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Laser Ignition of an IC Test Engine using an Nd: YAG Laser and the Effect of Key Laser Parameters on Engine Combustion Performance

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Abstract

The 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. Yet, the practical implementation of this laser application has still to be fully realised in a real world engine environment. Laser Ignition (LI), as a replacement for Spark Ignition (SI) in the internal combustion (IC) engines of automotive vehicles, could offer several potential advantages in terms of extending lean burn capability, reducing the cyclic variations between combustion cycles and reducing the overall ignition package costs, weight and energy requirements. The continued development of increasingly compact and efficient laser sources and new associated laser beam delivery techniques have provided the basis for significant steps forward in research towards practical proof-of-concept demonstration of LI in engines for automotive vehicles. This paper reports on some results of research recently undertaken at the University of Liverpool, in which a Q-switched Nd:YAG laser operating at 1064 nm wavelength has been used to successfully ignite and run (for extended periods) one cylinder of a 4-cylinder internal combustion (IC) test engine. The variation of several laser parameters and their effect on the engine performance are reported; namely, pulse energies of 5-20 mJ, pulse lengths of 6-15 ns and focused beam waist diameters at the combustion point of 40-100 μm. Engine performance was measured in terms of changes in Coefficient of Variation (COV) in both Indicated Mean Effective Pressure (IMEP) and the Peak Cylinder Pressure Position (PPP).

1. Introduction

There have been a number of studies into different aspects of laser ignition (LI) that may generally be divided into studies of the general mechanisms of laser ignition phenomena [1] and more specific studies relating laser ignition to individual applications. Published application based studies of laser initiated combustion phenomena are often associated with natural gas engines, but only a few papers address potential automotive internal combustion (IC) gasoline engine applications [2, 3].

For laser breakdown, due to photoionisation irradiance, fluence in excess of 10^{12} W/cm^2 is required [4, 5]. Conventional spark ignition (SI) by means of an electric spark plug is achieved with ignition systems supplying energy in the range 30-50 mJ. Some early theoretical studies [6] indicate that ignition of a stoichiometric fuel-air mixture might be achieved with a minimum ignition energy (MIE) as low as 0.2 mJ. However, the real values obtained in practice are greater and depend on the air-fuel ratio (AFR), pressure, temperature, turbulence and mixture distribution within the combustion chamber. Laser ignition of an air-fuel mixture can be achieved by one of four principal mechanisms:

1. Thermal initiation: Laser ignition from a heated surface: a high power laser pulse is focused onto an 'available' surface (metal or carbon). The glowing surface ignites the air-fuel mixture. For each ignition, some micrograms of the surface will be evaporated, suggesting surface wear and maintenance issues for this approach.

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. The laser energy decreases when the pressure is increased. To obtain laser induced breakdown in a gas, a laser power density in excess of 10^{11} W/cm^2 interacting with the gas mixture is required to cause breakdown due to photo-ionization. Q-switched Nd: YAG laser operates in the ns regime, so if the energy per pulse is 10's of mJ, then the laser beam would have to be focused to a minimum waist diameter of the order of microns to achieve the above irradiance.

3. Resonant breakdown. – Similar to non-resonant breakdown, this involves non-resonant multiphoton photodissociation of a molecule and is followed by resonant photoionisation of an atom. The electrons that are produced by the resonant multiphoton photoionisation process lead to breakdown similar to non-resonant breakdown.

4. Photochemical ignition. – A single photon, in UV, is absorbed by molecule and causes dissociation. This process does not involve photoionisation and does not lead to breakdown. There is little direct heating of the gas, but the dissociated species may be in thermal non-equilibrium and may combine with themselves or other molecules. This leads to thermal energy being released at this stage. The energy

required for this process is 10^{14} W/cm^2, which is much higher than that required for the non-resonant breakdown mechanism.

If the laser beam is Gaussian (i.e. having a beam quality factor M^2 equal to 1, indicates a true Gaussian beam), the following standard relationship for the focusing of the beam applies:

$$d_{\min} = \frac{4M^2 f\lambda}{\pi D_L} \quad [1]$$

Where $d_{\min}$ is the diameter of the minimum waist, M^2 is the beam quality factor, f is the focal length of the focusing lens, λ is the wavelength of the laser and D_L is the diameter of the laser beam incident on the focusing lens.

It follows from equation (1) that a large value of D_L will give a small minimum waist.

