Final Scientific and Technical Report

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Project Title: Practical Fiber Delivered Laser Ignition Systems

Principal Investigator: Prof. Azer P. Yalin (Colorado State University)

Topic (Subtopic): 8(b)

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Problem and Approach:

Improved ignition methods are needed for advanced vehicle combustion systems, in particular those that allow reliable ignition of lean mixtures in gasoline engines at elevated pressures. Laser ignition is a potential technology to address these needs. However, despite more than 40 years of laser ignition research, the technology is not yet in commercial use. The most critical impediment, which we seek to address, is the need for safe, reliable, and affordable laser delivery systems. We are developing a practical ignition system using advanced (kagome) fiber optics for high-power pulse delivery with a very compact laser source. In this way, a single laser source can be multiplexed (shared) to multiple engine cylinders thereby allowing substantially less complex (and lower cost) systems as compared to "laser-per-cylinder" approaches.

Executive Summary of Phase I:

Research has characterized advanced kagome fiber optics for their use in laser ignition systems. In comparison to past fibers used in laser ignition, these fibers have the important advantage of being relatively bend-insensitivity, so that they can be bent and coiled without degradation of output energy or beam quality. The results are very promising for practical systems. For pulse durations of ~12 ns, the fibers could deliver >~10 mJ pulses before damage onset. A study of pulse duration showed that by using longer pulse duration (~20 – 30 ns), it is possible to carry even higher pulse energy (by factor of ~2-3) which also provides future opportunities to implement longer duration sources. Beam quality measurements showed nearly single-mode output from the kagome fibers (i.e. M^2 close to 1) which is the optimum possible value and, combined with their high pulse energy, shows the suitability of the fibers for laser ignition. Research has also demonstrated laser ignition of an engine including reliable (100%) ignition of a single-cylinder gasoline engine using the laser ignition system with bent and coiled kagome fiber. The COV of IMEP was <2% which is favorable for stable engine operation. These research results, along with the continued reduction in cost of laser sources, support our commercial development of practical laser ignition systems.

NOTE: This report does NOT contain proprietary information.

1. Identification and Significance of the problem

1.1 Motivation for Laser Ignition of Advanced Vehicle Gasoline Engines

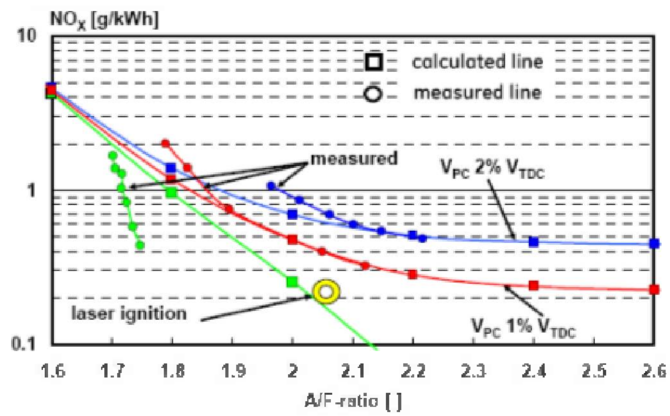

Figure 1. NO_x emissions for laser (yellow circle), spark plug (green), and prechamber (PC) (red circles and blue circles) for a single-cylinder research engine [5]. The engine's coefficient of variation (COV) of peak pressure is held constant at 2% to ensure consistent test conditions.

Laser ignition is of growing interest for a number of applications including reciprocating engines, ground based turbines, aero-turbines [1, 2], rocket engines [3], and scramjet engines [4]. The most substantial research has been for ignition of large-bore reciprocating gas engines as are used for (distributed) power-generation and for pumping and compression of natural gas [5-12], and the PI (Dr Azer Yalin, Colorado State University) and co-PI (Dr Sreenath Gupta, Argonne National Laboratory) have been at the forefront of this field. There are two primary motivations for using laser ignition in reciprocating engines: First, laser ignition tends to allow ignition of leaner mixtures as compared to conventional spark plugs owing to a combination of the lack of flame-quenching electrodes and the overdriven early flame speeds [13] and, second, the engines are trending towards higher-pressures (for higher efficiencies) for which spark plug erosion becomes increasingly problematic (due to higher breakdown voltages). Lean operation of engines is receiving significant attention as a means to increase efficiency while also maintaining low emissions. Figure 1 shows an example of lean operation and reduced engine emissions for laser ignition measured in a single-cylinder natural gas engine. The figure shows NO_X emissions for laser, spark plug, and prechamber. For each means of ignition, as the air-fuel ratio increases, the NO_X reduces [5]. Laser ignition (yellow circle) provides the lowest NO_X of all cases studied (note that the red and blue squares are calculations, while red and blue circles are measurements). For the gas engines, laser ignition has also been shown to provide a 3% improvement in efficiency for a base engine having 31% efficiency, i.e., 9.6% relative improvement [14]. Laser ignition is also, from a fundamental point of view, favorable for high pressure conditions. While spark plug breakdown voltages increase with pressure, the optical breakdown has a reverse dependence meaning that the laser breakdown *decreases* with increasing pressure [15].

Our project team are leaders in laser ignition systems for stationary gas engines, including fiber delivery system, engine testing, and basic research. Our team is, therefore, also strongly positioned to develop related technologies for light-duty gasoline engines. The continuing requirements for improved engine efficiency and compliance with ever stringent emission standards have motivated the light-duty engine manufacturers to look at low-temperature-combustion schemes. Various iterations performed over the last few years have converged on a combination of Gasoline Direct Injection (reduces pumping loss), boosting intake air (improves specific density), and lean-burn combustion (improves efficiency due to higher gamma value).

