PPPL Scientists Bring Mysterious Process Down to Earth

With the click of a computer mouse, a scientist at the U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) sends 10,000 volts of electricity into a chamber filled with hydrogen gas. The charge heats the gas to 100,000 degrees Centigrade. In an instant — one-thousandth of a second, to be precise — a process called "magnetic reconnection" takes place.

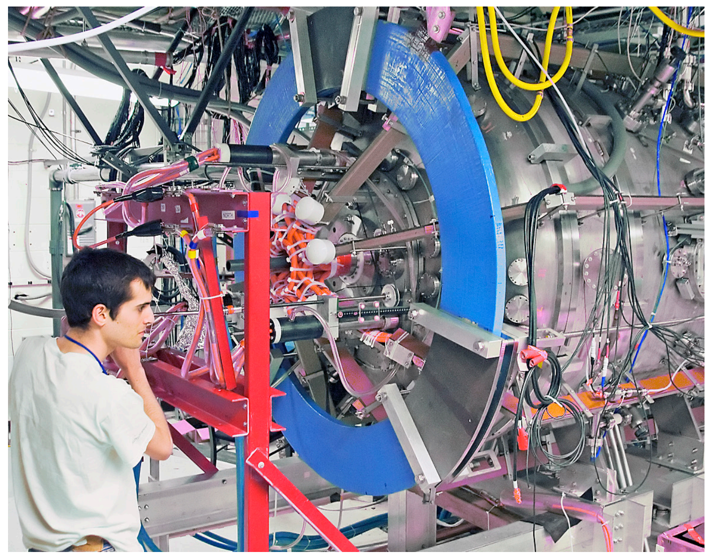
Researchers have run this and similar experiments — called "shots" — more than 100,000 times since 1995 and amassed volumes of data and numerous scientific papers. The carefully controlled shots recreate one of the most common but least understood phenomena in the universe—one that gives rise to the northern lights, solar flares and geomagnetic storms and that can disrupt cell phone service, black out power grids and damage orbiting satellites.

Researchers at PPPL have brought this basic process down to earth in miniature where it can be studied under laboratory conditions. "Here we can actually recreate reconnection," said Masaaki Yamada, a PPPL physicist and principal investigator for the Magnetic Reconnection Experiment (MRX), the leading project of its kind in the world. "This is not theory or a computer simulation." Hantao Ji, principal research physicist at PPPL for MRX, concurred: "This provides a chance to see what's really going on in reconnection."

The experiments seek to unravel the secrets of magnetic reconnection and gain insights whose benefits could include:

- Improved prediction of solar outbursts and dangerous geomagnetic storms to allow for advanced warning
- Greater control of the nuclear fusion reactions that PPPL researchers are studying as a clean fuel for generating electric power
- Increased understanding of the formation of the sun and stars

Magnetic reconnection takes place when magnetic lines of force—or field lines—break apart and reconnect with a violent burst of energy that in huge bodies like the sun and stars has the explosive power of millions of tons of TNT. This occurs when superheated and electrically



The Magnetic Reconnection Experiment (MRX).

charged gases called plasmas converge. Plasmas consist of electrons and ions—atoms that have been stripped of one or more electrons—and are the basic stuff of the sun and stars.

"Plasma processes, such as reconnection, influence the behavior of astronomical objects of all sizes, from solar flares to jets that travel through galaxies," said Stewart Prager, director of PPPL. "One of the goals of PPPL is to understand the plasma universe, and MRX is making enormous contributions to that mission."

A key puzzle is why magnetic reconnection takes place in the sun many thousands of times faster than the best theories say that it should — a puzzle that makes volatile "space weather" hard to forecast. "You can't predict solar storms when you don't understand reconnection," noted Princeton University astrophysicist James M. Stone.

Such tempests occur when reconnection causes huge plasmas to erupt from the sun and slam into the Earth's magnetosphere — the magnetic field that surrounds the planet—with a potentially damaging impact. One such eruption stirred up a geomagnetic disturbance that blacked out the Canadian city of Montreal and most of the province of Quebec for nearly 12 hours in 1989. Solar outbursts occur in 11-year cycles with a new cycle now starting and expected to reach a peak — or "solar maximum"— in 2013.

MRX researchers are gradually zeroing in on the mechanism behind the mysterious rate of reconnection that triggers the storms. Laboratory findings show that the electric current that is embedded — or "frozen into" — merged plasmas suddenly dissipates, enabling reconnection to take place. Further experiments have confirmed that part of the reason for the abrupt dissipation is that the ions and electrons inside the plasmas have different velocities. The electrons thus behave differently from the ions, as measured by a phenomenon called the "Hall effect," and carry away the current to help speed up reconnection.

