Opportunities and Context for Reversed Field Pinch Research

J.S. Sarff[1], A.F. Almagri, J.K. Anderson, D.L. Brower, B.E. Chapman, D. Craig, D.R. Demers, D.J. Den Hartog, W. Ding, C.B. Forest, J.A. Goetz, K.J. McCollam, M.D. Nornberg, C.R. Sovinec, P.W. Terry, and Collaborators

Research on reversed-field pinch (RFP) plasmas contributes in unique ways to the advancement of both fusion and basic plasma science. The behavior of RFP plasmas provides key inspiration for the basic science concept of magnetic self-organization, important in both laboratory and astrophysical settings. For fusion development, the RFP offers distinct solutions to major challenges, most importantly the possibility for reliable and efficient ohmic heating to ignition, which could be done with reduced magnet requirements. As a toroidal confinement system, the RFP allows validating critical fusion science in parameter space adjacent to, yet distinct from, that possible in tokamak and stellarator research. Thus, a vigorous, multi-faceted research program is needed to maintain U.S. leadership in RFP research. This includes support for theory and computation, in addition to a collaborative experimental program. MST is well known as and can continue to be a top-notch facility for mentoring students and postdocs. An emphasis on validation will continue to grow the scientific basis for the RFP, in addition to advancing predictive fusion science and the physics of self-organization. Moderate investments in the MST facility can bring the facility close to its intrinsic limits for current and pulse length, and funding sufficient to support the operation of MST's advanced diagnostic set is essential for all studies. Resolution of key issues that inform the efficacy of sustained ohmic heating requires a larger, higher current RFP device than any existing. The metrics established for the RFP proof-of-principle program are largely met, and planning for a next-step facility in the next decade is warranted.

1. Introduction

A proof-of-principle level program for RFP was adopted by FES in 2000 [1]. The centerpiece of this program is experimental research on the Madison Symmetric Torus (MST) facility at UW-Madison. Research on MST and the RFP is highly collaborative, with 20 groups involved, 7 of which are international. There is also a separate RFP theory grant, plus additional theory and computational research through single-investigator grants. As one of only four operating RFP experiments in the world and the only one in the U.S., MST has an important role in advancing the fundamental understanding of the RFP plasma configuration. Using current profile control, MST has demonstrated the largest energy confinement time and beta for RFP plasmas, establishing (transient) tokamak-like confinement [2]. Predictions for how to control tearing instability in the RFP preceded experimental application, derived from visco-resistive MHD, one of the principal models that describe the behavior of toroidal fusion plasmas. The RFP is also well known for its self-organizing behavior that stems from magnetic reconnection [3]. We therefore identify three synergistic research mission goals that guide the MST and RFP program:

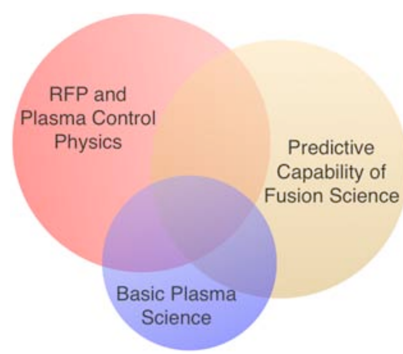

Fig. 1. MST research mission goals

- *Advance the physics and control of the RFP plasma configuration*
- *Advance the predictive capability of fusion science*
- *Discover basic plasma science and its links to astrophysics*

The synergy and approximate balance of these goals is visualized in Fig. 1. While MST provides a unique opportunity to advance the science and fusion potential of the RFP, as a cousin to the tokamak and

[1] Contact information: jssarff@wisc.edu, 608-262-7742

stellarator plasma configurations, the RFP is a valuable partner in establishing validated predictive capability for fusion science more generally. This diversity also enlarges the arena for scientific discovery, both for fusion and basic plasma physics.

2. Status of the RFP Program

The RFP toroidal magnetic configuration is nominally axisymmetric, like a tokamak, but current flowing in the plasma creates almost all of the magnetic field (Fig. 2). For the same volume-average magnetic field strength, the magnetic pressure at the coils is 1/10th that of a tokamak or stellarator, a consequence of dominant internal magnetization. The externally applied toroidal field is especially small, even allowed to be zero. From a fusion system perspective, the RFP's high engineering beta, $\beta_{eng} \sim \langle p \rangle / B^2_{\mathrm{coil,max}} \approx 4\langle \beta \rangle$, greatly reduces the magnet requirements, allowing the possibility for copper conductors [4]. Ohmic ignition is possible as a result of the relatively large plasma current density. Thus, auxiliary heating via rf or neutral beam injection is not essential. Also, the empirical density limit, $n_G \sim I_p/\pi a^2$, is large in its absolute value. Inductive current drive is maximized, which is reliable and efficient. Steady-state may be possible using ac magnetic helicity injection [4,5].

