and future experiments. High S computation is essential for interpretation of experiments, for a complete understanding of the MHD RFP plasma, and for treatment of special phenomena (such as oscillating field current drive, discussed below). As noted earlier, plasma behavior may depend on other dissipative and collisionless dimensionless parameters. Nonetheless, a key task it to

- Perform nonlinear MHD computation at high Lundquist numbers, characteristic of present and future experiments.

8. SHORT-SCALE TURBULENCE

RFP experiments display microturbulence at frequencies and wave numbers above that of the dominant tearing fluctuations. The present understanding of this turbulence is extremely limited, suggesting the following activities.

- Examine the origin of the turbulence – is it inertial range turbulence (perhaps suggested by the power law decay of the frequency spectrum), is it driven by nonlinear coupling to the large-scale tearing fluctuations, is it driven by direct energy input at the short scales from the mean field quantities?

- Apply MHD, gyrokinetic, or other computation suited to small spatial scale.

- Extend drift-Alfven turbulence models to the regime of small gyro-radius.

- Examine nonlinear instability as a mechanism for enhancing small-scale turbulence.

9. COMPREHENSIVE DYNAMO THEORY

The single-fluid MHD dynamo has been investigated extensively, both through analytical and computational studies. Other dynamo mechanisms have only received selective treatment. Examples of such mechanisms are the kinetic dynamo, Hall dynamo, and diamagnetic dynamo. A more complete theory of dynamo mechanisms is required to fully understand the relative roles of different effects under various physical conditions. Activities in support of this goal include

- Formulate improved quasilinear or hyper-resistivity models, including the effect of mean field evolution on fluctuations.

- Investigate dynamos via two-fluid theory and computation.

- Expand self-consistent treatment of the kinetic dynamo to include dissipation.

10. SELF-SIMILARITY AND AVALANCHES

In recent years, efforts have emerged in the fusion community to seek universal features of plasma turbulence, understandable from general principles of self-organized-criticality, self-similarity, avalanches. Turbulence in tokamaks and other configurations has been examined for universal power law behavior of frequency spectra (appropriately scaled), self-similarity, and non-Gaussianity. With the availability of nonlinear codes for the RFP the following tasks would be revealing.

- Determine the role of self-organized-criticality behavior in edge transport.
- Search for self-similar and avalanche behavior in nonlinear RFP computation, such as 3D MHD (perhaps adapted to small-scale fluctuations) and in 2D electron MHD.
- Provide guidance to experimental investigations of SOC in the RFP.

11. TURBULENT TRANSPORT

A theoretical understanding of the transport produced by the well-understood tearing magnetic fluctuations is a key topic of current research, and an understanding of even the cause of edge electrostatic fluctuations is absent. This is a large area of research, which includes the following activities

- Include dissipation, and possible other effects (such as rotation), in the set of self-consistent treatments of turbulent magnetic transport of particles, momentum, and energy.
- Incorporate an appropriate viscosity into the models and, conversely, evaluate momentum transport to determine the anomalous viscosity.
- Examine the cause of edge electrostatic fluctuations.
- Perform 3D MHD computation, including energy transport along the stochastic magnetic field using recently derived, long mean-free-path expressions for the parallel thermal conductivity, suitable for inclusion in computation.
- Test self-consistent magnetic fluctuation induced transport theories with gyrokinetic simulation.
- Evolve 1D tranport analysis for comparison of theoretical models with experiment.

12. AN OHMIC QUIESCENT, SUSTAINED RFP PLASMA

Within nonlinear MHD, the behavior of the RFP plasma is determined largely by the electric field at the plasma boundary. Since the applied fields can be axisymmetric or nonaxisymmetric, constant or oscillatory, significant freedom exists to influence the plasma. Thus, we aim to determine the space and time behavior of the applied surface vector electric field that is optimal for a quiescent, sustained RFP plasma. The time dependence of the applied field can be slow, in which case plasma relaxation is important, or fast, in which case Alfvenic effects dominate. Three physics problems, often considered distinct, can be grouped under this category. First, the plasma current density profile can be controlled by time-programming the axisymmetric electric field to enhance Ohmic current drive in the outer portion of the plasma. The goal of this technique, sometimes known as PPCD (Pulsed Parallel Current Drive) is to reduce the magnetic fluctuations. Second, if the toroidal and poloidal axisymmetric surface electric field (the loop voltages) are oscillated in time, 90 degrees out of phase, then helicity is injected steadily. This is a proposed method (known as Oscillating Field Current Drive) for possibly sustaining the plasma current in steady state. Third, Alfven waves may be launched by adding asymmetry and time oscillation to the electric field. This can be used to study nonlinear Alfven wave propagation in a stochastic field, and to determine whether the Alfven wave dynamo effect can be used to drive current in the RFP. These goals suggest many tasks, including the following.

Axisymmetric Fields:

- Optimize PPCD (Pulsed Parallel Current Drive), using nonlinear MHD, incorporating finite pressure effects, examining the effect of self-similar decay of profiles, and examining oscillatory steady-state versions of PPCD.

- Examine OFCD (Oscillating Field Current Drive) by studying the full dynamics, including the plasma relaxation in response to the applied fields. Optimize for both current sustainment and minimal fluctuations (current profile control).

