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TITLE

Technical specification of a optical diagnostic measurement system for the application of PLIF and HSC techniques to combustion study

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| APPROVED | Marini Marco | DATE | 21/05/2021 |
| AUTHORIZED | Salvatore Vito | DATE | 21/05/2021 |

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TITLE:

Technical specification of a optical diagnostic measurement system for the application of PLIF and HSC techniques to combustion study

ABSTRACT:

This document specifies components and instrumentation requirements of a PLIF and HSC measurement system. The system will perform experimental measurements within the HYPROB NEW project (16-COM-0020), for visualization of chemical species concentration, location of flame front and flux generated by combustion inside the test plant.

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Aerodinamica e Ghiaccio; Misura Meccaniche e Controlli non Distruttivi

# INDEX

# 0. INTRODUCTION

## *0.1. AIM OF THE DOCUMENT*

This document specifies components and instrumentation requirements of a PLIF and HSC measurement system.

The system will perform experimental measurements within the HYPROB NEW project (16-COM-0020), for visualization of chemical species concentration, location of flame front and flux generated by combustion inside the test plant.

This document specifies:

- Requirements for supply
- General requirements for the equipment
- Minimum requirements for the software
- User interface
- Documentation requirements
- EMC Requirements
- How to present the offer
- Testing and acceptance criteria

## *0.2. Applicability*

This document applies to the HYPROB NEW project - Modeling and Diagnostics (16-COM-0020).

## *0.3. APPLICABLE DOCUMENTS*

[1] CIRA "General conditions for CIRA supply contracts" CIRA-CF-07-0782

## *0.4. REFERENCE DOCUMENTS*

[1] HYPROB Program - Technical-Programmatic feasibility analysis and Industrial Development Plan - CIRA-CF-10-1426
[2] Feasibility study of the HYPROB plant - CIRA-GS-02-332 - 2002
[3] HYPROB propulsion laboratory (CCS Workshop of 09/17/2010)
[4] CIRA-CF-10-0953 - 2010
[5] Standard and advanced optical diagnostic preliminary design HPRB-0027 / CIRA-CF-11-0520 Rev. 2
[6] Proposal to update the HYPROB project to 31 December 2018 CIRA-CF-16-0766 Rev.1


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### 0.5. ACRONYMS

| | |
|---|---|
| CIRA | Italian Aerospace Research Center |
| CH | CH Radical |
| PLIF | Planar-Laser Induced Fluorescence |
| HSC | High Speed Camera |
| HW | Hardware |
| NIR | Near Infrared |
| OH | OH Radical |
| SW | Software |
| PC | Personal Computer |
| UV | Ultraviolet |
| VIS | Visible |
| WS | Workstation |

### 0.6. NOTES FOR REVISION

This document is at "1" state of revision.

# 1. OBJECT OF SUPPLY

### 1.1. Measurement techniques

In order to perform the analysis of physical phenomena inside combustion chamber, the investigation techniques that CIRA plan to adopt include Planar Laser Induced Fluorescence (PLIF) as well as acquisition of high-frequency images using High Speed Camera (HSC); both techniques rely on non-intrusive optical methods. They are able to acquire information on mixing processes during combustion in turbulent reagent flow.

The instrumentation supply consists in two packages including hardware and software to perform both HSC and PLIF measurements within the combustion chamber of the HYPROB plant. Since the components of the systems are highly specialized and strictly integrated, CIRA will acquire by the same supplier through a single evaluation procedure both system. Moreover, there will be advantage in this procedure in order to evaluate the most convenient solution for CIRA both from an economic and a functional point of view.

The capacity to integrate, by optional add-on, RAMAN measurement techniques in order to evaluate also temperature and concentrations of the species, as well as PIV, for flow structure and speeds visualization inside the combustion chamber, with original system by adding HW / SW modules to extend the capacity of the system is required. The option to purchase the aforementioned extensions will be positively evaluated in the offer evaluation.


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### 1.1.1. High-Speed Camera (HSC) Imaging

HSC imaging is a high-speed flow visualization technique that consists in placing a video camera, capable of continuously acquiring frames at a frequency of several tens or hundreds of kHz (depending on the resolution chosen for the frame) at 90 degree with the flow. These video cameras normally operate in the visible (VIS) frequency range.

