Sub Topic: Diagnostics

SAND2019-12421C

2019 WSSCI Fall Technical Meeting
Organized by the Western States Section of the Combustion Institute
October 14–15, 2019
Albuquerque, New Mexico

# Analysis of Laser Focusing Effect on Quantification of LII Images

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**Abstract:** Laser-induced incandescence (LII) is now a widely applied technique for measuring soot concentrations in flames, exhaust streams, and the atmosphere. For flame applications LII is frequently deployed as a planar diagnostic to yield the two-dimensional soot field. Unfortunately, the complex laser power dependence of the LII signal generation process introduces a significant variation in LII signal intensity across an LII image when the laser sheet is focused, as is typical. Here, we quantify that effect as a function of laser pulse fluence for LII excited with 1064 nm YAG laser light focused with a 1 m focal length lens. Further, we have measured the cross-sectional energy distribution in the laser sheet as it approaches the focal point and expands away from it, to correlate the details of the laser sheet focal properties with the resultant LII behavior. The results show that a unique laser fluence level exists whereby there is essentially no radial dependence of LII signal. However, at lower or higher fluences, the radial signals either decrease (low fluence) or increase (high fluence) rapidly with increasing radial position away from the focal point. For measurements using an LII 'plateau' laser fluence level, as is usual in environments with significant instantaneous optical depth (i.e. sufficiently strong soot levels), the LII signal is 2.5X larger 40 mm away from the focal point.
***Keywords: soot, laser-induced incandescence, laser, focus***

## 1. Introduction

One of the advantages of using laser-induced incandescence (LII) to measure soot concentrations is its ability to instantaneously sample a two-dimensional (or even three-dimensional) soot field through planar imaging of the LII signals. In such applications, an optical configuration is used to form a planar laser sheet that is typically brought to a focus at the image plane to achieve the necessary laser intensity to substantially heat the soot particles and excite LII. Many laser diagnostics often operate in a linear excitation regime, wherein the focusing effect of the laser has no impact on the magnitude of the resultant signals, as long as the laser beam thickness in the imaged region is always substantially less than the depth of field of the imaging optics, which is generally the case. However, LII has a highly nonlinear and complex laser excitation dependence, because of the interaction of laser absorption, convective loss, and particle mass removal on determining the instantaneous particle temperature, as well as the inherent non-linearity of the Planckian thermal emission that generates the measured signals [1-3]. Furthermore, the complex temporal dynamics of LII signals means that LII signals are typically integrated over a finite time interval that includes at a minimum the entire duration of the laser excitation pulse (particularly for imaging applications, wherein a gated image intensity is typically used), such that the dependence of LII signals on laser intensity is expressed on the basis of the laser pulse fluence.

Figure 1 shows simulated LII laser excitation curve for signals generated at the focus of laser beams or sheets. The top-hat response represents the idealized case wherein there is no spatial variation of laser intensity, in which case the depletion of soot mass during the laser pulse for high fluence levels actually results in a decreasing amount of LII signal. A Gaussian sheet has a Gaussian energy distribution in one dimension, such that at higher laser fluence levels the decreasing signal contributions from the center of the sheet (which is locally following the top hat fluence dependence profile) are almost exactly offset by additional signal contributions from the wings of the Gaussian. A Gaussian beam, on the other hand, has expanding contributions of LII signal generation in full 2-D space as the laser fluence increases, which more than offsets the decreasing LII signal generated from the center of the beam.

