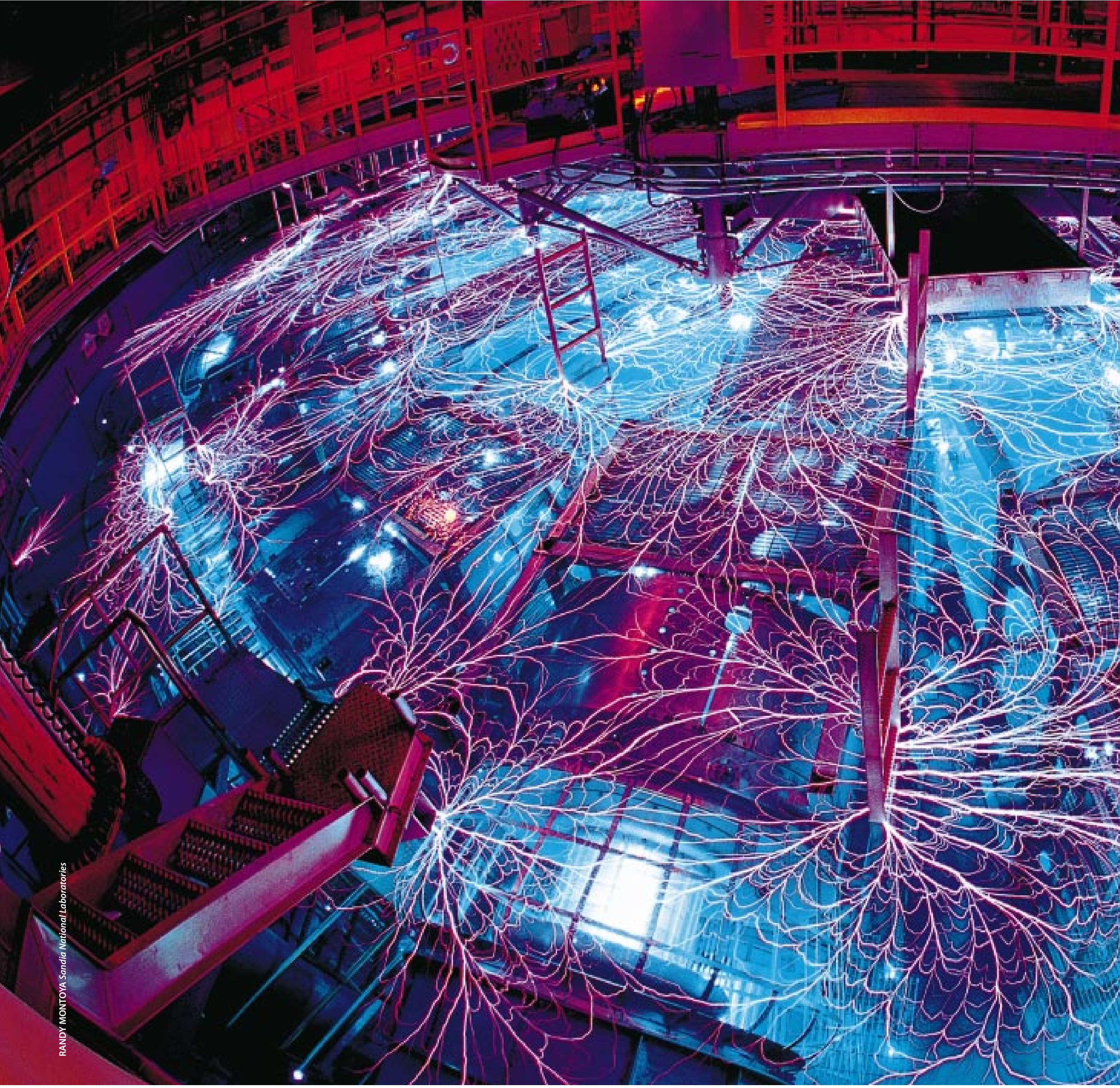
Fusion and the Z Pinch


RANDY MONTOYA *Sandia National Laboratories*

FIRING OF Z MACHINE produces a spectacular display. Z's primary transmission lines are submerged in water for insulation. A very small percentage of the huge energy used in firing the device escapes to the surface of the water in the form of large electrical discharges. As in a lightning strike, the high voltages break down the air-water interface, creating the visual discharges. The event lasts only microseconds. An automatic camera, with its shutter open, records the rapid discharges as a filigree of brilliant tracks.

