A Dynamo of a Plasma

With a view to eventually generating fusion electricity, a Livermore team is exploring a type of matter with an internal magnetic dynamo.

CRANK up the electrical current, mix in a magnetic field, add a puff of hydrogen, and—if conditions are just right—you will have the kind of magnetized plasmas that the Sun and other celestial bodies are generating perpetually. Huge solar flares are magnetized plasmas that separate from the Sun and bombard the Earth and other planets with a magnetic field large enough to interfere with communication systems. The magnetized plasmas in Lawrence Livermore's Sustained Spheromak Physics Experiment (SSPX) are much smaller and far shorter-lived than their celestial cousins, but the two varieties, nevertheless, share many of the same properties.

In both instances, fluctuating magnetic fields and plasma flows create a dynamo that keeps the ionized hydrogen plasma alive and confined in space. Magnetic fields pass through the flowing plasma and eventually touch one another and reconnect. When a reconnection occurs, it generates more plasma current and changes the direction of the magnetic fields to confine the plasma. This "self-organizing" dynamo is a physical state that the plasma forms naturally.

Magnetic reconnection is key for confining the plasma in space and sustaining it over time. In an experimental situation such as SSPX, an initial electrical pulse is applied across two electrodes, forming a plasma linked by a seed magnetic field. Reconnection events generated by the plasma itself convert the seed field into a much stronger magnetic field that shapes the plasma and prevents it from touching the walls of the spheromak's vessel.

The Laboratory's interest in creating such plasmas and learning how they function derives from Livermore's long history of exploring fusion energy as a source of electrical power. If a self-organizing plasma can be made hot enough and sustained for long enough to put out more energy than was required to create it, the plasma could prove to be a source of fusion energy. For several decades, researchers have been examining both magnetic and inertial confinement methods for generating fusion energy. The magnetized plasmas of Livermore's spheromak represent one possible route to a source of abundant, inexpensive, and environmentally benign energy. (See the box on p. 7.)

Now semiretired, physicist Bick Hooper was assistant associate director for Magnetic Fusion Energy in the mid-1990s when he participated in a review of data from Los Alamos National Laboratory's spheromak experiments conducted in the early 1980s. The reanalysis suggested the plasma's energy was confined up to 10 times better than originally calculated and that plasma confinement improved as the temperature increased. The reviewers theorized that as temperatures increase in the plasma, electrical resistance decreases and energy confinement improves, promoting the conditions for fusion. In light of this reanalysis, the scientific community and the Department of Energy (DOE) decided to pick up where the Los Alamos experiments had left off.

The magnetized plasmas of Livermore's Sustained Spheromak Physics Experiment (SSPX) represent one possible route to a source of fusion energy.

SSPX was designed to determine the spheromak's potential to efficiently create hot fusion plasmas and hold the heat.

Early investment in research on spheromak plasmas by Livermore's Laboratory Directed Research and Development Program was instrumental in the decision to build SSPX at Livermore. (See *S&TR*, December 1999, pp. 18–20.) Since 1999, when SSPX was dedicated, a team led by physicist Dave Hill has boosted the plasma's electron temperature from 20 electronvolts to about 350 electronvolts, a record for a spheromak. "We're still a long way from having a viable fusion energy plant," acknowledges Hill. "For that, we would need to reach at least 10,000 electronvolts." However, conditions obtained to date are a significant step toward achieving fusion with a spheromak.

"The science of these plasmas is fascinating," says Hill. "Not only might they prove useful for producing fusion energy, but also their physics is essentially the same as the solar corona, interplanetary solar wind, and galactic magnetic fields. However, we still have much to learn about magnetized plasmas. For instance, we do not completely understand how magnetic dynamos work. We know that Earth's magnetic core operates as a dynamo, but scientists have barely begun to model it. Magnetic reconnection, essential for containing and sustaining the plasma, is another phenomena that is not well understood."

