Revised Intermediate Milestones for Program Assessment Rating Tool (PART) of the Fusion Energy Sciences Program

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Ten Year Goals for Fusion Energy Sciences

- **Predictive Capability for Burning Plasma**: By 2015 demonstrate progress in developing a predictive capability for key aspects of burning plasmas using advances in theory and simulation benchmarked against a comprehensive experimental database of stability, transport, wave-particle interaction, and edge effects

- **Configuration Optimization**: By 2015, demonstrate enhanced fundamental understanding of magnetic confinement and in improving the basis for future burning plasma experiments through research on magnetic confinement configuration optimization.

- **High Energy Density Plasma Physics**: By 2015, demonstrate progress in developing the fundamental understanding and predictability of high energy density plasma physics, including potential energy producing applications.

Office of Management and Budget
Program Assessment Rating Tool (PART)
Long Term Measures for Fusion Energy Sciences

Predictive Capability for Burning Plasma: By 2015, demonstrate progress in developing a predictive capability for key aspects of burning plasmas using advances in theory and simulation benchmarked against a comprehensive experimental database of stability, transport, wave-particle interaction, and edge effects.

- Definition of "Excellent" – Predict with high accuracy and understand major aspects relevant to burning plasma behavior observed in experiments prior to full operation of ITER.
- Definition of "Good" – Validate predictive models against the database for some important aspects relevant to burning plasma physics (e.g. energetic particles, instabilities, control of impurities, etc…)
- Definition of "Fair" – Validate predictive models against the database for a few aspects relevant to burning plasma physics (e.g. energetic particles, instabilities, control of impurities, etc…)
- Definition of "Poor" – Achieve only limited success in improving models and validating them against the database.
- How will progress be measured? – Expert Review every three years will rate progress as "Excellent," "Good," "Fair," or "Poor"

Configuration Optimization: By 2015, demonstrate enhanced fundamental understanding of magnetic confinement and in improving the basis for future burning plasma experiments through research on magnetic confinement configuration optimization.

- Definition of "Excellent" – Resolve key scientific issues and determine the confinement characteristics of a range of innovative confinement configurations.
- Definition of "Good" – Develop understanding of the key scientific issues for several innovative magnetic confinement configurations currently under investigation.
- Definition of "Fair" – Develop understanding of the scientific issues for a limited number of innovative magnetic confinement configurations currently under investigation.
- Definition of "Poor" – Achieve little progress towards understanding the scientific issues concerning innovative magnetic confinement configurations.
- How will progress be measured? – Expert Review every three years will rate progress as "Excellent," "Good," "Fair," or "Poor"

Inertial Fusion Energy and High Energy Density Plasma Physics: By 2015, demonstrate progress in developing the fundamental understanding and predictability of high energy density plasma physics, including potential energy-producing applications.

- Definition of "Excellent" – Develop experimentally-validated theoretical and computer models, and use them to resolve the key physics issues that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to understand the scientific issues for inertial fusion energy and high energy density physics.
- Definition of "Good" – Use experimental data to develop understanding of the key physics issues that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to understand the scientific issues for inertial fusion energy and high energy density physics.
- Definition of "Fair" – Use experimental data to develop a limited understanding of the key physics issues that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to understand the scientific issues for inertial fusion energy and high energy density physics.
- Definition of "Poor" – Achieve little progress in understanding the key physics issues that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to understand the scientific issues for inertial fusion energy and high energy density physics.
- How will progress be measured? – Expert Review every three years will rate progress as "Excellent," "Good," "Fair," or "Poor"

