

Soot Volume Fraction Measurements in a Gasoline Direct Injection Engine by Combined Laser Induced Incandescence and Laser Extinction Method

2010-01-0346

Published
04/12/2010Loïc de Francqueville, Gilles Bruneaux and Benoist Thirouard
IFP

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ABSTRACT

In order to study the soot formation and oxidation phenomena during the combustion process of Gasoline Direct Injection (GDI) engines, soot volume fraction measurements were performed in an optical GDI engine by combined Laser Induced Incandescence (LII) and Laser Extinction Method (LEM). The coupling of these two diagnostics takes advantages of their complementary characteristics. LII provides a two dimensional image of the soot distribution while LEM is used to calibrate the LII image in order to obtain soot volume fraction fields. The LII diagnostic was performed through a quartz cylinder liner in order to obtain a vertical plane of soot concentration distribution. LEM was simultaneously performed along a line of sight that was coplanar with the LII plane, in order to carry out quantitative measurements of path-length-averaged soot volume fraction. The LII images were calibrated along the same path as that of the LEM measurement. A calibration factor was obtained for each pair of LII and LEM measurements. The analysis of the evolution of this calibration factor for varying measurement conditions was used to evaluate the validity of the methodology.

These techniques were then applied to study the in-cylinder soot concentration evolution in a GDI engine equipped with an outward-opening piezoelectric injector. The impact of injection strategy and EGR rate on soot concentration were studied in stratified operation. Results show that soot production is strongly correlated to hot fuel-rich regions. In competition with the soot production phenomena, soot oxidation processes are responsible for a dramatic decrease (1 to 2 orders of magnitude) of in-cylinder soot volume fraction during the expansion stroke until about 90 CAD after the combustion TDC. Soot oxidation is mainly governed by the

mixing between soot and hydroxyl radicals. Beyond ~90 CAD after TDC in-cylinder mean temperature seems to be too low for soot-oxidation reactions to occur. Additional measurement were performed under homogeneous fuel rich conditions in order to further validate the techniques. The soot volume fraction evolution showed that no soot oxidation occurred. This result is consistent with the fact that almost no oxidant is left after the main combustion process under these conditions.

INTRODUCTION

It is now well established that Direct Injection (DI) is a promising technology to reduce fuel consumption. However, the development of Gasoline Direct Injection (GDI) engines still requires further optimisation to achieve the future goals of fuel consumption and pollutants emission. In particular, the Euro VI legislation for European vehicles limits soot emissions for gasoline engine. Although it is not an issue for standard gasoline technology, soot emission is an issue in GDI engines because regions of high fuel concentration are generated and can form soot during the combustion process. Understanding the mechanisms of soot formation and oxidation in GDI engines is therefore of primary interest.

Laser Induced Incandescence (LII) is one of the most commonly used techniques to study soot formation processes in engine because it can provide in situ quantitative measurements of soot volume fraction [1]. However its application in the combustion chamber is not straightforward. Among the various technical difficulties three main issues have to be considered. First a calibration is necessary to derive soot volume fraction from the LII signal. A common procedure is to calibrate the LII signal from a well characterized sooting flame, for which soot volume fractions have been measured using another method, often extinction.

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Second, the interpretation of the LII signal intensity can be difficult in high soot concentration environment because of signal trapping. This phenomenon is due to the presence of soot particles in the combustion chamber between the laser sheet plane where soot particles are heated and LII signal is emitted, and the camera used to collect the signal. The absorption of the LII signal by those soot particles artificially decreases the collected signal. For instance, in high soot concentration environment, it has been shown that signal trapping can lead to complete attenuation of the LII signal [2]. The third issue is laser attenuation through the soot cloud and its potential effect on the LII signal in high soot concentration environment. However, compared to signal trapping this issue is believed to be a secondary effects, according to the results of ref.[2].

The objective of the work presented here is to propose and test a methodology to solve those difficulties. The idea is to couple the LII technique with a second soot particle diagnostic able to provide simultaneous in-situ calibration of the LII signal. The Laser Extinction Method (LEM) was selected for this purpose because it can provide complementary information. While LII provides two dimensional, non calibrated information on soot volume fraction, LEM provides a zero dimensional (integrated along the line of sight) calibrated information. Also, the advantage of coupling two soot particle diagnostics in the combustion chamber is that the coherence between the results obtained by the two techniques is an indication of the validity of each measurement point. Indeed, if signal trapping leads to a decrease of the collected LII signal, the correlation between the results obtained by the two techniques will differ from measurements where signal trapping is negligible.