The primary objective of this study has been to investigate, the development of a working laser ignition system on a test engine and then to evaluate the potential benefits of laser ignition compared to conventional spark ignition. Considerations would here include the less invasive nature of the laser ignition system and effects on engine combustion cycle to cycle variation (CCV). CCV is routinely evaluated through Coefficients Of Variation (COV) analysis of variables that are correlated with CCV. A strong combustion cycle will produce higher temperatures and pressures and, if engine knock occurs, it will occur first on the strong combustion cycles when pressures become so high that in some regions autoignition may occur. Weak, slow burning, cycles define the other end of the scale. The weak cycle becomes the misfire which leads to engine stall, or in less extreme cases, the weak cycle is merely inefficient and produces excess hydrocarbon emissions. It may be advantageous to acquire CCV data in engine operation in order to attempt to minimise cyclic variations and so increase efficiency. Such a minimum variance approach has been demonstrated using Peak cylinder Pressure Position (PPP) as an indicator of CCV [7].

Cycle to cycle variation in combustion occur routinely within combustion engines. These variations are due to such things as the differences in the precise fuel/air ratio near the ignition, in the precise ignition timing, in the formation of the flame kernel at combustion initiation. The transition between flame initiation and flame propagation will be affected by the turbulent flow of the fuel air mixture around the electrodes of a spark plug. Spark in the experiments was set to occur, 30° Before Top Dead Centre (BTDC). The PPP occurs after top dead centre (ATDC). The variation in the location of the peak in cylinder pressure is an indication of the degree of CCV. A standard method of measuring in-cylinder combustion is indicated mean effective pressure (IMEP). The coefficient of variation in IMEP is an industry standard method of assessing the degree of CCV and can be quoted as a percentage. IMEP is less indicative of CCV than PPP. However, PPP is not an industry standard and so both are presented here. Increased $\text{COV}_{(\text{IMEP})}$ or $\text{COV}_{(\text{PPP})}$ indicates an increase in CCV [8]. Increased CCV is generally undesirable in IC engines as this limits the amount of Laser Advance or Spark Advance (LA/SA) that may be used and so limits the overall efficiency of the engine. IMEP has the units of bar (pressure), while PPP has the units of degrees ATDC (position).

The COV of IMEP is defined as:

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{IMEP} \times 100 \quad [2]$$

Where COV_{IMEP} indicates the coefficient of variation in IMEP, σ_{IMEP} is the standard deviation in IMEP, and imep is the mean IMEP. One advantage of using IMEP is that a reduced sampling rate, for example at every 20°, still allows its accurate determination [9]. This has advantages in industrial applications because a reduced sampling rate also reduces costs. However, determination of IMEP is highly sensitive to crank phase errors, which a measure of COV (PPP) would be less susceptible.

2. Experimental

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. an almost Gaussian beam profile) with low $M^2 < 2$. Energy up to 20 mJ per pulse was available. The maximum repetition rate is 50 Hz. Initially tests were conducted using a pulse length of 6-8 ns, which is the standard pulse length for this laser when operated in Q-switched mode, but was then increased to values in the range 12-16 ns by extending the optical cavity length. An Agilent 54641A oscilloscope and an Alphalas UPD-300IR1 photodiode (operated between wavelengths of 800 and 1800 nm and having a rise time of <300 ps) were used to measure the pulse length by the Full Width Half Maximum value (FWHM). The fast photodiode shows the temporal shape of the pulse, which includes the non Gaussian 'modes' of the laser. The extended laser cavity also reduced the peak power density of the output laser beam, which was found to reduce the likelihood of laser-induced damage to transparent optical elements in the optical train (which had been an issue with the 6ns duration pulses). The 1.4mm diameter output beam from the laser was expanded and collimated using a Galilean telescope, before being further propagated via a turning mirror and a focusing lens to complete the optical train. This optical path was reproduced to the engine cylinder with the appropriate turning mirror(s). A schematic of the experimental arrangement is shown in Figure 2, while a photograph is shown in Figure 1. If the distance between the lenses in the telescope was varied, then the beam propagating to the cylinder would no longer be collimated, but would be either converging or diverging. In either case, the size of the beam incident on a final focusing lens element would then vary, hence also the minimum beam waist at focus according to equation [1].

