THE REVERSED FIELD PINCH
A Proposal for RFP Research in the U.S.

prepared by

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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, the development of a new path to improved confinement, 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.

The opportunity presently available to the U.S. in RFP research is rather remarkable. From the viewpoint of the world RFP program, there is a strong need for the U.S. to embark on a proof-of-principle program — an effort which attacks a broad range of the key scientific issues confronting the RFP. The world program outside the U.S. 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-U.S. 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 understanding and improvement by advanced techniques
- beta limits
- current sustainment
- control of resistive shell instabilities
- power and particle handling
- modifications to the RFP configuration for improved performance

The U.S. RFP program is poised to attack aggressively most of these outstanding issues. Since an existing experimental facility, properly utilized, can function as the proof-of-principle experiment, the U.S. can launch a national proof-of-principle program which will be at the world forefront, at relatively modest cost. Such a research plan will also have large impact on the very similar issues confronting the spheromak. Indeed, the RFP issues will be investigated in the context of broad fusion science issues, and comparative studies with other magnetic configurations will be pursued actively when pertinent.

The recent advances in RFP physics and performance build upon a long history of RFP research, beginning with the discovery of toroidal 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 construction began on the nonlinear MHD foundation of the RFP [7,8], following on the insight that the RFP can be described as a minimum energy, magnetically relaxed state [9]. This experimental and theoretical work 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. This result has altered our view of the RFP from a configuration 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.

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 [12] with normal (not superconducting) coils, high beta, very high engineering beta (pressure normalized to magnetic pressure at the field coils), high power density, low field and force at the coils, absence of disruptions (absent in experiments), and possibly free choice of aspect ratio (can be determined by engineering considerations possibly without physics constraint).

A strong scientific foundation supports the proposed program. RFP physics is sufficiently advanced that the key questions can be clearly formulated, and experimental and theoretical solutions posited. In part A of this proposal we articulate the present understanding and open questions for each of the crucial scientific areas for the RFP. In the past decade, many key discoveries have emerged, critical to RFP development, but also of large basic plasma physics importance. Some of the more pertinent results are:

- identification of magnetic fluctuations as resistive MHD modes
- experimental determination that magnetic fluctuations drive energy transport interior to the toroidal field reversal radius
- experimental determination that magnetic fluctuations drive particle transport interior to the toroidal field reversal radius
- experimental determination that electrostatic fluctuations drive edge particle transport
- experimental confirmation of the MHD dynamo in the collisionless edge

- discovery of a pressure-drive “diamagnetic dynamo” in the collisional edge
- fluctuation reduction and five-fold confinement improvement with current profile control
- feedback stabilization of ideal kink instability with a resistive shell
- observation of particle confinement improvement with induced radial electric field
- observation of flow shear in the edge of RFP plasmas with spontaneously reduced fluctuations and transport (under particular operating conditions)

The timeliness of the U.S. launch of a proof-of-principle RFP program, depicted in Part B of this proposal, arises from this state of scientific understanding and the status of the world program. The world RFP program consists mainly of four experiments: RFX in Italy, TPE-RX in Japan, MST in the U.S, and Extrap-T2 in Sweden. The first three devices are of about the same size, all large within the RFP context (minor radii of about 0.5 m). The plasma current capabilities of the devices differ: 0.5 MA in MST, 1 MA in TPE-RX, and 2 MA design value for RFX. The focus of these experiments has been confinement. The MST program has been very broad in its approach to understanding RFP transport physics, but it has also produced plasmas with record confinement through current profile control. The world program outside the U.S. will continue its emphasis on confinement scaling with plasma current (RFX and TPE-RX) and diagnosis of resistive shell instabilities (Extrap-T2).

Thus, the proposed U.S. proof-of-principle program will be unique. Its main scientific areas and goals are:

Confinement improvement and understanding: The improved confinement to date has been obtained with relatively coarse inductive current profile control. We propose to implement finer forms of current profile control: electrostatic current injection and lower hybrid current drive. The aims are to further improve confinement and to determine the ultimate lower limit to magnetic fluctuations and transport. Detailed core fluctuation measurements and well-diagnosed transport experiments are needed to improve our understanding of the basic transport mechanisms.

Beta limits: All RFP experiments produce plasmas with beta values in the range of 10%. However, beta limits to ideal MHD stability are in the range of 30-50%, depending on the details of the magnetic equilibrium. It is not known experimentally whether the achieved beta values are limited by the Ohmic input power or by a stability limit. The confinement of improved RFP plasmas is now sufficiently high that auxiliary heating can be accomplished with feasible amounts of power. We propose to implement lower hybrid heating and neutral beam heating to determine the beta limit in the RFP.

Sustainment of the plasma current: All RFP experiments have been sustained by Ohmic current drive. We propose to test the technique known as oscillating field current drive, in which magnetic helicity is injected into the plasma by applying oscillating toroidal and poloidal loop voltages. Plasma relaxation then maintains the desired current density profile. A definitive test of the technique has not been possible in smaller devices since the high plasma resistance mandates impractically large oscillating voltages for current sustainment. Today's large RFP experiments have sufficiently low resistance for a definitive test of the technique. Experiments will aim to determine the current drive efficiency and to examine whether the technique affects confinement.

Control of Resistive Shell Instabilities: In a long pulse reactor, resistive shell instabilities must be stabilized by techniques such as rotation, feedback, or "smart" shells. This study is suitable for a concept exploration experiment.

New RFP Configurations: RFP understanding has advanced to the point that modified RFP configurations can be developed. Possibilities include RFP plasmas with modified geometry (aspect ratio and shape) or profile control (of current, pressure, flow profiles). There is interest within the U.S. in low aspect ratio RFP plasmas which would likely contain a smaller number of dominant Fourier MHD modes. There is also interest in exploring RFP plasmas with external transform, in particular to determine whether field reversal provided externally will lead to reduced fluctuations.

The U.S. program designed to accomplish these goals consists of the MST experiment operated as a proof-of-principle facility, smaller concept exploration experiments, theory and computation, and system studies. It is not necessary, at this time, to construct a new, larger facility. We propose that the MST program be expanded to accomplish the first three goals listed above — confinement improvement, beta limit studies, and current sustainment. MST is capable of functioning as such a proof-of-principle facility *if* it is provided with adequate control systems (for current profile control, heating, sustainment) and appropriate diagnostics. Concept exploration experiments are needed to address specific issues, such as the latter two topics — resistive shell instabilities and new RFP configurations. RFP behavior is strongly influenced by MHD physics; hence, smaller experiments can be pertinent to RFP development.

Theoretical RFP research is extremely scarce worldwide. Theory is needed on numerous key issues such as the cause of electrostatic fluctuations in the RFP; the coupling of core to edge turbulence and transport; the influence of flow shear 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. Finally, systems studies are needed to guide the experiments, to incorporate RFP results as they evolve and to incorporate results from the larger fusion community.

We propose to base the evalutation of the U.S. RFP program on the following performance measures:

Confinement: Achieve 10 ms confinement time, at a temperature ≥1 keV, with some expectation of continued favorable scaling.

Beta: Achieve beta values of ≥15% at a plasma current of 0.5 MA and determine the origin and magnitude of the beta limit.

Current sustainment: Achieve efficient current sustainment compatible with good confinement, using oscillating field current drive.

Resistive shell instabilities: Demonstrate control of multiple resistive shell modes.

We anticipate that this program will require about six years to complete. Toward the end of that period, a decision will be made either to proceed to continued tests of favorable results in 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.

It is notable that the cost of the program is relatively modest since construction of a new, larger facility is not needed. The cost is in the vicinity of $10 million per year. This expenditure includes present RFP funding of about $2.5M per year; thus the proposed program would require additional funds of about $7.5M per year. Roughly half of the $10M will be dedicated to the MST experiment. The other half will be distributed among smaller experiments, theory, and systems studies. Theoretical research, including system studies, will require about $2M per year. The cost of the exploratory concept experiments is difficult to assess, since the experiments have not yet been formulated. However, once such experiments are in operation we anticipate the expenditure will be of order $3M per year. These costs are only meant to anticipate the scale of the program; they are not accurate cost assessments. Nonetheless, it is clear that the RFP represents an exciting research area in which the U.S. can be at the world forefront in physics and performance, at the proof-of-principle level, at modest cost. Indeed, the FESAC 1996 report on alternative concepts [13] identified the RFP as being ready for further advancement and recommended a “strengthening and broadening of the existing RFP program.” An 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.

This proposal enjoys the support and represents the views and interests of the scientists listed in Appendix I. This group consists exclusively of scientists who have been involved in RFP research in the past or present and have a continuing research interest. The group includes experimentalists, theorists, computationalists, and fusion system engineers. Hence, it includes the expertise needed to launch the proposed program. The U.S. program will also continue to be strongly interactive with the world program, coordinating activities to optimize the overall effort.

Contents

PART A: SCIENTIFIC ISSUES IN RFP RESEARCH

Below we summarize the dominant scientific issues relevant to the development of the RFP as a fusion concept. For each issue, we delineate the scientific status and the open questions. In Section I we summarize anomalous transport in the RFP. In Sections I.A. to I.E., 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 II), beta limits to plasma stability (Section III), current sustainment (Section IV), power and particle handling (Section V), and optimized RFP configurations (Section VI). The substantial contributions of RFP research to basic plasma science are outlined in Section VII.

I. TRANSPORT

A. The Origin of Fluctuations

Status: 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 attributed to 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 has revealed the dynamics by which the plasma maintains an approximate magnetically relaxed Taylor state.

Recently, magnetic fluctuation reduction has been demonstrated by controlling the current density profile [19]. This technique has succeeded in halving the fluctuation magnitude and 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 in the RFP 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]. These fluctuations are partly correlated with the magnetic fluctuations, implying a parasitic relationship. However, the correlation is not perfect. Fluctuations resemble, in their amplitude and broad-band nature, electrostatic fluctuations in tokamaks and stellarators. However, the origin of electrostatic fluctuations in the RFP is yet undetermined (as is the case for most other magnetic configurations). 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 RFP 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 partly 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 offer the model situation of MHD turbulence driven by large scale structure produced by the tearing modes [21]. Theoretical calculation is consistent with this view, but experimental work is needed for confirmation.

A major unknown is the cause of electrostatic fluctuations. It is possible that the search for a “mode” is not the optimal approach. For example, the strong core fluctuations may drive the RFP plasma edge into a self-organized critical state. Such a situation can form a basis for the commonality of edge fluctuation properties in several magnetic configurations. Analysis of fluctuation data indicates that the RFP, stellarator, and tokamak have similar long-range correlations. The self-similarity parameter for these three configurations is in a very narrow range of values. This approach to edge fluctuations may explain the universality of edge turbulence. Correlation data and further comparisons among different experimental configurations are needed to test these ideas.

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

B. 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 input power has been limited. Nonetheless, electron temperature profiles are relatively flat in the core region and steep in the outer portion of the plasma (although more peaked profiles occur in improved confinement plasmas). There has long been an expectation, supported by MHD computation, that the magnetic field in the core of the RFP becomes stochastic from the overlap 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 electron motion 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 radius) magnetic fluctuations do not drive transport, but interior to the reversal radius 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 it occurs 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 it is 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.

