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Research Needs Workshop for Magnetic Fusion Energy Science

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ABSTRACT

The process, organization and results of the Research Needs Workshop for Magnetic Fusion Energy Science are reviewed, and the Workshop Report is briefly surveyed.

1. Introduction

1.1. Background

Nuclear fusion – the process that powers the sun – offers an environmentally benign, intrinsically safe energy source with an abundant supply of low-cost fuel. It is the focus of an international research program, including the ITER fusion collaboration, which involves seven parties representing half the world's population. The realization of fusion power would change the economics and ecology of energy production as profoundly as petroleum exploitation did two centuries ago.

The 21st century finds fusion research in a transformed landscape. The worldwide fusion-community broadly agrees that the science has advanced to the point where an aggressive action plan, aimed at the remaining barriers to practical fusion energy, is warranted. At the same time, and largely because of its scientific advance, the program faces new challenges; above all it is challenged to demonstrate the timeliness of its promised benefits.

In response to this changed landscape, the Office of Fusion Energy Sciences (OFES) in the US Department of Energy commissioned a number of community-based studies of the key scientific and technical foci of magnetic fusion research. The Research Needs Workshop (ReNeW) for Magnetic Fusion Energy Science is a capstone to these studies. In the context of magnetic fusion energy, ReNeW surveyed the issues identified in previous studies, and used them as a starting point to define and characterize the research activities that the advance of fusion as a practical energy source will require. Thus, ReNeW's task was to identify (1) the scientific and technological research frontiers of the fusion program, and, especially, (2) a set of activities that will most effectively advance those frontiers. (Note that ReNeW was not charged with developing a strategic plan or timeline for the implementation of fusion power.).

1.2. The Workshop Report

The ReNeW Report can be found online at http://burningplasma.org/Renew.html. Presenting a portfolio of research activities for US research in magnetic fusion for the next two decades, it is intended to provide a strategic framework for realizing practical fusion energy. The portfolio is the product of 10 months of fusion-community study and discussion, culminating in a Workshop held in Bethesda, Maryland, from June 8 to June 12, 2009. The Workshop involved some 200 scientists from Universities, National Laboratories and private industry, including several scientists from outside the US.

Largely following the Basic Research Needs model established by the Office of Basic Energy Sciences, the Report presents a collection of discrete research activities, here called "thrusts." Each thrust is based on an explicitly identified question, or coherent set of questions, on the frontier of fusion science. It presents a strategy to find the needed answers, combining the necessary intellectual and hardware tools, experimental facilities, and computational resources into an integrated, focused program. The thrusts should be viewed as building blocks for a fusion program plan whose overall structure will be developed by OFES, using whatever additional community input it requests.

1.3. Research requirements

In the next two decades, the "ITER era," magnetic fusion will for the first time explore the burning plasma regime, where the plasma energy is sustained mostly by its own fusion reactions. We expect ITER to expand our understanding of fusion plasma science and to be a major step toward practical fusion energy. It will also, as the

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first burning plasma experiment, pose new requirements, including advanced diagnostics for measurement and control in a burning plasma environment, and analytical tools for understanding the physics of self-heating.

To benefit fully from its investment in ITER the US must maintain a broad research program, attacking fusion's scientific and technical issues on several fronts. We need in particular to acquire knowledge that ITER cannot provide: how to control a burning plasma with high efficiency for indefinite periods of time; how to keep a continuously burning plasma from damaging its surrounding walls—and the walls from contaminating the plasma; how to extract the fusion energy from a burning plasma efficiently and use it to produce electricity and a sustained supply of tritium fuel; and ultimately how to design economical fusion power plants. These requirements motivate a multi-disciplinary research program spanning such diverse fields as plasma physics and material science, and advancing a range of technologies including plasma diagnostics, magnets, radio frequency and microwave sources and systems, controls, and computer simulation.

The key scientific and technical research areas whose development would have a major effect on progress toward fusion energy production were systematically identified, categorized and described in the three resource documents that form the starting point for ReNeW: the report of the Priorities, Gaps and Opportunities Panel, chaired by Martin Greenwald; the report of the Toroidal Alternates Panel, chaired by David Hill; and the report of the Energy Policy Act task group of the U.S. Burning Plasma Organization.

1.4. ReNeW Organization: Themes

The structure of ReNeW was based on five themes, each comprising a major area of fusion research, and each being further organized into three to seven sub-panels. Three of the five themes were taken from the Greenwald Report. The remaining two themes focused respectively on ITER activities and alternate confinement concepts.

1.4.1. Theme 1: Burning plasmas in ITER

ITER participation will be a major focus of US fusion research during the time period considered by ReNeW. The many opportunities and challenges associated with the ITER project are treated in Theme 1.

1.4.2. Theme 2: Creating predict able, high-performance, steady-state plasmas

The US has been a leader in demonstrating advanced plasma confinement scenarios that allow higher confinement efficiency, steady-state operation, and other advantages. Theme 2 addresses the science underlying such schemes.

1.4.3. Theme 3: Taming the plasma–material interface

Magnetic confinement sharply reduces the contact between the plasma and the vessel walls, but such contact cannot be entirely eliminated. Advanced wall materials and magnetic field structures that can prevent both rapid wall erosion and plasma contamination are studied in Theme 3.

1.4.4. Theme 4: Harnessing fusion power

Fusion energy from deuterium–tritium (D–T) reactions appears in the form of very energetic neutrons. Theme 4 is concerned with the means of capturing this energy, while simultaneously breeding the tritium atoms needed to maintain the reaction.

1.4.5. Theme 5: Optimizing the magnetic configuration

Currently most large fusion experimental devices are based on the tokamak, a design using a strong, axisymmetric external magnetic field to achieve operating parameters close to those in a fusion reactor. Future fusion devices might also be tokamaks, but there are alternative design principles with potentially attractive features; the most interesting such designs are considered in Theme 5.

2. The ReNeW thrusts: a research portfolio

2.1. Thrust definition

The ReNeW thrusts listed below are the key results of the Workshop. They constitute eighteen concerted research actions to address the scientific and technological frontiers of fusion research. Each thrust attacks a related set of fusion science issues, using a combination of new and existing tools, in an integrated manner. In this sense each thrust attempts a certain stand-alone integrity.

Yet the thrusts are linked, both by scientific commonality and by mutual dependence. The most important linkages – for example, requirements that a certain thrust be pursued and at least in part accomplished before another is initiated – are discussed in Part II of the main Report. Here we emphasize that fusion advances along a broad scientific and technological front, in which each thrust plays an important role.