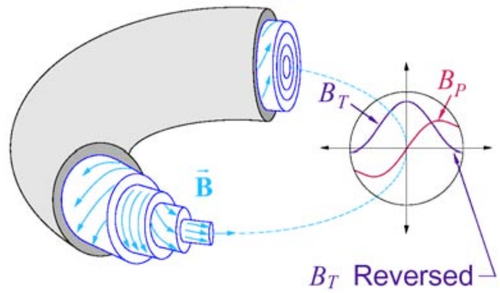

Fig. 2. Schematic of the RFP magnetic configuration. The toroidal and poloidal field components are similar in magnitude, yielding a highly sheared magnetic geometry.

A tradeoff for larger internal magnetization is that the RFP plasma experiences more inherent self-organization. This typically happens through current-driven instabilities that affect energy confinement [6]. The RFP plasma has been one of the principal laboratories driving the basic physics concept of magnetic self-organization, recognized important in astrophysical settings through processes like the magnetic dynamo [7], reconnection [8], and particle energization [9].

The world RFP program includes four operating experiments and one under construction (Fig. 3). The Madison Symmetric Torus (MST) facility at the UW-Madison is one of two larger facilities, the other being RFX-mod in Italy. The other experiments are Extrap-T2R in Sweden and RELAX in Japan. A new

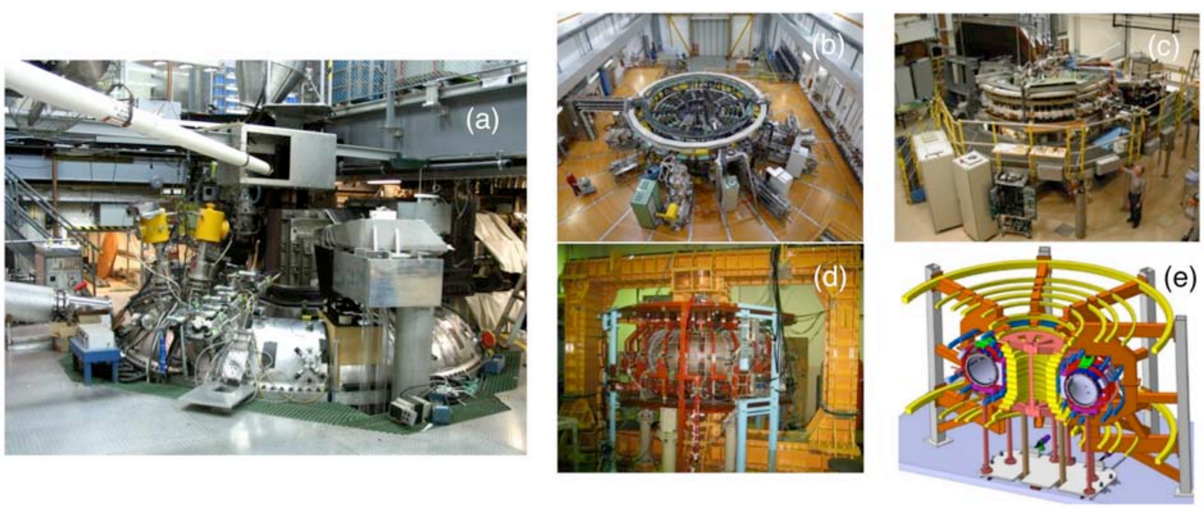

Fig. 3. World's RFP facilities: (a) MST, I_p =0.6 MA, a=0.5 m, R=1.5 m (b) RFX-mod, I_p =2 MA, a=0.4 m, R=2 m, (c) Extrap-T2R, I_p = 0.3 MA, a=0.18 m, R=1.24 m, (d) RELAX, I_p < 0.1 MA, a=0.25 m, R=0.51 m, (e) KTX, I_p =1 MA, a=0.4 m, R=1.4 m (under construction)

RFP facility, KTX, is under construction at the University of Science and Technology of China. First plasma in KTX is expected in 2015.

MST Program

The MST is an intermediate scale device (Fig. 4) that produces high temperature plasmas (2-3 keV) and is instrumented with advanced diagnostic capabilities and control tools such as neutral beam injection. It is the centerpiece of the RFP proof-of-principle program initiated by FES in 2000 [1]. Its dimensions are R/a=1.5/0.5 m with plasma current $I_p < 0.6$ MA. Its diagnostics rival those found on major tokamak experiments, including multi-point Thomson scattering (up to 250 kHz equiv.), an FIR interferometer-polarimeter for measuring density and magnetic field profiles, the U.S.'s only heavy ion beam probe, a diagnostic neutral beam for charge-exchange recombination spectroscopy for ion temperature and dynamics, full-spectrum motional Stark effect, neutral particle analyzers, and x-ray tomography and spectroscopy. The MST program is well known for its diagnostic advances, many of which impact designs for other facilities, including ITER. MST's 1 MW, 25 keV neutral beam injector used for creating energetic ions and auxiliary heating for beta limit studies is a unique capability in RFP research. The program also includes modest effort on electron Bernstein wave heating, taking advantage of MST's high beta plasma.

