aware of people in magnetic fusion getting interested in liquid walls. They almost dominated the discussion." Designing liquid walls for a magnetic fusion reactor is a challenge, because the strong magnetic fields they generate can interfere with the flow of liquid metals. But smallish, university-scale experiments could begin to address the challenges, says Logan.

Another intersection between these long-separated areas of fusion research emerged from IFE. The IFE effort is thriving, with plans—and funding—to briefly crush and ignite fuel pellets with 200 converging lasers at the $1.2 billion National Ignition Facility (NIF), scheduled to be in operation at Livermore sometime after 2001. Yet although no one doubts the utility of NIF for studying bomb physics, some MFE researchers say they don't believe the concept will lead to a practical energy source. Among the biggest problems: Lasers are far too expensive and inefficient for a power plant.

"Rightfully, the MFE community is saying we haven't worked out all those questions," says Logan. One possible answer came from Sandia National Laboratory in Albuquerque, New Mexico, where the so-called Z machine has achieved a series of striking results by imploding a pellet of fuel using x-rays generated with blasts of electrical current (*Science*, 18 July 1997, p. 306 and 3 April 1998, p. 28). But Siemon of Los Alamos suggested a hybrid approach that might solve both the IFE's driver problem and the challenge of producing a stable plasma in MFE.

Called magnetized target fusion, the concept would resemble the Z machine in using a burst of current to crush fusion fuel. But instead of a pellet, the fuel is a hot plasma caged in a magnetic field. The pulsed compression would not only compress and heat the plasma but also amplify the magnetic field, enhancing its insulating properties and relaxing the need to start with huge fields. "I think it's kind of intriguing," says Sandia's Craig Olson, who is working on the Z machine. "It's potentially relatively low cost."

The MFE community is also trying to get its house in order. As in a less comprehensive meeting last year (*Science*, 8 May 1998, p. 818), researchers generally agreed that creating a burning plasma should be their next major milestone. "What we're arguing about is the best way to do it," says Dale Meade, head of advanced fusion concepts at the Princeton Plasma Physics Laboratory. One route might be the so-called ITER Lite, a slimmed-down version of the original that would cost roughly half as much. Another option, with a price tag of about $1 billion, would be Meade's Fusion Ignition Research Experiment—a smaller tokamak that would eschew ITER's superconducting magnet coils for plain copper. A tokamak called the Ignitor, being designed at the Massachusetts Institute of Technology, would also create very strong magnetic fields with copper coils and be still smaller and less expensive.

The debate revealed that "there's a lot of potential yet to be discovered in the tokamak line," says Ron Stambaugh, a physicist at General Atomics in San Diego. At the same time, Snowmass participants agreed that MFE researchers should explore reactor designs that rely on alternative ways of caging a fusion plasma (see following story).

Similar conclusions about MFE appear in a draft report by the high-level Task Force on Fusion Energy of the Secretary of Energy Advisory Board, some of whose members were at Snowmass. Now its report and the results of Snowmass, along with a third report on fusion still being prepared by the National Research Council and other sources, will figure in the deliberations of the Fusion Energy Sciences Advisory Committee (FESAC). By September, FESAC will make comprehensive recommendations about fusion's roadmap, including the balance of funding between MFE and IFE and the next steps toward a burning plasma, to Martha Krebs, director of the office of energy research at the U.S. Department of Energy.

"We delayed answering the charge from Martha Krebs ... to be able to hear what people had to say at Snowmass," says John Sheffield, a physicist at Oak Ridge National Laboratory and the University of Tennessee, who is the FESAC chair. By bridging some of their differences, U.S. fusion scientists may have helped shape their future.

–JAMES GLANZ

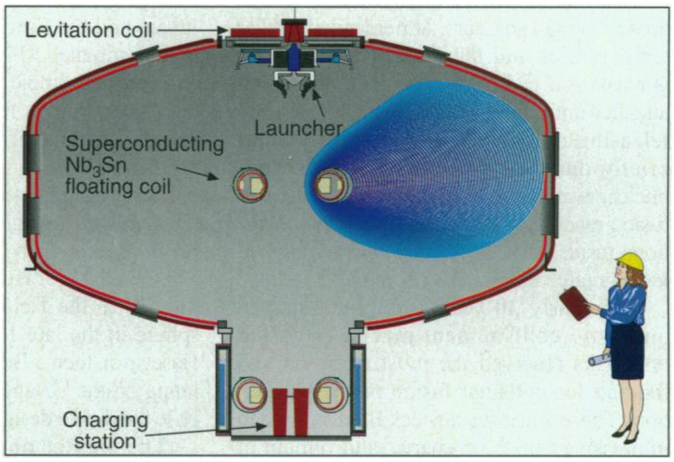
FUSION'S FUTURE

▶ **ALTERNATIVES**

Fusion Power From a Floating Magnet?

