# Ultra-fast Structured Laser Illumination Planar Imaging (SLIPI) for single-shot imaging of dense sprays

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**Abstract**

Recently, a novel imaging technique, called **S**tructured **L**aser **I**llumination **P**lanar **I**maging (SLIPI), has demonstrated great potential for the suppression of the multiple light scattering in spray imaging. The method uses a laser sheet which is modulated in the spatial domain. Photons which are directly scattered keep the structural information of the laser sheet; whereas, the photons that have experienced several scattering events lose this information, resulting in a variable offset on the recorded image. Using a spatially modulated incident light thus enables the directly scattered photons to be distinguished from the multiple scattering intensity contribution. However, to homogeneously illuminate the spray, three images are required, where the modulation of the incident laser beam is successively shifted one third of a period vertically. By adequately post-processing the three images the multiple scattering contribution can be diminished. However, the time interval within which these images are recorded must be short enough to freeze the flow motion, making "single-shot" SLIPI of highly atomizing sprays particularly challenging. In this article, we present an ultra-fast SLIPI system with the capability of freezing flow motions up to ~600 m/s. The instrument was tested on a hollow-cone water spray, running at 50 bar injection pressure, and high resolution single-shot images, in which multiple scattering effects were efficiently suppressed, were obtained. Such images provides detailed information of complex dynamic flow behavior occurring in the dense spray region, e.g. primary and secondary break-ups. In addition, we demonstrate that the RMS extracted from such single-shot SLIPI images enables statistical investigations of the break-up process as well as a better estimation of the liquid sheet length.

## Introduction

Planar laser imaging is widely employed in the field of spray diagnostics in order to provide qualitative and quantitative two-dimensional information on spray structures. During the past three decades an extensive number of planar imaging techniques have been developed, enabling different physical quantities to be measured [1-6]. Although these techniques use different properties of light scattering and approaches, one common approximation is to assume that the detected photons have only experienced one scattering event prior to detection. However, in the dense spray region and/or inside the spray, a large amount of photons are multiply scattered and the single scattering approximation is no longer valid. By using a new technique named **S**tructured **L**aser **I**llumination **P**lanar **I**maging (SLIPI), it has been recently demonstrated [7] that an increase in image contrast from 55% up to 80% could be obtained from averaged images of a hollow-cone water spray. Although these averaged images provide useful information, single-shot imaging is of fundamental interest for the analysis of flow dynamics. One direct application of single-shot imaging is the study of liquid break-up and atomization processes as well the determination of liquid flow velocity vectors. The major restricting factor for applying SLIPI on a single-shot basis is because the technique requires three images to be recorded successively. During this acquisition time the liquid flow motion must be frozen in time in order to obtain a so-called "single-shot" image. To date, such a measurement has only been performed for the study of a nebulizer, with water droplet velocities below 25 cm/s [8]. In highly atomizing sprays (e.g. Diesel sprays) the liquid flow can reach velocities above 200 m/s and the time interval within which the three images are recorded must be in the order of $\sim 1 \cdot 10^{-7}$ s (depending on the magnification). In this article, an ultra-fast SLIPI system is presented which enables single-shot imaging of such highly pressurized spray systems. The capability of the system is demonstrated here on a hollow-cone water spray with an injection pressure of up to 50 bar. It is shown that suppression of multiple light scattering by means of SLIPI results in higher image contrast and structures, such as voids and break-ups, which are concealed when using conventional planar laser imaging becomes visible.

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**Structured Illumination for planar imaging**

Structured illumination is a method developed in the field of microscopy [9] in 1997. The purpose of the technique was originally to remove, from a line-of-sight optical arrangement, the blurring effects induced by the detected out-of-focus light. In contrast to line-of-sight measurements, laser sheet imaging should in principle contain no out-of-focus light as the entire source is within the depth-of-field of the detection system. This is however only true as long as each photon undergoes only one scattering event prior to detection (i.e. optical depth below one). As optical depth increase, photons are multiply scattered within the sample and will appear to be originating from out-of-focus parts. Due to this similar effect, structured illumination can be implemented on a side scattering arrangement to suppress the unwanted contribution from multiple light scattering. The basic principle for planar structured illumination is to use an intensity modulated (in the spatial domain) laser sheet (see also Ref. [7] and [8]). Such a modulation can be created by projecting a transmission grating onto the sample of interest, leading to an image according to

