

Two-Dimensional In-Cylinder Soot Volume Fractions in Diesel Low Temperature Combustion Mode

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ABSTRACT

Soot Volume Fraction (SVF) measurements were performed in an IFP Energies nouvelles optical single cylinder Diesel engine operated in Low Temperature Combustion (LTC) conditions. The engine was equipped with a sapphire liner, a dedicated flat bowl piston and a six-hole common-rail high pressure injector. The piston design included four quartz windows allowing optical access into the bowl. The aim of this work was to study soot formation and oxidation during the LTC Diesel combustion process and to build a database providing soot formation and oxidation data under a set of engine conditions to help developing and testing Computational Fluid Dynamics (CFD) models. Two complementary optical diagnostic techniques were combined: Planar Laser Induced Incandescence (PLII) and Laser Extinction Method (LEM). The non calibrated two dimensional image of soot distribution obtained by PLII was coupled with the line of sight integrated absolute SVF value obtained by LEM to provide two dimensional SVF fields in a plane crossing the center of the chamber, perpendicular to the piston surface. The in-cylinder soot evolution was also compared to exhaust smoke measurements. The influence of injection quantity and timing, injection pressure, dilution rate, intake temperature and fuel nature on SVF was investigated. Three fuels were tested: a two component Diesel surrogate, a standard Diesel and a 5% biodiesel blend. The analysis of the 2D SVF fields showed that soot was systematically observed in two zones located symmetrically on both sides of the common cylinder and injector axis. The engine load and injection pressure, directly related to the local fuel/air ratio, were the main parameters impacting soot levels. The injection timing and the intake temperature were found to significantly affect the in cylinder soot levels but not the

exhaust soot emissions. It was proposed that the efficiency of soot post-oxidation is responsible for this result. The increase of the dilution ratio led to a decrease of in-cylinder soot levels but to an increase of exhaust soot emissions. The proposed mechanism for this behavior is a reduction of soot post-oxidation efficiency with increasing dilution. The surrogate Diesel fuel showed earlier and higher in-cylinder soot levels compared to the standard Diesel while lower soot levels were obtained with the 5% biodiesel.

INTRODUCTION

CONTEXT

The reduction of CO₂ emissions and regulated pollutant emissions from passenger cars and heavy duty engines is a major concern for engine OEMs. With a high thermal efficiency and low CO₂ emissions, Diesel engines are ideal candidates. However, they have to face more stringent pollutant emissions standards, with a drastic reduction of engine NO_x (nitrogen oxide) and particulate outputs. Future emission standards also plan to address the issue of particulate number added to their mass. One way to reach this challenge is to reduce the volumetric compression ratio (CR) combined with intake dilution by exhaust gas recirculation (EGR). However, the direct injection of the fuel and its auto-ignition lead to the formation of local rich zones where partial or incomplete combustion takes place. These are a source of pollutant formation. The excess of air surrounding the rich zones where HC, CO and soot are produced allows these pollutants to be partially or totally post-oxidized (depending on the operating conditions). Consequently, the comprehension of the mechanisms related to pollutant emissions in Diesel engines requires a spatial and temporal

analysis of combustion, soot production and oxidation inside the combustion chamber.

OBJECTIVES

This study was dedicated to the analysis of the mechanisms of soot production and oxidation in direct injection Diesel Engines on close to homogeneous combustion modes (or LTC for Low Temperature combustion). The objective was to acquire reliable experimental data for real and surrogate Diesel fuels in a real engine environment. Experiments were based on recently developed advanced soot visualization and quantitative measurement techniques (optical diagnostics) able to determine soot concentration and distribution inside the combustion chamber. The experiments were done with different fuels and different engine operating conditions. The objective was to build a database of quantitative soot measurements, coupled with a complete set of engine output parameters (pressure, heat release and regulated pollutant emissions). This database can be used for future testing and validation of CFD models which include soot production and oxidation. This will make CFD a valuable tool to understanding soot processes and helping design new and less pollutant engines.

IFP Energies nouvelles has proposed a set of experiments performed in an optical Diesel direct-injection engine fueled with both commercial and surrogate Diesel fuels. The main goals of the experiments were:

- To study soot production and oxidation during the engine cycle.
- To study the influence of engine operating conditions on soot production and oxidation during the engine cycle.
- To study the influence of fuel and engine operating conditions on exhaust emissions (namely soot).
- To build an extended experimental database for detailed soot modeling test and validation studies.

