International Collaboration in Fusion Energy Sciences Research: Opportunities and Modes during the ITER Era

FESAC Report
February 28, 2012

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1.0 Introduction

At the July 28, 2011 FESAC meeting, the Director of the Office of Science requested that FESAC address the opportunities for the US plasma and fusion research communities presented by new or soon-to-be commissioned fusion facilities outside the US. In addition, FESAC was asked to elucidate the research needed to fill the gaps in materials science and technology required to sustain fusion plasma operations and to harness fusion power. (see appendix for complete charge letter)

This is a draft report to FESAC covering the first two of the three charges in the request to FESAC namely:

1. What areas of research on new international facilities provide compelling scientific opportunities for U.S researchers over the next 10-20 years? Look at opportunities in long-pulse, steady-state research in superconducting advanced tokamaks and stellarators; in steady-state plasma confinement and control science and in plasma-wall interactions.

2. What research modes would best facilitate international research collaborations in plasma and fusion sciences? Consider modes already used by these communities as well as those used by other research communities that have significant international collaborations.

This report was prepared by a subcommittee of FESAC consisting of twelve members with experience in international and domestic collaboration in fusion and plasma research as well as non-fusion research. (see appendix for a list of members)

This draft report is submitted for discussion at the February 28-29, 2012 meeting of FESAC. The material in this report is not to be quoted or referenced until FESAC has completed its review process and finalized the draft material in this report.

Submitted by:

Dale Meade
Subcommittee Chair
February 23, 2012

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2.0 Executive Summary

Background

The next 10 - 20 years will be a crucial period for fusion energy research. The need for carbon free energy sources such as fusion is increasing and, while significant progress on many alternative forms of energy production is expected, none can fill the demand alone. Therefore, during this period, fusion research must continue to make rapid progress that will provide increased confidence that practical, economical fusion energy is possible.

The international fusion program is now embarked on ITER, the world's largest scientific project in history, whose programmatic goal is to establish the scientific and technological feasibility of fusion energy for peaceful purposes. Achieving these goals about 2030 will forever change the energy landscape and open the door for fusion energy development. At that point in time, the US should be among the world leaders in fusion energy research, and possess a strong research infrastructure with the skills, facilities, and technological capabilities required to move forward to develop fusion energy. To reach this position over the next 20 years, the US Fusion Energy Sciences (FES) program will not only require the technical capability and dynamic research infrastructure to take a leading role in ITER, but equally important, it must also develop the fusion nuclear science and technology required to apply the ITER scientific advances on a path towards a fusion power plant.

During this next decade while ITER is under construction, the US FES program needs to make effective use of limited resources to explore critical issues at the frontiers of fusion research with a balanced program that exploits both the strength of its domestic research program and new unique capabilities that are becoming available overseas.

The Charge

In a July 22, 2011 letter, the Director of the DOE Office of Science asked FESAC to consider the following:

1. What areas of research on new international facilities provide compelling scientific opportunities for U.S researchers over the next 10-20 years? Look at opportunities in long-pulse, steady-state research on superconducting advanced tokamaks and stellarators; in steady-state plasma confinement and control science and in plasma-wall interactions

2. What research modes would best facilitate international research collaborations in plasma and fusion sciences? Consider modes already used by these communities as well as those used by other research communities that have significant international collaborations.

The following report contains the results of a six month study carried out by 12 members of a FESAC panel that included nine experts from the fusion sciences community and 3 experts from non-fusion scientific fields. The membership of the Panel involved a balanced representation from universities, national laboratories and industry. The Panel benefited from previous reports including the 2007 FESAC report on Priorities, Gaps and Opportunities [1], the 2009 Magnetic Fusion Energy ReNeW Report [2], the 2011 Report on International Collaborations of the US Burning Plasma Organization (USBPO) [3] and from public input.

Strategic Context

The international fusion program has a history of successful international collaboration that spans several decades. Most of these collaborations were bilateral arrangements that were modest in size. However, within the next decade, there will be a sea-change as the US fusion program enters an era dominated by the ITER project physically located in Cadarache, France. When construction is completed, ITER will be the largest ground-based scientific project ever undertaken, and the US will have invested over $2 billion to participate as a partner in this historic world undertaking to establish the "…basis for practical fusion energy."

As construction of ITER is completed over the next decade, the highest priority of the US FES program will be to assemble and field the most effective team of scientists to join the on-site ITER international team and to strongly support that team with a domestic FES program to maximize US contribution to the success of the ITER research program. This will enable the US to benefit maximally from ITER, in the form of scientific knowledge and technology. Consequently over the 20-year timeframe contemplated in this charge to FESAC, the Panel foresees that the US FES program will be increasingly dominated by the tasks and domestic support required to ensure success and US leadership of this large international ITER undertaking. Hence, addressing the charge to FESAC to identify "compelling opportunities" for international collaboration needs to be strategically viewed as asking: "**what additional international collaborations should be pursued by a US FES program that is already expecting to be dominated by the large international ITER collaboration**?"

Recommendation: Selection of an international collaboration should be made only after careful consideration to both (1) our national goal to advance critical fusion energy science issues and (2) the need to maintain a US domestic research infrastructure that supports the US ITER mission, positions the US to benefit from ITER's success, and make an informed decision on the best approach to the design of a Fusion Nuclear Science Facility (FNSF) [4] now under consideration.

Key Scientific Issues for Fusion Research during the next 10 - 20 years

In organizing our response to the charge, the Panel structured opportunities for international collaboration around the key scientific issues needed to establish the basis for fusion energy over the next 10 to 20 year time frame. It took as primary input the scientific themes developed by the 2007 FESAC Report "Priorities, Gaps and Opportunities: Toward a Long Range Strategic Plan for Fusion Energy" [1]. This structure is well suited for analyzing the opportunities for significant international collaboration on the new or emerging superconducting facilities overseas, and provides a framework for connecting the experience gained from these collaboration activities to US participation in the ITER research program.

The FESAC International Collaboration Panel adopted the three plasma related themes from the 2007 FESAC Report with minor modification as the "Major Scientific Challenges" that serve as our framework for addressing the scientific issues and scientific collaborations:

I. Achieving High Performance core plasma regimes suitable for Long Pulse;

II. Development and Integration of Long Pulse Plasma Wall Solutions;

III. Understanding the dynamics and stability of the burning plasma state.

Recommendation: These three Major Challenges should be addressed in a coordinated and phased approach. Initially, research activities can be carried out productively on all these Challenges in parallel. Challenges I and II would then be integrated as time progresses to address the non-linear coupling of the high-performance core plasma with the steady-state plasma wall solutions. Finally, the non-linear dynamics of the burning plasma state (Challenge III) would be coupled to the core plasma dynamics (Challenge I) and steady-state plasma wall solutions (Challenge II) through our physics program on the ITER experiment.

The approach of the Panel was to describe research program and collaboration opportunities in terms of these Scientific Challenges with the specific facilities emerging from consideration of the gaps between our present state of knowledge, and that required for practical fusion. We took an integrated approach considering both domestic and overseas facilities. The Panel did not attempt to assess every conceivable collaboration opportunity, but focused on *compelling* opportunities that were available at the frontier of toroidal confinement science and carried forward by research on the closely related tokamak and stellarator magnetic configurations. In particular, the charge from the Office of Science requested a focus on opportunities provided by the new and emerging tokamaks and stellarators with superconducting coils in Asia and Europe that can access near steady-state conditions.

Criteria for Assessing Collaboration Opportunities

To identify *compelling opportunities* for international collaboration, the Panel developed a methodology based on a review of previous collaboration experience in fusion energy, as well as Space Science funded by NASA and High Energy Physics (HEP), both of which have a large component based on collaborative modes of operation. Central to that methodology is establishing a set of evaluation criteria to compare among the many facility and research issue options.

Finding: The Panel developed five evaluation criteria to provide guidance when assessing and developing compelling opportunities for international collaboration:

I. Importance of Scientific Issue to be Resolved

Potential impact of resolving this issue on the feasibility of fusion energy, urgency of resolving the issue and the link to other critical issues in our strategic plan for fusion energy.

II. Significance and Distinctiveness of US Contributions and Potential for Success
US contribution would be significant, recognizable and increase the potential for success in resolving the scientific issue.

III. Positions the US to obtain optimum benefit from ITER participation and builds foundation for potential future US development path in fusion energy.
Would develop experience and build working relationships that enable the US to engage in desired ITER research activities, and position the US to move forward in developing fusion energy after ITER.

IV. Strengthen, extend and regenerate the US scientific workforce
Strengthens and extends the US scientific workforce in areas needed to carry out the US fusion program in the longer term.

V. Resource requirements and impact
Is the most cost effective way to address scientific goals rapidly and has a positive synergy with domestic activities and US long term goals.

Compelling Opportunities for International Collaboration in the next 10 - 20 years

The panel reviewed the capabilities of major existing plasma confinement facilities worldwide and those under construction. We focused on the capabilities made available by the new and emerging superconducting confinement facilities in Asia and Europe, as well as the major JET facility in Europe. The panel used available material, particularly the US BPO International Collaboration Report, recent reports and presentations by project staff, and responses to panel questions to assemble the summary described in Chapter 5.0 of this report.

It is important to note that the experimental capability of the new and emerging facilities will be developed over time: we used the project's publicly announced plans to determine when expected capabilities (e.g., plasma heating power, plasma pulse length, exhaust power handling, etc.) would become available. In the cases of new facilities, we also took into consideration that capabilities in plasma diagnostics, plasma control, and research infrastructure would need time to develop in the new facilities.

Principal Finding: The Panel identifies three compelling collaborative opportunities each of which addresses one of the three Major Scientific Challenges. Each collaborative opportunity describes the present status of the US research capability to address the issue, the opportunity for a unique contribution to successfully addressing the Scientific Challenge by using foreign facilities, and the necessary contribution coming from the US domestic research program.

Recommendation for Collaborative Area 1: Extending High Performance Regimes to Long Pulse

The development of stationary regimes for fusion energy is an area of US world leadership, with the US having many unique capabilities to develop the physics basis, including profile flexibility, high β access, excellent diagnostics, current drive techniques, stability and ELM control tools, which it is able to apply for multiple current diffusion timescales to develop and optimize candidate solutions. But to extend solutions to ITER or an FNSF, some aspects would benefit from tests with longer pulse lengths or at larger device scale than available in the US. These particularly concern issues of plasma facing component exposure and the extension of control. However, it should be noted that in seeking such capabilities abroad, there are trade-offs in performance and device flexibility, particularly with longer pulse and larger scale facilities needing to be operated more cautiously. Thus a closely coupled collaborative program is necessary, with US facilities providing the performance, diagnostics and range to determine required approaches, while tests of long pulse compatibility and size scaling are made abroad.

Required Domestic Program Research: In domestic facilities, the US should explore the range of plasma configurations and techniques producing stable current and pressure profiles capable of self-sustainment with optimized confinement and control over instabilities including ELMs. This will provide a strong basis for US leadership in the collaboration, and determine the approaches and hardware needed. The physics understanding gained will also underpin the basis for extrapolation to ITER, FNSF and beyond.

Collaborative Opportunities Abroad: Principal elements are the size scaling and long pulse tests of the key techniques needed in regimes compatible with steady state. The former is best addressed by joint experiments and shared analysis with larger tokamaks (JET, and eventually JT-60SA). **For long pulse issues, the earliest opportunities at reasonable performance levels come on EAST in 2014, with significant heating power and cooled tungsten plasma facing components.** In the longer term, KSTAR will provide access to similar regimes for up to 300s, though initially with carbon PFCs, though possibly a tungsten divertor later. These devices could be used to adapt control to superconducting coil sets and develop longer timescale event response and performance recovery techniques using US developed control systems, as well as addressing long pulse compatibility of required current drive systems. Corresponding inward investments could help optimize control approaches (such as 3D fields or current drive systems) in US domestic facilities. In addition, diagnostic techniques will need to be proven in long pulse conditions, to assess issues of degradation due to the plasma environment and radiation. Thus tests of US-developed diagnostic approaches in long pulse tokamaks (EAST, KSTAR) and exploitation of any available neutron-irradiation facilities would form a key part of a wider program here. Finally, W7-X offers potential to boost US theoretical and modeling capabilities on the underlying transport and transient physics with 3D magnetic field geometry, as well as gain insight into these issues for the stellarator path. Here preparatory experiments on LHD will help lever the US role on W7-X.

Benefits to US: A strong collaboration on this Scientific Challenge would provide the basis for long pulse experiments in ITER, offer the potential for an integrated physics and technology solution for an FNSF, and exploit stellarator involvement for a broader understanding, while securing US leadership, intellectual property and valuable knowledge. A balanced collaboration should also provide for US inward investment in developing key tools and modeling interpretation.

Recommendation for Collaborative Area 2: Development and Integration of Plasma Wall Solutions for Fusion

Critical Plasma Material Interaction (PMI) challenges include integrating reactor-relevant materials at prototypical operating conditions with high performance long pulse core plasmas while successfully avoiding transient and off-normal events, maintaining plasma heating and current drive capability, providing adequate PFC lifetime, maintaining fuel inventory control, and ensuring this performance in the severe irradiation environment of a power reactor. The leading PFC concept for an FNSF is tungsten, with carbon and other possibilities as backups. Unlike current confinement experiments, PFCs in a reactor will need to be at high temperature (> 600 °C). Assessing and proving these concepts these will require a multipronged Fusion Nuclear Science program.

Required Domestic Program Research: Candidate materials should be evaluated in single-effect laboratory experiments, off-line plasma simulators and suitable neutron irradiation facilities. The US is a world leader in PMI diagnostics and physics, and has a number of relevant test facilities, including several, such as PISCES, DIONYSIS and TPE which are unique. Tests should be conducted in tokamaks to assess compatibility with high performance plasmas, including interaction with RF waves for heating and current drive, fuelling, impact of transients, and material migration. Alcator C-Mod has FNSF and power plant level divertor heat fluxes and is planning the first tests (worldwide) of tungsten divertor PFCs at reactor-relevant temperatures. DIII-D and NSTX are testing carbon and lithium PFCs respectively.

Collaborative Opportunities Abroad: The US should collaborate with Asian superconducting tokamaks to upgrade to reactor-relevant PFC material and temperature at long pulse. **The proposed upgrade of EAST in 2017 to a hot tungsten divertor appears the most compelling medium term opportunity.** The US could provide experience from its hot divertor program and novel real-time PMI diagnostics, and would gain critical information needed to validate solutions for an FSNF. In the longer term, collaboration on KSTAR and JT60-SA could assess other PFC options, and integration with scenarios with higher self-driven current.

PMI issues are also critical to the success of ITER. In addition to US experiments, the US would collaborate on JET experiments with the new ITER like wall and upgraded heating. The US could contribute PWI expertise and diagnostics, and would gain experience valuable to future participation on this topical area on ITER. Critical issues to be explored with the ILW are the levels of impurities, the effects of plasma transients, the retention of tritium and the formation of dust.

Stellarators offer steady state confinement regimes eliminating transient events such as disruptions at the expense of a more complicated PMI configuration. Collaboration on LHD and W7-X provides an opportunity to develop and assess 3-D divertor configurations for long pulse, high performance stellarators. The US already has a significant collaboration in place on W7-X and is responsible for key high heat flux elements, 3D analysis codes and diagnostics. This will strengthen the US capability to pursue the stellarator as a potential path to fusion energy

Recommendation for Collaboration Area 3: Burning Plasma Research in Advance of ITER

The US FES program has identified the study of burning plasmas, in which self-heating from DT fusion reactions dominates plasma behavior, as a key frontier and the next major step in magnetic fusion energy research. The US already has experience in operating DT experiments, developing and exploiting alpha-particle diagnostics and leading expertise in the theory of alpha dynamics and alpha-driven instabilities. Through a close coupling of theory to experiments in US facilities, which provide access to a wide range of plasma regimes, the US has developed extensive and validated predictive modeling capabilities applicable to burning plasmas.

Required Domestic Program Research: The US should continue its very successful development of theoretical models for the nonlinear evolution of energetic particle driven instabilities, and test these models in the full range of experimental conditions available in US tokamaks using results from innovative diagnostics. This is crucial to understanding burning plasma instabilities and the resulting transport. This will maintain the US at the forefront of the field, positioning it for a valuable role in JET and leadership in ITER. It should also continue to develop alpha diagnostics compatible with the fusion environment. Through its involvement in the ITPA, it should conduct experiments on its domestic facilities to develop and optimize JET DT experiments and the operating modes for ITER.

Collaborative Opportunities Abroad: The US is providing to JET both a new detector for alpha particles (and other fast ions) lost from the plasma, and diagnostics for the mode-structure of fast-particle instabilities. **Support should be provided to compare the data from these diagnostics during the planned DT experiments with modeling of the alpha particle dynamics, including the mode structures and possible mode overlap, using the comprehensive suite of codes developed in the US.** Performing predictive modeling in advance of these experiments would provide a stringent test of the models and strengthen the foundation for predicting and optimizing the performance of ITER. The US should collaborate with JET to apply its experimental analysis and modeling codes to investigate alpha heating during the DT experiments thereby extending the capabilities of these codes in preparation for their application to ITER.

Optimizing the fusion performance in ITER requires understanding the interplay between the many factors involved in tokamak operation and building this into simulation codes. The US has made important strides in this area but to be confident of extrapolating to ITER-like conditions, it is important to validate the underlying models at the largest available scale. Critical issues for ITER remain the scaling of confinement with respect to size and the effects of isotopic mass and of alpha particles. **The US should leverage its successes in developing our understanding of tokamak confinement and in improving it by participating actively in the JET DT experiments**. Through this, the US will gain valuable knowledge about plasma transport in the conditions most closely approaching those in ITER. The ITER-like Wall in JET also provides a unique opportunity for studying performance optimization for ITER.

The US could also pursue collaboration in experiments to optimize the performance in JT-60SA as full heating power becomes available by 2020. In JT-60SA, electron heating will be provided by both high-energy neutral beams and ECRH power, making it possible to simulate aspects of alpha-heating by using advanced feedback control of the external power in response to the plasma properties measured in real-time. This could be used to test the extrapolation of plasma control strategies and techniques developed by the US for their application to ITER.

Research Modes to Best Facilitate International Collaboration

The present US fusion program is highly collaborative, both nationally and internationally, with many years of experience. Most fusion experiments in the US participate in a wide variety of collaborations with other groups in the US, involving of the order of 10-20% of their total budgets. The three major tokamak facilities in the US (C-Mod, DIII-D, and NSTX) are complementary in terms of facility capabilities, basic geometry, plasma parameters, and program emphases. All the domestic facilities are well diagnosed for conducting a wide range of research. In recent years, with the formal start of the ITER project, the scope of international collaborations has grown, with significant US investment in ITER and ITER-supporting research conducted on overseas facilities such as JET, JT-60U, and ASDEX-U. In parallel, the related ITPA process functions as a coordinated set of individual scientific exchanges. Collaborations with the superconducting tokamaks in Asia (KSTAR and EAST) and stellarators (LHD and W7-X) are now in place.

In developing its findings and recommendations on Modes of Collaboration, the Panel spent considerable time reviewing past and present experience with international collaborations in fusion and in other areas, most notably in High Energy Physics.

High Energy Physics (HEP) research in the US pushes on three interlocking scientific frontiers, the Energy, Intensity, and Cosmic frontiers. After more than 20 years of global leadership at the Energy frontier, the US HEP program now relies on international collaborations at an overseas collider facility, the Large Hadron Collider (LHC) at CERN, near Geneva, Switzerland, for future scientific advances in this frontier area. At the same time, the US-HEP program maintains strong domestic efforts at both the Intensity and Cosmic frontiers.

Energy Frontier Science at the LHC is done by two competing experiments, ATLAS and CMS, operated each by an international collaboration of roughly 2000 physicists from close to 200 institutions across 40 countries. The US LHC community accounts for roughly one-third of the total. About 25% of the US LHC personnel are presently stationed at CERN for one year or longer supported by the balance of US LHC personnel based at domestic universities and laboratories.

Like our HEP colleagues, after more than 30 years of US leadership in magnetic fusion energy research, the US FES program will now become reliant on an international collaboration to fulfill its goals in research on burning plasmas on the ITER facility being constructed in Europe. While the HEP experience on the LHC is most applicable to our developing an effective ITER collaboration, their experience also bears consideration in developing smaller scale international collaborations. The HEP community identifies four crucial elements for successfully maintaining future competitiveness when the only Energy Frontier facility is overseas:

- Maintain centers of excellence in the US.
- Establish a culture of remote participation.
- Maintain the ability to station personnel overseas for extended periods of time.
- Establish cohesive US-ATLAS and US-CMS projects and collaborations.

Finding: Experience in both fusion and HEP collaborations has shown that it is essential to have effective onsite presence for the collaboration to be successful.

Finding: Since the cost per researcher sited overseas is significantly higher than for research at a home laboratory, it is critical that opportunities be carefully selected to focus on critical issues which cannot be addressed in the US and provide clear benefit to the US program, and that their scale be no larger than is necessary.

Finding: International collaborations on overseas facilities pose significant challenges to building a strong scientific workforce that must be addressed. Challenges common to all researchers and institutions include:

- Extended overseas assignments challenge families.
- Extended overseas assignments can create impediments to career advancement.

Recommendation: Developing a team approach that allows for flexibility and the use of remote communication tools can mitigate these challenges, as they have in HEP.

Finding: There are additional issues for university participation in international collaboration which include:

- Extended overseas assignments reduce program visibility at home institutions, which can affect faculty hiring and student recruitment. While this concern is not as serious for world-class international activities like the LHC and ITER, it will be a factor in collaborating with the smaller overseas facilities.
- Overseas assignments challenge PhD graduate education programs.

Recommendation: Given the important role played by universities in supporting faculty working on fusion research, providing fusion research with a broad connection to the larger scientific community, and the recruitment and education of future fusion researchers for ITER and beyond, universities must be included in the international collaboration program. Solicitations should be planned accordingly. Experience on successful university collaborations on major domestic fusion facilities, and in HEP, has shown the importance of supporting a linked on-campus research program

General Recommendations for Modes of Collaboration

Based on our examination of existing collaborations in fusion and other fields, along with expectations for future opportunities for fusion research, including US participation in ITER, we make the following recommendations regarding modes of collaboration and their effective implementation:

1. The portfolio of international collaborations should include a range of appropriately scaled and structured collaborations that provide opportunities for new participants on a regular basis. These include large national teams, institutional collaborations and individual exchanges, each of which has its own advantages.
2. For large-scale collaborations, an integrated national team with a flexible mix of full time, on-site researchers and shorter-term visitors should be employed, structured according to

scientific roles, with support flowing directly from DOE to relevant team member institutions wherever possible.

3. The structure of these international collaborations should be viewed as an opportunity to develop US fusion program collaboration modalities that prepare for effective participation in ITER.
4. The solicitation and selection process should allow a range of modalities, partnerships, and opportunities in order to best utilize expertise in the US fusion program, and it should be clearly defined on the national level with open calls to establish new international collaborations or to renew existing collaborations.
5. While solicitations should seek issue-based collaborations, it should be recognized in the solicitation and award process that it may be most effective to establish separate collaborations with each overseas facility utilizing a DOE-FES umbrella collaboration agreement with the host facility as needed.
6. DOE-FES should plan to assist collaborating institutions navigate the complex Intellectual Property, and Export Control issues, and ensure safety of their personnel.
7. The division and funding of collaborations should be structured according to scientific roles, with support flowing directly from DOE to relevant team member institutions wherever possible.
8. Capabilities for effective remote collaboration from a number of locations should be provided and expanded as remote communication technology advances.

3.0 International Collaboration in Fusion during the ITER Era

Vision for the US Fusion Program during the ITER Era

The Fusion Energy Sciences (FES) program mission is to expand the fundamental understanding of matter at very high temperature and density and to build the scientific foundation needed to develop a fusion energy source. Remarkable progress has been made in understanding the science of magnetically confined plasmas, the ability to produce and control high temperature plasmas and in the plasma related technologies needed to carryout research on plasma behavior at the frontier of fusion relevant conditions.

The world fusion research community is now embarked on the construction of ITER, the world's largest scientific facility, to demonstrate the scientific and technological feasibility of fusion energy. The US is one of seven international partners (EU, JA, RF, IN, KO, CN and US) who are collaborating in this historic endeavor which is scheduled to begin operation in ~2020.

At that time, it is a goal of the US Fusion Energy Sciences (FES) program that the US be a leader in burning plasma science to obtain the maximum benefit from participation in the ITER research program. It is also the goal of the FES program for the US to significantly increase capabilities in the areas of long-pulse, 3D magnetic confinement science, and fusion materials science research within the next decade. In addition to the burning plasma physics and fusion technology experience which will be gained from ITER, a significant effort will be required to develop the materials needed to withstand the intense power densities and neutron irradiation that will be required for the plasma facing components of a fusion power plant. It is envisioned that a Fusion Nuclear Science program will be established in the US to enable a decision on a Fusion Nuclear Science Facility (FNSF) by the end of the decade.

The strength of US FES program resides in a highly skilled and experienced scientific infrastructure, a suite of world class major confinement facilities (DIII-D, C-Mod and NSTX) that have complementary flexible capabilities and comprehensive plasma diagnostics which are supported by experts in theory, plasma simulation and enabling plasma technology. These unparalled strengths have kept the US in a world leading position in fusion research for many decades. During the next decade, these resources need to be focused on addressing the key issues required to prepare for ITER experiments, and to establish the design basis for FNSF. In the next five years, a number of new experimental capabilities will become available on overseas facilities that will enable research on issues related to steady-state plasma control, plasma material interactions and use of 3-D magnetic fields for plasma control and control of plasma material interactions. These new overseas facilities provide an opportunity to leverage US resources through international collaboration to address a selected set of key scientific challenges.

International Collaboration

The United States has already pursued international collaboration in large science projects to share costs and technical risks, increase the likelihood of scientific success for large complex projects, and take greater advantage of international scientific expertise and facilities. International collaboration, however, poses special challenges, such as maintaining stable funding mechanisms that ensure the long-term stability of projects and striking an appropriate balance between the resources dedicated to collaboration and the need for maintaining a strong domestic research infrastructure to sustain and profit from the collaboration. A more detailed discussion of the Opportunities and Challenges of International Collaboration is given in the Office of Technology Assessment Report [5].

The worldwide fusion program has a long history of successful international collaboration that spans several decades. Most of these collaborations were bilateral arrangements that were modest in size. Within the next decade, however, there will be a sea change as the US fusion program enters an era dominated by the ITER project based in Cadarache, France. When construction is completed, ITER will be the largest ground based scientific project ever undertaken, and the US will have invested over $2 billion to participate as a non-host partner in this historic world undertaking to establish the scientific and technological feasibility of fusion energy for peaceful purposes.

As construction of ITER is completed over the next decade, the highest priority of the US FES program will be to field the most effective team of scientists to the on-site ITER international team and to support that team with a vibrant domestic US FES program to maximize US contribution to the success of the ITER research program. Consequently over the 20-year timeframe contemplated in the charge to FESAC, the US FES program will be increasingly dominated by the tasks and associated domestic support directed toward insuring success and US leadership of this large international ITER undertaking. Hence, addressing the charge to FESAC to identify "compelling opportunities" for international collaboration needs to be strategically viewed as asking: *What additional international collaborations should be pursued by a US FES program that is already planned to be dominated by the large international ITER collaboration?* Criteria for selection of a compelling international opportunity need to be carefully considered with respect to advancing critical fusion energy science issues while maintaining the necessary US domestic research infrastructure to support the US ITER mission as well as to position the US to benefit from ITER's success.

Criteria for Assessing International Collaboration Opportunities

In selecting the areas for international collaboration, the fundamental strategic question is: *How will pursuing this collaboration strengthen the US program?*

With this basic question in mind, the Panel developed five criteria to provide guidance when assessing opportunities for international collaboration. They are:

I. Importance of Scientific Issue to be Resolved
   Potential impact of resolving this issue on the feasibility of fusion energy, urgency of resolving issue and link to other critical issues in strategic plan for fusion energy.

II. Significance and Distinctiveness of US Contributions and Potential for Success

US contribution would be significant, recognizable and increase potential for success in resolving scientific issue.

III. Positions the US to obtain optimum benefit from ITER participation and builds foundation for potential future US development path in fusion energy.

Would develop experience, and build working relationships that would enable the US to engage in desired ITER research activities, Would position the US to move forward in fusion energy after ITER.

IV. Strengthen, extend and regenerate the US scientific workforce

Strengthens and extends the US scientific workforce in areas needed to carryout the US fusion program on ITER and in the longer term.

V. Resource requirements and impact

Is the most cost effective way to address scientific goals rapidly and has a positive synergy with domestic activities and US long term goals.

In the following sections, we examine the potential for utilizing international collaboration on the new, emerging and unique capabilities of overseas fusion confinement facilities to address critical scientific challenges for fusion energy and strengthen the US fusion program.

4.0 Overview of Scientific Issues to be addressed in the 10 - 20 Year Time frame

Previous studies have identified the scientific issues that need to be resolved to make fusion power a reality. The 2007 FESAC Report on "Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Energy" [1] documented an in-depth analysis of the major problems that must be solved on the path to practical fusion energy. Fifteen broad scientific questions were identified and organized under three major themes. Nine initiatives were identified as a means to close critical gaps. The MFE Research Needs Workshop (ReNeW) [2], carried out by the fusion community in 2009, provided a very detailed analysis and identified eighteen research thrusts with 51 sub-tasks that could serve as building blocks in developing a fusion program plan. The 2011 US BPO report on International Collaborations Opportunities [3] presented a detailed assessment of which of those sub-tasks could be addressed collaboratively on overseas facilities during the next 10 years.

