ATTOSECOND SCIENCE

Electrons on a winning streak

A new optical technique enables electron beam currents to be measured with a femtosecond temporal resolution.

Dave Kielpinski

Optical science has been using slow detectors to image fast phenomena since at least 1879, when Eadweard Muybridge took the first pictures of a horse in mid-gallop using a camera with a fast mechanical shutter. In the twentieth century, the development of cathode ray tube displays gave rise to a new kind of electronic shutter. In such displays, an electron beam (the 'cathode ray') strikes a phosphor screen, generating fluorescence at the striking point. When a rapidly changing electric field is applied to the electron beam, each electron in the beam is deflected by a distance proportional to the field amplitude at its moment of transit. By using high-voltage, fast electronic pulses to create this 'streaking' field, one can achieve a time resolution on the order of 100 fs.

To further improve the time resolution, one might consider using intense laser pulses to generate faster and stronger streaking fields. The problem here is that the optical streaking field oscillates many times during the electron transit, so that the deflection averages away to a small, nearly time-independent value. The attosecond streak camera[1–3] realizes an abrupt transition in the streaking field by using extreme-ultraviolet pulses of attosecond duration to ionize matter inside the streaking laser pulse. As the suddenly freed electrons are 'born into' a particular phase of the streaking field cycle, the electric field during that cycle is not averaged away and the electrons can exchange energy with the field. The temporal resolution of this technique is a small fraction of an optical cycle, being on the order of tens of attoseconds.

Writing in *Nature Photonics*, Friedrich Kirchner and co-workers describe a major step towards an attosecond streak camera for electrons that are already freely propagating as a beam[4]. In their experiment, an electron pulse is created by laser-induced photoemission from a cathode, and the electrons are accelerated to 25 keV. Downstream, the electron pulse and a streaking laser pulse simultaneously strike a thin metal foil. The foil is thick enough to reflect the streaking laser pulse, but thin enough to transmit the electron beam, so that each electron abruptly leaves the streaking field in the middle of an optical cycle (Fig. 1). This abrupt change in the field is analogous to the abrupt appearance of photoelectrons in a conventional attosecond streak camera. Hence, these freely propagating electrons can exchange energy with the optical field.

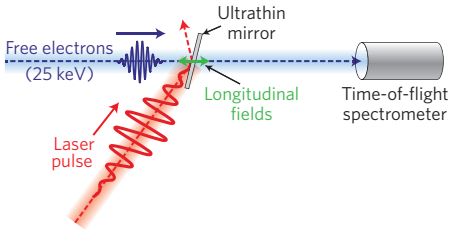

Figure 1 | Schematic of the attosecond streak camera for freely propagating electrons. An electron bunch and a laser pulse simultaneously strike a thin mirror. The laser pulse is reflected by the mirror, whereas the electron bunch passes through the mirror in a time that is short compared with an optical cycle, so that it exchanges energy with the laser electric field. The change in the electron energies is read out downstream by a spectrometer.

To verify the streaking effect, Kirchner *et al.* direct their electron beam to a time-of-flight spectrometer, which measures the energy spectrum of the electrons. As the photocathode source is driven by the same femtosecond laser used to produce the streaking field, both the streaking pulse and the electron pulse are expected to be a few hundred femtoseconds long. Indeed, Kirchner and colleagues find that the electron energy spectrum is significantly perturbed when the delay between the streaking pulse and the electron pulse is shorter than a few hundred femtoseconds.

The duration of Kirchner *et al.*'s electron bunch is much longer than the optical period, so the effect of the streaking field does not depend on the optical phase in their experiments. Instead, a subtler quantum-mechanical effect is observed (Fig. 2). As the de Broglie wave of each electron is extended over many optical waves, different parts of the de Broglie wave gain different amounts of energy. This process may seem exotic, but its outcome can be readily described in terms of signal modulation theory. As is well known, a periodic frequency modulation of light gives rise to optical frequency sidebands with a frequency spacing equal to the inverse of the modulation period. In the same way, the velocity modulation of the electron de Broglie wave creates sidebands in the electron energy spectrum, which are spaced by the optical photon energy.

By studying the dependence of the electron energy modulation on the intensity and polarization of the optical field, Kirchner and co-workers have carefully distinguished their streaking effect from the much more commonly observed ponderomotive effect of light on electrons. Unlike the streaking effect, which can occur in a uniform field, the ponderomotive force is proportional to the local gradient of the optical intensity. Moreover, the electric field polarization sets the direction of acceleration for streaking, whereas it plays no role in the ponderomotive force. Kirchner *et al.*'s experiments confirm that the force on their electron beam is proportional to the magnitude and direction of the electric field — as expected for streaking.

The key experimental issue that Kirchner and colleagues address is the engineering of a streaking interaction for free electrons, which is more significant than the achievement of an attosecond time resolution. Their primary achievement is the overthrowing of the conventional wisdom that a free electron cannot exchange energy directly with the electric field. However, to be widely useful, the technique must be extended to sub-optical-cycle temporal resolutions. Through simulation, Kirchner *et al.* show that this is indeed possible. Few-femtosecond electron bunches streaked by few-cycle optical pulses show a simulated energy shift that tracks the optical electric field. The same simulations reproduce the observed effects when the actual experimental parameters are used.

Kirchner *et al.*'s work points the way to direct and straightforward characterization of electron devices that produce few-femtosecond pulses of electrons. Femtosecond electron pulses are now opening new frontiers in molecular, materials and biological science, with the development of ultrafast electron microscopy, diffraction and crystallography[5]. Electron-based dynamic imaging with a time resolution on the order of a few hundred

femtoseconds has now been achieved in several laboratories. However, many more phenomena await investigation at even shorter timescales, requiring us to understand and improve present ultrafast electron sources. Electron streaking at an attosecond temporal resolution would play a major role in these improvements.