However, such a combination introduces adverse conditions for reliable ignition using spark plugs [16]. A key challenge is to ignite lean mixtures which are very near their flammability limits. Per a recent Department of Energy annual report [17]: "*Furthermore, reliable ignition and combustion of lean (dilute) fuel-air mixtures remains a challenge. ... Several new ignition systems have been proposed (high-energy plugs, plasma, corona, laser, etc.) and need to be investigated.*"

Recent statistics show that 16-17 million light-duty vehicles are sold per year in the United States; however, after the dramatic improvement of spark plug performance and life with the elimination of tetraethyl lead in the 1970's very little has changed. The recent shift towards engine downsizing by the passenger vehicle industry has provided an impetus for improving ignition system performance. The motivations for using laser ignition for advanced light-duty engines for trucks) are similar to those for stationary engines. Laser ignition, owing to its lack of electrodes facilitates efficient energy transfer from the spark kernel to the flame front. Also, the elevated flame speeds that result from laser ignition and the favorable surface area/ energy of the plasma kernel are capable of extending the lean limit thus providing the needed ignition source. The required ignition source, however, must also be sufficiently reliable, robust, safe, and inexpensive for practical engines. As is further discussed below, these needs strongly call for the use of fiber delivered laser ignition. Competing approaches, based on using one laser source per cylinder, or a multiplexed laser pump coupled to individual gain elements on each cylinder, while technologically viable, are inherently more expensive.

1.2 Challenges for Practical Laser Ignition Systems – Need for Fiber Delivery

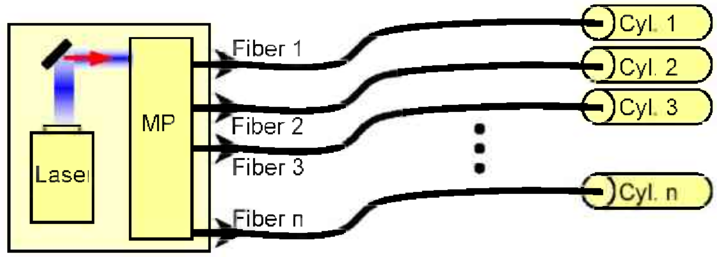

Figure 2. Schematic of multiplexed fiber delivery system proposed here. Such a system uses a single laser and simple multiplexer (MP) device to transmit light to individual cylinders via optical fibers. Such a system will be significantly less complex (and lower cost) relative to competing "laser-per-cylinder" approaches.

Despite the potential benefits of laser ignition, it remains an exotic ignition method that has not been practically implemented for field use or on production engines. As mentioned above, the ultimate ignition system must provide sufficient combustion performance while also being safe, reliable, and affordable. The majority of laboratory research has employed scientific grade lasers as light sources and open-path beam delivery using mirrors to transmit the laser pulse to the combustion volume. While appropriate for laboratory studies, such hardware configurations are clearly impractical for vehicle use owing to lack of alignment robustness, especially in the face of thermal drift and vibrations, and due to obvious safety concerns with the open-path high power beams. To avoid the unacceptable open-path configurations, two main approaches for beam delivery systems have been considered. The first approach, termed "laser-per-cylinder", is based on using multiple compact lasers mounted in close proximity to the ignition locations (engine cylinders). The second approach is to use fiber optic cables to transmit pulses from a single remotely located laser source to the multiple ignition locations. The fiber-based approach shown in Fig.2, and which we propose, has been under development for stationary gas engines by the PI's group at Colorado State University (CSU) for several years. Significant progress has been made including demonstration of fiber delivery with several fibers [7, 18-20], integrated combustion diagnostics [6], and engine testing [11, 20-24]. The present proposal seeks to improve the reliability and performance of such an approach, in particular the fiber optics, and to test it on a representative gasoline engine. Because this approach requires only one laser, it has potential to meet cost requirements; this in stark contrast to laser-per-cylinder approaches which inherently require multiple lasers making them cost-prohibitive for multi-cylinder vehicle engines. We do not emphasize research on the multiplexer since switching the light to the different fibers is quite straightforward and has been demonstrated by our group [11, 25] and other researchers including Woodruff and colleagues at the National Energy Transportation Laboratory – such research will be included in a Phase II effort.

We provide a short overview of research on reliable industrial lasers suitable for ignition. While, in our view, the use of these lasers in laser-per-cylinder implementations is cost-prohibitive, similar lasers are of interest as the sole laser in our approach. Lasers are being developed that meet the technical requirements (pulse energy, beam quality, repetition rate etc.). The cost of such lasers has been falling strongly in recent years and one can expect a future cost of ~$300-$2000 in several years if purchased in volume. (This projection is based on the raw-material cost trajectories of the main components, i.e. Nd:YAG rod and passive Q-switch crystal.) In a multiplexed fiber system, considered in large volumes, the fibers may be ~$100-1000 (depending on type of fiber) leading to an overall system cost of~$500-2,000. In comparison, for a 6-cylinder engine with the laser-per-cylinder approach an optimistic cost would be ~$6,000 which is likely prohibitive for vehicles. (Note that while some of these lasers are being explicitly developed for laser ignition, they are aimed at large stationary gas engines where significantly higher cost can be tolerated.) Also note, as is further discussed in the Commercialization Plan, the allowable cost of a laser ignition system should consider the benefits it provides (e.g. improved engine efficiency and fuel-savings) and not be limited to direct comparison with today's spark-plug systems.

