FINAL PRESENTATION
ESA TDE: OPTICAL FIBRE-BASED IGNITION TECHNOLOGY FOR LAUNCHER RCS
ESA CONTRACT NO. 4000128882/19/NL/MG
DLR-LA-RAK-ZU-DO-031

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ESA/ESTEC, hybrid meeting, 13.12.2022

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Outline

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4. LIS Trade-Off Studies and Design
5. Fibre-based ignition system tests at SAL
6. Experimental set-up & test matrix
7. Test Results
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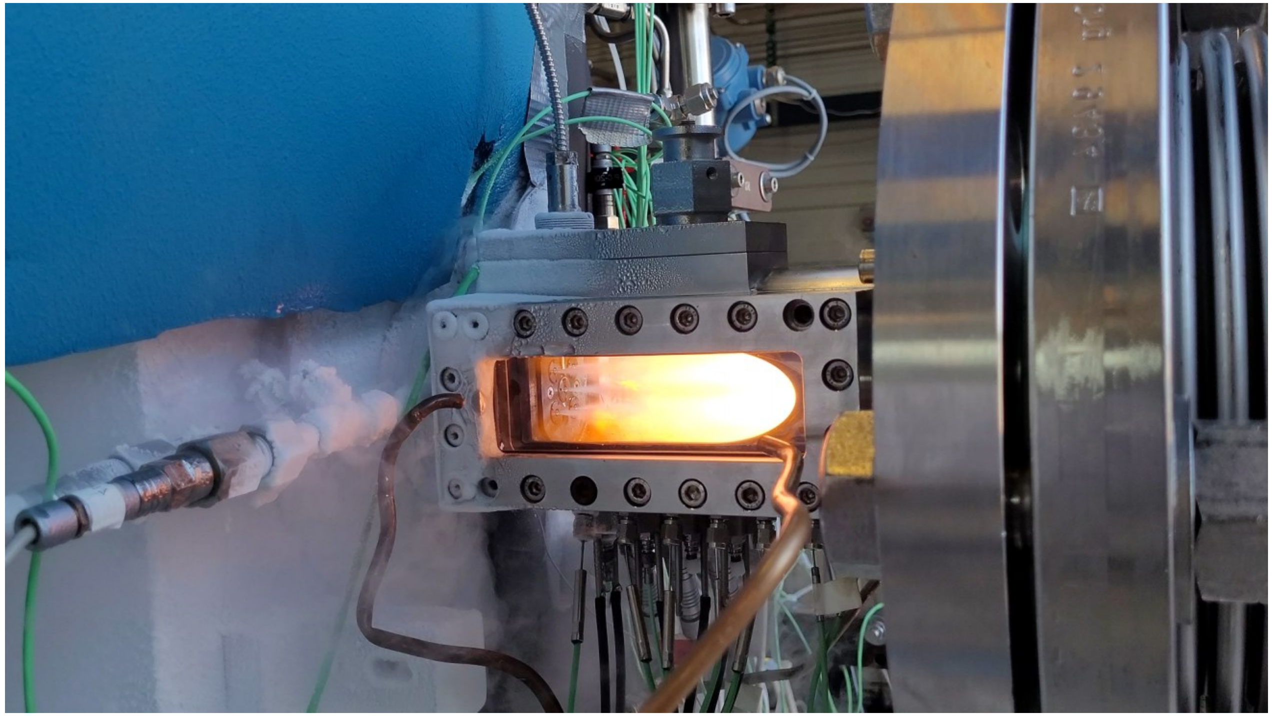
    2. Ignition sucess & reliability
    3. Minimum pulse energy needed
8. Economic assessement
9. Summary & Outlook



Motivation of laser ignition

- Technical goal: ignition systems needed for various applications
  - new, green launcher RCS
  - (Re-startable) cryogenic engines

- Ignition system requirements
  - 100% ignition reliability
  - low weight
  - cheap & compact
  - independent of engine transients
  - simplicitiy in handling
  - little impact on assembly & launch procedures

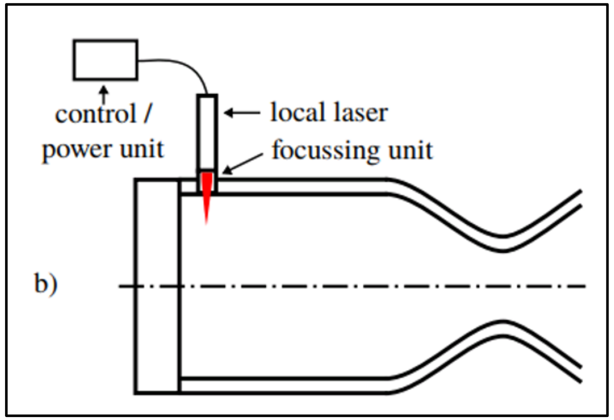
- boundary conditions:
  - Sub-atmospheric combustion chamber pressure before propellant injection & ignition

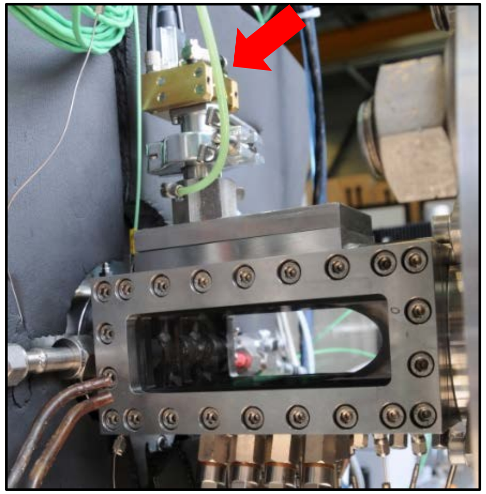
→ Fibre-based laser ignition as a candidate

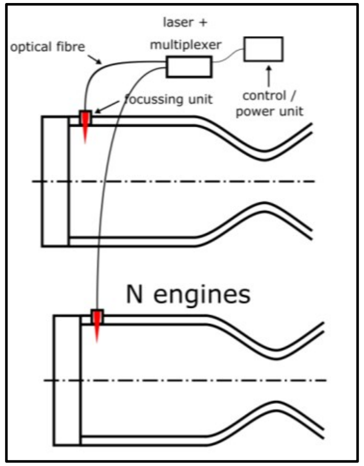
Overview and project goals

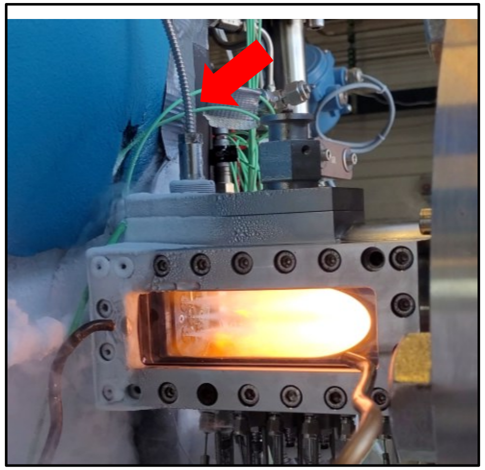
- **Previous ESA TRP: Laser Ignition Technology** (4000111442/147NL/SFe)
  a) design a laser ignition system able to ignite cryogenic propellants in high altitude conditions
  b) to manufacture and integrate this system in a breadboard thruster
  c) perform ignition tests with GH2/LOX to characterize ignition parameters
  d) propose a set of laser ignition parameters for a full scale upper-stage cryogenic expander engine demonstration and development

- **Current ESA TDE: Optical fibre-based ignition technology for launcher RCS** (4000128882/19/NL/MG)
  a) Assess **potential system simplifications and cost reductions** wrt optical fibre-based ignition system for cryogenic RCS
  b) Design and manufacture an optical fibre-based ignition system using a pre-existing laser ignition system
  c) Implement the prototype into a breadboard thruster
  d) Perform a test campaign for ignition validation and characterization under relevant conditions









Overview and project goals

- Task 1: **Economic assessment of a fibre-based ignition system** for
  - RCS thrusters for launcher application
  - Multiplexed laser ignition for main engine application (main or upper stage)
- Task 2: **Breadboard design**
  - design a fibre-based ignition system for use on a breadboard subscale cryogenic liquid rocket engine for ignition conditions representative of a cryogenic expander engine and LOX/GH2
- Task 3: **Manufacture and test**
  - build and characterise the prototype fibre-based ignition system
  - prepare a test plan featuring a wide range of ignition tests with GH2/LOX propellants comparable to the last ESA TRP
- Task 4: **Test execution**
  - test the prototype fibre-based ignition system on the breadboard subscale cryogenic liquid rocket engine in accordance to the test plan
- Task 5: **Test report and outlook**
  - evaluation of the test data and the performance of the LIS
  - evaluate the suitability of the LIS design
  - define further development needs

Overview and project goals: CCN1

- CCN 1
  a) A1: **Re-design**, optimize, integrate and test of the **LPI** concept of the laser ignition system to ensure the LPI ignition based on the results of the recently finished test campaign which failed to ensure LPI in order to fully complete task #3 of the SoW
  b) A2: A significantly simplified ignition concept was identified during the test activities called **direct fiber ablation** in the PTR, which should be further investigated due to its simplicity and simple integration leading to a more robust design and less components

- Technical approaches to be tested
  a) Optimized LPI concept by higher intensity
  b) Optimized direct fiber ablation by GRIN lenses

WP overview

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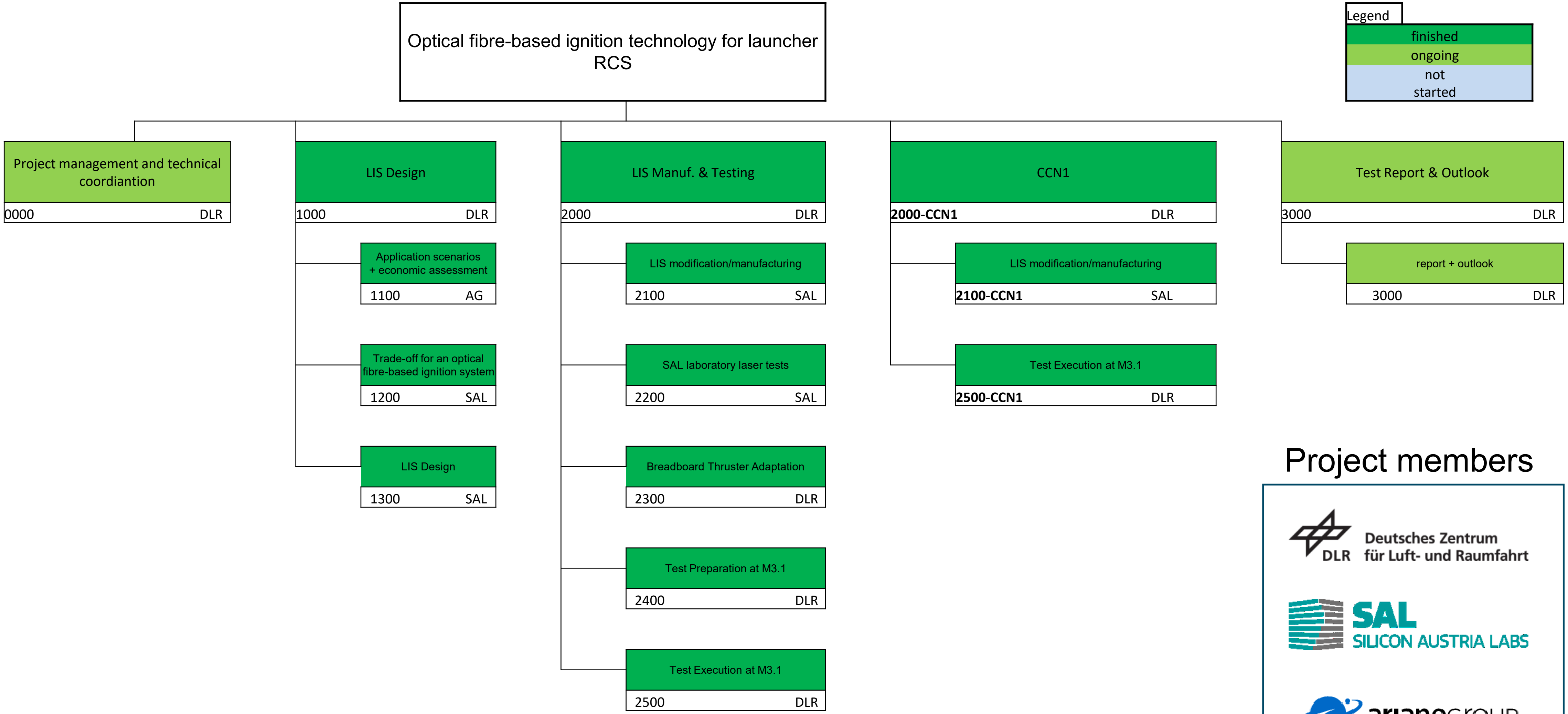


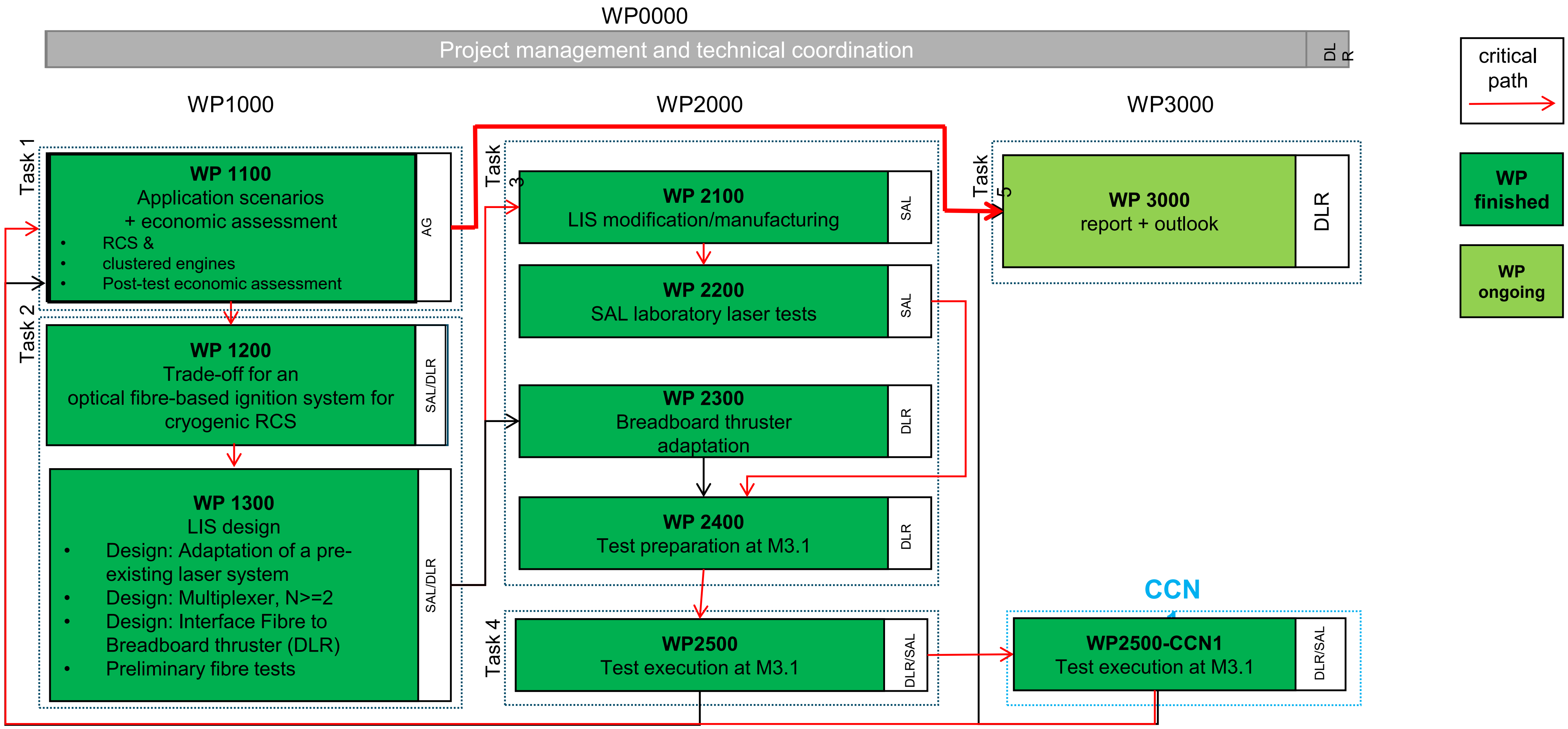
Project members

DLR Deutsches Zentrum für Luft- und Raumfahrt

SAL SILICON AUSTRIA LABS

arianeGroup

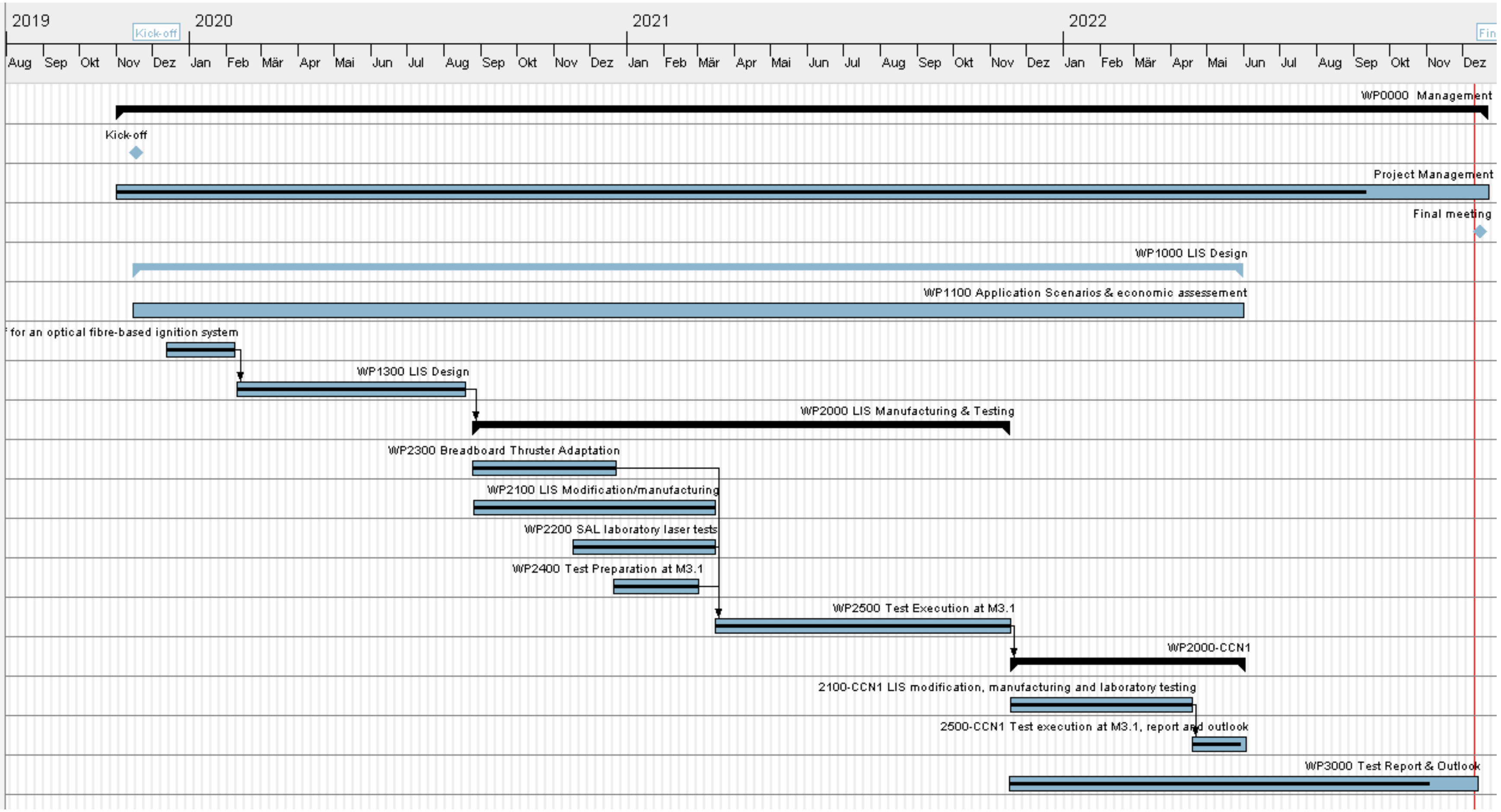
Project Structure



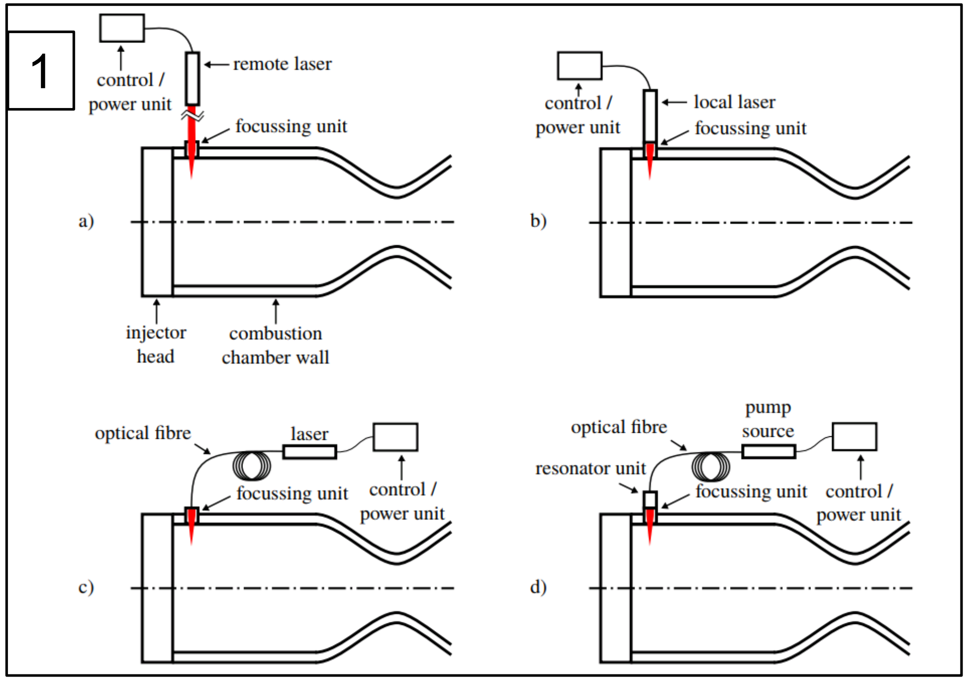
Project overview: Project Gantt-chart

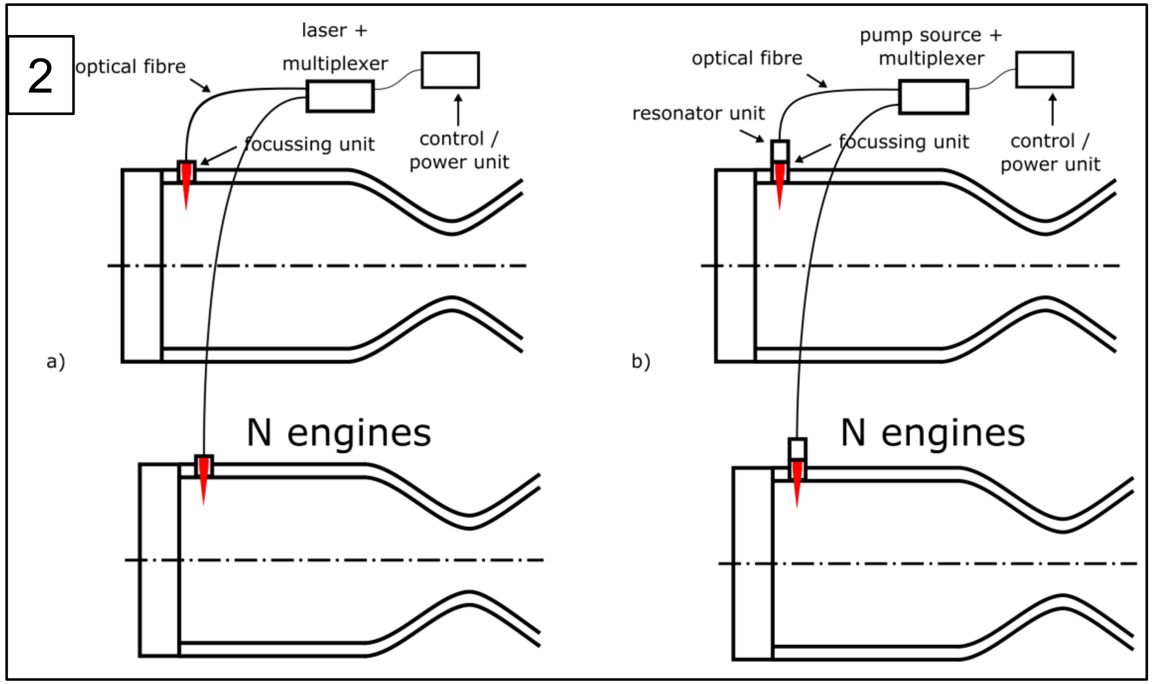
GANTT project

Vorgang	Anfang	Ende
WP0000 Management	01.11.19	22.12.22
Kick-off	15.11.19	15.11.19
Project Management	01.11.19	22.12.22
Final meeting	13.12.22	13.12.22
WP1000 LIS Design	15.11.19	31.05.22
WP1100 Application Scenarios & economic asses...	15.11.19	31.05.22
WP1200 Trade-off for an optical fibre-based igniti...	13.12.19	07.02.20
WP1300 LIS Design	10.02.20	18.08.20
WP2000 LIS Manufacturing & Testing	25.08.20	17.11.21
WP2300 Breadboard Thruster Adaptation	25.08.20	22.12.20
WP2100 LIS Modification/manufacturing	26.08.20	15.03.21
WP2200 SAL laboratory laser tests	17.11.20	15.03.21
WP2400 Test Preparation at M3.1	21.12.20	01.03.21
WP2500 Test Execution at M3.1	16.03.21	17.11.21
WP2000-CCN1	18.11.21	02.06.22
2100-CCN1 LIS modification, manufacturing and ...	18.11.21	18.04.22
2500-CCN1 Test execution at M3.1, report and ou...	19.04.22	02.06.22
WP3000 Test Report & Outlook	17.11.21	13.12.22



Technical Introduction: fibre-based ignition systems

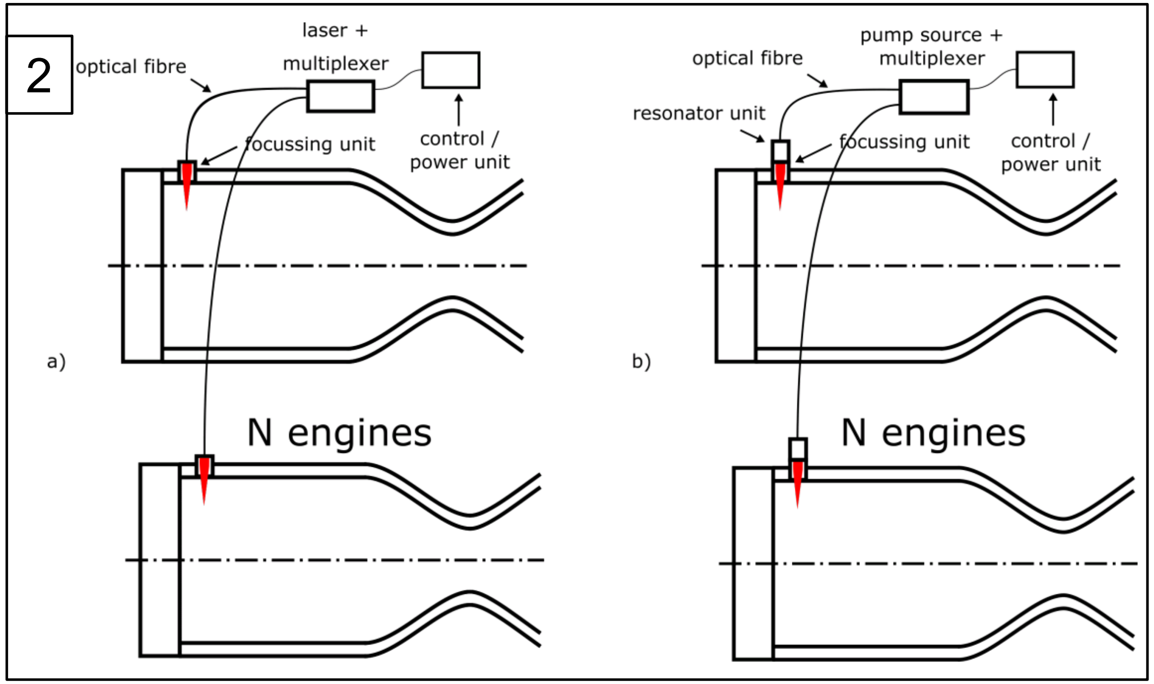




ID	# of core laser systems for N engines	# of resonator units for N engines	# of multiplexer units for N engines	High energy fibres needed?
1a	N	0	0	No
1b	N	0	0	No
1c	N	0	0	Yes
1d	N	N	0	No
2a	1	0	1	Yes
2b	1	N	1	No

