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Laser ignition of a multi-injector research combustion chamber under high altitude conditions[1]

Michael Börner and Chiara Manfletti** and Gerhard Kroupa*** and Michael Oschwald**

**DLR Institute of Space Propulsion, Hardthausen, Germany*

***now at European Space Agency, Paris, France*

****CTR AG, Villach, Austria*

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Please refer to it for further details and citing.

Abstract

In order to investigate into the laser ignition process for a multi-injector configuration under low pressure conditions, a test campaign at the M3.1 test bench of the DLR Institute of Space Propulsion in Lampoldshausen was realized. Two fundamental laser-based ignition concepts were tested: The laser-plasma based ignition LPI and the laser-ablation based ignition LAI. The former is realized by the generation of a spark by focusing the laser pulse directly into the propellants, whereas the latter is realized by focusing the laser onto an ablation surface. The potential applications of fibre-based ignition systems are discussed.

1. Introduction

The laser-based ignition technology for space propulsion systems has been investigated extensively throughout the last decade [1-7]. Due to several advantages described in these papers, laser ignition was investigated for LOX/kerosene [5], LOX/hydrogen [1-4,6] and LOX/methane [7] for combustion chambers of liquid rocket engines. It is a lightweight and reliable ignition method and re-ignition by laser of combustion chambers has been proven for LOX/H2 and LOX/CH4 at ambient and low pressure levels [3]. In comparison to torch igniter systems, the energy input of laser-based ignition systems is localized in the order of mm^3 and very short in the order of ns for a single laser pulse. A qualitative comparison for the energy input in function of time and ignition volume is shown in Fig. 1.

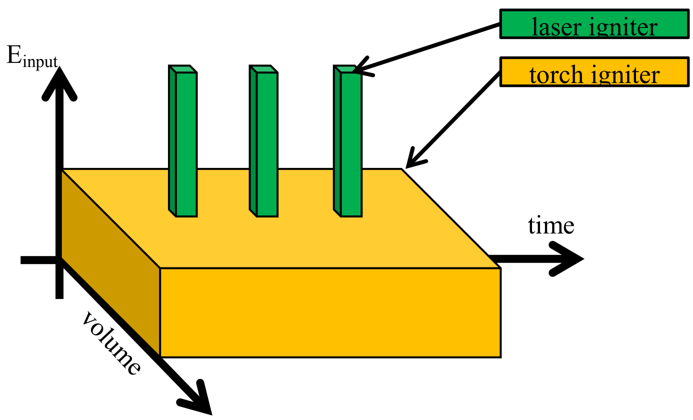

Figure 1: Schematic comparison of the energy input into the combustion chamber of a laser ignition system and a torch igniter system.

The ignition by optical breakdown induced by a laser pulse in rocket combustors involves 4 consecutive steps which are detailed in [1]:

1. Generation of a laser-induced plasma
2. Transformation of the plasma kernel into a localized, self-sustained combustion zone
3. Transformation into macroscopic combustion, including flame propagation from injector to injector

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4. Stable anchoring of the flames at all injector elements

For an application scenario for upper stage engines of launchers, the low pressure atmosphere prior to propellant injection and its impact on the ignition process have to be considered in particular. The low pressure levels can imply flashing of the propellants and lead to a modified flow field within the combustion chamber when compared to injection at ambient pressure levels. In 2011, the compatibility of laser ignition with a single injector element configuration and high altitude conditions has been shown [3].
To study an application scenario of laser ignition systems for restartable upper stage cryogenic engines, the tests presented in this conference paper have been performed to investigate the feasibility and characterize the ignition process induced by optical breakdown of the propellants. The term high altitude conditions is to be understood as pressure levels within the combustion chamber prior to propellant injection lower than 0.1 bar. Main goals of the test activities were to perform a wide range of ignition tests with LOX/GH_2 in an optical accessible subscale combustor with more than one shear coaxial injector element and to characterize the ignition process in function of

- the ignition method used
- the LAI ablation target material
- the laser pulse energy and
- the combustion chamber pressure prior to ignition.