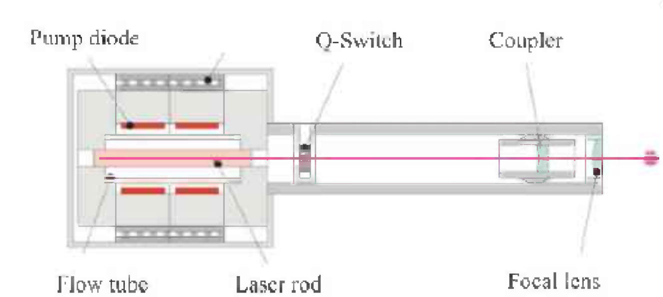

Figure 3. Schematic of compact laser, designed for laser-per-cylinder approach to laser ignition, of Kroupa et al. [23]. See text.

The compact lasers being developed for ignition applications are typically passively Q-switched Nd:YAG lasers using diode pumping. For example, as shown in Fig. 3, Kroupa et al. [26] have developed a compact source with a side-pumped configuration consisting of a pump ring with several high-power diodes arranged radially around a cylindrical laser rod. Tsunekane and colleagues have also developed diode pumped Nd:YAG lasers for ignition applications [27, 28]. A similar group of authors has more recently reported on diode pumped laser that uses ceramic materials for the Nd:YAG rod and Cr:YAG passive Q-switch [29]. Related approaches use a single laser pump source to fiber deliver pump light to multiple engine cylinders (thereby at least lower cost and complexity by sharing the pump) but they still require an active laser gain element (and Q-switch crystal) on each cylinder. McIntyre et al. [30] have developed such a system using a fiber coupled 400 W diode pump to pump individual Nd:YAG rods that would mount on each cylinder, while Kofler et al. [31] have also developed an end-pumped Nd:YAG laser using a fiber-coupled diode array with 600 Watt pump power. The use of vertical cavity surface emitting lasers (VCSELs) are also being developed as pump sources for solid state lasers [32], owing to their improved thermal stability and efficiency at elevated temperatures, but this approach is also cost-prohibitive for vehicles as it requires an Nd:YAG gain element on each crystal.

1.3 Past Research on Fiber Optic Delivered Laser Ignition

In this section we discuss the challenge of fiber optic delivery and past research (prior to our Phase I) in this area. Results from our Phase I effort are described below. While fiber optic delivery is clearly attractive, the use of fibers is challenging owing to the need to transmit high peak-power Megawatt (MW) pulses with relatively high beam quality (low M^2). Indeed, the lack of success with conventional step-index fibers [1, 7, 10, 33-35] has been a main factor spurring the development of the abovementioned laser-per-cylinder approaches.

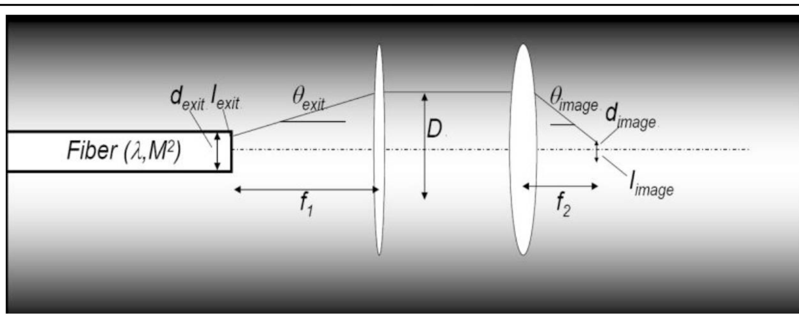

Figure 4. Schematic diagram showing the parameters specifying the fiber output and focused spot size.

Figure 4 shows a schematic of light exiting the fiber from which one can find requirements for the fiber output parameters and focusing [7]. A first essential requirement for fiber delivery is to reliably transmit high peak-power (megawatt) pulses with sufficient beam quality (low M^2) to allow refocusing of the output beam to an intensity exceeding the breakdown threshold of the gas, i.e., $I_{BD,Air}\cong$100-300 GW/cm^2 for 10 ns, 1064 nm pulses at atmospheric pressure, and scales with pressure as ~ $p^{-0.5}$ [12, 36]. Typical fuel-air mixtures of interest have air volume fraction >90% so that the breakdown threshold is comparable to that of pure air. A second essential requirement is to deliver sufficient laser pulse energy to exceed the minimum ignition energy meaning >~10-20 mJ for the case of gas engines [9, 37].

If one considers conventional solid silica fibers (similar to those used in telecom) then relatively large (~100-1000 μm core) multi-mode fibers are needed to deliver the required pulse energies, since smaller cores would damage due to the high intensity. But there is a trade-off which is that with the larger cores the output beam quality (and ability to focus the output light to high intensity for spark formation) degrades since more modes are supported in the fiber. Owing to this trade-off it has been very difficult to deliver laser sparks with conventional multimode silica fibers [1, 7, 18] and only limited progress has been made. By paying close attention to the fiber launch and focusing optics, El-Rabii et al. have achieved a sparking rate of <1% in air at atmospheric pressure (increasing to 90% in air at 6 bar) with a demagnification of ≅10 using silica fiber with 940 μm core diameter [1]. The higher spark rate at elevated pressure is due to the pressure dependence of breakdown threshold mentioned earlier. As discussed below, much more promising results are found from large clad fibers and kagome fibers.

