X-ray Holography Experiment Planned

Lawrence Livermore National Laboratory seeks collaborators for biological imaging, suggesting that its rumored—but secret—x-ray laser is real

If all goes well, researchers will soon be startled to read an account of the first x-ray holography experiments. The report will be doubly surprising because nowhere will there be a description of the x-ray laser (x-raser) used to make the holograms. Because the laser invokes a nuclear explosive as its source of energy and because it may also have military applications, even its existence is classified and has never been publicly confirmed. But the laboratory said to have constructed the x-raser, the Lawrence Livermore National Laboratory, has begun recruiting experts in x-ray spectroscopy, x-ray imaging, and biology for a holography experiment. Although basic physics experiments have been carried out before at nuclear weapons tests, the prospect of biologists journeying to the Department of Energy's (DOE's) Nevada Test Site to obtain high-resolution (100 angstroms or better), three-dimensional images of the innards of live specimens is novel to say the least.

Livermore has disclosed to no one what it proposes to use as the x-ray source for holographic imaging. Since no unclassified project holds the promise of making anytime soon an x-raser with a wavelength short enough and a power high enough for the experiment being discussed, it is difficult to avoid concluding that a report leaked last spring of a classified x-raser at the laboratory is true. Needless to say, no details have been presented that would show that lasing at x-ray wavelengths had in fact occurred. An x-ray hologram, however, would be nearly incontrovertible, if indirect, proof of an x-raser. If DOE's security classifiers were willing to permit publication of an x-ray hologram, Livermore's scientists could signal to the research community their considerable technical achievement in making an x-raser work without publicly saying the forbidden words.

X-ray holography is one application of an x-raser that has long been on the minds of Livermore scientists. Several years ago, George Chapline and Lowell Wood coauthored a review article on x-rasers that prominently featured x-ray holography and its promised capabilities. Much more recently, at the Lasers '81 meeting held by the Society for Optical and Quantum Electronics in New Orleans in December, Johndale Solem and George Baldwin of the Los Alamos National Laboratory and Chapline jointly presented a paper on the considerable challenges of making holograms at x-ray wavelengths, assuming a source of the requisite properties was available.

It is Chapline who has begun sounding out the interests of non-Livermore investigators in a holography experiment. In particular, Jonathan Costa of the National Institute of Mental Health, Janos Kirz of the State University of New York at Stony Brook, and David Sayre of IBM's Yorktown Heights laboratory have met with Chapline and discussed a collaboration between their groups and Livermore. All three researchers have expressed their enthusiasm about working on a holography project, but they have also made it clear that they do not know any specific details of the x-ray source that would be used. As for the reports of a classified x-raser, Kirz said, "He [Chapline] doesn't confirm or deny the press stories."

According to Costa, the considerations involved in the proposed holography experiment are fairly described in the paper presented in New Orleans, which lists three objectives: in vivo, high-resolution holograms of cells in three dimensions, the ability to distinguish individual atomic species, and the ability to freeze mechanical action within a cell on the time scale of picoseconds.

The paper outlines a number of approaches to making holograms and finds difficulties with all of them. The one chosen as most likely to succeed is also the simplest. Holography, it will be recalled, requires two laser beams (which usually are derived from the same laser). The first beam strikes the specimen, is scattered, and then forms an interference pattern where it meets the second, unscattered, reference beam. The interference pattern is the hologram, which may be recorded on photographic film. A three-dimensional image of the specimen can be extracted by shining a laser beam through the film.

In the x-ray case, the researchers suggest the use of a single x-raser beam that acts as both scattered and reference beams. Rather than a film, the recording medium is a polymer of a type similar to that used in the microelectronics industry for the photolithographic printing of integrated circuit patterns. Absorption of x-rays breaks bonds in the polymer, making it more susceptible to chemical solvents when the "exposed" polymer is "developed." Polymethylmethacrylate is widely used in research laboratories for x-ray lithographic printing of microcircuits, an experimental process that has not reached the commercial stage. The same material would be used to record x-ray holograms with a resolution, limited ultimately by the size of the polymer molecule, of about 50 angstroms.

Shining a laser through such a hologram to make an image would be of little help because it would not be magnified and hence would not be viewable. The solution adopted is to use a transmission electron microscope to make an image of the x-ray hologram. Shining a visible wavelength laser beam through a photographic film containing the magnified electron micrograph would then give a viewable picture of the specimen. In a quite different x-ray imaging technique called contact microscopy, Ralph Feder of IBM, Costa, Praveen Chaudhari of IBM, and Sayre used polymethylmethacrylate to record images of human blood platelets and a transmission electron microscope to magnify them and achieved a resolution of 50 angstroms (*Science*, 19 June 1981, p. 1398).

Getting a significant fraction of the x-raser beam to be scattered by the sample presents another problem for would-be x-ray holographers. Solem, Baldwin, and Chapline claim in their paper that to achieve this requires recourse to resonant coherent scattering. Resonant means that the wavelength of the x-rays in the laser beam has to match an electronic transition within one species of atom in the sample. The most familiar thing that happens under the resonance condition is absorption of the x-rays followed by one or more decay processes.