In this report, we use the 2007 FESAC scientific themes to provide the framework for organizing the scientific issues to be addressed within the next 10-20 years as requested in the charge. We have found this particular framework well suited for identifying significant international collaboration opportunities, particularly on the new or emerging superconducting facilities overseas, which could provide a bridge to the most productive US participation in the ITER research program

The FESAC Priorities Panel (2007) themes with the highest priority sub-issues are:

• Creating Predictable High-Performance Steady-State Burning Plasmas.
  - Integration of a high performance steady-state burning plasma core.
  - Control high performance plasmas for long pulse without disruptions or major transients.

• Taming the Plasma Material Interface
  - Understand and control of all processes that couple the plasma and nearby materials
  - Development of plasma facing components for high-performance steady-state burning plasmas

• Harnessing the Power of Fusion
  - Materials in Fusion Environment
  - Power Extraction
  - Fusion Fuel Cycle

The three charges contained in the July 2011 letter to FESAC are covered by these themes, with the International Collaboration panel primarily addressing the first three plasma related sub-issues and the Fusion Nuclear Science panel addressing the last four sub-issues. These activities are linked, in that the collaborations identified here will help prepare the basis for needed fusion nuclear science testing. Thus, both programs will advance the development and testing of plasma facing components.

The FESAC International Collaboration Panel adopted the plasma related themes with minor modification as major Scientific Challenges that would serve as a framework for addressing the scientific issues and scientific collaborations as shown below:

I. Achieving High Performance core plasma regimes suitable for Long Pulse

II. Development and Integration of Long Pulse Plasma Wall Solutions

III. Understanding the dynamics and stability of the burning plasma state.

Initially, research activities can be carried out in parallel on these challenges. Challenges I and II then become integrated to address the non-linear coupling of the high-performance core plasma with steady-state plasma wall solutions. Finally, the non-linear dynamics of the burning plasma state (Challenge III) become coupled to the core plasma dynamics and control (Challenge I) and steady-state plasma wall solutions (Challenge II)

Our approach has been to describe research tasks and collaboration opportunities in terms of these Scientific Challenges with the specific facilities on which they might best be performed emerging from consideration of the gaps between our present state of knowledge, and that required for practical fusion. The panel did not attempt to assess every conceivable collaboration opportunity, but focused on compelling opportunities that were available at the frontier of toroidal confinement science as carried forward by research on the closely related tokamak and stellarator magnetic configurations. In particular, the charge from the Office of Science requested a focus on opportunities provided by the new and emerging tokamaks and stellarators with superconducting coils in Asia and Europe that can access near steady-state conditions.

4.1 Present Status relative to Fusion Needs

4.1.1 Achieving High Performance core plasma regimes suitable for Long Pulse

During the past two decades considerable progress has been made in developing a detailed understanding of plasma confinement, stability and control that has provided a predictive capability for achieving high plasma performance for moderate pulse durations. This understanding has led to the achievement of high fusion performance for short durations (1-20s) that require a modest extrapolation to reach the performance needed for ITER. However, for both existing tokamaks and stellarators, plasma fusion performance $n_i(0)\cdot\tau_E\cdot T_i(0)$ tends to decrease as the plasma duration increases, as shown in Fig 4.1. This figure is an update of a figure originally developed by M. Kikuchi [6]. For the highest performance tokamaks, the duration of the toroidal magnetic field is limited by heating of the copper magnets. In addition, RF power or neutral beams

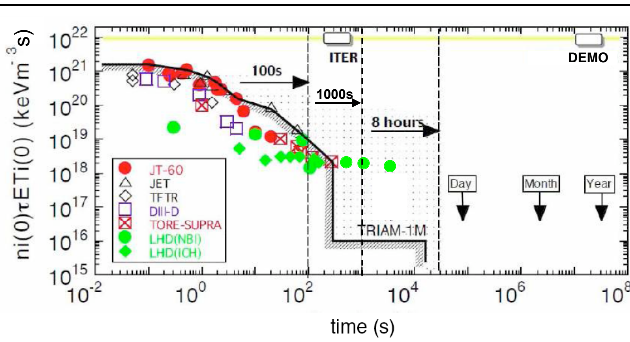

Fig 4.1 Achieving High Performance core plasma regimes suitable for Long Pulse Challenge

capable of coupling high power for long pulses are needed to heat the plasma and drive plasma current that generates the poloidal magnetic field required for confinement in the tokamak. Finally, the high power injected by the RF and neutral beam systems must exhausted from the system resulting in strong plasma material interactions (PMI) at the first wall and divertor.

For the stellarator (LHD) data shown, the magnets are all superconducting, and no current drive is required. In this case, the decrease in plasma performance is due plasma heating and plasma heat removal challenges, most notably PMI issues. This leads to the second scientific challenge.

4.1.2 Development and Integration of Long Pulse Plasma Wall Solutions

The importance of the plasma material interaction (PMI) issue has been long recognized as a critical issue for fusion energy. As the size of fusion confinement facilities has increased, the power density and total fluence has also increased significantly and it has become crucial to understand this issue in more detail, and thereby improve our predictive capability for the plasma material interaction.

The materials for the plasma facing components (PFC) and the first wall in a fusion device must withstand high thermal power fluxes, retain a small fraction of incident fuel particles and maintain structural strength under intense neutron irradiation. One measure of the capability gap with respect to PMI is illustrated in Figure 4.2 where the average power density through the outermost surface of the plasma is shown versus plasma duration for present day experiments. A power density approaching that of a fusion power plant [7] has been attained, on a US facility, but only for a very short time. In large tokamaks and stellarators, power densities comparable to ITER’s needs are currently tolerable only for < 10s. Also, these experiments used PFC materials not suitable for the eventual fusion environment involving tritium fuel and intense neutron irradiation. PMI research is needed for plasma wall solutions using fusion relevant materials such as tungsten under the high temperature conditions > 500°C required for an efficient fusion power system.

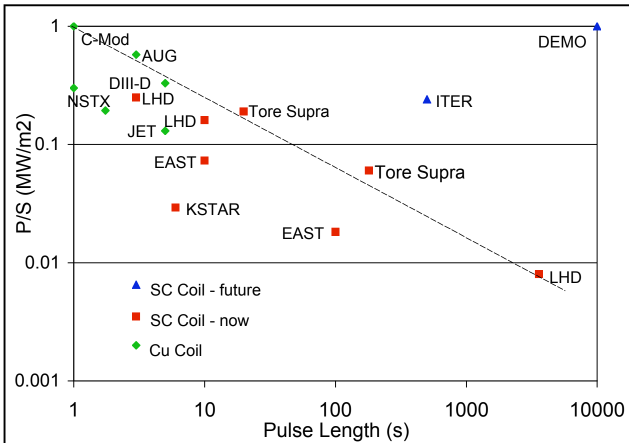

Fig 4.2 Development and Integration of Long Pulse Plasma Wall Solutions

4.1.3 Understanding the dynamics and stability of the burning plasma state.

In a burning plasma, the plasma heating will be provided by energetic alpha particles produced by the DT fusion reactions that are confined by the magnetic field and transfer their energy by collisions to the plasma. The distinguishing characteristic of a burning plasma will be the close coupling between the plasma heating and pressure. The pressure profile, in turn, defines the self-generated plasma current, the plasma stability limits and affects the turbulent plasma loss mechanisms, resulting in a complex highly-coupled system. For burning plasmas in a tokamak, this coupling is critical since the self-generated (bootstrap) current generates a large fraction of the confining magnetic field. For stellarators, this issue may not be as severe but the stability of pressure profiles defined by alpha heating could still be an important issue. The available fraction of alpha-heating, defined as $f_\alpha = Q/(Q + 5)$, where Q in the fusion power gain, attained to date is compared with that expected in ITER, and that required for a fusion power plant in Fig 4.3. The DT experiments on TFTR and JET achieved Q values of 0.3 – 0.7 with $f_\alpha < 12\%$. While small, this was sufficient to observe alpha-heating in agreement with expectations.

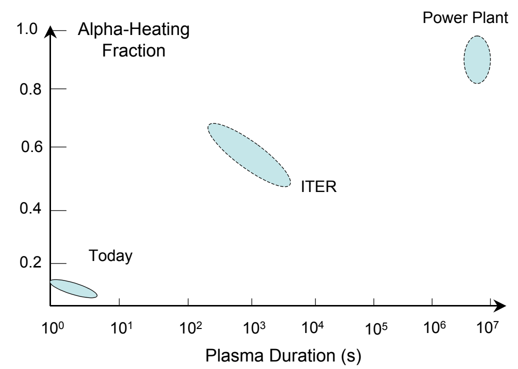

Fig. 4.3 Dynamics of the Burning Plasma

The pressure of energetic alpha particles in a burning plasma can be sufficient to generate large amplitude Alfvén waves that can affect the alpha-particle orbits and reduce the efficiency of alpha-heating. The excitation of Alfvén waves by alpha particles was investigated in the DT experiments in TFTR and JET during the 1990s. These experiments spurred the development of comprehensive theory and quantitative modeling capabilities for these plasma instabilities and their effects. Since the original DT experiments, many aspects of the alpha dynamics expected in a burning plasma have been studied in non-DT tokamaks and stellarators by using energetic particles produced by RF waves or neutral beam injection as surrogates for the fusion alpha particles. These studies have refined the theory and modeling, but there remain some issues of their extrapolation to a burning plasma such as ITER. The planned DT experiments in JET in 2015 will provide an opportunity to test aspects of the theory not amenable to validation with the types of energetic particles available in the current non-DT experiments. Furthermore, if ITER is to provide the major tests of burning plasma physics, it is important to develop and test the diagnostics for alpha particles and their effects to be deployed on ITER during the next decade. The only opportunity to test such diagnostics in a fusion environment will be on JET in 2015.

5.0 Experimental facilities available to address Scientific Challenges[†]

5.1 The significance of superconducting coil magnets in fusion research

Historically, magnetic confinement devices have usually been built using normally conducting copper coils since high-performance plasma regimes with pulse lengths sufficient for stability and confinement studies could be achieved at lower cost and operated with greater experimental flexibility than with superconducting coils. As success has been achieved in understanding plasma behavior at moderate pulse length, there is a growing need to explore plasma behavior in longer pulses and eventually in steady-state. Within the past decade, a number of tokamak and stellarator experiments with all superconducting (SC) magnetic field coils have started operation or are under construction, including LHD, EAST, KSTAR, W7-X, JT-60SA and ITER. Tore Supra, a limiter configuration tokamak with SC toroidal field coils, has been operating since 1988. All of these are located outside the US. The biggest impact of SC coils is that the plasma duration can be extended well beyond the 1 – 10 seconds typical of experiments with resistive coils. While superconductors allow continuous magnetic fields, the plasma duration then becomes limited by other constraints, including the capabilities of the plasma heating and current-drive systems, the plasma particle and heat exhaust systems, and restrictions on the number of fusion neutrons produced to limit activation of the structure. The main challenge for achieving the very long pulses needed for fusion energy production is associated with controlling the nonlinear coupling of the high performance core plasma with the plasma wall interactions produced by the intense power flux. The time scales for existing medium size MFE experiments and those now under construction are summarized in Table 5.1.

Time Scales for Medium Size Experiments (excludes: JET, JT-60SA, ITER)	Range
Plasma Transport (energy confinement time τ_E)	0.1 – 0.5 s
Plasma Stability Control	0.1 – 10 s
Plasma Current profile relaxation(τ_{CR})	1 – 5 s
Plasma Material Interaction (particle inventory)	1 – 100 s
Plasma Facing Component (thermal equilibration)	5 – 100 s
Wall Material Migration (cumulative operating time)	10^4 – 10^5 s
Goal: Plasma Facing Component Operating Temperature	>500 °C
Goal: Plasma Exhaust Power Density (Power/ Plasma Surface Area)	~1 MWm^{-2}

Table 5.1 Typical Plasma Timescales and Plasma Material Interaction Parameters

For SC tokamaks, the duration can also be limited by the ability to maintain and control stable plasma pressure and current profiles without relying on the transformer used to drive current in most pulsed tokamaks.. Thus, it is important that SC experiments focus on sustaining high-performance, very long pulse non-inductive operating scenarios suitable for fusion energy.

[†] These facility descriptions are based on information contained in the US BPO Report on International Collaboration (August 2011), recent presentations and personal communications.

Table 5.2 Major International Fusion Facilities (including planned upgrades)

	EAST	KSTAR	JT-60SA	ITER	LHD	W7-X	JET-IW	Tor Sup	DIII-D	C-Mod	AUG	NSTX-U	MAST
Location	**CH**	**ROK**	**JA**	**FR**	**JA**	**Ger**	**UK-EU**	**FR**	**US**	**US**	**Ger**	**US**	**UK**
Status (1st Plasma)	2006	2008	2016	2019	Mature	2014	2011/M	Mature	Mature	Mature	Mature	2014/M	Mature
Configration	AT	AT	AT	AT	Heliotron	Stell	AT	Cir T	AT	AT	AT	ST	ST
fuel	H, D	H, D	H, D	**DT**	H, (D)	H, D	**DT**	H,D	H, D	H, D	H,D	H,D	H, D
Major Radius (m)	1.85	1.8	2.96	6.2	3.9	5.5	3	2.25	1.67	0.67	1.65	0.86	0.85
Minor radius (m)	0.45	0.5	1.18	2	0.65	0.5	1.2	0.7	0.67	0.22	0.4	0.42	0.61
Plasma Vol(m3)	13	16	130	837	32	30	140	22	27	1	12	5.4	11
Plasma Surf (m2)	44	48	180	638	100	110	180	63	60	7	40	19	27
B(T)	4	3.5	2.25	5.6	3	3	4	4.5	2	5	3.1	1	0.7
Ip (MA)	1.5	2	5.5	15	~0	~0	5	2	2	1.5	1.2	2	2
B<a> (T-m)	2.1	2.3	3.7	13.1	2.0	1.5	6.3	3.2	1.8	1.1	1.6	0.6	0.6
Coil Technology	SC	SC	SC	SC	SC	SC	Cu	SC-TF	Cu	LN-Cu	Cu	Cu	Cu
Pulse Length (s)	1000	300	100	2,500	3,600	1,800	20	180	5	5	5	5	5
Paux(installed)(MW)	30	28	41	150	36	20	35	15	25	7	28	12	7.5
Divertor	DN,SN	DN,SN	DN	SN	HD	Island	SN	Limiter	DN,SN	DN,SN	DN/SN	DN,SN	DN,SN
Cooling	H2O,He	H20	H20	H2O	H20	H20	H20	H20	inertial	inertial	inertial	inertial	inertial
Plasma Facing Mat'l	C=>W	CFC	CFC	Be/W	C	C=>W	W/Be	C	CFC	Mo	W on C	CFC	CFC
P/S(MW/m2)	0.68	0.58	0.23	0.24	0.36	0.18	0.19	0.24	0.42	1.00	0.70	0.63	0.28
P/R(MW/m)	16	16	14	24	9	4	12	7	15	10	17	14	9

P/S is the average power density through the surface of the plasma at its edge using installed power at short pulse length
P/R is measure of the power density in the boundary plasma at short pulse assuming a constant boundary width as size increases
Note: the power densities achieved are significantly lower at longer pulse length.

5.2 New Capabilities for Addressing the High-Performance Steady-State Challenge

The significant parameters of the major international magnetic fusion facilities are compared with ITER in Table 5.2. EAST, KSTAR W7-X and JT-60SA are tokamaks that employ fully superconducting coils like ITER. JET has copper coils and ITER-like plasma facing materials, large size and the ability to use DT fuel. Plasma current is a measure of performance capability for tokamaks. B<a> is proportional to the number of gyro-radii across the plasma, and is a measure of size that provides a comparison of stellarators and tokamaks. One measure of the power handling challenge is the plasma heating power/plasma surface area, P/S. Another measure of the power handling challenge for divertors is P/R (implicitly assumes that the plasma scrape-off width is independent of size). The capabilities and plans for these international facilities are described in sections 5.2.1 through 5.3.6.

5.2.1 EAST

http://202.127.204.25/asipp-english/index.html

EAST is a tokamak slightly smaller than DIII-D with superconducting PF and TF coils at the Academica Sinica Institute of Plasma Physics (ASIPP) in Hefei, China. The key long-term goal of EAST is advanced tokamak, fully non-inductive operation, with a target pulse length of 400 s and a possible extension up to 1000 s. EAST has a pair of copper in-vessel coils (IVCs) for vertical stability control, a configuration similar to ITER. The current EAST divertor has actively cooled carbon tiles with an ITER-like vertical target. The actively cooled main chamber PFCs have recently been changed from carbon to molybdenum. The PFCs are conditioned using 250°C bake, between-shot RF discharges, and lithium coatings. In 2014, EAST plans to upgrade the divertor tiles to a tungsten surface sprayed on a chromium-copper substrate. This will be upgraded for operation at 400°C in 2017. EAST is also exploring the use of liquid lithium PFCs. The 2014 upgrade will also add an array of internal non-axisymmetric control coils for MHD stabilization up to $\beta_N \leq 3.8$. The EAST program will have ~10 MW (source) of LHCD and ICH heating power in 2012, and an aggressive upgrade program to add NBI and ECH reaching a total heating power of 20 MW in 2013 and 30 MW in 2015 as shown in Fig. 5.1.

EAST has operated since mid-2006. It can produce single and double null shaped plasmas with elongations above 1.9 and has achieved H-mode confinement with LHCD and ICH heating, each in the 1 MW range. It has reached a plasma current of 1 MA and, at lower current, plasma pulses lasting longer than 100 s have been produced with LHCD.

EAST is part of an extensive program at ASIPP and elsewhere to establish the basis for fusion energy development in China. This includes a technology development program preparing components for ITER and for development of a fusion pilot-plant in the 2020s. As part of this, they are participating in the ITER TBM program, and are designing, modeling, and testing blanket module technologies, including operating a hot lithium-lead loop.

5.2.2 Korea Superconducting Tokamak Advanced Research (KSTAR)

http://kstar.nfri.re.kr

KSTAR is a superconducting tokamak at the National Fusion Research Institute in the Republic of Korea, similar in major radius to DIII-D but with higher aspect ratio. Its mission is to develop high-performance, steady-state physics operation and technology essential for ITER and fusion reactor development in Korea. KSTAR has superconducting PF and TF coils (Nb_3Sn and NbTi), internal copper stabilizing plates, and an array of normal-conductor in-vessel control coils (IVCC) for fast vertical position control and control of MHD instabilities with toroidal mode-number $n \leq 2$. This array has coils at three poloidal locations, similar to that planned for ITER, providing control of the helical field structure. It started to investigate control of ELMs in 2011. KSTAR currently has carbon PFCs, which will be upgraded for active cooling in 2011–2012. A divertor cryopump is planned for 2012. The PFC bake was upgraded from 200°C to 350°C in 2011. In 2015, KSTAR plans to upgrade the lower divertor with tungsten tiles that are water cooled. KSTAR will have 8.5 MW (at the sources) of heating power (NB, ICH, ECH, LHCD) at the end of its Operations Phase I in 2012. This is planned to increase to ~20 MW in 2018 and ~30 MW in 2023. During Operations Phase II (2013 – 2017), the experiments will focus on extending plasma operation to 300 s duration and preparing for ITER experiments. Operations Phase III (2018 – 2022) will focus on high performance and advanced scenarios, with a target of steady-state operation at twice the no-wall beta-limit at full field and current.

KSTAR has operated since 2008, producing limited, single null, and double null shaped plasmas up to 7s duration with NB heating up to 1.5 MW and has achieved H-mode confinement.

KSTAR is a central part of the fusion energy development program in Korea. Its role as a test-bed for ITER physics and technology development and assessment is strongly emphasized and integrated into its planning. It is viewed as a key step to establishing the basis for construction of a future DEMO in Korea.

5.2.3 JT-60SA

http://www.jt60sa.org/

As part of the agreement on the ITER site, Japan and the EU entered into an agreement called the Broader Approach. One element of that agreement is a “satellite” tokamak facility to be sited in Japan at the JAEA Naka Center. Both Japan and the EU are partners in the design, construction, and eventual exploitation of this tokamak, called JT-60SA (Super Advanced). The tokamak assembly will be completely new, but the JT-60U infrastructure, including the auxiliary heating and current drive systems and diagnostics, will be reused allowing the project to reach fusion-relevant regimes more rapidly than would be possible in a completely new facility. The goal is to start operation in 2016, well in advance of the ITER first plasma (Fig. 5.1). However, high-performance operation will require deuterium plasmas that may be limited in total fluence until full remote handling capability becomes available in 2021.

JT-60SA will have superconducting toroidal and poloidal magnetic field coils and remote handling capability to permit the study of very long pulse, high performance plasmas. Since a fundamental mission of JT-60SA is to support ITER, single-null divertor operation will be the starting configuration. However, the machine design provides for eventual full double-null divertor operation to explore steady-state advanced tokamak scenarios for burning plasma devices beyond ITER. Internal coils for feedback control of MHD instabilities are integrated into the design to facilitate operation above the no-wall MHD β-limit. The control coil design is considered more DEMO relevant than those on other present or planned experiments, consistent with the long-range mission to explore steady-state operation relevant to power plant designs. The dominant heating will be from neutral beam injection, including the negative-ion based system developed on JT-60U, which is prototypical in several aspects of the system planned for ITER. Pulse lengths will be limited by the energy capacity of the auxiliary heating systems and ultimately by the neutron budget of the site. The first-wall heat handling will use water-cooled graphite. While this has the advantage of robustness, which will facilitate a thorough exploration of parameter space, it comes at the cost of not testing the physics and technology of metallic or high ambient temperature first-walls.

5.2.4 Wendelstein 7-X (W7-X)

http://www.ipp.mpg.de/ippcms/eng/for/projekte/w7x/index.html

The Wendelstein 7-X stellarator, presently under construction at the Max Planck Institute for Plasma Physics (MP-IPP) in Greifswald, Germany, will be the first ”fully-optimized” stellarator device that combines a quasi-isodynamic magnetic field configuration sustained by superconducting coils with a steady-state exhaust concept, steady-state heating at high power and a size sufficient to reach reactor relevant $nT\tau$ -values. The mission of the project is to demonstrate the reactor potential of the optimized stellarator approach.

The W7-X will have a magnetic field of ~3T, plasma major radius of 5.5m, minor radius of 0.53m, a plasma volume of ~30 m^3 and plasma durations of at least 30 minutes. It will be equipped with a helical-island divertor, for controlling particle and heat exhaust. The coil system is designed to provide shaping flexibility around the optimized design configuration.

The first experimental campaign is expected to start in 2015 with 8 MW of ECH and 7 MW of neutral beam heating. At the outset, the divertor will not be actively cooled, which will limit the pulse duration to ≤10 s at 8 MW. The second campaign is planned to start in 2019 with installed plasma heating power of 10 MW of ECH and 10 MW of NBI. The installation of an actively cooled carbon divertor will allow a pulse duration of 10 s at 18 MW, and 1,800s at 10 MW. Replacing the carbon divertor plates with tungsten is being considered for a later upgrade.

5.2.5 ITER

http://www.iter.org

ITER is now under construction at Cadarache, FR, and is scheduled to complete formal construction in 2019, with initial plasma experiments beginning in 2023, and DT experiments beginning in 2027. ITER is a superconducting coil tokamak at physical size near that of a fusion power plant. ITER is expected to produce 500MW of fusion power for a pulse length of ~ 500 s with fusion power gains Q ~ 10, and to operate under near steady-state conditions for 2,500 s while producing ~300 MW at a gain Q ~ 5.

ITER is included here to provide some perspective on the relative capabilities of recently constructed superconducting tokamaks and stellarators that will be available within the next 5 year period compared with that of ITER which will begin operation in about 10 years.

5.2.6 Summary of new facilities

EAST and KSTAR are medium size tokamaks similar in size to DIII-D and C-Mod in the US, and ASDEX Upgrade in Germany. The latter facilities are well developed with extensive plasma heating, advanced plasma control, comprehensive diagnostic systems, and powerful data collection and analysis capabilities. EAST and KSTAR are in the early stages of their development, and plans are in place to significantly increase their experimental capabilities during the next five years,

JT-60SA will be a large size advanced tokamak with a physical size comparable with JET, and will carryout a complementary research program emphasizing high performance long pulse operation in advanced plasma regimes relevant to ITER and to DEMO. JT-60SA is expected to begin operation in 2016, and has a staged program for attaining full capability by ~ 2020.

The plans for the development of EAST, KSTAR and JT-60SA are shown in Fig. 5.1.

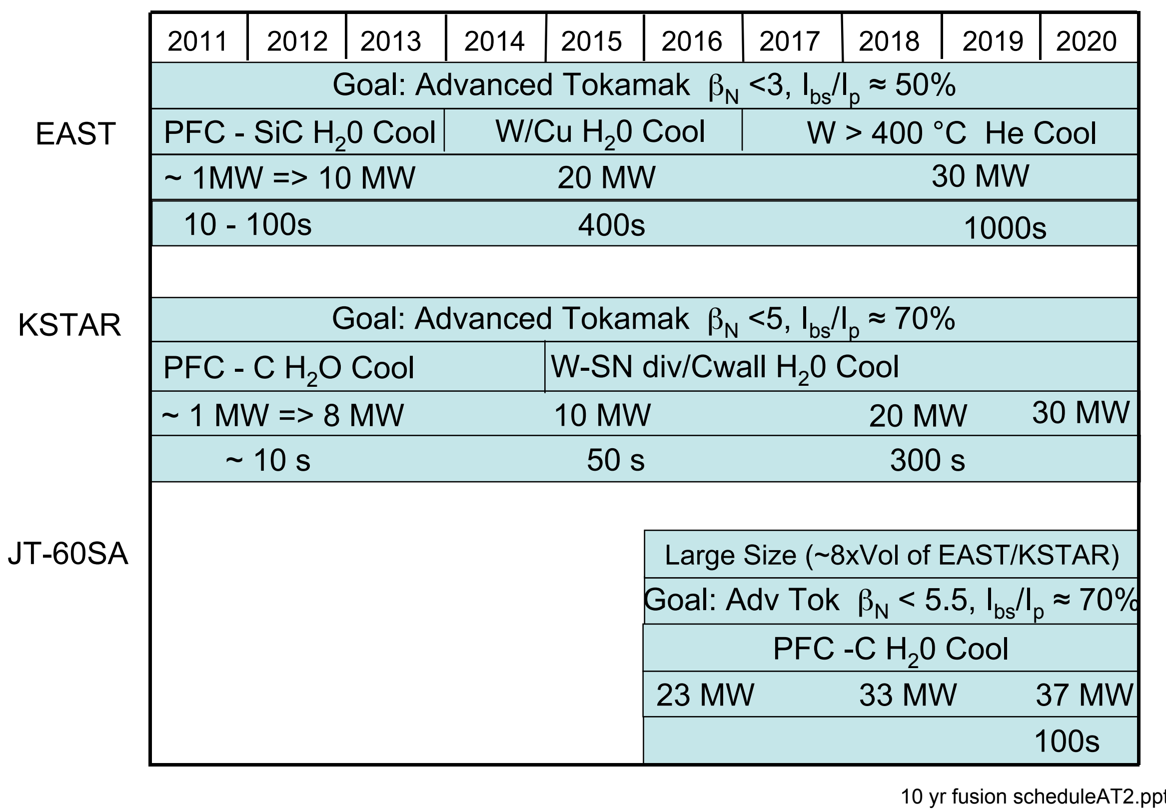

Fig. 5.1 Operating Plans for EAST, KSTAR and JT-60SA

W7-X is a large optimized stellarator, which is scheduled to begin operation in 2014, with a significant upgrade in heating power and plasma heat removal in 2017-2018. This would allow

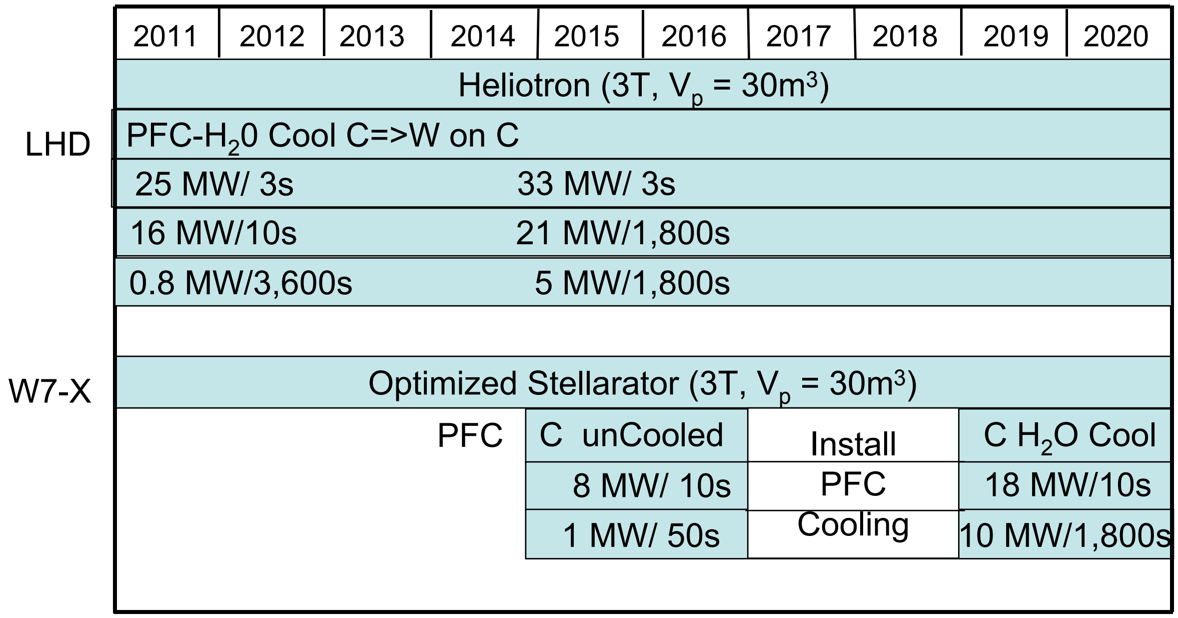

Fig. 5.2 Operating Plans for LHD and W7-X

high performance "steady-state" experiments to begin in 2019. The timetable for the development of W7-X and the currently operating Large Helical Device (LHD – see Sec 5.3.2) are shown in Fig 5.3.