2. Experimental set-up

2.1 The test bench set-up and diagnostics

The tests were executed at the M3.1 test bench of the DLR Institute of Space Propulsion in Lampoldshausen, Germany. The test bench has a dedicated vacuum system connected to the nozzle of the combustion chamber and injection conditions for low pressures down to 50 mbar before propellant priming were realized. Using an optically accessible combustor and combined high-speed Schlieren and OH* diagnostics, the ignition process was monitored from propellant injection, local ignition and flame development until anchoring of the combustion zone at the injector faceplate. A detailed description of the set-up can be found in [1].
An image of the combustor and the ignition system is shown in Figure 2 and the injector element pattern is given in Figure 3. The laser ignition system consisted of the laser system HiPoLas Gen. IV developed by CTR AG, generating the laser pulse train of 20 individual laser pulses (λ=1064nm; ~2.3 ns FWHM) each separated by ~20 ms. The laser was directly attached to the combustor via a lens tube holding the focusing lens. In addition, filter were introduced in the lens tube unit to reduce the laser pulse energy.

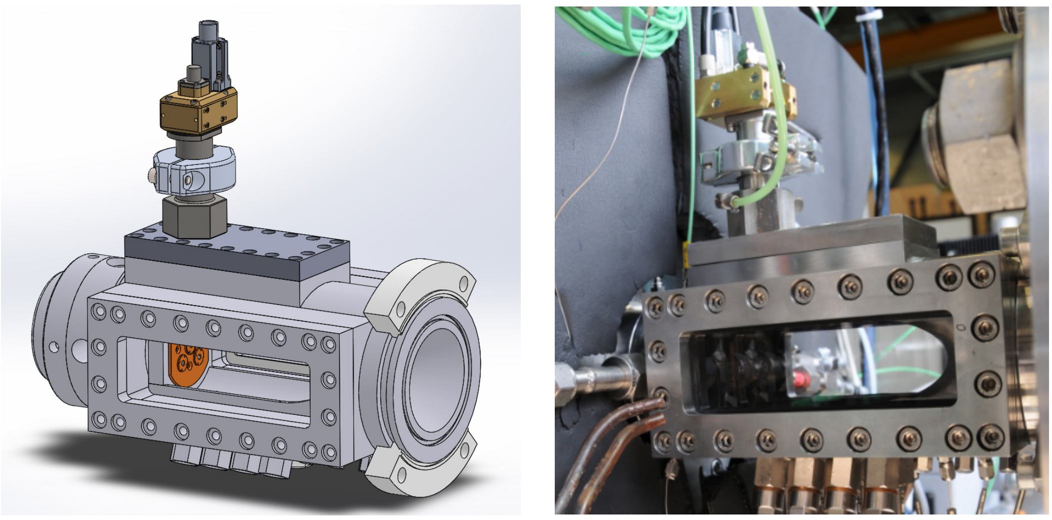

Figure 2: Optically accessible combustor with attached laser igniter [1]

2.2 The ignition configuration

Two fundamental laser-based ignition concepts were tested:

- laser-plasma based ignition LPI and

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- laser-ablation based ignition LAI

The former is realized by the generation of a spark by focusing the laser pulse directly into the propellants, whereas the latter is realized by focusing the laser onto an ablation surface located at the injector faceplate.
In total, 4 LPI locations were chosen at increasing distances from the injector faceplate representing different levels of atomisation and mixing of the propellants and injector/injector interaction. For LAI, the two ablation materials CuCrZr and WCu were selected and tested at 3 different locations (LAI1-3) within the combustion chamber shown in Figure 3. In Figure 3, the LAI locations are also shown with optical breakdown under ambient condition.
In the following, the combination of ignition concept (LAI or LPI) and material will be called "ignition configuration".