C. Particle Transport

Status: Particle transport in the RFP is anomalous by about 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 the electron flux from magnetic fluctuations (from the correlated product of the fluctuations in the parallel electron flux and radial magnetic field) proves that the transport is magnetic interior to the toroidal field reversal radius [34]. However, outside the reversal radius, in the extreme edge, the particle flux is measured to be driven by electrostatic fluctuations [22-25].

Open issues: As is the case for energy transport, the core particle transport from fluctuations remains largely undiagnosed. Impurity transport and plasma-wall interactions (recycling, particle sources, etc.) are not well understood in the RFP.

D. 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 instabilities. 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]. While this theory is 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 (inferred from the measured fluctuating electric field) and magnetic field fluctuations [43]. Spectroscopic measurements of velocity fluctuations in the core are underway [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 received little theoretical treatment. A thorough understanding requires a two fluid treatment.

E. 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 profile 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 tailor finely 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 $\mathbf{E}\times\mathbf{B}$ flow shear layer and by a reduction in both magnetic and electrostatic fluctuations (both large and small scale) in the edge. The applicability to the RFP of the paradigm of flow shear reduction of turbulence, highly developed for the tokamak, is a topic of present research.

Open issues: The improvement of confinement by current profile control is still an emerging research area. The next steps are to develop profile control techniques that 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 it 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 $\mathbf{E}\times\mathbf{B}$ flow shear on RFP fluctuations and transport is a new research area. Many fundamental questions remain. Does $\mathbf{E}\times\mathbf{B}$ flow shear affect large-scale electrostatic fluctuations and magnetic fluctuations, in addition to the small-scale electrostatic turbulence typical of tokamaks? What governs the spontaneous generation of flow shear in the RFP? Does coupling of electrostatic fluctuations to the large magnetic fluctuations alter the dynamics? Research to answer these questions is beginning.

Another approach to improved confinement in tokamaks is core fueling, particularly when coupled with auxiliary heating. The applicability of this approach to the RFP should be explored.

II. 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 [55,56]. 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 constant current 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 [57]. Modest rotation produces near to perfect conducting boundary conditions for resonant modes, but for nonresonant modes, near-Alfvenic velocities may be required for stabilization [58].

Experiments in the HBTX device operated with a resistive shell displayed growing modes in rather close agreement with prediction [59]. 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 [60]. 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 [61]. 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 [62].

III. BETA LIMITS

Status: The poloidal beta value (ratio of volume-averaged plasma pressure to surface magnetic pressure) is believed to be 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 magnetic field has average bad curvature, dominated by the poloidal field since q <1. Stability is provided by magnetic shear; the field rotates more than 90º from the center to the edge. Pressure profiles are found which can be ideal MHD stable with poloidal (and total) beta values <50% [63]. 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 they merely set by the limited Ohmic input power.

Large-scale pressure-driven resistive 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 instability is reduced, the pressure will increase and become the dominant driver of tearing instability 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.

IV. SUSTAINMENT OF THE PLASMA CURRENT

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. Current drive is more challenging for the RFP 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 [64,65, 66]. 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 [67].

Open issues: OFCD requires a definitive experimental test in a plasma large enough (with resistance small enough, as in existing experiments) 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 which transports the edge-driven current inward will also transport energy outward.

V. 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 Extrap-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 [12]. 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 [68].

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 [54,69]. 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 [70]. 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. The dispersal of the heat load by deliberately forming a highly radiating plasma is a key TITAN design feature likely to be incorporated in any high beta, compact reactor concept. It is critical to develop experimentally a radiative edge and/or core while not affecting core transport — a task which the RFP shares with the tokamak. A related issue that 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 area of intense RFP research.

VI. OPTIMIZED RFP CONFIGURATIONS

Understanding of the RFP has evolved to the point that modified RFP configurations can be devised: “advanced RFP” concepts that 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 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 observed values of beta, the pressure gradient contributes weakly to the generation of instability. The dominant source of fluctuations and transport is the parallel current gradient. However, as current profile control reduces fluctuation-induced transport, it is expected that the plasma beta will increase until the pressure gradient determines the MHD stability. 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: Flow shear can affect MHD fluctuations in several ways. First, flow shear at the resonant surface is known to be stabilizing to tearing modes [71,72]. The effect may be altered for the RFP situation in which islands overlap as the field becomes stochastic. Second, flow shear 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. Also, electrostatic and magnetic turbulence may be affected by flow shear through the turbulent decorrelation mechanisms uncovered in tokamak H-mode confinement research.

Effect of Noncircularity: Noncircularity introduces at least three ingredients of interest. First, the poloidal asymmetry yields linear mode coupling that 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 showed that a circular cross-section was optimal [73]. But this result is limited to Mercier stability, and noncircularity must be studied in combination with other parameter variations, requiring substantially more research. 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 [74]. 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 [75] (and thereafter through a variation called a helical D-pinch [76]) 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 than current-driven field reversal. This conjecture requires theoretical support, which is within the scope of state-of-the-art MHD computation.

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

VII. RFP CONTRIBUTIONS TO PLASMA SCIENCE

The RFP is 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. In particular, the RFP offers a test of the applicability of relaxation principles to driven/damped systems.

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 clearly and quantitatively the nonlinear mode coupling which underlies much more complicated problems. The situation is, in part, simpler than fully developed turbulence in which individual nonlinear three-wave 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 and the partitioning between magnetic energy and kinetic energy (e.g., the Alfven effect).

Flow Shear Generation: Sheared $\mathbf{E} \times \mathbf{B}$ flow is observed in RFP plasmas with spontaneously improved confinement. The existence in the RFP of large magnetic turbulence, torques associated with field errors, and weak neoclassical flow damping make both the driving forces and dissipation of flow different than for the tokamak. Study of flow and flow shear generation in the RFP can thus shed new light on this still poorly understood process.

PART B: A U.S. PROOF-OF-PRINCIPLE RFP PROGRAM

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

VIII. THE WORLD RFP PROGRAM

The world RFP program consists mainly of four experiments: RFX in Italy, TPE-RX [77] in Japan, MST in the U.S., and Extrap-T2 [78] 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. Extrap-T2 is a refurbishment of the resistive shell OHTE experiment which operated at General Atomics in the 1980s. There are, in addition, several smaller RFP devices in Japan investigating specific issues.

Device	**Minor radius, *a***	**Major radius, *R***	**Current, *I***	**Pulse length, τ_{pulse}**
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 that 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 below in more detail within the context of the U.S. program.) Extrap-T2, which began operation in 1996, will focus on issues related to resistive wall operation. The RFP world database on confinement performance is often summarized in a plot which indicates the energy confinement time achieved at different values of plasma current [79], 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; however, 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.

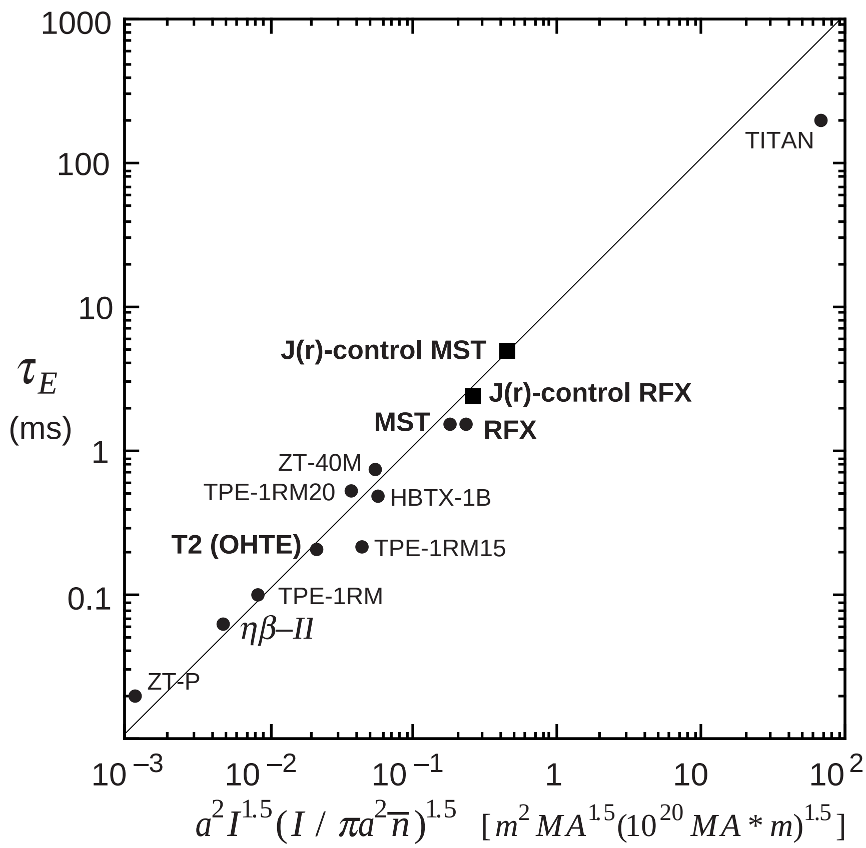

Figure 1. The world RFP best confinement time database.

IX. THE RECENT U.S. ROLE IN RFP RESEARCH

The role of the U.S. in RFP research since 1990 sets a platform from which the suggested program discussed below can be launched. It also typifies the vision of the restructured U.S. program: providing innovative niche world leadership despite larger fusion expenditures elsewhere. As a result of the complementarity between U.S. RFP research and that elsewhere, the U.S. 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 U.S. 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 U.S. 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 five-fold. 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 U.S. 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 I.

X. OUTSTANDING SCIENTIFIC ISSUES FOR U.S. RESEARCH

The RFP program outside the U.S. 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 as 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 a beta limit greater than 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 using 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 in the edge).

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 I.

Systems Studies: The most recent RFP systems study, TITAN, was completed in 1990 [12]. This multi-institutional study 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 is extremely scarce worldwide. Theory is needed on numerous key issues such as the cause of electrostatic fluctuations in the RFP; the influence of flow shear on fluctuations; the understanding of flow shear generation; 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.

The issue of power and particle handling will be partially covered in the world RFP program. Although there are no specific plans for divertor studies, the investigation of highly radiating plasmas is included in the research plans of the existing RFP experiments.

XI. A U.S. PROOF-OF-PRINCIPLE RFP PROGRAM

The level of scientific understanding of the RFP and its potential contributions to fusion energy research warrant an upgrade of the existing U.S. RFP effort to one which, when combined with the programs in Europe and Japan, becomes a proof-of-principle program. There are several notable features of a U.S. proof-of-principle program. (1) It does not, at present, require the construction of larger RFP facilities. Through the effective exploitation of present facilities, a proof-of-principle RFP program can be assembled with extreme cost-effectiveness. (2) At relatively modest expenditure the U.S. can have a huge impact on the development of the RFP concept, and it can maintain and expand its world leadership in this area. (3) The research affects directly the evolution of the spheromak and investigates a variety of issues generic to several concepts. A key attribute of the program is that it will be closely coordinated with the international RFP program, including substantial collaboration. This will be a natural extension of the present working agreements between the main RFP laboratories.

