Laser induced ignition of gasoline direct injection engines

G. Liedl[*a], D. Schuöcker[a], B. Geringer[b], J. Graf[b], D. Klawatsch[b], H.P. Lenz[b], W.F. Piock[c], M. Jetzinger[c], P. Kapus[c]

[a]Institute for Forming- and High Power Laser Technology, TU Vienna, Arsenal Obj. 207, 1030 Vienna, Austria;
[b]Institute for Internal Combustion Engines and Automotive Engineering, TU Vienna, Getreidemarkt 9, 1060 Vienna, Austria
[c] AVL List GmbH, Graz, Austria

ABSTRACT

A q-switched Nd:YAG laser as well as an excimer laser with an unstable resonator have been used for ignition of combustion processes. Following first experiments with a combustion bomb a gasoline direct injection engine has been modified for laser ignition by installation of a focusing element and a beam entrance window. It was possible with the q-switched Nd:YAG laser which delivers short pulses with a duration of less than 6 ns to ignite the engine for several 100 hours without problems. Compared to conventional spark ignition, laser ignition allows a more flexible choice of the ignition location inside the combustion chamber with the possibility to ignite even inside the fuel spray. Measurements of fuel consumption and emissions prove that laser ignition has important advantages compared to conventional spark ignition systems. Experiments with the direct injection engine have been carried out at the fundamental wavelength of the Nd:YAG laser as well as with a frequency doubled system. No differences in the minimal pulse energy needed for ignition could be found, since the minimal pulse energy for ignition is mainly determined by the ablation thresholds of combustion deposits at the surface of the window to the combustion chamber. Such combustion deposits reduce the transparency of the window where the laser beam enters the combustion chamber and a "self-cleaning" mechanism of the window by ablation is essential for successful operation. Experiments show that above a certain threshold intensity of the laser beam at the window even highly polluted surfaces could be cleaned with the first laser pulse which is important for operation in real-world engines. Theoretically calculated energy values for laser ignition are much lower since such mechanisms are usually not considered. Power and space requirements on possible future developments of laser ignition systems are discussed briefly. Several concepts for laser ignition, like diode-pumped solid state lasers (DPSS) with and without fiber coupling are presented and chances on realization are discussed.

Keywords: laser ignition, direct injection, q-switch, solid-state laser

1. INTRODUCTION

Economic as well as environmental constraints demand a further reduction in the fuel consumption and the exhaust emissions of motor vehicles. At the moment, direct injected fuel engines show the highest potential in reducing fuel consumption and exhaust emissions. Unfortunately, conventional spark plug ignition shows a major disadvantage with modern spray-guided combustion processes since the ignition location cannot be chosen optimally. It is important that the spark plug electrodes are not hit by the injected fuel because otherwise severe damage will occur. Additionally, the spark plug electrodes can influence the gas flow inside the combustion chamber.

It is well know that short and intensive laser pulses are able to produce an "optical breakdown" in air. Necessary intensities are in the range between $10^{10} \ldots 10^{11} W/cm^2$.[1,2] At such intensities, gas molecules are dissociated and ionized within the vicinity of the focal spot of a laser beam and a hot plasma is generated. This plasma is heated by the incoming laser beam and a strong shock wave occurs. The expanding hot plasma can be used for the ignition of fuel-gas mixtures.

[*]gerhard.liedl@tuwien.ac.at, phone +43 1 798 33 21, fax +43 1 798 33 21-20

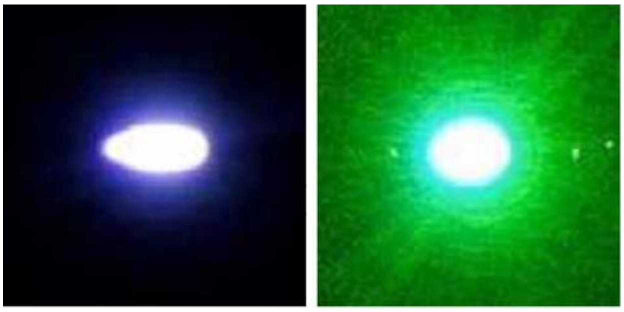

Figure 1. Optical breakdown in air generated by a Nd:YAG laser. Left: at a wavelength of 1064 nm, right: at 532 nm

In the past, this optical breakdown has been used for ignition of gas mixtures many times.[2–6] Nevertheless, the work which has been done so far was mainly basic research and only few experiments have been performed on combustion engines.

This article will present basics of spark plug and laser ignition together with results achieved by operating a laser ignition system on an internal combustion engine for a long period of time.

