THE REVERSED FIELD PINCH

Status and Plans for RFP Research in the U.S.

prepared by

Members of the

U.S. RFP Research Community

April, 1998

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I EXECUTIVE SUMMARY

The 1990s has seen a rapid growth in the scientific understanding of the RFP, a dramatic increase in energy confinement through exploitation of this understanding, a start of relatively large (in the RFP context) RFP experiments worldwide demonstrating improved operational characteristics, an articulation of possible solutions to many of the scientific challenges confronting the RFP as a reactor, and an affirmation of the potential positive reactor attributes. These advances build upon a long history of RFP research, beginning with the discovery of field reversal in the ZETA device in the 1960s [1]. The intriguing, favorable stability properties that accompanied reversal stimulated research in the 1970s. Experiments then were characterized by short pulse (hundreds of microseconds), dense plasmas with confinement times in the 100 μsec range [2]. The 1980s were marked by a group of very productive experiments, with confinement times up to 0.5 ms, minor radii of about 0.2 m, and plasmas that were sufficiently long-lived (tens of ms) to accommodate detailed studies of RFP equilibrium and fluctuations [3,4,5,6]. During this decade the nonlinear MHD foundation of the RFP began construction [7,8], following on the insight that the RFP can be described as a minimum energy, magnetically relaxed state [9]. The work in these experiments laid the basis for the experiments of the 1990s which increased the plasma size two-fold (to minor radii of 0.5 m) and the confinement time ten-fold (to 5 ms) [10,11]. Most importantly, recent physics results led to new insights and a reappraisal of the RFP.

Until recently, the RFP had been viewed as a configuration plagued with large-scale, large amplitude magnetic turbulence. Whereas much of the reactor advantage of the RFP is connected to its relatively weak confining magnetic field, the weak field also carries the penalty of reduced plasma stability. As with other configurations with safety factor q less than unity, strong magnetic fluctuations arise which lead to anomalous transport. In recent years it was discovered that control of the radial profile of the current density can diminish the magnetic fluctuations and transport. To date, this approach has increased the energy confinement time of the RFP by a factor of five in experiment, opening up a path to improving RFP confinement.

The opportunity presently available to the US in RFP research is rather remarkable. The world program outside the US contains experiments that are at the scale of proof-of-principle devices. However, the research programs are emphasizing the scaling of confinement with plasma current and, to a much lesser extent, the effect on stability of a resistive wall. The outside-the-US world program by itself does not constitute a proof-of-principle program since it does not explore the full breadth of crucial scientific issues for RFP development. The outstanding issues are confinement improvement by advanced techniques, beta limits, current sustainment, control of resistive shell instabilities, power and particle handling, and modifications to the RFP configuration for improved performance. The US RFP program is poised to attack aggressively most of these outstanding issues. Such a research plan will also have large impact on the very similar issues confronting the neighboring $q < 1$ configuration of the spheromak.

At present, the US program is focused on confinement improvement by current profile control, coupled to basic physics studies of fluctuations and transport. This focus has produced the best confinement yet achieved in an RFP, as well as a plethora of key physics results. If the US expands its program to encompass a more vigorous attack on confinement improvement and an expansion into studies of beta limits, current sustainment, and modified RFP configurations, then the world RFP effort will sum to a comprehensive proof-of-principle program. The RFP is one fertile area in which the US can be a leader worldwide. Moreover, the nature of the existing and envisioned RFP experiments in the US is such that the cost of a proof-of-principle RFP program is relatively modest.

The purpose of this report is two-fold. In Part A we synopsize the scientific status of the RFP concept and the key, unanswered questions that can be addressed by further research. Part B advances the argument that the RFP is scientifically ready for and in need of a proof-of-principle US research program (a readiness articulated by the FESAC 1996 report on alternative concepts [12]), and we define the components and goals of such a program.

The reactor interest in the RFP stems from its low magnetic field. The RFP is similar to a tokamak with its toroidal magnetic field reduced ten-fold. This yields a reactor concept [13] with normal (not superconducting) coils, high beta, very high engineering beta (pressure normalized to magnetic pressure at the field coils), low field and force at the coils, absence of disruptions (observed in experiments), and possibly free choice of aspect ratio (can be determined by engineering considerations possibly without physics constraint). The many challenges which must be met in the areas of confinement, beta limits, stability with a resistive wall, current sustainment, and power and particle handling are described in detail below. The enduring view is that investigation of plasma properties in a very low field configuration permits study of a broad range of issues critical to a broad class of concepts.

Contents

PART A: SCIENTIFIC ISSUES IN RFP RESEARCH

Below we summarize the dominant scientific issues for the development of the RFP as a fusion concept. For each issue, we delineate the scientific status and the open questions. In Section II we summarize anomalous transport in the RFP. In Sections IIA to IIE, we treat the origin of fluctuations in the RFP, energy transport, particle transport, current transport and dynamo, and control of fluctuations and transport. We then describe plasma stability with a resistive shell (Section III), beta limits to plasma stability (Section IV), current sustainment (Section V), power and particle handling (Section VI), and optimized RFP configurations (Section VII). The substantial contributions of RFP research to basic plasma science are outlined in Section VIII.

II TRANSPORT

IIA The Origin of Fluctuations

Status: As described below, both magnetic and electrostatic fluctuations are important for transport in the RFP. It has long been realized that magnetic fluctuations in the RFP and other configurations with safety factor $q<1$ will be large. Large scale resistive MHD instabilities are predicted to be linearly unstable [14]. Nonlinear MHD computation is now very advanced, and can predict the spatial structure of magnetic fluctuations. Quasilinear flattening of the current profile and nonlinear mode coupling determine the saturated amplitude of the modes. The results of MHD computation have been compared in detail to experimental measurements of magnetic fluctuations, including the mode amplitude, wavelength spectra [15], radial structure [16], magnetic field polarization, and nonlinear mode coupling [17]. There is excellent agreement, subject to modest differences which may be accountable by the relatively low Lundquist number (normalized electrical conductivity) permitted in computation. The magnetic fluctuation amplitude is about 1%, much larger than in a tokamak. The number of dominant modes is about equal to the aspect ratio R/a, and the dominant toroidal mode numbers are centered about $n=2R/a$, all with poloidal mode number $m=1$. The modes are resonant with the equilibrium magnetic field ($m/n = q$) and cause magnetic reconnection. Fluctuations in flow velocity are being measured by fast Doppler spectroscopy, revealing qualitative agreement with computation [18]. The combined nonlinear MHD and experimental study of fluctuations have revealed the dynamics by which the plasma maintains an approximate magnetically relaxed Taylor state.

Recently, magnetic fluctuation control has been demonstrated by controlling the current density profile [19]. To date, this technique has succeeded in halving the fluctuation magnitude. This result is discussed below in the context of transport control. The scaling of magnetic fluctuations with Lundquist number (S) is important since it influences the scaling of confinement. Limited Lundquist number scaling studies in MHD computation and in experiment indicate that fluctuations scale with a small inverse fractional power of S [20]. At shorter wavelength, the magnetic fluctuations in experiment reveal a power law falloff with frequency, characteristic of an inertial range of microturbulence [21].

