

Experimental demonstration of multi-point laser ignition on a sub- and small-scale rocket combustor

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ABSTRACT

We report multiple successful ablative laser ignitions of a LOX/H₂ sub-scale rocket combustor and a small-scale rocket combustor at the M3 and P8 test-bench at DLR Institute of Space Propulsion in Lampoldshausen, Germany. These results represent the first multi-use distributed laser ignition system, capable of simultaneous ignition at two separate locations within the same combustion chamber or two combustors. This approach offers a pathway toward reduced weight for the ignition system, efficient ignition system redundancy and lower environmental impact per launch. These results were enabled by a fiber-coupled beam delivery system for a compact high-energy laser (HiPoLas Gen V), emitting 40 mJ, 2 ns pulses at 1064 nm wavelength, followed by ns-laser-induced damage studies of fibers with 250, 600, 800 μm core sizes and optical conduits that led to the development of a custom four-fold distributed laser ignition system.

Keywords: Ignition, high-energy lasers, laser ignition, fiber beam delivery, LOX/H₂ propulsion, multi-point ignition

1. INTRODUCTION

Laser ignition represents a mature and actively developing research area with applications spanning energy,¹ automotive² and launcher technologies.³ This ignition method offers several advantages over conventional approaches combining low weight (less than 2 kg), precise ignition timing, high repeatability and multi-use capabilities.^{4,5} As the system can also be used for a variety of environmentally friendly propellants, propulsion systems and ignition sequences,⁶⁻¹⁰ it enables lowering emissions and cheaper missions. As the engine is one of the main contributors to the launch cost, reducing the overall weight and cost and allowing for multi-use has a high impact. However, laser ignition systems and conventional ignition systems share a common limitation: each ignition point requires a dedicated ignition system.

To further leverage the laser ignition capabilities and provide scalability, the fiber distributed laser ignition approach was studied, where a single laser source, coupled to a beam delivery system can be used for a precisely sequenced ignition of multiple engines, thus reducing the cost per ignition point due to the reduced number of core laser systems and less strict environmental constraints on the laser head itself, which could be positioned further away from the combustion chamber. To validate this approach, we extended our previous study of laser-induced damage of multi-mode fibers¹¹ to additional fiber geometries and optical conduit options, prototyped a fiber beam delivery system based on these findings, and performed the combustion chamber tests, using such systems.

2. FIBER CHARACTERIZATION

Using a characterization setup that is similar to the work described by Tabakaev et al.,¹¹ in which 400 μm core and 720 μm cladding fibers from Artphotonics were investigated, we tested the coupling efficiency and throughput of a different set of Artphotonics multimode fibers, with following core/cladding parameters: 250/275 μm , 600/840 μm , 800/1200 μm . As a possible alternative to all-fiber delivery systems we also studied a fiber-to-conduit system, which comprised of the same ns-laser coupled to the 800/1200 μm fiber, whose output in turn was coupled to a 304.8 mm-long optical conduit, consisting of 3000 fused, 24 μm core fibers (Edmund Optics #38-306).

The laser source used for all tests and measurements was a HiPoLas Gen V compact high-energy laser with 40 mJ pulse energy, 2 ns pulsewidth and 1064 nm emission wavelength.³ The primary objective was to establish damage-threshold limits for the laser ignition system, as there is a clear tradeoff between energy throughput and output mode diameter. This is alleviated by using high cladding-to-core ratios.¹² It was demonstrated that it is possible to achieve an $M^2=2$, when a beam with $M^2 \approx 1$ was coupled to a 400/720 μm fiber. This approach therefore offers a potential means of maintaining a relatively low beam quality factor while increasing the energy-handling capability of the fiber.

The test protocol was as follows: After maximizing the coupling efficiency, defined as a ratio between output and input pulse energies, the input energy was increased gradually until irreversible damage of fiber occurred, resulting in a rapid decline of throughput. Then, with another patch cord, we determined the input energy that was sustained for more than 100 pulses without observable damage. The results of these tests are shown in Table 1. All tested patch cords were about 3 meter length and terminated with SMA connectors representing a configuration relevant to the practical implementation of a laser ignition system on a test bench. The coupling efficiency is mainly limited by the highly-multimode output of the HiPoLas laser, as it has a few-pass monolithic cavity, optimized for a maximal pulse energy.

Table 1. Fiber coupling efficiencies and maximum energy output for the fibers and the optical conduit under test.

