Gate time effects on ballistic imaging of Diesel sprays

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Abstract

Diesel engines are an important aspect of our transportation infrastructure, whose performance is greatly affected by the characteristics of the spray from their injectors. Characterization of the injector's sprays is therefore imperative to produce clean-running efficient diesel motors. Recently, ballistic imaging has been applied to the study of diesel sprays using the optical kerr effect (OKE). These studies have required the use of not commonly available femto-second capable pulse lasers. In this study, an attempt is made to use a more common ~15 ps pulsed Leopard D-10 laser along with an OKE gate to achieve ballistic imaging capabilities. By varying the temporal overlap of the gate and imaging beams an effective high speed shuttering effect is obtained. We are able to show that it is possible to produce ballistic images when the OKE gate turns on early relative to the arrival time of an imaging pulse. When the OKE gate turns on late relative to the arrival time of an imaging pulse the images contain much less apparent structure. Additionally, through the use of the ballistic imaging capabilities of the 15 ps pulse laser, basic information about the transient cross-section of the spray is obtained.

Introduction

Diesel Engines are a well known and important energy conversion device with enormous importance to transportation. These engines rely on the classic "diesel" cycle where fuel is introduced into the engine cylinder at near-top-dead-center; the fuel subsequently ignites and a fraction of the energy release associated with combustion is converted to shaft power. Diesel engines are both cost effective and, as deployed into the transportation sector, more efficient than the Otto cycle which is commonly used for personal automobiles. The nature of the diesel cycle, i.e. reliance on self-ignition and combustion of a transient combustible charge that is formed by mixing between fuel spray and the surrounding air, makes fuel spray physics critical to performance. This is then the motivation for this work: diesel sprays set the overall stage for engine performance.

As with most complex thermo-chemical systems, diesel sprays have been the subject of many years of high quality research that has included both modeling and experimental measurements. Modeling challenges range from identifying the important physical processes associated with spray breakup to producing appropriate model fidelity in a two phase, turbulent flow. Experimental measurements have focused on measurements of drop size and volume fraction in the dilute regions of the spray, extensions of these measurements into the more optically thick regions of the spray [1], and finally, more recent work that has focused on the very near nozzle (or so-called breakup) region of the spray [2,3,4]. One of these efforts uses a technique known as "ballistic-imaging." This technique relies on the transmission of coherent light through the spray and uses an ultrafast "shutter' to separate ballistic photons that represent the variation in optical transmission as a function of position in the spray from scattered photons which typically do not carry image information. The technique relies on an optical Kerr effect and as implemented has used a regeneratively amplified laser system that produces a high frequency series of 150 fs laser pulses. This paper reports on ballistic imaging from a more commonly available laser system that produces ~15 ps laser pulses and carefully controls the effective "on" time of the Kerr cell for the imaging pulse. Results are promising and indicate that ballistic imaging can be implemented with a more common laser system. Sensitivity of image quality to the on-time for the Kerr cell is demonstrated and the images in themselves indicate a significant transient for the spray beyond the initial microseconds where the spray is initialized.

Materials and Methods

An experimental schematic is shown in Fig. 1. The 532nm output from a Coherent Leopard D-10 laser operating at 10 Hz repetition rate with 12±1 mJ per pulse was used for ballistic imaging. The pulse length of the laser is measured at 15±2ps FWHM using autocorrelation. Beam diameter was 10mm. The laser was split into an OKE (optical Kerr effect) gate beam and an imaging beam with a 90/10 cube beam splitter; 90% of the pulse energy output

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from the laser was to produce the OKE gate beam. The OKE gate beam traveled across the table to a prism (Pr) mounted on a translation stage and was then directed through a CS_2 cell. The prism and translation stage provide several 10's of picoseconds of time delay of the OKE gate beam relative to the imaging beam. A pair of linear polarizers, P1 and P2, were used to reduce the pulse energy on the imaging leg. The imaging beam was typically limited to < 30 μJ. P2 was aligned to pass vertically polarized light to assure linear polarization and P1 rotated to reduce the pulse energy on the imaging leg. The ½ waveplate (WP) was oriented to rotate the imaging beam 45º. The linear polarization of the imaging beam was then improved a second time with P3 oriented to pass light at 45º to vertical. The imaging beam was then directed through the spray with a turning mirror. The imaging optics were optimized for ballistic imaging using a Zemax model. The OKE gate was formed by a pair of crossed polarizers, P4 and P5, and the OKE gate cell. P4 was oriented to pass the non-scattered image beam, while the output linear polarizer (P5) of the OKE gate was set to be crossed with P4. The OKE gate cell was composed of a pair of laser optical windows separated by 1.7mm. The intervening space was filled with spectroscopic quality CS_2. The assembly was sealed with o-rings in a 2 inch optical tube. The CCD is a Photometrics Cascade:650 imaging array (653x492 pixels, 7.4 μm square).