The aim of this technique is to visualize the flow and study its instabilities, turbulences and characteristic frequencies, analyzing the variation of spontaneous light emitted by the flow itself. The acquired frames must be post-processed using processing techniques in both time and frequency domains. Studying combustion processes, HSC Imaging generally is applied to OH and CH radicals, which represent a flame front marker.

A basic scheme of the experimental set-up is presented in Fig. 1; in Fig. 2 it is instead possible to see an example of visualization of OH radical obtained by HSC technique.

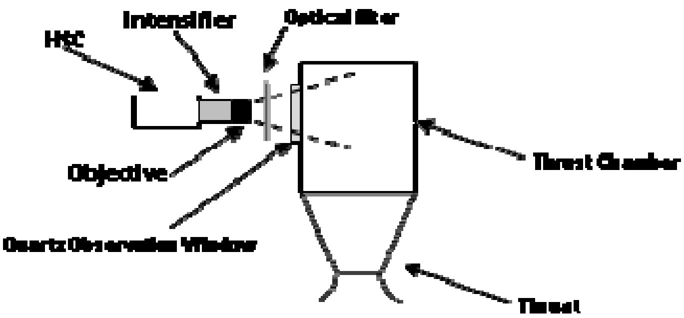


Figure 1. Schematic arrangement of experimental set-up for the HSC imaging technique

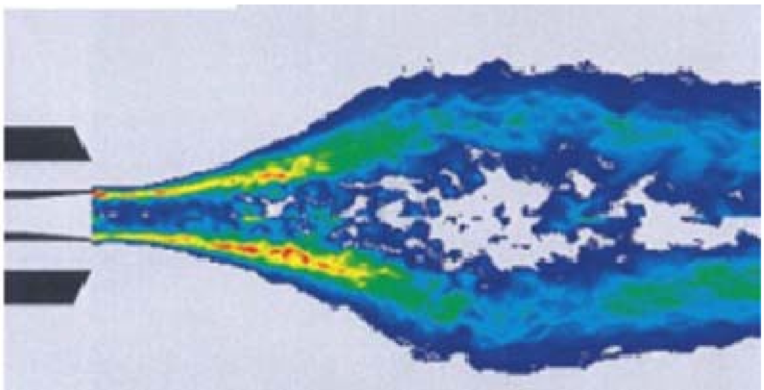

Figure 2. Example of OH imaging, LOx / GH2, 10 bar [R6]

The video camera, equipped with a photographic lens to allow focusing on region of interest of the flow, will be supported by a suitable tripod enough rigid and stable to avoid any vibrations.


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In front of the HSC an optical bandpass filter can also be mounted, in order to select the visualization of spontaneous emission at specific wavelengths, corresponding to the chemical species of interest (OH and CH).

In order to visualize chemical species characterized by emission in the ultraviolet (UV) range (such as OH radical) it is required to install an intensifier module in front of the camera. The purpose of the intensifier is to collect photons emitted in the UV and transform them into visible emission (therefore suitable to the HSC) through a phosphor screen.

### 1.1.2. Planar Laser Induced Fluorescence (PLIF)

Planar Laser Induced Fluorescence (PLIF) is a flow visualization technique well suited to the analysis of a combustion process. PLIF is mainly used in OH and CH radicals study, resulting in a flame front marker. The technique rely on the excitation of atoms / molecules towards states with higher energy by means of absorption of a thin sheet of laser light with a specific wavelength and subsequent emission of fluorescence at longer wavelengths. Fluorescence is collected perpendicularly to the light sheet, generally through a camera with intensified CCD detectors, obtaining spatially resolved 2D images, which, properly processed, can provide species distributions and display the flame front.

Since the intensity of fluorescence is directly related to the incident laser radiation intensity, in order to obtain good fluorescence signals it is required to employ lasers with high energy power such as Nd:YAG lasers. Moreover, to ensure a good temporal resolution it is necessary that the duration of the impulse is sufficiently small (i.e. 10 ns or less).

