The future is fibre accelerators

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Could massive arrays of thousands of fibre lasers be the driving force behind next-generation particle accelerators? The International Coherent Amplification Network project believes so and is currently performing a feasibility study.

The challenge of producing the next generation of particle accelerators, for both fundamental research at laboratories such as CERN and more applied tasks such as proton therapy and nuclear transmutation, has been taken up by the high-intensity laser community. With the advent of chirped pulse amplification (CPA) in 1985[1] came the ability to generate ultrashort laser pulses with intensities in excess of 10^{18} W cm^{-2}. At these intensities, the electromagnetic field drives electrons into relativistic motion, opening the door to useful effects like wakefield acceleration[2] and hard X-ray production by bremsstrahlung, Compton or betatron emission[3]. Ion motion becomes relativistic[4] at intensities above 10^{22} W cm^{-2} — an intensity regime demonstrated or anticipated with development projects for very-large-scale lasers like the HERCULES laser at the University of Michigan in the USA, which has generated some of the highest peak intensities ever delivered to a target[5], and ELI[6] (the Extreme Light Infrastructure project), which will create four linked high-intensity laser facilities across Europe. In recent experiments[7], electrons have been accelerated by laser wakefield schemes to gigaelectronvolt energies over distances of just a few centimetres — a length that is orders of magnitude smaller than that required by conventional radiofrequency-based accelerators. These exciting developments suggest that, in principle, laser-based schemes could offer a far more compact, cost-effective approach to making high-energy particle accelerators in the future.

The issue for creating laser-based accelerators that match or exceed the performance of conventional accelerators is the requirement that the drive lasers simultaneously produce high peak and average powers with high efficiency. Even state-of-the-art petawatt lasers like BELLA[8] at the Lawrence Berkeley National Laboratory in California typically have average powers of only a few tens of watts with a wall-plug efficiency of 10^{-4}. To produce high average beam currents, practical laser-based accelerators will require much higher pulse repetition rates (tens of kilohertz) and thus average laser powers of hundreds of kilowatts with a wall-plug efficiency of >20%. Such characteristics are still out of reach of today's conventional laser technology.

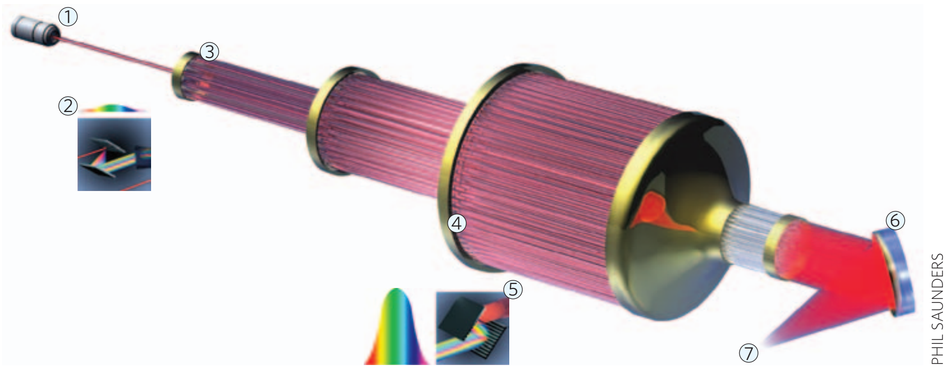

Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

Fibre benefits

Fibre lasers, where the active gain medium is confined within the core of an optical fibre and pumped using semiconductor laser diodes, have seen unprecedented increases in both average power and efficiency over the past ten years. Continuous-wave fibre lasers with average powers in the kilowatt regime were first demonstrated in 2004[9,10], and are now commonplace, with wall-plug efficiencies of over 30%.

