# La bougie de demain !!

## Le laser remplacera peut être la bonne vielle étincelle ?



# Lasers for engine ignition

The pollutant emissions and high-energy consumption of combustion engines using conventional spark plugs have long been serious environmental problems. Now, it has been demonstrated that lasers can provide a feasible green alternative. **Duncan Graham-Rowe** reports.

You might think that the idea of using a state-of-the-art laser to replace something as cheap and simple as a spark plug was over the top and an excessive use of technology. As it turns out, though, the benefits of making such a switch are so great that perhaps within the next decade we can expect laser-ignition systems to become commonplace in a wide range of combustion engines, initially in large-scale power plants then cars.

This is because there is growing evidence to suggest that using lasers to ignite fuel in combustion engines (Fig. 1) will bring about higher efficiencies and improved reliability compared with conventional spark plugs. What is more, they could also dramatically reduce the levels of harmful pollutants produced.

In light of this, it is hardly surprising that governments and big names in industry, such as Ford, Toyota and General Electric, are now showing a growing interest in laser ignition. According to Ernst Wintner, one of the pioneers in this field at the Photonic Institute of the Vienna University of Technology, in Austria, the race is now on to see who can get a laser-ignition system to market first.

But whether it is being used for automobiles or power plants, the principle is essentially the same. With sufficient intensity, of the order of 100 GW $cm^{-2}$, such pulses can be used to cause a plasma spark at the focal point of the laser, igniting the mixture of fuel and air, and ultimately driving a piston and crankshaft. According to Wintner, to reach the high intensity needed for laser ignition, the important thing is to get tightly focused laser pulses with pulse energies higher than 10 mJ, a beam quality factor, $M^2$, of lower than 3 and pulse durations of lower than 10 ns.

The advantages of using lasers for ignition are numerous, according to Wintner. Arguably, the biggest driving force is the potential improvement in efficiency that lasers offer. In both power plants and cars, there has been a move towards using leaner fuel mixes,

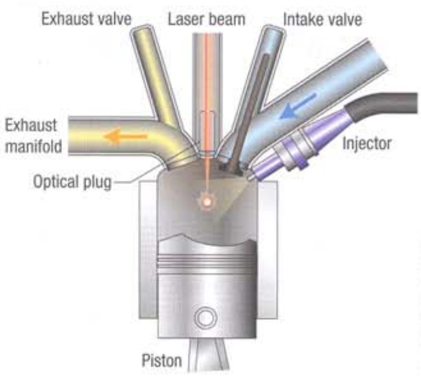


**Figure 1** Schematic of laser ignition in a combustion engine.

where the ratio of air to fuel is greater than normal. This enables greater efficiencies because less fuel is burned per cycle, but has the trade-off of being more difficult to ignite using conventional spark plugs. Not so with laser ignition, as Wintner points out. "Lasers allow you to work even leaner than you could with a normal spark plug, so you can get better efficiencies," he says.

A Japan Science and Technology Agency (JST) project, which involved several companies including Toyota, Nippon Soken and Denso, recently designed a passively *Q*-switched Cr:YAG/Nd:YAG microlaser pumped by a 120-W fibre-coupled quasi-continuous-wave laser diode for the purpose of ignition. A maximum output energy of 4 mJ per pulse and 16 mJ per four-pulse train with a pulse width of 0.6 ns and an $M^2$ value of 1.2 were obtained. The optical–optical conversion was 23 per cent and the brightness of the microlaser was calculated as 0.3 PW $sr^{-1}$ $cm^{-2}$. A comparison between the performance of a conventional spark plug and laser ignition in a constant-volume combustion chamber showed that a laser igniter accelerates the combustion and can ignite a leaner gas mixture that has an air:fuel ($C_3H_8$) ratio of 17.2 in atmospheric pressure. The ignition limit of the air:fuel ratio of a conventional spark plug was 15.7.

Combustion efficiency was also investigated for the above microlaser system. Takunori Taira from the Institute for Molecular Science, Japan, who is the leader of the JST project, and co-workers found that an input electrical power of 35 mJ is needed for a conventional spark plug, whereas 9 mJ optical energy from a microlaser is able to provide a flame kernel with a cross-sectional area three times bigger than that of the spark plug (Fig. 2). The research team is confident that 3 mJ optical energy is therefore sufficient for ignition with this system. "We attribute these improvements to the short pulse width, high beam quality and high brightness of our microlaser, which successfully reduce the air-breakdown energy and the ignition energy," says Taira.

