Fusion energy advances are threatened by budget axe

Breakthroughs are still being made, but the goal of achieving cheap, plentiful fusion energy is little helped by budget-slashing that has reduced funding to a 20-year low. Mark Wilsey reports.

Recent experiments at General Atomics (GA) in San Diego, California and the Princeton Plasma Physics Laboratory (PPPL) in New Jersey, have shown greatly improved performance of their tokamaks, large donut-shaped machines used in fusion research. These results, if they bear out, are the kinds of developments that could have a significant impact on the size and cost of a future fusion power plant. All of which goes to highlight the shortsightedness of Congress, which has moved this year to slash the Department of Energy's fusion budget by more than one-third, and has cancelled the next-generation fusion device, which would have continued these experimental developments.

Scientists have striven for decades to harness fusion energy as an economical, plentiful energy source for mankind: It is now commonly pointed out that there is enough of the fusion fuel deuterium in one gallon of seawater to equal the energy content of 300 gallons of gasoline. Fusion energy powers the Sun and stars, but creating the same conditions here on Earth has been an elusive goal for researchers. The situation is little helped, when, in this era of budget-balancing mania, the whole fusion program is threatened, as funding has now been reduced to its lowest levels in more than 20 years.

If one were to look back, over the past two decades, at the number of experiments and approaches to fusion that have been neglected, it would not be hard to argue that the United States has failed to follow a policy to develop fusion energy. The mandate of the McCormack Magnetic Fusion Energy Engineering Act of 1980 was never fully funded. Over time, as funding became tighter, programs which were deemed too high risk to be successful, or, if successful, unlikely to lead to a commercial reactor, were squeezed out of the mainstream fusion program. As a result, today, we have too few machines to carry out the work needed and too little funding to operate them, with few prospects for the future.

However, nature can have a keen sense of irony: The experiments at GA and Princeton give us a glimpse into a new physics regime within their tokamaks. While it may have been anticipated 15 years ago, the new physics regime is only now being realized in machines that were not designed to investigate it. It is precisely such unexpected results that highlight how important it is for the United States to foster a broad-based fusion research effort.

Experimental efforts

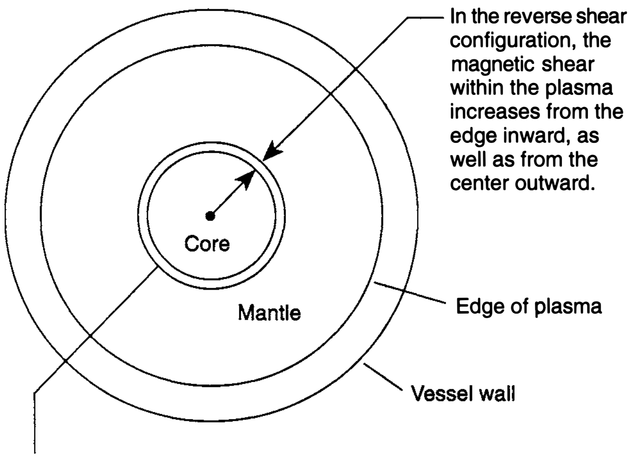
In the fusion process, under extremely high temperatures and pressure, hydrogen atoms can fuse and release a burst of energy. Tokamaks use magnetic fields to contain the hot hydrogen ions, or plasma. Confining and maintaining the stability of the plasma have been key concerns in the production of fusion energy. Recent results obtained in the General Atomics DIII-D (pronounced "dee-three-dee") Tokamak and Princeton's Tokamak Fusion Test Reactor (TFTR) show improvements in both these areas, and more.

There was marked improvement in plasma confinement and plasma densities at General Atomics, for experiments conducted last year on the DIII-D. Moreover, GA researchers were able to achieve these results in three different modes of operation in the DIII-D. At Princeton, for tests that were run this spring on the TFTR, particle confinement was improved by a factor of 40, with core plasma density boosted by a factor of 3 over conventional operations. Both groups of researchers have recently submitted papers to the *Physical Review Letters*.

General Atomics has an interesting background. It was founded in 1955 as a division of General Dynamics to explore the peaceful uses of atomic energy. Two of its earliest nuclear projects, which are continuing today, are the TRIGA research reactor which is used by universities and hospitals for training and isotope production; and the high-temperature gas-cooled reactor, an inexpensive and versatile nuclear reactor with unique saftey features. (See *EIR,* May 21, 1993, for our interview with General Atomics Vice Chairman Linden Blue.)