Some things never change—or do they? In 1978 fusion research had been under way almost 30 years, and ignition had been achieved only in the hydrogen bomb. Nevertheless, I declared in *Scientific American* at the time that a proof of principle of laboratory fusion was less than 10 years away and that, with this accomplished, we could move on to fusion power plants [see "Fusion Power with Particle Beams," SCIENTIFIC AMERICAN, November 1978]. Our motivation, then as now, was the knowledge that a thimbleful of liquid heavy-hydrogen fuel could produce as much energy as 20 tons of coal.

Today researchers have been pursuing the Holy Grail of fusion for almost 50 years. Ignition, they say, is still "10 years away." The 1970s energy crisis is long forgotten, and the patience of our supporters is strained, to say the least. Less than three years ago I thought about pulling the plug on work at Sandia National Laboratories that was still a factor of 50 away from the power required to

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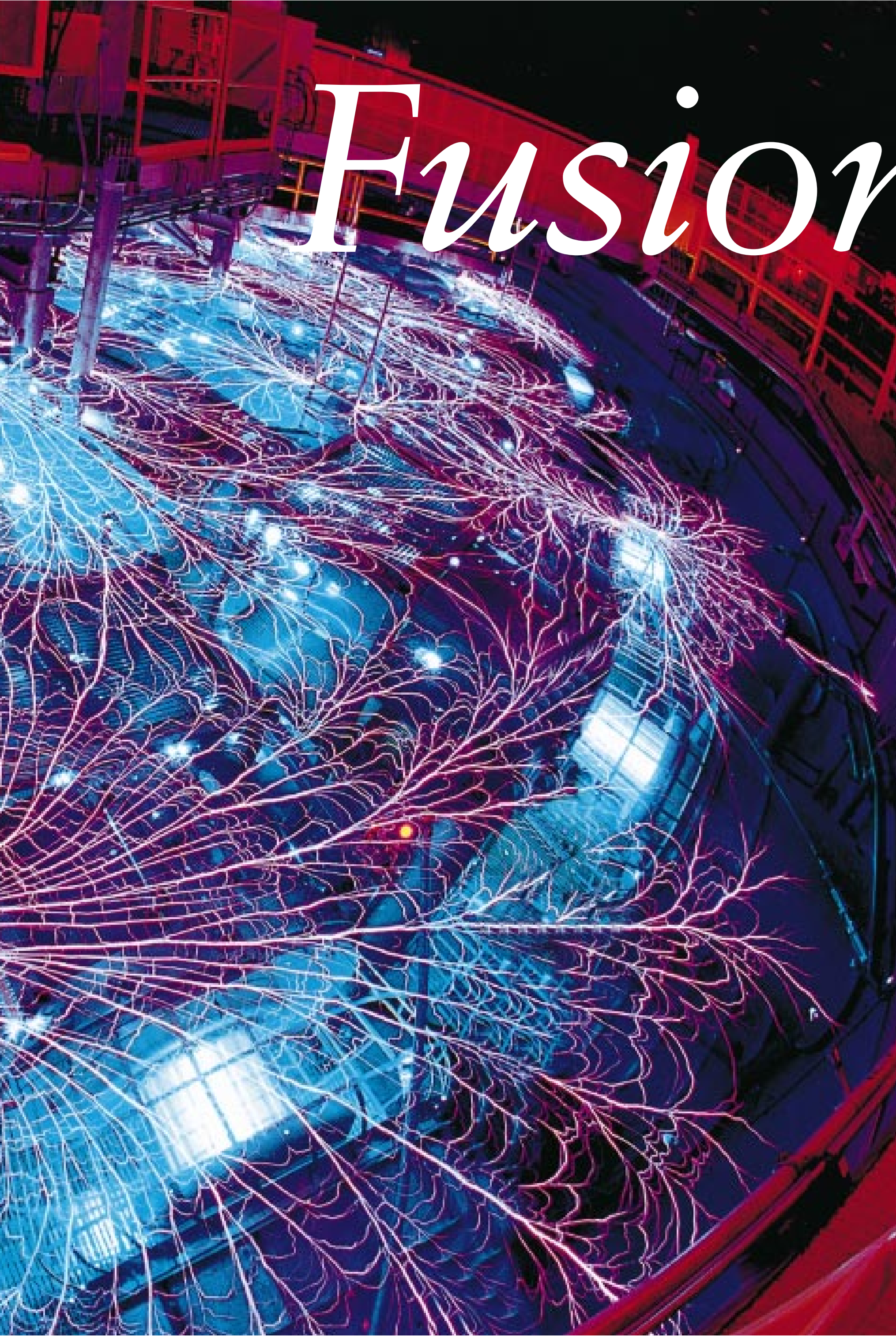