Core diameter, μm	Cladding diameter, μm	Coupling efficiency, %	Maximum output, mJ
250	275	57	2.3
400	720	≈ 100	16.6 ¹¹
600	840	≈ 100	28.7
800	1200	≈ 100	40
Optical conduit	N/A	66	19

3. FIBER DELIVERY SYSTEM

The premise of the fiber delivery system is based on previous studies, demonstrating that a pulse energy as low as 2.9 mJ from the same HiPoLas Gen V laser is sufficient for reliable ignition when focused onto a metallic surface inside a combustor.¹³ In this approach, ignition is achieved through the formation of an ablative plume rather than through optical breakdown, which requires substantially higher pulse energies and energy densities. This considerably relaxes the requirements on the delivered pulse energy and allows to develop a fiber beam delivery system (see Fig 1) that splits a single laser pulse and couples the laser beam into multiple fibers each terminating at a separate ignition target. Such a configuration allows multiple ignition points to be addressed using a single laser source, providing a potentially cost-effective and scalable approach to multi-point ignition.

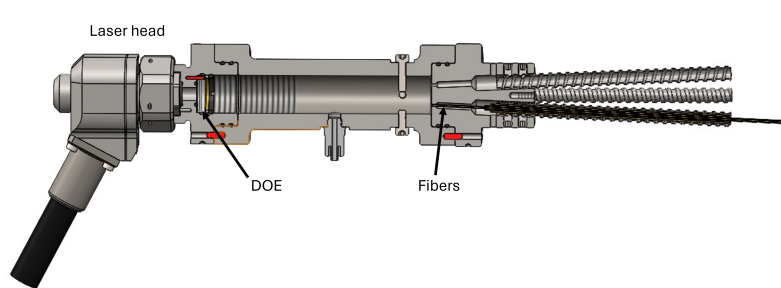


Figure 1. A cut through the splitting and coupling part of the fiber delivery system: Laser head - HiPoLas Gen V; DOE - diffractive optical element; Fibers - array of four fibers

A key element of the fiber delivery system is a custom diffractive optical element (DOE), that splits a laser beam in 4 beams and focuses them at 75 mm distance. To exactly position the fibers into the diffracted beams we marked a blank fiber holder using the laser (see Fig 2), drilled 740 μm holes on the marks and glued in the 400/720 μm fibers. On the opposite end of the fiber we install a target tube with a sapphire biconvex lens, that focuses fiber output on an Inconel 625 target, angled at 45° to the beam axis (see Fig 3).

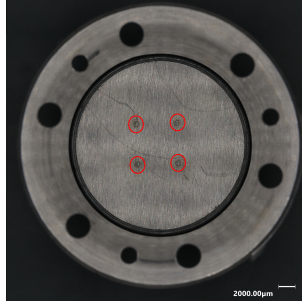


Figure 2. An image of a blank fiber holder with laser-induced marks, demonstrating beam splitting and focusing by DOE

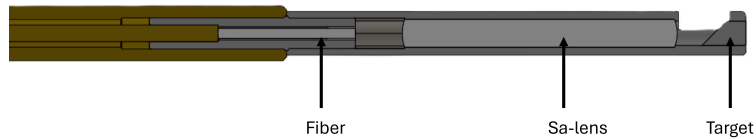


Figure 3. A cut through of the target tube: Fiber - an output end of the fiber; Sa-lens - 11-mm biconvex Sapphire lens, Target - Inconel 625 target

4. SUB-SCALE ROCKET COMBUSTOR TESTS

The multiplexed fiber-based laser ignition system was experimentally evaluated at the DLR M3.1 test bench using a four-injector-element subscale LOX/GH₂ combustion chamber designed to reproduce the relevant geometric and ignition transient characteristics of the planned ENLIGHTEN engine demonstrator. In particular, the element-to-wall and inter-element distances were retained from the corresponding medium-scale configuration, while the chamber geometry was adapted to provide representative recirculation regions and optical access. The resulting four-element configuration and its derivation from the medium-scale injector arrangement are shown in Fig. 4. A more detailed overview of the M3 subscale test campaign can be found in the work of Bee et al.¹⁴

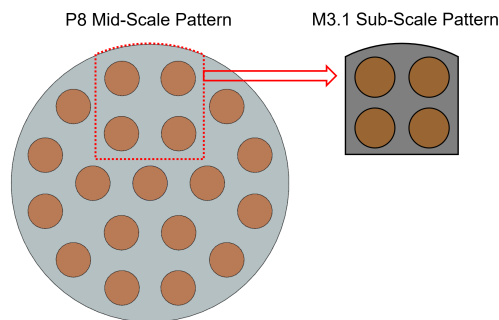


Figure 4. Four-element subscale combustion chamber configuration and derivation of the injector-element pattern from the medium-scale ENLIGHTEN configuration.¹⁴

