THE REVERSED FIELD PINCH

In this document we present the motivation for use of the RFP as a fusion energy system and as a vehicle for discoveries in fusion energy science (Section I), the long-term objectives for both parts of the RFP program (Sect. II), the scientific issues (status and unknowns) for development of the RFP configuration (Sect. III), the available means to address the issues (Sect. IV), and the gaps in the present program and facilities needed to fill those gaps (Sect. V).

I. Motivation

I.A The RFP as a fusion energy system

The distinctive feature of the RFP that motivates its interest as a fusion energy system is the weak applied toroidal magnetic field. The RFP configuration is similar to a tokamak, but the applied toroidal field is 10 – 100 times weaker. This offers the potential for high engineering beta, the use of normal (rather than superconducting) coils, high mass power density, efficient assembly and disassembly, and possibly free choice of aspect ratio.

High engineering beta: The physics beta of the RFP (volume-averaged pressure/surface-averaged magnetic pressure) is automatically high since the toroidal field is weak (and the magnetic pressure is dominated by the poloidal field). In present experiments beta has been increased to 26%. If measured relative to the vacuum toroidal magnetic field the beta value can be over 100%. But a more germane measure for fusion energy application is the engineering beta, in which the magnetic field pressure is measured at the coils. For configurations with high safety factor the maximum field at the magnet is of order twice the field in the plasma, whereas in the RFP the field at the magnet is less than in the plasma. The engineering beta in an RFP reactor might be as much as twice the physics beta.

Normal magnets: Superconducting magnets are not necessary, reducing the need for neutron shielding of the magnets.

High mass power density: The high engineering beta and normal coils lead to a reactor system with high ratio of fusion power to the reactor system mass (relative to other toroidal systems with aspect ratios greater than unity). This is a favorable economic indicator.

Single piece maintenance: The high mass power density yields a compact design (relative to other toroidal systems) that enables the fusion power core to be removed from the plant as a single piece. This facilitates system maintenance, a significant factor in reactor reliability and the cost of electricity.

Possibly free choice of aspect ratio: To date, the physics of the RFP does not depend strongly on aspect ratio. Thus, the choice of aspect ratio can be made on engineering grounds. There might be some physics advantage to lower aspect ratio (where the number of unstable tearing modes decreases), but this feature has not yet been explored in detail.

These advantages have been validated through the comprehensive TITAN system study, completed around 1990. However, the study was predicated on a set of physics assumptions. It is the understanding and achievement of these physics assumptions, combined with new approaches to RFP development, that is the main subject of the remainder of this document.

I.B The RFP for fusion energy science research

A comprehensive understanding of toroidal magnetic confinement would imply that plasma behavior would be predictable over a wide range of magnetic field strengths (or safety factors). The tokamak provides a fairly broad range for q > 1, but the approximate lower bound on q is a strong restriction. Generally, the RFP (with q < 1) provides new information since it extends our understanding to low field strength, testing the understanding derived at high field. In many of the topics listed below, the RFP provides unique information unavailable elsewhere, while for some topics the information is complementary. We identify RFP contributions that will be made in the areas of electrostatic-fluctuation-induced transport, resistive wall instabilities, beta limits, and magnetic self-organization (which itself incorporates a large array of fusion science topics). We also comment on RFP contributions to astrophysics – as a spin-off topic, not as motivating for the current exercise.

Electrostatic transport at weak field: RFP plasmas in which confinement is improved by suppressing magnetic fluctuations represent a new physics regime for fusion: q < 1 plasmas with transport believed to arise mainly from electrostatic fluctuations. Understanding electrostatic transport in such plasmas, for which magnetic shear and the gyroradius are relatively large, would extend and test the knowledge base acquired from tokamaks (at high field). The scaling of confinement in these plasmas is a new area of study. RFP contributions in this area are unique.

Resistive wall instabilities: The RFP is susceptible to resistive wall instabilities, much like those experienced in high beta tokamaks. However, in the RFP there are multiple unstable modes driven by the parallel current, even at zero beta. Thus, RFP research has and will continue to develop and demonstrate feedback techniques for multiple mode stabilization that is directly applicable to and complementary to other configurations.

Beta limits: All RFP experiments operate at high beta, and recently beta values have been achieved that exceed theoretical MHD stability limits for localized interchange and global tearing modes. High beta is achieved simultaneous with improved confinement, and no limitation associated with these theoretical limits has been identified as yet. Plasmas that exceed interchange limits have also been produced in other configurations, such as the stellarator. The RFP is an excellent testbed for understanding the behavior of high beta plasmas, including those that exceed MHD stability limits (local or global), as well as to study the behavior of such instabilities when they are excited. Such studies are complementary to and directly applicable to other toroidal configurations.

Magnetic self-organization: In its standard regime (without confinement improvement) the RFP exhibits a set of phenomena that are associated with magnetic self-organization. Particularly relevant to many configurations are RFP studies of reconnection, dynamo alteration of the current density profile, momentum transport, reconnection heating of ions, transport from magnetic stochasticity, and magnetic helicity transport. Each of these phenomena is very active in the RFP and is driven by magnetic fluctuations. Each is broadly relevant to many configurations such as the tokamak and ST during strong MHD activity and during sawtooth crashes, the tokamak with an ergodic divertor, and the spheromak. The RFP has been and can continue to be a prime venue to develop the broad physics associated with reconnection and magnetic fluctuations. The RFP program is arguably unique in this endeavor.

Linking fusion energy science to astrophysics: Through magnetic self-organization, RFP physics has strong links to related phenomena in astrophysical plasmas. Through funded collaborations with plasma astrophysicists, RFP researchers have been applying understanding gained in the laboratory to astrophysics (as well as applying physics learned through astrophysical studies to the RFP). This work is perhaps outside the scope of the present FESAC exercise, but is an important spin-off of the RFP program. The RFP program has been unique among fusion configurations in the scope of this spin-off.

II Long-term Objectives

II.A For the RFP as a fusion energy system

For the RFP program, we have identified the overall mission and a programmatic focus for the next 15 – 20 years.