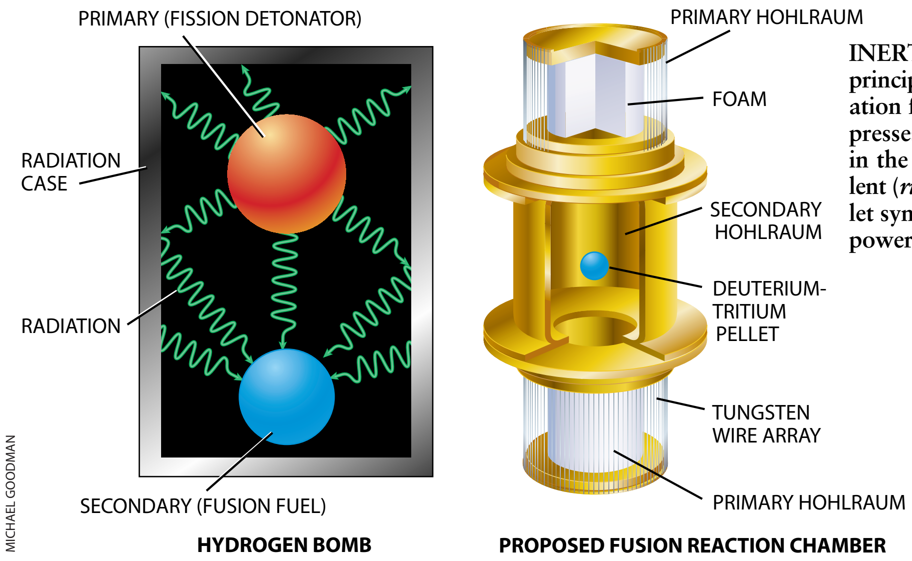
A device called the Z machine has led to a new way of triggering controlled fusion with intense nanosecond bursts of x-rays

by Gerold Yonas

light the fusion fire. Since then, however, our success in generating powerful x-ray pulses using a new kind of device called the Z machine has restored my belief that triggering fusion in the laboratory may indeed be feasible in 10 years.

The hydrogen bomb provides the proof that fusion can be made to happen. In an H-bomb, radiation from an atomic fission explosion acts as a trigger, heating and compressing a fuel container to ignite and burn the hydrogen inside. That sounds simple, but causing a fusion reaction to ignite and burn means forcing together the nuclei of two forms of hydrogen, deuterium and tritium so that they fuse to form helium nuclei, giving off enormous energy. The compression must be done with almost perfect symmetry so that the hydrogen is squeezed uniformly to high density.

In the early decades of fusion research, the prospect of making a laboratory version of the H-bomb seemed remote. Instead efforts to control fusion relied on the principle of magnetic confinement, in which a powerful magnetic field traps a hot deuterium-tritium plasma long enough for fusion to begin. In 1991 deuterium-tritium fusion was achieved in this way by the Joint European Torus and later by Princeton University's Tokamak Fusion Test Reactor (TFTR). The next step on this road is the International Thermonuclear Experimental Reactor (ITER), a project involving the U.S., Europe, Japan and Russia. ITER's anticipated expense and technical difficulty, however, as well as disagreement



INERTIAL CONFINEMENT FUSION uses the principles of the hydrogen bomb (*left*), in which radiation from a fission bomb (called the primary) compresses and heats the fusion fuel, which is contained in the secondary. The minuscule laboratory equivalent (*right*) aims to bathe the peppercorn-size fuel pellet symmetrically in radiation and to concentrate the power into the pellet so that it implodes uniformly.

over where it should be built, have already slowed progress on the engineering design phase.

As far back as the early 1970s, researchers at Los Alamos, Lawrence Livermore and Sandia national laboratories turned their attention to another way of achieving fusion. In the inertial confinement approach, typified by the H-bomb, the idea is to use radiation to compress a pellet of hydrogen fuel. Whereas the H-bomb relies on radiation from an atomic bomb, the first attempts at laboratory inertial fusion made use of intense laser or electron beams to implode a fuel pellet.

