Assessment of Progress towards Long Term Goals of the Fusion Energy Sciences Program

Fusion Energy Sciences Advisory Committee
2 March 2007

The Office of Fusion Energy Sciences (FES) established three long-term (FY2015) performance measures of the FES program for the OMB Program Assessment Rating Tool (PART). The PART process requires that the progress of the FES program towards reaching these long-term performance measures be assessed on a triennial basis with progress towards each long-term performance measure rated on a scale of excellent, good, fair, or poor. A detailed set of rating criteria for this four level scale was established for the long-term performance measures (attached).

The Fusion Energy Sciences Advisory Committee was asked to conduct the first triennial assessment of progress towards the long-term performance measures and to "…use the short and intermediate-term milestones from FY05 to FY09 … as a guide in assessing the programs progress toward achieving the three long-term PART measures." In April 2005 the FESAC was requested to review and comment on these long-term performance measures and the short and intermediate-term milestones. The FESAC recommended that the FES program "…reconsider and revise the intermediate milestones shown on the fusion program roadmap, using the Priorities Panel Report as a guide…" to aid the PART assessment of long-term performance measures. A revised set of short and intermediate-term milestones was established in consultation with FESAC and these were used in carrying out our assessment.

As discussed below for each of the long-term PART performance measures, we find that the FES program has already achieved or is making excellent progress towards accomplishing the near and intermediate-term milestones. A performance rating of "excellent" is therefore recommended for the program for the 2006 assessment of progress towards the three long-term performance measures.

Fusion Energy Sciences Program Long-Term Performance Measures

The three long-term performance measures for FY 2015 established for the FES program are shown below:

Predictive Capability for Burning Plasma: 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

Configuration Optimization: Progress toward demonstrating enhanced fundamental understanding of magnetic confinement and improved basis for future burning plasma experiments through research on magnetic confinement configuration optimization

High Energy Density Plasma Physics: Progress toward developing the fundamental understanding and predictability of high energy density plasma physics

The FES program progress towards each of these was evaluated based on the revised set of short and intermediate-term milestones established to aid that assessment.

Predictive Capability for Burning Plasma

Shown below is the revised set of short and intermediate-term milestones used for assessing progress towards FY 2015 burning plasma long-term performance measure.

- Establish the Department's role in ITER **(2005)**
- 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)**
- 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)**
- Develop integrated plasma scenarios with high plasma pressure, good confinement, and efficient sustainment based on experimental results **(2012)**
- Make progress towards the characterization and understanding of electron thermal and momentum transport (**2013**)
- 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)**

Achieving this goal is one of the highest scientific priorities in the Fusion Energy Sciences Program, and very significant progress was made by the FES program in the past three years. The centerpiece of this effort is to build and operate ITER, which if successful will be the world's first sustained burning plasma experiment where the plasma is dominated by fusion self-heating. The program met its key intermediate milestone for 2005 with an agreement by the international partners on a site in Europe for the construction of the ITER facility, the agreement with the international ITER partners on the scope of work to be supplied by the United States as part of the ITER facility construction, and the approval of Mission Need CD-0 by the DOE in July 2005. This was followed by the establishment of the US ITER Project Office (USIPO), now based at ORNL, that is supporting the International ITER Organization headed by Dr. Kaname Ikeda of Japan being formed at the ITER facility site in Cadarache. In 2006 the international agreement to legally establish the ITER international project was signed by the seven ITER partners (China, Europe, India, Japan, Russia, South Korea, and the United States) and the US began contributing personnel and resources to the international ITER project meeting it 2006 intermediate milestone. The US Burning Plasma Organization (US BPO) was formed in 2006 to coordinate scientific support in the domestic fusion energy science research program for achieving the burning plasma goal.

Significant progress was made in the past three years on the intermediate scientific milestones, as briefly summarized below:

