this fusion as a marriage, where the new husband and wife find they can live more cheaply together than they could apart, and so they have some extra money – or energy, in the case of the nuclei – to spare. Although the amount of energy made available by each individual fusion is small, billions of billions of these nuclear marriages can generate megawatts of power per second.

It's not easy, however, to bring the nuclei close enough together that they will fuse. All nuclei have positive electrical charges and hence naturally repel one another until they are very close, at which time a more powerful force (called the "strong force") draws

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yielded with the 100 percent deuterium that has been used to date.

How will fuel perform?

But the increase in power, as impressive as it may be, is not the most important part of the experiment, says Dale Meade, PPPL's deputy director. Of even more interest to scientists is the way experiments. If all goes as expected, fusion will be one giant step closer to practical application, but if the machine defies calculations, Meade says, then future reactors could be "in trouble."

Up to now almost no experiments anywhere have included tritium in the fuel mixture, since it is radioactive, and adding it to the fuel creates a variety of on the deuterium plasma and estimated what would happen if D-T were used.

At some point, however, the guessing has to end, and researchers must add tritium to see how the reaction really does proceed. "We don't think we're going to see any total surprises," Meade says, but it's essential that the researchers under-

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Language of the lab

Princeton Plasma Physics Lab (PPPL): a research facility managed by Princeton University, funded by the U.S. Department of Energy, located on the Forrestal campus off Route One

fusion: an atomic reaction in which nuclei join together and release energy

plasma: an ionized gas in which fusion takes place at high temperatures

deuterium-tritium (D-T): a plasma mixture of two heavy isotopes of hydrogen

tokamak: a doughtnut-shaped container in which plasma is confined by magnetic fields

Tokamak Fusion Test Reactor (TFTR): a tokamak at PPPL that operates in pulses

Tokamak Physics Experiment (TPX): a planned tokamak at PPPL that will operate in a steady state

International Thermonuclear Experimental Reactor (ITER): a proposed tokamak designed to develop the engineering systems for a working nuclear power plant

TPX – the next machine

Planned fusion test reactor at Princeton site to explore steady state operation

By **Marcia Bartusiak**

In the early 1970s tokamak fusion devices were capable of generating only fractions of a watt of power. Today these machines, the most successful design for confining the fiery plasma necessary for fusion, are capable of producing more than a million watts of fusion power.

"We've gone from milliwatts to megawatts," points out Robert Goldston, chief scientist of the Tokamak Physics Experiment (TPX) and professor of astrophysics. "And there's been steady progress in controlling tokamaks and in optimizing how they work. We've gotten to the point where we can just about see what steps are needed to build a working power plant."

Current tokamak devices, however, can only operate in short, seconds-long pulses. The plasma – the hot ionized fuel – must be heated afresh in every pulse in order for the charged hydrogen nuclei to fuse and release those substantial amounts of energy. "We're exploring new ways to make the pulse continuous," notes Goldston. The mission of TPX is to heat and maintain a plasma in a steady state. In addition, modifications will be made to achieve more stability, leading to a more compact and more economical fusion reactor – a design likely to be attractive to commercial power companies.

If its construction is fully funded, at a cost of some $600 million, TPX could be up and running at PPPL by the turn of the century. Set to replace the Tokamak Fusion Test Reactor (TFTR), TPX would be the fourth in a series of major tokamak experiments located at PPPL and would operate as a national fusion facility, with teams of physicists and engineers from Massachusetts Institute of Technology, the University of California, Los Angeles and other major universities, several national laboratories and high tech industries.

Fiscal necessity

TPX was born out of practical needs and fiscal necessity. Its roots can be traced to the '70s, when construction began on the TFTR, presently the nation's most advanced tokamak facility. TFTR's objectives were to achieve the high plasma temperatures necessary in a fusion reactor and to set world records in power generation. Yet, even as TFTR was being built, the U.S. fusion community began looking ahead to two other critical steps: steady state operation and ignition, the long-sought goal to sustain the plasma with the energy

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TPX

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generated from the fusion reaction itself.

