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Laser-Wakefield Accelerators: Glass-guiding benefits

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A main attraction of laser-driven electron accelerators is their absence of cavity walls, which can break down in the presence of intense electric fields. Now it seems that the inclusion of a hollow glass fibre cavity could lead to more efficient acceleration at lower laser intensities.

Particle accelerators are ubiquitous devices that have applications across a wide range of fields, from probing the composition of matter to diagnosing and treating cancer. A recent innovation in accelerator design is the use of intense laser light to create the necessary electric field for accelerating charged particles (usually electrons). Although such laser-driven accelerators are relatively new devices, they have already demonstrated the ability to accelerate particles to giga-electronvolt energies over acceleration distances ten-thousand times shorter than those of conventional radiofrequency accelerators. This laser-enabled miniaturization is analogous to the way that the development of solid-state transistors helped to shrink the size of electronic devices such as computers. Novel nuclear radiation devices that are compact enough to fit in hospitals (or are even portable) are sure to follow, which will have important applications in science, medicine, defence and homeland security.

Efficient laser-driven acceleration requires the laser beam to be focused close to its diffraction limit over as long a distance as possible. Because high-power lasers have matured to the point at which they can be reliably focused to intensities of 10^{18} W cm^{-2} and compressed to pulse durations of $<10^{-13}$ s, accelerator physicists are now trying to find better ways of propagating intense laser light through the acceleration region.

Writing in *Applied Physics B*, Genoud *et al.*[1] describe how they have used a glass capillary to guide focused ultrahigh-intensity laser light over a distance of more than 1 cm, which is a significant improvement over conventional schemes. The researchers describe how this method of guiding light differs from conventional cavity-free devices and thus allows their accelerator to operate with lower peak laser intensities. For a better perspective on this important work, it is necessary to review some of the physics of laser-driven accelerators.

Electric fields of any wavelength can be used to drive an electron accelerator, but shorter wavelengths provide higher acceleration gradients. This principle has generated intense interest in finding ways to drive accelerators with the submicrometre-wavelength fields of high-power lasers, instead of the centimeter-wavelength radiofrequency waves of klystrons (used to drive conventional accelerators).

Irrespective of the choice of wavelength, accelerating electrons requires the electric field to point in the same direction as, and stay in phase with, the electron motion. This presents a challenge, particularly for light waves, because their oscillating electric field points in a direction that is orthogonal to their propagation direction. The solution is either to use a structured cavity waveguide (as in a conventional radiofrequency accelerator) or to excite an electrostatic plasma wave (as in a laser-wakefield accelerator)[2]. Although the maximum field gradient in a structured cavity waveguide is limited by the dielectric breakdown threshold of the cavity, no such limitation exists when exciting an electrostatic plasma wave, making this scheme attractive for use in a compact high-energy accelerator.

In laser-wakefield accelerators, a laser light pulse ionizes a jet of gas to create a plasma[3]. The gas can also be ionized through other means, such as applying an electric discharge prior to the arrival of the laser pulse[4]. Irrespective of how the plasma is generated, the laser pulse's presence redistributes charge within the plasma to create a strong electrostatic field (a plasma wave) that can be used to accelerate electrons. Because this happens in the wake of the laser pulse, the scheme is commonly known as laser-wakefield acceleration.

However, merely focusing the laser light to its smallest spot size and thus maximum field strength is not enough for the acceleration scheme to work; this high-intensity focusing must also be maintained throughout the length of the interaction region with the accelerated electrons. In vacuum, the length over which a laser stays focused is governed by diffraction, over a length known as the Rayleigh range (Figure 1a). For most practical focusing systems this length corresponds to (at most) a few hundred micrometres, which is much shorter than the distance required for the accelerator to achieve maximum electron energy (giga-electronvolts). Several methods have been developed to help guide such high-intensity laser light over distances beyond the Rayleigh range.

The first technique takes advantage of the natural ability of high-intensity light to guide itself, through the mechanism of relativistic self-guiding[5]. In this case, the Gaussian radial profile of the light pulse causes the plasma medium through which it propagates to act as a lens; modifying the transverse quiver motion of the electrons creates a radial gradient in the plasma's refractive index (Figure 1b). In a laser-wakefield accelerator, this mechanism has been shown to be naturally present without the need for additional mechanisms, thus extending light propagation to well beyond the Rayleigh range[6]. Other light-guiding methods have also been investigated. For instance, the radial plasma-density gradient caused by a pre-heating electric discharge pulse in a dielectric capillary also causes a lensing effect. This mechanism has been used to accelerate electrons up to energies of around 1 GeV (Ref. 4).