ITER is scheduled to complete construction with a first plasma in 2019, and would begin initial operation with non-burning plasmas in 2023, and with burning plasmas in ~ 2027.

The relative sizes of experiments leading into the ITER era are shown in Figure 5.3.

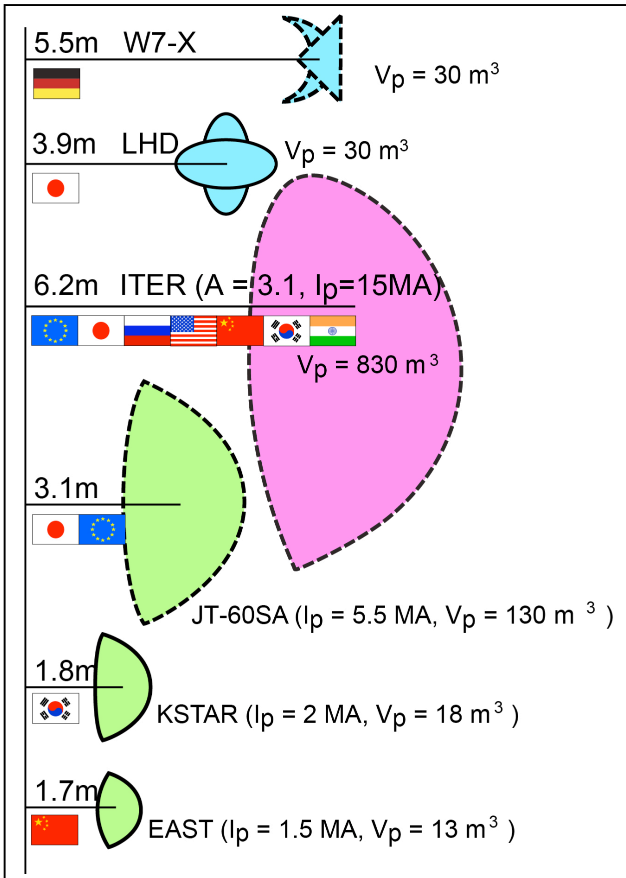

Figure 5.3 Experimental Fusion Facilities utilizing all superconducting coils

5.3 International facilities currently in operation with well developed capabilities and active ongoing international collaborations.

5.3.1 The Joint European Torus (JET)

http://www.jet.efda.org/

JET is the largest operating tokamak in the world with the highest heating power, and is currently the only magnetic fusion experiment able to use tritium. JET has operated since 1983 and is a mature research facility with a well developed research program, studying a broad range of tokamak physics and technology issues. JET has the same plasma shape and single null divertor configuration as ITER, and its current program is focused on preparing for ITER. The main characteristics of JET are:

- plasma size and normalized plasma size (ρ^*) within a factor of 3 of ITER, providing confinement and stability data closest to reactor scale,
- water cooled copper coils and with a plasma pulse duration limited to ~20 seconds at a toroidal field of 3.4 T.
- plasma current of $\leq$ 4MA, highest of all tokamaks, allowing it to investigate and test disruption detection, dynamics, and mitigation closest to reactor scale.
- a neutral beam heating system capable of $\leq$35 MW for 20 s starting in 2013.
- plasma facing components (PFCs) now comprised of tungsten (divertor) and beryllium, similar to the first wall design of ITER, to test its integration with ITER prototypical plasmas
- the ability to use deuterium-tritium (DT) plasmas, producing a significant energetic alpha particle population at fusion gain $Q \leq 0.5$ and fusion power of $\leq$ 20 MW in 1997.
- extensive remote maintenance capability, for maintaining and installing in-vessel components.

JET research will focus on the effects of the tungsten / beryllium ITER-like wall through 2012. The next phase will emphasize the development of high performance plasma scenarios for ITER in 2013-14. The European Fusion Development Agreement (EFDA) proposes to follow these experiments by operating with deuterium-tritium plasmas in 2015. The extension of JET operation beyond 2015 would provide the opportunity for other ITER parties to contribute to and benefit from JET as a training ground in advance of ITER operation. This phase would be carried out with the full capability of operating with tritium and consist of interleaved campaigns in deuterium, full tritium and DT.

5.3.2 Large Helical Device (LHD, Japan)

http://www.lhd.nifs.ac.jp/en/

The LHD at the National Institute for Fusion Science in Toki, Japan, is currently the largest stellarator in the world, with a major radius of 3.9 m and a plasma volume up to 30 m^3, and supports a broad research program on all aspects of plasma confinement and heating. It uses superconducting helical and PF coils, and has produced plasmas lasting an hour. LHD has achieved the highest temperature, average pressure, and peak pressure of any stellarator. However, its magnetic configuration has regions with a magnetic hill, limiting stability, and has significant magnetic ripple, which limits ion confinement, particularly of energetic ions. LHD continues to increase its heating power and is now equipped with 32 MW of NB heating (16 MW from negative-ion sources and 16 MW from positive-ion sources), 4 MW of ECH power at up to 150 GHz and 2 MW of ICH power from a launcher with variable $k_{||}$ capability. It is now investigating the first elements of a full closed helical divertor designed to cope with steady-state power and particle exhaust. In 2011, two of the 10 periods had divertor modules, in 2012 six more will be added and in 2013 all ten periods will have divertor modules. Plans are being developed to apply a tungsten coating to the CFC composite tiles of the divertor modules.

5.3.3 DIII-D

http://www.ga.com/energy/d3d.php

DIII-D is a medium sized tokamak located at General Atomics in La Jolla, CA. Its long-range goal is to demonstrate high-performance inductive and non-inductive advanced tokamak (β_N>4) operation, including not only high-performance core plasma scenarios, but also integration of solutions for handling the heat and particle fluxes at the boundary, operational control and machine protection techniques, and credible start-up and normal shutdown scenarios. DIII-D has a strongly shaped cross-section ($\kappa_x \leq 2.1$ and $\delta_x \leq 0.8$), with a single null or double null poloidal divertor configuration, which includes close coupled cryo-pumps. The water cooled copper toroidal magnet is capable of 2.1 T for 10 s, with plasma currents of 3.0 MA for 3 s and 2 MA for 10 s. A non-axisymmetric coil system, consisting of 12 coils mounted inside the vacuum vessel and 6 external coils, provides stabilization of ELMs and resistive wall modes. The plasma-facing components are carbon-fiber composite (CFC) tiles that are cooled between pulses. Auxiliary heating is provided by up to 20 MW of neutral beams at 80 keV with pulse length of 6 s with 5 MW directed counter to the plasma current to provide rotation control and 5 MW with variable off-axis deposition for steady-state regime studies. An ECRF system with a capability of 6 MW for 6 s is available for localized heating, and current drive. There are plans to extend the neutral beams and ECRF to 10 s. An ICRF system producing 6 MW for 10 s will be available for heating and current drive. DIII-D has comprehensive, mature diagnostics and data analysis capability.

5.3.4 Alcator C-Mod

http://www.psfc.mit.edu/research/alcator/index.html

Alcator C-Mod, located at the Massachusetts Institute of Technology in Cambridge, MA, is a compact, high-field tokamak and RF systems for heating and current drive. C-Mod is currently the only divertor tokamak operating with solid all-metal PFCs. The magnets use copper conductor cooled to LN temperatures prior to the pulse. Magnetic fields up to 8 T are available for 1 s, or 5.3 T for 5 s. The plasma major and minor radius are 0.67 m and 0.22 m, respectively. The plasma cross section is elongated with $\kappa_x \leq 1.85$ and $\delta_x \leq 0.8$ and plasma currents up to 2 MA can be produced. At reduced parameters, pulse lengths can be ~5 current relaxation times. A single null divertor with cryo-pump is available. Plasmas are heated with ≤ 6 MW of ICH at 40 – 80 MHz, with plasma current drive being provided by a 3 MW LHCD system at 4.6 GHz. The PFCs are molybdenum tiles that are cooled between pulses. A set of tungsten divertor tiles, with an ITER-like design, has been recently tested. Power and particle fluxes are similar to those expected on ITER, though with much shorter discharge lengths. A new toroidally continuous solid tungsten divertor, with controllable temperature up to 600°C, will be installed in 2013, to handle these heat fluxes for several sec pulses and to test for the first time PFCs at DEMO-relevant temperatures in a confinement device.

There are three main components to the C-Mod research program: 1) support the ITER inductive H-mode baseline scenario; 2) investigate advanced scenarios with high bootstrap fraction in quasi-steady state; 3) conduct research into the areas of transport, plasma boundary, wave-particle interactions and macrostability to improve predictive capability. C-Mod can operate at the same toroidal field and plasma density as ITER and with similar ICRF and LH frequencies, so its plasma dielectric properties are nearly identical. Plasmas are usually produced without momentum or particle sources and with equilibrated current profiles and equilibrated ion and electrons.

5.3.5 ASDEX-Upgrade (AUG, Germany)
http://www.ipp.mpg.de/ippcms/eng/for/projekte/asdex/ziele/index.html

AUG is a medium scale, short-pulse tokamak, heated by neutral beams, ECH, and ICRF with a plasma size similar to DIII-D and shape similar to ITER. The PFCs and divertor on AUG are coated with a layer of tungsten, providing experimental data on integrating ITER-like scenarios with a tungsten wall. AUG is developing methods to control plasma interaction with the metallic wall, including controlling plasma radiative losses via impurity doping and design of ICRF launchers to minimize edge electric fields. AUG is adding a new set of in-vessel magnetic coils to stabilize and control ELMs using resonant magnetic perturbations with $n \leq 4$, and to access higher-β by stabilizing resistive wall modes. These coils provide opportunities for new collaborations by US researchers on controlling such transient events. This capability will allow AUG to test the compatibility of advanced tokamak scenarios with metallic walls. AUG invites and facilitates collaboration by researchers around the world community, with an open planning and decision process.

5.3.6 Tore Supra (France)
http://www-fusion-magnetique.cea.fr/gb/cea/ts/ts.htm

Tore Supra is a superconducting, steady-state capable tokamak located at the Institute de Recherches sur Fusion Magnétique (IRFM) at the Euratom-CEA site at Cadarache, France and has operated since 1988. It has a plasma major radius of 2.25 m, a circular minor cross-section of radius 0.7 m, a maximum toroidal magnetic field on axis of 4.5 T, and a maximum plasma current of 1.8 MA. It is heated by ~15 MW of LH, ICRF, and EC power from steady-state sources. All plasma facing components are actively cooled, and steady state particle and heat exhaust is effected through a graphite toroidal pumped limiter. Notable results include sustainment of a lower hybrid current-driven plasma for 6.5 minutes with injection of 1.1 GJ of energy. IRFM has proposed to modify Tore Supra with the addition of poloidal divertor coils and tungsten internal components, the modified device is to be called WEST [Tungsten (**W**) **E**nvironment in **S**teady-State **T**okamak] which could be used to develop and test plasma-facing components for ITER and other advanced fusion experiments. The plasma facing components will be fully metallic and actively cooled, with ITER tungsten (W) monoblocks technology for the lower divertor, and W coatings for the upper divertor, for the antenna protection limiters and for the other guard limiters. Such a facility would provide additional opportunities for collaboration on ITER PMI issues and for a fusion nuclear science program.

5.3.7 National Spherical Torus Experiment Upgrade (NSTX-U)

http://nstx-u.pppl.gov

The National Spherical Torus Experiment Upgrade (NSTX-U), located at Princeton Plasma Physics Laboratory, Princeton, NJ, is a medium-sized facility designed to explore the physics of plasmas confined in a low-aspect ratio tokamak or spherical torus (ST) configuration. NSTX, which began operation in 1999, is now undergoing a major upgrade and is scheduled to resume operation in 2014 as NSTX-U. The magnets of NSTX-U are water-cooled copper designed to produce a toroidal field up to 1 T field and plasma currents up to 2 MA for up to 5 s. As part of the upgrade, a second NB system will be added providing a total of 12 MW of NB power. ICH power of up to 6 MW is also available for heating and current drive. The major radius of NSTX-U is 0.93 m, minor radius 0.62 m and it is designed to produce and control plasma cross-sections with very high elongation κ up to 2.8. A set of six external coils will provide non-axisymmetric fields for controlling MHD instabilities at high beta, β_N up to 6(%.m.T/MA), β_T up to 40%, and modifying the plasma rotation. The extensive diagnostics installed on NSTX will be retained in the upgrade.

The research goals of NSTX-U are to study advanced high-β scenarios at low collisionality and to produce 100% non-inductive operation including non-inductive current ramp-up using NBI heating and current drive. Advanced divertor and PFC concepts such as liquid lithium and a high-flux-expansion snowflake divertor will be studied at moderate pulse length and high power density.

5.3.8 Mega Ampere Spherical Tokamak (MAST, UK)

http://www.fusion.org.uk/MAST.aspx

MAST is a spherical torus (ST) experiment at the Culham Centre for Fusion Energy (CCFE) in Oxfordshire, UK, with similar size to the NSTX experiment in the US. It is currently being upgraded to increase its plasma current to 2 MA, toroidal magnetic field to 0.8 T, and heating power to 7.5 MW of neutral beams. While these overall parameters are similar to those for NSTX-U, other key capabilities and approaches are complementary. In particular, MAST-U will have (i) a carbon-faced divertor with very high flux expansion (a so-called super-X configuration) and a cryo-pump, (ii) electron Bernstein wave heating (2 MW), and (iii) extensive internal non-axisymmetric coils to control and study MHD instabilities such as edge localized modes (ELMs) and Alfven Eigenmodes.

An ongoing US collaboration has contributed the EBW gyrotron system to MAST. Other US collaborators are investigating solenoid-free plasma startup and ramp-up in MAST. MAST research targets ST-specific issues, and developing predictive understanding of toroidal confinement and stability. MAST/MAST-U has a very high resolution Thomson scattering system for detailed pedestal structure, ELM stability, and NTM physics studies. Its super-X divertor will explore ways to reduce and control the heat flux density to the divertor plates. Refractory metal PFCs are under consideration for the expanded divertor**.** The non-axisymmetric coil array will provide more control over the 3D perturbation spectrum than present experiments, for improved understanding of the physics of ELM control. These new capabilities provide additional opportunities for US collaboration, to apply US expertise and to contrast the results with complementary US experiments.

5.3.9 MST (University of Wisconsin-Madison)

http://plasma.physics.wisc.edu/viewpage.php?id=mst

MST is a large reversed field pinch that has attained record values for RFP plasma temperature, beta, and energy confinement time using inductive current profile control. A new feedback-controlled power supply for the toroidal field has been installed to maximize current profile control. This supply also permits low-current tokamak operation. A recently added 1 MW neutral beam injector (NBI) enables unique studies of energetic ion confinement and stability in the RFP configuration. Momentum transport research is assisted by the tangential injection geometry. MST is equipped with an array of advanced diagnostics, including FIR interferometry/ polarimetery/scattering, high rep-rate Thomson scattering (250 kHz equiv.), active charge-exchange spectroscopy (CHERS), motional Stark effect (MSE) using a full-spectrum method that may be employed on ITER, and the only heavy ion beam probe operating in the US. A high-power 4 GHz RF system is being prepared for investigation of electron Bernstein wave heating and current drive. MST plasmas exhibit self-organized helical states as first observed in the RFX-Mod experiment.

Achieving maximum plasma current and pulse length on MST requires the addition of a companion feedback-controlled power supply for the poloidal field. This would help further increase the Lundquist number to assess high-priority confinement issues. It would also maximize capability for oscillating field current drive, an inductive scheme for steady-state current sustainment.

5.3.10 RFX-Mod (Italy)

http://www.igi.pd.cnr.it/wwwexp/index.html

RFX is a large reversed-field pinch with the highest plasma current capability among RFP experiments. It uses a unique array of "saddle coils" surrounding the plasma for active feedback stabilization of the MHD instabilities. This allows RFX to operate with a relatively thin stabilizing conducting shell, unique for an RFP. The high plasma current gives access to plasmas with larger Lundquist numbers, which is important for understanding RFP confinement scaling. RFX can also be operated as a tokamak at low current, to compare the two magnetic configurations. The RFX program is currently focused on understanding the tendency of the plasma to self-organize into a helical configuration with reduced magnetic turbulence and fluctuations. US researchers collaborate on RFX experiments, and have applied codes developed for stellarators to analyze and understand the helical RFX plasmas.

With a substantial upgrade of the RFX power supplies and other systems, it may be possible to significantly increase the RFX plasma current, evaluate methods to sustain the current, and assess the impact of sustainment techniques on RFP plasma confinement, which are high priority RFP issues. Such an upgrade program could motivate an increased US collaboration.

6.0 Opportunities to Address Scientific Challenges with International Collaboration

In this chapter, we use the Scientific Challenges indentified in Chapter 4.0 as a framework within which to describe the US Research goals, determine the research needed on that issue and then identify potential collaboration opportunities to address these issues. When identifying the potential collaborations, we used our criteria - *that we are looking for distinctive activities, where collaboration focuses on adding capability not available in US, and focuses on providing important deliverables to the US program, and enables US to retain leadership.(see Chapter 3.0)*

The panel did not attempt to assess every conceivable collaboration opportunity, but focused on compelling opportunities that were available at the frontier of toroidal confinement science as carried forward by research on the closely related tokamak and stellarator magnetic configurations. In particular, the charge from the Office of Science requested a focus on opportunities provided by the new and emerging tokamaks and stellarators with superconducting coils in Asia and Europe that can access near steady-state conditions.

6.1 Extending High Performance Regimes to Long Pulse

6.1.1 US Research Goals

The development of techniques for producing high performance plasmas compatible with long pulse operation is an area of world leadership for the US. In addition to spearheading the development of so-called 'advanced tokamak' operating regimes for non-inductive discharge sustainment, the US has also pioneered many of the control schemes and much of the physics basis development required. Nevertheless, the preparation for future fusion facilities poses further challenges to reach the performance and sustainment targets necessary, create robust control solutions, and resolve long timescale compatibility with plasma facing components. These aspects must be addressed hand–in-hand with leading-edge model development and validation, so that behavior can be predicted and solutions developed with confidence for next step devices.

These issues need to be resolved with varying levels of demand and urgency for three priorities in the US program. For shorthand, we will refer to the design of the requisite integrated non-inductive operating regimes as the 'steady state':

1. For ITER, the US would expect to take a leadership role in its steady state program, both in order to ensure ITER meets its second mission to demonstrate steady state operation with $Q>5$ [8], and to position the US with leading expertise gained from ITER to take the regime forward in burning plasma conditions for an FNSF or a power plant. For ITER, the principal challenges lie in elucidating the design and control schemes for the regime, and in particular, the hardware requirements, with the possibility that additional heating and current drive systems will be needed [9]. These are important to understand in the near term, so that scope can be built into the ongoing ITER construction to ensure compatibility with this mission. Thus regime and control solutions must be developed from which ITER operational modes and plant requirements can be derived.

2. Steady state issues are more demanding for a Fusion Nuclear Science Facility (FNSF), where the plasma must be operated on a timescale of weeks rather than an hour. This poses new challenges, most significantly on plasma facing components to avoid erosion and maintain functionality, and in achieving reliable control. The more compact nature of the device leads to greater demands in terms of required plasma performance, stability, and particularly plasma exhaust fluxes. These challenges are at a more fundamental level than for ITER, with the facility viability and its entire design approach dependent on identifying satisfactory solutions. External current drive and profile control will be even more challenging at FNSF parameters. Thus more advanced steady state regime solutions must be developed and understood through excellence in diagnosis and modeling, with stronger and more robust control, and compatibility with plasma facing components.

3. The greatest challenge for the steady state lies with the fusion power plant. This needs to go beyond ITER and FNSF performance, to create an almost entirely self-sustaining solution with internally self-driven currents, at large enough scale for commercial energy production. As a consequence, power plant solutions will need to exceed the parameters of the earlier devices in many ways (eg in β, fluxes and fluences, or 3D geometry). To some extent ITER and FNSF can be regarded as staging posts to this end, resolving key questions as they proceed. But it is important to develop operating regimes that go beyond these devices, and understand the additional physics challenges and technical approaches required for a power plant. This is necessary in order to identify a credible path to fusion energy, determine the scale and type of the challenges that must be addressed before the power plant step, and start to develop the additional expertise and technical solutions required.
    - For the tokamak, the staging post approach is a good one – developing viable integrated solutions for FNSF will be a significant step in terms of plasma performance, materials and plant technologies. But it will also be important to explore higher β scenarios, with fully self-sustaining current, developing validated physics models to understand performance limits and the means to achieve control. These are areas the US can and should scope out in the near term.
    - For the stellarator, the issue is more fundamental. The stellarator represents an attractive possibility for a fusion power plant, but the concept is at an earlier stage of development – not contemplated for an ITER-like mission or FNSF device yet. Thus the near term challenge for stellarators is the validation of many elements of the basic concept itself, and the understanding of behavior. It is important that the US retain a strong stake in this line in order to be well positioned for a future stellarator power plant, which may (or may not) provide a more attractive approach, folding in lessons from ITER and FNSF. The focus of such work could run a large gamut of issues, but should particularly include involvement in key elements of the stellarator specific expertise required for future initiative – achieving performance goals through transport and configuration optimization, developing control, and the stellarator specific boundary interaction.

6.1.2 Research Needed

To meet these goals requires a demanding and multi-faceted research program, partnering pioneering experimental work with innovative modeling to develop and extrapolate the solutions needed. On the one hand the development of the plasma core solution requires extensive configuration flexibility – to explore the range of possible solutions and understand the transport and stability properties in detail, as well as the dynamics of the current profile evolution consistent with transport behavior. A robust and well-controlled solution must be developed to determine required hardware tools for future larger scale nuclear devices, ensuring disruption free operation and effective disruption mitigation as the fall back. Further this solution must be made compatible with the required mitigation of transient heat leads from edge localized modes (possibly provided by 3D fields – this too must be established), as well as an overall power handling solution that results in a plasma exhaust which poses a tractable challenge for plasma facing materials. These latter aspects are particularly important to address in preparing for longer pulse operation in superconducting devices, which may otherwise be rapidly eroded or seriously damaged by prolonged exposure to intolerable plasma exhaust loads.

The other side of this problem is the development of the requisite technology to operate such plasma regimes. The greatest challenge is the development of materials to handle the enormous fluence of plasma exhaust. While a solution is planned, and expected to work, for ITER, the scale of the problem is considerable greater for FNSF and a fusion power plant, requiring new solutions. Ultimately, materials need to be developed for the nuclear environment, with the high neutron fluence and displacements per atom of an FNSF or power plant. But a pre-requisite is ensuring they have sufficient ability to survive the necessary fluxes and fluences of heat and particles. These issues are primarily the topic of section 6.2, but there is a strong interaction, and likely a trade-off, between steady state regime performance and degree of mitigation of the plasma exhaust. Thus a facet of the long pulse development must include assessment of materials behavior under steady state plasma conditions, its impact back on regime performance, and the mutual optimization for ITER, FNSF and a power plant.

Further aspects on the technical side concern design of plasma facing components and control systems. The adaption of control techniques to superconducting devices must be made, and approaches extended to long timescale evolutions of the plasma state. Measurement systems and current drive systems must be made compatible with the hot plasma environment for long pulse operation. Furthermore additional plasma facing systems may be required to ensure robust control, such as 3D field coils, where again physics understanding through modeling is important to have confidence in next step solutions or to advise collaborative partners. As with the materials problem, solutions ultimately need to be tested and optimized in realistic long pulse plasma operation. It should be noted that the purpose of making such tests would be to assess the long pulse compatibility, not to embark on a lengthy campaign to work out how to make the component perform its basic function (which would hamper operation of the long pulse facility). Thus one should foresee a considerable development path to identify the appropriate approaches for each aspect of technology, requiring at least proof of techniques, before equipment is installed in a long pulse device where it would be expected to perform reliably.

The US already has some of the best capabilities to address many of these challenges, and indeed should be regarded as a world leader in the steady state field, including the underlying physics, and many of the associated technologies, such as control, heating and current drive of all considered techniques, and diagnosis. It has unique abilities to explore both the range of solutions required, and the underlying physics and control, through both its experimental facilities and theory and modeling capability. Nevertheless, further facilities outside the US offer the potential for distinctive additional capabilities, which could provide key tests of the approaches developed. Thus, as we discuss in detail below, the attainment of a rigorous physics basis and viable integrated solution for devices such as FNSF depends on pursuing a strong program both domestically and collaboratively – both elements are essential.

6.1.3 Analysis of Capabilities Leading to Collaborative Opportunities

The identification of collaborative opportunities, and the roots of a strong collaboration that enables US leadership and achieves US goals, comes from an analysis of the capabilities of the domestic and potential collaborative facilities. Necessarily, as discussed in chapter 7 and learned from the experience in High Energy Physics, each element of collaboration requires the US to have a strong associated base program, providing support and expertise that ensures a distinctive US contribution, and thereby US recognition and leadership, as well as ensuring the US stay at the forefront in that field. The facilities are summarized in chapter 5, but it is helpful to draw out the key physics aspects for development of the steady state.

The US facilities can be characterized as an outstanding basis to explore the underlying physics and optimization of plasma operating regime solutions. US facilities have unparalleled flexibility to explore the parameter space and design of such regimes. They have highly flexible configurations, different types of wall and divertor, and a variety of heating and current drive systems. Not least all of the main facilities are being equipped with off axis current drive tools to allow them to explore highly advanced steady state plasma configurations. But more generally they can explore a wide range of further relevant parameters, such as high β operation, low to high torque, electron heating, and fast ion content, decoupling these to understand trends. US facilities are also equipped with many of the key control tools required to ensure stability in such conditions, with for example localized current drive and a variety of 3D field techniques. They are therefore the key proving ground for the development of disruption-free operation. Further, with short-pulse operation and compact scale, and with two devices having more forgiving carbon walls, US facilities can explore the limits with much lower device risk than larger or superconducting devices, which have to be operated more cautiously. This makes them ideal to explore characterization and mitigation of disruption processes, essential requirements for future longer pulse and metal walled devices.

Coupled with this flexibility, the US facilities have world leading diagnostic capabilities, having implemented many leading edge innovative techniques and ultra-high resolution systems, as well as a range of perturbative tools to investigate plasma behavior. These play a critical role in resolving physics mechanisms, and so providing validated models for extrapolation of results. To further facilitate this, the US facilities have established, world leading research teams, integrated with theory and modeling efforts, which provide a powerful basis to understand the physics.

Considering potential collaborative facilities abroad, one can immediately draw out two key complementary capabilities for the steady state. These are size (or more precisely, normalized gyro-radius, ρ^*) and pulse length. We analyze these in turn below, identifying the key opportunities abroad, how this meets US goals, and outlining a two way collaboration with opportunities for US inward investment. It should be noted that we concentrate on the main distinctive opportunities, focusing particularly on new capabilities and US gaps (in line with the charge for this report). Nevertheless, we also flag further possibilities for collaboration (perhaps at lower-level) in other devices, which are set out in an appendix at the end of this report.

In considering the approach, we also note a considerable mutual benefit between the tokamak and the stellarator, with both able to test aspects of steady state technology. They also share similar physics phenomena, thereby offering valuable physics insights and codes for mutual interpretation. Thus potential stellarator contributions have been flagged alongside tokamak-

oriented work below. The 'physics outreach' to and from the tokamak is further addressed in a US stellarator specific section at the end.

Collaborative Opportunity #1: ρ^* and Size Scaling of Regimes

Starting with device scale, steps in size and toroidal field, are important because they enable tests of the extrapolation of US developed solutions towards next step devices. In particular, regimes developed in the US might be implemented on JET or JT-60SA to understand how a range of properties scale – from basic confinement, to detailed transport properties, pedestal and SOL widths, or stability physics.

- This would provide a strong basis for a continued US leadership position, with the US facilities providing an in-depth understanding of regime design, trade-offs and underlying physics, partnered with collaborative checks of size and ρ^* scaling via similarity experiments. This would be a collaboration of equal partners, with equal participation of each collaborating party in the other's experiments, and joint model development and testing. Arguably, however, the US would retain an edge through an increased physics flexibility and diagnosis capability in its devices. Such a collaboration might principally be based on collaborative experiments and analyses, rather than specific exchange of hardware systems or other technologies.
- *Specific opportunities abroad:* In the near term JET is the only facility to fulfill this role. Its single null divertor configuration and ITER-like wall make it ideal to help understand how physics regimes developed in the US might map to ITER and beyond. In 2016, JT-60SA will come on line with ~ 20 MW of plasma heating, and full heating capability of 37 MW for high performance regimes is expected to arrive in 2020 or so. Thus, this would be a priority for the next decade, where its potential for higher β_N operation and longer pulse length (~100s) would provide valuable further tests of how integrated solutions extrapolate to larger scale devices. On this basis JT-60SA might form the key basis or 'gateway' in the next decade, on which to extrapolate US solutions up in size and ρ^* to future devices such as DEMO and FNSF.