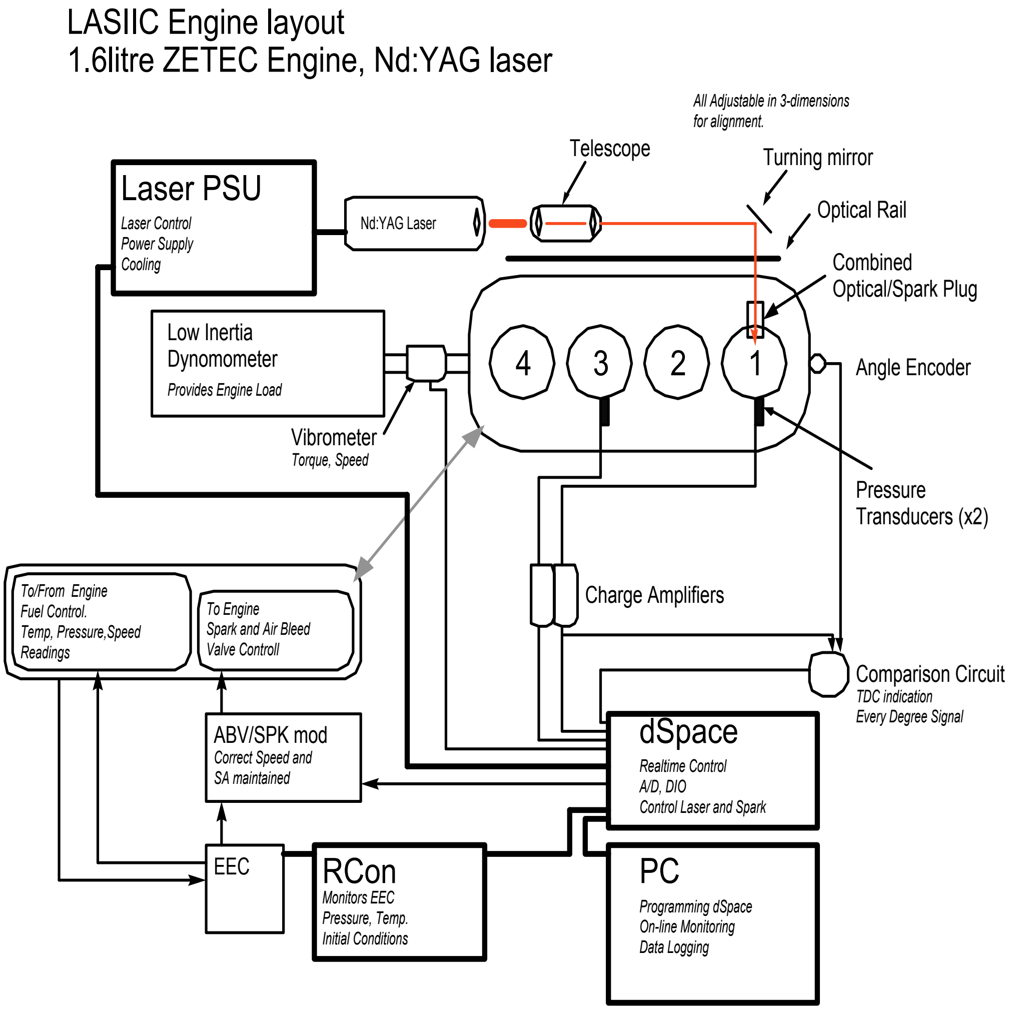

Figure 1. Schematic of the laser and optics on the engine

Figure 2. Photograph of the laser and optics on the engine. The final focusing lens cannot be seen as it is in the cylinder

To verify the viability of the laser ignition concept, an experiment using a specially designed combined electrical spark / optical plug, Figure 3, was devised. The combined plug was a modified Kistler type 6117 combined pressure sensor and spark plug, with the pressure sensor removed. The plug had the focusing lens at the top and a window at the bottom to protect the lens and to prevent pressure waves in the optical cavity.

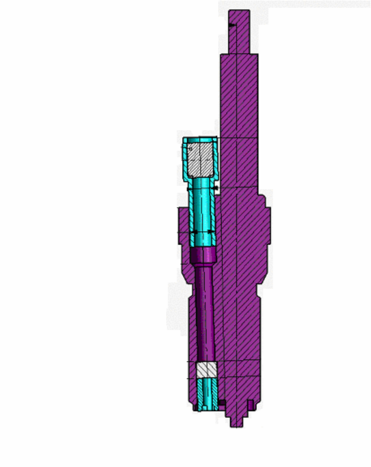

Figure 3. Schematic of dual electrical and optical plug. The optical path has the focusing lens and a window

2.1 Off line optical experiments

For measurement and analysis of laser beam parameters at various locations along the optical train (including beam energy / average power, beam diameter, transverse intensity profiles and divergence), a series of 'off-line' tests were first performed by using a 'dummy leg' test arrangement which mimicked the optical path to the engine. In the analysis of beam diameter and transverse intensity profiles, both near field and far field profiles were obtained. The camera system initially used for this analysis was a Spiricon 100A Laser Beam Analyzer (LBA), and then later an infrared Photon 7290A camera system, with either being placed at different locations along the optical path to obtain intensity profiles and beam diameter [10].

The laser pulse energy, pulse-to-pulse variation and average power were measured using a GENTEC ED-200+ meter with a GENTEC Solo PE monitor laser energy meter and a Ophir 30A-P-RP-NIR head with Ophir Nova display laser power meter respectively. Combining the near and far field profiles with the energy per pulse, energy density was obtained. During engine laser ignition tests, a small percentage of the laser beam was diverted with a beam splitter and used for online monitoring of energy levels.

