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Keeping in Sync at a Quadrillionth of a Second

A Master Clock for Accelerators

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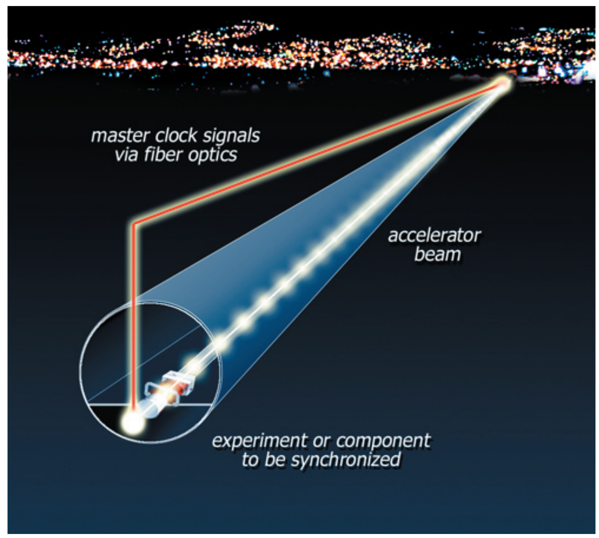
"In the new generation of accelerators, the accelerator components and accelerator diagnostics, and the time signals sent to experimenters, all have to be timed relative to one another within femtoseconds"—quadrillionths of a second—"by means of a master clock," says John Staples, a physicist in the Center for Beam Physics of Berkeley Lab's Accelerator and Fusion Research Division. "And because accelerators have large footprints, the accuracy of the clock has to be guaranteed over kilometer lengths."



The newest accelerators and free-electron lasers will require accurate timing to within femtoseconds or better. Berkeley Lab researchers are developing a master clock system based on signals transmitted by fiber optics.

Compared to experiments using only lasers, this is a significantly greater challenge. "Typically a laser experiment sits on a table top, so travel times are short and the different components are not hard to synchronize," says Russell Wilcox, Staples's colleague in the Engineering Division. "A two-kilometer-long accelerator is another problem altogether."

A laser clock

Staples and Wilcox have come up with a system that uses a near-infrared laser as the master clock, its light traveling through optical fiber of the kind developed for the telecommunications industry.

"At the center of the optical fiber is a glass core made of germanium-doped quartz, nine micrometers in diameter," Staples explains. (A micrometer is one millionth of a meter.)

"The glass core is more transparent than air," Wilcox adds. "It's so transparent that the laser light propagates for many kilometers with very little loss."

Transmitting the laser signal through the fiber is not a problem, but maintaining the fiber's precise length is. Temperature variations from day to night vary the velocity of signals through the fiber, so that they arrive too late or too early. "All kinds of things affect the fiber, not just temperature," says Wilcox. "For example, optical fibers are acoustically sensitive—in fact they make good microphones. And accelerators are inherently noisy."

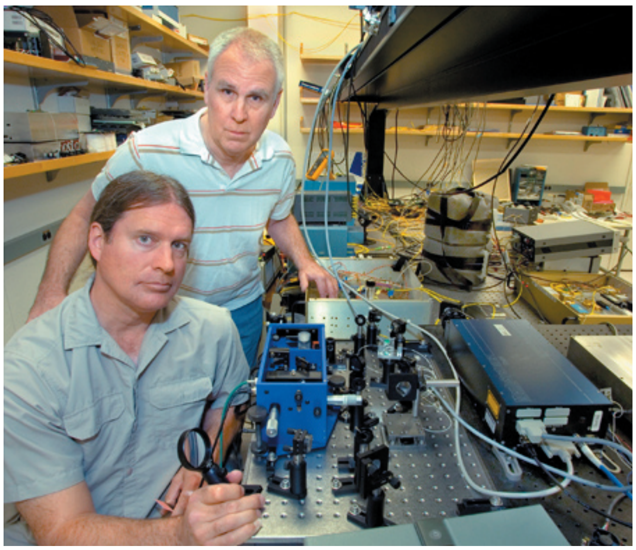
The guarantor of precision in a clock system of this kind is the number of wavelengths (cycles) of laser light of a specific frequency in a length of fiber. By reflecting the light back on itself at the end of its long journey, the light waves are made to interfere with one another and produce interference fringes, which can be counted. Any change in the length of the fiber, or other influence on the transit time, will change the number of fringes per unit length.

"So we monitor the number of fringes and add or subtract length to maintain the right number," Staples says. Two kinds of compensating mechanisms do the job. In one, a length of fiber is wrapped around a piezoelectric core, which changes size in response to changes in an electric field: when the core expands, the spooled fiber stretches. Although the response time is rapid, the length change is slight, adding only a few picoseconds (trillionths of a second) to the travel time along the entire length of the fiber.

The other compensating method is a variable air gap. The laser light leaves the fiber and travels through open air for a few millimeters, before striking a mirror and being reflected back into the continuation of the fiber. The mirror is moved forward or back to shorten or lengthen the travel distance. The motor drive that moves the mirror is slow but can change the path length substantially.

Neither compensator would be adequate unless the frequency of the laser itself were kept absolutely accurate. “Otherwise you could fool yourself,” Staples says. “You could keep the same number of fringes, but the length of the fiber could be changing as the frequency changes.”

The laser frequency is precisely maintained by passing a sample of the beam through an acetylene gas cell and tuning it to the gas’s absorption line, the timing system’s fundamental reference.



Russell Wilcox (left) and John Staples with test equipment that produces the original laser signal, compares its phase with the reflected signal, and continually compensates for changes in path length using a piezo-electric spool and air gap. (Photo Roy Kaltschmidt, CSO)

Testing the feedback

To test their laser-optic timing system, Staples and Wilcox needed a real-world environment. “What better place than a couple of kilometers of fiber optics running around Berkeley Lab, under roads, in and out of buildings and communications closets?” Staples asks. “We called up Ted Sopher and Ed Ritenour in the Information Technology Division and asked, ‘Do you have an extra loop of fiber a couple of kilometers long?’”

Ritenour and Sopher identified a loop of high-speed fiber optics cable from Staples and Wilcox’s lab to a building halfway across the Berkeley Lab campus, a round trip of 1.97 kilometers.

“We send the light out on the fiber and it returns to our lab 1.97 kilometers later,” Staples says. “We impose a frequency shift and change polarization and reflect the light, which goes back out and returns another 1.97 kilometers later to where it originated—a total path length of 3.94 kilometers. We analyze the light upon its return and impose the corrections needed to stabilize it.”

Now that the optical carrier has been stabilized to a single optical fringe, less than five femtoseconds, maintaining synchronization via compensation mechanisms has been solved for experiments that require only narrow-band signals, But for experiments requiring more complex signals, temperature variations must be compensated even more precisely. “The next step is to send more complex clock signals over this path,” Wilcox says.

In the finished system, Staples says, separate fibers will go to experiments and accelerator components to synchronize them with other components, each fiber “emanating from the central laser clock in a star configuration, and each individually stabilized, placing the client at the end of each fiber in femtosecond-level synchronism with all the others.”

The first customer for the fiber-optics-based femtosecond timing system is the Linac Coherent Light Source at the Stanford Linear Accelerator Center. Other potential applications include the FERMI free-electron laser (FEL) facility under construction at the Elettra synchrotron in Trieste, Italy; the timing systems for the proposed International Linear Collider; and, not least, Berkeley Lab’s proposed “FEL Farm,” a linac that will power 10 free-electron lasers.

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