EXPERIMENTAL SETUP

ENGINE CONFIGURATION

Experiments were made on an IFP Energies nouvelles optical single cylinder common-rail direct-injection Diesel engine based on a recent commercial PSA DW10, four cylinder engine. The main specifications are summarized in [Table 1](#). The engine was equipped with a Bosch CRI1, six holes injector with a spray cone angle of 144° and a static flow rate of 347 ml/30 s/100 bar placed at the center of the cylinder head in a vertical position. Engine firing was continuous in order to guarantee realistic thermal behavior and to allow the measurement of engine exhaust pollutant emissions.

Table 1. Optical engine characteristics.

Optical Single-cylinder Engine	
Number of cylinders	1
Cycle	4 stroke
Number of intake valves	2
Number of exhaust valves	1
Combustion	Flat optical bowl
Cylinder head type	Flat
Displacement	499.3 cm ³
Bore	85 mm
Stroke	88 mm
Connecting rod length	144 mm
Compression ratio	14:1
Swirl BDC	2.2
Injection system	Common Rail Bosch

The cylinder head is a typical Diesel four valves flat engine head. A cylinder pressure transducer was implemented on the side and only one exhaust valve was activated for this experiment as shown in [Figure 1](#). The other valve has been disconnected and replaced by a visualization window. This window has not been used during the present study. Optical observations were performed through the piston and the liner.

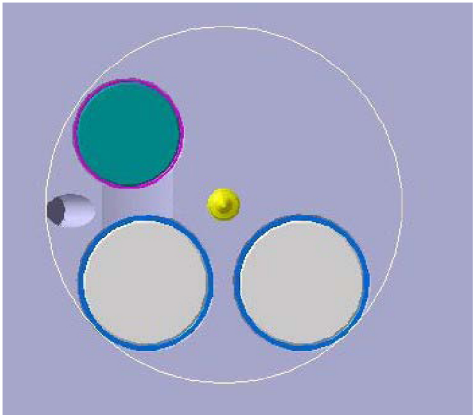


Figure 1. View of the valves plus injector configuration (front the piston). Upper part: Exhaust; lower part: Intake.

For this experiment, the engine was equipped with a newly designed optical piston including several optical accesses as shown in [Figure 2](#). The side faces of the piston bowl are equipped with three quartz windows: two opposed narrow windows for the laser sheet and a larger one forming a 90° angle with the previous for the visualization of the soot excited by the laser sheet. The quartz windows were specifically designed to maximize the view field while minimizing image distortion. The lower piston bowl face is also made of a quartz window allowing direct combustion observation. A flat piston bowl was used rather than a more

realistic Diesel combustion chamber bowl in order to guarantee a perfectly free path for the LII laser sheet and LEM laser beams. To allow access and visualization of the combustion chamber, a transparent sapphire crown was installed at the top of the cylinder liner in front of the piston at TDC.

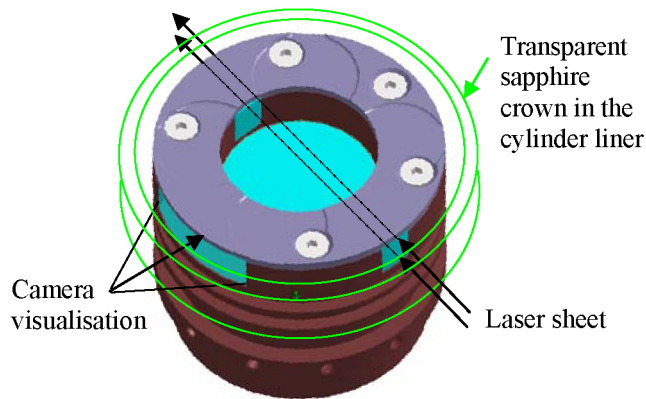


Figure 2. View of the piston and its optical accesses.

The distance between the top of the piston and the cylinder head was adjusted to 1.02 mm for a theoretical volumetric compression ratio of 14:1. A low compression ratio is required to attain Diesel LTC conditions. These are necessary in order to obtain low level of soot production inside the chamber and thus guarantee the validity of the laser LII quantitative measurement technique described below. Low compression ratios (from 14:1 to 16:1) are necessary for reducing Diesel engine combustion emissions to values compatible with Euro 6 standards. Reduction of combustion emissions leads directly to decreasing after-treatment efforts and therefore the cost and complexity of after-treatment systems (SCR, NOx traps, DPf...).

The real experimental compression ratio, based on thermodynamic evaluations from in-cylinder pressure traces and flow analysis was 12.8:1. This value was checked before every engine run and was coherent throughout the study. The reduction of the theoretical value of 14:1 to 12.8:1 is mainly due to a combination of compression and inertial efforts carried out on the optical extended piston used here. Kashdan and Thirouard [1] evaluated such efforts and provided the experimental conditions for which the IFP Energies nouvelles optical and all metal single cylinder engine behaviors match well.