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

A. 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 necessary to measure and 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 U.S. 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. In the following paragraphs, after a brief description of the MST facility, we outline the proposed activities in current density profile control for transport reduction (via inductive, electrostatic, and lower hybrid current control), in beta limit studies using auxiliary heating, in current sustainment by oscillating field current drive, in transport measurements through profile diagnostics, and in fluctuation and fluctuation-induced transport measurements. Finally, we discuss briefly the MST program schedule, staff, and cost.

The MST Facility

MST is very well-suited, in many ways uniquely suited, to all the proposed tasks. MST is unusually flexible and robust, technically capable of accommodating plasmas with temperature >1 keV, confinement time >10 ms, and auxiliary input power >2 MW. The MST facility is pictured in Fig. 2 showing the torus surrounded by diagnostics and other supporting equipment. Figure 3 shows a view of the disassembled lower half of the torus with the center column of the 2 V-s iron core protruding in the center. MST contains four unique design features. (1) The aluminum shell functions as a single-turn toroidal field winding, producing a very low ripple toroidal magnetic field and eliminating the need for a separate toroidal field windings. (2) The poloidal field windings are wrapped around the iron core, leaving the torus entirely unencumbered by magnet windings and relatively easy to disassemble. (3) The 5-cm-thick aluminum stabilizing shell also serves as the vacuum vessel, eliminating the need for a thin, fragile vacuum liner characteristic of other RFP devices, and (4) the vacuum pumping occurs through 193 small holes (1.5" D) spread around the torus (Fig. 3), obviating the need for large holes which produce deeply penetrating field errors.

These design features yield the following machine properties, suitable for a proof-of-principle facility:

Accommodation of high wall loading: The MST is particularly robust to wall damage and amenable to first-wall modifications. MST can operate at high power without fear of damage to the 5 cm thick vacuum vessel. This is in sharp contrast to other RFPs in which the potential for

Figure 2. The Madison Symmetric Torus (MST).

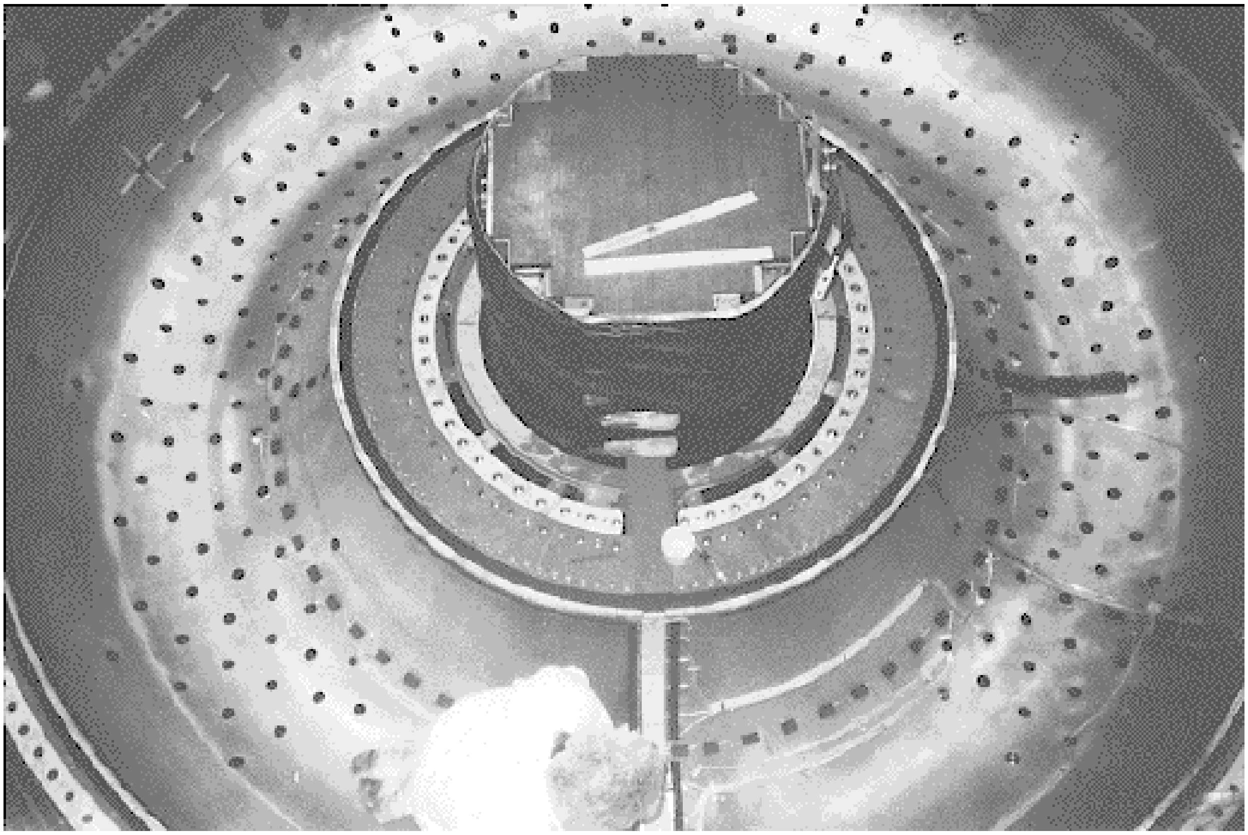

Figure 3. The lower half of MST disassembled. The 193 pumping holes dot the surface.

catastrophic damage to the fragile vacuum liner provides a severe constraint on operation. Indeed, MST operates without difficulty with Ohmic input power of 15 MW and edge localized input power (by electrostatic injection) of 3 MW. However, under good confinement conditions, MST operates with reduced Ohmic input power between 1 MW and 3 MW. Hence, the improved plasma conditions hoped to be obtained with auxiliary power input will actually operate with smaller wall loading than that already accommodated by MST. Naturally, the challenge of impurity control will be enhanced as we inject RF power and strive further for improved confinement. Fortunately, as a result of the easy disassembly of MST, a variety of first wall materials can be tested and accommodated. The time for mechanical disassembly and reassembly is less than two weeks (not including time for diagnostic recommissioning and wall conditioning). At present the aluminum vessel is fully boronized, and delicate instrumentation mounted inside the vacuum vessel is protected with graphite armor (covering about 10% of the wall area). If required, essentially any combination of liners and limiters can be installed. The plasma equilibrium is presently established by the thick conducting shell which has a resistive penetration time of several hundred milliseconds. Improved control of impurity influx may be aided by the addition of an externally applied dc vertical field.

Accommodation of Advanced Diagnostics: The absence of field windings leaves nearly the entire surface of the torus accessible for diagnostic view. The excellent diagnostic access is limited mainly by the rather severe constraint on the size of portholes chosen to minimize magnetic field errors.

High data acquisition rate: MST is designed to operate with extreme reliability. Indeed, the device is operated six days per week, with one day for routine maintenance. Except for planned shutdowns, MST operates in this manner essentially indefinitely. Roughly two weeks per year may be lost to minor repairs not covered in the weekly maintenance. Hence, except for planned shutdowns, MST operates about 50 weeks per year, six days per week, producing an average of nearly 100 shots per day. As MST expands its program to that of a proof-of-principle facility, the machine protocols and program management will be appropriately adjusted. However, the high data rate and machine flexibility will persist.

The size (a = 0.5 m, R = 1.5 m) and plasma current (0.5 MA) of MST are sufficient for the proposed tasks. MST has operated transiently with energy confinement times of 5 ms and a central electron temperature of 0.6 keV. So the physics parameter goals (described in Section XII) are a reasonable technical extension of the present activity. The Ohmic pulse length of MST is between 50 ms and 100 ms (depending on plasma conditions). This is limited by the volt-seconds of the iron core. The pulse length is five to ten times larger than the targeted energy confinement time.

Fluctuation and Transport Reduction by Current Profile Control

Current profile control will be enacted by three techniques: inductive, electrostatic, and lower hybrid wave current drive. The sequence is ordered in chronology, level of difficulty, and degree of profile control. The factor-of-five gain in confinement achieved to date was obtained inductively, by applying a poloidal electric field to drive current in the outer region of the MST plasma. Future plans call for programming the toroidal electric field in addition to the poloidal electric field. The aim is to adjust the radial dependence of the electric field vector to optimize the current profile. This technique is limited in that it is transient, and the current profile control is rather coarse.

Electrostatic current injection is a steady technique in which electron current is injected into the MST edge from electron emitters. In MST each emitter is a small plasma discharge contained in a housing of about one cubic inch. Presently, sixteen emitters are distributed around MST, each injecting 1 kA of current. Initial results indicate a factor-of-two difference in energy confinement time between co-injection (current-flattening) and counter-injection (current-peaking) [80]. These experiments are still emerging and will be pursued vigorously. However, although nontransient, the technique is limited in its control; inward diffusion of the injected current is required to produce a desirable profile.

The optimal current profile control technique for present RFP experiments is expected to be lower hybrid wave injection. Lower hybrid wave physics for the RFP is similar to that for the tokamak, although modest differences arise since the ratio of electron plasma frequency to cyclotron frequency is higher for the RFP than for the tokamak. It has been established through computation (the GENRAY code) that the lower hybrid ray penetrates effectively into the RFP plasma [81]. The parallel wave number can be selected such that the ray circulates poloidally several times and is absorbed at $r/a \approx 0.7$, as desired for fluctuation suppression. Computation of the current drive efficiency has been performed with quasilinear Fokker-Planck theory (using the CQL3D code), predicting an efficiency of about 0.4 A/W [81]. With this theoretical motivation, lower hybrid current profile control is proposed for MST. A frequency of 800 MHz with parallel refractive index of about 8 has been selected since the ray penetrates appropriately, the efficiency is high, the frequency is well above the lower hybrid frequency (as high as 250 MHz in the core) to avoid ion heating, and RF sources are available. From MHD considerations we estimate that several megawatts of absorbed RF power may be required for fluctuation reduction in 0.5 MA MST plasmas. Issues beyond the scope of the above calculations, which will be resolved through a combination of theoretical work and low power experiments, include fast electron effects on current localization and density limits to wave absorption by electrons.

The presence of a close-fitting conducting shell imposes two constraints on antennas: the radial extent must be small (about 3 cm) and the RF power feeds must pass through small ports. A combline antenna concept [82] has been identified which satisfies these constraints. These experiments will constitute the first application of auxiliary RF power to the RFP and will be conducted in a staged manner.

Other Confinement Control Techniques

The technique for confinement improvement with the strongest theoretical foundation and with the most encouraging experimental results is current profile control. However, we will also pursue more exploratory avenues, including rotating magnetic perturbations and flow control. We will apply resonant, nonaxisymmetric rotating magnetic perturbations at the insulated shell gap which extends the long way around the torus. In this manner we can apply a single toroidal mode number to control the rotation of a single core-resonant mode (for example, to control mode locking), or multiple toroidal modes. Through application of multiple rotating perturbations we will attempt to alter the nonlinear mode coupling (and thereby perhaps the degree of magnetic stochasticity).

