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D11 Executive Summary Report

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ESA TDE Optical fibre-based ignition technology for launcher RCS

DLR

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1. Scope of this document

This document is the Deliverable D11"Executive Summary Report" within the ESA TDE "Optical fibre-based ignition technology for launcher RCS" (ESA Contract No. 4000128882/19/NL/MG) which is the output of the complete project.

2. Executive summary

The reliable ignition of a propulsion systems is essential for any space transportation systems. In case of non-hypergolic propellants, the ignition process is initiated by an appropriate ignition system that has to be as reliable, robust, simple and cost effective as possible for the envisaged application.

In this ESA TDE project "Optical fibre-based ignition technology for launcher RCS", a fibre-based laser ignition system for cryogenic launcher reaction control systems or upper stage rocket engines and in space propellant injection conditions was designed, manufactured and tested on a breadboard thruster at the DLR Institute for Space Propulsion. The application scenarios of fibre-based ignition systems were described for RCS systems and main stage engines in clustered and non-clustered configurations. Furthermore, the economic benefits and potential cost savings compared to traditional igniter solutions were formulated and evaluated. The essential findings are summarized in the following.

The developed and tested fibre-based laser ignition system (FB-LIS) consists of the following essential elements, sketched in Figure 1:

1) the core laser system that generates the laser pulses:
    - CTR HiPoLas® Generation-5 HR laser system
2) the breadboard multiplexer that splits each laser pulse into two fibres based on a diffractive optical element, holographic beam splitter
3) the fibre coupling that focusses the laser pulse into to fibres via lenses into two fibre cores with SM-905 connectors
4) high energy fused silica fibres that guide the pulses towards the combustion chamber with different core diameter of 400 µm, 600 µm and 800 µm
5) the focusing unit that focuses the laser pulse into the combustion chamber (see below for details) and
6) the dedicated adapter plate connecting the focusing unit to the breadboard thruster

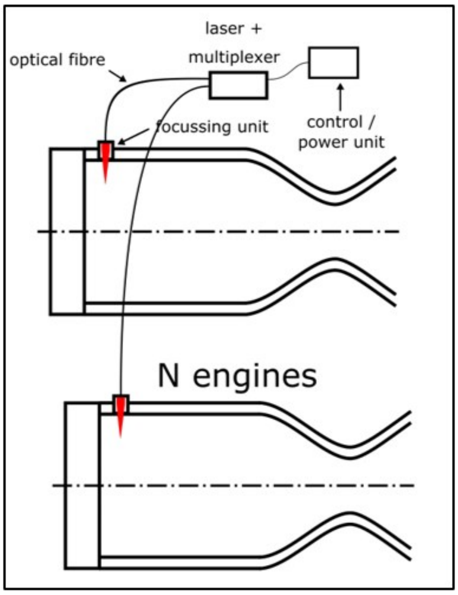
The focusing unit was designed and tested in two major configurations:

1) a lens tube unit holding the focusing lens to generate an optical breakdown
    a. within the propellants at two axial distances from the injector faceplate (laser-plasma driven ignition (LPI), configuration "FU1a-LPI1" and "FU1a-LPI2") and
    b. at the surface of the injector element via laser-ablation driven ignition (LAI), configuration "FU1a-LAI" and configuration "FU1b-LAI")
2) a copper tube holding the fibre
    a. without an additional focusing element (configuration "FU2-LAI") and
    b. with a Gradient-index (GRIN) lens to refocus the laser pulse ("FU2-LAI-GRIN").

Details on the configurations can be found in the deliverable 2 "Design Report: Fibre Distributed Laser Ignition System". Further details on the individual elements are given in table 1.

Table 1: Overview of the optical fibre-based ignition system and design solution

component ID	component name	description
C1	High energy core laser source	HiPoLas GenV-HR by SAL AG
C2	High energy optical fibres	Step index fused silica fibres with different core diameters and cladding thicknesses are assembled and tested with the setup to assess their performance. Fibres with 600 and 800 µm core diameter and with an numerical aperture of 0,39 and laser polished end faces are identified for testing.
C3	Multiplexer unit	A multiplexer for two optical fibres based on a DOE holographic beam splitter will be set up in a prototyping enclosure.
C4	Fibre coupler units to couple the laser pulse into the fibres	The two output beams of the DOE splitter will be refocused, separated and coupled into two fibre cores with SM-905 connectors
C5	Focusing unit and concept for fibre based ignition systems integration into breadboard thruster	The output of each fibre will be collimated and refocused using an arrangement of spherical lenses integrated into the combustion chamber optical access port Two solutions will be tested: 1. A direct integration of the optical tube for LAI and potentially LPI at the central injector 2. A purely ablative approach at the injector element exit without focal optics