Another reason for being able to get better efficiency is the flexibility of localizing the ignition point, which comes with using a laser. For practical reasons spark-plug contacts are usually positioned relatively close to the wall of the combustion chamber, as opposed to its centre. But with a lean fuel mix this is less than ideal when trying to get the most efficient burn, according to Andrew Scarisbrick, supervisor for government and university collaborations at Ford Motor Company's Dunton Research and Engineering Centre in Basildon, UK.

This is particularly relevant with direct-injection engines that allow ultralean burns. "This is where instead of injecting petrol into an intake port you inject it directly into the cylinder," says Scarisbrick. The aim is to improve efficiency even further and reduce pollutants by surrounding a smaller amount of fuel with a layer of air, so that it is well away from the cylinder walls. The challenge here is that ideally you would want to spray the fuel near the spark-plug contacts, but for practical reasons these are anchored close to the engine wall away from the centre of the chamber.

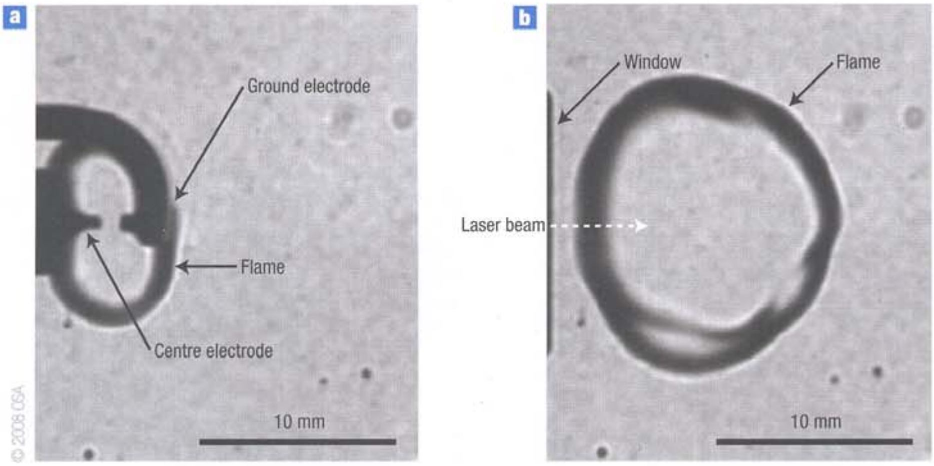


**Figure 2** Laser-ignition conbustion efficiency. **a**, Flame kernel ignited by a spark plug at 35 mJ electrical power and, **b**, a microlaser at an optical energy of 9 mJ in a constant-volume combustion chamber 6 ms after ignition is triggered at atmospheric pressure.

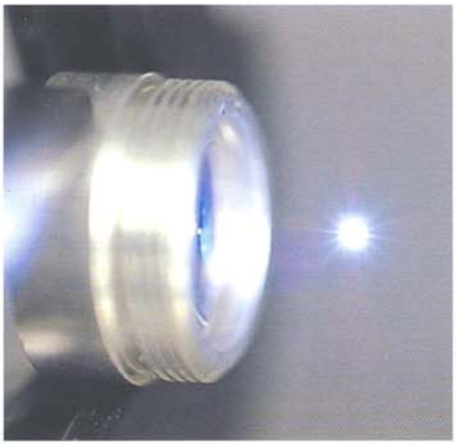

**Figure 3** Breakdown in air by a microlaser with a pulse energy of 2.7 mJ. Optics allows greater freedom over the location of fuel ignition.

With a laser, however, this is simply not a problem because optics allows you to choose where within the chamber you ignite the fuel (Fig. 3). In fact there is great potential to create multiple-spark laser-ignition systems, which could increase efficiencies even further by igniting the fuel at different points within the chamber, as Scarisbrick points out. "There are ways to focus lasers incredibly quickly," he says.

