Written Testimony of Stewart Prager
Director, Princeton Plasma Physics Laboratory
Professor of Astrophysical Sciences
Princeton University

Delivered to the
Committee on Science, Space and Technology Subcommittee on Energy
For the hearing on April 20, 2016

Thank you for the opportunity to appear before this subcommittee and to offer testimony on the Princeton Plasma Physics Laboratory, PPPL (its mission, current activities, and future opportunities) and the ITER project (its importance and relation to American fusion research). My name is Stewart Prager, and I have been director of PPPL since 2009. I am also a professor of astrophysical sciences at Princeton University. I have been involved in fusion energy research for my entire career, including 31 years at the University of Wisconsin and two years at General Atomics.

The PPPL Mission

The Princeton Plasma Physics Laboratory (PPPL) is a Department of Energy national laboratory managed by Princeton University. It has the dual mission to (1) develop the knowledge to realize fusion energy and (2) develop fundamental plasma science and its many applications in science and industry. The two missions are complementary in that plasma physics is the scientific field that underlies the quest for fusion energy (the core of a fusion energy system is a 100 million degree plasma). PPPL is the only national laboratory dedicated to plasma physics and fusion energy. Within these fields, its scientific activities and interests are very broad. In addition, as the national laboratory for fusion and plasma physics, PPPL has a unique responsibility to nurture the field in the US – contribute to the health of the national effort, particularly that of the university community. PPPL employs a staff of nearly 500, all employees of Princeton University, with an annual budget of about $100M.

The applications of plasma science, beyond the huge application of fusion energy, are significant; at PPPL we study processes in astronomical plasmas, plasma space weather, plasma for synthesizing nanostructures, plasmas under extreme conditions of high density, and plasma centrifuges for nuclear waste remediation. Our work leads to interesting spin-offs, from electromagnetic wave pasteurization of eggs to miniaturized detectors for nuclear hazardous materials.

For the remainder of my testimony I will focus on our research in magnetic fusion energy science, which constitutes the majority of PPPL's research effort. In this approach, the hot plasma is contained by a strong magnetic field.

Current Research in Fusion Energy Science at PPPL

Research at PPPL concentrates on projects and ideas that are innovative, unique, and at the world forefront. Such criteria are particularly key in the current budget-constrained environment of fusion energy research in the US. In the past decade, nations in Asia and the European Union have invested substantial research dollars in new fusion facilities to establish scientific capabilities not previously available. In S. Korea, China, Germany, and Japan, new facilities (with construction costs in the range of $1B) have recently begun operation or are under construction. All of them operate with superconducting magnets, which allow sustainment of the plasma for long periods of time. For the US to contribute uniquely, to move fusion forward aggressively, and to be internationally competitive in the face of larger investments elsewhere, we must focus on activities with breakthrough potential.

Research at PPPL aims for innovation in four major areas: the challenge of how one surrounds a 100 million degree plasma by a survivable material; plasma behavior in new confinement regimes that offer the possibility of reduced-size steps in the development of fusion; the use of large-scale computational capabilities for new insights in the complex fusion systems; and physics research that is key to the success of ITER (the international fusion project currently under construction). These research areas, and PPPL activities within them, are fully aligned with the mission and plans of the DOE Office of Fusion Energy Science.

We are currently at a propitious moment at PPPL. We have recently begun research operations of an essentially new experimental facility – the National Spherical Torus Experiment - Upgrade (NSTX-U). This experiment cuts across all of the four topic areas above. It is the result of a four-year, $94M upgrade of its predecessor (NSTX), and was completed on schedule and on cost. We are grateful for the support of Congress and the Administration, and the investment in this upgrade. NSTX-U explores the plasma configuration known as a spherical tokamak (ST). The ST is a tokamak – a donut-shaped plasma confined by a magnetic field – but with a very small hole in the center of the donut. NSTX-U is a DOE user facility, with about 350 research participants from nearly 60 institutions in the US and abroad. It is the most capable spherical tokamak in the world (working in partnership with a sister facility – MAST-U – in England).

NSTX-U is an experiment in fundamental science, with application to fusion energy. Its mission is to understand how the plasma confinement behaves at high temperature, and how it varies with size and shape of the donut. It will explore novel approaches to the plasma-wall interface, and it will test theoretical predictions of plasma behavior in ITER and other future experiments.