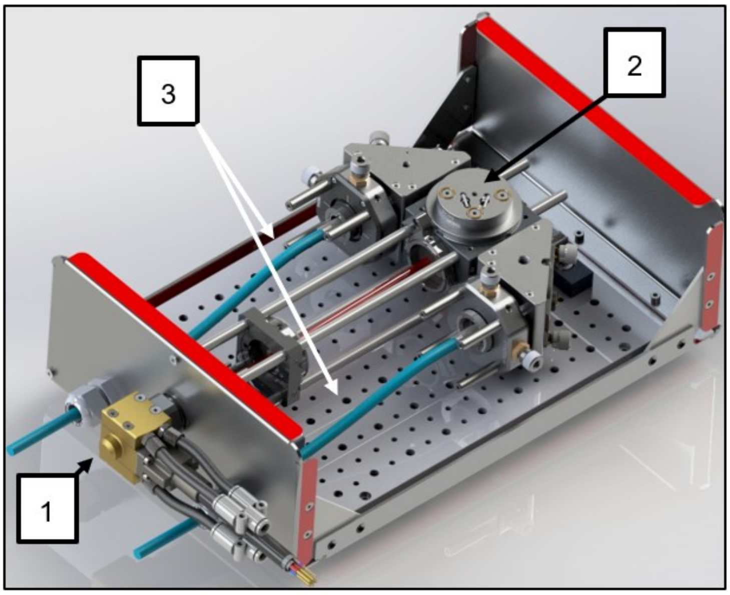


Figure 1: Concept and CAD of the laser (1), multiplexer (2) and optical fibres (3) of the fibre-based laser ignition system

After the design and manufacturing of the BF-LIS prototype system and a laboratory test phase, a test campaign of 120 test runs was conducted at the M3.1 test bench of the DLR Institute of Space Propulsion. As the TDE project was extended by a CCN, two test campaigns were realized: The test campaign for the original TDE activity and a test campaign for the CNN1.

The laser-ablation driven ignition (LAI) configuration and laser-plasma driven ignition (LPI) configuration were tested for the propellant combination LOx/GH_2.

The main focus of the test campaigns was to determine the reliability of the FB-LIS for different ignition locations and focusing unit concepts. A special focus was degradation of the fibres due to testing.

Further test goals were the determination of the minimum laser pulse energy (MPE) needed for 100% ignition probability out of three repetitions for each configuration to identify the possibility of laser pulse energy reduction and therefore of multiplexing options of the laser pulses into more than two fibres.

A representative photo during a successful ignition for the test configuration "FU2-LAI-GRIN" of the CCN1-test campaign is shown in Figure 2.

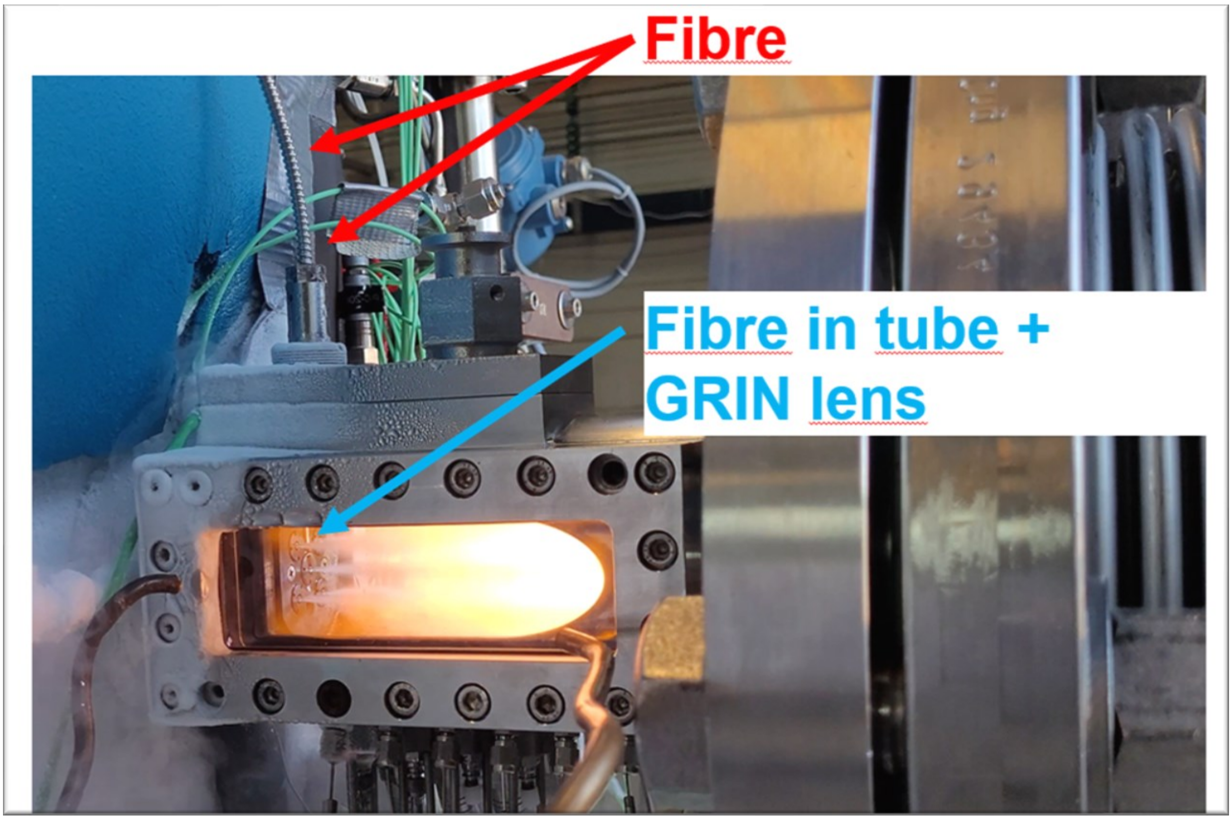


Figure 1: successful ignition for the test configuration "FU2-LAI-GRIN" of the CCN1-test campaign

