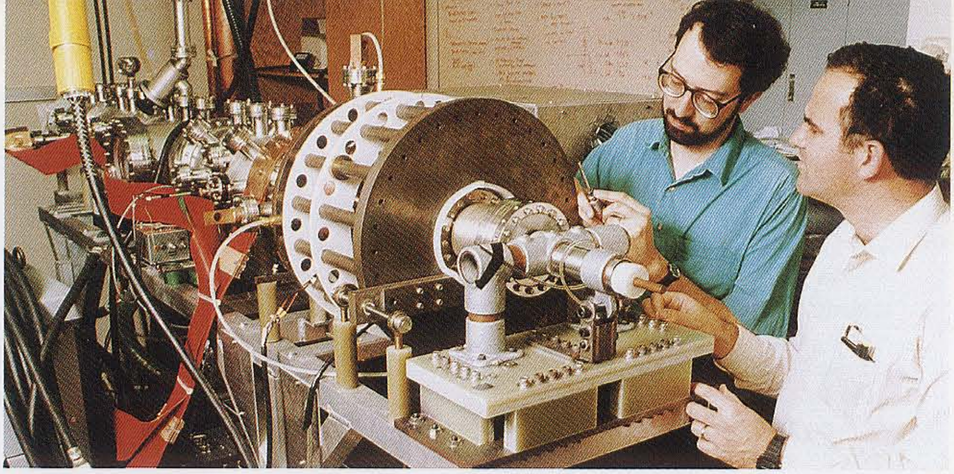
Lab Notes



Brown (left) and Bellan at the spheromak-generating end of their new gun. Brown is holding one of the fuel injectors used to squirt the puffs of gas into the plasma generator.

Plasma Donor

Faithful readers will recall Caltech's participation in the cold-fusion excitement of two years ago (*E&S*, summer '89). Although the dream of producing controlled nuclear fusion in a jar of water at room temperature fizzled, hot nuclear fusion—which makes energy the way the sun does—may be turning generators in the 21st century. Hot fusion occurs in a "plasma"—matter heated to such a degree that its atoms dissociate into a froth of freewheeling electrons and atomic nuclei. If the plasma is sufficiently hot and dense, the nuclei will slam into one another hard enough to overcome their mutual repulsion and fuse together, releasing energy. The sun's vast bulk of hydrogen acts as both pressure vessel, by compressing under its own weight, and fuel supply, by providing a constant flow of dense, ready-to-burn plasma to the solar interior. The most promising terrestrial design, called a tokamak, confines the plasma within a donut-shaped magnetic field. Stoking a tokamak is a bit like shoveling coal into the hottest furnace imaginable—the stoker has to stand back a safe distance, yet throw the fuel hard enough to get it into the fire. Figuring out how to do this is a basic goal of fusion research.

Most designers throw ice cubes into the tokamak to fuel it, but Paul Bellan, professor of applied physics, is blowing bubbles into it instead. "The conventional method is to shoot little pellets of frozen deuterium—heavy hydrogen—into the tokamak with some variation of a catapult or a blowgun. These pellets travel at several kilometers per second (several thousand miles per hour), but it's dicey whether they can reach the tokamak's center, where the burning occurs. [Try throwing an ice cube into the center of the sun sometime.] We're looking at a much more speculative refueling scheme that instead shoots small plasmas, called spheromaks, into the tokamak." A spheromak is a donut-shaped plasma, perhaps as large as a pineapple, that's contained by its own magnetic field the way a bubble is enclosed by a soap film. An electric current coursing around the plasma ring generates the field. The field doubles as a handle by which the spheromak can be flung into the tokamak at incredible speeds. Achieving these high speeds is critical to the method's success—the spheromak has to be hurled with enough force for its charged particles to penetrate the tokamak's magnetic field.