GA began its fusion research in 1958, sponsored by a group of Texas utilities; later the work was picked up by the U.S. Department of Energy. For a time the Japanese were working with GA in experimenting with their D-shaped tokamak and were intrumental to upgrading it to the current DIII-D configuration.

FIGURE 1
Reverse shear configuration for the Tokamak Fusion Test Reactor (TFTR)



Source: Mark Wilsey

Reverse shear

The technique used to improve confinement and plasma stability in both tokamaks is called reverse shear, although the researchers at General Atomics refer to it as "negative central magnetic shear," which they consider more precise, and Princeton's researchers use the term "enhanced reversed shear," to differentiate it from earlier reverse shear experiments, over which this is a clear improvement.

Reverse shear, in this case, is achieved by adjusting the magnetic fields of the tokamak such that the electrical current density profile of the plasma is maximized, not at the center of the plamsa, as in typical tokamak operations, but at a radial distance off-center. The result is a "hollow" current profile, which, in effect, partitions the plasma into a highly stable "core" region and a surrounding "mantle" of plasma (see **Figure 1**). The plasma in the core is practically quiescent, and so well confined that it approaches what was thought to be the theoretically best possible confinement, and, in some cases, surpasses it. This, of course, begs the question: Just how good is our theoretical understanding of plasma under these conditions?

Charles Kessel, a physicist at Princeton whose theoretical work aided their success there, points out that the reverse shear yields some distinct improvements. There is the suppression of particle and energy transport out of the plasma; that is, particle and energy confinement was improved, which gave rise to higher densities and temperatures in the core. In addition, the current profile inside the plasma coincides with the current generated by the plasma itself, which is important, because it means that less external energy is needed to drive the current in the plasma, and the plasma actually generates its own current. In the case of TFTR, it can generate as much as 80-90% of its own current.

A self-generated current in the plasma that could be made to fully supply the current needed to sustain the fusion process in the tokamak, is called the "bootstrap current." Fusion researchers are hopeful that the bootstrap current can be employed in future fusion devices, such that the experiments can be extended for several minutes or perhaps indefinitely. Presently, machines can only operate in pulses of a few seconds at best. But, next-generation fusion devices will explore this steady-state, continuous mode of operation, which would be highly desirable for future production of fusion power.

It was in part out of the design studies for the now-cancelled Tokamak Physics Experiment (TPX) that Kessel and his colleagues were investigating the reverse shear approach for tokamak operations. The TPX was to be the successor to TFTR, and would operate in steady-state mode for pulse lengths of up to 1,000 seconds. "TPX was a pioneering experiment, where, for the first time, a lot of the reactor research and the experimental research were coming together in a single device," said Kessel. He added that its demise is unfortunate and that the program will likely suffer for it.

General Atomics came to investigate reverse shear as part of a range of advanced tokamak physics concepts being explored on the DIII-D. Tony Taylor, a scientist at General Atomics who has been involved in this work since 1991, explained that the object is to use the best physics we know, to come up with ideas that may lead to a more attractive tokamak power plant. The approach taken at General Atomics was to try to change the current profile in the plasma to improve what is called the "beta limit."

Beta is the ratio of the plasma pressure at the center to the magnetic pressure being applied to the tokamak, and can be thought of as a measure of how well the device is able to confine the plasma. As the pressure builds up, instabilities occur in the plasma which lets the pressure out. Hence, the plasma becomes hot enough that it reaches its stability limit, or "beta limit." The economics of building a power plant is proportional to beta to the fourth power: A small improvement in beta can greatly affect the size and cost of a fusion plant.

The experiments of TFTR and DIII-D show that reverse shear yields higher pressures and densities in the core by suppressing instabilities. The achievement of higher densities would then lead to increased fusion reactivity. Researchers at Princeton are confident that it may now be possible to double TFTR's output, from 10 megawatts, its record set in 1994, to 20 MW or higher, using deuterium-tritium (D-T) fuel, two isotopes of hydrogen. So far, experiments have only been conducted with deuterium.