The thrusts span a wide range of sizes, from relatively focused activities to much larger, broadly encompassing efforts. This spectrum is expected to enhance the flexibility of OFES planning.

ReNeW participants consider all the thrusts to be realistic: their objectives can be achieved if attacked with sufficient vigor and commitment. Three additional elements characterize, in varying degrees, the ReNeW thrusts:

- Advancement in fundamental science and technology—such as the development of broadly applicable theoretical and simulation tools, or frontier studies in materials physics.
- Confrontation with critical fusion challenges—such as plasma-wall interactions, or the control of transient plasma events.
- The potential for major transformation of the program—such as altering the vision of a future fusion reactor, or shortening the time scale for fusion's realization.

2.2. Thrust organization

The resource documents used by ReNeW organized the issues into five scientific and technical research areas. Correspondingly, the ReNeW organizational structure was based on five Themes, each being further sub-divided into three to seven panels. The thrusts range in content over all the issues delineated in the five Themes.

Many of the ReNeW thrusts address issues from more than one Theme. For this reason the scientists contributing to most thrusts are from a variety of research areas, and key elements of a given thrust may stem from ideas developed in several Themes. In other words, the content of a typical thrust transcends that of any single Theme. Nonetheless, it is convenient to classify each thrust according to the Theme that contains its most central issues.

The following Thrust descriptions are excerpted from the ReNeW report. However, we emphasize that the Report describes each Thrust and its motivation in much more detail; readers are encouraged to view the complete Report.

2.3. ReNeW thrusts

2.3.1. Thrust 1: Develop measurement techniques to understand and control burning plasmas

The impressive progress in fusion science understanding has been enabled by the development of an extensive suite of advanced measurement techniques. Such measurements have also been instrumental in achieving active control of high-performance plasmas. As we move toward the “burning plasma era” of ITER and beyond to DEMO, the instruments making these measurements will be exposed to an increasingly hostile environment, and many existing techniques will be severely challenged and risk potential failure. The fusion science community must immediately begin the development of new and improved diagnostic systems to guarantee availability of the measurements essential for advanced plasma control and improved understanding of steady-state burning plasmas.

Key issues:

- Developing diagnostics critical to the burning plasma research goals.
- That provide the essential tools for scientific discovery in burning plasmas and reliably support real-time plasma control and machine protection.
- That survive the hostile, long-pulse environment of ITER, and the even harsher, steady-state environment of a DEMO device.
- Developing techniques to measure uniquely important properties of burning plasmas, such as the behavior of confined fusion alpha particles.

Key questions:

- *What creative, new measurement techniques can fill acknowledged “measurement gaps” in present ITER plans?*
- *What opportunities for new measurement techniques arise through operation at high-performance, burning plasma parameters?*
- *What technological advances would mitigate the known risks and optimize measurement reliability in the harsh ITER environment?*
- *What are the minimum measurement requirements for DEMO, and what techniques can be developed to satisfy them in a DEMO environment?*

The US ITER Project is currently focused on delivering “in-kind” contributions of a few diagnostic systems based on existing measurement techniques. However, the US diagnostic community could also contribute to these and to a much broader range of essential measurement needs through a new, targeted burning plasma diagnostic development program. Targeting would be coordinated with efforts elsewhere, with preference for developments supporting US burning plasma research interests. This is a high-leverage way to maximize the US investment in ITER research and to contribute substantially to preparations for DEMO.

Proposed actions:

- Prioritize burning plasma measurement needs, including those for DEMO.
- Perform phased developments targeted to high-priority needs, including prototyping on operating devices.
- Evaluate the success of these developments, and where appropriate, work to transfer techniques to ITER or other burning plasma devices.

2.3.2. Thrust 2: Control transient events in burning plasmas

Transient events such as disruptions and edge localized modes (ELMs) cause high peak heat loads on plasma facing surfaces, potentially leading to rapid erosion or melting. Disruptions also have the potential to cause damage through large electromagnetic forces and intense beams of high-energy electrons. Although ELMs and disruptions are generally tolerated in present tokamaks, the consequences will be much more severe in future burning plasmas because of the larger thermal and magnetic energies and longer pulse lengths; such events will reduce operational availability and shorten the lifetime of plasma facing components. It is vital to minimize such events in ITER and to mitigate their consequences when they occur.

Key issues:

- Characterization of disruptions. *What are the causes of disruptions in present facilities? Do they always have detectable precursors? How do the consequences of disruptions extrapolate to ITER and other burning plasmas?*
- Capability to predict disruptions. *Can plasma stability be assessed accurately enough in real-time to predict stability limits? Can disruption precursors be reliably detected?*
- Capability to avoid disruptions. *If disruptions can be predicted, what remedial actions can be taken to suppress the instability or move the discharge to a more stable operating point?*
- Means to minimize the impact of disruptions. *What is the best means to mitigate the effects of disruptions in ITER? What are the consequences of a mitigated disruption?*
- Means of robustly avoiding or suppressing ELMs. *Can ELMs be reliably eliminated or their impulsive power loading sufficiently reduced through 3-D magnetic fields and other means of modifying the plasma edge? How do ELM avoidance techniques extrapolate to ITER?*

Proposed actions:

- Characterize the causes and consequences of disruptions in existing facilities. Benchmark predictive models of disruptions and disruption mitigation against existing data.
- Use existing tokamaks to develop and test tools for real-time prediction and measurement of plasma stability, and detection of disruption precursors.
- Use existing tokamaks to develop techniques for suppressing instabilities or steering the operating point away from stability limits. Demonstrate these techniques in longer pulses on the emerging generation of superconducting devices.
- Assess strategies for mitigating disruptions through a rapid but benign shutdown of the discharge. Demonstrate solutions in medium and large tokamaks for extrapolation to ITER.
- Develop techniques to mitigate ELM s through modification of edge plasma transport and stability. Demonstrate the solutions in medium and large tokamaks for extrapolation to ITER.

The US fusion program is well positioned to carry out much of the required work in existing tokamaks, with modest upgrades to diagnostics and auxiliary systems, but substantial increases in experimental time and human resources. Further technology development will be required to extend these techniques to the burning plasma regime in ITER.