The ST concept investigated by NSTX-U can operate at high plasma pressure (which provides more fusion power) and at relatively weak magnetic field (which reduces cost) compared to conventional tokamaks. The practical impact is that this offers the possibility, for example, of designing a fusion pilot plant or fusion nuclear science facility of a size significantly reduced from that based on conventional tokamaks. A fusion pilot plant would generate net electricity and perform an integrated test of a full fusion energy system, including testing materials components in the presence of copious fluxes of neutrons that are produced in the fusion reaction. A fusion nuclear science facility provides an integrated test, but does not aim for net electricity production. The pilot plant would employ high temperature superconducting magnets because they offer reduced magnet size (but require technological development). Either facility would be a huge step forward toward practical fusion energy.

NSTX-U will establish the physics basis for these next steps. We do not currently know whether the plasma confinement properties of the ST are sufficient for a pilot plant of fusion nuclear science facility. The results of NSTX-U will determine whether or not the physics is in hand to move, with reasonable confidence, to those next steps. To do so, NSTX-U will produce plasmas in physics regimes substantially closer to that of a reactor than prior ST facilities. Thus, it will explore new physics that pushes the frontier of our understanding of plasma turbulence and stability.

NSTX-U will study novel solutions to the major challenge of the interface between the hot plasma and its surrounding material. This is accomplished by two approaches. First, we will investigate the concept of whether the plasma can be surrounded by a liquid metal, rather than a solid. This is potentially a breakthrough solution to this problem (discussed below). Second, we will investigate advanced techniques to use a magnetic channel to spread out the huge flux of heat (reducing the intensity of heat bombardment on materials) and direct it to specially prepared surfaces.

NSTX-U is also exploiting its special configuration to provide information in many areas for ITER, the future centerpiece of the world fusion program. To cite just two examples: (1) NSTX-U is able to produce plasmas that can study deeply the effect on plasma stability of the energetic particles that are produced in the fusion reaction and (2) NSTX-U has a program for a comprehensive study of plasma disruptions – sudden terminations of the hot fusion plasma – that are essentially unallowable in a fusion energy system.

At PPPL, many efforts are underway to study the challenge of the plasma-material interface. Surrounding the plasma by solid tungsten is successful for current experiments which do not operate for long periods of time. However, it remains unknown whether such a solid will survive in a fusion energy system, and if it does survive, whether it will have a deleterious effect on the hot plasma that it surrounds. A complementary approach is to surround the plasma by a liquid, such as a liquid metal, rather than a solid. Liquids are not damaged by plasma, are not damaged by neutrons and, if moving, a liquid can carry out the heat from the plasma. Liquid lithium has a large additional advantage: the remarkable property that it is highly absorbing. Cold gas is not injected into the plasma, and confinement is improved.

Thus, liquid metal for fusion materials offers a breakthrough solution to a major challenge for fusion energy – a survivable material, possibly with improved confinement. However, research into this solution is at an early stage. We do not yet know whether it will work. PPPL is carrying out a program, although budget-constrained, to determine the answer. It requires advances in both the fundamental material science of liquids and the plasma physics associated with the plasma-material interaction. It is a unique, innovative, science program of central importance to the future of fusion.

Much of modern science is being transformed by new opportunities in computing. The fusion plasma system is a complex merger of phenomena and is ideally suited to advances through large-scale computation. Indeed, the fusion community has long been a leader in scientific computing. The fusion plasma system is characterized by phenomena that occur over a range of time scales from billionths of a second (the time it takes an electron to complete a circular orbit about the magnetic field) to hours (the time over which the large plasma evolves). Correspondingly the spatial scales vary from sub-millimeter (the radius of an electron orbit) to meters (the size of the plasma). The phenomena that occur at these scales are both fascinating and complex – involving waves, turbulence, sudden changes in magnetic field, superthermal particle behavior, macroscopic stability and more. And these phenomena, at widely disparate space and time scales, all couple together to determine the behavior of the fusion plasma system.

With the dramatic evolution of computing capability we can solve the equations that describe integrated aspects of fusion plasmas. Such computational solutions of plasma equations, merged with analytic theory and experiment, is providing new insights into plasma behavior and new predictive capability. PPPL has developed codes that treat the disparate phenomena and scales, and is leading a focused, national initiative to propose to exploit new supercomputer (exascale) capabilities. The PPPL program provides codes of use worldwide, applies these capabilities to the most scientifically challenging problems (such as turbulence and disruptions), compares code results to experiments around the world, and works jointly with the NSTX-U experimental team.