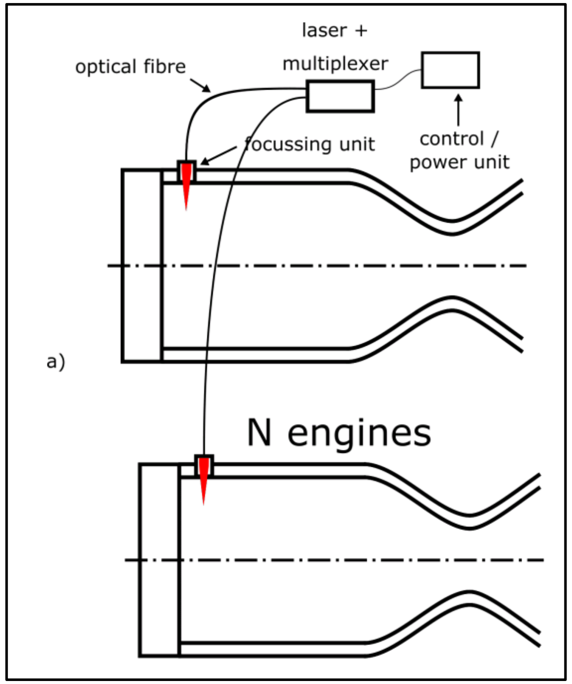
Technical Introduction: preliminary trade-off

Configuration	Advantage	Disadvantage
2a	• reduced number of laser components attached to the combustion chamber • only one core laser system needed for multiple thruster or combustion chamber • core laser available (see SoW)	• high energy laser beam guiding and multiplexing needed • laser pulse energy that can be transported by fibres has to be evaluated
2b	• no high energy laser beam guiding and multiplexing needed	• **local resonators for each combustion chamber needed** • pre-existing components not available (see SoW)



Technical Introduction: summary

- **C1** A single **high energy core laser source** that generates the high energy laser pulses
- **C2 High energy optical fibres** to deliver the laser pulses from the core laser to the multiplexer and/or from the multiplexer to the focussing unit(s)
- **C3** A **multiplexer** unit to direct the laser pulse into the fibres to the thruster(s)
- **C4 Fibre coupler units** to couple the laser pulse into the fibres
- **C5 Focusing units** to focus the laser pulse and to generate an optical breakdown at a pre-defined location inside the thruster



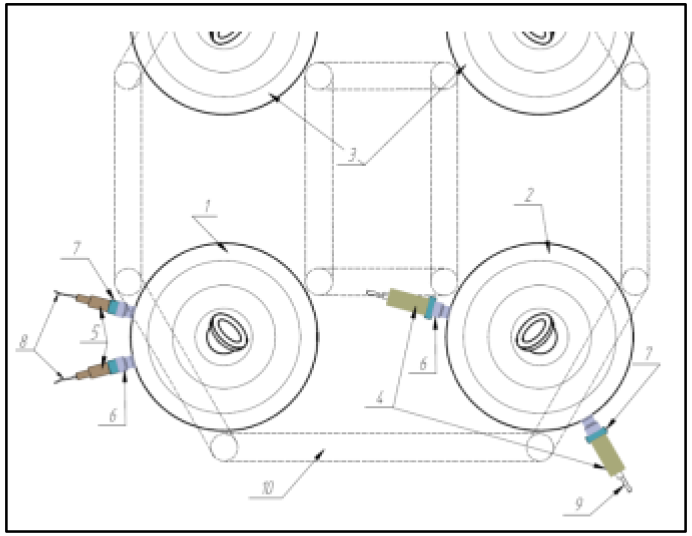
Literature study (WP1200): Summary

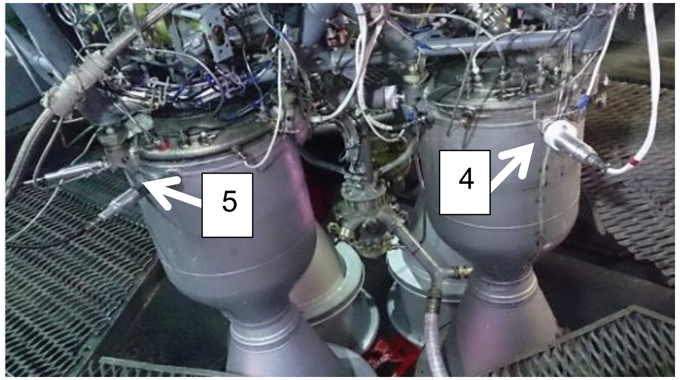
- a limited number of published work of complete laser ignition systems exist
- mostly: investigations of individual components and not fibre-based systems
- all papers: lasers with pulse durations of more than 5 ns
  - HiPoLas laser: ~ 2 ns

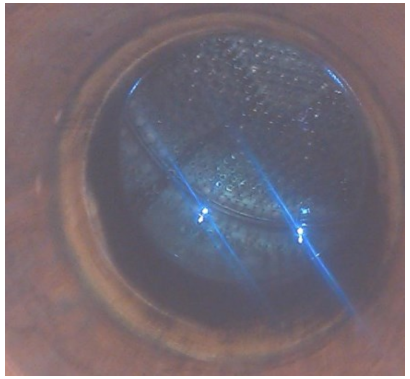
$$I = \frac{E_{pulse}}{A * \tau_{pulse}} = \frac{E_{pulse}}{\pi * w_0^2 * \tau_{pulse}}$$

Literature study (WP1200): Examples

- Central pump source with fibre-based pulse transport and local resonator unit for pulse amplification for the RD107 (RD108) engine



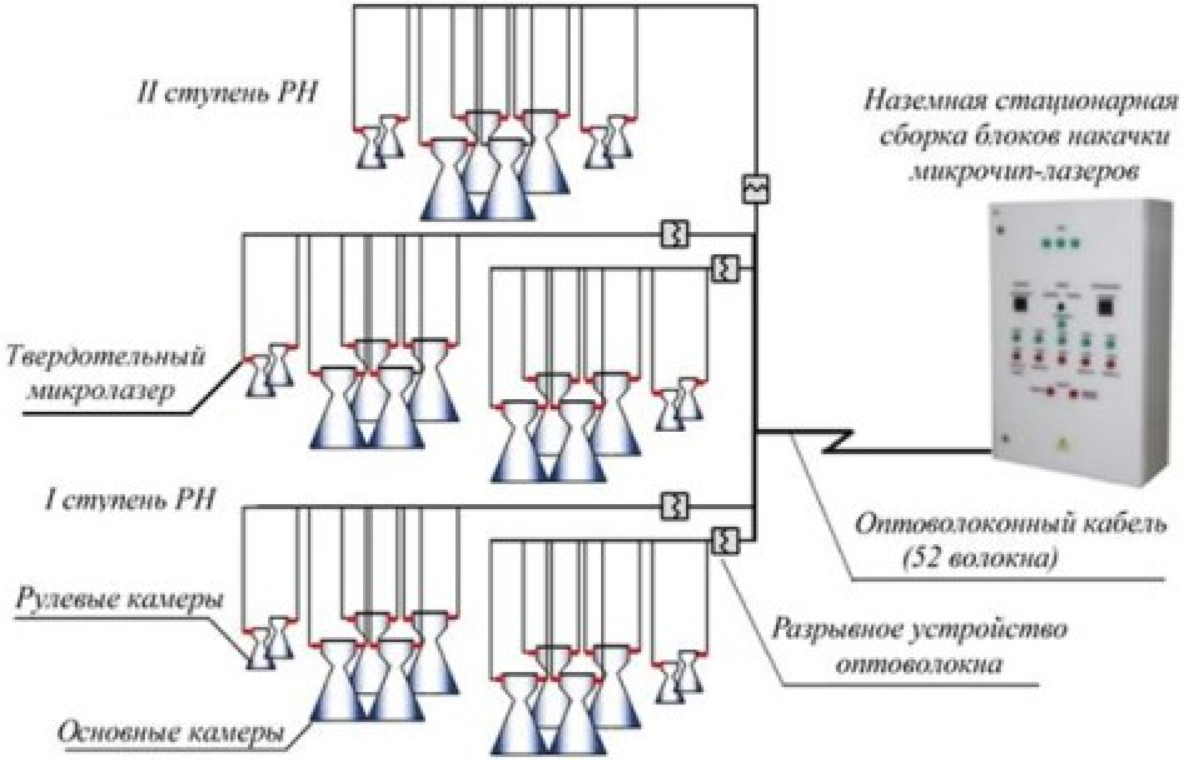




Sudakov, V., Chvanov, V. K., Levochkin, P. S., Romasenko, E. N., Ivanov, N. G., Ganin, I. A., and Surkov, B. I., “Laser Ignition of LOX-kerosene Propellant in Liquid Rocket Engine of "Soyuz" LV,” SPC-3124645, Space Propulsion Conference 2016, 2016

Literature study (WP1200): Examples

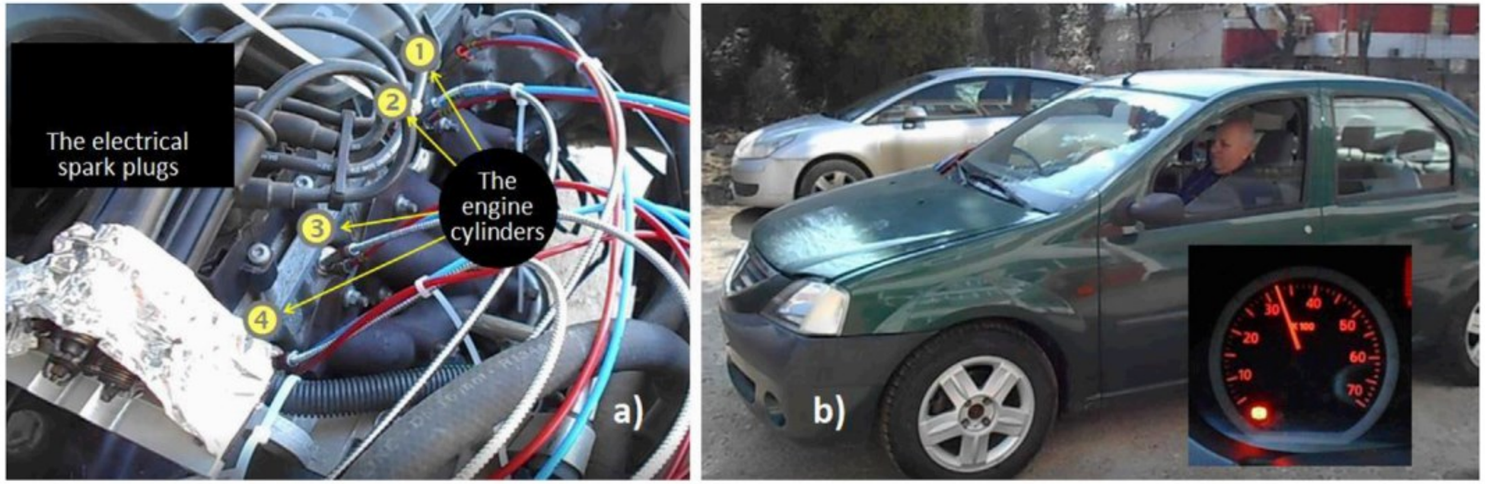
- Fibre-based ignition concept for the Soyuz launcher main stage

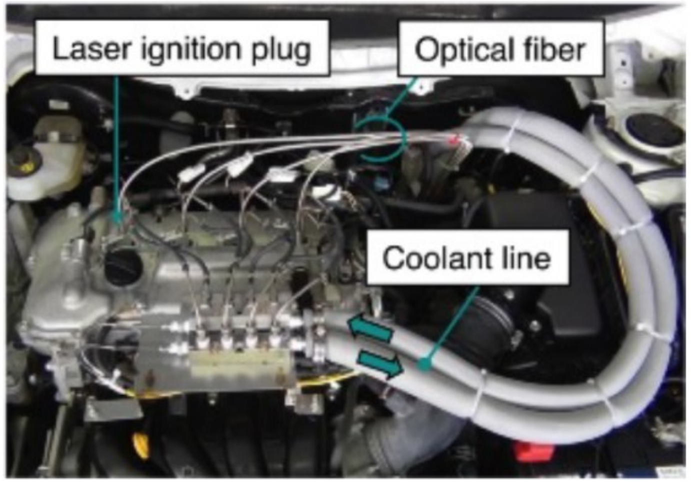


Rebrov, S. G., Golubev, V. A., and Golikov, A. N., “Laser Ignition of Oxygen-Kerosene Fuel in Rocket Technique: From Igniters to Rocket Engines,” Trudy MAI, Vol. 95, 2017

Literature study (WP1200): Examples

- A fibre-based laser ignition system mounted on the Renault engine

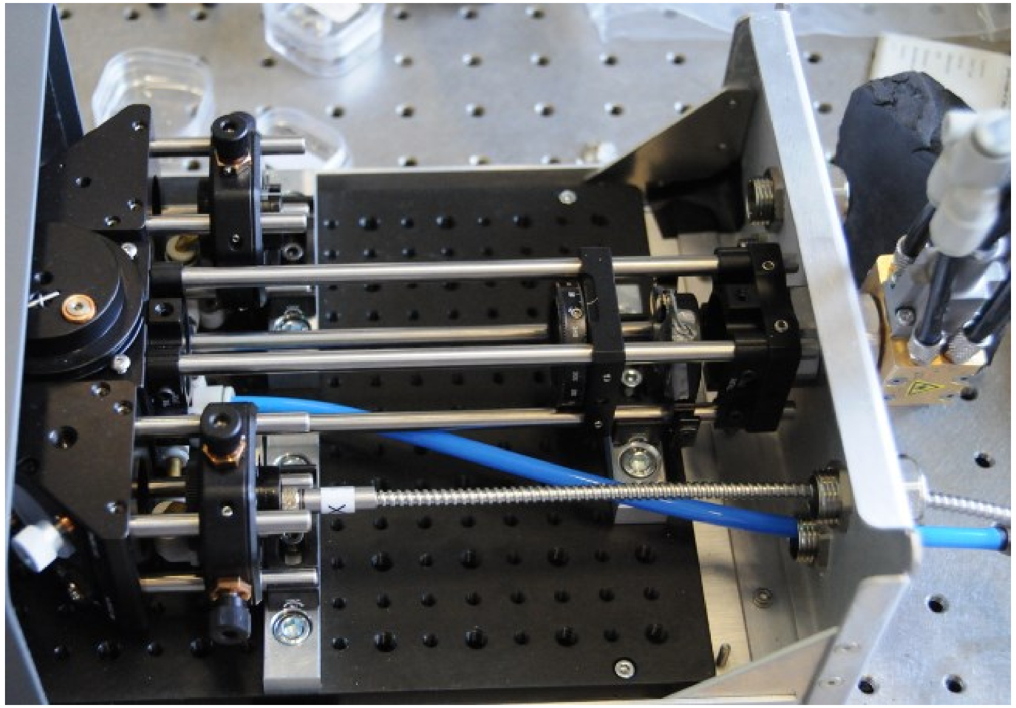




N. Pavel, A. Birtas, G. Croitoru, M. Dinca, N. Boicea, T. Dascalu, Laser ignition of a gasoline engine automobile, in: Laser Ignition Conference 2017, OSA, Technical Digest (Online), Optical Society of America, 2017 paper LWA4.3.

LIS Trade-Off Studies and Design (WP1300)

Component #	Component name	design solution
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



LIS Trade-Off Studies and Design (WP1300)

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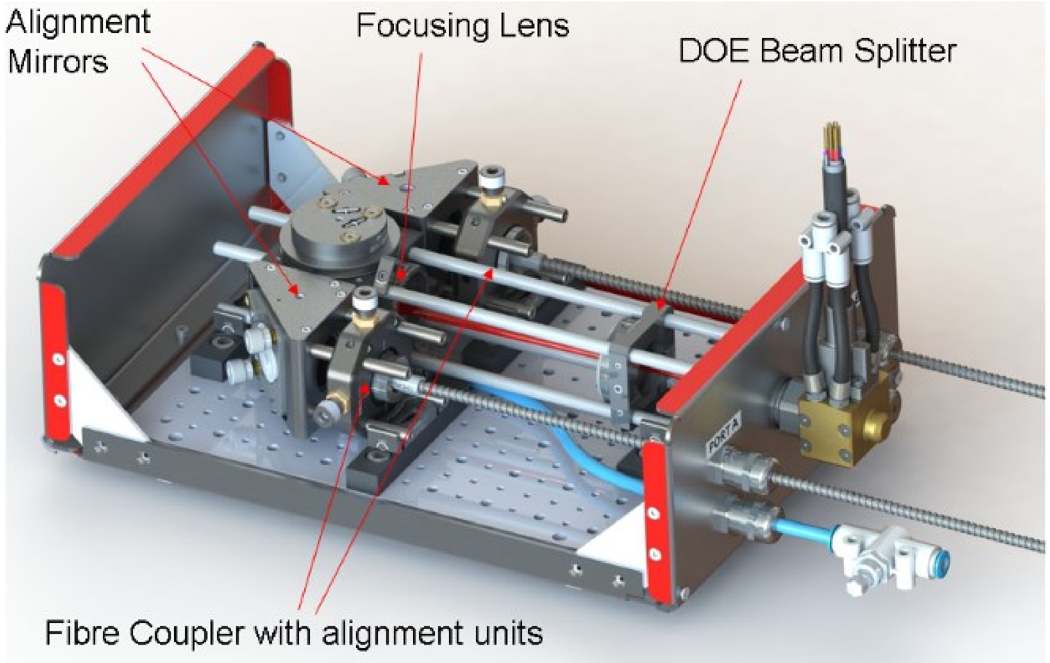

LIS Trade-Off Studies and Design (WP1300)

Component #	Component name	design solution
C1	High energy core laser source	HiPoLas GenV-HR by SAL AG
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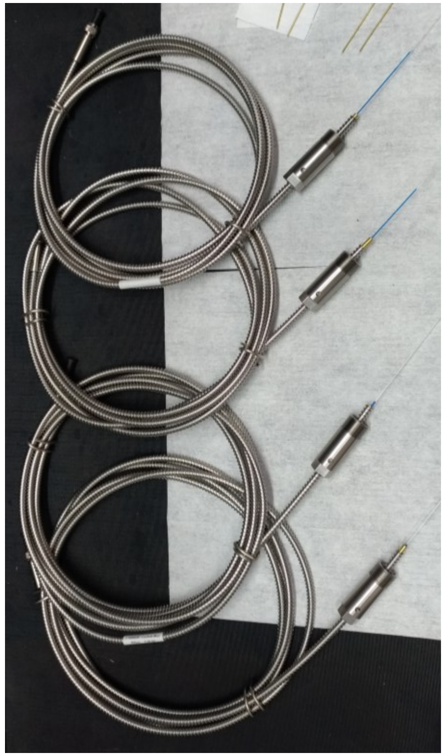
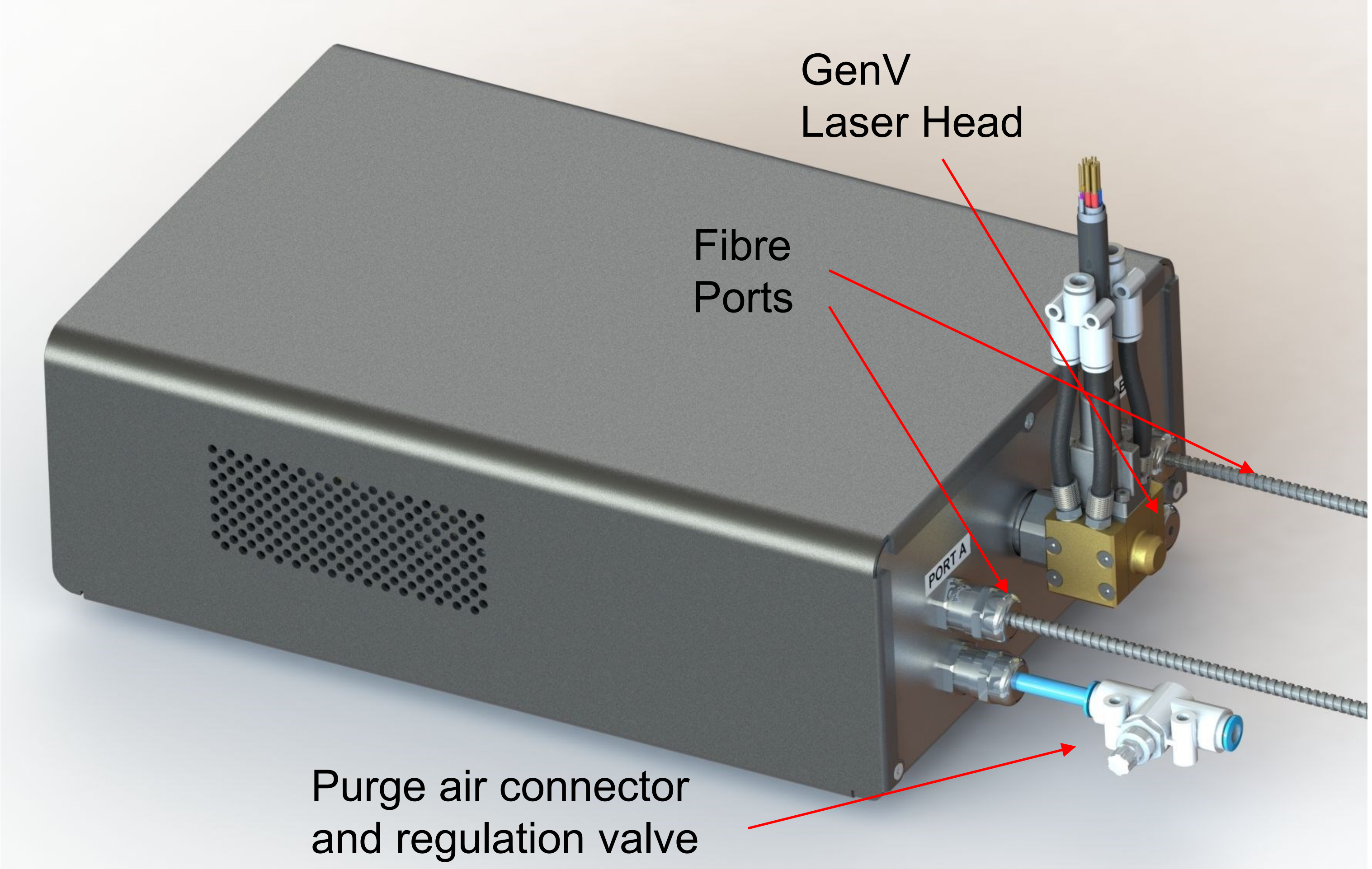


LIS modification/manufacturing (WP2100)
SAL laboratory laser tests (WP2200)

- Presentation by Gerhard Kroupa (SAL) on
  - LIS modification/manufacturing (WP2100)
  - SAL laboratory laser tests (WP2200)

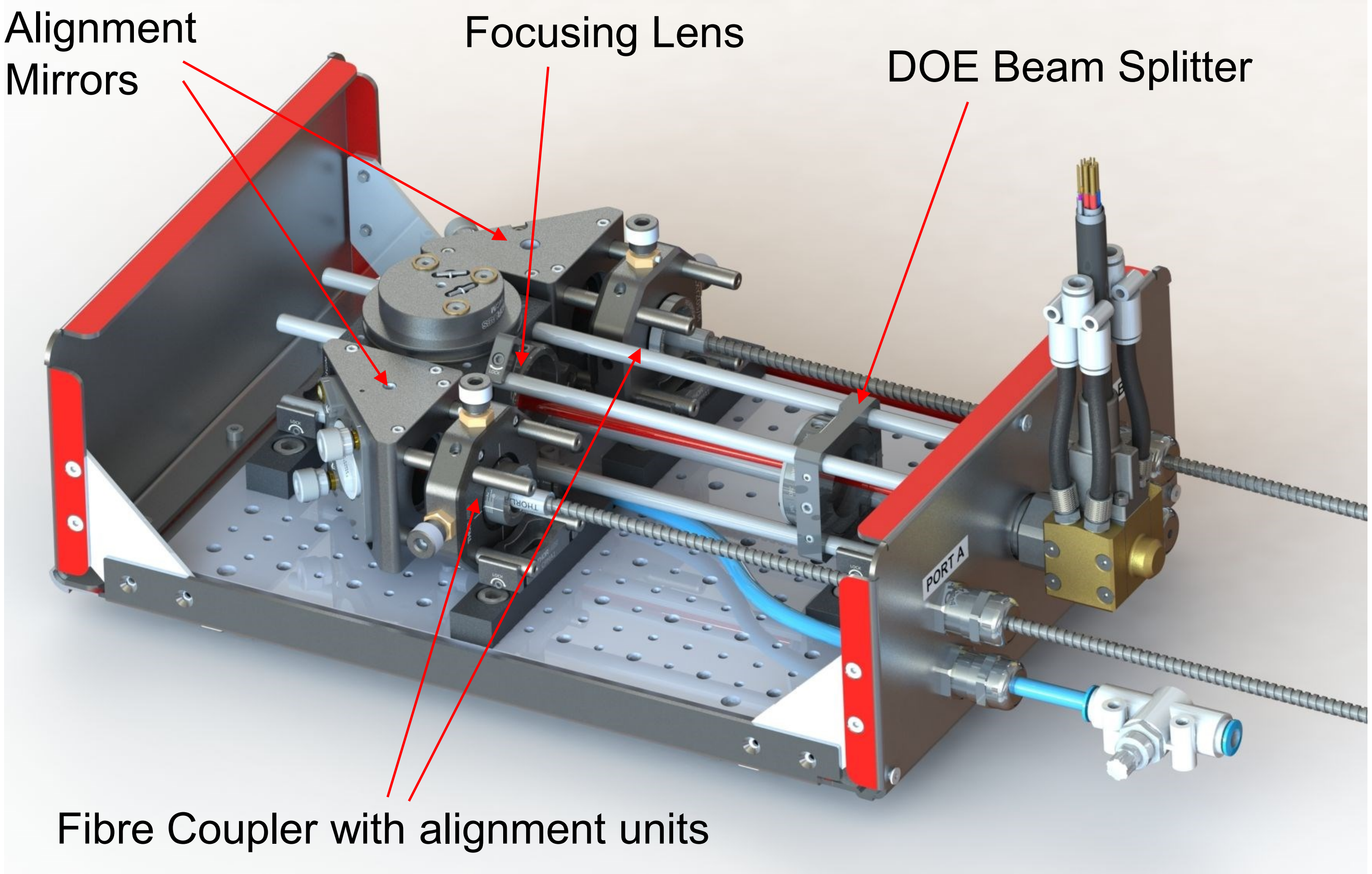
Fibre Coupler Assembly and Test at SAL

- Fibre Coupler final implementation
  - Integration in a metal enclosure
  - Two fibre output ports for metal armoured fibres
  - Added purging option to avoid focal spot plasma breakdown at the fibre input



