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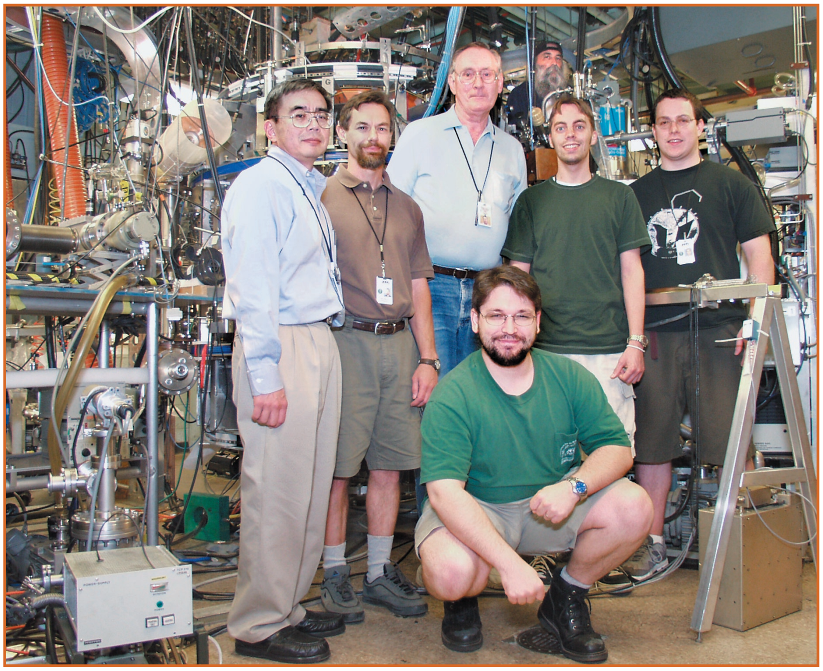
U.S. DEPARTMENT OF ENERGY'S
PRINCETON PLASMA PHYSICS LABORATORY
JAMES FORRESTAL CAMPUS, P.O. BOX 451
PRINCETON, NEW JERSEY 08543

CDX-U

Liquid Lithium Experiments on CDX-U

Among the greatest technological challenges in the creation of a practical fusion power reactor is the development of the so-called "first wall." This is the material surface surrounding the hot fusion plasma, which physicists estimate will be subject to power densities in excess of 25 million watts per square meter from fusion neutrons, escaping plasma particles, and radiation. Present designs call for a lithium blanket behind the first wall. Fusion neutrons will react with the lithium to produce tritium that would be extracted and used as fusion fuel. These neutrons will also react with the materials in the first wall itself, producing radioactive isotopes (activation) and causing chemical changes that may lead to its erosion and loss of structural integrity.