2.2 Laser, optics and engine experiments.

Once the off line testing had been completed the laser and optics were placed directly onto the engine. The focus of the laser beam was positioned where the electrical spark would occur. This is the optimum position for the engine in use and would give a good position when comparing the performance of the optical and electrical spark plug, when placed onto the engine. The beam path from the laser head to the engine was entirely in free space with optical rails mounted on the engine. Tests were conducted using retarded spark timing, of 5° BTDC and advanced LI to discern whether combustion had been initiated by the laser or spark through observation of the pressure trace.

The laser was triggered via a dSpace digital signal processing unit synchronized with the engine crank. The laser was triggered at a crank angle of 25° BTDC on cylinder 1.

The conventional Spark Advance (SA) was set to 5° BTDC. A normally aspirated Port Fuel Injected (PFI) 1.6L Ford Zetec engine was used for engine testing. The engine was set up in accordance with Figure 1a. Control of the laser system was through a dSpace DS1005 card in a bus linked expansion box. Cylinder pressure data was taken from cylinders 1 and 2 for comparison of SI to LI combustion cycles. During testing cylinder 1 was fired optically, using LI, while cylinders 2, 3, and 4 were ignited using conventional SI. The conventionally fired cylinders were ignited at the crank angle corresponding to the triggering of the laser Q-switch. The laser pulse energy was varied up to 20 mJ until successful ignition was achieved.

Once laser ignition had proven to be successful an optical only plug was designed, Figure 4 and tested off-line. This optical plug replaced the dual spark plug.

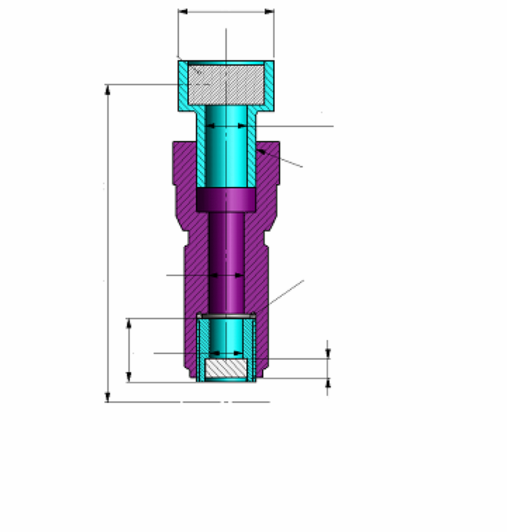

Figure 4. Optical only plug. The focusing lens and the window have been increased in diameter

Ignition was generally successful, but some misfires occurred. It was decided to move the laser off the engine to reduce the vibrations to which the laser was subjected, as this was believed to have contributed to the engine misfiring during testing.

It was then decided to lengthen the pulse by extending the laser cavity in order to reduce the peak power density and so reduce the likelihood of damage to the optical elements which was found to be a problem with 6 ns pulse duration. Also, the time scale of the laser operation is of an order of magnitude higher than an electrical spark and so lengthening the pulse may be beneficial. A photograph of the resulting set up can be seen in Figure 5.

Further investigation of the laser operating range, was undertaken using the optical spark plug. The minimum waist was varied, by using different Galilean telescope settings; also the energy per pulse was varied, until zero misfires were observed, without a secondary spark back-up.

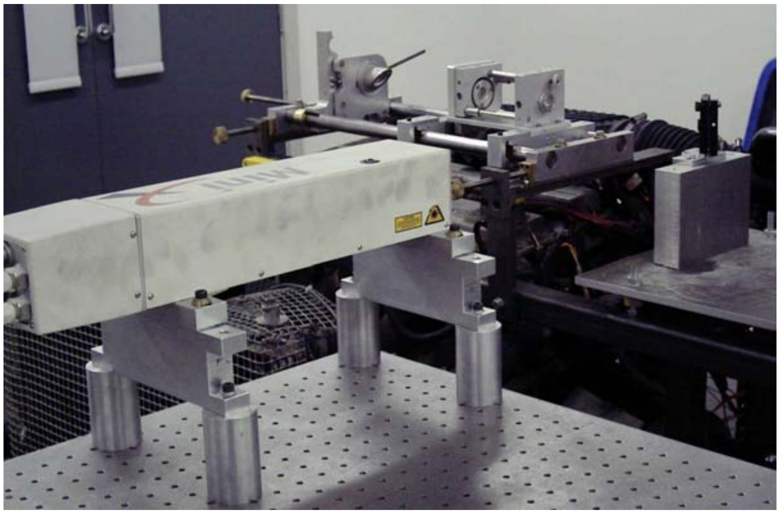

Figure 5. The laser off the engine with the optics on the engine. The final focusing lens cannot be seen as it is in the cylinder

The engine was operated at a laser advance LA/SA of 25° BTDC. Cylinder pressure was sampled every 1° of crank. The engine was operated across a narrow speed range of 1000 to 2000 rpm, (revolutions per minute) with COV data collected specifically at 1500 rpm +/-100 rpm. The engine was operated without load. Cylinder pressure data from over 1000 continuous combustion cycles were used to calculate COV values. The laser beam energy delivered to the cylinder was approximately 8 mJ +/- 0.9 mJ. Tests were conducted at three separate waist sizes; 65 µm, 75 µm, and 85 µm. Tests were also conducted from 5 to 8 mJ.

