Laser Re-Ignition of a Cryogenic Multi-Injector Rocket Engine

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Abstract
We present results of 1328 laser ignition tests of a multi-injector cryogenic experimental rocket engine chamber. The feasibility of multiple re-ignition by a laser igniter for LOx/hydrogen and LOx/methane is demonstrated and its reliability for propellant temperatures at ignition of T_{Ox}=110-281 K and T_{H2}=122-282 K and T_{CH4}=279-290 K is proven. Optimal positioning of the point of ignition within the shear layer of a coaxial injector is verified and the tolerance for focal point misplacement is greater than +/-1 mm. The time until flame anchoring after laser-plasma generation at the injector is in the range 0.1 to 5 ms. The results demonstrate the robustness of laser ignition and the potential applicability of laser ignition systems for cryogenic rocket engines.

1 Introduction
Cryogenic rocket engines need a reliable ignition system. Additionally, future upper stage engines of launcher system have to be re-ignited to fulfill mission and de-orbiting requirements. As a failed ignition leads the loss of the mission, special attention has to be paid to the reliability and robustness of the ignition technology and to its compatibility with the engine for a smooth ignition leading to nominal functioning of the engine. Nowadays, there are a number of conventional ignition systems: Pyrotechnical igniter are cheap and compact, but allow only one ignition per device and need high safety precautions for launch preparation and pad procedures. Electrical torch igniters with spark plugs feature re-ignition of an engine but imply disadvantages like higher additional structural mass for igniter propellant feed lines or increased sequence complexity due to additional valves and high voltage electronics for the spark plugs. Catalytic igniters also allow re-ignition of the engine but suffer catalytic bed depletion and time delay associated with heating of the catalytic bed. Hypergolic ignition, induced with the injection of a third medium, require an additional feed system.
Laser ignition is considered as a possible candidate for future cryogenic rocket engines as it is a low weight, compact igniter technology that is easy and safe in handling.,. A typical laser ignition system consists of a pulsed laser system mounted directly to the combustion chamber and a lens for focusing the laser pulse. The two technical relevant concepts of laser ignition are

- direct, laser-plasma initiated ignition via non-resonant breakdown of the propellants within the combustion chamber and
- indirect ignition via laser ablation of a solid target.

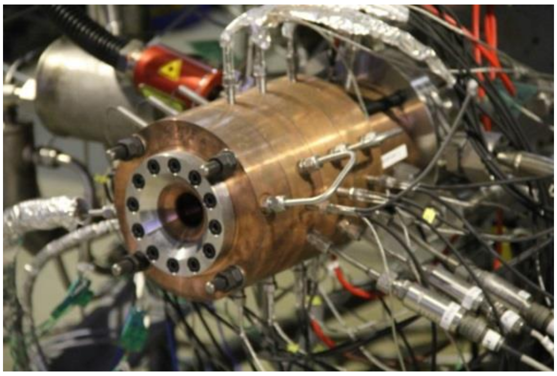
Only the direct, laser-plasma initiated ignition is dealt with in this paper. Due to the fast technical development in laser physics of recent years, light-weighted miniaturized diode pumped solid state laser systems are commercially available and are continuously being improved. At the focal point of the lens, non-resonant optical breakdown takes place due to the high laser beam intensity. For pressures of 1 bar and temperatures of 300 K intensities higher that T_{thr} = 10^{11} W/cm^2 are necessary for breakdown. The laser-plasma has a temperature of about 10^5 K and ignites the propellants [1].
Due to these characteristics, laser ignition is precise in time limited only by the laser electronics and is precise in the location of the point of ignition down to a sub-millimeter scale. It features a very high number of ignition cycles up to several million laser pulses without requiring hardware maintenance. As modern laser systems run at up to 50 Hz, the start-up sequence of the engine can be covered by multiple laser-plasma sparks. As soon as an ignitable propellant mixture is within the area of breakdown, the laser plasma is transformed into a flame kernel. Several research groups proved that a wider range of mixture ratios can be ignited by laser ignition compared to