Mission*: Develop the scientific and technical basis for a fusion power source that uses a small externally applied magnetic field.*

Twenty year focus*: Form the basis for a burning plasma experiment by developing an attractive self-consistent integrated scenario: favorable confinement with resistive wall stabilization in a sustained or long pulse, high beta plasma.*

Worldwide, the RFP is at the status of a proof-of-principle program, although at a modest scale. It is estimated, and discussed below, that with appropriate resources it would be possible to establish the basis for a burning plasma experiment within 20 years. The remainder of this report (beginning in Sect. III) is devoted to describing the issues and challenges to obtain this objective.

II.B For fusion energy science

The RFP can contribute fundamental and unique knowledge to fusion energy development in two distinct ways, as captured in two objectives

- *Understand the influence of magnetic self-organization on fusion plasmas*
- *Understand the behavior of low-field toroidal plasmas with magnetic self-organization suppressed*

The first objective aims to develop a predictive understanding of a specific set of effects arising from magnetic self-organization. These effects are strongly related to each other, so that understanding the individual phenomena sums to a general understanding of magnetic self-organization in fusion plasmas. The effects include:

The influence of multiple, coupled reconnections: There is evidence that when reconnection occurs at multiple resonant surfaces, the nonlinear coupling between the different resonant modes greatly amplifies self-organization (i.e., all of the effects listed below). Coupling might also be key to the occurrence of impulsive reconnection. Understanding this effect has two components. First is understanding effects beyond MHD associated with individual reconnection. It is known that in the RFP (and likely in all fusion configurations) two-fluid, and perhaps kinetic, effects are important. The second component is to understand the physics of nonlinear coupling. Nonlinear coupling can alter the structure of the modes and phases between fluctuating quantities.

Transport from stochastic magnetic field: Mainly, a heuristic theoretical model has been used to describe transport due to particles streaming along a stochastic magnetic field – essentially a test particle model. While this model has shown reasonable agreement with experiment, it is incomplete – it does not include the effect of the enhanced transport on the magnetic stochasticity. The RFP, with the new ability to vary the stochasticity, can be a vehicle for the development of a self-consistent theory.

Momentum transport: It is observed that during magnetic self-organization toroidal and poloidal angular momentum is transported radially at a rate far exceeding classical transport. There is substantial evidence that this arises from Maxwell and Reynolds stresses associated with tearing modes. However, prediction of single-fluid MHD does not match the magnitude of the transport or the strengths of the individual stresses.

Dynamo effects: The hallmark of magnetic self-organization is the dynamo effect: the radial transport of parallel current (or redistribution of magnetic field). A complete MHD theory has been developed to explain this effect. However, experiment has shown that two-fluid Hall effects are strong. We aim to develop a complete theory of the dynamo effect, validated by experiment.

Conversion of magnetic energy to thermal energy: It is observed that the magnetic energy in the RFP plasma decreases by nearly 10% during a self-organization event (i.e., a reconnection event, or sawtooth crash). The thermal energy of the ions simultaneously roughly doubles (in 100 μs). The mechanism for the ion heating is unknown. Understanding this phenomenon offers the opportunity for major insight into how reconnection dissipates energy – a process that generally accompanies reconnection.

The linkage between the above phenomena is explicit. For example, the fluctuation-induced Lorentz force that transports momentum is identical to the Hall term that transports current through Ohm's law. Understanding the above phenomena goes a long way toward establishing a general understanding of magnetic self-organization in fusion plasmas, as occurs in the tokamak under certain conditions, in the spheromak generally and in the RFP. With adequate diagnostics, and the parameter variations needed for the development of the RFP as a fusion system, this mission will be accomplished. Thus, within the scope of this report, we do not identify the specific gaps in facilities for this mission.

The second objective - understand the behavior of low-field toroidal plasmas with magnetic self-organization suppressed – offers new knowledge from the second regime of RFP operation. In a sense, the standard RFP is becoming obsolete. The new physics regime offers new knowledge on electrostatic transport and other areas, with significant likelihood of surprises. More specific goals are described below, as this regime must be explored thoroughly to develop the RFP as a fusion source.

III Scientific issues for the development of the RFP configuration

III.A Confinement

Status: Confinement of energy and particles in the standard RFP (i.e., formed and maintained by toroidal Ohmic induction alone) is limited mainly by magnetic fluctuations that arise from global tearing modes. This causality is well-established through detailed measurements of fluctuations, correlation of fluctuations with transport, measurement of selected fluctuation-induced fluxes, and comparison between measured transport and simple theory due to stochastic fields. At the present level of plasma current, the measured transport is large – about ten times higher than a tokamak at comparable size and current. In recent years, two new approaches to improving RFP confinement have been introduced and are being developed. These have altered entirely the view of confinement in the RFP.

First, it has been shown that current density profile control improves confinement dramatically. The concept is simple: eliminate the free energy source (the current density gradient) that drives the tearing modes that cause the transport. Suppression of the modes by current density profile control has been established by MHD theory and computation. The idea has been implemented experimentally by programming in time the surface loop voltages, thereby transiently altering the current density profile. The result is that energy confinement increases ten-fold to a level that is comparable to that of a tokamak of similar size. With current profile alteration, magnetic fluctuations decrease several-fold, electron temperature increases by a factor of about three, and input Ohmic power decreases. To date, improved confinement is obtained with an electron temperature of 2 keV, an ion temperature of 1 keV, with a beta about 10% (which, as explained below, can be further increased with pellet injection). It is also observed that energetic electrons are well-confined (measured up to 100 keV). Fokker-Planck modeling of hard x-ray Bremsstrahlung emission indicates that the electron diffusion coefficient is roughly independent of electron velocity in the improved confinement regime, but is roughly proportional to velocity in the standard regime. This suggests that transport has shifted from being dominated by magnetic fluctuations (diffusion proportional to velocity) to being dominated by electrostatic fluctuations (diffusion independent of velocity). This is consistent with measurement that shows that electrostatic transport (measured by heavy ion beam probing) in the core is too small to account for the transport in standard plasmas. Through neutral beam injection, it has been shown that energetic, large-orbit ions are well-confined in all RFP plasmas (the large-orbit ions can have well-confined trajectories in the presence of stochastic magnetic field). Thus, RFP plasmas now have been shown to favorably confine thermal electrons, thermal ions, energetic electrons and energetic ions. The fusion triple product ($nT\tau$) achieved to date is 1.7×10^{17} keV-s/m^3, comparable to earlier tokamaks at the scale of MST. In an effort to subtract the size of the experiment from the figure of merit, some have proposed using the related intrinsic figure of merit β/χ (where χ is the thermal diffusivity). For the RFP, $\beta/\chi \sim 0.03$ s/m^2, a relatively high value.