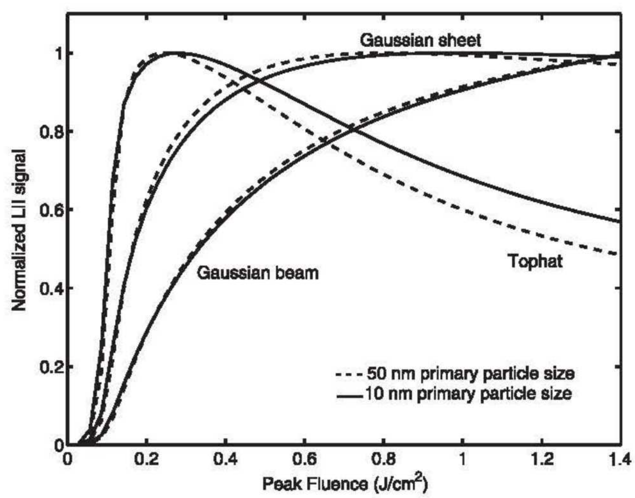


Figure 1: Calculated LII fluence dependence as a function of the spatial distribution of the laser beam and primary particle size, using a 100 ns detector gate that opens before arrival of the laser pulse [4].

One can apply these same concepts to understand what happens as a laser sheet expands (and thereby locally reduces its fluence) away from the focal point. Because the LII signal generation for a Gaussian sheet is relatively constant with fluence level, once a suitable fluence level has been reached, if the fluence at the focal point is above this critical fluence, moving away from the focal point will result in greater LII signal, as a broader region of soot will be heated by the laser pulse and therefore contributing to the incandescence signal. Indeed, Shaddix and Smyth [5] first reported this phenomenon in 1993, as shown in Fig. 2, wherein a 20% increase in LII signal was evident 10 mm away from the focal point and even larger increases in signal magnitude occurred for some distance further away. As large as this signal correction was, subsequent LII imaging studies have not investigated or accounted for this phenomenon, perhaps under the belief that by using a longer wavelength laser excitation (e.g. at 1064 nm) and/or a longer focal length lens that it would become insignificant.

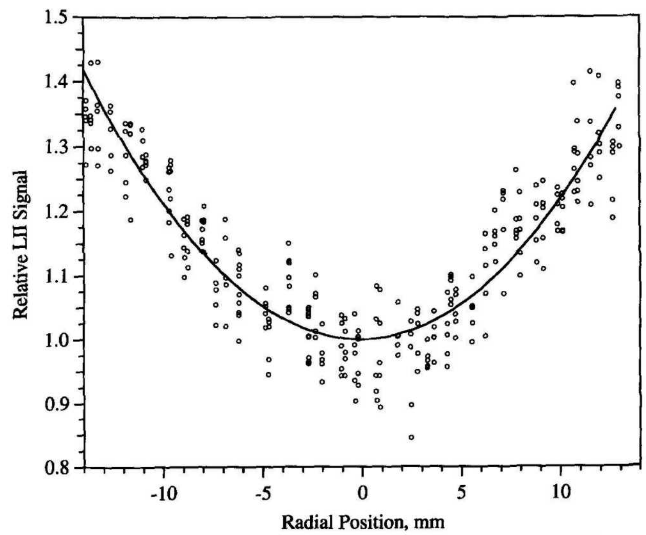


Figure 2: Measured LII signal dependence as a function of radial position in a line image of LII for a Gaussian laser beam [5]. The estimated fluence level at the focal point was 5.0 J/cm$^2$ and the 560 nm laser beam that excited the LII was focused with a 300 mm focal length lens.

In the study reported here, a 1064 nm laser excitation source and a 1 m long focal length optical system is used to investigate the magnitude of the effect of laser sheet focusing on LII imaging signals when using this common excitation wavelength and a typical extent of laser sheet focusing. Further, to develop a concrete understanding of how the details of the laser focusing properties affect the LII signal, the laser sheet cross-section has been imaged at discrete locations as it approaches and moves away from the focal point.

## 2. Methods / Experimental

To investigate the laser focusing effect on LII imaging, a non-premixed jet flame burner was used to establish both laminar and turbulent oxy-fuel methane flames. The burner consists of coannular fuel and oxidizer tubes surrounded by a well-conditioned air stream flowing at 0.49 m/s to provide a stable flame environment and establish definitive boundary conditions. It has been previously described in detail in the literature [6]. For the current study, both laminar and turbulent flames were established of methane burning in 50% $O_2$ in $N_2$. The turbulent flame had a visible flame height of approximately 60 cm and a fuel tube Reynolds number of 7700 (mean fuel exit velocity of 38 m/s), surrounded by oxidizer with a Reynolds number of 3700 (mean oxidizer exit velocity of 10.4 m/s). Figure 3 shows a schematic of the burner, a visible flame image of the turbulent jet flame, and a corresponding stacked-image representation of the mean soot volume fraction, as determined from calibrated LII.