The principle of the LII and LEM techniques as well as the coupling method are presented in the first part of the paper. The second and third part presents the application of the methodology to in-cylinder soot concentration measurements in a GDI engine. The experimental set-up and the validation tests are described in the second part and the results are presented in the third part.

DIAGNOSTICS AND MEASUREMENTS

LASER INDUCED INCANDESCENCE (LII)

LII uses the light emission properties of soot particles heated by a laser sheet. When the laser power is high enough, soot particles reach their vaporization temperature ($\sim 4500K$). The near-ultraviolet light emitted by such heated particles is much more intense than that emitted by particles at flame temperature (typically $\sim 2200K$): for example, at $400nm$, the ratio of light intensity between particles at $4500K$ to that of

particles at $2200K$ is of the order of 10^4 [1]. Therefore, the light emitted by combustion-heated particles can be removed from LII images using an appropriate filter (Figure 1). Also, the lifetime of LII signal is very short, hence the signal to noise ratio can be improved by using appropriate camera gating.

The time evolution of the LII signal is characterized by a first rapid increase ($\sim 10ns$) due to particle heating by the laser, followed by a slower decrease ($\sim 100ns$) during the cooling of the particles. The dominant cooling mechanism for the particles is conduction to the surrounding gas; second order mechanisms are sublimation and radiative emission [4]. Two dimensional imaging of the peak LII signal can be obtained by a short camera gate (typically $\sim 10ns$). Previous work has shown that this gated LII signal is proportional to the soot volume fraction although a more precise determination should take into account possible deviations from linearity due to the variation of primary particle size in the measurement volume [1, 4]. The decrease of LII signal during the cool down is known to significantly depend on the primary particle size and the ambient conditions.

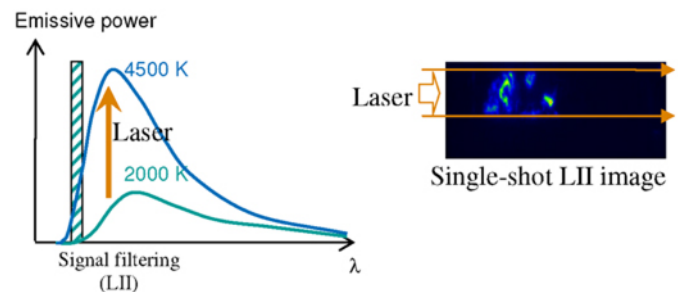


Figure 1. Schematic of the principle of LII : influence of laser heating on soot emissive power.

The objective of the work presented here is to measure the soot volume fraction in the combustion chamber of a GDI engine by two dimensional imaging of the peak LII signal. It is based on the previously discussed proportional relation between soot volume fraction and peak LII signal (Eq. 1):

$$f_v = \alpha \cdot I_{LII} \quad (1)$$

where f_v is the soot volume fraction, I_{LII} is the peak LII signal intensity, and α is a proportionality factor.

To convert the LII signal to an absolute volume fraction a calibration is required to determine α , this is one of the aim of the coupling with the LEM technique presented in the next section.

LASER EXTINCTION METHOD (LEM)

The LEM technique relies on the measurement of attenuation of a laser beam through a soot cloud as illustrated by [Figure 2](#). The transmittance of the beam can be related to its optical density using a form of Beer's law [1] ([Eq. 2](#))

$$\tau = \frac{I}{I_0} = e^{-\int_0^L k dx} = e^{-KL} \quad (2)$$

where L is the path length through the cloud, k is the extinction coefficient at the position x in the beam path, K is the mean extinction coefficient along the path length, and τ is the transmittance, i.e., the ratio of the transmitted intensity, I , to the original beam intensity, I_0 .

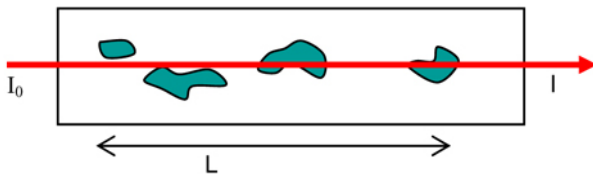


Figure 2. Schematic of the principle of LEM, beam crossing a measurement volume with soot particles.