The M3.1 test bench reproduced the pressure, temperature, and propellant mass-flow dynamics of the ENLIGHTEN demonstrator engine start-up transient, with the tests conducted using liquid oxygen and gaseous

hydrogen and extending to 750 ms after the intended ignition time. Four radial ignition positions were investigated, ranging from the central baseline position between the four injector elements (IP1) to locations closer to the chamber wall (IP2–IP4), while the axial position was kept constant, as illustrated in Fig. 5. High-speed

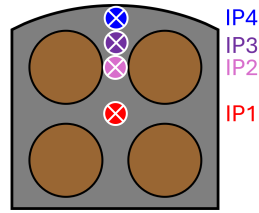


Figure 5. Radial ignition positions investigated during the M3.1 subscale test campaign.¹⁴

Schlieren and OH* chemiluminescence imaging were employed to characterize the ignition process, flame propagation, and subsequent flame anchoring, with the corresponding optical diagnostic arrangement shown in Fig. 6.

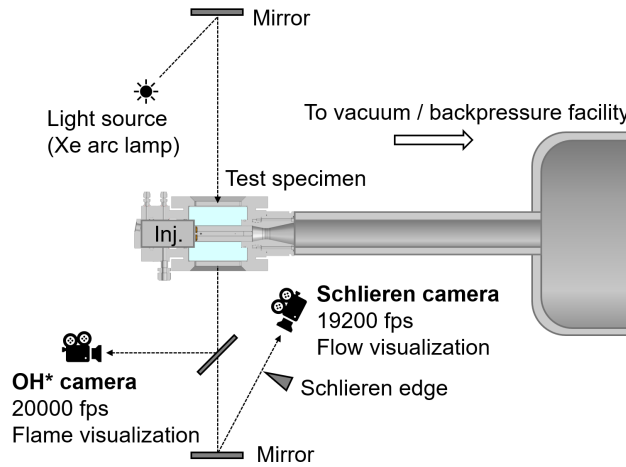


Figure 6. Optical diagnostics setup at the M3.1 test bench with the two high speed visualization systems.¹⁴

In total, 46 test runs were conducted, comprising 37 ignition attempts and 9 cold-flow runs. Successful ignition was demonstrated at all four investigated locations, with 19 successful ignitions corresponding to an overall apparent success rate of 51%; however, all unsuccessful ignition attempts were associated with identified cases of insufficient laser pulse-energy transmission through the optical system, resulting in an effective ignition success rate of 100% when these hardware-related failures were excluded. The observed transmission issues were attributed to multiplexer alignment, degradation at the hot-gas-side fiber exit, degradation at the multiplexer-side fiber entry, and, in one case, deliberate laser-power reduction. For the nominal operating condition, the ignition process was characterized by an early ignition event without detectable ignition overpressure. Schlieren imaging showed the initial flame propagation from the igniter region, while the subsequent OH* chemiluminescence measurements confirmed stable flame anchoring at the injector exits, with no evidence of flame lift-off or flashback, as shown in Fig. 7.

The ignition position influenced both ignition timing and the thermal environment. IP1 provided the earliest ignition but exhibited the largest timing variability and the highest measured thermal loading, whereas the other positions showed reduced timing scatter and lower thermal exposure. Despite these differences, all four investigated locations remained viable from the perspective of ignition reliability and the avoidance of significant overpressure. Repeated hot-fire operation revealed degradation of the igniter target and associated optical hardware, motivating improvements in the subsequent hardware iteration, including increased thermal resistance of

the target material and improved protection of the optical components, as illustrated in Fig. 8. Overall, the M3.1 campaign demonstrated the feasibility of multiplexed fiber-based laser ignition under representative subscale LOX/GH₂ conditions and provided the basis for subsequent hardware improvements for the following medium-scale test campaign.

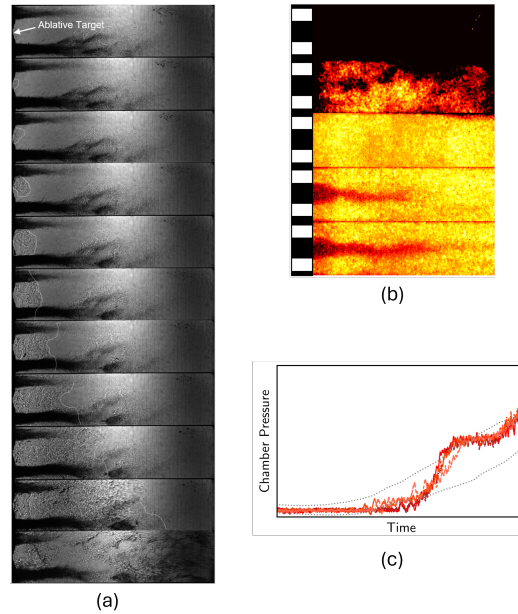


Figure 7. Subscale ignition visualization at central ignition location IP1 with (a): Schlieren imaging time series, (b): OH* imaging time series and (c): static chamber pressure evolution (adapted from¹⁴)