Previous attempts to use multimode solid silica fibers for igniting engines have also been limited [38, 39]. Biruduganti et al. reported use of a 1 mm diameter core regular silica step index fiber to deliver 35 mJ of 532 nm light for igniting a single cylinder natural gas engine [39]. The published details of the optical setup used in their experiment are sparse, though they stated that they could not reliably spark in atmospheric pressure air or start the engine without altering the ignition timing. Mullett et al. used conventional 400 and 600 μm solid core step index silica fibers to operate an engine [38], but reported an ignition rate of only 35% while using 65 mJ pulse energy delivered through 600 μm core fiber, and 8% ignition rate with 50 mJ pulse energy delivered through 400 μm core fiber. They attributed the high misfire rate to poor beam quality at the fiber output.

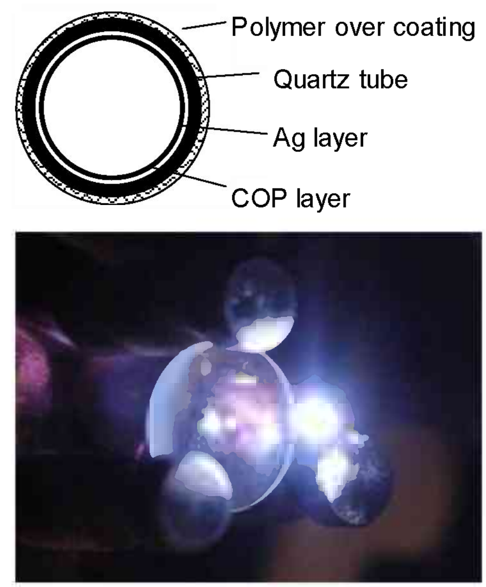

Figure 5. Top: Schematic diagram of coated hollow fiber. Bottom: Photograph of spark formation at output of coated hollow fiber.

Another type of fiber which has been investigated for laser ignition is coated hollow fiber. The PI of this grant showed the first fiber delivery of laser sparks and engine operation (with any type of fiber) using coated hollow fibers [18]. A photograph of an optical spark after delivery with the coated hollow fiber is shown in Figure 5. The fibers used in these experiments were cyclic olefin polymer-coated silver hollow fibers developed and manufactured at Tohoku University (Japan) [40, 41]. The experiments showed breakdown of atmospheric pressure air (spark formation) by 10 nanosecond laser pulses with 32 mJ pulse energies delivered via a 700 μm hollow core fiber having output beam quality of M^2 = 15. However, the practicality of hollow core fibers is limited by the degradation in output beam quality with increasing bending [18]. While the fibers are still of high interest in some applications, we do not further consider them in this proposal owing to the bending losses.

Other recent work at Colorado State University (Prof. Yalin) that has demonstrated the use of large clad silica fibers for spark delivery and engine ignition [19, 20]. The large clad fibers have been developed primarily for material processing applications where high average powers are needed and the large clad helps heat dissipation. Because they are based on conventional silica fiber technology these fibers are very inexpensive (<~$1-10/meter). The benefits of the large-clad fiber can be seen in Fig. 6 which shows beam profiles of the (unfocused) light exiting. The speckle pattern in the beam profile from the regular clad fiber (right of Fig. 6) is due to interference between multiple modes exiting the fiber, while the profile from the large clad fiber (left of Fig.6) is closer to that of single mode light. The improved beam quality of the large clad fibers is attributed to increased mechanical rigidity of the large clad fibers, which leads to reduced mode coupling at the core-clad interface [42, 43].

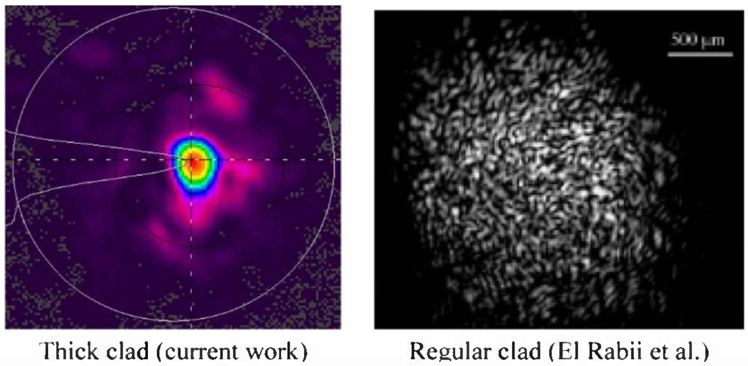

Figure 6. Improved beam quality at exit of large clad fiber. The beam profile on the left was obtained at the output of a large clad fiber while that on the right is from a regular clad fiber of the same core diameter [18,19]. The large-clad fiber has light largely concentrated into a single peak due to its higher spatial coherence, while the latter shows a speckle pattern typical of a multi-mode output.

We have also performed engine testing on a single cylinder gas engine with fiber delivered laser ignition with large clad fibers with length of 2.85 m, core diameter of 400 µm, and clad diameter of 720 µm [20, 24]. The system was installed on a single cylinder engine (Waukesha co-operative fuel research engine) converted to run on bottled methane. The engine was boosted with compressed air so that various loads and air-fuel ratios could be achieved. The final output beam from the optical plug could form sparks in pressures as low as 3.5 bar which guaranteed sparking at higher pressures and allowed engine startup without changing the ignition timing. At higher pressure operation (NMEP or 8 and 12 bars) we found that the laser ignition provided an average increase in fuel efficiency of ~1-2% relative to electrical ignition (corresponding to a relative increase of ~5-15%). It is likely that further increases in laser ignited engine performance may be achieved with higher pulse energy [28]. We also found that the laser ignition extended the lean limit of engine operation [2] and we note that the comparisons of NMEP and efficiency were performed within the lean limit found for the laser, i.e. air-fuel ratios (by mass) of 20, 26, and 32 for NMEP levels of 6, 8, and 12 bar respectively. It is possible that the relatively poorer efficiency and NMEP (at fixed intake pressure) for electrical ignition may be related to the engine being operated overly lean for the electrical ignition.