Flow control has been shown to double the particle confinement time. We will continue to explore this effect through rotating magnetic perturbations (which affects the flow profile since magnetic plasma flow couples to mode rotation) and through electrical biasing using the electron emitters installed for current injection described above. We will examine the feasibility of flow control with RF waves, which has been proposed for tokamak studies. Also, in analogy with observations in tokamaks and stellarators, auxiliary heating (proposed to test beta limits) might induce a transition to an improved confinement state associated with flow shear.

Beta Limit Studies

Lower hybrid waves can also be used to heat the electrons, without driving current, if the antennas are nondirectional. Such experiments are proposed to test the beta limits and to examine the dependence of transport on physics parameters which are determined by the electron temperature, such as the Lundquist number. These experiments will be accomplished with the antennas, concepts, and techniques developed for current drive, as described above. Central power deposition can be implemented by an appropriate selection of the parallel wave number.

Neutral beam heating is also proposed for MST. A constraint is set by MST's relatively small portholes. Initial estimates indicate that roughly 2 MW of absorbed power may be feasible at the present MST density for a beam injected through existing portholes. The optimal beam energy for absorption is about 30 keV. Neutral beam absorption in MST will first be investigated using the diagnostic neutral beam available on MST, which will have the same energy as the beam planned for heating. A design similar to that used for the diagnostic beam should be suitable for the larger intensity beam required for heating.

Oscillating Field Current Drive

Oscillating field current drive (OFCD) for bulk current sustainment will be studied by applying oscillating voltages at the insulated gaps in the conducting shell. The shell contains gaps in both the short way and long way around the torus. Helicity balance arguments imply that replacement of the dc Ohmic current with OFCD requires voltage oscillations at each gap of about 100 V for an oscillation frequency of 1 kHz. Partial Ohmic current replacement can occur at reduced voltages. Experiments prior to MST were limited in their ability to test OFCD since the plasma resistance was high. With its larger size and improved confinement, the resistance of the MST plasma is sufficiently low that the required voltages are feasible in two respects. First, the insulated gaps can support the required voltages without arcing through the plasma, and second, the plasma edge $\mathbf{E}\times\mathbf{B}$ oscillation will be sufficiently modest so that plasma-wall interactions should be controllable. Experiments will aim to determine the current drive efficiency and the effect of OFCD on confinement. The estimated power required for complete current drive (ignoring possible confinement degradation) is several megawatts. The power source will be an ignitron-switched oscillator. Should the current not fully penetrate, OFCD may work to modify the edge current and favorably alter the current density profile.

Equilibrium Profile Measurements

All the above studies require detailed measurements of slowly-varying, equilibrium quantities. Confinement studies require measurement of thermal, particle, and momentum diffusivities of electrons, ions, and impurities; energy confinement studies require measurements of Ohmic input power, evaluated in part from magnetic field profile measurements; current profile modification studies require current profile measurements; beta limit studies require local pressure gradient measurements; studies of the effects of flow on transport requires measurement of ion flow profiles. The present set of MST diagnostics, listed in Table II, consists largely of single point or single chord measurements, with profiles of a few selected quantities available on a discharge-to-discharge basis. Below we list quantities which must be measured to accomplish the physics program, with corresponding planned diagnostics (limiting the list to major diagnostics only).

Thomson scattering (single point)	H-alpha detector array
FIR interferometer (11 chords)	Impurity line monitors
CO_2 interferometer (single chord)	EUV spectrometer
Charge eXchange Analyzer	NIR bremsstrahlung detector array
Fast UV Doppler spectrometer	Magnetic coil arrays (>400 coils)
Insertible fiber optic spectroscopic probe	Fast, insertible pyroelectric bolometer
Impurity monochromator array	Current density probes
CCD spectrometer for UV-visible	Langmuir probes
NIR spectrometer	Electrostatic Energy Analyzer

Table II. Existing MST diagnostics.

Electron temperature: At present the central electron temperature is measured with a single-point, single-time Thomson scattering system. It is being upgraded to infer profile information by translating the system on a shot-by-shot basis. We propose to add a multi-point, multi-pulse system to obtain single-shot radial profiles over time, both on the slowly varying equilibrium time scales and on faster fluctuation timescales. Slow variations will be examined by firing several Nd:YAG lasers in sequence, while fast phenomena will be captured by double-pulsing single lasers with a delay between 20 μs and 200 μs.

Majority ion temperature: Presently, a charge exchange analyzer yields a chord-averaged measure of the ion temperature. Local measurement of the majority ion temperature will be accomplished through a Rutherford scattering diagnostic employing a diagnostic neutral beam. In this process, a neutral beam atom is Coulomb-scattered by a majority plasma ion. The scattered neutrals are detected and the breadth of the detected energy spectrum yields the ion temperature. Spatial localization (about 4 cm $\times$ 13 cm in MST) is provided by the intersection of the detector line-of-sight and the beam cross-section. The technique has been employed successfully in the TEXTOR [83] and JT-60 tokamaks [84]. Although the ion temperature was determined in TEXTOR, the utility and accuracy of the measurement was limited by the low intensity of the neutral beam. For MST, we are purchasing a beam which is about 100 times more intense (3 A equivalent current at 20 keV) and very compact (3 cm $\times$ 3 cm beam cross-section). A cost-effective beam will be purchased from the neutral beam group at Novosibirsk, and experiments will be conducted, in part, collaboratively. A secondary use of the beam will be to measure the dynamics and confinement of fast ions in the RFP. In particular, it has been suggested that large gyroradius ions will average over the magnetic stochasticity, and may be well-confined. The diagnostic beam will be used to test this conjecture.

Minority ion temperature: At present, chord-averaged temperature of selected impurity ions is measured with fast, passive Doppler spectroscopy [85]. The spectrometer has fast time resolution (10 μs) arising from high light throughput and parallel data collection. Thus, it can follow temperature changes through a sawtooth cycle. To localize the measurement we propose to upgrade the system to a charge exchange recombination (CHERS) diagnostic. We will use a Novosibirsk diagnostic neutral beam, combined with fast Doppler spectroscopy, to obtain time-dependent profiles.

Current density profile: An 11-chord FIR laser polarimeter has been installed on MST, in collaboration with UCLA, to measure the poloidal magnetic field profile (from which the toroidal current density profile can be calculated). The system simultaneously serves as an interferometer to measure the density profile. Magnetic field information is obtained from rotation of the laser electric field vector upon transmission through the plasma. The polarimeter system is being brought into operation, and the initial results are very promising. Expansion of the polarimeter to include a tangential view, which would yield the poloidal current density, will be considered. We will also attempt to measure the central current density using our Thomson scattering system to detect the toroidal Doppler shift of the scattered light, as tested previously [86] and implemented successfully in the RTP tokamak [87]. Finally, we will examine the possibility of using the motional Stark effect (by measuring the Stark manifold) to measure the magnetic field with the 30 keV diagnostic neutral beam.

Electric potential: A heavy ion beam probe will be installed in MST in collaboration with Rennselear Polytechnic Institute. A 160 keV beam will be used. Heavy ion beam probing in the RFP is similar to that in a tokamak, where it has been used extensively, although the trajectory of the secondary ions is more complex. The diagnostic will also provide local electron density measurements, to complement interferometry.

Fluctuations and Fluctuation-Induced Transport

A focus of MST has been the measurement of fluctuations and, in particular, the transport directly driven by fluctuations. To measure the magnetic fluctuation induced energy and particle flux in the outer portion of MST, new insertable diagnostics were invented. For example, the electron energy flux was measured by the correlated product of the fluctuating parallel heat flux and the radial magnetic field, and the particle flux was measured by the product of the fluctuating parallel electron current and radial magnetic field. In the core, we are measuring the dynamo effect by the product of the fluctuating impurity flow velocity (assumed equal to the majority velocity) and the fluctuating magnetic field. We propose to extend our focus to the plasma core and to critical quantities not yet measured. These measurements are essential to the goal of understanding the physics necessary to develop scientific opinions on the extrapolation to the proof-of-performance stage. Below we list areas in which new measurements are planned.

Core electrostatic transport: The contribution of electrostatic fluctuations to core transport is undetermined. The heavy ion beam probe is capable of measuring both the fluctuating potential and electron density, as has been accomplished in tokamaks. We will measure the correlated product of density and potential fluctuations to determine the electrostatic particle transport.

Majority ion dynamics: We will employ Rutherford scattering to measure the fluctuating flow velocity, temperature, and density of hydrogen ions. These measurements will extend the use of the Rutherford scattering diagnostic from what has been established elsewhere. Detailed feasibility studies indicate that the beam intensity is sufficient for this application. If successful, these measurements would yield the fluctuation induced ion particle flux (by correlating fluctuating velocity with density) and energy flux (by correlating fluctuating velocity with pressure). Correlating the velocity with magnetic field will yield the strength of the MHD dynamo. It is not yet possible to measure the magnetic field directly in the core, except in very low current discharges through probe insertion. However, it is known that, in the RFP, edge magnetic fluctuations are very well correlated with core fluctuations, as expected for large-scale modes. Hence, correlation of core velocity fluctuations with edge magnetic fluctuations is a sufficient measure of the core dynamo. Appropriate correlation between velocity components can yield the fluid Reynolds stress, which may contribute to the large flow seen in the RFP.

Minority ion dynamics: The CHERS system, with fast Doppler spectroscopy, will be used to obtain the fluctuating flow and temperature of minority ions. This will, in particular, permit a localized measurement of the MHD dynamo, complementary to that measured by Rutherford scattering. The fluctuating velocity signal detected in an RFP should exceed that of a tokamak since the spatial scale of the fluctuations is larger; the CHERS diagnostic need not be as finely localized as in a tokamak. Localized, fast flow diagnostics are also key to investigate the effect of flow on fluctuations in the RFP, particularly whether flow suppresses turbulence similar to H-mode effects in tokamaks.

Magnetic field fluctuations: Core magnetic fluctuations remain to be measured non-perturbatively in the core of fusion plasmas. The task may be somewhat easier in the RFP than the tokamak since magnetic fluctuations are relatively large in amplitude and spatial scale. Thus, after establishing use of the heavy ion beam probe and FIR polarimeter for their more reliable uses, we will attempt to employ them to detect magnetic fluctuations. A beam probe was able to detect Mirnov magnetic oscillations in the TEXT tokamak through oscillations in the particle trajectory. These results were not fully developed, but lend encouragement to the beam probe's utility in the RFP. For large scale fluctuations, the FIR interferometer presently measures density fluctuations. Combining density fluctuation measurements with FIR polarimetry may enable deduction of the magnetic fluctuations associated with MHD activity [88].