Although semiconductor diode lasers can provide very high average laser powers at very low costs (projected to be as low as \$5 W^{-1} in the near future), and with very high efficiency (50–60%), they have poor beam quality. Fibre lasers act as highly efficient brightness converters, taking poor-quality diode beams and using them to generate coherent light with a much better beam quality with very high efficiency — their optical-to-optical conversion efficiency can be nearly 90% at kilowatt powers. High average powers are possible because the residual heat generated in the core can be easily removed owing to the high surface-to-volume ratio of the fibre geometry and because the silica from which the fibres are manufactured has favourable material properties. In addition, as the thermal load produced by the lasing process is distributed over a long length, the thermal load per unit length is rather low. Furthermore, waveguiding dominates over thermally induced refractive index changes up to very high powers. The fibre laser has thus become the tool of choice in many industrial applications for which high-average-power laser beams are required together with the ability to manufacture reliable lasers in large quantities; 10-kW single-mode continuous-wave lasers with nearly diffraction-limited beam quality are already commercially available.

The generation of high-energy ultrafast pulses in fibres is limited by the same core geometry that makes high average powers possible. Pulses with high peak powers experience nonlinear effects during propagation, resulting in unwanted pulse distortion and lengthening. In bulk gain media, the beam can be expanded, reducing peak intensity, to mitigate nonlinear effects. However, in a fibre, increases in beam size are limited without compromising single-mode light guidance, and large-core fibres start to lose their thermal and geometric advantages. Just as with bulk lasers, CPA can be used to prevent nonlinear effects, and in this way, in-fibre generation of 2.2-mJ pulses has been demonstrated[11] with peak powers of ~3.8 GW.

Fibre-based systems produce longer pulses than bulk ultrafast lasers because the gain bandwidth of a typical fibre host, Yb^{3+} in silica glass, is significantly smaller than that of the most common bulk host, Ti^{3+} in sapphire. However, pulse lengths down to 250 fs (ref. 12) are certainly achievable in Yb-doped fibre CPA systems, and further reduction should be feasible.

To generate both high average and peak powers using fibres, peak powers must be increased from present levels of gigawatts to the desired level of tens or hundreds of terawatts. The key technology for achieving this is coherent beam combining, as pursued by the International Coherent Amplification Network (ICAN) and the Coherent Amplification Network (CAN)[13], in which pulses from many fibre lasers are coherently combined on very large scales.

Massive parallelism

The technology to allow coherent combination of several continuous-wave laser beams to create extremely high average powers has been developed over the past ten years. In a typical system, a single seed laser is split (using fibre technologies developed for multichannel optical communications) and amplified in several separate fibre amplifiers. The relative phases of the outputs are controlled so that when the beams are combined they constructively interfere and produce a single, higher power output beam. Combinations of multiple continuous fibre laser beams up to 4 kW have been demonstrated using commercial fibre amplifiers[14] with good beam quality (vertical beam quality is 1.25 times the diffraction-limited beam quality) and with 78% efficiency.

The ability to combine a much larger number of amplified beams is necessary for ICAN. Towards this end, phase locking of 64 fibre amplifiers into a single beam[15] has recently been demonstrated. The amplifier outputs were tiled in a square lattice, and the relative phase between each amplifier and its four nearest neighbours measured using a lateral shearing interferometer, which diffracts the output of each fibre in four directions to overlap with the diffraction patterns from each of its nearest neighbours.