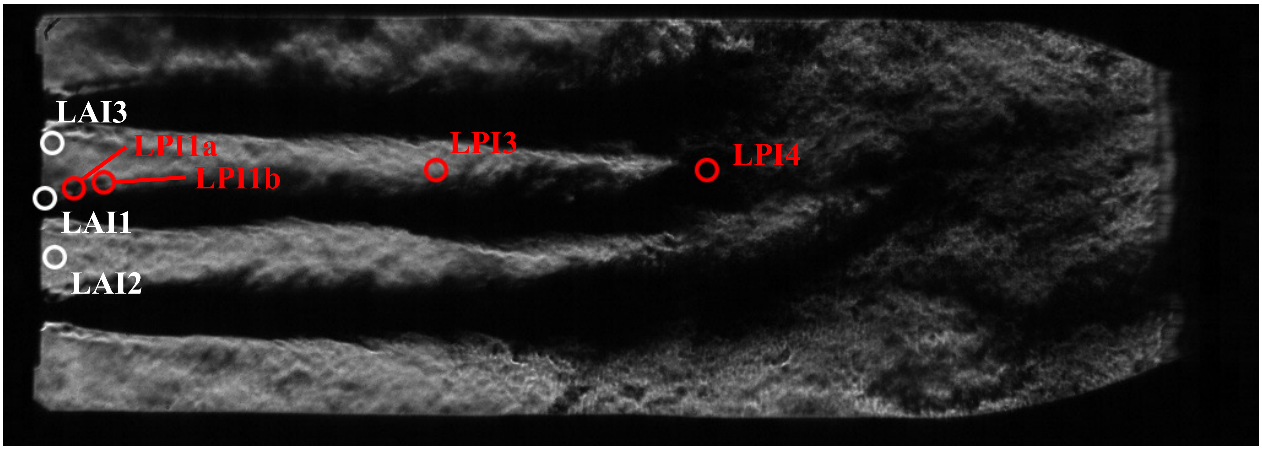

Figure 3: Ignition locations. In the background, a single Schlieren image of a cold flow test is shown [1].

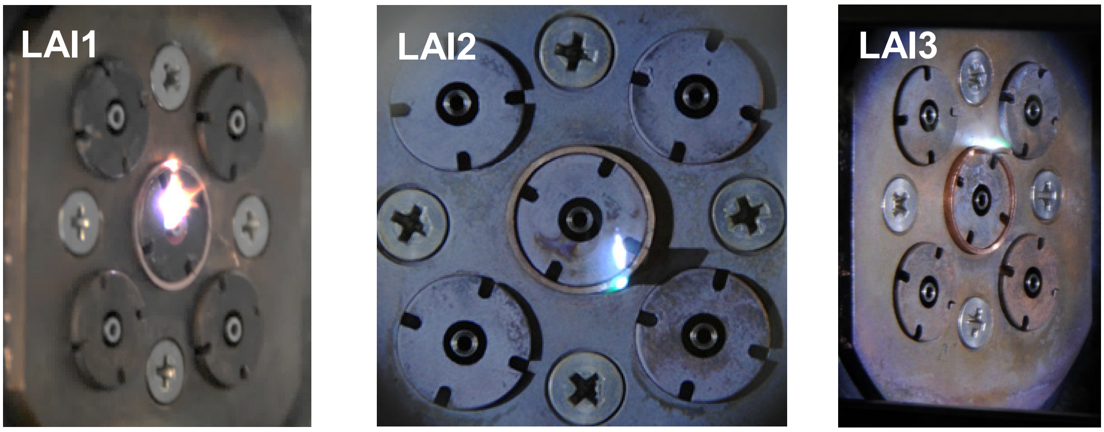

Figure 4: Ablation configurations [1]

