

Strategy to Develop Laser Spark Ignited Hydrogen Car Prototype

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ABSTRACT: This study focuses on development of efficient laser ignited H₂ fueled multi-cylinder prototype car. Pre-ignition and backfire remain the biggest challenges for development of hydrogen engine. This can possibly be overcome by electrode-less ignition technologies such as laser ignition. Especially for hydrogen, safety is mainly a function of storage method used, and both refueling and vehicle storage systems require extensive development. To operate multi-cylinder car engine, either an appropriate indexing system will be developed which distribute one laser into multiple fibers or individual spark system will be used for individual cylinder of multi-cylinder engine.

Aim and objective: The aim & objective of this study is as follows:

- Knocking and electrode erosion could be reduce using electrode less ignition system,
- NO_x emissions can be reduce by increased lean burn limit,
- Lower thermal efficiency improved by lean burning.
- Lower flame speed can be enhanced by using H₂.

I. INTRODUCTION:

Motivation and genesis: The ongoing effort to increase thermal efficiency while reducing emissions of natural gas spark-ignition engines presents a set of unique problems [1, 2]. The efficiency and power output of an engine may be increased by increasing the compression ratio or boost [3]. But this eventually produces auto-ignition, or knock, in engines. In order to reduce knock, the air-to-fuel ratio must be increased or enriched in hydrogen [4]. Eventually, two limiting factors are reached for a conventional spark plug: the 'lean-limit,' where there is not enough fuel in the mixture to properly ignite; and the declining performance with boosting, which requires higher

spark plug voltages and leads to increased spark plug wear and therefore more frequent replacement and downtime[5]. LI extend the lean-limit, thus reducing the NO_x emissions, and a laser produced spark is more easily formed as pressures are increased. Therefore, laser ignition is a promising alternative to spark plugs for higher engine efficiency and lower emissions [6]. Both gaseous fuels and laser ignition system are emerging technologies to counter the stringent emission norms which are evolving non-stop worldwide[7]. Laser ignition system is not new to IC engines. Their application started long back in the late 1970's. Till date, various research groups are trying to find its feasibility. There are several research papers indicating the use of various lasers types, difference delivery methods, and multiple fuels, for overall improvement in engine operations and reducing the emissions. The first demonstration of plasma breakdown of air using a frequency-tripled Q-switched ruby laser pulse was reported in 1962 [8]. In 1969, LI of chemically reactive gaseous mixtures was investigated in a combustion chamber (or 'explosion bomb') by Knystautas et al. [9]. For this, they used a Q-switched ruby laser along with saturable absorber (SA) dye cell, which yielded 10 ns pulse. The minimum ignition energy (MIE) was found to be 1.2 J. In 1971, Weinberg et al. [10] performed combustion of stoichiometric methane-air mixtures in a combustion chamber using a passively Q-switched ruby laser (30 J/20 ns). Flame kernel growth was studied as a function of pressure and composition using schlieren technique. The plasma front facing the incident beam absorbed the incoming energy already in excess of the minimum ignition energy, and the formation of a blast wave, which may be powerful enough to initiate a detonation rather than a deflagration. Compared to conventional spark plug, laser spark plug initiated plasma with shorter pulse duration and higher energy per pulse, which resulted in

smaller volume plasma. Therefore plasma formed by laser was more intense, used lower MIEs and exhibited smaller quenching distance.

It was observed that LI delivered improved combustion stability (COV_{IMEP}) and could ignite leaner air-fuel mixtures, compared to SI. The many studies on combustion characteristics of LI included a review and comparison of initiation processes in SI and LI by Ronney in 1994 [11]. It was also reported that LI provided free choices of spark position and timing, faster burning and expansion of product gases at low temperatures (minimizing NO_x production). These fundamental aspects were reviewed by Bradley et al. in 2004 [12] and by Phuoc in 2006 [13]. Other important aspects of LI were reviewed more recently by Tauer et al. [14], Morsy [15] and Dearden et al. [16]. These identified the need for compact LI sources, robust enough to work reliably in adverse conditions of pressure, vibration and temperature and that can be installed directly on an engine, similar to SI plugs.

