FUNDAMENTAL STUDIES of IGNITION PROCESSES in LARGE NATURAL GAS ENGINES USING LASER SPARK IGNITION

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Abstract

The current report details project progress made during the first quarterly reporting period of the DOE sponsored project “Fundamental studies of ignition processes in large natural gas engines using laser spark ignition”. The goal of the overall research effort is to develop a laser ignition system for natural gas engines, with a particular focus on using fiber optic delivery methods. In this report we present our successful demonstration of spark formation using fiber delivery made possible through the use of novel coated hollow fibers. We present results of (high power) experimental characterizations of light propagation using hollow fibers using both a high power research grade laser as well as a more compact laser. Finally, we present initial designs of the system we are developing for future on-engine testing using the hollow fibers.

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Acronyms

AFRL	Air Force Research Laboratory
ALIS	Advanced Laser Ignition Systems
ARES	Advanced Reciprocating Engine Systems
CRADA	Cooperative Research and Development Agreement
He:Ne	Helium Neon Laser
Nd:YAG	Neodymium:yttrium-aluminum-garnet
NETL	National Energy Transportation Lab

1 Executive Summary

The current report details project progress made during the first quarterly reporting period of the DOE sponsored project “Fundamental studies of ignition processes in large natural gas engines using laser spark ignition”. The overall goal of the research project is to develop a laser ignition system for natural gas engines. Past research in national labs and universities has shown the combustion benefits of laser (as opposed to spark) ignition [1]. The particular focus of our current research is on using fiber optic schemes to deliver the laser light; a decision made in consultation with major engine manufacturers who view fiber optic delivery as a key to practical implementations. Fiber optic delivery of laser light for spark formation has significant challenges associated with the choice of fiber, propagation of sufficient optical power through the fiber, and the need to re-focus the light exiting the fiber to high peak intensity in order to breakdown (spark) the air.

In this period, we report on our recent efforts concerning the use of coated hollow fibers for light delivery. Specifically, we report the delivery of nanosecond laser pulses through flexible fibers to produce optical sparks in atmospheric pressure gases. The work represents the first demonstration of the use of fiber optics to deliver (nanosecond) laser pulses to form sparks in gases; and thus may be considered a significant milestone. These recent investigations employ a Nd:YAG laser beam (1064 nm) in conjunction with a cyclic olefin polymer-coated silver hollow fiber (as opposed to a solid core fiber) provided by Matsuura and Miyagi of Tohoku University. We detail our studies of the dependence of beam parameters at the fiber exit on the fiber launch geometry, and on the effect of fiber bending. Based on these studies, we ascertain conditions required to make sparks. Preliminary designs for an on-engine test system are also described.

Additionally, as first reported in the previous Semi-Annual Technical Progress Report, we are continuing to develop a CRADA (Cooperative Research and Development Agreement) with the Air Force Research Laboratory (Sandia, NM) to investigate the use of fiber lasers in laser ignition applications. We anticipate testing AFRL systems in 2005. Discussion of fiber lasers will be provided in future reports.

2 Use of Hollow Core Fibers to Deliver Laser Sparks

Previous reports have detailed our work with cyclic olefin polymer-coated silver hollow fibers. Low power tests were performed using a continuous wave (CW) helium-neon (He:Ne) laser. The He:Ne laser is useful for profiling the light path through the fiber and associated optics, and provides a starting point for high power testing (and subsequent spark formation). Here, we focus on recent tests with high power pulsed beams: We find that through appropriate design of the optical launch, hollow core fibers can be used to deliver laser pulses and form optical sparks. To the best of our knowledge, the work reported here is the first demonstration of spark formation using light delivered through fiber optics. While other related work has employed picosecond pulse trains through hollow-core photonic-crystal fibers for delivery of intense laser pulses [2], spark formation was not reported in the gas phase. Similarly, there have been no published reports of spark formation in this regime using solid step-index silica fibers. (Using large diameter multi-mode silica fibers allows high power delivery, but does not generally aid in high intensity delivery.)

