Doing a Stretch of Time

A new way of "stretching out" very fast signals in time promises to reveal never-before-seen details in experiments at the National Ignition Facility and elsewhere.

Finding new and inventive ways to measure fast-moving, transient signals has always been a research area in which Lawrence Livermore's scientists and engineers excel. Beginning in the 1950s, in the days of nuclear weapons testing, diagnostic systems were needed to capture the nuances of data produced from single-shot underground experiments. In the 1970s, the same need arose for experiments conducted on the Laboratory's big laser systems such as Shiva. In these experiments, researchers had only one opportunity to catch and record the data—they had no second chances once a test device exploded or a laser target imploded.

Because commercial support was limited for developing these diagnostic systems, Livermore scientists and engineers took the initiative to invent what was needed to get the job done. (See the box below.) In the 1950s, one-of-a-kind detectors were developed for transmitting electrical signals up copper coaxial cables to aboveground banks of oscilloscopes. In the 1980s, diagnostic systems incorporated the latest in fiber-optic technology to deliver optical signals to streak cameras. Although oscilloscopes and streak cameras captured and recorded signals with detail in the 1-nanosecond (a billionth of a second) time frames of yesterday, the single-shot laser experiments of tomorrow will need instrumentation to capture signals with much more detail and in shorter time frames.

Experiments being planned for the National Ignition Facility (NIF)—the world's largest laser—will require instrumentation that can capture ultrafast signal details in the realm of a single picosecond (a trillionth of a second). In a

Fast, Faster, Fastest

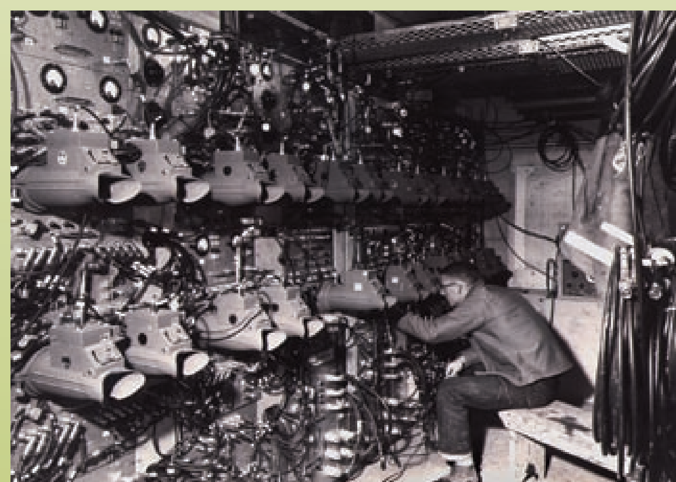
When Livermore's Nuclear Test Program began, engineers faced the extreme challenge of creating diagnostic systems that would measure the performance of an exploding nuclear device. In such an explosion, matter is accelerated to millions of kilometers per hour while experiencing densities and temperatures found only in stars. The Laboratory's early engineers had to design instruments and radiation detectors that could capture data on the reaction history, time history, and overall yield of an explosion.

"It was a challenge," says Mark Lowry, a physicist in the Defense and Nuclear Technologies Directorate. "The early aboveground tests relied on signals transmitted through the atmosphere. However, once the tests were moved underground, signals from downhole had to be transmitted with high resolution through cables to trailers at the surface."

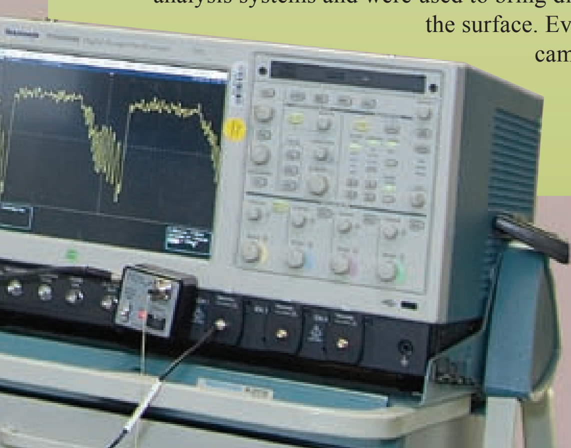
The diagnostic systems that evolved over four decades of testing were incredibly complex, often consisting of dozens of specially designed oscilloscopes, hundreds of electronic chassis, numerous control systems, and thousands of Livermore-developed detectors. Connecting these components was no less an engineering feat than developing the parts. Timing accuracies, for instance, had to be less than a nanosecond between oscilloscopes connected to detectors over coaxial cables spanning hundreds to thousands of meters in length.