Whereas understanding of magnetic fluctuations is highly advanced, the theoretical study of electrostatic fluctuations is at a rudimentary state. Fluctuations in density, electric potential, and temperature have been measured in the outer region of the RFP [22,23,24,25]. Part of the fluctuations correlate highly with the magnetic fluctuations, implying a parasitic relationship. However, part is not correlated. Fluctuations resemble, in their amplitude and broadband nature, electrostatic fluctuations in tokamaks and stellarators. However, the origin of electrostatic fluctuations in the RFP is yet undetermined. It has long been expected that resistive interchange modes should be substantial [26], and perhaps rippling modes, but these views have not yet been validated. Nonetheless, recent experiments are demonstrating a degree of control of electrostatic fluctuations, discussed below in the transport context.

Open Issues: Three issues of importance remain open for the dominant large scale magnetic fluctuations. First, the scaling with Lundquist number is not fully established in either experiment or theory. As the plasmas become larger and hotter, the Lundquist number will increase, and the variation of fluctuation amplitude becomes an important determinant of transport scaling. More broadly, as the plasmas become increasingly collisionless, the fluctuations may depend on different parameters than the Lundquist number, as has been investigated in other situations displaying collisionless reconnection [27]. Second, the nonlinear mode coupling, although predicted computationally, is not yet quantitatively understood. The fluctuations in the RFP consist of several nonlinearly coupled tearing modes. Hence, the situation is intermediate between the case of a single mode and that of fully developed turbulence, and offers an opportunity to develop an understanding of nonlinear mode coupling in a tractable situation. A related third issue is the interaction of these modes with stationary field errors, which can cause the entire mode structure to lock to the field error. Mode locking is an important issue for the operation of RFP experiments [28,29]. The problem is more complex than that of a tokamak since the locking involves multiple modes [30] rather than a single mode, and a stochastic magnetic structure, rather than a rotating island.

The microturbulent magnetic fluctuations, at shorter scale and higher frequency, possibly offers the model situation of MHD turbulence driven by large scale structure produced by the tearing modes. Theoretical calculation is consistent with this view, but experimental work is needed for confirmation.

A major unknown is the cause of electrostatic fluctuations. Recent experimental results imply that fluctuations can be reduced by sheared $\mathbf{E} \times \mathbf{B}$ flow, as discussed below in the transport context. The applicability to the RFP of the sheared flow model, as developed for tokamaks and other configurations, requires further work.

IIB Energy Transport

Status: The observed energy transport in the RFP is about one hundred fold larger than the classical prediction (in the RFP, since the poloidal and toroidal magnetic fields are of comparable magnitude, neoclassical effects are weak). Radial profiles of the thermal diffusivity are not well known experimentally since profile information on the stored energy and Ohmic power input has been limited. Nonetheless, electron temperature profiles are relatively flat in the core region, with large gradients in the outer portion of the plasma (although profiles steepen during improved confinement plasmas, as discussed later). There has long been an expectation, supported by MHD computation, that the magnetic field in the core of the RFP is stochasticized by the overlapping of magnetic islands associated with the several dominant magnetic Fourier modes. This view is consistent with inferences from the electron temperature profile. A compelling test of the stochastic diffusion theory was accomplished by measuring the electron energy flux specifically driven by motion of electrons along a fluctuating magnetic field [31]. The magnetic fluctuation driven electron energy flux is obtained from the product of the fluctuations in parallel heat flux and radial magnetic field. Measurements of this energy flux over the outer 20% of the RFP plasma indicate that in the extreme edge (roughly beyond the toroidal field reversal surface) magnetic fluctuations do not drive transport, but within the reversal surface the entire energy flux is driven by magnetic fluctuations. These results are consistent with the expectation that the magnetic field is stochastic inside the reversal surface, where the dominant modes are resonant, but well-ordered beyond. An interesting feature of the energy flux is that it is consistent in magnitude with that expected from stochastic field diffusion (the Rechester-Rosenbluth formula [32]), but with a speed characteristic of the ion thermal speed, not the electron thermal speed. Hence, it appears that an ambipolarity-like constraint operates in the energy transport [33].

Energy flux from electrostatic fluctuations has also been measured in the edge of the RFP, and is observed to be small.

Open issues: Magnetic fluctuation induced transport has been investigated in detail only in the outer portion of the RFP, and only for a very limited range of plasma parameters. Hence, it is critical to extend our understanding to the plasma core and to higher values of Lundquist number. Energy transport in the extreme edge remains a mystery since neither measurements of magnetic transport nor electrostatic transport have yet revealed the cause. Also it is necessary to continue to expand profile diagnosis for determination of the thermal (and other) diffusivity profile, particularly in the core.

IIC Particle Transport

Status: Particle transport in the RFP is anomalous by the same factor as for energy transport. The situation with regard to magnetic fluctuation induced particle transport is also similar to that for energy transport: direct measurement of electron flux from magnetic fluctuations (from the correlated product of the fluctuation in the parallel electron flux and radial magnetic field) proves that the transport is magnetic within the reversal surface [34]. However, outside the reversal surface, in the extreme edge, the particle flux is measured to be driven by electrostatic fluctuations [22-25].

Open issues: As for energy transport, the core particle transport from fluctuations remains largely undiagnosed.

IID Current Transport and Dynamo

Status: The RFP exhibits the special property that the confining axisymmetric magnetic field is, in part, self-generated by the plasma [35]. The self-generation of current and magnetic field, by mechanisms related to plasma flow, is referred to as the dynamo effect, in analogy with similar effects in nature (astrophysical and planetary dynamos). In the RFP, the current generation may also be cast as the radial transport of parallel current. There are several theoretical models, or ideas, which have been developed or posited to explain the RFP dynamo. The explanation most highly developed, with a strong theoretical grounding, is the MHD dynamo [36,37,38,39]. In the MHD dynamo, current is driven by the electromotive force experienced by the moving plasma, arising from the product of fluctuations in the plasma fluid velocity and magnetic field. The fluctuations are tearing fluctuations. A fully self-consistent, nonlinear model predicts dynamo action. Alternatively, the “kinetic dynamo” mechanism depicts the radial transport of current by the parallel motion of electrons along the chaotic magnetic field generated by the tearing fluctuations [40]. Appealing from an intuitive viewpoint, the inclusion of the self-consistent reaction of the transported electrons on the fluctuations diminishes the effect [41]. Finally, mechanisms resulting from pressure fluctuations have been suggested (a “diamagnetic dynamo”) [42].

The MHD dynamo agrees with experimental measurements in the edge of collisionless plasmas in which the electromotive force has been measured by separate measurements of the velocity and magnetic field fluctuations [43]. Spectroscopic measurements of velocity fluctuations in the core also support the MHD model [44]. However, the presence of energetic electrons in the edge plasma with energies characteristic of the core, are consistent with the kinetic dynamo mechanism [45]. Finally, the diamagnetic dynamo has been measured to be active in the edge of collisional RFP plasmas [42].