Schedule, Staff, and Cost

An approximate schedule for the major MST projects in the next five years is depicted in Fig 4. Three current profile control techniques are pursued for transport reduction. Inductive current profile control continues to respond to optimization measures. We expect that the optimization will be complete and the task will conclude during the second year. Electrostatic current injection with the present 16 sources will be fully optimized by the middle of the first year; if experimental results suggest, as do MHD considerations, that about 32 sources will be necessary for fluctuation suppression, then about 16 additional sources will be added during the second year. Completion of electrostatic current injection will occur by the end of the third year, having optimized the effect on fluctuations and investigated the current diffusion mechanism of the edge-injected current.

Lower hybrid wave current profile control (and heating) is a major endeavor which will be implemented in stages. In the first year we will design, construct, and install a single antenna suitable for coupling to a 200 kW source. The second year will be dedicated to studying the physics of wave propagation, antenna effects, and current drive. After the second year, we will begin either a staged ramp up of the power or further antenna development, should it be mandated by the second year results. We anticipate that, in the fourth year, we will begin experiments in the 1 MW range, a level sufficient to begin to investigate current profile effects on transport. Since this experiment will be the first application of auxiliary RF power to an RFP, the schedule will be strongly influenced by the unfolding results.

Beta limit studies will proceed by lower hybrid heating and/or neutral beam heating. Development of lower hybrid heating will follow a schedule similar to that for lower hybrid current drive. Hence, heating experiments sufficient for substantial alteration of beta and for other physics studies (such as Lundquist number scaling) can be underway in the fourth year. Neutral beam heating will be developed over a similar timescale. In the second year, neutral beam absorption (including fast ion losses) will be tested using the diagnostic neutral beam. The diagnostic beam is of the same energy as that which optimizes absorption and heating. Hence, it is suitable to test the feasibility of heating. If successful, one neutral beam source (at about 1.5 MW injected power) will be installed in the latter part of the third year. At the end of the fourth year, data from both lower hybrid and neutral beam heating in the range of 1 MW will be available. At that time, we will decide on the optimal mix of heating techniques and decide whether to increase the power of either technique.

The rotation of a single magnetic mode will be controlled by the application of a rotating magnetic perturbation in the first year. In the second year, multiple mode rotation control will be applied, with physics studies of transport and flow effects concluding in the third year.

Current sustainment by oscillating field current drive will be tested at full power in the third year. During the first year we will complete the circuit design and system testing. Low

Schedule for Major MST Projects

TASK	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5
J(r)-Control:					
Inductive	optimize	maintain for physics studies			
Electrostatic	optimize 16-sources	install 32-sources	test 32-sources		
RF (LHCD)	design & install antenna	200 kW tests	optimize antenna, etc.	1 MW current drive	higher power?
Beta Limit:					
RF (LH heating)				~1 MW RF heating	higher power?
NBI		DNB absorption; construct ~1MW beam	install	~1 MW NBI heating	higher power?
Flow-Control:					
Rotating Magnetic Perturbations	test single mode	install multi-mode	test multi-mode		
Current Sustainment:					
OFCD	install oscillators	low power test	high power (test current sustainment)		
Transport &Fluctuations:					
Multi-point Thomson	design	construct		install; measure Te profile	
DNB	construct	install & test; Rutherford scattering & CHERS			
FIR Polarimetry	install; measure J(r) profile				
HIBP	install	commission	measure potential, potential flucts., B(?), B–flucts. (?)		

Figure 4. Proposed schedule for major MST projects.

power tests will be conducted through the second year. The purpose of these tests is to examine the penetration of fields into the plasma, current drive at a perturbative level, the plasma-wall interaction induced by the voltage oscillations, and the dependence of these on the frequency.

The program of measurements of transport and fluctuations, critical to all the control experiments, will continue for the entire five years. The variety of important measurements is very broad. To illustrate the flow of progress, we indicate in Fig 4 the schedule for the major new diagnostics. Multi-point, multi-pulse Thomson scattering will undergo a 1-1/2 year design, followed by a 1-1/2 year construction period, and a half-year commissioning on MST. The first temperature profiles will be obtained in the fourth year. The diagnostic neutral beams for Rutherford scattering and CHERS will be constructed during the first year. Both diagnostics will be fully installed and commissioned during the second year, with physics results beginning in the third year.

The commissioning of FIR polarimetry will be complete during the first half of the first year. It will be employed for measurements of the poloidal magnetic field thereafter. Pending a positive outcome, the polarimeter will be upgraded for toroidal magnetic field and/or fluctuation measurements. The heavy ion beam probe will be assembled and installed during the first year, commissioned during the second year, and employed for physics studies beginning in the third year.

The present MST staff and collaborators contains the core expertise to plan and coordinate nearly all the proposed work. However, implementation of all the projects will require substantial enhancement of the physics and technical staff. The cost and staff requirements for the MST program plan are outlined in Appendix II. The present MST activity includes substantial collaboration, both domestic and international, which is critical to its program. Within the U.S., key MST collaborators include UCLA and RPI in major diagnostic systems and associated physics experiments, SAIC and Los Alamos National Laboratory in MHD computation, the University of Montana and CompX Corporation in RF wave computation, and Princeton Plasma Physics Laboratory in dynamo experiments and RF hardware development. As an outgoing collaboration, MST staff have installed electrostatic current injectors for current drive on the HIT tokamak at the University of Washington. Internationally, MST collaborates closely in a variety of ways (joint experiments and working groups) with the RFP programs in Italy, Japan, and Sweden. The collaborations are formally coordinated through an RFP agreement under the auspices of the International Energy Agency. In addition, MST staff have performed magnetic transport measurements in the stellarator in Madrid, using diagnostics developed for MST research. We anticipate that the MST proof-of-principle facility will be yet more collaborative, particularly as the national RFP program develops.

B. Exploratory RFP Experiments

There is a rich set of opportunities which warrant investigation at the exploratory level. These include well-defined issues and modified RFP configurations which promise advantages. Below we describe possible themes for such experiments: RFP behavior at low aspect ratio, control of resistive wall instabilities, and the effect of external field reversal on fluctuations and transport. We then describe a proposed low aspect ratio RFP, the SPIRIT device. Which, and how many, of these and other exploratory concept RFP experiments will be most profitable as part of a national RFP effort awaits further study.

Low aspect ratio RFP: All RFP experiments have operated at moderate to large aspect ratio A = 3-8. Clearly, a more compact RFP may carry reactor advantages. Experiments and MHD computation indicate that the number of dominant Fourier magnetic modes is about equal to $A + 1$. Cylindrical MHD computation predicts that at $A \approx 1$ (where A is the ratio of the cylinder length to circumference) about two toroidal modes are dominant. If true, the ease of mode control may be enhanced (by either current profile control or feedback) and the degree of magnetic stochasticity may be reduced. As $A \rightarrow 1$, the RFP essentially becomes a spheromak. A low aspect ratio experiment would test many aspects of MHD fluctuations and relaxation; if favorably altered, low aspect ratio could offer reactor advantages. Such an experiment is under consideration by PPPL as part of its proposed compact torus experiment SPIRIT.

Control of Resistive Shell Instabilities: With a resistive shell, both ideal and resonant, resistive MHD instabilities grow on the resistive shell timescale. The Extrap-T2 experiment in Sweden will diagnose resistive shell instabilities. However, it is ill-suited to the development of control techniques since it has a large aspect ratio (A = 6) and consequently about seven growing modes, complicating the control problem. The challenge of the resistive shell problem in the RFP exceeds that of the tokamak since the number of modes is larger; the feedback problem is one of multiple mode control, which presents both the practical problem of the placement of feedback windings and the theoretical questions of multiple mode control and coupling. The problem is more tractably treated in an experiment with an aspect ratio of three or less. Such an experiment can test a variety of feedback techniques, including “smart” shell concepts.

An RFP with external transform: In an RFP the reversal of the toroidal field produces a high magnetic shear, minimum energy state. The field reversal and high shear are produced by plasma currents which are, in part, generated by magnetic fluctuations (in the MHD model). An intriguing conjecture is that if field reversal and shear are partly generated by an external transform, the need for fluctuation-induced current will be reduced. Hence, fluctuations will be reduced. The external transform can be created by nonaxisymmetric helical windings or, equivalently, by a nonaxisymmetric bounding magnetic surface. This conjecture is analogous to replacement of the dynamo-driven magnetic field by auxiliary current drive. In both cases, a fluctuation-induced electric field is believed to be unnecessary. The external transform conjecture formed the basis of the OHTE experiment at General Atomics. OHTE displayed properties similar to that of a conventional RFP. However, the external transform may not have been sufficiently strong. RFPs with stronger transforms have been considered at General Atomics. This conjecture requires a test by MHD computation. We propose that nonlinear

MHD computation be employed to test the concept, as it is within the capability of present MHD codes with appropriate boundary modification. If the conjecture proved true in computation, an experimental test would then be compelling.

Low Aspect Ratio RFP Research in SPIRIT: A compact torus experiment, called SPIRIT, has been proposed by the Princeton Plasma Physics Laboratory. The SPIRIT device will be capable of producing an RFP at low aspect ratio. The goals of RFP research in the SPIRIT are (1) the exploration of the advantages of the low aspect ratio RFP configuration, (2) optimization of the plasma shape, and (3) the possible testing of the advanced features of the RFP, including edge current drive and suppression of resistive shell modes by feedback stabilization.

In MST, plasma transport is reduced by current density profile control. A complementary approach to suppress the stochasticity-induced transport is to reduce the number of unstable modes and increase the distance between neighboring resonant surfaces, as should occur at low aspect ratio. When the aspect ratio approaches unity, it is expected that the number of unstable modes decreases to about two and the distance between their rational surfaces increases significantly. This physical intuition is supported by preliminary results of nonlinear resistive MHD simulations in which the aspect ratio can be varied in a cylindrical geometry [74].

The goals of the RFP study in SPIRIT are to determine the MHD stability and global confinement characteristics of low aspect ratio RFPs. The SPIRIT device is sketched in Fig. 5. The unique formation method to be employed in SPIRIT — the merging of compact tori — can generate RFPs with aspect ratio as low as A=1.05, since only a small TF coil is needed in the center stack. With an OH transformer installed in the center stack, a sustained aspect ratio A=1.3 discharge can be formed. Design of a close-fitting, conductive shell will be carried out using MHD computation to identify necessary shapes of the shells to stabilize external (tilt/shift) modes. Unlike traditional RFP devices, the shell must have two openings ("toroidal gaps"), one at each end through which the merging spheromaks enter. The gap-generated field errors may not be deleterious since it is primarily field errors at the poloidal gaps which cause locked modes to form, degrading plasma performance. In SPIRIT, each of the four sections of the shell (or cage) is supported by a single rod with an adjustable distance from the center, resulting in an adjustable poloidal gap between sections. This flexibility will facilitate the search for an optimized shell or cage. The aspect ratio can be controlled externally by inserting center stacks of different sizes or by plasma compression/expansion. The MHD mode structures will be measured by external and internal magnetic arrays, soft-X ray detector arrays, and a fast CCD camera. Global confinement can be studied by monitoring the input power and plasma kinetic energy.