The power then thought necessary to achieve ignition was much smaller than we now know it to be. By 1978 (as discussed in my earlier *Scientific American* article), the estimated requirement had risen to one million joules delivered in 10 nanoseconds to the outside of a peppercorn-size fuel pellet—a power demand of 100 terawatts and the equivalent of condensing several hours' worth of electricity use by half a dozen homes into a fraction of a second. To meet this need, we at Sandia and scientists in the Soviet Union began research with a novel technology called pulsed power.

In a pulsed power system, electrical energy is stored in capacitors and then discharged as brief pulses, which are made briefer still to increase the power in each pulse and compressed in space to increase the power density. These bursts of electromagnetic energy are then converted into intense pulses of charged particles or used to drive other devices. Laser fusion systems, in contrast, start with much longer electrical pulses, which are amplified and shaped within the lasing system itself. Pulsed power was seen as an attractive alternative to lasers because of its proved efficiency and low cost.

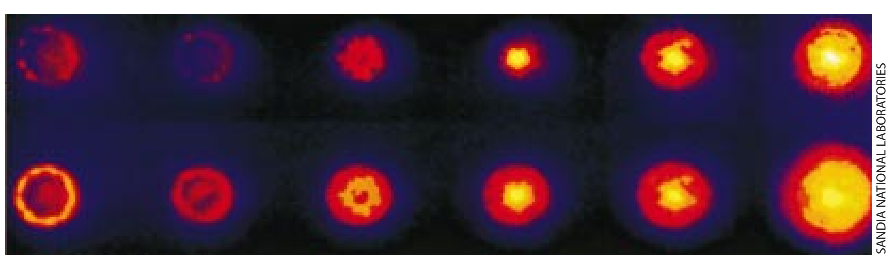
The technology began in 1964 at the U.K. Atomic Energy Authority and developed through the mid-1960s in the Soviet Union, the U.K. and the U.S. with support from the Energy and Defense departments. But the technique had limited power output, making it a dark horse in the race to fusion. Instead its preferred purpose was to simulate, in the laboratory, the effects of radiation on weapon components.

In 1973 funded programs in inertial confinement fusion began in the U.S. at Sandia under my direction and at other national laboratories and in the U.S.S.R. at the Kurchatov Institute under Leonid Rudakov. Since then, we have learned a tremendous amount about the technology for creating the power to reach ignition and the ignition requirements themselves, whether with lasers or with pulsed power. Decades of carefully diagnosed experiments using powerful lasers have improved and validated the computer codes that design fuel pellets. Today these simulations indicate that almost 500 terawatts and two million joules of radiation at a temperature of three million degrees for four nanoseconds are required to ignite the fuel.

Lasers can do this. After 13 years of research using the 30-kilojoule Nova laser, Lawrence Livermore is now building a much more powerful laser as the heart of the National Ignition Facility (NIF). If successful, the NIF will produce at least as much energy from fusion as the laser delivers to the pellet, but that will still not come close to producing the several 100-fold greater energy required to power the laser itself. That goal requires high yield—that is, fusion energy output much greater than the energy put into the laser. The NIF will take the next step toward high yield, but present laser technology is too expensive to go further.

Reviving the Z-Pinch

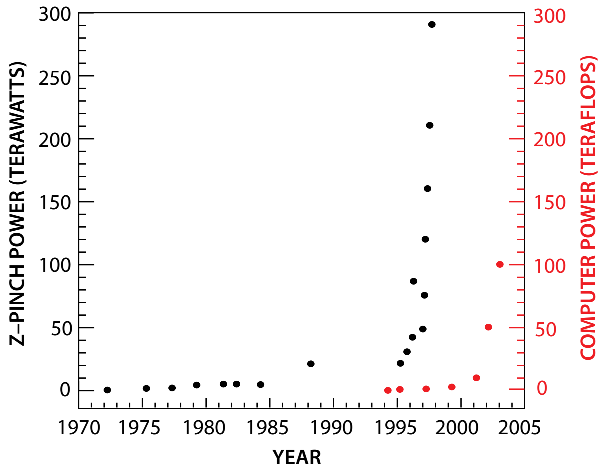
Just a few years ago, despite 25 years of effort, we at Sandia were still far from achieving fusion through pulsed power technology. The decision to continue the program was not easy, but our perseverance has recently been rewarded. For one, power output has grown enormously: pulsed power was producing one thousandth of a terawatt of radiation in the mid-1960s; recently we have reached 290 terawatts in experiments on the Z machine. We are confident that we can achieve high-yield fusion with radiation pulses of 1,000 terawatts, and we have come within a factor of three of that goal.