Collaborative Opportunity #2: Extending Control to Long Pulse.

The role of improved pulse length requires more in-depth consideration to draw out the distinctive collaborative opportunities, as pulse length touches on a range of issues, each with a different characteristic timescale. This is explored in Table 6.1.1. From this table it can be readily perceived that the US already has capabilities for identifying stationary steady state solutions and their control. Profiles can be developed and evolved up to a few current redistribution timescales to test whether they have converged to a stationary solution. This timescale is, in turn, much longer than that needed to determine stability or confinement properties, or indeed establish ELM mitigation. Given the improved physics flexibility and diagnostic capability of the US devices, this makes them the ideal facilities for exploration of the physics basis and design of the regime solution. (This aspect can also be regarded as way of ensuring US strength and leadership in the above collaborative opportunity #1).

		Ratio to target:	
Characteristic Timescale or Other Parameter	Target	**US facilities**	**Super/C Facilities**
Confinement & transport	τ_E ~ 0.1s	~100 ✓	~10000 ✓
Stability Control	~0.3s	~50 ✓	~5000 ✓
Steady State Profile Evolution	τ_R ~ 2-5s	~5 ✓	~100 ✓
Wall equilibrium and recycling	~5-100s	~0.1-1 ≈	10-100 ✓
PFC Thermal Equilibrium	~10^2s	~0.1 ✗	1-10 ✓
Material Migration (Total discharge time per year)	~10^5s	~0.1 ✗	~5 ✓
PFC Temperature (NB: exponential dependence gives high sensitivity to value)	>800K	~1.2 ✓	~0.8 ≈
Heat Flux Challenge, P/S:MW/m^2	~1	~1 ✓	~1 ✓

Table 6.1.1: Characteristic timescales and other parameters of US and superconducting devices, compared to typical values to be relevant for various physical processes.

A key element of the regime challenge lies with developing control schemes to maintain plasmas within stable operational boundaries and actively manage deleterious events such as tearing modes, ELMs and disruptions. This requires exploration of the operational limits to identify and optimize these limits, as well as the development and optimization of specific control tools such as 3D field coils or localized current drive systems. However, in long pulse devices, the effects of control failures on the plasma facing components, particularly if actively cooled, can lead to major damage, requiring them to adopt a high degree of operational caution*. Nevertheless, while it may be undesirable to explore too wide a range of such potentially adverse events and conditions in long pulse devices, ultimately solutions will need to be developed and tested for such devices, to enable them to safely reach their desired goals. This is therefore an area of natural partnership and strong mutual benefit, to obtain the validated and reliable control solutions to meet performance objectives on facilities abroad, while maintaining leadership and preparing for an FNSF domestically. Here US devices might develop a range of techniques for stability control, ELM amelioration or disruption mitigation, and explore limits; work that may be far less desirable to pursue in longer pulse, larger size or metal walled devices. Once developed these approaches would need to be optimized and qualified for long pulse in superconducting devices.

* *This is already observed in the super-conducting TORE-SUPRA device, which has had to endure major water leaks and shut-downs due to unacceptable load events, and as a result has to be highly cautious in varying operational modes. Similarly on JET, potentially disruptive regimes are extremely carefully assessed, and access to them is highly restricted; a primary goal of JET as it pushes to high performance, plasma current and toroidal field (its key strengths and program priority) is to avoid such events entirely.*

- From the US perspective, this will aim to test the compatibility of control approaches with long-pulse plasma conditions, to understand how to adapt them to superconducting devices (where rapid change in some parameters is precluded), and to resolve control algorithms for extended sequences of discharge evolution (where for instance an event response may need to be accompanied by a series of discharge evolutions to recover performance).

- Here collaboration might potentially involve greater exchange of assets between the parties than for opportunity #1. This should be pursued on a mutually beneficial and balanced basis. For example, the US might provide control systems and associated expertise (where it already the world leader and the provider for several devices) while the international partner might invest in particular hardware in US facilities, such as 3D field coils, current drive systems or key diagnostics – part of an integrated effort to resolve optimization of control and application to both the US and the collaborative facility. Again, this will be a collaboration of US strength and leadership, as it retains and builds on its leading expertise, and brings unique insights from its domestic contributions and its control platforms.

- *Leading opportunities abroad:* Here the clear best opportunity comes with the EAST device in China. This is pursuing a rapid development path towards high heating power and very long pulse lengths (400s, up to 1000s). This is an aggressive and well-resourced program, with the flexibility and apparent will to try out many ideas, including a heated metal wall planned in 2017. A strong US collaboration here (which might also span further opportunities below) would provide value in helping EAST prepare its technical approaches and enable key tests of US technologies for FNSF.

- In the longer term, Korea's KSTAR facility provides interesting potential. This facility aims to access very high β_N regimes for up to 300s. However, it has a slower path of development with high performance towards the end of this decade. As the US already has a collaboration with KSTAR, providing its control system, it is logical that this continue at modest level now, in anticipation of an increase in collaboration later. Similarly on this somewhat slower timescale, JT-60SA will provide further validation of how control techniques scale up through a larger scale device.

- In addition to tokamak studies, exploration of these control issues is a logical topic for stellarator collaboration, where the US already has a collaboration with LHD and plans a significant role on W7X. This can provide important insights into the challenges of control with superconducting coils and issues of the diagnosis-control cycle in long pulse conditions. It is therefore logical to build this element into US stellarator collaborations.

- *Inward US investment:* Given the material benefits the US is providing to international facilities in this area, further collaboration <u>should seek to maintain a two way street</u>, so that related work in the US is supported by collaborative efforts. This might include sending people to assist in control developments and/or associated hardware, such as 3D coil systems, localized current drive or computers and control hardware. The US might seek to test these on its facilities, with a view to resolving control approaches ahead of implementation on superconducting devices.

Collaborative Opportunity #3: Integration of Plasma Regime and Boundary Solution.

Progressing further down Table 6.1.1, one sees that the main opportunities arising from superconducting facilities come in the interaction of the regime with plasma facing materials. Here the characteristic timescales to observe behaviors are much longer than can be readily obtained in US facilities. Of greatest concern is the long term survivability of plasma facing components due to materials degradation, erosion and migration[†]. This is particularly a fluence issue – US facilities can access (or will be adapted to access) relevant PFC temperatures and heat fluxes to study parts of this interaction. The US can also develop candidate materials domestically, and assess them in test bed and tokamak facilities, though they may not have reached full thermal equilibrium. But many facets of the structural evolution of materials under plasma exposure develop on a longer timescale. The scale of this challenge depends on the nature of the plasma operating regime, and the ELM and exhaust mitigation solutions adopted. Thus integrated tests are required of materials evolutions in the presence of steady state plasma solutions on the timescales of superconducting facilities. *We address this integrated scenario-PFC issue briefly here, noting that it also forms a part of the wider strategy on the plasma wall solution in section 6.2.*

Here a key US strategic goal is to assess how materials behave in a long-pulse device operating regimes compatible with steady state, to qualify materials for FNSF and assess their potential for a fusion power plant. An aspect of this question lies in understanding the impact of the material back on the plasma itself. In addition, as highlighted in Table 6.1.1, this study also requires the PFC to come into thermal equilibrium, and to reach a 'wall equilibrium' of recycling of particles between wall and plasma.

- This is another area of potentially strong and equal collaboration. As discussed in section 6.2 and the FESAC materials report, the US would bring a very strong base program to develop materials and potential boundary solutions, which includes exploring the requisite divertor physics and short pulse tokamak compatibility. But it would need to qualify the materials for future devices such as an FNSF in long pulse conditions abroad. Further, because the opportunities for full scale tests internationally will be limited (collaborative facilities can only try out so many walls), a strong science-based program is essential. The program would start with smaller tests and explorations of underlying physics, as discussed in section 6.2, then to tests in our shorter pulse but higher heat flux facilities, prior to more complete studies with steady state plasmas, divertor solutions and wall tests. This might involve considerable exchange of hardware to test components on relevant devices (domestically and abroad) according to their physics and diagnostic capabilities. Ultimately it would need to extend to integrated long pulse steady state regime tests in superconducting devices abroad.

- *Leading opportunities abroad:* Over the next decade, the strongest opportunity for collaboration on this issue comes from EAST. They plan an early transition to a heated metal wall in 2017, although the feasible PFC temperature remains to be determined. This capability is a more distant and tentative prospect in either KSTAR or JT-60SA, which both

[†] *The fuller elaboration of collaborative opportunities in materials program is described in section 6.2. Here we focus on specific elements (possibly with some overlap with 6.2) that require integrated tests in long-pulse steady state regime.*

foresee this as a long term option (mid 2020's), after the development of high heating power regimes. Also EAST has a more FNSF-relevant double null capability (an option in JT-60SA around ~2026), and expects longer pulses than the other two devices. Thus, the US might start an early collaborative program with China, first based on exchange of samples and collaborative materials science, then qualifying approaches in US devices while exploring long-pulse evolutions of materials in EAST, iterating (as the self-consistent plasma operating scenario is developed) towards a fully integrated wall-plasma solution.

- In the longer run, it will also be important to qualify such a solution at higher loads and in regimes closer to those anticipated for FNSF or power plants. Thus a build up of collaborative links in the next decade (2020s) with JT-60SA will be an important part of a fuller US strategy here.

- Stellarator aspects: The plasma operating regime in a stellarator will be quite different from a tokamak, placing different demands on the boundary solution. Thus it is hard to see stellarators greatly informing the specific regime optimization for a tokamak FNSF or ITER, although it might provide insights into underlying mechanisms. Nevertheless, the US has a strong opportunity with its W7X collaboration, particular with its role in providing divertor components and trim coils, to take a leadership position in addressing these issues for a future stellarator power plant. This would further help establish US expertise and leadership in the whole boundary solution field, building its strength in the underlying physics.

- *Inward US investment:* As highlighted above, this can and should be a balanced collaboration. The collaborating partners should become involved in US domestic efforts, providing support with materials science development, modeling, and the provision and testing of relevant materials and components. This would be a strong two-way process.

Collaborative Opportunity #4: Long Pulse Capable Diagnostics.

Related to the issue of materials and a boundary solution, is the development of other plasma facing components such as diagnostics and current drive systems. Each brings specific challenges. For diagnostics, as with materials, there are issues of wear and exposure to the harsh plasma environment – particularly for mirrors, but also other components. It is also likely that some diagnostics will need to be actively cooled. But also for diagnostics there are particularly significant issues arising from the high levels of radiation encountered, which can have major impact on diagnostic sensors such as CCDs. Thus there is a need for significant testing to qualify diagnostic solutions in suitable facilities. As with opportunity #3, there is some overlap with section 6.2 – a broad program should be foreseen, for which one facet is the testing in relevant steady state regime solutions:

- This will aim to evaluate US-developed diagnostic techniques in steady state relevant environments not accessible in the US. Specifically this involves two types of test. Firstly, simple exposure to long pulse plasma environments will provide valuable insights into the degradation and build up that may occur on long timescales. Second, tests of the impact of radiation on diagnostic performance need to be made. Prior to the availability of D-T fusion plasmas, this can best be done in offline test facilities.

- Such a program can be strongly collaborative with either party developing techniques and testing them out in relevant devices. In particular the US has world leading expertise in diagnostic development, and so might expect to take the lead on this activity. Diagnostic techniques should be developed and qualified in the domestic program, being shown to work before being tested in more relevant conditions

- *Leading opportunities abroad:* Any of the superconducting long-pulse facilities abroad (LHD, W7X, EAST, KSTAR, JT-60SA) would be useful for the generalized testing, though of course some may provide more relevant loads, or achieve this earlier than others – but all would provide useful insights. For radiation issues, the US should seek out and encourage development of relevant sources outside the fusion program – for example a spallation neutron source may provide an opportunity in the US or in China.

- *Inward US investment:* Specific inward investment options are harder to identify for this opportunity. Here the US is likely the leader in the design and construction of relevant equipment, as well as the underlying expertise. The main US benefit is in qualifying diagnostic solutions through additional tests abroad, by gaining access to those facilities. Nevertheless, the collaborative partner could, and should, assist with provision of relevant components for testing of diagnostics in the US and abroad. The activity will directly support our research goals on ITER as well as an FNSF.

Collaborative Opportunity #5: Current Drive Systems in Long Pulse Conditions.

The other critical component for steady state regimes is the current drive system. This is essential to provide the control needed for steady state scenarios generally, and for maintaining a substantial fraction of the plasma current for an FNSF specifically. Some methods, such electron cyclotron resonance do not require plasma facing antennae, but may need plasma facing mirrors. Where antennae are needed (ion cyclotron and lower hybrid heating) these have to be placed in close proximity to the plasma, usually on the outboard midplane, and so need to be tested for performance and erosion on long timescales, as well as with active cooling implemented. As these devices are also tools needed and planned to enable long pulse operation on EAST, and KSTAR (and might be considered for JT-60SA), this naturally leads to a collaboration. Again this has some overlap with section 6.2, but requires a careful integration with the scenario development, as the scenarios are crucially reliant on the active use of such systems to maintain control.

- Here the US might use its expertise to partner in the design and operational assessment of current drive systems on new collaborative facilities. The US is already a leader in development and optimization of antennas to maximize coupled power while minimizing deleterious effects such as impurity generation, taking a science based approach using validated models of the launcher and edge plasma. This work leverages developments in the SciDAC program. Relevant materials and plasma parameters for ITER and FNSF are being addressed. This should be partnered with operational development of such systems domestically which would be key levers to secure some involvement in collaborative designs. Prototype designs for overseas facilities could be more easily and less expensively tested on our short pulse facilities, without the need for active cooling, and issues of efficiency and absorption assessed.

- *Leading Opportunities Abroad:* EAST and KSTAR provide the best opportunities to explore these issues for long pulse in the next decade, since they each plan to use the full spectrum of H&CD techniques, although the metal wall of EAST may be more relevant. Our contributions could range from expertise on design and diagnostics to provision of launchers and other system components. These provide the best scope to assess issues for the design of FNSF. In the longer term JT-60SA could expand this assessment to more demanding conditions, if it adopted the same RF H&CD systems envisaged for an FNSF; this might require a larger US investment. Such a mission would, though, be compatible with the US long term goal to prepare a basis for a fusion power plant.

- *Inward US investment:* This collaboration might be based primarily on an exchange of expertise, with joint design work on collaborative devices (followed by assessment of operational performance and further design improvement), based on experience in US devices. The US would then derive relevant current drive tools validated for an FNSF. Care must be taken to lock in and maintain US involvement (and intellectual property rights in the technology solution) as the knowledge base is transferred to the collaborative party.

Collaborative Opportunity #6 Stellarator Core Performance & Edge Compatibility.

The US main interest in the stellarator lies in its potential as a future option for a fusion power plant. The US was a pioneer in the early development and theory of this concept, and needs to retain a strategic interest to ensure it can build on ongoing developments in both stellarator and tokamak lines to pursue either as a power plant option when the time arises. There are also synergies with the tokamak line to be exploited in terms of ability to resolve technical issues (flagged in above opportunities) and contribute to the physics basis (flagged further below).

Without a large domestic stellarator, the US basis of stellarator expertise will in the long term be through theory and modeling, which therefore requires validation against experiments. This is being pursued now through LHD, but the focus will transfer considerably this decade towards Wendelstein-7X (W7X, which starts operation in 2015), where a major new US role has been negotiated as part of a new collaboration agreement. Thus the US stellarator priorities reflect a balance between pursuing longstanding broader interests and prioritizing a successful engagement on W7X (listing as highest priority first):

1. The US primary focus for stellarator research in coming years must relate to its hardware responsibilities on W7X. Here it has a crucial role in the power handling solution through provision of trim coils, diagnostics (IR cameras) and a high heat flux "scraper element". It is also developing a pellet injector with ITER-proto-type extruder. Simply put, the US must provide these and associated experts to support their operation to the W7X program. In return, the US gets high level participation and leadership on the facility. This collaboration should involve a significant modeling component to understand and optimize the edge behavior, its control, and heat fluxes.

Theabove aspects are discussed in more detail in section 6.2, but an element flagged here relates to understanding compatible core-edge solution. This leads to the second priority:

2. The US should also seek to broaden it stellarator role on the physics side into the key strategic area of device performance and optimization. It should aim to secure this role

through excellence in modeling and theory capability, by developing codes and pursuing validation on LHD (β~5% underway) that can be translated into leading expertise and insight on W7X. In this way the US levers its interaction with W7X to gain a wider expertise.

3. The other key area for the stellarator to explore in the near term is the understanding of limits and transients – exploring the nature of pressure and density limits, and testing for mode resonances that might lead to ELMs or tearing. This may particularly have cross-over application in tokamaks, where some code capabilities (eg 3D equilibria, stability in 3D geometry) will be valuable to both concepts, and underlying physical processes such as flows or resonances may be closely related. This area might therefore further build on the US's strong modeling arm and include application to collaborative stellarators (LHD, W7X) abroad, and tokamaks domestically.

Considering the activities associated with this collaboration, a significant part must be provision of the planned hardware for W7X, which is presently dominated by the US national laboratories. But the strong modeling and interpretation theme throughout these priorities raises many opportunities for US universities. These range from developing theoretical understanding and new code capabilities, to testing out key physics aspects in the US's smaller but novel 3D devices. <u>Ways must be opened up to ensure these programs can engage in the national collaboration on stellarators</u>.

This physics basis can and should be extended further by integration with US tokamaks. Here, variable 3D field coil geometries and good diagnostic capabilities raise further possibilities for testing and developing the physics base, to provide validated models for W7X and beyond. Indeed collaboration with tokamaks should be actively pursued, as the application of '3D benefits' inherent in the stellarator concepts offers considerable potential to further improve tokamak performance – a recent rich vein of progress that could go further. For example 3D stellarator stability codes could be used to help interpret stability of 3D modified tokamak plasmas, such as those arising with magnetic field perturbation ELM control.

To summarize, the key approaches for US stellarator-related interests should include:

- *Ensuring successful construction of the US's components for W7X.*
- *Preparing a strong theory and modeling basis, with leading edge code capabilities.*
- *Exploiting LHD to validate this basis, and to prepare and lever the W7X role.*
- *Expanding US national stellarator collaborations to US university participation.*
- *Inclusion of tokamak capabilities to further help develop models, and to lever 3D benefits to tokamak operation.*

Achieving these results principally revolves around suitably structuring the US approach.

6.1.4 Programmatic Approach to the Steady State Collaboration:

To conclude, the consideration of US goals to prepare long-pulse regime solutions for ITER, FNSF and a fusion power plant, together with capabilities of US and international devices, has identified six main opportunities for collaboration. Each of these would add capability not present in the US to close a key gap on US strategic goals for fusion energy:

- ρ^* and size scaling of regimes
- Extending control to long pulse
- Integration of plasma regime and boundary solution (see section 6.2)
- Long pulse capable diagnostics
- Current drive systems in long pulse conditions
- High performance steady-state 3-D confinement regimes

A careful analysis of the research needs and capabilities of each party reveals potential for a strongly collaborative program. In this program, each party would bring unique strengths. In particular the US has unparalleled device flexibility and diagnosis capability to resolve the physics basis and develop candidate solutions – aspects the collaborative partners are less well equipped for, as actively cooled superconducting facilities inherently more cautious in their experimentation, and the facilities have some way to go to develop mature control and diagnosis capability. However, the facilities abroad can be used to test key aspects of the dynamic such as size scaling, PFC interaction and long pulse sustainability, enabling qualification of US developed solutions.

This approach would work as a partnership, as set out in Fig. 6.1 below. The US would work on elements of the physics basis and technical solutions in its universities, laboratories and national facilities domestically (possibly with inward collaborative involvement), developing and testing solutions in the national facilities. This would also form the basis of approaches to be explored in

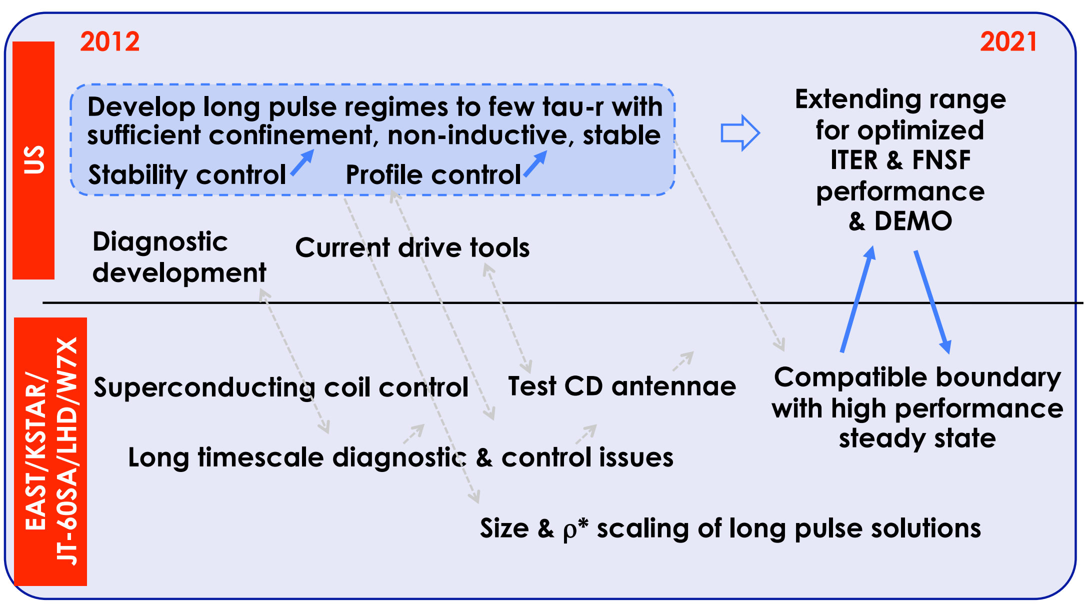

Fig. 6.1: Collaborative model foresees exchange of information and possibly hardware back and forth between US and collaborative parties. This would therefore have a strong basis in the US while ensuring additional key tests are attained abroad.

collaborative facilities. The results of the collaborated studies might be fed back into the US program and an iterative process pursued. Ultimately one might demonstrate how to achieve the key long pulse or size scaling tests of compatible boundary-steady state solutions in the collaborative facility, while the US goes on to extend the optimization, performance and physics basis for the techniques involved to prepare the basis for its involvement in ITER, FNSF and beyond.

<u>This program needs to draw on the broad expertise of the US fusion program</u>, harnessing theory and modeling expertise in the university community, and exploiting the flexibility in the national facilities, together with the innovation from their US collaborating institutions – the national laboratories and universities involved. In this way the US will retain its world-leadership positions and secure key intellectual property in the path towards fusion energy. It will ensure recognition and influence with collaborative partners, by bringing substantive and needed capability to the table. And it will secure its key objective from collaboration, to obtain validated solutions for US long-pulse goals in ITER, FNSF and beyond.

The approach and content of this collaboration opportunity is appended in single page format overleaf, *noting that plasma materials interaction has now been held back to a different collaboration area in section 6.2, for a logical division of material that avoids duplication.*

Summary of Collaborative Area 1: Extending High Performance Regimes to Long Pulse

The development of stationary regimes for fusion energy is an area of US world leadership, with the US having many unique capabilities to develop the physics basis, including profile flexibility, high β access, excellent diagnostics, current drive techniques, stability and ELM control tools, which it is able to apply for multiple current diffusion timescales to develop and optimize candidate solutions. But to extend solutions to ITER or an FNSF, some aspects would benefit from tests with longer pulse lengths or at larger device scale than available in the US. These particularly concern issues of plasma facing component exposure and the extension of control. However, it should be noted that in seeking such capabilities abroad, there are trade-offs in performance and device flexibility, particularly with longer pulse and larger scale facilities needing to be operated more cautiously. Thus a closely coupled collaborative program is necessary, with US facilities providing the performance, diagnostics and range to determine required approaches, while tests of long pulse compatibility and size scaling are made abroad.

Required Domestic Program: In domestic facilities the US should explore the range of plasma configurations and techniques producing stable current and pressure profiles capable of self-sustainment with optimized confinement and control over instabilities including ELMs. This will provide a strong basis for US leadership in the collaboration, and determine the approaches and hardware needed. The physics understanding gained will also underpin the basis for extrapolation to ITER, FNSF and beyond.

Collaborative Opportunities Abroad: Principal elements are the size scaling and long pulse tests of the key techniques needed in regimes compatible with steady state. The former is best addressed by joint experiments and shared analysis with larger tokamaks (JET, and eventually JT-60SA). For long pulse issues, the earliest opportunities at reasonable performance levels come on EAST in 2014, with significant heating power and cooled Tungsten plasma facing components. In the longer term, KSTAR will provide access to similar regimes for up to 300s, though initially Carbon PFCs, and possibly a Tungsten divertor later. These devices could be used to adapt control to superconducting coil sets and develop longer timescale event response and performance recovery techniques using US developed control systems, as well as addressing long pulse compatibility of required current drive systems. Corresponding inward investments could help optimize control approaches (such as 3D fields or current drive systems) in US domestic facilities. In addition, diagnostic techniques will need to be proven in long pulse conditions, to assess issues of degradation due to the plasma environment and radiation. Thus tests of US-developed diagnostic approaches in long pulse tokamaks (EAST, KSTAR) and exploitation of any available neutron-irradiation facilities would form a key part of a wider program here. Finally, W7-X offers potential to boost US theoretical and modeling capabilities on the underlying transport and transient physics with 3D magnetic field geometry, as well as gain insight into these issues for the stellarator path. Here preparatory experiments on LHD will help lever the US role on W7-X.

Benefits to US: A strong collaboration on this Scientific Challenge would provide the basis for long pulse experiments in ITER, offer the potential for an integrated physics and technology solution for an FNSF, and exploit stellarator involvement for a broader understanding, while securing US leadership, intellectual property and valuable knowledge. A balanced collaboration should also provide for US inward investment in developing key tools and modeling interpretation.

6.2 Development and Integration of Plasma Wall Solutions for Fusion

6.2.1 Background:

Plasma-material interactions (PMI) play a key role in determining both core plasma performance and plasma facing component (PFC) lifetime and thus are critically important in determining the feasibility of magnetic fusion as an energy source. Plasma facing components include the divertor target, the first wall (integrated with the blanket), heating and current drive injection structures, and a wide range of diagnostic components that face the plasma. Key regions of these components include the ion stopping region (comprising a distance of a few tens of Angstroms into the material, a plasma particle diffusion region that is a few microns deep, and finally a deeper region reaching to the underlying cooling channels.

As discussed in Chapter 4, the difficulty of handling the large amounts of energy input to, and eventually produced by, a magnetic fusion device increases dramatically as the device size, which directly impacts the power per unit surface area P/S, and pulse length increase. We do not yet have proven solutions to deal with this challenge. Moreover, strong interactions between the edge plasma, which provides the key boundary conditions for the burning core, and the core plasma dynamics mean that any proposed solutions must be compatible with the steady operational scenario envisioned for a reactor. These compatibility issues will vary with the magnetic configuration, and integrated tests are thus required.

For the tokamak, a key near-term step, which is the current focus of much of the US and world PMI research effort, is ITER. This will have relatively high power loading and pulse length, posing considerable challenges particularly in handling transient events. However, ITER is still some distance from the power density and pulse length of a fusion reactor, and the selected divertor and PFC material solutions do not extrapolate to DEMO.

A next-step device (referred to here as an Fusion Nuclear Science Facility (FNSF)) in which 14 MeV fusion neutrons can be produced with sufficient flux and fluence to study critical materials science and fusion nuclear science issues has been identified as a critical element of fusion energy science research [see e.g. MFE ReNeW Report], and PMI issues will play an important role in this next step. Such a device will be the first in which

1. the plasma pulse will need to extend to durations of days to weeks, with suitably rare disruption events;
2. plasma particle and thermal loading and nuclear loading are integrated together;
3. the PFC lifetime and impact of PMI effects on plasma duration issues will be seen (including large scale material migration which can lead to dust and debris formation);
4. continuous plasma exhaust and rapid turn-around fueling will be needed, and
5. long timescale tritium behavior in the integrated plasma chamber/PFC/Blanket system will be observed.

Mission success in an FNSF requires that all of these aspects be integrated in robust operating scenarios. Developing the knowledge base to design and realize a next-step fusion nuclear science capability provides a realistic and concrete target to be met on the 10-20 year time frame envisioned in this report. Providing this knowledge base will greatly advance the fusion program towards the even more challenging requirements of a DEMO. Technical requirements are described in the following section.

Since it is not assured that non-inductive tokamaks will ultimately emerge as the most feasible and attractive fusion reactor, integrated PMI solutions for alternate configurations, in particular the stellarator which should most easily extend to steady state, also need to be developed. There has been much less effort to date on developing divertor solutions for these devices which are challenging due to the 3-D geometry and sensitivity to the pitch of, and perturbations to, the edge magnetic field lines. The 2008 FESAC Report "Advancing the Science of Alternate Toroidal Magnetic Fusion Concepts" [10] and the 2009 MFE ReNeW report [2] each identified development of 3-D divertor solutions as priority areas for near term research. As discussed in section 5 this goal is being pursued on the two largest stellarators, LHD in Japan and particularly W7-X in Germany, with substantial US involvement. While divertor design and integrated scenarios differ between tokamaks and stellarators, much of the basic information on plasma material interactions should be transferable across configurations. Thus many of the issues and research plan elements discussed below can be viewed as generic issues, relevant to both tokamak and stellarator approaches for an FNSF.