Research key to ITER physics is an integral part of the program at PPPL. The computational initiative just described, as well as NSTX-U, is aimed for particular relevance to ITER, such as through a comprehensive study of disruptions and studies of instabilities from energetic particles generated in the fusion reaction. Finally, PPPL operates a program of off-site research in tokamaks in the US and abroad that is aimed to establish physics results for ITER. The largest such collaboration is with the DIII-D tokamak in the US. PPPL also contributes actively to fabrication tasks for ITER – in particular delivery of electrical systems for plant operation and management of US contributions to ITER diagnostics.

Future Opportunities for PPPL Research

Current PPPL research activities span the next decade. NSTX-U has a robust, exciting ten-year research plan. Assessing the scientific implications of a liquid metal plasma-surrounding materials is at its early stages. Computation using exascale is an emerging opportunity. And the next decade will remain important for contributions to ITER, which is expected to begin operation in about ten years.

However, scientific opportunities abound for world-leading, major initiatives for PPPL and the US. To be ready to seize opportunities over the next decade, we are developing options now. In addition, PPPL is a greatly under-utilized resource for the nation, in two respects. First, the physical infrastructure includes capabilities that are unexploited, such as large experimental high bay areas and electrical power. Second, and even more importantl\, the PPPL staff has broad, world-class expertise and ideas that are not being fully tapped. At present, the laboratory can contribute much more to the national and international effort in fusion energy.

Currently, we are scoping three possible future opportunities for PPPL and the US (in addition to active US participation in ITER research). The first would initiate in about ten years, after we learn more from NSTX-U; but the times of initiation of the other two opportunities are simply limited by resource constraints.

The spherical tokamak path for fusion development: NSTX-U will establish the physics basis for the ST path to major next steps in fusion energy development. If the results are favorable, a compelling next step might be to begin design of a fusion pilot plant or a fusion nuclear science facility (FNSF). Such a leap forward would bring the world enormously closer to commercial fusion energy. A pilot plant or FNSF, both described above, would provide an integrated test of a fusion energy system, achieving major demonstrative milestones such as net electricity generation from fusion (if a pilot plant were to move forward). PPPL aspires to be the scientific leader of the design and research operations of the facility. Such an endeavor would be a major, national effort.

Three-dimensional magnetic confinement (the stellarator path to fusion energy): With the advent of supercomputing capabilities, new designs for fusion systems have been developed which were inconceivable 20 years ago. We can now incorporate our full knowledge of the physics of fusion plasmas – as well as new theoretical insights - to produce designs that are highly optimized for an attractive system. The tokamak has a feature that it is symmetric the long way around the donut. However, once that design constraint is relaxed, a wide array of new designs becomes possible. Such designs are called stellarators, and are arguably the most physics-optimized designs for fusion. They can possess the favorable energy confinement of the tokamak, but also have the crucial features that they operate indefinitely, are free of disruptions (events that terminate the plasma and can sometimes damage the facility) and have a higher energy gain. In one view of fusion energy development, the tokamak will very successfully establish the science of burning plasmas (through ITER), but the stellarator should be developed in parallel as the ultimate commercial reactor. Recently, a new, optimized stellarator began operation in Germany (the W7-X experiment, with a construction cost in the range of $1B), for which PPPL is the US's primary interface. This experiment will establish key features of stellarator confinement. However, there are a variety of different stellarator designs. The W7-X design scales to a very large commercial reactor. Complementary stellarator designs have been developed that are substantially more compact, and have an interesting feature of having a near-symmetry similar to the tokamak, while retaining the additional favorable features of the stellarator. Operating such an experiment at PPPL, in the context of a national stellarator program, would place the US at the world forefront in the development of possibly the most optimized route to an energy-producing reactor.

Liquid metals for the plasma-facing material: As discussed above, a crucial obstacle to overcome for fusion is to develop a material that will survive in a fusion reactor environment and, conversely, that the plasma will remain hot in the presence of the reflux of cold gas from the wall into the plasma. Over the next 5 – 10 years, PPPL has a vision for a comprehensive study of liquid metals – from the fundamental materials science to partial tests in tokamaks. If this near-term research produces favorable results, a possible next step would be to perform an integrated, decisive test of the concept in a fusion facility designed and optimized to accommodate the most advanced liquid metal scheme derived from prior research. Such a facility would study the full, integrated effects of liquid metals – on confinement, on the plasma-liquid interaction, on the fluid dynamics of a flowing system. Individual effects can be investigated in focused tests, setting the stage for the integrated study. If the concept proves successful, it would then be a key advance for inclusion in all future burning plasma facilities.