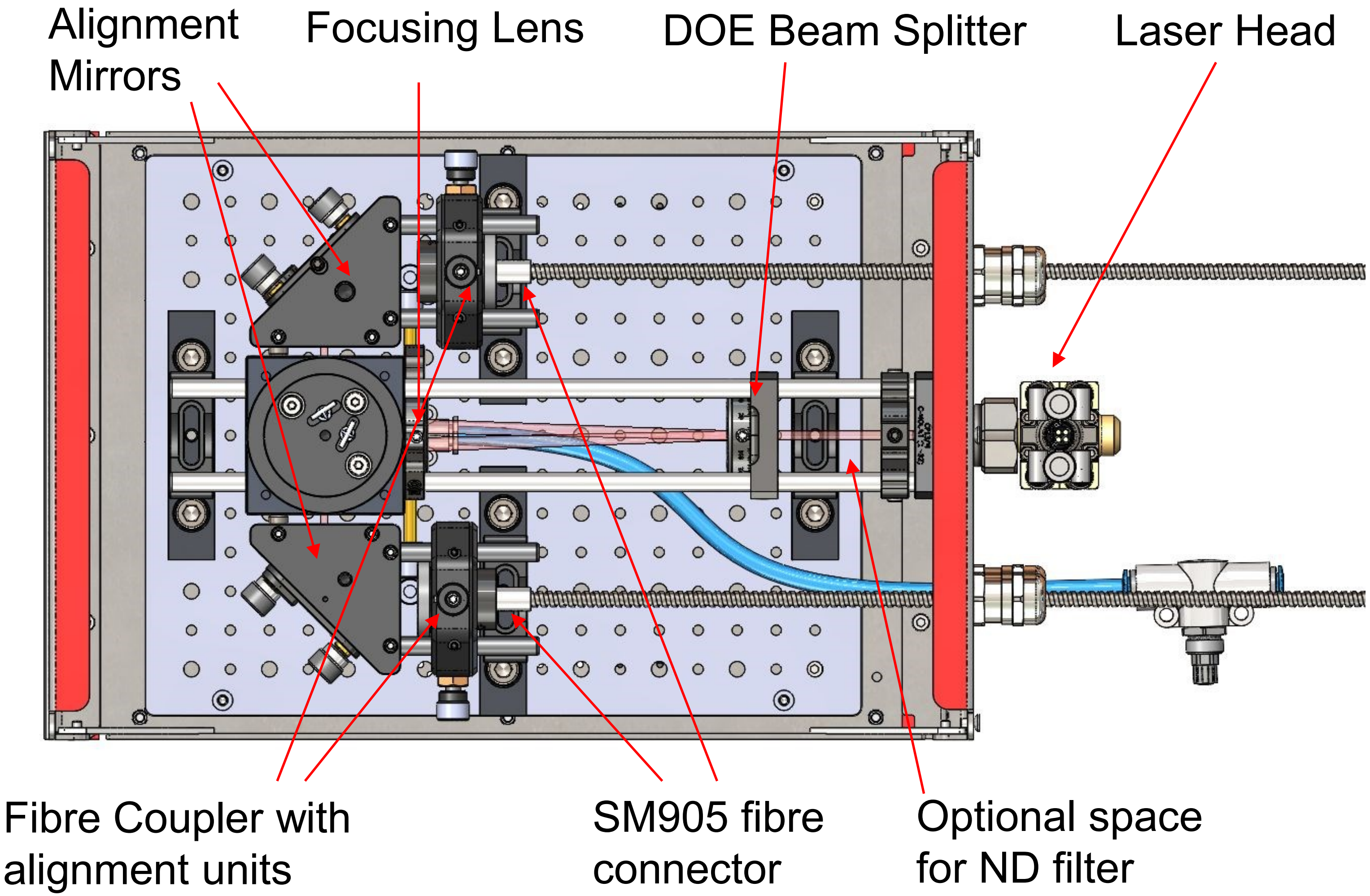
Fibre Coupler Assembly and Test at SAL

- Fibre Coupler internal assembly



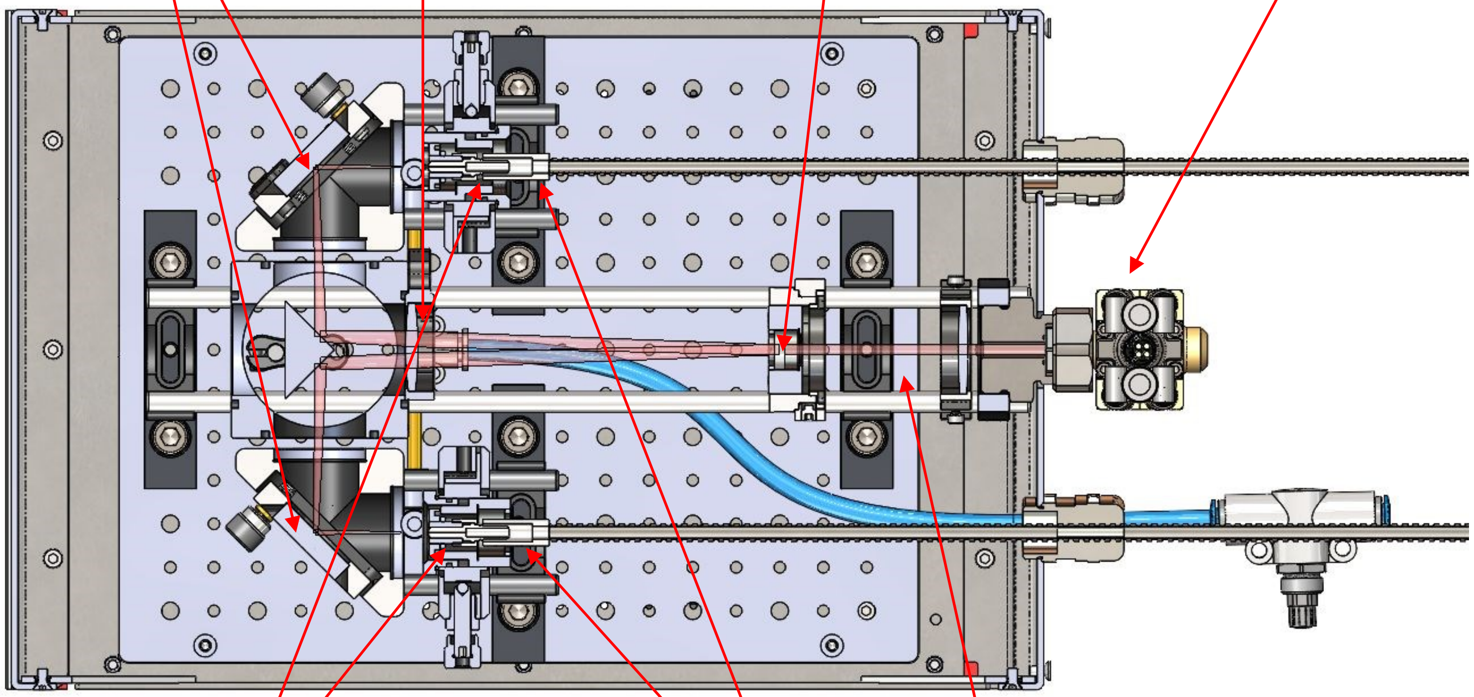
Fibre Coupler Assembly and Test at SAL

- Fibre Coupler internal assembly CAD



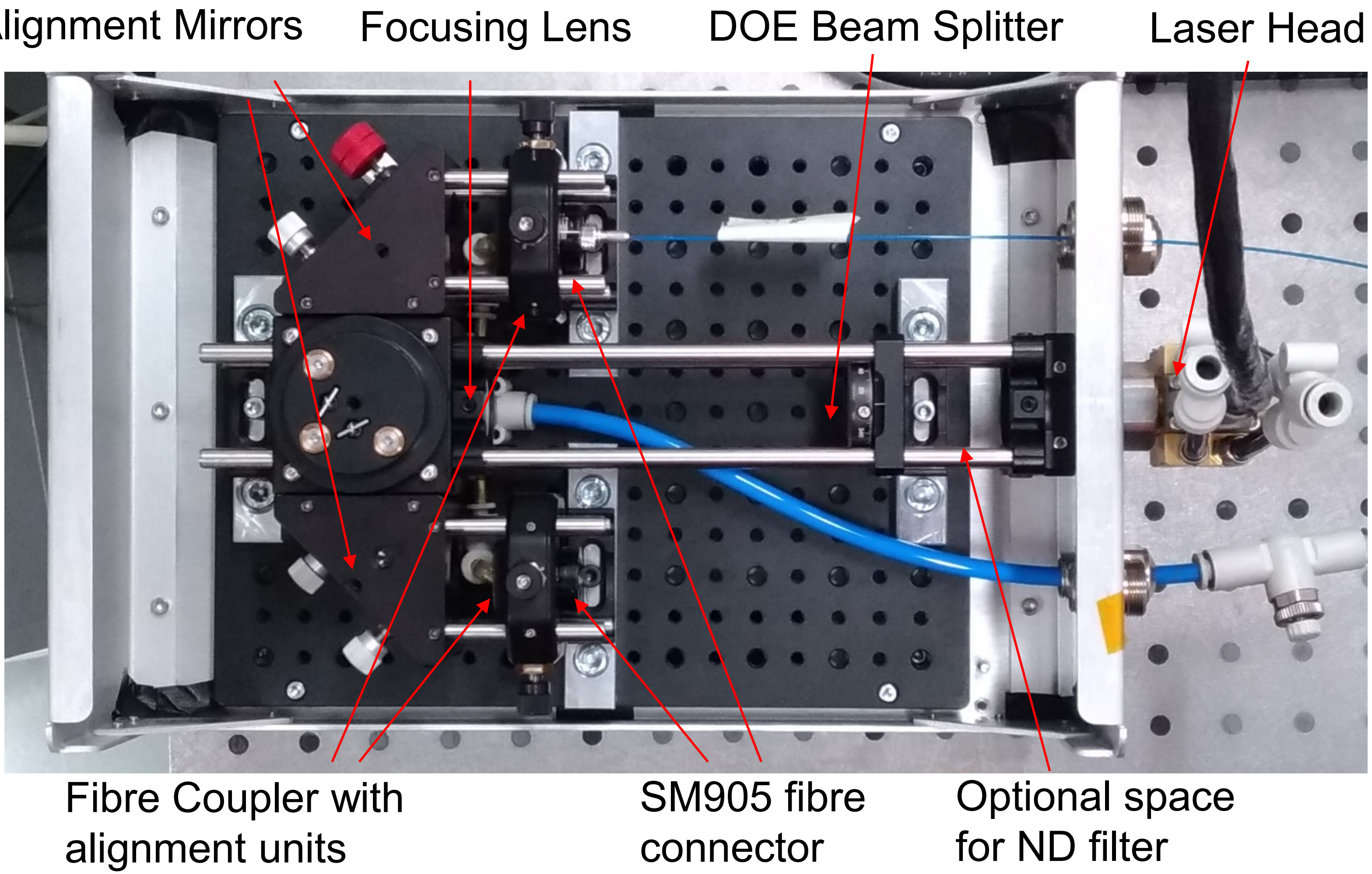
Fibre Coupler Assembly and Test at SAL

- Fibre Coupler internal assembly CAD



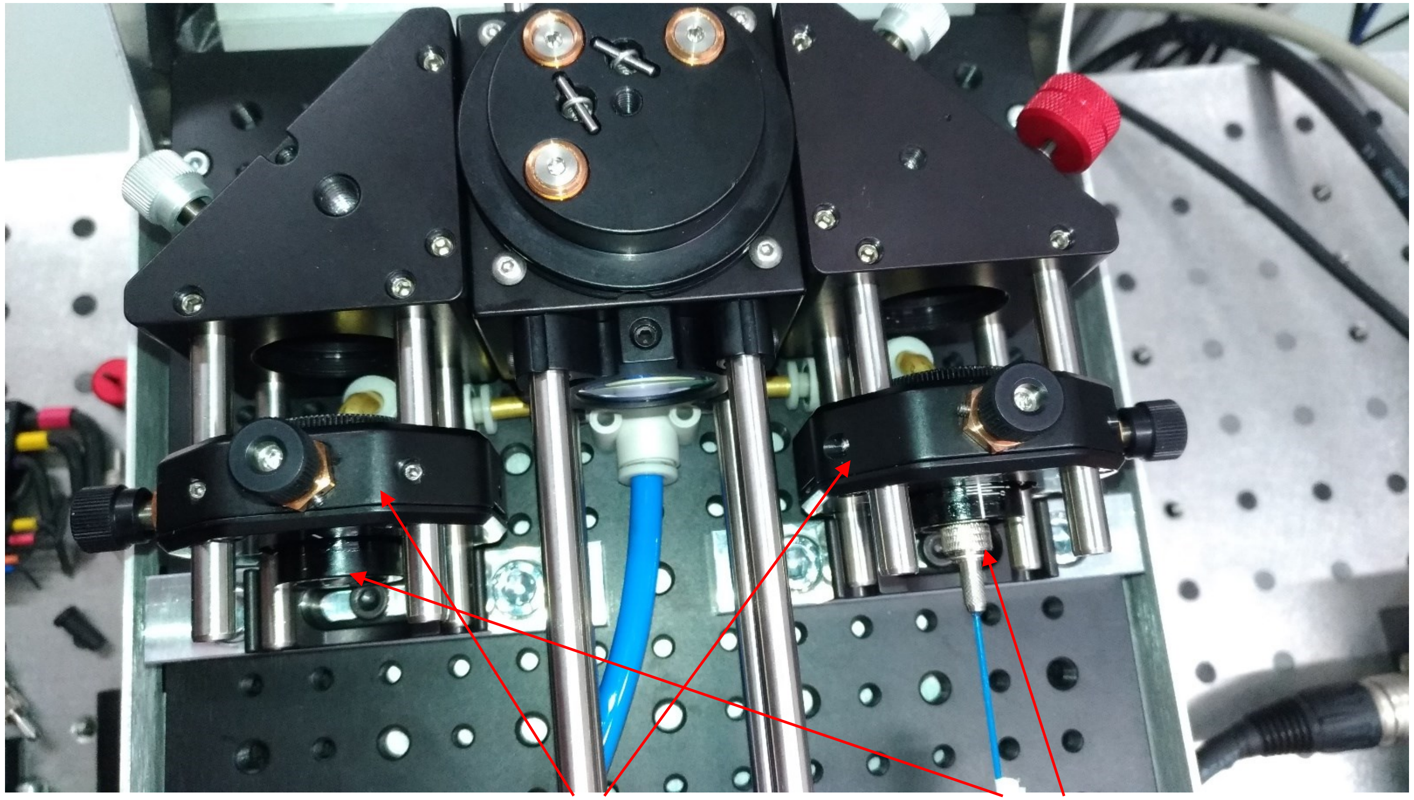
Fibre Coupler Assembly and Test at SAL

- Fibre Coupler internal assembly



Fibre Coupler Assembly and Test at SAL

- Fibre Coupler Alignment
  - Fibres are mounted on XYZ adjustment stages
  - Pre-alignment done using cage mount 600µ aperture alignment target card and Kapton foil to adjust axis of laser beam exactly to the centre of the units

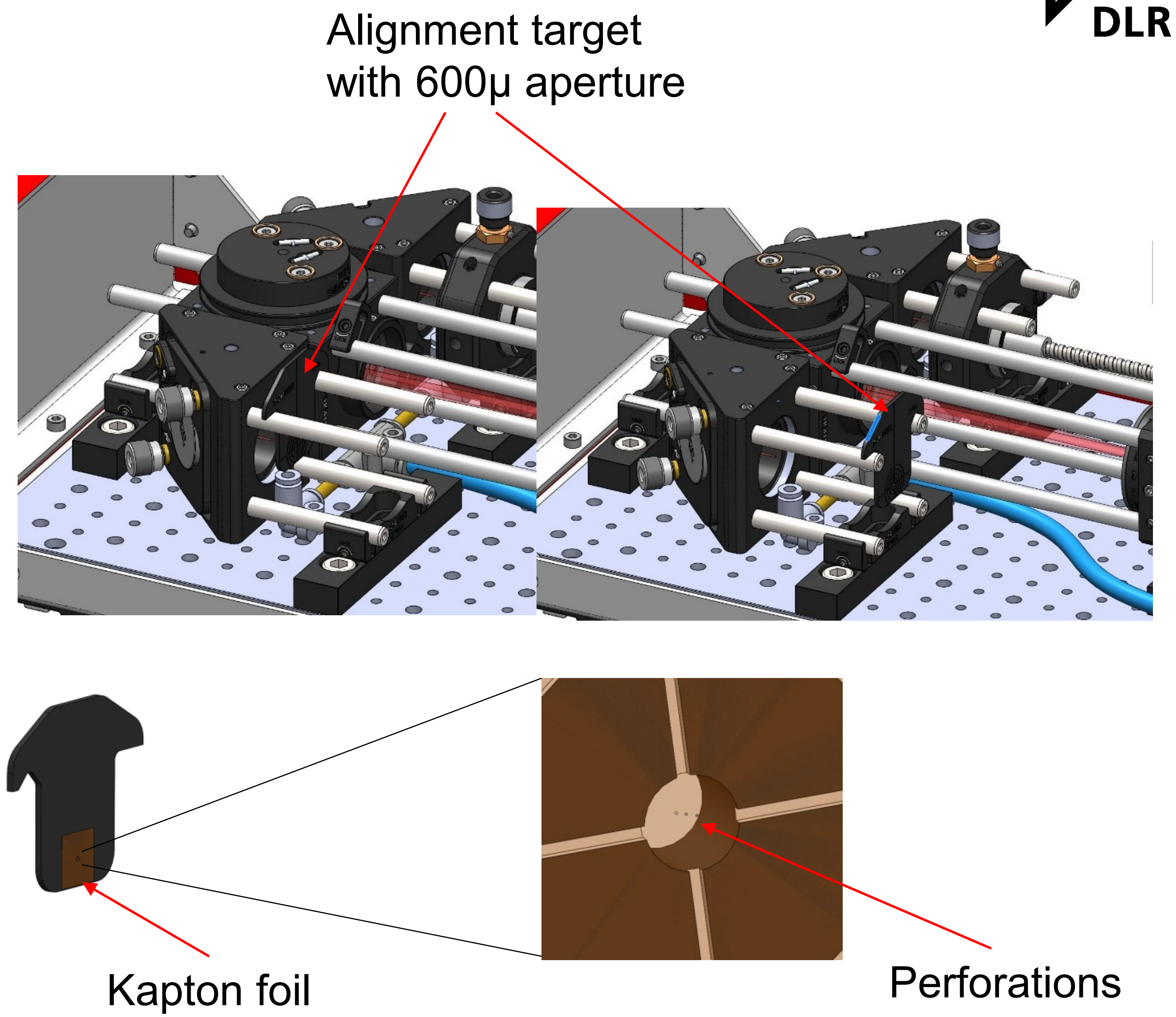


Fibre Coupler with alignment units

SM905 fibre connector

Fibre Coupler Assembly and Test at SAL

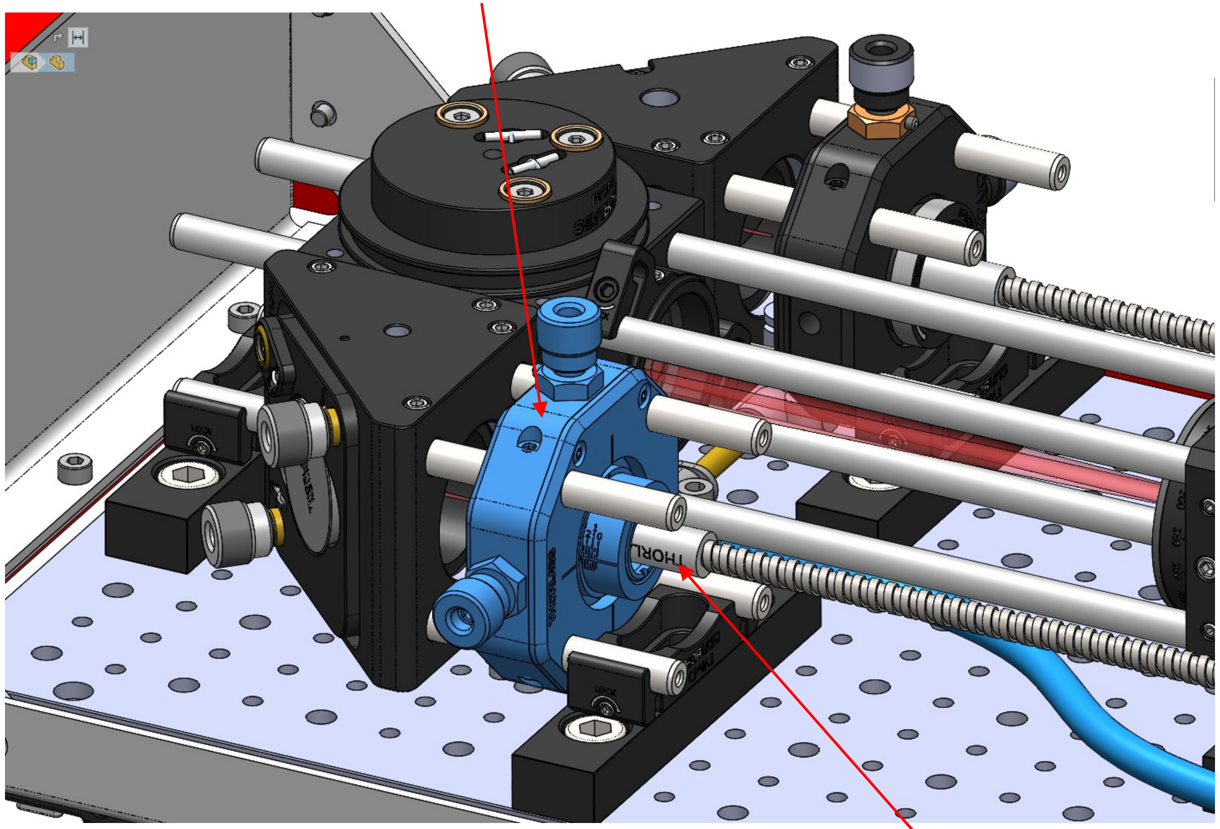
- Fibre Coupler Alignment
  - Kapton foils will get perforated by the focused laser beam
  - Sliding the alignment target with the foil along the rails and pulsing the laser at different locations will show the beam path
  - Iterative alignment of mirrors and capturing of beam path till the focal spot is exactly aligned with the axis



Fibre Coupler Assembly and Test at SAL

- Fibre Coupler Alignment
  - After installation of the XYZ aligner and the SMA905 fibre, the laser beam is always centred to the fibre
  - XY alignment of the fibre relative to the beam till the output power is at the maximum
  - Alignment of the fibre is necessary due to manufacturing tolerances, especially centring

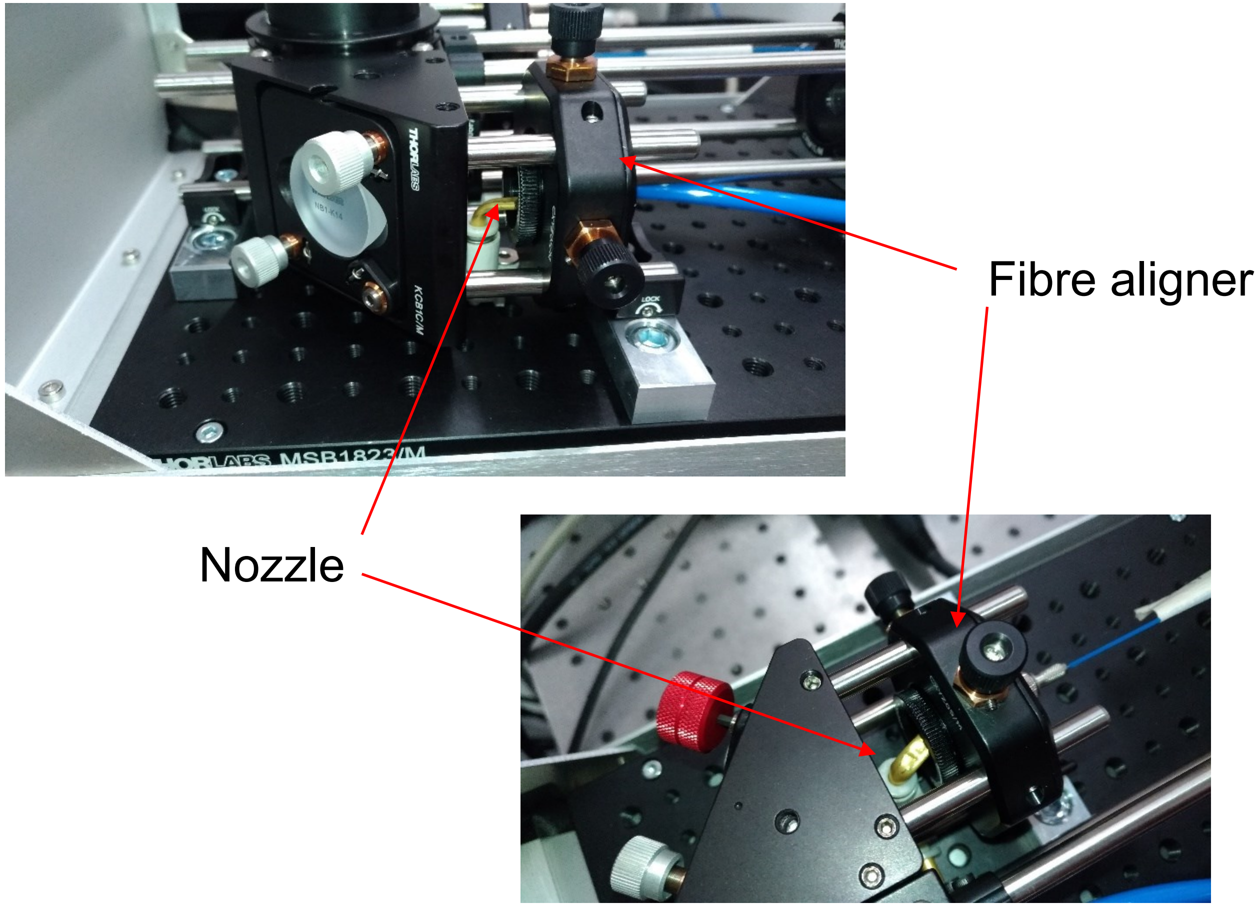
Fibre XYZ aligner



SMA 905 connector

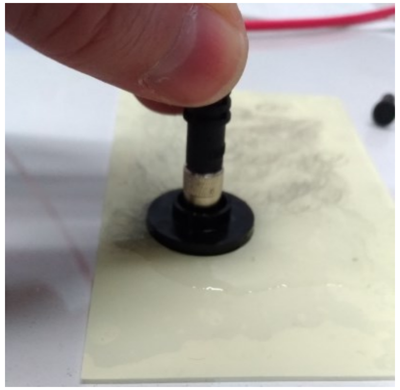
Fibre Coupler Assembly and Test at SAL

- Fibre Coupler Alignment
  - The focal spot had to be located in front of the fibre in order to not damage the fibre end
  - The still high focal spot energy density in front of the fibre end face may produce an optical breakdown if particles are present
  - Gas purging system was added to avoid plasma generation during laser burst



Fibre Coupler Assembly and Test at SAL

- Fibre Coupler Tests
  - Initial tests with off-the-shelf polished fibres showed very poor results, damage was often seen after even one single pulse
  - Specialize fibres with large cladding and slightly roughened (1µ diamond paper polished) end faces showed most promising results
  - **800µm, 600µm and 400µm** core diameter fibre were tested
  - 800µm and 600µm fibres could successfully be operated with about 10mJ transmission
  - 400µm fibre showed random damage after some pulses, complete damage usually occurred at less than 100 shots



Manual fibre polishing

Fibre inspection microscope

Fibre Coupler Assembly and Test at SAL

- Fibre Coupler Tests
  - All shipped fibre have been polished using 1µm polishing paper
  - Specialize fibres with large cladding and slightly roughened (1µ diamond paper polished) end faces showed most promising results
  - **800µm, 600µm and 400µm** core diameter fibre were tested
  - 800µm and 600µm fibres could successfully be operated with about 10mJ transmission
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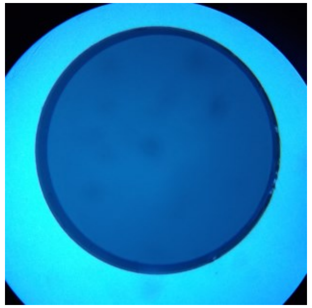
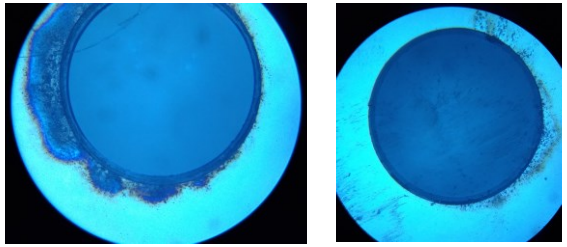
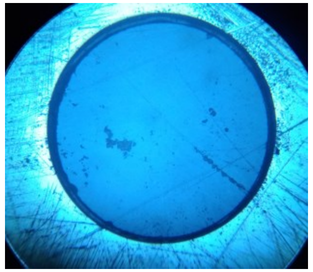