2.1 Background

Prior to reporting our experimental results, we consider the theoretical requirements for fiber spark delivery. The intensity required to create optical breakdown (sparks) in atmospheric gases is generally on the order of $\sim 10^2$ - 10^3 GW/cm² [e.g 3-6], which is significantly above the damage threshold for propagation of nanosecond pulses in most optical fibers. For both silica and hollow fibers, past experiments have typically found intensity damage thresholds for nanosecond pulses of about 1-3 GW/cm² [7 and references therein, 8-11]. Therefore, to achieve breakdown after fiber transmission, the light exiting the fiber must be significantly demagnified using downstream focusing optics. In order to enable reasonable demagnification, a low divergence angle at the fiber exit is required. This conclusion can be readily reached from paraxial ray-tracing. If we assume a (uniform) area source at the fiber exit; then one finds a linear de-magnification of $\theta_{\text{spark}}/\theta_{\text{exit}}$, where θ_{exit} represents the divergence angle (of the widest rays) leaving the fiber and θ_{spark} represents the divergence angle (of the widest rays) converging at the focal spot (desired spark location). Therefore, for a given imaging system (which determines θ_{spark}), the intensity at the desired spark location is proportional to $\left(1/\theta_{\text{exit}}\right)^2$. The result is equivalent to requiring low M^2 at the fiber exit. If we assume that there is a beam waist at the fiber exit equal to the fiber radius, and that the fiber exit divergence angle corresponds to the beam far-field divergence angle, then the same expressions result.

2.2 Experiment

Flexible cyclic olefin polymer-coated silver hollow fibers have the potential to deliver laser pulses with relatively high exit intensity and relatively low exit divergence. The manufacturing process for these fibers has been previously described [8-11]. The coated fiber used has an inner (hollow) diameter of 700 nm, a length of 1 m, and has been coated for optimal transmission at 1064 nm. The fiber is illustrated in the left of Fig. 1. The right of Fig.1 shows the overall experimental set-up.

Figure 1: Left – Hollow fiber design. Right - Schematic diagram of setup.

The light source is the fundamental 1064 nm beam of a Q-switched Nd:YAG laser (Continuum 8050) with pulse duration = 7 ns, repetition rate = 5 Hz, and near diffraction-limited spatial quality (M^2 as given by manufacturer). A single lens (left of fiber) is used to launch the laser light into the fiber while a lens pair is used to focus light exiting the fiber into a small spot where a spark may form.

We have examined the effect of the launch geometry (angle) on the fiber exit parameters. Empirically it is known that reducing the fiber input angle (θ_{launch}) causes the fiber exit angle (θ_{exit}) to reduce. To quantitatively investigate this behavior we vary the launch angle by using a series of different launch lenses: plano-convex lenses of 15, 30, and 50 cm focal length (f_{launch}). The (collimated) beam diameter incident on the launch lens is about 1 cm. The focused beam waist following each launch lens is made to be coincident with the plane of the fiber input face. To enable optimal energy transmission and exit beam quality, we follow Matsuura et al [8] and precisely align the initial ~10 cm of fiber length (relative to the input beam) using a 5-axis mount (3 spatial axes and 2 tilt axes). A weak helium purge is employed at the fiber input location to counter possible breakdown, and the fiber is held in a nominally straight position. For each configuration, we measure the launch input angle (θ_{launch}), beam waist (w_{launch}) at the fiber input face, the exit angle (θ_{exit}), and the energy transmission. Beam waists are taken as twice the variance of the spatial intensity profile (following M^2 conventions) and are measured using an optical profiler (Spiricon LBA710). Uncertainty in all reported parameters is about 10%. We also employ a pair of positive double-convex lenses located 30 cm downstream of the fiber exit to refocus the light and assess the possibility of forming sparks. The first

