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## *A miniaturized high energy laser for ignition of rocket engines*

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# A miniaturized high energy laser for ignition of rocket engines

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## ABSTRACT

During the last years the CTR HiPoLas ignition system, originally developed for the ignition of automotive engines, has reached a sufficiently high level of stability and miniaturization to enable competitive operation on space craft engines <sup>1</sup>. The fifth generation of this Nd:YAG laser system has been customized especially for the ignition of cryogenic thrust chambers and has been tested on a variety of combustors reaching more than 1500 successful engine ignitions. The high reliability and compactness of the system lies within the monolithic, side-pumped resonator concept requiring no adjustments of any optical element during assembly and thus rendering the laser unsusceptible against vibrations and thermal influences. The standard version of the system is able to generate up to 35mJ at 2ns with repetition rates up to 100 Hz in burst mode, a new high energy version uses an additional amplifier stage to boost the energy output up to 70mJ. Applications of the laser ignition system include high thrust engines as well as combustion chambers at thrust levels of orbital maneuvering and reaction control systems. Technology readiness tests verified the applicability, stability and reliability of the laser ignition system for a variety of injector configurations, furthermore, ignition based on laser ablation was investigated. The laser igniter system was used to re-ignite a high thrust combustor up to 60 times in a row and in total more than 1500 times within one test campaign without laser system failure<sup>2</sup>.

**Keywords:** high energy laser, laser ignition, green propellants

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## 1. INTRODUCTION

The reliable ignition of combustion chambers in rocket and spacecraft engines is a critical step for the success of any space transportation system. Self-igniting fuel combinations which are often toxic are being replaced by environmentally friendly or long term storable propellants as hydrogen or methane, which require ignition. For launch systems, restartable engines are necessary to reach certain target orbits or for multiple payloads that have to be placed in different orbits.

Commonly used igniter solutions have various disadvantages. Pyrotechnical charges do not allow multiple ignitions and require additional safety protocols, increasing costs at the launch facility. Spark-torch igniters allow an engine to be restarted but require additional propellant feed lines, valves, and a separate combustion chamber to create hot gas for ignition of the main chamber. Therefore, those systems are heavy and increase the complexity of the start-up sequence for the complete rocket engine.

Laser ignition of engines has been investigated since the invention of the ruby laser in the seventies of last century. Though, due to the large size and cost of available systems, the integration on engines under harsh environmental conditions has been problematic till the availability of high power, high efficiency pump diodes during the last ten years. The CTR HiPoLas, originally invented for the ignition of automotive engines in 2002, has been continuously improved and adopted to the newest technologies. Size and components count and thus hardware cost could be reduced considerably over the generations while the reliability requirements and in turn the performance of the system have grown continuously.

Now, the fifth generation laser system is available, featuring an extremely robust and miniaturized laser core, enclosed into a hermetically sealed housing which is suitable for the direct integration onto the injector head of cryogenic rocket engines. Numerous tests of the ignition capabilities and the operating reliability under ground level and upper stage engine conditions have been performed in cooperation with CTR, DLR and Ariane Group. In this paper we present an

overview on the HiPoLas laser system and the motivation for its application to space propulsion systems as well as an overview of some recent applications.

## 2. LASER REQUIREMENTS

In order to be able to ignite cryogenic rocket engine fuel using a laser, a number of requirements have to be met. First of all, the required laser pulse peak power has to exceed the minimum ignition energy threshold (MIE) for the intended fuel combination. Two main variants of laser ignition are suitable for rocket engines, direct plasma ignition and ablative ignition. The values for MIE have been extensively investigated for both methods during the recent years<sup>3,4</sup>. In order to be suitable for both variants, the design goal for the ignition laser has been defined with an optical peak power of higher than  $10^{11}$  W/cm<sup>2</sup> in the focal spot location. Power density in this range may only be achieved in reasonable form factor and cost by using a diode pumped Q-switched solid state laser. Under the assumption of a multimode beam profile with a minimum focal spot diameter of 50  $\mu$ m and a pulse duration of 3 ns the necessary minimum laser pulse energy can be estimated to about 5 mJ. To account for losses in the guiding optics and focusing elements as well as lens contamination and absorption due to scattering along the path to the focal spot, the design energy for the laser was specified at 30 mJ.