2. IGNITION OF FUEL/AIR MIXTURES

2.1. Spark plug ignition

Conventional spark plug ignition has been used for many years and is a well established and reliable technology. The steps for ignition of a fuel-air mixture with an engine are as follows: First, the fuel-air mixture is compressed and at the right moment a high voltage is applied to the electrodes of the spark plug. The field strength reaches values of approximately $3 \cdot 10^4 V/cm$.[2,7] Electrons are accelerated by the electric field and hit other atoms, thus ionizing additional atoms and an avalanche-like reproduction of ionized atoms occurs. For ignition of an inflammable gas mixture, the energy balance has to be positive within a small volume. The supplied energy together with the exothermal heat of the reaction have to be greater than the necessary activation energy and losses due to heat conduction or radiation.

This technology has been used very successfully a million times in combustion engines from the very beginning till now. Nevertheless, problems occur due to the fact that the ignition location cannot be chosen optimally. Additionally, spark plug electrodes can disturb the gas flow within the combustion chamber. Modern combustion engines use direct injection of the fuel into the combustion chamber and require complicated injector geometries and piston shapes for operation since near the electrodes of the spark plugs the fuel-air mixture has to be inflammable which means that the ratio between fuel and air has to be within the correct range. On the other hand, it is essential that the spark plug electrodes are not hit by the injected fuel spray since otherwise severe damage will occur. Although wall-guided and air-guided combustion processes have have already found their way into modern engines, there is still a need for improvements, especially for spray-guided combustion processes.

2.2. Laser ignition

Laser ignition uses an optical breakdown of gas molecules caused by an intense laser pulse to ignite gas mixtures. The beam of a powerful short pulse laser is focused by a lens into a combustion chamber and near the focal spot a hot and bright plasma is generated, see fig. 1.

2.2.1. Mechanisms of laser ignition

By comparing the field strength of the field between the electrodes of a spark plug and the field of a laser pulse it should be possible to estimate the required laser intensity for generation of an optical breakdown. As already mentioned, the field strength reaches values in the range of approximately $3 \cdot 10^4\, V/cm$ between the electrodes of a conventional spark plug.[2,7] Since the intensity of an electromagnetic wave is proportional to the square of the electric field strength $I \propto E^2$, one can estimate that the intensity should be in the order of $2 \cdot 10^6\, W/cm^2$, which is several orders of magnitude lower as indicated by experiments on laser ignition. The reason is that usually no free electrons are available within the irradiated volume. At the electrodes of a spark plug electrons can be liberated by field emission processes. In contrary, ionization due to irradiation requires a "multiphoton" process where several photons hit the atom at nearly the same time.[8] Such multiphoton ionization processes can only happen at very high irradiation levels (in the order of $10^{10} \ldots 10^{11} W/cm^2$)[1,2] where the number of photons is extremely high. For example, nitrogen has an ionization energy of approximately 14.5 eV, whereas one photon emitted by a Nd:YAG laser has an energy of 1.1 eV, thus more than 13 photons are required for ionization of nitrogen.

The pulse energy of a laser system for ignition can be estimated by the following calculation. The diameter d of a focused laser beam is

$$d = 2 \cdot w_f = 2 \cdot M^2 \frac{2}{\pi} \frac{\lambda F}{D} \,, \tag{1}$$

where M^2 is the beam quality, F is the focal length of the optical element and D is the diameter of the laser beam with the wavelength λ.

Now it is assumed that the laser beam irradiates a spherical volume $V = \frac{4\pi w_f^3}{3}$. From the thermodynamical gas equation the number of particles N in a volume V is

$$N = \frac{pV}{kT} \,, \tag{2}$$

with the pressure p, temperature T and Boltzmann's constant $k = 1.38 \cdot 10^{-23} J/K$. Inside the irradiated volume N molecules have to be dissociated where first the dissociation energy W_d is required and finally $2N$ atoms are ionized (ionization energy W_i). Using known values[9] for $W_d = 9.79\,eV$ and $W_i = 14.53\,eV$ for nitrogen, the energy for dissociating and ionizing all particles inside the volume can be calculated as

$$W = \frac{\pi}{6} \frac{pd^3}{kT} \cdot (W_d + 2W_i) \,. \tag{3}$$

For a spot radius of about 100 μm the equation gives a maximum energy of approximately 1 mJ. Since not all particles inside the irradiated volume have to be ionized, even smaller energies should be sufficient for generation of an optical breakdown.

It is assumed that the intensity which is necessary for the generation of an optical breakdown processes is related to the pressure of the gas.

$$I \propto \frac{1}{p^n} \,, \tag{4}$$

with $n = 1 \ldots 5$, depending on the mechanism of the multiphoton process.[1] Higher pressures, like in a combustion chamber should ease the ignition process what favors the laser induced ignition.