(upstream) lens has a focal length of 35 mm, while the second lens has focal length of 9 mm and is located 30 mm behind the first. This lens pair is positioned to yield the minimum spot size (without overfilling the optics) and has been experimentally found to offer high demagnification. Experimental results are given in Table 1 and discussed below.

f_{launch} (cm)	θ_{launch} (rad)	w_{launch} (μm)	θ_{exit} (rad)	Spark Formation
15	0.033	47	0.031	No
30	0.017	65	0.018	Intermittent
50	0.010	77	0.009	Yes

Table 1: Effect of launch geometry on fiber output and on ability to spark.

Similar to Matsuura et al, we find transmission efficiencies (through the 1 m fiber) of about 80% at low power and a reduced transmission of $\sim 70\%$ at the peak transmitted energy of ~ 50 mJ (corresponding to an average intensity of ~ 1.9 GW/cm² at the fiber exit). We find the peak energy and transmission values to be quite insensitive to the launch lens within the range of focal lengths tested, so that these values apply to each of the three launches. The measured beam waists at the launch are consistent with those from M² theory. For example, for the 50 cm launch the waist of 76 μm on the fiber input face is consistent with that predicted by M² theory ($w \approx M^2(\lambda/\pi)(f/w_0) \approx 67$ μm), with the slight under-calculation likely due to aberration by the launch lens. For the shorter focal length launches the measured waists become higher relative to the calculated values (40 μm for 30 cm launch, and 20 μm for 15 cm launch) consistent with aberration effects become more prevalent as the launch $f\#$ (focal length) decreases. In each case, the waist at the launch is small compared to the 700 μm fiber inner diameter which allows effective energy coupling.

We find that that reducing the fiber input angle (θ_{launch}) causes the fiber exit angle (θ_{exit}) to reduce (and the two values mirror one another within experimental uncertainty). Since the optical intensity at the fiber exit is similar for each launch, we expect that the lowest angle launch will be most amenable to spark formation. Indeed, of the configurations tested (and using the focusing optics described above) only the 50 cm launch lens allows reliable spark delivery. For this case, we find a beam waist (at the spark location) of approximately 30 μm and a minimum energy required to spark of 39 mJ. These parameters correspond to an average optical intensity of ~ 200 GW/cm² at the spark location, consistent with published breakdown thresholds in atmospheric pressure air (order $\sim 10^2$ - 10^3 GW/cm² [e.g. 3-6]). With the 50 cm launch lens we find that the system sparks $\sim 97\%$ of the time. Figure 2 shows a photograph of the optical spark.

Figure 2: Photograph of spark formation.

The occasional misfires coincide with spark formation in the gas at the fiber input, which we attribute to inadequacies of our helium purge system. The 30 cm launch case (for peak delivered energy of 50 mJ) corresponds to an intensity at the spark location of ~ 60 GW/cm², and sparks intermittently, likely due to varying local hot-spots (inhomogeneities) in the multi-mode beam (see Figure 3). The salient conclusion is that a low divergence launch is needed to enable a low divergence at the fiber exit, which in turn allows the possibility of refocusing the transmitted light to sufficiently high intensity to form sparks. Note that a relatively low M^2 input beam is required to achieve the necessary combination of low launch angle and sufficiently small beam waist at fiber input.

To assess practical implementations, we explore the effects of fiber bending on system performance. Tests are conducted using the 50 cm launch configuration, which generates sparks when straight. In these experiments the first 40 cm of the fiber length was held straight while the remaining 60 cm of length was bent into arcs of different radii (R). Measurements of exit divergence angle (normalized by the divergence angle for the straight fiber case), fiber transmission (at peak transmitted energy), and percentage of laser shots resulting in sparks are given in Table 2. Straight fiber results are also included ($1/R = \text{curvature} = 0$). Similar to Matsuura et al, we find that as the curvature increases, the fiber exit angle increases and transmission decreases. Both trends lead to a reduction in optical intensity at the desired spark location, and a lower percentage of laser shots creating optical sparks. The intermittent sparking at bent conditions is again attributed to varying intensity profiles of the multi-mode (exit) beams. A profile of the multi-mode beam for a bent fiber ($1/R = .73 \text{ m}^{-1}$) measured 15 cm downstream of the fiber exit is shown in the right of Figure 3.