Throughout the two test campaigns, the core laser system worked without failure. The fibres tested showed significant degradation depending on the fibre core diameter. The 800 µm fibres were not destroyed during testing, whereas the 600 µm and 400 µm fibres were damaged or destroyed after up to 5 tests.
The minimum pulse energies found were as follows for the two test campaigns

- Original TDE activity

test configuration name	description of test configuration	test result / minimum laser pulse energy
FU1a-LPI1-600µ and FU1a-LPI1-800µ	• normal optical tube • tube with 25mm focal length • fibres: 600µ and 800µ	• no ignition achieved
FU1a-LPI2-600µ and FU1a-LPI2-800µ	• normal optical tube • tube with 25mm focal length • fibres: 600µ and 800µ	• no ignition achieved

FU1a-LAI-600µ and FU1a-LAI-800µ	• normal optical tube • tube with 25 mm focal length • fibres: 600µ and 800µ	• 6,5 mJ (600 µm) • 3,6 mJ (800 µm)
FU1b-LAI-600µ and FU1b-LAI-800µ	• tilted optical tube for LAI • tube with 25 mm focal length • fibres: 600µ and 800µ	• 2,9 mJ (600 µm) • 4,9 mJ (800 µm)
FU2-LAI-600µ and FU2-LAI-800µ	• direct LAI without focusing at the injector exit • fibres: 600µ and 800µ	• no ignition achieved

- CCN1

		chamber pressure before propellant injection	
		50 mbar	1 bar
FU2-LAI-GRIN: Direct fibre ablation (GRIN-lens)	400 µm fibre	one ignition, then fibre/GRIN lens destruction due to high laser pulse energy density	No ignition success, probably due to previously damaged GRIN lenses.
	600 µm fibre	• LAI at faceplate sucessful, • also, with reduced energy level of 75 % laser pulse energy	Not tested due to destroyed 600 mum fibres during 50 mbar tests
FU1a-CCN1: Optimized laser plasma Ignition (LPI)	600 µm fibre	No ignition success, LPI2, 2 radial focal positions & sequence variation	No ignition success, LPI2, 2 radial focal positions & sequence variation
	800 µm fibre	No ignition success, LPI2, 2 radial focal positions & sequence variation	No ignition success, LPI2, 2 radial focal positions & sequence variation

The project proved the significant potential of fibre-based laser ignition systems space propulsion systems. The maximum energy transported of ca. 10 mJ via the fibres are significantly higher than communicated so far in open literature. The 800 µm fibres proved to be reliable in terms of number of pulses transmitted before destruction. The limited number of laser pulses transmitted via the 400 µm and 600 µm fibres before destruction need to be addressed in follow up research activities.

The economic assessment based on the test results considered three scenarios:

- a RCS system

- a re-ignitable, cluster-able engine and
- a Vulcain type engine

In all three cases different clustering and ignition options have been set up and the cost has been calculated. For all three cases the calculation shows massive cost saving potential using fibre transmission and multiplexing.

For some cases, cost reduction of one order of magnitude is possible compared to conventional ignition system. These involve highly clustered applications and the use of ground-based laser systems for expendable 1st stage engines. For the RCS study, clustering presents a cost advantage compared to implementation of individual systems for each CC. The entire cost case, however, depends on the savings generated by skipping the usual cold gas system.

Summarizing, it can be stated that the usage of multiplexing of a laser system, where possible, decreases the cost of the ignition system drastically and makes this option economically interesting. Low cost torch system can be competitive for non-clustered applications. However, the mass of such a system will be considerably higher than the one of a laser system.

The ablative laser option is economically clearly in advantage compared to the plasma option as it offers higher levels of multiplexing. Technically, the preference between the options is not as clear, as ablative ignition may be less robust and needs to be assessed in more detail.

In the project, a certain level of hardware development and operating maturity as well as experimental data have been gained. On the hardware side, this constitutes a breadboard multiplexer to two outputs which can be used with the existing laser hardware. On the operating side, it has been shown that ablative ignitions (LAI) can be achieved with laser pulse energies as low as 3,6 mJ (800 µm) and 2,9 mJ (600 µm). So far, laser plasma ignition (LPI) could not be achieved.

Further development need is given in terms of TRL increase in particular for the multiplexer and in the area of suitable fibers including the coupling of the beam into the fiber.