In 2009, Kroupa et al. of Carinthian Tech Research AG in Austria developed a spark-plug like laser (HIPoLas®), based on side pumping of discrete Nd:YAG and Cr⁴⁺:YAG, and reported on the use of their first prototype in a single cylinder engine [17]. Composite Nd:YAG/Cr⁴⁺:YAG lasers, end-pumped by fibre-coupled diode lasers, were investigated in Japan by the Laser Research Centre, IMS, Okazaki with Nippon Soken, Nishio and in Austria at the Technical University of Vienna. The IMS team in Japan then reported on an Yb:YAG/Cr⁴⁺:YAG ceramic laser in 2013 [18]. In 2013, a review of high-power fibre delivery research for LI applications by Yalin [19] concluded that fibre beam delivery methods and the realization of combustion initiating sparks still faced numerous technical challenges. Key issues were the transmission losses due to bending and lifetime of various fibre types. Multiplexed fibres can reduce the number of lasers necessary for LI of an engine and therefore were considered of future interest.

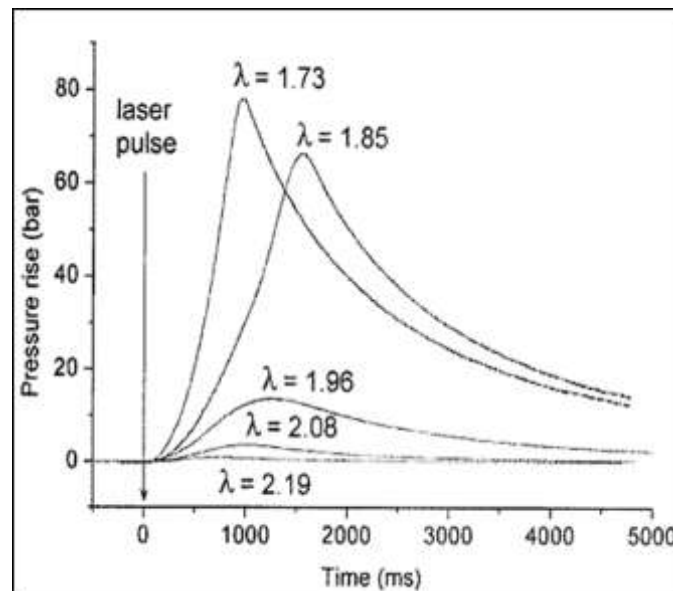


Fig. 1: Effect of Air-fuel ratio [14]

Kopecek et al. [20] found that the breakdown threshold decreased as the pressure inside the combustion bomb was increased and the

presence of fuel did not affect the energy required for breakdown of the fuel/air mixtures (refer Fig. 1).

