Technology Development of a Fiber Optic-Coupled Laser Ignition System for Multi-Combustor Rocket Engines

Huu P. Trinh
NASA Marshall Space Flight Center, Hunstville, Alabama

Jim Early
DOE Los Alamos National Laboratory, Los Alamos, New Mexico

Robin Osborne
ERC, Inc., Hunstville, Alabama

Matthew E. Thomas and John A. Bossard
CFD Research Incorporated, Huntsville, Alabama

ABSTRACT

This paper addresses the progress of technology development of a laser ignition system at NASA Marshall Space Flight Center (MSFC). The first two years of the project focus on comprehensive assessments and evaluations of a novel dual-pulse laser concept, flight-qualified laser system, and the technology required to integrate the laser ignition system to a rocket chamber. With collaborations of the Department of Energy/Los Alamos National Laboratory (LANL) and CFD Research Corporation (CFDRC), MSFC has conducted 26 hot fire ignition tests with lab-scale laser systems. These tests demonstrate the concept feasibility of dual-pulse laser ignition to initiate gaseous oxygen (GOX)/liquid kerosene (RP-1) combustion in a rocket chamber. Presently, a fiber optic-coupled miniaturized laser ignition prototype is being implemented at the rocket chamber test rig for future testing. Future work is guided by a technology road map that outlines the work required for maturing a laser ignition system. This road map defines activities for the next six years, with the goal of developing a flight-ready laser ignition system.

INTRODUCTION

A current study of the third-generation launch vehicle envisions that a Rocket-Based Combined Cycle (RBCC) engine will be used to power the future vehicle. The RBCC configuration will be composed of clusters of ejector rocket thrusters. Although combustion wave technique is considered as a baseline for the ignition system, the use of such a system to provide independently synchronized ignition sources with the inclusion of an engine restart capability might become overly complex.

Large combustion chambers for future launch vehicle may require baffles on the injector face to suppress combustion instability. To avoid localized pressure surges among the chamber compartments, which are formed by the baffle arrangement, ignition should occur simultaneously in all compartments. Although ignition systems in existing rocket engines are operationally reliable, they are composed of multiple parts. One such system, an augmented spark igniter (ASI), which has been used in many engines including the

Space Shuttle Main Engines, would become even more complex if used to simultaneously ignite multiple combustion chamber compartments.

In order to meet the goals of operational reliability and mission life requirements of the future ignition system for the next generation launch vehicles, technology for developing advanced ignition systems should be explored. Recent progress in the laser ignition technology has created an interest at MSFC to further advance this technology for multiple combustor rocket engine applications.

A primary advantage of laser ignition is the capability of igniting a combustion chamber with laser-induced spark (LIS) ignition at pre-determined optimal ignition locations within the chamber, eliminating the need for premixed and propellant valves such as those used in the ASI. Hence, the implementation of a laser ignition system would reduce mechanical ignition system parts and simplify the ignition operation sequence. Furthermore, with an optical multiplexing technique, the laser system could be conveniently manipulated to direct the laser light distribution and laser firing frequency to provide multiple ignition sources. Such an ignition system could be used in RBCC, reaction control system rockets of future space crafts, as well as large scale combustion chambers.

There have been limited studies in the past of single-pulse laser ignition. In 1994, Liou[1] carried out a series of laser ignition hot-firings in a small-scale rocket engine with several propellant combinations. His experiment utilized an Nd:YAG laser with a wavelength of 1064 nm, a beam diameter of 9.5 mm, and a pulse duration of 9 nanoseconds. The laser was operated at single pulse or multiple pulses up to 20 Hz. Liou reported that ignition delay times within single-digit milliseconds were observed in all tested propellant combinations under his combustion chamber conditions. He also found that electromagnetic emission interference (EMI) generated from the laser-induced spark was below the permissible level for space flight.