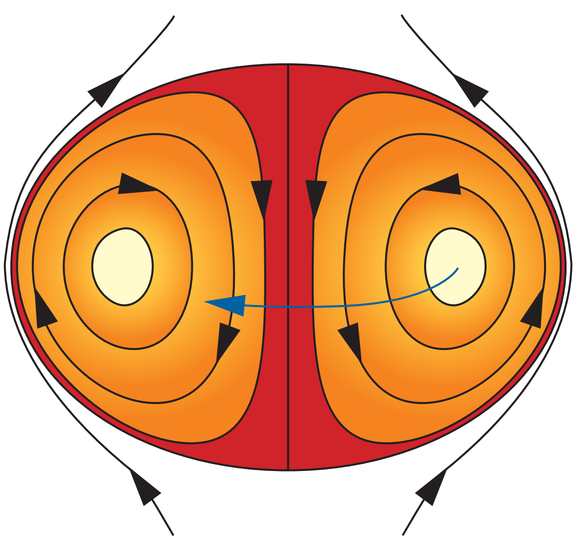
Livermore's spheromak research is aimed primarily at increasing the plasma's temperature and gaining a better understanding of the turbulent magnetic fields and their role in sustaining the plasma. "We need some turbulence to maintain the magnetic field, but too much turbulence kills the plasma," says Livermore physicist Harry McLean, who is responsible for diagnostics on SSPX. "It's a complicated balancing act."

Because scientists want to learn more about what is going on inside the fusion plasma and find ways to improve its behavior, experiments on SSPX are augmented by computational modeling using a code called NIMROD. The code was developed by scientists at Los Alamos, the University of Wisconsin at Madison (UWM), and Science Applications International Corporation. Results from SSPX experiments and NIMROD simulations show good agreement. However, NIMROD simulations are computationally intensive. Modeling just a few milliseconds of activity inside the spheromak can take a few months on a parallel supercomputing cluster.

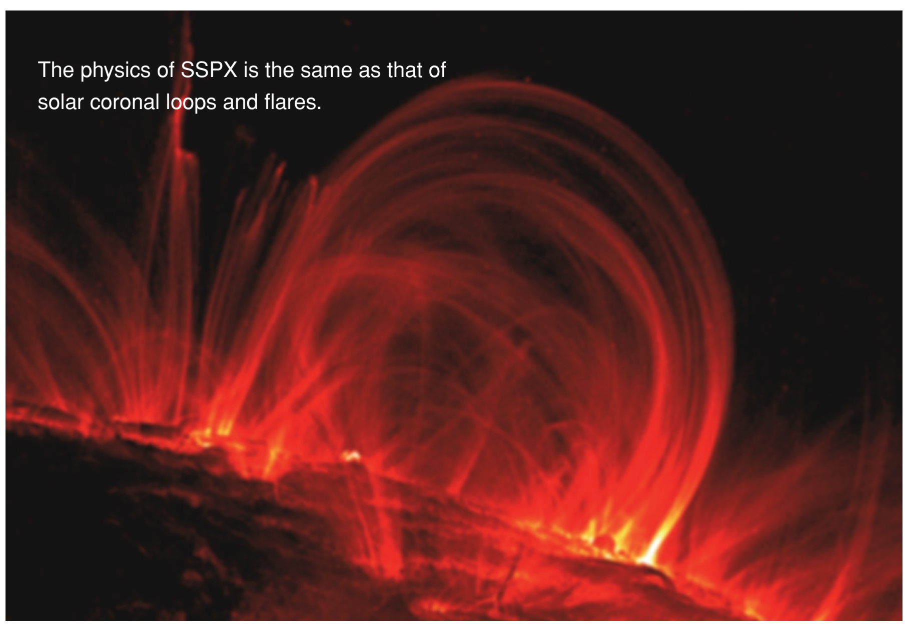
Collaborators in the SSPX venture include the California Institute of Technology (Caltech), UWM, Florida A&M University, University of Chicago, Swarthmore College, University of Washington, University of California at Berkeley, and General Atomics in San Diego, California. Through the university collaborations, an increasing number of students are working on SSPX and making important contributions. Livermore is also a participant in the National Science Foundation's (NSF's) Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas.

A Spheromak Up Close

When spheromak devices were first conceived in the early 1980s, their shape was in fact spherical. But now the vessel in which the plasma is generated, called a flux conserver, is cylindrical in shape.



Inside the SSPX's flux conserver, the hot plasma forms a doughnut shape called a torus.



The physics of SSPX is the same as that of solar coronal loops and flares.

Inside the flux conserver, the swirling magnetized, ionized hydrogen looks like a doughnut, a shape known as a torus.

