A Laser Spark Plug

Saves Fuel and Reduces Emissions

Lasers may soon conquer another common application: igniting engines. Tests on a first prototype were shown to reduce fuel consumption and nitrogen oxides emissions.

 All images courtesy of Fraunhofer IOF and INFLPR, Romania.

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Many of us will recall the science fiction comics of the 1970s, when lasers were imagined for everything from free-space communications to rocket propulsion. Some of these ideas have become reality — such as a new level of laser-based data transport around the world. Others, meanwhile, never made it past our wildest dreams.

One application that several companies and research institutions have pursued is laser ignition of combustion engines. But so far, a breakthrough has eluded these efforts.

Now, a joint German-Romanian collaboration of scientists and engineers from research institutions and one engine building company have presented a solution that worked for 19 h — until it was turned off by the operator.

Though the solution is not yet for sale at the car shop next door, the team has developed and tested prototypes and today has a clear road map for what to try next.

Combustion engines meet the task

Even at a time when wind and solar energy infrastructure are ramping up, there is a solid need for gas engines for energy generation. Combined heat and power (CHP) systems are highly desirable technologies for industrial, commercial, and municipal entities, often reaching energy efficiencies of >90%. The requirements for future energy-generation systems such as these are obvious: maximum efficiency with ever-lower emissions. Hydrogen engines allow for zero emission. As long as hydrogen remains unavailable, natural gas or biogas can be used to power CHP systems.

The German firm 2G Energy AG, a publicly traded supplier of CHP systems ranging from 20 to 4500 kW was the industry partner for the laser spark plug tests in real engines. These components are used in many settings, from private housing to data centers, and from agriculture to the packaging industry.

2G Energy's gas engines are sophisticated combustion engines, and the company suggested developing the laser spark plug for a highly charged lean-mixture engine. The so-called lean mixture is a mix of air and gas in which the share of air is larger than that which is stoichiometrically needed. In other words, if a gas molecule needs one oxygen molecule for combustion, then these engines use a mix where there are a few more air molecules than are needed.

In a car, a lean mix would lead to sputter, and the engine would stall, and the overcompensation could lead to backfiring. In a stationary engine with fixed rotation numbers and controlled conditions, this can be avoided. Burning all the fuel, a lean mix therefore allows for higher efficiency. Furthermore, the mix leads to lower combustion temperatures, and lower formation of nitrogen oxides (NOx) as a result.

Lean-mix engines require higher pressure, which leads to earlier degradation of the electric spark plugs. Laser ignition works better at higher pressure, and, as other published results have shown, leads to more stable ignition processes.

Also, the laser focus can be placed in an almost free-to-choose distance from the spark plug, and a train of several ignition pulses for one combustion can be generated.

The laser inside the spark plug

Conventional spark plugs generate an electric arc between two electrodes. A laser spark plug, in contrast, can generate a plasma spark at a point that is defined by its focusing optics for a pulse energy of several millijoules. This spark can be placed deeper in the prechamber since electrodes do not hinder the movement of the flame front.

The engineers' task was to develop a laser powerful enough to create a plasma spark that is compatible with regular engine operation. This meant that the laser system had to fit into the socket for an electrical spark plug, and its optics must create a laser focus at a proper distance of 8 to 11 mm.

The collaborators developed a small but powerful laser concept for this purpose. A composite Nd:YAG/chromium-doped yttrium aluminum garnet (Nd:YAG/Cr^{4+}:YAG) combination, purchased from France's Cristal Laser, was at the heart of this solution. The Nd:YAG ceramic laser medium is bonded to a piece of Cr^{4+}:YAG saturable absorber ceramic. One side of the Nd:YAG is coated for

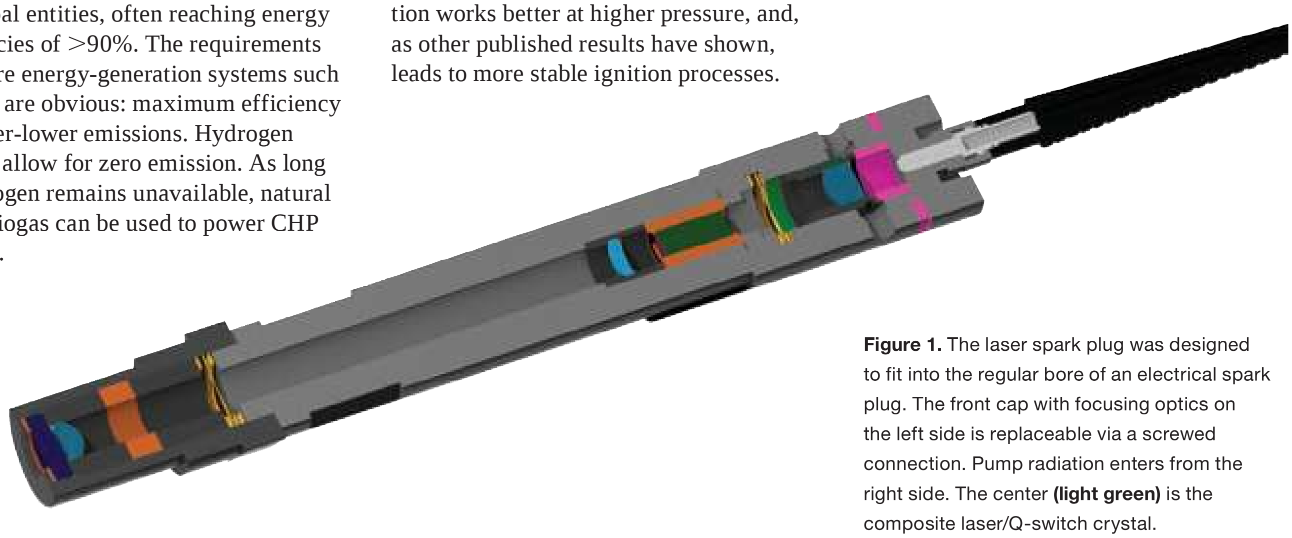

Figure 1. The laser spark plug was designed to fit into the regular bore of an electrical spark plug. The front cap with focusing optics on the left side is replaceable via a screwed connection. Pump radiation enters from the right side. The center **(light green)** is the composite laser/Q-switch crystal.