The laser-induced incandescence was excited using the fundamental (1064 nm) output from an injection-seeded 10-Hz Nd:YAG laser that was subsequently expanded into a two-dimensional beam and mildly focused at the burner, as shown in Fig. 4. To vary laser power without otherwise perturbing the laser characteristics, a half-wave plate was used, in conjunction with a glan laser polarizer. An iris placed downstream of the polarizer provided a modest amount of clipping of the outer edge of the laser beam. To image the laser sheet energy profile as it approached and departed from its focal point, a WinCamD CMOS laser beam profiling camera was placed on a horizontal translation stage downstream of a beam sampler, which reflected 1% of the incident laser sheet. A combination of an ND4 and an ND1 filter were placed in front of the camera to further reduce the laser power to an acceptable level. 64 individual laser shots were collected at each location to define mean laser sheet profiles. The camera has an 11.3 mm x 11.3 mm square sensor, divided into 2048 pixels in each direction (5.5 μm pixel dimension). To interrogate the full height of the laser sheet, the camera was mounted on a lab jack and vertical images were stacked together.

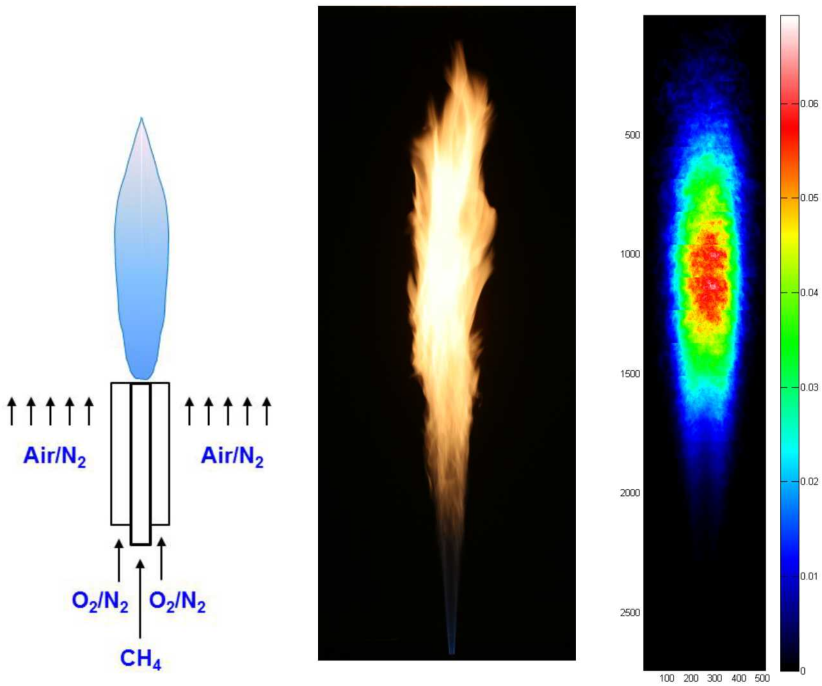


Figure 3: Schematic of the oxyfuel jet flame burner (left), photograph of the turbulent methane flame burning in 50% $O_2$ (center), and mean soot volume fraction measured for this flame (right). The units of the false color scale for soot volume fraction are ppm.

LII signals were collected using a Princeton Instruments fast-gating PIMAX CCD camera, with 512 x 512 pixels and a HQf GEN III intensifier. A 600 nm low-pass filter was placed in front of the camera, to distinguish LII signals from flame luminosity, and a prompt 100 ns gate was employed. Calibration of the processed LII images for soot volume fraction was performed by comparing the LII field measured for a laminar $CH_4$ flame against 532 nm cw laser extinction measurements in the same flame that were tomographically inverted using the 3-pt Abel technique. Further details are provided in ref. 6.