Livermore physicist Reg Wood is operations manager for SSPX and managed the team that built the device in the late 1990s. Hooper and others were responsible for its design. According to Wood, "The design incorporates everything anyone knew about spheromaks when we started designing in 1997. The injector has a large diameter to maximize the electrode surface area. The shape of the flux conserver and the copper material used to form it were selected to maximize the conductivity of the walls surrounding the plasma. The vessel would be somewhat more effective if we had been able to build it with no holes. But we needed to be able to insert diagnostic devices for studying the plasma."

The earliest SSPX experiments in 1999 were not a success. "The first few yielded no plasma at all," says Wood. The electron temperature in the first plasma was just 20 electronvolts, but it has climbed steadily ever since.

Getting a spheromak plasma started requires a bank of capacitors to produce a high-voltage pulse inside a coaxial gun filled with a small seed magnetic field. Two megajoules of energy zap a puff of hydrogen, and a plasma then forms inside the gun with a now much larger magnetic field, called a helicity. A lower current pulse from a second capacitor bank helps to sustain the magnetic field.

As shown in the figure below, magnetic pressure drives the plasma and the magnetic field within it downward into the flux

The Promise of Fusion Energy

For 50 years, scientists worldwide have been striving to harness the energy source of the Sun and stars and use it to generate energy on Earth. On our Sun, hydrogen nuclei are continually fusing and, in the process, releasing enormous amounts of energy.

The nuclear power plants in use around the world today fission, or split, heavy atoms to release energy for electricity. A fusion power plant, on the other hand, will generate energy by fusing atoms of deuterium and tritium—two isotopes of hydrogen, the lightest element. Deuterium will be extracted from seawater, and tritium will be produced by the transmutation of lithium, a common element in soil.

A fusion power plant would produce no greenhouse gas emissions, operate in a continuous mode to meet demand, and produce lower levels of radioactive by-products than current fission power plants. A fusion power plant would also present no meltdown danger. Because nuclear fusion offers the potential for plentiful, safe, and environmentally benign energy, the Department of Energy (DOE) has made fusion a key element in the nation's long-term energy plans.

The Sustained Spheromak Physics Experiment (SSPX) at Livermore is part of a DOE program to study options for eventually producing power from magnetic fusion. Most research in magnetic fusion energy has centered on the doughnut-shaped tokamak. Livermore collaborates in experiments using the DIII-D tokamak at General Atomics in San Diego. Computational and experimental work there will have important implications for the performance of the International Thermonuclear Experimental Reactor, a major international tokamak project with significant U.S. participation.

SSPX is one of about 20 alternative concepts to the tokamak funded by DOE's Office of Fusion Energy Science through a program called Innovative Confinement Concepts. Experiments are being fielded at universities and national laboratories to study the spherical torus, the stellarator, and other self-organized mechanisms besides the spheromak. Livermore's SSPX is the largest experiment among these alternative concepts.

The plasma inside a spheromak is more complex and difficult to control than the plasma in a tokamak. If challenges can be overcome, a spheromak reactor offers several advantages over the tokamak for eventually generating electricity. The magnetic fields that confine the spheromak plasma are generated by currents flowing in the plasma itself rather than by the external magnet systems used for the tokamak. The tokamak's large, external magnetic coils are expensive and complex. If one coil needs repair, the entire unit must be taken offline. A spheromak reactor could be smaller than a comparable tokamak and would require far fewer magnets than a tokamak. A spheromak would be less costly to construct, less difficult and expensive to maintain, and could generate fusion energy at a lower cost.

Livermore collaborates on experiments being performed at the DIII-D tokamak at General Atomics in San Diego. The photograph shows an upper inside view of the tokamak.

conserver. As the plasma continues to expand further down into the vessel, magnetic fluctuations increase until magnetic field lines abruptly pinch off and reconnect.

When a magnetic reconnection event occurs, the magnetic field in the core disconnects from the incoming electrodes. Soon, the plasma's magnetic field is arranged in nested flux layers, some of which reconnect and close, while others closer to the wall of the vessel remain open. The overall magnetic field is nonuniform, more poloidal (parallel to the poles) at the outer edge and primarily toroidal (parallel to the equator) at the torus's closed core. The temperature is also nonuniform, hotter at the center and cooler at the walls. In this initial chaos, many small and large reconnection events occur until an equilibrium is reached. If the plasma and its confining magnetic field form a smooth, axisymmetric torus, a high-temperature, confined plasma can be sustained.