Electronics innovations—from vacuum tubes to solid-state devices to integrated circuits—revolutionized the systems used in the underground experiments. Later, Livermore engineers explored replacing oscilloscopes with digital systems. Fiber-optic cables appeared in underground electronic-imaging and spectral-analysis systems and were used to bring digitized data to the surface. Eventually, streak cameras replaced some oscilloscopes.

"In the early 1980s, a key emerging technology was fiber optics," says Lowry. "This breakthrough technology allowed us to measure signals 100 picoseconds long, compared to the 1-nanosecond length achieved with the oscilloscope–coaxial cable systems." This leap in measuring signals opened a new world to weapons researchers in the 1980s. "Suddenly, it was as if someone had thrown open a closed window," adds Lowry. "We could see structures in signals that we had never seen before." These fiber-optic-based systems used streak cameras to obtain a fast time response. "We pushed the streak camera technology of the time," remembers Lowry. The systems were fielded for only a few events before underground nuclear testing ended in September 1992.



Banks of oscilloscopes were used to capture data at the Nevada Test Site during Operation Teapot in 1955.



technical leap that combines old and new technologies, engineer Corey V. Bennett of Livermore's Engineering Directorate has designed a fiber-optic-based "time microscope" that can be attached to the front end of an oscilloscope or streak camera, improving the time resolution and dynamic range of these instruments by two orders of magnitude—from tens of picoseconds to hundreds of femtoseconds (where 1 femtosecond equals 10^{-15} second). Just as a scanning electron microscope's powers of magnification can reveal nanometer-size details of an object's structure not viewable with an ordinary desktop microscope, the time microscope's powers of time magnification can reveal the peaks and valleys in a 1-picosecond signal not detected by a stand-alone oscilloscope or streak camera.

The Need for Speed

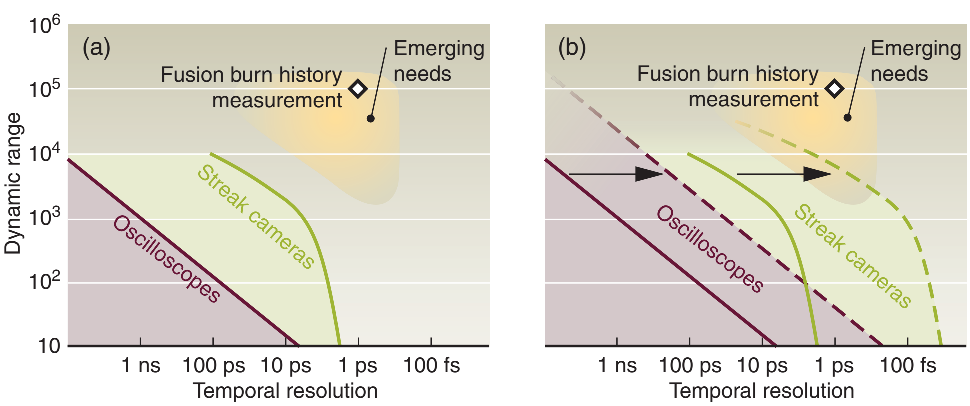
NIF is a key component of the National Nuclear Security Administration's (NNSA's) Stockpile Stewardship Program, which is responsible for ensuring the safety, security, and reliability of the nation's nuclear stockpile in the absence of underground nuclear testing. NIF is crucial to the program because it is the only facility that can create the extreme temperature and pressure conditions found in stars and in exploding nuclear weapons. In addition, NIF is the only facility that can create fusion ignition and thermonuclear burn in the laboratory. Nuclear fusion is the process that modern nuclear weapons use to achieve their immense explosive power. The understanding of these conditions and the data provided by NIF will allow the country's weapon stewards to assess and certify the aging stockpile using supercomputer modeling tools that have been experimentally validated.