Recent work at CFDRC and LANL has included gas turbine injector ignition experiments characterizing the performance of a multi-pulse laser ignition method relative to that of a single-pulse laser ignition method. A laser beam, which was generated from a Nd:YAG laser operated at a maximum pulse energy of 150 mJ, was focused into the gas turbine injector fuel cloud using a 10 cm focal length lens. For multi-pulse testing, a separate long pulse duration laser was tested. The results showed that the dual pulse laser format provided more reliable ignition than a single pulse with equivalent energy. LANL and CFDRC then demonstrated the maturity of the laser ignition technology by building a fiber optic-coupled laser ignition prototype with the dual-pulse laser format.This progress has provided MSFC an incentive to evaluate the dual-pulse laser ignition concept and to further advance it for application to a rocket engine.

DUAL PULSE LASER-INDUCED SPARK (DPLIS) IGNITION AND ITS POTENTIAL BENEFITS

The dual-pulse laser ignition concept is a novel variation of the commonly used DPLIS ignition method. In DPLIS, the ignition process is accomplished by a two-step approach, utilizing two distinct laser pulses. First, a very short duration, high power laser pulse is focused directly into the combustible medium in order to initiate a plasma that pre-conditions the gas volume to maximize the absorption of the second laser pulse. The second pulse provides additional photon energy and extends the plasma lifetime. By utilizing a long duration pulse for the second laser pulse, and by inserting an appropriate temporal delay relative to the first laser pulse, it is speculated that the breakdown plasma is sustained over an interval of the time greatly exceeding the combined temporal lengths of either a single laser pulse of equivalent energy or two identical laser pulses not optimally timed. Compared to single pulse LIS ignition, the DPLIS ignition method allows a higher percentage of the input laser energy to be absorbed into the gas volume, and therefore makes more efficient use of the laser energy. Additional input energy into the gas volume also results in a larger plasma. The combination of more absorbed energy, larger plasma size, and increased plasma lifetime is expected to improve the initial conditions for development of a flame kernel, and therefore should allow operation over a wider range of mixture ratios, propellant phases, propellant temperatures, and chamber pressures as compared to a single pulse system with the same input energy.

DPLIS ignition also offers the uniqueness of distributing the total energy in a manner that can be delivered to the combustion chamber in a practical way, such that multiple fiber optics lines can be used to carry the laser energy. The DPLIS technique requires less peak power yet allows a higher total energy to be delivered to combustion chamber. This minimization of the peak power also lessens the likelihood of damage to the fiber optics as well as the optical windows.

DESCRIPTION OF THE LASER IGNITION SETUP

Lab-Scale Lasers

Three laboratory-scale laser units including two Nd:YAG lasers and a Cr:LiSAF laser are used to emulate the dual-pulse laser format for this demonstration. Initially, two 1064 nm Nd:YAG lasers are used to produce the dual pulse. These lasers are synchronized in time, typically about 80 ns apart, and are operated at 10 Hz. The first pulse produces a 6 mm diameter beam with a pulse duration of 5-7 ns. The energy for the first pulse was set from 130 up to 200 mJ, depending on the test parameters. The second Nd:YAG produced a pulse with similar characteristics, except the energy used for this pulse was 75 mJ.

For later experiments, a Cr:LiSAF laser was substituted for the second pulse. The Cr:LiSAF has a shorter wavelength of 850 nm, and a longer pulse duration of 80 ns. The beam diameter is 7 mm. A pulse energy of 111 mJ was used. Because the existing Cr:LiSAF is designed for a maximum repetition rate of 4 Hz, the synchronized

Nd:YAG/Cr:LiSAF dual pulse was operated at 4 Hz. The pulse separation was again set to 80 ns.

Miniaturized Laser

A miniaturized dual pulse laser system designed by LANL and CFDRC is currently being refurbished at MSFC. The system is shown in Figure 1. This laser system is a novel design that delivers laser light produced by an exciter laser to a small igniter laser via fiber optics. The igniter laser, which is powered only by light energy delivered through the fiber optics, is close-coupled to the rocket chamber. This laser system produces a dual pulse format with a 1064 nm, 130 mJ, 5 ns beam for the first pulse, and an 850 nm, 100 mJ, 80 ns beam for the second pulse. Both laser beams are about 6 mm in diameter.