6.2.2 PMI and PFC Issues for an FNSF

The expected environment for the PFCs in an FNSF is quite severe. It is expected that the first walls will be integrated with the blankets while the divertor PFCs will be separate components. These structures will be He gas cooled and operate at temperatures of 500-800 deg C. This elevated PFC temperature, which is considerably higher than in any current fusion experiment, is required to provide efficient thermal conversion to electricity in a fusion reactor. Since many material and surface reaction rates depend exponentially on temperature, these operating temperatures are likely to dramatically change important PMI effects. Some issues, such as tritium retention, are likely to become easier, while many other effects cannot be predicted or become more severe at elevated temperature. Other key loading conditions expected to be imposed on these components are summarized in 6.2.1 below.

Ion flux ~10^{23} ions/m^2-sec at the divertor strike point ~10^{19}-10^{20} ions/m2-sec at the first wall,
Heat flux of ~10 MW/m^2 at divertor and approximately ~MW/m^2 at the first wall,
Neutron flux & fluence few MW/m^2 for fluences of several MW-yr/m^2
High temperature (~500-800 deg °C) walls with He gas cooling;
First Wall Integrated w/ Blankets

Table 6.2.1: Key plasma particle, thermal and neutron loading conditions for PFCs in an FNSF.

There are a variety of time-scales for PMI which are important to keep in mind, as they impact the necessary timescales for future experiments. Table 6.2.2 below shows order-of-magnitude estimates of these time scales; clearly exploring the third through sixth timescales, which are necessary and perhaps even prerequisites for FNSF mission success would require experiments that run at fusion conditions for a minimum for many hours or perhaps stretching to a day of continuous operation. The FNSF radiation damage mission element would then require extending these timescales to weeks. While there are still many issues of SOL and PWI physics and of compatibility with non-inductive high performance regimes which can be resolved on short pulse confinement devices with the addition of better diagnostics and suitable program focus, ultimately these long duration high performance discharges are needed.

Wall Thermal Equilibration	few seconds
Core Plasma Response to Boundary Changes	1-10 sec
Surface morphology evolution	100's -10^3 sec
Near-surface (few microns) saturation with incident ions	100s – 1000s sec
D/T Permeation into bulk	10^3-10^4 sec
Macroscopic migration leading to significant redeposition (e.g. flaking, spalling, impacts on density control, dust formation)	> 10^3 - 10^4 sec
Radiation damage microstructural effects	>10^5-10^6 sec
PMI/PFC Component Lifetime (Minimum)	few 10^7 sec

Table 6.2.2: Estimated time-scales for various PMI-relevant processes in an FNSF

Combining these expected PFC operating conditions on the relevant timescales with the required plasma conditions to achieve the mission of an FNSF, a number of critical PMI issues emerge. These include:

- Successfully integrate DEMO-relevant walls (i.e. >500 °C, He cooled) Wall/PFCs with a high performance core plasma
- Maintain robust core plasma performance without ELMs, which requires either ELM-free H-mode operation, a robust active ELM Control system, or an edge plasma that is not in H-mode;
- Demonstrate disruption-free operations for suitably long periods (>10^6sec) combined with a workable disruption mitigation scheme to prevent unacceptable first wall damage from runaway electrons should a disruption occur;
- Proving acceptable rates of material erosion, migration & redeposition with co-deposition of D/T/He gaseous species;
- Providing adequate in-vessel tritium inventory control taking into account co-deposition and permeation processes such that safe operations can be maintained and that fuel self-sufficiency is not impacted;
- Ensuring that the PFCs can accommodate the anticipated steady-state and possible transient thermo-mechanical loadings across the component lifetime while providing acceptable response to PMI effects;
- Resolving the physics and engineering challenges of launching electromagnetic waves required for heating and current drive.

Demonstrating all of these features in present experimental facilities is not possible. Therefore design of PFCs for a robust FNSF will require a multi-pronged research program involving work on existing single-effect and multi-effect off-line facilities combined with work on existing toroidal confinement devices (in some cases with suitable upgrades), in other offline non-nuclear and nuclear testing facilities and in emerging long-pulse confinement devices located in Asia or Europe in order to develop the confidence in the performance of the PFC system design in the severe PMI environment that will occur within an FNSF. The research program to resolve steady state operation without disruptions or large ELMs was discussed in Section 6.1. Here the focus is on the solutions that will eventually need to be integrated with the plasma walls having relevant materials, conditions and temperature.

6.2.3 The Grand Challenge of PMI in the FNSF Era

Taking these topics into account, it seems clear that a FNS Research Program is needed in order to provide the scientific basis for PFCs that have reasonable lifetime, with validated performance predictions, in the severe plasma and nuclear PMI environment of an FNSF. These components must provide acceptable in-service component lifetimes in a manner that provides for safe and economic facility operations, the necessary core plasma performance, tritium inventory control, fuel self-sufficiency and device availability consistent with facility mission objectives.

A number of key scientific topics germane to the scope and focus of this subpanel report underpin this high level challenge and include:

Understand the steady-state boundary and core plasma and PFC response to the high operational materials temperatures that will occur in a FNSF device.
These effects impact key aspects of mission success in any FNSF device. For example, can tritium co-deposition and retention be held at levels that permit fuel self-sufficiency in the presence of significant co-deposition and trapping? Second, it is important to note that the entire tokamak confinement and performance experience has been obtained with carefully conditioned, pre-treated walls. These techniques saturate and begin to fail after 100s of seconds of plasma operations. Thus another critical question emerges: Can adequate improved confinement regimes such as H-mode be maintained when the walls become saturated and neutral particle recycling into the plasma comes to equilibrium? Can the required divertor particle and power handling be confidently achieved consistent with steady-state plasma operations? Understanding these integration issues is a prerequisite for FNSF mission success, and requires assessing the highly temperature-sensitive plasma-material physics issues that drive the coupling between the wall and plasma e.g., divertor power deposition physics, self-fuelling , material migration and redeposition, T fuel cycle, surface evolution and neutral recycling in fusion-relevant conditions. The altered recycling is likely to change the properties of edge transport barriers, and thus the core profiles which both in turn will affect heating and current drive via RF waves, and impurity seeding techniques typically used to control divertor heat fluxes. No confinement device currently operates with the PFC temperatures required for DEMO. As discussed above, the timescale for these issues lies in the range a few to 10's of seconds up to perhaps ~1000 seconds, suggesting that some of these topics could be addressed in suitable shorter-pulse facilities; others will eventually require investigation in the new superconducting long pulse devices. Regardless of these considerations, achieving the depth of understanding needed to credibly resolve these issues in the design of an FNSF requires that we not only devote existing and new confinement

facilities to these studies, but that we also develop new instruments capable of performing *in-situ* and in *real-time* measurements of both edge and divertor plasma physics and PMI issues within the plasma facing components in a fusion environment**.** These need to then be used with theory to develop validated models of the relevant processes which can then be used to predict future FNSF device performance.

Understand, predict and manage the long-term material migration that will occur in a long-pulse FNSF/DEMO like device due to plasma-material interaction.
The high particle and thermal loading imposed on PFCs causes these components to suffer net erosion of their surfaces. These eroded atoms and molecules then enter the SOL plasma and are entrained within the flows occurring in that plasma region which then carry them elsewhere in the device where they are deposited in more remotely located surfaces. As a result these regions accumulate the material that was eroded from the PFCs. Hydrogenic and helium species can also be trapped in these redeposited surfaces, leading to the formation of co-deposited layers. These effects begin to emerge on timescales of 100s to many 1000s of seconds of plasma operation, and thus require suitable facilities for detailed study. Indeed, experiments have shown that these processes seem to occur throughout the duration of the plasma discharge, and thus lead to cumulative impacts on component lifetime, material migration, T inventory management and control, fuel self-sufficiency, and plasma fueling. In addition, these redeposited materials have thermo-mechanical properties that are considerably different than the original uneroded materials. As a result, the response of the newly formed surfaces to imposed plasma loads will deviate significantly from that of the origin material. This can lead to formation of particulates and dust within the vessel that contain tritium and could potentially form safety hazards. Current understanding is insufficient to reliably predict the magnitude, rate, and impact of these processes and, if needed, develop mitigation approaches. Thus research efforts are required to provide for credible predictions of both the material migration problem as well as its impact on FNSF performance, safe operation, and mission success. These issues are also of concern for ITER, which must limit its inventory of tritium.

Optimize the configurations for magnetic divertors to spread the heat load over a sufficient area for steady state removal, while maintaining high performance steady state
In modern confinement devices, a magnetic 'divertor' is used to channel most of the exhaust power and particles to a region relatively isolated from the confined plasma, where it can be efficiently extracted. This has been effective at reducing impurities and has resulted in significantly improved core plasma confinement. However, as average heat loads increase, practical heat flux limits on PFCs are being reached and may even be exceeded, leading to risk of PFC failure. These loads depend on the scaling of SOL profiles and parallel heat fluxes, which need to be better understood. Solving the PMI challenge beyond ITER will likely require not only developing better materials and designs for higher local flux, but also will likely need new divertor configurations and control tools which spread heat over a wider area. A number of ideas have been proposed. For the tokamak, these include for example "snowflake" and "Super-X" divertors. Improved alignment and uniformity of simpler divertor geometries can also be effective. For the stellarator, ergodic island divertor concepts are being considered. There are necessarily tradeoffs between peak flux and the device volume used for power handling, likely to be larger than in current devices.

Resolve the physics and engineering challenges of launching waves required for heating and current drive.
Any magnetic fusion device will require externally driven heating and current drive (H&CD) to reach burning conditions, to control plasma profiles and, in the case of tokamaks, to sustain a significant fraction of the plasma current in steady-state operations. We need to understand and predict the interactions of waves with the SOL plasma, including sheath and RF absorption effects which can locally modify edge profiles under conditions that are self-consistent with solutions that yield acceptable PFC thermal and particle loading. These include ion cyclotron, electron cyclotron and lower hybrid range of frequencies, each of which has its own issues. We also need to predict the resulting plasma load on the launchers and the efficiency of the waves at heating and driving current. Launcher materials and designs are needed which both meet the H&CD objectives and have acceptable erosion, performance and lifetime.

6.2.4 A Science-based Program to Resolve These Issues

These issues motivate a coherent multi-faceted research program to support ITER, provide the basis for a credible FNSF PFC design and facilitate the stellarator development path. Such a program will naturally include both an increased and better-focused US research effort with existing and upgraded off-line and confinement experiments. However, it is also clear that some critical issues that cannot be fully addressed in domestic facilities could benefit immensely from carefully conceived collaborations on foreign facilities. In the following discussion we outline a high-level research plan that could address these PMI and PFC topics, and use this discussion to identify compelling collaboration opportunities that exist in overseas superconducting confinement experiments.

Understand the steady-state boundary and core plasma and PFC response to the high operational materials temperatures that will occur in a FNSF device. Success in this topic is perhaps the first PFC/PMI milestone on the pathway to a FNSF capability. A program to address the key physics would first provide tests in non-tokamak facilities of hydrogenic retention, diffusion and other relevant properties of candidate materials, at a range of temperatures up to those envisioned for FNSF/DEMO. (i.e. up to 800 °C) with realistic particle and thermal fluxes and bulk material thermal gradients. Experiments should examine effects of radiation damage on these properties and, if needed, develop ion-beam/plasma exposure and/or sequential neutron-damage/plasma exposure capabilities to include radiation damage effects as needed.

The US has number of existing experimental facilities that could make significant contributions to these issues. These include single effect facilities including e-beams for intense thermal loading studies of high heat flux materials response, ion beam for studies of sputtering as a function of ion composition, energy & incidence angle dependence, fission reactors for low energy neutron irradiation studies and also incorporating novel approaches to study damage from fusion-like neutron energies. In addition, a number of off-line plasma simulator devices can study multiple effects. These include studies of erosion/redeposition/co-deposition, surface morphology evolution and PMI of highly nonequilibrium surfaces at high ion fluxes; use of Irradiated Samples to study PMI and retention in radiation-damaged materials; and ion-beam/plasma irradiation to provide in-situ real-time near-surface diagnosis of materials during PMI studies. Several of these test facilities, such as PISCES, DIONYSIS and TPE, are unique in the world. The US facilities could, with modest upgrades in some cases, accommodate these research elements.

Experiments in existing confinement devices to allow controllable tungsten-based PFC temperatures would provide important understanding of PMI issues under DEMO-relevant conditions. US is a world leader in PMI diagnostics and physics. Alcator C-Mod has DEMO-level divertor heat fluxes and solid metal walls. A planned upgrade to the W divertor in 2013 will provide the first experience worldwide at high (>600 °C) temperatures. DIII-D and NSTX are testing carbon and lithium respectively. Real-time in-situ surface diagnostics that monitor changes in surface condition, PFC system performance, and core plasma performance with wall temperature would allow development of a detailed understanding of fusion device PMI issues, much in the way that such in-situ real-time diagnosis provides for detailed understanding of core plasma physics issues. Novel accelerator-based diagnostics for this purpose are being developed in the US. These unique capabilities will then be used to study how core plasma performance, RF coupling, fueling, recycling and retention are affected by wall temperature and other wall conditions, maintaining world leadership in the PMI science area.

In order for the tokamak to be a viable pathway to DEMO, it is essential that adequate disruption detection, avoidance and mitigation, as well as adequate ELM control or avoidance capability be convincingly demonstrated. Repeated discharges might allow effects that take place on timescales from 10's of seconds up to a few 100s of seconds to be studied in this approach, and statistics about avoidance of transients can be accumulated across 100's or 1000's of discharges in an experimental campaign. Using these approaches, this work can be performed on US confinement experiments provided the necessary facility and diagnostic investments are made.

As seen earlier in this section, there are important PMI mechanisms such as material migration that exceed these types of timescales and thus cannot be studied directly in current confinement experiments. Furthermore, final demonstration of adequate transient control and avoidance will ultimately require much longer discharges in which these long duration PMI effects emerge. The superconducting devices will be capable of performing single discharges with pulse lengths of 100s to 1000 seconds; with repetitive duplicate discharges, these timescales could potentially be extended to timescales of order an hour or more with high performance core plasmas and PFC loading conditions that are close to those expected in next step experiments. Such experiments, coupled with core and edge plasma modeling and an understanding of PFC evolution under such conditions (obtained from off-line laboratory experiments) should provide much deeper understanding of the mechanisms that cause the strong link between core plasma performance and PFC conditions, and should provide a more robust test and demonstration of our ability to avoid disruptions. Such work can only occur in the new superconducting devices in Asia and Europe.

Successful integration of high performance core plasmas with PFCs under prototypical FNSF conditions will then open the door to the next challenge, namely to **understand, predict and manage the long-term material migration and associated co-deposition, retention and permeation that will occur in ITER and in a long-pulse FNSF/DEMO like device due to**

plasma-material interaction. The timescales for these processes lie in the range of 1000s to > 10^4 -10^5 seconds, which exceeds even the anticipated pulse lengths of any existing or under-construction superconducting device. Thus achieving the understanding needed to achieve predictive capability for PFC design efforts will require a multi-level approach.

First, off-line experiments at prototypical conditions would permit development of predictive models of the novel properties of plasma-modified materials, and of the retention, removal and permeation of co-deposited D/T isotopes under prototypical plasma particle and thermal loading conditions. Adding sub-component type target designs would allow the study of the self-consistent evolution of near-surface composition, morphology, and D/T/He inventory, combined with D/T/He transport into the bulk material with relevant bulk thermal gradients. Radiation damage effects on near-surface responses could be studied with suitably combined Ion Beam-Plasma Exposure experiments which mimic primary knock-on atom (PKA) and He Damage effects on retention, permeation and thermo-mechanical performance, and search for any possible synergistic effects requiring simultaneous plasma/rad-damage exposures. Sequential studies of neutron-damaged material samples in off-line facilities could then complement these studies. Again, the US has a number of existing off-line facilities that, with modest upgrades, could accommodate these research elements.

Second, work in short pulse confinement experiments with improved edge diagnostics, combined with theory and modeling, would lead to a clearer understanding of the large-scale plasma flows in the SOL and divertor, of parallel heat transport on open field lines, and the resulting particle and thermal loads on PFCs. In-situ real-time PMI diagnostics, which will soon be available in the US, would provide detailed surface interrogation during plasma experiments and could permit, over multiple short-pulse discharges, evaluation of erosion, deposition and surface property changes and compare to model predictions. Linking this knowledge with the results from the off-line experiments would permit tests of material migration models in existing short-pulse US confinement devices, ideally upgraded to use hot PFCs, and would provide for predictions of migration in hot-wall long-pulse experiments.

Third, these predictive models would be applied to and validated within hot-wall long-pulse confined fusion plasmas. Such an experiment could only be performed on one or more of the new superconducting confinement devices, and would need to implement many of the key diagnostics developed on the short pulse experiments described above. Again, avoidance of transients such as disruptions and ELMs will also be important to develop and demonstrate in these facilities where material migration and other long-pulse PMI effects emerge. Multiple long-pulse discharges in such a device could then provide the credible design basis for PFCs in next step devices such as an FNSF. This forms a second key opportunity for a new compelling international collaboration. Clearly this task requires experiments on the long pulse superconducting devices, and would be greatly enhanced and accelerated with US expertise.

In parallel to these two foci, it is also necessary to **optimize the divertor configuration to spread the heat load over a sufficient area for steady state removal, while maintaining high performance steady state plasmas**. This work is perhaps best suited for study in short pulse tokamaks with normal conductors in order to clarify the physics that determines the divertor target heat flux footprint so as to predict future heat fluxes on ITER, FSNF and DEMO, and perhaps identify new divertor configurations that could provide significant reductions in PFC heat fluxes while maintaining plasma edge conditions that are consistent with RF current drive antenna-plasma coupling requirements. It seems premature to plan on such experiments in a long-pulse superconducting device until an optimum geometry is determined and demonstrated. Because modifying divertor configurations is a major upgrade, it will be impractical to test many ideas on a single device. Both US and international tokamaks will contribute. Tests of the "snowflake" configuration are planned on one US experiment, and the "Super-X" configuration, first proposed by US scientists, will be tested on MAST in the UK. Other tokamak divertor modifications are being considered elsewhere. Comparisons of results, via both incoming and outgoing collaborations, will be of benefit to maximize the benefit of these experiments. It is expected that this activity would be at a modest level and would not involve contributions of hardware.

Different means of handling the divertor heat load in 3-D stellarator configurations are also being assessed. LHD uses a helical divertor with periodic baffles and cooled graphite cooling panels), while W7-X will use the resonant magnetic island divertor concept that was tested on W7-AS. This approach relies on control of the edge rotational transform and appropriate design of divertor strike zones.

We must also **resolve the physics and engineering challenges of launching waves required for heating and current drive.** The physics challenge of launching waves, particularly in the lower frequency ranges of ICRH, Fast Wave (including high harmonic) and Lower Hybrid heating is intimately coupled to that of plasma surface interactions and the scrape-off-layer plasma. Waves can significantly modify the SOL profiles, and perhaps also fluctuations and flows, which in turn affect the coupling. For efficient heating and current drive, it is essential that a high fraction of power is coupled to the core plasma rather than being reflected or lost in the edge. EC and LH waves have also been observed to modify edge transport barriers in ways which are not yet understood. Much better diagnostics of edge profiles, their fluctuations and of waves themselves, at multiple locations both near and far from launchers, are needed to resolve these issues. Advances in models, which need to incorporate in a more unified way the launchers, edge and core plasmas, are needed. Improved understanding from predictive capability must then be used to improve launcher designs to maximize effectiveness while minimizing deleterious effects such as impurity generation, which can result from waves not absorbed in the core plasma. This is a particular concern for long pulse devices with metal walls, including ITER, since between shot conditioning or low Z coating methods are no longer practical. Much of this work can be conducted on short pulse confinement devices, and the US has a robust science based, program on this topic which takes advantage of ICRF, Lower Hybrid Current Drive, High Harmonic Fast Wave and ECRH systems on all three major facilities and smaller confinement experiments, as well as a growing simulation effort, including the SciDAC program.

The engineering challenges of H&CD are greatly increased at higher pulse length. In addition to the above physics issues, launchers must handle heat loads from both the waves and the plasma in steady state; localized heating can lead to outgassing, arcing and impurity injections which can in turn cause disruptions. Launcher designs must often be modified to allow active cooling; an example is the Passive Active Multi-junction technology pioneered at Tore Supra.

Long pulse superconducting devices will play a key role in this development. For example, on Tore Supra limitations in ICRF and LHCD were often encountered after 10s of seconds. Due to the large thermal loads on either ITER or an FNSF it will be necessary to locate launchers further from the confined plasma and to couple across longer SOL distances. Techniques to locally modify the SOL so as to maintain good coupling need to be developed and tested. Asian superconducting devices will all need robust, long pulse ICRF and LHCD systems to fulfill their primary steady state missions, and have expressed interest in collaboration with the US in the plasma-wave physics and the design of these launchers. Superconducting stellarators also require long pulse RF heating to obtain high pressures, and may use some current drive to modify the rotational transform for control purposes.

6.2.5 Opportunities for collaboration:

Taking these considerations and issues into account, several PMI/PFC motivated collaboration opportunities seem to be both compelling and timely:

Integration of High Performance DT Plasma with ITER Relevant PMI
Although it is not a superconducting facility, the JET tokamak does present unique capability that should not be overlooked. The ITER Like Wall (ILW) experiment on JET has been fielded by the EU and has begun operations in 2011. The ILW experiment uses a Be first wall combined with a W-based divertor in order to mimic the ITER PFC design and provide operational experience with these materials. The primary focus of the experiment is to provide an experimental basis for the tritium inventory estimates for ITER, which are required in order for ITER licensing to occur. The ILW experiment is also providing operational experience with the ITER wall material combination. This research program is currently active and the top priority of the EFDA-JET program through 2012. Several US groups are already involved in these experiments. It should be noted that the material combination, operational temperatures, and cooling technologies used in the ILW experiment are not extendable to an FNSF.

Integration of High-Power Density Long Pulse with Fusion Relevant PMI
EAST: Given the research issues identified in this section, the device capabilities and timeline, it appears to this panel that the EAST device at the ASIPP in Hefei, China, provides the best near-term opportunity to pursue the PMI and PFC issues identified here. In particular the anticipated heating power, current drive and pulse length provide highly relevant plasma conditions that are prototypical for nearly any conceivable next-step device operating in parallel with ITER. Furthermore, to our knowledge EAST is the only facility that is planning on implementing a hot He-cooled tungsten wall and divertor in a long-pulse device in the foreseeable future (by ~2017), and thus the facility provides a unique opportunity to address issues in this configuration, and to determine if the leading PFC armor candidate material can in fact be integrated with a high performance steady-state core plasma. A key factor, and possible limitation to this program, will be the temperature of the PFCs; the upgrade target is 400 °C, lower than the 500-800 °C envisioned for an FNSF, and it will not clear until engineering designs are complete whether this temperature can be attained.

The subpanel thus recommends that serious consideration be given to defining a collaborative program with the ASIPP, and then implementing it in parallel with a supporting domestic program that provides the necessary detailed understanding that could, together with results from EAST, provide for a credible W-based PFC solution. The EAST team currently has much less experience and expertise in the PMI area than the US or EU, and in particular lacks the novel real time, in-situ diagnostics which will be required. US experience with engineering and operating a heated W divertor will also be valuable. Thus, in comparison with collaborations on EU devices, it seems that a US-EAST collaboration could have a large impact in enabling and accelerating this facet of their research program, providing timely and critical information for FNSF. EAST plans to deploy ICRH, LCHD, ECH *and* NBI, on an aggressive time scale, providing opportunities to collaborate on wave/particle–plasma interactions and long pulse technologies for all of these H&CD methods.

KSTAR and **JT60SA** : These devices will both provide interesting and useful capabilities for PMI studies, albeit on a longer time frame that in the EAST device. As discussed in section 5.0, KSTAR will provide prototypical particle and thermal loads to the PFC components within a 5-7 year time horizon, for periods of up to 300 seconds. At the present time, the PFC materials on both devices are planned to be carbon based, with water cooling technologies, and thus will be limited to operating temperatures that are well below those expected in next-step devices such as an FNSF. These capabilities would permit study of high performance core plasmas with walls and PFCs that are approaching a steady-state; furthermore the carbon material design basis provides a facility to study this material should the W-based experiments on EAST determine that there are insurmountable problems with W-walls and/or PFCs.

Having an ability to operate the carbon walls at significantly elevated temperatures, where carbon erosion is reduced significantly and thus where a window of feasibility may exist for carbon walls in next-step devices, could be quite useful. It is likely that this would require a change to gas-cooling (likely He cooling) and thus represents a very significant engineering change for KSTAR. The KSTAR group indicates that they are also considering adopting a W-based divertor design with water cooling. Should that occur, the resulting divertor conditions would provide some useful data, particularly relevant for ITER. However, continued use of C-based first walls and operations at temperatures consistent with water cooling would not permit full exploration of the PMI and PFCs issues discussed here. Like EAST, KSTAR plans to deploy long pulse ICRH, LCHD, ECH and NBI, though on a slower time scale, so collaborations on H&CD physics and launchers may be of interest.

The timeline for operation of JT-60SA is such that prototypical conditions are not likely to be obtained until approximately a decade from now. Because of this extended timeframe, we cannot determine what a suitable international collaboration would entail at this time, but we suggest that the US community keep clear lines of discussion open with the JT-60SA team and look for emerging opportunities as work progresses in the next several years.

Control of High Performance 3-D plasmas and Heat Flux

The US has recently already established a collaboration with the IPP-Griefswald for work on W7-X. Although PFC material issues per se are not central to the objectives of this collaboration, the anticipated plasma conditions will permit testing of actively cooled PFCs in this complex 3D geometry. The US is responsible for the design of the high heat flux divertor ‘scraper’ elements using carbon monoblock technology. The US will also be responsible for key divertor diagnostics, including visible and IR imaging systems to assess and prevent hot spots in real time; these draw on US experience with domestic and overseas experiments and will also be applicable to future devices, both tokamaks and stellarators. While the divertor material and temperature are not directly relevant to FNSF the experiment would provide an ability to test models of magnetic configuration control, material migration, co-deposition and fuel retention in this complex geometry. A science program element within the US stellarator collaboration containing both experimental and modeling components could provide valuable experience in testing models of these important PMI processes. It should be well coordinated with the broader US PMI program so that tokamak and stellarator experience can be readily integrated.

6.2.6 Summary of Recommended Collaborative Program

Taking into account the domestic and overseas capabilities, the following integrated research program is recommended to address the issues of “*Development and Integration of Plasma Wall Solutions for Fusion covered in this section*”:

Critical Plasma Material Interaction (PMI) challenges include integrating reactor-relevant materials at prototypical operating conditions with high performance long pulse core plasmas while successfully avoiding transient and off-normal events, maintaining plasma heating and current drive capability, providing adequate PFC lifetime, maintaining fuel inventory control, and ensuring this performance in the severe irradiation environment of a power reactor. The leading PFC concept for an FNSF is tungsten, with carbon and other possibilities as backups. Unlike current confinement experiments, PFCs in a reactor will need to be at high temperature (> 600 °C). Assessing and proving these concepts these will require a multipronged Fusion Nuclear Science program.

Required Domestic Program Research: Candidate materials should be evaluated in single-effect laboratory experiments, off-line plasma simulators and suitable neutron irradiation facilities. The US is a world leader in PMI diagnostics and physics, and has a number of relevant test facilities, including several, such as PISCES, DIONYSIS and TPE which are unique. Tests should be conducted in tokamaks to assess compatibility with high performance plasmas, including interaction with RF waves for heating and current drive, fuelling, impact of transients, and material migration. Alcator C-Mod has FNSF and power plant level divertor heat fluxes and is planning the first tests (worldwide) of tungsten divertor PFCs at reactor-relevant temperatures. DIII-D and NSTX are testing carbon and lithium PFCs respectively.

Collaborative Opportunities Abroad: The US should collaborate with Asian superconducting tokamaks to upgrade to reactor-relevant PFC material and temperature at long pulse. **The proposed upgrade of EAST in 2017 to a hot tungsten divertor appears the most compelling medium term opportunity.** The US could provide experience from its hot divertor program and novel real-time PMI diagnostics, and would gain critical information needed to validate solutions for an FSNF. In the longer term, collaboration on KSTAR and JT60-SA could assess other PFC options, and integration with scenarios with higher self-driven current.

PMI issues are also critical to the success of ITER. In addition to US experiments, the US would collaborate on JET experiments with the new ITER like wall and upgraded heating. The US could contribute PWI expertise and diagnostics, and would gain experience valuable to future participation on this topical area on ITER. Critical issues to be explored with the ILW are the levels of impurities, the effects of plasma transients, the retention of tritium and the formation of dust.

Stellarators offer steady state confinement regimes eliminating transient events such as disruptions at the expense of a more complicated PMI configuration. Collaboration on LHD and W7-X provides an opportunity to develop and assess 3-D divertor configurations for long pulse, high performance stellarators. The US already has a significant collaboration in place on W7-X and is responsible for key high heat flux elements, 3D analysis codes and diagnostics. This will strengthen the US capability to pursue the stellarator as a potential path to fusion energy

6.3 Understanding the Dynamics and Stability of the Burning Plasma State

6.3.1 US Research Goals

The United States Fusion Energy Sciences Program has identified the study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, as a key frontier and the next major step in magnetic fusion energy research. To this end, in 2003 the US announced it would join the international project to construct and operate ITER and is now a partner with China, India, Japan, Russia and South Korea, with the EU as host partner. The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy. ITER aims to accomplish this objective by demonstrating controlled self heating and extended burn of deuterium-tritium plasmas, with steady-state as an ultimate goal, by qualifying technologies essential to a reactor in an integrated system, and by performing integrated testing of the high heat flux and nuclear components required to utilize fusion energy for practical purposes.