Open Issues: Despite the persuasiveness of the standard MHD model of the dynamo, it remains to determine experimentally which dynamo mechanisms are active under which physical conditions. Definitive measurement of each dynamo mechanism requires local measurement of a variety of fluctuating parameters, including flow velocity, electron pressure, parallel electron pressure, and magnetic field. It remains a rich topic for research. Theoretically, the kinetic and diamagnetic dynamos must be brought to the level of the MHD dynamo. Indeed, pressure effects have not yet been treated theoretically. A thorough understanding requires a two fluid treatment.

IIE Control of Transport and Fluctuations

Status: Above we argue that the magnetic fluctuations are understood to be tearing instabilities fueled by the spatial nonuniformity of the current density profile. We also describe evidence that the magnetic fluctuations produce the anomaly in energy and particle transport in the RFP core, as expected from computed stochasticity in the magnetic field. From this understanding, it is expected that control of the current density profile may reduce or eliminate the energy source for the fluctuations, and thereby reduce the fluctuations and transport. Nonlinear MHD computation with auxiliary current profile control supports this view [46,47]. Current profiles can be obtained which suppress the dominant global modes. The auxiliary driven edge current provides the field reversal, eliminating the need for the fluctuation-driven dynamo.

An initial experimental implementation of a coarse form of current density control has increased the energy confinement time by roughly a factor of five (from about 1 ms to 5 ms) [19]. The current profile was altered by applying an inductive poloidal electric field (which is mainly parallel to the edge magnetic field) during a discharge. This produces a transient edge current. The plasma responds with a halving of magnetic fluctuation amplitude, an increase in electron temperature by about 50%, and a factor-of-three reduction in Ohmic input power (leading to the five-fold confinement increase). Inductive current profile control is transient and unable to finely tailor the profile. Hence, the present five-fold confinement increase does not represent a confinement limit, but rather the limit of the current profile control technique.

Recently, a second form of confinement improvement has emerged through alteration of the $\mathbf{E} \times \mathbf{B}$ velocity flow profile. This has occurred in two manifestations. First, electrical biasing of the RFP plasma (through insertion of biased electrodes in the plasma edge) has doubled the particle confinement time [48]. Second, under certain operating conditions (deep reversal, low density, clean walls) the plasma confinement time increases about three-fold [49]. The confinement increase is accompanied by a narrow edge $\mathbf{E} \times \mathbf{B}$ shear layer, and reduction in both magnetic and electrostatic fluctuations (both large and small scale) in the edge. The applicability to the RFP of the paradigm of shear flow reduction of turbulence, highly developed for the tokamak, is a topic of present research.

Open issues: The improvement in confinement by current profile control is still an emerging research area. The next steps are to develop profile control techniques which can finely control the current continuously. Experiments are underway to drive edge current continuously by the electrostatic injection of current from miniature current (plasma) sources inserted into the edge of the RFP plasma [50]. Such a technique is steady-state, but does not offer fine control. Current drive by electromagnetic waves is expected to be the optimal technique. Lower hybrid waves have been shown theoretically to be appropriate for profile control [51,52], and experiments are beginning. The larger issue for confinement improvement by current profile control is the determination of the ultimate confinement limit. Can magnetic fluctuation induced transport be eliminated? Can a current profile be achieved for which the magnetic fluctuations are smaller scale and localized to a narrow edge region with little effect on transport? If so, how severe will be the residual electrostatic transport?

The influence of shear flow on RFP fluctuations and transport is a new area. Many fundamental questions remain. Does shear flow affect large scale electrostatic fluctuations and magnetic fluctuations, in addition to the small-scale electrostatic turbulence typical of tokamaks? Does coupling of electrostatic fluctuations to the large magnetic fluctuations alter the dynamics? Research into these questions is beginning.

III STABILITY WITH A RESISTIVE SHELL

Status: MHD stability of a stationary RFP without feedback of instabilities requires that the plasma be surrounded by a close-fitting conducting shell. In the absence of a perfectly conducting shell, the plasma is linearly unstable to ideal, nonresonant kink instabilities which grow on the resistive timescale of the shell [53,54]. Nonlinear MHD computation has been used to study the resistive wall problem in detail [55]. In addition to kink modes, it is observed that resistive tearing modes, which exist at a saturated amplitude with a conducting shell, also grow. The growing tearing modes produce a fluctuation induced electromotive force field which opposes the plasma current in the core. Thus, to maintain the current constant in the computation, the loop voltage increases steadily. Hence, MHD predicts that an RFP plasma persisting for a time longer than the shell penetration time will require additional stabilization (e.g., feedback or rotation). Initial computational study of feedback of the resistive modes, indicates that targeting a few dominant modes is sufficient [56]. Modest rotation produces near to perfect conducting boundary conditions for resonant modes, but for nonresonant modes, near-Alfvenic velocities may be required for stabilization [57].

Experiments in the HBTX device operated with a resistive shell displayed growing modes in rather close agreement with prediction [58]. Both external kink and resonant modes experienced growth on the resistive shell time scale. As the modes grew, the reversal deepened (as the dynamo increased in strength) and the loop voltage increased, also in agreement with prediction. The current terminated as the applied loop voltage could not match the required increase. Although, this picture appears to be convincing, similar experiments in the OHTE RFP with a resistive shell produced different results [59]. Resonant modes grew in amplitude, but would then decay without terminating the plasma. Both experiments were ended before the reason for the differences was discovered.

Feedback of the ideal external kink modes was accomplished in HBTX [60]. Application of feedback from magnetic coils suppressed mode growth in the presence of a resistive shell, and maintained the mode amplitude at a selected noise level. Whereas feedback was successful, the growth of resistive modes, which were not feedback controlled, continued to enhance the loop voltage and lead to plasma termination. The next step in the experiment was to apply similar feedback to the resistive modes. However, the experiment was shut down prior to the test.

Open issues: The next steps in the resistive shell issue are to determine the behavior of the modes experimentally (i.e., to resolve the difference between the HBTX and OHTE results) and, if needed, to devise and apply stabilization techniques. The problem is similar to that of the advanced tokamak at high beta, with the added complexity that in the RFP several modes are simultaneously unstable and nonlinearly coupled. The RFP plasma is an excellent candidate for tests of multi-mode feedback control schemes and "smart" shell concepts [61].

IV BETA LIMITS

Status: The poloidal beta value (ratio of volume-averaged plasma pressure to surface magnetic pressure) is limited by pressure-driven MHD instabilities. A key feature of the RFP is that the total beta value (taking, for example the volume-averaged magnetic pressure) is about equal to the poloidal beta, since the poloidal and toroidal fields are comparable. Hence, the total beta can be relatively large.

The RFP contains average bad curvature, dominated by the poloidal field, since $q < 1$. Stability is provided by magnetic shear—the field line rotates more than 90º from the center to the edge. Pressure profiles are found which can be ideal MHD stable up to poloidal (and total) beta values of about 50% [62]. Ballooning effects are weak, since the curvature does not vary strongly along a field line.

All RFP experiments operate routinely at beta values of about 10%, and values of 20% have been obtained at relatively low plasma current. These values are obtained in plasmas with Ohmic heating only (auxiliary heating has not yet been applied to the RFP). It is not yet determined whether the beta values presently achieved represent a stability limit, or are merely set by the limited Ohmic input power.

