Viewing the ultra-fast at SSRL: First pump-probe experiments under way

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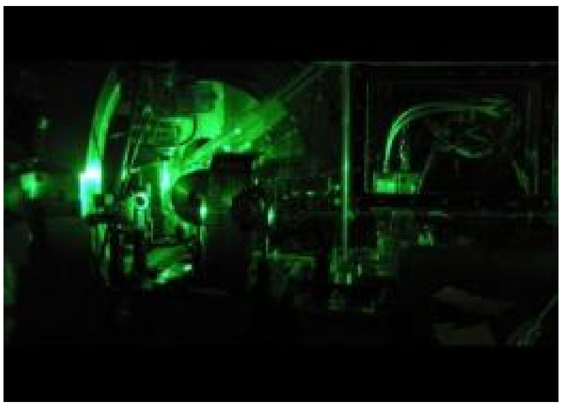

"For 40 years at SSRL, we have been taking very high-resolution photographs—photographs of atoms in molecules and crystals and of electronic structures. But now we want to make movies," said SSRL Staff Scientist Apurva Mehta. He and his colleagues are developing a new "pump-probe" facility that promises to expand SSRL's capabilities and complement those of SLAC's X-ray laser, the Linac Coherent Light Source. Credit: Aaron Lindenberg

(PhysOrg.com) -- X-rays have been used for more than a century to expose the invisible in many of its forms. When a family doctor studies an X-ray of a broken leg or an agent scans a carry-on bag at an airport security gate, hard X-rays, with their ability to penetrate beyond the surface of a material, reveal hidden objects. Pharmaceutical researchers on the trail of new drugs to combat illnesses use the tiny wavelengths of X-rays to illuminate miniscule viruses. Biologists identify particular pollutants, such as arsenic leaching into ground water or lead particulates in air by exposing samples to X-rays and seeing with which wavelengths they resonate.

Both the Linac Coherent Light Source and the Stanford Synchrotron Radiation Lightsource at SLAC take advantage of the ways X-rays can peer at, into and through materials in an effort to learn how matter behaves biologically, chemically or electronically. However, the LCLS, in operation since 2009, has a head start on the nearly 40-year-old SSRL in exploiting one area -- ultrafast atomic and molecular processes. That head start gives the LCLS an edge on some vital areas of research, such as catalysis, where the questions address a process instead of a state of being -- how things change, not what things are.

The third scientific instrument to come online at LCLS, the X-Ray Pump Probe instrument, uses an optical laser to "pump," or excite a sample with photons of light, thereby triggering some sort of physical transformation. It then uses the X-rays from the LCLS as a probe to monitor the progression of that transformation. Using XPP, researchers can watch as excited electrons bounce among levels and molecular structures adjust to changes in internal electromagnetic fields, all on a time scale of femtoseconds, or quadrillionths of a second. That's no time at all to us—invisible time.

By stacking together these snapshots of femtoseconds—these instants of instants—researchers at the LCLS can make stop-action animations of atomic processes. Staff Scientist Apurva Mehta, a fifteen-year veteran of SLAC, wants to bring this action to the SSRL.

"For 40 years at SSRL, we have been taking very high-resolution photographs—photographs of atoms in molecules and crystals and of electronic structures. But now we want to make movies," Mehta said. "What I'm proposing is that we do more at SSRL of what we're doing at the LCLS." Mehta said he wants to watch processes involved in artificial photosynthesis. He wants to answer some basic questions—why are certain substances better at trapping the sun's energy than others? What happens to the molecules that have their electrons stolen away to carry current?

SSRL can't provide the femtosecond resolution possible with the LCLS, but it doesn't have to. The amount of time a process takes depends on scale, Mehta said—electrons move at femtosecond speeds, but atoms are slower. For example, "It takes about one picosecond for sound waves [phonons] to travel one nanometer," he explained. Molecular rearrangements, therefore, often take tens of picoseconds—equating to thousands of femtoseconds—to occur. Phonons, not electrons, are what rattle the atoms in a crystalline structure and determine how the material is affected by heat.