Polished fibre end face



Laser damage at ferrule, due to heavy and slight misalignment

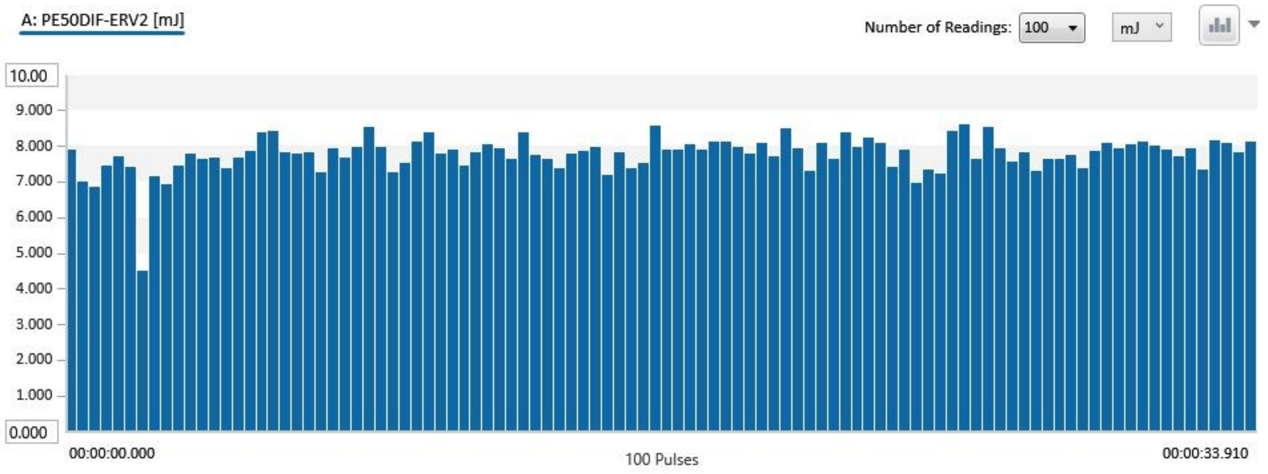


Laser damage at fibre end face

Fibre Coupler Assembly and Test at SAL

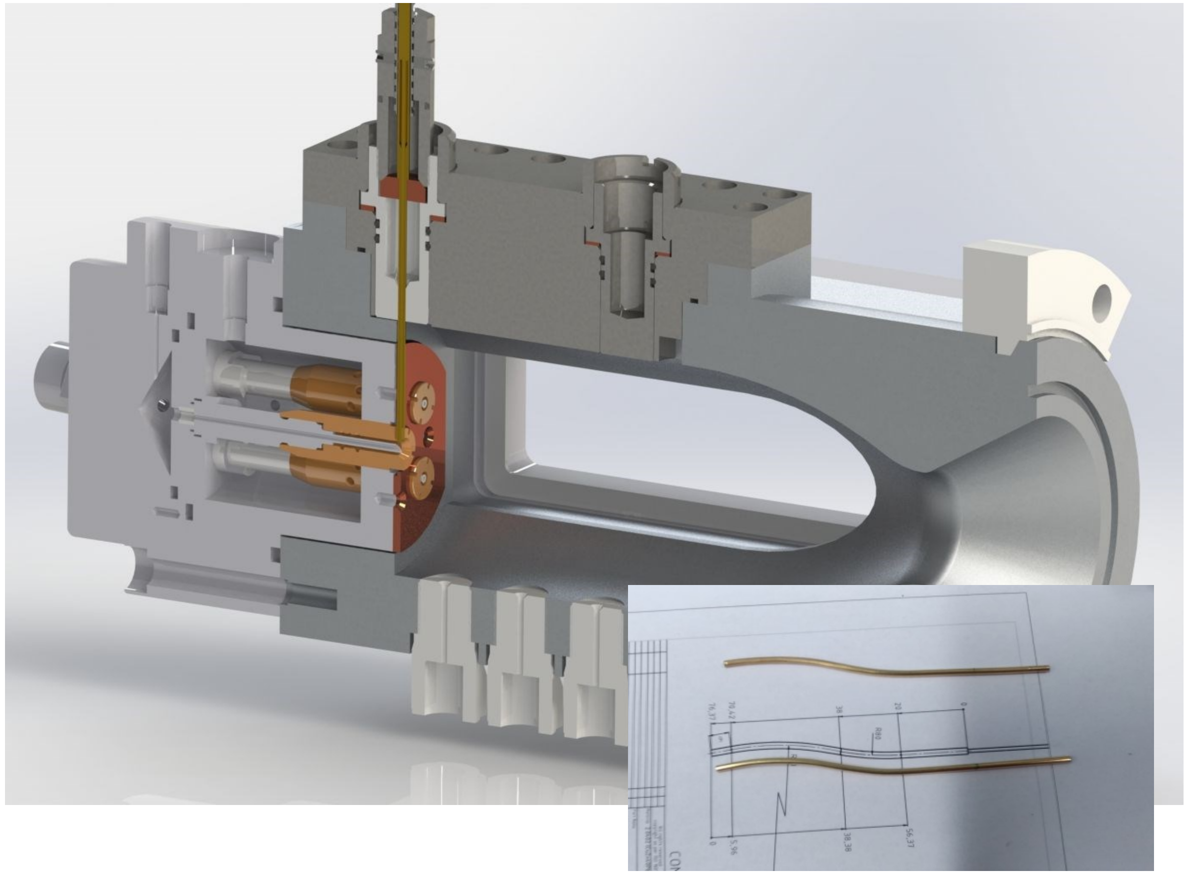
- Fibre Coupler Tests
  - After alignment of both ports, the transmitted energy per pulse was measured
  - Tests with bursts and longer pulse sequences were performed
  - Occurrence of optical breakdown before the fibre can be seen in energy decrease
  - Installation of gas purging in the focal spot could remove optical breakdowns

	Pulse energy at fibre output [mJ]	
Fiber core ø	Port-A	Port-B
600µ Sample 1	8	8
600µ Sample 2	9	7
800µ Sample 1	10	10
800µ Sample 2	9	10



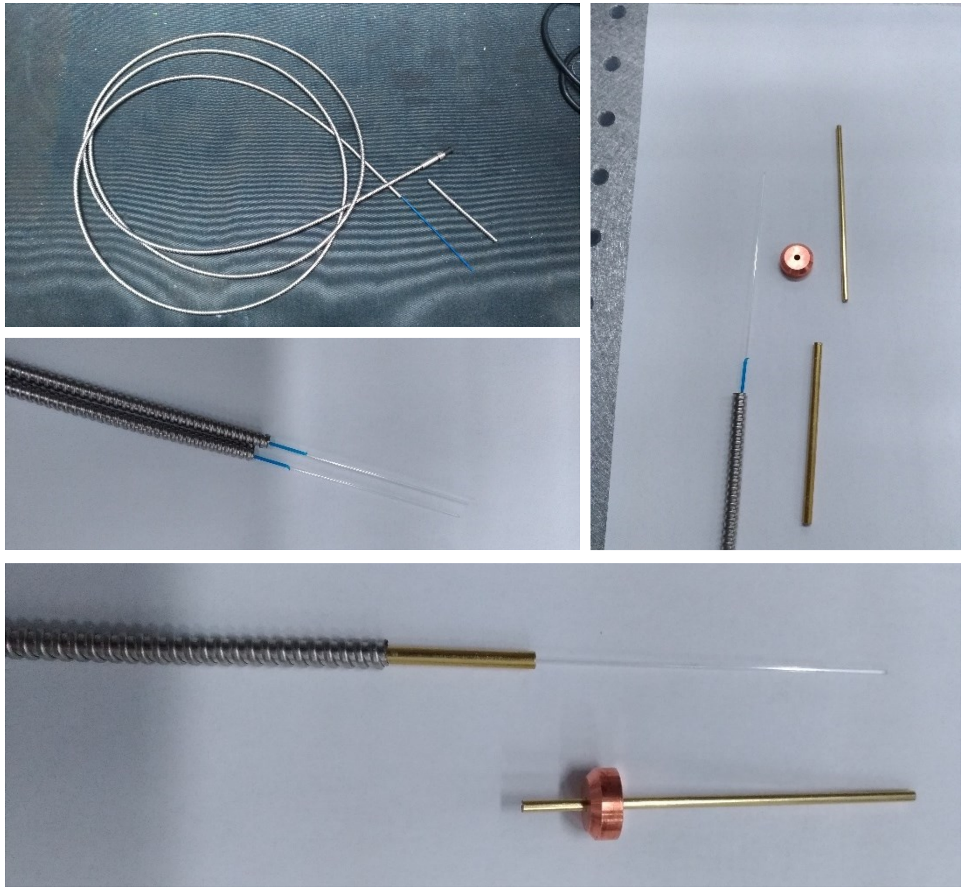
Fibre Coupler Assembly and Test at SAL

- Direct Fibre final implementation and assembling
  - Output of the fibre is directly guided to a target surface without focusing optics
  - Direct fibre tube had to be redesigned due to breaking of the fibre in the bent version
  - Straight version was possible with some modifications to the laser adapter plate



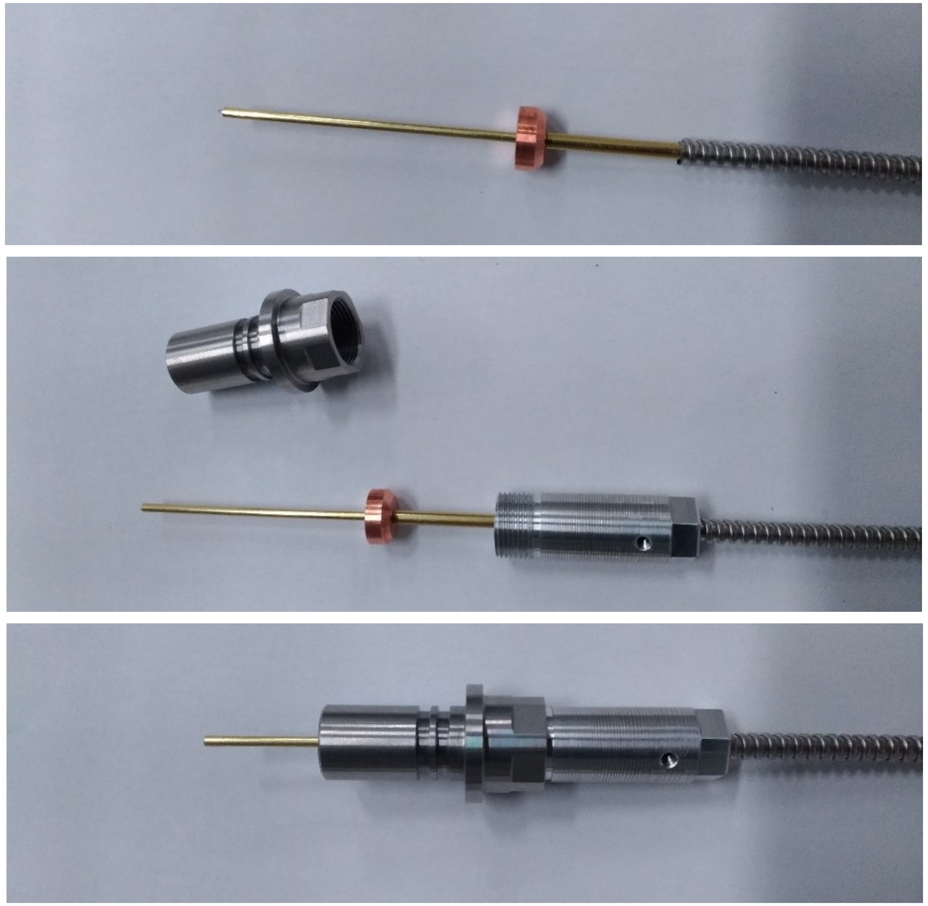
Fibre Coupler Assembly and Test at SAL

- Direct Fibre final implementation and assembling
  - Custom made 5m fibre patch cables with assembled SM905 connectors and steel armour were cut in half
  - Ends are stripped and the cladding was removed
  - Brass tube are cut at length and polished
  - Copper seal disk is soldered to the tube
  - Brass protection tube is added to fibre end for bending protection



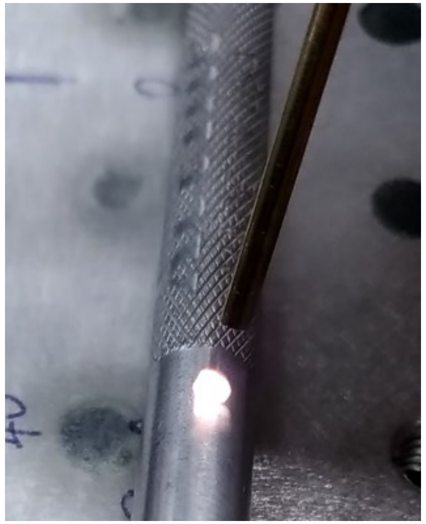
Fibre Coupler Assembly and Test at SAL

- Direct Fibre final implementation and assembling
  - Fibre is glued into the tube using ultra low outgassing compound (Master Bond EP29LPSP)
  - Sample is cured at 80° for 24 hours
  - Fibre tip is cleaved and polished down to 1µ
  - Cured fibre is integrated with the armour clamping sleeve and the access tube to the combustion chamber
  - Two specimens of each 800µ and 600µ core diameter where manufactured



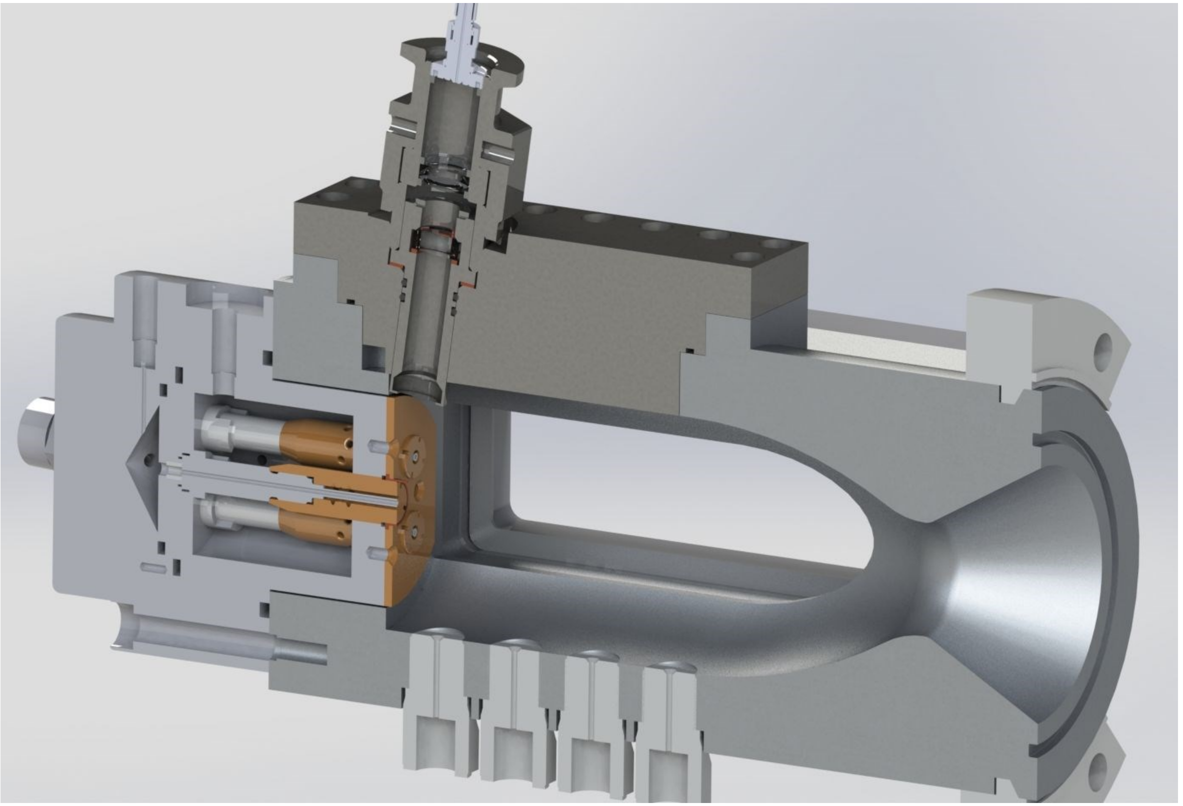
Fibre Coupler Assembly and Test at SAL

- Direct Fibre final implementation and assembling
  - All fibres were tested with single pulse and burst
  - Using a metal target in front of the fibre at a distance of about 10mm produced a nice surface plasma
  - No damage to the front and end faces was found after the tests



Fibre Coupler Assembly and Test at SAL

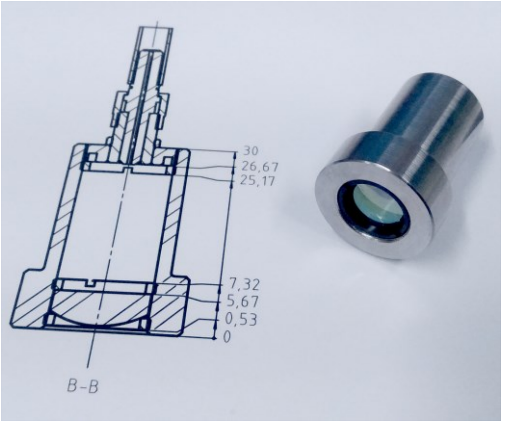
- Focused Fibre final implementation and assembling
  - Output of fibre is collimated and refocused
  - Focused laser beam can either be guided to a target or used in direct plasma ignition
  - Two lens tubes with different focal lengths were manufactured: 25mm and 15mm
  - Lab tests did not show air breakdown in both cases

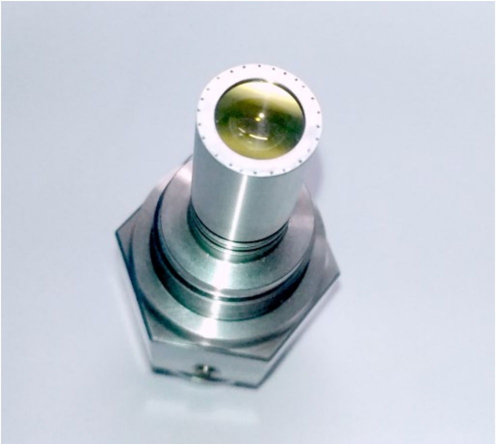
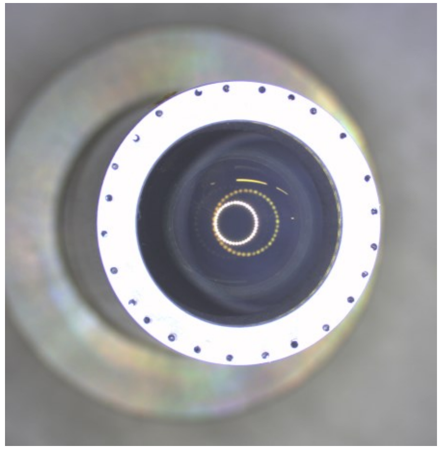


Fibre Coupler Assembly and Test at SAL

- Focused Fibre final implementation and assembling

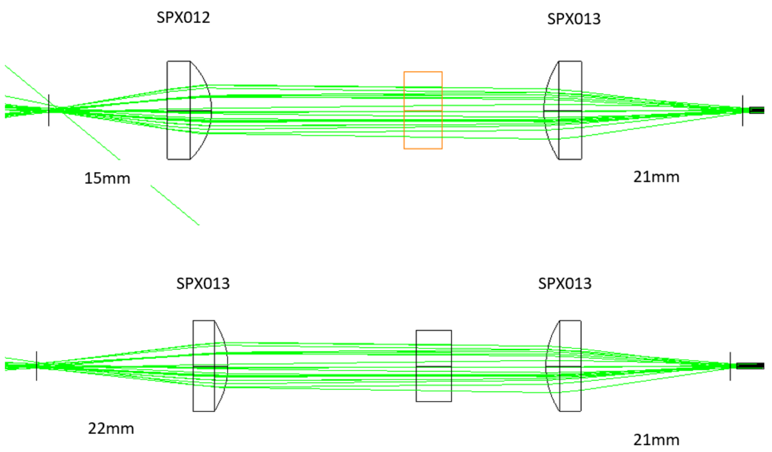
  - Fibre collimator has SM-905 connector that can be used for all fibre core diameters
  - Collimation lens is optimized for the numerical aperture of the used fibre material
  - Antireflection coated lenses are used to keep efficiency high
  - Lens tubes were assembled and laser brazed



Fibre Coupler Assembly and Test at SAL

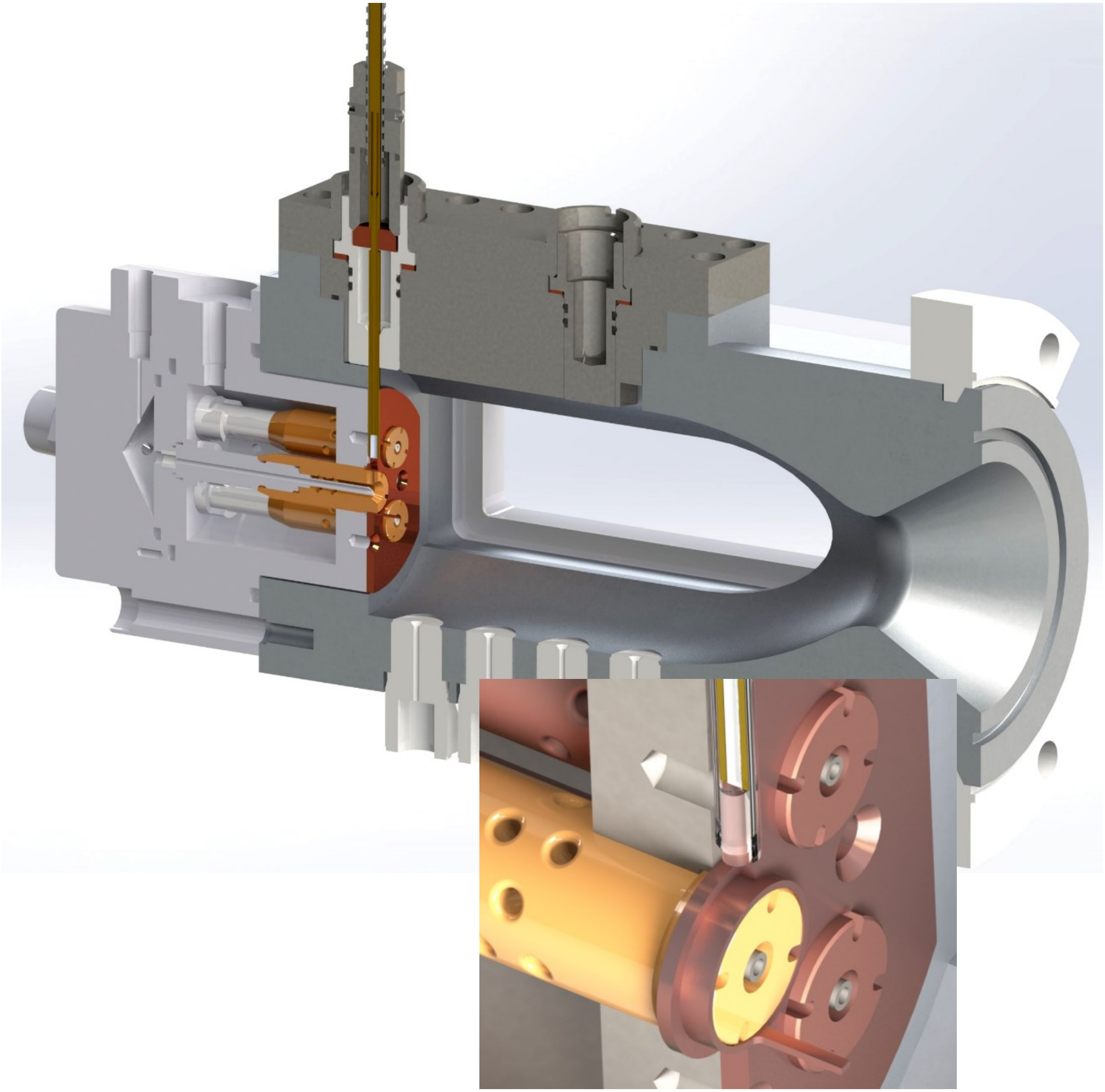
- Focused Fibre final implementation and assembling
  - Collimator Unit, Lens Tube and the Outer Tube are integrated into the Laser Adapter Plate
  - Measured focal lengths were 24mm and 15mm in good agreement with simulation



CCN-1 Direct Fibre GRIN Lens Modification

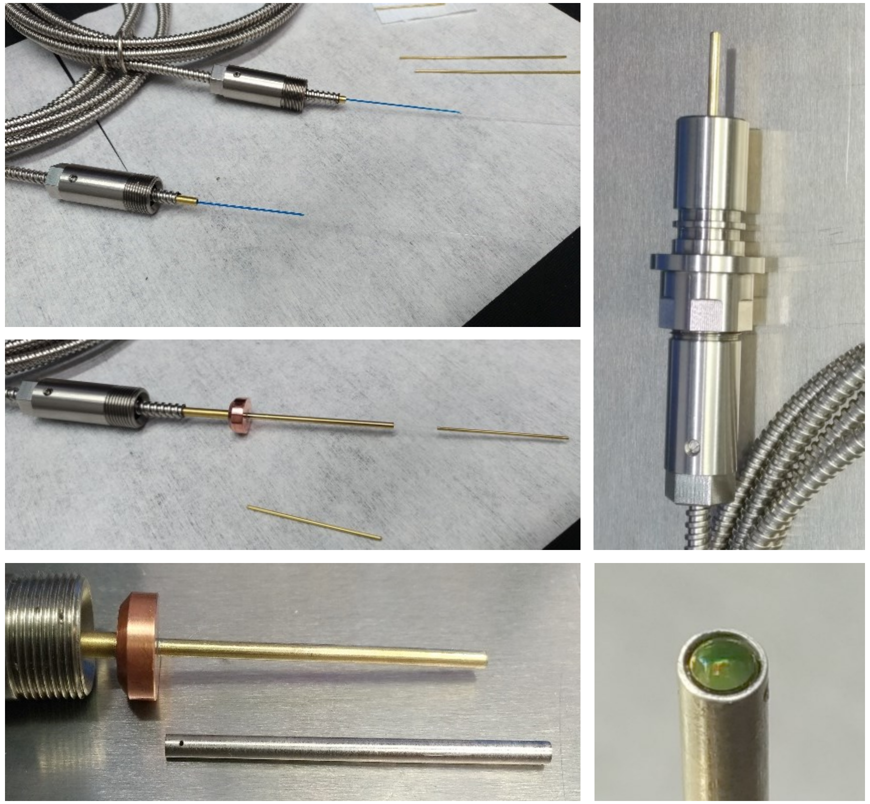
DLR

- Direct fibre GRIN lens addition
  - Output of the fibre is directly guided to a target surface through a straight metal tube to facilitate mechanical access
  - A gradient index (GRIN) lens was added to the end of the fibre tube to provide higher focal spot energy density at the target ring
  - The laser adapter had to be modified to allow the fiber tube to reach the target region using a straight tube



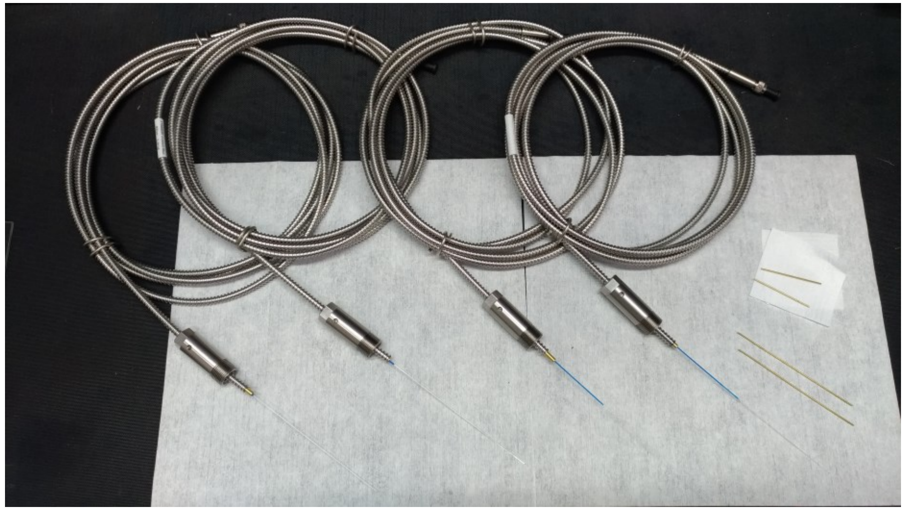
CCN-1 Direct Fibre GRIN Lens Modification

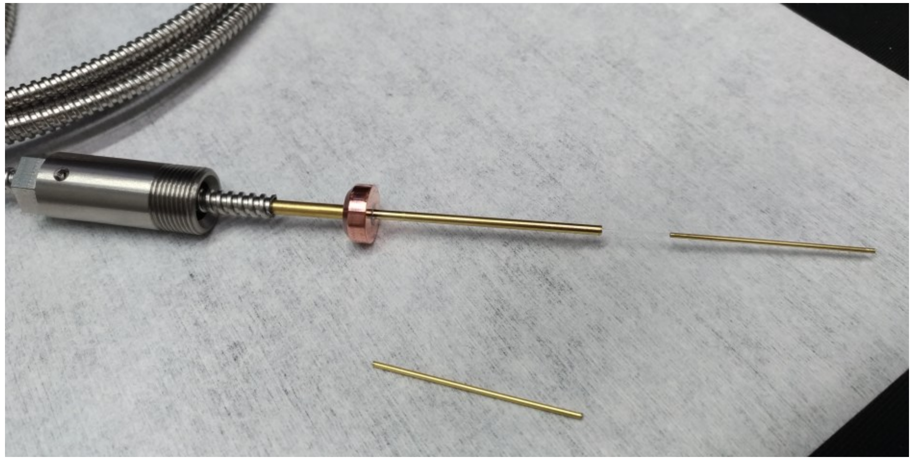
- Direct Fibre with GRIN final implementation and assembling
  - Integration of the fibres was performed similar to the previous direct guided fibre assemblies using an ultra low outgassing, cryo compatible potting compound and polishing the fibre end face after curing
  - The GRIN lens was integrated in a stainless steel tube and this lens tube was then bonded onto the fibre brass tube. This tube than can be attached onto the brass fibre tube using the same potting compound assuring a vacuum tight seal between fibre and tube