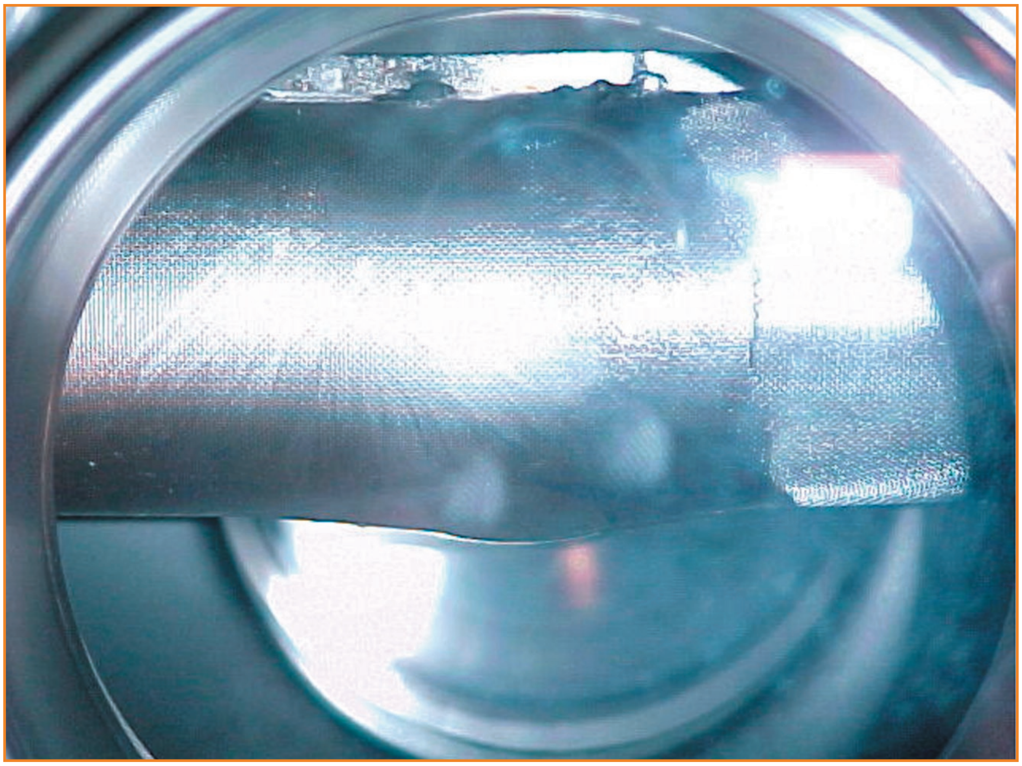


At CDX-U are members of the team. From left are Project Co-heads Bob Kaita and Dick Majeski, PPPL engineer John Timberlake, Princeton University graduate student Jef Spaleta (kneeling), PPPL technician James Taylor (back in hat), Drexel University student Douglas Rodgers, and Princeton University graduate student Timothy Gray.

Experiments now in progress on the Current Drive Experiment-Upgrade (CDX-U) may eventually yield a revolutionary solution to this materials problem, and, of equal importance, may demonstrate techniques for improved plasma performance in the near term. The work, performed in collaboration with the University of California, San Diego; Oak Ridge National Laboratory; Sandia National Laboratory; and others, involves studies of the interactions between plasma and liquid lithium. A liquid first wall would not be subject to the kind of damage a solid wall can experience, and would be able to handle higher heat loads. While present experiments are focusing on the near-term physics advantages, physicists envision the use of flowing liquid lithium as the first wall in a fusion power reactor.

Bob Kaita, who is leading the effort on CDX-U with Dick Majeski, noted that "the use of a flowing liquid lithium wall can potentially eliminate the erosion problem because the wall is continuously renewed. Furthermore, it may result in a substantial reduction of activation because neutrons will no longer react with materials that stay fixed in a solid first wall structure." Kaita went on to point out that lithium can withstand the onslaught of 25 million watts of power per square meter, and it may be able to soak up the helium that is produced in the deuterium-tritium fusion reactions, which must be removed from the plasma.

As remarkable as these potential benefits seem, they are not the end of the story. Significant physics advantages may also accrue, including control of the plasma oscillations and "kinks"— instabilities that can destroy plasma confinement. Experiments on the former Princeton Beta Experiment-Modification at



Shown is the rail limiter head, used in initial experiments, prior to plasma exposure. The view was through the side port of the probe drive assembly when the head was in its retracted position. The primary plasma contact position was the region on the bottom and toward the left of the head. The stainless steel mesh surrounding the head can be seen in the section without a lithium coating toward the right of the head.

PPPL and other tokamaks demonstrated that a conducting wall inhibits these plasma instabilities. Liquid lithium could also serve as a conducting wall, and if the lithium flows at rates of 10 to 20 meters per second, its ability to stabilize the plasma may actually improve.

Limiters are metal surfaces that are specially designed to protrude from the vacuum vessel wall toward the edge of the plasma. Their job is to prevent the plasma from striking the vacuum chamber and sputtering impurities, especially heavy metals, into the plasma. Metal atoms soak up energy and radiate it away, causing the plasma temperature to drop.

Plasma particles (deuterium ions) striking the limiter plates are neutralized and return to the plasma where they again become ionized. This process, called "recycling," tends to cool the plasma edge, and it limits the ability to achieve beneficial operational modes that require a hot plasma edge, such as the "H Mode," or High Confinement Mode. A liquid lithium wall may be the solution because of its capability for absorbing plasma particles. The reduction of the recycling due to the lithium would help establish the hot plasma edge needed for high confinement modes.

"For me the most exciting aspect of these experiments is the chance to investigate the behavior of plasmas with a new and different type of boundary. Experience from the Tokamak Fusion Test Reactor (TFTR) and other experiments tells us that when we change the wall conditions, we change the plasma contained by the wall," said Majeski. CDX-U researchers are hoping that the use of lithium as a wall material will lead to new and improved modes of plasma operation.

Initial Experiments

In preparation for lithium experiments which began in the fall of 2000, a portable handling assembly was designed and built by the University of California, San Diego. The handling assembly contained a unique rail limiter on a retractable probe. The rail limiter consisted of a cylindrical surface about 20-cm long and 5-cm wide. Because the limiter is a cylinder, the area in actual contact with the plasma was a strip about a centimeter wide.