The indexation of the injector was set in order to guarantee a symmetrical angle of 30° between the laser sheet and the two nearest injector sprays as represented in Figure 3. This configuration was selected in order to avoid window fouling problems detected in preliminary tests and was kept constant throughout the whole experimental campaign.

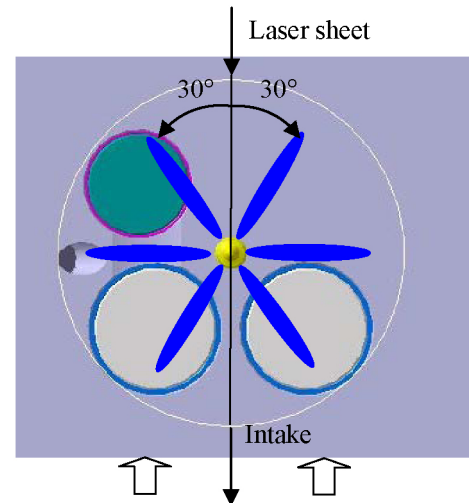


Figure 3. Injector/laser sheet and beam indexation.

FUEL SPECIFICATIONS

To facilitate fuel description in combustion models, the engine parametric variations were made with a surrogate fuel composed of two constituents: n-decane 70% + α -methylnaphthalene 30% (liquid volume percentages). This fuel has been widely used in past studies as a Diesel surrogate [2, 3, 4]. Two other standard Diesel fuels were tested. The three fuels used in this study were then:

- n-decane 70% + α -methylnaphthalene 30% called “surrogate or model” fuel (volume percentages).
- Standard Diesel fuel equivalent to a commercial Diesel fuel.
- B5 Diesel fuel containing 5% of a vegetable oil methyl ester biodiesel (volume percentage).

The main specifications of the three fuels are described in Table 2.

Table 2. Fuel specifications.

	Surrogate Diesel	Standard Diesel	B5 Diesel
%m C	87.04	86.40	85.77
%m H	12.96	13.50	13.57
%m O	0	<0.2	0.67
H/C	1.796	1.875	1.898
NCV (kJ/kg)	42935	42700	42940
ρ (kg/m ³)	789	834	836
Cetane Nb	53.2 calculated	54	54

ENGINE INSTRUMENTATION AND OUTPUTS

The engine was equipped with sensors to record typical engine parameters for each engine operating condition (engine speed, IMEP, SOI, injection duration, intake air flow,

etc.). At the intake, the air mass flow rate was controlled by a sonic nozzle system. The EGR was replaced by pure nitrogen added to the intake air in order to have total control of the dilutant flow rate also controlled by a sonic nozzle system. By adding pure nitrogen, the intake gas composition is also fully controlled which is fundamental for setting initial conditions on engine combustion simulation studies. A 6 kW air pre-heater was set up along the intake pipe to stabilize and regulate the intake air temperature which can be increased to a maximum of 80°C. At the engine exhaust, the average temperature and pressure were recorded and gas composition was analyzed with a gas system supplying UHC, NO_x, CO, CO₂ and O₂ concentrations. A smoke-meter (AVL 415 S) was also implemented to measure smoke levels (FSN) at the exhaust.

The acquisition system also recorded engine torque and speed, engine water and oil temperatures and the average intake and exhaust pressures. The global equivalence ratio was determined from the exhaust gas analysis concentrations.

The engine was equipped with high frequency sensors to record intake, cylinder and exhaust pressures with a 0.1°C resolution. Based on the in-cylinder pressure traces of 400 individual cycles, an adiabatic combustion analysis was carried out over the average cycle.

OPTICAL DIAGNOSTICS

In this experiment, two optical diagnostic techniques were coupled to characterize the soot field inside the combustion chamber: PLII (Planar Laser Induced Incandescence) and LEM (Laser Extinction Method). PLII provides quantitative information proportional to the SVF in a 2D measurement plane. However, the LII signal needs to be calibrated in order to determine the proportion factor. This is accomplished using the LEM measurement which provides a direct quantitative and calibrated measurement of SVF. The LEM measure is integrated along a 1D laser beam path and is therefore a scalar value. The coupling of the two techniques consists in calibrating the 2D PLII signal with its co-planar LEM measurement in order to retrieve a 2D quantitative measurement of the SVF.

In a previous paper, Snelling et al. [5] proposed an alternative way to calibrate a LII signal, based on the simultaneous recording of 2D LII and Two-Color-Time-Resolved (TCTR) LII signals. Boiarciuc et al. [6] applied the technique to Diesel HCCI in-cylinder SVF measurements. The 2D LII/TCTR LII technique used in references [5, 6] also enables quantitative calibration of the 2D LII signal. It has the advantage of providing complementary information on the local primary soot particle size. Regarding LII and LEM coupling, the technique used in the present work, its advantage comes from the control volume used for calibration, which corresponds to the LEM laser beam path.