CCN-1 Direct Fibre GRIN Lens Modification

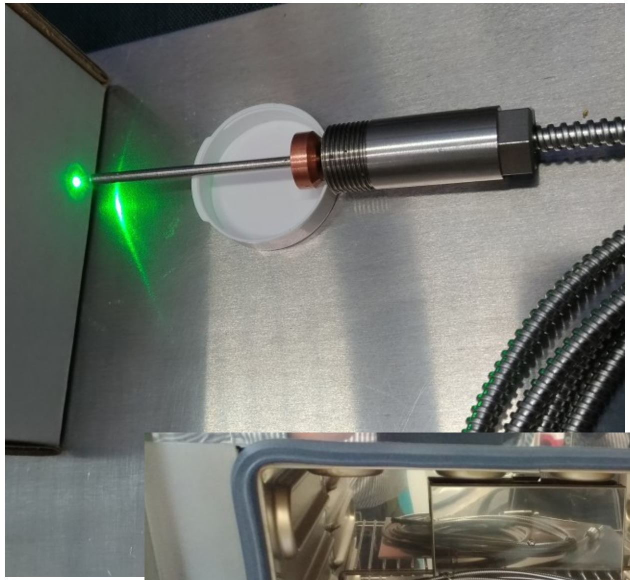
- Direct Fibre with GRIN testing
  - Two sets of each 400 µm and 600 µm fibres were manufactured
  - Due to their smaller outer cladding diameter, the 400 µm fibres required an additional padding tube to adopt to the inner diameter of the brass tube.
  - A calibrated precision brass tube with matching inner and outer diameters was used for this purpose and bonded to the fibre





CCN-1 Direct Fibre GRIN Lens Modification

- Direct Fibre with GRIN testing
  - The fibre assemblies were tested using a green laser before attaching the GRIN lens tubes
  - The potted lens tube assemblies were cured for 24 hours in an oven at 80°C to ensure highest strength of the potting compound

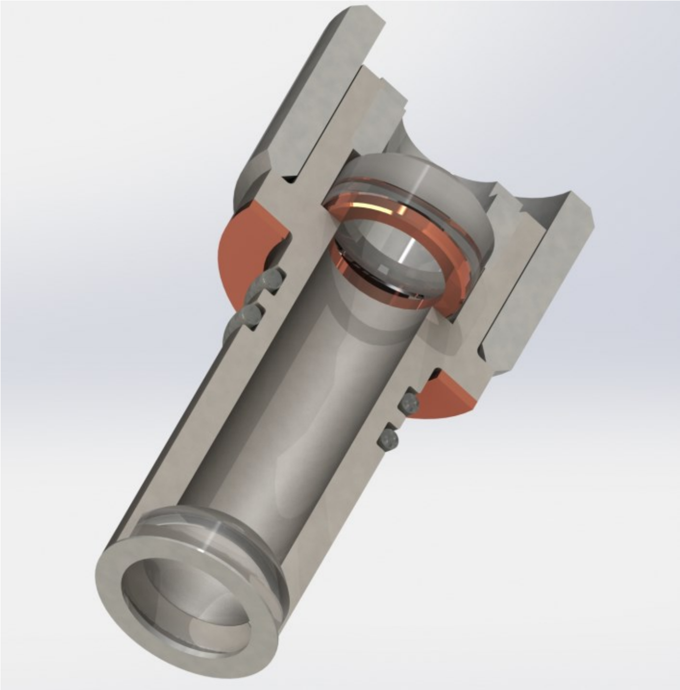


CCN-1 Direct Fibre direct focused plasma ignition test

- In order to increase the ignition probability of direct ignition, a direct focusing adapter with shorter focal length was manufactured

- The shortest available back focal length at this diameter is 11.4 mm, shorter focal lengths would require ball lenses

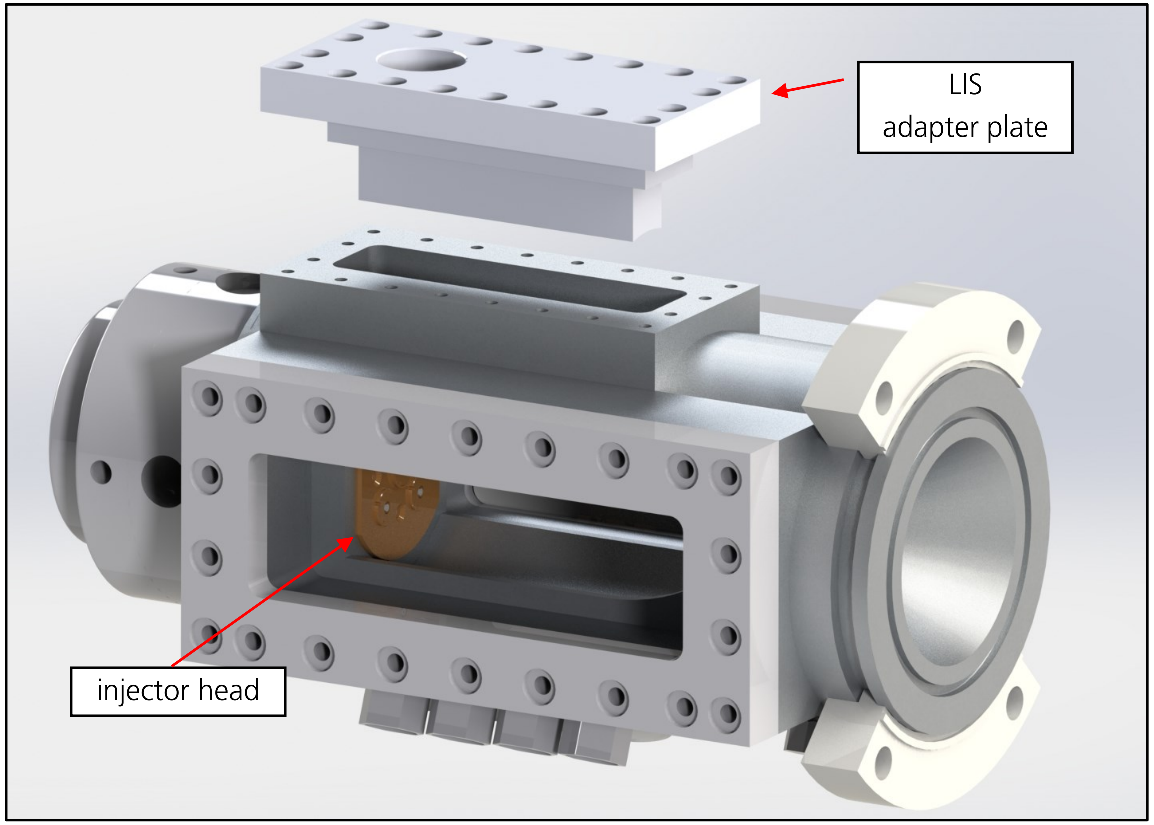
- The recess for the aspheric lens in the lens tube had to be modified to adopt to the smaller radius of curvature and larger center thickness



Thank you for your attention!

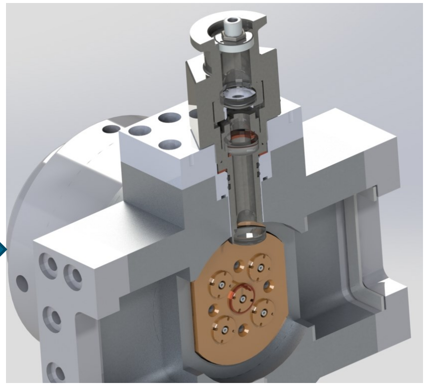
-> Back to Presentation by Michael Börner on LIS tests (WP2300 +)

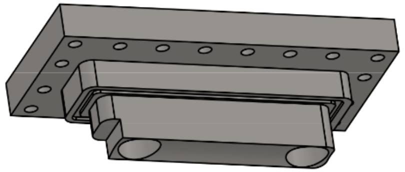
WP2300: Breadboard thruster adaptation
WP2400: Test preparation at M3.1
WP2500: Test execution



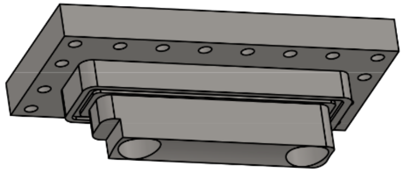
Test configurations (1)

FU1a-LPI1-600µ and FU1a-LPI1-800µ	• **normal optical tube** • **tube with 25mm focal length** • **fibres:** ○ **600µm** ○ **800µm**
FU1a-LPI2-600µ and FU1a-LPI2-800µ	• **normal optical tube** • **tube with 25mm focal length** • **fibres:** ○ **600µm** ○ **800µm**
FU1a-LAI-600µ and FU1a-LAI-800µ	• **normal optical tube** • **tube with 25 mm focal length** • **fibres** ○ **600µm** ○ **800µm**

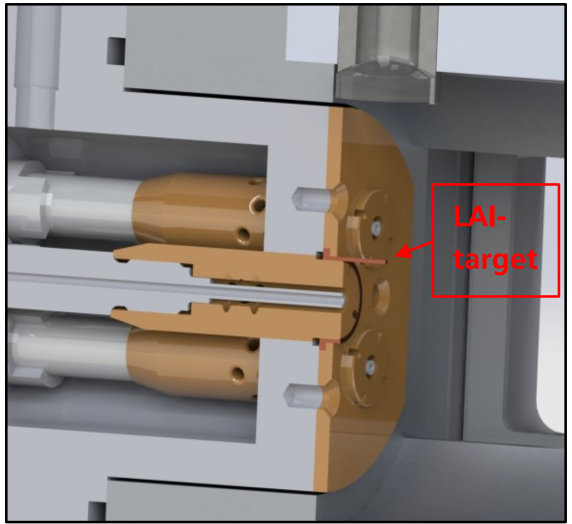




LPI1



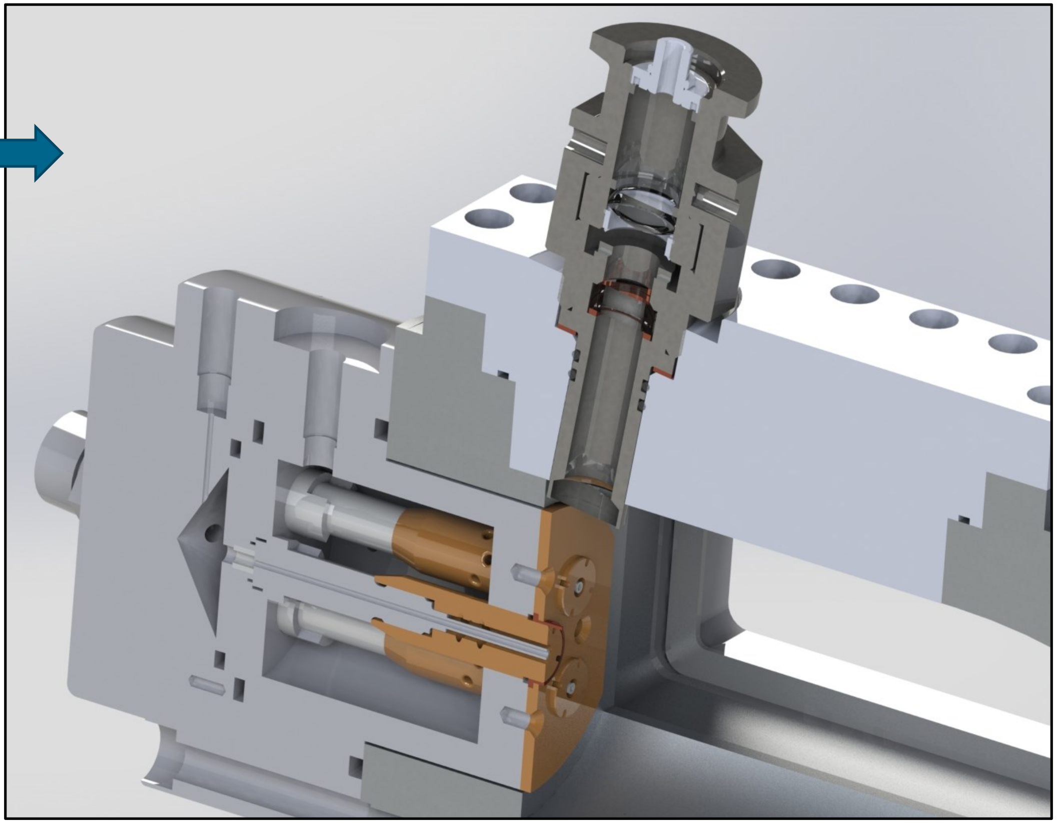
LPI2



Test configurations (2)

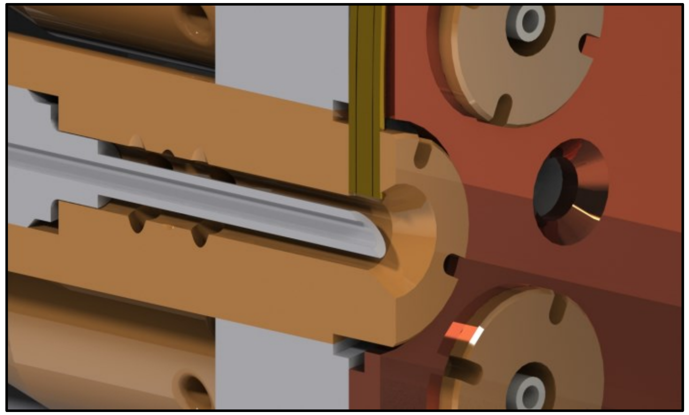
FU1b-LAI-600µ
and
FU1b-LAI-800µ
	• tilted optical tube for LAI
	• tube with 25 mm focal length
	• fibres
	  ○ 600µm
	  ○ 800µm

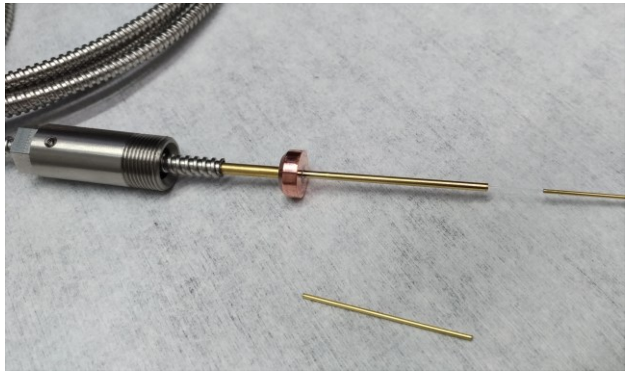
FU2-LAI-600µ
and
FU2-LAI-800µ
	• direct LAI without focusing at the injector exit
	• fibres
	  ○ 600µm
	  ○ 800µm

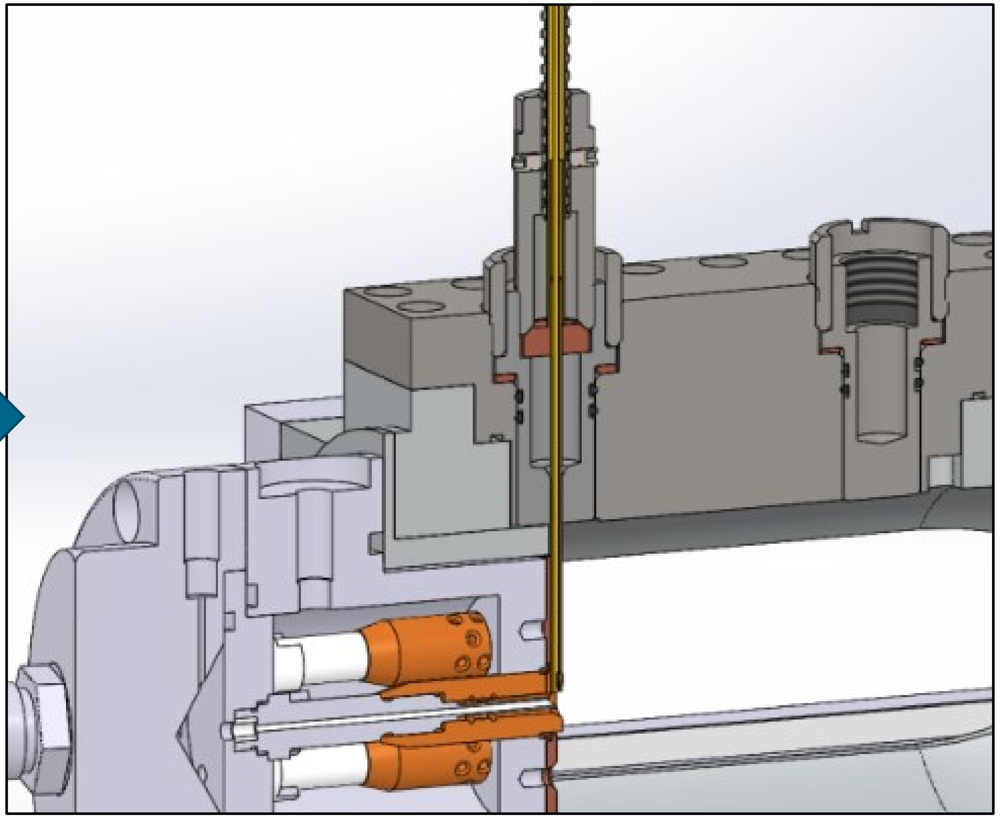


Test configurations (2)

FU1b-LAI-600µ and FU1b-LAI-800µ	• tilted optical tube for LAI • tube with 25 mm focal length • fibres ○ 600µm ○ 800µm
FU2-LAI-600µ and FU2-LAI-800µ	• direct LAI without focusing at the injector exit • fibres ○ 600µm ○ 800µm

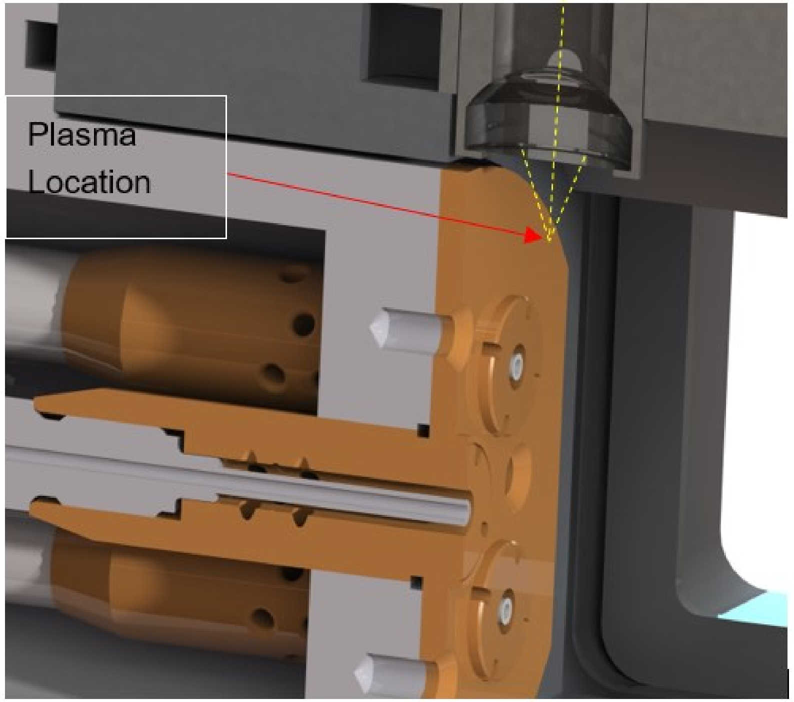






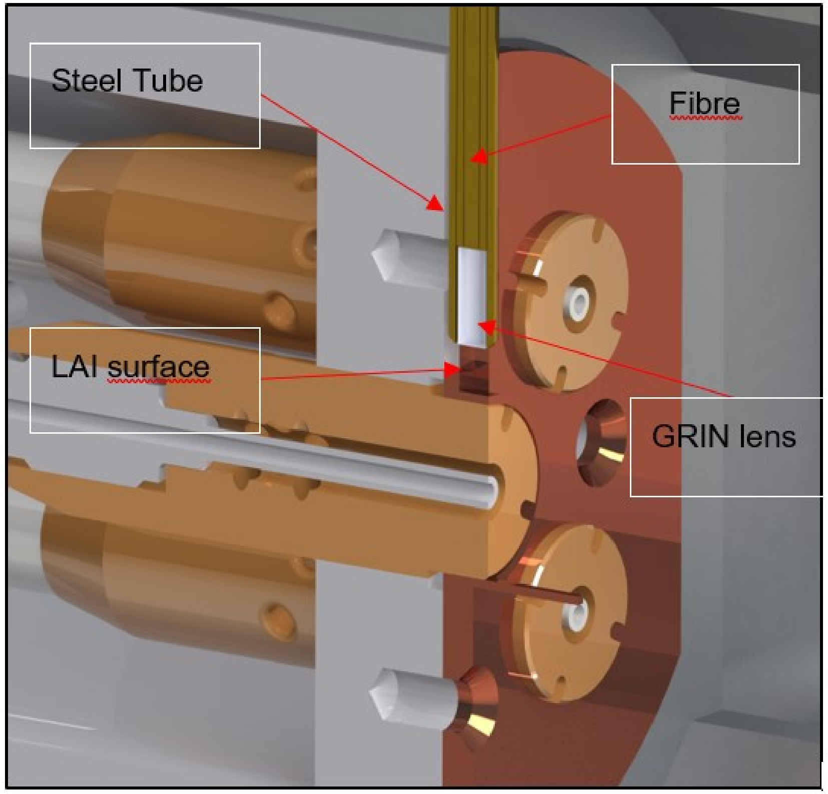
Test configurations (3)

○ FU1a-CCN1-400µm ○ FU1a-CCN1-600µm	• Lens Tube with optimized 11mm focal length
○ FU2-LAI-GRIN-400µm ○ FU2-LAI-GRIN-600µm	• direct LAI without focusing at the injector exit • fibres ○ 400µm ○ 600µm

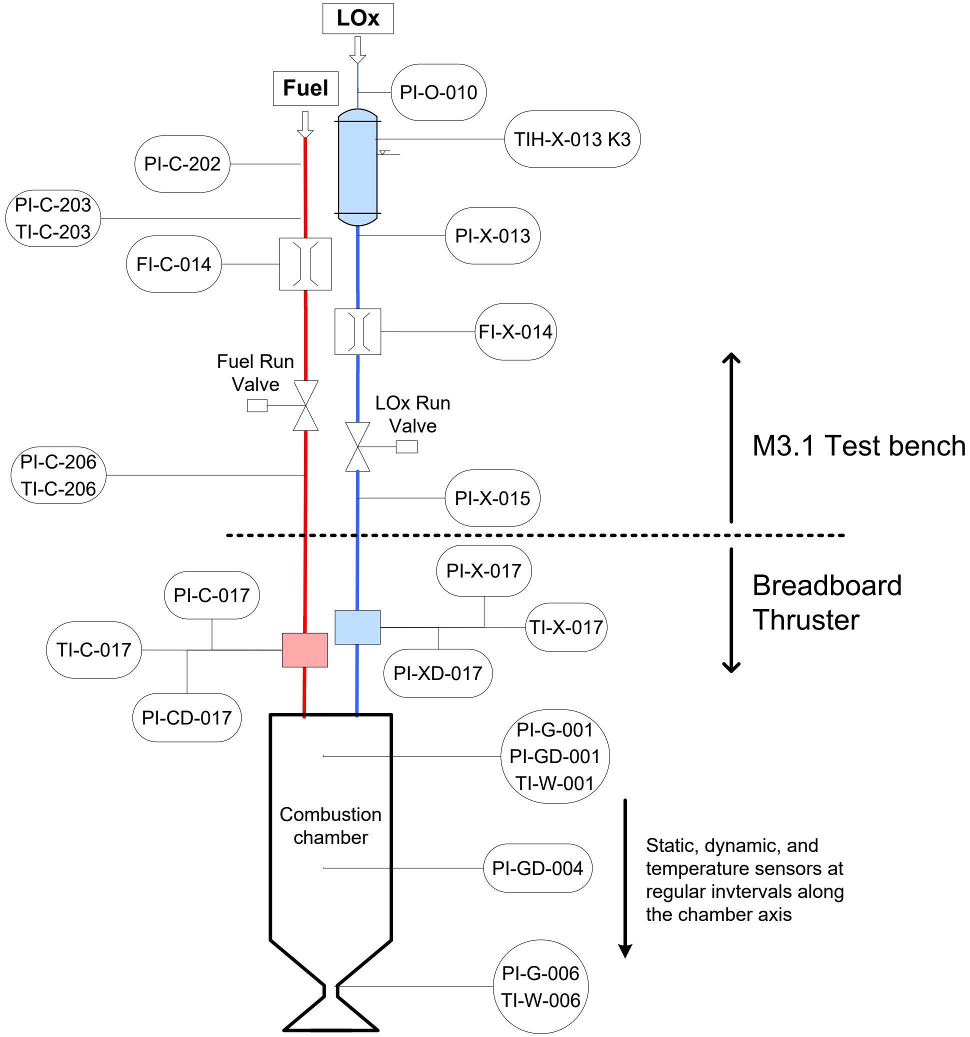


Test configurations (3)

○ FU1a-CCN1-400µm ○ FU1a-CCN1-600µm	• Lens Tube with optimized 11mm focal length
○ FU2-LAI-GRIN-400µm ○ FU2-LAI-GRIN-600µm	• direct LAI without focusing at the injector exit • fibres ○ 400µm ○ 600µm