X-RAYS are generated when a plasma from many fine tungsten wires collapses onto a carbon-deuterium straw placed on the axis of a Z-pinch. End-on views run from left to right at intervals of three nanoseconds. The top series shows x-rays that have energy greater than 800 electron volts; the bottom series shows x-rays around 200 electron volts in energy.

Equally important has been progress in concentrating the intense energy onto a tiny fuel pellet. In the 1970s we began with electron beams and, in the 1980s, switched to beams of ions, which should heat a target to higher temperatures. But charged particles are hard to steer and to focus tightly into beams. X-rays have, in principle, a much more promising characteristic: they can uniformly fill the space around a fuel container, just as heat in an oven envelops a turkey. The prospect of initiating fusion by using pulsed power systems to create intense bursts of x-rays within a small reaction chamber has now emerged from research on a concept called the Z-pinch, which dates back to the beginnings of magnetic confinement fusion research in the 1950s.

POWER from wire-array Z-pinches increased slowly from 1970 to 1995. The rapid advances of the past two years in particular are the result of evolution to complex multiple-wire experiments using high-current accelerators and of improved computer modeling of plasmas. Red dots and scale show the increasing computer power available for simulations.



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Originally, the Z-pinch was an attempt to initiate fusion by passing a strong electric current through deuterium gas. The current both ionizes the gas and generates a magnetic field that "pinches" the resulting plasma to high temperature and density along the current path, conventionally labeled the *z* axis. But the technique proved unable to compress a plasma uniformly: fluid instabilities break the plasma into blobs, making the Z-pinch inadequate to support fusion. The compression of the plasma, however, also generates x-rays, with energies up to 1,000 electron volts. For 30 years, research on Z-pinches in the U.S., the U.K. and the U.S.S.R. focused on optimizing the subkiloelectron-volt x-ray output, using those x-rays to test the response of materials and electronics to radiation from nuclear weapons.

The Z-pinch has now acquired new life as a way of initiating inertial fusion. In the past three years we have shown that by combining the efficiency and low cost of fast pulsed power with the simplicity and efficiency of the Z-pinch as a radiation source, we should reach ignition by using subkiloelectron-volt x-rays to compress a fusion fuel pellet. Moreover, the affordability of a pulsed power x-ray source should allow us to go beyond that, to efficient burn-up of the fuel and high yield.

To trigger fusion, the Z-pinch must be enclosed in a radiation chamber (or *hohlraum,* German for "cavity" or "hollow") that traps the x-rays. In one system we have explored, the Z-pinch would be placed in a primary hohlraum, with the fuel contained in a smaller, secondary hohlraum. In another method, the pellet would sit in low-density plastic foam at the center of the imploding pinch inside the primary hohlraum. The key is that the x-rays generated as the pinch crashes onto itself, either onto the z axis or onto the foam, are contained by the hohlraum so that they uniformly bathe the fuel pellet, just as the casing of an H-bomb traps the radiation from the atomic trigger. Experiments over the past three years show that both methods should work, because we can now make a Z-pinch that remains uniform and intact long enough to do the job.

Finding the Secret

What is different now compared with the long, earlier period of slow progress? Like Thomas Edison, who tried a thousand materials before finding the secret to the lightbulb, we discovered that the instability of the Z-pinch can be greatly reduced by extracting energy quickly, in the form of a short burst of x-rays, before instabilities destroy the geometry. In effect, the energy of the pinch is removed before it transforms into rapid and small-scale motions of plasma.