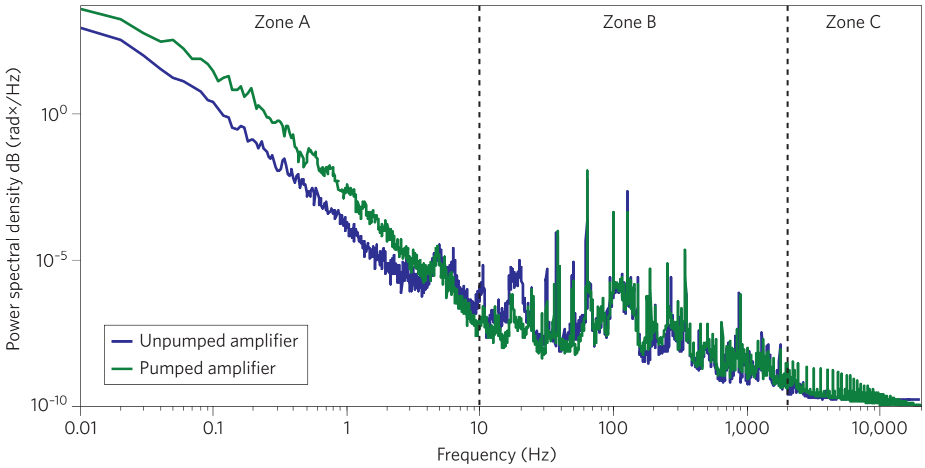

Figure 2 | Phase noise spectra of a fibre amplifier unpumped (thin line) and pumped (thick line). In zone A phase noise mostly originates from thermal noise, in zone B from acoustic noise and in zone C from electrical noise. Most of the phase noise is thermal (zone A), and can be corrected with slow feedback loops if acoustic noise (zone B) is reduced passively (data from L. Lombard and G. Canat, ONERA).

The resulting interference patterns can be used to determine the relative phase differences between adjacent fibres to within $\lambda/60$ (where λ is the wavelength) with a bandwidth of 20 Hz, which is limited by the speed of the camera used to record the interference pattern. Extensions to larger numbers of fibres, faster loop speeds and a more efficient hexagonal tiling geometry are possible using this technique. The phase noise spectrum of a typical ~10-W ytterbium-doped fibre amplifier[16], depicted in Fig. 2, reveals that the main noise source is low-frequency (<10 Hz) thermal fluctuations, and can thus be easily corrected by using phase modulators.

Coherent combination of pulsed amplifiers requires similar technology to that used in continuous-wave experiments, but with the additional constraint that higher orders of pulse dispersion must be considered. Both phase delay and group delay must be matched using phase modulators and delay lines. The second-order pulse dispersion should also be matched as pulses become shorter, but this has not yet become a limiting factor. Coherent combination of small numbers of femtosecond lasers has been achieved in several labs. A combination of two 325-fs pulses with an efficiency of 90% and an average output power before compression of 7.2 W has been demonstrated[17], implying a pulse energy of about 200 nJ. Furthermore, a CPA-based combination of two fibre amplifiers has been used to produce 3-mJ pulses with 5.5 GW peak power[18], and four fibre amplifiers have been used to produce an average power output of 300 W after compression, and a pulse energy of greater than 1 mJ (ref. 19). All three schemes used beamsplitter-based techniques for beam combination, and in none was it found necessary to use matching of second-order dispersion.

System design

In 2011, the joint ICFA–ICUIL (International Committee for Future Accelerators–International Committee for Ultra-Intense Lasers) taskforce specified target parameters for a laser for a 10-GeV acceleration stage[20]: a laser pulse energy of 32 J, a repetition rate of 13 kHz and a 240 TW peak power were identified as being reasonable values. Ideally, the laser wall-plug efficiency should be 50%, giving an overall efficiency from laser to electron beam of 20%. A 1-TeV collider would require 100 of these stages. To produce a single stage using the ICAN model requires the addition of pulses from between 1,000 and 10,000 fibre lasers. The key questions are: are there scientific or engineering issues that would make this impossible, and can such a system be produced at a reasonable cost?

The above-mentioned advantages of using fibres mean that many of the engineering problems associated with handling such large numbers of amplifiers can be solved. Before final amplification to very high energies, pulses can be manipulated in-fibre using techniques derived from telecommunications, where modular integrated components exist without the complexity of free-space optics. The use of amplifier modules that can be mass-produced reduces the complexity of the final system. At the final stages of amplification, the pulse energies are much