conventional spark plug systems. For a laser igniter mounted directly onto the combustion chamber, no additional tubes and fluid control systems are needed which reduces the sequence complexity.
The main technical challenge integrating a laser ignition system to cryogenic rocket engines is the optical access to the chamber that is potentially exposed to large heat fluxes, temperature and pressure changes during the start-up of the engine.
In the last decade, laser ignition of thrusters has been investigated by the DLR Institute of Space Propulsion [3]-[8]. During these studies, RCS breadboard thrusters with one coaxial injector and also with five coaxial injectors have been successfully ignited with lasers. The feasibility of laser ignition for direct in-chamber ignition under high-altitude conditions was demonstrated in over 300 tests and fundamental phenomena like ignition probability as a function of the location of ignition and propellants and the chamber flow field have been studied. We recently presented the feasibility of direct in-chamber laser ignition for cryogenic rocket engines with global mass flows of up to 750 g/s [9]. Nevertheless, the temporal characteristics of the pressure and flame development for laser-ignited multi-injection configurations are still unexplored as well as the feasibility of multiple re-ignitions of rocket engines by laser systems. The tests presented here are set up in order to investigate and answer these questions.
In the following chapters, we present the test results obtained from a laser ignited cryogenic multi-injector rocket engine tested at the European Research and Technology Test Bench P8 at the DLR Institute of Space Propulsion in Germany:
Section 2 presents the experimental set-up, the associated diagnostics and test run parameter. The general results of the test campaign, feasibility and ignition reliability for re-ignition are shown in section 3. The following section 4 deals with the location of ignition and its spatial sensitivity for successful ignition. Section 5 gives details on the pressure development within the combustion chamber after laser ignition.
Anchoring of the flame at the injector at which ignition takes place and subsequently across the injector faceplate is characterized and the results are detailed in section 6. This paper finishes with a short summary.

2 Experimental set-up and diagnostics

2.1 Hardware set-up

The test specimen used for the tests consists of a segmented cylindrical combustion chamber with a diameter of 50 mm and a 15 coaxial injector head (see Figure **1**, right).
The injector pattern is shown in Figure **1**, left. The central element is the spark plug torch igniter, whose ignition characteristics are compared to those of the laser igniter. The injector head can be cooled actively with liquid nitrogen to decrease the temperature of the injected propellants so that the influence of the propellant injection temperatures on the ignition characteristics can be tested. All combustion chamber segments and the 33 mm nozzle are water cooled to stabilize the temperature of the segments.
The first segment, the igniter ring, is equipped with two ports for the laser igniter (port #1 is labeled as 3 and port #2 is labeled as 6 in Figure **1**), two dynamic pressure sensors (1 and 4, Kistler 6042A60) and three ports for optical sapphire probes. The optical probes are connected to an optical filter at 306 nm (5) or via a splitter to 306 nm and 430 nm filters (2) followed by photomultipliers (Hamamazu H9307-05). The third port (7) is connected to a spectrograph for laser-induced breakdown spectroscopy (see [13] for details).
Except for laser port #2 (3), all ports of the igniter ring are located in the same r-φ plane at a distance z = 10 mm from the injector face plate (see Figure **1** and Figure **2** for a definition of the cylindrical coordinates). Laser port #2 is at a distance of 4.5 mm from the injector faceplate.
The following three combustion chamber segments (see Figure **2**) are equipped with four dynamic pressure sensors at the azimuthal positions of φ = 0°, 90°, 180° and 270° (Kistler 6042A60), one thermocouple of type K and one static pressure sensor (Gems) each.



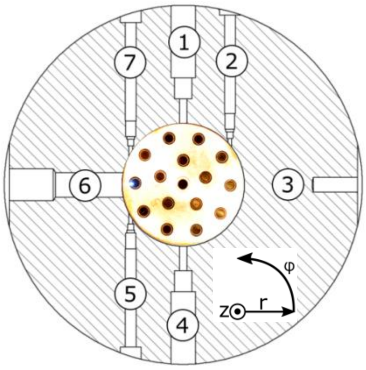


Figure 1: Combustion chamber mounted at the test bench (left) and diagnostics of the igniter ring: dynamic pressure sensors (1 and 4), optical probe connected via a splitter to 2 photomultiplier sensors for 306±5 nm and 430±5 nm (2), laser port #1 (3), laser port #2 (6), optical probe connected to a photomultiplier, filtered at 306±5 nm (5), and optical port connected to a spectrometer (7).

The pressure sensors are used to record the temporal and spatial pressure field development during ignition. The thermocouples in each segment allow the detection of the temperature rise associated with macroscopic combustion.