Future high-energy-density and inertial confinement fusion experiments on NIF will generate neutrons, gamma rays, and hard x rays. During these shots, the reaction histories, dynamic temperatures of targets, and dynamic opacities must be measured. Capturing the nuances of these measurements—such as the detailed shape of a signal over time—is a challenge. Scientists will require ultrafast diagnostics that can reveal, for instance, when high-energy photons first appear and what happens from their first appearance to their peak production. The experiments will require diagnostics with time resolutions on the scale of 1 picosecond or less. In addition, these diagnostics must detect and record a high dynamic range of signal strengths—from very weak signal intensities to very strong—far beyond the capabilities of existing systems.

NIF is not the only facility that will require improved diagnostics for measuring superfast events. In 2009, the Linac Coherent Light Source (LCLS) at the Stanford Linear Accelerator Center will begin operation as the world's first x-ray free-electron laser. Pulses of x-ray laser light from LCLS will be many orders of magnitude brighter and several orders of magnitude shorter than those produced by any other x-ray source available now or in the near future. These characteristics will enable researchers to discover and probe new states of matter, follow and understand chemical reactions and biological processes in real time, image chemical and structural properties of materials on the nanoscale, and image noncrystalline biological materials at atomic resolution. For these experiments and others, LCLS will need diagnostic systems that can measure the timing and pulse shapes of its 100-femtosecond x-ray pulses.

Bennett says, "Upcoming experiments at NIF, LCLS, and elsewhere will involve faster physics on shorter timescales than on past single-shot events. It's now a different world in terms of scale. The question is: How do we measure the resulting signals at a resolution that will allow the extraction of information needed to understand what happened in the experiment?"

Mark Lowry, a physicist in the Defense and Nuclear Technologies Directorate, participated in the last underground tests in the early 1990s. He says, "You can use simple scaling arguments to estimate the relationship between instrumentation requirements for the underground experiments and NIF. At the underground test sites, we were interested in measuring signals emanating from sources about 1 centimeter in size. The experiments used diagnostics that could capture 100-picosecond signals. We could see details of interest that yielded important information on the



(a) The current technologies available to record fast events—digital oscilloscopes and streak cameras—cannot reach the temporal resolution and dynamic range required for planned experiments at the National Ignition Facility. (b) Adding the time microscope to the front end of these recording devices "stretches out" the signal over time, augmenting the capabilities of these systems: ns = nanoseconds, ps = picoseconds, and fs = femtoseconds.

performance of a device." NIF target sources will have diameters of 100 micrometers or less, about two orders of magnitude smaller than the underground test sources. "It takes a certain amount of time for a signal to transit a given dimension, which sets a minimum timescale of interest," says Lowry. "We must capture signals at a rate at least two orders of magnitude faster to see the interesting data. The 1-picosecond temporal resolutions will be extremely useful."

A Matter of Resolution

Both the dynamic ranges and temporal resolutions of current technologies fall short of what will be needed to capture the details of fast-moving, complex events such as fusion burn history for NIF experiments. To reveal important nuances in the burn history, such experiments will require a dynamic range of about 10^5 and time resolutions of 1 picosecond. Engineer John Heebner of the Engineering Directorate says, "A challenge of extending existing instruments such as oscilloscopes and streak cameras to reach these regimes is that dynamic range and temporal resolution on these systems are coupled. The more temporal resolution we need, the less dynamic range we get, and vice versa."

For example, an oscilloscope can capture a signal with a dynamic range of 10^4 only when the duration of the signal details are 10 nanoseconds or longer. Conversely, a 10-picosecond pulse recorded by an oscilloscope reveals almost no dynamic range. Streak cameras are somewhat better able to capture these signals—a dynamic range of 10^3 can be captured on a 5-picosecond pulse—but still fall short of what is required for NIF experiments. "If these instruments are going to be used, we need technologies that can extend their performance capabilities," says Heebner.