The second approach (as yet theoretical) to improving confinement is to obtain a single helicity RFP state. In such a state the tearing mode spectrum condenses to one mode. The RFP equilibrium then becomes helical and non-stochastic. MHD computation shows that at sufficiently high dissipation (resistive or viscous) the plasma naturally evolves to a single helicity state. In experiment, plasmas have been produced in which one tearing mode dominates over all others, although the secondary modes are nonzero (the so-called quasi-single helicity state). In this state, a single large magnetic island develops. Inside the island the temperature increases significantly; outside the island the field remains stochastic. Achievement of a single helicity state and improvement in global confinement will require further reduction of the secondary modes.

Unknowns: There are three large unknowns whose answers will determine the future course of RFP evolution with regard to confinement: confinement physics and scaling of the standard RFP undergoing magnetic self-organization, confinement physics and scaling of the electrostatic-dominated RFP, and the realization of the single helicity state. A favorable results within at least one of these paths is necessary.

Historically, it had been argued, from somewhat heuristic theoretical considerations, that as current and electrical conductivity (or Lundquist number, S) increases in the standard RFP, magnetic fluctuations from resistive tearing modes would decrease, and confinement would improve rapidly. However, the limited scaling permitted in experiments to date (mostly operated well below 1 MA) and within MHD computation implies that the decrease of magnetic fluctuations with S is weak. Initial results beyond 1 MA do indicate an increasing temperature, and effects beyond MHD might be important. Thus, how confinement physics will change with controllable parameters, such as plasma current, is yet unsettled.

The physics of transport in the new regime of improved confinement is largely unknown. While the reasons for reduction of transport are well-understood (tearing mode suppression by current profile control), determination of the mechanism, optimization, and scaling of transport in the new regime awaits future study. In addition, extension of the approach beyond the transient, relatively coarse current profile control of inductive programming to a fine, steady control technique (such as RF wave current drive) is likely needed to optimize and understand confinement. A key control issue is the power requirement for RF current drive. This is a relatively unexplored confinement regime that offers substantial potential for new discoveries.

The major next step for single helicity states is to achieve such states experimentally. A pathway needs to be defined. It is not known whether the states can be achieved passively since, in the absence of anomalous dissipation (e.g., viscous damping) the dissipation of hot plasmas is likely too weak to satisfy the condition dictated by MHD computation. Another route is to develop active techniques to achieve the state, such as imposing a helical boundary condition on the magnetic field. Finally, if a single helicity state is achieved, this too would represent a new regime with unknown confinement properties.

II.B Beta limits

Status: At sufficiently high beta, localized interchange instabilities and global tearing instabilities are predicted to be unstable by linear MHD calculation. When beta reaches about 20% the pressure gradient becomes a major source for tearing instability, in addition to or replacing the current density gradient. Most RFP experiments (without improved confinement) automatically operate at relatively high beta (~ 10%). The toroidal beta value (pressure normalized to applied toroidal magnetic field) is of order 100%. These typical experimental beta values are not limited by pressure-driven stability, but by transport from current-driven instability. This is made clear by experiments in which pellets are injected into improved confinement plasmas, leading to a beta value of 26%. At this beta value, MHD predicts that both the interchange and tearing modes should be unstable. However, in the experiment no apparent limit is observed.

Unknowns: Although reactor level beta values are achieved in experiment, the limit to beta is yet unknown. The absence of this knowledge is due to the absence of auxiliary heating in existing RFP experiments. Thus, beta cannot be controllably varied independent of other parameters. Theoretical expectation for the nonlinear evolution of pressure-driven instabilities in the RFP has also not yet been established. Also, the theoretical optimization of the RFP shape, geometry, and profiles (for ideal and resistive stability) has not been studied exhaustively.

III.C Resistive wall instabilities

Status: It has long been established through MHD theory and computation that multiple current-driven ideal instabilities arise in the absence of a surrounding conducting shell. In addition, computation reveals that the resistive tearing modes grow without bound in the absence of a shell (whereas with a shell they reach a saturated level). Experiments have validated these expectations. With a resistive shell, it is observed that all the expected modes grow on the time scale of the shell resistive diffusion time. Eventually, the instabilities terminate the plasma (for finite applied loop voltage), also in agreement with computation. However, it has now been demonstrated in experiment with a resistive shell that all of these instabilities (of order 10 – 20 modes) can be suppressed (with the tearing modes held to their conducting wall value) through feedback. This is accomplished in RFX-mod with an array of 192 independently controlled feedback coils completely covering the shell surface. Thus, in a physics sense, this long-standing RFP problem has been largely solved.

Unknowns: Having established that all the instabilities can be suppressed with a feedback system, the next step is to develop a scenario that is most compatible with the engineering of an attractive reactor. This requires determination of the allowed flexibility in the feedback system, such as the required proximity of the coils to the plasma surface, the number of coils, and the extent of surface coverage with coils.

III.D Current sustainment

Status: The weak toroidal magnetic field of the RFP implies that the parallel neoclassical (bootstrap) current tends to be small. Hence, except possibly at ultra high $\beta \sim 1$ and low aspect ratio, most of the plasma current must be driven by an external source. Even in the ultra high beta limit, residual external current drive is needed in localized regions of the plasma. The upper limit to beta in the RFP is still an open issue, as described in section III.B, but it is prudent to consider lower beta scenarios. This is made clear from the TITAN study where modest $\beta = 25\%$ is sufficient to enable a compact reactor scenario.