The optical probes in the igniter ring are connected to photomultipliers. One probe is oriented toward the ignition point (5 in Figure **1**). It allows the identification of the laser-induced plasma and the determination of the time period until the flame anchors at this injector after ignition. The second optical probe (2 in Figure **1**) is located across the faceplate, in order to evaluate the time until the flame anchors at the most distant injector at the opposite end across the injector faceplate.

The laser ignition system used consists of a HiPoLas® laser by CTR (Carinthian Tech Research AG, Austria) [5] which is directly mounted onto the combustion chamber via a tube containing the plano-convex sapphire lens with a focal length of 15 mm for focusing of the laser beam. The CTR laser system is a miniaturized solid state diode pumped laser delivering 30 mJ laser pulses of about 2 ns FWHM at a wavelength of 1064 nm. The lens focal length was optimized to allow a recessed mounting of the lens tube with respect to the inner combustion chamber wall, to reduce the temporal heat flux gradient and the temporal temperature gradient that the lens is exposed to during the transient ignition phase.

In order to reduce the thermal load onto the optical surface facing the combustion chamber, the optical access was positioned close to the injector faceplate. As mentioned above, two laser port positions have been realized and tested. The first port (port #1) was located at 4.5mm center distance of the port from the faceplate. The second port (port #2) was positioned at a distance of 10 mm from the injector faceplate. The azimuthal position is fixed by the port and the radial position can be changed to investigate into the sensitivity of the location of optical breakdown.

In the tests presented here, the ignition system is always mounted at port #1 (6 in in Figure **1**) unless otherwise indicated. The tube containing the lens and therefore the focal point can be displaced radially along vector r in Figure **1**. This allows investigating the effect of the radial displacement of the focal point onto the ignition process. The focal point was placed into the shear layer of the corresponding coaxial injector to ensure the presence of oxidator and fuel at the time of ignition (see section 4).

The laser system delivers a pulse train of 20 pulses at 50 Hz thus each pulse is separated by 20 ms, covering a total time interval of 400 ms. This aspect is of high relevance for the ignition process if the precise timing of the propellant injection is associated with some degree of uncertainty: Each laser pulse can be considered as a single ignition test as it is a single laser-generated spark.

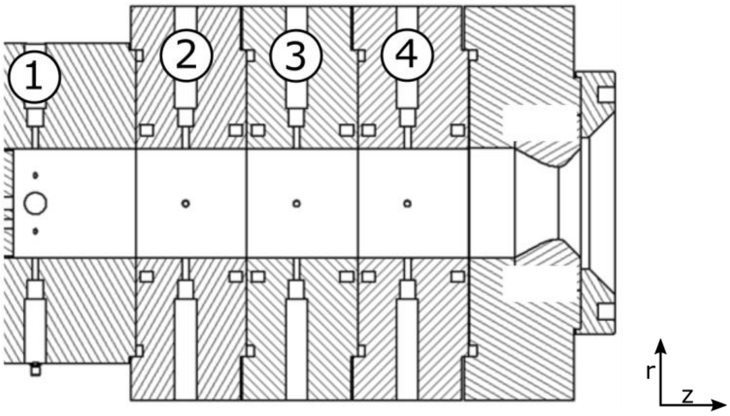


Figure 2: Position of the dynamic pressure sensors within the igniter ring (1) and each segment (2-4). z=0 is defined to be at the injector faceplate.

2.2 Test run parameter and logic

Each test run at the test bench consisted of 60 consecutive ignition tests, each separated by 30 seconds which led to a total test run time of 1800 seconds (see Figure **3**). For each ignition test, one pulse train was triggered covering the first 400 ms of propellant injection.

The propellants combinations tested were liquid oxygen/gaseous hydrogen (LOx/GH2) and liquid oxygen/gaseous methane (LOx/GCH4). The temperatures of the propellants at the moment of ignition were 110±15 K or 281±5 K for oxygen, 122 K to 282 K for hydrogen and 279 K to 290 K for methane. The lower injection temperatures of LOx and hydrogen were achieved by active cooling of the injector head with liquid nitrogen. Thermal stabilization of the injector head was reached after about 300 s after the first ignition test. After this time, near-constant injection temperatures are achieved and which are necessary to evaluate the repeatability of the laser ignition process for a specific test case.

The propellants characteristics are summarized in Table **1**.

