COMPACT X-RAY SOURCES

Towards a table-top free-electron laser

Synchrotron radiation generated using an electron beam from a laser-driven accelerator opens the possibility of building an X-ray free-electron laser hundreds of times smaller than conventional facilities currently under construction.

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Synchrotron radiation sources have become an indispensable tool in a wide range of disciplines, including physics, biology, materials science, chemistry and medicine. The reason they are so useful is the high intensity of X-rays they produce — generated when the path of a beam of electrons moving at relativistic speeds is bent by a periodic magnetic field — in comparison with other X-ray sources. Such utility is expected to grow still further with the development of X-ray free-electron lasers (FELs) — devices that operate on a similar principle to synchrotrons but which produce X-rays in intense, coherent, femtosecond bursts, enabling the dynamics of chemical reactions, materials and biomolecular systems to be studied with unprecedented spatial and temporal resolution[1]. Several X-ray FEL facilities are currently under construction[2–4], at a cost of the order of US$1 billion each; the particle accelerators that produce the multi-GeV electron beams on which their operation relies span many kilometres in length. But on page 130 of this issue[5], Schlenvoigt and colleagues describe an approach that could substantially reduce both the size and cost of synchrotron and FEL X-ray sources, through the use of electron beams produced by a laser-driven particle accelerator[6].

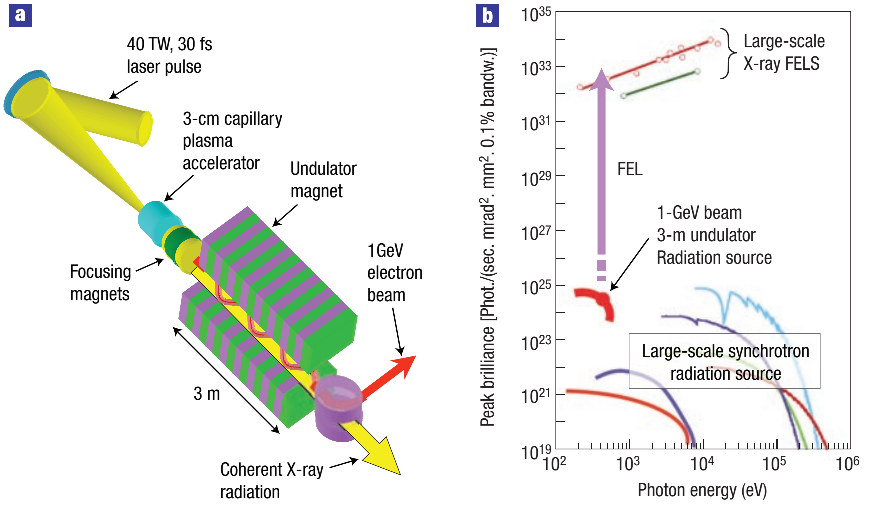

Figure 1 The path to X-rays on a table top. **a**, By combining the ability to produce 1-GeV electron beams from a 3-cm-long capillary laser wakefield accelerator recently demonstrated by Leemans *et al.*[7] with the synchrotron radiation scheme demonstrated by Schlenvoigt *et al.*[5], a compact, high-brilliance source of coherent X-rays could soon become a reality. **b**, Peak brilliance of undulator synchrotron radiation sources as a function of photon energy. Data from ref. 3. Taking the beam parameters reported by Leemans *et al.* (energy of 1 GeV, and an electron bunch length and charge of 10 fs and 30 pC), a high-brilliance source comparable to existing large-scale synchrotron radiation should be readily achievable. In the FEL regime, such radiation could be amplified by many orders of magnitude, to levels of brilliance similar to kilometre-scale FELs[2–4] currently under construction.

Although still in their infancy, great progress has been made in the development of so-called laser-wakefield particle accelerators. These devices use the immense electric fields produced at the focus of modern ultra-high-intensity lasers to accelerate electrons, protons and ions over distances of just centimetres — thousands of times shorter than a conventional particle accelerator. In their set-up, Schlenvoigt *et al.* focus the light from a 5-TW laser pulse into a 2-mm-wide gas jet. The interaction of the laser with the jet produces a beam of electrons with a peak energy of between 55–75 MeV. Directing this beam into a 1-m-long undulator — which consists of a series of alternating magnets — causes its electrons to wiggle back and forth, transverse to the beam direction, producing light at the red end of the visible spectrum (with wavelength in the range of 950–550 nm). The authors therefore provide the first demonstration of the production of resonant-like synchrotron radiation from a laser-generated electron beam. The results of several runs of their experiment show that the emission wavelength scales with beam energy just as theory predicts, suggesting that the generation of much shorter wavelengths by this approach should be relatively straightforward. By extending the length of the undulator to 3 m, and feeding it with a more energetic beam — such as the 1-GeV, 30-pC beams recently demonstrated in a 3-cm capillary laser-plasma accelerator[7] (see Fig. 1a) — it should soon be possible to reach 3 nm in the soft-X-ray range, at a peak brilliance comparable to that of even the largest modern synchrotron radiation sources.