Full non-inductive current drive by rf or neutral beam injection is generally considered impractical because the current drive efficiency is too small. This conclusion is not particular to the RFP, but it accentuates the need for efficient current drive.

Inductive current drive is very efficient and can support reactor scenarios with high fusion gain. Pulsed current scenarios are potentially more attractive at low field, bearing in mind that pulsed tokamak scenarios (e.g., PULSAR) are not considered fundamentally flawed (but less desirable). The plasma resistivity in the RFP is in good agreement with neoclassical physics (the Spitzer value enhanced < 2x by the trapped electron correction).

Oscillating Field Current Drive (OFCD) theoretically is a (nearly) steady-state inductive current drive scenario for the RFP. This is the current sustainment method employed in the TITAN system study. In OFCD (also known as AC helicity injection), purely AC toroidal and poloidal inductive loop voltages are applied at low (audio) frequency, and magnetic self-organization sustains the current density profile near marginal tearing stability. In this way the plasma current is maintained nearly constant, with a small AC ripple (associated with the plasma's inductance). The physics basis for OFCD has recently been strengthened through nonlinear, resistive MHD computation. This work shows that the magnetic self-organization process operates similarly to that in an RFP with steady induction. The process is also in reasonable agreement with magnetic helicity balance considerations which were used to invent the OFCD concept.

Low power OFCD experiments in MST have so far demonstrated 10% current drive, in good agreement with theoretical expectations for the experimental loop voltage amplitudes and plasma impedance. It is very challenging to demonstrate 100% OFCD in a plasma with MST parameters, since the AC modulation causes large variation in the magnetic equilibrium. At reactor parameters, the plasma resistance is much smaller, and the projected AC modulation is only a few percent. Also, the L/R time for current settling is comparable to MST's pulse length, and saturated OFCD is difficult to attain.

Unknowns: The OFCD concept will not be confirmed until a 100% current drive demonstration occurs. However, the physics underlying OFCD can be assessed as the fraction of current driven by OFCD is increased. Perhaps the most important uncertainty is OFCD's compatibility with energy confinement requirements. The Lundquist number scaling for magnetic turbulence (discussed in III.A above) is particularly relevant for OFCD, for both the required oscillation in the magnetic equilibrium, and the effect on relaxation. Although theoretically the relaxation process appears to be similar for both steady induction and OFCD, experimentally the scaling should be established specifically for OFCD. If sufficient confinement cannot be attained simultaneously with OFCD, then some degree of pulsed operation is required (for $\beta<<1$). If an RFP with $\beta\sim1$ is achievable, large fraction bootstrap with residual rf current drive might be plausible, if the recirculating power fraction is not too large.

III.E. Plasma-boundary interaction

Status: The majority of RFP experiments to date have been performed in circular cross-section, limited plasmas. A few small-scale experiments have been performed in a poloidal divertor geometry, but these were investigated mainly for stability, not for boundary control per se. A poloidal divertor for the RFP is not the obvious choice, since this requires diverting the main field component. The TITAN system study employed a toroidal field divertor configuration for particle control. The core and edge plasma were also assumed to be highly radiating by impurity doping, so that the heat conducted into the divertor was a very small fraction of the total power outflow. Experiments on ZT-40M at LANL with Xe doping around the time of the TITAN study showed only weak impact on confinement and beta. There have been no experimental tests of a toroidal divertor, or other possibilities such as a pumped limiter, which are more natural options for the RFP.

The first wall in RFX-mod is smooth, with 100% graphite coverage. The first wall in MST is aluminum, protected by graphite limiters covering 10% of the surface. The Extrap-T2R metallic first wall is similarly protected by a discrete set of molybdenum “mushroom” limiters, on which the power density reaches ~2MW/m^2. Boronization and other coating techniques are used, but less frequently than on many tokamak experiments. The control of impurities is therefore less advanced, but the radiated power fraction is typically in the 10-20% range for operation below the density limit. The density limit in the RFP is quantitatively similar to that for the tokamak, although sometimes “soft” through increased radiation fraction to near 100% and increased plasma resistance. Identification and comparison of density limiting behavior is receiving more attention in recent RFP research. For reference, TITAN was assumed to operate at $n/n_G=0.6$, which is high in absolute density because the plasma current density is large.

Localized heating of the first wall is an issue if magnetic structures associated with resistive wall modes are allowed to form. This has been investigated extensively in RFX-mod. With active control of the RWM spectrum, the plasma surface is maintained nearly axisymmetric. Pulse lengths of ~ 0.5 s at 1.5 MA are now routinely obtained in RFX-mod, and localized heating of the first wall is much less an issue.

Unknowns: The present state of RFP research might be very similar to the tokamak era where attention to boundary plasma control began to have an enormous influence on plasma behavior and performance. Simply put, the best means to control the boundary in the RFP is not known. The large physics database from poloidal divertor tokamaks ought to be helpful in identifying appropriate solutions, but it is unclear if a poloidal divertor geometry itself is the optimum choice (maybe even clear that it is not). Advanced techniques such as a liquid lithium first wall might be strongly enabling for compact, high power density (in any magnetic configuration). Control of the plasma boundary is clearly an opportunity for RFP research, but the existing facilities are limited in ability to address options.

III.F. Burning plasma

Status: Issues for the burning plasma regime in the RFP are similar to other magnetic configurations. Of course alpha confinement is important, but more for protection of the first wall, given that Ohmic heating may be sufficient for ignition in the RFP. Fast-ion-driven instabilities are of concern if they cause alphas to be lost at high energy, or if they couple to the thermal distribution and degrade confinement.

Short pulse neutral beam injection experiments on MST and TPE-RX have established that fast ion confinement is good, even in the standard RFP with magnetic stochasticity. This is explained by particle orbit physics. The gyroradius for beam-injected 20 keV deuterium ions in MST is roughly the same as for alphas born in a TITAN-like plasma, so good single-particle alpha confinement is implied for the RFP.

