Perspective on: The future of fusion

May 13 2011, By Kitta MacPherson

Caption: PPPL scientist Charles Skinner works on the National Spherical Torus Experiment, the lab's main experimental facility.

Stewart Prager, a well-known plasma physicist and fusion scientist with a distinguished career and a record of discovery at the University of Wisconsin, arrived in January 2009 as director of PPPL, the United States' leading magnetic fusion facility. Fusion energy, which is fueled by hot gases of charged particles known as plasma, has the potential to become a safe, clean and abundant energy source for the future. For nearly 60 years, Princeton has been a world leader in research on magnetic fusion energy due to efforts by scientists and engineers at PPPL. In 1994, an experimental device built at the lab, known as the Tokamak Fusion Test Reactor (TFTR), yielded an unprecedented 10.7 million watts of fusion power. As head of the lab, Prager is directing fundamental inquiries to establish the knowledge base for fusion energy, to understand how plasmas behave and to apply this understanding to a wide range of applications. The facility is managed by Princeton University and funded by the DOE's Office of Science.

What new initiatives have you been focusing on since assuming the leadership at PPPL?

PPPL scientists regularly generate intriguing new ideas. We have made great progress toward a major enhancement of our major experimental facility – the National Spherical Torus Experiment or NSTX. We have funding for an upgrade that will yield an order-of-magnitude improvement in its physics capabilities – a doubling of the plasma current, doubling of the heating power, and quintupling of the plasma duration. This will expand the physics parameter space, advancing all the NSTX missions. We expect to complete the upgrade in three to four years, so the upgrade will guarantee the scientific vitality of NSTX for at least a decade into the future.

Before the upgrade starts, we will be running experiments on NSTX starting in July and running eight months where researchers will study how heat escapes as hot magnetized plasma, and what materials are best for handling intense plasma powers.

We have also moved forward with new studies of a liquid boundary for a fusion plasma, in contrast with the more common solid boundary, with expanded operation of our exploratory Lithium Tokamak Experiment (LTX), and have enjoyed very promising interactions with materials and surface scientists in the engineering school.

PPPL has led a two-year national planning effort to define a program to apply the most powerful computers to model the whole, complex fusion plasma system. We have plans for expanded work in plasma astrophysics, and have led a national study to define opportunities in this field. Looking into the fusion future, we have completed a conceptual study of a fusion pilot plant as a possible next step for the U.S. fusion program, investigating various designs and the strategic implications of such a step. At PPPL we are generating many new ideas and initiatives, even in this difficult budgetary climate.

Fusion scientists, like you, have been working to produce fusion reactions for many decades. Why is it so hard to create fusion energy?

In a nuclear fusion reaction, two atomic nuclei fuse and release energy. In a fusion reactor, the core will contain the plasma producing this energy. It's a difficult process because it requires making a hot gas that is 10 times hotter than the core of the sun -- 100 hundred million degrees -- and confining that for long periods of time in a controllable way. Plasmas exhibit complex behavior that is difficult to understand. The engineering challenge is also huge, because you have to surround this hundred million degree plasma by a material structure. We often say that fusion is maybe the most or one of the most difficult science and engineering challenges ever undertaken.

Also, researchers had to create an entirely new area of science to work through this problem. It's as if you said, "Let's go cure cancer," but the field of microbiology did not exist. You'd first have to go and establish this field of science. So that's what began in the very late 1950s, establishing this field of plasma physics, with the goals of understanding how plasmas behave and learning how to control plasmas.

Why should the U.S. maintain its funding of the fusion program?

The first reason is U.S. competitiveness, both the specific competitiveness in fusion and the general competitiveness in science and technology. Whoever controls the energy sector, whoever innovates with the science, is going to be economically dominant. Fusion is a perfect case study of where we can be either retaining our competitiveness or we can give it up. If the latter, we will be importing fusion reactors.

Second, in fusion, our contributions are needed. The U.S. has a workforce for fusion that is second to none. In other countries, they have outbuilt us and they may have better hardware. But, since the U.S. has been at this for quite a while and has operated world-class facilities, we have a broad and deep workforce of fusion physicists and engineers. That's a fabulous workforce that takes time to nurture. Also, producing fusion energy is a complex, multi-faceted problem and others are not doing everything. We have ideas for facilities here in the U.S. that are needed in the world fusion program.