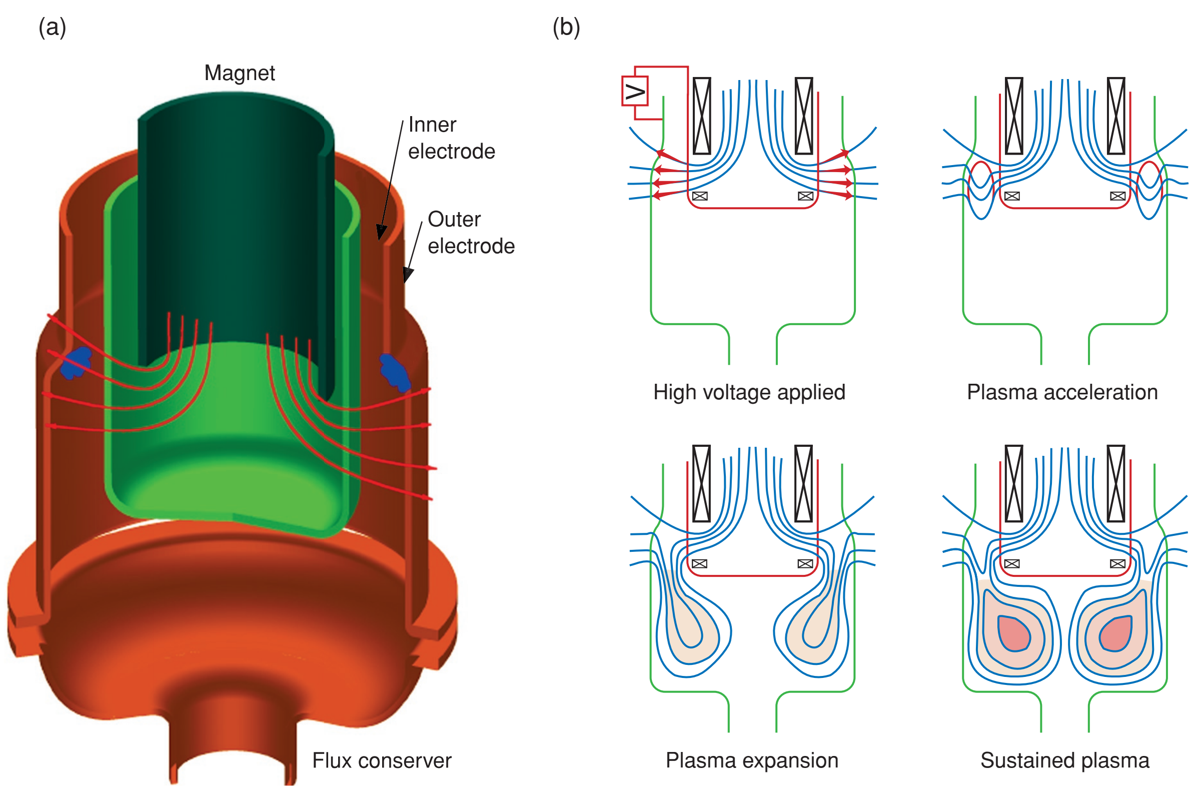
A certain amount of turbulence in the plasma's interacting magnetic fields is essential for the dynamo to sustain and confine the plasma. But magnetohydrodynamic instability can cause small fluctuations and islands in the magnetic fields, undercutting axisymmetry and lowering confinement and temperature. Controlling fluctuations is key. "We want a nice tight torus," says Hooper, "but if it is too tight, that is, it has too little fluctuation, electrical current can't get in. We want to hold in the existing energy and also allow in more current to sustain the magnetic fields." Even under the best conditions, plasmas in SSPX have lasted a maximum of 5 milliseconds.

The team pulses SSPX 30 to 50 times per day, usually three days a week, and each experiment produces an abundance of data. "Our ability to run experiments rapidly outstrips our ability to analyze the data," notes McLean.

Taking the Plasma's Measure

The plasma formed in a spheromak is highly sensitive to many kinds of perturbations. For example, if a diagnostic probe is inserted into the hot plasma, the probe's surface can be vaporized, which will introduce impurities and cause the plasma's temperature to drop. Another challenge is that the plasma's fast motion, high heat, and low emissivity can damage cameras and similar optical devices if they are mounted too closely. Therefore, few direct measurements are possible.