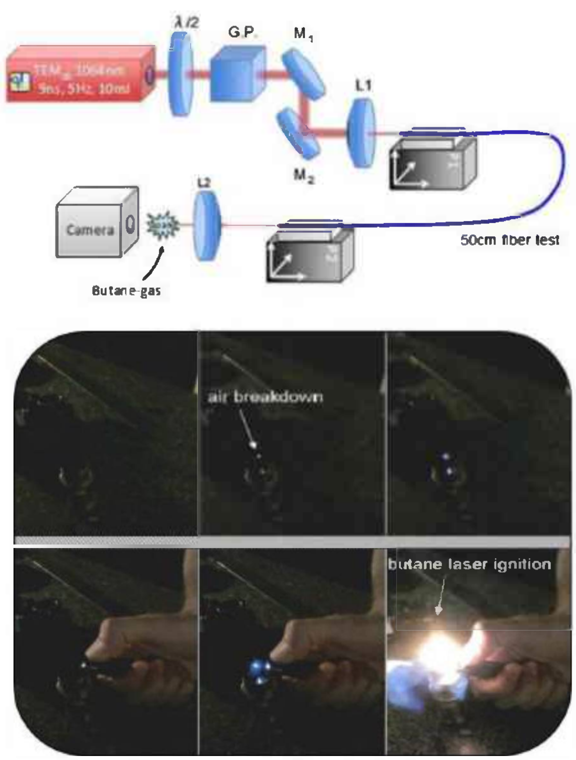

Figure 7. Top: Experimental setup for the laser ignition with kagome fibers (from [34]). Bottom: Spark formation and ignition of butane fuel using output of kagome fiber (from [34]).

Photonic crystal fibers (PCFs) and photonic bandgap fibers (PBGs) employ periodic hole structures within the (silica) fiber material to modify the refractive index in such a way that one has efficient light guiding including single mode operation [44]. Kagome PBG fibers have very recently been shown to ignite of simple butane flames [45]. Our Phase I efforts with these fibers are described below. These fibers feature much lower power overlap with the silica part of the fiber thereby allowing higher pulse energies (while maintaining the single-mode output amenable to tight focusing) [45]. Recent research has investigated two kagome fibers for high power delivery and ignition, one was a single-cell core with a cladding consisting of two rings of kagome lattice with a pitch of 28 μm and strut thickness of 640 nm, while the second was a 7-cell core with hypocycloid shape and three rings of kagome lattice cladding with a pitch of 20 μm and strut thickness of 320 nm – both fibers transmit light in the range ~700-1300 nm making them compatible with the Nd:YAG laser sources being considered for laser ignition.

2. Anticipated Public Benefits

It is well established that the transportation sector, and light-duty vehicles in particular, plays a prominent role in the nation's pollutant emission inventories and energy consumption (dependence on foreign fossil fuels). Given the high importance of possible climate change and environmental impact of engine emissions there is a strong and obvious need for engines with reduced emissions. Similarly, given the high importance of reducing our dependence on foreign energy sources and fossil fuels there is also an acute need to improve the efficiency of vehicle engines. The development of a laser ignition system for lean gasoline engines, as we propose, directly addresses the above needs and therefore would provide a very clear public benefit.

The possibility of laser ignition to provide leaner operation and reduced NOx emissions was discussed in Section 1 of this proposal. To recap, Figure 1 shows an example of lean operation and reduced engine emissions for laser ignition measured in a single-cylinder natural gas engine. The figure shows NO_X emissions for laser, spark plug, and prechamber. For each means of ignition, as the air-fuel ratio increases, the NO_X reduces [5]. Laser ignition (yellow circle) provides the lowest NO_X of all cases studied (note that the red and blue squares are calculations, while red and blue circles are measurements). Benefits of laser ignition for gasoline engines will be investigated in the engine-testing portion of the proposed work but should be similar [16].

Laser ignition has also been demonstrated to provide efficiency benefits which directly translate to fuel saving. For gas engines, project partners at Argonne National Lab have shown that laser ignition provided a 3% improvement in efficiency for a base engine having 31% efficiency, i.e., 9.6% relative improvement [14]. Similarly, past work by the PI's group at Colorado State University found that the laser ignition provided an average increase in fuel efficiency of ~1-2% relative to electrical ignition (corresponding to a relative increase of ~5-15%) – see Section 2.2

3. Overview of Phase I Research

3.1 Fiber Characterization

We have performed both low and high power characterization of the kagome fibers (Section 1.3 and Fig. 7) to assess their use in laser ignition systems. Low power measurements focused on output beam quality using the setup shown in Fig. 8. A continuous-wave (CW) diode laser (Lightwave Electronics A142) provided a 1064 nm beam with power of ~10 mW and beam quality of M^2=1.2. The beam (diameter ~4 mm) was launched into the fiber using a 60 mm focal length plano-convex lens creating a launch with numerical aperture of ~0.03 and focused diameter at the fiber input of 49 μm. The fiber was placed on a nanometer-precision five-axis holder that allowed three translational and two rotational degrees of freedom. The fiber output beam was collimated using a 50 mm focal length lens. Laser power was measured before and after the fiber (with beam-splitters) to determine fiber transmission. A 10x microscope objective attached to a CCD camera was used to image the light exiting the fiber tip. The M^2 of the fiber output was determined from CCD images of the beam diameter (4σ) at different axial positions downstream of a focusing lens [46].