2.3.3. Thrust 3: Understand the role of alpha particles in burning plasmas

Fusion-produced alpha particles will constitute the dominant heating source in burning plasmas and thus open a new regime of investigation compared to all previous experiments, which are based on the use of externally applied heat sources. This significant change in plasma heating raises a number of issues unique to burning plasmas. Therefore, a detailed understanding of alpha physics is essential for extrapolations from ITER to a DEMO device and the employment of fusion as a future energy source.

Key issues:

- Interaction with Background Plasma. *Will the alpha population in ITER cause significant plasma instabilities? If so, can these be avoided*

or tolerated? How will the alpha population interact with thermal plasma instabilities and turbulent transport?
- Impact on Achieving and Sustaining Burning Plasma Operation. *How will alpha particles affect other heating and current drive methods? What additional heat load on the first wall will high-energy alpha particles cause? Will self-regulated steady-state regimes exist with strong alpha self-heating?*
- Measurement. *Can alpha particle phenomena and instabilities be adequately diagnosed in burning plasmas?*
- Control. *Can the alpha power be controlled for optimization of plasma profiles, currents, and flows? Can control techniques be developed to channel alpha energy directly to ion heating?*

Proposed actions:

- Develop experimental scenarios to expand access to energetic particle behavior at high fast-particle pressure; explore energetic particle dynamics and interaction with instabilities, losses, and current drive.
- Identify operational regimes in burning plasma devices that are stable to alpha-driven instabilities and determine if alpha transport is tolerable in unstable regimes.
- Predict the alpha heating profile, alpha-driven currents, and impact on current drive requirements. Evaluate parasitic absorption of current drive power by alpha populations. Assess coupling of alphas with other fast ion beam components and the core plasma.
- Incorporate experimentally validated alpha physics transport models into integrated plasma simulation tools for the entire plasma.
- Simulate and validate alpha particle losses and their impact on first-wall integrity.
- Develop innovative high-resolution spatio-temporal measurements of the alpha particle energy distribution and instability mode structure.
- Exploit low-level Alfven wave excitation as a spectroscopic diagnostic tool.
- Control alpha heating feedback loops for steady-state operation. Develop control techniques for alpha-driven instabilities and attempt to expand stable operating regimes. Facilitate helium ash removal. Attempt the direct transfer of alpha particle energy to the core fuel ions.

2.3.4. Thrust 4: Qualify operational scenarios and the supporting physics basis for ITER

To attain high-performance states in ITER, we must form, heat, control, and safely shut down high-temperature plasma in a predictable and reproducible manner. Advancing our understanding of how to achieve these steps requires an integrated experimental campaign in plasma conditions similar to ITER, e.g., high-confinement mode (H-mode) plasmas with low input torque, equilibrated ion and electron temperatures, and low collisionality. Ensuring that ITER will efficiently achieve its objectives entails a high level of support by the US tokamak program. This requires upgrades to the tools for heating and current drive, particle control, and heat flux mitigation on existing tokamaks and, possibly, a new tokamak facility.

Key issues:

- **Plasma initiation:** *What wall-cleaning methods are suitable for ITER? Can techniques be developed to remove tritium from the walls without major loss of operating time?*
- **Transient phases:** *What is the energy and particle transport during current ramp-up and ramp-down, and how does it depend on the evolving current profile?*
- **H-mode access:** *What is the physical basis for extrapolating H-mode power thresholds adequately for ITER in the initial hydrogen and helium and eventual nuclear phases?*
- **H-mode sustainment:** *What is the physical basis for extrapolating H-mode confinement to plasmas with dominant electron heating, equal ion and electron temperatures, low collisionality, and low torque injection?*
- **Heating:** *Will the 20 MW of ion cyclotron resonance heating planned for ITER be effective, especially in transient phases and with plasma-antenna interactions taken into account?*
- **Fueling:** *What particle transport, pellet ablation, and fuel deposition models are appropriate to predict ITER density profiles and performance?*
- **H-mode pedestals:** *What physical processes form the edge pressure pedestal in H-mode plasmas, and how do they interact with core heat and momentum transport?*
- **Pulse length extension:** *What is the physics basis of the hybrid scenario, and does it extrapolate favorably to ITER? What is the optimum path to a steady-state advanced tokamak mode of operation, and what tools are needed to access it?*

Proposed actions:

- Develop wall-cleaning techniques that are compatible with large, stationary magnetic fields.
- Measure and characterize transport physics during transient tokamak phases as well as in steady H-mode plasmas with plasma conditions similar to ITER.
- Determine minimum heating power required to obtain and maintain (1) H-mode during ramp-up and ramp-down, (2) steady H-mode with (small, rapid) Type III edge localized modes (ELMs) and (3) steady H-mode with good confinement (compared to scaling relations).
- Elucidate the physics and minimize interactions of ion cyclotron resonance heating antennas with edge plasmas.
- Develop models for particle transport and for gas and pellet fueling applicable to ITER.
- Test models of H-mode pedestal structure against experiment, determine the effect of pellet fueling and low flow/torque, and pursue coupling to core models.
- Understand the physics of the hybrid scenario to make reliable predictions for ITER, develop predictive understanding of steady-state modes of operation, and define requirements for implementation in ITER.

2.3.5. Thrust 5: Expand the limits for controlling and sustaining fusion plasmas

A fusion reactor operating in a robust steady-state at pressures beyond conventional stability limits would bring enormous advantages in terms of economy and efficiency. To achieve and maintain such conditions in a tokamak will require an advanced tokamak scenario with an unprecedented level of active control.

Key issue:

What is the highest performance level of a tokamak fusion plasma that can be controlled and maintained for an unlimited period of time without unacceptable transients?

To maximize performance and achieve the necessary level of control, significant advances will be required in three areas:

Sensors: Diagnostic techniques for measuring the plasma state to enable regulation that are capable of operating robustly in a sustained-duration burning plasma nuclear environment.

Actuators: Means to sustain and affect the plasma through flexible heating, current drive and fueling systems, thus enabling reliable burn control and profile regulation.

Algorithms: Mathematical schemes using control-level reduced models to translate measurements into actuator commands, thus providing robust and quantifiable assurance of sustained operation. The control-specific engineering, physics, and mathematical solutions require a high degree of cross-community integration. The goal requires developing and integrating these three elements to enable operation in close proximity to or beyond passive stability limits. The integrated solutions must maintain robustness to transients and avoid (or mitigate when necessary) serious off-normal events. Although we will learn from present devices and ITER, these cannot operate in a regime requiring the active control level of a steady-state demonstration reactor.