Over the years fusion groups from around the country submitted proposal after proposal to the Department of Energy, principal supporter of fusion research in the United States. The leading candidate several years ago was the Burning Plasma Experiment (BPX), planned to achieve ignition and to investigate new tokamak physics. However, the Department of Energy declared the BPX too ambitious and too expensive, with its $1.8 billion price tag.

As a result, U.S. fusion scientists turned their attention to the other essential step – a steady state advanced tokamak – with ignition left to future devices, in particular the proposed International Thermonuclear Experimental Reactor (ITER).

Leave ignition to ITER

"If we take the technology we have now," says Goldston, "we could conceivably build a power source that delivers 2,000 megawatts of electricity. But with the pulsed reactor cycling up and down, fatigue would be a problem, and the reactor would be so big it might scare off the power companies."

Hence, the plans to construct TPX. While ITER is being designed on the basis of today's scientific knowledge, TPX will be testing new methods for improving a tokamak's performance. "Progress in fusion research does not necessarily occur strictly along one path. There are parallel activities as well," notes TPX project director John Schmidt. By leaving ignition to ITER and focusing on the physics of maintaining a stable plasma, TPX researchers have reduced their costs; the proposed price of TPX is a third the cost of BPX.

"We think we can make a better fusion reactor by going to a steady state machine. It would not only be smaller, it would also produce electricity more cheaply," stresses Goldston. Theoretical analyses, as well as recent experimental evidence, are leading fusion researchers to this conclusion.

TPX will retain the basics of tokamak technology. A tokamak is a doughnut-shaped vessel (torus) that confines its fuel, the hot ionized gases, within a structured weave of magnetic fields – some of the fields are directed along the chamber of the torus in the long direction, like horses running around a racetrack (toroidal field); the others loop themselves around the doughnut in the short direction (poloidal field). Electric currents flowing within a series of ring coils that encircle the doughnut set up the toroidal field; a current flowing through the plasma itself generates the main poloidal field. Both magnetic fields, working in concert, must be present to keep the plasma inside from drifting and dispersing.

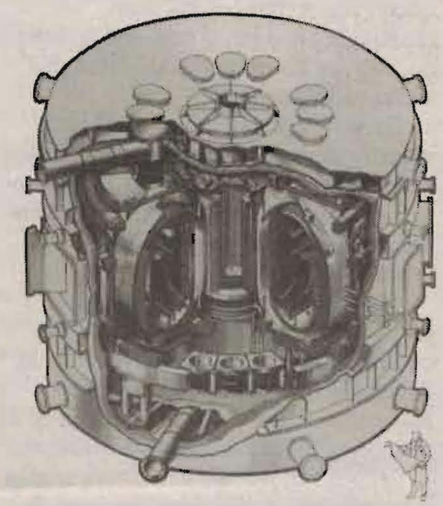
'Bootstrapped' current

In a conventional tokamak, the plasma current, so vital in containing the energetic electrons and ions, is largely induced by a central transformer. The current flows as long as the transformer's magnetic field keeps increasing. "But the transformer can only be driven so high," notes Goldston. "Soon it hits the rails, and then you have to stop and recharge the transformer," which makes continuous operation impossible.

The plasma current in TPX will be driven by other processes, ones that don't require recharging. Recent experiments conducted on TFTR, in fact, indicate that if plasma pressures and densities are driven higher and higher, much of the plasma current can be self-generated, spontaneously produced without the use of an outside transformer. This "bootstrapped" current, predicted theoretically in the 1970s, can then be sustained and supplemented with additional inputs, such as particle beams and radio waves injected into the plasma (techniques already tested in the TFTR and elsewhere).