As a consequence, this last method is able to provide information on possible signal trapping effects, which is not the case of the 2D LII/TCTR LII technique, based on two LII signals, both affected by signal trapping. This is an important advantage since signal trapping is a first order source of uncertainty in an engine environment as discussed in [15, 18].

PLII has been widely used in recent years to study 2D soot fields [7, 8, 9, 10, 11]. The LEM technique and the coupling between PLII and LEM was first proposed by Pickett and Siebers [12, 13] and used in several studies for soot diagnostics in Diesel spray configurations inside a high pressure combustion cell. More recently, Musculus and Pickett [14] have addressed important technical issues related to the LEM technique and proposed several improvements. These two advanced techniques have been implemented at IFP Energies nouvelles, validated and applied both in the IFP Energies nouvelles high pressure combustion cell and in a gasoline direct-injection spark-ignition engine [15]. One of the challenges of this work is to apply these diagnostics to Diesel engines where optical access has to be realized in the piston bowl and where high soot natural radiation levels can lead to LII signal absorption (image trapping).

A complete description of both laser techniques and their coupling was presented by De Francqueville et al. [15] in the gasoline direct-injection spark-ignition engine configuration and are therefore only summarized here.

PLII principle

The principle of PLII, presented in Figure 4, is to heat up the soot by means of a planar laser beam. Soot particles are assumed to behave like blackbodies and their emission can then be collected. Their temperature is around 2000 K in the reaction zone and the corresponding emission spectrum is schematically presented in Figure 4. When soot absorbs the laser beam energy, its temperature is rapidly raised to about 4500 K. The left hand side arrow in the figure represents the soot temperature increase due to laser energy absorption. For a laser energy density higher than 1 J/cm², the saturated regime is reached and some soot is sublimated.

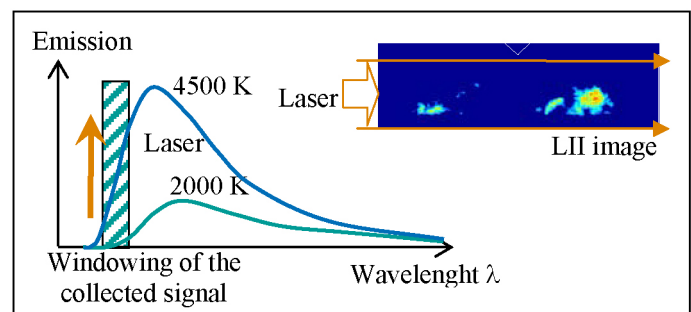


Figure 4. Principle of the LII technique.

Because of the temperature increase, soot emission properties are modified. An appropriate spectral windowing allows collecting the heated up PLII soot signal. Schulz et al. [16] shown that when only the peak LII signal is collected, effects of variations in the cool down process of soot are avoided. As described by De Francqueville et al. [15], the peak LII signal was determined from transient measurements of the LII signal. It can therefore be assumed that the resulting image provides a 2D signal proportional to SVF in the detection zone (I_{PLII} is the light intensity collected associated with the PLII signal), the proportion coefficient being α :

$$SVF = \alpha I_{PLII} \quad (1)$$

LEM Principle

The LEM SVF measurement is an integral along the laser beam pathway where a particle cloud is crossed by a laser beam of incident intensity I_0 . The technique is based on light absorption properties described by the Beer-Lambert law (cf. reference [15] and Figure 5):

$$\exp\left(-\int_0^{L_{LEM}} K dx\right) = \exp(-K L_{LEM}) = \frac{I}{I_0} \quad (2)$$

where $K L_{LEM}$ is the optical density of the particle cloud, K being the absorption coefficient [m^{-1}] and L_{LEM} the distance of the laser LEM beam in the medium where the absorption has to be measured [m]. I is the laser beam intensity after crossing the soot cloud through a distance L_{LEM} .

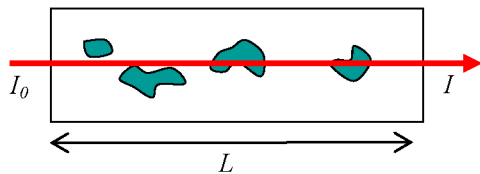


Figure 5. LEM principle.

