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

FESAC Meeting

1 March 2007

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.

Comment on Format of PART Assessment

- BES example discussed in June 2006 FESAC Meeting - brief summary paragraphs justifying Excellent ratings

III. Ratings of Progress Toward Long-Term Goals of OBES by Program

The COV was asked to rate each of the programs reviewed with respect to their progress in meeting the long-term (by 2015) goals of the Office of Basic Energy Sciences. The four goals are as follows:

Goal a. *By 2015, demonstrate progress in designing, modeling, fabricating, characterizing, analyzing, assembling, and using a variety of new materials and structures, including metals, alloys, ceramics, polymers, biomaterials and more – particularly at the nanoscale – for energy-related applications.*

Goal b. *By 2015, demonstrate progress in understanding, modeling, and controlling chemical reactivity and energy transfer processes in the gas phase, in solutions, at interfaces, and on surfaces for energy-related applications, employing lessons from inorganic, organic, self-assembling, and biological systems.*

Goal c. *By 2015, develop new concepts and improve existing methods for solar energy conversion and other major energy research needs identified in the 2003 Basic Energy Sciences Advisory Committee workshop report, Basic Research Needs to Assure a Secure Energy Future.*

Goal d. *By 2015, demonstrate progress in conceiving, designing, fabricating, and using new instruments to characterize and ultimately control materials.*

The ratings [Excellent, Effective, Insufficient, Not Applicable (N.A.)] are listed in the table below. Detailed justifications for each rating are given in *Appendix F* (pp. 48-58).

Program	Goal a	Goal b	Goal c	Goal d
AMO Science	Excellent	Excellent	Excellent	Excellent
Chemical Physics	Excellent	Excellent	N.A.	Excellent
Photochemistry & Radiation Research	Excellent	Excellent/ Effective	Excellent	N.A.
Catalysis & Chemical Transformation	Excellent	Excellent	Effective	Excellent
Chemical Energy & Chemical Engineering / Separations & Analyses / Heavy Element Chemistry	Excellent	Excellent	Excellent	Effective
Energy Biosciences	Excellent	Excellent	Excellent	N.A.
Geosciences	N.A.	Excellent	Excellent	Excellent

The ratings of each program generally fall in the “Excellent” category for most of the goals, with two “Effective” ratings, one Excellent/Effective rating, and no “Insufficient” ratings. Ratings of “Not Applicable” were given in four cases.

Appendix F: SUBPANEL RATINGS OF PROGRESS TOWARD LONG-TERM BES GOALS

A. Rating of Atomic, Molecular, and Optical Sciences Program

a. By 2015, demonstrate progress in designing, modeling, fabricating, characterizing, analyzing, assembling, and using a variety of new materials and structures, including metals, alloys, ceramics, polymers, biomaterials and more – particularly at the nanoscale – for energy-related applications.

AMO Science Program Rating (a): **Excellent**

Justification of Rating (a): The multiple quantum well nanostructure work done in this program under the nanoscale initiative (Klimov) has enormous breakthrough potential for impacting solar energy conversion. Although this is not a large activity in *AMO Science*, it is very high quality, world-leading work. The multiple ion research work (MIRF/ORNL) in *AMO Science* is also unique and critical to our development of fusion energy.

b. By 2015, demonstrate progress in understanding, modeling, and controlling chemical reactivity and energy transfer processes in the gas phase, in solutions, at interfaces, and on surfaces for energy-related applications, employing lessons from inorganic, organic, self-assembling, and biological systems.

AMO Science Program Rating (b): **Excellent**

Justification of Rating (b): The *AMO Science* program has led BES in emphasizing control science at the quantum level. The work in theory and experiment on coherent control of molecular processes is at the highest level, and is seeding additional work in other programs in the US, and at the national light source facilities. The program managers have done an excellent job in both building new research programs and redirecting existing programs towards this new focus.

c. By 2015, develop new concepts and improve existing methods for solar energy conversion and other major energy research needs identified in the 2003 Basic Energy Sciences Advisory Committee workshop report, Basic Research Needs to Assure a Secure Energy Future.