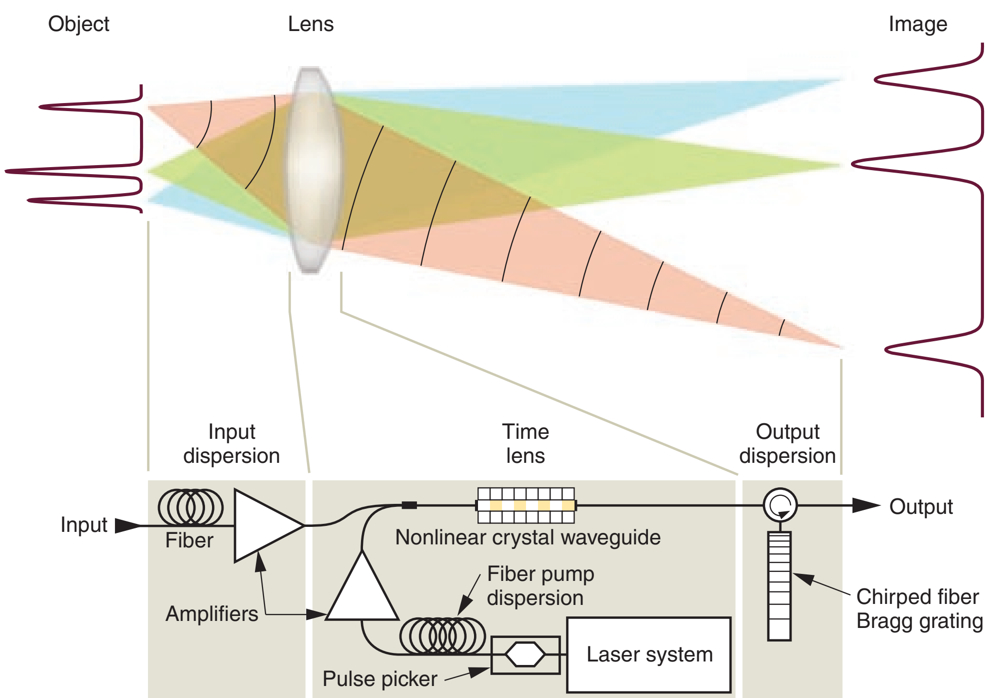
The beauty of Bennett's time microscope is that when it is attached to a recording instrument such as an oscilloscope or streak camera, the microscope will slow down or "magnify" time for these instruments, allowing signals to be captured that otherwise would be too fast to record in any detail. "Time magnification not only extends the resolution of a recording instrument but also increases its dynamic range at longer timescales," says Heebner.

A Microscope by Any Name

The time microscope that Bennett developed and built with engineering associate Bryan Moran of the Engineering Directorate had its genesis as a Laboratory Directed Research and Development project. The instrument works similar to an optical microscope but in the time domain rather than the spatial domain.

"The purpose of both instruments is to magnify something," says Bennett. "When using the time microscope, we are magnifying the detail and duration of a signal, such as an optical pulse (a short flash of light) being transmitted through a fiber-optic cable. Stretching out a signal over time allows us to see rapidly varying little peaks and valleys in a signal's strength."

In a conventional optical microscope, a glass convex lens is the main element for magnifying the object. When diffracting light passes through the lens, the wavefront of the light converges. At some point beyond the lens, a scaled or magnified image of the original object forms. Why the wavefront converges has to do with the physics of light as it propagates through materials of differing properties and the curved lens.