In one radical design for a magnetic fusion reactor, energy-producing plasma would be trapped around a levitating ring of superconductor

At first glance, something seems to be missing from the diagram Jay Kesner is describing. With a wave of a pointer he indicates a pumpkin-shaped vacuum vessel, 3 meters tall and 5 across, designed to contain a plasma of hot electrons and ions. Kesner, a physicist at the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center, explains that a ring hovering at the center of the diagram with no visible means of support is a superconducting magnet that weighs nearly 500 kilograms. The lack of supports is not a draftsman's oversight. Kesner and his colleagues plan to levitate the ring magnetically as part of a novel experiment that may ultimately lead to a simple, safe, and inexpensive fusion power source.



Concentration through levitation. In the Levitated Dipole Experiment, a floating superconducting coil traps plasma in its magnetic field (blue lines).

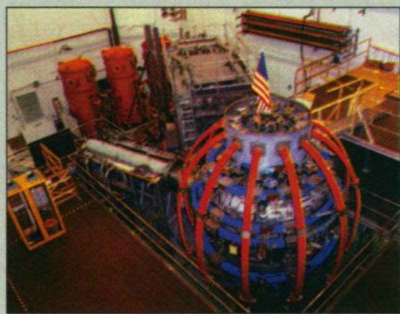
CREDIT: LANL

The Levitated Dipole Experiment (LDX) is a 5-year study of a plasma confinement scheme inspired by observations of ionized gases trapped in the magnetic fields of planets like Jupiter and Earth. Funded by the Department of Energy, the $6 million collaboration between MIT and Columbia University in New York City is under construction at the Plasma Science and Fusion Center on the MIT campus and should begin operation by the summer of 2000. In the current phase of the project, which will stop short of actual fusion, principal investigators Kesner and Michael Mauel of Columbia hope to determine whether a dipole-based machine—a sharp departure from current

Many Shapes for a Fusion Machine

Despite the recent troubles of the International Thermonuclear Experimental Reactor, a project to build a giant doughnut-shaped machine called a tokamak, other tokamaks continue to lead the magnetic-confinement fusion field. In late 1997, the Joint European Torus in Abingdon, England, set a new record by generating a 16-million-watt burst of fusion power—still short of breakeven, but nearly twice the previous record set in 1994 in the Tokamak Fusion Test Reactor (TFTR) at Princeton University. (TFTR was decommissioned in April 1997.) But in labs around the world, researchers are working on alternative fusion machines that they hope will confine plasma more effectively or efficiently. One is the levitated dipole reactor being developed at the Massachusetts Institute of Technology and Columbia University (see main text); here are a few of the other, less radical alternatives:

■ **Stellarators:** Often considered tokamaks' most serious competitor, stellarators include helical magnet coils wound around a plasma chamber. The kinky magnetic fields that result may control turbulence better than the smooth fields in tokamak configurations. Major stellarator experiments include Japan's Large Helical Device and the Helically Symmetric Experiment at the University of Wisconsin, Madison, as well as projects in Spain, Australia, and Germany.



Ball of fire. Princeton's National Spherical Torus Experiment.

■ **Spherical toroids:** Shrinking the hole at the center of a tokamak changes the doughnut-shaped machine to something resembling a cored apple. Spherical toroids rely on interlocking coils to generate fields much as tokamaks do, but achieve much higher confinement efficiencies by maximizing the length of stable magnetic field lines. Two new spherical toroids, the Mega-Amp Spherical Tokamak at the Cullham Science Centre in the U.K. and the National Spherical Torus Experiment at Princeton, produced their first plasmas early this year.

■ **Reverse-field pinch (RFP):** Relatively minor players in the fusion game for the moment, RFPs share the doughnut shape associated with tokamaks, but their magnets can be smaller because researchers induce a current in the RFP's plasma itself, making it flow around the machine like a river and generate its own magnetic field. The field squeezes—or pinches—the very plasma that produces it, helping to keep the plasma away from the chamber walls. Confinement efficiencies in the Madison Symmetric Torus at the University of Wisconsin rival those of tokamaks.

■ **Spheromaks:** Eliminating the hole in a tokamak altogether results in a spheromak, a device that, like the RFP, relies in part on plasma currents to generate confinement fields. Spheromak programs include the Swarthmore Spheromak Experiment at Swarthmore College in Pennsylvania and the Sustained Spheromak Physics Experiment at Lawrence Livermore National Laboratory in California.

–J.R.

reactor designs—can generate the conditions for fusion. The project is part of a wave of experimentation now sweeping through the field of magnetic fusion as experimenters seek alternatives to current reactor designs (see sidebar).