Stanford Professor Aaron Lindenberg of the PULSE Institute for Ultrafast Energy Science and the Stanford Institute for Materials and Energy Science, two institutes run jointly by SLAC and Stanford, is interested in applying these techniques to understand the functional properties of materials and devices. He said he wants to measure the ultimate speed limits associated with the first atomic-scale steps in materials of interest for next generation information storage and energy storage applications.

A series of challenges have slowed attempts to teach the old synchrotron some new tricks—first and foremost, according to Mehta: focusing both a laser beam and the synchrotron's X-ray beam on the same tiny spot, measured in nanometers, at the just the right time, measured in picoseconds.

"In SPEAR3 [the SSRL electron storage ring], you can get 40-picosecond X-ray pulses easily," he said. The 40-picosecond X-ray pulses come from bunches of electrons that are about 12 millimeters long. Unfortunately, that's too long to show picoseconds processes clearly. It's like leaving a camera shutter open as a hummingbird flits by. The result is a blur.

The only way to shorten the X-ray pulse is to shorten the electron bunch length, and one way to do that is to reduce the repulsive force between electrons by removing some of them from the bunch. That's been done with the development of what's called low-alpha mode. In this approach, the electron bunch size is reduced at the expense of simultaneously reducing the current in the storage ring. X-ray pulses of one picosecond in length are now possible.

But reducing the number of electrons speeding around the storage ring reduces the number of photons available to probe a sample. It's equivalent to taking a photo of a dark room with a broken flash.

The SSRL's particular strength—its "high repetition rate," as Lindenberg called it—turns the flash back on.

The SPEAR3 ring is 234 meters in circumference. Up to 372 bunches of electrons zoom around that circumference at any one time, though 280 bunches is a more standard number. And they circle about a million times a second. Mehta does the math.

"If an experiment grabs a few tens of photons from each bunch every time it comes around, that can add up to several million to a billion photons per second," he said. "If I can do that then that's better than pretty much anywhere except LCLS." In fact, he, Lindenberg, David Reis (also of PULSE) and their colleagues recently conducted the first pump-probe experiment at the SSRL. They pumped up bismuth telluride with a laser and used X-rays to "watch" the laser's electromagnetic energy caused the atoms in the sample to oscillate while dissipating as heat on a timescale of tens of picoseconds.

There are few more "buts" to get past. Detectors that can work at these high repetition rates are in short supply, said Mehta. Also, the high repetition rate can cause other problems—the pump and probe pulses can follow each other too quickly, never allowing the sample to return to its ground state before it gets zapped again. This requires either lowering the repetition rate and hence throwing away precious photons, or replacing the sample, at a million times a second, before it's hit by the next pump pulse. A sample delivery system that does the latter is currently in development.

According to Mehta, the stakes are too high not to succeed. "This is pretty challenging, but this is the kind of technology SLAC needs to do all the energy and catalysis science." Lindenberg says he's ready to take advantage of the SSRL's "unique capabilities" when compared to other ultrafast x-ray light sources. They both say they're looking forward to the synergy possible between the SSRL and the LCLS, calling the capabilities of the two instruments complementary.

"SSRL can stand alone scientifically," Lindenberg said, "but it's important to think of the connections between it and LCLS."

"A proposal is not going to get a lot of time on LCLS if the proposed change takes thousands of times longer than the LCLS pulse duration." Mehta explained. "These experiments don't take full advantage of the strengths of LCLS. They don't need LCLS. SSRL works nicely at slower speeds and is better suited for these slower experiments." Another, perhaps more synergetic option Mehta mentioned is to use the SSRL to determine the time scale at which a process or a transformation occurs. "At SSRL, capture the slower atomic rearrangements and phonon-driven processes and use LCLS to capture the truly ultra-fast parts of the transformation."