To investigate and verify the laser focusing effect on LII signals, measurements were made in a laminar methane/50% $O_2$ flame, a turbulent methane/50% $O_2$ flame, and a turbulent ethylene/air flame. For the laminar flame, the soot field formed more or less vertical profiles on either side of the burner centerline (for intermediate flame heights), allowing the radial variation in LII signals to be measured by translating the burner (and thus these vertical profiles) to the right and left. For the turbulent flames, the mean LII signals were interrogated, and they showed a broad peak about the burner centerline at mid-height in the flame (as evident in Fig. 3). Thus, translation of the burner allowed one to track variations in the intensity of the LII signal in the middle of the flame. In all cases, the LII imaging camera was fixed, as it had a field of view of 90 mm width at the flame, allowing ample side-to-side translation of the burner while still measuring the LII signals.

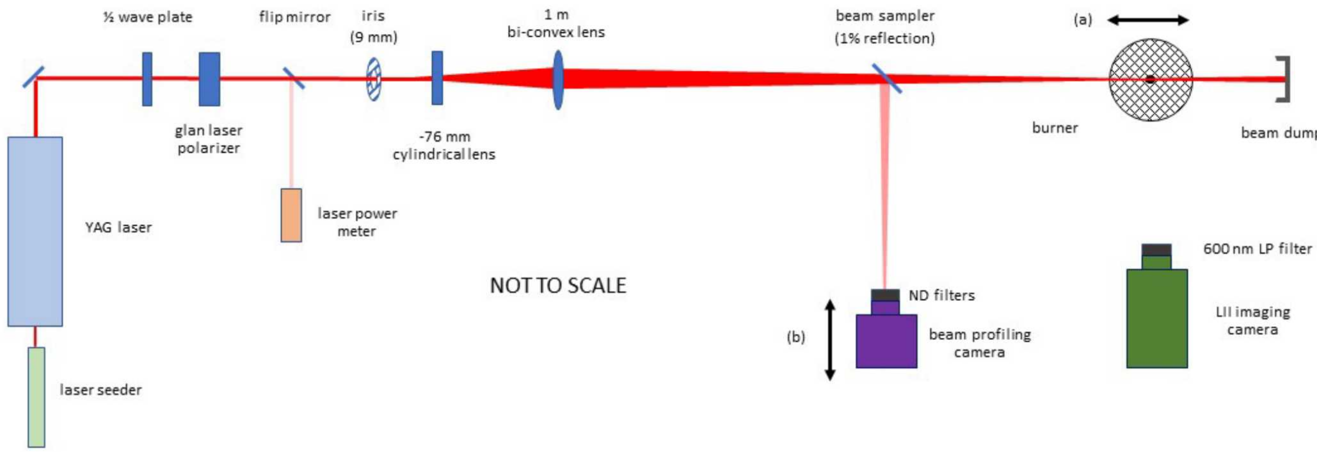


Figure 4: Schematic diagram (from an overhead view) of the configuration used to excite the LII signals in the flame and to image the variation in the 2-D laser sheet as it approaches and recedes from its focal point. The two arrows indicate (a) the movement of the burner to translate LII signals across the LII imaging camera, and (b) the movement of the laser beam profiling camera to capture the variation in the laser sheet energy distribution as the beam approaches and recedes from its focus.