Tokamak physics

To understand reverse shear, let us review how a tokamak works: Tokamaks, one of several devices that have been developed in the field of magnetic confinement fusion, are torus-shaped, or donut-shaped devices. External magnetic coils placed around the tokamak produce a magnetic field, the toroidal field, which travels the long way along the torus. The toroidal field induces a current in the plasma which, in turn, generates a second magnetic field, the poloidal field, which rotates about the centerline of the torus. Still other magnets are used to augment and control this current. It is the combination of these two fields, the toroidal and poloidal, that defines the magnetic fields inside the plasma; these are helical in shape, going around the length of the torus, as we see in **Figure 2.**

The twist, or tilt, of the helix changes within the plasma due to the increasing strength of the poloidal field toward the centerline of the torus. The helix tends to become more tightly twisted toward the center. As one moves inward along the minor radius, the varying twist defines different magnetic surfaces. This change in the twist of the magnetic field lines with respect to radius is called "shear."

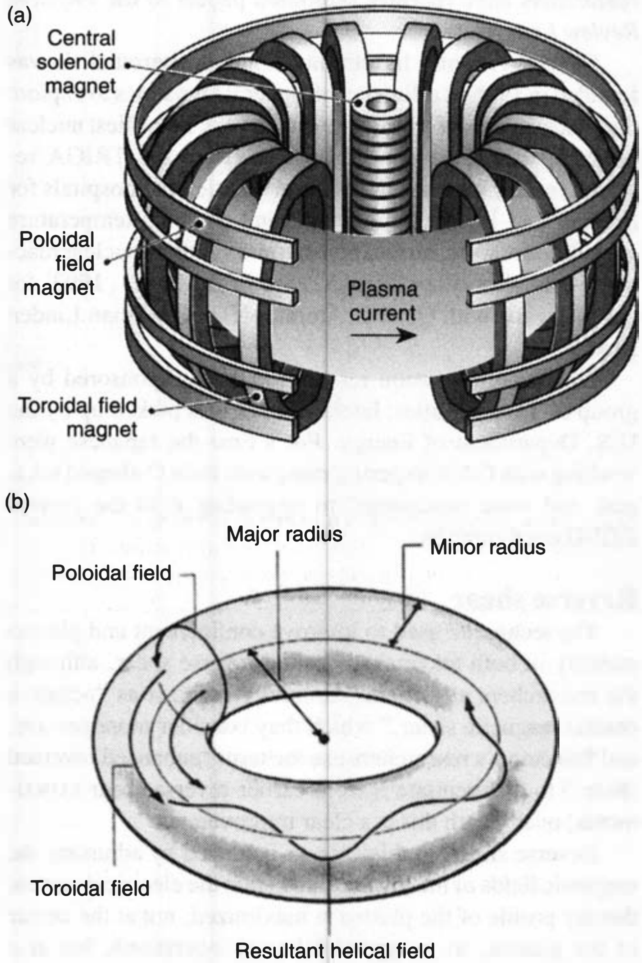
In reverse shear, the field lines increase in twist up to a point, and then decrease. In the TFTR, that point was found roughly one-third of the way along the minor radius. This is the point at which the plasma is divided into the core and mantle regions. Here the partition acts as a barrier to the transport of particles and energy out of the core.

Returning to the beta limit issue, Taylor explains, "You can think of the magnetic field lines like rubberbands, and when they all line up it's very easy for the squeeze between the rubberbands." The magnetic fields within the plasma are crossed, because of the changing pitch or shear. However, as the pressure is increased, these fields start to line up, at which point, the plasma becomes unstable.

With reverse shear, the field lines are crossed in such a way that they never line up again, and these types of instabilities can be avoided, thus increasing beta, the pressure of