In fact, Kirchner *et al.* apply their technique in just this way, performing a basic experiment to characterize their few-hundred-femtosecond electron source. A key effect that degrades ultrafast electron bunches is the mutual Coulomb repulsion of the electrons — known as the space charge effect. This effect causes an initially short electron bunch to spread out spatially, lengthening the bunch duration. An initially monoenergetic bunch will also spread out in velocity. Because a femtosecond electron bunch is so compact, even a few electrons represent a high charge density and can experience significant space charge effects. In the experiment, Kirchner and co-workers control the number of electrons in each bunch by varying the optical intensity on the photocathode. Measuring the charge received by the spectrometer enables the number of electrons in a bunch to be calibrated. As soon as each bunch contains more than one electron, optical streaking detects an increased spread in velocity. When the average number of electrons reaches 18 per bunch, the bunch duration is increased by 50%. The streaking measurement is clearly a sensitive diagnostic for the quality of the electron bunch.

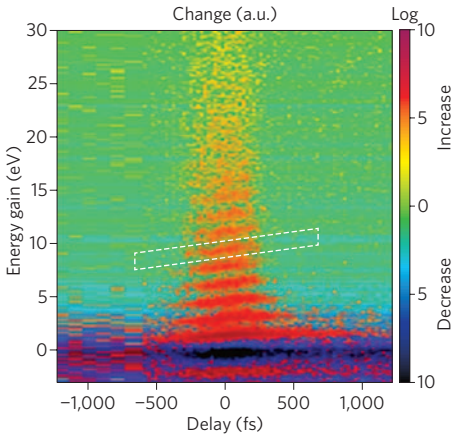

Figure 2 | Energy spectrum of streaked electrons. The electrons gain energy from the laser field in units of one photon energy (about 1.5 eV) owing to the modulation effect discussed in the text. Energy exchange occurs only when the electron bunch and the laser pulse are temporally overlapped.

Looking even further ahead, one could imagine scaling up the streaking energy in Kirchner *et al.*'s technique to provide *in situ* diagnostics for high-energy electron accelerators. Some of today's most impressive photonics experiments rely on free-electron lasers, which generate light through a self-consistent interaction of accelerated electrons and the laser field they generate. These ultrafast electron–photon dynamics also give rise to instabilities that can seriously degrade free-electron laser performance. By giving us the ability to sample the electron dynamics of free-electron lasers, an attosecond streak camera for electrons could indicate ways to tweak some of the world's biggest science experiments. ❐

Dave Kielpinski is Director of the Australian Attosecond Science Facility at the Centre for Quantum Dynamics, Griffith University, Nathan, Queensland 4111, Australia.
e-mail: d.kielpinski@griffith.edu.au

References

1. Itatani, J. *et al. Phys. Rev. Lett.* **88,** 173903 (2002).
2. Kienberger, R. *et al. Nature* **427,** 817–821 (2004).
3. Eckle, P. *et al. Nature Phys.* **4,** 565–570 (2008).
4. Kirchner, F. O., Gliserin, A., Krausz, F. & Baum, P. *Nature Photon.* **8,** 52–57 (2014).
5. Zewail, A. H. *Science* **328,** 187–193 (2010).

METAMATERIALS

Metamaterials go Gattaca

DNA tethers guide the self-assembly of colloidal metal nanoparticles into three-dimensional optical metamaterials. The observation of epsilon-near-zero behaviour in nanoparticle-based materials indicates that bottom-up assembly may be a viable solution to current challenges in the manufacture of metamaterials.

Andrea R. Tao

In recent years, optical metamaterials have been heralded for their ability to route, deflect and manipulate light. Engineered to display unusual optical behaviours not typically found in nature, optical metamaterials have captured the attention of both researchers and the general public; the latter are excited mostly about their potential function in cloaking devices[1]. Invisibility cloaks, popularized by fantasy fiction such as Star Trek and Harry Potter, could in principle be realized by optical metamaterials that bend light around an object so that it appears transparent. However, imagine what would happen if only a small fraction of a Klingon warship could be disguised, or if Harry Potter's invisibility cloak were only large enough to cover the tip of his fingernail. The ability to fabricate optical metamaterial structures over large, macroscopic areas is one of the problems currently facing real-world applications of these light-manipulating materials.

Fabrication difficulties stem from the multiscale nature of optical metamaterials. They are composed of individual subunits, sometimes called 'meta-atoms', that are significantly smaller than the wavelength of light[2]. Hence, for visible wavelengths, meta-atoms are inherently nanoscale entities. They are typically composed of noble metals such as Ag or Au, and they have diverse shapes, ranging from nanorods to split rings to bow ties. Metamaterials are constructed by arranging these nanostructures into two- or three-dimensional arrays with a period sufficiently small compared to the operational wavelength. To achieve a homogeneous electromagnetic response over the entire array, long-range order must be achieved at the microscale and beyond. Few fabrication tools are able to meet these stringent size and geometry requirements. Although optical metamaterials have been successfully patterned using 'top-down' fabrication methods such as electron-beam writing or photolithography, these methods can be time consuming and costly, and are limited to wafer-scale production.

Researchers are now harnessing the self-assembling ability of DNA to construct optical metamaterials using a 'bottom-up' method that could provide a solution to the issues encountered in top-down fabrication. Writing in *Advanced Materials*, Kaylie Young and colleagues from a team led by George Schatz and Chad Mirkin at Northwestern University in the USA present evidence that DNA linkers can be used to guide the spontaneous assembly of colloidal