An essential element of the ITER program is producing and sustaining for many hundreds of seconds, the conditions where the fusion reaction energy itself is the dominant source of heating sustaining the plasma state. ITER has established as its goal achieving an overall energy gain, Q, defined as the ratio of the fusion power production divided by the input power required to sustain the plasma, of $Q > 10$. Since one fifth of the energy released in deuterium-tritium (DT) fusion reactions is in the form of electrically charged helium nuclei (alpha particles) which can be retained in the magnetically confined plasma, this means that at least 2/3 of the power heating the plasma could be provided by the fusion process itself, thereby qualifying this as a ‘burning plasma’ state.

The dynamics and stability of the burning plasma are expected to exhibit fundamentally different behavior from the present generation of fusion experiment in three key respects:

- There will be a substantial population of energetic alpha particles (created with initial energy 3.5MeV) contributing to the total plasma pressure. Since their velocity exceeds the Alfvén speed that characterizes the speed of low-frequency electromagnetic waves in the plasma and the spatial gradient in their normalized pressure, β_α, is large, the alpha particles can drive plasma instabilities which in turn will affect their confinement. The dimensionless scaling parameters that characterize the potential for these effects are $v_\alpha/v_{Alfvén}$ and $R\nabla\beta_\alpha$.

- The larger device size required to achieve the necessary energy confinement for a burning plasma will move experiments into a new regime where there are many resonantly overlapping alpha-driven instabilities. Reliable predictive simulation capability for the resulting transport of the energetic alpha particle population will not be possible without experimental information from a burning plasma. The dimensionless parameter that characterizes entry into this new instability regime is the ratio of the alpha-particle gyro-radius to the plasma radius, ρ_α/a.

- A burning plasma is an exothermic medium with strong non-linear couplings between the local heating rate, the energy and momentum confinement, the self-generated plasma current, and therefore its MHD stability. Managing this complex interplay to achieve the best fusion performance for extended durations will be a major scientific and engineering challenge which, because many different processes and timescales are involved, must be performed in conditions as close as possible to those of an eventual fusion reactor.

Understanding the dynamics and stability behavior of this new physical regime of a burning plasma is a prerequisite to the design of a demonstration fusion power system (DEMO). It is for this reason that the US has joined with the other developed nations of the world to produce in ITER the first sustained burning plasma state on earth.

6.3.2 US Capabilities and Research Needs

During the 1990s, significant progress was made towards achieving a burning plasma in a tokamak through the first experiments with deuterium-tritium plasmas in TFTR in the US and JET in the UK. These DT experiments reached a maximum fusion power gain Q of about 0.6. While these experiments were still strongly dominated by external plasma heating sources, they provided important information on the confinement of alpha particles, the first indications of self-heating of the plasma by the alpha particles and on the excitation of alpha driven instabilities.

A key conclusion from these DT experiments was that the confinement of fusion produced alpha particles was in agreement with classical models and that no significant 'anomalous' loss processes were observed. This positive, but initially somewhat surprising, result spurred the development of more comprehensive theory which showed that the fusion alpha particle driven instabilities originally predicted did not occur in the TFTR or JET experiments due to the strong damping of such modes by the population of lower energy externally injected particles used to heat the DT plasmas. As a result, the theory and predictive models were extended to include the damping of alpha-driven instabilities by supra-thermal, but sub-Alfvénic, ions. This development underscores the importance of validating predictive models under the most realistic conditions available.

The advent of DT experiments propelled the US to develop world-leading capabilities both in diagnostics for the fusion alpha particles, and in the theory and quantitative simulation of alpha-driven instabilities. The US remains a leader in these areas of research, sustained by a close linkage between theory, simulation code development and measurements made in a number of devices, both in the US and abroad, with diagnostics developed in the US. In non-DT experiments, the energetic particles driving the instabilities are produced either by neutral beam injection (with energies in the range up to about 120 keV) or by ICRF heating coupled to a minority population in the plasma which can be accelerated to very high energies (extending to multi-MeV). While these populations do not perfectly simulate the isotropic thermalizing distribution of alpha-particles expected in a burning plasma, they have allowed the determination of instability thresholds and the mode structure of a variety of instabilities for validating theory and simulations. Since the original DT experiments in the 1990s, sensitive diagnostics such as 2D ECE imaging, 2D interferometry, phase-contrast imaging and reflectometry, have been developed to measure the instability mode structure on non-DT experiments, and can now be applied to measuring mode structure in burning plasmas. Quantitative spectroscopy has been performed on a variety of modes by applying external excitation and measuring the plasma response. These studies have been facilitated by the development of innovative diagnostics for the energetic ion population, for example the alpha-particle charge-exchange spectroscopy for the DT experiments and the fast-ion D_α-emission technique for NBI-heated plasmas.

In preparing for full participation in ITER, the US should strive to maintain its leadership in this area critical for the ultimate viability of magnetic confinement fusion. This will require continuing the development of theory, simulation and diagnostic capabilities for all relevant fast-ion instabilities and the testing of those capabilities to the fullest extent in well diagnosed experiments conducted both in the wide variety of non-DT plasma regimes available in US facilities and in DT plasmas in JET which will provide the closest possible approach to a burning plasma in advance of ITER.

Apart from alpha-particle confinement and heating, there are many other research needs which must be addressed for ITER to succeed. For the US to reap the full benefit from its contribution to ITER, it should seek collaborations in those areas where its domestic research program can be strengthened by participation in research on devices with complementary strengths or with capabilities beyond what is available within the US. While several of the issues critical for ITER can be studied in smaller tokamaks and other toroidal confinement systems, it remains to be demonstrated that the understanding gained and techniques developed at smaller scale are transferable to ITER with appropriate, validated scaling. This can best be accomplished by active participation in the largest scale tokamaks foreseen to be operating between now and the beginning of ITER operation, namely JET in the short term and JT-60SA in the longer term. On the stellarator side, LHD in the immediate future and W7-X in the future can provide such opportunities.

6.3.3 Collaborative Opportunities in Burning Plasma Research in Advance of ITER

6.3.3.1 Developing Understanding of and Predictive Capabilities for Alpha Particle Confinement, Heating and Instabilities

The US has recently provided to JET a new detector for alpha particles (and other fast ions) lost from the plasma which is now being brought into operation. It is planned for the US to operate and exploit that diagnostic through the DT phase by comparing its measurements to modeling of the confinement of the alpha particles using the comprehensive suite of codes available in the US.

Since the DTE-1 experiments ended in 1997, JET has undertaken several upgrades to both its heating systems and its diagnostics, in addition to the recent installation of the ITER-Like Wall (ILW). Assuming that the experiments in the next two years demonstrate adequate power handling of the ILW, projections of plasma performance are that JET should now be capable of maintaining its previously attained Q, or even slightly higher, for a longer time, thereby allowing the alpha-particle population to evolve to a steady state. With improved resolution and accuracy of its diagnostics for the density and temperature profiles, it should be possible to demonstrate electron heating from confined fusion alpha particles more convincingly than the original DTE-1 experiment. That important demonstration will involve detailed analysis and modeling with transport codes, such as the US-developed TRANSP code. Active, continuing involvement in the development and application of such codes would both be a valuable contribution to JET and extend the capabilities of the codes in preparation for their application to ITER.

The US has unsurpassed capabilities for measuring, predicting and modeling fast-particle driven instabilities which could be applied to the forthcoming DT experiments on JET. By contributing analysis and modeling of the linear stability limits, the expected mode structure, including especially possible mode overlap in the large JET plasmas, and nonlinear effects, the US would make a major contribution in this area. The improved diagnostic capabilities now available will test the predictions for the mode structure of alpha-driven instabilities. These include measurements of fast-particle interactions with waves, particularly Alfvén eigenmodes, with diagnostics on JET provided by a collaboration amongst universities in the US and abroad. Performing predictive modeling in advance of the experiment would provide a stringent test of the models and ultimately strengthen the foundation for predicting the performance of ITER and designing experiments to maximize its fusion performance.

In considering the development of new US collaborations with JET on alpha physics, it must be borne in mind that the experimental program leading up to its planned DT experiments in 2015 is already well defined. In particular the opportunities for installing new diagnostics as part of such a collaboration will become quite limited as final preparations are made for the reintroduction of tritium to JET.

6.3.3.2 Exploration and Optimization of ITER-Prototypical Operating Modes

Compared to the present generation of tokamaks, the operation of ITER will present considerable challenges because of its complexity, size, relatively low shot rate and the regulatory environment in which it will operate (also related to its scale). The optimization of the DT fusion performance needed for ITER's success will depend on developing our understanding of the interplay between the many factors involved in tokamak operation (*e.g.* operating mode, profile evolution, plasma-wall interactions, stability boundaries, transients) and building that understanding into simulation codes which can be applied confidently to ITER-like conditions. That development has already started and has been applied with reasonable success to designing plasma operating scenarios in existing and recently built tokamaks. The US has made and continues to make important, and well recognized, strides in this area. However, to be confident of extrapolating our simulation capabilities to ITER, it is very important to test the underlying models by applying them at the largest available scale, in advance if possible, and then refining and validating models *post facto*. This will best be accomplished by active US involvement in the experimental program of JET over the next few years.

The scaling of confinement with respect to size (characterized by the dimensionless parameter $\rho*$ the ratio of the thermal particle gyro-radius to the system size) at the collisionality characteristic of a burning plasma is critical to the success of ITER. Furthermore, the way in which confinement changes with isotopic mass and in the presence of alpha-particles and their associated heating of the plasma will affect the design of experiments in ITER. The US has made many contributions to understanding, and improving, tokamak confinement in the past 30 years and continues at the forefront of this activity worldwide. It should seek to leverage its successes and capabilities by participating actively in the design and execution of experiments in this important area, guided by its involvement in the ITPA and using the data from complementary, targeted experiments on its domestic facilities. Through this, the US should seek to learn as much as possible from the JET DT experiments about the determinants of plasma transport in the conditions most closely approximating those expected it ITER.

JET provides a unique opportunity for studying fusion performance optimization because, in addition to its scale and its DT capability, it is now operating with its ITER-Like Wall, consisting of tungsten-coated tiles in the high heat flux regions of the divertor and beryllium tiles on the remainder of the plasma-facing surfaces. Critical issues to be explored with the ILW are the levels of impurities, particularly high-Z impurities, the effects of plasma transients on the integrity of the PFCs, the retention of tritium in the vessel and the formation of dust. While these are issues considered under the rubric of the preceding section (Development and Integration of Plasma Wall Solutions for Fusion), they are mentioned here because they will impact the optimization of fusion performance, possibly very significantly.

After the completion of the JET DT program, the US could also pursue collaboration in experiments in JT-60SA to study performance optimization and confinement scaling when it becomes equipped with its full complement of heating power in 2020. Heating of the electrons will then be available from both its high-energy negative-ion neutral beam injectors and ECRH power. Thus it should be possible to perform simulations of aspects of the alpha-heating occurring in a burning DT plasma using advanced feedback control of the external power in response to the plasma properties measured in real-time.

6.3.4 Summary of Recommended Collaboration Program in Burning Plasma Research

The US FES program has identified the study of burning plasmas, in which self-heating from DT fusion reactions dominates plasma behavior, as a key frontier and the next major step in magnetic fusion energy research. The US already has experience in operating DT experiments, developing and exploiting alpha-particle diagnostics and leading expertise in the theory of alpha dynamics and alpha-driven instabilities. Through a close coupling of theory to experiments in US facilities, which provide access to a wide range of plasma regimes, the US has developed extensive and validated predictive modeling capabilities applicable to burning plasmas.

Required Domestic Program Research: The US should continue its very successful development of theoretical models for the nonlinear evolution of energetic particle driven instabilities, and test these models in the full range of experimental conditions available in US tokamaks using results from innovative diagnostics. This is crucial to understanding burning plasma instabilities and the resulting transport. This will maintain the US at the forefront of the field, positioning it for a valuable role in JET and leadership in ITER. It should also continue to develop alpha diagnostics compatible with the fusion environment. Through its involvement in the ITPA, it should conduct experiments on its domestic facilities to develop and optimize JET DT experiments and the operating modes for ITER.

Collaborative Opportunities Abroad: The US is providing to JET both a new detector for alpha particles (and other fast ions) lost from the plasma, and diagnostics for the mode-structure of fast-particle instabilities. **Support should be provided to compare the data from these diagnostics during the planned DT experiments with modeling of the alpha particle dynamics, including the mode structures and possible mode overlap, using the comprehensive suite of codes developed in the US.** Performing predictive modeling in advance of these experiments would provide a stringent test of the models and strengthen the foundation for predicting and optimizing the performance of ITER. The US should collaborate with JET to apply its experimental analysis and modeling codes to investigate alpha heating during the DT experiments thereby extending the capabilities of these codes in preparation for their application to ITER.

Optimizing the fusion performance in ITER requires understanding the interplay between the many factors involved in tokamak operation and building this into simulation codes. The US has made important strides in this area but to be confident of extrapolating to ITER-like conditions, it is important to validate the underlying models at the largest available scale. Critical issues for ITER remain the scaling of confinement with respect to size and the effects of isotopic mass and of alpha particles. **The US should leverage its successes in developing our understanding of tokamak confinement and in improving it by participating actively in the JET DT experiments**. Through this, the US will gain valuable knowledge about plasma transport in the conditions most closely approaching those in ITER. The ITER-like Wall in JET also provides a unique opportunity for studying performance optimization for ITER.

The US could also pursue collaboration in experiments to optimize the performance in JT-60SA as the full heating power becomes available in 2020. In JT-60SA, electron heating will be provided by both high-energy neutral beams and ECRH power, making it possible to simulate aspects of alpha-heating by using advanced feedback control of the external power in response to the plasma properties measured in real-time. This could be used to test the extrapolability of plasma control strategies and techniques developed by the US for their application to ITER.

7.0 Modes of International Research Collaboration

Introduction

In this section, we address the second charge question, namely:

> *What research modes would best facilitate international research collaborations in plasma and fusion sciences? Consider modes already used by these communities as well as those used by other research communities that have significant international collaborations.*

The present US fusion program is highly collaborative, both nationally and internationally, with many years of experience. In developing its findings and recommendations on Modes of Collaboration, the Panel spent considerable time reviewing past and present experience with international collaborations in fusion and in other areas (most notably in High Energy Physics). Four modes of collaboration were identified and deemed appropriate for future international collaboration. We describe these modes and their salient features in Section 7.2. Examples from fusion are presented in Section 7.2, along with a discussion of lessons learned from examining international collaboration in other areas of research.

As fusion research moves into the ITER era, first with new long-pulse superconducting tokamaks (and an optimized superconducting stellarator experiment), the scope and nature of international collaborations must change. Based on our review of existing collaborations, we point out important considerations for developing future international collaborations in Section 7.3, finally concluding this chapter with specific recommendations in Section 7.4 and 7.5. (Recommended modes) and 7.5 (Implementation).

7.1 Identification and Description of Modes of Collaboration

Our review of existing national and international scientific collaborations in fusion energy and other sciences led the committee to identify four basic modes of collaboration, *differentiated largely by the initial organizing entities and reporting structure*, which provided the context for our discussion to develop recommendations. The four modes are:

1. **Individual Scientific Exchanges**
2. **Group or Institutional Collaborations**
3. **National Teams**
4. **International Teams**

It is obvious that existing scientific collaborations managed by DOE or similar government agencies span a wide range in scale, duration, management structure, and emphasis and were created under a variety of contexts, so categorization of a given collaboration may not be exact. Consequently, we separately discuss the modes and the descriptors, providing examples as needed to connect with present experience and clarify our meaning. The four basic modes are as follows.

1. **Individual Scientific Exchanges.** These small-scale interactions are often initiated by university or Laboratory scientists, students, or post doctoral fellows with a common research interest who may first connect at workshops or larger scientific meetings. They typically have a specific topical focus related to physics, a diagnostic, or a particular fusion concept. Often informal and of limited purpose or scope, the work is frequently carried out with

existing funding under the auspices of a larger program or as part of an existing grant. Some collaborations in this category can be ongoing (indefinite term), while others set out to accomplish a specific task and have limited duration (months to a year or two including publication of results).

Examples include university sabbaticals to major fusion facilities, visits to assist in an experiment, or visits to install or learn how to run new simulation codes. ITPA experiments are often executed in this manner even though coordinated under the larger international umbrella framework of ITER.

2. **Group or Institutional Collaborations.** These collaborations may be motivated by individual initiative, but are organized from the start as institutional-level collaborations which involve higher levels of oversight and management. DOE or other funding agencies are involved in defining the purpose and scope of the collaboration, since existing funding may need to be redirected or additional funding required to carry out the work. The scope of work is typically larger than for an individual exchange, involving multiple scientists and support staff (5-10 full time equivalents). They generally feature a broader range of topics or increased depth on a single topic (e.g., instrumentation, experimental measurements, and simulation), and involve multiple scientists or support staff. The arrangements are more formal, are typically reciprocal, and continue over several years or longer.

   Examples include collaborations between LLNL and General Atomics supporting the DIII-D program, between MIT and U. Texas supporting the C-Mod program, General Atomics and KSTAR in Korea, PPPL and JET, GA and ADEX-Upgrade, or Columbia University and PPPL supporting the NSTX research program. University participation in major accelerator facilities in the US or abroad to install and operate detector assemblies or beam diagnostic instrumentation packages are examples from outside of fusion research.

3. **National Teams.** National teams involving several US institutions may form to accomplish a specific task or operate a single facility; one of the institutions may lead the team or may host the activity. Funding agencies are involved at the onset and may initiate the formation of the team. Coordinated planning and execution extends over multiple years and involves DOE or other funding agencies. Participation may include a broader range of expertise with 5-15 or more total staff participating, some full time and others only part time, some traveling regularly to one or more participating sites, and others relocating away from their home institutions for longer periods of time. Individual participation likely spans a significant period within a professional career (e.g., full term of post doctoral appointment).

   The new collaboration involving PPPL, ORNL, LANL, U. Wisconsin, and Auburn University participation in the W7-X program is one example. In some sense, the DIII-D National Fusion Program is the largest such “National Team” funded by the DOE FES program. NSTX and C-Mod also have significant collaborative National Teams as an integral part of their research programs. Recent DOE-theory funded simulation teams aimed at producing edge codes provide other examples, as do certain DOE HEP funded activities on the Large Hadron Collider.

4. International Teams. International teams or partnerships necessarily involve individuals from two or more countries joining together to accomplish high visibility tasks producing results with high impact. Size and scope can vary widely, depending on the task, ranging from a coordinated set of individual scientific exchanges to a large team assembling at a specific site for a particular task or experiment. For larger collaborations, multinational implementation agreements may be needed, travel arrangements and scheduling are complex and process and scope may require complex negotiations that take some time to complete. As in the case of national teams, individual participation may span a significant period within a participant's professional career.

The collaboration between JAERI and General Atomics to operate the Doublet-3 experiment in the 1970's is a well known example of such an international team. The JET project has always been a successful collaborative effort among many European countries, and has used different modes of operation at various stages. Initially a strong, permanent home team operated the experiment, while in recent years operations have been primarily by the host institution, with teams on scientific topics rotating on-site for given experiments. Very recently, an international team was formed to conduct experiments on DIII-D simulating the effect of the ITER Test Blanket Module on confinement. The W7-X facility now under construction is planning on forming an international team to carryout the research program. The ITPA also functions as a loose-knit international team as they meet twice a year to discuss, plan, and execute coordinated experiments on various tokamaks around the world in support of ITER. The US participation in the Large Hadron Collider supporting the ATLAS or CMS detectors are other examples of International Teams, with a multi-institutional US Team being part of a larger international team.

There is tremendous diversity of implementation or functionality within each of these four modes of collaboration, as suggested by closer examination of certain key characteristics in the examples above. Two institutional collaborations may look very different from one another when it comes to the scale, duration, collaborative structure, and reciprocity among the partners. Collaborations can also differ by their emphasis. This diversity of implementation is important to realizing the maximum benefit from international collaborations in fusion research.

Key Attributes of Collaborations

The committee identified a number of key attributes describing collaborations that are informative to generating and evaluating potential new collaborations using the 5 criteria outlined in Chapter 3. These attributes fall under two categories, one relating to the Purpose or Emphasis, and the other dealing with Implementation:

<u>Purpose or Emphasis of the Collaboration</u>

Science or Issue Driven Collaborations

- Aims to produce better scientific understanding on a specific topic or resolve a scientific issue needed for ITER, FNSF, or general fusion development.
- Generally a longer-term, possibly open-ended activity with varying scope that may include execution of experiments, theory, code development and numerical simulation, or hardware and diagnostic development and operation to resolve the issue.
- Publication and presentation of results are the main tangible deliverables defining "completion."

- May involve building a team to conduct experiments on a single facility or to compare results across multiple facilities (US & foreign), or a mix of such activities.

Task Driven Collaborations in Support of Programmatic Scientific Goals

- Deliver, install, and operate hardware or diagnostics in support of facility operation or new codes or algorithms in support of improved simulation or analysis capability, such as
  - Hardware: major device subsystems, components, diagnostics
  - Software: simulation codes, analysis codes, CODAC packages
- Perform specific tasks in support of science, such as
  - Calibration
  - Data reduction and error analysis
  - Database development and support
- May support a related, issue-driven collaboration or be part of a broader scientific exchange between parties

Implementation

Scale (US budget, level of effort, number of staff)

- Single PI: ≤1 FTE, with comparable hardware, diagnostic, or code, generally to accomplish a specific task, DOE awareness
- Institutional scale: >1 FTE, may involve on/off site support staff, comparably scaled hardware and computer support, DOE awareness
- National scale: > 3-5 FTE, with Staff and material from multiple institutions, DOE management
- International scale: > 5 FTE, involving multiple countries and institutions, DOE, IAEA, and/or other agencies involved in US and abroad

Reciprocity

- Unilateral: one way tangible resource flow – people, hardware, or money into or out of the US in order to benefit US fusion program and fusion development such as participation in burning plasma experiments in ITER
- Reciprocal: two way tangible resource flow – significant or matching foreign investment in US activities, either in-kind (hardware or personnel exchanges) or cash.
- Partnership: full integration by all participants into a single team to achieve a common goal using resources from US and abroad to conduct the research .

Presence

- On-site: Staff temporarily relocate to the collaborating site and work there on an ongoing daily basis. The duration may be for a fixed interval of 6 months or longer, the time required to complete thesis research or a post doctoral appointment, or indefinitely (the duration of the collaboration) for some staff scientists.
- Traveling: Personnel regularly travel to the collaborating site to participate in workshops, participate in planning activities, conduct experiments, or analyze data. One or more short duration (weeks to a month or two) trips per year with short-term housing arrangements.
- Remote Participation: Staff remain at their home institution and regularly connect to the collaboration site using remote control rooms or commercial videoconference technology, along with remote computer access to participate in meetings and experiments. Some travel to the remote site may be needed.

Duration

- Short Term: 18 months from initial discussion to completion (publication) is probably a realistic minimum; tasks based on focused R&D plan with a single deliverable; e.g., a single experiment resulting in a presentation and/or publication or delivery of simple hardware.
- Intermediate term: 2-3+ years from start to finish (perhaps the term of a single grant), with an adjustable R&D plan, involving multiple planning meetings, multiple experiments or simulations, resulting in several presentations and publications, with more complex, sequential deliverables.
- Long Term: 5-10 years or longer, usually with an adaptable on-going R&D plan involving one or more proposal renewals, spanning a significant fraction of the PI's professional career and/or the larger project's or program's lifetime.

Collaborative Structure and Management

- Informal: agreed verbal support of local management, with few little or no written agreements and minimal project tracking, separate budget tracking and reporting, perhaps existing under a broader umbrella agreement between institutions; usually suitable for smaller-scale or short-term collaborations; casual travel arrangements.
- Affiliation: agreed upon organization and governance, independent participants separately responsible to funding agencies, flexible arrangements.
- Formal: explicit, documented arrangements between institutions, possibly involving DOE sign-off or signed multi-party agreements or partnerships, often with a lead institution coordinating with DOE or international partners; usually applied to larger, longer-term, institutional scale collaborations.

7.2 US Experience With International Collaborations

Within the US, most fusion experiments in the US participate in a wide variety of collaborations with other groups in the US, involving of the order of 10-20% of their total budgets. The three major tokamak facilities in the US (C-Mod, DIII-D, and NSTX) are highly complementary in terms of facility capabilities, basic geometry, plasma parameters, diagnostics, and program emphases. In recent years DOE has established annual Joint Research Targets for these facilities which brings researchers together to plan and execute coordinated research plans on high priority topics.

Significant ongoing international collaborations involving US facilities and research groups exist. Many operate at the level of individual scientific exchanges, such as when scientists travel overseas to participate in fusion experiments. Others operate as institutional collaborations, such when a scientist from a foreign fusion facility brings an instrument to a US facility to make an important measurement. In recent years, with the formal start of the ITER project, the scope of international collaborations has grown, with significant US investment in ITER and ITER-supporting research conducted on overseas facilities such as JET, JT-60U, and ASDEX-U. In parallel, the related ITPA process functions like a coordinated set of individual scientific exchanges. Newer collaborations with the superconducting tokamaks in Asia (KSTAR and EAST) and stellarators (LHD and W7-X) are now in place and there is considerable interest in growing them on the part of the host institutions.

Funding for existing collaborations is provided either explicitly by DOE or indirectly through collaborations initiated and supported by US domestic research programs. Table 7.2.1 at the end of this Section provides a partial list of present explicitly funded international collaborations on magnetic fusion research. The panel reviewed many of these collaborations to evaluate the benefits and opportunities provided by various modes of collaboration. Outside of fusion research, other fields of science also have extensive experience with international collaboration, most notably High Energy Physics (HEP) and Space Sciences and Astrophysics. Members of the panel provided detailed reports on international collaborations in these areas, which the panel found useful in their discussions. However, some key distinctions were noted:

- For HEP and astronomy, the large facilities developed are *tools* to do experiments or make observations. In fusion, the operation of the facility, and integrated behavior of the plasma scenario, *is* the experiment; one cannot separate 'operation' and 'research' in the same way.
- Projects such as LHC at CERN and the International Space Station are the largest in their field, and clearly at the frontier of research. These collaborations most closely parallel those expected on ITER, and are not fully typical of the smaller scale, nearer term collaborations on smaller international fusion facilities currently being evaluated.

Four of the many existing international collaborations supported by the US fusion community are **illustrative examples of the four proposed modes of collaboration and the application of the proposed descriptors.**

1. ITPA cross-tokamak comparisons of H-mode pedestal properties

- **Type:** Individual Scientific Exchange. Typically 1-2 scientists per institution, consisting of short visits for experiments, or remote participation in specific experiments. Tend to be pair-wise experiments in different years (C-Mod/AUG, C-Mod/DIII-D, DIII-D/JET, C-Mod/JET, C-Mod/NSTX, C-Mod/JFT2M…)
- **Emphasis:** Science or Issue Driven
- **Structure:** Formal. Organized through the ITPA via the IEA Large Tokamak Implementing Agreement, but each exchange initiated and managed by individual scientists.
- **Duration:** Intermediate term. Each ITPA joint experiment typically takes 2-3 years to plan, complete, and publish results. Overall ITPA activity on the subject has been ongoing for >10 years.
- **Scale:** Fractional PI. Scientists involved spend only a small part of their time on this, generally having diagnostic and physics responsibilities at home. Some involved only remote participation and no travel. Funded by DOE-FES as a component of ongoing research at US Facilities.
- **Reciprocity:** Reciprocal scientific exchanges. No hardware or diagnostic involvement.
- **Benefit:** Despite small scale and low cost, produced multi-tokamak dimensionless profile comparisons and scalings which allowed robust model validation, produced new physics understanding, and motivated similar advances in other areas of tokamak research (e.g., boundary physics).

2. GA/DIII-D with EAST, KSTAR, and SST-1

- **Type:** Institutional. Specific agreements between GA(DIII-D) and ASIPP(EAST), NRFRI(KSTAR), and IPR(SST-1). Variety of personnel exchanges set by specific tasks.
- **Emphasis:** Task driven. Focus on supporting tokamak operations (plasma control) with long-term emphasis on developing steady-state advanced tokamak scenarios
- **Structure:** Formal. Separate agreements between GA and ASIPP/EAST, GA and NFRI/KSTAR, and GA and IPR.
- **Duration:** Long Term. Ongoing research program. EAST and KSTAR collaborations have been in place for >5 years.
- **Scale:** Institutional. Approximately \$0.5M/yr and 1.2 FTE (shared among ~ 4 scientists)
- **Reciprocity:** Reciprocal. GA provides support for plasma control and development of operational scenarios via on-site and remote participation, aimed at advanced tokamak development. Each overseas laboratory sends scientists to GA to support DIII-D operations and research.
- **Benefit:** Access to control with SC magnet systems, future access to long-pulse advanced tokamaks for non-inductive steady-state high performance tokamak research.