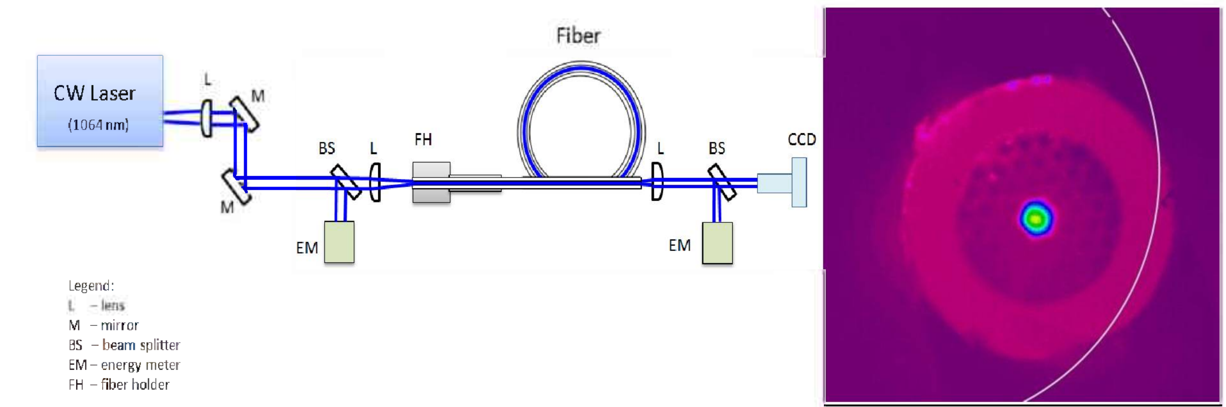

Figure 8. Left: Experimental setup for low power characterization of the kagome fibers. Right: CCD image of laser beam exiting the fiber.

The kagome fiber used for this experiment had a mode field diameter of ~50 μm and a length of approximately 3 meters. The right of Fig. 8shows an image of light exiting the fiber – note the beautiful hexagonal shape of the single-mode output. By carefully optimizing the position at fiber launch we obtained a power transmission through the fiber of 85% with output beam quality factor of M^2=1.24. (The M^2 parameter provides a measure of output beam quality with M^2=1 being the best possible value – as discussed in Section 1.3, low values of M^2 are needed to have sufficiently tight focusing for spark formation.)

Prior to engine testing, we have performed high-power fiber characterizations to consider the maximum pulse energies of the fibers. The setup was similar to that used for low-power testing but the laser was a Q-switched, pulsed, Nd:YAG laser (Continuum Powerlite 8010) at 1064 nm with beam quality of M^2=2. Owing to the poorer beam quality (higher M^2) of this source, a spatial filter was used to improve the beam prior to the fiber launch. The spatial filter consisted of a first lens (2000 mm) to focus light through a pinhole (diameter of 400 μm) after which the light was re-collimated with a second lens to a diameter of ~6 mm providing beam with improved M^2=1.18. Several launch configurations were tested with the best results found with a 125 mm focal length plano-convex lens creating a launch with numerical aperture of ~0.013 and focused diameter at the fiber input of 41 μm. For this launch, the maximum transmission was 93% with output beam quality of M^2=1.24. For the laser pulse duration of 12 ns the maximum output energy (prior to damage) was 11 mJ (see below).

To examine spark formation the light exiting the fiber was tightly focused with an aspheric lens of focal length 10 mm. The conditions described above (for 12 ns pulse duration) could readily form a spark at the focused output, which is expected given that the combination of delivered power and focal spot size yield an intensity exceeding ~300 GW/cm^2. To more fully examine the pulse energies that the fiber can deliver, and the conditions required for sparking, we have varied the laser pulse duration. Figure 9 shows a plot of the energy transmitted through the fiber as a function of the pulse duration (full-width-at-half-maximum). We plot the maximum energy that could be transmitted through the fiber, E_{Max}, and the minimum energy that was required to generate sparks, E_{Spark}, with 100% regularity in atmospheric pressure air (P=0.85 atm, T=298 K in Fort Collins, CO). The maximum energy that the fiber can deliver scales roughly linearly with pulse duration and is limited by fiber damage at the input facet. We were able to transmit as much as 30mJ of energy through the fiber by employing a pulse width of 30 ns. Previous studies on laser ignition have shown that ignition of fuel-lean mixtures requires sparks with ~15mJ of energy, with ignition around the stoichiometric mixture ratio requiring much less (~1 mJ) [47, 48]. Interestingly, while the maximum pulse energy transmitted through the fiber is linear with pulse duration, the energy needed to form sparks increases sub-linearly with pulse duration. This nonlinearity is due to the complex combination of multi-photon ionization and avalanche ionization involved in the breakdown process. These findings suggest the benefit of using somewhat longer duration sparks (e.g. 15-30 ns) since: 1) higher energies more capable of igniting lean mixtures and can be delivered, and 2) there is increased margin between conditions needed to spark versus those that damage the fiber (e.g. margin of factor of ~4 for 20 ns duration). In summary, the maximum fiber energies are very favorable for laser ignition.