But the laser beam can also drive the atoms into an excited state and back down to the initial state, whereupon the emerging, scattered beam has the same wavelength as when it started, and the coherence required for making a hologram is maintained. The intensity of the scattered beam is greatly enhanced under the resonance condition as compared to scattering when the wavelength does not match an electronic transition.

Finally, it is interesting to note that the specimen is destroyed during the making of a hologram. The incoming x-raser beam is so intense that it almost immediately heats any sample so drastically that it is violently torn apart. The time it takes components of a specimen to reach such high velocities as 10^6 centimeters per second imposes a strict limit on how quickly the hologram must be made. For an image of solid nitrogen with 50-angstrom resolution, an exposure of 10 picoseconds at most is allowed with an x-raser beam intensity of 10^{10} watts per square centimeter. The importance of resonant scattering can be appreciated in this example. Without the resonance effect, the required intensity would rise to 10^{18} watts per square centimeter and the exposure time could be no longer than 10^{-14} second, which the authors described as "clearly unreasonable."

In sum, the technique achieves the three goals of the project: holograms give three-dimensional images; resonant scattering means that only the atomic species with transitions matching the x-raser wavelength contribute to the hologram; and picosecond time scales certainly qualify as stop action.

Each of the three groups collaborating with Livermore would contribute a different expertise. Kirz at Stony Brook will have an experimental station on the soon-to-open National Synchrotron Light Source at Brookhaven National Laboratory. His group will be equipped to do precise spectroscopic determinations of the resonances of atomic species in different environments. Nitrogen, which is an element of great interest because of its presence in the proteins that make up cellular structures, could be imaged without interference from other cell components, such as water. But the precise wavelengths for resonances, some of which occur near 30 angstroms in nitrogen, and the scattering cross sections depend on the molecular environment. The idea is to find resonances that are strong enough and that occur at wavelengths emitted by the x-raser.

Among the specialties of the IBM laboratory are the properties of x-ray–sensitive polymers, called resists. It is not now known, for example, if resists such as polymethylmethacrylate can be exposed by x-ray pulses only a few picoseconds long, ten thousand times shorter than the pulses from nonlasing sources of x-rays that are being developed for x-ray lithography and other applications. For his part, Costa says that part of his group's work will involve the design of specimen holders for wet and possibly live cells. The very short times of the exposure make the geometry of the sample holder critical, as well.

What about the x-ray source? Research with x-rays is entering a kind of renaissance these days. Synchrotron radiation provides a bright source across a broad band of x-ray wavelengths; microfabrication techniques enable the making of lenses and mirrors for soft x-rays (wavelengths longer than 10 angstroms); and high-speed electronics is the key to position-sensitive area detectors. Still missing from this armamentarium is the x-raser. Laser scientists have always had as one of their frontiers the pushing of lasing action to shorter and shorter wavelengths. Despite a bewildering variety of proposals and some experimental progress in building an x-raser, researchers have not succeeded in getting one to work.

At least not officially. Last February, *Aviation Week* reported that investigators at Livermore had used x-rays from "a small nuclear detonation" to pump an x-raser. Most of the article described a futuristic scheme for orbiting x-raser battle satellites to defend the United States against missile attacks. Among the few technical details concerning the x-raser itself were that it consisted of long (1 to 3 meters), solid rods that emitted 14-angstrom x-rays in a pulse of a few nanoseconds duration and several hundred terawatts power. One hundred terawatts in one nanosecond would be 10^5 joules per pulse and would make the x-raser one of the most energetic lasers ever made. The experiment, said to be one in a series, was carried out in an underground nuclear test site in Nevada.

Although articles commenting on the purported breakthrough subsequently appeared in other publications, not much of substance has been added to the original revelation. Interestingly, Chapline has been suggested as the likely principal investigator. Livermore, for its part, refused to comment. Last spring, Chapline said, "I have seen the *Aviation Week* article, but no one at Livermore is free to say anything."

Could anyone else have made an x-raser? The answer is probably yes, but only if more funding had been available. It is noteworthy that in 1974 the Defense Advanced Research Projects Agency (DARPA) supported several x-raser projects with a total budget of about $1 million per year. Livermore was one of the beneficiaries. Unfortunately for Livermore and the other x-raser experimenters, in 1976 the agency was having second thoughts. A 1977 report by a DARPA contractor cast further doubt on the usefulness of an x-raser. Major Harry Winsor of the Air Force Office of Scientific Research, who ran the x-raser program at the time, says that the thrust of the report was that x-rasers could probably be made in a short time; there had already been significant progress. But there were no foreseeable applications that could not be handled more inexpensively in other ways. DARPA subsequently dropped all direct support of x-raser research.

Research with x-rays is entering a kind of renaissance these days, as new experiments get under way.

Livermore later got back into the x-raser business and is now involved in three unclassified projects. All depend on the production of a hot, dense plasma as the lasing medium. One way to make a plasma is by blasting a solid target with one or more beams from the huge infrared lasers constructed for laser fusion research. Depending on the target material and configuration, the laser power, and so on, the ions in the plasma may be partially or fully stripped of electrons. The biggest disadvantage of using these lasers is that the laser fusion people who oversee them are reluctant to give them up for x-raser experiments without a guarantee ahead of time that the proposed scheme will work, a promise that cannot be made.