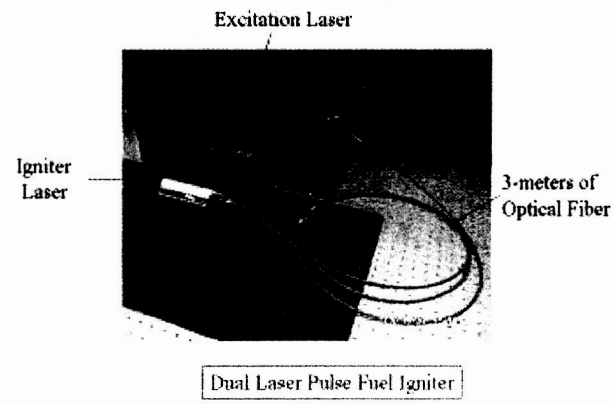

Figure 1. Miniaturized dual-pulse laser system.

DESCRIPTION OF THE SIMULATED COMBUSTION ENVIRONMENT

The rocket chamber test rig, shown in Figure 1, is composed of three modules including the injector, optical window adapter, and chamber/nozzle modules. The injector and chamber portions were existing hardware used for other past test programs. The injector was designed for propellant to be sprayed into the chamber with six "split triplet" elements. These elements were configured such that two angled fuel streams impinged on one axially flowing oxidizer stream. Although individual tests had slightly different conditions, they were aimed for a target GOX/RP-1 mixture ratio of 4, at which the oxidizer and fuel mass flow rates were 0.043 and 0.011 lbm/sec, respectively. This mixture ratio represented a slightly fuel-lean condition, with 3.2 being the stoichiometric mixture ratio for GOX/RP-1.

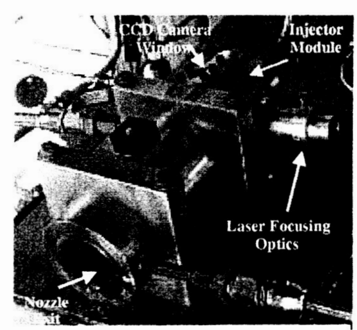

Figure 2. Chamber test rig used for laser ignition.

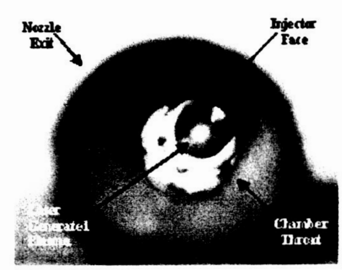

Figure 3. Laser spark as seen through the chamber's exit nozzle.

The chamber/nozzle module has dimensions of 1.25 and 0.537 inches for the chamber and throat diameters, respectively. The optical window adapter was a new module inserted between the injector and chamber. The adapter has two optical access ports with sapphire windows. One port is used as an observation port for a high speed CCD camera, while the second has a 5 cm focal length lens assembly that focuses the laser energy into the chamber. To avoid RP-1 spraying on the windows, gaseous nitrogen (GN2) is used to purge the two windows. Due to the concern of the RP-1 spraying on the windows, the chamber was only operated up to 30 psig during testing.

Figure 2 shows typical high-energy plasma of GN2 purge flow created from the focused laser light near the chamber center during the initial alignment of the laser spark.

RESULTS

A total of 26 laser ignition hot-fire tests were conducted on a GOX/RP1 subscale rocket chamber at MSFC. For the purpose of the concept demonstration, these were essentially pass/fail tests for ignition. However, for a test to be considered successful, the combustion needed to be sustained for the full duration of the test.

Initially, the dual pulse technique was tested with two Nd:YAG lasers with the pulses nearly identical in wavelength and pulse duration. The two Nd:YAGs each provided high peak power pulses. For later tests a Cr:LiSAF laser was substituted for the second pulse in order to evaluate if ignition could still occur with a lower peak power 2nd laser pulse. Finally, single-pulse laser ignition was also tested with an Nd:YAG laser for comparison to the dual pulse technique.