Goals and Milestones

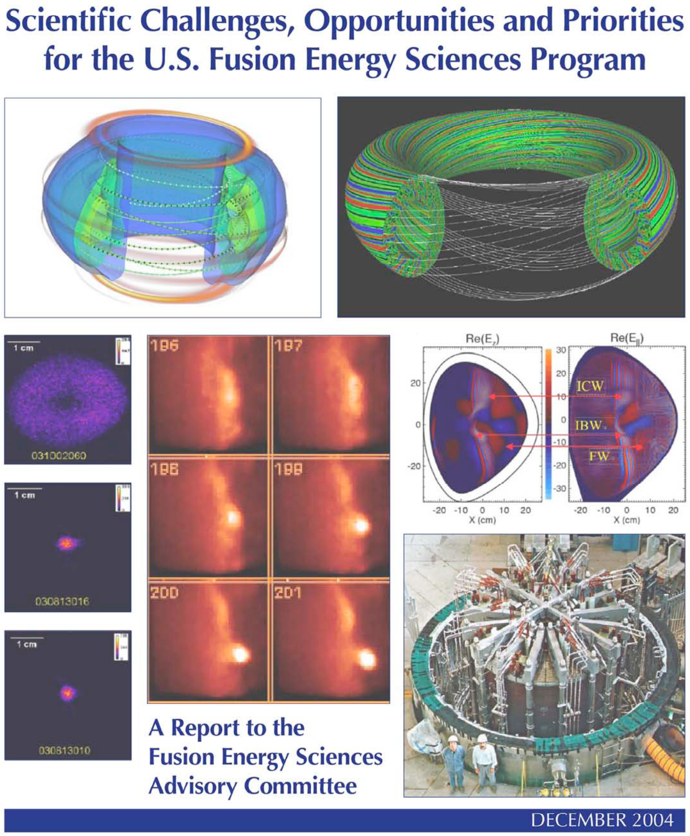
Burning Plasma

- ✓ Establish the Department's role in ITER **(2005) INTL**
- • Begin U.S. contribution to ITER for this international collaboration to build the first fusion burning plasma experiment capable of a sustained fusion reaction **(2006) INTL**
- • Continue vendor qualification for long lead procurements for ITER in the area of superconducting strand and jacket materials **(2006)**
- • Refine theoretical and experimental understanding of transport, stability, wave-particle interactions, and edge effects in tokamaks **(2009)**
- • Initiate design and fabrication of the first test blanket module to be installed on ITER **(2011) BES**
- • Evaluate discharge scenarios for ITER based on major tokamak results **(2012)**
- • Begin ITER operation **(2014) INTL**
- o Progress toward developing a predictive capability for key aspects of burning plasmas using advances in theory and simulation benchmarked against a comprehensive experimental database of stability, transport, wave-particle interaction, and edge effects **(2015)**

✓ = Key Intermediate Objective from DOE Strategic Plan
o = Long Term Success Measure from PART
INTL = with international community on ITER
BES = with BES on nano-designed materials
NNSA = with NNSA
Interdependencies: Broadly with **ASCR** on computational developments, both hardware and software, affecting all facets of basic research and advanced instrumentation.

At March 2006 FESAC Meeting:

FESAC recommended revision of PART Intermediate Milestones to be used in assessing progress using Priorities Panel and Facilities Panel report goals for Scientific Campaigns:



Research activities include:

- Establish the plasma confinement of helicity-driven spheromak configurations and assess prospects for study in more collisionless plasma regimes.
- Understand the pressure limits and confinement properties in sustained reversed-field pinch configurations in the presence of magnetohydrodynamic turbulence and for reduced turbulence states.

RELEVANCE TO ITER AND OTHER CAMPAIGNS

The physics of the macroscopic behavior of confined plasmas is inherently connected with almost all of the other campaigns. The plasma transport is strongly affected by the distribution of the magnetic field and plasma shaping. The magnetic configuration determines which instabilities participate in plasma turbulence, and can control the strength of turbulence-produced transport. The plasma shape and magnetic configuration also influence how the plasma interacts with the boundary interface, and how heat and particles are exhausted. The resulting edge plasma parameters set the boundary condition for the core confinement and influence global stability. Edge instabilities are highly sensitive to magnetic structure and can produce large transient heat loads on surrounding structures. The maximum stable confined pressure ultimately determines the fusion energy production and whether the plasma can burn.