The theory for fast-ion-driven instability, such as toroidal Alfven eigenmodes, is little studied for the RFP. Torodicity-induced eigenmodes should be possible, although configuration details like smaller safety factor and magnetic shear will create RFP-specific character. Experimentally there is little evidence for Alfven eigenmodes, except one result from Extrap-T2R. An edge-localized TAE was observed with the correct parameter sensitivity, but the excitation process was not clearly identified, possibly attributed to thermal tail ions, given the RFP's high beta. Similar modes have not been identified in MST or RFX.

Although current sustainment is coupled to transport and confinement in the RFP, 100% bootstrap sustainment is not possible, even in an ultra-high $\beta \sim 1$ scenario. Pressure profile self-consistency with dominant alpha heating is therefore not a substantial integration issue for the RFP. Of course the drawback is that efficient external current drive is required, as discussed in Sect. III.G.

Unknowns: Instability from energetic particles has not yet been carefully examined in either theory or experiment for the RFP. Self-consistent scenarios with alpha particle heating have not been substantially explored, although it might be a slightly smaller issue than for bootstrap-current driven configurations.

III.G. Self-consistent RFP reactor scenarios

The highest priority integration issue for the RFP is efficient current sustainment with good confinement. The discussion here will focus primarily on this particular linkage. Additionally, a self-consistent RFP scenario requires control of resistive wall modes and of the plasma boundary, in ways that might be distinct from other configurations. The physics demonstration of RWM control by active feedback has been established, although a practical implementation in a reactor must also be achieved. So far RWM control is not coupled strongly to other issues like confinement, especially since active stabilization does not require plasma flow. The boundary has received little attention in the RFP, and there are possible linkages to confinement and stability, for example nonaxisymmetry concerns if a toroidal divertor is employed as in TITAN. The boundary is clearly an area deserving of attention in the near term. Other issues such as plasma fueling and burn control are perhaps more similar in nature to other magnetic configurations.

In considering various scenarios, it is important to recognize that the RFP magnetic configuration can be MHD tearing stable. The scenarios which employ current profile control aim to stabilize tearing, and therefore avoid or minimize magnetic self-organization. It is also important to emphasize that confinement in the RFP may be ultimately limited by a non-magnetic mechanism. Evidence for non-stochastic transport exists in the energetic electron distribution for reduced-tearing plasmas attained with inductive current profile control. Nevertheless, efficient current sustainment must be obtainable without creating too large stochastic transport.

Several possible scenarios have been identified, for steady-state and pulsed sustainment. These are summarized below, in order of steady-state to pulsed.

OFCD steady-state (TITAN): A steady-state current is maintained using OFCD (see III.D). The modest Ohmic heating power leads to high fusion gain (Q=80) in the TITAN system study. At the same time, the Ohmic heating is large enough for ignition. Since OFCD relies on magnetic self-organization, the scaling of magnetic turbulence must be favorable, or the single-helicity relaxation mechanism must be accessible. Note that inductive current drive technology does not require components facing the plasma. A number of engineering aspects for OFCD were addressed in the TITAN study.

Ultra high beta steady-state: If very high beta plasmas with strong edge pressure gradient can be obtained, the bootstrap fraction at low aspect ratio is maximized, and steady-state without induction is possible. This is the extension of AT/ST to low safety factor. Residual rf current drive is required, and the recirculating power fraction must not be too large. The details are surely sensitive to the required pressure and current profiles for stability. Since the plasma pressure profile is important, integration with transport and confinement is more explicit (as in AT/ST). The physics basis for this scenario is least established.

"Hybrid" inductive (nearly) steady-state: Induction is extremely attractive in its efficiency and simplicity. If OFCD is not compatible with simultaneously good confinement, it might still be useful for efficient current drive, combined with inductive current profile control in a nearly constant fusion burn scenario. A self-similar current ramp-down (SSRD) method has been identified to inductively (and temporarily) maintain an RFP without magnetic relaxation. The physics is essentially identical to the inductive current profile control used in MST to establish improved confinement, but SSRD is only beginning to be tested experimentally. In SSRD, the plasma current is ramped down exponentially at a rate that scales with the resistive diffusion time $\tau_R=\mu_0 a^2/\eta$. The current profile is maintained by induction through the slow flux decay. There is little reason to continue the ramp-down beyond the point where the current is reduced ~10-20%, given the $\beta^2 I^4$ scaling for fusion power. At this point, OFCD is used to re-build the current, and the cycle repeats. This is a fully inductive scenario, without magnetizing flux accumulation. If fusion burn is accessible during the ramp-down, but not during OFCD, the fusion power is pulsed, but without a complete restart of the current (which never goes to zero). The OFCD re-build can be at a typical current ramp-rate, so the gap in fusion burn could be about a couple of seconds. The ramp-down time could be ~15-20 s, given that τ_R~1000-2000 s for reactor parameters. High fusion gain (>50% of steady-state) is possible, even if the electron temperature falls to the several keV level during the OFCD re-build.

Pulsed induction: This is the "standard" pulsed scenario, where steady toroidal induction maintains the plasma current. Plasma relaxation maintains the reversed-field configuration. As for OFCD, the scaling of magnetic turbulence must be favorable, or the single-helicity relaxation mechanism must be accessible for this scenario to succeed. The pulse length is limited by magnetizing flux accumulation. The transformer must be reset, or possibly the plasma current can be alternating, using one pulse as the reverse-magnetization of the transformer for the following pulse.

Pulsed induction plus current profile control: This scenario uses conventional pulsed induction, but with current profile control added to provide tearing stability. Steady toroidal induction alone leads to peaked current profiles and tearing instability. The current profile control is therefore aimed to broaden the current drive and directly maintain a tearing-stable configuration. Pulsed poloidal current drive (PPCD) has proven effective in experiment to improve confinement, and in general some optimum in the inductive electric field programming must exist. The programming for PPCD and SSRD (described above) bracket a range of possibilities. Non-inductive current drive could also be a viable option, if the recirculating power fraction is small enough. Most likely this would be rf current drive targeted to the outer region of the plasma. Options include lower hybrid and electron Bernstein waves, which are under investigation on MST. An analogy in tokamak research is neoclassical tearing mode stabilization.

