which have oppositely aligned electron spins, to break apart, because a phenomenon known as the Zeeman effect causes the spins to point in the same direction (Fig. 1). By contrast, spin-triplet Cooper pairs that have electron spins aligned in a single direction parallel to the field are compatible with such a spin effect and are not bound by the Pauli limit. The in-plane critical field strength measured by Cao *et al.* in MATTG is two to three times the Pauli limit and is therefore considered evidence of spin-triplet superconductivity.

Cao and colleagues also detected a second superconducting phase that exists at even higher in-plane magnetic field strengths than does the first one, persisting above 10 tesla. On the basis of the resistance behaviour of MATTG when the field strength is increased compared with when it is decreased, the authors suggest that the two phases might be connected by a type of phase transition called a first-order phase transition. Such 're-entrant' superconductivity is reminiscent of that observed in some 3D spin-triplet superconductors, such as uranium rhodium germanium[9] and uranium telluride[10], and in the spin-triplet superfluid (zero-viscosity liquid) helium-3 (ref. 11). This similarity might provide hints about the nature of the two superconducting phases in MATTG.

The evidence reported by the authors for quasi-2D spin-triplet superconductivity in MATTG paves the way for unconventional superconductors that can be manipulated experimentally. High in-plane critical field strengths can typically develop in various ways other than in spin-triplet Cooper pairs. But these sources are unlikely to occur in MATTG owing to the negligible coupling between the spin and orbital angular momentum of electrons in graphene. Nevertheless, further measurements are needed to show whether the orbital structure of the Cooper pairs in MATTG is consistent with spin-triplet superconductivity.

Crucially, being spin-triplet does not imply that the observed superconductivity would be useful for topological quantum computation. Future work needs to study the topological properties of the superconductivity. For instance, researchers should determine whether it breaks time-reversal symmetry — an indication of possible chiral *p*-wave superconductivity. They should also look for direct evidence of zero-energy states in vortex cores, which would signal the presence of Majorana zero modes. The understanding gained from such studies could help physicists to develop promising platforms for topological quantum computation.

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Optical physics

A step closer to compact X-ray lasers

Luca Giannessi

Light sources known as free-electron lasers can produce intense X-ray radiation for a wide range of applications. The process usually needs huge particle accelerators, but an experiment shows how to overcome this limitation. **See p.516**

The advent of new tools for investigating our world has always led to discoveries. Light sources called free-electron lasers (FELs) are examples of such tools. FELs can produce radiation in a broad array of wavelengths, including the extreme-ultraviolet[1] and X-ray[2] ranges, and can generate ultrashort pulses, at femtosecond[3] (10^{-15} s) or even attosecond[4] (10^{-18} s) timescales. At these spatial and temporal scales, there is little difference between biology, chemistry and physics, and FELs have revolutionized all three disciplines. FELs have enabled matter to be frozen in place and observed at the microscopic level, allowing scientists to resolve the motion of atoms or electrons, control chemical reactions and follow the dynamics of chemical bonds or energy-transfer processes. On page 516, Wang *et al.*[5] report a milestone in the development of compact X-ray FELs.

FELs generate radiation from a high-energy electron beam traversing an undulator, a long array of magnets of alternating polarity (Fig. 1). The undulator causes the electrons to oscillate transversely, and the oscillating beam emits light at a wavelength proportional to the spatial period of the oscillation divided by the square of the beam energy. Therefore, the beam energy is one of the main parameters used to tune the output wavelength of the FEL light.

Energy is efficiently transferred from the electron beam to the laser light if the beam has a high-enough current and is sufficiently monochromatic — that is, if the electrons have similar energies, follow similar trajectories and emit light with similar properties. When such a high-brightness beam interacts with the electromagnetic field of the light generated inside the undulator, the beam transfers part of its kinetic energy to the laser light. As a result, the light is amplified by several orders of magnitude while propagating through the undulator. FELs therefore require high-energy and high-brightness electron beams to generate intense laser light at short wavelengths, such as extreme-ultraviolet or X-ray wavelengths.

Electron beams are normally accelerated by injecting the electrons into a long sequence of hollow metal structures called resonant cavities, where the particles progressively gain energy by 'surfing' an electromagnetic wave. The final energy depends on the amplitude of the wave (that is, the strength of the accelerating field) and the length of the accelerator. Present technology limits the field strength in accelerating cavities to a few tens of megavolts per metre. Therefore, an accelerator several hundred metres to a few kilometres in length is required to reach the beam energy of several gigaelectronvolts (GeV) needed by an X-ray FEL. High-energy electron beams therefore tend to be available only at large accelerator facilities, limiting the number of scientists who can access FELs or advanced investigation tools needing high-energy electrons.