- Study behavior at high values of Lundquist number, particularly critical for OFCD studies.

Non-Axisymmetric Fields:

- Study nonlinear Alfven wave propagation.

- Investigate effect of stochastic field on Alfven wave propagation.

- Examine current drive by the Alfven wave dynamo effect, and optimize.

13. EDGE PLASMA MODELLING

Modeling of the behavior of the edge plasma – effects such as parallel transport on open field lines and atomic physics processes – has progressed far in the tokamak. For example, the results of the UEDGE code as been compared in detail with edge measurements. Thus, for RFP application we should

- Assess the applicability and utility of edge modeling, such as the UEDGE code, to the RFP.

14. ROLE OF FLOW SHEAR IN RFP CONFINEMENT

There is some evidence in the RFP experiment that flow shear can reduce electrostatic transport in the edge. The influence of flow shear in the RFP raises interesting questions beyond those that have been investigated in tokamaks and stellarators.

- Determine how localized flow shear is generated at the sawtooth crash.
- Model transitions to enhanced confinement regimes.
- Perform nonlinear analysis of the effect of localized shear on global modes.

Epilogue

Connection to General Plasma Physics and Physics

The role of the above list of theoretical challenges in advancing the RFP fusion concept is clear. The topics address the major challenges for the RFP concept, such as transport, sustainment, and beta limits. It is also evident that most of the topics directly advance the related spheromak fusion concept, and are also relevant to toroidal confinement physics in general. However, it is useful to call out the connections to more general physics, as a means of emphasizing the need both to export RFP results to other areas and to import results to our research. The magnetic turbulence of the RFP, and the varied phenomena associated with the turbulence, have always offered opportunities for large impact on physics. The areas of future contact with general physics are listed below.

1. Nonlinear Mode Coupling

In the RFP, the magnetic spectrum is dominated by several spatial Fourier harmonics which are strongly coupled through multiple three-wave interactions. Being a simpler situation than fully developed turbulence, this permits study of nonlinear mode coupling in a relatively simple system, applicable to many situations.

2. Nonlinear Phase Space Dynamics

The trajectory of the magnetic field line in the presence of various spatial harmonics presents a prototypical and vivid physical example of the transition from well-ordered trajectories to stochasticity or chaos. The RFP contains regions of magnetic islands and regions of magnetic chaos. Moreover the stochasticity of the field line trajectory may be controlled by techniques such as adjusting the mean field quantities or establishing single helicity states.

3. Multi-Mode Feedback Stabilization

If the RFP is surrounded by a resistive wall, then several MHD instabilities are expected to arise. Feedback stabilization by the application of surface fields is challenging since multiple interacting modes must be simultaneously stabilized. This problem connects to the more general problem of multi-mode feedback studied in control system theory.

4. The Dynamo

While spontaneous generation of magnetic field in the RFP has strong differences in physical setting from the astrophysical and geophysical dynamos, all of the situations have strong physics elements in common. A challenge to the RFP community is to extract information from the RFP which can influence research in natural dynamos.

5. Microturbulence

The RFP fluctuation spectrum consists of two components: large-scale, large amplitude fluctuations which are linearly unstable and small-scale turbulence with a frequency spectrum satisfying a power law decay. This may conform to the classic picture of driven large scale disturbances (the tearing modes) generating a smaller scale inertial range. In addition, the small-scale fluctuations are an excellent vehicle to study general MHD turbulence, and may have features in common with turbulence in the interstellar medium(in which the fluctuation have similar power law behavior).

6. Self-Organized Criticality

General concepts of self-organized criticality and self-similar spectra may be applicable to the RFP, as well as other fusion configurations. For the RFP, this is a new area in which the applicability of these concepts is being investigated.

7. Magnetic Reconnection

The RFP contains magnetic reconnection occurring at numerous resonant surfaces in the plasma. Thus, the RFP can serve as a basic laboratory investigation of reconnection. In addition to spontaneous reconnection (arising from tearing instabilities), it may also contain "driven" reconnection of spatial Fourier modes which are linearly stable, but excited by nonlinear mode coupling. Topics of interest include investigation of reconnection dynamics local to the resonant surface (e.g., the current, flow, magnetic field structure), anomalous ion heating arising from reconnection, and the influence of two-fluid effects.

Attendees of Workshop on RFP Theory
January 13 – 14, 2000
Madison, Wisconsin

H. Berk, U. Texas
A. Bruno, MIT
J. Carlson, ORNL
B. Carreras, ORNL
D. Craig, U. Wisconsin
D. Escande, Marseilles and Padua
F. Ebrahimi, U. Wisconsin
J. Finn, LANL
R. Fitzpatrick, U. Texas
R. Gatto, U. Wisconsin
C. Hegna, U. Wisconsin
H. Ji, PPPL
C. Litwin, U. Chicago
L. LoDestro, LLNL
R. Nebel, LANL
S. Prager, U. Wisconsin
J. Sarff, U. Wisconsin
D. Schnack, SAIC
C. Sovinec, LANL
P. Terry, U. Wisconsin
E. Uchimoto, U. Montana
J. Wright, U. Wisconsin