

Laser Light Sheet Flow Visualization of the Space Launch System Booster Separation Test

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Planar flow visualizations were obtained in a wind tunnel test in the NASA Langley Research Center's Unitary Plan Wind Tunnel using the laser-light-sheet method. This method uses a laser to illuminate fine particles generated in the wind tunnel to visualize flow structures. The test article was designed to simulate the separation of the two solid rocket boosters (SRBs) from the core stage of the NASA Space Launch System (SLS) at Mach 4 using a scale model. The test was run on of the SLS Block 1B Cargo (27005) configuration and the SLS Block 1B Crew (28005) configuration. Planar flow visualization was obtained only on the crew configuration. Air at pressures up to 1500 psi was used to simulate plumes from the booster separation motors (BSMs) located at the nose, and aft skirt of the two boosters. The facility freestream was seeded with water vapor, which condensed and froze into small ice crystals in the tunnel nozzle expansion. A continuous wave green (532 nm) laser sheet was used to illuminate the ice crystals, and the resulting Mie-scattered light was collected with a camera. The resulting images clearly identify shock waves and other flow features including BSM plume shapes. Measurements were acquired for different BSM pressures and booster separation locations.

I. Introduction

NASA is developing the Space Launch System (SLS)¹ as a heavy launch vehicle to enable missions beyond low-Earth orbit. The SLS consists of a core stage and two solid rocket boosters (SRBs), which separate from the core stage after their fuel is spent about 2 minutes after launch. Separation is assisted by booster separation motors (BSMs) that operate for about 1 second, pushing the boosters away from the core stage. This booster separation phase carries significant risk because the boosters could possibly re-contact and damage the core stage. Consequently, numerous wind tunnel tests and computational investigations have been performed to study this process²⁻⁶ including a wind tunnel test performed in 2017 to acquire detailed force and moment, surface and off-body data⁷ to compare with recent computational fluid dynamic (CFD) simulations of this flowfield. A large number of vehicle configurations were studied during this test, all at Mach 4 and a Reynolds number of 1.25 Million per foot.⁷ Vehicle configurations included both the SLS Block 1B Cargo (27005) configuration and the SLS Block 1B Crew (28005) configuration. Furthermore, numerous SRB positions were tested, varying both the distance from the vehicle and distance downstream of the original attachment location were tested. The yaw and pitch angles of the SRBs relative to the core were also varied. Pressure sensitive paint data was acquired during the test to determine surface pressure distributions.⁷ For a limited subset of conditions, quantitative velocity measurements were obtained using the cross-correlation Doppler Global Velocimetry (CC-DGV) method.^{8,9} These measurements were made with narrow (~0.1

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in.) diameter laser beams or small (1 in. wide) sheets, respectively, which did not offer wide-field-of-view flow visualization. Just prior to the conclusion of the CC-DGV test the laser beam was expanded into a wide (several inches wide) laser sheet and used to scatter off the ice crystals seeded into the flow. Images were captured with a color camera having a wide (>2 ft.) field of view. This method is known as “laser light sheet” or “laser vapor screen” flow visualization which identifies flow features such as shocks, expansions and plumes.¹⁰ While several sophisticated, quantitative measurement techniques¹¹⁻¹⁵ have been developed for and applied in this same facility, only laser light sheet visualizations, CC-DGV, pressure sensitive paint and schlieren imaging were employed in the current test.⁷ This paper describes the imagery and observations of the laser light sheet portion of the SLS test, which occurred only with the SLS Block 1B Crew model.

II. Experimental Setup

Experiments were performed in the high-Mach number leg of the Unitary Plan Wind Tunnel (UPWT), known as Test Section 2. The UPWT has optical access on two side walls but not on the floor or ceiling.¹⁶ The side windows cover a region approximately 4 ft. tall by 5 ft. wide but are segmented into 9 individual windows, each of which has a clear aperture of 5.5 in. wide and 48 in. tall. The windows are separated by spars that are available for mounting cameras, mirrors or other hardware. In the current setup, an 18 Watt Coherent Verdi continuous wave Nd:YVO₄ laser directed light through one of the windows on the east side of the test section. A collimated laser beam was directed from the laser to the tunnel where a single negative cylindrical lens (~1 in. focal length) was used to expand the beam into a planar sheet. A small, color, 2.5 Megapixel Marshall Electronics CV343-CS CMOS with a 1/3-inch sensor camera with a Cosmocar 8.5 mm focal length, f/1.5 lens was placed between two of the spars, providing an unobstructed view of most of the vehicle. The camera operated at 60 Hz and the aperture was fully open to increase the image brightness. The water seeding level, purposely injected to increase the humidity to create the ice crystals, and the laser intensity were adjusted to maintain a high enough level of scattered light intensity while not saturating the camera.