3. New Stellarator Collaboration

- **Type:** National Team. (ORNL, PPPL, LANL, U. Wisconsin, Auburn U.)
- **Emphasis:** Mixed. *Task driven* in the near term, providing trim coils, power supply design, and diagnostics. *Issue driven* in the longer term, focusing on more general stellarator issues (stellarators are 3D field devices).
- **Structure:** Formal. Agreement between PPPL/ORNL/LANL to provide hardware and support to IPP-Greifswald (W7-X host). Includes small effort at U. Wisconsin. Structure determined by DOE-FES in concert with PPPL and ORNL.
- **Duration:** Long Term. Ongoing (> 5+ years). W7-X operation set to begin in 2014 and continue for some years.
- **Scale:** National. Now: \$2.5M/yr, ~\$1M in hardware contribution ~3 FTE scientists and engineers. Future vision: \$10M/yr, with university involvement
- **Reciprocity:** Unilateral. Resources to Germany to support W7-X. No comparable stellarator facility in the US.
- **Benefit:** Future access to unique plasma conditions in 3D magnetic geometries (superconducting long pulse stellarator). Potential stellarator PMI solutions.

4. ITER Test Blanket Module (TBM) Error Field Simulator

- **Type:** International Team. Activities coordinated with ITER, including planning and execution of experiment, along with publication of results.
- **Emphasis:** Task driven. Determine effect of magnetic field errors arising from Test Blanket Modules to be installed in ITER.
- **Structure:** Formal. Funded by DOE under ARRA. Testing plan developed with ITER participation.

- **<u>Duration:</u>** Short-term, but ongoing. Less than 1 year from conceptual design to completing the experiment. Subsequent analysis led to a second and then third round of experiments.
- **<u>Scale:</u>** Institutional. DIII-D design team for the hardware and diagnostics. International team of ~10 scientists participated in the planning and execution of the experiments.
- **<u>Reciprocity:</u>** Bilateral. International team of experts traveled to DIII-D to plan and conduct experiments, with subsequent data analysis in their home countries.
- **<u>Benefit:</u>** Significant reduction in risk to ITER related to Test Blanket Modules. Additional funding and support for improving understanding of error field effects.

The International Collaborations in Space Science carried out by NASA easily dwarf (in dollar value) all other international science collaborations carried out by the United States. These collaborations range from "hardware" (e.g., rockets and other launch vehicles, satellites, and launch facilities) to "operations" (viz., launch services and operations), and to science and engineering programs.

Since the late 1970s, virtually all NASA missions have had some component of international collaboration; many missions carry onboard a mix of instruments build in the US or abroad. US scientists also contribute instruments to missions led by other nations. There is a long tradition of sharing of data deposited in mission databases. (There is some distinction based on whether a given mission is 'PI-led' or is regarded as a 'facility' – in the case of PI-led missions, which are usually the smaller satellite missions, there is often an limited time embargo on data sharing, after which the data must be made public to all.) NASA maintains a large variety of active data centers and management entities that deal with these collaborative programs (e.g., the "NASA Global Change Master Directory" for climate change related data at http://gcmd.nasa.gov/). Similar organizational structures exist for all other science areas within NASA's scope: astrobiology, geosciences, solar system sciences (including magnetospheric sciences), planetary sciences, and astrophysics.

NASA has described their general rules governing international collaborations, apart from the International Space Station, which we reproduce here. We have italicized the first three as particularly relevant to this report.

- *Cooperation is undertaken on a project-by-project basis, not on an on-going basis for a specific discipline, general effort, etc.*
- *Each cooperative project must be both mutually beneficial and scientifically valid.*
- *Scientific/technical agreement must precede any political commitment.*
- Funds transfers will not take place between partners, but each will be responsible for its own contribution to the project.
- All partners will carry out their part of the project without technical or managerial expertise provided by the other.
- Scientific data will be made available, for early analysis, to researchers all nations involved in the project.

Under the umbrella of these rules, over 2000 international collaborations have been put into place over the years; as of 2011, there are now of order 500 international agreements in place, and roughly 2/3 of all space science missions now involve international collaborations.

High Energy Physics research in the US pushes on three interlocking scientific frontiers, the Energy, Intensity, and Cosmic frontiers. After more than 20 years of global leadership at the Energy frontier, the US HEP program now relies on international collaborations at an overseas collider facility, the Large Hadron Collider (LHC) at CERN, Geneva, Switzerland, for future scientific advances in this area. At the same time, the US-HEP program maintains strong domestic efforts at both the Intensity and Cosmic frontiers.

Energy Frontier Science at the LHC is done by two competing experiments, ATLAS and CMS, operated each by an international collaboration of roughly 2000 physicists from close to 200 institutions across 40 countries. The US LHC community accounts for roughly 1/3 of the total, and roughly1/4 of these personnel are presently stationed at CERN for one year or longer.

The US-HEP program continues to successfully maintain a global leadership position in the LHC program as evidenced by:

- Senior leadership positions in the two experiments.
- Responsibility for development, deployment, and operations of major detector subsystems, software, and computing in the two experiments.
- Execution of the major physics analyses, e.g. the Higgs search, by scientists from US institutions.

The High Energy Physics community identifies four crucial elements for successfully maintaining future competitiveness when the only Energy Frontier facility is oversees:

1. **Maintain Centers of Excellence in the US.** Universities and National Labs must remain in the US which can design, develop, assemble, and operate major detector subsystems, software, and computing in/from the US, and which are able to send teams of scientists temporarily overseas to participate in the integration of these subsystems into the experiments there.
2. **Establish a culture of remote participation.** Today it is common to have subgroup meetings in ATLAS and CMS with more remote than local participants. Both experiments established Remote Operations Centers (ROC) at national labs in the US, and both depend on US-based computing infrastructure as crucial components of a globally distributed data analysis infrastructure.
3. **Maintain the ability to station personnel overseas for extended periods of time.** Leadership in the LHC program requires presence at CERN, either via residence or frequent travel. There are additional costs to US programs which must be funded in order to maintain this presence. This is especially important for university groups, which perform most of the data analysis from HEP experiments.
4. **Establish cohesive US-ATLAS and US-CMS projects and collaborations.** This is important for long term stability. It allows for coherent high-level negotiations of long-term commitments to the experiments at a national scale. The annual maintenance and operations budget managed by these projects comprises roughly 15% of the total US contribution to the construction of the LHC, ATLAS, and CMS.

Table 7.2.1 FES-Funded International Collaborations†

Short term assignments and attendance at international workshops are funded out of base funding. Some specific international collaborations are also funded out of base programs. Long term assignments, larger collaborations and equipment items are funded through the International Research FES budget line. Below is an incomplete list of international collaborations and the facilities and topical areas with which each funded institution is involved.

Princeton Plasma Physics Laboratory

- JET: Lost Alpha diagnostic, TRANSP analysis, analysis of ITER-like Wall experiments
- KSTAR: exp't operations, scenario modeling, design/fab of ECH mirrors and launchers
- Wendelstein 7-X: Fabrication of trim coils, design of power supplies for the trim coils
- LHD: Equilibrium reconstruction, X-ray crystal spectrometer, beta limits and transport
- EAST: diagnostics, RF, controls, discharge scenarios, liquid lithium,
- MAST: Non-inductive startup, ELM control & MHD stability, ECH, and next step design.

Oak Ridge National Laboratory

- JET: Ti and impurity measurements near the plasma boundary, edge modeling
- KSTAR: design of heat and particle control systems, divertor physics experiments
- EAST: filter scope diagnostics for divertor
- Tore Supra: RF heating, long pulse sustainment of tokamak plasmas
- ASDEX-U: helium and extrinsic radiator transport
- MAST: participate in electron Bernstein wave experiments
- LHD: rapid 3D equilibrium reconstruction (V3FIT)
- Wendelstein 7-X: coil engineering, 3D divertor design, pellet fueling

General Atomics

- EAST: development of EAST/DIII-D plasma control system, participation in control and long pulse steady state experiments, develop remote collaboration capabilities
- KSTAR: develop and support the plasma control system, development of ECH and NBI modeling and analysis tools, development remote collaboration tools

UC Davis

- KSTAR: development of ECE imaging diagnostic

Lawrence Livermore National Laboratory

- EAST and KSTAR: edge modeling and simulation

Columbia University

- KSTAR: MHD stability and active mode control

MIT

- JET: Fast particle-wave interaction and Alfven eigenmodes. Plasma-wall interactions.
- KSTAR: Lower Hybrid Current Drive,
- EAST: Ion Cyclotron Resonance Heating

University of Texas

- EAST: ECE diagnostics, DNB assessment, CXRS on HT-7, ECE diagnostics on HUST

University of Wisconsin

- KSTAR: design of BES diagnostic

The International Research budget (FY12 = $7.82M) funds a large part of the list above.

7.3 Considerations for Future Modes of Collaboration

There are a number of key considerations affecting the optimal modes of collaboration with international partners, in order to maximize the benefit to the US fusion energy sciences program. These are reflected in the criteria established by the panel (described in Section 3.0), that apply not only to the choice of topics for collaboration but the manner in which they are most effectively carried out. Other considerations relate to using international collaborations to prepare the US fusion energy sciences program for effective participation in ITER, as it relates recruiting and retaining the best and brightest people to carry out the research more than a decade from now.

Considerations derived from the selection criteria

Collaborations which address urgent or high impact issues (Criterion #1) will tend to require more resources to produce distinctive contributions with high probability of success (Criterion #2). Larger research institutions or national teams may best be able to organize the required expertise from across the US fusion program and to coordinate and leverage the efforts of smaller groups or single investigators, leading to a highly productive effort. When evaluating proposals, it will be important to consider not only the aggregate resources and expertise involved, but how the research will be managed to produce timely results.

Using international collaborations to position the US to benefit from ITER participation and to move forward in fusion development after ITER (Criterion #3) provides strong motivation to form international partnerships to build long-term working relationships with overseas partners. Starting now to build international teams with common, well defined scientific objectives should transfer directly to the ITER research environment. The present demographics for the US fusion science community will require that expertise gained during collaborations be retained by the US fusion program and that future scientist and engineers develop the requisite expertise to conduct ITER research and to move forward with follow-on devices. (Criterion #4). International collaborations have significant challenges in this regard, summarized below. They must be strongly coupled to fusion research and education programs in the US; it is critical that an appropriate balance between the two elements be maintained.

Based on experience in fusion research and in other fields, it is generally recognized that the cost per scientist for collaborative research overseas is higher than for research at domestic institutions (Criterion #5). Reducing this cost will favor collaborations which effectively utilize remote collaboration tools to minimize travel, keeping in mind that experience also shows the importance of maintaining on-site presence to maximize programmatic access and scientific leadership (both for institutions and for individuals).

Finding: Since the cost per researcher sited overseas is significantly higher than for research at a home laboratory, it is critical that opportunities be carefully selected to focus on critical issues which cannot be addressed in the US and provide clear benefit to the US program, and that their scale be no larger than is necessary.

Challenges for training, attracting and retaining world-class fusion scientists to the US fusion program in the ITER era

The need to recruit and train an experienced workforce for effective participation in ITER is clear. Magnetic fusion research in the ITER era will be highly collaborative in nature, and our impact on ITER will depend on having capable and experienced teams in place. Using international collaborations now to prepare the US fusion program for participation in ITER research a decade from now makes good sense if done well, but has risks if implemented poorly. Much will depend on the pace and scale of expanded overseas collaboration, and on the supporting program in the US.

Arguably the greatest strength of the current US fusion energy sciences program is its experienced and capable scientific and engineering workforce, which includes researchers at national laboratories, universities and industry. Expertise in design and operation of large and small facilities, in experiments and diagnostics, and in theory and simulation is respected worldwide. The US impact on the ITER project, and international fusion research generally, is as a result larger than its financial contribution would suggest. A 2004 FESAC report *"Fusion in the Era of Burning Plasma Studies: Workforce Planning for 2004 to 2014*" [11] noted that 1/3 of the current workforce was over 55 and concluded that over 40 new Ph.D.s per year would be needed to meet the future needs of the fusion program, including ITER and NIF.

Participating in D-T experiments in the near future and in experiments using new long-pulse superconducting tokamaks and stellarators offers potential opportunities for researchers including graduate students, post doctoral fellows, and faculty members. Along with these opportunities come several challenges. Our panel received a number of insightful comments from fusion researchers, and we were informed by experience in other fields. Challenges common to all types and size of institutions and to researchers at all levels, and *means of mitigating them*, include:

- **Extended overseas assignments challenge two-career families and those with children**

  The majority of scientific researchers in the 21st century are part of two-career families, both a lifestyle choice and a financial necessity. Extended stays in a foreign country, where researchers and their partners may not know the language or be able to work, have the potential to be disruptive; not all would be willing to accept such assignments. Education of school-age children is a particular concern. Studies have shown that offsite research tends to decrease the participation of female researchers. Language and cultural barriers are likely to be greater in Asia than in Europe. *Recognizing individual circumstances and allowing flexibility in travel arrangements among members of a team will be important to avoid attrition of skilled personnel. Remote participation can reduce travel requirements in many cases.*

- **Extended overseas assignments create uncertainty in career advancement and promotions**

  Researchers must be assured there is an attractive career path at their home institutions for long-term overseas assignments. It is also in the interest of the US program that they maintain involvement in domestic research, so that expertise and experience gained are retained, and available e.g. for ITER. *These objectives are advanced by maintaining a* *strong domestic effort in the topical areas which are the focus of collaborations, and encouraging common teams to work both in the US and internationally. Individuals would, over time, typically spend periods in both locations. Close links to the home institution must be maintained.*

- **Overseas travel and assignments increase costs**

  Travel and accommodation can increase by a significant fraction the cost per researcher. For fixed budgets, this means that fewer scientists can be supported. This can put collaborative research at a disadvantage compared to domestic research. While a general issue, the relative costs of travel tend to be more of a concern for small, single-investigator contracts. This is already problematic and often prevents researchers from small university groups from participating in opportunities for joint experiments and attendance at ITPA meetings which may arise in the course of a grant. *These concerns could be alleviated by providing modest travel funds outside of grants for small collaboration opportunities or by routinely including a travel component, and by weighting awards appropriately for research which is predominantly overseas.*

Recommendation: Developing a team approach that allows for flexibility and the use of remote communication tools can mitigate these challenges, as they have in HEP.

In addition to the general issues discussed above, university programs have particular challenges affecting both faculty and student education – a critical consideration given universities are by definition the source of the needed additions to the fusion workforce. University groups, of sizes ranging from a few faculty to interdisciplinary centers hosting large national facilities are currently engaged in the full spectrum of fusion research activities –e.g. theory, diagnostics, engineering, experimental research at varying scales. A large number of students are hosted at the major US tokamak facilities, notably Alcator C-Mod at MIT, and on Alternate and Innovative Confinement Concept facilities at a number of institutions, notably several at U. Wisconsin.

- **Extended overseas assignments reduce program visibility at home institutions**

  The core of university programs is their faculty, who are key to recruiting and training the next generation of fusion scientists. Visibility of an active fusion research program on campus is important to the status of this subfield within an academic department, which impacts the hiring and tenure of new professors. Extended overseas travel during the academic year can be problematic. The 2004 FESAC report [11] on the fusion workforce noted a skewing of faculty demographics to ages approaching retirement, and that retiring faculty were often not being replaced by professors in plasma physics or fusion. This trend will increase if university based facilities are curtailed in favor of international collaborations. Lack of visibility and participation by undergraduates can also reduce interest by prospective graduate students. *To reduce these concerns, collaborations should be complemented by on-campus research. DOE may in some instances need to provide funding to 'buy out' teaching responsibilities for a period of time, as is the case in HEP. Remote participation can help here also by providing a visible connection to a distant experiment, much like control rooms for space-based telescopes.*

- **Overseas assignments challenge PhD programs**

  Currently, most US Ph.D. programs include coursework for the first few years, in preparation for general exams. This is carried out in parallel with research, with students gaining valuable hands-on experience with hardware, running experiments, and developing capabilities to plan and lead experiments more independently in the later stages of thesis research. Even theory students often benefit from proximity to local experiments to validate their ideas. This sequence would have to change for research conducted primarily at an overseas facility. In HEP, students now complete their coursework earlier, and often relocate for their thesis work. Maintaining close relationships with both the local team, with an unfamiliar language and culture, and with the home institution, and providing good supervision, are difficult challenges. A safe working environment must be assured. It is unclear whether such arrangements will attract sufficient numbers of students, and provide the breadth of experience needed to prepare research teams for ITER and beyond. *It will be important to balance overseas opportunities for students with a sufficient number of exciting US-based projects, and to assure them of a viable career path in fusion research in the period leading up to ITER operation.*

Recommendation: Given the important role played by universities in supporting faculty working on fusion research, providing fusion research with a broad connection to the larger scientific community, and the recruitment and education of future fusion researchers for ITER and beyond, universities must be included in the international collaboration program. Solicitations should be planned accordingly. Experience on successful university collaborations on major domestic fusion facilities, and in HEP, has shown the importance of supporting a linked on-campus research program

For both present scientists and prospective students, **it will be compelling opportunities at the leading edge of fusion research which will provide the needed motivation to engage in collaborations.** This will certainly be the case with ITER, the world's first burning plasma. As discussed in Section 6, it will be critical to invest only in those additional overseas opportunities which offer unique new capabilities and address crucial questions for fusion.

Remote participation can reduce travel requirements for maintaining effective collaborations, and mitigate several of the above concerns, including cost, relocation and connectedness to US research teams. Experience with current fusion and HEP collaborations is that investments in this infrastructure are critical. Communications tools are rapidly improving, providing effective remote participation in meetings and in experiments. US research facilities often run experiments with a remote session leader from another laboratory or country, and hold regular group meetings attended by video conference by collaborators elsewhere. Data can be viewed and analyzed using common tools from any location. Such remote participation will aid in preparing for research on ITER, where the on-site facilities are not being designed to accommodate the large number of scientists expected to participate. It cannot, however, replace the need for an on-site presence

7.4 Recommendations Regarding Modes of Collaboration

Past and present international collaborations have provided significant benefit to US fusion research, providing many opportunities to advance scientific understanding. Flexibility in setting up collaborations has allowed them to be tailored to specific circumstances and to programmatic needs. However, at times the overall strategy behind the focus and implementation of various collaborations has been unclear. Chapter 6 dealt with identifying areas of opportunity and in this chapter we deal with implementation. Based on our examination of existing collaborations in fusion and other fields, along with expectations for future opportunities for fusion research, including US Participation in ITER, we make the following recommendations regarding modes of collaboration.

7.4-1. DOE should seek issue-based, goal-driven international collaborations that are aligned with national priorities, supported by task-based work where appropriate.

- Topics for collaboration should focus on activities that address key gaps in US capability to meet US strategic goals, evaluated using appropriate high level selection criteria such as those proposed in Chapter 1.
- Though topical in nature, it may be best to form international collaborations with single overseas facilities, recognizing their unique capabilities and program emphases, and simplifying legal arrangements to minimize administrative overhead (see Section 7.5).
- Supporting task-based activities should be aligned with the scientific goals of the collaboration where possible.

7.4-2. Mutually beneficial international partnerships should be arranged which strengthen US capabilities in fusion science.

- Research should be focused, with clear goals in mind, not broadly discipline based, so that progress towards the goal is clearly evident and cost effectiveness can be evaluated.
- Collaborations or partnerships between US teams and overseas groups with common goals are advantageous over simple "exchanges" since they better prepare the US fusion research community for ITER operation by establishing effective working relationships with ITER partners and testing models for joint research on a common facility.
- Unique and specific benefits to the US in terms of science and technology for fusion research that extend beyond what can be obtained from the published results should be clearly identified for each collaboration.
- The support and contributions provided by the international partners should be clear from the outset.

7.4-3. The portfolio of international collaborations should include a range of appropriately scaled and structured collaborations that provide opportunities for new participants on a regular basis. These include large national teams, institutional collaborations and individual exchanges, each of which has its own advantages.

- **Large national teams** may simplify arrangements and allow larger-scale activities. Smaller partners, such as University groups, should have opportunities to be part of such teams, and proposals should be coordinated. However, each institution may then be separately funded by FES, as is the case in HEP.

- **Institutional collaborations** offer more flexibility, and the benefits to the US program may be more clear. Effective partnerships may be more easily formed and managed, with less cumbersome management and decision-making processes.
- **Individual exchanges** can address particular needs in a cost effective and timely manner, offering opportunities to smaller groups, broadening participation in fusion research.

7.4-4. For large-scale collaborations, an integrated team with a flexible mix of full time, on-site researchers and shorter-term visitors should be employed, structured according to scientific roles, with support flowing directly from DOE to relevant team member institutions wherever possible.

- General experience suggests that some consistent presence of on-site personnel is very helpful to effective collaborations. On the other hand, as discussed in section 7.3, this may prevent some needed experts from participating, and can lead to isolation for the overseas researcher.
- Solicitations should encourage proposals which include a combination of longer and shorter term visits, supported by remote participation tools. The optimal mix will vary with time and the personnel involved.

7.4-5. The structure of these international collaborations should be viewed as an opportunity to develop US fusion program collaboration modalities that prepare for effective participation in ITER.

- While the detailed plans and structure for forming and operating the ITER experiment are not yet developed or in place, it is reasonable to expect that international collaborative teams will be executing the bulk of the ITER research program. Through international collaborations over the next decade, the US DOE can gain valuable experience building effective partnerships with other nations to develop successful teams for ITER participation.
- International collaborations based on multi-institutional national teams, with national lab, university and industry researchers, will provide experience relevant to making a smooth transition from existing national programs to broad US participation in ITER research.
- Issue-based collaborations addressing specific topics relevant to burning plasmas will position US research teams to make leading contributions towards the success of ITER in areas of fusion research of strategic interest to the US fusion program.
- International collaborations involving university programs will be an essential element in attracting the best and brightest young scientists and helping them develop the special skills needed to move the US forward in international fusion energy development.
- The US should be proactive in recommending to the ITER organization future modes of participation in ITER experiments; this process should involve a broad cross-section of our research community.

7.5 Recommendations Regarding Implementation

The overall success of international collaborations in fusion depends not only on the types of collaborations put in place, but also depends on a number of practical issues which can prevent or facilitate achieving desired goals. A long history of collaborations, both successful and problematic, informs our recommendations on how to proceed with establishing and expanding the US overseas collaboration program.

7.5-1. While solicitations should seek issue-based collaborations, it should be recognized in the selection and award process that it may be most effective to establish separate collaborations with each overseas facility utilizing a DOE-FES umbrella collaboration agreement with the host facility as needed.

- Each facility has unique capabilities and programmatic emphasis, with its own institutional mix, management structure, operating environment, and culture (ES&H, access, language, roles and responsibilities).
- Organizing and managing collaborations on a facility-by-facility basis can reduce management costs and complexity, streamline decision making, improve project coordination and tracking.
- Organizing collaborations on a facility-by-facility basis makes it easier to obtain reciprocal agreements or partnerships which result in significant tangible benefits to the US fusion program.

7.5-2. The solicitation and selection process should allow a range of modalities, partnerships, and opportunities in order to best utilize expertise in the US fusion program, and it should be clearly defined on the national level with open calls to establish new international collaborations or to renew existing collaborations.

- Solicitation and selection should be aligned with DOE priorities and scientific objectives for fusion research and the selection criteria for international collaborations recommended in this report or its equivalent.
- The process for obtaining funding to establish a new collaboration or grow an existing collaboration should be transparent on the national level; there should be open calls to establish new international collaborations or to renew existing collaborations.
- The selection process should recognize that increased travel costs to maintain on-site presence or to host visitors from abroad (as opposed to remote participation only) may be offset by producing much more effective collaborations and better return on investment. The benefits as well as costs should be considered when comparing proposals and allocating budgets.
- Regular renewals can offer opportunities to adjust the mix, goals, tasks, and participation for international collaborations. A balance must be maintained between the need for stability in long-term collaborations and commitments, and the need for flexibility, allowing for new participants and ideas.

7.5-3. The division and funding of collaborations should be structured according to scientific roles, with support flowing directly from DOE to relevant team member institutions wherever possible.

- US teams should seek full program integration at international facilities as appropriate.
- All large collaborations should have clearly defined arrangements between partners which not only include scientific responsibilities, but also identify governance structures such as personnel management, project teams, and advisory panels, as well as safety oversight and equitable travel support,
- Financial support from DOE should flow directly to US team members wherever possible to minimize cost.

7.5-4. DOE-FES should have a plan in place to assist collaborating institutions navigate the complex Intellectual property, and Export Control issues, and ensure safety of their personnel.

- US government regulations regarding export control are complicated and can pose a significant barrier to international collaborations involving transfer of certain hardware, software or even personnel. An informed contact at FES who can advise as to what is required and permitted will be important.
- Conflicts regarding intellectual property and publication rights for work produced during international collaborations are common. Each US and overseas institution has its own policy, and these can be contradictory; this is already preventing some collaborations, including contracts for the ITER organization. A coordinated policy negotiation, in consultation with the US laboratories, universities and companies likely to be participants, could be helpful in reducing the delays and difficulties encountered.
- Sending institutions must be assured that their personnel, including students, will have a working environment which is as safe as would be expected in the US. This may be a challenge if local language and regulations differ.

7.5-5. Capabilities for effective remote collaboration from a number of locations should be provided and expanded as remote communication technology advances

- FES should invest in the needed infrastructure, including videoconferencing, data access and analysis tools, to allow routine communication and effective work to be conducted with overseas facilities, from many US institutions. Use of common tools greatly eases complexity. The tools being developed and routinely used on US facilities and for communication within the US (such as for USBPO activities) can serve as an effective platform or model.
- Adequate and open high speed internet connections to overseas sites must be ensured as part of collaboration agreements.
- These investments will pay off in terms of increase participation, and reduced travel costs.

8.0 Findings and Recommendations

8.1 Charge 1: What areas of research on new international facilities provide compelling scientific opportunities for US researchers over the next 10 - 20 years?

Finding: Looking ahead 20 years as the ITER project reaches it goal "…to establish the scientific and technological feasibility of fusion energy for peaceful purposes " the US should be among the world leaders in fusion energy research, and possess a strong research infrastructure with the skills, facilities, and technological capabilities required to move forward to develop fusion energy. To reach this position, the US Fusion Energy Sciences (FES) program will not only require the technical capability and dynamic research infrastructure to take a leading role in ITER, but equally important, it must also develop the fusion nuclear science and technology required to apply the ITER scientific advances on a path towards a fusion power plant.

Finding: Over the 20-year timeframe contemplated in this charge to FESAC, the Panel foresees that the US FES program will be increasingly dominated by the tasks and domestic support required to ensure success and US leadership of the large international ITER undertaking. Hence, addressing the charge to FESAC to identify "compelling opportunities" for international collaboration needs to be strategically viewed as asking: "**what additional international collaborations should be pursued by a US FES program that is already expecting to be dominated by the large international ITER collaboration**?"

Recommendation: Selection of an international collaboration should be made only after careful consideration to both (1) our national goal to advance critical fusion energy science issues and (2) the need to maintain a US domestic research infrastructure that supports the US ITER mission, positions the US to benefit from ITER's success, and make an informed decision on the best approach to the design of a Fusion Nuclear Science Facility (FNSF) now under consideration.

Finding: The FESAC International Collaboration Panel adopted the three plasma related themes from the 2007 FESAC Report with minor modification as the "Major Scientific Challenges" that serve as our framework for addressing the scientific issues and scientific collaborations:

I. Achieving High Performance core plasma regimes suitable for Long Pulse ;

II. Development and Integration of Plasma Wall Solutions for Fusion;

III. Understanding the dynamics and stability of the burning plasma state.

Recommendation: These three Major Challenges should be addressed in a coordinated and phased approach. Initially, research activities can be carried out productively on all these Challenges in parallel. Challenges I and II would then be integrated as time progresses to address the non-linear coupling of the high-performance core plasma with the steady-state plasma wall solutions. Finally, the non-linear dynamics of the burning plasma state (Challenge III) would be coupled to the core plasma dynamics (Challenge I) and steady-state plasma wall solutions (Challenge II) through our physics program on the ITER experiment.

Finding: The panel developed five major evaluation criteria to provide guidance when assessing and developing compelling opportunities for international collaboration (described more fully in Chapter 3.0):

1) Importance of scientific issue to be resolved
2) Significance and distinctiveness of US contribution and potential for success
3) Positions the US to obtain optimum benefit from ITER participation and builds foundation for potential future US development path in fusion energy.
4) Strengthen, extend and regenerate US scientific workforce
5) Resource requirements and impact

Principal Finding: The Panel identifies three compelling collaborative opportunities, each of which addresses one of the three Major Scientific Challenges. Each collaborative opportunity describes the present status of the US research capability to address the issue, the opportunity for a unique contribution to successfully addressing the Scientific Challenge by using foreign facilities, and the necessary contribution coming from of the US domestic research program.

Recommendation for Collaborative Area 1: Extending High Performance Regimes to Long Pulse

The development of stationary regimes for fusion energy is an area of US world leadership, with the US having many unique capabilities to develop the physics basis, including profile flexibility, high β access, excellent diagnostics, current drive techniques, stability and ELM control tools, which it is able to apply for multiple current diffusion timescales to develop and optimize candidate solutions. But to extend solutions to ITER or an FNSF, some aspects would benefit from tests with longer pulse lengths or at larger device scale than available in the US. These particularly concern issues of plasma facing component exposure and the extension of control. However, it should be noted that in seeking such capabilities abroad, there are trade-offs in performance and device flexibility, particularly with longer pulse and larger scale facilities needing to be operated more cautiously. Thus a closely coupled collaborative program is necessary, with US facilities providing the performance, diagnostics and range to determine required approaches, while tests of long pulse compatibility and size scaling are made abroad.