For a known optical pathway length, SVF can be determined from the mean absorption coefficient K with the relationship established by the Mie theory for light diffusion by small particles [12, 17]:

$$SVF = \frac{\lambda}{ke} K \quad (3)$$

where λ is the laser wavelength [m] and ke is the dimensionless extinction optical coefficient which depends on the refraction index and is assumed equal to 4.9 [14].

With the LEM technique, a mean value of the LEM absorption coefficient KL_{LEM} is obtained along the laser

beam pathway. It is therefore an integrated 1D mean information with the advantage of being quantitative and absolute.

PLII and LEM coupling

The coupling of the two optical diagnostics can be made only if the LEM laser beam and the PLII laser sheet are on the same plane in the engine cylinder. Moreover, the PLII image field should cover the entire absorption zone of the LEM laser beam. If these conditions are fulfilled, there is a common spatial zone where the same measurement is performed by the two techniques. Since the LEM technique is quantitative and absolute, the LEM result is used to locally calibrate the PLII measurement. The PLII signal is then normalized along the LEM laser beam pathway. Finally, the result of this normalization is extended to the whole PLII measurement field and 2DSVF fields are obtained.

According to Eq. 1, SVF is proportional to the PLII signal intensity. After some mathematical manipulation, the proportionality constant α is determined from the ratio of the KL factors measured by LEM and PLII, L being the laser beam absorption length:

$$SVF(x, y) = \alpha I_{LII}(x, y) = \frac{\lambda}{ke} \frac{(KL)_{LEM}}{(KL)_{PLII}} I_{PLII}(x, y) \quad (4)$$

KL_{LEM} is a mean value integrated over the laser beam pathway and KL_{PLII} is obtained from the PLII signal extracted along the LEM laser beam pathway. It should also be noted that the PLII images normalization is performed with the KL_{PLII} value, and the resulting SVF is thus non-dependent on collecting parameters such as the camera intensification factor for example. The measurement method is thus iterative: for each PLII image, the α coefficient is computed, then with this value, the 2D soot volume fraction $SVF(x, y)$ is obtained (a constant α value is assumed for the whole image).

To improve the precision of the α coefficient determination, a mean value $\bar{\alpha}$ is computed. It is obtained by linear regression between KL_{PLII} and KL_{LEM} values obtained for a single operating point at a fixed crank angle and for multiple samples obtained from repeated acquisitions of 400 consecutive engine cycles. This operation is illustrated in Figure 6. The regression of KL_{PLII} values as a function of KL_{LEM} values also provides information on the quality of the coupling based on the correlation coefficient. The example presented in Figure 6 shows good agreement between LEM and PLII results with a correlation coefficient of 0.89. The dispersion of the data relative to the straight line correlation provides an estimation of the measurement uncertainty. This

is due to the fact that the optical techniques are independent from one another. Once the mean value $\bar{\alpha}$ is determined, it is used to calibrate the LII images obtained for the given operating point.

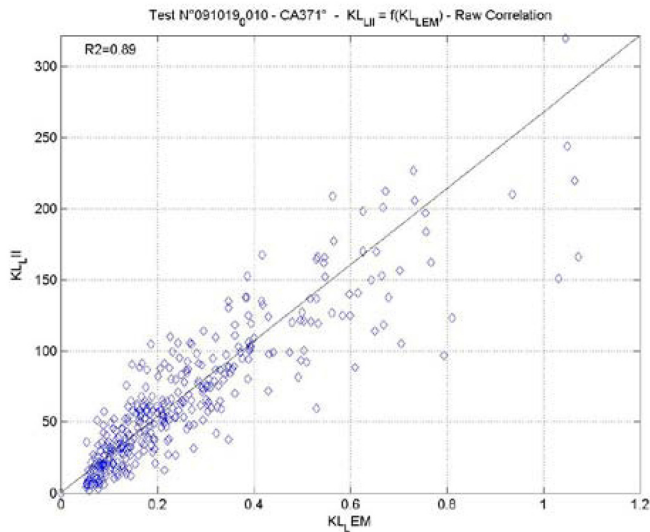


Figure 6. Example of a global correlation between KL_{PLII} and KL_{LEM} for one engine operating condition and one crank angle. 400 engine cycles were acquired and for each cycle, KL_{PLII} as a function of KL_{LEM} is plotted.

Optical diagnostic setup

The optical setup with the PLII-LEM coupling is presented in [Figure 7](#). The LEM laser beam and the PLII laser sheet were adjusted to be on the same plane. They both cross the combustion chamber through the transparent crown and the piston windows as shown in [Figure 2](#). The setup is similar to the one used by De Francqueville et al. described in [15]. Only a short description is given here. Some details are however specific to the Diesel engine operation and are detailed below.

