

LASER WAKEFIELDS

Bringing accelerators down to size

Laser-based accelerator technology has been given a boost thanks to researchers based in Korea, Japan and the USA. Their latest research could lead the way towards compact accelerators that can deliver brilliant electron and X-ray beams.

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The particle accelerator is one of the most successful pieces of apparatus born from twentieth-century science. It has contributed to the discovery of the most fundamental building blocks of matter and helped us to uncover the fascinating physical (and sometimes biological) nature of the world around us¹. Despite this grand success, conventional accelerators are hitting practical limits related to their sheer size and the cost of building them, and this could jeopardize the future of accelerator-based research. Twenty-first century scientists need a new approach, and the laser could provide this. On page 571 of this issue, Nasr Hafz and colleagues present results from one of the smallest and simplest giga-electronvolt-class laser-based accelerators developed so far².

Accelerator technology has evolved a great deal over the past century, leading to exponential increases in the energy to which particles can be accelerated. Conventional particle accelerators accelerate electrons (or other charged particles) to giga-electronvolt energies using radiofrequency (RF) electromagnetic waves, which have wavelengths that typically lie in the centimetre range³. However, with lengths on the order of kilometres and billion-dollar price tags, the sheer size and cost of these RF-cavity-based accelerators is starting to become problematic.

Laser beams have micrometre-scale wavelengths and can therefore be used as the basis for much more compact accelerators than those based on RF fields (Fig. 1). This, coupled with the recent achievement of ultrashort, high-powered laser beams, offers a

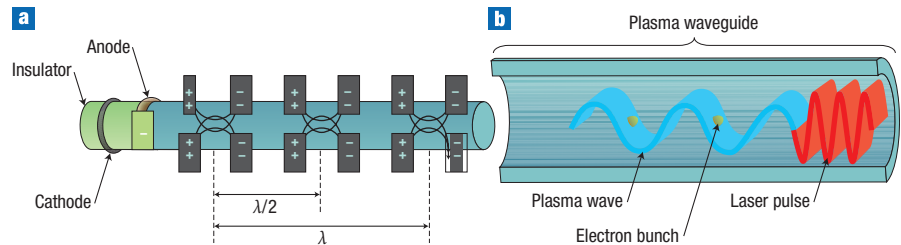


Figure 1 A comparison of accelerators. **a**, The conventional RF accelerator and **b**, a laser-driven accelerator. Even though the structures of the two resulting accelerating fields are similar, their dimensions (and the underlying physical mechanisms) differ widely. The dimensions of the interaction region of the RF machine are typically 10 cm, whereas those of laser-based devices are 10^{-2} cm. In **a** the RF waves are generated by an external metallic circuit, whereas in **b** the plasma sustains waves as a result of the driving laser pulse.

tremendous opportunity for laser technology to transform the accelerator landscape. However, because the driving wavelength of acceleration is so much smaller than that of RF fields, laser-based accelerators require an extremely precise level of control over the process. This remains one of the pressing problems that need to be solved to render laser acceleration practical.

The work by Nasr Hafz and colleagues constitutes the first stable generation of high-energy electron bunches², with energies of hundreds of megaelectronvolts. They use an established technique known as laser-wakefield acceleration⁴ (LWFA), which involves passing a very brief laser pulse through a plasma (a low-density gas in which individual atoms are ionized). As the light pulse travels through the plasma, its electric field causes the electrons and the atomic nuclei within the plasma to separate. Macroscopically it is as if a 'bubble' of charge is moving through the plasma at nearly the speed of light, and the pulse leaves in its wake a small area of very strong electric field. This wakefield can be used to accelerate charged particles to very high energies over very short distances, potentially offering field gradients unmatched by conventional RF cavities.

In practice, Hafz *et al.* use a table-top Ti:sapphire laser system that delivers 35-fs laser pulses at powers of 27 TW, 37 TW and 50 TW. The laser beam is focused onto 4-mm- and 10-mm-long helium gas-jet plasmas. Obtaining a high-quality electron beam using the LWFA mechanism requires careful optimization of various laser and plasma parameters, including the laser focal-spot size, plasma density, interaction length and laser pulse duration. Hafz and co-workers find that the energy of the accelerated electrons increases in direct proportion to the laser intensity. They also find that it increases with reduced plasma density, which is one of the cardinal signatures of LWFA. With careful optimization the authors are able to generate nearly monoenergetic electron bunches with giga-electronvolt-scale energies in a stable and repeatable manner, over length scales of just half a centimetre.

Importantly, the electron beams are generated without resorting to the use of externally imposed plasma channels, which have been adopted for many other recent experiments. Instead, the simpler design of Hafz *et al.* takes advantage of the stable self-focusing offered by the combination of a very high-powered laser beam propagating through a supersonic gas jet.

It may be envisaged that further technical improvements could lead to applications such as a table-top X-ray free-electron laser injector⁵. Furthermore, by combining the laser wakefield with another laser pulse, it may be possible to access physical regimes and parameters that may otherwise be inaccessible. The wakefield travels at close to the speed of light and acts as a high-density reflector or 'mirror' — if a second laser pulse enters the system, travelling in the opposite direction to the original driving pulse, the wakefield will reflect it. As such it may offer a new approach towards generating coherent, intense attosecond X-rays⁶ (Fig. 2).

