

Challenges for In-Cylinder High-Speed Two-Dimensional Laser-Induced Incandescence Measurements of Soot

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ABSTRACT

Laser-Induced Incandescence (LII) has traditionally been considered a straightforward and reliable optical diagnostic technique for in-cylinder soot measurements. As a result, it is nowadays even possible to buy turn-key LII measurement systems. During recent years, however, attention has been drawn to a number of unresolved challenges with LII. Many of these are relevant mostly for particle sizing using time-resolved LII, but also two dimensional soot volume fraction measurements are affected, especially in regions with high soot concentrations typically found in combustion engines. In this work the focus is on the specific challenges involved in performing high-repetition rate measurements with LII in diesel engines. All the mentioned issues might not be possible to overcome but they should nevertheless be known and their potential impact should be considered. The measurements, which, to the authors' knowledge, are the first in-cylinder high-speed LII published to date, were made using a Multi-YAG laser system, capable of producing a burst of eight high-power laser pulses during one combustion event. A high-speed framing camera was used as detector in order to match the high repetition rate of the laser. In an initial feasibility study, high-speed LII measurements were made in a laminar ethylene/air flame to test the characteristic features of high-speed LII. Excessive influence of soot sublimation was observed in the LII signals induced by later pulses in the pulse sequence for typical pulse separations of interest in the engine (139 μ s). This is a result of that each laser pulse partly sublimates soot particles in the measurement volume,

resulting in a lower signal yield. Analysis on the data from the in-cylinder measurements does not show signs of the same behavior. This is believed to be due to high mixing and/or very fast soot formation/oxidation in the measurement volume. This implies that time-resolved LII is a suitable technique to qualitatively follow the evolution of the soot distribution inside a reacting diesel jet.

INTRODUCTION

Laser-induced incandescence (LII) is nowadays a well-established optical diagnostic technique, used mainly for soot measurements in the combustion diagnostic community [1,2,3]. The LII signal originates from soot particles heated by a laser pulse to a temperature significantly higher than the surrounding gas. The peak value of the LII signal, which occurs essentially at the same time as the intensity maximum of the laser pulse, is approximately proportional to the soot volume fraction (f_v) [4, 5], whereas the decay of the signal after the laser pulse will be dependent on the particle size [3]. There are two major ways to detect the signal; time-resolved measurements, e.g. with a photo multiplier tube (PMT), or 2D detection with an intensified CCD (ICCD) camera. From time-resolved measurements it is possible to infer both soot volume fraction and particle size, the latter by comparing the experimental results with modeled LII signals obtained using a heat and mass transfer model for the soot particles heat-up and cooling processes [6, 7]. The time-resolved measurements are, however, usually limited to point measurements. Laser sheet illumination used together with an

ICCD camera enable 2D measurements. This scheme is mostly used for soot volume fraction imaging as sufficient time resolution for time resolved 2D LII measurements would require more than one ICCD camera [8] or a high-speed framing camera [9]

In diesel engines, LII is mostly used to obtain the soot volume fraction [10,11,12] but the time-resolved approach, which may provide particle size information, has also been used [13, 14]. Notable work in diesel engines include the pioneering work by John Dec's group at Sandia National labs, USA where planar LII imaging were carried out qualitatively, but also combined with other optical diagnostic techniques such as elastic light scattering and laser-induced fluorescence, providing valuable data on how the soot formed and propagated in the combustion chamber [10, 15,16,17,18]. Challenges with optical diagnostics and LII, including attenuation of laser energy, attenuation of the light as it propagates towards the camera (signal trapping), window fouling and beam distortion, makes it hard to perform quantitative in-cylinder measurements. Despite these problems, attempts to conduct quantitative LII measurements have been made by the group at Toyota Central R&D labs [19,20,21] and other groups the years after [22,23,24]. All these works rely on calibrating the LII technique towards a known soot source, e.g. a laboratory flame. The fairly recent methodology of auto-compensating LII proposed by Snelling et al, [7], where calibration is carried out using an incandescent lamp, has been applied to derive both volume fraction and particle size in engines [25]. It should be noted, however, that all attempts to make quantitative soot volume fraction measurements with LII in diesel engines require compensation for laser attenuation as well as signal distortion and trapping. Working with low-sooting fuels these effects can be reduced, but may still introduce large errors on absolute ppm levels [22].