Specific issues cover understanding and solutions for:

- Active control to robustly sustain the plasma in steady-state, including burn and fueling control.
- Robust active stabilization of instabilities and transient fluctuations.
- Regulation of the power flow to material surfaces.
- Active prediction, avoidance, detection, and response to disruptions and fault events.

Proposed actions:

Short-term: Begin development of nuclear-robust control-specific diagnostics, high-performance actuators, reduced models, and robust control algorithms with appropriate enhancement and exploitation of presently operating devices. Increase integration of relevant areas of expertise in diagnostics and actuators for control requirements, control model development, control algorithm mathematics, computational simulations, and physics understanding.

Medium-term: Use new experiments to demonstrate solutions with extended pulse duration in deuterium (D–D) plasmas, through international collaboration where possible.

Long-term: Use ITER and new deuterium–tritium (D–T) devices being proposed to develop and demonstrate the integrated control solutions required for DEMO.

2.3.6. Thrust 6: Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurement

Developing the tested computational models needed for fusion plasmas will require a coordinated effort substantially beyond the current level of activities and an unprecedented degree of cooperation among program elements. This Thrust would build on a remarkable period of progress, scientific achievement and discovery, and plays to US strengths, which include the most advanced first-principles codes and the best diagnosed experiments. It leverages developments in numerical techniques and software engineering to exploit the newest generations of powerful parallel processing computers. By demonstrating deeper physical understanding of relevant science through confrontation of theory and experiments, and by developing models that embody, test and codify collected scientific knowledge, the Thrust would directly address the mission of the Fusion Energy Science (FES) program. Progress on this Thrust is of great practical importance and urgency. It would enable maximum exploitation of experiments, especially ITER, and allow for more reliable design of new experiments or facilities, critical for progress toward a DEMO.

Key issues:

- *How well can the complex, multi-scale phenomena of fusion plasmas be understood through first-principles models, compared in detail to experimental measurements?*
- *What are the appropriate methods for integrating multi-physics and multi-scale effects, which are needed to increase the fidelity of practical computer models?*
- *How can reliable reduced, integrated models be constructed that support rapid exploration of operating scenarios and plasma control on experiments, especially ITER?*
- *What innovations in measurement techniques or experiments should be pursued that would facilitate comprehensive tests of these models?*

Proposed actions:

- Strengthen the basic theory program to address areas where current physical models are inadequate or incomplete.
- Develop a spectrum of powerful, robust, well-verified computer models shared by a large user community. The Fusion Simulation Program (FSP), if funded beyond the program definition phase, would be an important, but not exclusive part of this effort.
- Innovate in diagnostic techniques to enable measurements critical for validation.
- Provide a spectrum of experiments including both large and small facilities, a range of confinement concepts and adequate run time dedicated to model testing.
- Conduct a rigorous set of validation activities that would assess critical elements of physical models and test them through careful comparison with experiments. These would help to guide research in theory and computation by identifying important gaps in current models.
- Recruit, train and support dedicated analysts, who would bridge the gap between theorists, code developers and experimentalists, providing unbiased assessments.
- Provide substantial computer time for code verification and model validation.

2.3.7. Thrust 7: Exploit high-temperature superconductors and other magnet innovations to advance fusion research

An integrated program of advanced magnet R&D focuses on developing high-temperature superconductor (HTS) materials and magnet systems, which offer enormous potential for Magnetic Fusion Energy research experiments, and potentially transformational technological innovation. Magnets are an essential, enabling technology. They confine hot plasmas and have a significant impact on the plasma initiation, heating, control, and sustainment systems. Magnetic field strength limits the achievable plasma pressure needed for fusion—higher field would allow more compact devices and could significantly ease control requirements. Today's experiments and those planned, including ITER, use superconducting magnet technology that is decades old. The superconducting magnet system of large-scale fusion devices is about one-third of the core machine cost. Future reactors must be built with the best available superconductor technology. Almost any magnetic configuration of a practical fusion reactor requires superconducting magnets. Revolutionary new HTS materials such as Yttrium–Barium–Copper–Oxide (YBCO) are sufficiently advanced for next-step fusion applications. Besides having a high critical temperature, these materials can operate at extremely high magnetic field, offering a substantial increase in plasma performance.

Opportunity:

Success in this program can potentially revolutionize the design of magnetic fusion devices for very high performance in compact devices with simpler maintenance methods and enhanced reliability.

Key issues:

- Development of practical conductors and cables suitable for demanding fusion applications. Can the present fragile HTS tape geometry be integrated into high current cables with the high current density needed for fusion experiments? *Can HTS material be made into round wires with high critical current density for easier magnet application?*
- Integration of HTS cables into practical magnet systems for fusion experiments. *Can HTS be used to make magnet systems with increased performance, reliability and maintainability? Which applications will most enhance performance, and reduce costs, of fusion research experiments, and ultimately enable more attractive reactors?*

Proposed actions:

- Fabricate HTS wires, and integrate wires and tapes into high current density cables. A coordinated program of laboratory R&D in universities, national laboratories and industry.
- Develop magnet components, including improved structural and insulating elements, and assess performance for various fusion applications. Potential applications, which would greatly benefit several other ReNeW thrusts, include.
- High-field SC magnets for steady-state axisymmetric facilities with demountable joints, giving flexibility to test multiple divertor and nuclear science components.
- HTS tapes integrated into coils with complex shapes for 3-D and other alternate configurations.
- Test the most promising applications in prototypes, and ultimately incorporate into new Office of Fusion Energy Sciences (OFES) research facilities.

2.3.8. Thrust 8: Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas

This Thrust explores the challenging DEMO plasma regime in which plasma self-heating (Palpha) dominates over external heating sources (Pinput), the plasma's self-generated current dominates over external current drive, the plasma pressure is high, and the plasma radiates a significant fraction of its power. In this high fusion-gain regime $Q \geq 20$ (Q = Ptotal/Pinput, where Ptotal includes the energy carried by fusion neutrons), i.e., Palpha ≥ 4 Pinput, the temperature and pressure profiles are set by the plasma self-heating and underlying transport processes. The transport of energy, particles, momentum, and current, and magnetohydrodynamic (MHD) processes become strongly coupled in this regime, and the plasma reaches a self-organized state, raising several new questions.