The principle of the LEM technique is to measure the transmittance τ , and therefore the KL product according to [Eq. 3](#):

$$KL_{LEM} = -\ln(\tau) = -\ln(I/I_0) \quad (3)$$

here the subscript LEM indicates that the KL product considered is a result of the LEM technique.

The soot volume fraction can be derived from the LEM measurement using the following relationship derived from small particle Mie theory [1, 2] ([Eq. 4](#)):

$$f_v = \frac{\lambda}{ke} . k \quad (4)$$

where λ is the laser wavelength and ke is the dimensionless optical extinction coefficient. For usual application of the LEM technique, this relation is integrated along the beam path to relate the mean volume fraction along the beam path to the mean extinction coefficient K . The latter can be deduced from the KL_{LEM} product measured by LEM if the path length through the soot cloud L can be measured.

The value of ke is subject to discussion, as well as changes in ke due to the effect of particle size and morphology, ambient temperature and pressure... In the present work, a value of $ke = 4.9$ will be used according to the thorough investigation made in [ref. \[10\]](#). The uncertainty on the determination of this value will have to be taken into account when analysing the results. However it is interesting to note that, as discussed in [ref. \[10\]](#), no significant effect of ambient temperature and pressure is expected.

COUPLING LII & LEM

Principle

The principle of coupling the LII and the LEM techniques is to associate the two dimensional, non calibrated information on soot volume fraction provided by LII to the zero dimensional quantitative¹ information provided by LEM. As a consequence, it is necessary to measure the soot simultaneously and in the same measurement volume with the two techniques. The laser beam used for LEM has to be aligned with the laser sheet of the LII, and the LEM path length has to correspond to the field of view of LII. If those conditions are fulfilled the quantitative information of the LEM can be used to calibrate the LII image. More precisely, the LEM is used to calibrate the LII signal in the zone of the LII image corresponding to the LEM beam path. This calibration is then extended to the entire LII image in order to obtain a two dimensional soot volume fraction field. Also as discussed in the previous section, the conversion of the LEM information to soot volume fraction usually requires the determination of the path length through the soot cloud. When the two techniques are coupled, the information on the path length is included in the LII image.

In [ref. \[7\]](#), a similar strategy was used to obtain calibrated soot volume fraction fields in an atmospheric burner flame. The laser used for the extinction formed the same laser sheet as that of LII. As a consequence the whole LII image could be calibrated directly by the extinction information. In the present work a laser beam was used for the extinction measurement because it is possible to correct for beam steering effects using an appropriate set-up for the LEM [8]. In the engine significant contribution from beam steering effects can be expected, which could be more difficult to correct for if using a laser sheet for extinction measurements.

Processing

The coupling of the two techniques is based on the following processing of the LEM and LII results. First, the LII image is integrated along the path of the LEM laser beam in order to obtain the value KL_{LII}^* ([Eq. 5](#)):

¹Note that as discussed in the previous section, the quantification of the LEM signal relies on the assumption that $ke = 4.9$.

$$KL_{LII}^* = \int_0^L I_{LII} dx \quad (5)$$

A number of pixel in the transverse direction (y axis) corresponding to the diameter of the LEM laser (2 mm) is taken into account when performing this integral.

The superscript * is used here to indicate that contrarily to the KL_{LEM} product which is dimensionless, the dimension of KL_{LII}^* corresponds to a length scale.

Combining the equations leads to (Eq. 6):

$$KL_{LII}^* = \frac{1}{\alpha} \int_0^L f_v dx = \frac{\lambda}{\alpha \cdot ke} \int_0^L k dx = \frac{\lambda}{\alpha \cdot ke} KL_{LEM} \quad (6)$$

Therefore the proportionality factor between soot volume fraction and LII signal can be determined from the combination of the LEM and LII results according to (Eq. 7):

$$\alpha = \frac{\lambda}{ke} \cdot \frac{KL_{LEM}}{KL_{LII}^*} \quad (7)$$

Finally, the image of LII signal intensity can be converted to soot volume fraction using the following relation (Eq. 8):

$$f_v(x, y) = \alpha \cdot I_{LII}(x, y) = \frac{\lambda}{ke} \cdot \frac{KL_{LEM}}{KL_{LII}^*} \cdot I_{LII}(x, y) \quad (8)$$

Sources of uncertainty

This relation (Eq. 8) expresses a linear relation between the soot volume fraction and the peak LII signal collected by the camera. However possible deviation from linearity can be observed for several reasons. First, such deviation could be due to the measurement uncertainties related to each technique.