All aforementioned work with in-cylinder 2D LII imaging involves recording one single LII image in each engine cycle. Due to the highly stochastic nature of the combustion and fluid flow in these engines, this data cannot be compared between crank angle positions other than by its mean values or with correlation statistics. High-speed measurements, which enable tracking of the soot development in one cycle, are therefore highly relevant. In diesel engines, most of the soot mass formed during the combustion is oxidized later in the cycle. Both the formation and the oxidation process are highly dependent on the local environment where the soot particles prevail. Varying oxygen and fuel concentrations, temperature variations and the turbulent flow fields with jet-to-jet interactions make the process extremely difficult to predict. Hence, the correlation between the amount of soot formed during the early injection event and the soot in the exhaust, i.e. filtered soot number (FSN) may be quite small. Ultimately, what the researchers need is a tool to distinguish between the soot formation and oxidation rates in individual

engine cycles as function of various engine parameters. For the general case it is of course not possible to distinguish these rates just by measuring the soot volume fraction, as this quantity depends on both these rates simultaneously. However, by tracking the macroscopic soot clouds during the combustion event and combining this information with information on e.g. lift-off length and global engine parameters it should be possible to reach a stage at which the information can be correlated to the formation and oxidation rates.

This paper starts with a brief presentation of the LII technique. Challenges with LII measurements in combustion engines are then discussed together with some solutions with focus on the specific challenges introduced when pursuing high-repetition rate measurements. Thereafter, high-speed LII measurements in an atmospheric laminar ethylene/air flame are shown. Finally, measurements resulting in series of cycle-resolved 2D LII images of soot in a heavy duty diesel engine are presented and discussed. Influence of signal trapping and laser attenuation on the data has also been investigated.

THEORETICAL CONSIDERATIONS

Measurements of soot volume fraction using LII in diesel engines have been done extensively before (see for example [10, 17, 22, 26]). However, the concept will be briefly recapitulated here. The LII signal is created by a laser pulse heating particles to a temperature significantly higher than the surrounding media. The upper limit of the soot particle temperature is ~ 4000 K. At this temperature sublimation of mainly small molecules (e.g. C_2 and C_3) from the soot particles limits further temperature increase [27]. Measurements of the Soot volume fraction are usually conducted at high laser fluence (energy in each laser pulse per unit area). The reason for this deliberately intrusive approach is that it provides the experimentalist with certain advantages when compared to low-fluence LII. Firstly, the signal yield is higher than for LII at low fluence. Secondly, the LII signal dependence on the laser pulse fluence can be minimized, which means that the signal, to a certain degree, will be unaffected by laser intensity fluctuation and laser extinction through the sample [3, 28]. In the low-fluence regime there is a strong non-linear dependence between LII signal and pulse energy. In the high-fluence regime, however, the peak temperature of the soot particles will be nearly unaffected by the laser pulse energy, with excess energy going into the sublimation process reducing the mass of the particles. Using a Gaussian or near-Gaussian spatial laser beam profile it is possible to achieve a saturation level, where variations in the laser pulse energy do not alter the LII signal yield. This is usually called the plateau regime as a typical plot of LII signal vs. laser fluence would show a plateau. It is important to note that the shape of the fluence curve depends on the spatial profile of the laser beam [28]. Hence, it is not always straightforward to obtain a plateau. Although the

individual energy loss mechanisms vary somewhat with ambient pressure, the shape of the fluence curve has been found to be relatively unaffected by pressures up to 1.5 MPa [29].

Soot particles behave similar to grey bodies, i.e. they show a spectrally broad-band emission which can be described by the Planck radiation law combined with a suitable expression for the particle emissivity [27]. Since the laser-heated soot particles are much hotter than the surrounding gas their emission spectra are blue shifted compared to the surrounding cooler particles. The blue-shifted light is collected as the LII signal, in IC engines usually at wavelengths in the UV/blue region where the contribution from flame luminosity can be minimized. Many laser wavelengths can be used for LII as soot absorbs in a spectrally broad region. Shorter wavelengths should, however, be avoided due to the risk of inducing fluorescence, especially from polyaromatic hydrocarbons (PAH) [3]. Traditionally the 532 nm second harmonic from a Nd:YAG laser has been extensively used, not least in engine work [15, 17]. However, it has been found that the risk of introducing interferences exists also at this wavelength and general recommendations nowadays is to use longer wavelengths, for example the 1064 nm radiation from a Nd:YAG laser [3]. In this work the 532 nm wavelength had to be used for technical reasons, which will be explained later in the section: Laser and Camera Setup.