A typical PLIF experiment carried out on OH radicals requires the use of an Nd:YAG laser with a second harmonic generator (532 nm), which goes to pump a tunable Dye laser capable of emitting in a wide range of wavelengths (400 - 800 *nm*). In detail, in Dye laser, a chemical compound absorbs laser light from the main source and emits light at different wavelengths.

To obtain the correct wavelength suitable to excite the OH radicals (generally 283 nm) a frequency doubler crystal must be coupled to the Dye laser. Now, a system of cylindrical and spherical lenses, transform the laser beam into a thin light sheet used to illuminate the area of interest within the flame. In our applications, the measurement regions to be investigated with the laser sheet generated by the optical system will be 5x5 cm with a maximum thickness of 0.25 mm at 5 m from the laser source and 10x10 cm at 0,5-1 m from the laser source.

With the help of UV lenses, a portion of fluorescence radiation is conveyed through the detection system, suitably synchronized with the laser since the fluorescence phenomenon lasts only a few nanoseconds.

In order to apply PLIF to CH radicals (generally excited at the wavelength 390 *nm*), the experiment requires almost same components. The only difference will be that we employ in the Nd:YAG laser, rather the second harmonic generator, a third harmonic generator (355 nm) to pump the Dye laser, and instead of the frequency doubler crystal, a mixing crystal will be used. Figure 3 shows a basic diagram of the PLIF technique, and in Fig. 4 a typical OH fluorescence image.


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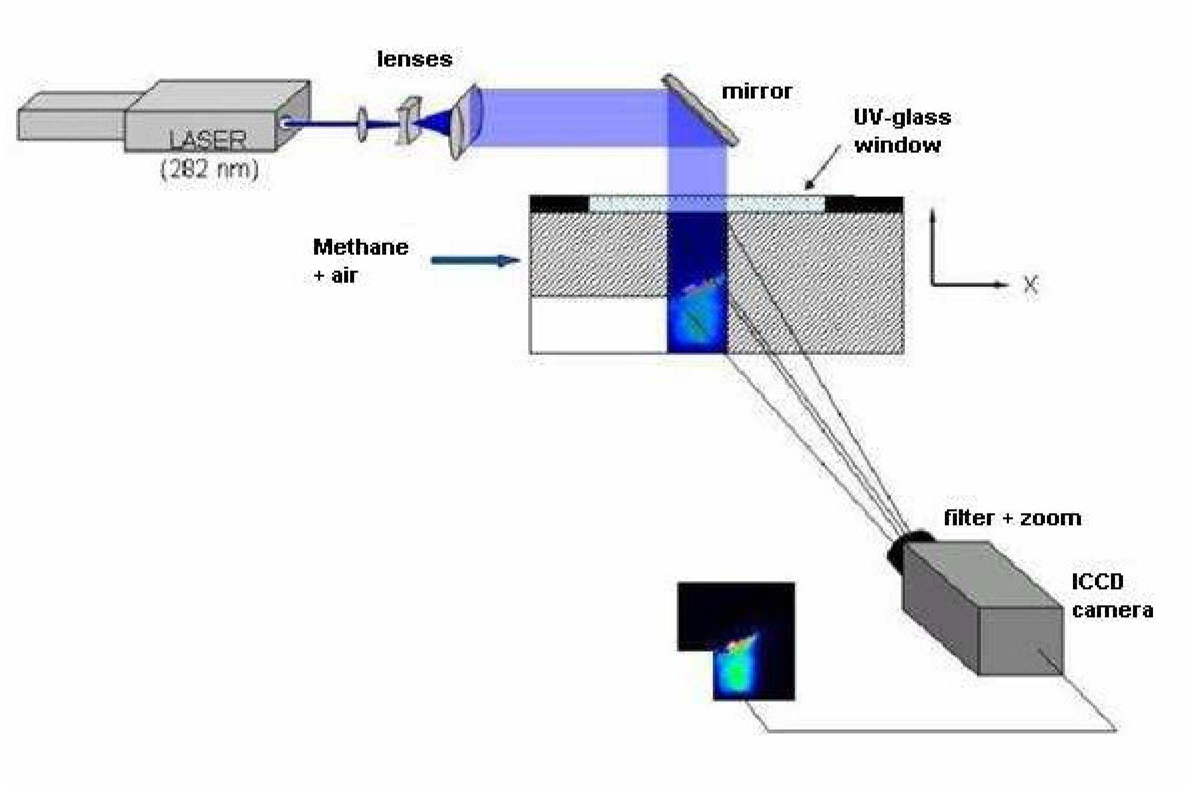