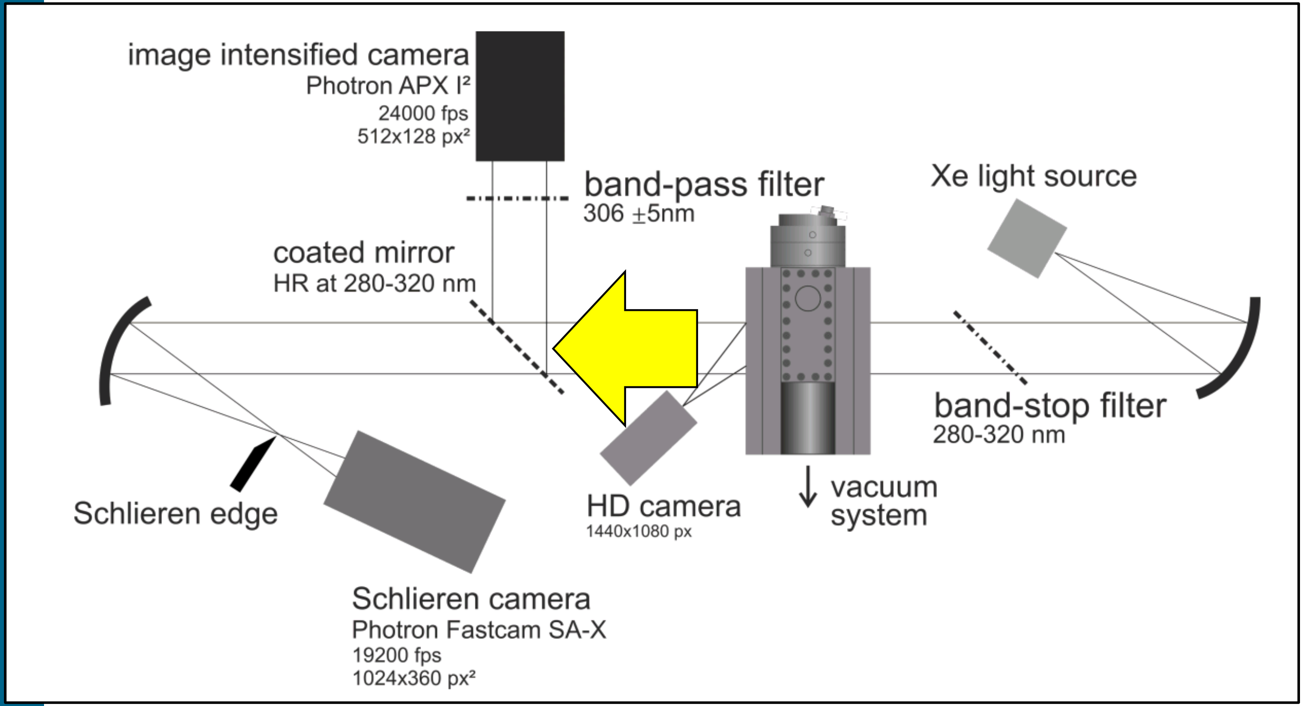


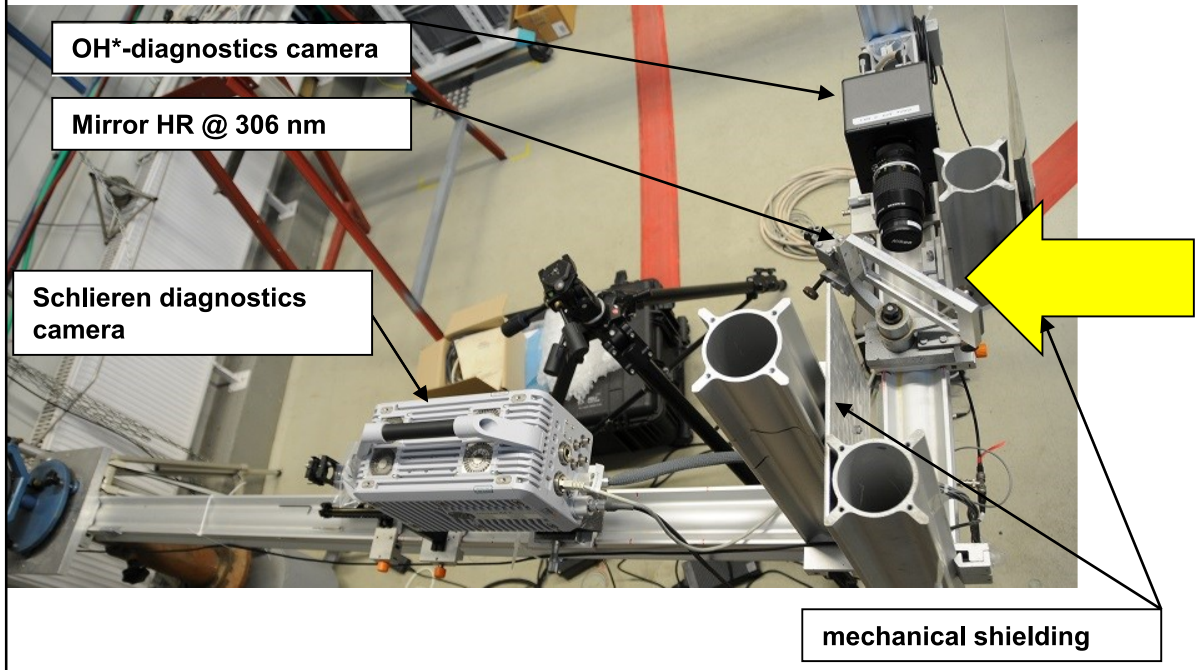
Experimental Set-Up: M3.1 Test bench



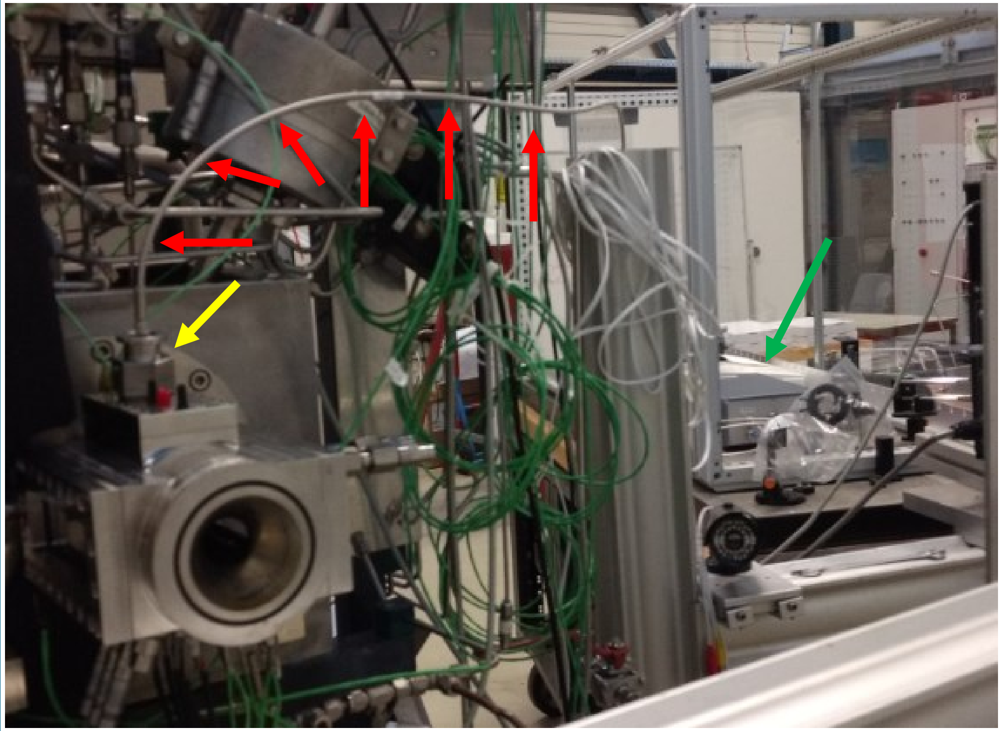
- Fast acting run valves (4 – 6 ms)
- Static and dynamic pressures sensors in injector heads and chamber
- Temperature sensors (Typ K)
- Coriolis flowmeters for massflow measurements

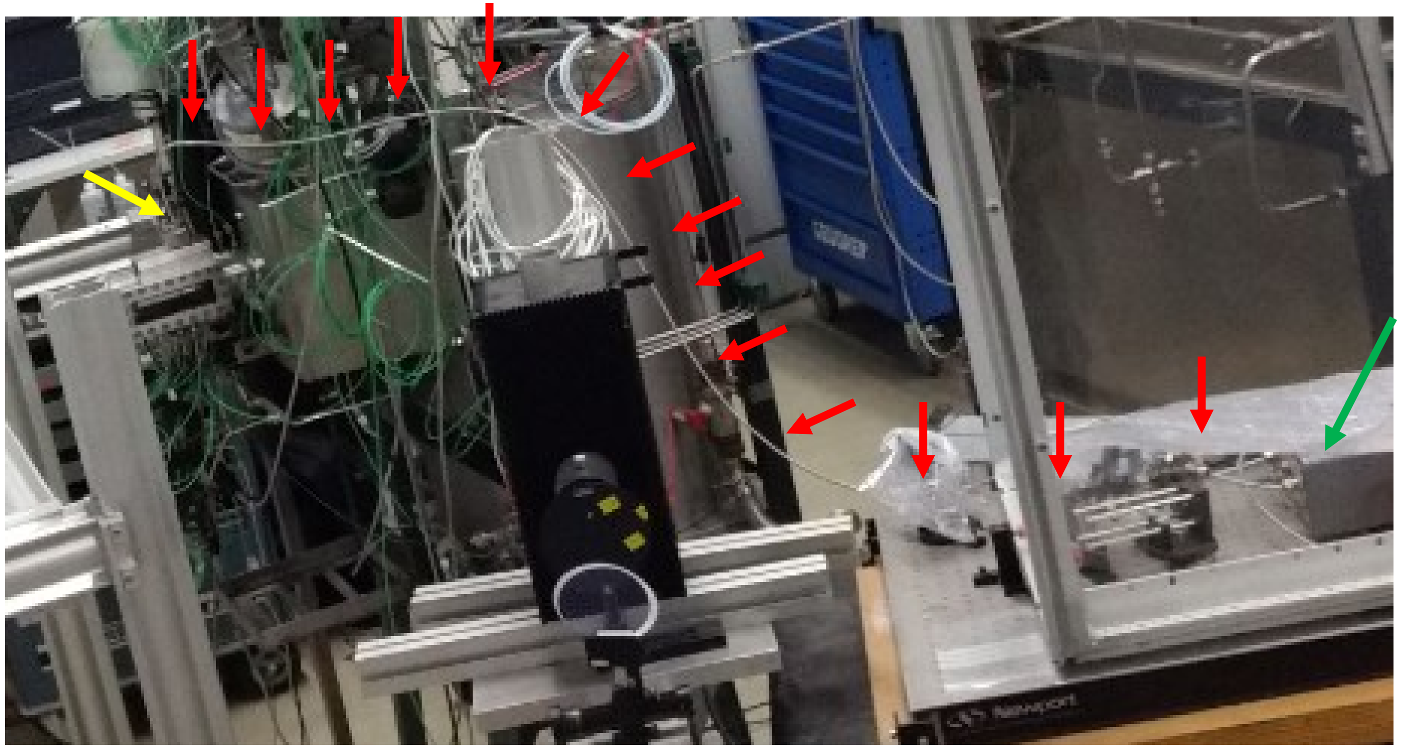
Experimental Set-Up: Optical diagnostics





Experimental Set-Up:
Fibre-based ignition system installation at M3.1





Test campaign goals

Objective		Category of objective	Success Criteria	Test campaign result
1	**To demonstrate the functionality of the LIS at a breadboard thruster at the M3.1 test bench**	**Primary**	• **Optical verification via schlieren diagnostics of plasma generation via ablation in air at ambient conditions.**	**?**
2	**To prove the reliability of the LIS during the test campaign**	**Primary**	• **Optical inspection of the LIS after the test campaign and its functionality by reliable generation of plasma via ablation**	**?**
3	**To demonstrate ignition for the fibre-based LIS for the test conditions of the last ESA TDE on laser ignition technology**	**Primary**	• **Detect combustion chamber pressure increase above 2 bar and the flame development via OH*-diagnostics**	**?**
4	To demonstrate ignition with **reduced laser pulse** energy for the fibre-based LIS	Secondary	• Detect combustion chamber pressure increase above 2 bar and the flame development via OH*-diagnostics for reduced laser pulse energy	**?**
5	To demonstrate ignition under **varying sequencing** conditions, for at least two different oxygen injection relative to start of fuel injection	Secondary	• Detect combustion chamber pressure increase above 2 bar and the flame development via OH*-diagnostics	**?**

Primary objective	The test campaign focuses on 100% fulfillment of primary objectives.
Secondary objective	DLR tries to reach the secondary objectives. In case of problems primary objectives are given priority and the secondary objectives are skipped.

Test campaign result overview

- 2 test campaigns
  - Original activity
  - CCN1 activity

1. Campaign 1 (Original activity)

- 12 test days realized
- 93 test run
  - including flow tests
  - excluding dry runs and laser test runs

2. Campaign 2 (CCN1 activity)

- 4 test days realized
- 27 test runs
  - including flow tests
  - excluding dry runs and laser test runs

Test campaign result overview

1. Campaign 1: Original activity

Challenges during test execution

1. No local test support of the SAL-team for LIS installation and testing at DLR M3.1 possible due to restrictions, only remote support possible

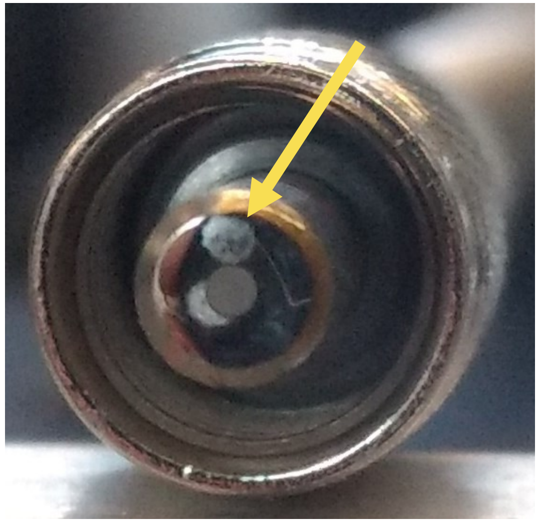
   -> Adjustment of the LIS after transport to DLR to obtain optimum of output energy by DLR team

2. Limited presence time at test bench for test engineers and technical staff (~2 days per week)

   - activities delayed due to restricted presence on site

Hardware status: fibre input

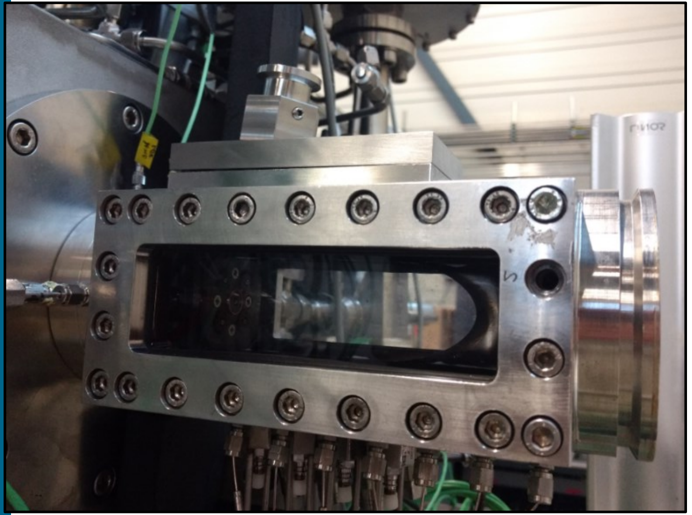
- Missalignment of multiplexer after / due to transport from SAL to DLR
- no visual damage on transport box or multiplexer

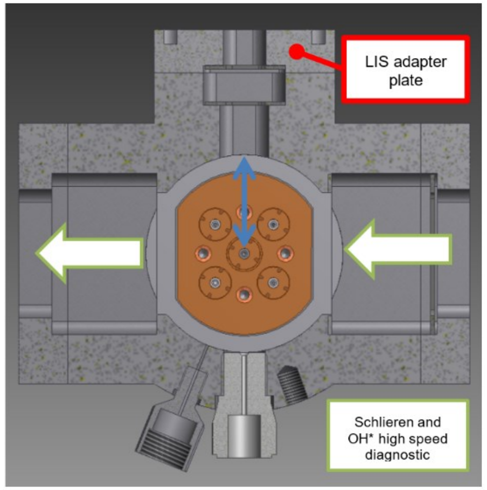



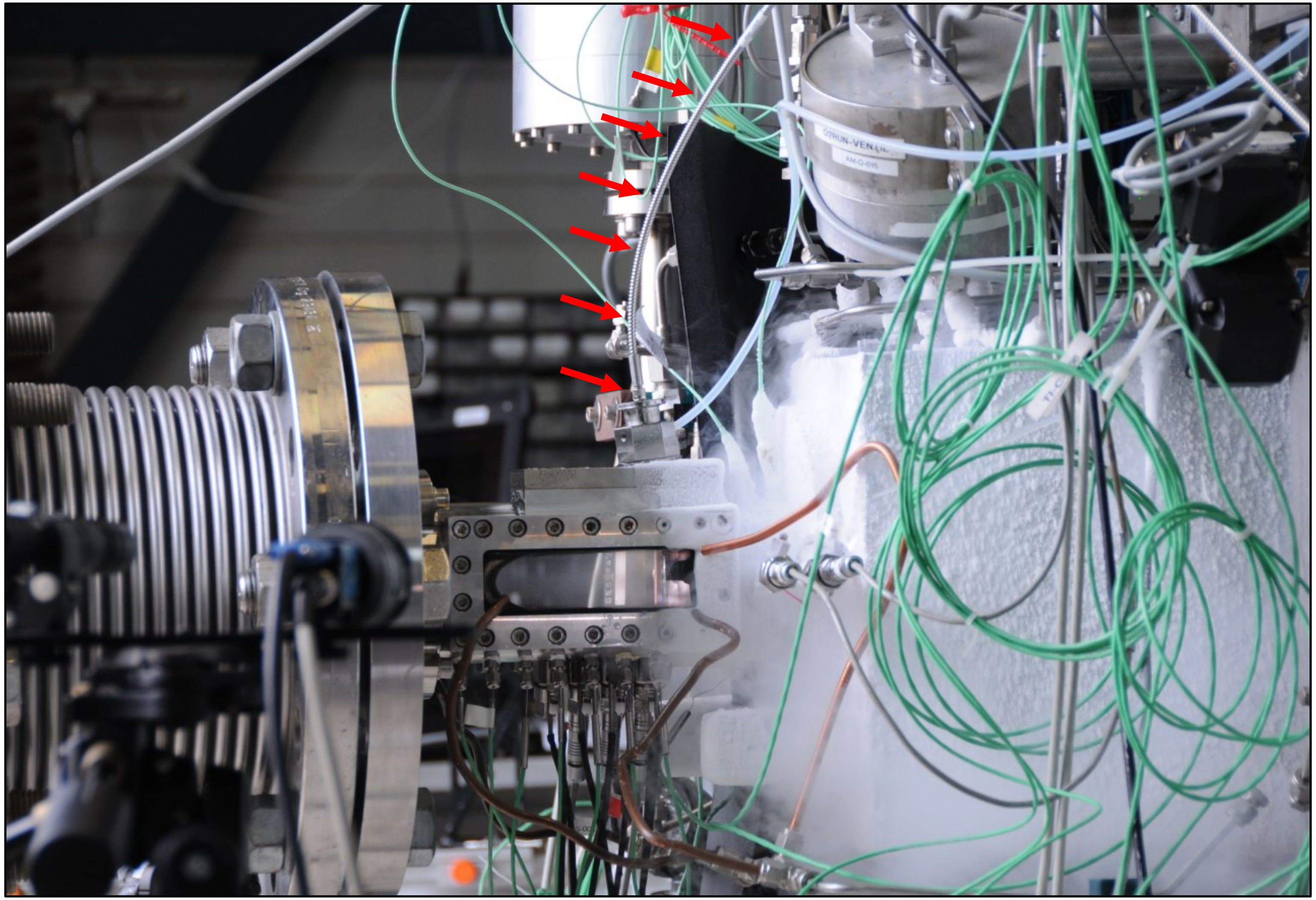

Test matrix: Summary of performed tests

configurations	number of tests	Test campaign result
cold flow checks and dry runs	11 tests	12 tests
FU1a-LPI1-600µ and FU1a-LPI1-800µ	**16 tests**	10 tests (due to 0 % ignition success at max. energy)
• 2 laser energy levels: EL 10, 09 (see Table 4)	3x2x2+4	
• 3 repetitions for each energy level		
FU1a-LPI2-600µ and FU1a-LPI2-800µ	**16 tests**	12 tests (due to 0 % ignition success at max. energy)
• 2 laser energy levels: EL 10, 09 (see Table 4)	3x2x2+4	
• 3 repetitions for each energy level		
FU1a-LAI-600µ and FU1a-LAI-800µ	**16 tests**	24 tests
• 2 laser energy levels: EL 10, 09 (see Table 4)	3x2x2+4	
• 3 repetitions for each energy level		
FU1b-LAI-600µ and FU1b-LAI-800µ	**16 tests**	15 tests
• 2 laser energy levels: EL 10, 09 (see Table 4)	3x2x2+4	
• 3 repetitions for each energy level		
FU2-LAI-600µ and FU2-LAI-800µ	**16 tests**	9 tests + 11 tests
• 2 laser energy levels: EL 10, 09 (see Table 4)	3x2x2+4	
• 3 repetitions for each energy level		
	91 tests	93 tests

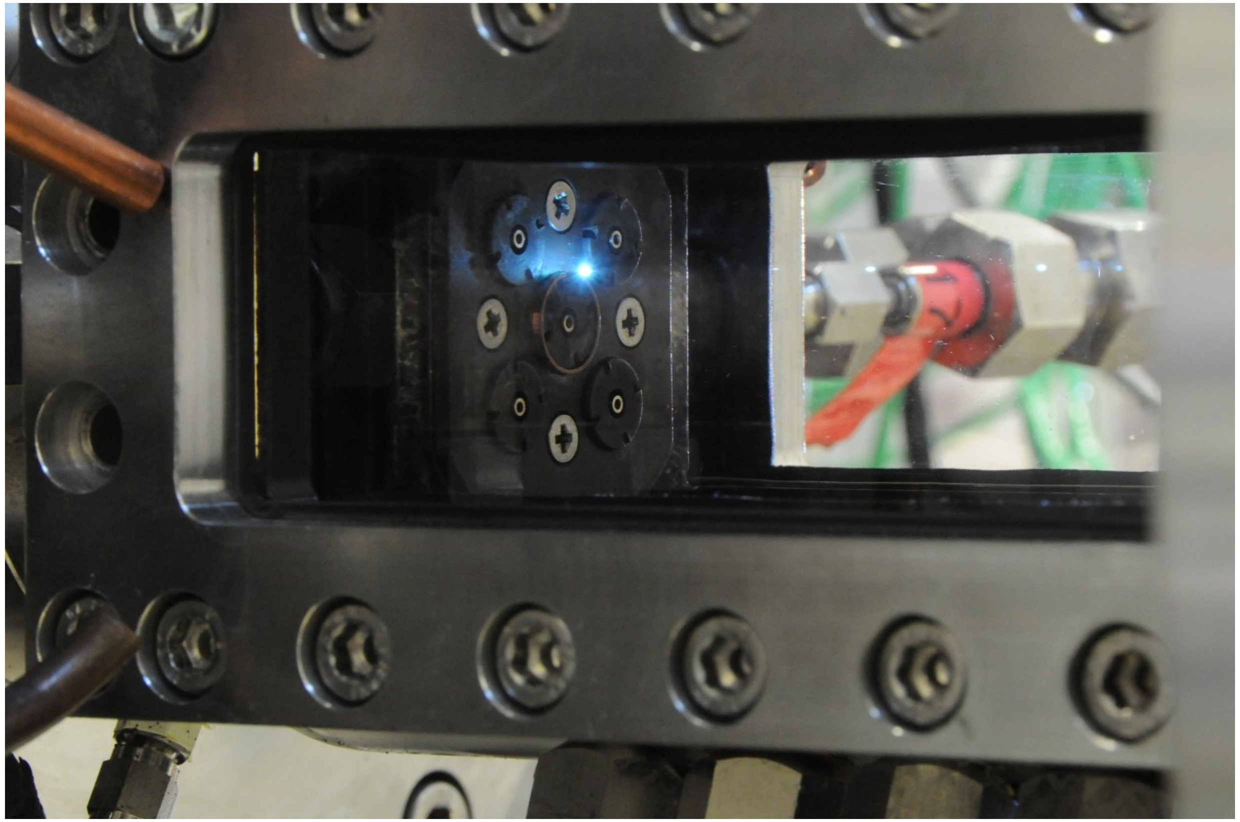
M3.1 & thruster: impressions

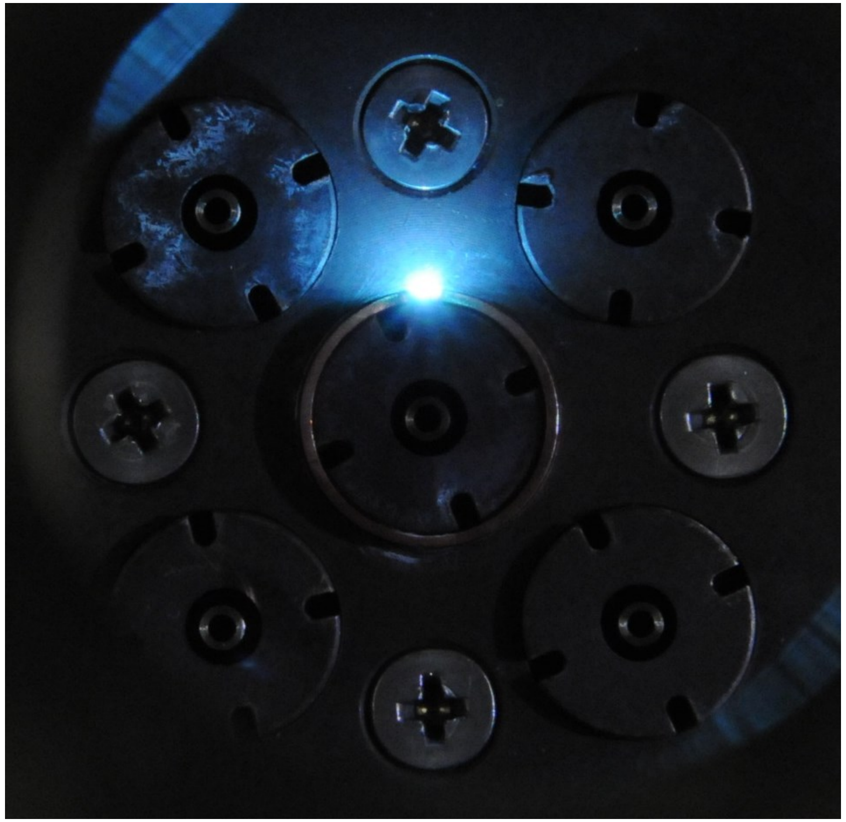




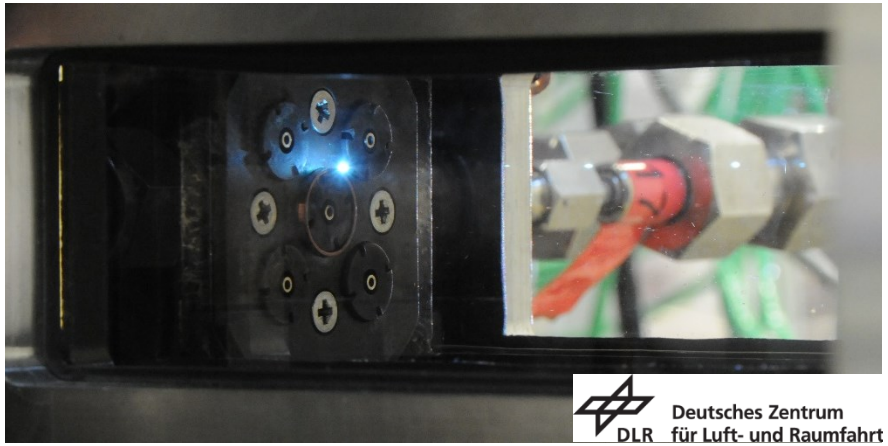


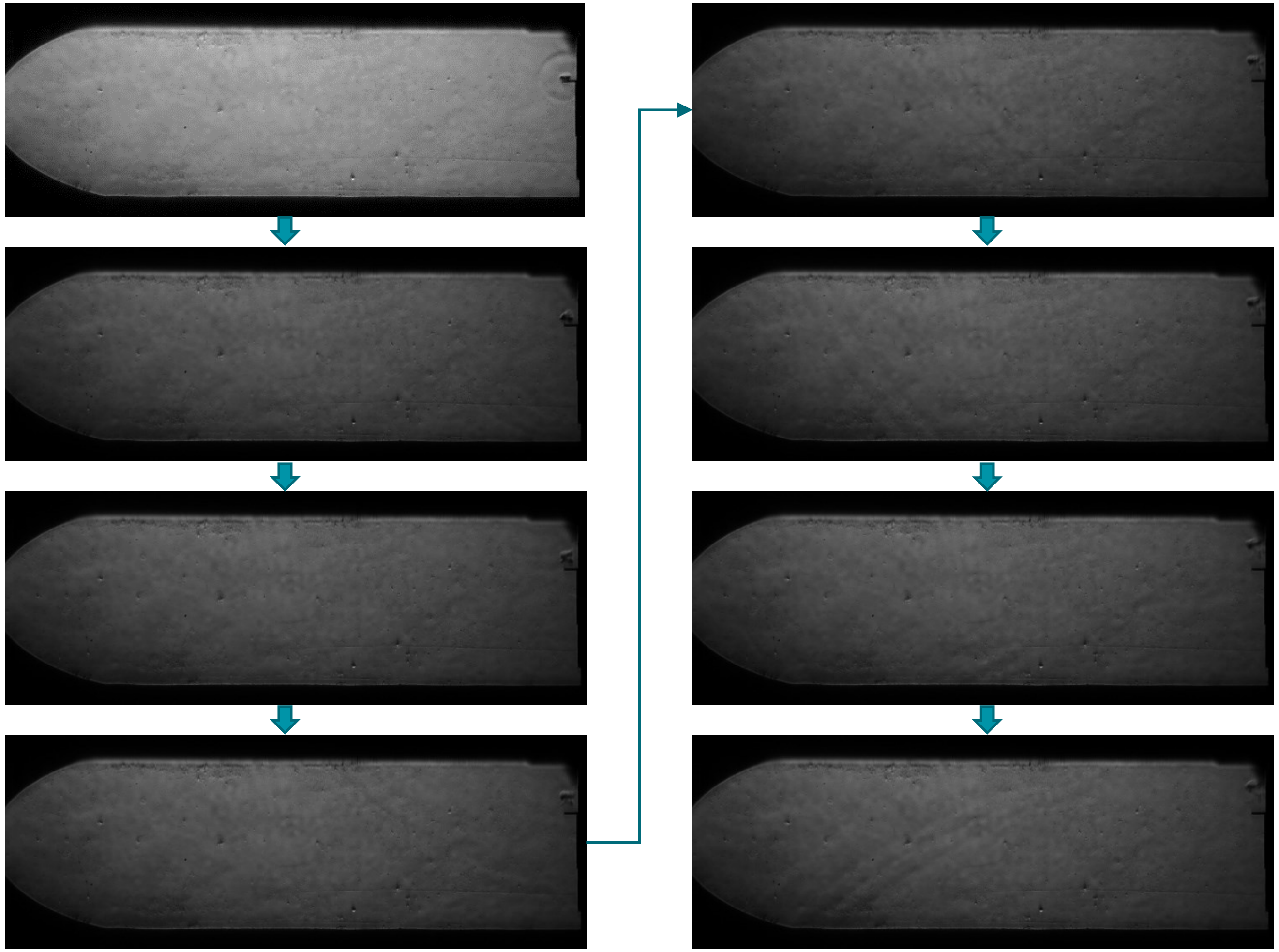
M3.1 & thruster: laser ablation (FU1b-LAI-800µ)