2.3 Test logic

To find the individual minimum laser pulse energy, each ignition configuration was tested for the highest possible laser pulse energy (33.2 mJ) and repeated three times. If the ignition probability was higher than zero, the laser pulse energy was consecutively reduced until the ignition probability of 0% was reached. The minimum pulse energy for ignition is defined here as the lowest laser pulse energy that guaranteed an ignition probability of 100% for three test repetition.
The test sequencing is was optimized based on cold flow tests to guarantee the propellant injection during the activation time of the laser igniter to ensure an ignitable mixture within the combustion chamber.
A priming of the LOX feed line was applied before the actual ignition test to minimize the two-phase flow of the oxygen and in consequence to avoid blocking of the oxygen injection by gaseous oxygen.

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3. Test results

3.1 Ignition reliability

For all ignition locations tested except for L1a, the ignition probability for laser pulse energies of 33.2 mJ was 100%. The impossibility to ignite at LPI1a can be attributed to the shock wave structure and the associated shear forces which inhibits flame kernel development after the optical breakdown. The optical breakdown was observed, but subsequent flame development was not detected. This effect was also described for the single injector test configuration [3].

For any location tested at low laser pulse energies close to the minimum pulse energy for ignition, the flame was quenched after ignition by the first laser pulses within the laser burst. This shows that the laser peak intensity was high enough to generate a gas breakdown (step 1) and the energy transfer from the laser pulse into the plasma was sufficient to overcome the minimum ignition energy (step 2), but that the local flow and mixture gradients inhibited further flame development (step 3). In those cases, ignition of the combustion chamber was realized by a consecutive pulse within the laser burst when the transient propellant flow field and mixture ratio distribution have changed. This observation underlines the necessity for burst modes of laser igniter systems to assure ignition and to increase the reliability.

3.2 Minimum pulse energy

The minimum pulse energies for each ignition configuration are given in table 1.
The following observation can be made:
The global minimum pulse energy was found for LAI2, independently of the material used.
For LPI, the lowest MPE-I was found to be 2.6 mJ for axial faceplate distances of 36.8 mm where mixing is fully developed. The MPE-I decreases with axial distance from the injector faceplate. Ignition is impossible upstream of the Mach disk of the hydrogen injection flow with laser pulse energies of 33.2 mJ or lower.

Table 1: Ignition characteristics for the configurations tested [1]

	Minimum pulse energy [mJ]	**Flame spreading [-]**
LPI1a	ignition, but no flame spreading	-
LPI1b	33.2±1	Type 1
LPI2	2.6±0.2	Type 1
LPI3	2.6±0.2	Type 1
LAI1	14.5±0.5	Type 1
LAI2-WCu	1.7±0.2	Type 2
LAI2-CuCrZr	1.7±0.2	Type 2
LAI3-WCu	6.23±0.3	Type 2
LAI3-CuCrZr	9.9±0.4	Type 2

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3.3 Pressure dynamics

Ignition overpressure is a function of the sequencing of the propellant injection resulting in different global mixture ratios within the combustion chamber at the time of ignition influenced by the flow field within the combustion chamber. Due to the open or closed nature of recirculation zones in a combustion chamber, pre-ignition sequencing of the propellants influence the ignition behavior and the level of ignition overpressure which is a function of the accumulated propellant mass within the combustion chamber at the time of ignition. In terms of maximum pressure levels during ignition, no differences were identified for any of the ignition configuration.
An example of the static pressure evolution during a test run is given in Fig. 5. The combustion chamber is ignited at about 137 ms and the pressure increases from the pre-ignition limit of about 0.55 bar to 2.2 bar within 13 ms.