## 3. Results and Discussion

The same trends in LII signal variation with radial position on the LII imaging camera (i.e. relative to laser focusing) were evident in all cases. In this paper, only the results for the laminar methane flame are shown, as they show less 'noise' than the results for the corresponding turbulent flames. Figure 5 shows the variation in LII signal as a function of laser power and distance downstream from the laser sheet focus. There are several things to note in this figure. The first is that the LII fluence dependence at the laser sheet focus (corresponding to the curve labeled '0 mm') shows a decrease in signal after an initial signal peak is reached, consistent with a number of previous experimental measurements (e.g. ref. 7) and with the theoretical modeling reported in ref. 4. As one moves downstream from the laser focus, the laser power level at which the LII signal peaks increases, together with a corresponding increase in the LII signal. This can be explained according to two phenomena: (a) the soot in the strongest portion of the beam is experiencing less evaporation and emitting stronger LII signals (i.e. there is less 'signal bleaching'), and (b) the physical expansion of the laser sheet in the tangential direction away from its focus results in excitation of a thicker segment of soot. For a given laser power, one can plot the variation in LII signal with position relative to the laser sheet focus, as shown in Fig. 6, for a laser power of 5 W (i.e. 500 mJ/pulse, corresponding to a laser fluence at the laser focus of approximately 0.6 J/cm$^2$). This laser fluence is the type of fluence one would typically use for making LII measurements in strongly sooting flames (with significant laser beam absorption) in order to keep the LII signal fairly impervious to instantaneous decreases in laser intensity [7]. As shown in Fig. 6, soot that is imaged 40 mm away from the flame centerline has **2.5x higher LII signal** (i.e. 2.5x higher indicated soot volume fraction) than soot imaged on the flame centerline. Clearly, this is a major factor impacting the quantification of LII images, particularly in turbulent flames, wherein the soot containing regions often extend 40 mm from the flame centerline [7].

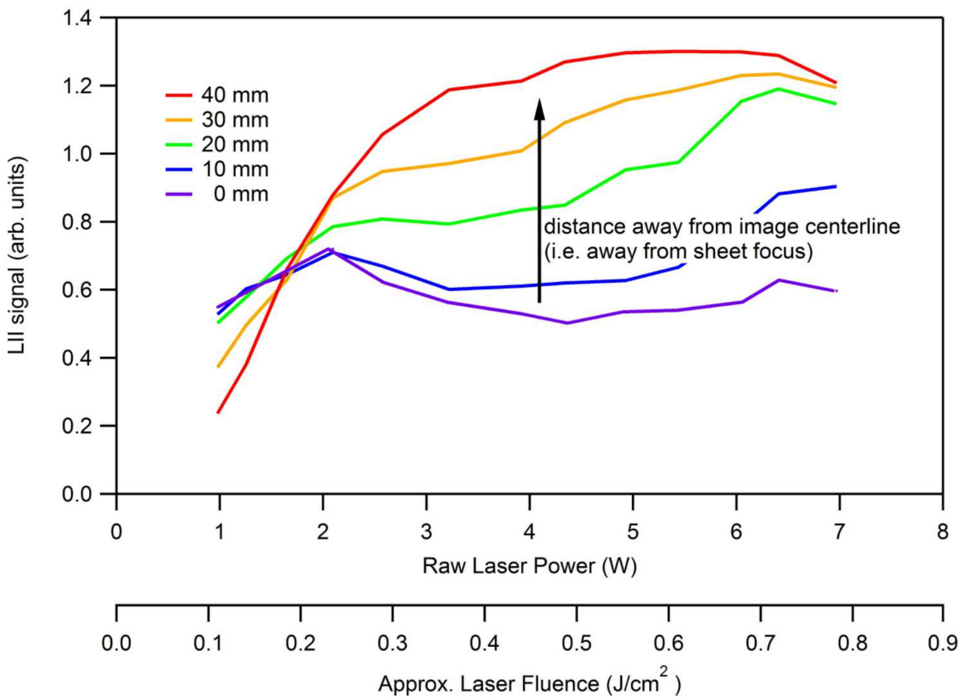


Figure 5: Relative LII signal measured as a function of laser power, for soot at different positions relative to the focus of the laser sheet (i.e. the curve denoted as ’40 mm’ refers to soot that is located 40 mm downstream of the laser sheet focus). The approximate laser fluence shown on the abscissa refers to the fluence at the laser sheet focus.