AMO Science Program Rating (c): **Excellent**

Justification of Rating (c): The core thrust of this area is the control and measurement of energy flow in matter, on the quantum scale. This fundamental knowledge is essential for making materials and understanding dynamical processes. The multicharged ion research facility is providing essential knowledge for fusion reactors. The *AMO Science* program is also demonstrating high-efficiency light energy conversion through new control of nanomaterials (Klimov).

d. By 2015, demonstrate progress in conceiving, designing, fabricating, and using new instruments to characterize and ultimately control materials.

***AMO Science Program Rating (d):* <u>**Excellent**</u>**

Justification of Rating (d): This is one of the central activities of the *AMO Science* program. New instruments in short wavelength, ultrafast, and high intensity photon physics have been developed under this program. Beamlines at the Advanced Light Source and the Advanced Photon Source have been developed and utilized to understand new materials. Ultrafast lasers have been developed to elucidate chemical and atomic processes on femtosecond, or even attosecond, time scales. These instruments are world leading, and have accelerated progress in basic atomic and chemical dynamics in the US. The control of materials at their natural time scales, and at the quantum level, is a major goal of this program, and it leads all others in its implementation in the US.

B. Rating of Chemical Physics Program

a. By 2015, demonstrate progress in designing, modeling, fabricating, characterizing, analyzing, assembling, and using a variety of new materials and structures, including metals, alloys, ceramics, polymers, biomaterials and more – particularly at the nanoscale – for energy-related applications.

***Chemical Physics Program Rating (a):* <u>**Excellent**</u>**

Justification of Rating (a): A small component of the existing program is focused on heterogeneous catalysis. This effort seeks to gain a molecular scale understanding of heterogeneous chemical reactions. Despite the fact that this research is relatively new, the quality is already excellent. Both the university and lab programs are uniformly of the highest quality, and seek to gain molecular understanding of complex heterogeneous chemical reactions. These relatively new endeavors are becoming as visible as the gas phase kinetics and dynamics studies, which have been the cornerstone of this program. A number of new programs have recently begun funding for nanoscale modeling and simulation and materials for hydrogen storage. It is too soon to evaluate those now, but they are promising initiatives.

b. By 2015, demonstrate progress in understanding, modeling, and controlling chemical reactivity and energy transfer processes in the gas phase, in solutions, at interfaces, and on surfaces for energy-related applications, employing lessons from inorganic, organic, self-assembling, and biological systems.

***Chemical Physics Program Rating (b):* <u>**Excellent**</u>**

Justification of Rating (b): This is the core activity of the *Chemical Physics* program, and many PI's are involved. The program has breadth, depth, and extraordinarily high quality PI's. There are two Nobel laureates, and much international visibility, NAS memberships, etc. They have

Comment on Format of PART Assessment

Approach for FES PART Assessment:

- Develop list of some key intermediate milestones for each long term goal
- Use progress towards these intermediate milestones to justify assessment of progress towards long term goal
- Prepare a concise ~ 1page summary of assessment - audience OMB/Congress staff

Comment on Format of PART Assessment

- High Energy Physics just released the HEPAP assessment towards their six long term program goals
- Format used similar to FES: nearer term intermediate milestones developed to assess progress with ~ 1 page concise summary of progress on each goal

Assessment of Progress towards HEP Long-term Goals High Energy Physics Advisory Panel December 22, 2006

The Office of Management and Budget requested in 2004 that the Department of Energy, Office of Science, Office of High Energy Physics (HEP) develop a set of long-term goals in Scientific Advancement to which the HEP program is committed. These goals (attached) are meant to be representative of the important priorities of the program, are not meant to be comprehensive, and are not necessarily goals of individual experiments in the field. Recent changes in the OMB PART evaluation system now require the definition of an additional level of achievement that corresponds to making good progress towards meeting each goal. We have added this performance measure in a column labeled "Good Performance".

HEPAP has now been asked to assess progress towards the long-term goals. To aid in the evaluation of the field's progress, DOE Office of Science developed a set of milestones that, if reached by 2008, would indicate that we are on track to meet the long-term Scientific Advancement goals. Where appropriate, we refer to these milestones in the following assessment.

We believe that this set of long-term Scientific Advancement goals is appropriate now. Some of the six have already been achieved in part, and nearly all are likely to be achieved in the 10-year timeframe. An appropriate time to set new goals is probably in 2008, when the funding plan for new proposals will be clearer.