The spray was generated by a Sturman ® diesel fuel injector operating on dodecane. The spray was driven by a pulsed hydraulic amplifier similar to the hydraulic system described in [5]. The spray duration was tracked using a HeNe laser beam aligned to cross directly below the tip of the injector. The HeNe beam was directed to PD2 and monitored on an oscilloscope. Spray duration as determined by attenuation of the HeNe beam was typically 3.0 to 3.5 ms. The imaging beam was monitored via PD1 on the same oscilloscope. The arrival time of the imaging beam relative to the initiation of the spray was determined from the oscilloscope traces.

The CCD and fuel injector were timed relative to the laser using an electronic trigger output pulse from the laser power supply. CCD exposure time was 1.0 ms and initiated with a TTL timing pulse controlled with an external delay generator. The fuel injector was triggered from a second delay generator. The CCD trigger was set by allowing the OKE to leak slightly (rotation of P5) without the presence of the spray. P5 was then rotated back to be crossed with P4 for ballistic imaging.

The OKE gate beam could be delayed relative to the arrival of the imaging pulse as shown schematically in Fig. 2. In Fig. 2 the imaging pulse is shown arriving after the OKE gate is turned "on" by the OKE gate pulse. In the subsequent figures we discuss the arrival time relative to simultaneous arrival of the image pulse and OKE gate pulse. The time of simultaneous arrive was determined without a spray as the prism location (OKE gate pulse delay) that maximized OKE gate transmission. Timing of OKE gate pulse relative to this was determined by conversion of linear translation as read from micrometers on the translation stage to time. OKE gate pulse time delays the OKE gate transmission decreased significantly relative to the peak transmission if imaging beam pulse energy were held fixed; however, we adjusted P1 to increase energy on the imaging leg such that the peak CCD count was similar for all OKE gate delays.

Results and Discussion

When an image is captured it is in a raw form which needs to be processed in order to garner an understanding of what information it contains. Before a data set is acquired, an image of the background noise as well as an image of the native laser pulse is obtained. Using Equation 1, where I is the image, I_o is the native laser pulse and B is the background image, the image is scaled. This way the values of all the pixels are from 0 to 1 and the background noise is removed from the scaled image. The final images are produced as *–ln(Θ)* with an appropriate color scale applied to accentuate the gradient on the edge of the spray.

$$\Theta = \frac{(I - B)}{(I_o - B)} \quad (1)$$

Image beam arrival after the arrival of the gate beam at the OKE cell produces a higher quality ballistic image than arrival prior or simultaneously. Fig. 3 illustrates this point, as clearly the outlying structure of the spray becomes harder to discern as one progresses from Fig. 3a to Fig. 3d. The late arrival times of Fig. 3a and Fig. 3b allow the gate to transmit the photons on the leading edge of the image beam while rejecting the later photons which contain multiply scattered photons. While Fig. 3c and Fig. 3d contain the whole beam and the trailing edge respectively. A clearer understanding of the structure which only ballistic photons can provide may be garnered through an examination of Fig. 4. Fig. 4 shows an enlarged portion of the spray periphery for each of the cases in Fig 3. In Figs. 4a and 4b, voids and particle shedding are plainly visible, indications of the presence of ballistic photons. In contrast, in Fig. 4c and Fig. 4d it is evident that the underlying structures are obscured by the scattered photons inherently contained in these images corresponding to earlier image beam arrivals.

Comparisons of the images in Fig.4 provide a sound basis for choosing a gate delay to examine the development of a spray over its lifetime. Fig. 5 presents a set of spray images captured with the image arriving 6.7 ps after the gate beam. Fig.6 contains a similar set of images captured with the image beam arriving 14.7 ps before the gate beam. There are features contained in the images of Fig. 5 which cannot be seen in Fig. 6. There are details about the nature of the spray structure that can be observed in Fig. 6 however, the more interior details are lost in comparison to Fig. 5.

Significant transient behavior of the spray is evident. As seen in Fig. 5, the spray is initially wide but begins to narrow down at 1.760 ms, stays narrow for approximately 1 ms before widening out towards the end of the spray. In Fig. 6 narrowing of the spray is also evident around 1.75ms.