Once the feasibility of a laser-driven soft-X-ray source is achieved, the next step will be to extend this approach to the more ambitious task of constructing an FEL. X-ray FELs rely on a self-amplification of spontaneous emission (SASE)[8], where coherent radiation builds up in a single pass through the interaction of spontaneously emitted (incoherent) undulator radiation with an electron beam. As a beam of electrons passes through an undulator, the interaction of the beam with the radiation it emits causes it to be modulated into small groups (micro-bunches) separated by a distance equal to the wavelength of the radiation. In turn, these micro-bunches emit further radiation at a wavelength equivalent to this distance, causing them to contribute coherently to the growing radiation field. This process requires the generation of electron beams of extremely high current and small emittance and energy spread, and the construction of a precisely engineered undulator exceeding a hundred metres in length. For an FEL based on a conventional radiofrequency particle accelerator[9], this necessitates the use of a long, multistage bunch compressor called a 'chicane', which, as electrons bunch, compresses from an initial length of a few picoseconds to the order of 100 fs, to increase the current density of the electron beam up to the kiloampere level before injection into the undulator. But for the beams produced by a femtosecond-pulsed laser, such constraints are significantly relaxed.

The present understanding of the mechanism for the production of intense quasi-mono-energetic electron beams from laser-plasma accelerators is that plasma electrons are blown out to form a cavity known as a bubble[10] behind the laser pulse. The blow out of these electrons causes the development of a so-called 'wakefield', arising from the positive ions left behind in the tail of the bubble, which can generate immense electric fields of the order of teravolts per metre. This wakefield traps short packets of electrons and accelerates them to energies determined by the characteristics of the driving laser and its interaction with the plasma. Most significantly, the bunch size of the resulting electron beam is inherently much smaller than the bubble, which is equivalent to the plasma wavelength. And through appropriate control of the laser parameters, the relative energy spread may be minimized to the order of 0.1% for a 1-GeV beam, and a normalized emittance down to 0.1–1π mm mrad achieved. Such improvements should enable the production of a beam with an electron bunch length as short as 10 fs, and an effective beam current of up to 100 kA. As well as removing the need for a compression stage, this substantially reduces the required undulator length to just a few metres[11] — dramatically improving its ease of manufacture and cost.

The spontaneous emission of such a set-up in itself should be of sufficient brilliance to be of use to those who would otherwise have to wait for time on a conventional synchrotron to conduct their studies. The action of SASE, however, should boost this by some seven to eight orders of magnitude[12], enabling it to operate at a level comparable to a much larger and much more expensive FEL (see Fig. 1b). Coupled with steady progress in the performance and reduction in cost of the terawatt laser systems, this has the potential to put an FEL in every major university in the world, with momentous implications for the ability of physicists, chemists and biologists to study the dynamics of the natural world at the atomic scale.

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BIOPHYSICS

Cell commuters avoid delays

The rates of chemical reactions in a cell are limited by the time it takes the reactants to find each other through brownian motion. Thus diffusion determines the timescales of life — but can some reactions beat the diffusion limit?

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Practically all reactions within the biological cell are catalysed, or facilitated, by enzymes. DNA duplication is catalysed by polymerases; food digestion is catalysed by proteases; and the conversion of sugars into alcohol in catalysed by zymases, the first enzymes to be discovered. Although enzymes can accelerate the chemical reaction when the required reactants are present, they have little control over the supply of reagents. Most reagents diffuse freely in the cell until they collide with an enzyme and are chemically transformed. In 1917 Marian Smoluchowski[1] calculated the relationship between the rates of chemical reactions and the diffusion coefficient of the participating molecules, thus setting the diffusion limit of reaction rates.

The diffusion coefficients for biological molecules vary significantly depending on the size of the molecules, according to the Stokes–Einstein equation. Small molecules, of about 0.5 nm diameter (such as sugars and nucleotides), diffuse quickly with a diffusion coefficient, D, of about 100 $\mu\text{m}^2\ \text{s}^{-1}$; molecules of the size of a protein (3–5 nm) diffuse more slowly ($D \approx 3$–$10\ \mu\text{m}^2\ \text{s}^{-1}$), whereas larger vesicles (more than 10 nm in diameter) diffuse as slowly as $D \approx 0.1\ \mu\text{m}^2\ \text{s}^{-1}$, requiring hours to travel across a typical human cell (15 μm in diameter). Molecular crowding and stickiness of the cellular environment can lead to subdiffusion[2], threatening to make such journeys even longer and significantly slowing all the reactions in a cell. But molecules can in fact reach their targets faster than by simple diffusion — and