FIGURE 2

Tokamak concept and geometry

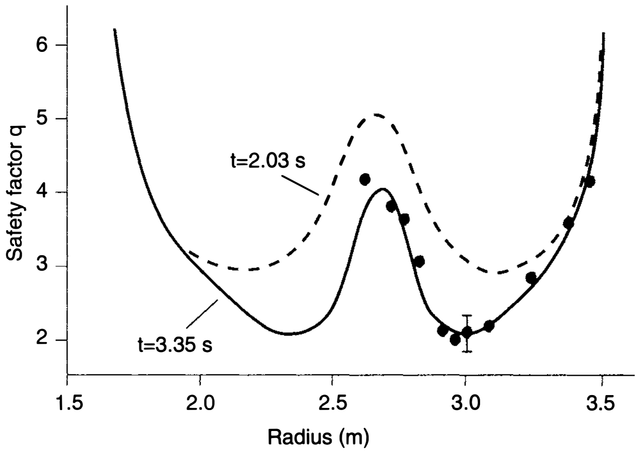


This artist's rendition of a typical tokamak fusion device (a), shows the magnets and plasma current. The bottom schematic (b) shows the configuration of the magnetic fields within a tokamak, in which the magnetic fields confine and heat plasma inside of a donut-shaped vacuum chamber. Within the plasma, the toroidal and poloidal magnetic fields combine to produce helical fields.

Sources: Joint European Torus, U.S. Department of Energy.

FIGURE 3

Safety factor (q) profile for the Tokamak Fusion Test Reactor (TFTR)



Safety factor q profiles for TFTR at two different times, center of core is at approximately 2.65 radii on the major radius. The two low points of the W-shaped curve are where the shear reverses.

Source: Levinton et al./PPPL

the plasma.

Another way to look at it, is to look at what is called the "safety factor," or q, which measures this magnetic twist by taking the ratio of the number of turns that the field line makes around the torus the long way before it makes one turn the short way. A lower q means a higher twist, showing that it takes fewer laps around the torus to make one twist.

A plot of the safety factor q, versus distance along radius for a reverse shear mode will show a characteristic W-shaped curve (**Figure 3**). The peak of the W is in the center of the core. The low points on either side of the core are the points at which the shear reverses, where it changes directions. By contrast, in the more typical tokamak operation, the q profile would be more U-shaped toward the center—that is, the q constantly decreases, or the twist of the magnetic field constantly increases.

The question becomes how to produce such a W-shaped q profile. This is accomplished by ramping up the current in the plasma and simultanously heating the core. For TFTR, since it can only operate for a few seconds, it therefore accesses this reverse shear regime transiently. By continuously changing the current in the magnetic field coils outside the plasma, researchers induce a current in the plasma. The current in the plasma tends to diffuse, starting at the edge and diffusing in toward the center. In these experiments, to avoid having the current peak in the center, since experimenters are seeking a hollow current profile, they try to slow this diffusion to create an off-axis peaked current profile.

The time that it takes for the current to diffuse is a function of the plasma temperature. By heating the plasma, using neutral beams, that time can be stretched out to tens or hundreds of seconds, an extremely long time in the scale of these experiments. By heating the plasma as the current is being driven into the plasma, the current seems to stay put as the heated plasma retards its further penetration.

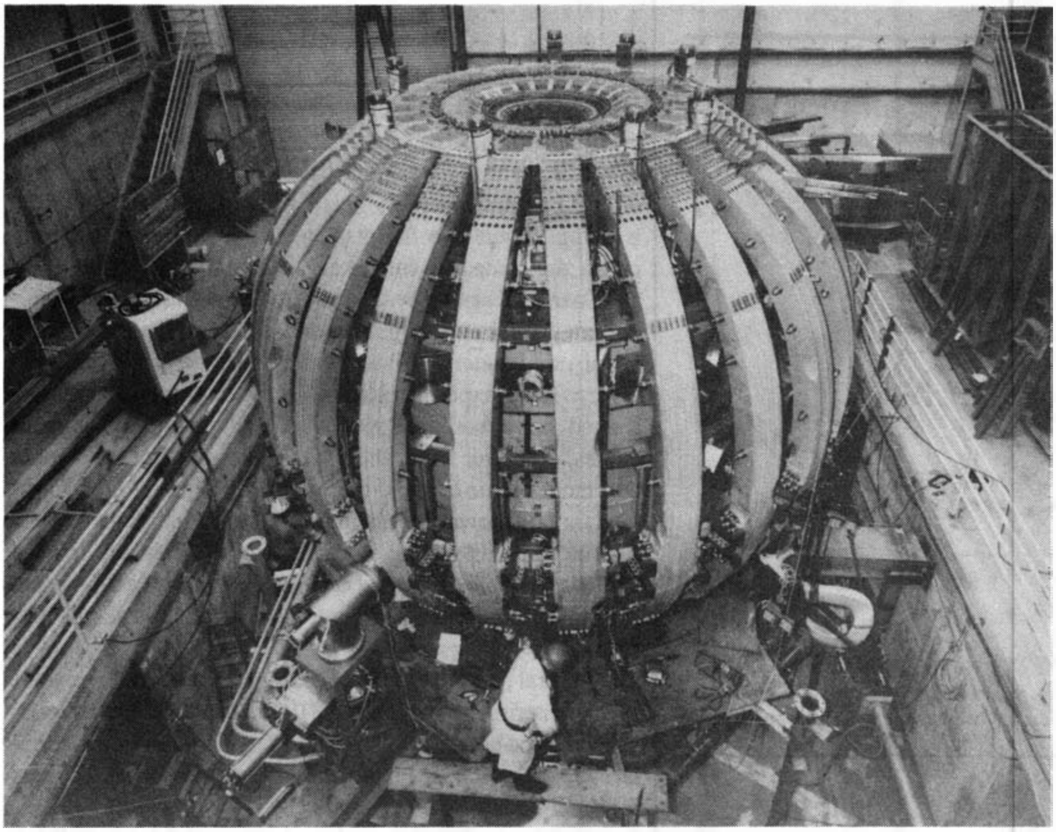
Charles Kessel notes that this will produce an off-center current peak, but "that peak is actually evolving and moving toward the center." A successive series of q profiles for a reverse shear experiment would show that, initially, the W-shaped curve would be somewhat shallow and have high q values. But over time, the W-shape would become deeper and more defined, while the twin low points of the W will tend to move toward the center, until eventually, the plasma becomes unstable and the experiment is concluded. For the TFTR the whole process is over in a couple of seconds, and the reverse shear configuration lasts only a few tenths of a second.