- *Understand pressure limits in rotating plasma with resistive walls* (2008): The US is the world leader in the study of this important problem. Since fusion power density scales with the square of plasma pressure, achieving high plasma pressure is critical to practical fusion power systems. One of the primary limits of the plasma pressure in toroidal fusion systems is set by the external kink instability. Pioneering experiments on DIII-D have reached the ideal pressure limit through plasma rotation stabilization of this instability when a resistive wall is near the plasma edge. Both DIII-D and NSTX are studying the stabilization physics of plasma rotation and active feedback stabilization, supported by theory & modeling and university scale experiments. The capability of ITER to exceed the stabilizing plasma rotation threshold for the resistive wall kink mode is being assessed in Alcator C-Mod, which is completing a study of plasma rotation values with low external momentum input. Our understanding of methods to control of these key pressure limiting modes are now being explored for implementation in the baseline ITER design.
- *Understand neoclassical tearing instability and methods of suppression and control* (2009): These internal instabilities limit the pressure in collisionless fusion plasmas. Experiments in the US on DIII-D as well as experiments on ASDEX-U in Europe and JT-60U in Japan have achieved complete stabilization of the NTM using local electron cyclotron heating and current drive in high-pressure plasmas. This work is supported with detailed analytic theory on the instability drive and stabilization physics as well as predictive modeling. The program is well positioned to meet this 2009 milestone.
- *Understand edge-localized modes and develop methods to minimize their impact on divertor components* (2010): Periodic bursts of energy loss from a fusion plasma through the onset of edge-localized modes presents a challenge to plasma facing componenets in the divertor of tokamak confinement devices. Experiment and theory of these important modes for fusion power systems have made significant advance in the past three years through work from Alcator C-Mod, DIII-D, and NSTX together with the world fusion program. An important recent discovery was made on DIII-D showing suppression of these instabilities when an ergotic layer in the magnetic field

at the plasma boundary was created by nearby external coils. This capability is now being explored for inclusion in the ITER baseline design.

The longer-term intermediate milestones are all parts of well-established elements of the US domestic research program pursued together with the world fusion program (particularly in Europe and Japan). This research is coordinated internationally through the International Tokamak Physics Activity (ITPA), which is aimed at providing scientific support to the ITER burning plasma physics program.

We find the FES program is making excellent progress towards the FY 2015 long-term performance measure to develop a predictive capability for key aspects of burning plasmas.

Configuration Optimization

Shown below is the revised set of short and intermediate-term milestones used for assessing progress towards FY 2015 configuration optimization long-term performance measure.

- Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus **(2010)**
- Understand the mechanisms by which plasma fluctuations cause transport in toroidal plasmas confined by weak magnetic field, and develop methods to control the fluctuations and transport **(2010)**
- 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 **(2012)**
- Understand the conditions and thresholds for formation and dynamics of edge and core transport barriers **(2014)**
- Understand the role of 3D shaping of the magnetic field under a variety of symmetries on plasma confinement **(2014)**
- 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)**

The goal of optimizing the configuration of a plasma confinement system for fusion energy application has been a critical element of the US Fusion Energy Sciences program since it’s beginning. It was called out in 1996 as one of the three program elements when the FES program was restructured with “concept innovation” as the central theme of the domestic US program. The Fusion Energy Sciences program is exploring the optimization of the advanced steady-state tokamak configuration on DIII-D and Alcator C-Mod, as part of the coordinated world program in tokamak research. The US is a world leader in exploring the spherical torus (ST) configuration in NSTX and the reversed field pinch (RFP) configuration in the MST facility at the “proof-of-principal” scale. The US leads the world studying compact quasi-symmetric stellarator configurations with the NCSX experiment now under construction, and the operating university scale experiment HSX. The US fusion program also supports the exploration of a broad spectrum of smaller scale concept innovation experiments at universities and national laboratories.

The ten-year goal aims at resolving key scientific issues and determination of the confinement characteristics of a range of innovative confinement configurations. The program is well positioned to achieve this goal. Progress on the near-term intermediate objectives for 2010 in the past 3 years has been excellent as briefly summarized below:

- *Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus* (2010): Coaxial Helicity Injection, previously used in smaller scale concept innovation experiments, was successfully applied in NSTX to generate over 160,000 Amperes of non-inductive current on closed magnetic surfaces. These results, together with the achievement of high fractions of self-generated bootstrap driven current in NSTX, are key steps toward achieving long-duration non-inductive sustainment of the ST configuration. Preliminary studies of the confinement time scaling in NSTX show a very strong scaling with plasma current of better than $I^{1.3}$ at fixed safety factor q, much stronger than in conventional tokamaks and favorable for ST based fusion power systems. Record levels of normalized plasma pressure supporting a high fraction of self-generated bootstrap current have been achieved and stabilized with active mode control in NSTX in agreement with theoretical expectations. The program is well positioned to meet this intermediate milestone.