$$I(x, y) = I_C + I_S \cdot \cos\left(2\pi \nu y + \phi_0\right), \tag{1}$$

where $x$ and $y$ denotes the spatial coordinates, $\nu$ is the modulation frequency and $\phi_0$ is an arbitrary spatial phase. $I_C$ and $I_S$ both describe the illuminated sample but are extracted differently. The first image, which later will be referred to as the *conventional* one, is the result of homogeneous laser sheet illumination and contains therefore both singly and multiply scattered light. As a consequence of detecting diffuse light, structures present in the illuminated sample will appear blurred. Additionally, pixel intensities are not fully trustworthy as multiple light scattering may either lead to an intensity contribution or reduction. Apart from degrading the image quality, multiply scattered photons are incapable of sustaining any structural information contained within the laser sheet (unlike singly scattered ones). Thus, when illuminating a sample with an intensity modulated laser sheet, only singly scattered light will properly depict this modulation whereas the diffuse light will appear as a non-modulated position-dependent intensity offset. Extracting only the part of $I(x, y)$ that is modulated therefore results in an image mainly constructed from directly scattered light. This is accomplished by recording three images, with a relative phase difference of 120 degrees, and by summing the absolute value of the pair-wise difference as shown in Eq. (2).

$$I_S = \frac{\sqrt{2}}{3}\sqrt{\left(I_0 - I_{120}\right)^2 + \left(I_0 - I_{240}\right)^2 + \left(I_{120} - I_{240}\right)^2} \tag{2}$$

In this equation, the subscript indicates the spatial phase of the modulation in degrees. By instead extracting the mean of the images, the conventional image is created according to

$$I_C = \frac{I_0 + I_{120} + I_{240}}{3} \tag{3}$$

The implementation of Eq. (2) and (3) allows a comparison between the conventional technique (homogeneous laser sheet) and SLIPI and the effectiveness of structured illumination can thus easily be evaluated.

**Experimental setup**

The first experimental setup for planar structured illumination was demonstrated for microscopy by Breuningen *et al.* [10] in 2007 where it was applied on a static biological sample. In the setup presented in that experiment, the total time required for recording an image triple was 0.3 to 1 s. Contrary to the study of static samples where time is not a restricted parameter, the investigation of dynamic flows require the motion to be frozen in time.

To reduce the acquisition time for an image triple down to a nanosecond scale, three individual Nd:YAG lasers were used in combination with a high speed multi-frame camera. With this SLIPI configuration, the time separation between pulses is only restricted by the camera system. Figure 1 shows an illustration of the current experimental setup, excluding the imaging part. Beam recombination is obtained using two beam splitters, one with a transmission of 50 % and one with 67 % as to obtain maximum output energy. Such an arrangement will obviously introduce significant energy losses but as the maximum output from each laser is ~1.4 J/pulse at λ = 532 nm this is not considered as a limiting issue. Furthermore, this high peak energy allows a large portion of the outer rims of the Gaussian laser profile to be discarded by the use of telescopes (one for each beam) and apertures, creating more of a top-hat profile. This is of great importance for SLIPI as any beam inhomogeneity in the three pulses may create residuals in the final image. Although, such residuals are often clearly noticeable by using Fourier analysis.

The intensity modulation is created by guiding each pulse through a transmission Ronchi grating (see Fig. 1). By using this experimental setup an image triple can be recorded within less than 40 ns, allowing droplet velocities up to ~600 m/s to be frozen in time (with the current magnification).