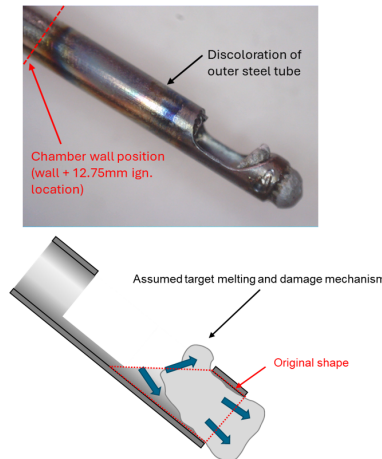


Figure 8. Image of the igniter hardware after 9 successive hot fires (top) with sketch of aluminum target damage mechanism.¹⁴

5. MULTI-POINT IGNITION OF A SMALL-SCALE COMBUSTOR

After incorporation of the lessons learned from the M3 tests, experiments on larger subscale specimens were performed at the P8 test bench at DLR Institute of Space Propulsion, Lampoldshausen, Germany. Two subscale, 19-element thrust chambers were installed in a parallel set up (see Fig. 9). The injector heads were largely identical with the main difference being that one of the two head featured a cooling film applied along the outer diameter of the combustion chamber wall.

Initial simulations of the flow field at the ignition location predicted a significant influence of the film cooling onto the local mixture ratio at the ignition location. These aspects were supported by physical considerations prior to the test campaign and were the primary reason for including the film-cooled thrust chamber in this experimental campaign.

The combustion chambers, despite of differences in appearance and technology, feature the same inner contour and can be considered equal for the test setting given. This was especially true since the tests were ignition only tests and did not include subsequent thrust-chamber ramp-up. Both thrust chambers (TC) were operated in a water-cooled configuration.

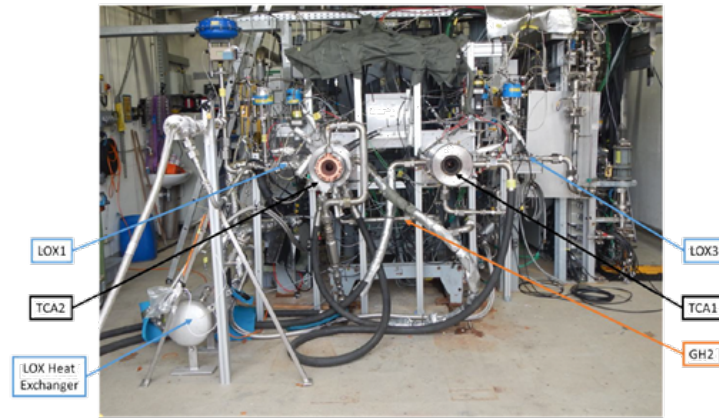


Figure 9. View of the setting on P8 test bench with two TCs mounted in parallel

An additional oxygen cooler was installed at the test bench, visible in the lower left of Fig. 9. The cooler was operated with liquid nitrogen to reduce the temperature of the liquid oxygen (LOX) supplied by the P8 test bench, particularly during the start-up phase. This ensured that LOX was available early in the transient, thereby providing test conditions more representative of a full-scale engine. This system could, however, be only operated for one of the two TCs. Initially, the TC with film cooling was connected to it. Each thrust chamber was equipped with interfaces for two laser igniters. The position of one of these igniters is shown in Fig. 10, where the igniter interface is represented by a dummy steel rod. Two multiplexed laser systems were installed