You can ask the question, if the U.S. just disappears from fusion will the rest of the world get there? I think so, but I don't think they'll get there as rapidly as they would if the U.S. contributed. And time is important in this problem.

Why is it that fusion is not always mentioned in discussions on alternative energy?

Fusion is not going to be affecting the electrical grid in 10 years, and most discussions focus on the very-near term. However, underfunding fusion becomes a self-fulfilling prophecy that keeps it always in the long term. Twenty years ago, we proposed building a small burning plasma experiment. It wasn't built. If it had been, we could have shown by now how a burning plasma works, and not be waiting for results on ITER in the 2020s. Fifteen years ago we proposed building a long pulse superconducting tokamak, which can be operated for long periods of time to investigate the science of controlling plasmas. We would have had that data by now instead of waiting to see the results on such experiments now starting up in Asia.

Have there been practical benefits from fusion research so far?

There are huge practical benefits and untapped potential benefits, as well. The plasma science learned from fusion has enormous application. We all know about plasma TVs, but plasmas are used to make computer chips, to develop more efficient lighting, to burn up wastes, to treat medical wounds, and to power rockets through plasma thrusters, to name but a few. Spinoffs from fusion technology include new techniques to detect nuclear materials and electromagnetic launchers for aircraft on carriers. Plasma science learned from fusion is now being used to enhance our understanding of the cosmos. Most of the visible universe, after all, is plasma. Plasma physics underlies some of the major questions in astrophysics.

Is commercially viable fusion energy truly achievable?

If you look where we are now, the progress is really quite remarkable. If a physicist who started the field went to sleep for 40 years and came back today, he or she would be amazed. We routinely produce plasmas that are hundreds of millions of degrees in temperature. We’ve learned how to control them in very fine ways so we can manipulate them with remarkable finesse. We’re not yet done but we can actually produce and tweak how a hundred million degree plasma behaves. We have come so far that we can approximate conditions of a fusion reactor in a laboratory. We’ve come so far that the world collectively is going ahead and building ITER (an international experiment designed to demonstrate the scientific and technological feasibility of fusion energy planned to go online in 2019), which will produce 500 million watts of fusion power. We’ve come so far that we can see the endpoint.

So it’s reasonable to believe that fusion reactors will someday exist?

That question has been largely answered with some degree of confidence. It's really a matter of deciding whether we really want to commit the resources to the remaining development that needs to be done. We have a clear choice before us: The United States can either design and build fusion energy plants or we can buy them from Asia or Europe.

In terms of scope and ambition, how does the lab compare to what it was in the 1980s and 1990s when the TFTR experiments were in full swing?

The laboratory today is equally as vital as it has ever been. But it's smaller. The laboratory's reduction in size has paralleled the evolution of the fusion program in the United States at large. Fifteen years ago and before, the United States was probably the world leader in fusion research. It was a well-funded program. Princeton headed a truly world-leading experiment in TFTR. It had this peak where it demonstrated the production of ten million watts of power as an experiment. After that, in the mid-90s, the fusion budget in the U.S. fell when Congress was reducing budgets severely. Since then, the U.S. fusion budget has been stable, but about one-third of the size of its former program. At the same time, other countries in the world have had fusion programs surge in size because they have recognized the power of fusion. Princeton once had a fusion facility that was second to none in terms of its capabilities and it produced a huge milestone for fusion of generating ten million watts of power, showing that fusion power is real. But today the facilities we have anywhere in the United States are not as up to date as facilities elsewhere. The U.S. and PPPL are still a leader in fusion but we're not "the" leader in fusion. At PPPL today, we do world-class research and we are looking at a spectrum of ideas that are key to the future of fusion, no question about it. But other countries are also leading because of their present and planned investments. We greatly need to collaborate with other nations with more powerful experiments. This will allow us to maintain our expertise and knowledge. It also will enable us to preserve the option for this nation to build fusion reactors in the future.

What kind of fusion research programs are being pursued in other countries?