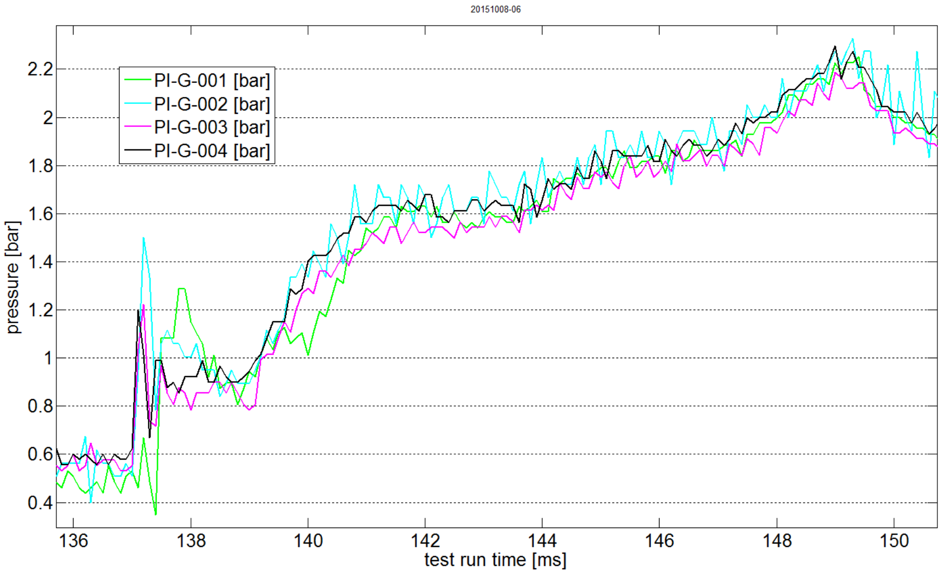

Figure 5: Zoom into the pressure rise due to ignition

3.4 Flame spreading

In general two different flame spreading mechanisms were observed:

1. The flame kernel was transported downstream towards the nozzle, spreads within the injector interaction region and then spreads back upstream along the injectors and the recirculation zones until the combustion zone anchors at the injector faceplate. This flame spreading (“type 1”) is observed for LPI1, LPI2, LPI3 and LAI1.
2. The flame kernel spreads within the recirculation zones close to the injector faceplate, is transported downstream while igniting all 5 injector elements. This flame spreading (“type 2”) is observed for LAI2 and LAI3.

Two examples of flame spreading are illustrated in Fig. 5.

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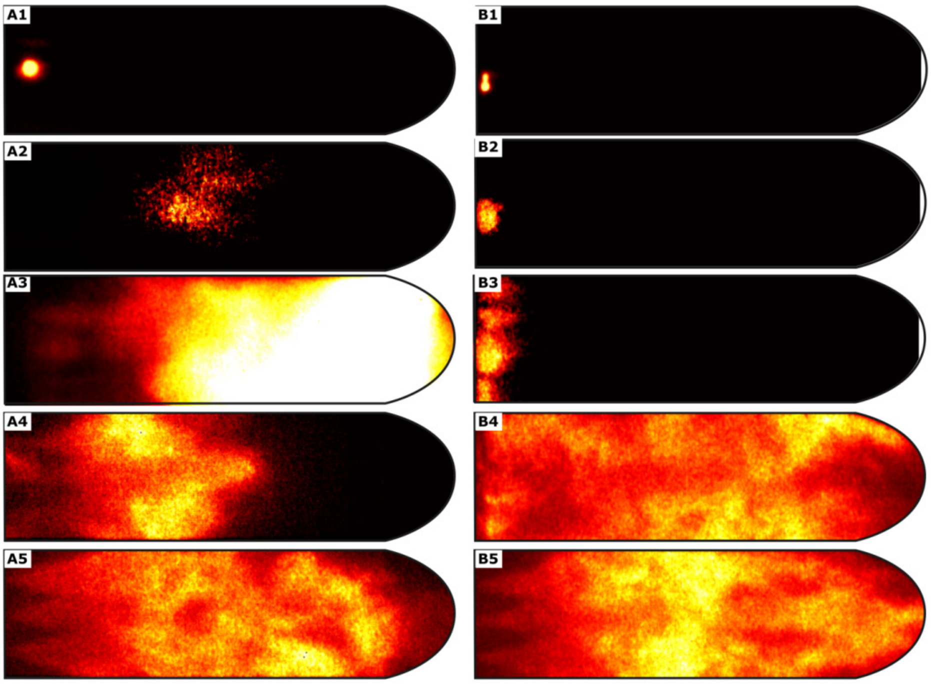

