

smaller than the electron thermal-energy density. However, the kinetic theory can be further generalized for the high-frequency elliptically polarized extraordinary electromagnetic wave, propagating transverse to the external magnetic field, with the spin-modified anisotropic Fermi–Dirac distribution function.

It is worth considering the implications of collective interactions in dense quantum plasmas that have quantum and spin forces. Collective interactions in quantum plasmas are truly interdisciplinary — they combine quantum mechanics, plasma physics, fluid dynamics, condensed matter and statistical physics. The potential for

using spin in practical applications has already been realized in a number of different fields (the award of the 2007 Nobel Prize in Physics to Albert Fert and Peter Grünberg for their work on giant magnetoresistance is just one example). It is hoped that the field of quantum plasmas will also find practical applications in the production of localized X-ray sources, quantum free-electron lasers<sup>8,9</sup> and plasma-assisted microelectronic components. Also, a better understanding of the role of electron spin in quantum plasmas may aid the development of intense-laser-beam compression for controlled nuclear fusion.

Padma Kant Shukla is in the Faculty of Physics and Astronomy, Ruhr University Bochum, D-44780 Bochum, Germany.  
e-mail: ps@tp4.rub.de

#### References

1. Brodin, G., Marklund, M., Zamanian, J., Ericsson, A. & Mana, P. L. *Phys. Rev. Lett.* **101**, 245002 (2008).
2. Harding, A. K. & Lai, D. *Rep. Prog. Phys.* **69**, 2631–2708 (2006).
3. Glenzer, S. H. *et al. Phys. Rev. Lett.* **98**, 065002 (2007).
4. Gardner, C. L. & Ringhofer, C. *Phys. Rev. E* **53**, 157–167 (1996).
5. Manfredi, G. *Fields Inst. Commun.* **46**, 263–287 (2005).
6. Shukla, P. K. & Eliasson, B. *Phys. Rev. Lett.* **96**, 245001 (2006).
7. Brodin, G. & Marklund, M. *Phys. Rev. E* **76**, 055403(R) (2007).
8. Piovella, N. *et al. Phys. Rev. Lett.* **100**, 044801 (2008).
9. Serbeto, A., Mendonça, J. T., Tsui, K. H. & Bonifacio, R. *Phys. Plasmas* **15**, 013110 (2008).

## ULTRAFAST SCIENCE

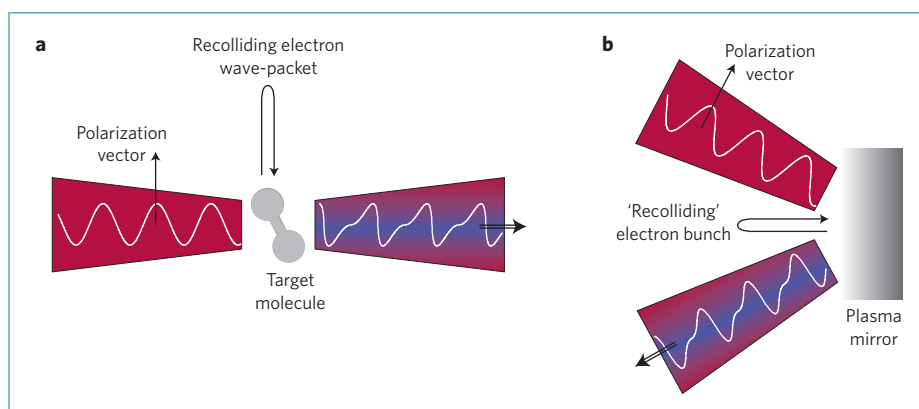
# Attosecond plasma optics

Using dense plasmas instead of atomic or molecular gases could enable the generation of attosecond light pulses with higher energy, shorter durations and more energetic photons.