Concerning the LEM, although as shown in ref. [8] the experimental set-up can be designed to minimize uncertainties due to beam steering by refractive index gradients, interference with the natural soot incandescence and with the forward scattering, photo elastic effects, some level of uncertainty might remain. Also some uncertainty are due to the precision of the collection system (photodiode, acquisition system...).

Concerning the LII, in addition to signal trapping effects, measurement uncertainties may arise from camera shot noise, quality of the laser sheet profile... Also the technique is based on a linear relation between soot volume fraction and peak LII signal, and sources of deviation from linearity have been discussed previously (mainly due to variation of primary particle size in the measurement volume).

Laser attenuation might also be an additional source of uncertainty. Indeed, the measured LII signal can be underestimated if the attenuation is high enough to decrease the laser fluence below the saturated regime. In the latter, the laser fluence is such that the LII signal is not dependant of the incident intensity [3] when using a Gaussian beam profile. In the present work the experimental set-up was designed in order to ensure that the laser fluence is well above this threshold, therefore it was supposed that laser attenuation is not a major source of uncertainty in the present case. This supposition is supported by the results of ref. [2] where LII measurements were performed in a highly sooting Diesel jet. The corresponding results showed that the laser attenuation was not significant while strong signal trapping effect leading to a complete absorption of the LII signal was observed.

Additional uncertainties can be due to the coupling of the two techniques. In particular due to differences between the laser sheet thickness and the beam diameter profiles, differences between the measurement volume of the two technique are difficult to completely suppress. Also, image distortion through the quartz liner was neglected since it is only significant in the peripheral zones where small amount of soot were observed. Finally, uncertainties can be due to the fact that ke might vary in the measurement volume as previously discussed, due to the effect of particle size and morphology, and temperature.

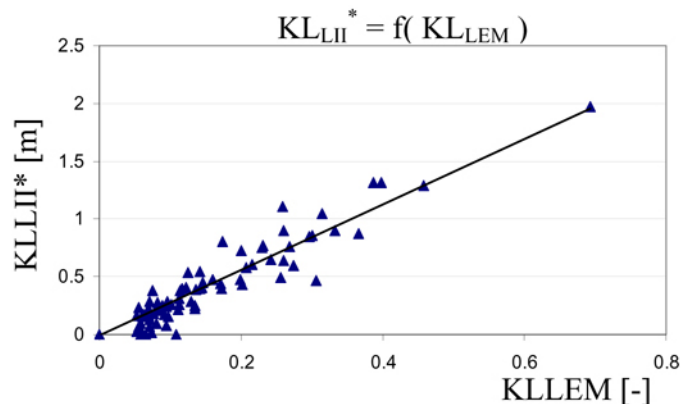


Figure 3. Correlation between KL_{LII}^* and KL_{LEM} for 300 consecutive cycles at 400 CAD. As discussed later in the Measurement Validation section, data with KL_{LEM} value < 0.05 were removed because they are under the LEM detection threshold.

An example of correlation between KL_{LII}^* and KL_{LEM} resulting from the measurements of 300 consecutive cycles is presented in [Figure 3](#). Those measurements were realized in conditions characterized with relatively low levels of soot concentrations in order to minimize signal trapping effects. The results show a good correlation between the two techniques (correlation coefficient of 0.92). Also, a linear behaviour is observed as expected. The observed dispersion around this linear relation can be attributed to the several sources of uncertainty discussed before. The relatively low amplitude of this dispersion shows that as expected, those sources of uncertainties are relatively small.

Calibration strategy

Since the dispersion around the linear relation is more likely due to those uncertainties than to physical effects, the average KL_{LII}^*/KL_{LEM} coefficient obtained for a set of experiments is used to calibrate the set of LII images. The amplitude of the dispersion around the linear relation is then used to estimate the overall uncertainty of the coupled technique. The estimation of the average KL_{LII}^*/KL_{LEM} coefficient is realized on a set of measurement points with low level of soot concentration to avoid signal trapping effects. The same coefficient is then applied to measurement points of the same set with higher levels of soot concentration (indicated by the value of KL_{LEM}) for which signal trapping is more likely to occur.