Although these tests were primarily demonstrations of the DPLIS technique, the time of the ignition-inducing pulse as well as the ignition delay (defined as the time difference between the ignition-inducing pulse and the first indication of an exponential rise in chamber pressure) were examined and compared for each test. It should be recognized that both of these parameters might be specific to the given rocket chamber configuration and test conditions.

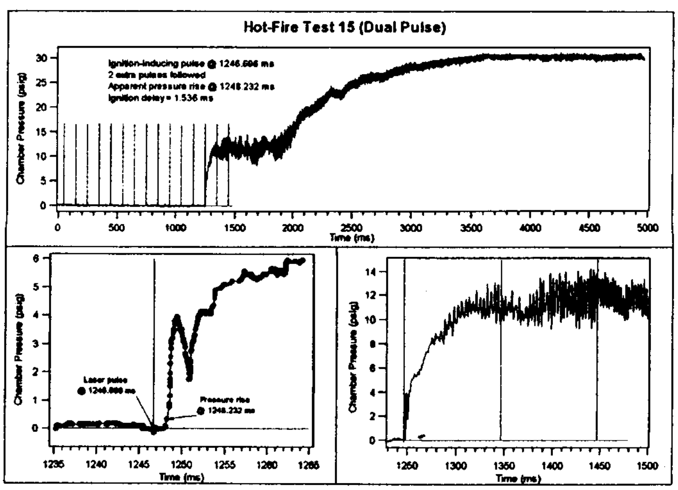

Figure 3. One of three dual-pulse tests that achieved ignition with sustained combustion. Vertical lines indicate the arrival time of the laser pulses in the combustion chamber.

Three laser ignition tests were conducted with dual pulse energy of 200 mJ / 75 mJ with pulse separation ranging from 50-100 ns, and all three tests successfully ignited and sustained combustion for the full test duration. The laser spark was positioned 0.28 in (7 mm) from the centerline of the chamber. The chamber pressure trace vs. time for one of the three tests is shown in Fig. 3. It should be noted that the pulse energies were measured far upstream of the rocket engine, and energy measurements taken in later tests indicated a considerable portion of the laser energy was absorbed by water vapor in the ambient air just prior to the rocket engine. Therefore, the actual pulse energy was likely to be less that the 200 mJ / 75 mJ values reported. All energy values reported in this paper are those measured at the exit of the laser.

For the chamber geometry, flow conditions, and test sequence used in these three tests, the average time at which the ignition-inducing pulse occurred was at 1346 ms after the start of the test sequence. This delay was due to the priming time of the fuel system. The average ignition delay time was 1.752 ms. After ignition, the chamber pressure rose to 15 psig, at which it remained for approximately 500 ms, and then gradually ramped up to a steady-state pressure of 30 psig. This pressure profile is attributed to the increase in fuel supply as a function of time. In general, most of the successful ignition tests discussed in this paper exhibited a similar trend in pressure rise.

Table 1 lists the test series, lasers and their associated pulse energies, and the results.

Table 1. Laser ignition tests with the laser spark located 0.28 in (7mm) from the centerline of the combustion chamber. For each test series, three identical tests were conducted.

Test Series	Lasers used	Pulse energy (mJ)	Successful sustained ignition (out of 3 tests)	Average time of ignition-inducing pulse (ms)	Average ignition delay time (ms)
1	Nd:YAG/Nd:YAG	200/75	3	1346	1.752
2	Nd:YAG/Nd:YAG	135/75	3	1444	1.675
3	Nd:YAG/Cr:LiSAF	145/111	3	1589	1.683
4	Nd:YAG	200	3	1311	1.691
5	Nd:YAG	130	2	1498	1.808
6	Nd:YAG	65	1	1371	1.848

Effect of Spark Location and Timing of Laser Pulse

Other tests were conducted, both single and dual pulse, to study the effect of the spark location and the timing of the laser pulse with respect to the introduction of propellants. When the location of the spark was changed from 0.28 in (7 mm) to 0.35 in (9 mm) from the centerline of the chamber, only one out of three single-pulse tests (with energy exceeding 200 mJ) resulted in sustained ignition. As stated previously, for a similar set of single pulse tests at 0.28 in, all three tests were successful.

