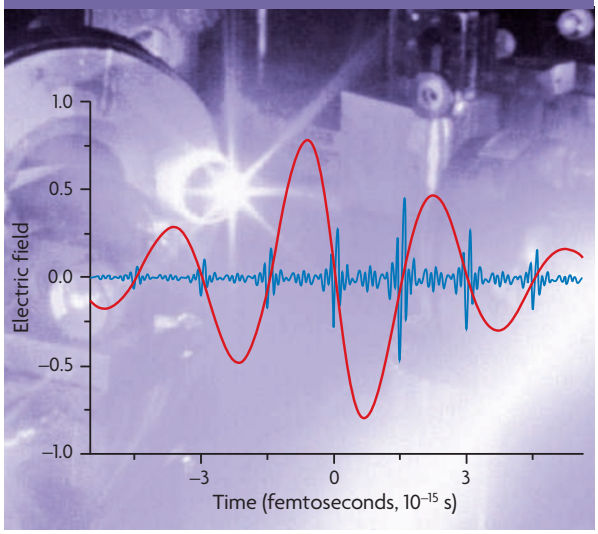
MILESTONE 22

Into the attoworld



The initial femtosecond pulse used to ionize atoms is shown in red, and the train of attosecond pulses of higher-frequency light that it produces is shown in blue. The offset between the peak of the initial pulse and the peak of the attosecond pulse corresponds to the length of time the liberated electron is catching a ride in the oscillating electric field of the femtosecond pulse, which moves it away from and then back to its parent ion.

The new millennium has heralded the arrival of attosecond light pulses, and with it the emergence of a radical new technology that is moving time-resolved spectroscopy and control techniques from the molecular (femtosecond) to the electronic (attosecond) timescale.

In fact, attosecond light pulses were created in the early 1990s, when physicists ionized rare-gas atoms with intense laser pulses to generate energetic radiation alongside the original optical pulse. Theory exploring such 'high-harmonic generation', from Kenneth Kulander and co-workers and from Paul Corkum, resulted in 1993 in a simple model for the process: during each half-cycle, the oscillating electric field of an intense laser pulse will tear electrons from atoms in a gas, accelerate them away and then drive them back to re-collide with their parent ion. In each collision, a short burst of extreme ultraviolet (XUV) photons is created.

Theoretical and experimental groundwork — notably by Anne L'Huillier and colleagues — showed that driving high-harmonic generation with a multi-cycle femtosecond laser should produce attosecond light pulses, which are repeated at twice the laser frequency. Rigorous proof of attosecond pulse trains arrived only in 2001, however, when Pierre Agostini and colleagues encoded the properties of the pulses in photoionized electrons and then measured the characteristics of these so-called photoelectron replicas.

A few months later, Ferenc Krausz and colleagues reported the first individual attosecond pulses, filtered out of pulse trains. The team then perfected the art of steering re-collision electrons, using the electric fields of intense few-cycle laser pulses, with their waveform judiciously adjusted (MILESTONE 16) so that each pulse generates only one reproducible re-collision event and, hence, one reproducible isolated attosecond pulse. Atomic Auger decay and the photoionization of atoms and solids have all been triggered by such isolated attosecond photon pulses, and the ensuing electron dynamics has been probed by the synchronized oscillating electric field of the laser pulse that generated the attosecond trigger.

The ionization process at the heart of high-harmonic generation itself launches electronic and structural changes, with the emitted attosecond electron and photon pulses providing a snapshot of the structure and dynamics of the system at the time of the re-collision. This structural and dynamic information can be retrieved: imaging of molecular structure through re-collision electron diffraction, and the measurement of attosecond proton dynamics and multi-electron dynamics in molecules have all been reported. When more intense attosecond pulses become available, such information could be obtained with ångström spatial resolution and attosecond temporal resolution.

We are only 10 years into the new millennium, but attosecond technology has already established itself. The hope now is that by moving from the mere shaping to the complete engineering of light waves — composed of frequencies from the UV to the infrared — unprecedented control over electron motion will become feasible. This promises access to attosecond pulses of coherent hard X-rays that would revolutionize X-ray laser research. Ultimately, light-wave engeneering should also give access to pulses rivalling the atomic unit of time (~24 as) in duration that would allow us to capture — and even control — the fastest motions outside the atomic core.

Magdalena Helmer, Senior Editor, Nature

ORIGINAL RESEARCH PAPERS Schafer, K. J., Yang, B., DiMauro, L. F. & Kulander, K. C. Above threshold ionization beyond the high harmonic cutoff. *Phys. Rev. Lett.* **70**, 1599–1602 (1993) | Corkum, P. B. A plasma perspective on strong field ionization. *Phys. Rev. Lett.* **71**, 1994–1997 (1993) | Antoine, P., L'Huillier, A. & Lewenstein, M. Attosecond pulse trains using high-order harmonics. *Phys. Rev. Lett.* **77**, 1234–1237 (1996) | Paul, P. M. *et al.* Observation of a train of attosecond pulses from high harmonic generation. *Science* **292**, 1689–1692 (2001) | Hentschel, M. *et al.* Attosecond metrology. *Nature* **414**, 509–513 (2001) | Drescher, M. *et al.* Time-resolved atomic inner-shell spectroscopy. *Nature* **419**, 803–807 (2002) | Baltuska, A. *et al.* Attosecond control of electronic processes by intense light fields. *Nature* **421**, 611–615 (2003) | Niikura, H. *et al.* Probing molecular dynamics with attosecond resolution using correlated wavepacket pairs. *Nature* **421**, 826–829 (2003) | Baker, S. *et al.* Probing proton dynamics in molecules on an attosecond timescale. *Science* **312**, 424–427 (2006) | Uiberacker, M. *et al.* Attosecond real-time observation of electron tunnelling in atoms. *Nature* **446**, 627–632 (2007) | Cavalieri, A. L. *et al.* Attosecond spectroscopy in condensed matter. *Nature* **449**, 1029–1032 (2007) | Meckel, M. *et al.* Laser-induced electron tunneling and diffraction. *Science* **320**, 1478–1482 (2008)
FURTHER READING Agostini, P. & DiMauro, L. F. The physics of attosecond light pulses. *Rep. Prog. Phys.* **67**, 813–855 (2004) | Krausz, F. & Ivanov, M. Attosecond physics. *Rev. Mod. Phys.* **81**, 163–234 (2009)