

Coherent x rays generate equally spaced ultrafast pulses

The adaptation of Nobel Prize-winning optics work to the x-ray regime brings new capabilities to the free-electron laser.

By Alex Lopatka

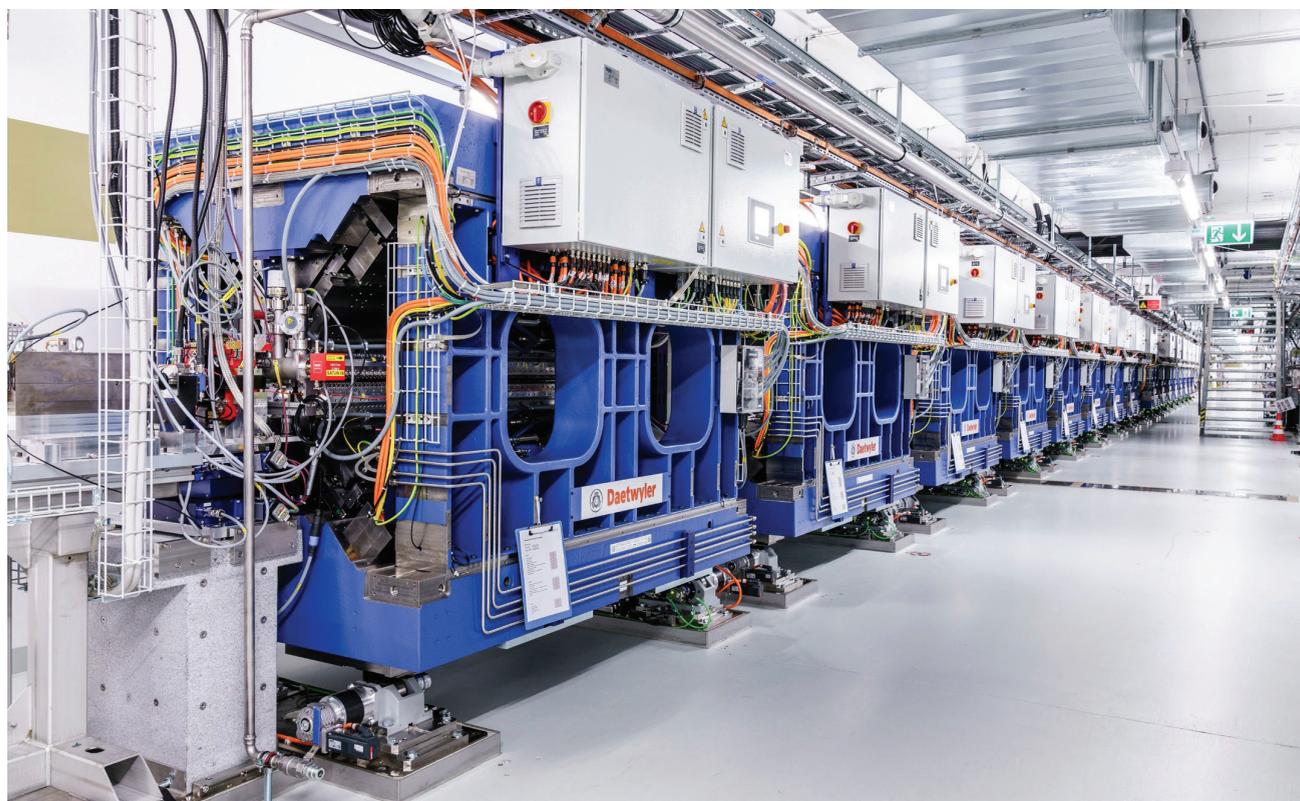
One of the most effective tools that researchers have to study small and fast particles and processes is the x-ray free-electron laser (XFEL). The extremely bright, ultrashort pulses of light resolve phenomena such as the folding of proteins, the motion of electrons, and the progression of chemical reactions at the attosecond time scale—a billionth of a billionth of a second. (To learn more about XFELs and their applications, see the 2015 *PT* article “Brighter and