Most diagnostic devices are mounted at the median plane of the vacuum vessel housing the flux conserver, with ports allowing access into the flux conserver. Probes and magnetic loops at the outer wall of the flux conserver affect the plasma only minimally. Spectrometers look for light emission characteristic of impurities. Data from a series of devices that measure the magnetic fields around the plasma as well as the plasma's temperature and



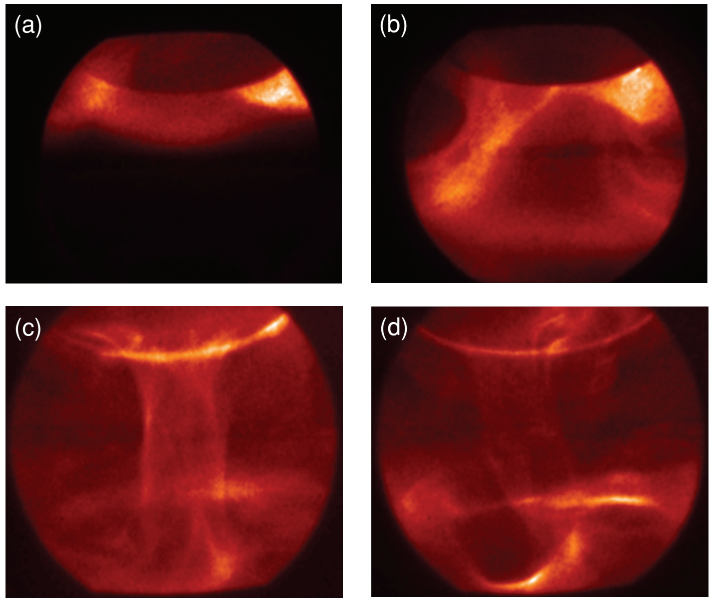
(a) An initial electrical pulse is applied across two electrodes (the inner and outer walls of the flux conserver), forming a plasma linked by a seed magnetic field. (b) In these cutaway views, the growing plasma expands downward into the flux conserver, which is a meter wide and a half meter tall. Magnetic reconnection events convert the seed magnetic field into a much stronger magnetic field that sustains and confines the plasma.

density are fed into CORSICA, a computer code that infers the plasma's internal electron temperature, electrical current, and magnetic fields. (See *S&TR*, May 1998, pp. 20–22.)

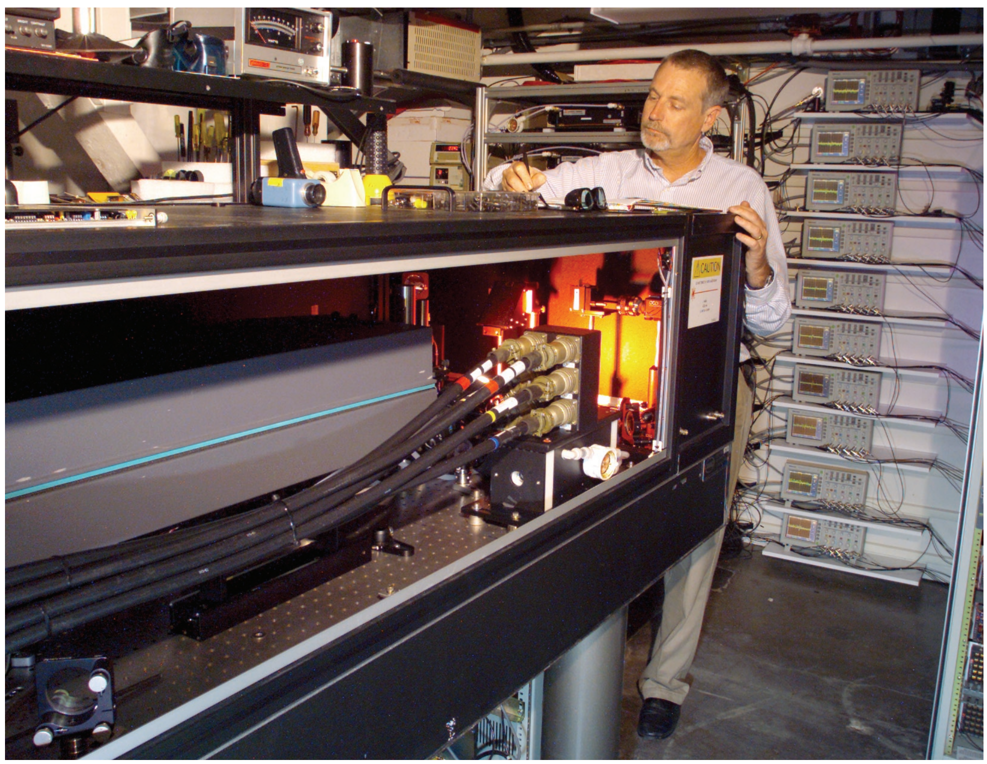
The primary diagnostic tool shines a laser beam through the plasma to scatter photons off electrons in the plasma—a process known as Thomson scattering. The scattered light is imaged at 10 spots across the plasma onto 10 optical fibers, which transport the light into polychrometer boxes commercially produced by General Atomics. Detecting the light's spread in wavelength provides temperature measurements from 2 to 2,000 electronvolts and is the best way yet to infer temperature with minimal disturbance to the plasma.