General Atomics uses a very similar approach for reverse shear experiments on their DIII-D. The DIII-D has a D-shaped cross-section, whereas TFTR's cross-section is circular. GA researchers have achieved reverse shear in three different operating modes with the DIII-D, one of which is very similar to TFTR's, and two others which are in "high mode," or "H-mode," meaning that the conditions at the edge of the plasma tend to reduce transport, and thus improve confinement.

Tony Taylor is particularly encouraged about the H-mode reverse shear experiments because the pressure profiles in the plasma are broader, or even across the plasma, compared to the first case which, like TFTR, has a rather steep pressure gradient, peaking in the center. To date, neither TFTR nor DIII-D has shown marked improvements in beta (the ratio of plasma pressure to magnetic pressure), in these reverse shear experiments. A doubling of the beta values over conventional operations is the payoff that the researchers are looking for. Taylor thinks that the broader pressure profile of the H-mode reverse shear may be a more productive route to higher beta values. It is in this regime that he hopes to find pressure profiles and current profiles which will match each other, and thereby allow higher pressures as well as a healthy self-generated bootstrap current, which will lead to longer pulses.

"I think it will be very exciting if TFTR can get very high fusion yield with short pulses," Taylor said, adding, "but I think it would be 100 times more exciting if they could make that pulse last for 10 seconds."

Indeed, both groups are moving in that direction. DIII-D can currently operate at pulse lengths of several seconds, and with the planned upgrades, they will be able to extend that to 20 seconds. Princeton is planning similar upgrades



General Atomics' Doublet III-D tokamak magnetic confinement fusion device.

to TFTR. However, it is doubtful whether funding for such upgrades will be forthcoming. TFTR has been slated for closure this year, though its fate has not yet been sealed.

Nonetheless, the means to overcome the limitations of using magnetic fields to drive and control the current in the plasma, which, in the case of TFTR, can only be sustained for a couple of seconds, is to use radio waves or other waves to drive the current. The DIII-D already has some wave-drive capability and there are plans to add to it. The Princeton team on the TFTR would like to follow suit, because it has the advantage of allowing the current profile to be shaped and mantained indefinitely. The plans for future reactors include the use of this means of current drive, as was the case for the TPX.

Implications and caveats

Tony Taylor cautioned against overselling the importance of these reverse shear results. While he is excited by them, he realizes that there is still much work ahead to prove out this approach. Still, these results do demonstrate that there is a great deal of interesting physics to be explored, much of which can be done with the tools at hand. For example, Princeton has shown on paper that, based on a reverse shear mode, they should be able to at least double the output of TFTR, and perhaps even achieve breakeven, where the energy produced by the fusion process equals the energy inputs needed to start it. But in order to achieve breakeven, they would need to achieve very high beta values, which remains a significant challenge. But, "it is not inconceivable," Taylor conceded.