For imaging LII measurements, detection is usually prompt, i.e. during a short time period overlapping the laser pulse. It has been shown that the soot volume fraction is approximately proportional to both the time-integrated signal and the peak signal level [4, 5]. Delayed detection is possible, but one should be aware that the assumption of linearity between LII signal and soot volume fraction is violated, especially for measurements at high-pressure conditions. For quantitative measurements delayed gating should therefore be avoided [4]. To suppress background contribution from the chemiluminescence and Planck radiation from the combustion, optical filters and a gated ICCD camera are used to filter the signal both in the spectral and temporal domain [3]. In this paper engine measurements are presented where the LII signal is integrated over 50 ns. This covers the entire soot particle radiation period as the elevated pressure in the engine makes the LII signal very short (on the order of 20 ns at 5 MPa) [4, 22].

There are several challenges with applying LII, a technique developed mainly at atmospheric conditions, to engine conditions where the pressure is elevated and the flow fields are turbulent and stochastic creating large, highly inhomogeneous, soot volume fractions. The challenges can be divided into two parts: general issues and challenges directly related to the LII technique. Issues introduced for all optical measurements in these harsh environments, such as influence of laser attenuation, signal trapping, strong

combustion luminosity, excessive window fouling and beam distortion both due to the sharp temperature gradients and due to the often curved optical parts in the engine [30,31,32]. These issues make it extremely challenging to perform quantitative measurements with an optical technique without compensating for the effects using additional measurements aiming to quantify the influence of the respective issue on the LII signals. Many of these effects are spatially inhomogeneous and three-dimensional measurements are required to compensate for them [32, 33]. For LII, the effect of laser extinction can be mitigated by carefully selecting appropriate laser profile and laser fluence so that measurements can be made where the LII signal is not dependent on the laser pulse energy (the plateau region).

There are also challenges directly related to the LII technique, some of these being the aforementioned interferences from PAH [34], the slightly non-linear behavior of the LII signal versus soot volume fraction [4] and the influence of the spatial profile of the laser on the LII signal response as function of laser energy [3, 28]. The last mentioned effect, which has its origin in laser-induced soot sublimation, is especially important when performing crank-angle resolved measurements. As previously mentioned, soot volume fraction measurements are usually conducted at high fluences ($>0.2 \text{ J/cm}^2$ at 532 nm), and high-fluence LII is intrinsically intrusive. The particles are heated to the sublimation temperature, which results in a significant reduction in soot mass in the measurement volume leaving the particles smaller after the laser pulse, a fact that was known already in the 80's when it was proposed to be used for velocity measurements [35]. Additionally, the particles have been shown to have compositional changes as a result from the rapid heating [36, 37], changes that are likely to affect their optical and physical properties and the LII signal with it. This was systematically investigated by Vander Wal et al. using double-pulse measurements in an atmospheric flame [37]. Two pulses from a Nd:YAG laser were aligned into the same measurement volume and fired with a time separation of 10 μs . The peak LII signal and the decay time of the time-resolved signal originating from the second laser pulse were both found to decrease with increasing laser fluence in the first laser pulse - a sign of particle size reduction due to sublimation of soot matter [37]. Time-resolved light scattering measurements during LII measurements by Yoder et al. have also indicated a reduction in soot volume fraction for high fluences [38]. They also showed that the reduction is temporally coincident with the incident LII laser pulse. Apart from affecting the soot particles themselves, the sublimation process also alters the concentration of molecular carbon radicals in the surrounding media and its influence on the kinetics cannot be ruled out.

The sublimation issues discussed above are not readily encountered for single-shot in-cylinder measurements where

fresh soot is available in the measurement volume at each laser pulse. However, when making several LII measurements with high repetition rate in the same engine cycle, the risk of multiple measurements on the same soot particles increases. Consecutive measurements within a period of time shorter than the general timescale of the flow might thus show a decline in soot volume fraction caused by the preceding measurements. Questions which remain unanswered are (1) how severe this problem would be in a diesel engine, and (2) how the LII signal would behave for more than 2 consecutive laser pulses. The considerably higher flow speeds and higher levels of turbulence during the combustion in a diesel engine will transport new soot particles into the laser sheet between laser pulses making the effect of previous sublimation less of an issue. Additionally, the sublimation effect is expected to be somewhat diminished in an engine. The higher pressure (60-70 bars) will result in greatly increased heat conduction to the surrounding medium from the laser heated particles. This will make the sublimation a less important energy loss mechanism for moderate laser fluences and thus the effect of sublimation from previous pulses is expected to be less significant compared to what would be the case in an atmospheric flame [4].