**Figure 3**. Principle scheme of the PLIF technique

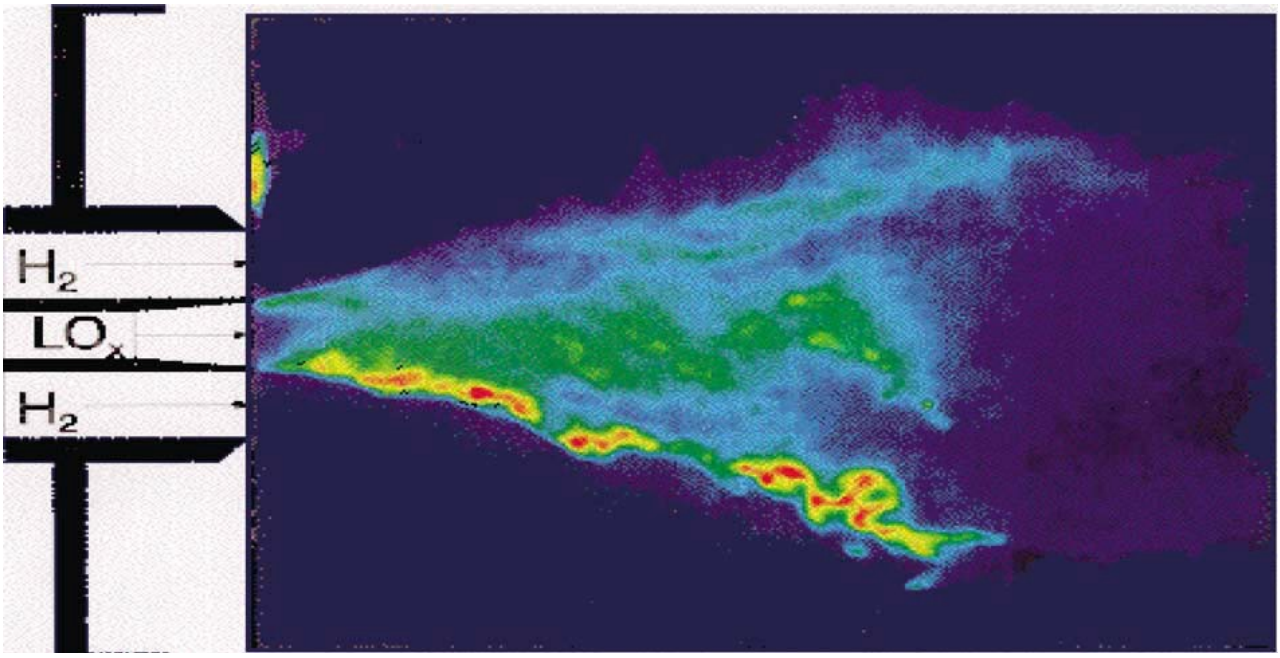


**Figure 4**. OH PLIF image of a LOx / GH2 mixture at 25 bar (the laser sheet is transmitted to the combustion chamber from below)

At CIRA we intend to join the PLIF measures with HSC Imaging measures. As a consequence, in addition to the intensified camera for recording fluorescence images (using either an integrated or external intensifier module), a high-speed intensified video camera will also be used (also to be intended as an integrated or external intensifier module), and specific optical bandpass filters for the emission of CH and OH have to be considered for each camera.
The distance between the laser source and the measurement point, depending on the specific experimental setup and goals, will be in the ranges of about 5 meters and 0,5-1 meters.


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### 1.1.3. Raman spectroscopy

In Raman spectroscopy, a laser light source is used to excite the vibro-rotational energy levels of molecules. Raman spectroscopy is a scattering spectroscopy where the incident monochromatic electromagnetic radiation, of known intensity and frequency, goes through the sample volume and the radiation diffused at 90º or 180º with respect to the optical path in the measurement volume is measured. The diffusion can be either Stokes type, anti-Stokes and Rayleigh (elastic scattering), each one characterized by different energy levels.
By analyzing the scattered radiation it is possible to identify the composition of gases and flame temperature.