Looking further into the future, Charles Kessel has begun to examine what reverse shear could mean for a future fusion power plant. The design work on TPX supported the idea that a steady-state, continuously operating fusion plant would be much more attractive than pulsed reactor based on current tokamak designs. A steady-state reactor would be four times smaller in size than a pulsed reactor, but produce the same amount of electricity; or, if the two reactors were the same size, the steady-state reactor would produce electricity at half the cost of the pulsed reactor. Kessel has found that when the reverse shear is applied to the operations of a steady-state reactor, the size and cost of plant is reduced yet another 50%.

"It really stems from the fact that you get this increased beta," Kessel explained, "and also because such a high fraction of the current is driven by the plasma itself. So there is very little power required to sustain the plasma." Clearly this would be a big improvement in the economics of the plant.

The response from the fusion community has been positive. Stephen Dean, president of Fusion Power Associates, an industry group, considers the reverse shear work to be very significant. "For the first time we are seeing a substantial volume of plasma in the middle that is very quiescent and well-confined," Dean said. "I think it is a major event."

Bruno Coppi, a fusion pioneer at Massachusetts Institute of Technology, finds the results to be very encouraging. Coppi was one of the persons who brought the tokamak concept to the United States from Russia, where it was invented, almost 30 years ago. He and his laboratory at MIT, in the mid-1970s, set a record for density of a confined plasma in their Alcator machine, beating the old mark at that time by two orders of magnitude, a superb achievement in its day.

In the late 1970s Coppi and others showed that, at high magnetic fields, one could acheive what he called a second stability region within the plasma, where the pressure and the beta values can be increased. The results at General Atomics and Princeton seem to be along this direction.

One implication that Coppi pointed out, is that at higher pressures, it may become possible to burn deuterium alone, or deuterium and helium-3. Such advanced fusion fuels have advantages over deuterium-tritium, because they do not produce as many high-energy neutrons, which damage materials and induces radioactivity. Use of these fuels would do away with most of the engineering problems associated with reactor design, for that reason.

Coppi noted that, "because of the limitations of the Princeton machine, this needs to be done in a regime where the transitory feature is eliminated." The question he raised was whether these favorable conditions can be maintained for any length of time, or whether the plasma would go back to a less favorable state.

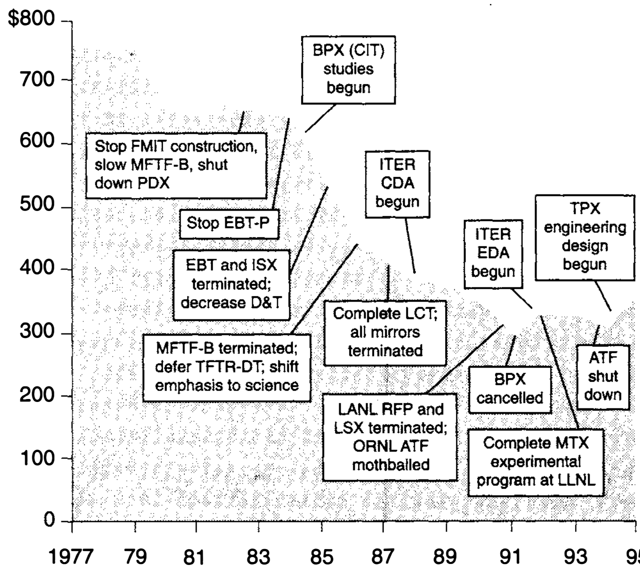
Coppi speculated that the low transport of particles and energy in these experiments may be due to some sort of inflow process, that is, that the particles are being transported inwards, toward the core.

One aspect of fusion research that has most occupied his thoughts has been that of building an ignition device, an experiment which would demonstrate a burning plasma, a self-sustained fusion reaction. He has long thought that this is possible, and that it would be the next logical step in fusion development. Coppi himself headed the Compact Ignition Tokamak project, which grew into the Burning Plasma Experiment (BPX), until cancelled five years ago (see **Figure 4**). Now the recent results achieved by on the DIII-D and the TFTR seem to indicate that ignition may not only be possible, but could prove to be highly successful.