The results presented in this paper are qualitative. It was not considered possible to make the necessary compensations for the quite large errors that could potentially be introduced due to the attenuation, signal trapping, combustion luminosity and window fouling with adequate levels of uncertainty.

LASER AND CAMERA SETUP

High speed 2D LII measurements require several high energy laser pulses to be fired within a very short time period. This is achieved in these measurements with a Multi-YAG laser cluster like the one shown in [Figure 1](#).

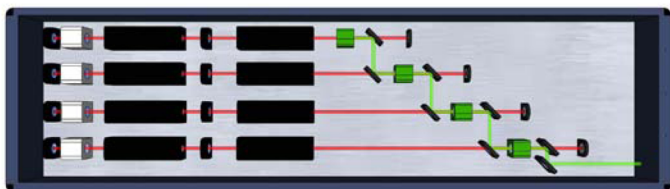


Figure 1. Sketch of the Multi-YAG laser cluster in 532 nm configuration.

The Multi-YAG laser cluster is composed of four Nd:YAG lasers producing 1064 nm laser radiation with a repetition rate of 10 Hz. The beams are combined into one beam using a specially designed doubling and recombination scheme as shown in [Figure 1](#). The beam from the first laser (top red line in [Figure 1](#)) is frequency doubled to 532 nm using a second harmonic generating (SHG) crystal. It is then separated from the fundamental 1064 nm beam and overlapped with the next 1064 nm beam from the second laser using two dielectric mirrors reflecting 532 nm radiation. The combined beam is then sent through a second SHG crystal where the fundamental from the second laser is frequency doubled to 532 nm but the first beam is left unchanged as the phase matching condition in the crystal is satisfied for 1064 and not for 532 nm. This scheme is repeated for the following two lasers so that a single beam with a wavelength of 532 nm is the output from the laser. Since all four lasers can be double pulsed, this setup can produce a train of eight laser pulses with time separations between 5 and 440 μ s (for equidistant time spacing of the pulses) and pulse energies up to 1.4 J/pulse. The overlapping of the laser beams as described above requires frequency conversion. Hence, in the measurements presented here, 532 nm laser radiation is used. Some of the parameters of this Multi-YAG can be seen in [Table 1](#). A more in depth description of a Multi-YAG laser system can be found in [39].

Table 1. Multi-YAG laser cluster parameters.

Laser type	4 Nd:YAG lasers,
Fundamental wavelength	1064 nm
Output wavelengths	532, 355 and 266 nm
Repetition rate	10 Hz
Pulse length	8-10 ns
Beam profile	Elliptical (10 by 12 mm), multimode
Pulse separation 4 pulses	$100 \text{ ns} < \Delta t < 25 \text{ ms}$
Pulse separation double pulse operation	$5 \mu\text{s} < \Delta t < 400 \mu\text{s}$
Maximum pulse energy at 532 nm for overlapping pulses	4 pulses: ~930 mJ/pulse 8 pulses: ~330 mJ/pulse

During the engine experiments the pulse separation is set to 139 μ s. This gives one crank angle degree (CAD) between the images as the engine is operated at 1200 rpm. A sketch of this pulse train can be seen in [Figure 2](#). A pulse separation of 139 μ s also allows the Multi-YAG laser to operate at the necessary high pulse power needed to produce the required fluence for the 2D LII measurements. For the flame measurements the time separation is varied but is to a large extent kept at 139 μ s for comparability.

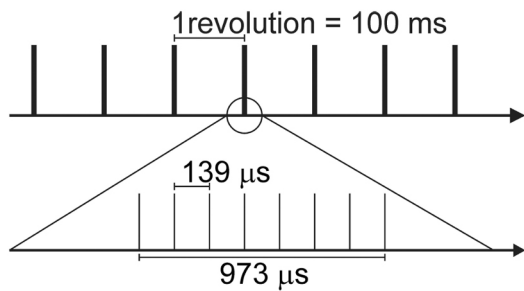


Figure 2. Laser pulse train timing. 139 μ s correspond to 1 CAD at 1200 rpm.