3. Results and discussion

3.1 Laser and optical system

The pulse width, energy density and variation in energy from pulse to pulse were varied in a series of experiments to characterise the laser ignition system. The pulse width of the laser can be seen in Figure 6.

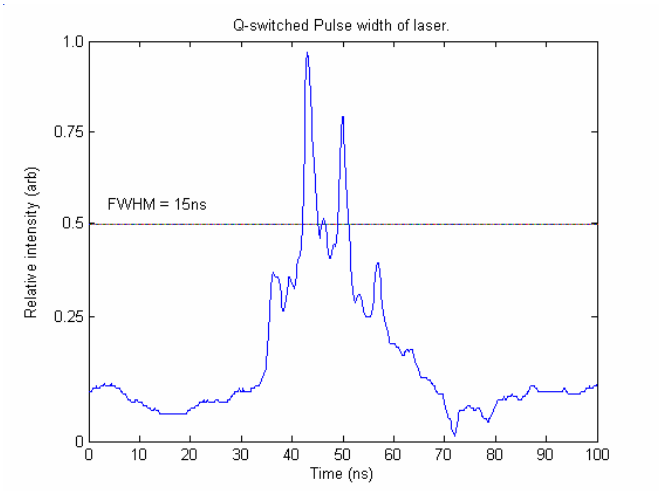

Figure 6. Pulse shape and duration obtained using the digital storage oscilloscope and photodiode

Using the camera based system energy profiles was obtained. Figure 7 shows an ideal Gaussian profile and an experimental energy profile. The beam intensity profile was measured with the camera system to capture the intensity profile and diameters of the beam at various distances along the optical axis, which then allowed calculation of the envelope of the laser beam propagation and provide data to calculate the M^2 parameter of the beam, shown in Figure 8.

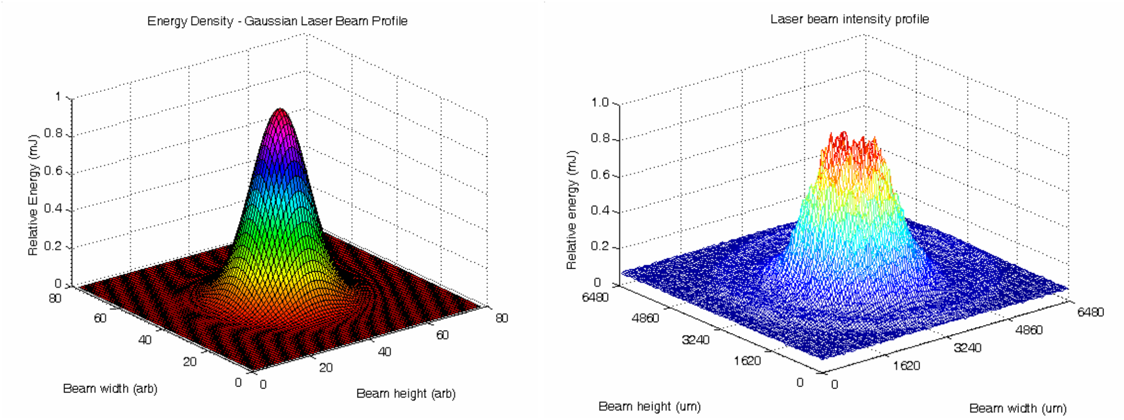

Figure 7. An ideal Gaussian energy profile compared to the experimental laser beam. The camera shows the spatial modes of the laser beam