Key issues:

- *Under these strongly coupled conditions, what is the plasma configuration that emerges from these self-consistent internal physics processes?*
- *In the strongly coupled burning plasma what maximum stability properties will the plasma access?*
- *Can such strongly coupled burning plasmas be established and sustained with much less external power and current drive than in present experiments? What is the most attractive core burning plasma regime that can be achieved?*
- *What is the self-consistent plasma core/scrape-off layer/divertor plasma state?*

ITER will provide critical information on obtaining and understanding burning plasmas. ITER's targets are to first demonstrate Q = 10 (Palpha ~ 2Pinput), in plasmas sustained by an inductive transformer (non-steady-state), and later to explore noninductively sustained plasmas with Q = 5 (Palpha ~ Pinput) for longer durations. DEMO requirements for a high-performance plasma surpass ITER's goals, and the US should explore a complementary D–T facility with a more focused physics program. The scrape-off layer plasma and its interaction with material surfaces can influence the core through particle transport, the effects of which can be observed on the multiple current profile redistribution time scale of these experiments.

Proposed actions:

- Pursue research on existing tokamaks and the Asian long-pulse tokamaks to establish fully noninductive and high-performance plasma targets for high-Q, steady-state plasmas.
- US researchers, together with international colleagues, should assess potential operating plasma scenarios and upgrades on ITER, which could enhance the performance of noninductively sustained burning plasma demonstrations.
- In parallel, examine design options for construction of a US facility, to supplement the ITER mission, focused on high Palpha/Pinput, high pressure, high density, high self-driven current fraction, D–T burning plasmas for durations of several current profile redistribution times. This design study should explore whether the flexible facility needed for this Thrust can be made compatible with the missions of other fusion energy science thrusts.
- Based on these assessments, proceed with either ITER enhancements or a US D–T facility, or both.

2.3.9. Thrust 9: Unfold the physics of boundary layer plasmas

A thin boundary layer surrounds the hot core of all magnetically confined plasmas. The layer naturally mediates interactions between the confined plasma and material surfaces. The magnetic field structure of the region is complex. Furthermore, the plasma pressure that can be maintained at the core-boundary interface has a strong impact on fusion gain. More than a dozen important new facets of boundary plasma behavior have been discovered over the past decade. Despite this progress, the basic processes that determine the local spatial scale lengths, and the heat and particle flow within the layer, are still not adequately understood. Hence, the heat and particle loads on plasma facing components, impurity intrusion, and core fusion gain are difficult to predict, making design requirements and operational strategies uncertain and necessarily conservative. The output of Thrusts 9, 10, and 11 will be an essential design component for any new fusion device and can be extensively tested in future facilities (e.g., Thrusts 8, 12, 13).

Key issues:

- Only a part of the physics controlling the boundary layer has yet been identified. *How can we fully identify and characterize the physics controlling the boundary layer and resulting plasma-wall interaction (PWI) sufficiently for physics-based scaling to future devices?*
- Models to predict the complex features of the boundary layer are immature. *How can we accurately describe the highly turbulent boundary layer plasma with material erosion in comprehensive simulations to create simplified models?*
- Specifications for active internal components, such as radio frequency antennas and launchers, and passive diagnostics, are limited by our ability to predict plasma fluxes to those components, and erosion caused by the radio frequency interaction with components at remote locations. *How can the predictive capability of plasma edge modeling, including material interaction with internal components, be improved?*

- The existing ITER design is projected to have little margin for managing the plasma heat load, and higher-power devices will require substantially increased power exhaust requirements. *How can the magnetic configuration of the boundary region be modified to spread out the heat flux at the material interface?*

Proposed actions:

- Develop and deploy new diagnostics in existing devices for comprehensive boundary layer measurements of plasma flow, density, temperature, electric field, turbulence characteristics, and neutral density in at least two dimensions and, as appropriate, three dimensions, to provide the data necessary to uncover the controlling physics.
- Increase the level of effort on validation of individual edge turbulence and transport codes, then expand this effort to involve more comprehensive boundary layer models.
- Develop measurements and predictive capability of the plasma fluxes to radio frequency antennas and launchers; develop models for the self-consistent modification of the boundary layer plasma by the radio frequency wave injection and other internal components.
- Design and implement innovations of the boundary magnetic geometry in existing devices to demonstrate optimized plasma heat exhaust that is within material limits, and design and implement such a configuration in a future fusion device.

2.3.10. Thrust 10: Decode and advance the science and technology of plasma–surface interactions

Plasma–surface interactions define the boundary condition for any magnetically confined plasma. Many improvements in core plasma performance have resulted from changes in the way the material surface responds to the incident plasma. Improvements in wall preparation techniques have optimized performance in present-day confinement devices, but the reasons for this success are poorly understood. Extrapolation of plasma–surface interactions from today's pulsed devices to future steady-state machines (i.e., with hot surfaces under intense plasma and neutron flux) provides little confidence in predictions of future core plasma performance.

Key issues:

- Plasma–surface interactions vary by orders of magnitude depending on temperature, incident species, surface material and exposure time. *Can we reliably extrapolate conditions at the wall of today's pulsed confinement machines to future steady-state reactors?*
- Transient expulsions of energy from the edge plasma cause unacceptable erosion of existing wall materials. *Can we develop clever new concepts to extend the wall operational limits?*
- Surfaces evolve when subjected to plasma, neutron and edge alpha irradiation. *Is it possible to predict the impact of this evolution on an equilibrium plasma state and on plasma facing component lifetime during steady-state operation? Can more resistant materials and coatings suitable for use in diagnostics, or high-power radio frequency and microwave components, be developed?*

Need for dedicated facilities:

Dedicated new and upgraded facilities are required to evaluate the impact of intense plasma flux, transient plasma events, long pulses, and elevated temperatures on the performance of surface materials and designs. Since many of the required assessments do not need the full complexity of a toroidal magnetic confinement device, dedicated laboratory experiments using linear plasma devices can provide a well-diagnosed, well-controlled, and cost-effective environment for performing plasma–surface interaction research. The effect of extended pulse lengths and elevated wall temperature on many plasma–surface interaction processes can be addressed more quickly in these devices. The fundamental science advances from this Thrust will be key in the design of plasma facing components and internal components for long-pulse, hot wall devices, e.g., Thrusts 12 and 13.

Proposed actions:

- Upgrade existing laboratory facilities and test stands, and build new facilities capable of extending plasma–surface interaction parameters closer to conditions expected in fusion reactors, including the capability to handle tritium, liquid metals, and irradiated materials.
- Build large-size test stands where full-scale internal component tests and design validations can occur.
- Develop and improve first-principle models of the material and plasma coupling for future fusion machines by validating against new experimental data.
- Invest in surface material diagnostics to quantify material behavior and evolution.
- Develop and test new surface materials to improve performance margins.