IV Available means

IV.A. The international RFP experimental program

There are four complementary RFP experiments operating in the world. These facilities are described below in terms of how they are being used to address key RFP issues. Their existing experimental capability is summarized.

The MST facility (UW-Madison)

The MST facility is the centerpiece of the US proof-of-principle RFP program. It is physically large in the RFP context (R/a = 1.5m/0.5m), but has medium plasma current (0.5 MA) and pulse length capacity (< 0.1s). The MST program focuses on confinement and beta studies, through current profile control and auxiliary heating. It is also testing the OFCD concept for steady-state current sustainment, but at a fractional current drive level (partial OFCD superposed on regular toroidal induction). The diagnostic capability is fairly complete, not too dissimilar from the advanced diagnostics found on most tokamak experiments. These include multi-point Thomson scattering, simultaneous FIR interferometry and Faraday rotation (polarimeter), heavy ion beam probing, Rutherford scattering (for majority ions), charge exchange recombination spectroscopy, and motional Stark effect. The last three are enabled by two diagnostic neutral beams. These diagnostics also support the magnetic self-organization studies in which MST is a major participant. The MST device contains a thick conducting shell surrounding the plasma, so study of resistive wall modes is not easily accessible (nor an issue in MST performance).

Inductive current profile control on MST has demonstrated a transient ten-fold confinement improvement by reducing tearing instability. Further optimization of the inductive loop voltage programming remains a high priority, and a new programmable power supply for the toroidal field (poloidal loop voltage) is presently being commissioned. Two rf current drive techniques are in development to facilitate more precise radial positioning of the auxiliary current drive, based on the lower-hybrid and electron Bernstein (EBW) waves. These systems will also add significant non-Ohmic heating power. No significant auxiliary heating has been used in RFP research to date. A 200 kW, 800 MHz system is operating for LH waves, and investigations of the wave propagation and absorption have begun. A multi-antenna, 1-2 MW system will likely be required for tearing control. A 4-wave-guide EBW system operating at 200 kW is presently in development. As with LHCD, a multi-antenna system will be required for tearing stabilization experiments.

A 1 MW neutral beam (20 ms) is in preparation, to assist assessment of beta limit physics, to investigate possible energetic ion driven instability (TAE, etc.), and to provide an external momentum source for momentum transport investigations.

The MST shell is aluminum, with graphite limiters covering approximately 10% of the surface at locations where plasma-wall interaction tends to be strongest. The average heat load to the first wall is modest, <0.5 MW/m^2, although the heat flux on limiters is surely larger. The boundary and plasma-facing-components are not yet well diagnosed in MST.

The RFX-mod facility (Italy)

The world's highest power RFP facility is RFX-mod (R/a=2.0m/0.46m), with a designed plasma current capability of 2 MA and pulse length to date τ_{pulse}~0.5 s. The plasma is surrounded by a metal shell with a vertical field penetration time of 50 ms. The centerpiece of a recent facility upgrade is a 192 coil system which fully covers the 2D toroidal surface for active and broadband MHD control. Each of these coils is independently driven. The feedback control system has demonstrated simultaneous control of more than 10 resistive wall modes. The program is rapidly progressing in studies of optimized feedback scenarios, for example projecting radially inward the control surface for the normal component of magnetic field to minimize plasma-surface interaction, and understanding side-band interactions that result with a finite number of coils.

The flexible active control system on RFX-mod can isolate and control a single Fourier mode. This enables possible investigation of stimulated production of the single-helicity state, with absent or reduced magnetic stochasticity. This program extends optimization of the quasi-single-helicity configuration.

The diagnostic capability on RFX-mod is also similar to MST and to that found on tokamak experiments. The edge plasma and facing-components are reasonably well diagnosed, and the higher current capability leads to higher heat flux. The first wall is 100% graphite.

The RFX-mod facility also employs flexible inductive programming for both the toroidal and poloidal loop voltages, but with limited range. For example, OFCD experiments are severely hampered by loop voltage limits. Building on their power engineering expertise, the RFX-mod program will host the test facility for ITER's negative-ion-based neutral beam sources.

The Extrap-T2R facility (Sweden)

The RFP community enjoys two complementary facilities with research emphasis on active MHD control. The Extrap-T2R (R/a = 1/24m/0.18m, 0.3 MA) is smaller than RFX-mod, but it similarly employs a full coverage active feedback coil system totaling 128 coils and independent power supplies. The vertical field penetration time of the resistive shell surrounding the plasma is 6.3 ms. Active control of all resistive wall modes has been demonstrated for 0.1 s (15 wall-times). The Extrap-T2R active control program aims to elucidate the linear and nonlinear physics associated with mode-sideband coupling in the control system. One practical goal is to understand what determines the minimum required number of control coils. A large part of this study is optimizing the magnetic sensors, e.g., comparing field components or combinations of components.

Wall locking of the usually rotating resonant tearing modes is an important issue that remains not completely understood. The versatile capability of the active control system permits pre-programmed action on a single mode, thereby adjusting the drag force created by the mode. Understanding the physics that determines the locking threshold and its parameter dependence will be a primary goal.

The internal surfaces in contact with the plasma are all-metal in Extrap-T2R, primarily molybdenum limiters. The heat loads on these limiters is fairly large, typically about 2 MW/m^2. Spatially resolved spectroscopic measurement are used to investigate the influx and accumulation of metal impurities, and surface collector probes are used to investigate impurity accumulation. The data will be compared with models for a heat pulse on the limiter surface.

The RELAX facility (Japan)

A new, low aspect ratio RFP has recently began operation at the Kyoto Institute of Technology. This is a much smaller scale facility (R/a = 0.51m/0.25m, I < 100 kA, pulse length < 10 ms)) than those above. Nevertheless this is an interesting experiment investigating parameter space rarely studied for the RFP. Generally, shape and aspect ratio optimization studies have not been systematically addressed for the RFP. At low aspect ratio, the safety factor is increased, and the spatial separation of major resonant surfaces in the core is therefore increased. This could impact plasma relaxation behavior and the formation of magnetic stochasticity. The trapped particle fraction is also increased at low aspect ratio, and although the pressure-driven bootstrap current is not expected to be dominant for $\beta<1$, it should be measurable.