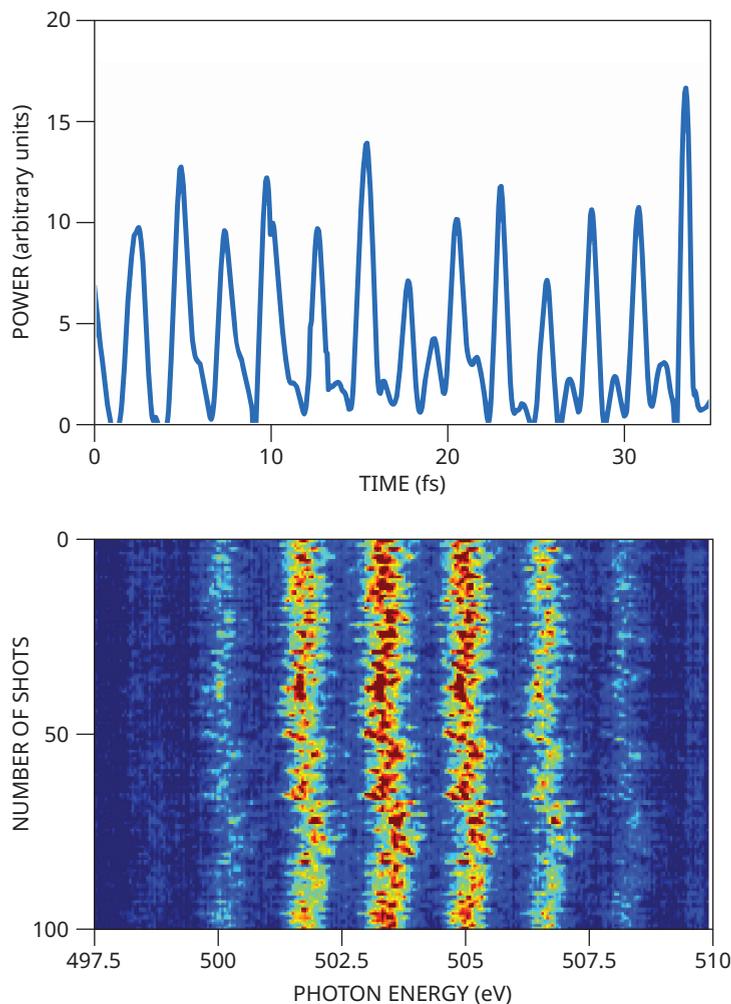
faster: The promise and challenge of the x-ray free-electron laser,” by Phil Bucksbaum and Nora Berrah.)

Despite the many capabilities of XFELs, their light pulses are only partially coherent. The limita-

tion means that individual pulses are randomly distributed in time and in their energies. (Some XFELs use seeding techniques to improve the coherence but not in the ultrafast time domain.) If XFEL light could be mode locked, periodic

▼ **Figure 1.** Undulator modules (blue) of the x-ray free-electron laser facility at the Paul Scherrer Institute in Villigen, Switzerland, generate magnetic fields. They slightly deflect the incoming x-ray electron beam to generate partially coherent femtosecond light pulses. Between each of the modules, researchers added a chicane—a group of four dipole magnets—to further deflect the electrons. The additional delay created by the longer path the electrons had to take increased the coherence of the laser output. In combination with a modulating external laser, the setup resulted in trains of periodic, phase-correlated attosecond x-ray pulses. (Photo courtesy of the Paul Scherrer Institute PSI/Markus Fischer.)





▲ **Figure 2.** Periodic, phase-locked attosecond pulses were recently generated at the x-ray free-electron laser at the Paul Scherrer Institute in Villigen, Switzerland. The reconstructed temporal profile (**top**) shows that the attosecond pulses are equally spaced a few femtoseconds apart from one another. The frequency comb (**bottom**) is produced from 100 consecutive single laser shots. The normalized spectral intensity ranges from low (blue) to high (red). The demonstration at x-ray wavelengths is analogous to the optical frequency comb, which was first developed at visible to IR wavelengths in 1999. (Plots adapted from ref. 1 and courtesy of Wenxiang Hu.)

trains of ultrashort pulses could be generated. That would provide researchers with a tool analogous to the optical frequency comb, which is critical for experiments with optical clocks, high-precision spectroscopy, and other applications.

Now Eduard Prat of the Paul Scherrer Institute in Villigen, Switzerland, and colleagues have achieved that goal for XFELs by coaxing the x-ray light to generate equally spaced periodic pulses in time.¹ The mode-locked scheme, which was accomplished at the institute's SwissFEL user facility,

is the first demonstration of its kind. The new result expands the capabilities of XFELs and may make them useful in new ultrafast applications.

Finding signals in the noise

A regular laser emits light by first stimulating emission from atomic or molecular excitations and then forcing the emission to bounce back and forth through a gain medium to become amplified. A free-electron laser operates similarly but uses

relativistic electrons as the gain medium instead of atoms or molecules.

As the electron beam is driven through a linear accelerator and an undulator structure of alternating dipole magnets, the electrons wiggle and interact with the radiation they produce. The constructive interference causes electrons to group into microbunches that emit coherent light.

The method works well with optical cavities for free-electron laser facilities that operate in the far-IR to visible wavelength range. For x rays, however, suitably reflective mirrors are hard to come by, so constructing an optical cavity is extremely challenging. High-power, tunable x-ray laser light can be generated with a single-pass approach. Self-amplified spontaneous emission (SASE) was first studied in the early 1980s,^{2,3} and it's what most of the handful of XFEL facilities in the world have settled on.

In SASE, the electron beam initially emits photons in a haphazard, incoherent cluster. As the electrons travel through the undulator structure, they gain or lose velocity as they interact with emitted photons that are in or out of phase with them. If the undulator structure is long enough, at least dozens of meters, the electrons can form microbunches and generate intense pulses on the femtosecond time scale. Figure 1 shows several of the undulator modules at the SwissFEL.