Large-scale resistive pressure-driven MHD instabilities have not been examined in detail. Initial MHD computation, in connection with studies of current profile control of tearing instabilities, indicates that as the current source of instabilities is reduced, the pressure will increase until pressure begins to drive tearing instabilities in the beta range of 25% [47]. In addition, resistive interchange fluctuations are always unstable and have been investigated as a possible cause of anomalous transport in the RFP, particularly in the edge.

Open issues: The next major step is to determine the beta stability limit experimentally. Present experiments operate below theoretical stability limits. Auxiliary heating is necessary to increase beta, and to distinguish the beta-limiting effects of stability and transport.

V CURRENT SUSTAINMENT

Status: Present RFP reactor concepts envision steady-state operation. Sustainment of the plasma current is a critical issue which has received relatively little focused effort. The current drive challenge for the RFP is larger than for the tokamak since the self-driven neoclassical bootstrap current is small and the poloidal beta value is relatively small (so that for a given plasma pressure the toroidal current drive requirements are severe). The technique of Oscillating Field Current Drive (OFCD) has been proposed which exploits the magnetic relaxation property of the RFP [63,64]. If the toroidal and poloidal loop voltages are oscillated 90º out of phase, net time averaged magnetic helicity is injected into the plasma. The injected helicity supports the helicity decay resulting from plasma resistance, and the plasma relaxation maintains the current density profile roughly constant. An equivalent view is that the oscillating voltages drive a net edge current which penetrates by the anomalous process associated with relaxation and reconnection. In the TITAN reactor study, it was estimated that OFCD could sustain the 18 MA toroidal current with an efficiency of about 0.3 A/W (including driver efficiency and transmission losses). OFCD (also known as F-Θ pumping or AC helicity injection) received an experimental test at a perturbative level. A trace amount of current (5% of the total) was driven by OFCD [65].

Open issues: OFCD requires a definitive experimental test in a plasma large enough (with resistance small enough) that the required voltage oscillations are manageably small. Two questions requiring experimental tests are the efficiency of the current drive and the effect of current drive on transport. A concern of the technique is that the relaxation process that transports the edge-driven current inward will also transport energy outward.

VI POWER AND PARTICLE HANDLING

Status: Power and particle handling are important issues for any reactor concept, but especially so for the RFP as a potentially compact, high power density reactor core. However, present and past RFP devices have not had to deal with these issues in detail given the relatively short duration of the plasma pulse. Typically RFP devices use graphite, molybdenum, or other refractory materials to protect sensitive areas in contact with the plasma. Only the RFX and T2 devices have full coverage graphite first walls.

Presumably much of the particle and power handling knowledge base currently being developed in the larger fusion research community (mostly the tokamak community) will directly transfer to the RFP. But there are several RFP specific features which need to be considered. For example, because the dominant magnetic field component at the plasma surface is poloidal, a poloidal divertor would require large divertor coil current. In the TITAN reactor study, a toroidal field divertor was chosen instead [13]. However, most of the power was not deposited in the divertor, rather it was assumed to radiate uniformly on the first wall surface by deliberately doping the plasma with a small amount of xenon. The divertor functioned primarily to exhaust helium. Consequently the uniform first wall heat load (radiation) in TITAN was 4.6 MW/m^2 and the neutron load was 18 MW/m^2. Impurity doping experiments were carried out in which the radiated power fraction could be increased to nearly 100% without affecting the central temperature or global confinement time of the plasma [66].

The RFP divertor (operating on either the toroidal or poloidal magnetic field) must be carefully designed to avoid decreasing MHD stability by moving the plasma far from the stabilizing shell. It is known that the stability of the RFP is decreased with a vacuum (current-free) interspace between the plasma surface and shell [54]. Also, the harmonic structure of the divertor field might need to be chosen so as not to interact with unstable modes. Only one (smaller) RFP device operates with a divertor, TPE-2M in Japan [67]. Both poloidal and toroidal magnetic field divertor configurations are produced, and the program emphasis is studying the divertor impact on MHD stability and impurity control.

Open issues: When TPE-2M completes its scheduled operation (roughly within a year), dedicated studies of diverted RFP plasmas and their MHD stability will be placed on hold. A related issue which affects power and particle handling is mode locking. The nonlinearly interacting band of tearing modes tends to form a spatially localized perturbation which concentrates the plasma-wall interaction. When these modes lock, the power flux to the first wall is not uniform. Learning how to prevent mode locking is already an intense area of RFP research.

VII OPTIMIZED RFP CONFIGURATIONS

Understanding of the RFP has evolved to the point that modified RFP configurations can be devised: “advanced RFP” concepts which are designed to improve the RFP. Perhaps the first successful example of a modified RFP is one with current profile tailoring for magnetic fluctuation reduction. However, an exciting prospect is to optimize the RFP profiles (current density, pressure and flow) and geometry (plasma shape, aspect ratio, and external transform). These features of the equilibrium can affect the stability and transport of the RFP. Theoretical study of the optimal mix of features is necessary. Below we outline the physics motivation of each parameter variation.

Effect of Current Density Profile: The current density is the one quantity that has already been investigated in some detail theoretically, with extremely promising experimental results. It has a powerful effect on fluctuations and transport. In further study it should be optimized in concert with the other parameters described below.

Effect of Pressure Profile: MHD indicates that at the present experimental values of beta, the pressure gradient contributes only weakly to the fluctuations. The dominant source of fluctuations and transport is the plasma current. However, as current profile control reduces fluctuation-induced transport, it is expected that the plasma beta will increase until the pressure gradient begins to destabilize resistive MHD fluctuations. At this point pressure profile control may prove critical. In addition, pressure gradient drive may be crucial to edge turbulent transport.

Effect of Flow Profile: Sheared flow can affect MHD fluctuations in two ways. First, shear flow at the resonant surface is known to be stabilizing to tearing modes [68,69]. The effect may be altered for the RFP situation in which islands overlap as the field becomes stochastic. Second, shear flow can affect the nonlinear coupling and phase relation between the different modes resonant at different radii in the RFP plasma. Control of the phase relations can in turn affect the degree of magnetic stochasticity in the plasma. Electrostatic and magnetic turbulence may also be affected by sheared flow through the turbulent decorrelation mechanisms uncovered in tokamak H-mode research.

Effect of Noncircularity: Noncircularity introduces at least three ingredients of interest. First, the poloidal asymmetry yields linear mode coupling which can affect the detailed dynamics of MHD modes. Second, noncircularity alters poloidal curvature, which dominates the magnetic curvature in the RFP. A coarse examination of the effect of curvature on interchange (Mercier) modes only, showed that circular cross-section was optimal [70]. However, this examination was limited to Mercier modes, and was not performed in combination with other parameter variations. Hence, the effect of noncircularity requires substantially more study. Third, noncircularity in part decouples the q-profile from the current density profile. For a circular shape, each is determined from the other.