A stainless steel mesh covered the limiter. Lithium, which melts at about 181 degrees Celsius, was liquified in a reservior above the stainless steel mesh.

As lithium was dripped on the mesh, it was automatically soaked up and spread across the surface of the mesh, because like mercury, it has a high-surface tension. The rail limiter was heated up to 300 degrees Celsius to insure that the lithium continued to flow evenly over the mesh surface.

Lithium, like other alkali metals, reacts vigorously with water, including moisture in the air. Consequently, limiter fueling was performed in a glovebox containing argon, an inert gas. The limiter was then inserted in the CDX-U vacuum vessel via a double gate valve airlock system. When the rail limiter was in position, it formed the upper limiting surface for the plasma.

During the fall of 2000, CDX-U staff successfully demonstrated the safe and efficient handling of lithium. Experiments underway during the latter part of 2000 were conducted with solid and liquid lithium limiters. During these preliminary tests there was evidence that the lithium was interacting with the plasma. Bands of very bright light around the limiter indicated that lithium was being driven off its surface.

Data from spectrometers showed that there was an influx of lithium into the core of the plasma. This caused energy to be radiated out of the plasma, not at a level detrimental to confinement. After each experiment, when the lithium was cooled, a coating was found on the limiter. CDX-U scientists believe that this was lithium hydroxide, which was formed when the hot lithium interacted with the small amount of water vapor that was inside the vacuum chamber. They were able to remove the coating by bombarding the limiter with argon ions in a process called "glow discharge cleaning."

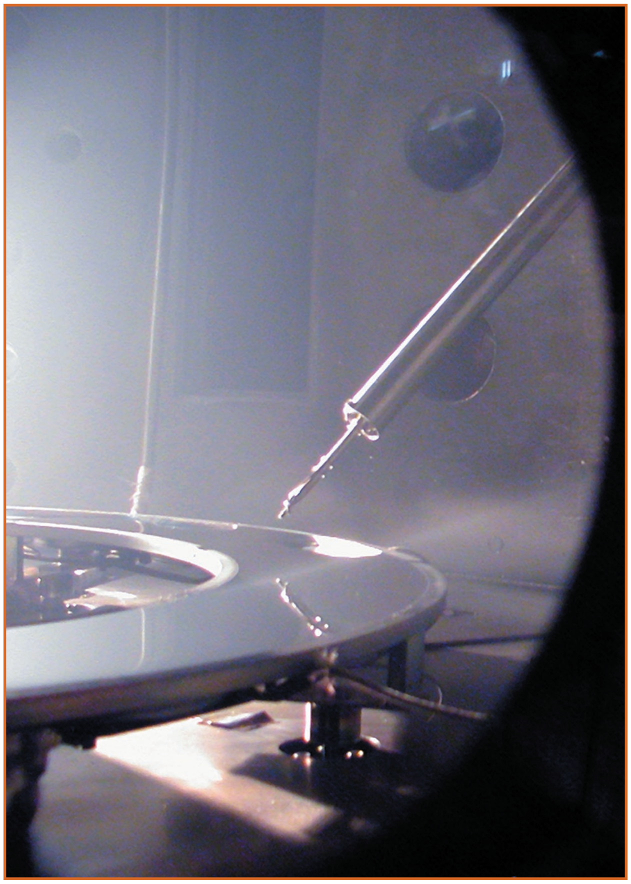
Measurements were made of the light from the deuterium atoms near the limiter, and the "pumpout rate" of the deuterium after a plasma was formed. They showed that while recycling was reduced, it was not completely eliminated.

Recent Work

In May 2003, the area of the plasma-lithium interaction was increased from the modest 20 cm^2 to 1900 cm^2 when CDX-U researchers began using a "belt" or "tray" limiter that runs all the way around the bottom of the vacuum vessel, below the entire plasma. A near complete fill of the tray was achieved by injecting liquid lithium onto the two halves of the tray under an argon atmosphere. "All of the elements were brought together successfully. This is not trivial, because we needed to prepare the tray surface correctly and prepare the injectors so the lithium would remain liquefied and flowing. If the surface of the tray is not clean enough, and not at the right temperature, the lithium will bead up," noted Kaita. The argon atmosphere acts as a buffer to prevent the lithium from evaporating rapidly and coating surfaces inside the vacuum vessel. Plasma discharges were initiated within hours after the tray was filled.