- *Understand the mechanisms by which plasma fluctuations cause transport in toroidal plasmas confined by weak magnetic field, and develop methods to control the fluctuations and transport* (2010): The MST experiment has made significant progress in the past three years in the understanding and control of the plasma turbulence that drives the dynamo process sustaining the reversed toroidal field in the RFP plasma edge. This includes the discovery that externally imposed current profile control can suppress MHD turbulence resulting in greatly improved the plasma confinement. Improved current profile control capability has been installed in MST to extend these results. The MST experiment also is part of a major joint NSF/DOE center to explore magnetic self-organization and the astrophysical applications of these MHD fluctuation and transport studies.

The longer-term intermediate milestones are all parts of well-established elements of the US domestic research program on innovative confinement pursued together with the world fusion program, particularly in Europe and Japan in the case of the advanced tokamak, the stellarator, the ST, and the RFP. The US domestic fusion program is also making a large investment in a new facility for the study of 3D magnetic shaping effects through the construction of the compact quasi-symmetric stellarator, NCSX, which is scheduled to begin operation in 2009.

We find the FES program is making excellent progress towards the FY 2015 long-term performance measure to develop enhanced fundamental understanding of magnetic confinement and an improved basis for future burning plasma experiments through research on magnetic confinement configuration optimization.

High Energy Density Plasma Physics

Shown below is the revised set of short and intermediate-term milestones for used for assessing progress towards FY 2015 HEDP long-term performance measure. Some of these milestones are dependent on use of NNSA supported facilties.

- Initiate experiments and simulations of petawatt laser-pulse interaction with non-cryogenic targets **(2009)**
- Understand the limits to neutralized drift compression and the focusing of intense ion beams onto targets **(2010)**
- Progress towards understanding 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)**
- 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)**
- Progress toward developing the fundamental understanding and predictability of high energy density plasma physics **(2015) NNSA**

The High Energy Density Physics (HEDP) program is a relatively small program element in the Fusion Energy Sciences Program that has been evolving to take advantage of the exciting new opportunities provided by the emerging HEDP field, while continuing to take advantage of the large NNSA supported inertial confinement fusion (ICF) program for application to developing Inertial Fusion Energy (IFE). The major activity in the FES supported program continues to be the development of a heavy ion accelerator as a driver for high gain inertial fusion targets for an IFE power plant. The recent development of peta-Watt laser technology has opened up a potentially improved approach to ICF/IFE through the “fast ignition” concept, as well as experiments on the production of high Mach number plasma jets. Pursuing these new research directions was also recommended by the NRC report on “Frontiers of High Energy Density Physics” and the 2004 FESAC Review of the IFE Program.

The ten-year goal for this program element aims to “develop experimentally-validated theoretical and computer models, and use them to resolve the key physics issues that constrain the use of IFE drivers in future key integrated experiments needed to understand the scientific issues for IFE and HEDP.” Excellent progress towards this goal was made in the past three years on the heavy ion driver experiments and the new program directions exploiting peta-Watt laser technology have been initiated as summarized below:

- *Initiate experiments and simulations of petawatt laser-pulse interaction with noncryogenic targets* (2009): Research activity has been started on this new direction in the HEDP program supporting work which leverages NSSA investments in facilities at the University of Rochester, LLNL, and LANL in the area of fast ignition.

- *Understand the limits to neutralized drift compression and the focusing of intense ion beams onto targets* (2010): The Neutralized Transport Experiment (NTX) which began operation in 2002 has demonstrated suppression of space charge effect on beam focusing with a ten-fold reduction in focal spot size by addition of a neutralizing plasma. In addition, compression of ion beams with an intensity multiplication of 50 using longitudinal compression in a neutralizing plasma with a "chirped" beam technique. These results are consistent with particle-in-cell simulations. This program is well positioned to achieve the 2010 intermediate milestone.

- *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): Efficient transport of the relativistic electrons through plasma corona and onto the high-density compressed fuel in an inertial fusion target is the key scientific issue for the fast ignition concept. Experiments and modeling efforts have begun in the past three years in the HEDP program to develop this understanding.

This program element is expected to continue to evolve with the proposal in FY08 to create a joint NNSA and SC High Energy Density Laboratory Plasmas program that is expected to facilitate coordination of FES HEDP research on NNSA facilities and supporting programs. Longer-term intermediate milestones are dependent on NNSA facilities like NIF beginning their ignition campaign experiments.

We find the FES program is making excellent progress towards the FY 2015 long-term performance measure to demonstrate progress in developing fundamental understanding and predictability of high energy density plasma physics.

Appendix – Rating Criteria for FES Long Term Goals

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”