In order to detect the LII signal generated by each of the laser pulses in the burst from the Multi-YAG system, a high-speed framing camera, SIM 8 from Specialized Imaging, is used. This camera has a Bernard-Halle quartz lens ($f = +100$ mm, $f/2$) mounted in front of the single optical input. A fast image intensifier (P46 phosphor, 300 ns decay time) is placed directly after the optical entrance of the camera in order to enhance the sensitivity and to enable UV detection. The intensified signal is then split up using seven 50-50 beam splitters onto the eight individual intensified CCD modules. This setup ensures minimal optical aberration in each image and good spatial overlap between the images. Each CCD module consists of a micro channel plate intensifier and a CCD image sensor with 1280×960 active pixels. Each intensifier module further amplifies the signal and function as shutter ensuring that each CCD only detect signal from the one laser pulse that it is synchronized with.

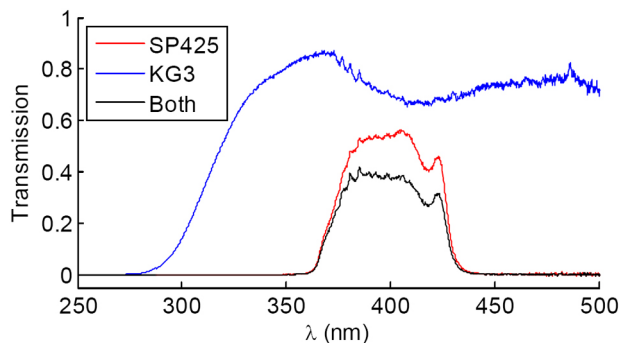


Figure 3. Transmission through the detection filters. During the engine measurements the KG3 filter was added to minimize the detection of background luminosity from the diesel flame.

The camera is for the LII measurements equipped with two optical filters. A band pass filter (SP425) which transmits between 372 and 427 nm, as seen in Figure 3, allows the LII signal to be detected and blocks both the laser light at 532 nm and most of the light from the combustion process. In order to minimize detection of infrared radiation from the combustion process a Heat-absorbing KG 3 filter is also used. Figure 3 do not show the IR region where the KG 3 filter is mainly useful

due to technical limitations in the optical setup used to measure the transmission curves.

FLAME MEASUREMENTS AND OPTICAL SETUP

An initial study is conducted in order to investigate any issues that could be found with high-speed LII measurements. For this study an atmospheric, sooting ethylene/air flame with $\Phi = 2.1$ on a McKenna burner [6] is selected as an initial test case. The flame is laminar and has a thoroughly studied soot distribution. All measurements are carried out using a laser sheet with a constant energy distribution as a function of height. However, as the energy profile of the laser sheet along the width of the sheet (along the line of sight for the camera) influences the LII signal, several such distributions are tested in the flame. First, a sheet formed by a cylindrical $f = -200$ mm and a spherical $f = 1000$ mm lens is used. The resulting curves can be seen in Figure 4. This setup is found to give an increasing LII signal as a function of fluence and no plateau region can be observed. This is most likely due to large wing effects in the laser beam profile along the width at the focal plane [28].

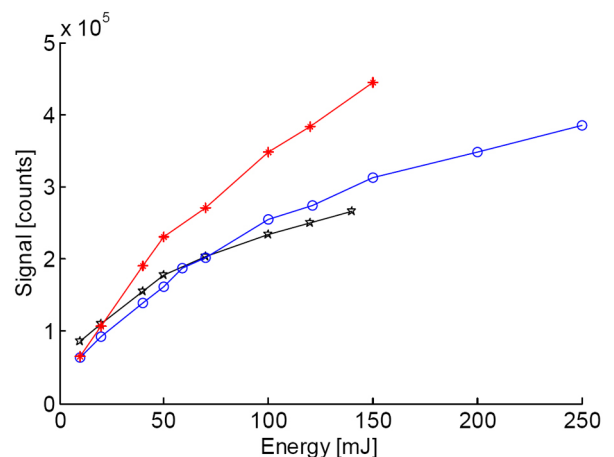


Figure 4. LII signal as a function of laser pulse energy for three of the lasers in the Multi-YAG. The laser sheets are focused in the horizontal direction in the middle of the flame using a $f = 1000$ mm lens and are 20 mm high.

Consequently, this first optical setup was abandoned for a slightly more complicated setup producing a spatial energy profile along the width of the sheet that more closely resembles a top hat. Figure 5 shows the optical components as they are positioned in the engine measurements. For the flame measurements discussed in this section the optical components are rotated 90 degrees around the laser beam to produce a vertical laser sheet.