US research on ITER: In parallel with one or more of the essential efforts above, PPPL research will continue to have a major focus on ITER and burning plasmas (described below). PPPL aspires to lead the US research team on ITER and is optimistic about applying a new model to this effort. Over the past few years, PPPL has established an effective new model for collaboration on facilities abroad, based on its work with the new W7-X stellarator in Germany. PPPL has assembled and coordinated a US research team, currently consisting of seven institutions, including other universities and national labs. This model has been effective for W7-X, and is also functioning as a testbed for a model that can be applied to ITER.

The Importance of ITER

ITER will be the first experiment to investigate the behavior and control of burning plasmas – a fusion plasma that is self-sustaining. In a burning plasma the heat from the fusion reactions themselves keep the plasma hot and fusing. A plasma that is burning can behave qualitatively differently than non-burning plasmas. When a plasma becomes self-heated, the complexity is enhanced and its study is at the forefront of plasma physics.

Investigating and understanding burning plasmas is an essential gateway to commercial fusion. ITER is the current path to this crucial goal. The results from ITER will critically inform fusion development, whether we head toward a tokamak reactor or a reactor based on a complementary concept. In addition, ITER will test key technologies at the scale of a fusion reactor. It will generate 500 million watts of thermal fusion power for periods of about 400 seconds. When successful, ITER will be a landmark experiment in science and energy of the 21st century. It will be the central focus of the world program in fusion research, complemented by strong domestic research programs in participating nations around the world.

The Relation of ITER to US Fusion Research

It is imperative that the US fusion research program maintains both active participation in ITER and simultaneously a very strong domestic research program. We need to participate in ITER so as to be fully engaged in the burning plasma science that is crucial to fusion energy development. We need a strong domestic program for two reasons. First, without a strong domestic program we will not have the capability either to extract information from ITER or to contribute strongly to it. The logic for US participation in ITER is predicated on a strong domestic program to allow us to benefit from our investment in ITER construction. Second, ITER does not solve all the challenges for commercial fusion energy. ITER attacks the crucial issue of burning plasmas, but is not aimed to solve the challenges of steady state operation, the plasma-material interface, fusion nuclear science or further magnetic configuration optimization. We can only arrive at fusion energy with a strong domestic program complementing ITER, and the vast contributions being made by many other nations. Thus, most ITER partners are enhancing their domestic programs as they contribute to ITER construction, as we should too.

The US fusion program currently consists of three major tokamak facilities, and a broad experimental and theoretical research program located at universities and national laboratories. The three major tokamak facilities form a triad of complementary capabilities that contribute critically to the world fusion program – the CMOD facility at MIT (planned to complete its operations in FY16), the DIII-D facility at General Atomics, and NSTX-U at PPPL. The facilities contribute directly to critical issues for ITER and to many of the remaining fusion plasma science challenges for fusion energy. The US university community provides foundational contributions to fusion energy research. University research essentially spans the full range of fusion challenges. Universities provide innovative solutions to these challenges, span a broad range of expertise, and couple to the broader scientific community available on campuses. Contributions are made through experiments conducted on-site, through university collaborations on user facilities in the US and abroad, and through theoretical and computational research. Currently, there is a strong need to reinvigorate US university research in fusion energy.

Stewart Prager

Stewart Prager is director of the Princeton Plasma Physics Laboratory, a Department of Energy national laboratory, and professor of astrophysical sciences at Princeton University. He received his Ph.D. degree in plasma physics from Columbia University in 1975. Following two years performing fusion energy research at General Atomics in San Diego he joined the University of Wisconsin – Madison as an assistant professor of physics. Prager remained at the University of Wisconsin, as Dexter Professor of Physics, until 2009 when he assumed his position at Princeton.

Prager's research has focused on basic plasma physics, particularly applications to fusion energy and, more recently, applications to astrophysics. While at Wisconsin, Prager was director of the Madison Symmetric Torus (MST) experimental facility. He also served as founding director of the Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas, established through the National Science Foundation program of "physics frontier centers." He has served as Chair of the Fusion Energy Sciences Advisory Committee for DOE, Chair of the Division of Plasma Physics of the American Physical Society, President of the University Fusion Association, and a member of the fusion review panel of the President's Council of Advisors in Science and Technology. Prager is a co-recipient of the American Physical Society Dawson Award for Excellence in Plasma Physics and is a fellow of the American Physical Society.