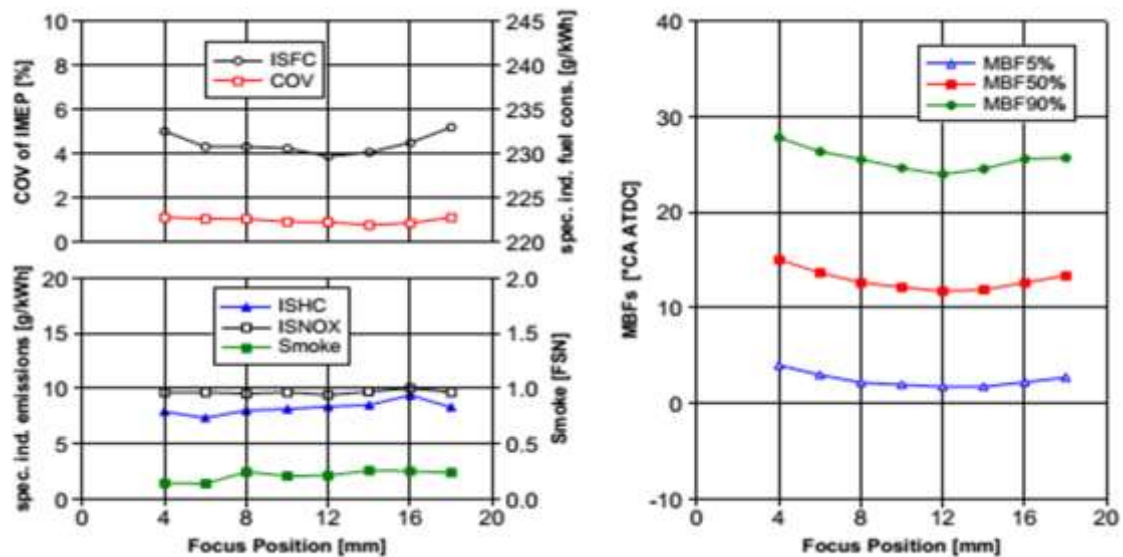


Fig. 2: Variation of the focus position at $n = 2000$ rpm, IMEP = 8 bar, homogeneous mode, $\lambda=1.0$, w/o EGR [15]

Weinrotter et al. [21] investigated effect of plasma position on engine performance and emissions (Fig. 2). It was observed that these parameters were optimum at a typical plasma position (12 mm) without EGR at 2000 rpm engine speed, IMEP of 8 bar, and $\lambda=1.0$. Any practical LI system needs to deliver the laser beam into the combustion chamber in a robust and reliable way. Open beam path approach has several disadvantages such as poor alignment stability, problem of contamination of the mirror and lens surfaces, and safety related issues to technicians with high-power lasers. One way of mitigating these disadvantages, attach individual laser in a direct line of sight into the chamber through any needed focusing optics. To ensure maximum flexibility and the ability to distribute one laser source to multiple cylinders, a closed path, fiber delivered laser ignition system is preferred. For this a multiplexing system is the desirable alternative by which one laser may be used to ignite multiple cylinders. For successful implementation to real engines optimize methods for multiplexing, for aiming the laser at multiple fibers at the right time, and for countering the problems associated with varied optical component. There are a few technical aspects, which must be resolved for practical application of LI in production grade engines. These are:

- Long-term endurance test of optical windows should be performed, which are used to allow laser beam transmission into the engine combustion chamber. Optical windows must be durable enough

to withstand harsh conditions such as high in-cylinder pressures and temperatures prevailing in the combustion chamber for a very long period of time.

- Development of a closed-loop mixture control system with ECU mapping, which can optimize fuel composition, vary the spark timing according to the hydrogen being used and the engine load.
- LI systems have to be mass produced so that the costs come down significantly, in order to make it commercially viable. A compact laser design is therefore essential pre-requisite in order to reduce its size equal to conventional spark plug. Hence, it is necessary to develop a passively Q-switched Nd:YAG/ Cr:YAG composite microchip laser, which can yield laser pulses of sufficient energy for application in a multi-cylinder engine.
- Diffractive optical elements could be used to create plasma at multiple locations within the combustion chamber. This can be also achieved by variable telescope which is relatively simple method of dynamically varying the ignition position.

National (Indian) Status Review

In India, only IIT Kanpur performed dedicated efforts to implement laser ignition in internal combustion engines. Engine Research laboratory, IIT Kanpur started laser ignition in 2006. Initially, laser ignition of compressed natural gas (CNG) was experimentally investigated in a custom-build constant volume combustion chamber (CVCC) to know the laser beam characterization, effect of pressure, pulse energy and plasma

position on flame kernel evolution and development. Information obtained from CVCC experimental results helped a lot to run CNG operated single cylinder engine. After that, engine was operated with Hydrogen with proper safety arrangement. In 2015, engine was modified to run on supercharged mode and fuelled with dynamic blended (in volume percentage) Hydrogen and Compressed natural gas mixtures in any proportion and achieved negligible emissions especially NOx. Till now, ERL, IIT Kanpur completed two successful projects on laser ignition and will be ready to move forward to implement laser ignition for multi-cylinder engines in automotive cars.