LEM configuration

The LEM laser beam (continuous laser HeNe 35mW) was modulated by passing through an acoustical-optical modulator (BFI Optilas, AOM 1205C-2 15 MHz, aperture 2 mm driver 232A1), controlled by an impulsion generator (Quantum Composer PG-9518+) at 100 kHz.

At the exit piston window, the laser beam was collimated into an integration sphere with a spherical lens ($f=200\text{mm}$ / dia. 50mm). A diaphragm was placed at the sphere inlet to adjust the collection solid angle. The results obtained in a previous study have shown that a solid angle of 125 mrad is a good compromise between the beam-steering (BS) and forward scattering effects. An integration sphere (Sphereoptics, diam.

150 mm) was used to collect the laser beam. At the sphere exit, a pass-band filter (633 nm, $\Delta=1$ nm, transmission 97%) was used to eliminate the main part of the large band soot incandescence emission. A telescope system is associated to the filter in order to eliminate effects of local variations of filter transmission. It consists of two spherical lenses $f=75$ mm, surrounding the filter. Finally, the transmitted part of the LEM signal was collected by a photodiode (Melles Griot Mounted Si detector 80ns RT diam. 11.4 mm) associated to a Lock-In amplifier (Perkin Elmer 7280) in charge of the signal demodulation. A high frequency acquisition system with 0.1 CAD between each sample was used.

LEM specific Diesel configuration limitations

Due to the Diesel engine configuration (combustion mainly inside the piston bowl), the LEM beam must cross two optical windows (one in the transparent liner and the other in the piston) before reaching the piston chamber when the piston is close to TDC ([Figure 2](#)). This leads to a reduction of the LEM reference signal around TDC. [Figure 8](#) shows that for a cycle without combustion and therefore without soot formation, the LEM reference signal is reduced from 2.9 V to 2.86 V between 335°CA and 385°CA. The lower LEM reference value must then be taken into account for calculating the optical absorption when the beam crosses soot on combustion cycles.

Another effect of the Diesel configuration is the fact that the piston top edge (upper opaque plate in the top of the piston represented in [Figure 2](#)) crosses the LEM beam in the cylinder. This occurs twice, as the piston goes up during compression, before TDC (325°CA), and then down during expansion, after TDC (395°CA) as shown on [Figure 8](#). No LEM measurement was then possible around these °CA values. However, this limitation has no influence on the presented results. The lower limit (325°CA) is before SOI. For the upper limit (395°CA), preliminary tests based on in-cylinder direct visualization of combustion and LII measurements shown that for all operating conditions, soot presence is only observed between 365 and 385°CA. Also, combustion analysis presented below on [Table 4](#) shows that CA90 (close to the end of combustion) never goes beyond 385°CA.