There has been a surge of interest in Asia. South Korea has blasted onto the fusion scene and recently begun operating a new experiment. This type of new experiment was designed to be built at PPPL, but it was cancelled by the Department of Energy because of lack of funds. Korean researchers picked up the idea and built it. They also are now discussing moving forward to a demonstration fusion power plant.

Exactly the same can be said about China. Chinese researchers also have built a similar kind of new experiment and recently begun operations. The Chinese fusion program is growing in leaps and bounds. The same can be said for the European Union. Parts of it have always been strongly supportive of fusion research. Germany is constructing a new facility. And, of course, the E.U. is hosting ITER (which is being built in France.) The Indian government is increasing its fusion program; it is presently constructing a new facility similar in type to the Chinese and Korean facilities but not quite as powerful. The Japanese government also is refurbishing the country's large tokamak to such an extent that it is also going to be a new, major facility. So those countries are really outbuilding the United States in fusion.

All of these new experiments are superconducting, which means they operate with superconducting magnets. Superconducting magnets are probably essential for a fusion reactor. They're advantageous because they consume no power to run them. Once you turn them on, they run without dissipating any energy. You need to enter the superconducting era if you want to do fusion research. None of the experiments in the U.S. operate with superconducting coils. All of the recently built and major new experiments being constructed abroad do and will operate with superconducting coils. So it's a kind of an indicator of how they are marching more directly to fusion energy than we are.

What's your explanation for the difference in outlook between the U.S. where investment in fusion has flattened, and countries like China and South Korea where investment in fusion is booming?

There are several things happening. Some of those countries feel the energy resource threat much more deeply than we do in the United States. In the U.S., we still have some natural resources -- oil and coal. Other countries import a larger sector of their energy, and to them, producing a clean energy source is felt in a much more jugular way. They take it much more seriously. For them, creating fusion energy is a way out of their energy problem. In Asia, particularly, in China and in South Korea, leaders recognize generally that research in science and energy is key to their economic and national security futures. They are ramping up in their science and energy sectors.

Fusion research has been described as a science without borders. Are collaborations with other countries a component of PPPL's program?

We have very strong collaboration programs with other countries. Other nations solicit the collaboration in PPPL because we have such deep expertise. And, conversely, we want to make use of the new facilities abroad.

We have many research partnerships. PPPL is a partner with Oak Ridge and Savannah River national laboratories in the U.S. collaboration on ITER construction. We have collaborations with essentially all the new facilities I mentioned previously. We have collaborations with the new tokamaks in South Korea and China. We have collaborations with a new fusion experiment in Japan, a superconducting stellarator. We have a collaboration that's growing with a new experiment that's being built in Germany. Germany has had a long-standing laboratory, the Institute of Plasma Physics, but they built a new branch of it in the former East Germany in a town called Greifswald. They are constructing a billion dollar class stellarator there right now.

What's the difference between ITER and Princeton's big current experiment, the National Spherical Torus Experiment or NSTX?

ITER will be the biggest fusion experiment ever built and will be the size of a commercial reactor. NSTX is smaller. ITER will operate with fusion fuel and will produce what is called a burning plasma, meaning it will be self sustaining. NSTX is more compact – smaller and rounder. When you make this variation in the geometry, the opportunities are so rich that there are many reasons to do this. The NSTX design is a leading candidate for the next major step in fusion research in the United States – the establishment of a facility that operates with fusion fuel, producing large fluxes of neutrons (products of the fusion reaction) to develop and test the material components that surround the plasma.

ITER and NSTX are in the family of fusion devices called tokamaks. They are doughnut shaped, tori. But NSTX has a small hole in the center of the doughnut and it's smaller and rounder on the outside. So it has the advantage of compactness. It also turns out, by getting smaller, the magnetic field in the plasma is shaped in way where you can get to high values of plasma pressure compared to the magnetic pressure that is confining the plasma. One figure of merit for a fusion system is how high the plasma pressure is. That is, how hot and dense it is compared with the strength of magnetic field, or the magnetic pressure that you used to confine the plasma. The higher the plasma pressure, the more fusion power you will get. The lower the magnetic pressure, the less expensive the reactor. NSTX operates with a high value of this ratio --

high plasma pressure and low magnetic pressure.