It is interesting to note that as long as the collection set-up remains unchanged (collection optics, camera position and intensification gain...), the KL_{LII}^*/KL_{LEM} coefficient should also be constant when changing the engine operating conditions. This is true if the laser sheet intensity is constant or if the LII is operated in the saturated regime where the LII signal is not dependant of the incident intensity [3]. In the present work, the laser fluence was set to operate in the saturated regime.

The interest of coupling the two techniques is that it provides a way to evaluate the validity of each measurement point, in particular concerning possible signal trapping effects. Indeed, if the KL_{LII}^*/KL_{LEM} coefficient for a particular measurement point deviates from linearity more than the standard deviation, it probably indicates that this particular measurement point is not valid, i.e. that uncertainties associated with this measurement are higher than what can be expected. In particular, this would be the case for measurement conditions where signal trapping effects are significant. As a consequence, it is possible to define a confidence interval based on the determination of the deviation from linearity. The linear behaviour is defined for a set of measurement points with low level of soot concentration (in order to avoid the effect of signal trapping). The acceptable uncertainty is defined by the standard

deviation of the dispersion around the linear relation. Then for each measurement point considered, the confidence interval is defined as the ratio of the deviation from linearity versus the acceptable uncertainty. If the confidence interval is greater than two (i.e. if the measurement point deviates more than twice the standard deviation from linearity), the measurement point is considered as invalid.

An additional uncertainty that has not been discussed yet is due to the fact that the calibration determined in the measurement volume corresponding to the LEM beam path is used to calibrate the entire LII image. Since the effect of possible variation of particle size or temperature on the determination of ke or on the linear relation between soot volume fraction and peak LII signal was shown to be small in the measurement volume common to the two techniques, we do not expect a significant effect when extending the calibration to the entire LII image. However, it is possible that, due to soot concentration heterogeneities, soot concentration levels in the beam path are below the levels where signal trapping is significant, whereas soot concentration levels in the LII image outside of the LEM beam path are higher, above levels where signal trapping become significant. Some care is therefore needed when interpreting the results. To verify this aspect, it could be possible to compare the maximum LII signal inside the LEM beam path to that outside. If the latter is significantly higher than the former, the possibility of signal trapping effect is probable. This latter verification has not been performed in this work, it is a way of progress for future work.

EXPERIMENTAL

OPTICAL SETUP

[Figure 4](#) shows the experimental set-up used for coupling LII and LEM measurements in the combustion chamber of the engine.

The optical set-up for the LEM technique is based on the work of Musculus et al. [8] to minimize various possible error sources such as beam steering effect, soot incandescence interference... The laser source is a 35-mW continuous-wave (CW) HeNe laser (632.8 nm). It is transmitted horizontally through the quartz cylinder liner and combustion chamber of the engine, 6 mm below the cylinder head gasket. The laser beam is modulated using an acousto-optic modulator (AOM) driven by a 100 kHz impulsion generator. A diaphragm is used to select the 1st order of deviation from the AOM. After exiting the engine, the beam is collimated into an integrating sphere using a lens of 50 mm diameter and 200 mm focal length (FL). A diaphragm placed in front of the sphere is used to adjust the collection solid-angle; as described in next section, a 25mm spot aperture size (equivalent to 125 mrad solid-angle) was used. The role of the integrating sphere in front of the photodiode detector is to

reduce the measurement sensitivity to variations of the position and incidence angle of the inlet beam, see ref. [8] for details. A narrow band-pass filter ($\lambda_0 = 633 \text{ nm}$, $\Delta\lambda = 1 \text{ nm}$) was placed between the sphere and the detector to filter out unwanted combustion luminosity and soot emission from the 632.8 nm extinction laser. This filter was placed between two 75 mm FL lenses (telescope-mount). Between the filter and the photodiode a 45°-1064 nm-mirror was added in order to filter out unwanted 1064 nm reflections from the LII laser excitation. As shown in Figure 5, the zone where the lasers cross the cylinder liner was shifted 1mm from the centre of the chamber towards the exhaust side. This adjustment allowed the unwanted 1064 nm reflections to be minimized. The transmitted laser intensity I is measured by a photodiode coupled to a current amplifier and a phase-lock-in amplifier.