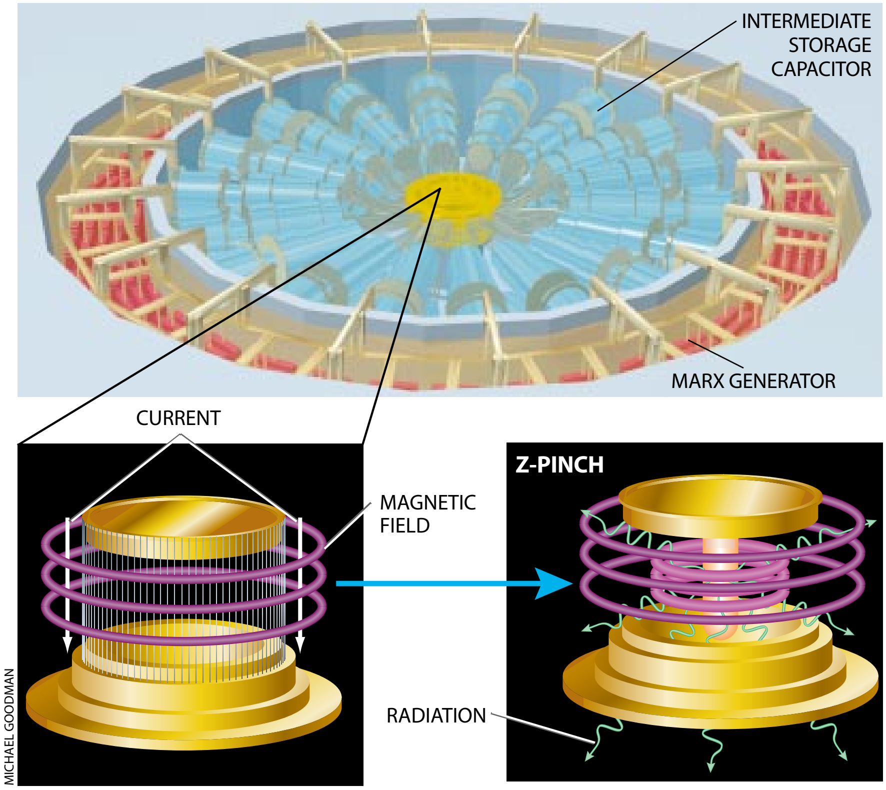
The instability that afflicts the pinch is the same one that makes a layer of vinegar poured carefully on top of less dense salad oil drop irregularly to the bottom of the jar. The instability is beneficial for salads when the jar is shaken, but it was a barrier to achieving fusion. From computer simulations by Darrell Peterson of Los Alamos and Melissa R. Douglas of Sandia, however, we knew that the more uniform the initial plasma, the more uniform and regular the pinch would be when it stagnated on axis and produced x-rays.

Researchers had tried many methods to make the plasma more uniform, such as using thin metal shells or hollow puffs of gas to conduct the electric current, but none met with great success. The breakthrough came at Sandia in 1995, when Thomas W. L. Sanford, using many fine aluminum wires, and then Christopher Deeney and Rick B. Spielman, using up to 400 fine tungsten wires, achieved the needed uniformity. Wire-array Z-pinches were first devised in the late 1970s at Physics International—a private company interested in generating x-rays as a source for testing radiation effects in the laboratory—for enhancing the energy output of one to five kiloelectron-volt x-rays. But the low-current accelerators then available could not deliver enough electric power to implode large numbers of many small wires.

After the 1995 experiments Barry M. Marder of Sandia suggested that the key was to have a number of wires arranged so that as they explode with the passage of the current, they merge to create a nearly uniform, imploding cylindrical plasma shell. Subsequent experiments at Sandia have shown that the desired hot central core is produced after the entire shell implodes onto a foam cylinder positioned on the *z* axis. Also, experiments at Cornell University indicate that each wire may not turn completely to plasma early on, as Marder's simulations suggest. Instead a cold core of wire may remain, surrounded by plasma, allowing the current flow to continue for a time and increasing the efficiency of the pinch.

These breakthroughs began three years ago at Sandia on the 10-million-ampere Saturn accelerator and, since October 1996, have continued on the 20-million-ampere Z machine, which now produces the world's most powerful and energetic x-ray pulses. In a typical experiment, we generate nearly two million joules of x-rays in a few nanoseconds,

PULSED-POWER GENERATOR



SEQUENTIAL CONCENTRATION of power in a pulsed-power facility begins in a circular array of 36 Marx generators, in which 90,000 volts charge a 5,000-cubic-meter capacitor bank in two minutes. Electrical pulses from the 36 modules enter a water-insulated section of intermediate storage capacitors, where they are compressed to a duration of 100 nanoseconds. Passing through a laser-triggered gas switch that synchronizes the 36 pulses to within one nanosecond, the combined pulse travels to the wire array (*far left*) along four magnetically insulated transmission lines that minimize loss of energy. The Z-pinch (*left*) forms as thousands of amps of electric current travel through wires one tenth the diameter of an average human hair. The illustrations on the opposite page demonstrate how x-rays from the pinch would implode a fuel pellet and initiate fusion in a schematic hohlraum design. In the proposed X-1 accelerator, the culmination would be the implosion, in about 10 nanoseconds, of a peppercorn-size fuel pellet to the size of the period at the end of this sentence.

for a power of more than 200 terawatts.