Fabien Quéré

Ultrashort light pulses can temporally resolve the evolution of dynamical systems such as excited molecules. Resolving faster and faster processes obviously requires shorter and shorter light pulses. Pulses with durations in the attosecond range ( $1 \text{ as} = 10^{-18} \text{ s}$ ) — short enough to start resolving the dynamics of electrons in matter — can be generated and measured<sup>1</sup> by exploiting laser–atom or laser–molecule interactions. However, applications of these pulses have been hindered by limits to pulse and photon energies. On page 124 of this issue<sup>2</sup>, Yutaka Nomura and colleagues demonstrate experimentally a new kind of attosecond light source that might eventually push these limits by taking advantage of ultrahigh-intensity laser–plasma interactions.

For more than twenty years, laser technology has exploited the chirped-pulse amplification technique to produce intense light pulses that only last a few tens of femtoseconds. Fifteen years ago, these pulses were identified theoretically as a promising tool for obtaining even shorter pulses — potentially of attosecond duration<sup>3,4</sup>. The basic idea is to make such a pulse interact with a system at high intensity, so that its waveform is temporally distorted by the nonlinear response of the system. Because this distortion generally has the same periodicity as the driving laser, the spectrum of the resulting light



**Figure 1** | Working in analogy. **a**, Laser-driven electron-ion recollision can create attosecond pulses. An input laser (red wave) frees an electron wave-packet from a target atom or molecule. An attosecond light pulse is generated when part of this wave-packet returns to the ion. **b**, Excitation lasers of much higher intensity create a plasma. Nomura *et al.*<sup>2</sup> show experimentally that this can generate attosecond pulses in much the same way. At even higher intensities, the Doppler effect induced as the laser beam reflects on the plasma has the potential to generate attosecond pulses with a shorter duration and with higher energy photons.

field consists of a comb of harmonics of the incident frequency. For a severe distortion, these harmonics reach very high orders, thus leading to a very broad spectrum — a prerequisite for very short pulses. If this distortion is temporally localized within each laser optical cycle — or, equivalently, if the harmonics making up the spectrum are approximately in phase — a train of sub-laser-cycle pulses can then be obtained

simply by filtering out the fundamental frequency and selecting a group of harmonics in the spectrum.

Distortions of the laser-field waveform have so far been achieved by exploiting a process called laser-driven electron–ion recollision<sup>1</sup>. Electron wavepackets are periodically freed from a target atom or molecule by tunnel ionization. Part of these wavepackets return to their parent

ion after having gained energy during their excursion in the continuum. This energy can be released in the form of an attosecond light pulse, emitted as the recolliding wavepacket overlaps and interferes with the remaining population in the initial ground state, thus creating a high-frequency dipole (Fig. 1a).

The maximum frequency generated in this interaction, and hence the shortest pulse duration that can potentially be obtained, are directly related to the maximum energy of the free electrons. This in turn is determined by the laser intensity. However, this delicate recollision process does not survive laser intensities that are too high. The fundamental reason for this is that at intensities approaching  $10^{18}$  W cm<sup>-2</sup> for a near-infrared field, the motion of electrons in the field becomes relativistic. The effect of the laser magnetic field can then no longer be neglected, and the associated force induces a drift of the electrons along the direction of laser propagation, preventing them from recolliding with their parent ions. Attosecond light sources based on laser-driven electron-ion recollision are therefore intrinsically restricted to intensities much lower than those produced by modern ultrafast, ultra-intense lasers, which commonly exceed this relativistic threshold by several orders of magnitude.

At these so-called relativistic intensities, all targets are rapidly ionized by the leading edge of the laser pulse, creating a plasma. These are generally considered as unstable and uncontrollable media — unlikely to produce coherent light. However, this is not necessarily the case when ultrashort laser pulses are involved. In particular, when such a pulse hits an optically polished surface it generates a dense reflective plasma that only has time to expand by a small fraction of the light wavelength. Thus, it behaves as a highly flat mirror — a plasma mirror. Such plasma mirrors can be used to generate collimated beams of very-high-order harmonics, even at the highest laser intensities<sup>5,6</sup>.