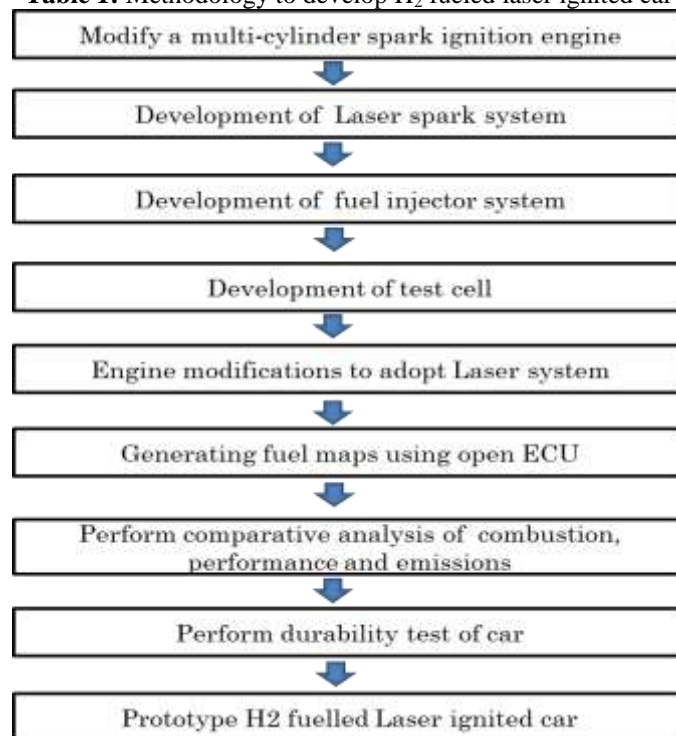
Current status and open questions: Any practical LI system needs to deliver the laser beam into the combustion chamber in a robust and reliable way. In an open beam path approach, in which mirrors are used to guide the laser beam into the cylinder through the open air. Unfortunately, this method has several disadvantages: (i) poor alignment stability, (ii) problem of contamination of the mirror and lens surfaces, and (iii) safety related issues to technicians with high-power lasers. Therefore, some means of mitigating these disadvantages must be found. One way of accomplishing this is to attach individual laser in a direct line of sight into the chamber through any

needed focusing optics. To ensure maximum flexibility and the ability to distribute one laser source to multiple cylinders, a closed path, fiber delivered laser ignition system is preferred. For this a multiplexing system is the desirable alternative by which one laser may be used to ignite multiple cylinders. For successful implementation to real engines optimize methods for multiplexing, for aiming the laser at multiple fibers at the right time, and for countering the problems associated with varied optical components placed along the high power beam path.

Justification and novelty – 'what is new': This proposed strategy is a step towards clean environment by reducing engine NOx emissions and GHG reduction using H₂ with efficient laser ignition system. Laser combustion is stand at the most advanced stage of research now a day and need to control few critical parameters to make it successful. Controlled combustion using laser plasma with slight engine hardware modification is the main key to make it possible towards first application in real world.

Experimental Setup & Methodology: A multi-cylinder SI engine will be modified to operate on H₂ fuel under SI and LI modes. The overall methodology is shown in table 1.

Table 1: Methodology to develop H₂ fuelled laser ignited car



Initially, a multi-cylinder engine will be selected and modified it to accommodate laser spark plugs and a pressure transducer. The second step is the design of laser spark plug which consist a converging lens and a window. The inlet system

will be modified to run using port fuel injection system. After that, the experimental test cell will be developed to compare the performance and emissions under LI and SI modes.