Bellan, senior research fellow Michael Brown, and electronic engineer Frank Cosso are building plasma bubble guns with funding from the Department of Energy. The latest model is a horizontal copper cylinder, some six inches in diameter and two feet long. An iron-alloy rod runs the length of the cylinder's axis, and the cylinder is enclosed in a stainless-steel vacuum casing. Like a wire loop supporting a soap film, a "birdcage" of iron bars outside the casing anchors a sheetlike magnetic field that emanates from the rod and stretches across the cylinder's front end. The rod and the cylinder are actually electrodes wired to a bank of 15,000-volt capacitors via an electronic switch called an ignitron. A puff of gas—hydrogen, deuterium, or helium—enters

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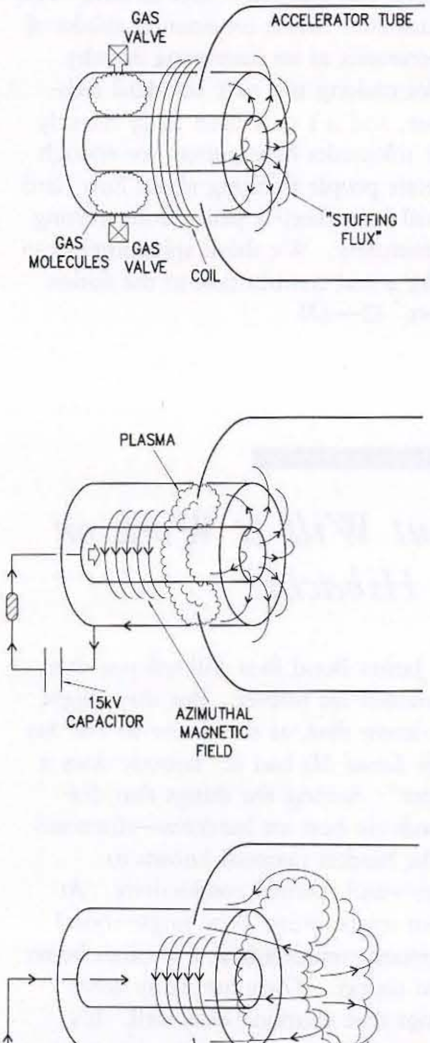

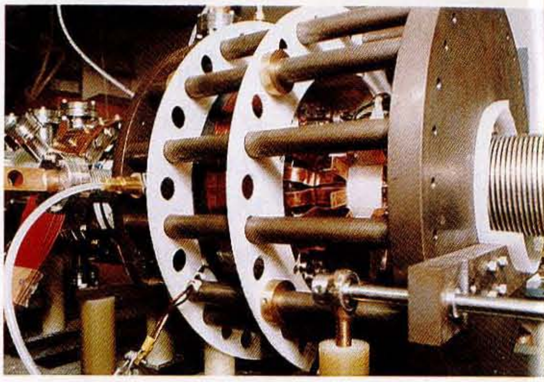

Left: How to blow a plasma bubble. The "stuffing flux" is the sheetlike magnetic field. The "azimuthal magnetic field" blows the plasma bubble. In the bottom figure, the spheromak is cut in half to show its ring current and the reconnected loops of magnetic force. Right: The "birdcage," with a fuel injector visible at left.

the cylinder just behind the magnetic film. The ignitron fires faster than the gas can disperse. For a few millionths of a second, 200,000 amps arc through the gas, blasting its molecules into plasma. Completing the circuit also sets up a rod-encircling magnetic field in the vacuum between the plasma and the cylinder's rear wall. This second field is the breath that blows the bubble, pushing against the plasma and hurling it into the field stretched across the cylinder. The plasma distends the field until a portion of it breaks free, wrapping itself around the plasma. Says Bellan, "It's like hitting a tennis ball into the net so hard that the ball breaks through, taking a piece of the net with it." The magnetic field, embedded in the plasma like string in a lump of Silly Putty, reconnects its broken lines of force with one another to form the bubble. The field is sustained by a swirl of 200,000-amp current trapped in the bubble.