Table 1: Propellants characteristics

parameter	unit	O_2	H_2	CH_4
maximum mass flow	[g/s]	600 ± 20	150 ± 30	200 ± 30
calculated injection velocities during steady state combustion	[m/s]	10.6 ± 1	1300 ± 200	450 ± 50
temperatures at ignition	[K]	110±15 or 281±5	120 - 282	279 - 290

3 Feasibility and ignition reliability

In total, 1755 ignition tests have been performed. These include for LOx/GH2 192 spark plug torch igniter tests and 1304 laser ignition tests and for LOx/GCH4 259 laser ignition tests.

After sequence optimization for the propellant injection and the laser timing, reliable laser ignition was achieved: For LOx/ GH2, 12 test runs in a row with 60 ignitions for each test run were realized with an ignition probability of 100% for these 720 ignition cycles. In Figure **3**, the combustion chamber pressure is shown for a complete test run. This demonstrates the reliability of the laser ignition method for re-ignition of cryogenic rocket engines. In Figure **4** a zoom into the first 3 ignitions is given. The 3 ignitions are characterized by pressure levels higher than 4 bar. The preceding and subsequent pressure rise is caused by the preconditioning and purging of the combustion chamber. In order to compare a successful ignition to a failed ignition, the pressure developments for both cases are superposed in Figure **5**. The time of ignition can clearly be identified by the fast pressure rise at about t_{ign}=0.23 s, where t=0 s is the trigger signal for the LOx run valve opening.

The same reliability of ignitions applies for LOx/ GCH4 with 55 consecutive re-ignitions of the combustion chamber. These results demonstrate the reliability of the laser system itself, the resistivity of the optical access to the combustion chamber to cyclic heat and temperature gradients and the reproducibility of the ignition process. In particular it demonstrates the re-ignitability of a cryogenic rocket engine with a multi-injector configuration.

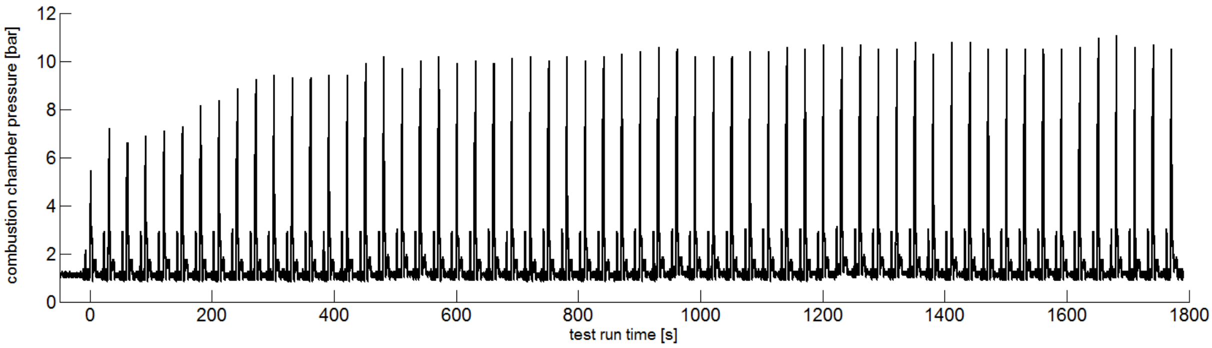


Figure 3: Combustion chamber pressure in function of time during a test run with 60 consecutive ignition tests, all leading to ignition.

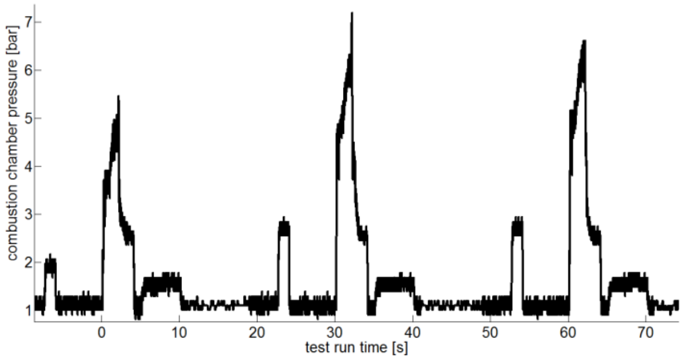


Figure 4: Zoom into 3 ignition tests separated by 30 s with a duration of about 2.5 s each.