The instrumentation required for this measurement technique shares main components, including laser, part of the optical system and setup, with other measurement techniques described in this document, which is why the possibility of integration of Raman spectroscopy with LIF system and the possibility of purchasing it as an option of a fully integrated system will be positively evaluated.

## *1.2. INSTRUMENTATION COMPONENTS*

The list of hardware and software components needed to implement the measurement techniques described is:

- High-Speed Camera (for HSC)
- Intensified Camera (for PLIF)
- Photographic lens
- Light Intensifier
- Set of optical band-pass filters
- Pump laser
- Dye Laser
- Dye solutions for radicals visualization
- Pump optics
- Laser shutter
- Energy monitor
- Optical system for laser beam guidance
- Optical system to generate the light sheet
- Beamdump
- Set of UV lenses
- Synchronization unit
- Optical bench for the laser system
- Optical bench for optics
- Computer with interface boards for instrumentation
- Control and acquisition software
- Safety glasses


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- Accessories and connection cables
- Calibration kit

## *1.3. TECHNICAL SPECIFICATIONS OF INSTRUMENTATION*

The requirements for each of the components listed in the previous point are described in the following section:

### 1.3.1. High-Speed Camera (HSC)

The HSC must allow a maximum resolution not less than 1280x800 pixels with an acquisition frequency above 5 kHz,

Furthermore, the HSC must be equipped with RAM memory at least of 18 GB and image acquisition and management software with the possibility of live display for adjustments and pointing.

The interface shall comply a standard type (e.g. Gigabit Ethernet or USB type) fast enough to avoid bottleneck in data transfer at the maximum acquisition rate. The coupling for photographic lens must be type C or F. It must also be possible to synchronize the acquisition with external events and with the other components of the system.

### 1.3.2. Photographic lens

The photographic lens must be quartz type and have a bandwidth between 200 nm and 1000 nm at least, thus including the UV, VIS and near infrared (NIR) regions. They must be characterized by largest aperture, highest transmissivity and lowest possible distortion.

The interface can be either type C or F, compatible with those adopted on the other components.
The lens must allow remote control of focal distance and aperture.

### 1.3.3. Intensifier

The intensification modules must either be integrated in the cameras or it must be able to be mounted on both the HSC and on the camera for the acquisition of fluorescence images (in this case it must therefore have a C or F type graft depending on the engagement of the camera).

The intensifier must allow to acquire images in a spectral range between 185 to 900 nm.

The intensifier must be able to operate in DC, in "single pulse" mode with repetition frequency not less than 200 kHz and in "burst" mode, i.e. with the capacity of a number of gate pulses at least equal to 10, with maximum temporal distance between pulses of 500 ns. The repetition rate in this mode must be greater than or equal to 10 kHz (for compatibility with PIV applications).

The minimum gate time must be 10 ns or less. The intensifier must be remotely controllable.


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### 1.3.4. Set of optical band-pass filters

The optical band-pass filters must be interferential and shall allow covering a range of wavelengths ranging from about 300 nm up to the whole VIS.

They allow the recording of the emission of investigated species only, thus blocking the laser beam and other secondary emissions. In particular, two narrow-band optical filters and high transmission are required, respectively for the OH emitting at about 308 nm and for the CH emitting at about 410 nm. Transmissivity must be greater than 75%.

The threaded connection must be compatible with the optics supplied with the system.

### 1.3.5. Pump laser

The pump laser must be a high energy pulsed Nd:YAG type, it must have either a second harmonic generator (532 nm) and a third harmonic generator (355 nm) to pump the Dye laser.

The energy per pulse must be at least 400 mJ at 532 nm, the repetition frequency of at least 10 Hz, the pulse duration = 10 ns, the beam diameter <10 mm with a divergence less than 0.5 mrad.

The laser must be interfaced and remotely controlled from the measurement SW.

### 1.3.6. Dye Laser

The Dye laser must be tunable in the wavelength range 370 - 760 nm, with holographic grating 2400 lines / mm and line width =0.080 $cm^{-1}$. The beam divergence must be equal to or less than 0.5 *mrad* with polarization higher than 95%.