The spheromak exits the cylinder at a very smart clip. Bellan and Brown's first plasma gun, built in 1987 and operated with help from Summer Undergraduate Research Fellowship (SURF) student David Cutter, now a junior in applied physics, achieved a respectable 65,000 mph. The new gun has an accelerator stage—an additional two meter's worth of rod and cylinder. Here a second capacitor bank creates another magnetic field that boosts the plasma to ramming speed. Bellan is shooting for upwards of 400,000 miles per hour—no mean feat. "While you can accelerate individual particles, like electrons, to this kind of speed fairly easily, a spheromak is a macroscopic object weighing several micrograms. If it were a piece of paper of the same weight, it would be big enough to see with your naked eye."

At more than 400,000 miles per hour, the spheromak will be moving a little too fast for the naked eye. Barry Stipe, a senior in physics, spent last summer designing, building, and testing spheromak detectors as a SURF project. One detector is a set of magnetic induction probes, tiny coils of wire that pick up the spheromak's magnetic field the way that a tape deck picks up music from a cassette. Spaced every five inches along the accelerator stage, each probe registers the magnetic field as the spheromak races by, allowing its speed to be calculated. The other detector, a laser interferometer, measures the plasma's density at a point midway down the accelerator. A high-speed camera, with a shutter speed of 25 billionths of a second, will also be used.

There's another reason for shooting spheromaks besides fuel injection. A tokamak plasma is somewhat like a very large spheromak. The tokamak's ring current needs constant stoking, which is usually provided by induction from transformer coils wrapped around the tokamak. But fueling the tokamak with spheromaks may relieve some of the transformers' burden. According to Bellan, "There's a bizarre theory that says if you shoot a spheromak into the tokamak, the spheromak current merges into the tokamak current. The contribution from any one spheromak is small—it's been compared to throwing flashlight batteries into the tokamak—but the cumulative effect can be substantial. Mike and I were the first ones to see that actually happen, in an experiment last year with our first gun."

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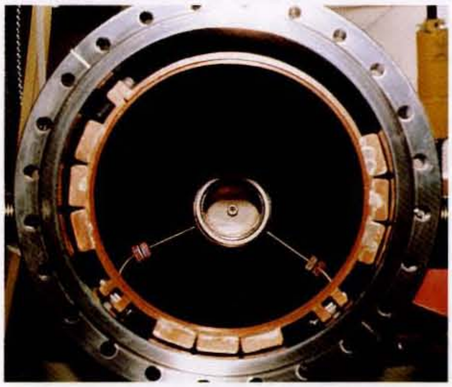


A tokamak's-eye view down the gun barrel, showing both the central rod and the copper cylinder electrodes.

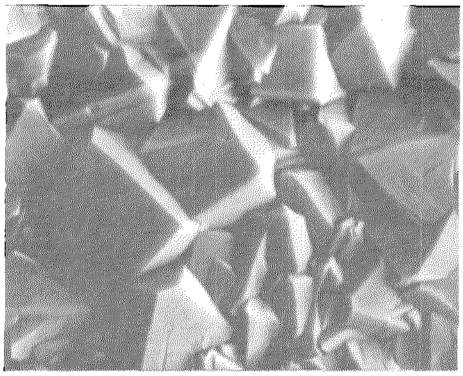
The new gun will be shipped off to the University of Wisconsin-Madison, where it will be mated to a research tokamak there called Phaedrus-T. Phaedrus-T is designed to study how a very hot plasma behaves, and to explore the engineering problems involved in confining it. Each shot from the new gun will replenish about 30 percent of Phaedrus-T's plasma. The gun will only fire about once a minute—insufficient to keep the plasma going, but more than adequate for studying the mechanics of the injection process.

