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# Laser Ignition of an IC Engine Using an Nd: YAG Laser

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*Abstract - T***he use of laser energy to ignite gas and liquid based fuel-air mixtures has been the subject of a number of studies and laboratory experiments at a fundamental level over the past 30 years. The practical implementation of this laser application has still to be fully realized in a commercial automotive application. Laser Ignition (LI), as a replacement for Spark Ignition (SI) in the Internal Combustion (IC) engines of automotive vehicles, offers several potential advantages including extending lean burn capability, reducing the cyclic variants between combustion cycles and reducing the overall ignition package costs, weight and energy requirements. This paper reports on the current research being undertaken which examines the effects of engine combustion performance and stability when specific laser parameters (beam energy, minimum spot size and focal length/volume) are varied. A Q-switched Nd: YAG laser operating at the fundamental wavelength 1064 nm was used to ignite gasoline and air mixtures**

*Keywords:* **Laser Ignition, IC Engine, Nd: YAG laser**

## 1. INTRODUCTION

Spark plugs reach their limits at the necessary high ignition pressures demanding for excessively high voltages. However, there are several alternative concepts like plasma ignition, high-frequency ignition, diesel micro-pilot ignition and laser ignition which might contribute to an improvement of the overall efficiency. To our knowledge, laser ignition represents the most promising future ignition concept .The main advantages of laser ignition are performance enhancing high effective mean pressures in the combustion chamber as well as the feasibility of very lean mixtures lowering the flame temperature and consequently the NOX emissions. In general, the mechanism of laser ignition is based on non-resonant gas breakdown of the tightly focused pulsed (ns) laser beam. Initial electrons absorb photons to gain energy via the inverse bremsstrahlung process. These energetic electrons can ionize gas molecules leading to the breakdown in the focal region via the electron cascade growth. It is important to note that this process requires initial seed electrons .These electrons might be produced from thermally heated or linearly ionized impurities like soot or dust in the gas mixture. The plasma formed by the mentioned mechanism can ignite the combustible mixture.

## II. OBJECTIVES OF LASER IGNITION SYSTEM

The objectives of Laser Ignition system are:

1. To get higher engine efficiency;
2. To reduce the nitrous oxide (NOx) emissions;
3. To ignite the lower quality fuels such as synthetic gas, bio fuels;
4. To avoid pre-ignition and post-ignition

## III. METHODS OF LASER IGNITION

Laser ignition of an air-fuel mixture can be achieved by one of four principal mechanisms.

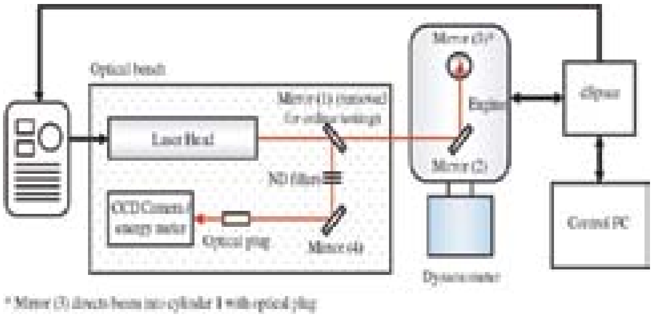

Fig. 1 Laser ignition from a heated surface

### *1. Thermal Initiation*

A high power laser pulse is focused onto an available metal or carbon surface. The glowing surface ignites the air-fuel mixture.

### *2. Non-Resonant Breakdown*

The electrical field of a focused laser beam causes electrical breakdown of the gas. This is comparable to electrical spark discharge. A laser power density in excess of $10^{11}$ W/cm$^2$ required to cause breakdown due to photo-ionization.

### *3. Resonant Breakdown*

Similar to non-resonant breakdown, this involves non-resonant multiphoton photo dissociation of a molecule and is followed by resonant photo ionization of an atom.

### *4. Photochemical Ignition*

A single photon, in UV, is absorbed by a molecule and causes dissociation. This process does not involve. Photo ionization and does not lead to breakdown. The energy required for this process is 1014W/cm$^2$).

## IV. EXPERIMENTAL ANALYSIS

The experiment is tested by two ways namely

1. Off- line pulse ignition; and
2. On-line pulse ignition.

A schematic of the experimental setup can be seen in figure, which shows two legs, one for offline testing and the other for online testing.