Out of four dual pulse tests (both pulses produced by Nd:YAGs), with the energy set to less than 200 mJ for the first pulse and 75 mJ for the second pulse, only one test resulted in ignition. The three other tests completely failed to ignite. However, for these four tests, the laser pulse was not allowed to enter the chamber until 2000 ms. Therefore, the timing might not have been favorable for laser ignition. This leads to inconclusive results on the effect of ignition location for the dual-pulse technique.

CONCLUSIONS

For these tests, as seen in Table 1, the highest success rate for ignition with sustained combustion occurred with a minimum total pulse energy of 200 mJ and an ignition time where the mixture ratio condition was most favorable to laser ignition. Also, since two of the three tests failed to ignite in Test Series 6 listed in Table 1, a single pulse energy of 65 mJ was determined to be near the ignition threshold for the given mixture ratio and spark location.

It is speculated that at the 0.35 in position, which is closer to the GN2-purged laser window, there might have been enough GN2 in the flowfield to dilute the propellants and therefore decrease the likelihood of ignition.

Although only a limited number of tests were conducted in the GOX/RP-1 rocket chamber, the test results presented here demonstrate the concept feasibility of dual-pulse laser ignition for igniting GOX/RP-1 in a rocket chamber.

Past results from LANL and CFDRC indicate that the dual pulse laser format provides more reliable ignition than a single pulse with equivalent energy. While the test series at MSFC show that the single-pulse technique with a pulse energy of a 200 mJ apparently ignited the chamber equally as well as the dual-pulse technique, there is not really enough data available to perform a meaningful statistical analysis to compare the two techniques. In any case, delivering the required higher peak power of a single laser pulse to the chamber would not be as practical as a dual-pulse technique which distributes the energy over a longer time period. More detailed, time-resolved studies of the ignition process will be conducted to determine other advantages the dual-pulse technique might offer.

TECHNOLOGY ROAD MAP AND FUTURE WORK PLAN

Initial hot-fire tests in a small-scale rocket chamber at MSFC have demonstrated the DPLIS concept having two main advantages over existing laser ignition concepts. First, the DPLIS ignition can be potentially optimized its laser pulse format to maximize the initial plasma volume, the plasma lifetime, as well as the flame kernel growth rate. Characterization studies of the laser pulse format are now underway with experiments of igniting gaseous hydrogen/air in a Hencken burner. Once ignition is achieved, the flame is open to the atmosphere. This open environment allows easy access for diagnostics of the ignition phenomenon. The quick turn-around time of conducting experiments on this burner make it more amenable for conducting a large number of experiments for statistical analysis of the sensitivity of the test parameters. The results from these experiments will help optimize the laser format for future testing in an H2/O2 subscale rocket.

Although considerable progress to study the DPLIS concept has been made, extensive efforts are still required for the next several years before this technology can be matured into the development of a flight-qualified ignition system. Not only does the characterization study of the DPLIS using the lab-scale lasers need to be continued, but the 1st generation prototype of the fiber optic-coupled laser ignition system should also be incorporated in the initial phase of the technology demonstration.

Figure 5 shows the technology road map, which outlines activities for the next six years, with the goal of developing a flight-ready laser ignition system. Comprehensive assessments and evaluations of all relevant technologies will be conducted in the next two years. System requirements for the target rocket application will be established in order to define the required laser power and to determine how the laser ignition system will be integrated into the vehicle. Issues such as the hardware interface, design of the optical windows and associated purge system, ignition location, and control system interface will be investigated. Recent advances in laser hardware, such as diode pumped systems and hollow fiber optics may provide a significant benefit to the laser ignition technology; however, the functionality of such a laser system under actual flight environments (thermal, vibration) must also be investigated. All these studies will lead to development a 2nd generation prototype that will be tested in a larger sub-scale rocket chamber. The hardware integrity and durability of this prototype will then be verified under simulated flight environments. The final refinements will be implemented on the flight-ready laser ignition system, which will undergo the final ground test verification in 2008.