Figure 5: False-coloured OH*-image sequences. *A1-A5*: LPI1b ("type1"), *B1-B5*: LAI2 ("type2"). The relative times are: A1: 0 ms, A2: 0.167 ms, A3: 0.251 ms, A4: 0.792 ms, A5: 2.875 ms. The times for sequence B are identical.

Former investigations [3] identified similar flame spreading phenomena for a single injector element with large recirculation zones between the central injector element and the combustion chamber walls.

3.5 Anchoring of the combustion zone

Independent from the type of flame spreading, the flame anchored at all injector elements, verified by the OH* emission and the Schlieren images. Figure 6 shows the injector configuration, a Schlieren image of a cold flow, a Schlieren image of the anchored flame and the corresponding false-colour OH*- image. Due to the projection of the injector pattern, three injector element rows are visible. The Mach structure of the accelerated hydrogen injection can be identified in image B and C. For image B, the pressure within the combustion chamber is between 0.2 and 0.4 bar whereas for image C, the pressure is about 2.5 bar. Because the combustion chamber pressure is increased, the shock wave structure is contracted.
Also, the effect of the anchored flame is visible in image C: The flame attached at the injectors generate a hot gas zone between the hydrogen and LOX jet that constricts the LOX jet and pushes the hydrogen jet radially outwards.

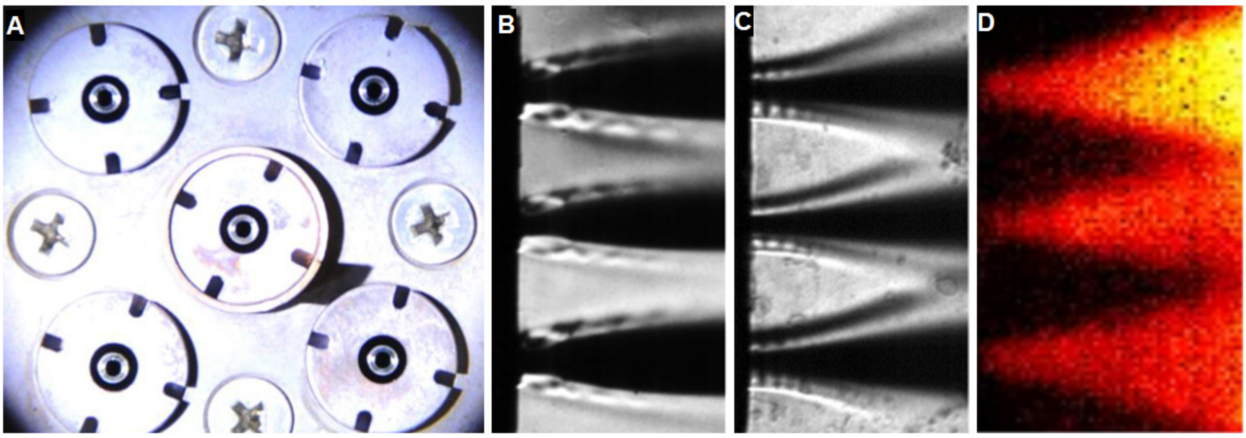

Figure 6: A) Injector configuration, B) time-averaged Schlieren image of a cold flow, C) time-averaged Schlieren image of the anchored flame and corresponding false-colour, time-averaged OH*- image [1]

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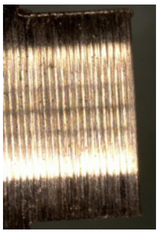
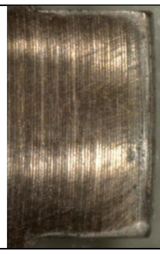
3.6 Ablation target degradation

The LAI target degradation was evaluated after the test campaign by using an optical microscope. The targets before and after the test campaign are shown in table 2. The effect of degradation is in the order of the manufacturing tolerance and is therefore considered as negligible for potential applications.