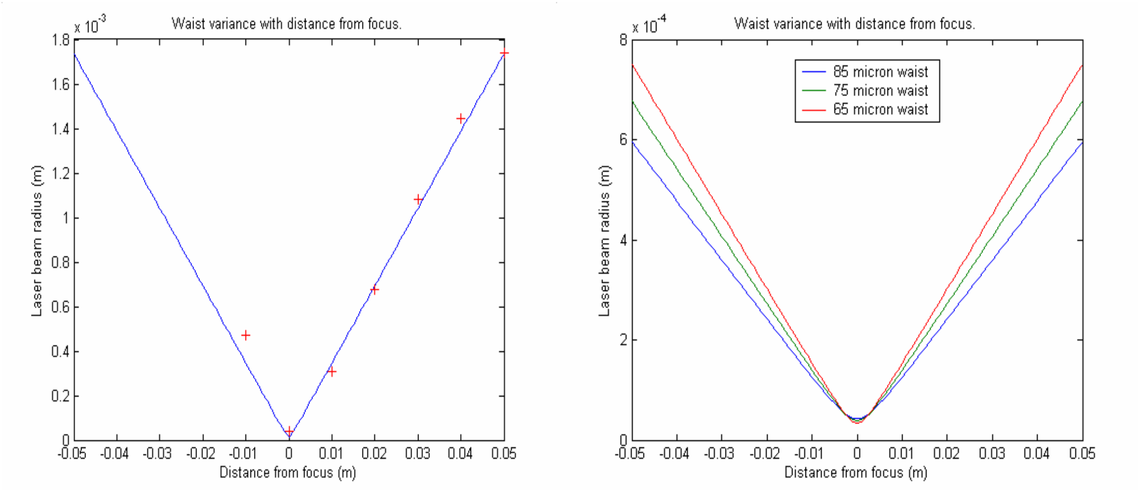

Figure 8. The variation of Nd: YAG laser beam radius from the minimum waist, using a collimated beam and un-collimated beams

The laser parameters show that the laser beam is high quality, having a low divergence, ($M^2 < 2$). The energy per pulse variation was small < 15 %. The energy at the ignition point was 20 mJ to 5mJ, pulse width between 6 and 15 ns, minimum waist between 40 and 85 μm giving energy densities ranges from 1590 to 140 J/cm^2 and peak power density ranges from 256 – 9.39 GW/cm^2. This is an order of magnitude lower than for gas break down, (10^{12} W/cm^2), and is due to the pressure and air/fuel mixture in the cylinder. This is closer the peak power density for non-resonant breakdown laser ignition mechanism (10^{11} W/cm^2).

Once the off line testing had been completed, the laser, the Galilean telescope and the combined plug, were fixed onto the engine. Once successful ignition had been achieved, with the combined plug, the optical plug was tested. Ignition occurred but misfires were evident, at a rate of about 25 %. The laser pulse energy was up to 20 mJ until successful ignition was achieved. Methods of eliminating misfires were investigated. By moving the laser off the engine; the misfires were reduced to about 15 %. An increase pulse length was undertaken, as the time scales for the laser is an order on magnitude faster than the electrical spark. The pulse width initially used was 6-8 ns and after modification to increase the laser cavity, a pulse length of 12-16 ns was obtained. Again the misfires were further reduced to about 2 %. Increasing the minimum waists was then tried, by using different settings on the Galilean telescope. This resulted in misfires being completely eliminated. Thus, the optimum waist and energy per pulse were investigated.

The pulse to pulse variation in energy, (which was < 15%) is shown in Figure 9.

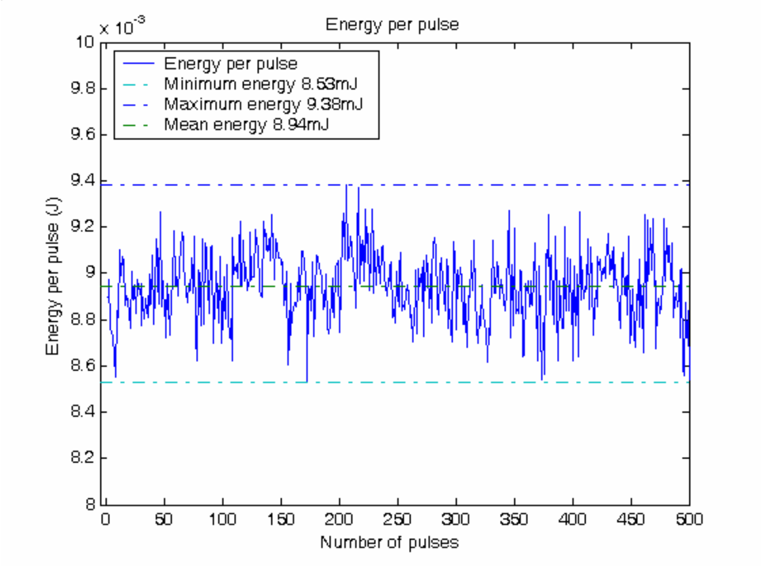

Figure 9. Energy per pulse variation over 500 pulses

3.2 The effect of laser parameters on engine performance.

The pressure traces were observed online and are shown in Figure 10, for the collimated beam with a minimum waist of 40 μm, using the combined spark plug. It is clear that the higher pressure traces are the laser ignited combustion. The electrical spark was significantly retarded, with respect to the laser ignition. This was done so that a spark event always occurred and to prevent the build up of soot.