3. EXPERIMENTAL

3.1. Combustion chamber experiments

Following the calculations above, even moderate pulse energies should be sufficient for laser induced ignition of combustibles. As a feasibility test, an excimer laser has been used for ignition of inflammable gases inside a "combustion bomb". The laser used for the first experiments was a Lambda Physik LPX205, equipped with an unstable resonator system and operated with KrF, delivering pulses with a wavelength of 248 nm and a duration of approximately 34 ns with maximum pulse energy of 400 mJ.[10] The combustion chamber has had a diameter of 65 mm and a height od 86 mm, with a resulting volume of $290\,cm^3$ and was made of steel. The laser beam was guided into the chamber through a window. Pressure sensors, filling and exhaust lines were also connected to the combustion chamber. The laser beam was focused into the chamber by means of a lens with a focal length of 50 mm. Variations of pulse energies as well as gas mixtures have been performed to judge the feasibility of the process. Results indicate that ignition-delay times are smaller and pressure gradients are much steeper compared to conventional spark plug ignition.

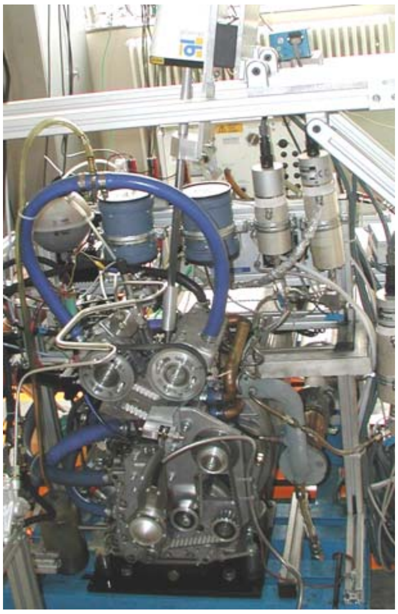

Figure 2. Research engine with the q-switched Nd:YAG laser system

3.2. Engine experiments

Since the first feasibility experiments could be concluded successfully, an engine was modified for laser ignition. The engine has been modified by a replacement of the conventional spark plug by a window installed into a cylindrical mount. The position of the focusing lens inside the mount can be changed to allow variations of the location of the initial optical breakdown.

First experiments with laser ignition of the engine have been performed with an excimer laser, later a q-switched Nd:YAG has been used, see table 1.

Table 1. Technical data of the research engine and the Nd:YAG laser used for the experiments.

Research engine		Q-switched Nd:YAG laser	
Number of cylinders	1	Pump source	Flash lamp
Number of valves	1	Wavelength	1064 or 532 nm
Injector	Multi-hole	Maxmum pulse energy	160 mJ
Stroke	85 mm	Pulse duration	6 ns
Bore	88 mm	Power Consumption	1 kW
Displacement volume	517 cm^3	Beam diameter	6 mm
Compression ratio	11.6	Type	Quantel Brilliant

The replacement of the excimer laser was mainly caused by the fact that especially at very low pulse energies the excimer laser shows strong energy fluctuations.

Pressure within the combustion chamber has been recorded as well as fuel consumption and exhaust gases. The laser was triggered at well defined positions of the crankshaft, just as with conventional ignition systems. Pulse energies, ignition location and fuel/air ratios have been varied during the experiments. The engine has

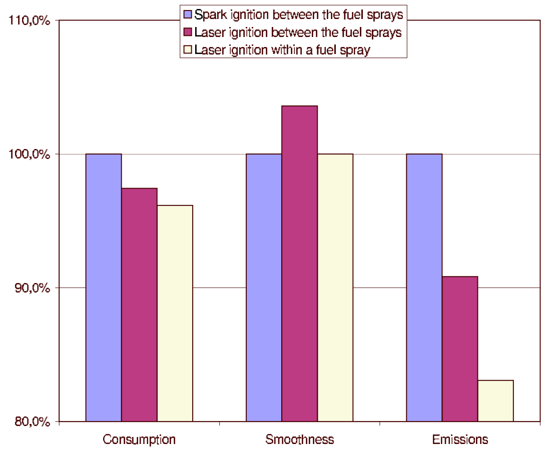

Figure 3. Comparision between conventional spark plug ignition and laser ignition. Laser ignition within the fuel spray of an injector shows the best results in reducing fuel consumption and exhaust emission at the same engine smoothness.

been operated at each setting for several hours, repeatedly. All laser ignition experiments have been accompanied by conventional spark plug ignition as reference measurements.

4. RESULTS

Results of the experiments are summarized in fig. 3. Fig. 3 shows that laser ignition has advantages compared to conventional spark plug ignition. Compared to conventional spark plug ignition, laser ignition reduces the fuel consumption by several per cents. Exhaust emissions are reduced by nearly 20%. It is important that the benefits from laser ignition can be achieved at almost the same engine smoothness level, as can be seen from fig. 3. Additionally, a frequency-doubled Nd:YAG laser has been used to examine possible influences of the wavelength on the laser ignition process. No influences could be found.