Thermonuclear fusion is the engine that powers the sun and stars. At tremendous stellar temperatures and the pressures of intense gravitational fields, hydrogen nuclei are driven together until they fuse, forming helium and releasing energy. Similar reactions occur briefly during the detonation of thermonuclear warheads. In magnetic confinement fusion machines, physicists mimic the conditions inside stars by heating plasma trapped in magnetic, rather than gravitational, fields.

For nearly 30 years, doughnut-shaped magnetic confinement machines called tokamaks received the most attention and funding for potential fusion power production. These intricate devices have produced impressive bursts of energy and remain at the forefront of fusion research. But according to Dale Meade, who heads the Advanced Fusion Concepts group at Princeton University, tokamaks and related machines are plagued by various types of turbulence that cause the plasma to leak out. Surmounting these challenges, says Meade, requires either advances in machine design or dramatically scaled-up, and expensive, devices. "We know that we can overcome plasma turbulences by building huge systems," explains Meade, "but it wouldn't be practical or attractive to persons interested in producing electricity." The United States recently withdrew from the International Thermonuclear Experimental Reactor (ITER) tokamak project, a collaboration with Russia, Japan, and the European Union, in part due to the estimated $10 billion price tag.

Levitated dipole reactors, in contrast, are the least complex fusion machines yet conceived. Current-carrying loops (like the superconducting ring at the heart of LDX) and common bar magnets generate dipole fields, the simplest of magnetic field configurations. So do planets, such as Jupiter. It was the Voyager II spacecraft's detection of plasma trapped in the fields of Jupiter's magnetosphere in the late 1980s that inspired Akira Hasegawa, then a Bell Labs physicist collaborating on the Voyager space missions, to propose the dipole design for a fusion machine.

The Jupiter observations, along with theoretical predictions, suggest that dipole magnets could confine plasmas more efficiently, with weaker magnetic fields, than the complicated coils in tokamaks and related fusion machines. As LDX physicist Darren Garnier explains, in tokamaks and related machines, magnets push on the plasma from the outside, while the dipole in LDX will pull on the plasma from the inside. "I think it was Richard Feynman," says Garnier, "who said trying to make [tokamak-style] magnetic confinement work is like trying to compress Jell-O with rubber bands." Dipoles, on the other hand, pull on the plasma, just as gravity pulls down on Jell-O sitting in a bowl.

In a planetary magnetosphere, plasma captured from the solar wind is lost as it follows the magnetic field lines into the poles, where the atmosphere neutralizes it. For a dipole formed by a current loop, however, field lines pass through the center of the loop unobstructed. The plasma forms a hot cloud trapped on the field lines surrounding the magnet and flowing through its center. To keep plasma from cooling down or sticking when it hits magnet supports or power cables, Hasegawa recommended doing without them. His scheme included a levitated, superconducting dipole loop with currents that flow perpetually once established.

After 20 years of steady progress in tokamak technology, however, the scientific community was not yet ready for his proposal. "Timing is everything," says Kesner, "and at that time only tokamaks were fundable." That has changed, as the LDX project testifies.

In the current design, a thermally insulated ring of niobium-tin wire will begin by resting in what Kesner calls a charging station at the base of the vacuum vessel. The wire, which becomes a superconductor below 15 kelvin, is cooled to about 5 degrees and a current is in-

CREDIT: PPPL

troduced. Researchers will use a crane to raise the ring about a meter and a half above the vessel floor, then switch on a magnet at the top of the chamber. Its field, while too weak to interfere much with the ring's, is strong enough to levitate the ring at the chamber center. There the coil should float for up to 8 hours, warming slowly, before it must be lowered and recooled.

In addition to being simple, levitated dipole reactors could also be safer than other fusion schemes. Tokamaks and most other reactor designs fuse the hydrogen isotopes deuterium and tritium. These reactions generate copious neutrons, which deposit heat in the reactor walls. The heat generates power, but the neutrons ultimately render the reactor components radioactive, resulting in tons of hazardous material that must eventually be discarded. Because neutrons pose severe biological hazards, a tokamak reactor would also need to be heavily shielded.

Dipole-based reactors, with their high plasma-confinement efficiency, should be able to generate higher temperatures and pressures, enabling them to burn more advanced fuels. These fuels mainly produce not neutrons, but energetic photons and electrically charged particles. The photons would heat the reactor, producing power, while the charged particles remain trapped in the magnetic fields. Dipole-based reactors must use these advanced fuels—neutrons, which can't be confined with magnets, would inevitably pierce the magnet, heating it until it ceased to function as a superconductor. As a bonus, the fusion products are less likely to make the reactor components radioactive or threaten bystanders.

The fuel most frequently touted for a levitated dipole reactor is a mixture of deuterium and He^3, a helium isotope containing two protons and one neutron. He^3 is scarce on Earth, although conventional fission reactors produce enough He^3 to conduct scientific experiments. But to fuel levitated dipole power plants, Kesner proposes that we eventually may have to mine the moon, where He^3 is relatively plentiful. Kesner can afford to relax about the source of fuel for his reactor, as commercial energy production based on D-He^3 fusion is several decades away—at best.