New Results are Dramatic

Following pump down in any magnetic fusion device, it is necessary to run a series of conditioning plasma shots, until all of the loosely bound water, oxygen, and carbon in the vacuum vessel walls is removed from the chamber. These materials pollute the plasma, preventing the required energy confinement time needed for experiments. In CDX-U, plasma currents are limited to 20 or 30 kA, until vessel surfaces are cleaned. This can take up to a day of condition-



In this photo, the pool of liquid lithium is shown in the toroidal tray the encircles the bottom of the CDX-U vacuum vessel. The tip of the liquid-lithium injector, which is removed before plasma operations, is reflected on the shiny surface of the liquid lithium.

ing. However, when CDX-U plasmas are started in the presence of lithium, full plasma currents of 70 to 80 kA can be produced after only a few shots — a dramatic demonstration of the ability of lithium to absorb impurities.

Physicists are never satisfied unless they can measure things, and the CDX-U team is no exception. "It's difficult to quantify these (edge) effects. However, we do have an optical diagnostic that can look for oxygen emission lines typically found at the plasma edge. This spectrometer looks directly at the tray through a port in the vacuum chamber. With no lithium, oxygen emission lines are quite measurable. With lithium in the tray, the measurable level of oxygen goes to zero — a dramatic effect," noted Kaita.

The Lithium Tokamak Experiment

Experiments such as Princeton's TFTR and the DIII-D at General Atomics, Inc. have demonstrated that even modest recycling reductions can significantly improve plasma performance. These results, and recent experiments with liquid lithium at PPPL, UCSD and other laboratories, suggest that it's time to assemble an experiment in which the entire plasma is surrounded with liquid lithium. Consequently, the CDX-U folks have submitted a proposal for the reincarnation of CDX-U as the Lithium Tokamak Experiment (LTX) in 2006.

The LTX would incorporate a shell, just inside the vacuum chamber walls, onto which a thin layer of liquid lithium, about 1000 Angstroms, would be coated evaporatively. The shell would be maintained at a temperature that would keep the lithium in the liquid state. The coating will be sufficiently thick to absorb and retain plasma particles, preventing recycling, and trapping impurities so that they do not re-enter the plasma from the vacuum vessel walls. "The idea is to put in a fresh coating of lithium after each shot. Conceptually the process is similar to the gettering done between shots on earlier tokamaks, where titanium was sublimated onto vacuum vessel components to reduce impurities. The difference is that we would make a thin liquid coating instead of a solid one," noted Kaita. He envisions that such a system is an important step toward a fast flowing, thin liquid lithium wall in a fusion reactor.

In parallel with the proposed operation of LTX will be a series of prototype studies on the National Spherical Torus Experiment (NSTX) beginning in 2004. The first experiments will involve a small area coated with liquid lithium. The longer-term goal for NSTX would be the design, installation, and operation of a flowing liquid-lithium divertor in 2008. In 2005-06, CDX-U would be used for preliminary tests of lithium coating technology in preparation for its conversion to LTX.

Divertor coils, located inside the vacuum chamber, modify the magnetic field at the plasma edge to divert plasma particles and impurities to a region within the vacuum chamber where they collide with a specially coated surface, are absorbed, and prevented from entering the plasma. Divertors eliminate the need for limiters, greatly reducing recycling, resulting in a hotter plasma edge and better confinement. Kaita asks, "if divertors are more effective than limiters for particle control, why not go ahead use lithium-coated surfaces in them as well?" The divertor envisaged for NSTX would employ a static thin film of liquid lithium first, and then a flowing lithium system.

Long -term Possibilities

The jury is still out on the role of divertors and/or limiters in a commercial fusion reactor. This depends on the practicality and effectiveness of the flowing liquid lithium wall in controlling recycling and impurities. If successful, can such a wall also be used to remove the excess tritium that gets embedded in a fusion reactor wall?

Deuterium and tritium, both isotopes of hydrogen, will be used as fuel in a fusion power plant. During its operation, a substantial quantity of tritium, which is radioactive, can accumulate in the power plant walls. Depending on how long the tritium is retained in the lithium, a flowing liquid-lithium wall could avoid this by moving the tritium out of the vacuum vessel — a major advantage over solid reactor walls.

With the exciting, innovative liquid-lithium experiments planned for the next several years on CDX-U, NSTX, and LTX, Princeton is positioned to make vital contributions to technological developments that are essential for practical fusion power in the 21st Century.

The Princeton Plasma Physics Laboratory is operated by Princeton University under contract to the United States Department of Energy. For additional information, please contact: Information Services, Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543. Tel. (609)-243-2750, e-mail: pppl_info@pppl.gov, or visit our web site at: http://www.pppl.gov .