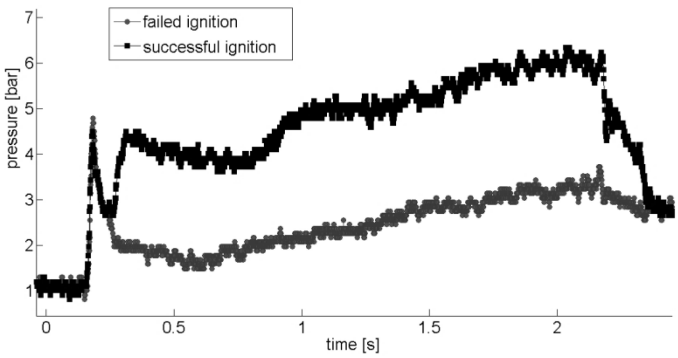


Figure 5: Comparison of a failed ignition (gray dots) and a successful ignition (black squares) test: The time of ignition can clearly be identified at about 0.23 s by the rise of the combustion chamber pressure

To assess the reproducibility of the time of ignition, this instant of time was identified by the rise of the combustion chamber pressure of the dynamic pressure sensors in the igniter ring recording data of up to 100 kHz. For 60 ignitions of a complete test run, 40 ignitions are initiated by the same pulse within the pulse train relative to the opening of the LOx run valve (see Figure 6). The laser pulse frequency of 50 Hz can be identified by the stepwise distribution of the time of ignition. This proves that the time of ignition is highly reliable within a 40 ms bandwidth which is equivalent to a shift of ±1 pulse within the pulse train.

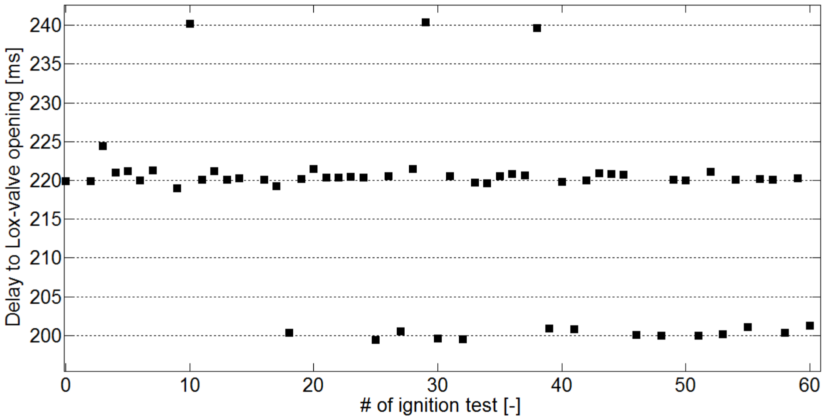


Figure 6: Time of ignition relative to the opening of the LOx run valve. The laser pulse frequency of 50 Hz or pulse-to-pulse distance of 20 ms can clearly be identified.

4 Location of ignition

The focal point of the lens of the laser ignition system defines the location of ignition: At this location, optical breakdown takes place and a plasma volume in the order of cubic millimeters is created. This plasma volume has to be in an area where an ignitable mixture of the propellants exists in order to create a flame kernel. Once the flame kernel is created, this small volume has to evolve into macroscopic combustion within the combustion chamber. Due to the high propellant velocities and the coaxial injection of the propellants, the point of ignition has to be chosen carefully. In the case of coaxial injection, possible points of ignition are within the shear layer of the injector, further downstream of the injector faceplate where atomization and mixing of the propellants is realized, or within the recirculation zone in the vicinity of the combustion chamber wall. As shown in our previous research activities ([5], [7]), the choice of the point of ignition has an influence on the reliability of the ignition and the minimum pulse energy needed to ignite the combustion chamber. Based on previous experimental results, the shear layer of the coaxial injector was chosen.

The position of the laser plasma was verified before each test run by taking a picture of the injector head faceplate with a SLR camera through the nozzle. By selecting a long exposure time, the position of the laser-generated plasma can be identified. In Figure **7**, such a picture is shown on the left side. From these pictures, the plasma boundary has been identified by detecting the area above a predefined intensities threshold. In the right figure, a post-processed, superposed picture is given. In this figure, the intensity scales from lower values colored blue to higher ones colored red. The direction of propagation of the laser pulse is from right to left. The dotted lines indicate the laser beam boundary in the geometrical optics limit. The locations of ignitions for all LOx/GH2 tests are given in Figure **8**. The shape of the plasma is approximated by an elliptical shape. Each ellipse represents an individual location of ignition tested.