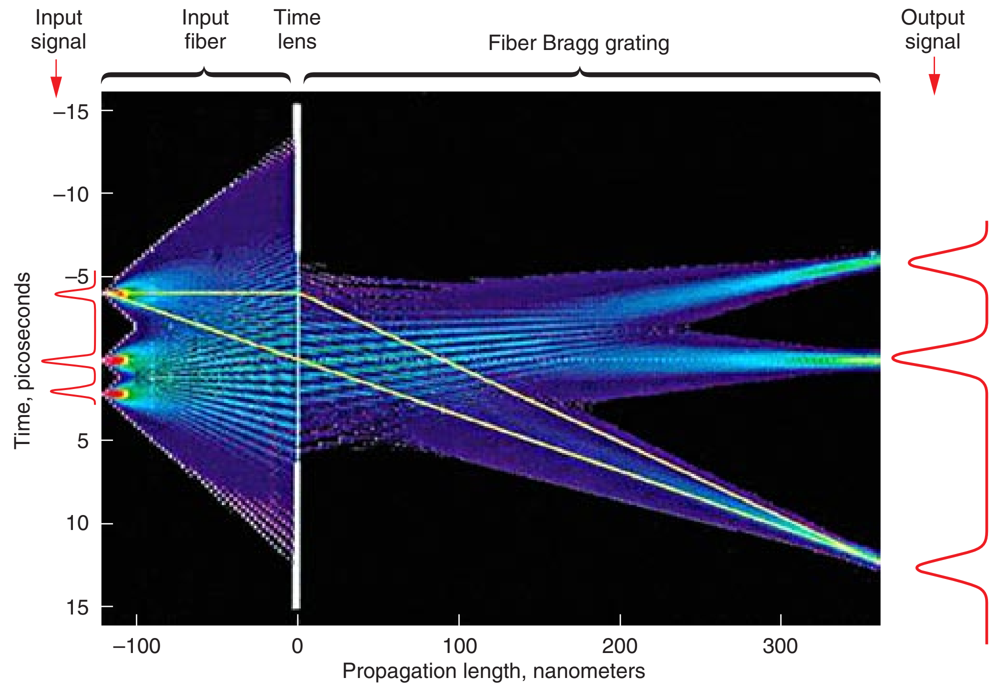
Optical and time microscopes work on the same basic principles. An optical microscope uses a convex glass lens to form a magnified image of the original object. The time microscope has a "time lens" consisting of a chirped pump pulse and a nonlinear crystal. Optical signals (flashes of light) arriving via a fiber-optic cable are the "object" of the time microscope. These signals pass through the time lens and are magnified, or stretched out, over time thus making them more recordable.

In the time microscope, magnification is provided by the so-called "time lens." The time lens has two parts, a chirped pump pulse and a nonlinear mixing crystal. The chirped pump pulse has an optical frequency (color) that changes linearly with time, similar to how the tone of a bird song might rise or fall smoothly over time. This pumped pulse performs the same functions as an optical lens. "The pulse has the characteristics that we want to impart to the input signal," says Bennett. The pump pulse also has a finite duration, functioning much like an aperture in an optical camera.

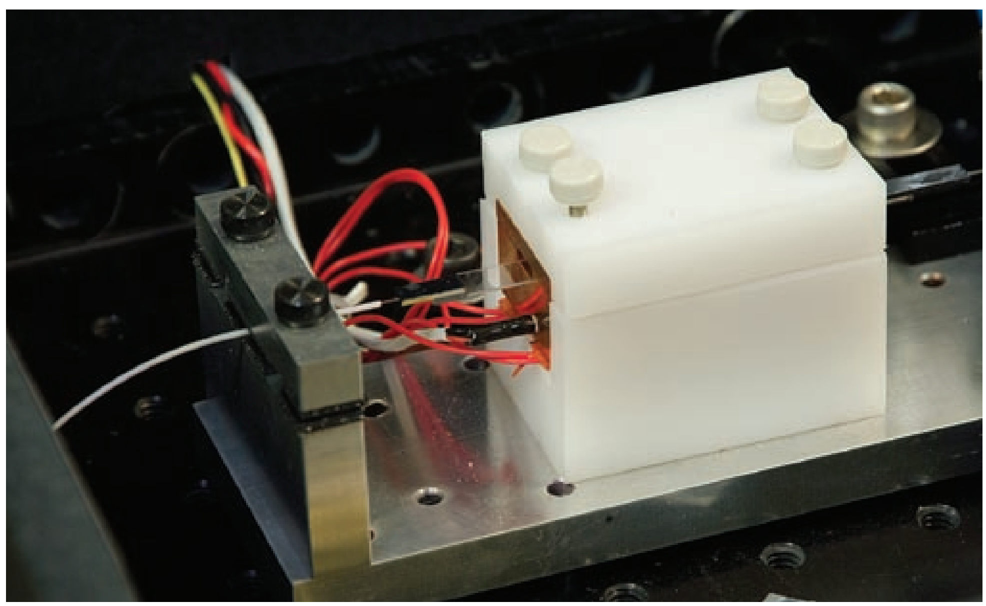
The second part of the time lens, the nonlinear mixing crystal, allows these characteristics to be imparted to the input signal. The dispersed input signal and the chirped pump pulse enter the crystal simultaneously, where they mix to form a third output signal, which contains characteristics of both the input and pump pulses. This output signal thus contains information from the input signal with the desired characteristics of the time lens.