IV.B. Computation and system studies

Extensive nonlinear resistive MHD computation has been performed to describe the multimode magnetic fluctuations in the RFP, and such codes (e.g., DEBS) are in active use. Nonlinear two-fluid studies are underway, particularly using the NIMROD code. PIC simulations of reconnection related to the RFP (in simplified geometry) are underway using a code written for astrophysical plasmas. Gyrokinetic simulation to examine electrostatic turbulence has begun using codes developed for tokamaks. Fokker-Planck studies have been performed using the CQL-3D code. At present, a modest, targeted system study (essentially an update to the TITAN study) is beginning.

V Gaps and facilities

VA Gaps

Having described the status and unknowns for the major issues for the RFP in the previous section, we describe the gaps for each of those areas – the portion of the unknowns that likely cannot be answered by present facilities.

Confinement: Understanding plasma behavior in the regime of improved confinement requires an extension of the physics parameter space available experimentally. In existing facilities, exploration of improved confinement is limited by constraints on plasma current and duration. Confinement has been highly optimized in MST (although optimization will continue as new tools are added over the next five years). However, once optimized, it is necessary to investigate improved confinement with expanded parameter space for two reasons: to vary physics parameters as a means to understand the limiting transport mechanisms and to assure that the confinement improvement persists as parameters are increased. More specific questions that motivate the parameter space expansion are

- *How does magnetic fluctuation induced transport scale with Lundquist number and plasma current?* In standard confinement plasmas, this question can be addressed over a substantial range in existing experiments (corresponding to current up to 2 MA in RFX). However, this question is also important for improved confinement plasmas since access to this regime depends on suppression of magnetic fluctuations. The ease and optimization of fluctuation suppression could vary with S. The Lundquist number at present can be varied in MST from about10^5 to 10^7 (with improved confinement) whereas a reactor will operate at about 10^{10}. Thus, more dynamic range is critical.
- *How does electrostatic transport depend upon parameters such as normalized gyroradius?* In the improved confinement scenario, RFP behavior will likely be determined by electrostatic fluctuations. Substantial understanding can be gained in existing experiments – on the detailed fluctuation properties and on the magnitude of electrostatic transport (determined from measurements of correlated fluctuation properties). These results can be compared with theory and computation (e.g.,

gyrokinetics) for electrostatic transport in the RFP. Currently, understanding of transport in this new regime is too primitive to pose a prediction of the appropriate dimensionless scaling, or even the relevant scaling parameters. One might expect the normalized gryoradius to be important, a parameter that will decrease about an order of magnitude from current experiments to a reactor. However, it is certain that the understanding derived from the limited parameter range presently available will have to be tested with expanded parameters.

- *Will the favorable trend suggested by current experiment continue?* Recent results indicate that the electron stored energy in improved confinement plasmas increases with plasma current (corresponding to electron temperature increasing from 0.6 keV at 0.2 MA to 2 keV at 0.5 MA). To date, confinement times have not been obtained for the high current plasmas, and the trend does not directly provide information on confinement scaling. However, should continuing experiments establish a favorable dependence of plasma parameters with current (in the improved confinement regime), it will increase the value of expanded parameter space as discussed in the previous paragraph.

Beta limits: There is a reasonable likelihood that present experiments have the capability to determine the beta limit. This requires increasing beta from its present value. Two complementary techniques are underway: pellet injection and neutral beam injection. Both techniques have limitations in present experiments. Pellet injection into improved confinement plasmas increases density and beta. But it is not known whether this will continue to the beta limit. Neutral beam injection in current experiments will enhance beta through the added pressure of the fast ions and, at the higher density provided by pellet injection, through thermal pressure. However, the plasma parameters (energy confinement time, fast ion slowing down time, and plasma duration) make thermalization difficult. Thus, these studies are supplemented by the development of RF systems for auxiliary heating in MST. However, plasmas of greater confinement time and longer duration will facilitate the use of neutral beam heating. In addition, since the expected pressure-limiting instabilities are resistive MHD modes that depend on S, extension of beta studies to higher Lundquist number will be useful.

Resistive wall instabilities: The RFX-mod facility has sufficient flexibility for extensive study of feedback stabilization of resistive wall instabilities. The feedback coil network can be configured to test various combinations of wall coverage – each of 192 feedback coils are independently controlled. Next steps beyond RFX-mod studies could include testing of the required proximity of coils to the plasma surface (although this might be able to be tested with movable limiters in RFX-mod) and studying the effects of plasma rotation (through neutral beam injection not possible in RFX-mod).

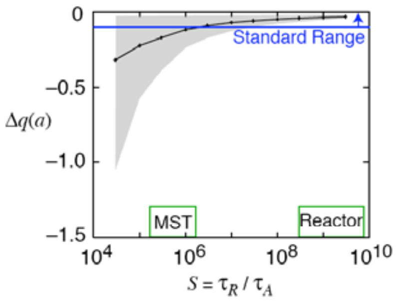

Fig. 1 Oscillation in edge safety factor that accompanies OFCD indicated by shaded gray area. Black curve is cycle-averaged q(a), and blue horizontal line is lower end of q(a) for standard RFP plasmas. It is desirable that S be sufficiently high for the oscillation to be less than the standard q value.

Current sustainment: Studies of oscillating field current drive depend crucially on Lundquist number and plasma duration. The amplitude of the required voltage oscillation decreases with Lundquist number, S. If the voltage swing is too large it will cause an unacceptably large oscillation in the q profile. Fig. 1 shows the necessity for tests at high S values to obtain acceptably small oscillations in q. It is also necessary that the plasma duration (and OFCD duration) be at least comparable to the plasmas L/R time. The driven current increases on a time scale of the plasma L/R time, requiring a sufficiently long plasma duration to observe the full effect of OFCD. The combination of the S of MST and its relatively short duration implies that the current driven by OFCD will likely be limited to about 20% of the total current. Thus, a complete test of the OFCD concept will require a plasma with large S and longer duration.