The technique of Genoud *et al*. also makes use of a dielectric (glass) capillary tube, but importantly without an electrical discharge pulse[1]. The glass capillary (typically 150–200 μm in diameter and 0.6–2 cm in length) acts not only as a cavity to confine the hydrogen gas used to form the plasma, but also as a multimode optical fibre, reflecting and refocusing some of the laser light from its walls. By utilizing the laser energy that is outside the central laser focal spot, the capillary extends the light propagation distance by 20–30% beyond what it would have been without the capillary (Figure 1c), which could permit the use of drive lasers with lower energies and thus higher repetition rates. For example, Genoud *et al*. observed electron acceleration for peak laser intensities of $(5 \pm 2) \times 10^{17}$ W cm^{-2} using the 10 Hz multiterawatt Ti:sapphire laser system (40 fs pulses containing 0.7 J of energy at a wavelength of 795 nm in a 50 μm focal spot) at the Lund Laser Centre in Sweden.

Numerical simulations of the interaction indicate that relativistic self-guiding still plays a primary role in guiding the laser light, despite the presence of the capillary. In fact, relativistic self-guiding may play the primary role in all present laser-wakefield accelerators—regardless of the target geometry—because the laser power must generally exceed the relativistic self-guiding threshold to effectively drive a wakefield[6].

It may seem paradoxical to introduce a dielectric waveguide when the principal selling point of laser-based accelerators is that they dispense with the need for cavity walls, which can suffer from dielectric breakdown and thus limit the achievable acceleration. The resolution to this apparent paradox is that the capillary walls in the work of Genoud *et al*. did not need to be exposed to electric field strengths approaching the breakdown threshold. This is because the cavity was not serving its usual purpose—to convert the transverse oscillating electromagnetic field into an accelerating field, as in radiofrequency accelerators[7], but was instead merely refocusing the relatively small amount of laser energy in the wings of the pulse, which could not be self-guided. Consequently, the capillary's inner diameter was kept large compared with the central self-focused laser focal spot and the field strength at the walls was kept below the breakdown threshold. It remains to be seen whether these capillaries can withstand such extreme conditions over extended periods of operation. If so, they could help to make the potential applications of laser-wakefield accelerators more practical. For instance, because of their micrometre-scale radiation source size, wakefield accelerators can dramatically improve the spatial resolution of X-ray images[8]. By increasing the accelerator efficiency, capillaries could help make this application practical for use in hospitals.

Further research will reveal which of the above methods for guiding light will ultimately prove best for future accelerator designs. In any case, although it is perhaps ironic that the relatively old technology of glass waveguides may benefit next-generation accelerators, it is nonetheless satisfying to see such a classic photonic solution come to the aid of a current research problem.

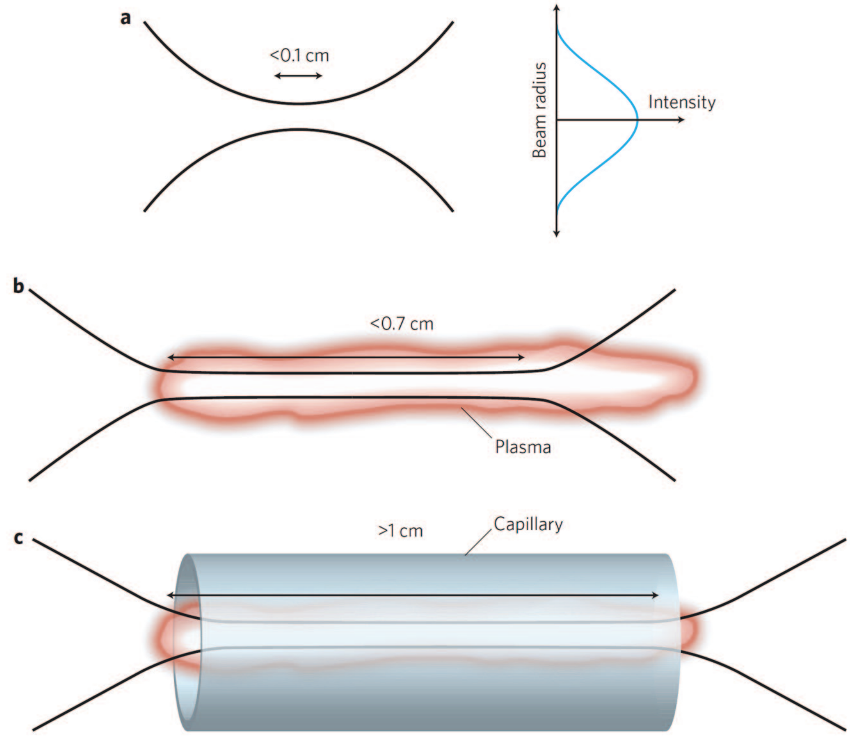

Figure 1. Laser pulses can be guided over distances greater than their diffraction limit. **a)** The unguided propagation of a Gaussian pulse in vacuum extends only over its Rayleigh range. **b)** Relativistic self-guiding in a plasma at relativistic laser powers occurs because of a radial variation in the refractive index, induced by the pulse's radial intensity profile on the plasma electron's quiver motion. **c)** Relativistic self-guiding as in **b**, plus capillary guiding of the pulse energy lying outside the central peak, thus permitting acceleration over a greater distance.

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