2.3.11. Thrust 11: Improve power handling through engineering innovation

Plasma facing components (PFCs) in a power reactor will receive high heat and particle fluxes from the plasma and will require active cooling. Water cooling technology used in ITER is inapplicable to a reactor that will operate with high-temperature solid walls or reactive liquid metals. For DEMO, either solid PFCs (cooled by high-pressure helium or liquid metals) or free-surface liquid PFCs (such as lithium or tin) could be used. Both PFC innovations will be developed for acceptable power and particle handling.

Key issues:

- Higher heat removal requirements are anticipated for DEMO due to the higher power and particle fluxes to the divertor and first wall, which must operate at elevated temperatures for optimum power conversion efficiency. *How do we develop better PFC designs that operate at higher temperatures and can remove higher heat loads with adequate design margin? Can we exploit larger area targets with smaller inclination angles (<1°) and obtain better alignment to the magnetic flux surfaces?*
- Our ability to design and fabricate PFCs for high-temperature operation is limited by the brittle nature of refractory metal alloys in the case of solid PFCs and by our lack of knowledge of magnetic forces and temperature limits on free-surface liquid metals. *How do we develop new low-activation alloys in the case of solid PFCs and assemble the necessary database for liquid PFCs? Is it possible to develop new materials that are radiation-tolerant while having minimal impact on the plasma during quiescent and transient plasma operation?*
- We do not understand the mechanisms of tritium permeation through PFC materials to the coolant, including the effect of neutron damage. *How do we study the synergistic effects of irradiation damage and tritium permeation for solid and liquid PFCs?*

Proposed actions:

- Design, fabricate and test refractory heat sinks with advanced cooling techniques for high-temperature operation (>600 °C) and deploy liquid metal PFC experiments in plasma devices.

- Develop fabrication processes and better joining techniques using reduced activation refractory alloys for both PFCs and internal components, e.g., radio frequency launchers.
- Construct and upgrade new lab facilities for synergistic testing including cyclic high-heat flux, irradiation and permeation, and liquid metal performance; and improve models of thermal performance, irradiation damage and tritium transport in PFCs.
- Provide improved PFCs for qualification on existing or new confinement experiments.
- Develop more robust PFCs for transient events with higher design margins and improved reliability and maintainability. Include engineering diagnostics to monitor PFC performance and provide data for lifetime prediction models.

2.3.12. *Thrust 12: Demonstrate an integrated solution for plasma–material interfaces compatible with an optimized core plasma*

The plasma facing components (PFCs) in a DEMO reactor will face much more extreme boundary plasma conditions and operating requirements than any present or planned experiment, including ITER. Solutions to make these boundary requirements compatible with a sustained core plasma in a regime attractive for fusion need to be validated under DEMO-like conditions. The goal of this Thrust is to integrate the plasma–material interactions thrusts (9–11) and control thrusts (2, 5) and demonstrate their compatibility with a high-power efflux, steady-state, optimized driven core plasma.

Key issues:

- Power density a factor of four or more greater than in ITER. *What techniques for limiting both steady and transient heat flux to surfaces are compatible with optimized core and boundary plasma performance?*
- Continuous operation resulting in energy and particle throughput 100–200 times larger than ITER. *How can material erosion, migration and dust production from plasma facing surfaces be made compatible with long-term operation and core plasma purity?*
- Elevated surface operating temperature for efficient electricity production. *How can plasma facing materials and configurations be optimized at elevated temperature for fuel recycling and plasma interactions?*
- Tritium fuel cycle control for safety and breeding requirements. *How can hydrogenic fuel retained in materials be reduced to acceptable levels?*
- Steady-state plasma confinement and control. *What techniques are simultaneously compatible with core plasma sustainment and edge plasma power handling requirements?*

Proposed actions:

- Develop design options for a new facility with a DEMO-relevant boundary, to assess core-edge interaction issues and solutions. Key desired features include high-power density, sufficient pulse length and duty cycle, elevated wall temperature, as well as steady-state control of an optimized core plasma. Hydrogen and deuterium operation would allow flexibility in changing boundary components as well as access for comprehensive measurements to fully characterize the boundary plasma and plasma facing surfaces. The balance and sequencing of hydrogen and deuterium operation should be part of the design optimization. Develop an accurate cost and schedule for this facility, and construct it.
- Extend and validate transient heat flux control from Thrust 2, plasma control and sustainment from Thrust 5, boundary plasma models from Thrust 9, plasma–material interaction science from Thrust 10 and plasma facing component technology from Thrust 11 with the new research from this facility, thereby demonstrating a viable solution to the challenging core–edge integration problem for DEMO.

2.3.13. *Thrust 13: Establish the science and technology for fusion power extraction and tritium sustainability*

As a practical energy source, a fusion power plant must create the tritium fuel it uses (by capturing fusion neutrons in the element lithium) and operate at high temperature so that the fusion energy can be converted efficiently to electrical power or other end uses. This Thrust aims to develop the scientific foundations of practical, safe and reliable processes and components that (1) harvest the heat produced by fusion, (2) create and extract the tritium from lithium, and (3) manage (radioactive) tritium that circulates in the plant. A continuous effort of experimental research and predictive model development, focused on the phenomena and interactions occurring in fusion nuclear components, is essential, both to prepare for next steps in burning plasma physics research as well as to accelerate progress toward practical fusion energy as the ultimate goal.

Key issues:

- *How can fusion power be extracted from the complex structures surrounding the burning plasma? Can these structures be engineered to operate reliably in this extreme environment?*
- *How do we contain and efficiently process the tritium fuel in a practical system? Can this unprecedented amount of mobile tritium be accounted for accurately?*
- *How should lithium-bearing materials be integrated into power extraction components to generate tritium fuel to replace that burned in the plasma? Can simultaneous power extraction and fuel sustainability be achieved?*

Proposed actions:

Perform fundamental research to establish the scientific parameters necessary to address the issues. An example activity is the exploration of tritium chemistry, heat transfer, and magnetic field interactions in lithium-bearing liquid metal coolants.