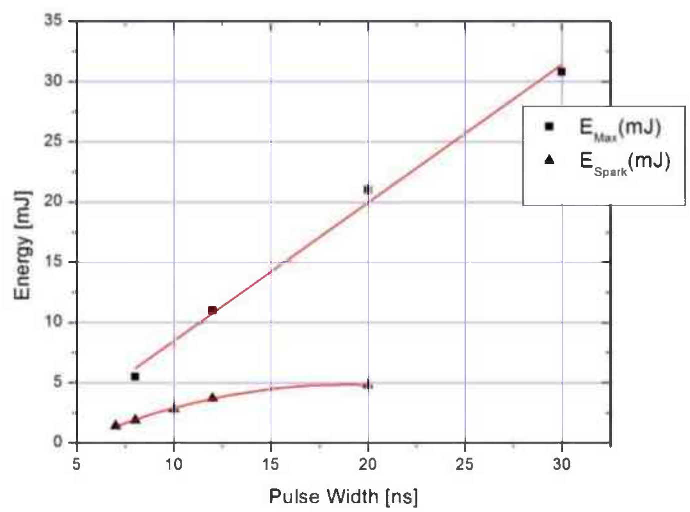

Figure 9. Dependence of maximum pulse energy, E_{Max}, and energy needed to spark, E_{Spark} on laser pulse duration. Sparking is at the focused fiber output in atmospheric air (Patm=0.85atm, T=298K in Fort Collins, CO).

3.2 Engine Testing

A major activity of Phase I was engine testing on a single cylinder gasoline engine at Argonne National Laboratory (ANL) during two separate week-long trips. The objectives were to demonstrate the basic capability of the fiber delivery system and, if possible, to obtain combustion data from the engine The tests used the same kagome PCF fiber described in previous sections. The optical setup was compressed onto an optical breadboard (2'x3'). The new setup also employed a more compact pulsed Nd:YAG laser (BigSky Ultra CFR). The 2-m long vacuum spatial filter components were shortened to ~40 cm while the telescoping length through the filter was also shortened by implementing a negative lens to expand the beam more quickly once it had exited the vacuum pinhole. Of course, our future setup for engine use in real applications will be much smaller (as described in Phase II proposal) but this setup was suitable for the testing at ANL.

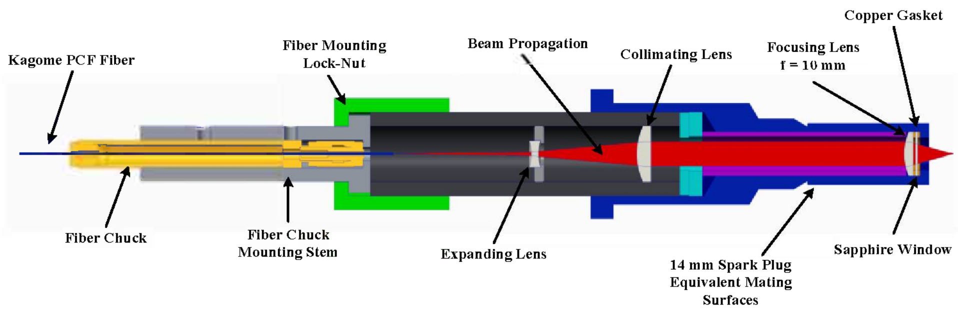

Figure 10. Schematic of optical spark plug used to focus light and interface to engine cylinder (ia regular 14 mm port).

In addition to laser and fiber, the system requires an optical spark plug to interface with the engine cylinder by screwing into the 14 mm port normally used by the conventional spark plug. Figure 10 shows a cross-section of the optical spark plug used in the engine testing. The beam was collimated after exiting the fiber using a negative lens followed by a positive lens to a diameter of 5.5 mm. A 10 mm focal length lens Gradium lens focused the beam into the engine cylinder. The Gradium lens was selected to provide a small focal spot to promote high focused intensity and spark formation. Copper gaskets on either side of a sapphire window at the tip of the spark plug seal the rest of the optics away from the engine cylinder and protect the optics from the engine fluids and high pressure conditions. Considerable effort went into a simple design allowing consistent optical and fiber alignment even as the plug was connected and removed from the engine cylinder.

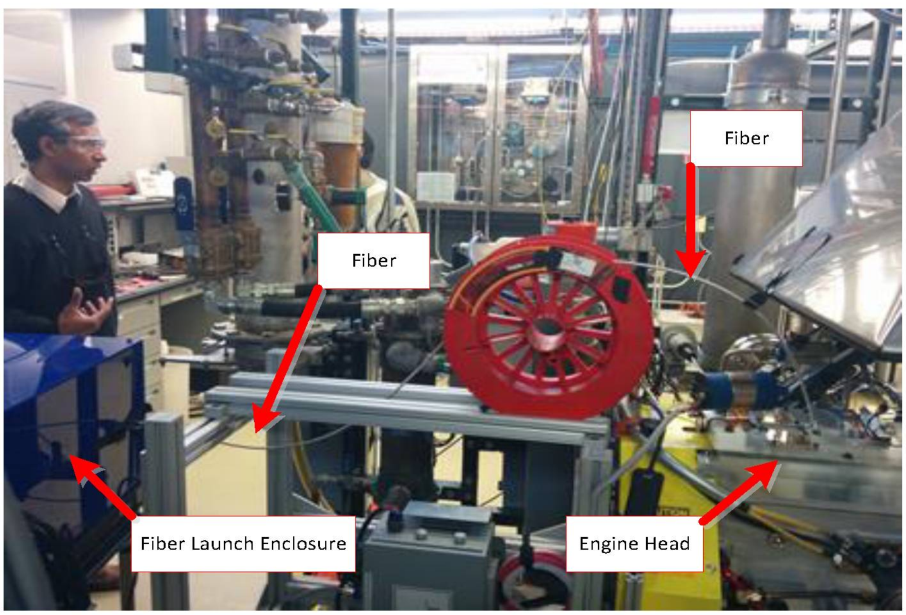

Figure 8. Fiber-delivered laser ignition apparatus on ANL engine.