Why do experiments on the NSTX?

When you make this variation in the geometry, the opportunities are so rich that there are many reasons to do this. But perhaps the most prominent reason at the present time is that the NSTX design is a candidate for the next major step in fusion research in the United States. That next envisioned major step for fusion in the United States is to build a facility that operates with fusion fuel, a deuterium-tritium facility. It will produce fusion power, do it completely steadily and in so doing generate large amounts of neutrons. Designers will be able to test the integrated science and engineering of a fusion reactor. In the U.S., this next-stage project is sometimes called a fusion nuclear science facility because it will begin to address the nuclear science associated with fusion, that is, the interaction of the neutrons produced in the fusion reaction with the surrounding material structure. This may be the penultimate step prior to a full-blown fusion power plant. The NSTX design is a potentially attractive design for this next step because it is compact, generates an intense flux of neutrons (due to its small surface area), and may be less expensive. NSTX is also a wonderful facility to develop the science and solution to the plasma-material interface. The high heat flux emanating from NSTX affords testing of materials that must survive exposure to the hot plasma. NSTX is also developing novel solutions, such as liquid boundaries and new ways to magnetically channel the heat exhaust to the boundary. NSTX researchers are also engaged in the broad range of physics issues essential for ITER and fusion in general, including plasma stability and turbulence.

What are some of the other fusion experiments at PPPL?

In fusion, we have several experiments aimed at novel approaches to some of the most thorny problems. Indeed, even NSTX is novel in its geometry in that it is different from the mainline tokamak.

One of the main challenges of fusion is finding the best way to surround a hundred million degree plasma with a material structure. So the main line approach to that is to surround it with a solid material, tungsten, which has been quite successful in present fusion experiments. However, there are many questions concerning its survivability in a fusion reactor. At PPPL, we are developing an alternative approach. We surround the plasma not by a solid but actually by a liquid, a liquid "wall." This is an alternative approach to the plasma materials problem. If a solid gets bombarded by some particles streaming out of a hot plasma, it can break, it can sputter, it can erode. Liquids, however, don't break. Liquids are automatically self-healing. So if we surround the plasma with a liquid, it could possibly erase a significant amount of the materials problems for fusion research. And if the liquid is flowing, the liquid can take the heat of the plasma. One particular liquid, liquid lithium, has a possibly remarkable effect on the plasma. Particles that hit it get absorbed very well, so when you surround a plasma by liquid lithium, it is like a sponge. Particles don't come back. They get stuck. Why is that good? If you have a standard material, cold particles from the material get ejected into the plasma due to sputtering. That cools down the plasma edge, can make the plasma more turbulent, the plasma can cool further, and the fusion reaction rate is diminished. A liquid lithium wall doesn't do that. The plasma stays hot. Plasma physicists predict that with the boundary condition of lithium, the plasma should be less turbulent. So liquid lithium is in the vision of plasma engineers because it is a material that won't break, and in the vision of theoretical physicists because it improves the properties of the plasma. So this is a major research thrust at PPPL.

We also operate an exploratory magnetic configuration in which the plasma is confined by a donut with no hole in the center. Sometimes called a compact torus, it is an elongated ball of plasma confined by a relatively weak magnetic field. In a very early stage of development, this approach is quite different from the tokamak – much more compact with higher plasma pressure (relative to magnetic pressure).

We are working on developing new variations of the magnetic configuration for fusion. We have produced 21st century magnetic field designs that could not have been designed without the use of modern computers. We can now evolve designs for modern fusion reactors that are really remarkable – highly three-dimensional magnetic shapes, almost non-intuitive, that are optimized according to a variety of physics guidelines. These designs produce magnet shapes that are perfected for fusion, if they are buildable. They are candidates for future experiments at PPPL.

What is fusion?

Fusion is the energy source of the sun and all the stars. In a nuclear fusion reaction two atomic nuclei fuse and hen produce other particles. In so doing a tiny amount of mass is converted to energy of motion in the products. With billions and billions of such reactions occurring in a gas – a hot plasma – substantial heat can be produced. In a fusion reactor, the core will be a hot plasma that produces heat from fusion. The heat is then converted to electricity by conventional means. The image of producing a star on earth captures the goal well.