## V. OFFLINE LASER IGNITION TESTING

Five different focal length (FL) lenses (15, 18, 24, 30 and 36 mm) were tested individually in a specifically designed optical plug. These were all uncoated BK7 plano-convex lenses, apart from the 36 mm FL lens, which had a visible to near infrared coating. An uncoated sapphire window was sealed at the bottom of the optical plug for each of these different lenses. The minimum beam waist produced by each lens was positioned at 4 mm from the bottom of the plug (which is at the same location as the electrical discharge of the spark plugs), as this was found from previous testing to be the optimum LI position for this engine. Mirror (1) was installed on the optical bench for offline testing to direct the beam into the optical plug, as shown in figure An energy meter (Gentec ED 200 head and Solo PE monitor) was used to measure the laser pulse energies at various laser drive levels, taking the average energy of a 200 pulse sample. The energies were measured before each optical plug on the bench, starting with 4 mJ, then increasing by set increments up to a maximum of 23 mJ.

The subsequent energies transmitted through the plugs for each energy increment were also measured by placing the energy meter at 40 mm after the plug, accounting for the plasma produced. From these tests, the transmissions of the optical plugs were measured in order to calculate the actual beam energy that would be delivered inside the engine's cylinder. An Electro physics Micro-viewer 7290A camera system was used to measure the minimum spot sizes produced by the different FL lenses in the optical plug to an accuracy of ± 5 µm. These minimum spots were used with the recorded energies to calculate laser irradiances in W/cm$^2$ for the various settings. The camera was also used to measure the beam sizes on the lenses in the optical plug for laser drive levels between 40 and 100%, to ensure that these were similar, as a variance in beam size would affect the minimum spots produced. The beam quality factor $M^2$ was calculated for each of the laser cavity apertures with these measured beam sizes, using the formula $M^2 = (dnD)/(4f\lambda)$Where $d$ is the minimum beam diameter produced by the focusing lens, $D$ is the beam diameter incident on the focusing lens, $f$ is the FL of the lens and $\lambda$ is the wavelength.

## VI. ONLINE LASER IGNITION TESTING

For the online testing, the plug was at a beam path length of 1.4 m from the laser head which was the same distance as it was for the online tests.The laser system was controlled through a dSpace DS1005 card in a buslinked expansion box using a Simulink laser timing model designed and run through MATLAB. The IC engine used was an unmodified Ford Zetec 1.6 liter that had 4 cylinders and 16 valves, with aspirated port fuel injection (PFI), which operated in a homogenous ignition mode. The engine was connected to a low inertia dynamometer, to provide a load to simulate real working conditions. Cylinder pressure data was taken from cylinders 1 and 4 for comparison of LI to SI combustion cycles. During testing, cylinder 1 was fired optically using the laser, while cylinders 2, 3, and 4 were ignited using conventional spark plugs.

For each cycle, the Simulink model sent a signal via dSpace to the laser to activate the flashlamp, where a set time period later the Q-switch was triggered internally by the laser power supply unit. The conventionally fired cylinders were ignited at the crank angle corresponding to the triggering of the laser Q-switch (i.e., all 4 cylinders fired at the same time). For each optical plug tested online, the laser energy was reduced to find the minimum ignition energy (MIE) for misfire free combustion. The energy was then increased in increments up to a maximum of 23 mJ, where the steady state values (assumed over 300 cycles ) of *COVIMEP* and *VarPPP* for cylinders 1 and 4 were recorded for each energy level.

Each test was performed at an engine speed of 1500 RPM and each cylinder was fired 30°C before top dead centre. The results were only recorded once the engine had warmed up (coolant temperature >80°C), to ensure that the conventionally fired cylinders were operating optimally.

## VII. RESULTS AND DISCUSSION

The laser used in engine testing was a Q-switched Nd: YAG laser (Neodymium doped Yttrium Aluminum Garnet) operating at the fundamental wavelength of 1064 nm and in single mode (i.e. with an almost Gaussian beam profile) with low M2 < 2. Energy up to 20 mJ per pulse was available. The maximum repetition rate is 50 Hz.