Improved understanding of plasma macroscopic behavior is crucial to achieve the goals of ITER and burning plasma experiments in general. Development of methods to increase the maximum plasma pressure will directly lead to increased fusion power and energy gain. In addition, improved understanding and control of plasma stability will reduce the likelihood of disruptions. Development of methods to sustain the plasma configuration at high pressure and high fusion gain will enable ITER to achieve its long-pulse goals and develop the strategies needed for follow-on experiments.

In many ways, ITER will be a natural integral part of this campaign to understand macroscopic plasma behavior. In particular, it will extend the exploration of confinement to larger effective-size than available in any other experiment. This will change the strength and character of instabilities and their nonlinear saturating effects. It will also give access to new phenomena, allowing the exploration and understanding of the dynamics of plasma self-heating in combination with the other plasma nonlinearities.

EXPECTED ACCOMPLISHMENTS WITHIN TEN YEARS

Substantial progress is expected on the thrusts of this campaign over the next ten years, even assuming constant level-of-effort. Here we summarize this expected progress followed by a discussion of the opportunities for significantly enhanced research progress in three particular thrust areas with increased resources.

At a constant level-of-effort, substantial progress is expected on many of the campaign's activities, broadening and advancing the understanding of the role of the magnetic field structure on plasma confinement, including the effect of 3D shaping and different types of symmetry. New experiments have begun or are under construction, testing novel magnetic configurations motivated by theoretical predictions and advances in understanding during the last decade. The studies of the role of internal magnetic structure on confinement will near completion for tokamaks, in preparation for ITER.

Experiments attempting to understand the pressure-limiting phenomena and overcome them are underway. Within ten years, a detailed understanding of pressure limits in rotating plasmas with resistive walls should be completed, and studies of active stabilization without rotation will be well underway. An understanding of neoclassical tearing instabilities, including methods of suppression, should be complete and documented in axisymmetric configurations. For both of these, predictions for ITER will be refined in preparation for ITER operation. Experiments exploring the pressure limit in 3D configurations and in reversed-field pinches will be underway, characterizing limiting phenomena, and initial comparisons with theoretical predictions will be available.

Studies of different types of plasma self-organization and their interaction with external control methods are underway for several magnetic configurations. These studies of the nonlinear interactions in the plasma will continue throughout the next ten years. Methods to sustain the plasma duration have been developed, including methods to enable operation of ITER as a long-pulse operation burning plasma (e.g., "hybrid" scenarios). Within the next ten years, these methods will be well understood and ready for application to ITER. The scientific issues associated with the integration of high plasma pressure, good confinement, and efficient sustainment of plasmas (e.g., high bootstrap current fraction) will be under study in several configurations.

OPPORTUNITIES FOR ENHANCED PROGRESS

While much progress will and should be made with level resources, the research opportunities associated with three particular areas are so compelling that increased funding should be sought to expedite scientific progress.

- Pursue an integrated understanding of plasma self-organization and external control, enabling high-pressure sustained plasmas. This is a combination of the research thrusts under T3, and will study sustained plasmas at the stability limit. It will result in an integrated understanding of the mutually interacting nonlinearities that self-organize and constrain high-pressure plasmas. It would include developing improved models of confinement and stability, including effects of 3D magnetic field structure, and the comparison of observed pressure limits for sustained plasmas to theory. Carrying out this research will involve developing plasma control tools and diagnostics to systematically vary and study the internal structure and profiles and control instabilities in a range of configurations.
- Optimize magnetic confinement configurations based on the expected improvement in the understanding of plasma confinement. Proposals to study new, optimized configurations would be expected in the second half of the next ten years. Such proposals could involve studying plasmas closer to burning plasma conditions to test and broaden the understanding.
- Simulate through experiment and modeling the synergistic behavior of alpha-particle-dominated burning plasmas, further developing the integrated understanding. This activity would enhance the optimization of magnetic confinement configurations (above) to better prepare for the burning plasma experiment. The effects of burning