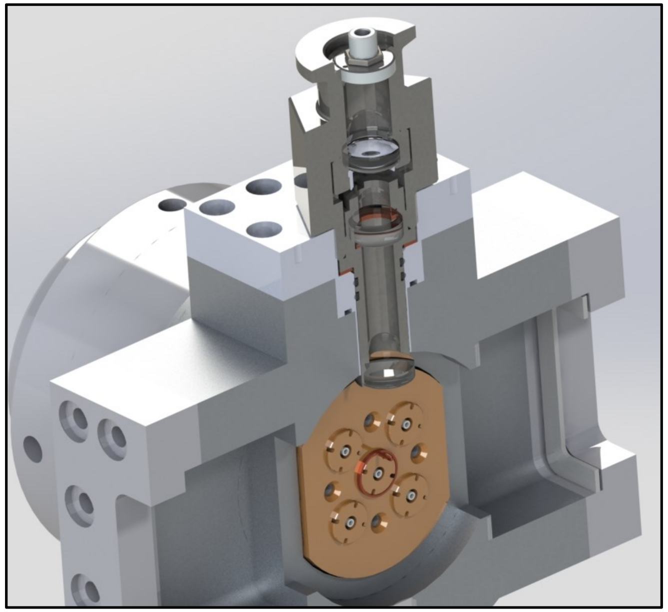
Fibre based LIS pre-tests:
Configuration FU1b-LAI-800µ, ambient air, ~ 8 mJ/pulse

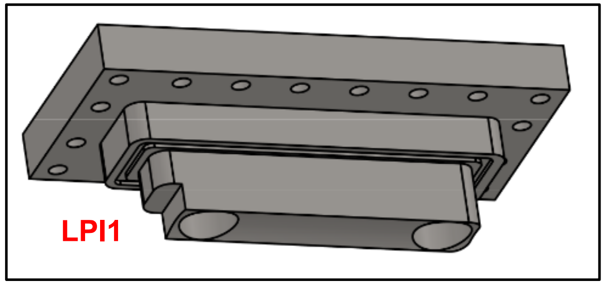


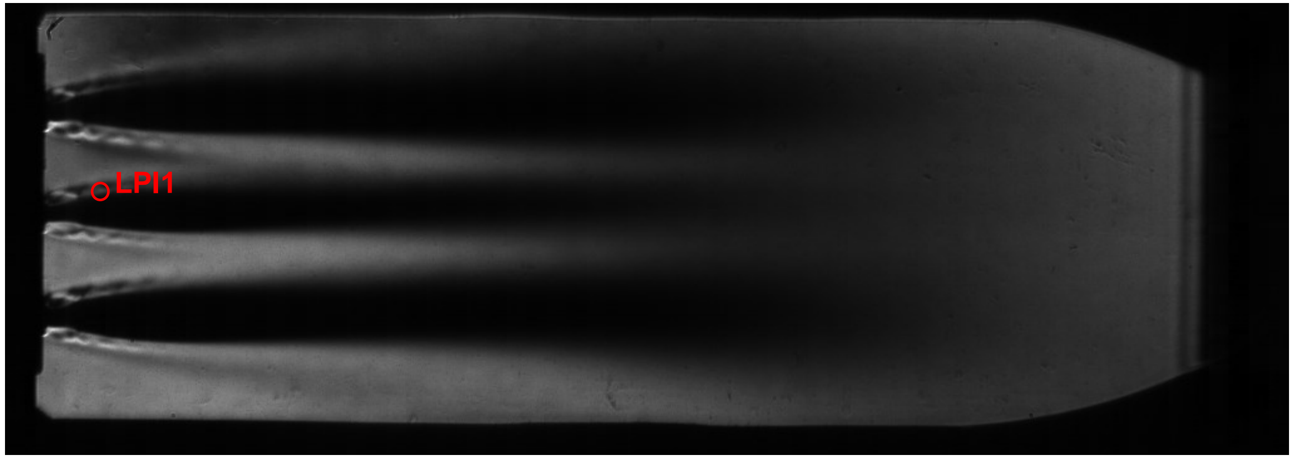


Test matrix: Hardware configurations

configuration	short description	# of configurations
FU1a-LPI1-600µ and FU1a-LPI1-800µ	• **normal optical tube** • **tube with 25mm focal length** • **fibres:** ○ **600µ** ○ **800µ**	**2**
FU1a-LPI2-600µ and FU1a-LPI2-800µ	• normal optical tube • tube with 25mm focal length • fibres: ○ 600µ ○ 800µ	2
FU1a-LAI-600µ and FU1a-LAI-800µ	• normal optical tube • tube with 25 mm focal length • fibres ○ 600µ ○ 800µ	2
FU1b-LAI-600µ and FU1b-LAI-800µ	• tilted optical tube for LAI • tube with 25 mm focal length • fibres ○ 600µ ○ 800µ	2
FU2-LAI-600µ and FU2-LAI-800µ	• direct LAI without focusing at the injector exit • fibres ○ 600µ ○ 800µ	2
	Sum of configurations:	10

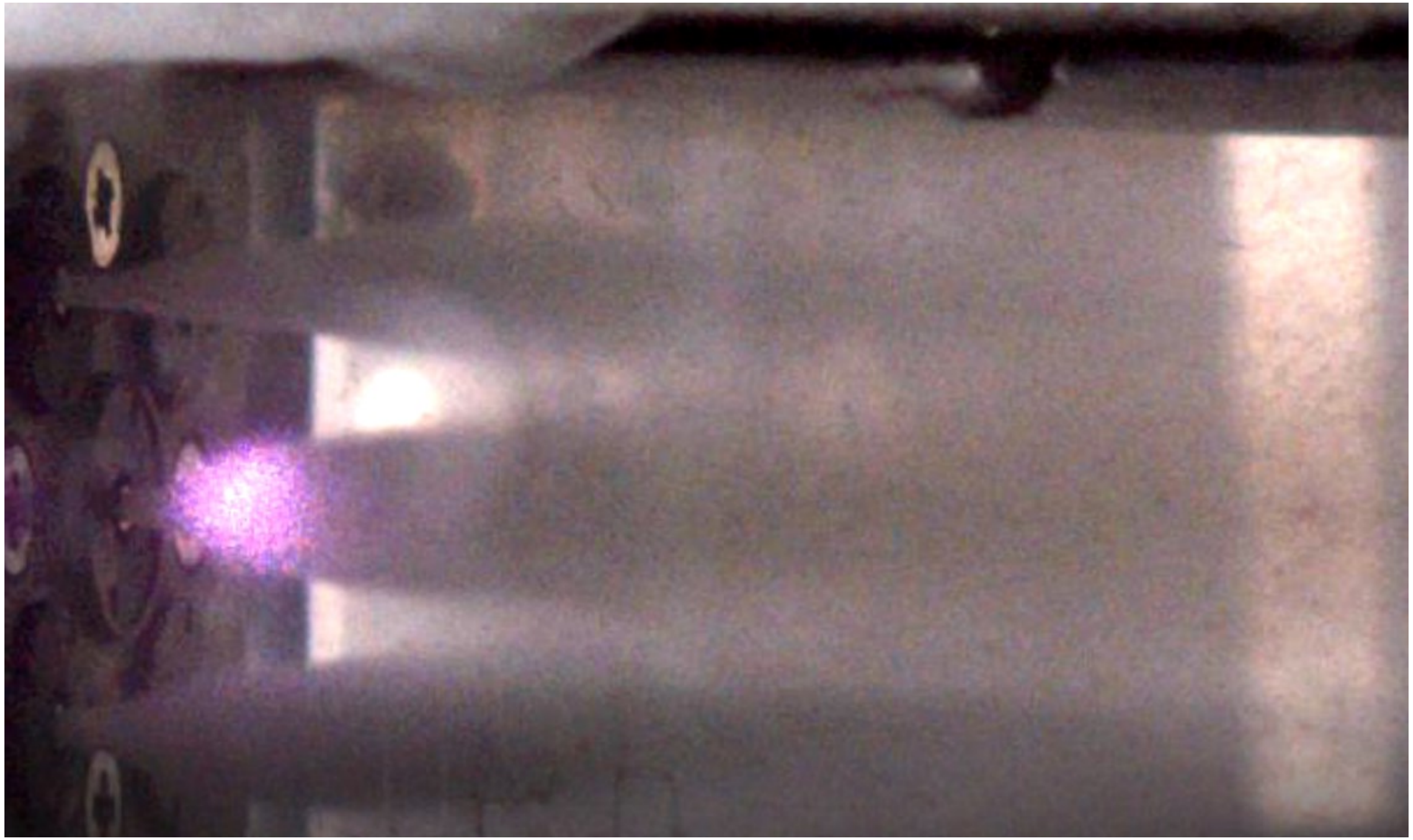






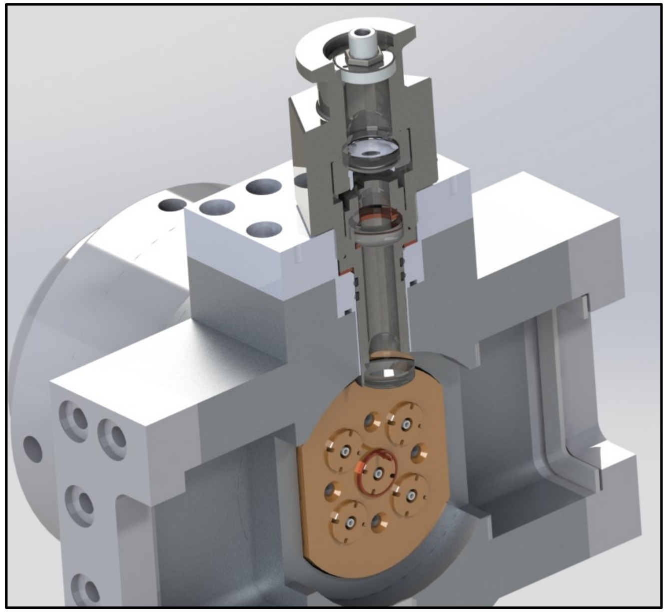
Minimum pulse energy: no ignition achieved

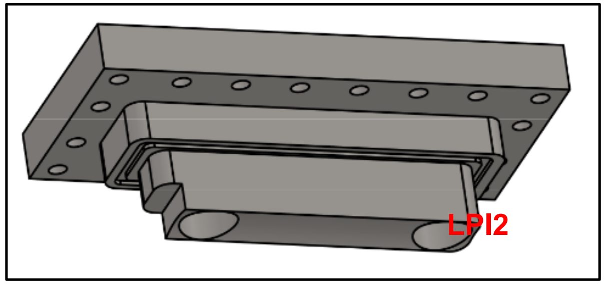
FU1a-LPI1: Scattered laser pulse, no breakdown

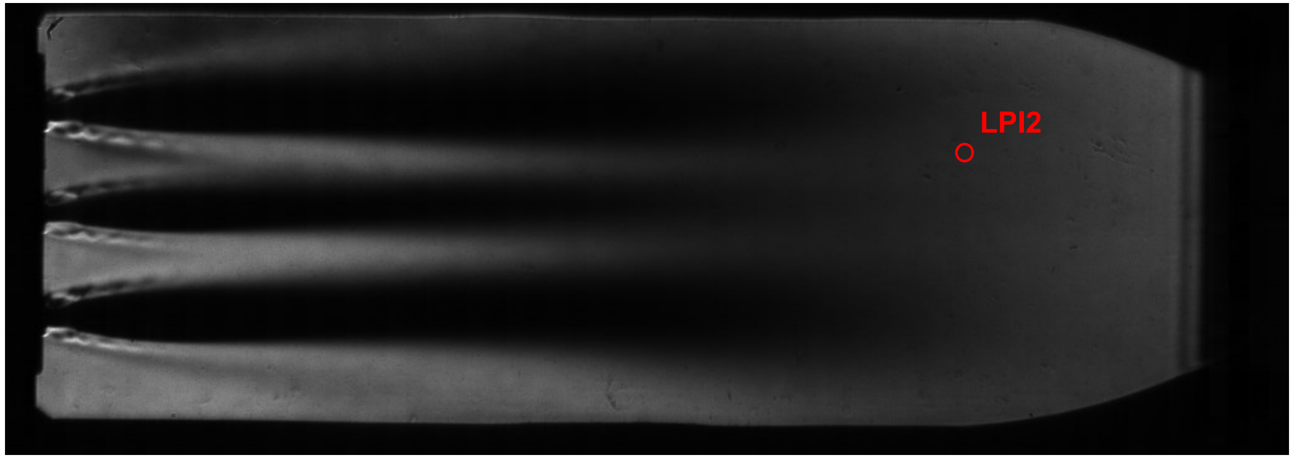


Test matrix: Hardware configurations

configuration	short description	# of configurations
FU1a-LPI1-600µ and FU1a-LPI1-800µ	• normal optical tube • tube with 25mm focal length • fibres: ○ 600µ ○ 800µ	2
FU1a-LPI2-600µ and FU1a-LPI2-800µ	**• normal optical tube • tube with 25mm focal length • fibres: ○ 600µ ○ 800µ**	**2**
FU1a-LAI-600µ and FU1a-LAI-800µ	• normal optical tube • tube with 25 mm focal length • fibres ○ 600µ ○ 800µ	2
FU1b-LAI-600µ and FU1b-LAI-800µ	• tilted optical tube for LAI • tube with 25 mm focal length • fibres ○ 600µ ○ 800µ	2
FU2-LAI-600µ and FU2-LAI-800µ	• direct LAI without focusing at the injector exit • fibres ○ 600µ ○ 800µ	2
	Sum of configurations:	10



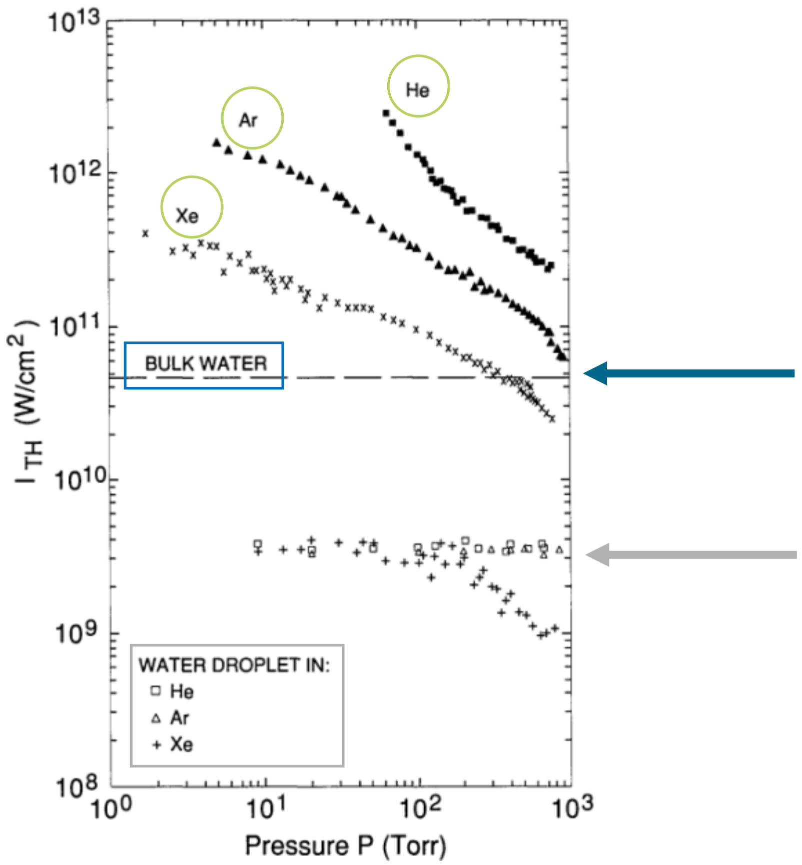




Minimum pulse energy: no ignition achieved

FU1a-LPI2: Scattered laser pulse, no breakdown

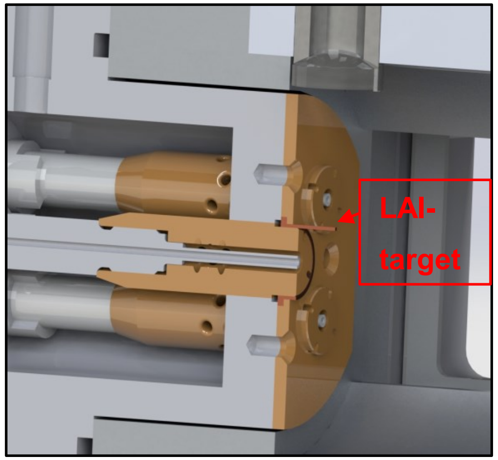
Why LPI could have worked and why it probably did not…



- CHÝLEK et al.: Effect of spherical particles on laser-induced breakdown of gases. Appl. Opt. 26 (1987), No. 5, S. 760–762
- Probably, the **limited maximum intensity** at the focal point and **scattering of the pulse** by the droplets led to no breakdown

Test matrix: Hardware configurations

configuration	short description	# of configurations
FU1a-LPI1-600μ and FU1a-LPI1-800μ	• normal optical tube • tube with 25mm focal length • fibres: ○ 600μ ○ 800μ	2
FU1a-LPI2-600μ and FU1a-LPI2-800μ	• normal optical tube • tube with 25mm focal length • fibres: ○ 600μ ○ 800μ	2
FU1a-LAI-600μ **and** **FU1a-LAI-800μ**	• **normal optical tube** • **tube with 25 mm focal length** • **fibres** ○ **600μ** ○ **800μ**	**2**
FU1b-LAI-600μ and FU1b-LAI-800μ	• tilted optical tube for LAI • tube with 25 mm focal length • fibres ○ 600μ ○ 800μ	2
FU2-LAI-600μ and FU2-LAI-800μ	• direct LAI without focusing at the injector exit • fibres ○ 600μ ○ 800μ	2
	Sum of configurations:	10



Minimum pulse energy:

- 6,5 mJ (600 μm)
- 3,6 mJ (800 μm)

Test matrix: Hardware configurations

configuration	short description	# of configurations

FU1a-LPI1-600µ and FU1a-LPI1-800µ	• normal optical tube
	• tube with 25mm focal length
	• fibres:
	  ○ 600µ
	  ○ 800µ
		2

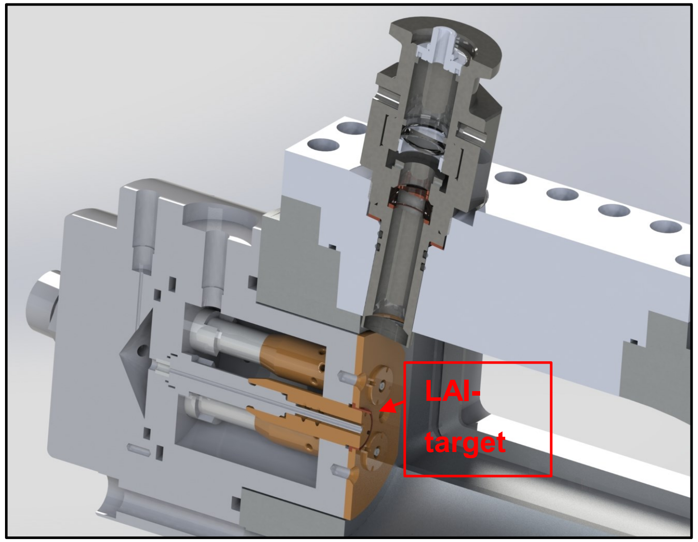
FU1a-LPI2-600µ and FU1a-LPI2-800µ	• normal optical tube
	• tube with 25mm focal length
	• fibres:
	  ○ 600µ
	  ○ 800µ
		2

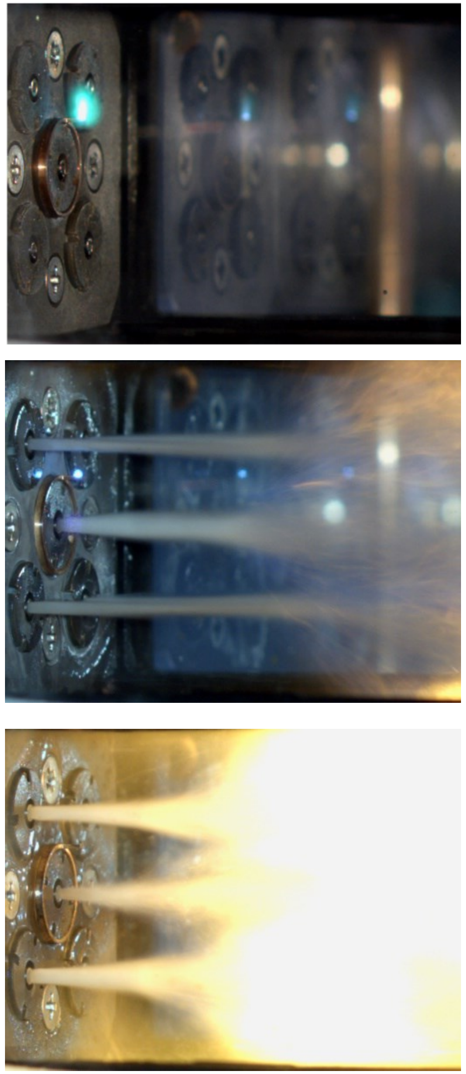
FU1a-LAI-600µ and FU1a-LAI-800µ	• normal optical tube
	• tube with 25 mm focal length
	• fibres
	  ○ 600µ
	  ○ 800µ
		2

FU1b-LAI-600µ and FU1b-LAI-800µ	**• tilted optical tube for LAI
	• tube with 25 mm focal length
	• fibres
	  ○ 600µ
	  ○ 800µ**
		2

FU2-LAI-600µ and FU2-LAI-800µ	• direct LAI without focusing at the injector exit
	• fibres
	  ○ 600µ
	  ○ 800µ
		2

	Sum of configurations:	10

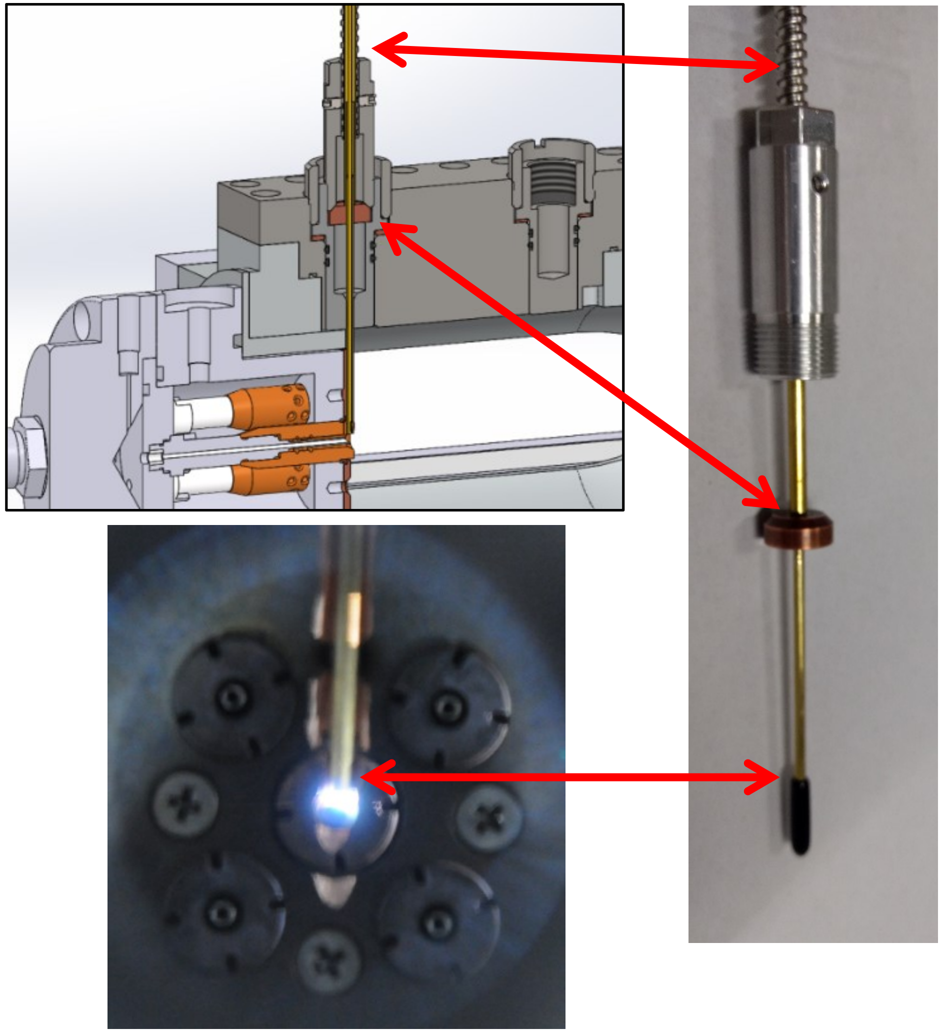




Minimum pulse energy:
- 2,9 mJ (600 µm)
- 4,9 mJ (800 µm)

Test matrix: Hardware configurations

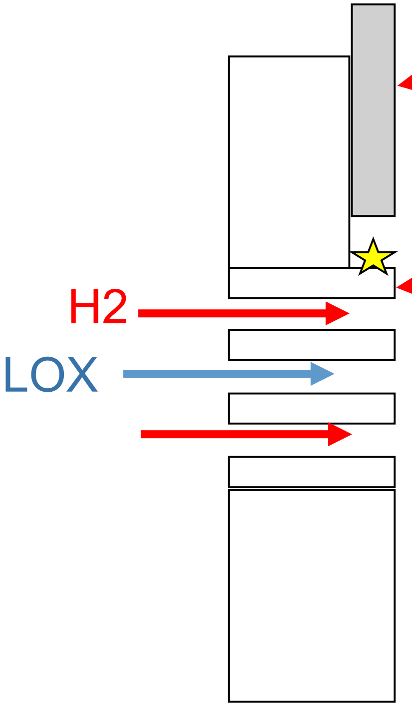
configuration	short description	# of configurations
FU1a-LPI1-600µ and FU1a-LPI1-800µ	• normal optical tube • tube with 25mm focal length • fibres: ○ 600µ ○ 800µ	2
FU1a-LPI2-600µ and FU1a-LPI2-800µ	• normal optical tube • tube with 25mm focal length • fibres: ○ 600µ ○ 800µ	2
FU1a-LAI-600µ and FU1a-LAI-800µ	• normal optical tube • tube with 25 mm focal length • fibres ○ 600µ ○ 800µ	2
FU1b-LAI-600µ and FU1b-LAI-800µ	• tilted optical tube for LAI • tube with 25 mm focal length • fibres ○ 600µ ○ 800µ	2
FU2-LAI-600µ **and** **FU2-LAI-800µ**	• **direct LAI without focusing at the injector exit** • **fibres** ○ **600µ** ○ **800µ**	**2**
	Sum of configurations:	10

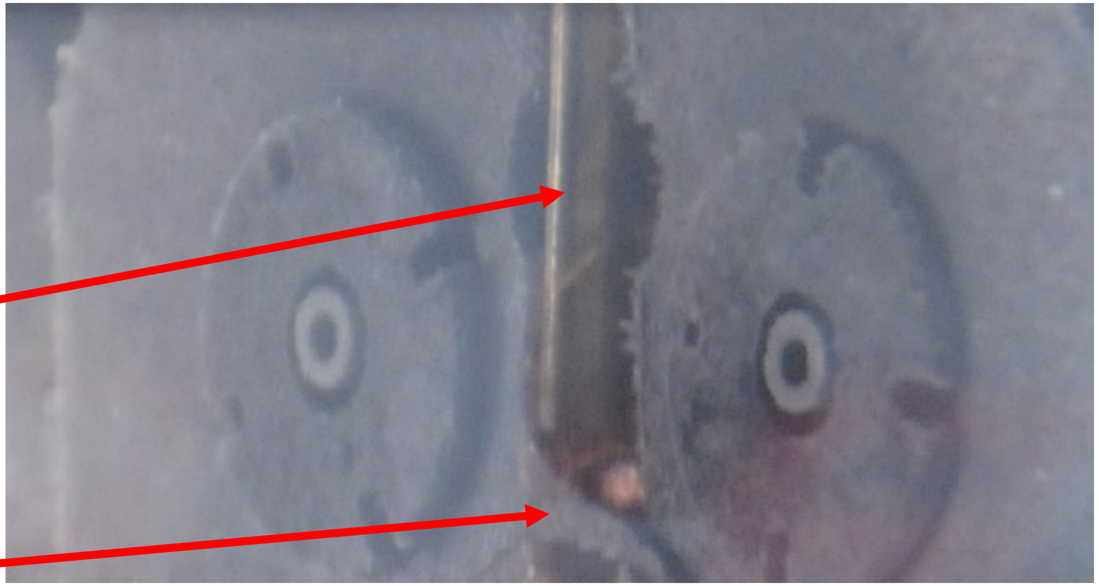


Minimum pulse energy: no ignition achieved

Additional configuration tested: direct fibre, laser ablation ignition

- direct fibre
- laser ablation ignition configuration
- no refocussing
- above central injector