Another important issue which will be actively addressed is the shape of the poloidal cross section. The effects of a noncircular RFP cross-section have not been studied experimentally and only slightly theoretically [73]. Although almost all RFP devices to date have been circular in shape, it is not clear that a circular cross-section is optimized for stability and confinement. Guided by computational MHD, different shapes of conducting shells (and therefore plasma cross-section) can be tested to identify the shape dependence of the MHD stability and global confinement properties. Combined with an optimization of the aspect ratio, this study will address the question of what is the best geometry for the RFP.

If the low aspect ratio RFP configuration proves to be very attractive, two advanced features can be added in a later stage of the RFP studies in SPIRIT: (1) suppression of resistive wall modes by feedback techniques and (2) edge current drive by plasma sources to stabilize current-driven tearing modes (eliminating the need for dynamo action). The expected fewer number of tearing modes may make feedback stabilization of internal modes easier in a spherical RFP. If Phase II of the SPIRIT experiments is carried out (installation of a few megawatts of NBI), two important RFP issues can be addressed: (1) suppression of resistive shell modes by plasma rotation though NBI and (2) testing of beta limits by NBI heating. A successful advanced spherical RFP experiment will also add a new possibility for a compact reactor core design.

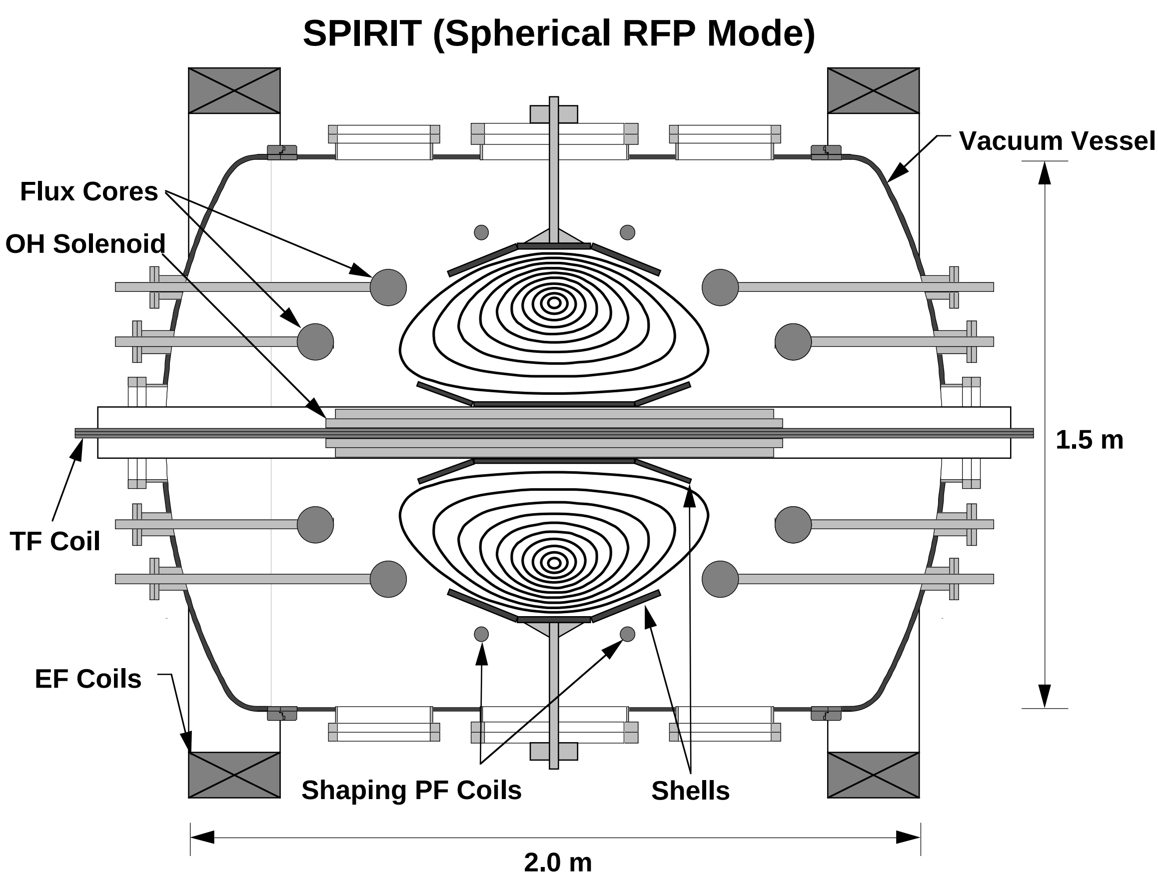

Figure 5. The proposed SPIRIT device.

C. Theoretical Studies

There is a critical need for theoretical research in the areas discussed in the previous section. The major advances in RFP research in the U.S. 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 far too small (worldwide, as well as in the U.S.) to address all of the critical RFP topics. An RFP program exploiting even the present experimental facilities requires a much more comprehensive U.S. theoretical effort. Below we provide an incomplete list of key theoretical issues we propose to attack within the U.S. program.

MHD optimization of the RFP: We propose to optimize the RFP (minimize magnetic fluctuations and maximize beta) with regard to geometry (shape, aspect ratio, external transform) and profiles (current, pressure, and flow). The physics issues underlying each parameter variation are described in Section VI. Nonlinear resistive MHD computation will be employed, primarily using the new TRIM [89] and NIMROD codes [90]. TRIM is a toroidal code with an adaptive mesh, suitable for geometric studies. NIMROD is a two-fluid code which will initially be operated in its single-fluid capacity, exploiting its full geometric capability.

The influence of flow shear on fluctuations: Flow may affect edge transport in present RFP experiments; moreover, as magnetic fluctuations are reduced, electrostatic transport, and its possible reduction by sheared flow may become relatively more important. Hence, we propose to examine the influence of flow shear in the RFP. The theoretical constructs developed for tokamaks will be adapted to the RFP, with particular attention given to its possible influence on large scale electrostatic fluctuations. We will also examine its effect on large-scale magnetic fluctuations.

Improved confinement regimes: Possible approaches to improving transport in the RFP will be explored through use of advanced transport models that have been developed for the tokamak. The models incorporate transition mechanisms, and have been used to explain transport barriers. The models are being incorporated into the ASTRA transport code. The use of externally-driven $\mathbf{E}\times\mathbf{B}$ flows, auxiliary heating, and core fueling will be considered, and may form a basis for experimental tests.

The origin of electrostatic fluctuations: Electrostatic fluctuations drive particle transport in the RFP edge. We propose a theoretical investigation of electrostatic fluctuations which includes a detailed comparison to experimental measurements. The investigation will have four components: analytic calculation of the characteristics and saturated amplitudes of fluctuations which are suspected to be important (such as interchange modes), use of flux tube computation of electrostatic turbulence such as has been developed in the tokamak context, evaluation of electrostatic fluctuations coupled to the large-scale resistive MHD core-resonant fluctuations, and treatment of the edge as a self-organized critical (SOC) state. The strong core turbulence may drive the edge into a SOC, perhaps accounting for the commonality of fluctuation properties in the RFP, tokamak, and stellarator. This approach could explain why particular “modes” have not been successful in explaining edge turbulence. We will apply SOC edge models to the RFP and compare to the tokamak and stellarator.

Feedback stabilization of resistive shell instabilities: The resistive shell instability problem for the RFP is more complex than that for the tokamak since several modes must be stabilized simultaneously. Thus, theoretical techniques which describe feedback stabilization of various types will be extended to include the nonlinear coupling between the modes.

Oscillating field current drive and other current sustainment techniques: OFCD offers the possibility of efficient bulk current drive. However, it is based on the conjecture that, given helicity injection, magnetic fluctuations will relax the current profile without excessive degradation of confinement. Prior MHD computation examined aspects of inward current diffusion of weak OFCD, but the computation did not study the physics of full current sustainment by OFCD. We propose to investigate the detailed dynamics of fluctuations and current diffusion during OFCD using the cylindrical nonlinear MHD code DEBS. The required amplitude of the voltage oscillation increases with plasma resistance, so the major challenge may be modeling sufficiently high Lundquist number plasmas such that the simulated oscillation produces plasma motion within experimentally realizable limits. We will also investigate other possible current sustainment techniques, such as Alfven wave current drive. Two approaches based on Alfven waves will be examined: resonant current drive and nonresonant Alfven-wave-induced dynamo current drive. Resonant current drive may prove efficient if RFP equilibria are found with a small percentage of trapped particles. Nonresonant current drive may prove useful if the effect is enhanced by magnetic stochasticity.

Two-fluid dynamo and relaxation: RFP theory and experiments have advanced to the point that effects beyond single-fluid MHD must be considered. A two fluid treatment is needed to understand the conditions under which different dynamo effects can arise. For example, the diamagnetic dynamo and the Hall dynamo (from the fluctuation-induced Hall term in Ohm’s law) are two-fluid effects. Moreover, the reconnection which underlies relaxation and dynamo in the RFP can be altered as the plasma collisionality decreases. Finally, experimental measurements detect relaxation and dynamo in each species individually. Clearly, experimental observations are at a level of detail which exceeds the predictive capability of MHD. We propose both an analytical treatment of two-fluid relaxation, through a combination of minimization techniques and dynamical reconnection calculations, and a computational treatment of this problem using the powerful NIMROD code when it becomes capable for this purpose.

Magnetic fluctuation-induced transport: Self-consistent theories of magnetic fluctuation-induced transport that account for granularity in the streaming electron distribution can explain the otherwise surprising observation of an ambipolar constraint on the electron heat flux. Ambipolar constraints enter into these theories through a fluctuation-mediated exchange of energy and momentum between electrons and ions. This process is likely relevant to long-time observations of anomalous ion heating in the RFP and recent indications of ion momentum in the same direction as the electron momentum. We will calculate the energy and momentum transfer to ions in the self-consistent theories of magnetic fluctuation-induced transport and compare with experimental observations.

Self-consistent simulation of RF heating and current drive: Improved characterization and modeling of the complex processes involving RF physics, profile modifications, resistive MHD instabilities, and radial transport will be indispensable in the design and interpretation of RF experiments. The RFP-adapted version of the quasilinear Fokker-Planck code CQL3D will be enhanced to include important, but presently neglected, effects such as radial transport and fast electrons. The TRIM code and/or a single-fluid version of NIMROD will be periodically coupled with GENRAY (generalized ray-tracing code) and the enhanced CQL3D to provide a more self-consistent simulation of RF heating and current drive.

Among the proponents of this document are experts in all the areas described above, and in all the required analytical and computational techniques.

D. Systems 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. We propose to incorporate new experimental information, which will arise from the proof-of-principle program, on confinement scaling, beta limits, and oscillating field current drive. The system studies will also incorporate new results from the larger community, such as information on new materials and on divertor operation. Finally, the possibility of a pulsed RFP reactor will be investigated.