Effect of Aspect Ratio: The aspect ratio affects the value of q, and consequently the number of dominant MHD modes and the toroidal coupling between the modes. Both of these effects can significantly alter the mode dynamics. The number of dominant modes decreases with aspect ratio, such that at an aspect ratio of near unity, about two modes are expected to be dominant

[71]. This would facilitate techniques of mode stabilization, as well as perhaps affect the degree of magnetic stochasticity.

Effect of External Transform: As proposed in the OHTE variation of the RFP [72] (and thereafter through a variation called a helical D-pinch [73]) external transform can provide field reversal, separate from that provided by the plasma current. The motivation for such configurations is the conjecture that field reversal provided by external fields is a more stable configuration that current-driven field reversal. This conjecture requires theoretical support, which is within the scope of the state of MHD computation.

It should be emphasized that these variations must eventually be performed together, since the various effects are coupled. This would lead to a comprehensive optimization of the RFP.

VIII RFP CONTRIBUTIONS TO PLASMA SCIENCE

The RFP is nearly unique in its role as a laboratory for the study of magnetic fluctuations and their macroscopic consequences. A few examples of such topics follow, with key open issues outlined in Part B.

The Dynamo Effect: The RFP is one of the very few laboratory examples of spontaneous magnetic field generation, with physics similarities to the naturally occurring planetary and stellar dynamos. Laboratory investigation permits a detailed investigation of the dynamics of various dynamo processes.

Magnetic Relaxation and Minimum Energy States: The Taylor minimum energy state [9] developed to describe the RFP has been applied to other situations in which magnetic relaxation occurs, such as the solar magnetic field. The conjecture of magnetic helicity conservation during energy minimization seems to be a relatively enduring principle.

Transport from Magnetic Chaos: Magnetic fluctuations in the RFP cause field lines to wander chaotically. Particle motion along the chaotic field results in anomalous transport of particles, momentum, and energy. The quantitative relationship between magnetic fluctuation properties, the chaotic wander of the field lines, and transport is a key element of RFP research. Much of the information is likely generic, applying to many situations in which the magnetic field is chaotic.

Nonlinear Coupling of Resistive MHD Modes: The RFP at medium aspect ratio consists of several dominant strongly coupled tearing modes. This is a model situation to study nonlinear mode coupling, which underlies much more complicated problems, clearly and quantitatively. The situation is much simpler than fully developed turbulence in which individual nonlinear triad interactions are difficult to assess.

Inertial Range MHD Turbulence: The high frequency MHD turbulence in the RFP displays a power law frequency spectrum, similar to that of the interstellar medium [21]. Both spectra suggest an inertial range of turbulence in which energy is cascaded from large to small scale with little dissipation, the magnetic analog of the fluid Kolmogorov spectrum. The challenge is, in part, to understand the reason for the particular exponent of the power law decay.

PART B: A US PROOF-OF-PRINCIPLE RFP PROGRAM

The timeliness of the US launch of a proof-of-principle RFP program arises from the state of scientific understanding and the status of the world program. In Section IX we describe the world RFP program outside the US, with the recent US role described in Section X. The outstanding key scientific issues which will not be addressed in the program outside the US are summarized in Section XI. All the above considerations lead to a definition of an exciting US RFP program, described in Section XII, which has the measures of performance described in Section XIII.

IX THE WORLD RFP PROGRAM

The world RFP program consists mainly of four experiments: RFX in Italy, TPE-RX [74] in Japan, MST in the US, and T2 [75] in Sweden, with parameters described in Table I. Three devices— RFX, TPE-RX, and MST —contain plasmas of similar size (minor radii of about 0.5 m). Each plasma is considered large in the RFP context, being about twice the minor radius of the RFP plasma experiments which existed throughout the 1980s. The three devices have different toroidal volt-second capability, which provides different plasma current and pulse length capabilities. RFX has a design current of 2 MA (with currently obtained values of about 1 MA), TPE-RX which just began operation in December, 1997 has a design current of nearly 1 MA, and MST operates at 0.5 MA. T2 is a refurbishment of the resistive shell OHTE experiment which operated at General Atomics in the 1980s.

Device	**Minor radius, *a***	**Major radius, *R***	**Current, *I***	**Pulse length**
MST	0.51 m	1.5 m	0.5 MA	≈0.08 s
RFX	0.46 m	2.0 m	1 MA (2 MA design)	≈0.1 s (~0.3 s design)
TPE-RX	0.45 m	1.72 m	1 MA	≈0.08 s
Extrap-T2	0.18 m	1.24 m	0.3 MA	≈0.01 s

Table I. The major devices in the world RFP program.

The four experiments have complementary activities which are coordinated through an agreement under the auspices of the International Energy Agency. The dominant goal of RFX and TPE-RX is to examine the scaling of confinement with plasma current. MST has been focused upon understanding and reducing anomalous transport (the MST program is described in more detail within the US program below). T2, which began operation in 1996, will focus on issues related to resistive wall operation. The RFP world data base on confinement performance is often depicted on a plot which indicates the energy confinement time achieved at different values of plasma current [76], as shown in Figure 1. The current is normalized in a way such that a straight line corresponds to constant beta and classical resistance. Each data point represents the best confinement achieved in a given device, and the data does not necessarily represent a scaling relation. Nonetheless, it illustrates the advances in confinement which have been accomplished over the years. The 1990s was a time of dramatic improvement in both the scientific understanding and the confinement performance in the RFP. The confinement time has increased a factor of ten in the past decade; however, a factor of five is attributed to fluctuation control which accrued from the evolving physics understanding of the RFP.

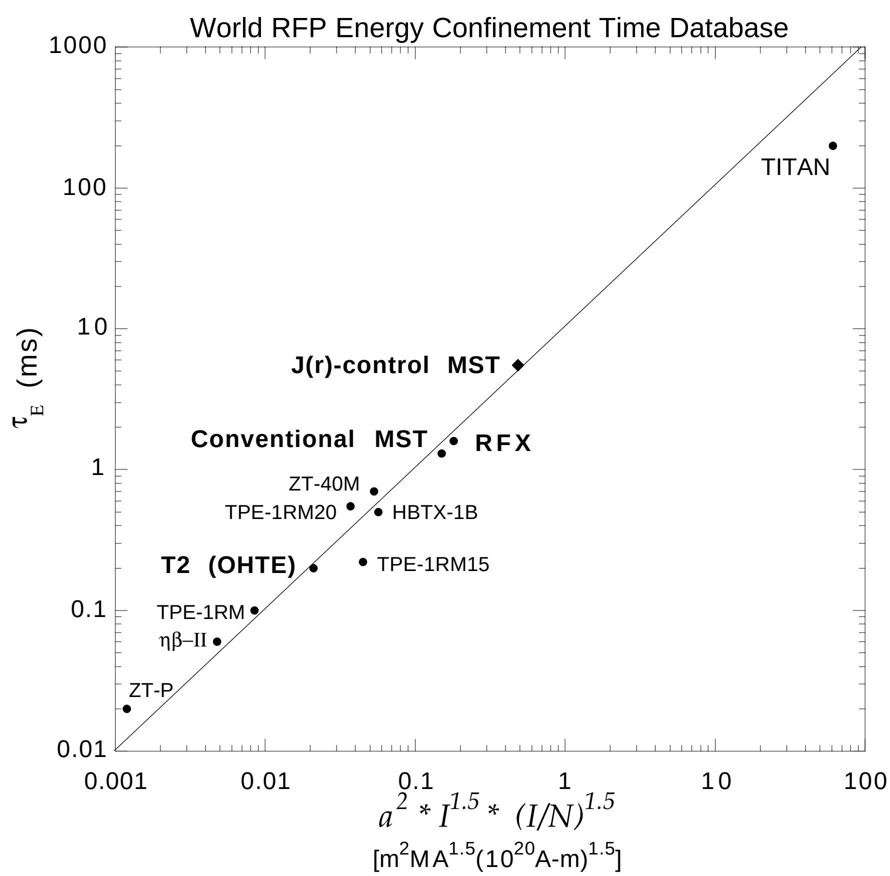

Figure 1. The world RFP best confinement time database.