FIGURE 4

U.S. magnetic fusion budget history, 1977-95

(millions FY 1993 $)



Key:
BPX/CIT=Burning Plasma Experiment/Compact Ignition Tokamak
DT=deuterium/tritium
EBT=Elmo Bumpy Torus, EBT-P=Elmo Bumpy Torus-P
FMIT=Fusion Materials Irradiation Test Facility
ISX=Impurity Studies Experiment (a tokamak)
ITER=International Thermonuclear Experimental Reactor; ITER CDA=ITER Conceptual Design Activities; ITER EDA=ITER Engineering Design Activities
LANL RFP=Los Alamos National Laboratory Reverse Field Pinch
LCT=Large Coil Test Facility (superconducting magnets)
LLNL=Lawrence Livermore National Laboratory
LSX=Large S Experiment (a field-reversed compact toroid device)
MFTF-B=Mirror Fusion Test Facility-B
MTX=Microwave Tokamak Experiment
ORNL ATF=Oak Ridge National Laboratory Advanced Toroidal Facility (a stellarator)
PDX=Princeton Divertor Experiment
TFTR=Tokamak Fusion Test Reactor
TPX=Tokamak Physics Experiment

Source: Dept. of Energy, President's Committee of Advisers on Science and Technology, July 1995.

Looking into the future

Reverse shear, as well as other advanced tokamak concepts, can only be completely demonstrated in a continuous operation, steady-state machine. This was the role that TPX was to have played in the U.S. fusion program (see *EIR*, Aug. 12, 1994). However, the budget-slashers in Congress have now cancelled TPX, which will leave the United States without a next-generation device for the foreseeable future.

In addition, Congress is calling for TFTR to be shut down. The fusion funding provisions passed by the House and Senate ($229 million and $225 million, respectively), are sharp reductions from this year's $349 million, nearly 40% lower than the $366 million requested by the administration. The House-Senate conference committee is meeting as we go to press to resolve the difference between the two figures.

As a small consolation, the Senate included wording in its bill, which would allow $56 million for the continued operation of TFTR, providing the funds could be found by making further cuts in the Department of Energy's administrative expenses, which have already taken a $200 million hit. Also, or perhaps alternatively, the Senate indicated that it would be willing to allow the cost of terminating these programs, $45 million, to be taken from somewhere else instead of from the fusion budget, after the DOE fusion office had argued that these termination costs would eat away at other fusion programs. Materials R&D, plasma technology development and other programs would have been ended.

The attack on fusion is not surprising. The Green Scissors Report issued jointly by the radical ecologist Friends of the Earth and the Conservative Revolution's National Taxpayers Union had targeted research into fusion energy—which is both the cleanest and cheapest form of energy yet known—for elimination (see *EIR*, July 28, 1995).

Rep. Robert Walker (R-Pa.), who chairs the House Committee on Science, speaking before a Fusion Power Associates meeting in June, stated that the primary focus of the U.S. fusion program is on the International Thermonuclear Experimental Reactor (ITER). Adding that he could not foresee any multibillion-dollar program unless it involves international cooperation.

In July, the administration weighed into the fusion debate with a somewhat timid set of recommendations from a panel of the President's Committee of Advisers on Science and Technology, which had examined the U.S. fusion program. They put forward a plan for funding fusion at a flat $320 million per year. The plan would be to delay TPX for three years, continue to operate existing machines, and, meanwhile, the U.S. would try to talk down the cost of ITER from $10-13 billion to around $4 billion. The President's Committee conceded that a U.S. withdrawal from international collaboration could lead to the collapse of such efforts, and that, at funding levels of $200 million, the United States could not participate in international fusion programs, much less be engaged in any meaningful domestic program.

DOE spokesman Jeff Sherwood said of the expected funding cuts, that the fusion community is bracing for 1,500 layoffs. Even if TFTR should survive another year, it seems unlikely that the United States will be able to mantain a viable fusion program, unless such low funding levels are reversed.

Bruno Coppi expressed his concern that not only will we no longer invest the funds to keep our fusion machines running, but that we will not have the people who are capable of designing and operating new machines. He said it reminds him of the dome on the Pantheon in Rome: It was not for 1,500 years, that the science was developed under Brunelleschi to build domes like that again.