In a series of experiments beginning in November 1997, we increased the x-ray power by 45 percent, to 290 terawatts, by using a double-nested array of wires. The current vaporizes the outer array, and the magnetic field pushes the vaporized material inward. The faster-moving parts strike the inner array and are slowed, allowing the slower parts to catch up and sweep material into the inner array. This geometry reduces the instabilities in the implosion, and when the vaporized materials collide at the *z* axis they create a shorter pulse of x-rays than a single array can. The nested array has produced a radiation temperature of 1.8 million degrees.

In other experiments on Z, led by Arthur Toor of Livermore, foam layers surrounding a beryllium tube within a single array provide a slower, more symmetrical implosion of the Z-pinch plasma, also resulting in increased hohlraum temperatures. It took 40 years to get 40 terawatts of x-ray power from a Z-pinch. Now, in the past three years, we have moved much closer to our final goal of 1,000 terawatts and 16 million joules of x-rays, which should produce the three-million-degree hohlraum temperatures required for high-yield fusion. We knew that pulsed power should be more efficient and less costly than the laser approach, and indeed our Z accelerator now produces a total x-ray energy output equal to 15 percent of its electrical energy input; for Lawrence Livermore's Nova laser the equivalent efficiency is 0.1 percent. Design improvements could increase that figure to 0.5 percent at the NIF, but the inherent inefficiency of the laser process prevents such devices from achieving any higher efficiencies.

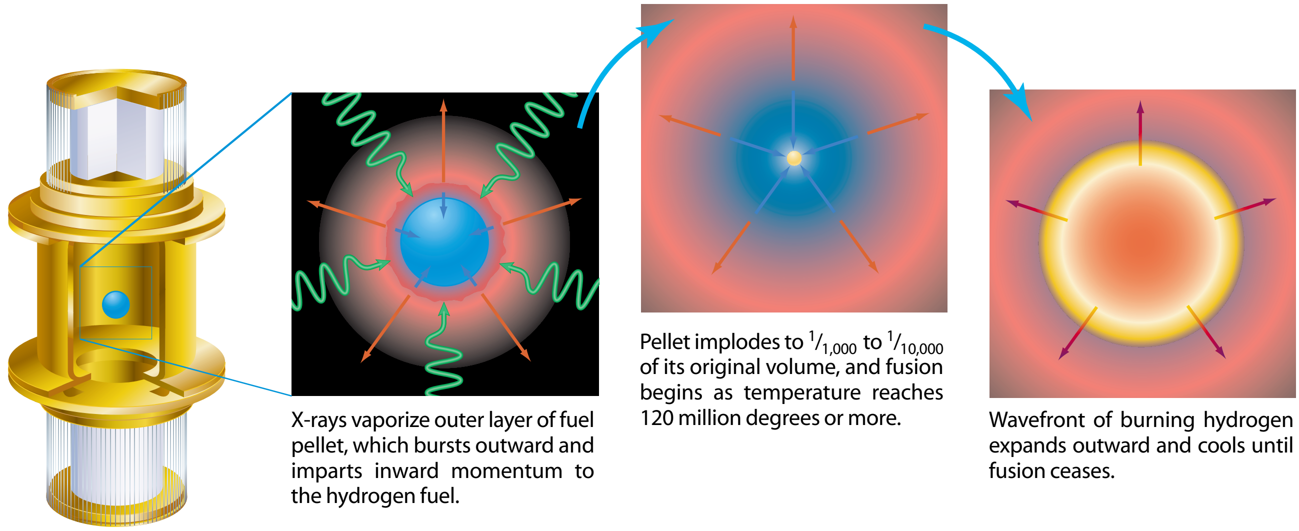
The Final Factor of Three

These intense x-ray pulses have many applications. The energies and powers attained with Z already allow laboratory measurements of material properties and studies of radiation transport at densities and temperatures that could previously be achieved only in underground nuclear explosions. These laboratory experiments, and the fusion yields that a higher-current device would permit, are part of the Department of Energy's stockpile stewardship program to guarantee the safety and reliability of aging nuclear weapons if the U.S. must use them in the future.