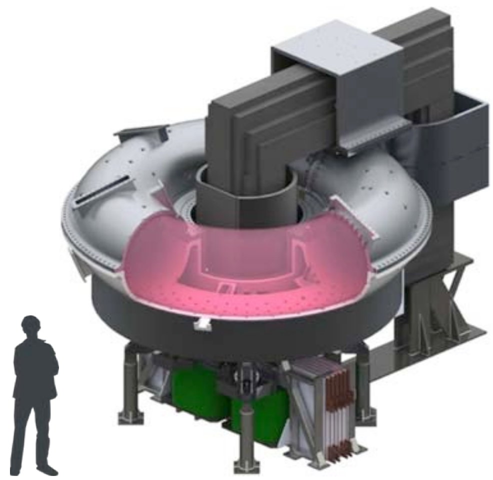

Fig. 4. Madison Symmetric Torus (MST)

MST research is highly collaborative. In addition to the UW home team, five groups are supported directly or indirectly under the "MST Research" umbrella: UCLA, Xantho Technologies, Wheaton College, LANL, and ORNL. There are 16 other collaborators (both national and international) involved in a variety of research topics. Approximately 60 individual scientists make use of the MST facility and data.

MST is a fantastic training facility. There are typically 12 graduate students and 4-6 postdocs mentored by MST's 11 staff scientists and senior collaborators. Totals of 23 graduate students and 11 postdocs completed their degrees and internships on MST in the last decade. Students and postdocs serve as MST operators, part of their excellent hands-on experience. Students also help with weekly facility maintenance. The MST group includes 15 engineers and technicians who provide a professional resource for all aspects of MST operation and research.

The scientific productivity of the MST program is large and sustained. For the period 2010-2014 there have been: 69 articles published in peer-reviewed journals, including 9 *Physical Review Letters;* 21 papers in major conference proceedings (e.g., IAEA FEC); and 118 presentations at major conferences, workshops, and seminars.

Funding from FES in FY 2014 for "MST Research" is $5.7M, which supports both the UW home team and collaborators. This is 20% smaller than MST's peak funding of about $7M/year in FY 2007-2011, which followed a roughly linear annual ramp from $3M/year beginning in FY 2002. While MST supports research for many users, it is not a "user facility" in the DOE designation, and therefore no separate funds for operations are provided. For the past 10 years there has been additional NSF funding at a ~5% level to support MST's participation in the Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas (CMSO). The Center was successful in reaching the highly competitive final review stage in its second 5-year renewal attempt, but unfortunately it was not selected for continuation.

RFP Theory and Computational Research

In addition to the MST experimental program, there is a (small) separate theory grant for RFP physics. Other single-investigator theory grants include RFP research topics. Modest support for RFP theory at

LANL and ORNL is included under the "MST Research" umbrella. This theory and computational research is vital to the RFP effort, especially in support of validation efforts, which requires coordinated collaboration between theory, computation, and experiment. Key opportunities for theoretical discovery are emerging in the areas of gyrokinetics applied to the RFP and energetic particle effects using codes originally developed for tokamak research. There are also important discoveries being made in the extension of nonlinear MHD to include two-fluid effects (e.g., NIMROD). Application of these codes to RFP problems is already yielding new physics and providing valuable tests of fundamental plasma theory and initial validation.

International Collaboration

The world effort in RFP research is very collaborative. Joint experiments and shared development of research tools are common and ongoing. These interactions are facilitated in part by an International Energy Agency (IEA) implementing agreement for a *Program of Research and Development on Reversed Field Pinches*. A workshop dedicated to RFP research is organized under IEA auspices about every 1.5 years, the next scheduled for Fall 2015 in Hefei, China. All of the RFP programs also have collaborations with tokamak and stellarator programs, both here and abroad. Areas of emphasis tend to be active control, development of 3D physics and analysis methods, and diagnostic development and applications.