The crystals, produced in collaboration with graduate student Carsten Langrock and professor Martin M. Fejer from Stanford University, require special processing and are key to making the entire system work. Typical crystals would have a weak output signal, producing a dark image. The Stanford-produced nonlinear crystals contain waveguides that improve the crystal's efficiency more than 100 times, yielding a brighter image. This brighter image provides a good signal-to-noise ratio, allowing better recording of weak signals and an extended dynamic range.

Once the output signal exits the time lens, it must be focused. The light pulse from the nonlinear crystal does not have time details resolved on it. The pulse is focused by adding more dispersion using a chirped fiber Bragg grating in the last segment of fiber optic. The fiber Bragg grating reflects specific wavelengths of light from different locations along the grating length and as a result can produce greater



A false-color image shows three pulses propagating through a temporal imaging system with a magnification of three times. Color here represents intensity or brightness, with red being the brightest. The simulation shows how three optical pulses occurring in a 6-picosecond time frame can be "time magnified" so that, at the output, they occur over 18 picoseconds.



The nonlinear crystal is housed in a heated copper block, which is surrounded by an insulator. The output end of the crystal (which looks similar to glass) protrudes from the insulated block. The crystal is glued to a silicon block (gray) that holds the output optical fiber (white-jacketed fiber at far left). The temperature of the crystal is set to tune the wavelength for which its frequency mixing is most efficient. The red wires power heaters under the copper block.

amounts of dispersion with less loss than traditional fibers.

"Different wavelengths in the spectrum of the signal are reflected with different delays," explains Bennett. "This increased dispersion in the back end of the time microscope leads to a greater magnification, but the balance of the input dispersion and time-lens modulation allows the fine temporal details to come back into focus." The fiber Bragg gratings are produced in collaboration with Morten Ibsen at the Optoelectronics Research Centre, University of Southampton, United Kingdom.