Best results in terms of fuel consumption as well as exhaust gases have been achieved by laser ignition within the fuel spray. As already mentioned, it is not possible to use conventional spark plugs within the fuel spray since they will be destroyed very rapidly. Laser ignition doesn't suffer from that restriction.

Another important question with a laser ignition system is its reliability. It is clear that the operation of an engine causes very strong pollution within the combustion chamber. Deposits caused by the combustion process can contaminate the beam entrance window and the laser ignition system will probably fail. To quantify the influence of deposits on the laser ignition system, the engine has been operated with a spark plug at different load points for more than 20 hours with an installed beam entrance window. As can be seen in fig. 4, the window was soiled with a dark layer of combustion deposits. Afterwards, a cold start of the engine was simulated. Already the first laser pulse ignited the fuel/air mixture. Following laser pulses ignited the engine without misfiring, too. After 100 cycles the engine was stopped and the window was disassembled. As can be seen from fig. 4, all deposits have been removed by the laser beam.

Additional experiments showed that for smooth operation of the engine the minimum pulse energy of the laser is determined by the necessary intensity for cleaning of the beam entrance window. Estimated minimum pulse energies from eq. 3 are to low since such "self-cleaning" mechanisms are not taken into account. Engine operation without misfiring was always possible above a certain threshold intensity at the beam entrance window. For safe operation of an engine even at cold start conditions an increased pulse energy of the first few laser pulses would be beneficial for cleaning of the beam entrance window.

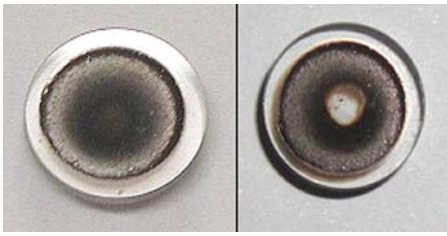

Figure 4. Beam entrance window: left side after 20 h operation with spark plug ignition, right side: immediately after 100 laser pulses. Beam area is cleaned by the laser beam.

5. SUMMARY

The applicability of a laser-induced ignition system on direct injected gasoline engine has been proven. Main advantages are are the almost free choice of the ignition location within the combustion chamber, even inside the fuel spray. Significant reductions in fuel consumption as well as reductions of exhaust gases show the potential of the laser ignition process.

Minimum ignition energy is mainly determined by the necessary "self-cleaning" mechanism at the beam entrance window from combustion deposits and not by engine-related parameters. No differences of the laser ignition process could be found at different laser wavelengths.

The main aim in development of a laser ignition system is of course to meet engine-specific requirements, like power consumption, robustness against changes in temperature, vibrations, space required and production costs. In principle, several possibilities exist for ignition of combustion processes, only diode-pumped solid state lasers can probably fulfill the requirements. For example, within an engine compartment, temperature can change from -30 ℃ up to more than 100 ℃. Additionally, electrical power consumption is limited in a car to about a maximum value of 100 W.

Although it seems fascinating to use one single laser as a source and to distribute the ignition pulses by optical elements, like fibers or mirrors to the different cylinders, it is almost impracticable in a car where changes in temperature or vibrations can cause misalignment very easily.

Future works requires the construction of a laser ignition system which meets the requirements mentioned above and which can be used within a car for long-term studies.

REFERENCES

1. M. Gower, "Krf laser-induced breakdown of gases," *Opt. Commun.* **36, No. 1**, pp. 43–45, 1981.
2. P. Ronney, "Laser versus conventional ignition of flames," *Opt. Eng.* **33 (2)**, pp. 510–521, 1994.
3. J. Syage, E. Fournier, R. Rianda, and R. Cohn, "Dynamics of flame propagation using laser-induced spark initiation: Ignition energy measurements," *Journal of Applied Physics* **64 (3)**, pp. 1499–1507, 1988.
4. M. Lavid, A. Poulos, and S. Gulati, "Infrared multiphoton ignition and combustion enhancement of natural gas," in *SPIE Proc.: Laser Applications in Combustion and Combustion Diagnostics*, **1862**, pp. 33–44, 1993.
5. J. Ma, D. Alexander, and D. Poulain, "Laser spark ignition and combustion characteristics of methane-air mixtures," *Combustion and Flame* **112 (4)**, pp. 492–506, 1998.
6. R. Hill, "Ignition-delay times in laser initiated combustion," *Applied Optics.* **20 (13)**, pp. 2239–2242, 1981.
7. Bergmann and Schaefer, *Lehrbuch der Experimentalphysik: Elektrizität und Magnetismus*, vol. 2, Walter de Gruyter Berlin, 1981.
8. T. Huges, *Plasma and laser light*, Adam Hilger, Bristol, 1975.
9. D. R. Lidde, ed., *CRC Handbook of Chemistry and Physics*, CRC Press, 2000.
10. Lambda Physik, *Manual for the LPX205 Excimer Laser*, 1991.