Such discoveries are redefining traditional notions of how reconnection works. "The MRX is uncovering new physics that is modifying the theories that we thought had explained reconnection," said astrophysicist Russell Kulsrud, a Princeton University professor emeritus who is participating in the project. Through the MRX, PPPL scientists have "made many detailed measurements and (are) discovering many new things that we don't understand," Kulsrud added.

MRX findings will help guide a four-satellite exploration of reconnection that NASA scientists plan to launch in 2014. The spacecraft will sweep through the magnetosphere on a multi-year mission to study the regions where reconnection takes place. "We hope to provide a database that will tell (NASA) what kind of data-taking is most efficient," Yamada said.

Knowledge of space weather will be vital to the safety of crews of possible future missions to Mars. The astronauts could be exposed to high levels of radiation if solar storms were to break out during flight. So the ability to pinpoint the timing of reconnection events that could lead to such storms is crucial, Yamada noted.

Magnetic reconnection underlies the brilliant auroras that light the night sky near the north and south poles. Auroras occur when relatively low-energy plasmas that stream from the sun connect with the magnetosphere and produce heated particles that give rise to the light shows. These plasma flows from the sun are known as "solar wind."

Magnetic reconnection is also suspected to be behind the extraordinary bursts of radiation that have emerged from the center of the Crab nebula—the remains of an exploded star — some 6,500 light years from Earth. Scientists trace the bursts to electrons that have accelerated to the highest level of energy ever observed in a fixed celestial body. "You need something like reconnection to explain these very high-energy particles," said astrophysicist Jonathan Arons of the University of California at Berkeley.

Perhaps the most basic issue related to magnetic reconnection is its role in the creation of stars, which begin as clouds of charged particles that collapse under gravity into fiery plasma spheres. Accompanying this process is the reconnection of magnetic field lines that are present in the original cloud and must separate out for the star to be born. All this happens much faster than current theory indicates, noted Kulsrud. So MRX experiments "are constructed to find out the physics of what's actually going on."

Closer to home, reconnection creates a disruption in plasmas during nuclear fusion experiments like those under way at PPPL. This disruption can force fusion reactors to shut down. Improved knowledge of reconnection would thus advance the development of fusion as a clean source of energy for generating electricity.

PPPL launched the MRX project in 1995 under the direction of Yamada to increase understanding of the disruptive turbulence. The experiment soon caught the eye of the astrophysical community, which saw a benefit for its own field of study. "If you're in space you observe what happens," said University of Maryland physicist James Drake. "In the lab you can vary the experiments, which provides a new avenue for exploring the process."

This approach centers on the MRX device, which resembles a large steel barrel attached to arrays of tubes and wires. Inside are two doughnut-shaped coil systems called "flux cores" that produce plasmas whose magnetic field lines reconnect while tiny probes measure the results. "The important part is that we can create with control and then study the reconnection process," Yamada said. "In nature you cannot."

Such hands-on capability is the key to the MRX project, which is funded by several federal agencies including: the U.S. Department of Energy; the National Science Foundation; the Office of Naval Research; and NASA.

THE MAGNETIC RECONNECTION EXPERIMENT

Magnetic reconnection is an explosive process that gives rise to phenomena that include auroras, solar flares, geomagnetic storms and the formation of stars, as well as to turbulence that can disrupt the development of nuclear fusion as a clean source of power for generating electricity. The explosive force of solar flares can be equivalent to millions of tons of TNT.

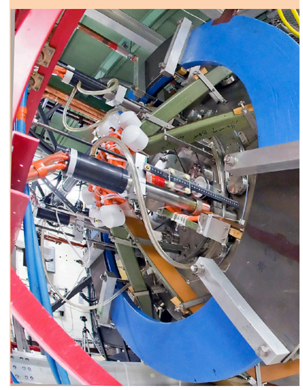
PPPL scientists were the first to confirm the role of a key factor called the Hall effect in producing the unexpectedly rapid rate of reconnection and the first to clearly resolve the region where this speeding up takes place.

The MRX device can discharge 30,000 kilowatts of power for one-thousandth of a second, or enough energy to briefly power 25,000 homes.

PPPL scientists have run more than 100,000 experiments—or "shots"—on the MRX device since 1995 at the rate of 100 to 200 per day. Each shot produces up to 20 megabytes of data.

Plasma, the medium in which reconnection takes place, makes up the sun and stars and more than 99 percent of the visible universe.

The Earth's magnetic field—or magnetosphere—that solar storms can disrupt extends nearly 40,000 miles into space.



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