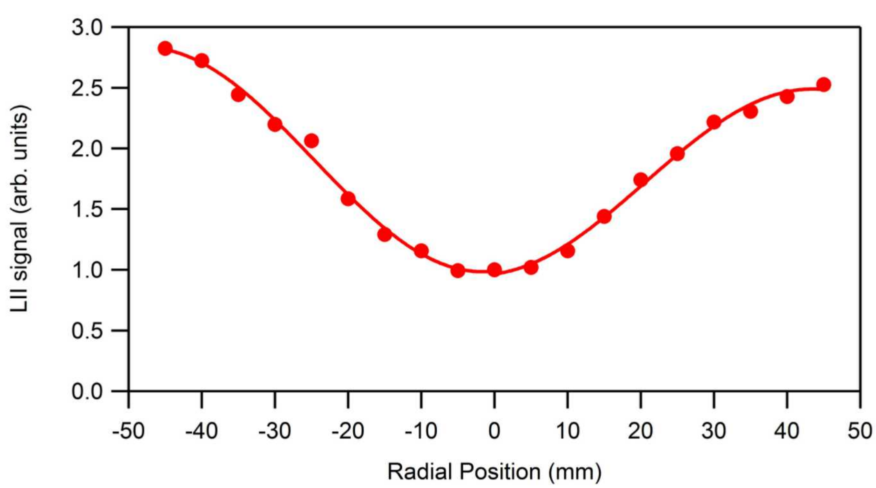


Figure 6: LII signal variation with position relative to the laser sheet focus, for a laser power of 5 W.

It is evident from Fig. 5 that using lower laser powers reduces the impact of the beam focusing effect on the LII signals, as indeed one would expect, because the signal bleaching effect is reduced and the opportunity to sufficiently excite a thicker segment of soot with an expanding beam decreases. Indeed, for a laser power of 1.8 W (or a laser fluence of 0.2 J/cm$^2$), there is almost no dependence of LII signal on the position of the soot relative to the laser focus. For imaging in low-sooting flames, this would be the preferred fluence to use, as long as the shot-to-shot laser power is quite steady.

For LII imaging in flames with significant laser absorption, it is important to excite the LII with a laser fluence that is somewhat greater than the threshold fluence that leads to peak LII signals at the laser sheet focal point, because with threshold fluence excitation any absorption of the beam would result in a rapid drop in LII intensity. Conveniently, Fig. 5 shows that for laser excitation intensities between 3 and 5 W, the LII intensity measured at different positions relative to the laser focus is relatively constant, meaning that a radial dependence profile such as shown in Fig. 6 is at least approximately accurate over this range of laser powers (one could plot out the deviation in radial dependence across this range of laser powers from the data in Fig. 5). Thus, one can employ a laser excitation of 5 W together with the radial correction shown in Fig. 6 to give approximately correct apparent soot volume fractions, as long as there is no greater than 40% absorption of the laser beam.

Currently, the measured laser sheet energy profiles are being analyzed as the laser sheet approaches and recedes from the laser focus. Fig. 6 shows that there is some asymmetry in the LII signal dependence approaching and receding from the focus, which should be explainable from the measured laser sheet profiles.

## 4. Conclusions

This work has investigated the variation in LII signals as a function of laser sheet position relative to its focal point, using a standard focusing lens with a 1 m focal length. For laser energies exceeding the ‘threshold’ LII fluence wherein soot particle vaporization presumably becomes important, a strong sensitivity is found in LII signals as one moves away from the laser focus, resulting in a factor of 2.5 variation in apparently soot concentrations when imaging soot 40 mm away from the burner centerline. When performing LII imaging measurements in lightly sooting flames, it is recommended to use the threshold laser fluence. On the other hand, for flames in which significant laser absorption occurs, it appears best to use a high fluence that yields ‘plateau’ fluence dependence over a range of positions relative to the focal point and to correct for the apparent radial dependence in LII signals on the imaging camera.

## 5. Acknowledgements

Support for this research was provided by Sandia National Laboratories’ Laboratory Directed Research and Development program. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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