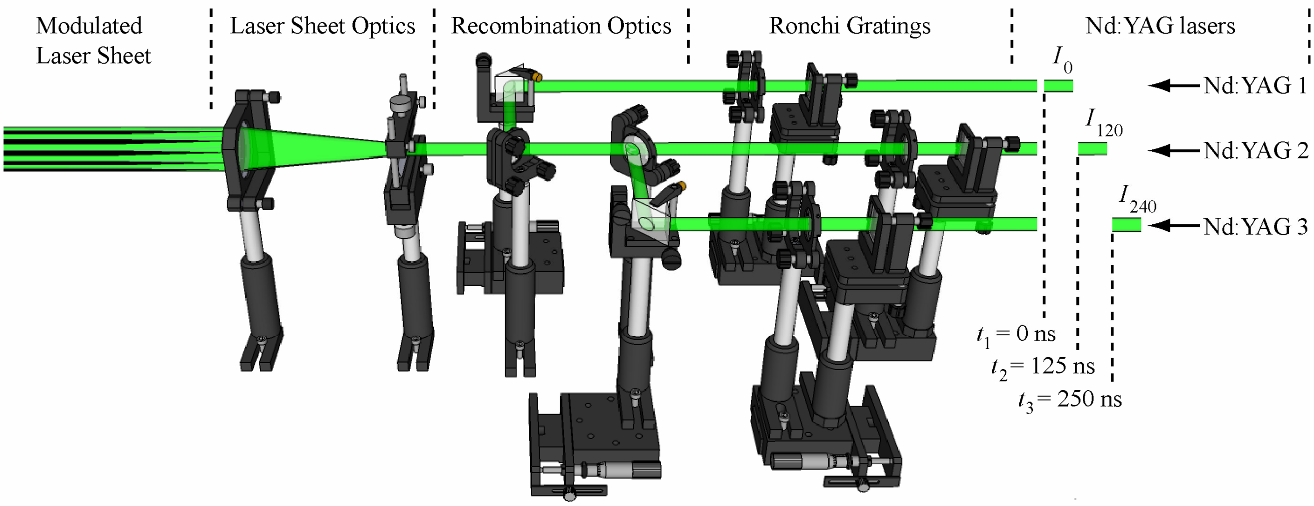


**Figure 1. Experimental setup for single-shot SLIPI. Three pulses are each guided through an individual transmission Ronchi grating. Recombination is achieved by using two beam splitters.**

**Results**

Figure 2 shows both an average SLIPI and conventional image of the hollow-cone spray under study, where the incident light enters from the right side. As can be seen, the contribution of diffuse light in the hollow region of the spray is highly suppressed with SLIPI. Average imaging, however, does not contain sufficient information for the complete characterization of the spray, especially concerning the dynamics of the flow. One of the main purposes of the single-shot SLIPI system is therefore to provide a diagnostic tool capable of studying primary and secondary break-ups as well as the full disintegration of the liquid sheet into fine droplets.

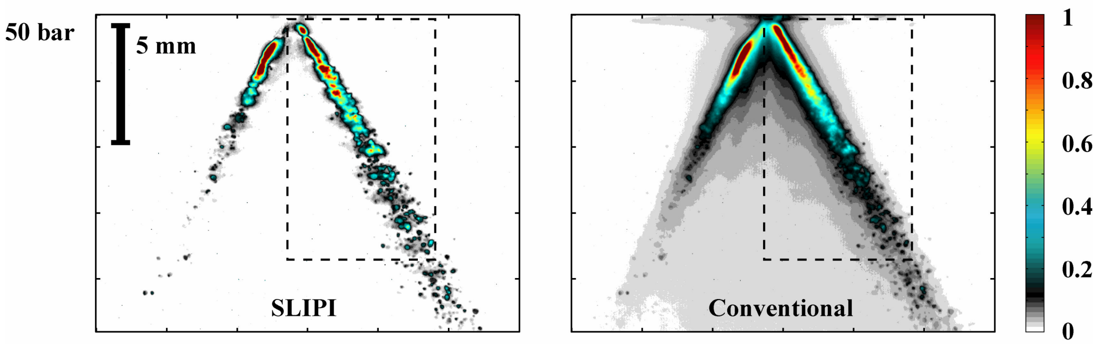


**Figure 2. Average images over 50 shots of the hollow-cone spray under study (50 bar injection pressure). The dashed line indicates the area of investigation. The laser sheet is entering from the right-hand side.**