X THE RECENT US ROLE IN RFP RESEARCH

The role of the US in RFP research since 1990 sets a platform from which the suggested program discussed below can be launched. It also, in microcosm form, represents the vision of the restructured US program as providing innovative niche world leadership despite larger fusion expenditures elsewhere. As a result of the complementarity between US RFP research and that elsewhere, the US has been able to operate in this manner despite factor-of-ten larger expenditures elsewhere. Only MST and the small REVERSATRON at the University of Colorado (terminated in 1994) operated in the US during the last decade.

Historically, perhaps the key weak point of the RFP, and other $q < 1$ configurations, has been the anomalous transport arising from large magnetic fluctuations. Hence, under constrained budgets, the US program focused on the understanding and reduction of fluctuation induced transport. The most tangible result of this focus has been the enunciation and development of an approach to the reduction of anomalous transport—fluctuation suppression by current profile control. An initial test of this approach has increased confinement fivefold. A more definitive test of its ultimate efficacy awaits future research. However, this result has altered our view of the RFP from one which is condemned to high turbulent transport to one which has a possible route to acceptable confinement. This view may also extend to other $q < 1$ configurations such as the spheromak. No less important, but more difficult to convey in this synopsis of the RFP, are the physics results which accrued from the US focus. Indeed, the route to confinement improvement was built on and succeeded physics discoveries in the area of fluctuation-induced transport, some of which are described in Section II.

XI OUTSTANDING SCIENTIFIC ISSUES FOR US RESEARCH

The RFP program outside the US is emphasizing the scaling of confinement with plasma current and, to a much lesser extent, effects of operation with a resistive shell. Thus, although the world program contains experiments that would be considered of a proof-of-principle scale, the integrated program is not yet at the proof-of-principle level. A proof-of-principle program, as described by FESAC, is one which investigates a broad range of scientific issues pertinent to a fusion concept. The outstanding issues which are not covered adequately in the European and Japanese programs are:

Confinement Improvement: Techniques, such a current profile control, to reduce fluctuations and transport must be tested to determine the ultimate confinement potential of the RFP. It is known that confinement is a sensitive function of magnetic fluctuations, which are a sensitive function of the controllable plasma equilibrium. Control of confinement is a relatively unexplored area of research, but one with early signs of great encouragement.

Beta Limit: Theory predicts beta limits greater than that achieved experimentally. It is unknown whether the beta of present experiments is limited by an instability or by the limitation in input power. The beta limit can be discovered experimentally by auxiliary heating. Ohmic input power in the RFP is now sufficiently low (i.e., confinement is sufficiently good) that auxiliary heating experiments are feasible. To date, auxiliary non-Ohmic power has never been applied to an RFP (with the one exception of electrostatic current injection).

Current Sustainment: All RFP experiments to date have operated with Ohmic current sustainment only. It is critical to test new techniques which have been proposed, such as oscillating field current drive, and to devise new techniques through theoretical research.

Control of Resistive Shell Instabilities: A long pulse or steady state reactor will persist for a time longer than the resistive penetration time of the surrounding structure. If it is confirmed that instabilities arise, as predicted, then techniques must be devised to stabilize the modes. The techniques may include rotation control, active feedback of helical plasma modes, or smart shell techniques.

Disruptions: Present RFP experiments operate without disruptions. With proper fueling, tens of thousands of plasma shots are achieved without sudden current terminations or any sign of a magnetic disruption event. The high density limit is “soft,” typically characterized by large radiated power. It has been conjectured that the large magnetic fluctuations of the RFP maintain the plasma in a continually relaxed state, alleviating the need for the sudden relaxation accomplished in the tokamak disruption. A key issue is whether disruptions will appear if the magnetic fluctuations of the RFP are reduced. Reduction of magnetic fluctuations, such as through current profile control, should answer this question. No disruptions have occurred in the current profile control experiments accomplished to date.

New RFP configurations: Understanding of the RFP has evolved to the point that modified RFP configurations can be devised: “advanced RFP” concepts which are designed to improve the RFP. Perhaps the first successful example of a modified RFP is one with current profile tailoring for magnetic fluctuation reduction. However, an exciting prospect is to optimize the RFP profiles (current, pressure, and flow) and geometry (aspect ratio, shape, and external transform), as described in Section II.

Systems Studies: The last systems study, TITAN, was completed in 1990 [13]. This multi-institutional study, organized by a “neutral” laboratory, was extremely useful at depicting important areas for research and for demonstrating the attractiveness of the RFP concept (under certain physics assumptions). A restart of systems studies is appropriate to incorporate the dramatic advances in the RFP since 1990, to incorporate new RFP results anticipated in the coming years, to incorporate advances in physics and engineering in tokamaks and other areas, and to provide guidance to RFP research. In addition to steady state reactor studies, the benefits and drawbacks of a pulsed reactor should be examined.

Basic Plasma Studies: Basic plasma physics studies underlie most of the issues described above, and the required advances are too vast to cite here in detail. However, as examples, we note that it remains to determine the active dynamo mechanisms under various plasma conditions, to understand the link between magnetic chaos and transport, to determine the dynamics of the high frequency turbulent cascade, to determine whether magnetic chaos and transport can be eliminated, and to determine the link between helicity (current) transport and energy transport. The capability to vary controllably the magnetic fluctuations by current profile control presents a unique opportunity for controlled experiments in this range of phenomena.

Theoretical RFP research: Theoretical RFP research outside the US is extremely scarce. Theory is needed on numerous key issues such as the cause of electrostatic fluctuations in the RFP; the influence of shear flow on fluctuations in the RFP; the role of current, pressure, and flow profiles on fluctuations and transport; the role of plasma shape, aspect ratio and external transform on fluctuations and transport; the effect of oscillating field current drive on transport; evaluation of beta limits and beta optimization; the role of collisionless reconnection on RFP behavior; the feedback or “smart” shell stabilization of resistive wall instabilities; the evaluation of nonlinear mode coupling; the understanding of the variety of possible dynamo mechanisms. This list is not exhaustive, but illustrative that the theoretical issues are both fundamental in their scientific nature and critical to RFP development.