3. Connections to FES Mission and Goals and Prior Planning Exercises

RFP research contributes primarily to two of FES's four strategic goals: (1) "advance the fundamental science of magnetically confined plasmas to develop the predictive capability needed for a sustainable fusion energy source" and (2) "increase the fundamental understanding of basic plasma science ..." In its new budget structure, FES places MST research in "Discovery Plasma/Fusion Science". While "discovery" very well captures the scientific opportunity for the RFP, in both the fusion and basic plasma contexts, it is vital to recognize that RFP research provides unique opportunities for developing predictive capability of fusion science. The issues for the RFP in the fusion context are quite similar to those of the tokamak and stellarator, hence there is a strong overlap with "Burning Plasma Science: Foundations" even if the fusion assessment of the RFP configuration is less mature. Furthermore, we emphasize and prioritize the strong synergy between the RFP's fusion science connections and basic plasma physics opportunities (Fig. 1). For example, the validation of nonlinear extended MHD is no less important for understanding the RFP than for predictive capability in toroidal fusion science generally, or for advancing the basic science of plasma self-organization through tearing-driven relaxation.

Connections to Gaps in Fusion Development

The RFP offers capabilities to help close the gaps in fusion development identified in "Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy" [10]. The most compelling potential is the elimination of auxiliary heating and control associated with Gap #7 "Reactor capable RF launching structures". The RFP represents the extreme of internal magnetization by plasma current. Ohmic heating (which defines the reference for "auxiliary" heating) is sufficiently large in the RFP to achieve burning plasma conditions, if energy confinement is comparable to that of a same-size, same-field tokamak. Such confinement is obtained transiently in existing devices [2], but no RFP experiment has been operated at the same size and field of high-performance tokamaks. There are many challenges and unknowns with regard to auxiliary heating, for example stable long-term operation and remote maintenance of rf antennas that face a burning plasma. Ohmic heating is very reliable, crosses material boundaries, and is the most efficient current drive known.

While RFP plasmas operate away from ideal stability boundaries and tend not to disrupt, abrupt plasma (and fusion power) termination will arise in any configuration through more mundane effects, and the consequences in the RFP are not well studied. The impact of sudden plasma termination could be severe for a reactor-grade RFP, simply given the proportionally large magnetic energy associated with the plasma current. This represents an opportunity to advance the science and control needed to resolve

Gap #5 "Avoidance of large-scale off-normal events". Some issues are different in the RFP, e.g., generation and confinement of runaway electrons is not as severe, since the plasma itself produces the particle-confining magnetic field. The termination process in tokamak plasmas involves a sequence of processes that includes resistive MHD instabilities similar to those that saturate relatively benignly in the RFP (non-disruptive but degrading confinement). The validation of nonlinear extended MHD in codes like NIMROD (described below) will help build confidence in understanding processes that involve this physics, like massive gas injection for disruption mitigation in tokamak plasmas [11].

RFP research provides major contributions to the science associated with Gap #4 "Control near limits with minimal power". The active control methodologies developed on the European thin-shell RFP devices, RFX-mod and Extrap-T2R, are highly successful. Many simultaneously occurring resistive wall modes are routinely controlled for pulses lasting >10 shell-times. The developed techniques are now being applied to tokamak experiments, e.g., the recent demonstration of stable $q_{95} < 2$ operation in DIII-D [12]. Current profile control of tearing instability is also a major theme in RFP research (as it is in tokamak research) used routinely to obtain the highest confinement plasma conditions [13]. The benefits of 3D shaping are also being explored through the spontaneous quasi-single-helicity regime that appears at high current in the RFP [14]. Optimizing and controlling this behavior are major goals.

Advancing Predictive Capability

In the next decade, a major opportunity and challenge for the RFP is to help close Gap #1 "Plasma Predictive Capability". As a cousin to the tokamak and stellarator, the RFP is a valuable partner in validating fusion science. Specific combinations of the major variables in toroidal confinement, like magnetic field strength, plasma current, and shaping, define the different magnetic configurations. By exploring adjacent regions in this major variable parameter space, the RFP exposes dependencies not otherwise accessible in the tokamak and stellarator. Validated predictive capability, in particular, will be robust only if it extends beyond a normal operating window [15,16].

The key scientific issues for the RFP are similar to those of the tokamak and stellarator. These issues are described and prioritized in Theme 5 of the ReNeW report [17], which was preceded by the FESAC Toroidal Alternate Panel (TAP) report [18]: (1) identify transport mechanisms and establish confinement scaling, (2) current sustainment, (3) integration of current sustainment and improved confinement, (4) plasma boundary interactions, (5) energetic particle effects, (6) determine beta-limiting mechanisms, (7) active control of MHD instabilities, and (8) self-consistent reactor scenarios. We note that Dr. Synakowski, Associate Director, FES, describes [19] the challenge for "Burning Plasma Science: Foundations" as "understand the fundamentals of transport, macro-stability, wave-particle physics, plasma-wall interactions". There is obviously large overlap with the RFP's scientific issues listed above, reflecting the cousin-like relationship of toroidal configurations.