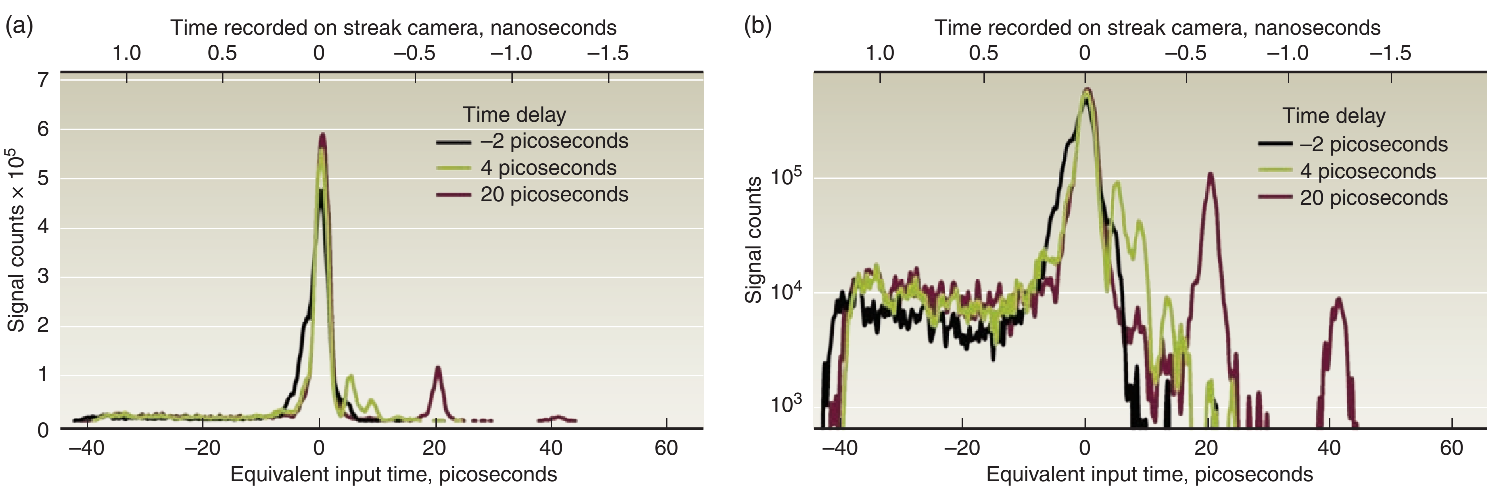
Testing, Testing

Bennett and his team built a proof-of-principle time microscope system designed to provide a recording length of 100 picoseconds and a magnification of 33 times. Two test series were conducted with a 1,534-nanometer input signal using different patterns and recording instruments.

The first series of tests used a ring-down pattern, in which a train of 2-picosecond pulses was sent through a fiber splitter. The splitter divided the strength of the signal and looped the split output back to the input with a time delay. The result was a large pulse followed by a train of increasingly weaker pulses. A single-shot streak camera recorded the magnified results. Bennett says, "The tests showed that the system has 1.8-picosecond resolution with a 1,000-to-1 dynamic range—an order of magnitude improvement in both the resolution and dynamic range over what the streak camera alone could do." In figure (b) below, a "noise pulse" can be seen from about –40 to –10, limiting the usable range at early times. This noise has recently been removed with a modified crystal design.

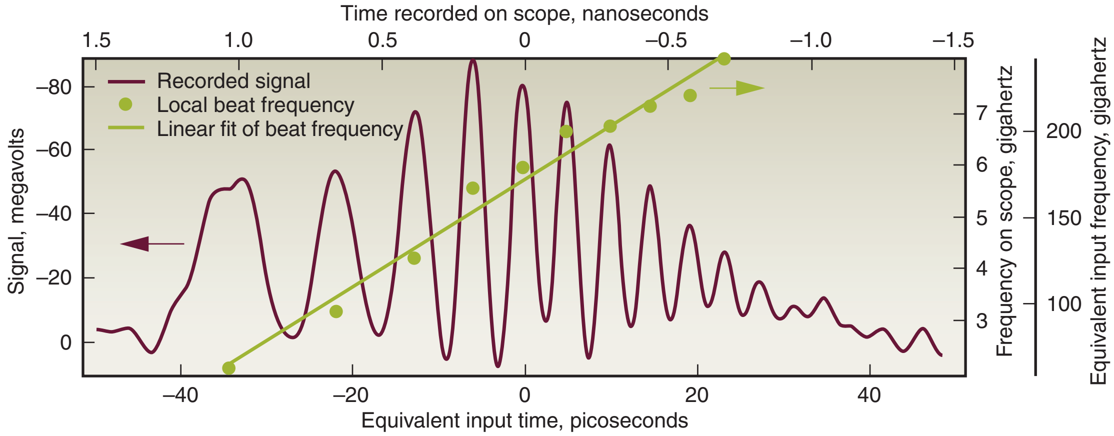
The second series of tests was for a project funded by the Defense Advanced Research Projects Agency's Optical Arbitrary Waveform Generation Program, which is exploring the next generation of arbitrary waveform generators. These signal generators will have terahertz bandwidths with femtosecond-timing resolution and will control both amplitude and phase of the optical fields. Bennett hopes to capture the fast signals that, unlike the single-shot application, occur with a high repetition rate. "Our goal is to record real-time signals that don't necessarily follow a pattern, such as signals from a radio but at much higher speeds," says Bennett. "A signal that has subpicosecond detail and changes every 100 picoseconds is very difficult to analyze."