In Fig. 3 single-shot measurements of the entrance side of the spray (see dashed area in Fig. 2) are presented. On the left-hand side a comparison between conventional planar imaging and SLIPI is shown at different injection pressures. The conventional images clearly show a broadening of the spray wall, especially towards the center of the spray. The effect is most noticeable in the near nozzle region where multiple scattering is more dominant. As a consequence, the hollowness of the spray becomes less apparent and only fully visible when applying a lower threshold (cutting out low intensities) on these images. Such an approach with a uniform threshold would, however, remove or highly reduce the smaller droplets downstream which have contributed with less intensity and vital information might be lost. SLIPI on the other hand evaluates the three images on a pixel-to-pixel basis to extract a non-uniform lower threshold and is therefore also able to keep the low intensity information. The right-hand side of Fig. 3 shows a detailed study of the spray at 50 bar. Different stages of the atomization process, such as primary and secondary break-ups, are indicated.

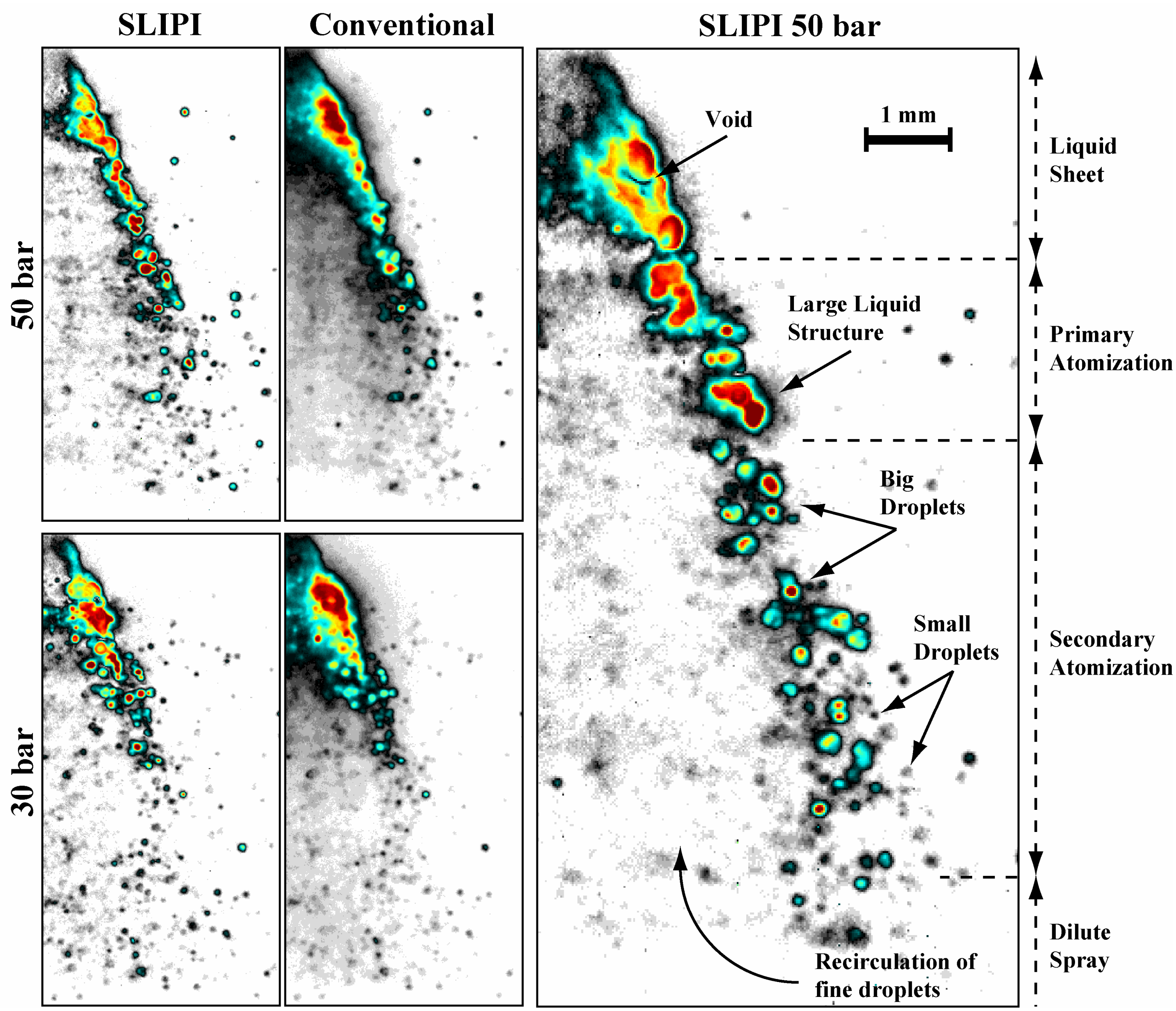


**Figure 3.** (*Left-hand images*) **Single-shot measurements for both SLIPI and conventional imaging. By comparing it is clear that SLIPI provides information that conventional imaging cannot.** (*Right-hand image*) **Detailed study of the entrance side of the spray, operating at 50 bar. Different stages of the atomization process are indicated together with features, some of which are only visible with SLIPI.**

Conventional planar laser imaging has a number of drawbacks when applied to dense media. Firstly, *multiple scattering* blurs the image and ads an unwanted diffuse offset which is difficult (if at all possible) to correct for. Depictured structure gradients are reduced and for instance droplet diameters can be overestimated if measured in the image. Secondly, *laser extinction* reduces the intensity exponentially along the path of the light. SLIPI does not correct for this but rather enhances the effect as multiply scattered light which illuminate the exit side of the sample is removed. To improve the signal to noise ratio in full spray measurements counter propagating laser sheets could be employed. Another issue concerning attenuation is the loss of the light while