Plasma-boundary interactions: Existing facilities are not equipped for study of means to control the plasma-wall interaction, such as magnetic divertors or liquid metal first walls. Research in these areas can be expected to have an impact on RFP behavior perhaps similar to its key role in the behavior of tokamak plasmas.

Burning plasma science: With an appropriate population of energetic ions from neutral beam injection, existing facilities should be able to address instabilities from energetic particles. Beyond this issue, study of most of the effects introduced by a burning plasma must await a burning plasma experiment.

Self-consistent reactor scenarios: Current facilities are not able to produce self-consistent plasma scenarios. For example, RFX-mod can examine resistive wall instabilities in depth, but lacks strong capability for current profile control, beta enhancement, and oscillating field current drive. MST can apply current profile control and possibly enhance beta, but cannot include reactor-relevant resistive wall mode stabilization (MST operates with a conducting shell) and is limited in OFCD. Self-consistent scenarios would require a facility that includes all these capabilities.

VB Needed facilities

The above needs translate into two categories of facilities. The first includes facilities that address a subset of issues that require a broader parameter space than presently available. Physics parameters should be sufficiently advanced to be able to establish the basis for the second category of facility - one that establishes an integrated scenario at advanced parameters that will form the basis for a burning plasma experiment. These fit the categories of proof-of-principle (but beyond MST capabilities) and performance extension experiments.

From the above section, we observe that confinement and OFCD strongly require facility capabilities beyond those available. Both topics require expansion in physics parameter space that is accomplished by higher current and longer duration than in present experiments exploring improved confinement and OFCD. Beta studies would benefit from this parameter space expansion, but this need is less critical since much of beta physics can be inferred at existing plasma parameters. Similarly, much of resistive wall instability questions can be settled in RFX.

For confinement studies we first provide the perspective based upon confinement scaling considerations. We consider three scenarios. The first, and most interesting, is scaling of the improved confinement regime which is thought to be dominated by electrostatic fluctuation induced transport. We believe that this is the most promising regime for the RFP. At present, there is not an existing model for transport in this regime. We observe that the transport is similar to that of a tokamak, as indicated in Fig. 2, which places the RFP data point on the tokamak H-mode scaling plot. These are only individual RFP data points, and are NOT shown to imply scaling. The second scenario is the historical RFP scaling, shown in Fig. 3, which derives from constant beta scaling. It is also consistent with confinement based on magnetic fluctuations if the fluctuations decrease rapidly with S. Note that MST improved confinement plasmas exceed this scaling. This scaling plot is also not shown to claim a physics scaling, because of the third scenario. The third scenario is that confinement changes only weakly with S. Limited S scaling studies in MST (and MHD computation) indicate a weak scaling of fluctuations and confinement.

A range of parameters beyond those available is needed to examine whether any of the above scalings (or something else) applies.

Two dimensionless parameters can be identified as important for confinement. The Lundquist number is expected to determine, in part, magnetic fluctuations. The normalized gyroradius is expected, in part, to determine electrostatic fluctuations (although this is not yet a well-established expectation for the RFP). A significant excursion in these two dimensionless parameters is desirable. Oscillating field current drive also requires an expansion in Lundquist number so that the voltage swing is acceptably small, as dictated by Fig. 1.

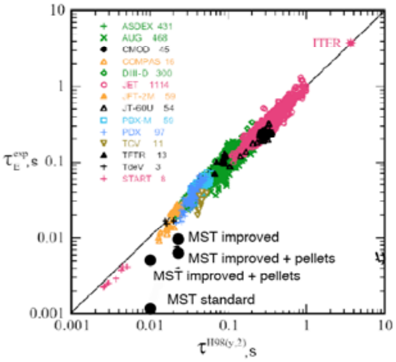

Fig. 2 MST improved confinement data superposed on ELMy H-mode tokamak scaling plot

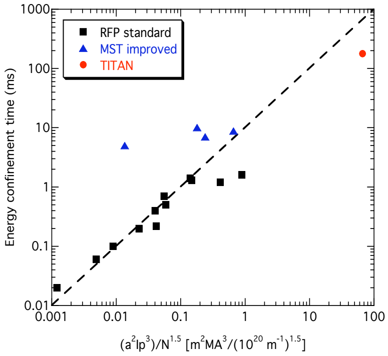

Fig. 3 RFP experimental data base showing multiple RFP experiments (black squares), MST improved confinement plasmas (blue triangles) and TITAN reactor design (red circle)

An example of a facility (at the proof-of-principle level) that satisfies all the above criteria is an RFP with similar size as MST but current increased to 1.5 MA and plasma duration increased to about 0.2 s. The confinement time would increase by a factor of 3 if the scaling is as for a tokamak dominated by electrostatic fluctuations, by a factor of 5 if the scaling is for the constant beta RFP, and almost not at all if the scaling is as for the standard MST plasma. The Lundquist number (in standard operation) would increase about ten-fold to 10^7 for standard RFP operation, sufficient for a strong test of OFCD with acceptably small oscillations (see Fig. 1). The normalized gyroradius would decrease about three-fold in improved confinement plasmas, suitable for examining scaling of electrostatic transport. Although the current of the facility is similar to that of RFX-mod, it would have added capability in inductive current profile control, OFCD, neutral beam injection, and RF wave injection.

A second proof-of-principle experiment is likely needed to explore methods to control the plasma-wall interaction. For example, an RFP with a toroidal magnetic divertor or with liquid lithium boundary (pending results elsewhere) would open up a new area of RFP research. Such concepts can first be tested at the relatively modest scale (in plasma current) of MST.

The experiment to demonstrate an integrated scenario should operate with improved confinement, resistive wall mode feedback stabilization, either oscillating field current drive or an alternative pulsed scenario, and appropriate control of the plasma-wall interaction. The physics parameters should be such that the extrapolation to a burning plasma experiment can be done with confidence. The specification of such parameters requires results from the above proof-of-principle facilities, but would be at the level of a performance extension experiment (e.g., temperature > 5 keV, plasma current > 4 MA).

Note: This report was written in May, 2008 for the FESAC panel on magnetic confinement configurations