For all these locations reliable and successful ignition was realized. This result underlines that the radial position of the focal point (therefore of the laser plasma) can be shifted by more than 1 mm in both radial directions from the estimated shear layer of the propellants. This applies for both laser ports, that are located at z_1=4.5 mm and z_2=10 mm from the injector faceplate as well as for all propellant injection temperatures listed in Table **1**.

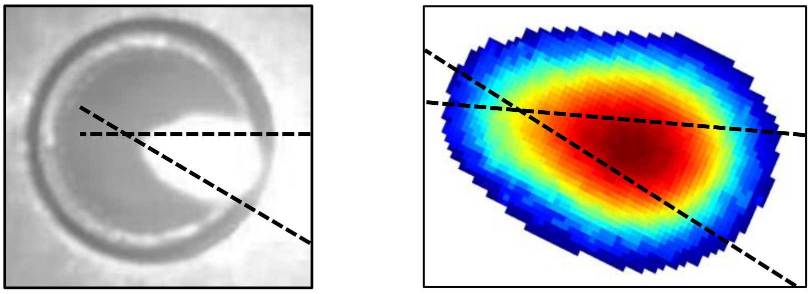


Figure 7: SLR camera picture of one injector with the laser-generated plasma before a test run (left) and intensity profile of the laser-generated plasma in false colors (right). The dotted lines indicate the laser beam boundary in the geometrical optics limit.

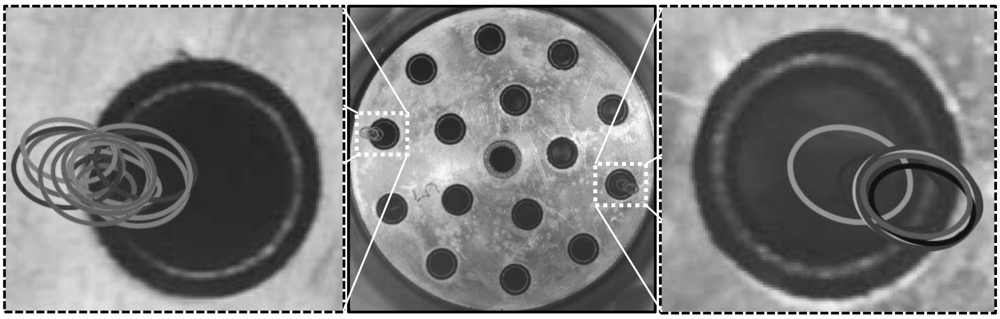


Figure 8: Injector faceplate (central image) and locations of laser generated plasma, enlarged in the left (laser port #1) and right image (laser port #2). Each ellipse represents a different ignition location.

5 Pressure dynamics after ignition

In order to characterize the pressure development after laser ignition, the dynamic pressure sensor signals are correlated in time. As the laser ignition is a point-like ignition method, the propellant mixture is ignited in a small, localized volume. In contrast, conventional spark plug or pyrotechnical torch igniters create a larger area of hot gas that is injected into the combustion chamber, impinging onto the injected propellants.

In theory, laser ignition could trigger high pressure peaks due to the fast ignition of the propellants accumulated within the combustion chamber before ignition and trigger asymmetric pressure loads on the combustion chamber wall or even combustion instabilities. In previous work, we found laser-ignition induced overpressures in smaller, single injector thruster configurations [10]. In the tests presented here, overpressures of up to 40 bars have been identified. By adaptation of the propellant injection sequence, this unfavorable effect was reduced until no ignition over-pressure was experienced.

In Figure 9, the pressure dynamic after laser ignition within the combustion chamber is shown for the line of pressure sensors located at the azimuthal position of $\varphi = 90°$: The pressure signals at each segment as a function of time allow to determine the direction of the pressure rise along the z coordinate. On the left side, the pressure sensor data is given for one laser ignition test: The pressure rises first close to the injector faceplate, followed by a pressure rise in each subsequent segment towards the nozzle. On the right side, the pressure dynamic is given for a provoked ignition from outside of the combustion chamber. The pressure rises in reverse order compared to the laser ignition test. An important observation is that for the ignition from outside of the chamber, the pressure peaks are higher by a factor of up to 4 compared to the laser ignition test.