$1/R \text{ (m}^{-1}\text{)}$	$\theta_{\text{exit bent}} / \theta_{\text{exit straight}}$	Transmission %	Spark Formation %
0	1.00	73	97
0.73	1.19	66	85
1.01	1.21	64	50
1.29	1.29	62	<1

Table 2: Effect of fiber bending on fiber output and on ability to spark.

Figure 3: Beam profiles downstream of fiber exit for straight (left) and bent (right) fibers.

The spatial profile of the light exiting the fiber is clearly multi-mode as illustrated in the left of Figure 3 (measured 15 cm downstream of the fiber exit). The beam profile is qualitatively similar to images found using these fibers by other researchers [e.g. 9,10]. Under the assumptions given earlier, the data in Table 1 can be used to estimate the M^2 of light exiting the fiber. For the 50 cm launch lens, we find $M^2 \approx 350 \mu\text{m} \cdot 0.009 / (1.064 \mu\text{m} / \pi) \approx 9$. While this M^2 value may be viewed as relatively high, it is considerably lower than that of a beam exiting a standard multi-mode step-index fiber of numerical aperture 0.11 and the same diameter. The latter would have $M^2 \approx 350 \cdot 0.11 / (1.064 / \pi) \approx 100$ and thus would be substantially more difficult to refocus (and impossible to use for gas-phase spark delivery).

3 Preliminary Development of On-Engine System

Having successfully demonstrated spark formation with a hollow core fiber, we have begun preliminary development of an on-engine fixture. The first task was to repeat the hollow core experiments with a more compact laser. A New Wave “Gemini” Nd:YAG laser (120mJ peak energy, 7ns pulse width) was implemented with similar results. The required energy needed to form sparks decreased from 39 mJ to 13 mJ due to a decrease in the number of optical components (mirror, lenses, etc.) in the beam path, and perhaps also due to increased focusing at the breakdown location. The results of these bench top lab tests guided our approach to on engine implementation. The first consideration was to improve or eliminate the helium purge used to suppress sparking at the fiber input face. Previous work by Matsuura [8] showed that operating at vacuum pressures is more effective at suppressing sparks than a helium purge. Therefore, the housing design for the fiber and associated optics is based on providing a vacuum environment for the fiber (by connecting a compact vacuum pump to a sealed fiber system). Additionally, the housing for the fiber must withstand the high levels of heat and vibration associated with typical engine environments. The first piece of our on-engine fixture is the vacuum fiber chuck shown in Figure 4. The chuck serves several functions: 1) it holds the fiber stationary; 2) it provides a mounting surface for the fiber sheath and launch lens assembly; and 3) it allows for alignment of the fiber and laser beam.

Figure 4: Vacuum fiber chuck.

Other important system components are a pair of “lens tubes”. One lens tube houses the launch lens and is thus used to launch (focus) light into the fiber. A second lens tube houses the focusing optics and serves to gather light exiting the fiber and focuses it at the desired spark location. The launch lens tube is shown at left of Figure 5. It holds the launch lens in the appropriate position and employs a pair of dowel pins to keep the tube and fiber chuck in alignment. The second (exit) lens tube is shown at right of Figure 5. It comprises a second vacuum fiber chuck that aligns the fiber with the final focusing optics (alternately referred to as the optical spark plug). The optical spark plug contains a pair of focusing lenses which demagnify the beam to the required intensity. Further development of this on-engine system will be provided in the next report.

Figure 5: Left - Launch lens tube. Right - Exit lens tube (optical spark plug).