Basic Plasma Physics of Self-Organization

Self-organization is a prominent basic plasma physics concept highlighted in the NRC decadal study "Plasma Science: Advancing the Knowledge in the National Interest" [20] and the community-led workshop on "Opportunities in Plasma Astrophysics" [21]. The behavior of the RFP plasma inspired, in large part, the concept of magnetic self-organization in laboratory and astrophysical plasmas. The seminal work of J.B. Taylor [22] established a relatively simple relaxation theory for how a reversed toroidal field could be maintained. The magnetic flux conversion process involved in relaxation dynamics gave rise to the concept of the RFP dynamo, closely related to astrophysical dynamos that convert mechanical energy into magnetic energy. While the theory of the minimum-energy relaxed state provides remarkable insight, the full challenge of understanding the dynamics and interrelationship of diverse self-organization phenomenology, including magnetic reconnection, turbulence, dynamo, and particle energization has come to light only in the last ten years. New questions have emerged, such as the nature of relaxation when both ion and electron fluids are coupled in current and momentum transport. Measurements of ion energization on MST have become much more detailed, but the processes that convert magnetic energy to kinetic energy through tearing mode magnetic reconnection are not well understood. There is a similar puzzle for particle energization in astrophysical settings such as the solar corona and wind [23].

4. RFP Research in Support of Discovery Fusion Science (and Foundations)

There are a number of ways RFP research advances fusion science. Here we describe the highest priority opportunities in the context of understanding the RFP and developing predictive fusion science more generally. Other opportunities are described in documents such as ReNeW [17].

Understanding the RFP Configuration and Developing Control Physics

Understanding and improving confinement remains the highest priority scientific issue for the RFP. Two pathways have developed in the last decade: current profile control for tearing stability and self-organization toward a single-helicity regime. These two paths (Fig. 5) share a common goal of reducing the impact of tearing modes that can cause the magnetic field to become stochastic, the dominant transport process in the standard RFP regime. Inductive current profile control has led to demonstration of the largest confinement and beta for the RFP to date [13]. In a number of ways the improved confinement can be described as tokamak-like [2]. A visualization of the improvement is shown in Fig. 6, where the confinement in MST standard and improved-confinement regimes is plotted in comparison to a same-size, same-field tokamak derived from empirical scaling. The ordinate for each data point is the measured confinement, and the abscissa is the expected confinement of a tokamak plasma with the same size, average $\langle B \rangle$, and heating power of the MST plasma.

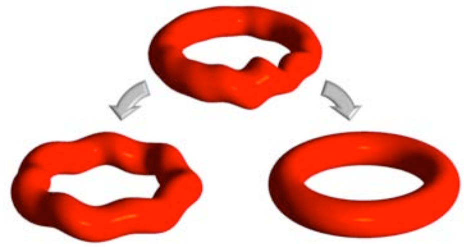

Fig. 5. Two pathways for improved RFP confinement: Quasi-single-helicity self-organization (left) and profile control for tearing stability (right). The plasma distortion is magnified for illustration purposes.

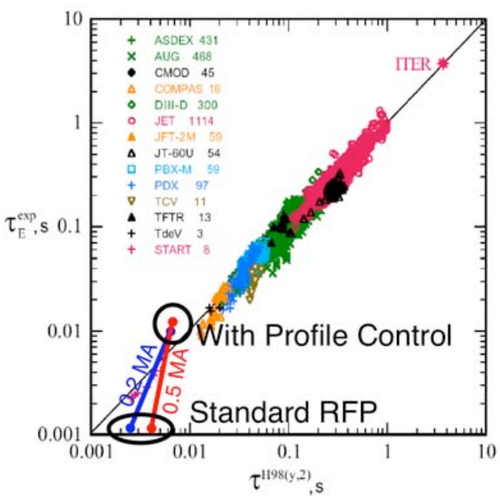

Fig. 6. MST confinement compared to tokamak H-mode empirical scaling. (Reprinted from ITER Physics Guidelines, ITER report N 19 FDR 1 01-07-13 R 0.1.)

The second path arises naturally through the self-organization process. The tearing mode spectrum narrows, becoming dominated by one mode. Hence this is called the quasi-single-helicity (QSH) regime. It is the favored regime at high plasma current, likely a placeholder for more fundamental dimensionless parameters such as the Lundquist number [14]. The narrower spectrum implies reduced stochasticity. The formation of an internal transport barrier is correlated with the QSH, most prominently appearing in RFX-mod, which operates at highest current (2 MA).

Inductive current drive and profile control are key to accessing and optimizing these improved confinement regimes. For this reason, a major upgrade of the inductive power supply for the poloidal field (plasma current) is proposed for MST. The present, passive power supply does not provide active control. Programmable power supplies will allow optimizing inductive control. Also, modeling suggests that it may be possible to attain 0.8 MA in MST. Maximizing the current in MST would allow assessing confinement over a larger parameter range and help optimize the QSH regime, which is limited to low density presently.