The small form factor and the environmental conditions, especially the high vibration and shock requirements up to several hundred G do not allow for any active or adjustable optical elements within the resonator. As the laser head will be mounted directly onto the injector head, the interface temperatures may range from cryogenic 90 K up to 320 K. The laser igniter has to sustain these conditions at least in standby mode. Before operation, the pump diodes may be heated up to their operating temperature range but cooling is not an option. Therefore the laser must be able to operate at the upper temperature limit.

Space and weight as well as thermal insulation from engine head environment were main considerations during the design of the laser housing. The overall mass of the ignition system including the electronic box, cable harness, connectors, the laser head and the optical access tube has been limited at 5 kg. As the application of the laser igniter is intended for ground as well as upper stage purposes, the corresponding ambient pressure and radiation environments has to be considered.

During engine startup, the flow of fuel to the injector head and thus the arrival time of a combustible mixture at the laser focus location may deviate in the range of several tenths of seconds. The laser has to be pulsed for some time at a higher repetition rate starting from the opening time of the valves to overcome this time lag. The location of the focal spot within the fuel flow pattern in front of the injector is essential for successful ignition. Extensive studies have been performed to identify regions of high ignition reliability for various injector configurations<sup>5</sup>.

## 3. LASER CORE

As the laser wavelength has only minor influence on the MIE, 1064 nm is utilized due to the readily available components based on ceramic neodymium doped YAG at this wavelength. Generation of second or higher harmonics, which would have a somewhat lower MIE was rejected due to the additional effort and the lower overall laser efficiency. Passive Q-switching using optically bonded chromium doped YAG is mandatory to keep the complexity of the laser as low as possible. The pulse duration is mainly given by the length of the resonator and the Q-switch initial transmission properties and is in the range of 2 to 3 ns.

The core of all HiPoLas generations is constituted by two main components, a set of customized pump diode modules which are arranged radially around a centered monolithic laser resonator (fig.1). A side-pumping configuration has been chosen for simplicity of design, requiring no additional focusing optics and minimizing thermal lensing effects in the laser rod. Stabilization of the pump wavelength is achieved by volume Bragg gratings which allows to operate the laser in the range of 280 K to 320 K without any further thermal control. Only coarse alignment of the laser rod is necessary within the pump configuration which allows for high tolerances against mechanical influences as deformation due to thermal effects and vibration. During assembly of the laser head, not a single adjustment is required which highly facilitates the manufacturing and maintenance. Due to the monolithic, single element nature of the resonator comprising

the active gain medium, the Q-switch, end mirror and output coupling mirror in one single element, the size could be reduced to about 30mm.



Figure 1. Monolithic, optically bonded Nd:YAG/Cr:YAG laser resonator, 4mm diameter.

The resonator features intrinsic long term stability against de-alignment and is virtually maintenance free. Specimens of the HiPoLas system are in operation at CTR for more than ten years without any need for adjustment or degradation of the laser output. Laser lifetimes in the range of at least  $10^8$  pulses may be expected under standard industrial conditions; under engine conditions the longest campaign with more than 1500 ignitions has not shown any deterioration of laser performance yet.



Figure 2. GenIV (left) and GenV (right) laser heads.

All components are embedded into a hermetically sealed stainless steel housing with a non-detachable cable harness. A comparison of the GenIV and the GenV housing is shown in figure 2. A sealed optical window made of antireflection coated sapphire forms the laser exit aperture. The housing is filled with inert gas upon assembly to avoid damage to the internal components under cryogenic conditions.

#### 4. LASER POWER DRIVER

Operation of the laser requires a pulsed current of 250 A to 300 A for a pulse duration in the range of 250  $\mu$ s. The power electronics of the laser consists of a storage capacitor array that is switched to the laser diodes using high performance Mosfet transistors. Control of laser timing is achieved by a microcontroller capable of generating a programmable sequence of pulses upon an external trigger during the ignition sequence. A commercial version of the driver is shown in figure 3; a prototype of a reduced component count space compatible power electronics has recently been taken into operation but yet requires final development and certification. The power driver requires a 28V DC power supply and has an energy consumption of about 0.6 J per laser pulse.



Figure 3. Laser control and power electronics.

## 5. OPTICAL ACCESS

The laser beam has to be guided through the wall of combustion chamber and subsequently focused to the zone of optimum fuel conditions in front of an injector nozzle (fig. 4). With the HiPoLas ignition system, the chamber window and lens are designed into a single element, a focusing sapphire window which is brazed into a kovar steel tube. The brazing process uses a high temperature solder that may withstand temperatures up to 800 K and chamber pressures up to 250 bar. The varying distances between the laser exit window and the focusing lens on different engine heads require a low divergent laser beam. Collimation is achieved by a second sapphire window which also acts as safety pressure barrier in case of damage to the primary window.