Furthermore, the Dye laser must be equipped with frequency doubling or mixing crystals that guarantee an extension in the UV range, in order to obtain the specific wavelength for OH radicals excitation. These crystals, as well as the Dye, must be easily interchangeable to allow measurements of different species of radicals with reduced time expenditure to change configuration.

The dye laser must be equipped with the dye solutions needed to produce excitation wavelengths for the radicals CH and OH and all the accessories for replacement and configuration change in the shortest possible time shall be supplied.

The laser must be interfaced and controlled remotely from the measurement SW.


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### 1.3.7. Pump Optics

Pump optics consist of the optics system used to lead the beam from the Dye laser to the pump laser. In particular, the optics must be specific for the 532 nm and 355 nm wavelengths and both must be equipped with supports and micrometric adjustments to adjust and align the laser beam.

### 1.3.8. Laser Shutter

The shutter shall block the laser beam of the main source Nd:YAG, at both wavelengths 355 nm and 532 nm. The blocking capability must exceed the maximum emitted power of the laser source considered in the offer by at least 25% and the repetition frequency must be at least equal to the emission frequency.

The closing and opening time must be $\leq 20ms$. For safety reasons in the event of a power failure the shutter must be closed automatically and shall remain in this condition until the opening command is given after restarting the system.

It must also be controllable via software.

### 1.3.9. Energy Monitor

The Energy Monitor allows the energy measurement of the laser pulse. It is required in the alignment phases of the optics and tuning of parameters before test.

It must be controlled by software in order to allow the continuous monitoring of laser beam energy during test and the measured power can be used by the measurement SW for eventual data correction aimed to improve measurement accuracy.

The power measurement has to be carried out on various laser wavelengths in a simple way. Ability of triggering for synchronization with pulsed lasers is required.

The energy monitor must allow the power measurement for both pump and Dye lasers.

### 1.3.10. Light sheet Optical system

The optical setup to produce the light sheet is composed by lenses optimized for the excitation wavelengths of OH and CH radicals allowing to focus the laser beam to an appropriate thickness and to adjust its aperture and height.

The dimensions in the measurement region of the laser sheet generated by the optical system will be 5x5 cm with a maximum thickness of 0.25 mm at 5 m from the laser source and 10x10 cm at 0,5-1 m from the laser source, depending on the specific experimental setup.


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#### 1.3.11. Beamdump

The beamdump must allow the light sheet generated by the class 4 laser source to be absorbed at the exit of the analysis area in order to prevent the spread of harmful radiation, in compliance with current safety regulations.

#### 1.3.12. Set of UV lenses

UV lenses are used to direct a suitable amount of fluorescence emitted by CH and OH radicals inside the intensified camera and maximize their quantity at the same time. They must be characterized by high transmission rate (> 90%).

The connection for acquisition camera will be type C or F and front thread for filter support is required.

#### 1.3.13. Synchronization unit

The synchronization unit must have a time resolution lower than $1ns$ to allow precise synchronization between laser and camera for image acquisition.

It must have a sufficient number of output channels (higher than 6) and must include all cables for camera and laser connection.

It must also be completely controllable via software and accept, in addition to the connected equipment signals, user-defined trigger signals with variable delay, also defined by the user.

#### 1.3.14. Optical bench for laser system

The optical bench must house both the pump laser and the Dye laser.

The optical bench includes all the accessories needed to fix the systems and allow the micrometric adjustment of the beam. In order to change the system position the optical bench mast be equipped with lockable wheels.

It must be composed by modular structures available on the market in order to be modified for future needs.

#### 1.3.15. Optical bench or support for optics

The optical system for the laser light sheet generation is fixed on an optical bench or other suitable support that guarantees its correct mounting and setting beside the analysis area.

All the accessories needed to fix the optics and to allow the micrometric adjustment of the beam must be included.


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It is also required to secure the setup in the working position to avoid unexpected misalignments.

It must be composed by modular structures available on the market in order to be modified for future needs.

### 1.3.16. Computer

The computer is dedicated for the installation and run of the control and acquisition software.