traveling towards the camera, also known as *signal attenuation*. One final major limitation, somewhat associated with multiple scattering, is the reduction of the *optical sectioning* strength. When traveling in a turbid medium, the laser sheet will be broadened (in all spatial directions) and thus probing a thicker volume. As a consequence, sample structures either behind or in front of the "true" laser sheet can be illuminated and, if the depth-of-field is large, imaged with relatively sharp gradients (in contrast to the diffuse offset). These structures will therefore appear to be present within the cross section induced by the laser sheet with the risk of concealing, due to spatial overlapping, wanted information. However, when applying SLIPI, such structures, as well as the diffuse offset, are highly suppressed as they originate from multiple scattering.

Apart from providing quantitative information, such as droplet size and velocity, planar imaging can aid the understanding of the atomization process, which for instance could improve CFD modeling. For this purpose the root mean square (RMS) approach can be utilized. The RMS highlights the variations in a set of images, relative to an average case, while de-emphasizing all similar features. Liquid structures whose size and location are relatively constant in time, such as the liquid sheet, will give a low intensity contribution in the RMS image. The primary break-up which occur at the end of the liquid sheet is on the contrary less temporally stable, where both the size and position of the isolated liquid structures fluctuate, and thus gives a higher intensity in the RMS image. Further downstream, where the secondary atomization occurs, the variation in droplet size and position is expected to increase even more. A comparison between SLIPI and conventional RMS is shown in Fig. 4 together with the average image for each measurement case. In this study the hollow-cone water spray was running with an injection pressure of 30 bar and for each case a set of 20 single-shot images were recorded. The root mean square was calculated according to Eq. (4), where $\bar{I}_{Av}$ represents the average image and $I_i$ indicate the *i*:th image. Single-shot imaging is thus imperative for this type of analysis.

$$\bar{I}_{RMS} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\left(\frac{I_i}{\bar{I}_{Av}}-1\right)^2}\,, \qquad (4)$$