Conclusions

The use of a turn-key picosecond pulse laser coupled with an Optical Kerr Cell can produce ballistic images previously only obtainable with more expensive femtosecond capable pulse lasers. The best results were obtained by allowing the OKE gating pulse to enter and activate the Kerr cell before the imaging beam. Further studies will investigate the theoretical aspects of the beam interactions in the Kerr cell.

References

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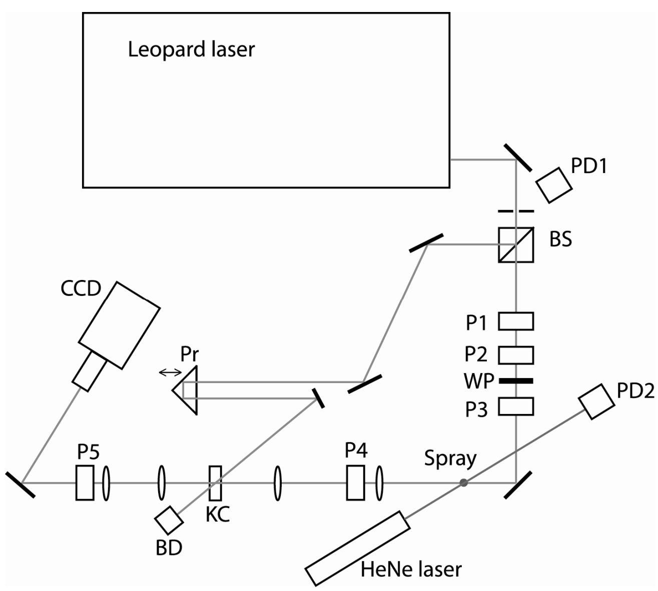


Figure 1. Experimental schematic. PD: photodiodes, BS: 90/10 beam splitter, P: polarizers, WP: waveplate, KC: OKE gate cell, CCD: Camera, Pr: delay prism, BD: beam dump.

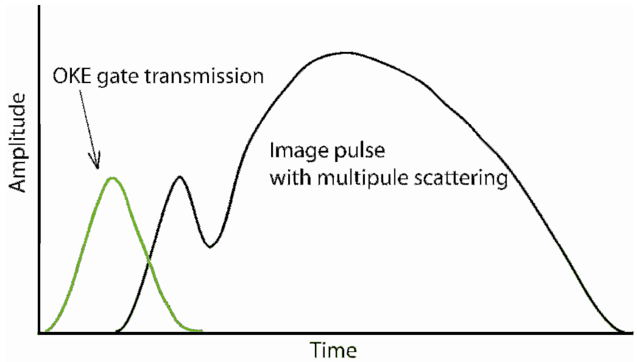
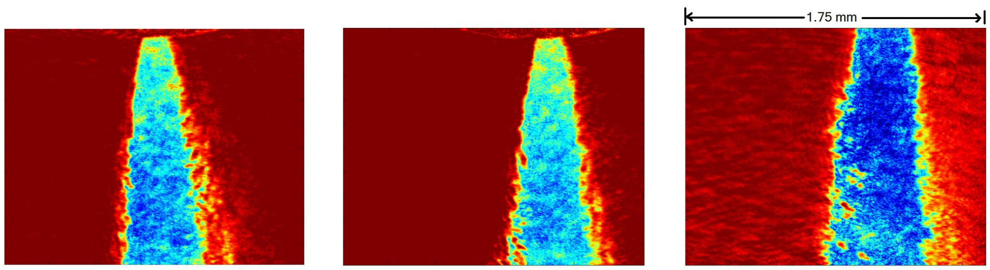


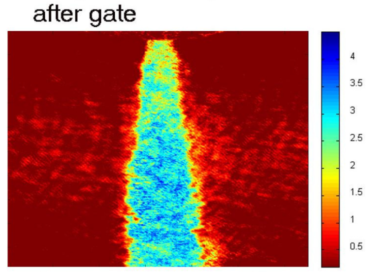
Figure 2. Time dependence of ballistic, snake, and diffuse photons relative to OKE gate transmission. In cartoon shown the image pulse arrives at the OKE cell after the OKE gate pulse.