The minimum specifications are:

| | |
|---|---|
| CPU | 3.6GHz 8core 12mb cache |
| RAM | 16 GB or more depending on the software installed |
| HD | 256 GB SSD for operating system +<br>4000 GB or more (RAID 1) for measurement data |
| Controller | RAID |
| graphics | PCI Express with more than 2 Gb DDR RAM |
| Optical Drive | 16x DVD +/- RW or 16x Blue Ray |
| Monitor | 27 inch Widescreen, adjustable in height and inclination |
| network | 10/100/1000 Ethernet |
| WLAN | b / g / n |
| keyboard | Italian |
| mouse | 3 button USB optical |
| operating system | compatible with the control and acquisition software. |

### 1.3.17. Control and acquisition software

The control software of the measurement system and image acquisition must allow:

- manage all hardware of the measurement chain that need parameter settings (laser, Dye, HS camera, energy monitor, synchronization unit, calibration systems and more)
- Perform system calibration, with capacity to save, recall and comparison of calibration images
- Delete the background from the image to be analyzed
- Correct distortion and perspective effects
- Apply image enhancement filters
- Give information on the measurement parameters and about the quality obtained
- Allow a quantitative analysis of the flame front geometry
- import and export data, images and videos
- compare images and results of different sizes
- Include algorithms to correct laser sheet energy fluctuations and laser attenuation
- LIF measures data analysis and species concentration
- Raman measurements of temperature and concentration of species (Option)


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Furthermore, the software shall allow eventually extension by the user through interfacing specially developed external modules, such as linking Matlab and Labview software routines.

The software license shall be perpetual, without annual fee and software update/upgrade shall be included when available.

#### 1.3.18. Safety glasses

Safety glasses are required in all maintenance and use operations of both pump and dye laser. They must comply with current laser safety standards and cover the power range and wavelengths of the lasers supplied.

Number of pieces required: 4

### *1.4. Additional instrumentation for Raman measurements*

In addition to the instrumentation described in the previous paragraphs it is required to list, as a non-binding option for the purchase, all the components, both HW and SW, necessary to extend the measurement capabilities of the system proposed to the Raman technique.

The supply of a spectrograph with relative calibration lamp and other components required for coupling with the camera, a system for changing the polarization, filters and measurement SW are expected.

The Raman option, as already mentioned, shall be closely integrated with the PLIF and HSC system, which is the main subject of the present specification.

## 2. COMPLEMENTARY ACTIVITIES CHARGED TO THE SUPPLIER

The supply includes all the engineering services necessary to design the measurement system, process and order the material, carry out assembly, connections, configuration and tests.

- Detailed definition of material supply and procurement;
- loading / configuration of the basic software;
- loading of applications (graphics, databases, ...) on PCs;
- equipment assembly and connection
- PC installation
- Checks and tests for correct operation

Furthermore, it is required to provide:

- Integration and installation by specialized technicians of all the components listed above.
- System integration and final test


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- Inspection of all components of the set up and test run of the entire system to check its performance, to be carried out at the supplier site (with CIRA witness on request).
- Installation and training
- The installation and training, to be carried out at CIRA site during the supply acceptance tests, include supplier travel time, travel expenses and accommodation costs.

# 3. TRAINING

At the end of mounting and setup activity, during functional acceptance tests, a training session on the SW environment, installation, optical alignment and setup and HW operations will be carried out by the supplier aimed at tuning the specifications, navigating between logics, compiling and downloading the configuration, managing the database.

# 4. WARRANTY

All the equipment included in the measurement system described in this specification must be covered by the 24-months warranty as specified by current laws and by the general supply conditions of CIRA [1];

The inclusion of at least 1 year of on-site technical assistance/maintenance will be positively evaluated.
The inclusion of an extension of the warranty, under the same conditions, for at least 3 years will be positively evaluated.