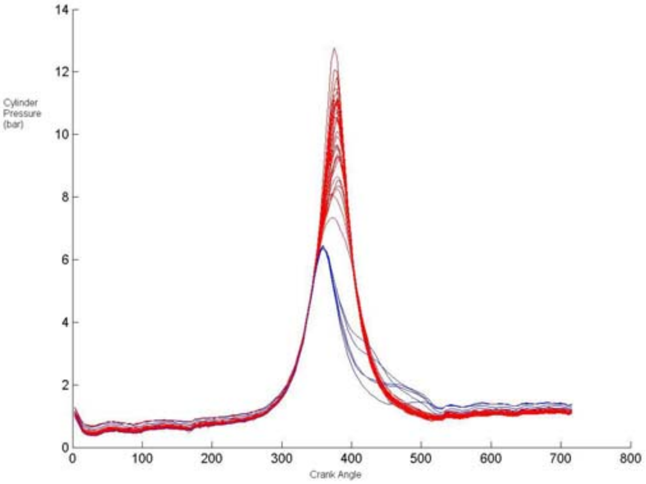

Figure 10. Combined optical spark/pressure traces. The electrical spark can clearly be seen to have been retarded compared to the laser spark. The pulse energy was a maximum of 20 mJ

The engine was run at 1200 rpm. This equates to the laser operating with a repetition rate of 10Hz. The engine speed was further increased to 2000 rpm, which equates to a repetition rate of about 17Hz. Running the engine at 4000 rpm, (~35Hz); was on the limit of flash lamp laser operation. The laser became unstable above 35Hz.

Un-collimated beams waists of 65, 75 and 85 µm, with a constant energy, were used to obtain COV (IMEP) and COV (PPP) graphs, which are seen in Figure 11 and 12.

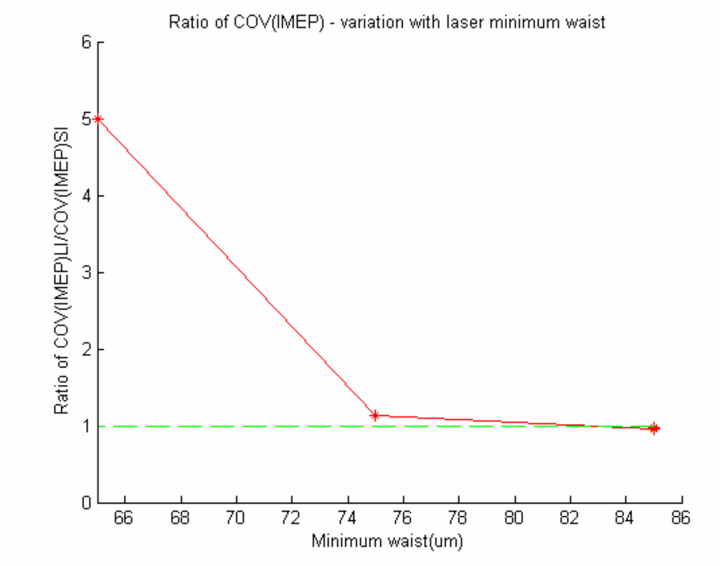

Figure 11. Laser ignition and electrical spark ratio of COV (IMEP) versus minimum waist. This was achieved with different minimum waists ranging from 65 to 85 μm. Larger waists induced laser damage on the window

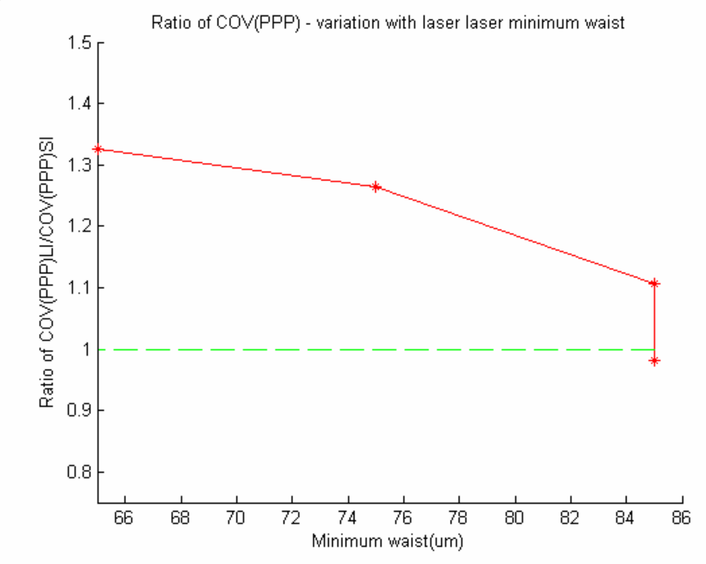

Figure 12. Laser ignition and electrical spark ignition ratio of COV (PPP) versus laser minimum waist

The effect of maintaining a fixed energy level while altering the waist size may clearly be seen in Figures 11 and 12. In these Figures the ratios of the COVs for LI and SI are shown to simplify comparison. As the minimum waist is increased, the ratio of COV (IMEP) and COV (PPP) tend towards one. This indicates that the laser ignition is comparable to that of spark ignition and in some cases better. The CCV is not constant, as can be seen in Figure 12, as two sets of data produce different ratios of COV (PPP), at a given minimum waist. There will logically be an upper limit to this i.e. a waist size at which ignition will no longer occur, but in the described experimental setup the waist size could not be increased further as damage to optical surfaces occurred.