The SSPX team has hosted several graduate students whose doctoral research involved developing and applying diagnostics for the experiment. A University of Washington graduate student, Chris Holcomb, installed a novel diagnostic tool that shot a glass bullet through the plasma at 2 kilometers per second in an attempt to measure magnetic field profiles inside the plasma. "Although the instrument never produced the kind of data I wanted," says Holcomb, "the experience of developing an instrument for a fusion experiment was invaluable." Holcomb is now a Livermore postdoctoral fellow assigned to General Atomics, where he is designing diagnostics that ultimately will be used on the International Thermonuclear Experimental Reactor, an international project aiming to produce 500 megawatts of fusion power in a tokamak.

Carlos Romero-Talamás, a Livermore postdoctoral fellow since February, developed a way to insert the lens for a high-speed camera up close to the SSPX plasma as part of his Ph.D. thesis for Caltech. This camera, installed 3 years ago, offers the most direct images of the plasma. Three ports mounted at the vessel's median plane allow the camera to be moved to take wide-angle, 2-nanosecond images from different



A camera captures (false-color) images of the plasma forming inside the flux conserver. (a) The plasma begins to balloon out of the injector gun at about 35 microseconds and (b) reaches the bottom of the flux conserver at 40 microseconds. (c) A column forms at about 50 microseconds. (d) At 80 microseconds, the column bends, which researchers think may precede an amplification of the magnetic field.



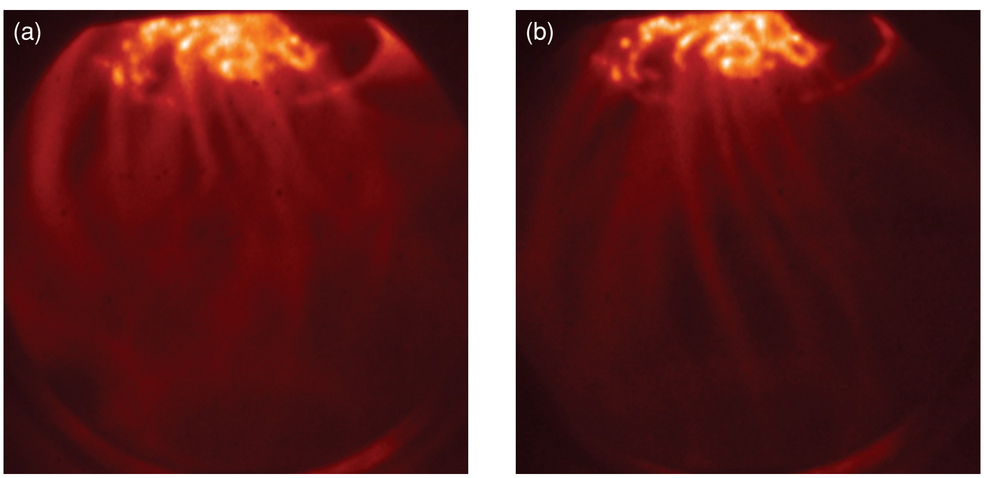
Measurements of electron temperature and density are obtained using Thomson scattering. This 1-micrometer-wavelength pulsed laser sends photons into the plasma where they scatter off free electrons. Data from 10 spots across the plasma are collected in 10 polychrometer boxes behind physicist Harry McLean.

viewpoints. An intensifier increases the brightness of the images from the short exposures.