Those increased pressures and densities will be obtained by "sculpting" the plasma – "in other words, controlling the shape of the plasma and current flow within the tokamak," explains TPX program director Keith Thomassen. If you could slice through a TFTR plasma, you would discern basically a circular cross section. TPX will manipulate its magnetic fields and currents in such a way that the plasma profile will look more elliptical or D-shaped. "Such a configuration tends to compress the magnetic fields, holding the plasma more firmly," explains Goldston. And that makes for more stability, which increases the tokamak's efficiency tremendously.

A further large improvement is possible by adjusting the pitch of the twisting field lines so that they loop



TPX

around in the poloidal direction more rapidly at the outside of the plasma than in the center. Theoretically, this should also greatly strengthen the configuration. Such an effect, albeit on a very brief time scale, has been observed experimentally on other tokamaks, including the Joint European Torus (JET) in England and the Tore Supra in France. TPX will at last be able to examine this behavior in a relatively steady state plasma environment (initially TPX will attempt to sustain the plasma for up to 1,000 seconds, some 500 times longer than the pulse length in TFTR). The tools used to sustain the overall current in TPX will give researchers steady control over the pitch profile inside the plasma.

Physics objectives

TPX will not be solely limited to demonstrating continuous tokamak operation and high plasma pressures. "Even though the end objectives of TPX are primarily physics," points out Schmidt, "we still have to build a variety of hardware that will pose a number of technological challenges." These include:

- *Superconducting magnets*. TPX will be the first tokamak facility to use all superconducting magnets. This is going to be tricky, as poloidal fields must be able to change quickly to control the plasma, and superconducting magnets normally have difficulty varying rapidly.
- *Shielding*. TPX will be sustaining a plasma at temperatures of some 100 million degrees, yet the superconducting magnets, situated just outside the vessel, will be continually cooled with liquid helium at a tempera-ture near absolute zero. As a result, the shielding, the first of its kind in a tokamak, must be substantial.
- *Heat divertors*. Until now, any heat generated in a conventional tokamak could just dissipate between pulses. But TPX, with its continuous operation, will have to remove heat actively to protect the vessel. TPX researchers will be testing various ways to disperse the plasma exhaust.
- *Robotics*. With a steady state plasma, energetic neutrons will eventually transmute some of the materials that make up the interior of the TPX torus, causing them to become radioactive. Consequently, sophisticated robotic systems must be developed to take care of routine maintenance inside the vessel.

'Keen machine'

The experience that TPX researchers gather during the development of these advanced technologies and continuous plasma operation is expected to benefit ITER and eventually the demonstration power plant that the fusion community hopes to build by 2025. At the same time, U.S. industry, which will be a partner in constructing the TPX facility, will strengthen its capabilities in super-conducting magnets, shielding, robotics, computer controls and heat-transfer technologies, all in advance of ITER's construction.

There are critics who believe that the TPX design will be too intricate to use in a future power plant -- too many technological challenges to keep the plasma shaped and in exquisite balance. A pulsed tokamak, though cruder, is still simpler to operate. But according to Goldston, the economic benefits of a steady state fusion reactor could far outweigh the engineering complications.

"Suppose we can pull off one of these keen machines, which we have both theoretical and experimental reasons to believe in," he says. "Then you could bring down the plant size by a factor of four, or, if you kept the same size as a pulsed reactor, you could bring the cost of electricity down by a factor of two. Plus you get a power plant that runs steadily, without a transformer ramping up and down causing thermal and mechanical fatigue." Supporters of the TPX concept like to think of its design as the "jet engine" of tokamaks, conventional tokamaks being more comparable to propeller aircraft.

Upon finishing its mission at the end of 1994, after more than a decade of operation, TFTR will be dismantled. "And that means the top U.S. machine will be gone," says Thomassen. "So, there's a new urgency in this effort that wasn't there before."

Marcia Bartusiak is a contributing editor of Discover *magazine and the author of* Thursday's Universe *and* Through A Universe Darkly. *In 1982 she became the first woman to receive the American Institute of Physics Science Writing Award.*