There are even astrophysical applications, because the x-ray sources powered by the Z machine produce plasmas similar to those in the outermost layers of a star. The light output from a type of pulsating star, the Cepheid variable, is now better understood because of data obtained by Paul T. Springer of Lawrence Livermore from Z-pinch experiments on the Saturn accelerator in 1996. We expect other data to lessen the mystery of stellar events such as supernovae. Laboratory plasmas also offer the potential for new studies in atomic physics and x-ray lasers.

As an x-ray source, the Z-pinch is remarkably efficient and reproducible; repeated experiments yield the same magnitude of x-ray energy and power, even though we cannot predict in detail what happens. What we can forecast is scale: every time we double the current, the x-ray energy increases fourfold, following a simple square law. And as theoretically expected for thermal radiation, the pinch temperature increases as the square root of the current. If this physics holds true, another factor-of-three increase in current—to 60 million amperes—should allow us to achieve the energy, power and temperature needed to trigger fusion and reach high yield.

What questions must be resolved before that next step? The first is whether we can cram a factor-of-three-higher current into the same container. The reason that the enormous concentration of power into small cavities in a Z-pinch is possible at all was discovered almost 30 years ago at the Kurchatov Institute, at Physics International and at Sandia. Ordinarily, electric fields tend to disrupt



X-rays vaporize outer layer of fuel pellet, which bursts outward and imparts inward momentum to the hydrogen fuel.

Pellet implodes to $^1/_{1,000}$ to $^1/_{10,000}$ of its original volume, and fusion begins as temperature reaches 120 million degrees or more.

Wavefront of burning hydrogen expands outward and cools until fusion ceases.

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the current that generates them, but a phenomenon called magnetic insulation allows short, powerful electrical pulses to be transmitted along a channel between two metal surfaces without breaking down and with almost no energy loss. The magnetic field of the powerful pulse acts to contain the pulse itself, overcoming the electric field that would otherwise cause breakdown. In Z experiments by John L. Porter of Sandia in April 1998, a gap of 1.5 millimeters between a wire array and the surrounding stationary hohlraum wall remained open in the face of the intense radiation because of magnetic insulation, allowing the hohlraum temperature to reach 1.7 million degrees.

Fifty terawatts are transmitted into the tiny space between the wires and the hohlraum wall, and the power density reaches 25 terawatts per square centimeter. If we increase the power to 150 terawatts at 60 million amps, the power density would rise to 75 terawatts per square centimeter. That increase raises new questions, because the material pressure in the metal wall rises to 1.5 to three million atmospheres. Other questions are whether the efficiency of conversion to x-rays remains at the 15 percent level seen at 20 million amps, whether instabilities stay under control, and whether we can achieve the symmetry and shape of the radiation pulse onto the pellet that computer calculations suggest are needed.

Another important step is developing predictive models to scale the complex physics. The two-dimensional simulations available today have provided a great deal of insight into the physics of pinches but, even though restricted to two dimensions, require tremendous computer power. Simulation of the full three-dimensional magnetic, hydrodynamic and radiative character of the pinch is beyond our current capability, but advances in high-performance computing and diagnostics for x-ray imaging are rapidly catching up with our advances in radiated power. In 1998 we have been operating the Janus computer at 1.8 trillion floating-point (multiplication or division) operations per second (teraflops). Colleagues at Sandia and Los Alamos are developing a computer model to simulate the pinch physics and the transport of radiation to the pellet. With the advent of these tools on the new generation of supercomputers, we expect to continue our rapid progress in developing Z-pinches for fusion.

We at Sandia now hope to begin designing the next big step. At the end of March we requested approval from the Department of Energy to begin the conceptual design for the successor to Z, the X-1. This machine should give us 16 megajoules of radiation and, we believe, allow us to achieve high yield. Quoting a cost is premature, but we expect it will be in the neighborhood of $400 million. It is important to remember that Z, X-1 and the NIF are still research tools. Z may achieve fusion conditions; the NIF should achieve ignition; and X-1, building on the lessons of the NIF, should achieve high yield—but none of these experiments is expected to provide a commercial source of electrical power.

As Yogi Berra pointed out, "It is tough to make predictions, especially about the future," but if we can get started soon on design and construction of the next big step, we really think we can do the job in 10 years. SA

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Further Reading

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