- Perform multiple-effect studies to understand the combined impact of the operating conditions and component complexity typical of a fusion environment. An example activity is utilizing the ITER burning plasma as a test environment to perform tritium breeding and power extraction experiments with relevant materials, instrumentation, component designs, and operating temperatures with necessary ancillary systems.
- Perform integrated experiments to characterize the complete effect of fusion conditions and facility performance. An example would be construction and operation of a Fusion Nuclear Science Facility (FNS F) to perform testing that resolves the remaining gaps stemming from the effects of significant surface heat flux and neutron irradiation over a long period of time in concert with all other fusion environmental conditions.
- Develop the accompanying theory and predictive models necessary to understand and apply the experimental results, and collect reliability, tritium accountability and safety data at all stages.

2.3.14. *Thrust 14: Develop the material science and technology needed to harness fusion power*

Fusion materials and structures must function for a long time in a uniquely hostile environment that includes combinations of high temperatures, reactive chemicals, high stresses, and intense damaging radiation. Ultimately, we need to establish the feasibility of designing, constructing and operating a fusion power plant with materials and components that meet demanding objectives for safety, performance and minimal environment impact.

Key issues:

- *What thermal, mechanical, and electrical properties are needed to meet fusion objectives?*
- *How does radiation damage affect the properties of materials?*
- *How do synergistic effects involving radiation damage, high temperatures, high stresses and corrosion phenomena affect the feasibility of operating a fusion power plant?*

Proposed actions:

- Improve the performance of existing and near-term materials, while also developing the next generation of high-performance materials with revolutionary properties.
  Understand the relationship between material strength, ductility and resistance to cracking.
  Design materials with exceptional stability, high-temperature strength and radiation damage tolerance.
  Understand how interactions with the plasma affect materials selection and design.
  Establish the scientific basis to control the corrosion of materials exposed to aggressive environments.
  Develop the technologies for large-scale fabrication and joining.
  Determine the underlying scientific principles to guide discovery of revolutionary high-performance materials while minimizing radioactive waste and maximizing recycling.
- Develop and experimentally validate predictive models describing the behavior and lifetimes of materials in the fusion environment.
- Establish a fusion-relevant neutron source to enable accelerated evaluations of the effects of radiation-induced damage to materials.
- Implement an integrated design and testing approach for developing materials, components, and structures for fusion power plants.
- Use a combination of existing and new nonnuclear and nuclear test facilities to validate predictive models and determine the performance limits of materials, components and structures.

2.3.15. Thrust 15: Create integrated designs and models for attractive fusion power systems

Capturing the energy released by a burning plasma and converting it to a useful power flow in a safe, reliable, and sustainable manner requires the successful integration of many systems and physical processes. This Thrust includes two primary aspects: (1) conducting advanced design studies; and (2) developing integrated predictive models. Detailed advanced design studies bring to light key design trade-offs and constraints within an integrated system for DEMO. For example, maximizing power cycle thermal efficiency requires operation at high temperatures, with upper limits set by coolant and structure compatibility, thermal stress, material behavior and plasma thermal loading considerations. Identifying serious limiting factors and design issues can guide research toward high-leverage and high-payoff issues while minimizing program risk. Such detailed advanced design studies also allow the assessment of integrated safety, environmental and RAMI (reliability, availability, maintainability and inspectability) issues for fusion.

Advanced design activities are also essential in evaluating alternatives for a Fusion Nuclear Science Facility (FNSF), which is an important and necessary step on the path to fusion energy. Integrated models are used to help reveal important science and technology interrelationships and interpret the results of fusion experiments and component tests, thereby reducing the risks and costs in the development of fusion nuclear systems. They will also support the advanced design studies for future fusion facilities.

Key issues:

- *What advanced design studies are needed to identify system integration issues; optimize facility configuration; extend the operating parameter space for future fusion facilities that meet availability, maintainability, safety and environmental goals on the path to fusion power; and guide the R&D on high-leverage, high-payoff issues?*
- *How can separate physics, nuclear, and engineering models be most effectively coupled to address highly integrated fusion system behavior?*

Proposed actions:

- Determine and improve essential aspects of fusion energy through advanced design and integration activities for DEMO, including:
  Optimizing the integrated configuration and maintenance approach to minimize risk and achieve the availability, maintainability, safety and environmental requirements for DEMO to be attractive.
  Determining the scientific basis for sustainable fusion power and identifying research efforts to close the knowledge gap to DEMO.
  Evaluate, through advanced design and system studies, alternative configurations and designs for FNS F and the extent to which they address the research requirements.
  Develop predictive modeling capability for nuclear components and associated systems that are science-based, well-coupled, and validated by experiments and data collection.
  Extend models to cover synergistic physical phenomena for prediction and interpretation of integrated tests (e.g., ITER Test Blanket Module—TBM) and for optimization of systems.
  Develop methodologies to integrate with plasma models to jointly supply key first wall and divertor temperature and stress levels, electromagnetic responses, surface erosion, etc.

2.3.16. Thrust 16: Develop the spherical torus to advance fusion nuclear science

The spherical torus (ST) is a low aspect ratio (low-A) tokamak that offers unique physical properties due to its very strong magnetic curvature and compact geometry. This configuration delivers high plasma pressure relative to the external magnetic pressure, and strongly affects plasma stability and confinement. It offers the promise of simple magnet design, reduced size, cost, and ease of maintainability. The ST program has made substantial progress. Non-solenoidal startup currents have reached 25% of required initiation levels. A strong favorable dependence of plasma thermal confinement on magnetic field was found. A fivefold increase in electron confinement was demonstrated in a small device with liquid metal walls. Stability needed for a component testing device was shown for several current relaxation times, with a majority of the current provided noninductively. The ST program is now poised to generate the knowledge base to confidently construct and operate a low-A Fusion Nuclear Science and Technology (FNST) component testing device, and to aggressively pursue improvements to advance the ST for energy production.

Key issues:

- The ST has little room for a central solenoid to produce and drive plasma current. *Can plasma current be initiated and raised to high values without a solenoid?*

- The compact geometry of the ST increases the heat loading to the wall. *Can plasma exhaust power be effectively dissipated in the ST?*
- The ST energy confinement improves faster with magnetic field and plasma temperature than at high aspect ratio. *Can predictive models for ST confinement be developed and validated?*
- The broad current profiles and near-spherical geometry of the ST strongly affect stability. *Can stable and continuous operation be produced at low aspect ratio?*
- The lower magnetic field and enhanced energetic particle drive of the ST may challenge the sustainment of high plasma current. *What are viable means to maintain the current and control the plasma profiles in the ST?*
- The compact geometry of the ST precludes the use of shielded superconducting magnets. *Can suitable magnets be developed for ST applications?*

Proposed actions:

- Exploit and understand magnetic turbulence, electromagnetic waves, and energetic particles for megampere plasma current formation and ramp-up.
- Develop innovative magnetic geometries and first-wall solutions such as liquid metals to accommodate multi-megawatt per square meter heat loads.
- Utilize upgraded facilities to increase plasma temperature and magnetic field to test the understanding of ST confinement and stability at fusion-relevant parameters.
- Implement and understand active and passive control techniques to enable long-pulse disruption-free operation in plasmas with very broad current profiles.
- Employ energetic particle beams, plasma waves, particle control, and core fueling techniques to maintain the current and control the plasma profiles.
- Develop normally conducting radiation-tolerant magnets for low-A applications.
- Extend the ST to near-burning plasma conditions in a new or further upgraded device.