Meade, for example, thinks plenty of problems with the levitated dipole concept could yet emerge. He believes that tokamaks, or devices related to them, are still the best bet for future controlled fusion machines. "Nevertheless," he says, "I think LDX is a wonderful research tool to help us understand the stability issues of plasma confinement in other machines and, of course, in astrophysics." And after the recent ITER troubles, says Steve Fetter, a professor at the University of Maryland School of Public Affairs who studies energy and environmental policy, long-term research efforts like LDX are what the magnetic fusion field needs. "At this stage, it is better to let a hundred flowers bloom rather than focus so narrowly on the tokamak," he says.

In any case, few physicists expect fusion to be a viable energy source before the middle of the next century. Levitating a half-ton magnet may seem like an impressive feat of engineering sleight of hand, but it's a small trick compared to bottling the fusion genie that powers the sun and stars—the ultimate goal of plasma physicists like Kesner, Mauel, and their LDX colleagues.

–JAMES RIORDON

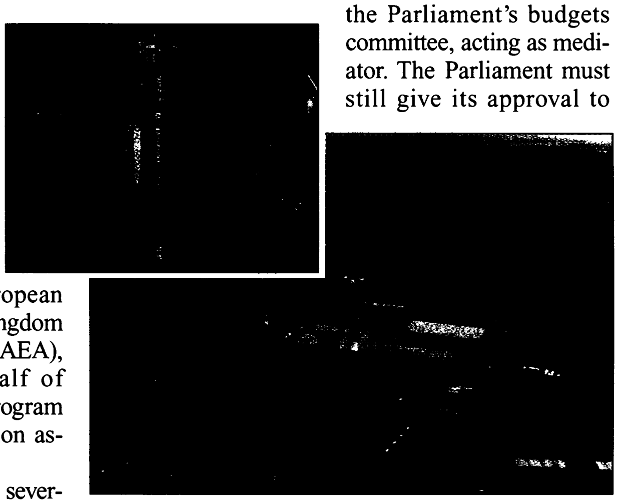
James Riordon is a science writer in Greenbelt, Maryland.

FUSION'S FUTURE
EUROPE

JET Staff OKs Pay Settlement

The end is in sight for a 20-year-old dispute over disparities in pay and working conditions at Europe's premier fusion laboratory, the Joint European Torus (JET) near Oxford, U.K. Last month a majority of the 217 professional U.K. staff members voted to accept a 24 million euro (US$24.7 million) compensation package. Half of the money is expected to come from tightening JET's 1999 operating budget, including reducing the number of hours the machine will be running.

The out-of-court settlement clears the way for changes in the management of JET, which since 1979 has been Europe's major contributor to the international effort to design a next-generation fusion machine. In January responsibility for the facility will be transferred from the European Commission to the United Kingdom Atomic Energy Authority (UKAEA), which will run it on behalf of the commission's Euratom program and Europe's 17 national fusion associations.



Pay up. Deal compensates for pay disparity at JET.

Fearing a costly settlement, several associations had threatened to pull out if the dispute wasn't settled. The UKAEA had said that it couldn't afford to operate the facility alone and that it needed an agreement this month in order to prepare properly for the new management scheme. "Now I think our doubts will fall and we will take part," says Roberto Andreani, head of the Italian fusion association.

Historically, all of JET's professional staff members have been commission employees, except for U.K. nationals, who remained on UKAEA's payroll and salary structure. As a result, U.K. staff members worked side by side with nationals from other European countries who, as an inducement to sign up, earned higher salaries and were promised preferential treatment when applying for other Euratom posts. The U.K. staff complained to the European Court of Justice, which in 1996 found that this practice was discriminatory and ordered the commission to change its employment practices and negotiate a settlement. The European Parliament tried to mediate, but the staff turned down a 9 million euro offer and decided to go back to the European court.

The cases were unlikely to be heard until the middle of next year, however. So once again the European Parliament stepped into the breach, with Detlev Samland, chair of the Parliament's budgets committee, acting as mediator. The Parliament must still give its approval to transfer public money to pay for the settlement, but little opposition is expected. "The Parliament has always considered that there has been a discrimination," says one Parliament official.

As for financing the settlement, some 9 million euros were set aside after the 1996 compensation offer, and an operating reserve contains another 3 million euros. The remainder will be drawn from JET's 80 million euro operating budget this year. In addition to a freeze on hiring, the lab's electric bill, a major expense, will be pared by reducing the hours of operation. "JET will have to walk for the rest of the year, at best," says Francis Troyon, chair of the JET council.

–JUDY REDFEARN

Judy Redfearn writes from Bristol, U.K.

CREDITS: JET JOINT UNDERTAKING