a. Image arrives 6.7 ps after gate

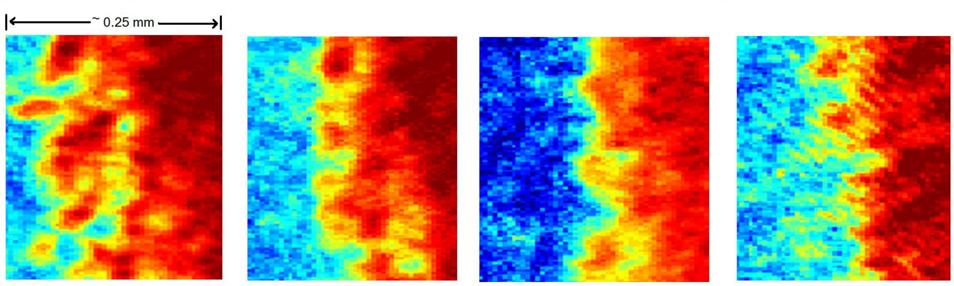
b. Image arrives 5 ps after gate

c. Simultaneous arrival of gate and image
Tip is 1 mm out of picture



d. Image arrives 14.7 ps before gate

Figure 3. Images taken at 1.700 ms into the spray duration at varying image arrival times



a. 6.7 ps after gate b. 5 ps after gate c. Simultaneous Arrival d. 14.7 ps before gate arrival

Figure 4. Enlarged images of the spray edge taken at 1.700 ms into the spray duration demonstrating the degradation of image quality as the gate position changes.

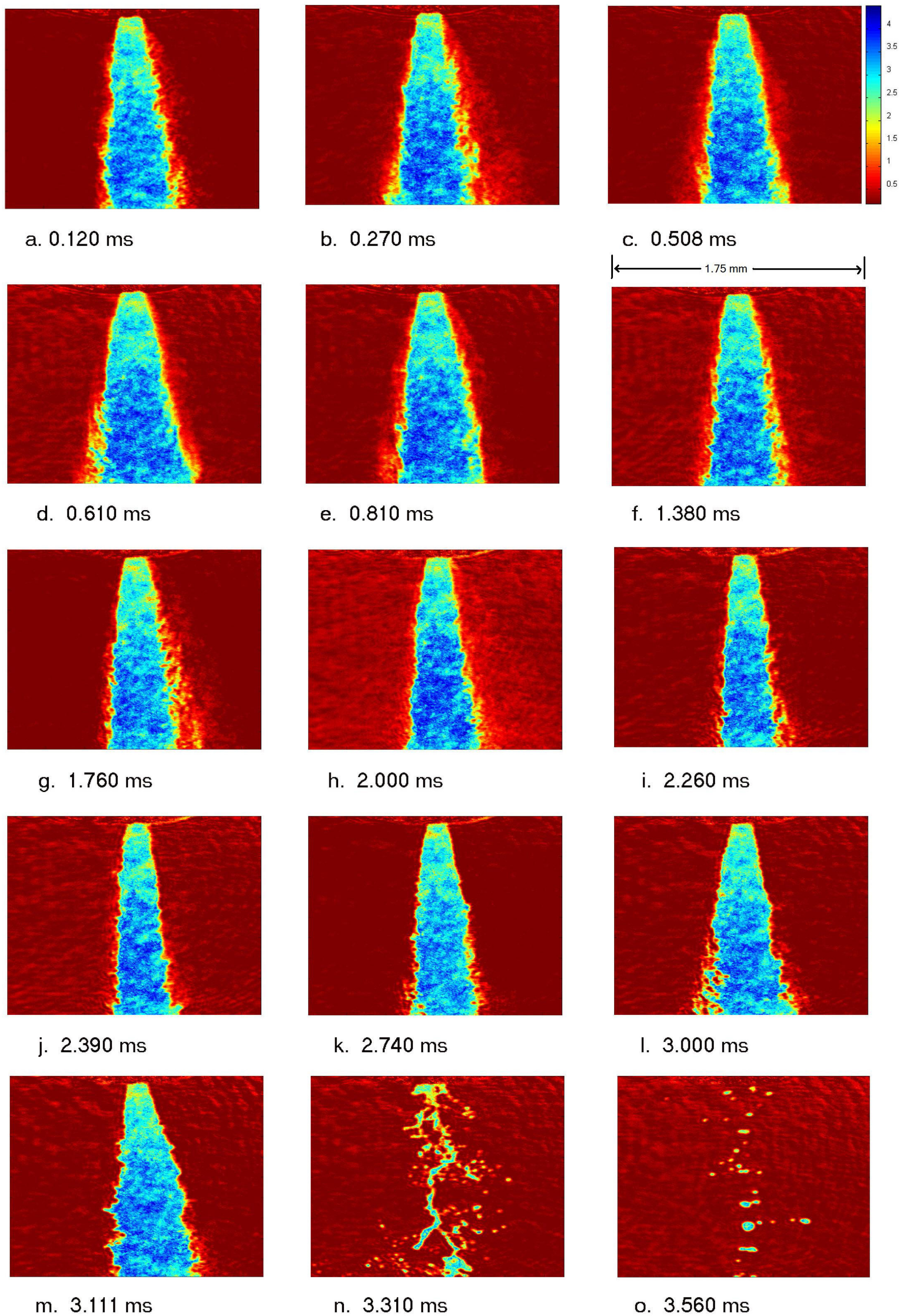


Figure 5. Images taken in which image beam arrives at OKE cell 6.7ps after OKE gate beam.