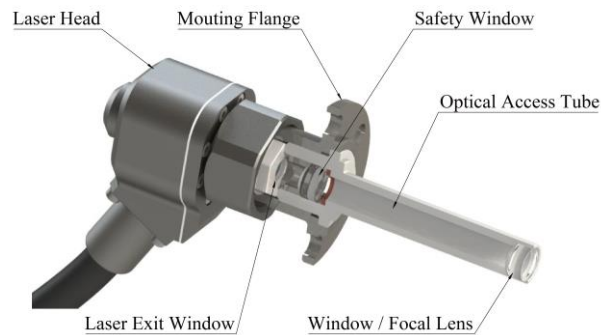


Figure 4. Optical access to the combustion chamber.

Ignition systems for space propulsion usually require redundant operation of the ignition system. In cooperation with Ariane Group, a dual head laser igniter has been implemented as an in-place replacement of the conventional igniter utilizing a common optical guide and side-viewing, angled focusing lenses (figure 5).



Figure 5. Dual laser head redundant optical access.

## 6. LASER PERFORMANCE

Extensive shaker vibration test at Ariane Group and temperature cycling tests down to cryogenic regions have been performed to successfully demonstrate the capabilities of the laser igniter system for rocket engine applications.

A sequence of ten laser bursts generated by a GenV laser head with each burst consisting of 20 pulses at 50 Hz is shown in figure 6. Average pulse energy of about 34 mJ was achieved at a pulse duration of 2.5 ns. Beam size ( $1/e^2$ ) at the laser exit window is 3.2 mm and the half angle of the beam divergence was measured with 11.5 mrad.

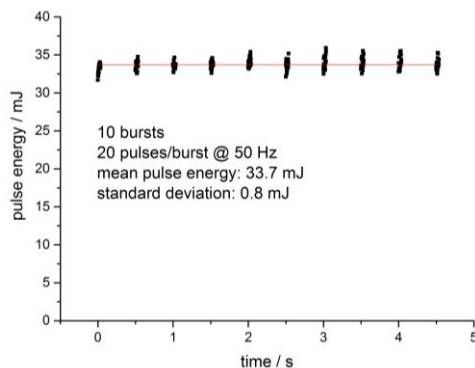


Figure 6. Pulse energy in a sequence of laser bursts.

A typical beam profile with a multimode, nearly top hat shape is shown in figure 7.

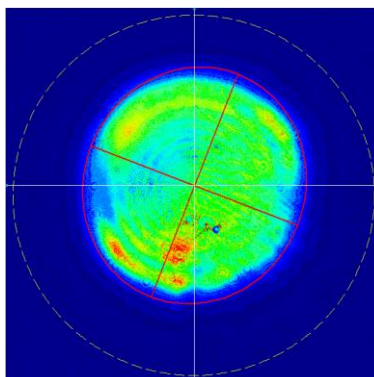


Figure 7. Typical top hat beam profile of a GenV laser head.

## 7. APPLICATION TO SPACE PROPULSION SYSTEMS

In search of ignition systems for combustion chambers that are reliable, light-weight and easy to handle, laser ignition for space propulsion systems has been studied intensively during the last decade in Europe by CTR, DLR, Ariane Group and ESA. The investigation into laser-based ignition in Europe started in 2001 with first laboratory tests and feasibility studies using table-top laser systems and robust subscale combustors. In those days, miniaturized laser systems were not yet considered for application. Due to the successful test results, further technology development and research programs were initiated. In consequence, the TRL level of laser ignition was increased by

- miniaturizing and maturing the laser igniter<sup>1</sup>,
- investigating the impact of propellant conditions and test sequencing onto the ignition process<sup>2,3,8</sup>,
- numerical investigations of the ignition process<sup>10</sup>
- and application to more representative conditions by Ariane Group<sup>9-11</sup>

Laser ignition is performed by focusing a laser pulse into the propellants injected into the combustion chamber. Once the laser pulse intensity surpasses the threshold for optical breakdown of the propellants, laser-induced plasma is generated which then ignites the combustion chamber.

The feasibility and reliability of laser ignition has been proven for

- sea level and low pressure combustion chamber conditions,
- with LOX/hydrogen and LOX/methane propellants,
- and in RCS and high thrust combustors.