Discover or rule out the Standard Model Higgs particle, thought to be responsible for generating mass of elementary particles.

A long-term goal of the HEP program is to discover or rule out the Standard Model Higgs particle and, if it is exists, to measure its decays into a variety of final states. This goal is part of the larger goal of understanding the origins of electroweak symmetry breaking and of particle masses.

In its simplest form, the gauge theory that describes the weak and electromagnetic forces predicts that both the photon and the W and Z bosons are initially massless as a consequence of a symmetry, SU(2)×U(1). This symmetry is spontaneously broken, and the W and Z bosons acquire mass; in this model, a massless spin-zero (scalar) boson is predicted. Peter Higgs showed how a theory with a massless gauge particle (such as the photon) and a scalar particle can become a theory of a massive vector particle. This mechanism makes it possible for the W and Z to acquire mass by coupling to a scalar field, leading to at least one massive scalar boson, the Higgs particle. The scalar Higgs field, which exists everywhere, also couples to all other particles (quarks and leptons), thereby generating masses for these particles, the values depending on the unknown coupling to each of the particles. Due to its role in electroweak symmetry breaking, the Higgs mass is thought to be of the same order as the mass of the W and Z, i.e. 100 GeV/c^2. Verifying the existence of the Higgs particle is essential to verifying the Standard Model of particle physics.

occurs through a virtual W boson being produced and decaying to a t and anti-b quark pair. The Standard Model predicts that the parameter V_{tb} is very close to one.

Very recently, the D0 collaboration announced the first evidence of single top production using 0.9 fb^{-1} of data. Their signal corresponds to a 3.4 standard deviation significance. Using these data, they have shown that V_{tb} is in the range $0.68 < V_{tb} < 1.0$ at 95% confidence level. An earlier analysis of a smaller data set by CDF did not see a signal. Based on both the recent D0 result and the earlier CDF analysis, it is expected that a data sample of 4-8 fb^{-1} will allow the extraction of V_{tb} with a statistical error below 10%. This is consistent with the projected data sample for D0 and CDF through the end of the Fermilab Tevatron running; hence the long-term goal is likely to be reached with these data.

At the LHC, single top production will occur at a much higher rate and the backgrounds will also be larger and the experimental environment more challenging. The ATLAS and CMS collaborations estimate that they can eventually measure V_{tb} to an accuracy of about 5% within the timescale of the long-term goals. These estimates will have a much higher confidence level after the relevant backgrounds and detector performance are evaluated with real LHC data in 2008.

Measurements of couplings to other quarks rely on indirect processes: decays of mesons containing b quarks that proceed through virtual intermediate states containing a top quark. In the case of V_{td}, the most precise measurement comes from the difference in mass of the two mesons made from b and d quark anti-quark pairs (Δm_d). The value of V_{td} obtained in this way is $V_{td} = 0.0074 \pm 0.0008$, which nearly meets the long-term goal. The uncertainty is dominated by theoretical uncertainty and is expected to improve. The third parameter, V_{ts}, is determined from measurements of mixing in the decays of meson with b quarks to particles containing strange quarks. The value is $V_{ts} = 0.041 \pm 0.003$, which meets the long-term goal.

Nearly all of the long-term goals have been met, and good progress is being made towards the last of the goals, the measurement of V_{tb}.

Measure the matter-antimatter asymmetry in many particle decay modes with high precision.

A long-term goal of the HEP program is to measure the matter-antimatter asymmetry in many particle decay modes with high precision. This goal can be achieved at the B-factory experiments, BaBar at PEP-II and Belle at KEK-B, and good progress is being made towards that goal. Additional information will come from the Tevatron program, in particular for particles containing both b and s quarks.

Our understanding of particle physics includes the concept that for every particle in the universe, there is an anti-particle with equal mass yet opposite properties such as charge. We believe that particles and antiparticles existed in equal quantities at the time of the Big Bang, yet today the universe consists dominantly of particles, with hardly any antiparticles. For the Universe to evolve from particle anti-particle equality at the time of the Big Bang to the current matter anti-matter asymmetry requires violation of a property called CP symmetry. CP (charge-conjugation parity) symmetry states that the Universe would look the same if particles were exchanged for antiparticles and all space coordinates were inverted. CP symmetry is mostly respected; CP violation has been observed in nature only at a very tiny rate, too small to account for the matter anti-matter asymmetry. This presents a problem for the Standard Model, and further tests of CP symmetry in other modes are important to search for new physics that could contribute to explaining the matter anti-matter asymmetry. These tests require extremely precise measurements of the relative decay rates of particles and anti-particles into specific final states, tests that are best done at the BaBar and Belle experiments.