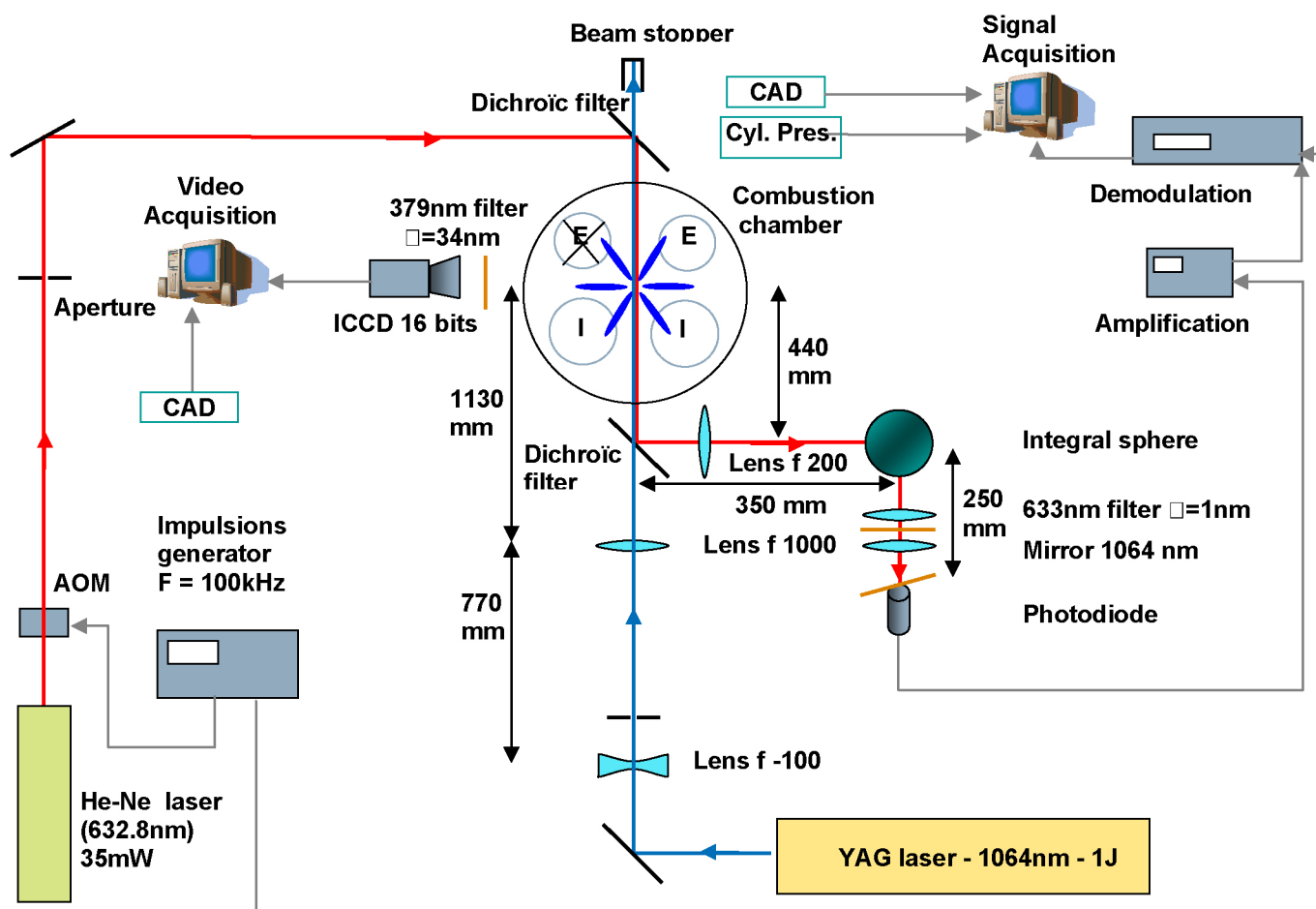


Figure 7. Experimental setup of PLII + LEM (top view).

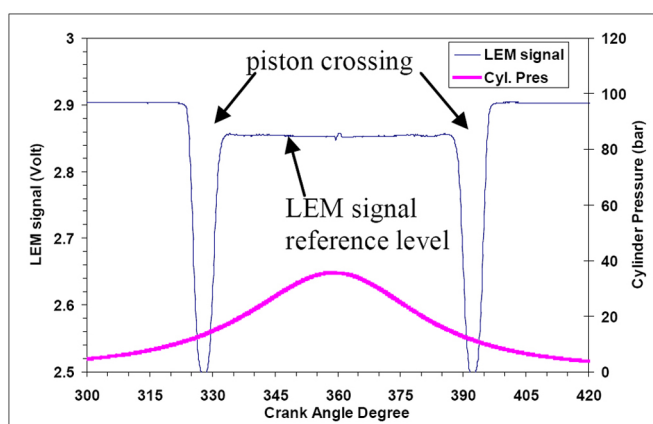


Figure 8. Effect of piston crossing and piston windows on the LEM signal during a cycle without combustion and soot.

PLII laser sheet

For the PLII images, a vertical laser plane (1064 nm) is generated by a YAG laser (1J/pulse). The laser sheet height is adjusted so that it corresponds to the height of the transparent

crown (placed on the top of the cylinder liner). The active part of the laser sheet has a height of 15 mm and is delimited by the edges of the piston window when the piston is at the TDC position. In order to measure the soot incandescence emission independently of laser intensity fluctuations, PLII was carried out in the saturated regime [16]. Typically, the saturation regime is reached for a laser energy density over 0.2 J/cm^2 . For the present setup, the laser energy density was around 0.5 J/cm^2 in the cylinder chamber (the laser beam energy is 80 mJ/pulse with a section of $15 \text{ mm} \times 1 \text{ mm}$). A variation of laser energy was carried out in order to confirm that PLII occurred well into the saturated regime. This confirms that the PLII signal does not depend on the incident laser energy variations.

PLII plane visualization

The PLII signal was collected perpendicularly to the excitation plane through the transparent crown and the piston window with an ICCD 16 bits Princeton camera equipped with a Nikkor lens ($85 \text{ mm} / f\# 1.4$). A pass band filter centered at 379 nm ($\Delta=34 \text{ nm}$) was placed in front of the camera lens. The acquisition timing was synchronized with the laser and the camera exposure time was set to 20 ns .

corresponding to the best compromise between the signal level and a reduced influence of soot particle size and ambient conditions.