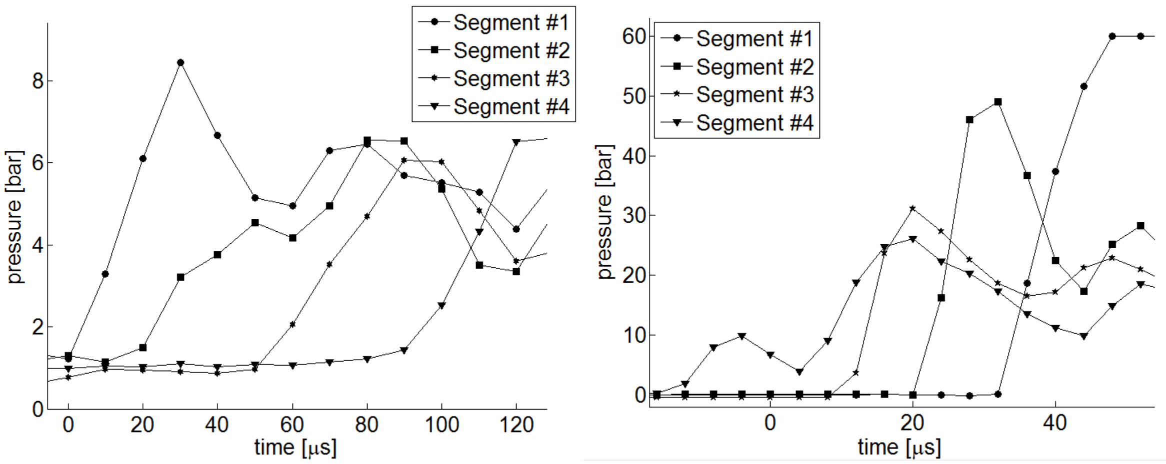


Figure 9: Left: Pressure rise within the combustion chamber after laser ignition. The time shift in pressure rise indicated the axial direction of the flame front development from the injector faceplate towards the combustion chamber nozzle. Right: Pressure rise due to an ignition from outside of the combustion chamber.

6 Combustion diagnostics and flame anchoring at the injector faceplate

The details of the flame development and anchoring after laser ignition are an important aspect for the understanding of the ignition process. For this aspect, the signals of the optical sapphire probes are used. As the probes are connected to photomultipliers equipped with optical filters only transmitting light at 306±5 nm, the laser-generated plasma and the combustion process emitting radiation at 306 nm can be detected.

In a first approach the photomultiplier signal allows to verify the creation of the plasma. This allows to assess the reliability of plasma generation. If the laser pulse energy transmitted through the optics is insufficient to create an optical breakthrough, this would have been detected using this approach. For all tests and all pulses within the pulse train, breakthrough was achieved, proving the reliability of the used optical access to the combustion chamber and its resistance against the pressure and temperature cycles associated with the combustion process. As the diameter of the optical probe is only 1.5 mm and the probe is recessed with respect to the inner combustion chamber wall, the line of sight is limited to the geometrical diameter of the drilling. Therefore it also allows verifying the location of the laser-generated plasma to some extent. The voltage signal of the photomultiplier for a single ignition test is given in Figure **10**. The laser-generated plasma can be identified by the peaks at a distance of 20 ms which is the laser system pulse frequency of 50 Hz. The onset of combustion is characterized by the continuous signal above 100 mV at about 180.23 s. All ignition tests show a time delay between the laser-generated plasma and the rise of the combustion signal (see Figure **11**). This time delay varies between 0.5 and 5 ms. So far, no governing parameter has been identifies for this characteristic time.

Still this finding is in good agreement with previous test results from ignition tests from optical accessible combustion chamber tests ([3],[7]): After the generation of the plasma, a small flame kernel is created. This flame kernel is moving with the surrounding propellants towards the nozzle and the flame then expands back stream up, until the flame anchors at the injector faceplate and therefore enters the line of sight of the optical probe.