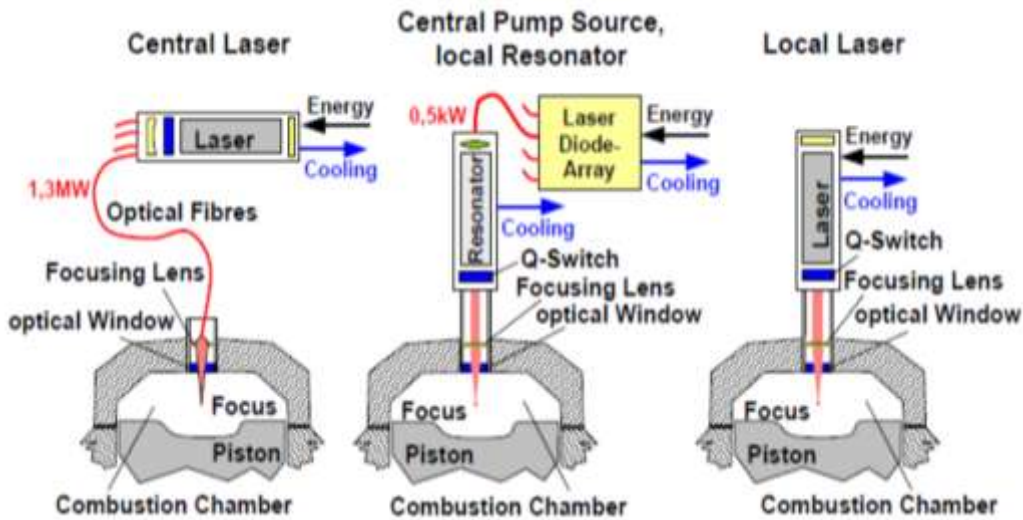


Figure 1 (a): Different approach for laser triggered H₂ engine

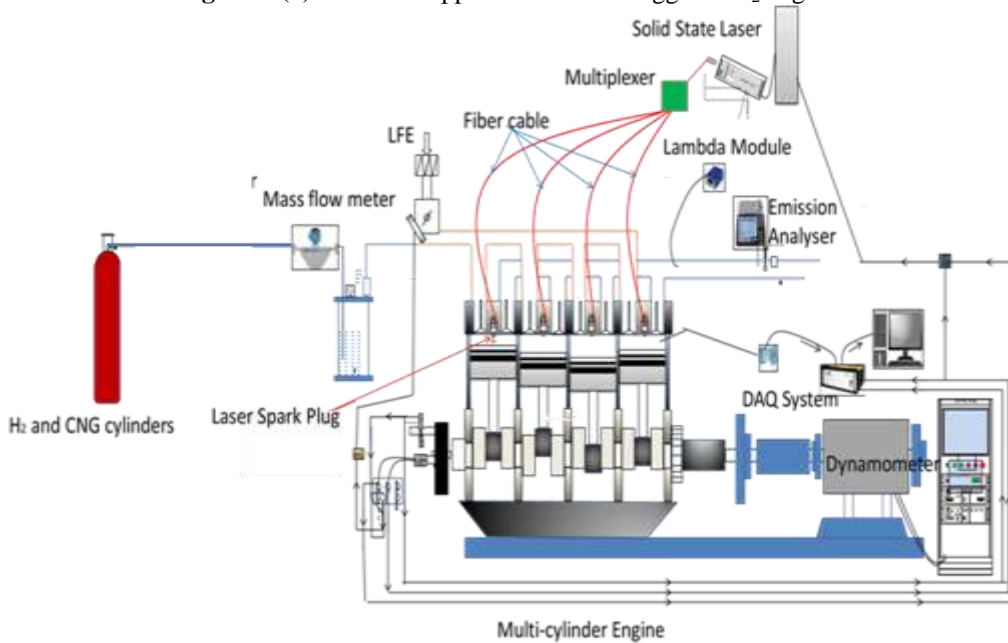


Figure 1 (b): Experimental Setup for laser triggered H₂ engine

Figure 1 (a) shows alternate approach for laser application on engine and Figure 1(b) shows the schematic of the engine experimental setup. The main challenges for planned strategy are to design of laser spark plug, fuel induction system, fuel injection strategy development, multiplexing system, triggering circuit development. A custom built high flow rate solenoid gas injector will be used to supply H₂ into the intake port. Exhaust line

consisted of a lambda sensor, a muffler and two openings for exhaust sampling. For simulating road-like conditions, a dynamometer will be used for loading and unloading the engine. A flame trap or water trap will need to design and fabricate to prevent severe damage in case of backfire and trapping the flames propagating towards the gas cylinders. For practical realization, an improved laser ignition system will be designed, developed

and experimented for automotive application. For this a high power solid state laser will be used as ignition source. To ignite multi-cylinder engine, a multiplexer system will design and develop, which

will placed next to laser and the output fibers at other end. In another approach, individual spark plug will be mounted on each cylinder.