This restriction is one of the motivations behind the search for alternative ways of producing strong accelerating fields to reduce the footprint and costs associated with accelerators. One promising idea involves exciting an electromagnetic wave in a plasma — an ionized gas — using the high power density of optical lasers[6]. Accelerating fields that are thousands of times stronger than those in conventional accelerating cavities can be generated in a plasma. With such fields, the electron-beam energy required by an X-ray FEL could be reached in a few tens of

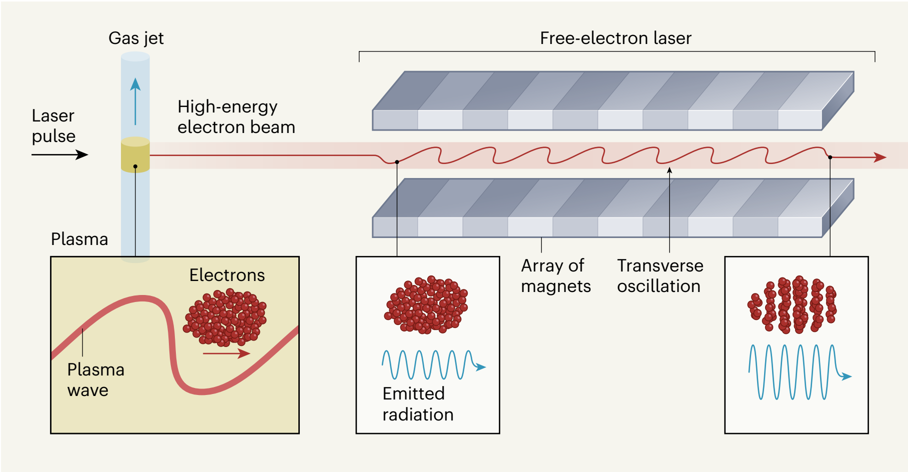

Figure 1 | A free-electron laser driven by electrons accelerated in a laser-excited plasma wave. Wang *et al.*[5] fired a laser pulse at a gas jet to produce an ionized gas called a plasma. Electrons in the plasma were accelerated as they 'surfed' an electromagnetic wave known as a plasma wave. The authors directed the resulting high-energy electron beam into a light source called a free-electron laser, which comprises an array of magnets of alternating polarity (indicated by the two shades of grey). These magnets caused the beam to oscillate transversely and emit radiation. Initially, the electrons were randomly distributed and generated low-amplitude light. However, when leaving the magnets, the electrons were bunched into regions about the size of the radiation wavelength and emitted high-amplitude light. This demonstration shows that high-energy electron beams for free-electron lasers can be produced in compact set-ups (Wang and colleagues' set-up was about 12 metres long), rather than requiring particle accelerators several hundred metres to a few kilometres in length.

centimetres instead of a few kilometres.

A plasma wave can be excited by a laser pulse or the electron beam itself. Indeed, it is possible to shape the beam current in such a way that one part of the beam excites the wave, which then accelerates a second part of the same beam. Both approaches were explored previously, and enormous field strengths, similar to those predicted[6], were demonstrated[7,8]. But one of the missing ingredients to drive FELs successfully using these beams concerned the beam quality. Specifically, the energy difference between the electrons was too large, and the emitted radiation behaved as though generated by randomly distributed electrons, rather than by electrons bunched into regions about the size of the radiation wavelength, for which the light amplification is several orders of magnitude larger.

Various teams are concentrating on finding the conditions for stable and reliable acceleration of an electron beam that is sufficiently monochromatic for FEL amplification[9]. Wang *et al.* have demonstrated, for the first time, that this amplification can be achieved using electrons accelerated in a laser-excited plasma wave (Fig. 1). The authors produced the plasma wave by firing a laser pulse at a gas jet that had a diameter of only 6 mm. By manipulating the density of the gas, they shaped the plasma density along the acceleration direction and loaded electrons from the plasma into the accelerating phase of the plasma wave. This technique ensured that the generated beam, with an energy of about 0.5 GeV, was of sufficient quality to amplify radiation in an extreme-ultraviolet FEL at an output wavelength of 27 nm.

The performance of Wang and colleagues' FEL cannot yet match that available in existing FEL facilities that produce radiation at similar wavelengths[1,10]. However, this laser represents a technological breakthrough, and its stability, reproducibility and efficiency in transferring energy from the electron beam to the radiation will probably be improved in the future. The authors' experiment paves the way for FELs driven by extremely compact accelerators[11], which could be managed in university-scale facilities. One of the requirements for a new tool that will favour discoveries is its availability, and this work promises to increase the availability of FEL light in the world.

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Biomechanics

Fluid flow through Venus's flower basket

Laura A. Miller

Sophisticated numerical simulations reveal that the beautiful structure of a sponge known as Venus's flower basket reduces hydrodynamic drag, and probably aids the capture of food particles, as well as sperm for sexual reproduction. **See p.537**

The deep-sea sponge *Euplectella aspergillum*, also known as Venus's flower basket, is celebrated for its intricate glass skeleton. This structure provides remarkable mechanical support and has inspired a generation of strong, lightweight bridges and skyscrapers[1]. Water is continuously drawn into and out of the sponge's central body cavity through pores, to filter food particles and exchange gases. Although the mechanical properties of the sponge's skeleton are well documented, little is known about the detailed fluid flows around and through the organism. On page 537, Falcucci *et al.*[2] use state-of-the-art fluid-dynamics simulations to resolve these flows. Their results show that the sponge's structural elements reduce the impact of hydrodynamic forces on the organism and generate internal circulation patterns that might be used for feeding and sexual reproduction.

The skeleton of *E. aspergillum* consists of a regular square lattice that is diagonally reinforced and forms scaffolding for the sponge's hollow cylindrical body[3] (Fig. 1). In addition, external ridges spiral around