No tokamak has yet achieved fusion. Encore, the Caltech machine where the current-merging was seen, sustains a plasma ring roughly two feet in diameter for a few thousandths of a second. Phaedrus-T maintains its six-foot ring for a tenth of a second. And behemoths at Princeton, New Jersey, and Culham, England, keep 20-foot rings going for about 10 seconds. The next step will be achieve the break-even point, where fusion reactions generate more energy than is consumed in maintaining the plasma. The fusion rate depends on the plasma's density and its temperature. The plasma at the sun's core is about twelve times denser than lead, and roughly 15,000,000° C. Tokamak plasmas are a few millionths the density of air, and so have to be hotter in order to burn—an estimated 100,000,000° C for a sustainable reaction. Spheromaks are a frigid 50,000° C. The new gun's spheromaks are about one-thousandth the density of air, a tenfold density increase compared to the previous gun's output. A power-plant-sized tokamak would probably contain a plasma donut about 40 feet across. Such a plant would need several spheromak guns around its perimeter, each one firing a thousand or more times per second.

The new spheromak gun's power supply has been successfully test fired, but wiring up the accelerator is proceeding more slowly than anticipated. Says Bellan, "These power supplies aren't off-the-shelf items. They have to be built very carefully so that the power goes where you want it. If you don't keep the system's internal inductance way down, the power is lost before it gets to the gun." The heaviest wiring has to be done with copper sheets—putting that much current through a wire would blow it apart. Once the wiring is done, the gun will be put through its paces before being shipped to Wisconsin, an event Bellan hopes will happen this summer. Says Brown, "The mainstream fusion community thinks of spheromaks as an interesting novelty. Pellet-making is a very standard technique, and it's only been fairly recently that tokamaks have gotten hot enough to start people thinking about how hard it will be to keep a pellet from melting prematurely. We think spheromaks can make a real contribution to the fusion effort." □—*DS*

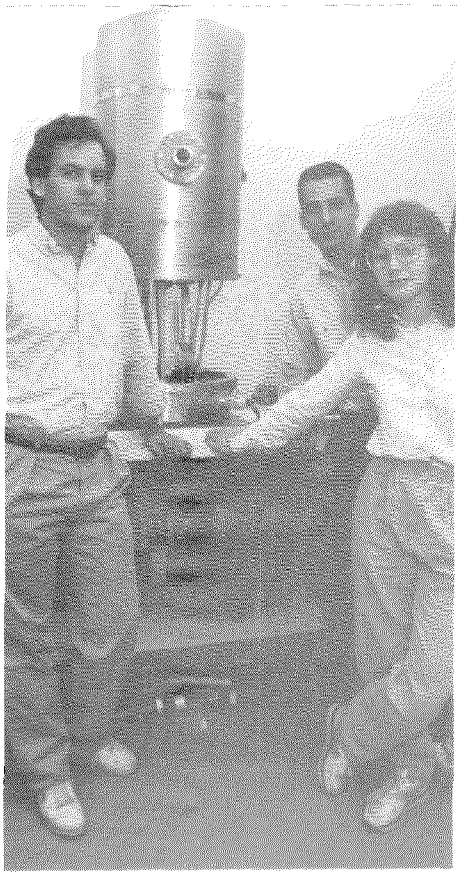
But Will It Work on a Hibachi?

James Bond fans will tell you that diamonds are forever. But they might not know that, as the theme to *The Spy Who Loved Me* had it, "nobody does it better." Among the things that diamonds do best are hardness—diamond is the hardest material known to man—and thermal conductivity. At room temperature, pure single-crystal diamond conducts heat five times better than copper. There are many other things that diamond does well. It's one of the best electrical insulators. It's transparent to x rays as well as to visible, ultraviolet, and infrared light. It has a very high melting point (approximately 3550° C) and is chemically inert. Diamond's hardness and transparency make it the ultimate in scratch-proof coatings for everything from delicate lenses to digital watches, while its inertness and high melting point let it do its job in all sorts of harsh environments, including outer space. Add its thermal and electrical properties, and you have an ideal "heat sink" coating for diode lasers and other electronics, one that dissipates excess heat while protecting the circuitry.



Left: A typical polycrystalline diamond film, grown by Goodwin's group in a small "hot-filament" reactor that is now being used to grow diamond films in a freshman engineering lab. The individual diamond crystals are three to six millionths of a meter on a side.