XII A US PROOF-OF-PRINCIPLE RFP PROGRAM

The level of scientific understanding of the RFP and its potential contributions to fusion energy research warrant the upgrade of the existing US RFP effort to one which, when combined with the programs in Europe and Japan, is a proof-of-principle program. There are several notable features of a US proof-of-principle program: (1) it does not, at present, require the construction of larger RFP facilities. Through the exploitation of present facilities, a proof-of-principle RFP program can be assembled with extreme cost-effectiveness. (2) at relatively modest expenditure the US can have huge impact on development of the RFP concept, and can maintain and expand its world leadership in this area, and (3) the research affects directly the evolution of the spheromak, and investigates a variety of issues generic to several concepts.

A US proof-of-principle RFP program should consist of the MST experiment investigating a range of RFP issues, one or more specialized experiments investigating specific scientific issues or optimized RFP configurations, theoretical research complementing experimental work and investigating fundamental issues, and systems studies. The individual elements are elaborated below.

The MST Experiment as a Proof-of-Principle Facility: At present, MST is dedicated to understanding and reducing transport. In these endeavors, it is limited severely in both diagnostics and auxiliary systems to control the current density profile. The MST facility is capable of an aggressive attack on confinement improvement by current profile control, and of studies of beta limits and current sustainment. The US is in the fortunate position that it can attack these issues without construction of a new large facility. Rather, upgrades are required only in control systems and diagnostics. With auxiliary current drive systems (for example, lower hybrid current drive) MST can examine the limits of confinement improvement by current profile control; with auxiliary heating MST can discover the RFP beta limit; with appropriate power systems MST can test oscillating field current drive for current sustainment; with appropriate diagnostics MST can expand its unique, fundamental studies of RFP dynamics.

MST can accommodate antennas for lower hybrid current drive, likely employing combline antennas which have a small radial build, suitable for placement in the narrow space between the plasma and the close fitting shell. Ray tracing and current drive efficiency calculations indicate that 800 MHz is an acceptable frequency, as well as a frequency at which high power klystron sources are available. Lower hybrid waves will also be used for auxiliary heating. Confinement in MST is now sufficiently good, and the Ohmic input power sufficiently small, that the required auxiliary heating power for beta studies is becoming feasible.

Similarly, the resistance of the MST plasma is sufficiently low that a test of Oscillating Field Current Drive is feasible. Substantial bulk current drive requires oscillations of poloidal and toroidal loop voltages of about 100 V, which is consistent with the electrical properties of the gaps in the MST shell. A capacitor bank driven oscillating power supply can be employed.

The injection of auxiliary power into MST will likely require alterations in other operational characteristics of MST, such as control of the plasma-wall interaction and magnetic field errors. MST was designed for relatively easy disassembly so that the limiters, liners, or armor systems could be optimized. It presently has effective boronization and discharge cleaning systems. Magnetic field error control, critical for minimizing plasma-wall interactions, can be upgraded from the present mostly passive control system, to an active feedback system. There are no known intrinsic obstacles in the MST design with regard to achieving the physics and performance goals outlined in the performance measures of the Section XIII. The plasma size, current, and pulse length are all sufficient.

The MST diagnostic set must be upgraded to accommodate the new physics goals. Diagnostics are needed for basic transport measurements (such as multi-point Thomson scattering for electron temperature profiles and FIR polarimetry for current density profiles), for basic equilibrium measurements (such as charge exchange recombination spectroscopy for ion flow and heavy ion beam probing for electric potential), and for specialized fluctuation measurements (such as CHERS and Rutherford scattering for ion dynamics, and HIBP for density and potential fluctuations).

It is anticipated that the MST program will expand its program of collaborations, which is already rather active.

Exploratory RFP Experiments: There is a rich set of opportunities which warrant exploration at the exploratory level. These include well-defined issues and modified RFP configurations which promise advantages. One example of a key issue which can be explored in devices of modest scale is the resistive wall problem. Resistive wall instabilities are governed by MHD which is active in RFP experiments of all scales. One example of a modified RFP configuration is a low aspect ratio RFP. At low aspect ratio the number of dominant resistive MHD modes decreases such that the level of stochasticity might be decreased or the feasibility of mode control might be increased.

Theoretical Studies: There is a critical need for theoretical research in the range of areas discussed in the previous section. The major advances in RFP research in the US in the past five years have been a result of strong connection between experiments and focused theoretical work. However, although theoretical research has been significant, it has been nearly negligibly small in magnitude (worldwide, as well as in the US). An RFP program exploiting even the present experimental facilities requires a much more comprehensive US theory effort.

System Studies: RFP research would be greatly aided by a systems studies effort appropriately scaled to the experimental effort. Elaborately detailed power plant investigations may be premature. However, an appropriately quantitative assessment of the reactor embodiment of the RFP concept can be a crucial guide to the broader RFP research program.

The cost of the proof-of-principle US RFP program described above is likely in the vicinity of $10 million per year. Roughly half of the expenditure would be dedicated to the MST experiment, with the other half distributed among smaller experiments, theory, and systems studies. These costs are only meant to anticipate the scale of the program, and are not accurate cost assessments. Nonetheless, it is clear that the RFP represents an exciting research area in which the US can be at the world forefront in physics and performance, at the proof-of-principle level, for a relatively modest cost.

XIII PERFORMANCE MEASURES

The US proof-of-principle program, combined with the international program, will yield key results on most of the major scientific issues presently known to confront the RFP. These results will have impact on many aspects of fusion science. But they will also enable an informed decision on whether to proceed further with RFP development, either to RFP studies at parameters closer to a reactor (a proof-of-performance experiment) or to a modified RFP configuration. Below we outline the results anticipated in the four areas of confinement, beta limits, resistive wall stability, and current sustainment. In each case we provide measures of success—results which would contribute to a positive decision on further RFP research.

Confinement: The confinement goal is to obtain an energy confinement time of at least ten ms, with temperatures of at least 1 keV, and with sufficient physics understanding to construct at least a plausibility argument for favorable scaling. There are two approaches to achieve this goal in the world program. In the US, profile control will be employed to reduce fluctuations and thereby improve confinement at a fixed plasma current of 0.5 MA. Some understanding of the residual fluctuations must be acquired to permit a scientifically-based assessment of the confinement prospects at higher current. In Europe and Japan, increased confinement time will be sought through operation at high current, up to 2 MA in RFX. If the confinement time increases from the present 1 ms (in RFX discharges without profile control) to 10 ms, some understanding of the scaling of magnetic fluctuation induced transport should accrue. The value of 10 ms is chosen as a target since the optimistic oft-used constant beta scaling predicts such confinement for 2 MA RFX discharges, which is the stated goal of that program. Achieving such confinement through profile control at 0.5 MA would clearly be an extremely encouraging result.

Beta limits: Present experiments operate readily at beta values (ratio of volume averaged pressure to edge magnetic pressure) of about 10%, with excursions to higher beta (up to 20%) at very low current. The goal of beta studies in the planned program is to obtain a beta value of 15% at plasma current of 0.5 MA or greater, and to determine the beta limit to stability. These goals can be achieved by transport reduction by profile control and/or auxiliary heating. The RFP beta limit may occur as a hard ideal MHD stability limit or a softer beta limit (such as arising from resistive MHD instabilities) which appears as degraded confinement at high beta. These studies will be included within the US program. The value of 15% is selected using the TITAN RFP reactor design as a guide. TITAN assumed a poloidal beta value of 23%, with cost increasing significantly as beta drops below 10%.