What is plasma physics?

Plasma physics is the study of how this complex state of matter, plasma, behaves. One can put that in the context of physics, more generally, even science more generally. Historically, the direction of physics has been to study smaller and smaller bits of matter. In the 19th century, it was understood that the air in the room was made up of molecules. Molecules are made of atoms, and atoms are made of protons, electrons and neutrons. And physicists kept trying to understand the smallest bits of matter and the forces between them. And then they understood that nuclei are made up of quarks. So this lineage has proceeded from atomic physics to nuclear physics to particle physics and beyond, in a way. The reductionist approach to nature has been the dominant direction of physics and it makes sense. But it's also been realized in recent decades that not everything can be understood by looking at the smallest bits of nature. There are properties that emerge as systems become more complex. This is the science of complex systems. It's the direction opposite to the reductionist approach. They are not in competition. The most complex system that we know, a living organism, might be understood in some way by knowing what nuclei are made of. But practically speaking it cannot. Plasma behavior is determined by billions of particles interacting simultaneously with each other. This produces a fascinating array of phenomena. Our goal is to discover basic principles that describe these phenomena. In the 19th century, the powerful concept of entropy production was discovered to describe the relatively simpler case of a gas of neutral particles in equilibrium. Unraveling the behavior of the plasma state is teaching us how to produce fusion energy, understand the plasma universe, and make computer chips.

Congress has been debating budgets for months with much talk of cuts to research, including the budget of the DOE's Office of Science, which funds the American fusion program. What is your view on proposed reductions to research budgets?

Cutting research and development in science, engineering and energy research is counterproductive to our economic health. Yes, one has to control spending. But one has to do it to make us more economically competitive, not less. If times are tight economically and one erodes our science and energy research infrastructure, it will make us more poor, not more prosperous. As is said: to lighten the load in an airplane in flight, you don't throw the engine overboard.

What is your position on cuts specific to the fusion research budget?

Fusion is almost a special case. The U.S. investment used to be about three times what it is today. So the fusion program is already pretty lean. We are trying to stay at the world forefront despite our resources. Significant further cuts would knock the U.S. off the world stage in fusion and consign us to third world status in fusion.

What are your priorities and vision for PPPL?

The vision for the lab is that it be at the world forefront of fusion research, in basic plasma physics, and in many applications of plasma science. We aim to aggressively enhance the knowledge base to deliver fusion to the world as quickly as possible. We also wish to expand our activities across the broad frontier of plasma science and technology.

Within fusion, we wish the lab to continue its leading role in planning the next step in fusion research in the U.S. PPPL should play a key scientific role in such a fusion nuclear facility, wherever it is constructed. We wish to develop new solutions for fusion that require major facilities at PPPL. We want to use our talents to fill the need to solve the remaining problems, such as how to control the plasma and how to surround the plasma with the proper material. There is an enormous need for new ideas. That’s where we can thrive.

Can you discuss the lab’s working relationship with Princeton University?

One of the terrific aspects of PPPL is that it is part of Princeton University. We host the plasma physics graduate program through the Department of Astrophysical Sciences, with 35 graduate students working at the lab. We have scientific links and collaborations with many parts of the university. Scientists at PPPL are working with material scientists on campus to find the best substances to contain plasmas during fusion reactions. PPPL plasma physicists are collaborating with theoretical astrophysicists on campus to solve problems from the how solar flares work and why matter accretes so rapidly onto black holes. And PPPL is wonderfully managed by the University.

Why did you pick plasma physics as your area of research?

Two reasons – fascinating physics and potentially momentous application. While a graduate student in the 1970s, it appeared to me that we were running out of energy. Now we have the added issue of global climate change. As time goes on, the need for fusion only becomes greater. People often think that fusion scientists are frustrated every day because fusion is not yet available on the commercial power grid. But the physics and engineering of this problem are captivating. When we discover something in the lab, it is just a pleasure to learn it. And it's useful because of all the spinoffs to science and technology. It's gratifying the way that art is gratifying. The only frustration is that our progress toward fusion could be more rapid if called for.

Source: Princeton Plasma Physics Laboratory

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