According to the theory, these harmonics are associated, in the time

domain, with trains of attosecond pulses, like those generated in gases. But this prediction had not been confirmed experimentally — this is precisely what Nomura *et al.*<sup>2</sup> have now done by measuring the nonlinear intensity autocorrelation function of a superposition of several of these harmonics. Because it is an extreme ultraviolet beam, the difficulty was finding a suitable nonlinear effect. Nomura and co-workers' technique relies on two-photon ionization of helium atoms, an approach already demonstrated with gas sources. Its implementation using plasma mirrors, however, is a tour de force. This is particularly the case because of the lower repetition rate required to refresh the target between each shot. Because of large signal fluctuations, these results do not yet provide an accurate temporal characterization of the generated pulses, but by setting an upper limit on their duration, they show that harmonics generated in this way can indeed have a suitable phase relationship for attosecond pulse generation.

The physics of the process used by Nomura *et al.* to produce these pulses — referred to as coherent wake emission<sup>5,7</sup> (Fig. 1b) — has some strong qualitative analogies with electron-ion recollision in gases. Within each laser cycle, electrons at the sharp plasma surface are pulled out into the vacuum by the laser electric field, before being pushed back towards the target when this field changes sign. This creates extremely short electron bunches, which 'recollide' with the dense plasma where they trigger high-frequency collective electron oscillations in their wake. These oscillations subsequently emit attosecond light pulses.

The maximum frequency of these oscillations is limited by the plasma properties<sup>5,7</sup>, and therefore this 'electron-plasma recollision' process is not yet suitable for obtaining higher photon energies or shorter attosecond pulses than is already available from gas targets. Reaching this goal will require increasing the laser intensity even further, sufficiently beyond the relativistic limit,

and truly exploiting the relativistic character of the resulting interaction. In this regime, the plasma mirror surface oscillates at the laser frequency with a peak velocity approaching the speed of light. This oscillating mirror induces a large periodic Doppler shift on the reflected light, thus potentially leading to extremely high harmonic orders. Collimated light beams with photon energies of several keV have already been obtained in this way using one of the most intense lasers existing today<sup>6,8</sup>. Measuring the phase relationship of the extreme harmonics produced by such a source remains one of the challenges of attosecond metrology: the technique used by Nomura *et al.*<sup>2</sup> does not apply at these higher frequencies, which can ionize helium with a single photon.

In a more general context, many schemes have now been demonstrated experimentally that put plasmas to work as high-intensity optical elements. Such 'plasma optics' can, for instance, be exploited to further amplify<sup>9</sup> ultra-intense lasers and improve their temporal contrast<sup>5</sup>, or to tailor or temporally compress<sup>10</sup> ultrashort pulses down to the few-femtosecond range. By demonstrating the feasibility of a plasma-based attosecond light source, the work of Nomura *et al.* has added an important functionality to these fascinating optical elements. □

Fabien Quéré is at CEA, IRAMIS, Service des Photons Atomes et Molécules, F-91191 Gif-sur-Yvette, France.  
e-mail: fabien.queré@cea.fr

## References

1. Corkum, P. B. & Krausz, F. *Nature Phys.* **3**, 381–387 (2007).
2. Nomura, Y. *et al. Nature Phys.* **5**, 124–128 (2009).
3. Hänsch, T. W. *Opt. Commun.* **80**, 71–75 (1990).
4. Farkas, G. & Toth, C. *Phys. Lett. A* **168**, 447–450 (1992).
5. Taury C. *et al. Nature Phys.* **3**, 424–429 (2007).
6. Dromey, B. *et al. Nature Phys.* **2**, 456–459 (2006).
7. Quéré, F. *et al. Phys. Rev. Lett.* **96**, 125004 (2006).
8. Dromey, B. *et al. Phys. Rev. Lett.* **99**, 085001 (2007).
9. Ren, J., Cheng, W., Li, S. & Suckewer, S. *Nature Phys.* **3**, 732–736 (2007).
10. Faure J. *et al. Phys. Rev. Lett.* **95**, 205003 (2005).