Table 2: LAI target degradation

Material	CuCrZr	CuCrZr	WCu	WCu
Location	C2	C3	C2	C3
# of laser pulses	300	400	220	260
before test campaign				
After test campaign				

4. Conclusions and outlook

4.1 Trade-off for LAI and LPI

In general, the test results prove the reliability of laser ignition under low pressure conditions for multi-injector configurations. LAI show lower minimum pulse energies for ignition compared to LPI, but the integration of the positioning and design of the laser igniter is restricted by the positioning of the ablation surface. In contrast, LPI is more flexible in terms of positioning of the optical access but needs up to two times more laser pulse energy.
It is important to underline that the ignition configuration LPI1a did not lead to ignition, whereas ignition was possible for LAI1. A detailed discussion on the results is given in [1].

4.2 Fiber based ignition systems

For LAI2, LPI2 and LPI3, the laser pulse energies needed for reliable ignition are in the order of pulse energies and intensities that were reported to be transported via optical fibres (see table 3). Fiber-based transport would allow placing the core laser system away from cryogenic structures like the propellant domes or hot structures of the engine and facilitates the integration of the ignition system into an existing engine structure. Additionally, a multi-point ignition scheme would be possible by multiplexing of the laser pulses and pulse transportation by fibers.
The following section is dedicated to a short review of the state of the art of fiber-based ignition technologies published. It focusses on the application of nanosecond laser pulses for LPI or LAI. A detailed review on “High power fiber delivery for laser ignition applications” is given by Yalin [9].

In general, two technical approaches are formulated:

1. The first technical solution consists of a central laser, generating a high power pulse that is transported towards the engine by a fiber and is then focused to generate a breakdown.
2. The second technical solution is a central pump source like a laser diode array connected to local resonators attached to the engine to be ignited.

A third approach of active fibres, where the fibre itself is the active gain medium, is not considered here. These systems are designed for continuous wave operation which is not suitable for laser-based ignition as the necessary peak intensity for breakdown is not reached and the laser system size and weight available are too high.

Table 3: Summary of the MPE and minimum gaussian profile peak intensity

Ignition configuration	Gaussian profile peak power calculated according to [8] [kW]
LPI1a	n/a
LPI1b	13280
LPI2	1040
LPI3	1040
LAI1	5558
LAI2	680
LAI3-CuCrZr LAI3-WCu	2492 3960
Power available by fiber transport [11]	1581

The highest pulse intensities that are transported by fibers are reported by Dumitrache et al. [10] and Matsuura [11]. The first paper reports on laser pulse energies of 30 mJ in 30 ns before damage of the optical fiber. This is equal to 920 kW peak power if a gaussian pulse profile is assumed. In the second publication, the authors report to have transported 11.16 mJ in 7 ns equal to 1581 kW peak power if a gaussian pulse profile is assumed. Both conclude that the major limiting factor is the maximum bending radius of the fiber before being damaged by the high power pulses. As a fiber has to tolerate small bending radii to be attractive for engine integration, the application of high intensity pulse transport is limited today.

As mentioned above, the second technical approach would be a core laser system generating low intensity pulses that are transported by fibers to the engine to be ignited and coupled into an amplifier stage directly mounted to the combustion chamber. A similar approach is followed by Sudakov et al. [5] to realize multi-point ignition within a combustion chamber.

For future multi-engine configurations of reusable launcher systems, distributed fiber-based ignition systems would allow a significant reduction of weight while introducing the possibility of redundancy of each ignition system and nearly unlimited re-ignition capabilities.

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