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- • Understand pressure limits in rotating plasma with resistive walls **(2008)**
- • Understand neoclassical tearing instability and methods of suppression and control **(2009)**
- • Understand edge-localized modes and develop methods to minimize their impact on divertor components **(2010)**
- • Develop predictive capability for ion thermal transport in a tokamak **(2012)**
- • Integration of high plasma pressure, good confinement, and efficient sustainment plasma scenarios for ITER will be understood based on major tokamak results **(2012)**
- • Identify character of Alfvén turbulence and evolution of energetic particle distribution based on major tokamak results and modeling to predict alpha-particle transport in a burning plasma **(2014)**
- ○ Progress toward developing a predictive capability for key aspects of burning plasmas using advances in theory and simulation benchmarked against a comprehensive experimental database of stability, transport, wave-particle interaction, and edge effects **(2015)**

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Goals and Milestones (continued)

Configuration Optimization

- Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus sufficient to begin design of a Next-Step Spherical Torus **(2008)**
- Demonstrate use of active plasma controls and self-generated plasma current to achieve high-pressure/well-confined steady-state operation for ITER **(2009)**
- Evaluate the ability of the compact stellarator configuration to confine a high temperature plasma **(2012)**
- Begin construction on the Next-Step Advanced Facility (NSAF) to test an advanced fusion concept for magnetically confining a fusion reaction **(2014)**

o Progress toward demonstrating enhanced fundamental understanding of magnetic confinement and improved basis for future burning plasma experiments through research on magnetic confinement configuration optimization **(2015)**

✓ Advance plasma science and computer modeling to obtain a comprehensive, and fully validated, plasma configuration simulation capability **(2020)**

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Configuration Optimization

- Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus sufficient to begin design of a Next-Step Spherical Torus **(2008)**
- Demonstrate use of active plasma controls and self-generated plasma current in present experiments which extrapolates to achieve high-pressure/well-confined steady-state operation for ITER **(2009)**
- Identify the dominant mechanisms by which turbulence generates and sustains large-scale magnetic fields in high temperature plasmas **(2010)**
- Understand the role of 3D shaping of the magnetic field under a variety of symmetries on plasma confinement **(2012)**
- Understand the conditions and thresholds for formation and dynamics of edge and core transport barriers **(2012)**

o Progress toward demonstrating enhanced fundamental understanding of magnetic confinement and improved basis for future burning plasma experiments through research on magnetic confinement configuration optimization **(2015)**

✓ Advance plasma science and computer modeling to obtain a comprehensive, and fully validated, plasma configuration simulation capability **(2020)**

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Goals and Milestones (continued)

High Energy Density Physics

- Evaluate the process affecting the transport of petawatt laser energy in dense plasmas **(2009) NNSA**
- Initiate experiments on the National Ignition Facility (NIF) to study ignition and burn propagation **(2012) NNSA**
- Create and measure properties of high energy density plasmas using intense ion beams, dense plasma beams, and lasers **(2012)**
- Begin construction of an intermediate-scale, Integrated Beam Experiment (IBX) to understand how to generate and transmit the focused, high energy ion beam needed to power an inertial fusion energy (IFE) reaction **(2014)**

o Progress toward developing the fundamental understanding and predictability of high energy density plasma physics **(2015) NNSA**

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High Energy Density Physics

- Initiate experiments and simulations of petawatt laser-pulse interaction with hydrogenic plasmas and noncrogenic cone targets **(2009) NNSA**
- Understand the limits to neutralized drift compression and the focusing of intense ion beams onto targets **(2010)**
- Understand the electron output phase space for high-incident-laser intensities (10^{18} - 10^{21} W/cm^2), angles of incidence and pulse lengths (> 10 ps) relevant to fast ignition **(2010) NNSA**
- Initiate experiments on the National Ignition Facility (NIF) to study ignition and burn propagation **(2012) NNSA**
- Create and measure properties of high energy density plasmas using intense ion beams, dense plasma beams, and lasers **(2012)**

o Progress toward developing the fundamental understanding and predictability of high energy density plasma physics **(2015) NNSA**

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