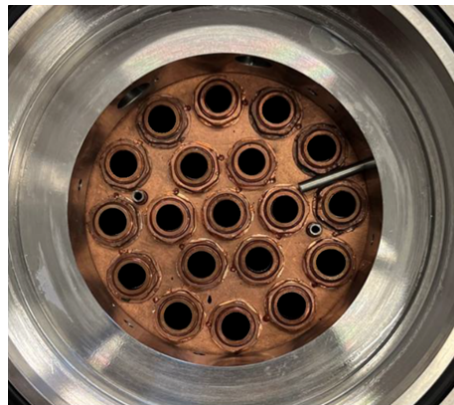


Figure 10. View of the 19 element injector with a steel rod showing the location of one of the Laser igniters

on the test bench, with each system connected to one of the two igniter ports of each thrust chamber. Each laser system provided four outputs, of which only two were used during the tests. For one ignition test, the laser generates a sequence of 50 pulses in 1s, heats up causing the pumping diodes' peak emission wavelength to drift away from the Nd absorption maximum and reducing the lasing energy. Thus lasers require some cool down

time to emit the next pulse burst. By operating the two lasers in an alternating way, a high cadence of ignition attempts could be achieved per test run without overheating the lasers. The test procedure was designed in two stages: First, a suitable sequence by operating the chambers individually was identified. In a second step, the chambers were operated synchronously to assess the feasibility of simultaneous ignition.

For the TC without film cooling and with non cooled oxygen, a suitable sequence could be found relatively straightforward. For the other TC, however, the success of ignition was erratic and stochastic. To investigate the cause of this behavior, the oxygen cooler was subsequently switched to the other thrust chamber. However, even with further cooled oxygen, the film-cooled thrust chamber did not exhibit a predictable ignition behavior.

The non-film-cooled thrust chamber assembly (TCA) could still be ignited reliably when operated with cooled oxygen, although with narrower operating margins. These results further demonstrate the suitability of the laser ignition system (LIS) for this type of configuration without film cooling.

The ignition difficulties observed with the film-cooled thrust chamber are attributed to the disturbance of the injector's outer recirculation zone by the cooling film. Consequently, the mixing of the oxygen into the hydrogen is also disturbed and no suitable mixture for ignition is present at the ignition location.

Finally, synchronous ignition tests of both thrust chambers were performed (see Fig. 11). The success rate was higher than expected at first glance - especially for the film cooled TCA. A closer analysis of the test data, however, revealed that ignition of the film-cooled TCA was not initiated directly by the laser igniter. Instead, it occurred through cross-ignition by the ignition plume generated by the adjacent TCA.

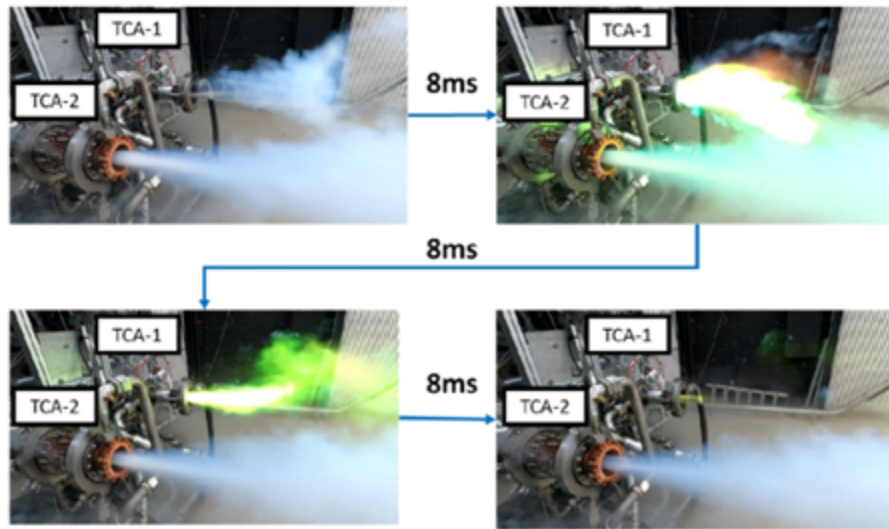


Figure 11. View of the synchronous ignitions with cross ignition via the plume from one TCA to the other.

In summary, the multiplexed laser ignition system demonstrated reliable performance in a representative combustion chamber configuration. However, the results also show that careful consideration must be given to the local conditions at the ignition location which is induced by the point-like ignition characteristics of laser ignition systems. In particular, the flow and mixing characteristics near the ignition location must provide a suitable combustible mixture for reliable laser-induced ignition.

6. RESULTS AND DISCUSSION

We investigated the laser-induced damage threshold of passive components of a laser ignition system based on ns-pulsed laser and a fiber beam delivery system and identified a possible parameter space for technical application. We tested these systems on sub- and small-scale combustors, demonstrated robust single-point laser ignition and for the first time multi-point distributed laser ignition under representative start-up conditions. The experiments

also revealed a strong dependence of ignition reliability on the local conditions at the ignition point. In particular, further investigations are required to establish a technical implementation of film-cooled combustion chamber and laser ignition concepts.

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