Minimum pulse energy:

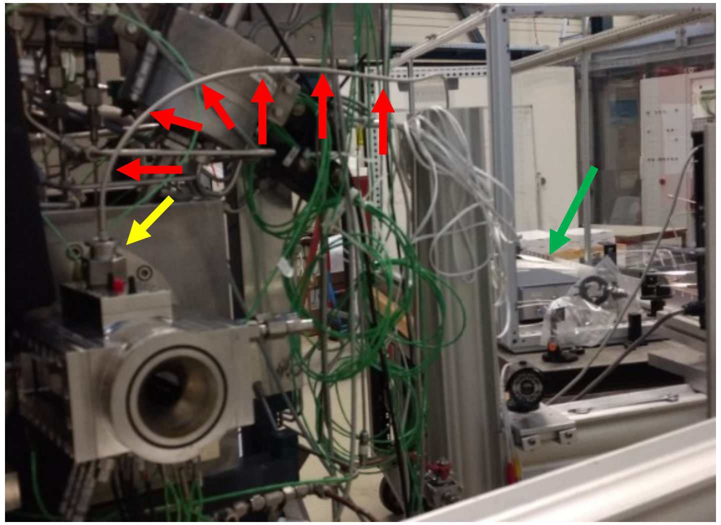
- 4,9 mJ (800 µm)
- 600 µm not tested

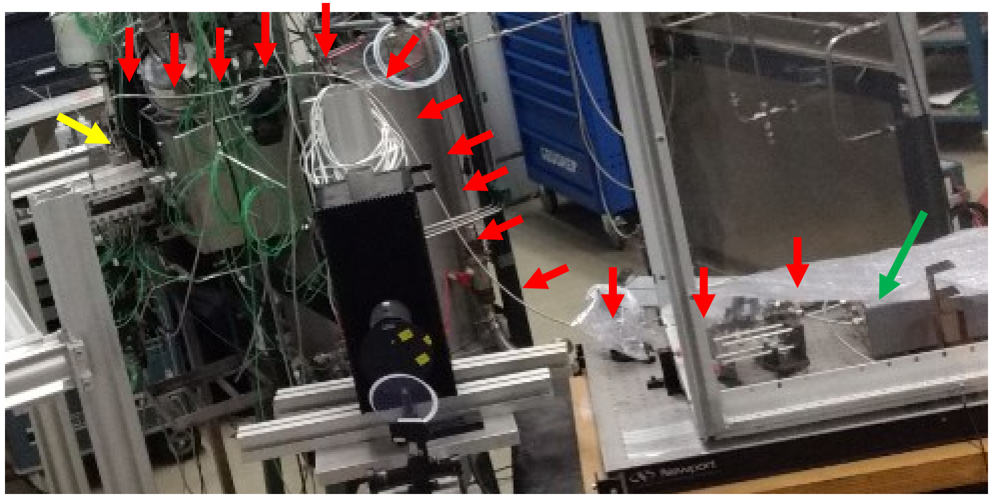
Test campaign 1 result overview

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

Hardware status after test campaign 1

hardware	status	comment
laser source	Ready for use	-
multiplexer	Ready for use	-
fibres	laser ablation at fibre coupler unit	due to misalignment after transport, not critical for functionality
lens tubes	two lens tubes destroyed	first tube: lens destroyed second tube: holder ring disconnected from tube
target elements	no damages except ablation effects	-
chamber adapters	Ready for use	-
thruster & injector head	Ready for use	-



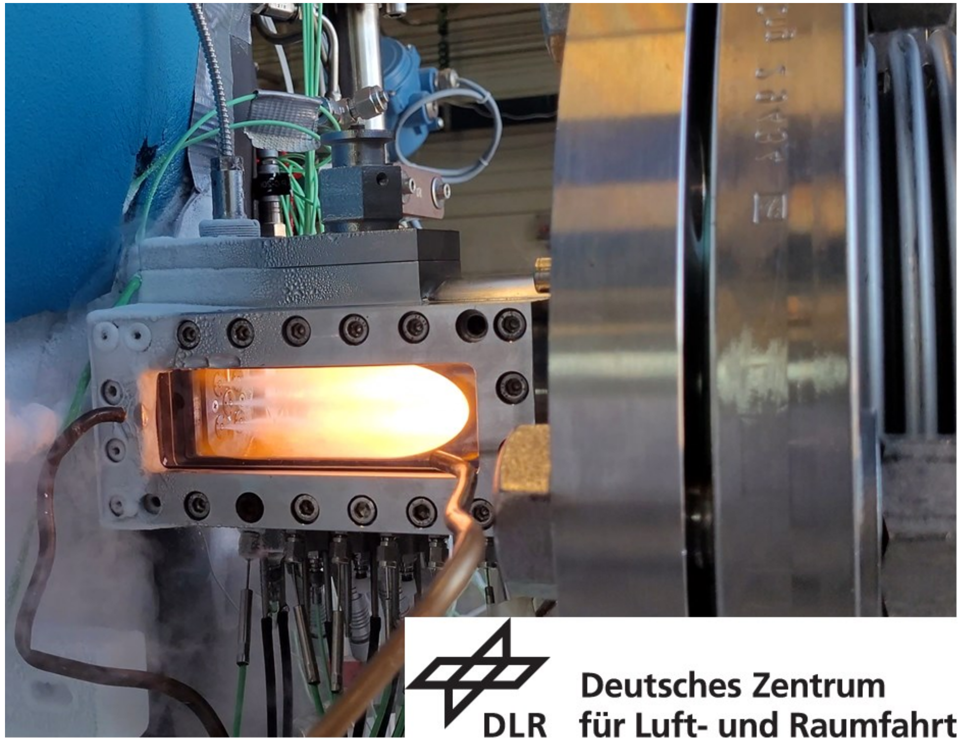


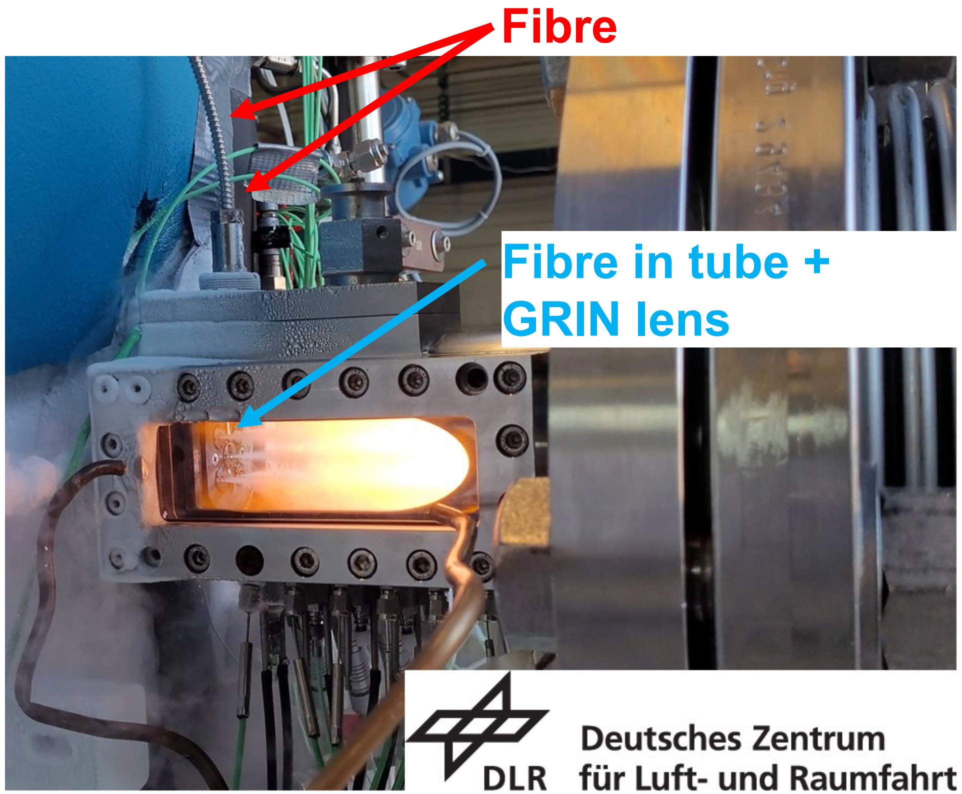
Test campaign result overview

2. Campaign 2: CCN1 activity

CCN1: Test campaign result overview

- Picture of a hot fire test during CCN1 test day 4 (direct fibre ignition with GRIN lens)



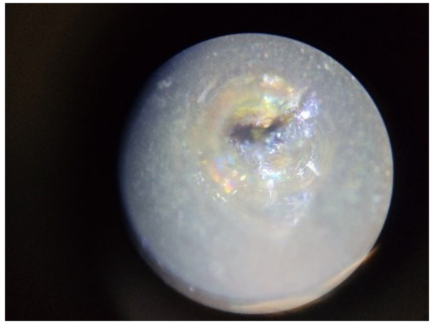


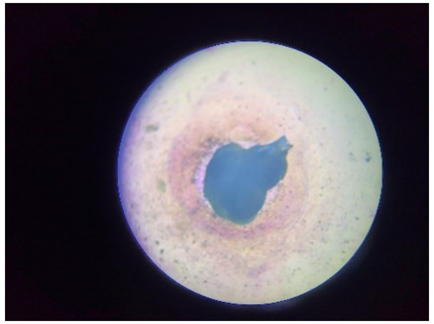
CCN1: Test campaign result overview

- **Test day 1 (18.05.2022)**
  - Goal: "Direct fiber ablation" with 600 μm fiber
  - Result:
    - Successful ignition: technological approach was demonstrated.
    - After some pulse energy reduction testing with the same fiber: transmitted laser pulse energy decreased significantly and ignition was no longer possible.
    - <u>The fibers continue to be the critical component of the LIS setup.</u>
- **Test Day 2 (08.06.2022)**
  - Goal:
    - "Laser plasma Ignition (LPI)" with 800 μm fiber and 600 μm fiber.
  - Result:
    - Laser plasma Ignition (LPI) with 800 μm fiber: Measured transmitted energy before and after the tests: ~7.5 mJ/pulse. **No ignition success, not even by sequence optimization and increasing of the background pressure**.
    - Laser plasma Ignition (LPI) with 600 μm fiber: **No ignition success, not even by sequence optimization and increasing of the background pressure**.

CCN1: Test campaign result overview

- **Test day 3 (22.06.2022)**
  - Goal: "Laser plasma Ignition (LPI)" with 800 µm fiber and 600 µm fiber
  - Result:
    - tests were repeated with both fibers for a modified ignition location and varied the background pressure as well as the sequencing.
    - No ignition success for LPI for this configuration & no plasma was generated
    - -> Despite all efforts we did not manage to generate a sufficiently high energy density at the focal point to ensure LPI.
- **Test day 4 (29.06.2022)**
  - Goal: "Direct fiber ablation" with 400 µm fiber.
  - Result: Successful ignition (1x). Afterwards, no more ignition under varying boundary conditions. The assumption that the fiber/grin lens was destroyed during the tests was confirmed after testing (see pictures showing the exit plane of the GRIN lens).





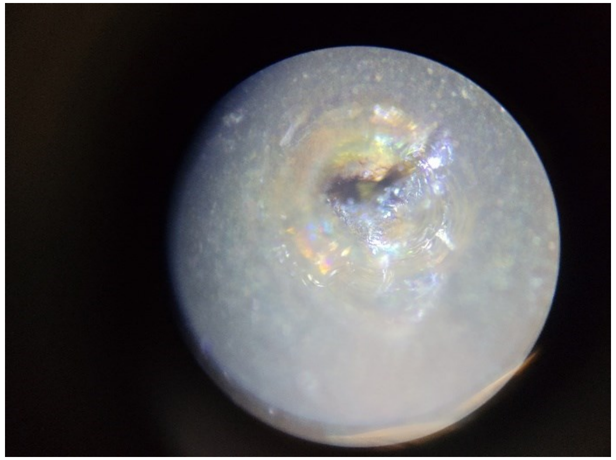
CCN1: Test campaign result overview

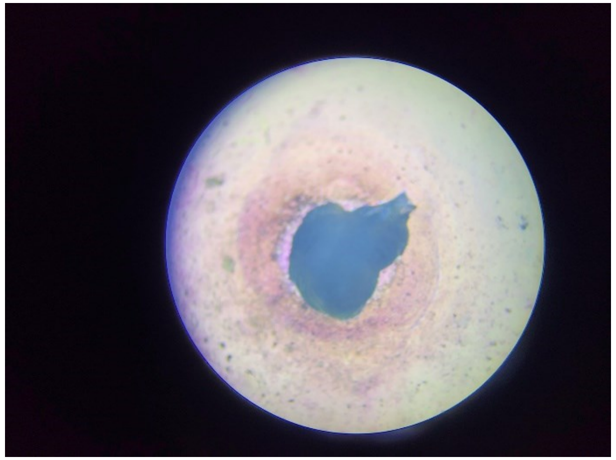
- Overall test results:
  1) LPI: not successful ignition due to insufficient energy density reached
  2) Direct fibre concept: successful ignition, but energy density too high for GRIN lens (COTS element)

		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 vacuum 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

Hardware status after test campaign 2

hardware	status
laser source	Ready for use
multiplexer	Ready for use
fibres	GRIN lens destroyed
lens tubes	one lens tube destroyed
target elements	no damages except ablation effects
chamber adapters	Ready for use
thruster & injector head	Ready for use





Test campaign goals and results

Objective		Category of objective	Success Criteria	Test campaign result
1	**To demonstrate the functionality of the LIS at a breadboard thruster at the M3.1 test bench**	**Primary**	• **Optical verification via schlieren diagnostics of plasma generation via ablation in air at ambient conditions.**	**achieved**
2	**To prove the reliability of the LIS during the test campaign**	**Primary**	• **Optical inspection of the LIS after the test campaign and its functionality by reliable generation of plasma via ablation**	• **LAI: achieved** • **LPI: not achieved**
3	**To demonstrate ignition for the fibre-based LIS for the test conditions of the last ESA TDE on laser ignition technology**	**Primary**	• **Detect combustion chamber pressure increase above 2 bar and the flame development via OH*-diagnostics**	**achieved**
4	To demonstrate ignition with **reduced laser pulse** energy for the fibre-based LIS	Secondary	• Detect combustion chamber pressure increase above 2 bar and the flame development via OH*-diagnostics for reduced laser pulse energy	• **LAI: achieved** • **LPI: not achieved**
5	To demonstrate ignition under **varying sequencing** conditions, for at least two different oxygen injection relative to start of fuel injection	Secondary	• Detect combustion chamber pressure increase above 2 bar and the flame development via OH*-diagnostics	Not achieved for all configurations

Primary objective	The test campaign focuses on 100% fulfillment of primary objectives.
Secondary objective	DLR tries to reach the secondary objectives. In case of problems primary objectives are given priority and the secondary objectives are skipped.

MULTIPLEXED LIS - ECONOMIC CONSIDERATIONS

Kaess, 13.12.2022

ASSUMPTIONS FOR ECONOMICAL ASSESSMENT

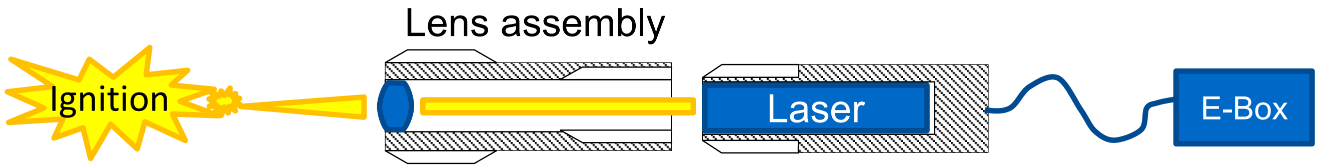
- **Component Prices of LIS and competing systems are subject to uncertainties due to ongoing developments**

- **Handing costs and mass savings are not quantified in the numbers**

Component	Price	Comment
E-box	10.000€	Estimated price after industrialization
Laser head	35.000€	Present SAL Price
Lens assembly ablative	500€	Estimation (reduced due to simplified optics for abl.)
Lens assembly plasma	1.000€	Estimation
Splitter/Multiplexer	5.000€	Estimation
Fibre ablative (per meter)	100€	Estimation
Fibre plasma (per meter)	200€	Estimation (doubled due to higher requirements for plasma fibers)
Cable (per meter)	100€	Estimation
Torch system	100.000€	As is IGFS
Low Cost Torch	35.000€	Low cost IGFS
Pyro starter	17.000€	Internal estimation

BASELINE

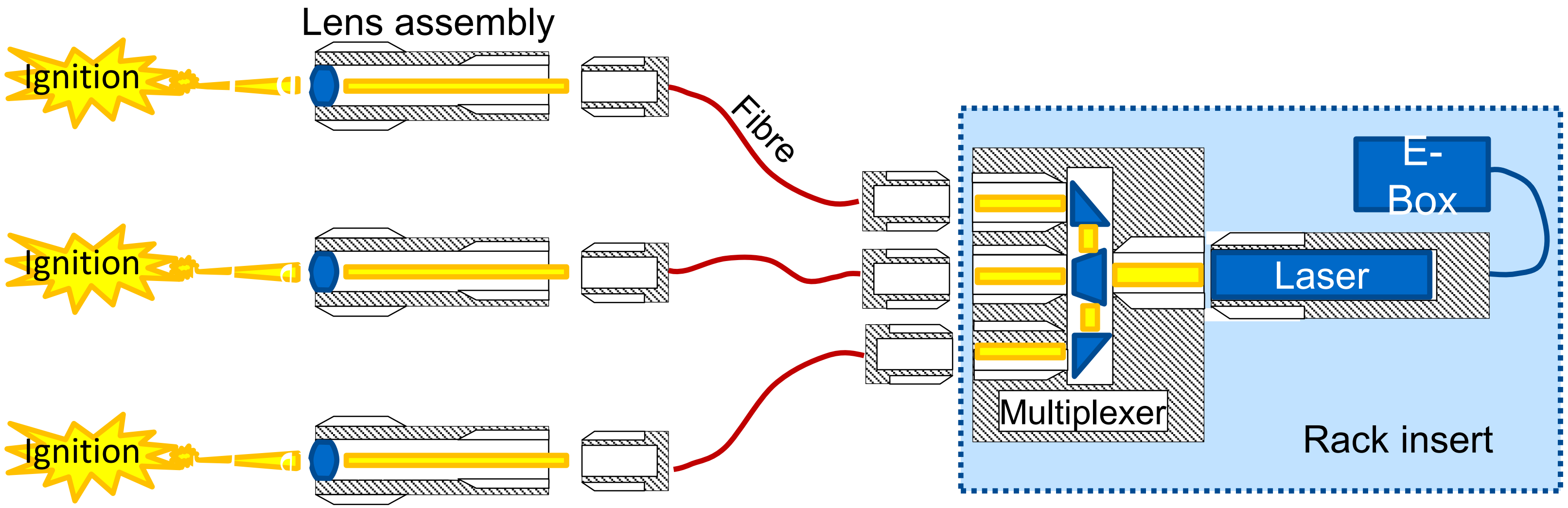
Single Laser



- **Proven in various tests for H2 and CH4**
- **Price per item: ~46.000€ / Target**
- **Very lightweight, but economically not fully convincing for single application**

CONCEPT: MULTIPLEXED LASER

Multiple Beams

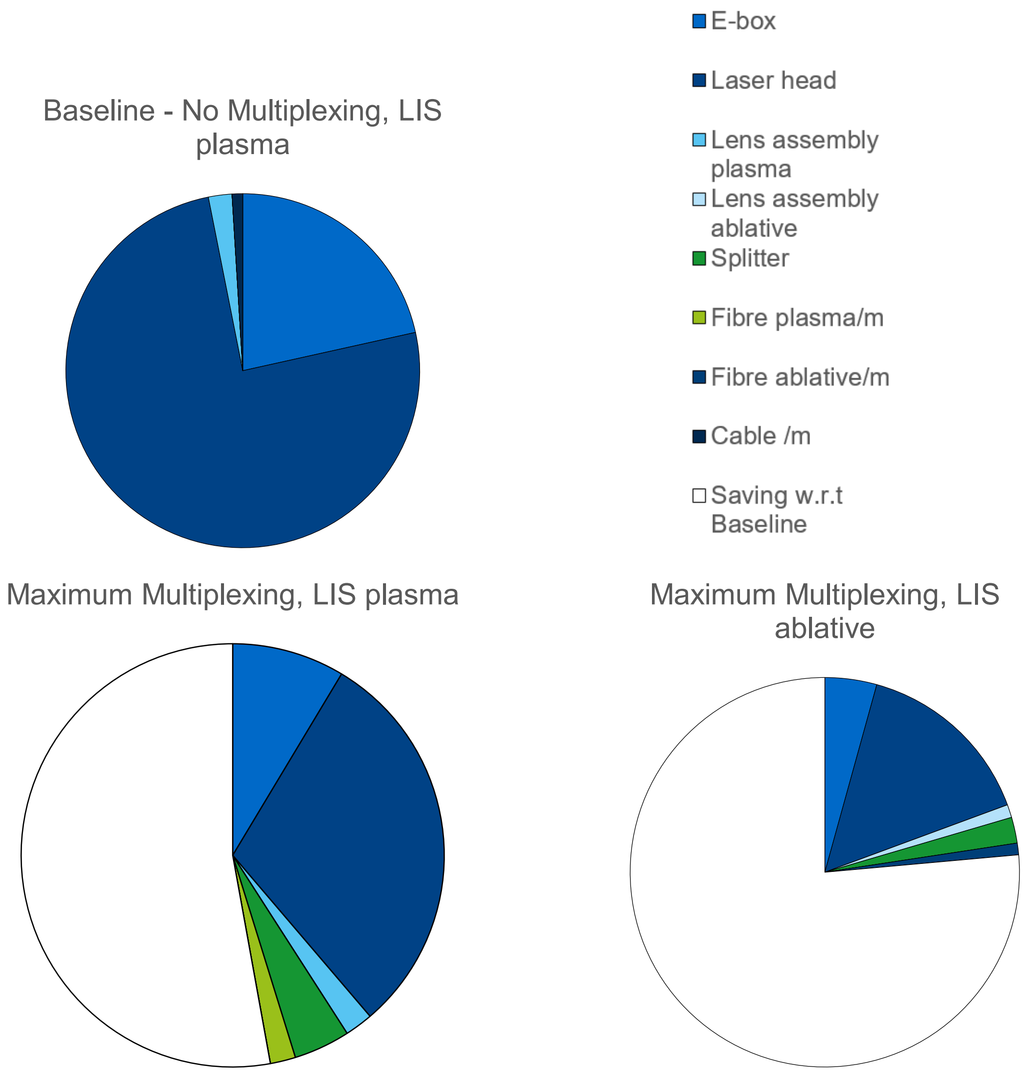


- **Uses expensive components for multiple targets**
- **Technology was on concept level and has been demonstrated on small scale in this TDE for ablative ignitions**
- **Cost depends on the number of ports that can be realized → plasma/ablative**

CASE: SPACECRAFT RCS

Multiplexing can cut the cost by factor 4

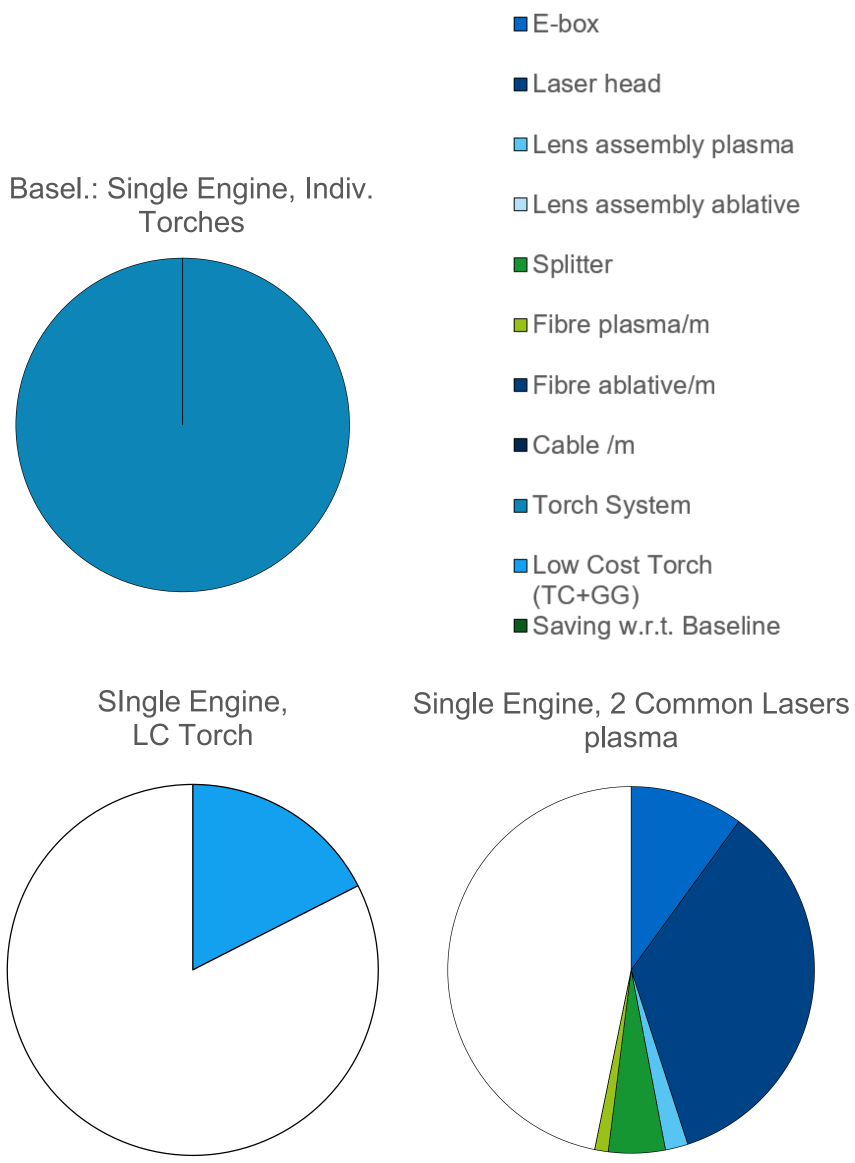
- **Most optimistic scenario for ablative with 5 targets/laser**
- **Even for plasma ignition factor 2 can be achieved**
- **Splitter and fiber costs gain significant portions of the cost**



CASE: GG CYCLE ENGINE

For comparison, a cost baseline of 2 torches a 100k€ is assumed

- **Optimized torch (LC torch) can save significant costs (but with less redundancy)**
- **Redundant LIS could be be at ca 50% of the cost of the baseline torch**
- **Non redundant LIS would be at 25% - half of above**
- **➔ Serving 2 targets non-redundantly is coming in the price region of a low cost torch.**
- **Clustering brings further advantages**
- **Mass advantages + Handling is not quantified here!**



CONCLUSION

- **Multiplexing brings significant cost advantages**
- The advantages **scale directly** with the **number of targets/laser**
- **Ablative configurations** have an advantage compared to plasma systems, as they need considerably **less energy for generating sparks**
- **Plasma configurations** are more limited in their cost reduction potential due to the higher pulse power required - but based on AG test experience **plasma breakdown is favorable**
- **Mass and Handling costs** have not been included but pose **further factors in favor of LIS**

→ **Need for further basic research on**
maximizing power per fiber and
minimizing power required for plasma breakdown

Summary of the ESA TDE: Optical fibre-based ignition technology for launcher RCS

- development of an **optical fibre-based ignition technology**
- **multiplexing with 2 outlets**
- maximum energy transported of ca. 10 mJ via fibres
- 800 µm fibres proved to be reliable
- laser ablative ignition (LAI) can be achieved
- laser plasma ignition (LPI) was not reached
- prototype level of hardware development: TRL ~ 3-4

Outlook

1. further development need is given in terms of TRL increase
   - for the multiplexer –> robustness
   - for the fibres & coupling into the fibres -> lifetime of the fibres

2. for LPI
   - maximizing power per fiber
   - minimizing power required for plasma breakdown

3. increase of numbers of multiplexer outputs needed to increase economic benefits

Thank you for your attention!