Below: (From left) Goodwin, Glumac, and Melnik with their diamond-growing chamber, raised into its "open" position. The apparatus underneath the chamber includes actuators that can move the burner and the substrate independently, to adjust the spacing between them, or as a unit, to bring the instruments to bear on any part of the flame.



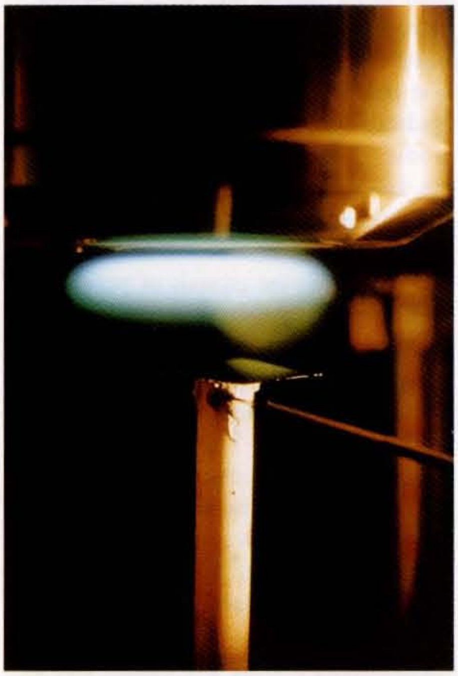
Exploiting all these wonderful attributes in a coating obviously requires that the coating be formed without destroying the object being coated. Since 1958, diamonds have been synthesized industrially—to the tune of $1 billion's worth of abrasive grit and cutting-tool coatings a year—by mimicking the conditions that occur some 75 to 90 miles underground, where diamonds form naturally. However, such high pressures (about 50,000 atmospheres or 1,000,000 pounds per square inch) and temperatures (1500° C) lack the finesse required to make, say, scratch-proof coatings for watches. More recently, methods have been developed that deposit diamond films from a hydrocarbon vapor at low pressures and comparatively mild temperatures, greatly expanding the list of materials that can be coated.

Assistant Professor of Mechanical Engineering David Goodwin's research group is exploring some of those methods. Goodwin, with help from Guillaume Gavillet (MS '89), has developed computer models of the steps leading up to deposition, while Goodwin and grad student Susan Melnik have been collaborating with a group led by William Goddard, Ferkel Professor of Chemistry and Applied Physics, to develop a theoretical description of exactly what happens when an atom hits the growing surface. "There are a lot of different growth-chamber designs," says Goodwin, "and a lot of ways of adding energy to the vapor. They all have different characteristics." Although the details vary, the overall scheme prescribes a gaseous hydrocarbon—methane or ethylene, for example—flowing through some energy source such as an electric arc, a hot tungsten filament, or a flame. The zap (or the heat) dissociates some of the hydrocarbon molecules into fragments (called "radicals") and individual hydrogen atoms. Generous amounts of hydrogen gas are usually present as well, some of which dissociates to create even more loose hydrogen atoms.

Diamonds are crystals of pure carbon, so those hydrogen atoms might seem superfluous, but they're actually the key to the whole operation. The hydrogen atoms "activate" the growing diamond surface. They react with the exposed carbon atoms, forming carbon-hydrogen bonds that stick out perpendicular to the surface. An incoming hydrogen atom can then pick off one of these surface-bound hydrogen atoms, forming a molecule of hydrogen gas and momentarily leaving the carbon end of the former carbon-hydrogen bond dangling from the diamond surface. A hydrocarbon radical—the methyl radical CH_3, for example—can then attach itself to the dangling bond in an atomic version of musical chairs. Atoms don't like to have a bond dangling free, so were it not for the place-holding hydrogen atoms, diamond's three-dimensional crystal—an array of tetrahedrons joined at their points—wouldn't form. Carbon prefers to form flat layers of graphite, a two-dimensional crystal whose molecular structure resembles chicken wire.