Figure 2. A set of four laser spark plugs during assembling and performance tests. The small sparks are laser plasmas, created due to air breakdown.

high reflectivity of the laser radiation at 1064 nm and high transmission of the pump radiation at 807 nm. The end facet of the Cr^{4+}:YAG is used as an out-coupling mirror. The short resonator length of ~11 mm and the characteristics of the composite Nd:YAG/Cr^{4+}:YAG ceramic medium yielded laser pulses shorter than 1 ns.

The team consists of researchers from the University of Bayreuth, Germany; the Fraunhofer Institute for Applied Optics and Precision Engineering IOF (Fraunhofer IOF) in Jena, Germany; and the National Institute for Laser, Plasma and Radiation Physics' (INFLPR)'s Laboratory of Solid-State Quantum Electronics, in Măgurele, Romania. Researchers at Fraunhofer IOF devised the mechanical design of the laser ignition system based on specifications provided by 2G (Figure 1). Fraunhofer IOF additionally manufactured and tested the laser spark plugs with assistance from INFLPR and the University of Bayreuth for the general flame-front formation properties during combustion (Figure 2).

Tests reveal limits — and opportunities

In motor tests, the energy and duration of a laser pulse reached 3.4 mJ and 0.9 ns, respectively, corresponding to a peak power of almost 3.8 MW. By adjusting the pump pulse duration at 807 nm, the Nd:YAG/Cr^{4+}:YAG laser spark plug could generate a single laser pulse or operate in pulse train mode with up to 10 laser pulses per train. The researchers designed the laser spark plugs to allow lenses with different focal lengths to be used for focusing the laser beam, as well as for in-chamber and prechamber configurations (Figure 3).

Initial experiments, performed in 2022, proved that laser ignition can be used in a gas engine. During the following months, the team performed a series of modifications on its first prototype; for example, the scientists redesigned the front cap housing the optics, making it replaceable and screwing it into place. This adjustment allowed further modifications to the optics without changing the laser itself (Figure 1).

At the end of 2023, the team began testing on a standard six-cylinder engine for lean-mix natural gas. The tests were designed for unsupervised operation within a laser-safe cabinet. Laser triggering was initiated via pump laser modulation, and issues with moisture inside the laser as well as soot on the windows were identified and resolved. The team also identified self-cleaning capabilities, which enabled the system to resolve the issue of soot on the laser windows.

The engineers applied standard engine testing methods such as high-speed pressure measurements. This enabled them to characterize combustion stability and peak pressure.

They then tested the spark plugs at several stationary operating points. The speed was kept constant at 1500 rpm and power levels were set to 200 kW, 250 kW, and 275 kW. This corresponds to mean pressures of 14 bar, 17.5 bar, and 19 bar, respectively. After the initial tests at 8 mm, the laser focus was set to 11 mm, and spark plugs with and without a prechamber were tested. The spark plugs were also tested with a clamped/glued window.

With an engine output of 200 kW, tests showed that the laser spark plug is, at minimum, as good in every tested mixture versus a regular electric prechamber spark plug. Moreover, if the engine is operated with a highly lean-gas mixture, the laser spark plug shows clear advantages in combustion. This advantage is discerned in a few-percent higher maximum pressure, faster combustion, and a decrease in NOx emissions.

At higher power levels, the laser spark plug loses this advantage. While it performs almost equally at 250 kW, it trails behind the electrical spark plug at the maximum power of 275 kW.

Another important parameter is the combustion stability, which is determined as the variance over several combustion cycles (coefficient of variation). For 200 kW, tests showed that the combustion was more stable with a laser spark plug that had a prechamber. Without a prechamber, the laser triggered combustion that is less stable than with an electrical spark plug, which always had a prechamber. The stability was higher for mixtures with less air — 500 NOx in exhaust — than for the leanest mixture — 120 to 190 NOx. Still, the laser ignition was more stable than the electrically ignited combustion.

One interesting issue involves the durability of the laser spark plug. For a too-short focal length of 8 mm, the lenses were fractured. However, this fracture did not occur at a focal length of 11 mm. The problem of debris on the windows, made of sapphire, was prevalent with the prechamber and nonexistent without the prechamber. In some cases, the laser burned through the debris, which established a self-cleaning process.

Figure 3. A close-up view of the type of laser spark plug used in the ignition experiments. A plug without a prechamber **(left)**.

Next steps

The laser spark proved to be a viable solution for a serial gas engine. In certain conditions, the laser ignition was better than the electrical ignition. Future investigations will focus on modifications to the prechamber geometry, which is where the experts expect further optimization potential.

The team conducted tests with natural gas, such as methane. Hydrogen-fueled engines, for example, will require a different geometry. This should also eliminate any debris problems. In such a case, the laser ignition will offer a reliable solution for maximum efficiency and lifetime.

Based on the results of this project, laser spark plugs for stationary engines, such as those used in CHP systems, are now one step closer to reality. Other applications, such as laser-based rocket ignition, could become feasible as well.

This may again sound like a story from a 1970s comic book. But, as recent advancements in space technology have shown, many of these dreams have now become reality.

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