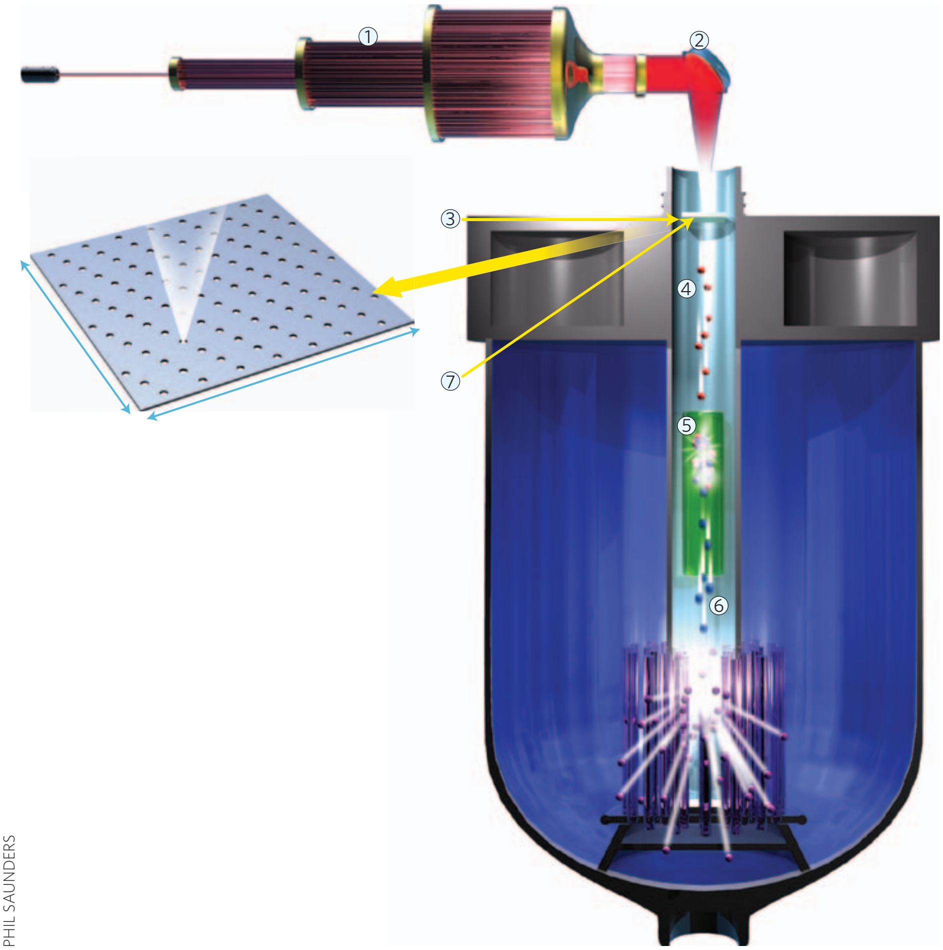

Figure 3 | Schematic of an ADR system with fibre front end. The fibre-based proton accelerator drives a spallation neutron source, which can be used to transmute minor actinides into less toxic elements. The high-energy, high-average-power laser pulses (1) are focused onto a proton-containing target (2) at intensities $>10^{23}$ W cm^{-2} (3). GeV-energy protons produced by radiation pressure acceleration (4) are incident on a Pb–Bi target and produce high-energy neutrons by spallation (5), which are used to transmute the spent fuel (6). The condition of the entrance window (7) needs to be carefully monitored to ensure safe operation.

greater than those used today and so new technologies must be developed for mass production. At this stage, system cost has to be considered as it will influence component design as much as other factors such as stability and lifetime.

Cost estimates for a single-stage laser with appropriate parameters for acceleration require assumptions about how costs will change with high-volume manufacturing. However, some estimates can be made with relatively high reliability. The cost of laser diodes for amplifier pumping at large volumes has been projected to be as low as \$5 W^{-1} in the near future, and it may decrease with time. Thus, for a 10-J, 10-kHz amplifier system, the laser diode costs will be about one to two million dollars. The key costs will lie in the amplifier stages, because associated components will have to be produced in very large volume; the seed lasers and beamsplitting and beam-combining units are not high-volume components. If each amplifier produces 1-mJ pulses at 10 kHz, then 10^4 amplifiers will be needed. Thus, for a budget of, for example, \$10M, each amplifier must cost less than \$1,000 to include the costs of fibres, isolators, phase modulators and other components including couplers. Cost reduction at this stage is extremely challenging, and may require the development of array-based components. Effective collaboration with industry will be critical for success.