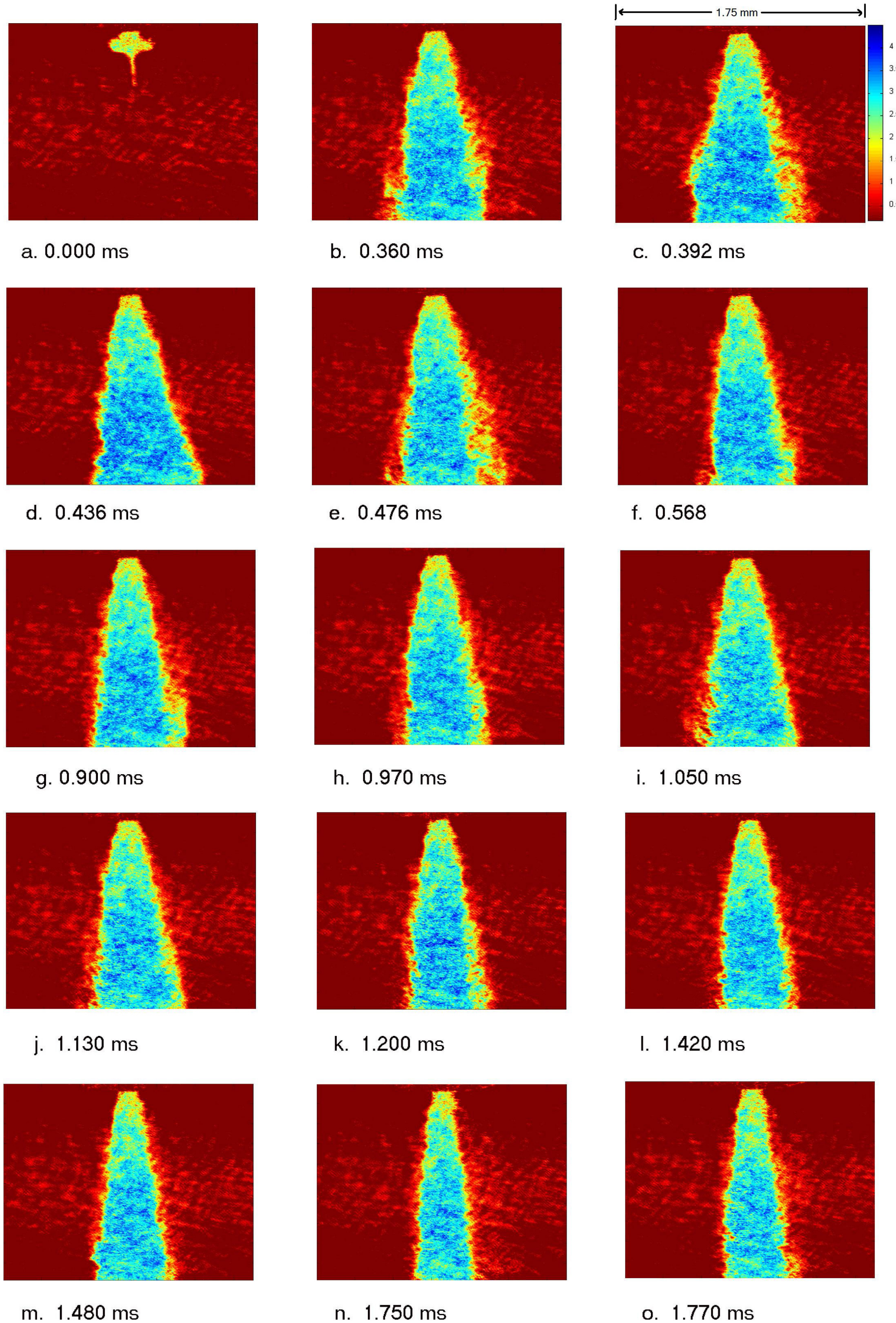


Figure 6. Images taken in which image beam arrives at OKE cell 14.7ps before OKE gate beam.