Improved power supplies will also allow tests of novel inductive sustainment scenarios. Most compelling is oscillating field current drive (OFCD), which could sustain dc current using ac induction

[5]. Partial current drive experiments using OFCD are consistent with theoretical expectations, but operation at larger plasma current is needed to demonstrate full sustainment [24,18].

Inductive control in the RFP is a powerful way to manipulate resistive MHD stability and dynamics. Hence, the power supplies and experiments motivated to understand RFP confinement and sustainment are also fantastic opportunities to develop validated predictive capability for nonlinear extended MHD, described below.

Validation of Fusion Physics Models

A vital ingredient in developing predictive science is experimental breadth that spans key variables. The named configurations (tokamak, stellarator, RFP, etc.) together represent an experimental portfolio for the major variables in toroidal confinement that are impossible to optimize using a single device. These variables map to important characteristics found in theoretical models, e.g., the safety factor, magnetic shear, and particle orbits. The RFP therefore represents an essential partner to grow predictive capability of models that govern toroidal confinement, e.g., MHD and gyrokinetics.

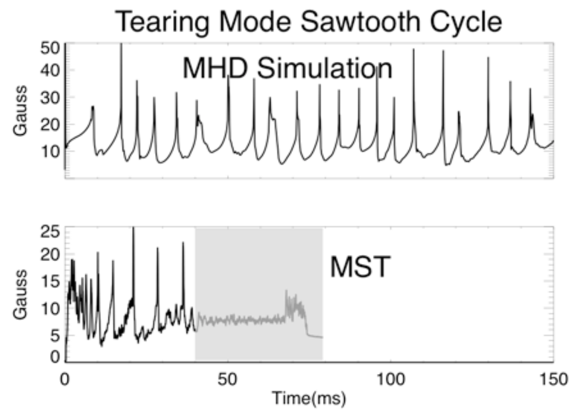

Fig. 7. Sawtooth cycle in MST and MHD computation, representing the opportunity for validation of nonlinear MHD. The shaded region for MST is the ramp-down phase when the drive for tearing instability is reduced.

RFP research offers great opportunities to advance methodologies aimed specifically to advance the predictive capability. MST research has begun to adopt methods of rigorous verification and validation (V&V) that have been advocated for fusion research, e.g., ReNeW Thrust 6 "Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurement". We assess visco-resistive and extended MHD as most ready for application of validation methods to RFP research. Nonlinear MHD theory and codes (NIMROD and DEBS) are well established due to the dominance of tearing instability (Fig. 7). The theory and codes are presently being extended to include two-fluid effects [25], necessary for understanding both electron and ion momentum balance [26]. This provides a potent validation arena to distinguish plasma behavior that can or cannot be explained by single-fluid versus extended MHD.

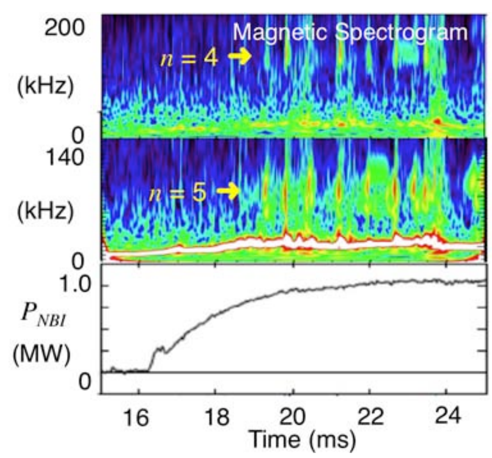

Fig. 8. Energetic particle modes excited by NBI in MST plasmas.

Looking ahead, high-power NBI on MST has created a new opportunity to understand kinetic extensions to MHD, although both the theory and experiment are exploratory at present. Despite magnetic stochasticity, fast ions are well confined [27], and for the first time, energetic particle modes are excited in the RFP (Fig. 8) [28,29]. Progress has been rapid in characterizing these modes, and the opportunity for modeling is beginning to challenge existing codes and theory.

Evidence suggests confinement in improved-confinement regimes could be dominated by micro-instability, as it is in tokamak plasmas [30]. These instabilities are described in gyrokinetics and codes like GENE and GYRO, which have already been adapted for application to the RFP geometry [31,32]. Theoretical predictions are that the critical gradient threshold is larger (Fig. 9) and the mode structure is more extended along the field, consequences of weaker toroidicity in the RFP. We aim to validate this physics using codes like GENE, a significant opportunity to expand the breadth of the most important physics governing confinement in toroidal plasmas.

A rigorous validation effort is extremely demanding on measurements, spanning a hierarchy from fundamental parameters to derived quantities such as turbulence-induced transport fluxes. MST already owns a complement of advanced diagnostics. A priority initiative is enhancement of these diagnostics for greater reliability and maintainability with reduced personnel resources. This would facilitate their routine operation. New diagnostic capability needs are primarily in the area of energetic particle effects.