The specific long-terms goals are to measure the matter anti-matter asymmetry in the most sensitive modes to a precision of 4% and to measure it in many (15) other modes to a precision of 10%. The DOE established milestones towards achieving this goal: collect a large data set with detectors working well and announce new results by 2008. Through the end of the 2006 run, PEP-II delivered a total integrated luminosity of 410 fb^{-1} and BaBar recorded 391 fb^{-1} of data. The performance by the PEP-II accelerator far exceeds the design luminosity of the original proposal. The BaBar collaboration submitted 114 paper contributions to the 2006 ICHEP meeting and gave 26 presentations. This performance by BaBar more than meets the milestone. At this meeting, BaBar reported a measurement of $\sin(2\beta)$ (the parameter that quantifies the matter anti-matter asymmetry) using ψK final states with a precision of 5%. The combined average with Belle yields a world-wide accuracy of 3.8% in this channel; this measurement meets the first of the long-term goals. Nine other $b \rightarrow s$ penguin channels that are used to measure $\sin(2\beta)$ have been measured. All are currently statistically limited, with the best precision at BaBar being ~20% in the $\eta' K_s$ channel. It is expected that an accumulated luminosity of 1000 fb^{-1} will result in more than 20 modes being measured, with 10% precision in at least 15 of them. Additionally, the Tevatron experiments expect to measure a number of B_s decay modes, with 10% asymmetry measurements in some of them.

One of the long-term goals is met, and excellent progress has been made towards the other.

Confirm the existence of new supersymmetric (SUSY) particles, or rule out the minimal SUSY "Standard Model" of new physics.

A long-term goal of the HEP program is to confirm the existence of supersymmetric particles, or rule out the minimal supersymmetric standard model (MSSM) of new physics at the weak scale. This goal can be achieved at the ATLAS and CMS experiments at the LHC and the CDF and D0 experiments at the Tevatron. Because processes involving virtual supersymmetric particles can affect particle decays, e.g. of b-mesons, the BaBar and Belle experiments will constrain some models of supersymmetry.

The description of physical laws are independent of the coordinate system in which they are tested, in particular, independent of whether two such coordinate systems are displaced, rotated, or moving with constant velocity with respect to each other. This property is captured in the Poincare symmetry group. Supersymmetry is an extension of the Poincare symmetry to include symmetry with respect to transforming all integer spin particles (bosons) into half integer spin particles (fermions); this requires the existence of a fermion for every boson and vice-versa. In its unbroken form, all particle properties, including mass, of the superparticles are identical to those of their Standard Model partners except that their spin differs by a half-unit. The model with the minimum additional set of particles and new types of interactions is called the minimal supersymmetric model (MSSM). It accommodates most models of supersymmetry breaking and predicts a well described superparticle phenomenology at colliders. Supersymmetric particles at this scale also provide dark matter candidates, and allow for unification of the forces at very high energies.

Goals and Milestones - REVISED

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**
- 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)**
- 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.

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"

Burning Plasma: Excellent

This goal is one of the highest scientific priorities in the Fusion Energy Sciences Program, and very significant progress was made by the Program in the past three years. 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. 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. These results 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 and 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): Experiment and theory of these important modes for fusion power systems have made significant advance in the past three years through work from all three US major facilities 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.

Goals and Milestones - REVISED

Configuration Optimization

- 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)**

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)**

✓ = 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.

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.

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

Configuration Optimization: **Excellent**

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 $I^{1.3}$, 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.

Goals and Milestones - REVISED

High Energy Density Physics

- Initiate experiments and simulations of petawatt laser-pulse interaction with hydrogenic plasmas and noncrogenic targets **(2009)**
- 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)**
- 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**

✓ = 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.

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"

High Energy Density Physics: Excellent

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 begun as summarized below:

- *Initiate experiments and simulations of petawatt laser-pulse interaction with hydrogenic plasmas and noncrogenic 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. 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.