Using a constant minimum waist, the energy was varied from 5 to 8 mJ, were used to obtain COV (IMEP) and COV (PPP) graphs, which are seen in Figures 13 and 14.

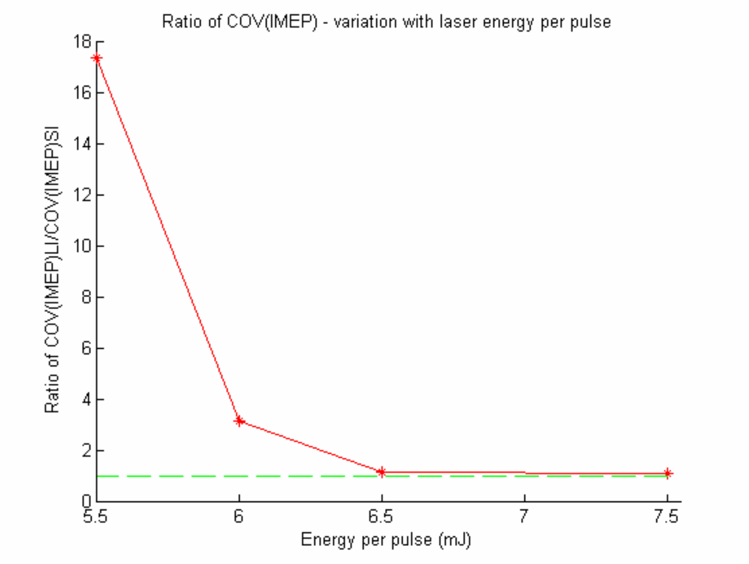

Figure 13. The graph showing the ratio of COV (IMEP) against laser energy

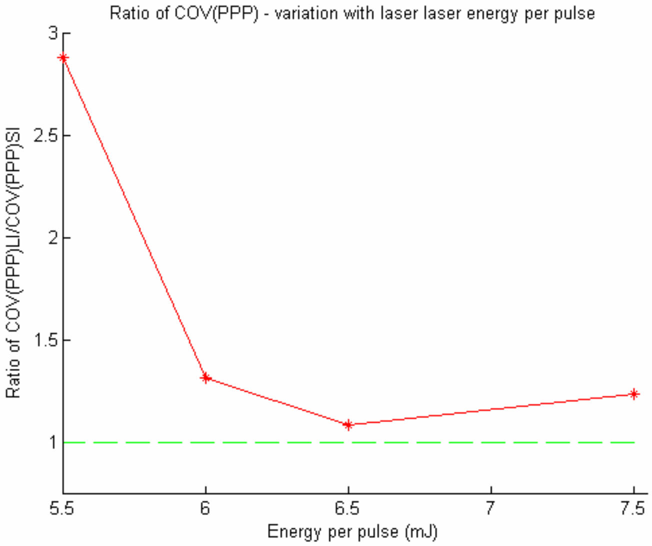

Figure 14. The graph showing the ratio of COV (PPP) against laser energy

In Figures 13 and 14 the power settings, 55 % to 80%, equates 4mJ to 8 mJ. The energy per pulse was also varied with a constant minimum waist. As the energy is increased, the ratio of COV (IMEP) and COV (PPP) tend towards one, which is a similar performance to spark ignition. In both the COV (IMEP) and COV (PPP) increasing the laser energy has a similar effect, when comparing Figures 11 and 12. However, there was a limit to how much laser energy can propagate, before laser induced damage of the optical surfaces occurred.

It should also be noted that the collimated beam, at a minimum waist of 40 µm produced misfires. However, the larger minimum waists gave no misfires so the COV graphs could be obtained. This allowed engine runs using LI for several hours.

3. Conclusions

Experiments have been conducted and results obtained on a laser ignition concept for a test IC engine, which has demonstrated successful firing of a single cylinder in continued operation over several hours. Results are reported on the analysis of key laser parameters, laser ignition experiments on the test engine and the effect of key laser parameters on engine performance characteristics. As the laser used had a low M^2 small minimum waists can be achieved. Only one cylinder could be operated up to 3000 rpm. This was due to the repetition rate of the laser.

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.

By optimizing the laser parameters, including minimum waist and energy per pulse, it was possible to provide COV (IMEP) and COV (PPP) values for LI that were at least equivalent to values obtained by conventional SI**.** The result was that the engine was run with LI with no misfires.

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Author Biography.

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