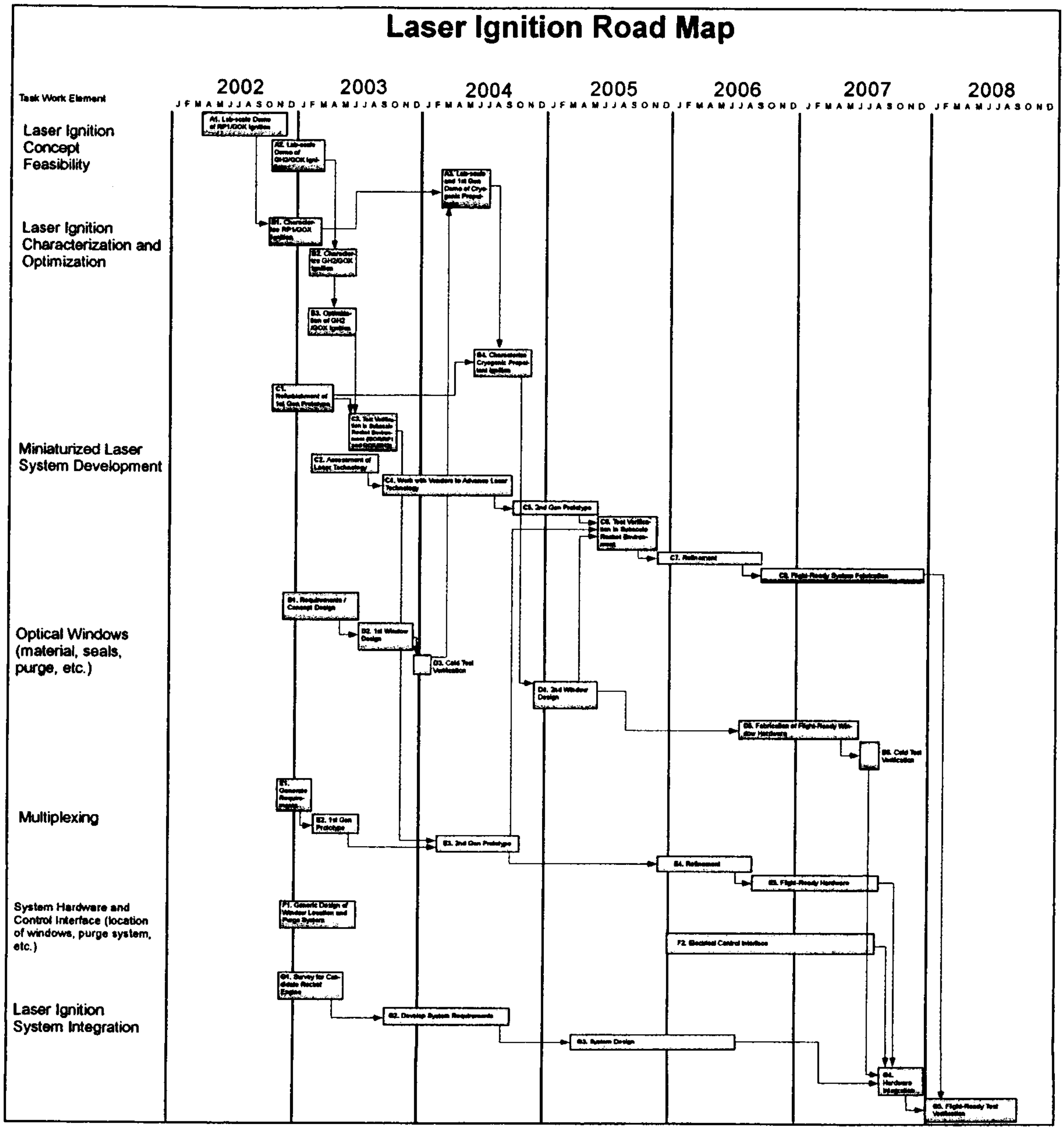

Figure 5. Road map for maturing the laser ignition technology.

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