2.3.17. Thrust 17: Optimize steady-state, disruption-free toroidal confinement using 3-D magnetic shaping, and emphasizing quasi-symmetry principles

The stellarator concept relies on currents in external coils to confine plasmas magnetically. Stellarators can therefore operate continuously if supplied with heating power and effective means of heat and particle exhaust (divertor). They have experimentally demonstrated sustained plasmas with good confinement, high normalized pressure, and do not suffer from virulent current or pressure-driven instabilities that abruptly terminate the plasma. The magnetic field in a stellarator is not symmetric in the toroidal direction, but has three-dimensional (3-D) structure. Three-dimensional shaping provides additional control of plasma confinement not available in the axisymmetric tokamak, and permits designs that are passively stable to major instabilities, with minimal feedback control. The lack of symmetry in a conventional stellarator, however, can reduce the confinement of energetic ions, including alpha particles. The application of innovative *quasi-symmetric* (QS) shaping is predicted to resolve this issue, leading to stellarator designs that confine high-energy particles, and permit plasma flows (also favorable for plasma confinement), while retaining the robust stability of the stellarator. The QS stellarator is thus a transformational concept, offering a timely, effective solution to the challenges of severe transient events and control in steady-state, high-pressure plasmas. In addition, 3-D fields affect all configurations through self-organization or external perturbations. Understanding of 3-D effects is thus a core competence, required for the success of all magnetic configurations. There is a need to understand 3-D shaping in an integrated manner in plasmas with higher levels of performance.

Key issues:

- Simultaneous achievement of QS confinement at high-pressure without disruptions. *Does quasi-symmetry lead to improved confinement at high plasma pressure? Is there an optimal type of QS shaping?*
- Three-dimensional shaping requires magnets that are more complex than planar coils. *How can optimized magnet design ease construction, reliability, cost and maintenance of 3-D systems while meeting the physics requirements?*
- Divertors for 3-D configurations require development. *How do we integrate an effective divertor into the optimization of quasi-symmetric stellarators?*
- Three-dimensional fields have application to all toroidal systems. *What is the optimum amount and type of 3-D shaping to effect improvements?*

Proposed actions:

1. Conduct two quasi-symmetric experiments spanning a broad range of internal plasma current, with plasma parameters sufficient to demonstrate low collisionality, disruption-free operation at high plasma pressure. Examine the merits of completing NCSX as part of this effort. Expand efforts in non-axisymmetric theory and computation to develop predictive models of QS confinement. Extend the understanding of QS plasmas to near-burning conditions.
2. Investigate quasi-symmetric configurations with simpler and maintainable magnet systems.
3. Design 3-D divertors compatible with QS geometry. Integrate with 3-D coil simplification.
4. Explore the addition of 3-D shaping to other magnetic configurations.

2.3.18. Thrust 18: Achieve high-performance toroidal confinement using minimal externally applied magnetic field

Alternate configurations with magnetic field generated largely by electrical current flowing within the plasma represent potentially high-payoff options for the fusion energy program. They require relatively modest external magnets, reducing engineering challenges and costs. They also have high plasma pressure, at 10–80% of the magnetic pressure. Their large ohmic heating may allow fusion ignition without complex auxiliary systems. Two of the configurations have no physical structure threading the plasma volume. These “compact torus” (CT) configurations have cylindrical plasma containment vessels that improve the accessibility and enhance the maintainability of prospective power plants. The US is a leader in the international exploration of low external-field concepts. The reversed field pinch (RFP) looks much like a tokamak but generates most of its own magnetization. The spheromak and field-reversed configuration (FRC) are CT plasmas with distinct approaches to stability and sustainment. Magnetic fluctuation control techniques have led to important advances. These include increased energy confinement (obtaining values comparable to those in tokamak plasmas) and longer plasma lifetimes (ten times longer than without active control). Together with the tokamak and stellarator efforts, research on these configurations broadens the scientific approach to grow and validate fusion science over a wide range of plasma conditions and enhances the opportunity for scientific discovery and innovation in toroidal confinement. Also, low-field configurations exhibit processes resembling those in space and astrophysical plasmas and provide versatile laboratories for fusion, basic plasma science, and education.

Key issues:

- Understanding confinement and stability in reactor-relevant conditions. *Will confinement continue to improve at high plasma current? How can plasma-profile and boundary control be used to achieve high performance? Can a population of energetic ions enhance stability?*
- Improving the efficiency of formation and sustainment. *Can low-frequency AC induction, waves, and neutral beams efficiently drive DC plasma current? How can formation and penetration of current sourced from outside the plasma be optimized?*
- Demonstrating the compatibility of confinement, sustainment, and plasma-boundary control. *What shaping is optimum, and how can plasma self-organization be used? What is the optimal active control system for stability? Will auxiliary heating be necessary?*

Proposed actions:

- Develop and deploy new plasma diagnostics to measure profile information and fluctuations for the scientific goal of understanding transport and stability in low external-field devices.
- Improve and apply theoretical and computational models to analyze nonlinear effects in low-field configurations. Validate models through comparison with improved measurements.
- Study FRC stability at small ion gyroradius in a new or upgraded facility with energetic ion sources. Success will enable integrated tests of stability, confinement, and sustainment.
- Develop improved current sustainment methods for the spheromak. Small experiments will feed transformational ideas to a larger facility to test integrated confinement and sustainment.
- Extend confinement scaling and demonstrate current sustainment at high temperature in a new large-current RFP. A staged, upgradeable facility would eventually demonstrate near-burning plasma conditions with integrated plasma-boundary and magnetohydrodynamic (MHD) stability control.
- Quantify the benefits of low external field and CT geometry in system studies with updated physics and engineering information. Evaluate pulsed vs. steady-state reactor operation.

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