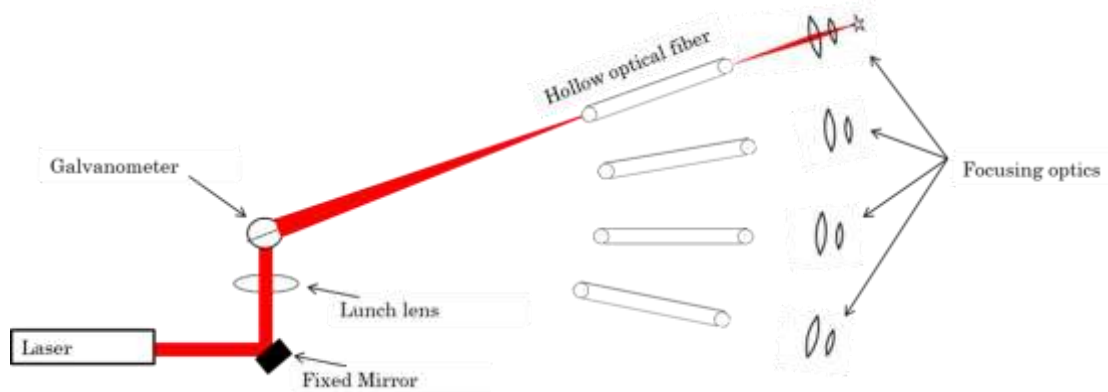


Figure 2: Schematic for multiplexing system to ignite multi-cylinder engine

Figure 2 shows the arrangement of laser, multiplexer system along with optics and fiber cable to ignite multi-cylinder engine. A dedicated optical spark plug will also design and develop to couple and focus the laser beam exists from the fibers into the combustion chamber. At last, durability test is performed to know the reliable operation of laser ignition system and different optics used in it.

In order to prove LI viability as an alternative ignition source, a comparative study will be performed to compare performance and emission characteristics under SI and LI modes.

Pressure vs. crank angle degree plot, rate of pressure rise and rate of heat release will be used to characterize the combustion parameters. Engine performance can be characterized by break thermal efficiency, break specific fuel consumption and exhaust gas temperature. Emissions will be compared based on the concentration of carbon monoxide, oxides of nitrogen and unburnt hydrocarbons in the engine exhaust.

Proposed milestones and time frame: This project will follow the following sequence as shown in table below until completion:

Activity	Months							
	0-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24
Procurement of instrumentation/equipment	→							
Development of test cell		→						
Experimentation			→					
Data analysis				→				
Durability test					→			
H2 fuelled car						→		

Benchmark and specifications of the product: The H₂ fuelled engine will be tested as per BIS VI (or EURO VI) norms and compared combustion, performance and emissions results with baseline gasoline and CNG engines under identical operating conditions.

Target Beneficiaries:

There is tremendous scope for this research in view of pressure for reducing the emissions from automobiles to meet BS-VI norms/ Euro-VI norms by 2020. These norms are going to be increasingly tighter with time. The EURO-VI norm will be effective in India from 2020 onwards. After successful completion of this project, it is expected that automotive industry and stationary gas power generator manufacturers will be interested in taking up the technology developed in this project into commercial production. Prototype of laser ignited Hydrogen fuelled car will be the main deliverable and the technology developed will be applicable to other fuels as well. The automotive industries, both national and international, such as TATA/ Mahindra/ Suzuki/ Ashok Leyland/ Ford/ Volvo/ Nissan/ Ford/ Mercedes/ Toyota etc. are expected to be interested in deployment of this technology.

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