Images of the plasma during the first 100 microseconds of its lifetime show the central column in the torus forming and bending (see the sequence in the figure on p. 9). At 100 microseconds, the electrical current continues to increase, making the plasma highly ionized and too dim to see. "Unfortunately," says Romero-Talamás, "we can't see into the plasma as the column is 'going toroidal.' It's the most interesting part of the process."

As the current falls and is set to a constant value, the flux becomes more organized. The contrast improves, and images reveal a stable plasma column. Measurements of the column's diameter based on these images compare well with the magnetic structure computed by the CORSICA code. At about 3,800 microseconds, the column expands into a messy collection of filaments and then reorganizes itself by 3,900 microseconds. The team is unsure why this process occurs.

Measurements of local magnetic fields within the plasma are not available with existing diagnostics. But they are necessary to make better sense of some of the camera's images and to help determine when and where reconnection occurs. More magnetic field data may also show whether the bending of the plasma column precedes reconnection. A long, linear probe to measure local magnetic fields in the plasma was installed this summer. If the probe survives and does not perturb the plasma beyond acceptable levels, two more probes will be installed. The three probes together will provide a three-dimensional (3D) picture of changes in the torus's central column.



Toward the end of the plasma's lifetime, its central column may become (a) a messy collection of filaments and then (b) reorganize itself. (Images are false color.)

Help from Supercomputers

The design of a spheromak device is relatively simple, but the behavior of the plasma inside is exceedingly complex. Diagnostic data about the plasma are limited, and CORSICA calculations, although valuable, reveal a picture of the plasma that is restricted to be cylindrically symmetric. Obtaining dynamic 3D predictions is possible only with simulations using the most powerful supercomputers. In addition to an in-house cluster, the team also uses the supercomputing power of the National Energy Research Scientific Computing (NERSC) Center at Lawrence Berkeley National Laboratory.

Livermore physicists Bruce Cohen and Hooper, working closely with Carl Sovinec of UWM, one of the developers of NIMROD, are using NIMROD to simulate SSPX plasma behavior. They and their collaborators use simulations to better understand and improve energy and plasma confinement.

To date, the team has successfully simulated the magnetics of SSPX versus time. The differences between the experimental data and simulations are at most 25 percent and typically are much less. The team found no major qualitative differences in the compared results, suggesting that the resistive magnetohydrodynamic physics in the code is a good approximation of the actual physics in the experiment. More recently, with improvements in the code, they have been able to compute temperature histories that agree relatively well with specific SSPX data. Even so, because of the complexity of spheromak physics, NIMROD still cannot reproduce all the details of spheromak operation.

Cohen notes that, "Simulation results are tracking SSPX with increasing fidelity." The simulations are using more realistic parameters and improved representations of the experimental geometry, magnetic bias coils, and detailed time dependence of the current source driving the plasma gun. The latest simulations confirm that controlling magnetic fluctuations is key to obtaining high temperatures in the plasma.

Higher Temperatures on the Way

Now that the team has learned how to produce temperatures above 300 electronvolts, they can begin using SSPX experiments to examine magnetic reconnection in astrophysical objects. Livermore physicist Dmitri Ryutov, a theorist, notes that the relatively high temperatures and conductivities achieved recently in SSPX make its plasmas look enough like the magnetic plasmas of solar flares and sunspots for this research to be possible. "Typically, laboratory experimental facilities do not achieve a high enough conductivity level," says Ryutov. "SSPX is one of the better experimental facilities for duplicating the conditions of astrophysical objects. However, SSPX must be able to produce even higher temperatures and conductivities than it does now."

SSPX is one of four experiments participating in the NSF Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas. The other three experiments are at UWM, Princeton Plasma Physics Laboratory, and Swarthmore College. Because scientists want to learn more about how magnetic structures on the Sun and elsewhere in the universe rearrange themselves and generate superhot plasmas, the experiments focus on various processes of magnetic self-organization: dynamo, magnetic reconnection, angular momentum transport, ion heating, magnetic chaos and transport, and magnetic helicity conservation and transport.