4 Conclusion

Our current focus on fiber optic delivery is a consequence of input from the ALIS consortium, which recognized the greater-than-anticipated difficulty in delivering a high quality beam through a fiber optic. In the first two years of this project, significant progress in several of the task areas was achieved. An ARES class engine was installed, several optical plugs were designed with various types of fibers, and a single cylinder of the engine was operated with laser ignition (through sparking off of the piston head).

In this period, we describe the use of coated hollow fibers for light delivery. We have succeeded in using the flexible hollow fibers to deliver nanosecond laser pulses in a way that allows production of optical sparks in atmospheric pressure gases. The work represents the first demonstration of the use of fiber optics to deliver (nanosecond) laser pulses to form sparks in gases; and thus may be considered a major project milestone. At optical frequencies, both the intensity breakdown and combustion ignition threshold reduce with increasing pressure [e.g. 3-6]. Thus, we expect the hollow fiber delivery system should readily spark and initiate combustion at the elevated pressures (~20 atm) typical of the targeted engine combustion environments. In this report we have detailed the spark delivery as well as more basic studies of the dependence of beam parameters at the fiber exit on the fiber launch geometry, and on the effect of fiber bending. We have also presented preliminary designs for an on-engine test system.

Additionally, we are currently developing a CRADA (Cooperative Research and Development Agreement) with the Air Force Research Laboratory (Sandia, NM) to investigate the use of hollow fibers in laser ignition applications. We anticipate testing AFRL systems in 2005. Further discussion of fiber lasers will be provided in subsequent reports.

5 Milestone Update

In this reporting period of the project, no milestones were scheduled. The first milestone for year three of the project “Demonstration of high power fiber optic delivery appropriate for engine sparking” is scheduled for April 2005. The demonstration of spark creation though a fiber reported in this period nearly represents completion of milestone one (ahead of schedule), however, further improvements are ongoing to improve the reliability of sparking and hence fully complete milestone one.

6 Cost and Schedule Status

We have operated within budget and have performed ahead of schedule during this reporting period.

Period 2 Total Approved Budget \$662,619

	Federal Budget	Non- Federal Budget	Total Budget	Federal Expenditures	Non-Federal Expenditures	Total Expenditures
Total	\$530,095	\$132,524	\$662,619	\$50,626	\$0	\$50,626

Year 3 – Laser Ignition

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
Research Management Plan		◆										
Year 3 – High Intensity Fiber Delivery							MS-1					
Year 3 – Engine Testing									MS-2			
Year 3 – Implementation											MS-3	

Milestones. **We specify one major milestone per year for each task.**

MS-1: Demonstration of high power fiber optic delivery appropriate for engine sparking.

MS-2: Demonstration of single cylinder operation with fiber delivered laser ignition.

MS-3: Identification of multiplexing strategy.

◆ Planning Summary submitted for review/approval

7 Summary of Significant Accomplishments

In this period, we report the first delivery of sparks through an optical fiber. To the best of our knowledge, we are the first group to demonstrate this ability. This achievement was enabled by the use of novel hollow core fibers made available to us through our cooperation with Tokohu University. Our examination of the optimal conditions for launching and refocusing laser light has provided a valuable benchmark in the combined efforts of the ALIS consortium to develop a laser ignition system.

8 Problems and Delays

At this point we anticipate no significant problems or delays in the project.

9 Technology Transfer Activities

In addition to monthly updates via teleconference with our ALIS consortium partners and engine manufacturers, we have submitted a paper entitled “*Use of Hollow Core Fibers to Deliver Nanosecond Nd:YAG Laser Pulses to Form Sparks in Gases*” to the peer reviewed journal “Optics Letters” for publication. In addition, we have submitted an abstract to the 2nd Annual Advanced Stationary Reciprocating Engines Conference entitled “*Moving Forward in Low-Emissions and High-Efficiency Technologies*” presented by the DOE and California Energy Commission.

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