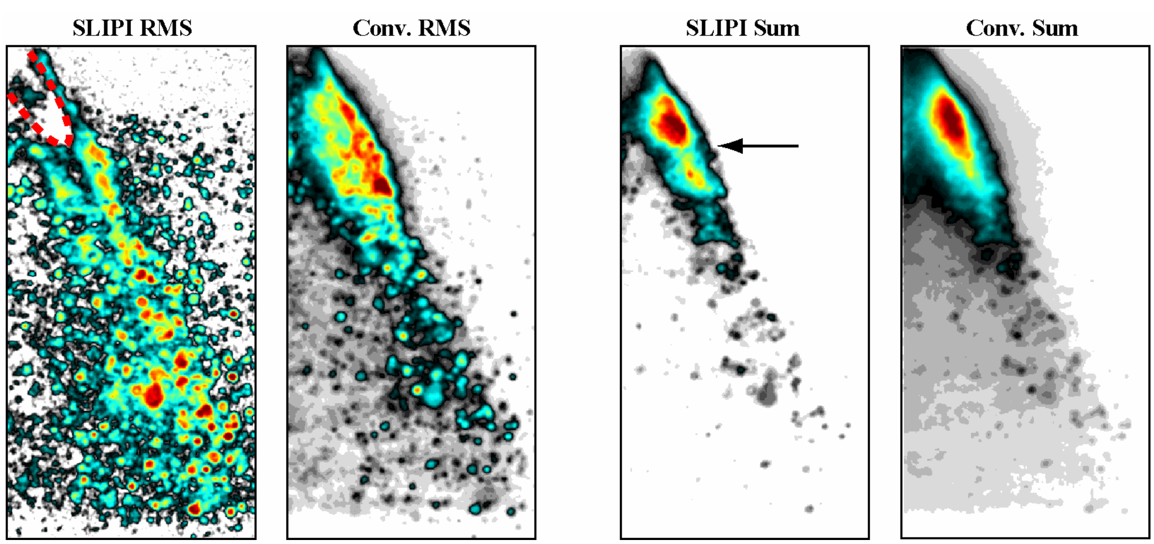


**Figure 4. (*Left-hand images*) RMS of 20 single-shot SLIPI and conventional images (30 bar). The red line indicates an estimate of the liquid sheet location. (*Right-hand images*) Average of 20 single-shot SLIPI and conventional images. The arrow indicates the estimated end of the liquid sheet.**

When comparing the RMS from the two techniques few similarities can be found. Although conventional RMS is capable of highlighting the formation of droplets, at least in the downstream region, it does not provide much additional information compared to what is obtained by averaging. The liquid sheet for instance, which is expected to appear as a low intensity region cannot be distinguished.

As previously mentioned, SLIPI performs a non-uniform lower thresholding, affecting the downstream region less than the dense region. The effect of this can clearly be seen in the SLIPI RMS image, in which the single droplets are strongly emphasized, thus allowing statistical studies of the atomization process. Additionally, close to the nozzle a region with low intensity can be noticed (indicated with a red dashed line), most probably arising from the relatively temporally stable liquid sheet. An arrow in the average SLIPI image indicates its estimated end, which seems to coincide with a region of reduced intensity, further supporting the result.

**Conclusion**

In summary, we have developed an illumination system capable of producing three intensity modulated laser sheets within less than 50 ns. This was accomplished by avoiding mechanical phase shift solutions, leading to a reduction of the time separation between consecutive images by a factor of 2000 (compared to the previously presented instrumental arrangements [7,8]). Such an improvement enables SLIPI to freeze displacements up to ~600 m/s, allowing imaging of highly pressurized sprays. The resultant single-shot images, in which most multiple scattering has been suppressed, helps to further understand liquid flow dynamics, which is of fundamental importance in CFD modeling. In addition, by extracting the RMS from single-shot SLIPI images, the statistical study of stable and instable liquid structures can be performed.

To our knowledge, only two other imaging techniques, in which multiple scattering is mitigated, currently exist: Ballistic [11] and X-ray imaging [12]. Ballistic imaging uses temporal and polarization filtering to inhibit detection of multiple scattering, while the latter is based on the low interaction between the X-ray and matter. We propose here a novel technique with similar advantages but with the main difference that SLIPI provides images which are optically sectioned and information, only extractable with depth-resolution, is gained. Furthermore, by doping the injected liquid with fluorescing dye, SLIPI can be used to visualize the Stokes shifted fluorescence, in contrast to Ballistic and X-ray imaging.

**Acknowledgements**

The authors wish to show their appreciation to the Linné Center within the Lund Laser Center (LLC) as well as the Centre for Combustion Science and Technology (CECOST) through SSF and STEM for financial support.

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