Resistive wall instabilities: The goal of resistive wall studies is to determine the instability properties of ideal and resistive MHD modes with a resistive wall and, if unstable, to demonstrate adequate control. Control can occur through techniques such as helical feedback of specific modes or a smart shell. Study of resistive wall instabilities, and their stabilization, can be accomplished in exploratory concept experiments. Large size, current, or temperature is not required. These topics will be, at least in part, addressed in the T2 experiment in Sweden, and may be candidates for an exploratory concept experiment in the US.

Current sustainment: The US proof-of-principle program will determine whether oscillating field current drive is a sustainment technique which is both efficient and compatible with good confinement. Hence, the goal is to obtain a current drive efficiency of ~0.1 A/W with energy transport compatible with the confinement goals stated above. The value for the efficiency is selected again using the TITAN design as guidance.

In summary, the proof-of-principle program will encourage procession to the next step in RFP research if it produces plasmas with energy confinement times of 10 ms at temperatures of at least 1 keV with some expectation of continued favorable scaling, with beta values of 15% at a plasma current of 0.5 MA and a determination of the beta limit, with control of resistive wall modes, and with efficient current sustainment compatible with good confinement. These goals provide quantitative measures with which to assess the RFP next steps, if any, at completion of the planned program. However, a realistic appraisal is only made with consideration of the following two points. First, the numerical guidelines are based on reactor studies which are themselves approximate. The parameters achieved will be most meaningful when judged in the context of scientific understanding. Second, the planned RFP program will incorporate study of modified RFP configurations (modified geometry and profiles) with the aims, for example, of improved confinement or beta values. These studies can proceed, in part, through exploratory experiments. If successful, these results may be incorporated into future RFP plans in ways not anticipated presently.

The flow of progress anticipated in an integrated world RFP program, with the US program recommended above, is depicted in Figure 2. The proof-of-principle program will require roughly six years to complete. Towards the end of that period, a decision will be made to either proceed to a test of the continuation of favorable results to plasmas of higher current and longer duration and/or to proceed to an RFP with a modified configuration, or to reduce RFP research if the results are unfavorable.

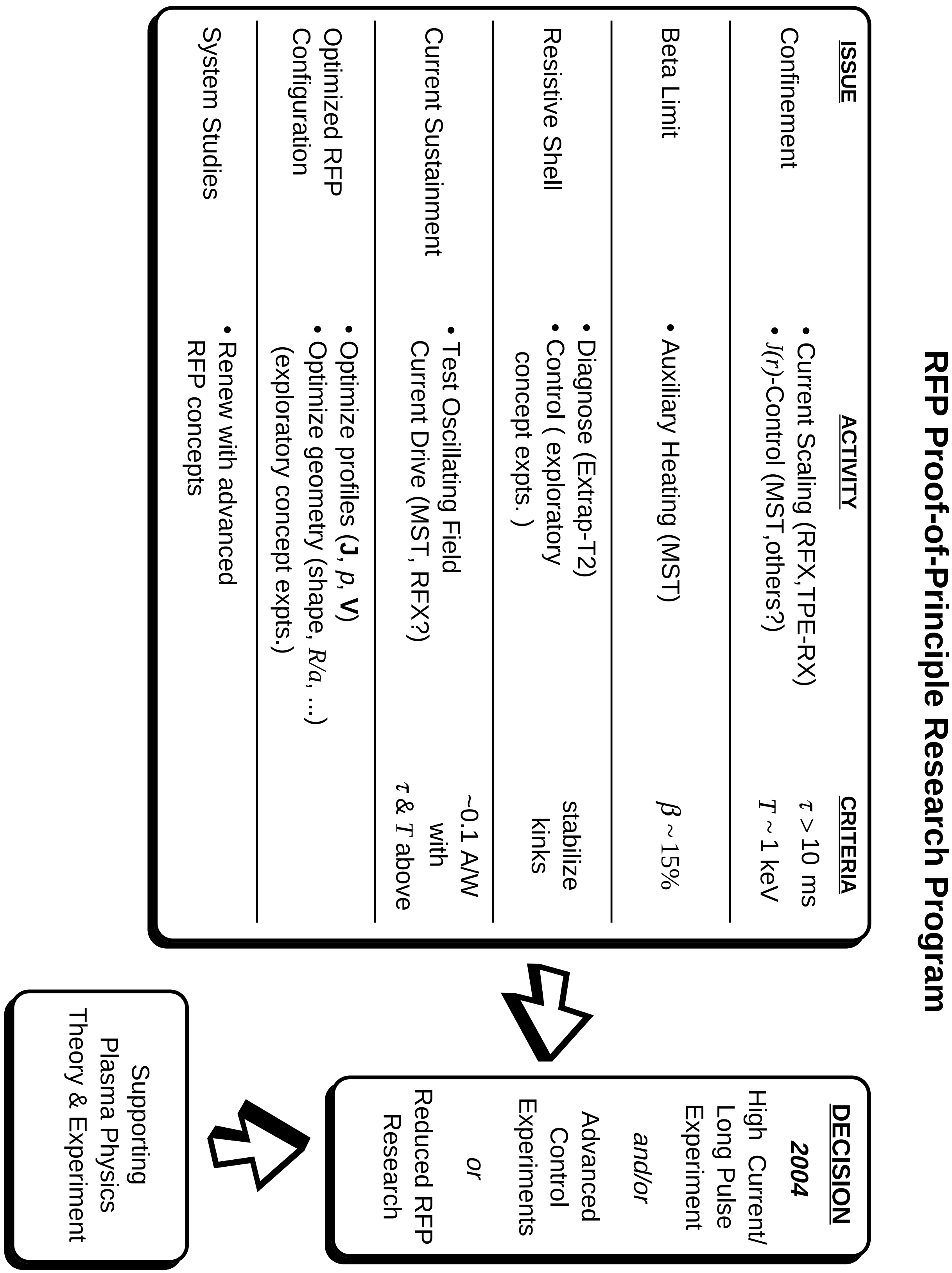
RFP Proof-of-Principle Research Program
ISSUE
ACTIVITY
CRITERIA
Confinement
• Current Scaling (RFX,TPE-RX)
• J(r)-Control (MST,others?)
τ > 10 ms
T ~ 1 keV
Beta Limit
• Auxiliary Heating (MST)
β ~ 15%
Resistive Shell
• Diagnose (Extrap-T2)
• Control (exploratory concept expts.)
stabilize kinks
Current Sustainment
• Test Oscillating Field Current Drive (MST, RFX?)
~0.1 A/W with τ & T above
Optimized RFP Configuration
• Optimize profiles (J, p, V)
• Optimize geometry (shape, R/a, ...) (exploratory concept expts.)
System Studies
• Renew with advanced RFP concepts
DECISION
2004
High Current/ Long Pulse Experiment
and/or
Advanced Control Experiments
or
Reduced RFP Research
Supporting Plasma Physics Theory & Experiment

Figure 2

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