Most of the dissociated hydrogen atoms recombine to make hydrogen molecules long before reaching the carbon surface. According to Goodwin, "You really need to do fairly detailed modeling that simultaneously solves for the chemistry happening in the gas, the surface chemistry, the fluid mechanics of

The diamond-growing flame burns upside down over the substrate, which is the small square tile in the middle of the picture. The glass tube supporting the substrate allows gas samples to be drawn from the flame while it's burning. A thermocouple, leading off to the right, measures the flame's temperature.



"Under certain conditions, an oxyacetylene welding torch burning in the open air can deposit a diamond film."

the vapor's bulk motion, the heat transfer, and the diffusion of the atoms, in order to get some idea of how the hydrogen-atom concentration at the surface depends on the chamber's parameters. Our models are the first ones in this particular field that model the whole problem in detail.

"One easy way to make diamond is in a flame. Yoichi Hirose in Japan first demonstrated that under certain conditions, an oxyacetylene welding torch burning in the open air can deposit a diamond film on a substrate. The film grows quite fast—50 microns (millionths of a meter) per hour—and the quality, if you do it right, is no worse than other techniques and in many cases better." The catch is that the area covered by the film is only as big as the flame's diameter, typically about a quarter of an inch—far too small for most applications. And the flame, although an improvement over the high-pressure method, isn't exactly the mildest of environments. Many potential substrates simply can't take the heat. Trying to cool something that you are simultaneously torching seems like an exercise in futility on the face of it, and things are further complicated by the fact that diamond won't form unless the substrate is heated to some minimum temperature. The welder's torch, with its tightly focused nozzle that produces a pencil-thin flame, is obviously the wrong design for this job. Building an infinitely large blowtorch out of an array of small nozzles would cover a larger area, but at the expense of exacerbating the cooling problem and creating the new problem of exorbitant fuel consumption. What's needed is some way of making a much more diffuse flame.

Goodwin and grad student Niko Glumac have borrowed a burner design, frequently used in combustion studies, that makes just such a flame. The burner's business end is a sintered brass plate the size and shape of whatever's to be coated. The gas mixture seeps up through the porous plate, forming a hovering miasma just above it. When ignited, the gas burns evenly across the plate's entire surface, rather like marsh gas on fire in a bog. "We'd like to deposit a diamond film over a four-inch-diameter area. A lot of people have that goal right now—it's the size of a silicon wafer. Ultimately we'd like to do much larger areas, like turbine blades, but for now, four inches is a very large area." The burner operates inside a vacuum chamber, with the oxygen needed for combustion provided as part of the gas mixture. The gas feeds the burner at about five percent of atmospheric pressure, creating a very diffuse vapor over the burner that produces an even, cool-burning flame. Coolness, of course, is relative. A welder's torch burns hotter than 3000° C. The "cool" flame burns at about 1600° C, heating the substrate to an almost-balmy 700° C—still a bit hot for some potential substrates, such as plastics, but well within silicon's comfort zone. Preliminary trials with the new burner have grown what appear to be diamond particles in isolated deposits on the substrate. Tests are still underway to confirm the deposits' identity.

Several people have hit upon the sintered-plate burner idea independently, Goodwin notes, but he adds that the Caltech contingent's comprehensive theoretical models should give them a leg up in learning how the process works. Goodwin and company scrutinize the goings-on inside their diamond-growth chamber with the sort of intense scrutiny normally associated with IRS audits, or a supermarket tabloid's coverage of Elizabeth Taylor. An assortment of instruments identifies and measures the concentrations of the dozen or so important chemical species present in various parts of the flame and on the surface. Says Goodwin, "Our model allows us to predict everything we could want to measure. We can diagnose how the flame is burning, using laser techniques to measure the distribution of important radicals in the flame, and sampling probes to look at stable species. We can predict how changing the fuel mixture should change the flame—and thus the diamond's growth—and then we can measure what actually happens. Our model enables us to understand other peoples' experiments as well as our own, and will help us seek out the optimal conditions for diamond growth." □—*DS*