But the other benefit of a direct-injection engine is to reduce the harmful nitrogen oxides ($NO_x$) produced by the high-temperature liberation and recombination of nitrogen and oxygen gases. With a direct-injection engine this can be mitigated because the flame front, buffered by the layer of air, is able to cool rapidly before reaching the cylinder walls, thereby reducing its ability to form $NO_x$ emissions.

Tests carried out last year on a prototype gas engine by Sreenath Gupta and colleagues at the Argonne National Laboratories, in Illinois, USA, suggest that this sort of approach can reduce $NO_x$ emissions by up to 70 per cent, while improving efficiency by 3 per cent. An improvement of 3 per cent may not sound like much but even so this can go a long way, particularly with automobile engines, according to Scarisbrick. "Even if it was a just a few per cent fuel economy, that's significant," he says.

Another benefit of laser ignition comes from the further efficiencies achieved by increasing the pressure during combustion. This is particularly the case for large gas engines used for generating mains electricity, which operate at considerably higher pressures than car engines. Wintner says that a plant generating megawatts of electricity will achieve pressures of about 35 bar compared with the 10 bar found in a petrol or gasoline engine.

But doing so with a conventional spark plug comes at a cost, because achieving combustion becomes more difficult. "The higher the pressure, the more voltage you have to apply to ignite it," says Wintner. And higher voltages cause erosion on the spark-plug contacts, which eventually leads to early failure. Because of this, these expensive industrial spark plugs have to be replaced several times a year. In contrast, Wintner explains that with laser ignition the higher density of gases at increased pressures actually makes it easier to generate a plasma spark.

And indeed last year also saw the principle demonstrated in a petrol engine by Geoffrey Dearden and colleagues at the University of Liverpool, in the UK, working with Ford and GSI Lumonics as part of a project funded by the UK Department of Trade and Industry.

But practical demonstrations and commercial viability are two very different games, as Wintner points out. Since first carrying out his own experiments in 2000, he has identified two key challenges that need to be overcome before laser ignition can begin to deliver leaner, greener engines.

"One is the laser itself," says Wintner. What is needed is a laser capable of delivering sufficient energy for ignition, which is both reliable and has high spatial coherence and yet is durable and compact enough to be useful. "There is no laser on the market that can fulfill all the demands, so we have had to develop our own laser system," he says.

The problem is partly an issue of delivery. Combustion engines used in power plants normally require powerful sparks to work, typically on the order of 40 kV. To get the same results from a laser requires a plasma intensity at the focal spot of the order of 1,000 GW $cm^{-2}$. Not only does this require pulses on the order of nanoseconds, but also an optical transmission system capable of delivering it.

Conventional fibres cannot cope with this large intensity as, at present, they have transmission limits about three orders of magnitude less than this intensity so they would be destroyed, according to Wintner. Hollow glass waveguides (HGW) and photonic-bandgap (PBG) fibres use air instead of silica as the guiding medium and so can transmit up to 40 times the power of conventional fibres. The trouble is that the losses due to fibre bending with HGWs can dramatically reduce their peak power intensity and ability to generate a spark, as Gupta points out. And Wintner explains that, similarly, although PBG fibres are capable of transmitting large laser energies of high beam quality, they will probably still fall way short of the energy levels required by laser ignition.

Gupta's solution so far has been to use free-space optics. But Wintner believes there is another way. Working in partnership with GE Jenbacher based in Austria, Wintner has developed a diode-pumped, Q-switched laser in a form factor equivalent to the size of a conventional industrial spark plug. The pump laser diode and multiplexer are off-mounted,