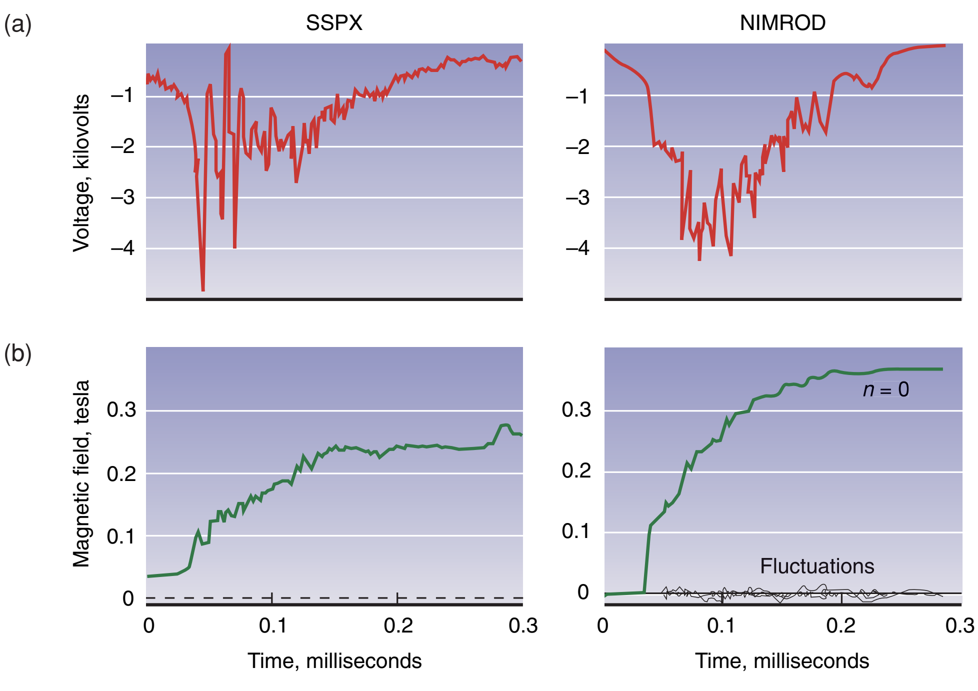
Ryutov is not alone in wanting SSPX to produce a higher temperature plasma. Anything closer to fusion temperatures is a move in the right direction. The Livermore team was able to make the leap from 200 to 350 electronvolts by learning how to optimize the electrical current that generates the magnetic fields. However, achieving still higher temperatures will require new hardware. Today, a larger power system that includes additional capacitor banks and solid-state switches is being installed. More current across the electrodes will increase the magnetic field, which will translate into a considerable increase in the plasma's temperature, perhaps as high as 500 electronvolts. The solid-state switches offer the additional benefit of doing away with the mercury in the switches now being used.

With the larger power source, the team can better examine several processes. They hope to understand the mechanisms that generate magnetic fields by helicity injection. They will explore starting up the spheromak using a smaller but steadier current pulse to gradually build the magnetic field. A higher seed magnetic field may improve spheromak operation. Data from both simulations and experiments also indicate that repeatedly pulsing the electrical current may help control fluctuations and sustain the plasma at higher magnetic fields.

The team hopes to add a beam of energetic neutral hydrogen particles to independently change the temperature of the plasma core. Besides adding to the total plasma heating power and increasing the peak plasma temperature, the beam would also allow the team to change the core's temperature without changing the magnetic field. The group will then have a way to discover the independent variables that control energy confinement and pressure limits.

Only by understanding the complex physics of spheromak plasmas can scientists know whether the spheromak is a viable path to fusion energy. The potential payoff—cheap, clean, abundant energy—makes the sometimes slow progress worthwhile. At the moment, the science occurring within a spheromak is well ahead of researchers' understanding. But this team is working hard to close that gap.

—Katie Walter



Time histories of data from an SSPX experiment (left column) and a NIMROD simulation (right column) show considerable similarity. Shown here are the (a) injector voltage and (b) poloidal magnetic field measured by a probe near the midplane of the flux conserver ($n = 0$ denotes the toroidally averaged edge magnetic field). These data are for the first 30 microseconds of a plasma's lifetime, the time during which a plasma is being formed.

Key Words: fusion energy, magnetic reconnection, NIMROD code, Sustained Spheromak Physics Experiment (SSPX).

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