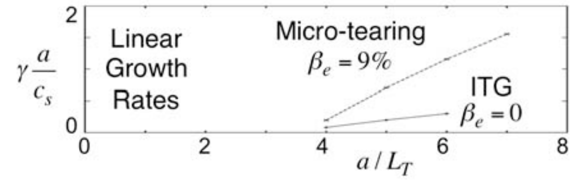

Fig. 9. Example linear growth rates for the RFP plasma. As for the tokamak, different modes appear depending on the equilibrium.

3D Physics and Tools

The QSH regime in the RFP corresponds to (self) 3D shaping comparable to that found in stellarator plasmas. For this reason, understanding the QSH regime is presently one of the principal drivers for the development of 3D equilibrium reconstruction tools like V3FIT [33]. The advanced diagnostics available in MST and RFX-mod are systematically being incorporated into the reconstruction toolbox. Since the 3D state is a spontaneous transition, it is naturally included in the nonlinear MHD validation discussion in the desire to understand the physics that governs the transition. It is also of interest for the basic physics of magnetic self-organization for nearly identical reasons. The internal transport barrier associated with the QSH onset resembles those in tokamak plasmas. In general these barriers and transitions are not well understood, and the QSH regime has already stimulated new theory in this context [34].

5. RFP Research in Support of Discovery Plasma Science

The RFP is one of the best laboratory plasmas in which to study magnetic self-organization, which refers to the interplay of processes that govern the large-scale structure (e.g., the magnetic equilibrium) through dynamics of instabilities. Free energy associated with large-scale structure drives magnetic instability (with both spatial and temporal variations), which feed back through nonlinear processes that govern transport and energy transfer thereby controlling, in part, the large-scale. The processes involved in the RFP are magnetic reconnection (tearing instability) [8], current transport (dynamo) [7], momentum transport [26,35], and particle energization [9,36]. The processes are impulsive, correlated with the sawtooth cycle, as shown in Fig. 10.

The famous minimum energy relaxed state described by Taylor [22] reflects part of the self-organization in the RFP, i.e., current transport and a dynamo-like mechanism that allows the nonlinear saturation of the tearing instability. The self-organization is in fact much more comprehensive. Momentum relaxation is explicitly coupled to current relaxation through the Hall term, $\langle \tilde{\mathbf{J}} \times \tilde{\mathbf{B}} \rangle_{\parallel}$, which appears as an emf in the extended MHD Ohm's law, and as the Maxwell stress in momentum balance. This new physics is only recently being explored in nonlinear, extended MHD simulations using codes like NIMROD [25]. Indeed, the self-organization process in the sawtooth represents a ripe opportunity for validation discussed above. For example, some parts of the process seem to be captured in single-fluid MHD, e.g., the sawtooth period, while other parts

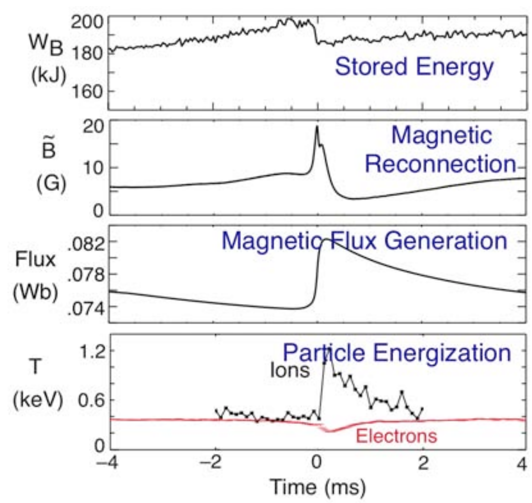

Fig. 10. Magnetic self-organization processes at the sawtooth crash, like those in Fig. 7.

required a more complete model. One aspect of rigorous validation is to identify the essential physics needed to describe specific processes or behavior, and contrasting single-fluid versus extended MHD will be especially valuable in this context.

Particle energization is another intriguing part of the self-organization in the RFP. Ions can be hotter than electrons (Fig. 10), a clear signature of non-collisional energy transfer [9]. Many features of ion heating and energization have been measured in recent years, but the process is not fully explained, despite several theoretical models. Recently uncovered features include anisotropy in the heating relative to the magnetic field direction and the spontaneous formation of an energetic ion tail [36]. MST's neutral beam injector has also proved useful to explore aspects of the ion dynamics by creating a test ion population at high energy. These ions are observed to obey runaway expectations during the sawtooth crash event, one of the possible means by which a tail could form [37].