Engine testing was performed on a Ford Single Cylinder Research Engine set up for Gasoline Direct Injection (GDI) operation with variable equivalence ratio and load condition capabilities. The engine is also equipped with exhaust gas analyzers, dynamometer, and an in-cylinder pressure transducer to monitor engine performance and efficiency. Figure 11 shows the fiber delivery setup next to the engine with the optical spark plug mounted in the engine before testing. <u>Note that the fiber was coiled around the red spool, i.e. in a configuration where the fiber is routed along a very non-straight path.</u> The engine block was preheated to 95° C and motored to 2400 rpm. The engine was successfully ignited by the laser 100% of the time with no misfires. During this test, the fiber delivered pulses of 5 mJ energy with 12.5 ns pulse duration at a repetition rate of 20 Hz (engine speed of 2400 rpm). The left of Fig. 12 shows an example pressure trace from a single combustion cycle while the right of Fig. 12 shows the variation of the indicated mean effective pressure (IMEP) from one cycle to another. The engine was operated at a stoichiometric fuel-air ratio and exhibited a 5.85 bar IMEP with a coefficient of variatione (COV) of 1.84%. The relatively low COV value, below 2%, indicates that the laser ignition provided stable repeatable combustion. The low COV is also favorable in terms of the outlook for igniting lean mixtures), and this will be further investigated in Phase II.

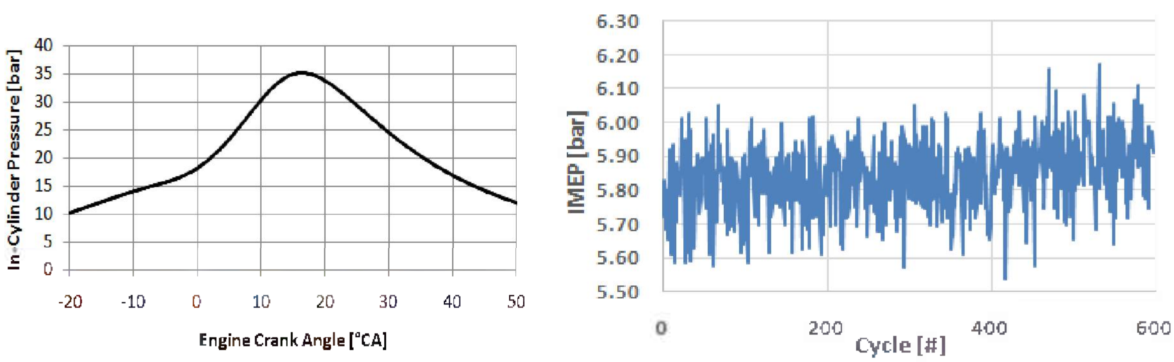

Figure 12. Left: Pressure trace from one combustion cycle. Right: Indicated Mean Effective Pressure (IMEP) variation over multiple cycles.

3.3 Technical Feasibility Shown by Phase I

The Phase I efforts have made significant progress towards showing technical feasibility of our approach. Here, we discuss our progress relative to the objectives of the Phase I proposal which were as follows:

- <u>Phase I – Objective 1: Perform optical damage studies to optimize the maximum pulse energies that can be delivered through candidate fiber optics (while maintaining sufficient output beam quality to allow spark formation).</u>
  Progress Achieved: Fiber characterization focused on kagome fibers. Results given in Figure 9 are very promising for practical laser ignition systems. For pulse durations of ~12 ns, we could deliver >~10 mJ pulses before damage onset. <u>Such pulse energy is sufficient for ignition in many cases, in particular for stoichiometric mixtures. Based on these results we plan to continue working with kagome fibers in Phase II and plan to expand the effort by using larger core fibers that should (be area scaling) allow ~2x higher pulse energy, thereby even being sufficient for lean mixtures.</u> The Phase I results also show that, by using longer pulse duration (~20 – 30 ns), it is possible to carry even higher pulse energy (by factor of ~2-3) which also provides future opportunities to implement longer duration sources.
- <u>Phase I – Objective 2: Perform measurements of the spatial beam quality (M^2) at the fiber output.</u>

Progress Achieved: Beam quality measurements of spatial quality (Section 3.1) show nearly single-mode output from the kagome fibers (i.e. M^2 close to 1) which is the optimum possible value and, combined with their high pulse energy, shows the suitability of the fibers for laser ignition.

- Phase I – Objective II: Perform tests of fiber delivered laser ignition on representative single-cylinder gasoline engine.

Progress Achieved: We have been partially successful in this objective. We have shown reliable (100%) ignition of a single-cylinder gasoline engine using our laser ignition system. Clearly this is an important milestone as it was the first such demonstration with kagome fibers. The COV of IMEP was <2% which is favorable for stable engine operation. We were not yet able to obtain detailed combustion data at different operation conditions due to two reasons. First, our fiber mounting and alignment procedures improved considerably during the course of the project leaving only limited time to test the final configurations at ANL. Second, while ANL research was very productive, there were operational challenges associated with their safety requirements (such as fact that we could not adjust the laser and fiber near the engine) which limited our progress. These "lessons learned" will be very valuable in Phase II.

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