Livermore's oldest x-raser project is based on the use of the laboratory's own fusion lasers. The largest of these is Shiva, a 20-beamed neodymium-glass laser that emits 1.06-micrometer light. It has just been shut down while an even larger laser is built. Peter Hagelstein, a recent MIT graduate whose Ph.D. thesis was to develop x-raser designs while working in Wood's group, notes that no experiment was ever done, although theoretical work was extensive on two neon systems that would lase at 460 and 82 angstroms.

In a second laser-based project, Robert Carman of Los Alamos and Chapline plan to use the eight-beamed Helios laser at Los Alamos. Helios is a carbon dioxide gas laser that emits light at 10.6 micrometers. Chapline reported at New Orleans that there may be experiments with copper targets this year and that additional theoretical work was needed even to predict what the lasing wavelengths would be in the range from 220 to 327 angstroms.

The third x-raser project with Livermore's participation is also based on a high-temperature plasma, but it does not use a laser to produce it. Richard Fortner is working with Glen Dahlbacka and Ray Dukart of Physics International in San Leandro, California. The company has a machine called Pithon, originally built for nuclear weapons effects simulations, that generates extremely high bursts of electric current (up to 3.5 million amperes) into a gas or solid laser medium and thereby creates a plasma. A first round of experiments has been completed, but only one test produced any evidence of x-rays being emitted at the correct wavelength. The plasma was very inhomogeneous in both temperature and density, and the prospects for achieving lasing in future tests with krypton and molybdenum that emit at 149 or 97 angstroms are viewed as uncertain.

Livermore, of course, is not the only laboratory in the world with x-raser projects. But, as with the laboratory's unclassified work, all are far from fruition or else are concentrating on wavelength ranges far from those required for x-ray holography in the soft x-ray region of interest for biological imaging.

How interesting is x-ray holography? John Sedat of the University of California at San Francisco, who has also been contacted by Livermore about collaborating on a holography project, says that the technique would "really change the whole field of structural biology." For example, the importance of the aqueous environment in maintaining structures without distortions is crucial, and x-ray holography would allow this. Sayre at IBM is a bit more cautious in noting that there are two or three other methods that promise three-dimensional imaging capabilities similar to holography. Both researchers enthusiastically hold that x-ray holography should be tried. Now it looks as though it will, although under rather unusual circumstances. Meanwhile, laser scientists hope that the details of the putative x-raser will soon be declassified so that work can begin on the possibility of making a laboratory version of the device that will use a more conventional pumping source.

—ARTHUR L. ROBINSON

Just How Hazardous Are Dumps?

Everyone knows toxic wastes are hazardous, but there is little agreement about how to assess the potential risks to health

In October, the United States Environmental Protection Agency (EPA) finally issued a list of 115 hazardous waste storage sites that represent the most serious potential danger to human health. These sites were among the first candidates to be cleaned up with support from Superfund, a $1.6-billion kitty accumulated primarily from taxes on industrial chemicals. In November, however, the Congressional Office of Technology Assessment (OTA) sharply criticized that list, arguing that EPA had used inappropriate criteria in preparing the rankings. States and environmental groups have had their own thoughts about which dump and storage sites deserve first call on the funds.

These conflicting opinions symbolize the most crucial problem confronting individuals and agencies that must deal with the hazardous waste problem: There is no firm consensus about how to determine the potential hazard of chemicals at a dump site, the risk of exposure, and the potential health effects from such an exposure. The problems are not simply academic. A 1979 survey by EPA of 100 waste disposal sites produced an average estimated cost for cleanup of more than $8 million, with the cost at some sites running as high as $25 million. There are hundreds of such sites—perhaps thousands—and even $1.6 billion will not go very far. Hard choices are going to have to be made—and soon.

Part one of two parts

A good example of the problems involved is the highly publicized Love Canal area in Niagara Falls, New York, where homes were built immediately adjacent to a waste disposal site that was disturbed. Despite the great amount of time and effort that has been devoted to this volatile problem, it has been extremely difficult to document the extent of exposure of area families to the chemicals. There has been no conclusive evidence linking any such exposure to health effects in humans—particularly since some potential effects may not become apparent for at least another 15 years.

Investigators have even had problems defining precisely which questions should be asked about hazardous waste sites. There is consensus about only a few of the most general:

- What do we know about how chemical waste disposed onto and into the land contributes to pollution of air and ground water?
- In sampling and analyzing air, water, and other media, what strategies are most promising?
- How can human exposure best be estimated?
- What is the extent of normal human exposure to the chemicals in dumps?
- How can exposure to chemicals be related to human health problems?
- What are the health effects of mixtures of chemicals? Are they additive or synergistic?
- Are there existing technologies that have not been applied to the problem? What new technologies need to be developed?

These questions and others have been addressed at three major meetings during the past year. Proceedings of two of the meetings are now available in book form