For these tests, Bennett used a high-frequency chirped heterodyne signal, which is a combination of two signals of differing frequencies that beat together. A chirped 100-picosecond pulse with an approximate 300-gigahertz bandwidth was added to a laser signal with constant frequency tuned to the far edge of the pulse's spectrum. (See the figure on p. 10.) This combination produced a beat with intensity from nearly 0 to 300 gigahertz over the 100-picosecond pulse duration. "No real-time oscilloscope exists that can record such a beat," says Bennett. "The fastest scopes in existence today can only record up to 20 gigahertz, producing a



A series of experiments looked at how the time microscope recorded the details of ring-down signals that had increasingly shorter delays between pulses. Results from a streak camera augmented with a time microscope are shown with signal counts on (a) linear and (b) logarithmic scales. In this data set, all input pulses are 2 picoseconds (ps) wide, and weaker pulses are timed before (–2 ps) or after (4 ps and 20 ps) the main pulse as shown in the legend. With a –2-ps delay between pulses (black line), the weaker and overlapping pulses appear as small bumps on the left. With a 4-ps delay (green line), the pulses are clearly separated, with dips between pulse peaks. With a 20-ps delay (red line), three separate pulses are clearly indicated. In all three cases, a streak camera alone—without the time microscope—would blur the pulses together and record just one pulse approximately 20 ps wide.

In this experiment, a time-magnified heterodyne beat signal recorded a single shot on an 8-gigahertz oscilloscope. The recorded signal changes beat frequency –3.45 gigahertz per nanosecond indicating that the color of light in the input pulse was chirped at a rate of 313 gigahertz per 100 picoseconds.



digitized sample every 20 picoseconds. They would record five data points in the digitized pulse, and the high-frequency modulation would be completely missed." The time microscope expanded the timescale, and the oscilloscope captured the fine detail of the high-frequency beat. Each recorded pulse was captured in real time in a single shot, and the process was repeated up to 155-megahertz, capturing every fourth pulse in the laser's pulse train.

Signal for Success

The time microscope system is generating interest from scientists in the Defense and Nuclear Technologies Directorate, who are planning experiments for NIF. "In addition to fusion burn history measurements, we have the potential to get a closer look at equation of state," says Lowry. "Evidence exists that changes are occurring on the subpicosecond timescale, and we may finally begin to see these with the time microscope. A benefit of the time microscope is that we can use some of our existing recording instruments such as streak cameras. We only need to attach the time microscope to see details of phenomena that occur on much shorter timescales."

Ted Perry, also a physicist in the Defense and Nuclear Technologies Directorate, is equally enthusiastic. "The time microscope is a wonderful technology, and I foresee it having a variety of uses in any number of areas, including the Test Readiness Program." The Department of Energy through NNSA maintains this program, which is charged with retaining essential skills and improving the diagnostics needed to conduct a nuclear test. "Should nuclear weapons testing become necessary sometime in the future, we must be ready to resume underground testing within two years," explains Perry. As part of the program, researchers look at old diagnostics from previous underground nuclear tests and consider what, given the technological advances over the past decade or two, might be improved. Perry asks, "If testing were to resume, what would we want to do better by a factor of 10? The time microscope could vastly improve some of our diagnostic systems. It's a novel idea and a major leap in technology."

Lowry agrees, adding, "Whenever a new diagnostic instrument or capability is developed, it suddenly provides a clearer view into what's going on. We need to be prepared to see new and unexpected phenomena. No doubt, some of those phenomena will surprise us, and that's a good thing because it means we have made scientific progress."

—Ann Parker

Key Words: Bragg grating, diagnostic system, dynamic range, fiber optic, free-electron laser, Linac Coherent Light Source (LCLS), National Ignition Facility (NIF), nonlinear crystal, oscilloscope, Stanford Linear Accelerator Center, Stockpile Stewardship Program, streak camera, time microscope, underground nuclear testing, x-ray pulse.

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