Borrowing from laser optics

In 1999, Theodor Hänsch and colleagues demonstrated that a mode-locked laser can generate a train of equally spaced femtosecond pulses in the visible to IR wavelength range.⁴ The advance was achieved by stabilizing the relative phases in the train of pulses. During stabilization, the light waves that form in an optical cavity remain in phase with one

another and constructively interfere in time.

In the frequency domain, the narrow, well-defined spectral peaks of the laser output resemble the teeth of a hair comb. (For more on how optical frequency combs were first produced, see the *PT* story “Glauber, Hall, and Hänsch share the 2005 Nobel Prize in Physics.”)

Frequency combs are critical for synchronizing large astronomical radio-telescope arrays, better understanding quantum communications, and other applications. Frequency combs are also related to high-harmonic generation, which is the idea that underlies the creation of attosecond pulses of light from tabletop sources. (For more about that research, see the 2023 *PT* story “Attosecond pioneers win physics Nobel.”)

By 2008, researchers proposed that the mode-locking technique from laser optics could be implemented in free-electron lasers.⁵ The technique starts with a series of magnetic chicanes. Each chicane is a group of four dipole magnets that slow the electrons with respect to the photons; the delay allows for the production of the axial laser modes that are needed to generate a frequency comb.

Next, the photon emission is periodically modulated by an external laser with a wavelength tuned to 263 nm or 790 nm, both of which match the mode spacing set by the chicanes. The laser, therefore, effectively organizes the random SASE noise into a train of equally spaced pulses of just a few hundred attoseconds each.

Generating coherent light

When the mode-locking theory paper was published in 2008, XFELs weren't yet operational. “Many people thought SASE would not work,” says Prat, “because you need a very high brightness electron beam and

a very precise control of the undulator.” A year later, the first XFEL facility—Stanford University's Linac Coherent Light Source—began operation. After that, researchers spent years focused on generating light pulses on the femtosecond time scale by tweaking the SASE technique to be more effective and increasing the brightness of the x rays.

The goal of creating a mode-locked XFEL proved challenging. In 2024, Prat and colleagues published a paper describing the implementation of magnetic chicanes at the SwissFEL. The chicanes induced equal, periodic delays of a few femtoseconds between the electrons and their radiation. Although the result was encouraging—the researchers succeeded in generating a frequency comb—the structure of the light in the time domain was still random.⁶

For the 2025 paper, Prat and colleagues added an external laser to stabilize the x-ray emission and generate a periodic train of attosecond pulses in the time domain. Prat says that “the true challenge was the temporal measurement.” To prove that the frequency comb exists and measure the train of attosecond pulses, the researchers needed a device capable of resolving the ultrafast time structure of the x-ray beam. Typically, that's done with an RF deflector, which bends the electron beam in the transverse direction and allows for the time profile of the bunch to be measured. But almost all RF deflectors have been limited in resolution to about 1 fs.

To make measurements at sub-femtosecond resolution, Prat and colleagues maximized the power of their RF deflector and almost doubled the width of the electron beam at the deflector. With those upgrades and the modulating laser, Prat and colleagues demonstrated at the SwissFEL a mode-locked frequency comb with a periodic time structure.

For the first time, ultrafast x rays

had equally spaced light pulses. Figure 2 shows plots of the controlled x-ray light in the time and frequency domains.

Coauthor Sergio Carbajo of UCLA says that “we're in the nascent stage of what we can do with mode-locked XFELs.” One possibility is the ultrafast detection of atomic and subatomic particles and their configurations, which could reveal new isotopes.

Another application is measuring inner-core electrons and their dynamics at subangstrom spatial and attosecond temporal resolution. The observations, Carbajo says, could be critical to the study of several research areas, including cellular aging, surface catalysis, and quantum electrodynamics. **PT**

References

1. W. Hu et al., “Demonstration of mode-locked frequency comb for an x-ray free-electron laser,” *Phys. Rev. Lett.* **135**, 265001 (2025).
2. A. M. Kondratenko, E. L. Saldin, “Generation of coherent radiation by a relativistic electron beam in an undulator,” *Part. Accel.* **10**, 207 (1980).
3. R. Bonifacio, C. Pellegrini, L. Narducci, “Collective instabilities and high-gain regime in a free electron laser,” *Opt. Commun.* **50**, 373 (1984).
4. T. Udem et al., “Absolute optical frequency measurement of the cesium D_1 line with a mode-locked laser,” *Phys. Rev. Lett.* **82**, 3568 (1999).
5. N. R. Thompson, B. W. McNeil, “Mode locking in a free-electron laser amplifier,” *Phys. Rev. Lett.* **100**, 203901 (2008).
6. E. Prat et al., “Experimental demonstration of mode-coupled and high-brightness self-amplified spontaneous emission in an x-ray free electron laser,” *Phys. Rev. Lett.* **133**, 205001 (2024).