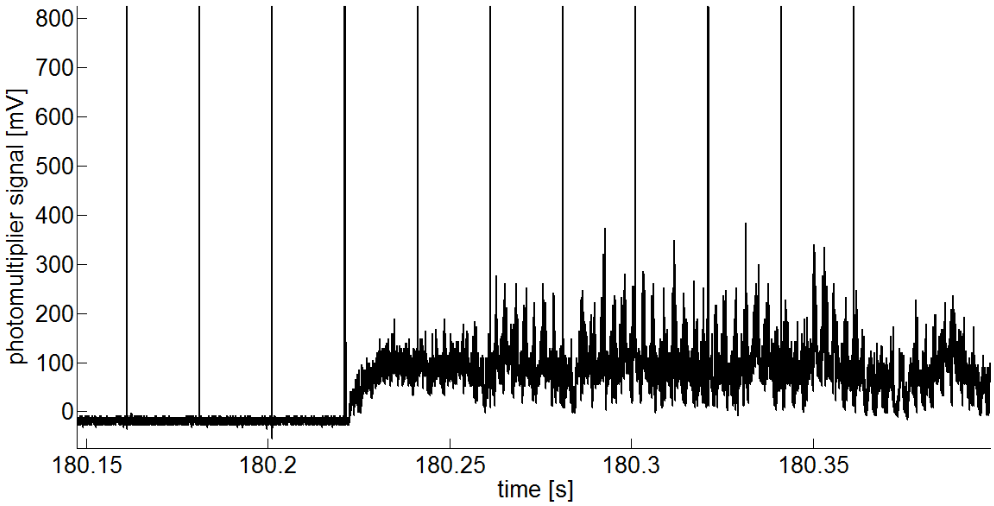


Figure 10: Photomultiplier voltage signal in function of time. The laser generated plasma is generated at 50 Hz, which is the laser pulse frequency. The macroscopic combustion is identified by the continuous signal above 100 mV following the laser pulse starting the ignition at about 180,23 s.

The igniter segment of the combustion chamber is equipped with a second optical probe pointing toward the injector directly across the faceplate from the point of ignition (2 in Figure **1**). By comparing the signals from both photomultipliers, the simultaneity of the flame anchoring at the faceplate is studied. For the photomultiplier signals shown in Figure **11**, both signals rise within a time period of about 40 µs. Although in this case the simultaneity is given for flame anchoring, the time delay between the flame anchoring at these two injectors is ≤2.0 ±0.1 ms, a value that we cannot correlate to any other experimental parameter and is statistically distributed among the ignition tests. This indicates inhomogeneous propellant injection by the injector head leading to inhomogeneous propellant flows and therefore inhomogeneous mixture ratios for the 15 coaxial injectors that influences the flame propagation within the combustion chamber. Optical data from a camera investigating the propellant injection process and the ignition process confirm these results as discussed in [13].

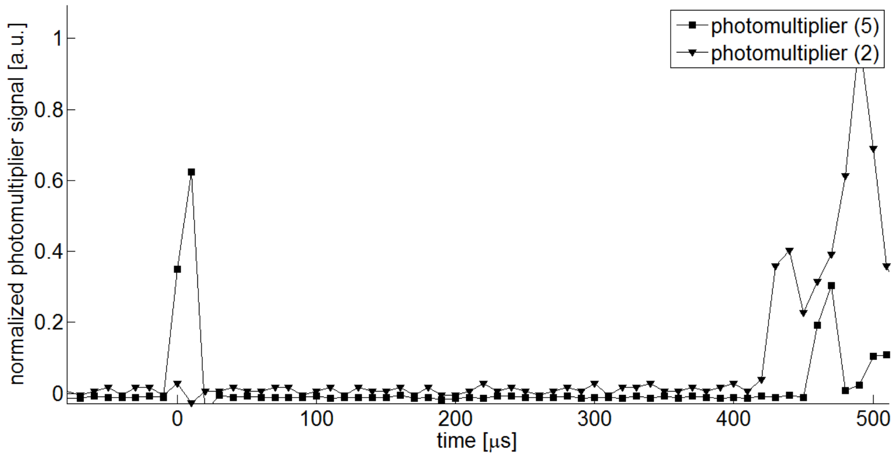


Figure 11: Comparison of the photomultiplier signals pointing onto the most distant injectors of the faceplate. Both signals indicate the anchoring of the flame at the corresponding injector within a time period of about 40 μs.

7 Summary and outlook

In this paper, we presented characteristics of an experimental laser-ignited cryogenic multi-injector rocket engine. The reliability of re-ignition as well as the reliability of the ignition system was demonstrated. The location of ignition is shown to be insensitive to a misplacement in the radial direction to an extent of 1 mm in both directions and the two axial distances of 4.5 and 10 mm from the injector faceplate have been verified to be reliable points of ignition.

The pressure field development after ignition has been characterized and the process of flame anchoring for the injector at the location of ignition as well as across the injector faceplate has been monitored using optical probes. These diagnostics allow a detailed insight into the ignition process for, but not limited to, laser-ignited rocket engines.

In future a detailed comparison to the ignition tests with the spark plug torch igniter will be performed.

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