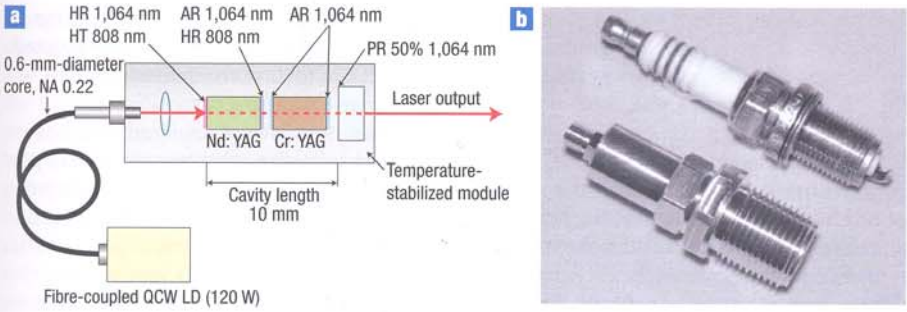


**Figure 4** Comparison of a conventional and a microlaser spark plug. **a**, A schematic of the passively *Q*-switched microlaser module with a length of 57 mm. **b**, A comparison of the microlaser module (bottom) and a conventional spark plug (top). NA: numerical aperture; HR: high-reflection coating: HT: high-transmission coating: AR: antireflection coating; PR: partial-reflection coating; QCW LD: quasi-continuous-wave laser diode. The wavelengths for the transmission properties are labelled in nanometres.


**Figure 5** Application of laser ignition in an industrial gas engine.

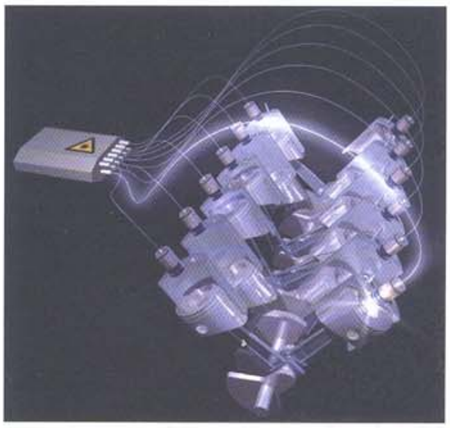


**Figure 6** The futuristic look of a laser multiplexing ignition system.

and conventional fibres connect them to a compact laser spark plug consisting of a passively *Q*-switched Nd:YAG laser crystal that sits in the position of a conventional spark plug.

Although this may be practical on an industrial scale, for the automotive industry, where space is at a premium and components are valued in terms of cents, this solution would be too large and the cost astronomical, as Scarisbrick points out. Dearden's group has also used free-space optics for their demonstrations, but such a set-up would be impractical in a car engine.

According to Taira, one of the major problems of laser igniters for actual engine systems is the dimension of the laser head. The commercially available lasers have large volumes owing to the complexity of the laser cavity. The passively *Q*-switched microlaser developed by his group has a simple structure and no external driver for optical switching is needed, leading to size reduction of the laser-head volume (Fig. 4). "The length of our microlaser module is 57 mm, which is comparable to that of a conventional spark plug for car engines, and this can still be reduced by using a smaller output coupler or by a direct cavity mirror coating on the Cr:YAG crystals," says Taira.

The other main challenge with laser ignition lies with getting the laser light inside the cylinder itself. Ideally, to maintain beam quality and reduce losses, the chamber window should also act as a lens. But given the harsh environment the window must endure, this can potentially be quite expensive, as Scarisbrick explains. "We have broken quite a few windows." So, both a hardwearing window and a separate lens may be required.

Wintner points out that the other issue with the chamber window is keeping it clean. "An oily engine environment and an optically clean window are not a good combination," he says. Wintner believes he has solved this problem, but his solution is proprietary so he is unwilling to discuss the details.

As things stand, then, there is still some way to go before we will see laser ignition in use. Scarisbrick and Dearden have now begun a new project aimed at optimizing their laser-ignition system, funded by the Carbon Trust, a UK government-fund-independent company set up to encourage businesses and industry to cut carbon emissions. But with the added challenges faced by the automotive sector, it will take the best part of a decade to bring the technology to market, according to Scarisbrick. So, when laser ignition does make its commercial debut it will most probably be within the energy sector (Figs 5,6).

"Direct collaboration with automobile companies is definitely going to help progress the commercialization process of laser ignition," says Taira, who is now working together with Toyota Central Research and Development Laboratories in Japan towards miniaturizing the laser-ignition system, as well as lowering its power consumption.

"GE Jenbacher wants to be the first to bring laser ignition to the market," says Wintner. Given the current cost of energy and the push to reduce pollutant emissions, it couldn't come soon enough.

*Duncan Graham-Rowe is a freelance science and technology journalist based in Brighton, UK.*
*e-mail: duncangr@gmail.com*

*Additional reporting by Rachel Won, an associate editor of* Nature Photonics *based in Tokyo, Japan.*
*e-mail: r.won@natureasia.com*