Direct generation of 10-J pulses would require the combination of an unprecedented number of amplifier channels. One promising alternative is to use time combination of multiple pulses from a single channel. Researchers at the University of Jena in Germany have proposed a 'stack and dump' technique, in which pulses are 'stacked' inside an enhancement cavity and then 'dumped', achieving a higher pulse energy at the expense of a lower repetition rate. Each enhancement cavity represents a huge increase in channel pulse energy (typically by a factor of ~1,000), which significantly reduces the number of channels and allows for a more realistic cost model for each channel. However, it also increases the complexity, so that there is a trade-off between the complexity in the manufacturing of many fibre amplifiers against the complexity of the bulk components necessary for the enhancement cavities. Other time-combination techniques have been suggested — scientists at the University of Michigan in the USA have proposed techniques based on pulse combination using non-collinear second-harmonic generation with a similar goal. These alternatives are all being actively explored in the ICAN project.

Beyond electron acceleration: laser-driven transmutation

A combined fibre-laser system could, in theory, provide intensities that are high enough to produce, over a very short distance (millimetres), relativistic protons with an efficiency close to unity[4]. Such a system could have important applications associated with neutron generation by spallation[21]. Typically, one relativistic proton (1 GeV) can produce 20–30 neutrons. Both scientific and societal applications abound for this kind of neutron source.

In science, a CAN system could become the front end of a neutron source like the SNS (Spallation Neutron Source) at Oak Ridge in the USA or the future ESS (European Spallation Source) in Lund, Sweden, where the generation of relativistic protons with conventional accelerators is impaired by the long propagation distance (hundreds of metres) required before protons become relativistic. During the sub-relativistic propagation phase, the proton beam is difficult to maintain because of stability issues. Laser-driven proton acceleration could eradicate this problem because the protons become relativistic over only millimetre distances[22].

As for applications, a CAN system could provide the high-power proton beam used to generate spallation neutrons in accelerator-driven systems used for nuclear waste treatment by transmutation[23], and sub-critical reactors[24]. An accelerator-driven reactor relies on additional neutrons produced by a spallation source to operate, and is thus inherently safe. The accelerator-driven reactor also provides a safe route to transmutation of the long-lived minor actinides produced by fission reactors, reducing their long-term toxicity[25]. At present, accelerator-driven systems rely on conventional technology, involving accelerators with a size that may exceed nuclear reactors. The CAN system offers a path to more compact, more efficient and less costly proton accelerators, which could be termed laser-driven transmutators (Fig. 3). They would have the potential to make accelerator-driven systems commercially viable.

The ICAN consortium

ICAN requires expertise in many technical areas, which has been sourced from around the world. The four main project partners are: Ecole Polytechnique in Paris, France, led by the ICAN project leader Gerard Mourou, the optical fibre laser groups at the Fraunhofer Institute for Applied Optics and Precision Engineering and the Institute of Applied Physics of Friedrich-Schiller University in Jena, Germany, (Andreas Tünnermann) and at ORC, University of Southampton in the UK (David Payne) and CERN. Experts from other related organisations such as KEK (Japan), MPQ Garching (Germany), Thales (France), ONERA (France), Institut d'Optique (France), University of Michigan (USA), and University of Oxford (UK) bring their own areas of expertise to the project. A series of workshops and conferences will be held until July 2013, at which stage the first hardware designs will be summarized for a single-stage demonstrator laser system aiming for >10 J per pulse, >10 kHz performance with pulses of 100–200 fs. ❐

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