Only with stable beam generation can LWFA move towards becoming a practical solution for accelerator technology, and as such the work

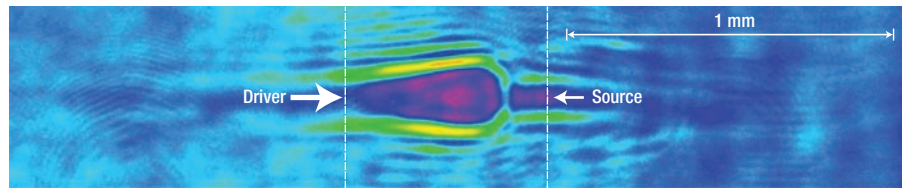


Figure 2 Use of a laser wakefield to generate intense, coherent attosecond X-rays. The wakefield is driven by the first laser (driver, left), as illustrated in Fig. 1b. A second laser incident from the right (source, right) is then allowed to collide with the first driving laser beam. This interaction has been shown to produce coherent attosecond X-rays recoiling from the head of the first driver laser in the plasma⁶. Reprinted with permission from ref. 6.

presented here represents an important milestone. Moreover, it demonstrates a much needed confirmation of the strong dependence of LWFA on the laser and plasma parameters, namely the laser power and plasma density.

References

1. Lawrence, E. O. & Livingston, M. S. *Phys. Rev.* **38**, 834 (1931).
2. Hafz, N. *et al. Nature Photon.* **2**, 571–577 (2008).
3. Chao, A. & Tigner, M. *Handbook of Accelerator Physics and Engineering* (World Scientific, Singapore, 1999).
4. Tajima, T. & Dawson, J. M. *Phys. Rev. Lett.* **43**, 267–270 (1979).
5. Nakajima, K. *Nature Phys.* **4**, 92–93 (2008).
6. Kando, M. *et al. Phys. Rev. Lett.* **99**, 135001 (2007).

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Bright white light on demand

Supercontinua — bright broadband light pulses — are helping a plethora of applications in imaging, sensing and defence. *Nature Photonics* reports from Sydney, Australia.

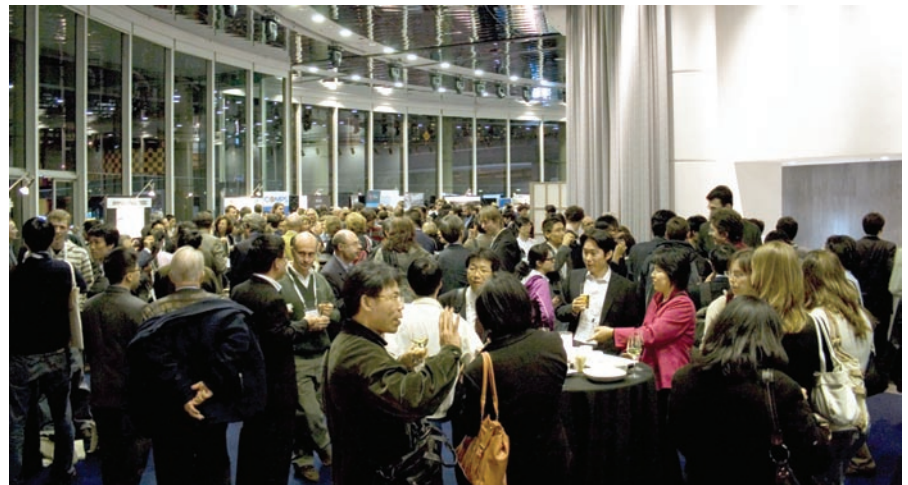
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The generation of supercontinuum light in microstructured optical fibres in the year 2000 by Jinendra Rana and co-workers from Bell Labs (*Opt. Lett.* **25**, 25–27; 2000) was considered by many a milestone in nonlinear optics and so far the paper has received over 740 citations. Certainly, research activity in the area is still intense, as *Nature Photonics* found out at recent co-located conferences in Sydney, Australia — the 21st Congress of the International Commission for Optics (ICO-21), the 13th Optoelectronics and Communications Conference (OECC) and the 33rd Australian Conference on Optical Fibre Technology (ACOFT).

From 7 to 10 July 2008, researchers from around the world flocked to Sydney to listen to the latest research progress in optics. The triennial ICO-21 provided an international forum to present exciting results in a diverse range



Food for thought — the conference reception is always an inspiring place for exchanging ideas.

of topics in optics, such as biophotonics, optical storage, X-ray optics, atom optics and photonic metamaterials. At the same time, the OECC and ACOFT conferences, both annual events but held jointly this year together with ICO-21, focused on significant

progress in research, development and applications in optical communication systems and optoelectronics. The trio attracted more than 600 attendees and altogether there were 10 plenary talks, 63 invited talks, 402 oral presentations and 178 poster presentations.