The cost of the proof-of-principle U.S. RFP program described above is in the vicinity of $10 million per year. This expenditure includes present RFP funding of about $2.5M per year; thus the proposed program would require additional funds of about $7.5M per year. Roughly half of the $10M would be dedicated to the MST experiment, as described above and in Appendix II. The other half will be distributed among smaller experiments, theory, and systems studies. Theoretical research, including system studies, will require about $2M per year, covering at least the nine topics listed above. The cost of the exploratory concept experiments are difficult to assess, since they have not yet been formulated. However, once in operation we anticipate that of order $3M per year might be an appropriate expenditure. 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 U.S. can be at the world forefront in physics and performance, at the proof-of-principle level, for a relatively modest cost.

XII. PERFORMANCE MEASURES

The U.S. 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 10 ms, with temperatures of at least 1 keV, and 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 U.S., 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 the 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 through transport reduction by profile control and/or auxiliary heating. The RFP beta limit may occur as a hard, disruptive ideal MHD stability limit or a softer beta limit (such as arising from resistive MHD instabilities) which appears only as degraded confinement at high beta. These studies will be included within the U.S. 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 Extrap-T2 experiment in Sweden, and may be candidates for an exploratory concept experiment in the U.S.

Current sustainment: The U.S. 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 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

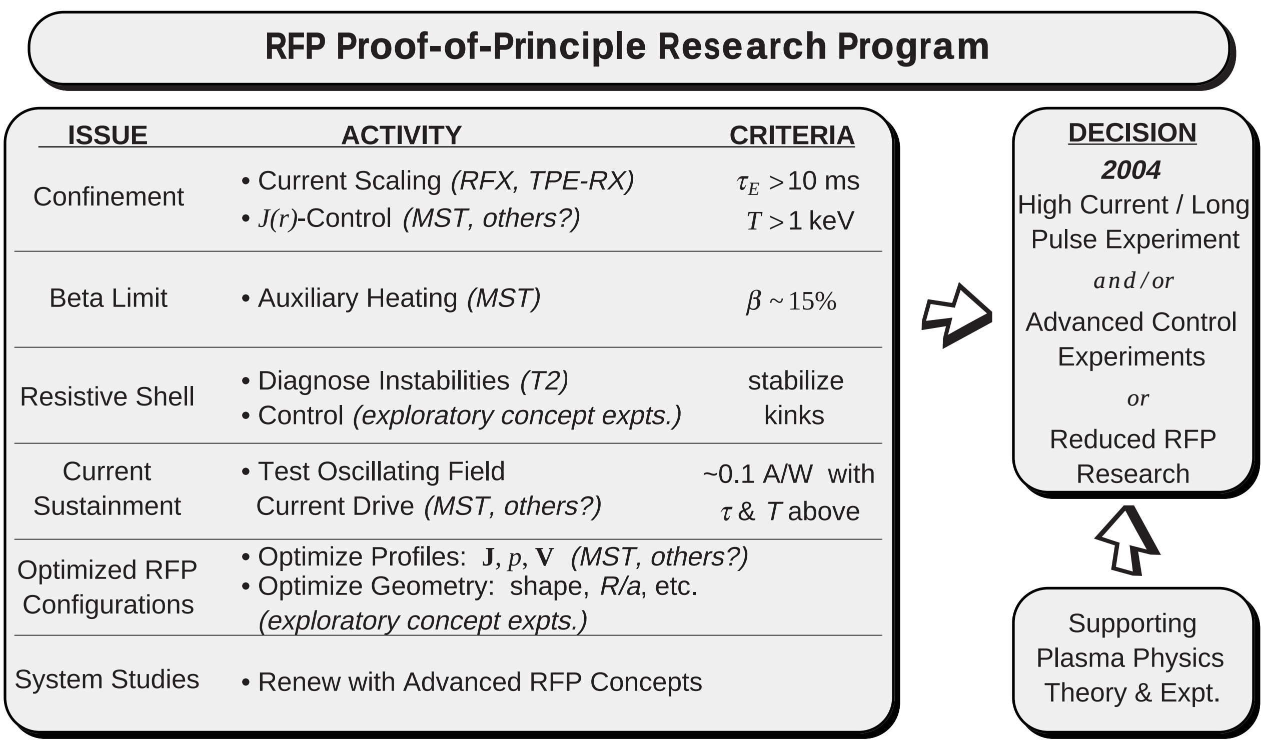

Figure 6. World-integrated RFP proof-of-principle research program.

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 presently anticipated.

The flow of progress anticipated in an integrated world RFP program, with the U.S. program recommended above, is depicted in Fig. 6. 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.

REFERENCES

1. E.P. Butt et al., in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 2nd Int. Conf. Culham, 1965), Vol 2, IAEA, Vienna (1966) 751.
2. See H.A.B. Bodin and A.A. Newton, Nucl. Fusion 20, 1255 (1980) for a review of “fast” RFP experiments.
3. R.S. Massey et al., Fusion Tech. **8**, 1571 (1985).
4. A. Buffa et al., in *Plasma Physics and Controlled Nuclear Fusion Research* (Proc. 10th Int. Conf. London, 1984), Vol 2, IAEA, Vienna (1985).
5. H.A.B. Bodin, C.A. Bunting, P.G. Carolan et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1982* (Proc. 9th Int. Conf. Baltimore, 1982) Vol 1, IAEA, Vienna (1983) 641.
6. T. Tamano et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1984* (Proc. 10th Int. Conf. London, 1984) Vol 2, IAEA, Vienna (1985) 431.
7. See, for example, E.J. Caramana, R.A. Nebel, and D.D. Schnack, Phys. Fluids **26**, 1305 (1983).
8. Sergio Ortolani and Dalton D. Schnack, *Magnetohydrodynamics of Plasma Relaxation*, World Scientific Publishing Co., Singapore (1993).
9. J.B. Taylor, Rev. Mod. Phys. **58**, 741 (1986).
10. G. Rostagni, Fusion Eng. Des. **25**, 301 (1995).
11. R.N. Dexter, D.W. Kerst, T.W. Lovell, S.C. Prager, and J.C. Sprott, Fusion Technol. **19**, 131 (1991).
12. *The TITAN Reversed-Field-Pinch Fusion Reactor Study, Final Report*, report UCLA-PPG-1200, University of California-Los Angeles (1990).

13. Fusion Energy Sciences Advisory Committee, *Advice and Recommendations to the U.S. Department of Energy*, report DOE/ER-0690, U.S. Department of Energy, Office of Energy Research (1996).
14. D.C. Robinson, Nucl. Fusion **18**, 939 (1978).
15. I.H. Hutchinson, M. Malacarne, R. Noonan, and D. Brotherton-Ratcliffe, Nucl. Fusion **24**, 59 (1984).
16. R.J. La Haye, T.N. Carlstrom, R.R. Goforth et al., Phys. Fluids **27**, 2576 (1984).
17. S. Assadi, S.C. Prager, and K.L. Sidikman, Phys. Rev. Lett. **69**, 281 (1992).
18. D.J. Den Hartog et al., in *Fusion Energy 1996* (Proc. 16th Int. Conf. Montreal, 1996), Vol 2, IAEA, Vienna (1997) 83.
19. J.S. Sarff, N.E. Lanier, S.C. Prager, and M.R. Stoneking, Phys. Rev. Lett. **78**, 62 (1997).
20. M.R. Stoneking, J.T. Chapman, D.J. Den Hartog et al., Phys. Plasmas **5**, 1004 and references therein.
21. E. Fernandez and P.W. Terry, Bull. Am. Phys. Soc. **42**, 2047 (1997).
22. H.Y.W. Tsui, Ch. P. Ritz, G. Miller et al., Nucl. Fusion **31**, 2371 (1991).
23. H. Ji, H. Toyama, K. Miyamoto et al., Phys. Rev. Lett. **67**, 62 (1991).
24. T.D. Rempel, C.W. Spragins, S.C. Prager et al., Phys. Rev. Lett. **67**, 1438 (1991).
25. V. Antoni, Plasma Phys. Control. Fusion **39**, B223 (1997).
26. B.A. Carreras and P.H. Diamond, Phys. Fluids B **1**, 1011 (1989).
27. D. Biskamp, E. Schwarz, and J.F. Drake, Phys. Rev. Lett. **75**, 3850 (1995).
28. A. Buffa et al., in *Controlled Fusion and Plasma Physics* (proc. 21st EPS conference, Montpellier) Vol. I (1994) 458.
29. A.F. Almagri, S. Assadi, S.C. Prager et al., Phys. Fluids B **4**, 4080 (1992).
30. C.C. Hegna, Phys. Plasmas **3**, 4646 (1996).
31. G. Fiksel, S.C. Prager, W. Shen, and M.R. Stoneking, Phys. Rev. Lett. **72**, 1028 (1994).
32. A.B. Rechester and M.N. Rosenbluth, Phys. Rev. Lett. **40**, 38 (1978).
33. P.W. Terry, G. Fiksel, H. Ji et al, Phys. Plasmas **3**, 1999 (1996).
34. M.R. Stoneking, S.A. Hokin, S.C. Prager et al., Phys. Rev. Lett. **73**, 549 (1994).
35. E.J. Caramana and D.A. Baker, Nucl. Fusion **24**, 423 (1984).
36. A.Y. Aydemir and D.C. Barnes, Phys. Rev. Lett. **52**, 930 (1984).
37. D.D. Schnack, E.J. Caramana, and R.A. Nebel, Phys. Fluids **28**, 321 (1985).
38. H.R. Strauss, Phys. Fluids **28**, 2786 (1985).
39. A. Bhattacharjee and A. Hameiri, Phys. Rev. Lett. **57**, 206 (1986).
40. A.R. Jacobson and R.W. Moses, Phys. Rev. A **29**, 3335 (1984).
41. P.W. Terry and P.H. Diamond, Phys. Fluids **B** 2, 1128 (1990).
42. H. Ji, Y. Yagi, K. Hattori et al., Phys. Rev. Lett. **75**, 1086 (1995).
43. H. Ji, A.F. Almagri, S.C. Prager, and J.S. Sarff, Phys. Rev. Lett. **73**, 668 (1994).
44. J.T. Chapman, T.M. Biewer, D.J. Den Hartog et al., Bull. Am. Phys. Soc. **42**, 2046 (1997).