For example, a test campaign was conducted at the European Research and Technology Test Facility P8 of the DLR Institute of Space Propulsion in Lampoldshausen (Germany) in 2014 and 2015 (see Figs. 9-11). In this test campaign, a high number of ignition test were realized to investigate the reliability of laser ignition. For the test activities presented here, the laser igniter was mounted directly onto the combustion chamber. During this test campaign

- 1195 ignition cycles for liquid oxygen/hydrogen and
- 133 ignition cycles for liquid oxygen/methane

were realized. In particular, 60 successful ignition attempts, each separated by 30 seconds, have been achieved during a single test run underlining the re-ignition capability and robustness of the laser ignition technology. Based on these tests, a large database of varying ignition sequences and corresponding fluid transients was established which represents reference data for future for LOX/methane engines like the DLR project “Liquid Upper Stage Demonstrator Engine” (LUMEN) for which a laser ignition module will be used to ignite the combustion chamber<sup>12</sup>.

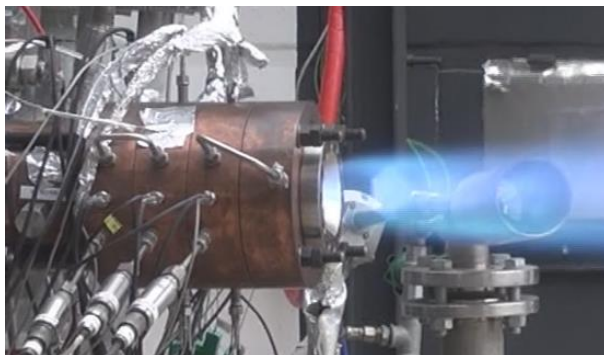


Figure 8. LOX/CH4 subscale combustor “BK-A” equipped with a laser ignition system<sup>8</sup>.

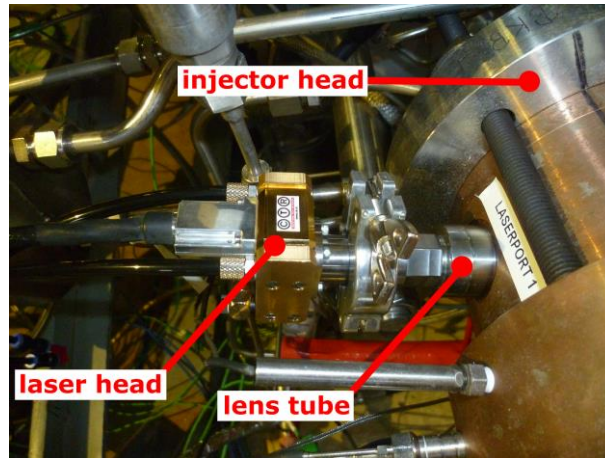


Figure 9. Radially attached laser head close to the injector head at the subscale combustor “BK-A”<sup>8</sup>.

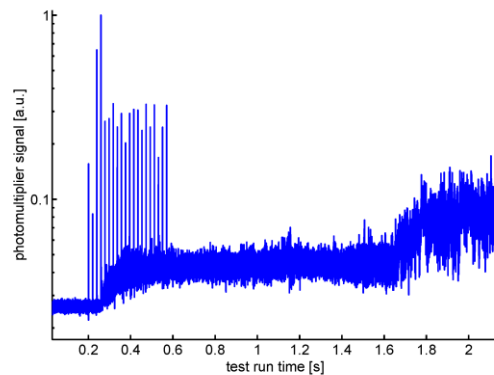


Figure 10. Signal of a photomultiplier connected to a sensor pointing at the laser induced breakdown region. Each peak corresponds to a single breakdown signal. The increased signal level after ignition by laser pulse #4 is caused by the radiation of the combustion zone anchoring at the injector element<sup>8</sup>.

## 8. THE FUTURE OF LASER-BASED IGNITION TECHNOLOGIES

Due to the low minimum pulse energies needed for reliable ignition<sup>2</sup> and the increasing transport capacities of laser pulses via optical fibres<sup>13</sup>, future investigations will aim at the feasibility of fibre based ignition systems. Such systems would allow even simpler integration of the igniter into existing engine architectures and the development of multi-engine ignition systems for clustered engine configurations being studied for future launcher systems in Europe<sup>14</sup>. Simultaneous fiber ignition of a larger number of thrusters could require an even increased energy output of the HiPoLas system and first demonstrator setups have already shown the capability to increase energy output to more than 70mJ.



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