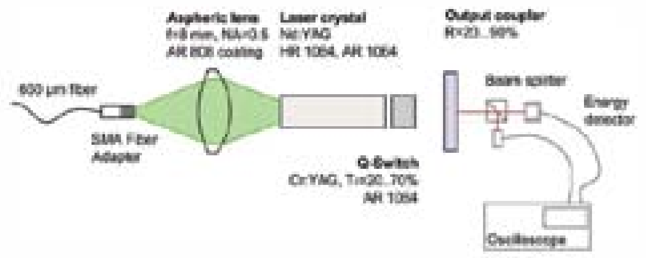

Fig.2 Schematic view of the laser system.

Therefore Nd3+: YAG as laser active medium and Cr4+:YAG as passive absorber has been chosen.

The Nd-doping of the laser crystal was around 1.0 at 0% and the fluorescence lifetime of the upper laser level 4F3/2 amounts to τfl ≈ 255 µs. The absorption line of Nd3+:YAG is centered around λdiode = 808 nm being suitable for a GaAs high power laser diode as pump source. Pump pulses up to a power Ppump = 300 W @ 500 µs can be generated by this laser diode. Since the laser diode shows a temperature gradient of 0.3nm/K, temperature stabilization was necessary. Furthermore, as shown in Figure 3, temperature stabilization enables the exact adjustment of the diode emission line and the crystal absorption wavelength with the aim of highest conversion efficiency.

A step-index fiber for transportation of the pump pulse with a core diameter of 600 µm and a numerical aperture NA = 0.22 were employed. Different aspheric collimating lenses with effective focal lengths lf,eff = 1.5 – 18 mm were tested, however, the lens with lf, eff = 8 mm and NA = 0.5 turned out to be the most suitable for in-coupling the pump beam into the laser crystal. The in-coupling mirror of the resonator was directly coated onto the crystal in order to reduce the length of the system and, as a result, the pulse duration. Moreover, the end face of the crystal was coated with an anti-reflection (AR) layer for the 808 nm pump beam reducing the reflection losses. The output-coupler was separated from the crystals since the adjustment of the mirror allows flexibility in pulse energy and beam profile.

Passive absorbers with initial transmissions T0 = 25% - 70% and output-couplers with reflectivities R = 25% - 90% cover the field of laser operation. All passive absorber crystals were coated with an AR layer for the laser wavelength λem = 1064 nm. In order to achieve highest output power the in-coupling optics were always adapted with respect to the resonator conditions (length, reflectivity, initial transmission).

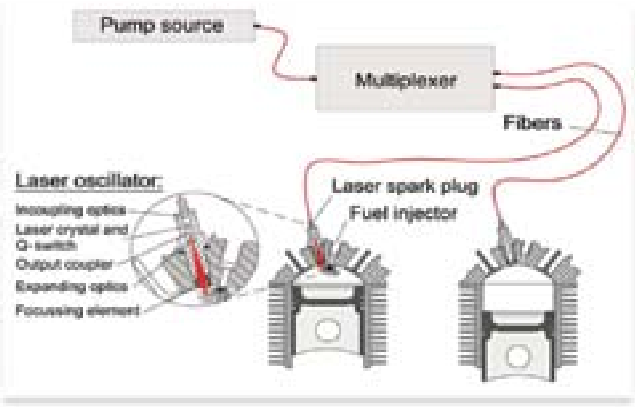

Fig. 3 Temperature stablization

## VIII. CONCLUSION

In this paper we showed that Diode Pumped Solid State (DPSS) Laser technology is suitable for engine ignition application. A Multiplexing approach that distributes the output of a single laser to various engine-cylinders was identified to be suitable and the development of the related components was pursued.

The energy per pulse was reduced from 20 to 4 mJ with successful ignition. However, 7–8 mJ proved to give combustion with no misfires and no laser damage to the optical surfaces. Reducing the amount of energy for combustion is desirable to allow delivery via an optical fibre. A reduced energy solution however must obtain successful ignition with no misfires and no damage to the optics. A solution to this would be compact high powered lasers that can operate at sufficient repetition rates.

The result was that the engine was run with LI with no misfires. Extending the pulse length did not affect the combustion; however, it reduced the damage to the optical surfaces. The laser ignition occurs at approximately 4 mm from the top of the cylinder wall which is the optimal location for the conventional spark plug. Optimal focal points in different technology engines may however be in locations unobtainable by conventional spark plug electrodes.

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