45. J.C. Ingraham, R.F. Ellis, J.N. Downing et al., Phys. Fluids B **2**, 143 (1990).
46. Y.L. Ho, Nucl. Fusion **31**, 341 (1991).
47. C.R. Sovinec, Ph.D. thesis, University of Wisconsin-Madison (1995).
48. D. Craig, A.F. Almagri, J.K. Anderson et al., Phys. Rev. Lett. **79**, 1865 (1997).
49. B.E. Chapman, C-S. Chaing, S.C. Prager et al., Phys. Rev. Lett. **80**, 2137 (1998).
50. G. Fiksel, A.F. Almagri, D. Craig et al., Plasma Sources Sci. Technol. **5**, 78 (1996).
51. S. Shiina, Y. Kondoh, and H. Ishii, Nucl. Fusion **34**, 1473 (1994).
52. E. Uchimoto, M. Cekic, R.W. Harvey et al., Phys. Plasmas **1**, 3517 (1994).
53. C.G. Gimblett, Nucl. Fusion **26**, 617 (1986).
54. Y.L. Ho and S.C. Prager, Phys. Fluids **31**, 1673 (1987).
55. Y.L. Ho, S.C. Prager, and D.D. Schnack, Phys. Rev. Lett. **62**, 1504 (1989).
56. D.D. Schnack and S. Ortolani, Nucl. Fusion **30**, 277 (1990).
57. E.J. Zita, S.C. Prager, Y.L. Ho et al., Nucl. Fusion **32**, 1941 (1992).
58. J. Friedberg et al., in *RFP Workshop*, proceedings of IEA RFP Workshop, University of Wisconsin-Madison (1996).
59. B. Alper et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1988* (Proc. 12th Int. Conf. Nice, 1988) Vol 2, IAEA, Vienna (1989) 431.
60. R.R. Goforth, T.N. Carlstrom, C. Chu et al., Nucl. Fusion **26**, 515 (1986).
61. B. Alper, Phys. Fluids B **2**, 1338 (1990).
62. R. Fitzpatrick and T.H. Jensen, Phys. Plasmas **3**, 2641 (1996); T.H. Jensen and R. Fitzpatrick , Phys. Plasmas **4**, 2997 (1997).
63. D.C. Robinson, Plasma Phys. **13**, 439 (1971).
64. M. Bevir and J. Gray, in *Proceedings of the Reversed Field Pinch Theory Workshop*, report LA-8944-C, Los Alamos National Laboratory (1981) 176.
65. K.F. Schoenberg, R.F. Gribble, and D.A. Baker, J. Appl. Phys. **56**, 2519 (1984).
66. Douglas S. Harned, D.D. Schnack, H.R. Strauss, and R.A.Nebel, Phys. Fluids **31**, 1979 (1988).
67. K.F. Schoenberg, J.C. Ingraham, C.P. Munson et al., Phys. Fluids **31**, 2285 (1988).
68. M.M. Pickrell, J.A. Phillips, C.J. Buchenauer et al., Bull. Am. Phys. Soc. **29**, 1403 (1984).
69. J.S. Sarff, A.F. Almagri, S. Assadi et al., Nucl. Fusion **29**, 104 (1989).
70. K. Hattori, Y. Sato, K. Hayase et al., in *Plasma Physics and Controlled Nuclear Fusion Research 1994* (Proc. 15th Int. Conf. Seville, 1994) Vol 2, IAEA, Vienna (1995) 363.
71. X.L. Chen and P.J. Morrison, Phys. Fluids B **2**, 495 (1990); L. Ofman, X.L. Chen, P.J. Morrison, R.S. Steinholfson, Phys. Fluids B **3**, 1364 (1991).
72. M. Peerson, Nucl. Fusion **31**, 383 (1991).
73. D.A. Skinner, S.C. Prager, and A.M.M. Todd, Nucl. Fusion **28**, 306 (1988).
74. Y.L Ho, D.D. Schnack, P. Nordlund et al., Phys. Plasmas **2**, 3407 (1995).
75. T. Ohkawa, M. Chu, C. Chu, M. Schaffer, Nucl. Fusion **20**, 1464 (1980).

76. M. Schaffer, private communication
77. Y. Hirano et al., in *RFP Workshop*, proceedings of IEA RFP Workshop, University of Wisconsin-Madison (1996).
78. S. Hokin et al., in *Controlled Fusion and Plasma Physics* (Proc. of 23rd EPS conference, Kiev) Vol. II (1996) 625.
79. J.N. Di Marco, Update of RFP Scaling Data, Report LA-UR-Revised-88-3375, Los Alamos National Laboratory, 1988.
80. D. Craig, A.F. Almagri, J.K. Anderson et al., Bull. Am. Phys. Soc. **42**, 2047 (1997).
81. E. Uchimoto, R.W. Harvey, A.P, Smirnov et al., Proceedings of the 1998 International Sherwood Theory Conference, Atlanta, paper 2C11 (1998).
82. C.P. Moeller, R.W. Gould, D.A. Phelps, and R.I. Pinsker, proceedings of the Tenth Topical Conference on Radio Frequency Power in Plasmas, Boston, 1993; H. Ikezi and D.A. Phelps, Fusion Tech., **31** 1995.
83. H.F. Tammen, A. J. Donne, T. Oyevvar, and F. C. Schuller, Plasma Phys. Reports **2**, 158 (1993).
84. J. Takeuchi et al, Rev Sci Instrum. **59**, 1652 (1998).
85. D.J. Den Hartog, A.F. Almagri, J.T. Chapman et al., Phys. Plasmas **2**, 2281 (1995).
86 V.A. Baukov et al, Plasma Physics Reports **20**, 52 (1994).
87. F. A. Karelse et al, Proceeding of European Physical Society, Plasma Physics Conference (1997).
88. D.L. Brower et al, Rev. Sci. Instrum. **68**, 419 (1997).
89. D.D. Schnack, I. Lottati, Z. Mikíc, and P. Satyanarayana, J. Comp. Phys. **140**, 71 (1998).
90. D.D. Schnack, A.H. Glasser, and the NIMROD Team, Bull. Am. Phys. Soc. **41**, 1360 (1996).

APPENDIX I: ACTIVE SUPPORTERS OF THE RFP PROPOSAL

A. Bhattacharjee	University of Iowa
A. Boozer	Columbia University
D. Brower	University of California at Los Angeles
B. Carreras	Oak Ridge National Laboratory
K. Connor	Rennselear Polytechnic Institute
R. Fitzpatrick	University of Texas
R. Harvey	CompX Corporation
H. Ji	Princeton Plasma Physics Laboratory
R. Krakowski	Los Alamos National Laboratory
R. La Haye	General Atomics
C. Litwin	University of Chicago
N. Mattor	Lawrence Livermore National Laboratory
F. Najmabadi	University of California at San Diego
R. Nebel	Los Alamos National Laboratory
D. Newman	Oak Ridge National Laboratory
M. Schaffer	General Atomics
D. Schnack	Science Application International Corporation
C. Sovinec	Los Alamos National Laboratory
H. Strauss	New York University
E. Uchimoto	University of Montana
M. Yamada	Princeton Plasma Physics Laboratory

University of Wisconsin: J. Callen, B. Chapman, D. Den Hartog, G. Fiksel, C. Forest, C. Hegna, S. Prager, J. Sarff, P. Terry

APPENDIX II: MST BUDGET

	FY99	FY00	FY01
MST Operations (see detail below)	$1,162,000	$1,162,000	$1,162,000
Major Projects:			
Oscillating Field Current Drive	$270,800	$373,900	$292,400
Inductive Current Profile Control	$120,700	$52,000	$0
Lower Hybrid Current Drive and Heating	$160,500	$759,000	$996,000
Rutherford Scattering	$200,800	$268,900	$231,800
Neutral Beam Heating	$24,800	$416,500	$894,600
CHERS	$104,400	$301,700	$584,500
Rotating Magnetic Perturbations	$160,700	$176,100	$56,600
FIR - Support	$78,400	$99,400	$125,200
Thomson Scattering	$79,200	$382,900	$639,900
Field Error Feedback	$28,600	$160,100	$0
Pulse-Shaping	$40,000	$70,000	$28,600
HIBP - Support	$40,800	$52,200	$89,400
Electrostatic Injection and Biasing	$139,200	$320,400	$218,900
Fueling	$54,400	$37,200	$0
Other not included above (including graduate students)	$455,000	$305,000	$245,000
TOTAL	**$3,120,300**	**$4,937,300**	**$5,564,900**

MST Operations	
Electrical and Mechanical Equipment	$100,000
Data Acquisition Equipment	$100,000
Instrumentation Technician	$56,000
2 Electronic and Mechanical Technicians	$114,000
Electrical Engineer	$86,000
Database Administrator	$67,000
Information Processing Consultant	$57,000
Research Program Manager	$67,000
Undergraduate Student Employees	$155,000
Supplies and Services	$360,000
Total Operations	**$1,162,000**

Staff and Equipment by Major Project

Major Project	Year	Engineers & Technicians	Scientists	Post Docs	Graduate Students	Equipment
Oscillating Field	1	1.40	0.50	0.00	0.00	$100,000
Current Drive	2	0.95	1.00	1.00	1.00	$80,000
	3	0.70	1.00	1.00	1.00	$20,000
Inductive Current	1	0.25	0.30	0.50	0.00	$30,000
Profile Control	2	0.00	0.00	0.50	0.00	$20,000
	3	0.00	0.00	0.00	0.00	$0
Lower Hybrid	1	0.80	0.20	0.40	0.00	$50,000
Current Drive	2	3.00	1.50	1.00	1.00	$250,000
and Heating	3	3.50	1.50	2.00	2.00	$350,000
Rutherford	1	0.10	0.30	0.00	0.00	$155,000
Scattering	2	0.60	0.50	1.00	1.00	$70,000
	3	0.30	0.50	1.00	1.00	$50,000
Neutral Beam	1	0.00	0.20	0.00	0.00	$0
Heating	2	0.25	0.25	1.00	0.00	$300,000
	3	0.55	0.50	1.00	1.00	$700,000
CHERS	1	0.20	0.30	0.00	0.00	$50,000
	2	0.70	0.50	1.00	1.00	$100,000
	3	0.50	0.50	1.00	1.00	$400,000
Rotating	1	0.70	0.30	0.20	0.50	$50,000
Magnetic	2	0.30	0.50	0.50	0.50	$50,000
Perturbations	3	0.00	0.10	0.30	0.50	$10,000
FIR - Support	1	0.10	0.20	0.00	1.00	$15,000
	2	0.20	0.30	0.00	1.00	$15,000
	3	0.50	0.30	0.00	1.00	$15,000
Thomson	1	0.20	0.50	0.00	0.00	$0
Scattering	2	1.50	0.60	1.00	1.00	$100,000
	3	1.00	0.60	1.00	1.00	$400,000
Field Error	1	0.40	0.00	0.00	0.00	$0
Feedback	2	0.80	0.00	0.00	0.00	$100,000
	3	0.00	0.00	0.00	0.00	$0
Pulse-Shaping	1	0.30	0.00	0.00	0.00	$20,000
	2	0.30	0.00	0.00	0.00	$50,000
	3	0.10	0.00	0.00	0.00	$20,000
HIBP - Support	1	0.30	0.00	0.00	0.00	$15,000
	2	0.50	0.00	0.00	0.00	$15,000
	3	0.50	0.30	0.00	0.00	$15,000
Electrostatic	1	0.00	0.30	0.50	1.00	$40,000
Current Injection	2	0.70	0.50	1.00	1.00	$110,000
and Biasing	3	0.45	0.50	1.00	1.00	$30,000
Fueling	1	0.40	0.00	0.00	0.00	$20,000
	2	0.20	0.00	0.00	0.00	$20,000
	3	0.00	0.00	0.00	0.00	$0
TOTAL	**1**	**5.15**	**3.10**	**1.60**	**2.50**	**$545,000**
	2	**10.00**	**5.65**	**8.00**	**7.50**	**$1,280,000**
	3	**8.10**	**5.80**	**8.30**	**9.50**	**$2,010,000**