# 5. DOCUMENTATION

At the conclusion of the installation and test activity the supplier will produce the following documentation:

- Connection schemes
- Operating instructions for lasers setup and alignments
- Safety plans, indications and instructions
- CD with system configuration, drawings, manuals
- List of materials
- Instruction manuals
- Procedures for using the SW
- Maintenance plan
- List of critical parts
- Any needed MSDS - material safety data sheets
- Any needed instructions about special/hazardous waste and their disposal


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# 6. DELIVERY

The material must be delivered, at supplier's expense and under his responsibility, within 90 working days starting from the date of confirmation of the purchase order, with all the accessories and software included in the offer at the CIRA premises, at the following address:

**CIRA scpa**
**Via Maiorise s.n.c.**
**81043 Capua**
**Italy.**

# 7. CE CERTIFICATION

The manufacturer must be certified with ISO 9001 (version 2000).

All the components of the supply must comply with CE regulations

# 8. HOW TO PRESENT THE OFFER

The offer, unless otherwise indicated in the offer request letter, must be presented on a lump basis in order to highlight the total cost of everything defined "Subject of the supply". The cost of the individual devices included in the bids must also be specified, including any options, with respect to the basic configuration, necessary for compliance with the minimum requirements indicated in this document.

Alternative solutions proposed by the supplier, which may include different components than that shown in this document may also be taken into consideration provided that all the requirements and performances stated in this document are satisfied.

It will be a title of preference:

• offer of a modular and expandable system for use of different measurement techniques with high sharing of hardware and software components
• flexible configuration and setting of the measurement parameters in the control SW
• SW utility for calibration
• Real-time control of laser emission power and possible correction for power variations

All components of the measurement system must correspond to the last version available at time of the offer submission.

It is required to join to the offer a copy of the manuals and any scientific publications based on the use of the proposed instrumentation.

It is also required to indicate reference of the main installations of similar instrumentation.


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CIRA reserves the right not to purchase some non-essential components from those listed, deducting the cost from the total indicated in the offer.

CIRA reserves the right, after reviewing the offers, to confirm the purchase of the options proposed or not to purchase them without, for this reason, the use of the PLIF and / or HSC system impaired.

The supply will be carried out in accordance with the agreement with CIRA scpa and according to all contractual documents provided by CIRA itself.

CIRA scpa requires the supplier to identify, inside its organization, a Technical Manager of the activity that will interface and share all the possible interventions necessary to achieve the objectives.

# 9. TESTING AND ACCEPTANCE

The main planned activities, included in the supply, are:

- HW and power-up testing
- Functional communication / start-up tests

The supplier will install all equipment on CIRA premises and test the functionality of the whole system for acceptance within 15 days from the delivery date. The compliance with the specifications requirements and submitted offer, the proper working and the accessories present will be verified.

## *9.1. ACCEPTANCE TEST*

The test for the PLIF and HSC Imaging system must be carried out on a flame, produced by a standard laboratory burner fed with methane and air, at atmospheric pressure and in a turbulent regime. The burner must be made available for testing directly by the Supplier. In addition, the Supplier may be required to perform the acceptance test in CIRA's laboratories even with distance, between the burner position and the laser sources, at 0,5-1 meter or up to 5 meters.

In particular, as regards the PLIF system, a test campaign must be conducted with at least four different operating conditions in terms of fuel and comburent flow; for each condition at least three different sections of the flame must be investigated. The images data processing will be performed to allow the evaluation of the concentration distribution of OH and CH radicals.

With reference to HSC Imaging, measurements must be carried out in accordance with the same flow conditions investigated with the PLIF. The images data processing must be completed with visualization of flow characteristics and allow analysis in terms of flame dynamics.

Furthermore, it is required to prove the reproducibility of the measurements performed.


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### 9.2. ACCEPTANCE METHODS

CIRA scpa will consider the supply accepted once the outputs defined in § 9.1 have been verified and formally accepted. To this end, CIRA scpa reserves the right to request any additions and modifications to the components delivered within a period of 15 days following delivery.

## 10. ROLES AND RESPONSIBILITIES

The supplier is responsible for complying with all requirements of defined in the present document and the timescales relating the commitments provided up to their acceptance by CIRA scpa.

## 11. CONFIDENTIALITY

The Supplier will guarantee confidentiality and non-disclosure of information which it will become aware during the course of the activity.

Any copy of the drawings and / or documents made available by CIRA, as part of this contract, must be returned to CIRA and permanently deleted from the HW platforms and by any IT support owned by the supplier at the end of the activities.


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