PLII signal interpretation

The interpretation of the PLII signal intensity can be difficult in a high soot concentration environment because of signal trapping. This effect is due to the presence of high levels of soot particles between the laser sheet plane and the camera which can decrease the collected signal by absorption of the emitted PLII signal [18]. In this experiment, the engine operating conditions were selected so that relative low soot levels were obtained in order to minimize signal trapping effects. Diesel LTC conditions, due to the longer ignition delays and hence the better mixing between fuel and oxidizer, generate low soot and are therefore naturally fit. Finally, the coupling methodology between LII and LEM is able to evaluate the validity of the measurement, hence to evaluate the contribution of signal trapping in the SVF fields. In the present paper, it was verified that signal trapping effects were not significant in the presented results.

Specific Diesel configuration limitation

With the Diesel configuration of the present study, the viewing window (of the PLII plane) was restricted to the transparent crown height (20 mm) and to the piston window height (15mm). The piston window dimensions were adjusted in order to guarantee the entire laser sheet visualization in the piston bowl. Around TDC, visualizations were available in the piston bowl from 335°CA (25°BTDC) to 385°CA (25°ATDC). Then, between 385°CA and 400°CA, the piston top edge is moving down just in front of the observation field. After 400°CA, the visualizations could be made directly through the transparent crown. Since preliminary tests showed that soot was only observed between 365 and 385°CA, visualizations were performed only inside the piston bowl.

LEM and PLII coupling

As mentioned before, coupling the PLII and the LEM techniques requires an association of the 2D non calibrated soot volume fraction information provided by PLII and of the 0D calibrated information provided by the LEM. The two techniques have therefore to be applied simultaneously in the same measurement volume.

The quality of the data depends on a certain number of precautions. In the experimental setup used here, the LEM laser beam and the PLII laser sheet are aligned in the same plane. However, their directions are opposed in order to minimize the interaction of the PLII beam with the photodiode. Since parasite reflections from the PLII laser beam are still collected on the LEM photodiode, a reflecting mirror at 1064nm / 45° is placed in front. Moreover, the PLII and the LEM laser beams were aligned slightly off-axis

(about 1mm between the two beams) in order to minimize the effect of the PLII laser beam reflections on the external side of the transparent crown (Figure 9).

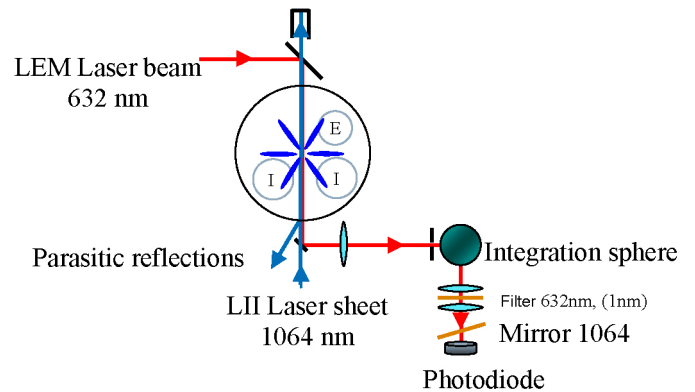


Figure 9. Diagram of the reduction of the impact of the PLII laser sheet on the LEM signal detection.

Combustion visualization

A direct visualization of combustion was provided through the transparent piston bowl. As shown in Figure 10, the piston is equipped with a large optical access allowing, with the help of a 45° mirror and a camera, collection of direct combustion images. The camera was a high speed colored non intensified Miro LCD 800×600 resolution model with a frame rate of 1000 FPS (Frames per Second), a sensitivity of 1200 ISO and an 8 pixel bit depth. Its aperture was adjusted between 100 and 130 μ s. The setup allowed recording of an image every crank angle degree during the combustion phase. A series of images was recorded for each engine operating condition immediately after the PLII/LEM acquisitions.

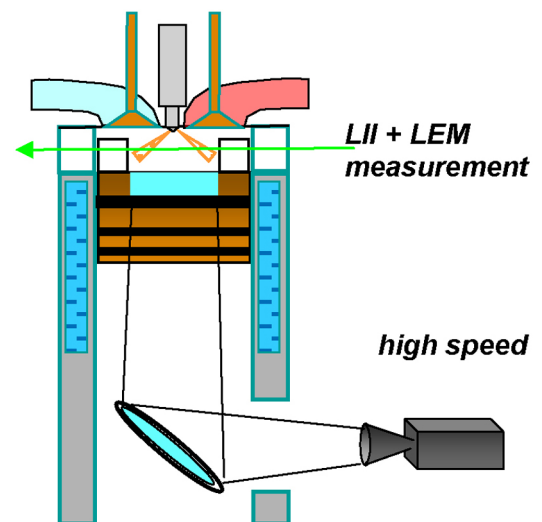


Figure 10. Experimental configuration for direct combustion visualization.