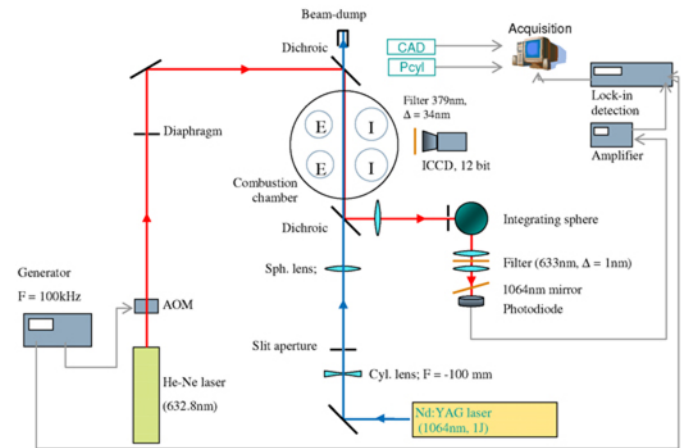


Figure 4. Optical set-up

The LII diagnostic was performed using a 1064 nm, 10 Hz (1J/pulse) Nd:YAG laser that formed a vertical laser sheet, coplanar with the 632.8 nm laser. The laser sheet in the combustion chamber was about 1 mm thick and 30 mm high so that the energy density (laser fluence) is estimated to be about 1 to 2 J/cm² (12 to 25 MW/cm²). This value was chosen because previous work has shown that for such laser fluence, and for a Gaussian beam profile (which is the case of the Nd:YAG laser), the LII signal is not dependant of the incident laser intensity, i.e. the LII is operated in the saturated regime[1, 3].

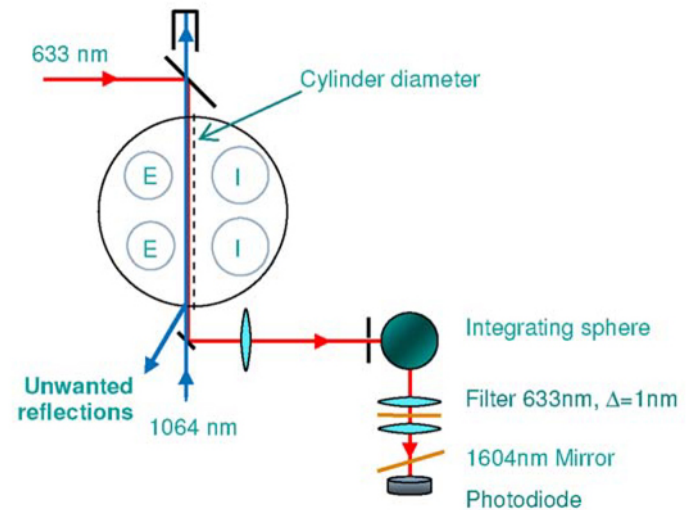


Figure 5. Illustration of the set-up used to minimize unwanted 1064 nm reflections

The evolution of the LII signal intensity versus laser fluence was not measured in the present work, mainly because obtaining such an information is quite difficult in the environment of the optical engine where significant cycle-to-cycle variations occur. Nevertheless, it was measured in another experiment where different operating conditions were investigated with a similar LII set-up. For this set-up, the observed behaviour was similar to the result observed in the literature with a Gaussian beam: the LII signal was proportional to the laser fluence up to a threshold fluence, after which the LII signal was constant with increasing laser fluence. This threshold was three times lower than the laser fluence used in the present work. This last result confirms that in the present work the LII signal is operated in the saturated regime.

In order to minimize unwanted LII laser intensity in the photodiode, the two laser beams crossed the combustion chamber in opposite directions. LII signal detection was performed with a 12bit intensified CCD camera equipped with a 50 mm / $f\#$ 1.2 objective coupled to a band pass filter ($\lambda_0 = 379 \text{ nm}$, $\Delta\lambda = 34 \text{ nm}$). Camera gate was fixed to 15 ns.

Measurements were possible from 390 to 675 CAD when the piston is sufficiently low under the cylinder head gasket to let both LEM and LII lasers pass through the combustion chamber.