Most of MST's advanced diagnostics have been specified to measure key quantities involved in the self-organization process. This tends to add design challenge, e.g., frequency bandwidth to resolve fluctuations associated with tearing modes, but the capability to measure fluctuation dynamics benefits other measurements, e.g., equilibrium changes on the timescale of a sawtooth crash. The techniques used on MST have had significant impact on diagnostics used on other facilities, for example, simultaneous interferometry-polarimetry using FIR lasers and fast Thomson scattering.

Astrophysical plasmas exhibit processes similar to those observed in RFP plasmas. This commonality was one impetus for the creation of the Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas, an NSF Physics Frontier Center founded in 2003 [38]. The Center brought together laboratory and astrophysical plasma scientists to study self-organization and its underlying processes. In this context, it was explicitly a partnership between NSF and DOE-FES. In particular, FES funded the operations of all of the laboratory experiments involved. In MST's case, the added NSF funding was about 5% that provided by FES, enough to support several students and postdocs primarily. While the Center was successful in a first five-year renewal in 2008, NSF recently declined a second renewal, and the Center will cease operation after 2015.

6. Recommendation and Outlook

A vigorous program will maintain U.S. leadership in RFP research. This includes support for theory and computation, in addition to a collaborative experimental program. Near term emphasis on validation will continue to grow the scientific basis for the RFP, in addition to advancing predictive fusion science and the physics of self-organization.

Moderate investments in the MST facility can bring it close to its intrinsic limits in terms of current and pulse length. In particular, a programmable power supply for the poloidal field is needed to maximize inductive control, important in all area of MST research, including validation and basic science. Validation requires close collaboration between theory, computational modeling, and experiment. While MST already possesses many advanced diagnostics, adequate support for their operation and maintenance requires scientific and engineering staff at or above the current level. The planned initiative to maximize the availability of these major diagnostics through improvements to reliability and maintainability are necessary to maximize the impact of personnel resources. The current level of funding ~\$5.9M/year (experiment and theory) is 20% smaller than peak funding ~\$7.2M/year in FY 2011.

Resolution of the RFP's key scientific issues requires a larger, higher current RFP device. The physics context can be cast as resolving dependence on the Lundquist number for many of the RFP's scientific issues. Progress in establishing the RFP's scientific base at the present experimental scale is excellent, and the metrics identified for gauging success of the proof-of-principle program [1] have largely been achieved in the context of the world RFP program. The requirements for a next-step device are outlined in the FESAC Toroidal Alternates Panel report [18]. One possible path forward was identified in Thrust 18 "Achieve high-performance toroidal confinement using minimal externally applied magnetic field" of ReNeW, summarized in Fig. 11. The upgrades noted above for MST would allow maximizing its capability in producing highest performance plasmas. The RFX-mod group is proposing an upgrade of their device over the next few years, which will include a substantial change in the shell structure and plasma-facing components [39]. Also, KTX, the new RFP at the University of Science and Technology of China will commence operation in 2015. Their plan emphasizes studies of the plasma-material interface, with a device design that accommodates easy access to in-vessel components. They also plan a second phase that would include installation of saddle coils for active control, similar to the sets installed on RFX-mod and Extrap T2R. The world RFP program is impactful and highly collaborative at a proof-of-principle level of research, but realizing the potential of a gap-closing game-changer like ohmic ignition requires advancing the RFP to the performance extension level.

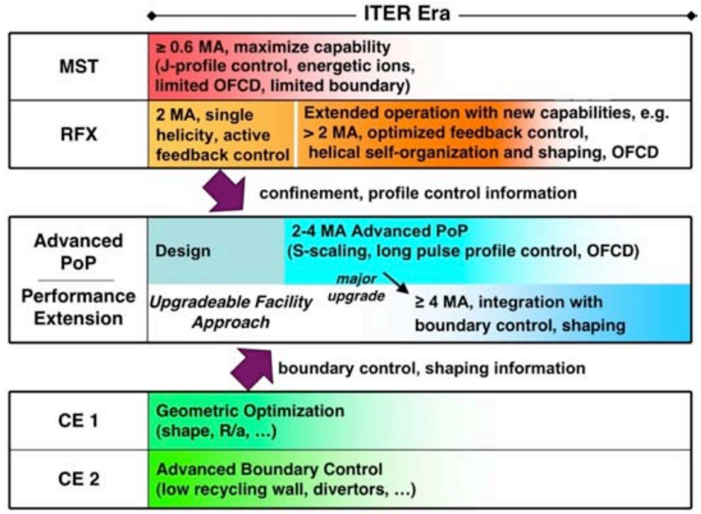

Fig. 11. Conceptual RFP development path described in Thrust 18 of ReNeW. The RELAX low-aspect ratio device helps address geometric optimization (CE 1), and the new KTX program in China aims to advance boundary control (CE 2) at an experimental scale close to MST and RFX.

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