Required Domestic Program Research: In domestic facilities, the US should explore the range of plasma configurations and techniques producing stable current and pressure profiles capable of self-sustainment with optimized confinement and control over instabilities including ELMs. This will provide a strong basis for US leadership in the collaboration, and determine the approaches and hardware needed. The physics understanding gained will also underpin the basis for extrapolation to ITER, FNSF and beyond.

Collaborative Opportunities Abroad: Principal elements are the size scaling and long pulse tests of the key techniques needed in regimes compatible with steady state. The former is best addressed by joint experiments and shared analysis with larger tokamaks (JET, and eventually JT-60SA). **For long pulse issues, the earliest opportunities at reasonable performance levels**

come on EAST in 2014, with significant heating power and cooled tungsten plasma facing components. In the longer term, KSTAR will provide access to similar regimes for up to 300s, though initially with carbon PFCs, and possibly a tungsten divertor later. These devices could be used to adapt control to superconducting coil sets and develop longer timescale event response and performance recovery techniques using US developed control systems, as well as addressing long pulse compatibility of required current drive systems. Corresponding inward investments could help optimize control approaches (such as 3D fields or current drive systems) in US domestic facilities. In addition, diagnostic techniques will need to be proven in long pulse conditions, to assess issues of degradation due to the plasma environment and radiation. Thus tests of US-developed diagnostic approaches in long pulse tokamaks (EAST, KSTAR) and exploitation of any available neutron-irradiation facilities would form a key part of a wider program here. Finally, W7-X offers potential to boost US theoretical and modeling capabilities on the underlying transport and transient physics with 3D magnetic field geometry, as well as gain insight into these issues for the stellarator path. Here preparatory experiments on LHD will help lever the US role on W7-X.

Benefits to US: A strong collaboration on this Scientific Challenge would provide the basis for long pulse experiments in ITER, offer the potential for an integrated physics and technology solution for an FNSF, and exploit stellarator involvement for a broader understanding, while securing US leadership, intellectual property and valuable knowledge. A balanced collaboration should also provide for US inward investment in developing key tools and modeling interpretation.

Recommendation for Collaborative Area 2: Development and Integration of Plasma Wall Solutions for Fusion

Critical Plasma Material Interaction (PMI) challenges include integrating reactor-relevant materials at prototypical operating conditions with high performance long pulse core plasmas while successfully avoiding transient and off-normal events, maintaining plasma heating and current drive capability, providing adequate PFC lifetime, maintaining fuel inventory control, and ensuring this performance in the severe irradiation environment of a power reactor. The leading PFC concept for an FNSF is tungsten, with carbon and other possibilities as backups. Unlike current confinement experiments, PFCs in a reactor will need to be at high temperature (> 600 °C). Assessing and proving these concepts these will require a multipronged Fusion Nuclear Science program.

Required Domestic Program Research: Candidate materials should be evaluated in single-effect laboratory experiments, off-line plasma simulators and suitable neutron irradiation facilities. The US is a world leader in PMI diagnostics and physics, and has a number of relevant test facilities, including several, such as PISCES, DIONYSIS and TPE which are unique. Tests should be conducted in tokamaks to assess compatibility with high performance plasmas, including interaction with RF waves for heating and current drive, fuelling, impact of transients, and material migration. Alcator C-Mod has FNSF and power plant level divertor heat fluxes and is planning the first tests (worldwide) of tungsten divertor PFCs at reactor-relevant temperatures. DIII-D and NSTX are testing carbon and lithium PFCs respectively.

Collaborative Opportunities Abroad: The US should collaborate with Asian superconducting tokamaks to upgrade to reactor-relevant PFC material and temperature at long pulse. **The proposed upgrade of EAST in 2017 to a hot tungsten divertor appears the most compelling medium term opportunity.** The US could provide experience from its hot divertor program and novel real-time PMI diagnostics, and would gain critical information needed to validate solutions for an FSNF. In the longer term, collaboration on KSTAR and JT60-SA could assess other PFC options, and integration with scenarios with higher self-driven current.

PMI issues are also critical to the success of ITER. In addition to US experiments, the US would collaborate on JET experiments with the new ITER like wall and upgraded heating. The US could contribute PWI expertise and diagnostics, and would gain experience valuable to future participation on this topical area on ITER. Critical issues to be explored with the ILW are the levels of impurities, the effects of plasma transients, the retention of tritium and the formation of dust.

Stellarators offer steady state confinement regimes eliminating transient events such as disruptions at the expense of a more complicated PMI configuration. Collaboration on LHD and W7-X provides an opportunity to develop and assess 3-D divertor configurations for long pulse, high performance stellarators. The US already has a significant collaboration in place on W7-X and is responsible for key high heat flux elements, 3D analysis codes and diagnostics. This will strengthen the US capability to pursue the stellarator as a potential path to fusion energy.

Recommendation for Collaboration Area 3: Burning Plasma Research in Advance of ITER

The US FES program has identified the study of burning plasmas, in which self-heating from DT fusion reactions dominates plasma behavior, as a key frontier and the next major step in magnetic fusion energy research. The US already has experience in operating DT experiments, developing and exploiting alpha-particle diagnostics and leading expertise in the theory of alpha dynamics and alpha-driven instabilities. Through a close coupling of theory to experiments in US facilities, which provide access to a wide range of plasma regimes, the US has developed extensive and validated predictive modeling capabilities applicable to burning plasmas.

Required Domestic Program Research: The US should continue its very successful development of theoretical models for the nonlinear evolution of energetic particle driven instabilities, and test these models in the full range of experimental conditions available in US tokamaks using results from innovative diagnostics. This is crucial to understanding burning plasma instabilities and the resulting transport. This will maintain the US at the forefront of the field, positioning it for a valuable role in JET and leadership in ITER. It should also continue to develop alpha diagnostics compatible with the fusion environment. Through its involvement in the ITPA, it should conduct experiments on its domestic facilities to develop and optimize JET DT experiments and the operating modes for ITER.

Collaborative Opportunities Abroad: The US is providing to JET both a new detector for alpha particles (and other fast ions) lost from the plasma, and diagnostics for the mode-structure of fast-particle instabilities. **Support should be provided to compare the data from these diagnostics during the planned DT experiments with modeling of the alpha particle dynamics, including the mode structures and possible mode overlap, using the**

comprehensive suite of codes developed in the US. Performing predictive modeling in advance of these experiments would provide a stringent test of the models and strengthen the foundation for predicting and optimizing the performance of ITER. The US should collaborate with JET to apply its experimental analysis and modeling codes to investigate alpha heating during the DT experiments thereby extending the capabilities of these codes in preparation for their application to ITER.

Optimizing the fusion performance in ITER requires understanding the interplay between the many factors involved in tokamak operation and building this into simulation codes. The US has made important strides in this area but to be confident of extrapolating to ITER-like conditions, it is important to validate the underlying models at the largest available scale. Critical issues for ITER remain the scaling of confinement with respect to size and the effects of isotopic mass and of alpha particles. **The US should leverage its successes in developing our understanding of tokamak confinement and in improving it by participating actively in the JET DT experiments**. Through this, the US will gain valuable knowledge about plasma transport in the conditions most closely approaching those in ITER. The ITER-like Wall in JET also provides a unique opportunity for studying performance optimization for ITER.

The US could also pursue collaboration in experiments to optimize the performance in JT-60SA as its full heating power becomes available in 2020. In JT-60SA, electron heating will be provided by both high-energy neutral beams and ECRH power, making it possible to simulate aspects of alpha-heating by using advanced feedback control of the external power in response to the plasma properties measured in real-time. This could be used to test the extrapolation of plasma control strategies and techniques developed by the US for their application to ITER.

8.2 Charge 2: What research modes would best facilitate international research collaborations in plasma and fusion sciences? Consider modes already used by these communities as well as those used by other research communities that have significant international collaborations.

Finding: Existing collaborations are the result of a case by case opportunity, and span the spectrum, as appropriate, from: individual investigator, institutional group, multi-institutional group and loose international groups organized by topic.

Finding: The US-HEP collaboration with LHC is an example of a successful structure for carrying out an effective collaboration on a complex megaproject located overseas. A significant presence is required at the host overseas facility to acquire positions of leadership and to work effectively within the large collaboration. The overseas presence is supported by strong technical capabilities at the National Labs and at Universities in the US that is ~75% of the overall budget. The experiences of the US team approach for LHC can provide a model for how the US should prepare to attain maximum benefit from participation in the ITER Research Program. However, the LHC may not provide a model for smaller collaborations

Finding: The formation of national and international research teams organized by scientific topic can be an effective research structure for international collaboration. Gaining experience with this structure in the near term would help prepare the US for participation in ITER Research.

Finding: Experience in both HEP and fusion collaborations has shown that it is essential to have effective onsite presence for the collaboration to assume a leading role in the overseas research program.

Finding: Since the cost per researcher sited overseas is significantly higher than for research sited at a home laboratory, it is critical that opportunities be carefully selected to focus on critical issues that cannot be addressed in the US and which provide clear benefit to the US program, and that their scale be no larger than necessary.

Finding: International collaborations on overseas facilities pose significant challenges for building a strong scientific workforce that must be addressed. Challenges that are common to all researchers and institutions include:

- Extended overseas assignments challenge families.
- Extended overseas assignments can create impediments to career advancement.

Recommendation: Developing a team approach that allows for flexibility and the use of remote communication tools can mitigate these challenges, as they have in HEP.

Finding: There are additional issues for university participation in international collaboration which include:

- Extended overseas assignments reduce program visibility at home institutions, which can affect faculty hiring and student recruitment. While this concern is not as serious for world-class international activities like the LHC and ITER, it will be a factor in collaborating with the smaller overseas facilities.
- Overseas assignments challenge PhD graduate education programs.

Recommendation: Given the important role played by universities in supporting faculty working on fusion research, providing fusion research with a broad connection to the larger scientific community, and the recruitment and education of future fusion researchers for ITER and beyond, universities must be included in the international collaboration program. Solicitations should be planned accordingly. Experience on successful university collaborations on major domestic fusion facilities, and in HEP, has shown the importance of supporting a linked on-campus research program

Recommendations regarding modes of collaboration

Based on our examination of existing collaborations in fusion and other fields, along with expectations for future opportunities for fusion research, including US Participation in ITER, we make the following recommendations:

DOE should seek issue-based, goal-driven international collaborations that are aligned with national priorities, supported by task-based work where appropriate.

- Topics for collaboration should focus on activities that address key gaps in US capability to meet US strategic goals, evaluated using appropriate high level selection criteria such as those proposed in Chapter 3.
- Though topical in nature, it may be best to form international collaborations with single overseas facilities, recognizing their unique capabilities and program emphases, and simplifying legal arrangements to minimize administrative overhead.
- Supporting task-based activities should be aligned with the scientific goals of the collaboration where possible.

Mutually beneficial international partnerships should be arranged which strengthen US capabilities in fusion science.

- Research should be focused, with clear goals in mind, not broadly discipline based, so that progress towards the goal is clearly evident and cost effectiveness can be evaluated.
- Collaborations or partnerships between US teams and overseas groups with common goals are advantageous over simple "exchanges" since they better prepare the US fusion research community for ITER operation by establishing effective working relationships with ITER partners and testing models for joint research on a common facility.
- Unique and specific benefits to the US in terms of science and technology for fusion research that extend beyond what can be obtained from the published results should be clearly identified for each collaboration.

- The support and contributions provided by the international partners should be clear from the outset.

The portfolio of international collaborations should include a range of appropriately scaled and structured collaborations that provide opportunities for new participants on a regular basis. These include large national teams, institutional collaborations and individual exchanges, each of which has its own advantages.

- Large national teams may simplify arrangements and allow larger-scale activities. Smaller partners, such as University groups, should have opportunities to be part of such teams, and proposals should be coordinated. However, each institution may then be separately funded by FES, as is the case in HEP.
- Institutional collaborations offer more flexibility, and the benefits to the US program may be more clear. Effective partnerships may be more easily formed and managed, with less cumbersome management and decision-making processes.
- Individual exchanges can address particular needs in a cost effective and timely manner, offering opportunities to smaller groups, broadening participation in fusion research.

For large-scale collaborations, an integrated team with a flexible mix of full time, on-site researchers and shorter-term visitors should be employed, structured according to scientific roles, with support flowing directly from DOE to relevant team member institutions wherever possible.

- General experience suggests that some consistent presence of on-site personnel is very helpful to effective collaborations. On the other hand, this may prevent some needed experts from participating, and can lead to isolation for the overseas researcher.
- Solicitations should encourage proposals which include a combination of longer and shorter term visits, supported by remote participation tools. The optimal mix will vary with time and the personnel involved.

The structure of these international collaborations should be viewed as an opportunity to develop US fusion program collaboration modalities that prepare for effective participation in ITER.

- While the detailed plans and structure for forming and operating the ITER experiment are not yet developed or in place, it is reasonable to expect that international collaborative teams will be executing the bulk of the ITER research program. Through international collaborations over the next decade, the US DOE can gain valuable experience building effective partnerships with other nations to develop successful teams for ITER participation.
- International collaborations based on multi-institutional national teams, with national lab, university and industry researchers, will provide experience relevant to making a smooth transition from existing national programs to broad US participation in ITER research.
- Issue-based collaborations addressing specific topics relevant to burning plasmas will position US research teams to make leading contributions towards the success of ITER in areas of fusion research of strategic interest to the US fusion program.

- International collaborations involving university programs will be an essential element in attracting the best and brightest young scientists and helping them develop the special skills needed to move the US forward in international fusion energy development.
- The US should be proactive in recommending to the ITER organization future modes of participation in ITER experiments; this process should involve a broad cross-section of our research community.

Recommendations Regarding Implementation

The overall success of international collaborations in fusion depends also depends on a number of practical issues which can either facilitate or impede achieving desired goals. A long history of collaborations, both successful and problematic, informs our recommendations on how to proceed with expanding the US overseas collaboration program in fusion research**.**

While solicitations should seek issue-based collaborations, it should be recognized in the selection and award process that it may be most effective to establish separate collaborations with each overseas facility utilizing a DOE-FES umbrella collaboration agreement with the host facility as needed.

- Each facility has unique capabilities and programmatic emphasis, with its own institutional mix, management structure, operating environment, and culture (ES&H, access, language, roles and responsibilities).
- Organizing and managing collaborations on a facility-by-facility basis can reduce management costs and complexity, streamline decision making, improve project coordination and tracking.
- Organizing collaborations on a facility-by-facility basis makes it easier to obtain reciprocal agreements or partnerships which result in significant tangible benefits to the US.

The solicitation and selection process should allow a range of modalities, partnerships, and opportunities in order to best utilize expertise in the US fusion program, and it should be clearly defined on the national level with open calls to establish new international collaborations or to renew existing collaborations.

- Solicitation and selection should be aligned with DOE priorities and scientific objectives for fusion research and the selection criteria for international collaborations recommended in this report or its equivalent.
- The process for obtaining funding to establish a new collaboration or grow an existing collaboration should be transparent on the national level; there should be open calls to establish new international collaborations or to renew existing collaborations.
- The selection process should recognize that increased travel costs to maintain on-site presence or to host visitors from abroad (as opposed to remote participation only) may be offset by producing much more effective collaborations and better return on investment. The benefits as well as costs should be considered when comparing proposals and allocating budgets.
- Regular renewals can offer opportunities to adjust the mix, goals, tasks, and participation for international collaborations. A balance must be maintained between the need for stability in

long-term collaborations and commitments, and the need for flexibility, allowing for new participants and ideas.

The division and funding of collaborations should be structured according to scientific roles, with support flowing directly from DOE to relevant team member institutions wherever possible.

- US teams should seek full program integration at international facilities as appropriate.
- All large collaborations should have clearly defined arrangements between partners which not only include scientific responsibilities, but also identify governance structures such as personnel management, project teams, and advisory panels, as well as safety oversight and equitable travel support.
- Financial support from DOE should flow directly to US team members wherever possible to minimize cost.

DOE-FES should have a plan in place to assist collaborating institutions navigate the complex Intellectual property, and Export Control issues, and ensure safety of their personnel.

- US government regulations regarding export control are complicated and can pose a significant barrier to international collaborations involving transfer of certain hardware, software or even personnel. An informed contact at FES who can advise as to what is required and permitted will be important.
- Conflicts regarding intellectual property and publication rights for work produced during international collaborations are common. Each US and overseas institution has its own policy, and these can be contradictory; this is already preventing some collaborations, including contracts for the ITER organization. A coordinated policy negotiation, in consultation with the US laboratories, universities and companies likely to be participants, could be helpful in reducing the delays and difficulties encountered.
- Sending institutions must be assured that their personnel, including students, will have a working environment which is as safe as would be expected in the US. This may be a challenge if local language and regulations differ.

Capabilities for effective remote collaboration from a number of locations should be provided and expanded as remote communication technology advances.

- FES should invest in the needed infrastructure, including videoconferencing, data access and analysis tools, to allow routine communication and effective work to be conducted with overseas facilities, from many US institutions. Use of common tools greatly eases complexity. The tools being developed and routinely used on US facilities (such as for USBPO activities) can serve as an effective platform or model.
- Adequate and open high speed internet connections to overseas sites must be ensured as part of collaboration agreements.
- These investments will pay off in terms of increase participation, and reduced travel

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Appendices

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Appendix a: Charge Letter

Department of Energy
Office of Science
Washington, DC 20585

Office of the Director

July 22, 2011

Dr. Martin Greenwald
Plasma Science and Fusion Center
Massachusetts Institute of Technology
77 Massachusetts Avenue, NW16
Cambridge, MA 02139

Dear Dr. Greenwald:

I request that FESAC address the opportunities for the U.S. plasma and fusion research communities presented by new or soon-to-be commissioned fusion facilities outside the US. In addition, I would like FESAC to elucidate the research needed to fill the gaps in materials science and technology required to sustain fusion plasma operations and to harness fusion power.

There are two reasons to investigate the international research opportunities now. First, plasma dynamics and control may well be defined by the capabilities of facilities that use superconducting magnet technology – currently all overseas. These facilities are at the forefront of advanced tokamak and stellarator research, and they present significant new opportunities for U.S. engagement. In fact, in some cases the U.S. has been invited to participate in setting program direction. Second, budget realities make it unlikely that the U.S. will construct a major new domestic facility for some time, and certainly not during the period of ITER construction. Regarding materials science, technology, and harnessing fusion power, you are already aware of the gaps that have been identified in the world program that must be filled if ITER is to be the penultimate step to a DEMO, and the opportunities for U.S. leadership through well-posed initiatives in these areas of research.

With this in mind, I ask FESAC to consider the following.

1. What areas of research on new international facilities provide compelling scientific opportunities for U.S. researchers over the next 10 – 20 years? Look at opportunities in long-pulse, steady-state research in superconducting advanced tokamaks and stellarators; in steady-state plasma confinement and control science; and in plasma-wall interactions.

2. What research modes would best facilitate international research collaborations in plasma and fusion sciences? Consider modes already used by these communities as well as those used by other research communities that have significant international collaborations.

3. What areas of research in materials science and technology provide compelling opportunities for U.S. researchers in the near term and in the ITER era? Please focus on research needed to fill gaps in order to create the basis for a DEMO, and specify technical requirements in greater detail than provided in the MFE ReNeW (Research Needs Workshop) report. Also, your assessment of the risks associated with research paths with different degrees of experimental study vs. computation as a proxy to experiment will be of value.

I look forward to receiving your assessments by January 31, 2012.

Sincerely,

W. F. Brinkman
Director, Office of Science

Appendix b:

FESAC International Collaboration Panel 2011

David Anderson, U. Wis. – Fusion research

Michael Bell, PPPL – Fusion research

Richard Buttery, GA – Fusion research

Jeffrey Harris, ORNL – Fusion research

David Hill, LLNL – Fusion research

Amanda Hubbard MIT – Fusion research

Gerald Navratil, Columbia University – Fusion research

Robert Rosner Univ of Chicago – Astronomy research

George Tynan, UCSD – Fusion research

Frank Wuerthwein, UCSD – High Energy Physics research

Wesley Smith, U. Wis. – High Energy Physics research

Dale Meade, Chair, FIRE – Fusion research

Martin Greenwald, MIT – FESAC Chair

Albert Opdenaker, DOE-FES – FESAC DFO

Appendix c:

Panel Process and Meetings

The panel held two in person meetings
November 17, 2011, APS-DPP Meeting, Salt Lake City, Utah
December 19-21, 2011, General Atomics, La Jolla, CA

The panel held 28 meetings by conference calls using ESNet Collaboration Service Ready Talk with video support.

A presentation was made at the University Fusion Association meeting at the APS-DPP meeting on November 14 with public discussion. A special public input session was organized and held at the APS-DPP meeting on November 16, 2011. Several requests were made to the fusion community requesting White Papers related to the FESAC Panel charge on International Collaboration. A total of 18 white papers were received from the community, and were posted on a public information web site at http://fire.pppl.gov/fesac_intl_collab_2011.html.

White Papers submitted to the FESAC Panel

Baylor, Larry – Experience, Success factors, Exploitation of US Pellet Injection Capability
Doyle, Ed – Diagnostics, Funding Mechanism for Spectrum of Opportunities and Challenges
Finn, John – MHD Control on RFPs for Tokamaks
Greenwald, Martin – Technology for Remote Experimental Participation
Hutchinson, et. .al – Domestic and International Plasma Fusion Facilities in Education
Hwang, David – Compact Torus Injection for Fueling and Disruption Mitigation
Lipschultz, Bruce – PFC Issues Related to DEMO, esp PFCs at High Temperature
Lombardo, Lynette – Imaging and Visualization Diagnostic for Collaboration
Mordijck, Saskia – Travel Issues for University groups to attend ITPA
Okabayashi, Michio – Joint US/Japan MHD workshop as a Model
Raman, Roger – Collaboration with the QUEST-ST in Japan for Long Pulse Tokamaks
Ruzic, David – Lithium as PFC and Specific Funding for Students
Sabbagh, Steve – MHD Issues and IC Issues for University groups
Stangeby, Peter – Unique Opportunities for US Collaboration in Plasma-Wall Interaction Research in JET and EAST
Smith, Roger – Pulsed Polarimetry Diagnostic for ITER and DEMO
Wurden, Glen – Observations based on 20 Years of Experience with International Collaborations
Xu, X. Q. – International Collaboration on Plasma Science and Control
Young, Ken – Operational Considerations for U.S. Scientists Collaborating on Experimental Magnetic Fusion Devices Abroad

Appendix d:

Acronyms and Abbreviations

2-D	Two-dimensional, sometimes used to describe axisymmetric systems
3-D	Three-dimensional, sometimes used to describe non-axisymmetic systems
AE	Alfvén Eigenmode, a plasma wave
Alpha	product of DT fusion reaction, at 3.5 MeV has 20% of the reaction energy
APS	American Physical Society
APS/DPP	American Physical Society/Division of Plasma Physics
ARIES	Advanced Reactor Innovation Evaluation Studies
ARIES-AT	ARIES -Advanced Tokamak Design of a fusion power plant
ASDEX	A tokamak experiment at Max-Planck Institute, Germany
AT	Advanced Tokamak has high beta and large self-driven plasma current
AUG	ASDEX-Upgrade, tokamak at Max Planck Institute for Plasma Physics, Germany
B	Magnetic field produced by current flowing in coils, used to confine plasma
BES	Beam Emission Spectroscopy
Beta	β = the ratio of plasma pressure to magnetic field pressure
Bootstrap	refers to Bootstrap current, a self generated current within a toroidal plasma
CER	Charge Exchange Recombination (spectroscopy diagnostic)
CFC	Carbon Fiber Composite, used as a material for plasma facing components
C-Mod	(or Alcator C-Mod) A tokamak at the MIT Plasma Science and Fusion Center
CTF	Component Test Facility for integrated testing in a fusion environment
CTH	A compact stellarator-tokamak hybrid at Auburn University in Alabama
D-D	Deuterium-Deuterium, low reactivity fusion fuel used in laboratory experiments
DEMO	Demonstration fusion power plant
DIII-D	A tokamak at General Atomics (GA)
DOE	Department of Energy
D-T	Deuterium-Tritium, high reactivity fusion fuel for fusion power plants
EAST	Experimental Advanced Superconducting Tokamak in China
EBW	Electron Bernstein Wave
ECCD	Electron Cyclotron Current Drive
ECH	Electron Cyclotron Heating
ECRF	Electron Cyclotron Range of Frequencies
ELM	Edge Localized Mode, of interest because it releases bursts of energy to PFCs
EPM	Energetic Particle Mode, instability driven by energetic particles
EU	European Union
eV	Electron Volt, a unit of energy
FES	Office of Fusion Energy Science in the Department of Energy
FESAC	Fusion Energy Sciences Advisory Committee
FNSF	Fusion Nuclear Science Facility for integrated tests of components and scenarios
FSP	Fusion Simulation Program
FTU	Frascati Tokamak Upgrade, a tokamak in Italy
GA	General Atomics, California
GHz	Gigahertz, a billion cycles per second

GW	Gigawatt, a billion watts
H-Mode	High-confinement Mode, regime with edge transport barrier
HSX	Helically Symmetric Experiment, a stellarator at the University of Wisconsin-Madison
IBW	Ion Bernstein Wave
ICRF	Ion Cyclotron Range of Frequencies
IFMIF	International Fusion Materials Irradiation Facility
INL	Idaho National Laboratory, Idaho
ITER	International burning plasma experiment being built in Cadarache, France
ITPA	International Tokamak Physics Activity
JAEA	Japan Atomic Energy Agency
JET	European tokamak sited in the UK
JT-60SA	Japanese Tokamak-Super Advanced (under construction) at JAERI
JT-60U	Japanese Tokamak-Upgrade at JAERI (decommissioned)
kA	Kiloampere
keV	Kiloelectron Volt
KSTAR	Korea Superconducting Tokamak Advanced Research device in South Korea
low-A	Low aspect ratio
LANL	Los Alamos National Laboratory, New Mexico
LHCD	Lower Hybrid Current Drive
LHD	Large Helical Device, a stellarator experiment in Japan
LHRF	Lower Hybrid Radiofrequency
Li	Lithium, of interest as a coating for PFCs
LLNL	Lawrence Livermore National Laboratory, California
LTX	Lithium Tokamak Experiment at PPPL
MA	Mega Ampere
MAST	Mega Ampere Spherical Tokamak at Culham Laboratory, UK
MAST-U	Mega Ampere Spherical Tokamak-Upgrade at Culham Laboratory, UK
MeV	Million Electron Volt
MFE	Magnetic Fusion Energy
MHD	Magnetohydrodynamics
MIT	Massachusetts Institute of Technology, Massachusetts
MHz	Megahertz, a million cycles per second
MJ	Megajoule, a million joules
MST	Madison Symmetric Torus, a reversed field pinch experiment at the University of Wisconsin-Madison
MW	Megawatt, a million watts
NBCD	Neutral Beam Current Drive
NBI	Neutral Beam Injection
NCSX	National Compact Stellarator Experiment (cancelled) at PPPL
NNBI	Negative-ion-based Neutral-beam Injection
NRC	National Research Council
NSTX	National Spherical Torus Experiment at PPPL
NSTX-U	National Spherical Torus Experiment-Upgrade at PPPL
NTM	Neoclassical Tearing Mode
ORNL	Oak Ridge National Laboratory, Tennessee

PEGASUS	A spherical torus experiment at the University of Wisconsin-Madison
PF	Poloidal Magnetic Field
PFC	Plasma Facing Component
PMI	Plasma-material Interaction
PoP	Proof of Principle
PPPL	Princeton Plasma Physics Laboratory, Princeton University, New Jersey
PSFC	Plasma Science and Fusion Center, MIT, Massachusetts
PSI	Plasma-surface Interaction
PWI	Plasma-wall Interaction
Q	The ratio between fusion power produced and heating power supplied
QS	Quasi-symmetric
R&D	Research and Development
ReNeW	Research Needs Workshop (Magnetic Fusion Energy Sciences)
RF	Radiofrequency
RFP	Reversed Field Pinch, a magnetic confinement system with low toroidal field
RFX	A reversed field pinch experiment in Padova, Italy
RMP	Resonant Magnetic Perturbation, method of ELM control
RWM	Resistive Wall Mode, plasma instability allowed by a resistive first wall
SciDAC	Scientific Discovery through Advanced Computing
SC	Superconducting, conductor used to construct magnets requiring low power
SiC	Silicon Carbide, a candidate material for PFCs
SOL	Scrape-off Layer, boundary layer between hot fusion plasma and first wall
ST	Spherical Torus, a low aspect ratio tokamak confinement system
Stellarator	a magnetic confinement system using strong 3-D magnetic fields
TAE	Toroidal Alfvén Eigenmode instability driven by energetic particles (e.g. alphas)
TBM	Test Blanket Module
TF	Toroidal Magnetic Field
TFTR	Tokamak Fusion Test Reactor (decommissioned) at PPPL
Tokamak	a magnetic confinement system with 2-D magnetic fields and a plasma current
Torus	a 3-D surface topologically similar to the surface of a donut
Tore Supra	A superconducting tokamak experiment in France
TRANSP	A time-dependent tokamak transport analysis code
UCLA	University of California at Los Angeles
UCSD	University of California at San Diego
UEDGE	A two-dimensional plasma-fluid transport code
USIPO	US ITER Project Office
W	Tungsten, a candidate material for PFCs in a fusion environment
W7-AS	Wendelstein-7 Advanced Stellarator, a stellarator experiment in Germany (decommissioned)
W7-X	Wendelstein-7X, an optimized stellarator being built in Germany
Z	Atomic number
Zeff	Effective atomic number, a measure of impurity content