The test article consisted of the SLS Block 1B Crew (28005) configuration as shown in Fig. 1. The SRBs could be moved in three dimensions as well as angularly relative to the core stage. Measurements in this paper were made upstream of the left-hand SRB as shown in the figure (LH SRB). For details, see Ref. 7. In Fig. 1, the flow is from right to left but the laser and camera were placed on the other side of the tunnel from this photo, so subsequent images herein show the flow from left to right. A detail of the BSMs, both forward and aft are shown in Fig. 2.

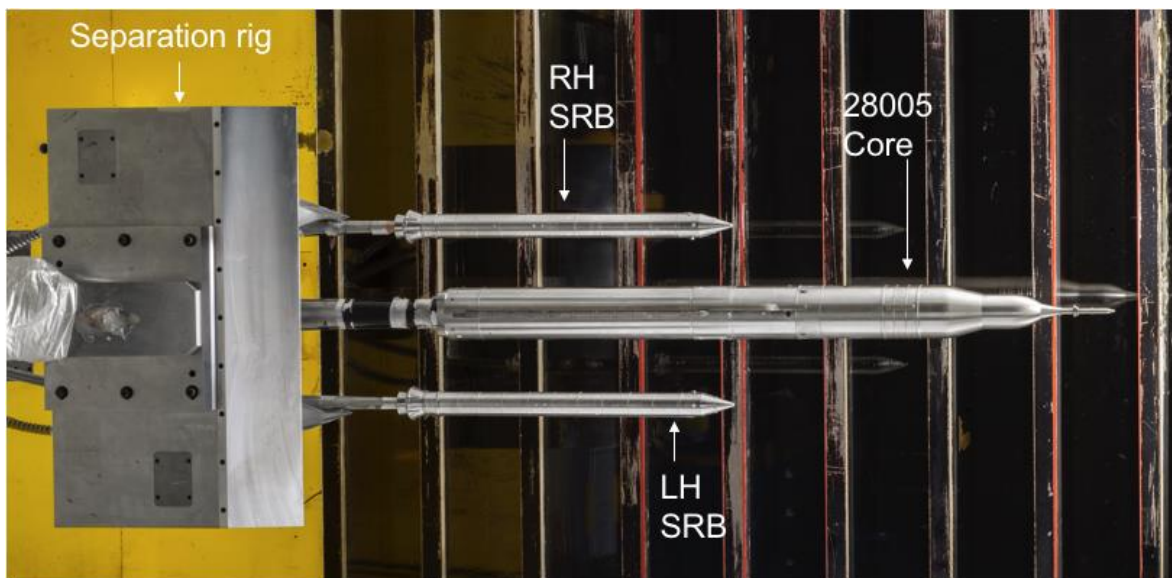


Figure 1. SLS-28005 Configuration Installed in the UPWT. Reprinted from Ref. 7 with permission from the authors.



Figure 2. Detailed images of the SRB's forward (left) and aft (right) BSMs, oriented to show the left-hand BSMs studied in the current paper. Modified from Ref. 7 with permission of the authors.

III. Results

A. Overview of Configuration and Results

Figure 3 shows a typical image acquired by the color video camera after it has been processed a variable overlay by the wind tunnel's data system. The model, consisting of the core stage and SRBs, can be seen in the middle of the image. The laser enters the image from the bottom right and propagates leftward. At least one streak in this laser sheet is caused by the presence of debris on, or a chip in the facility window. A bright line of scattered light is seen where the laser sheet impacts and diffusely scatters off the model surface. Scattering from the ice crystals is seen as relatively uniform bright green light in the flowfield. Shock waves are clearly visible as sudden changes in image brightness, as the density of the gas (and consequently density of the ice crystals) increases across the shock waves. Higher density regions generally have higher signal intensity (at least in regions uncontaminated by plume fluid from the BSMs). The lower SRB blocks the laser beam, creating a sharp shadow as indicated to the left of the image. An x, y, z coordinate system is shown towards the bottom left of the figure. The facility data system acquires the tunnel operating conditions and other information and displays them on the video stream. Shown on the display, starting in the top left, the Mach number, unit Reynolds number, the tunnel stagnation pressure in PSF, the tunnel stagnation temperature in degrees Fahrenheit are shown. Below that, the relative x, y and z locations of the solid rocket booster are indicated, followed by the SRB jet plenum supply pressure. Due to export control limitations these x, y and z locations have been omitted from this paper. An appendix containing un-redacted images is available upon request from the first author. On the right side of the image, the date, time, test number, run number, and point number are shown, followed by the dew point in degrees F. On the bottom right are the core stage pitch and SRB pitch and yaw angles. These are defined in Ref. 7.

In Fig. 3, a conical shockwave originating from the nose of the SRB is clearly visualized near the middle of the image. A pair of shock waves originating from the nose of the core stage is also observed further from the vehicle. All three of these shocks are predicted by computations as shown in Reference 7. As will be discussed in detail below, the positions of the shock waves move as the conditions of the experiment change.

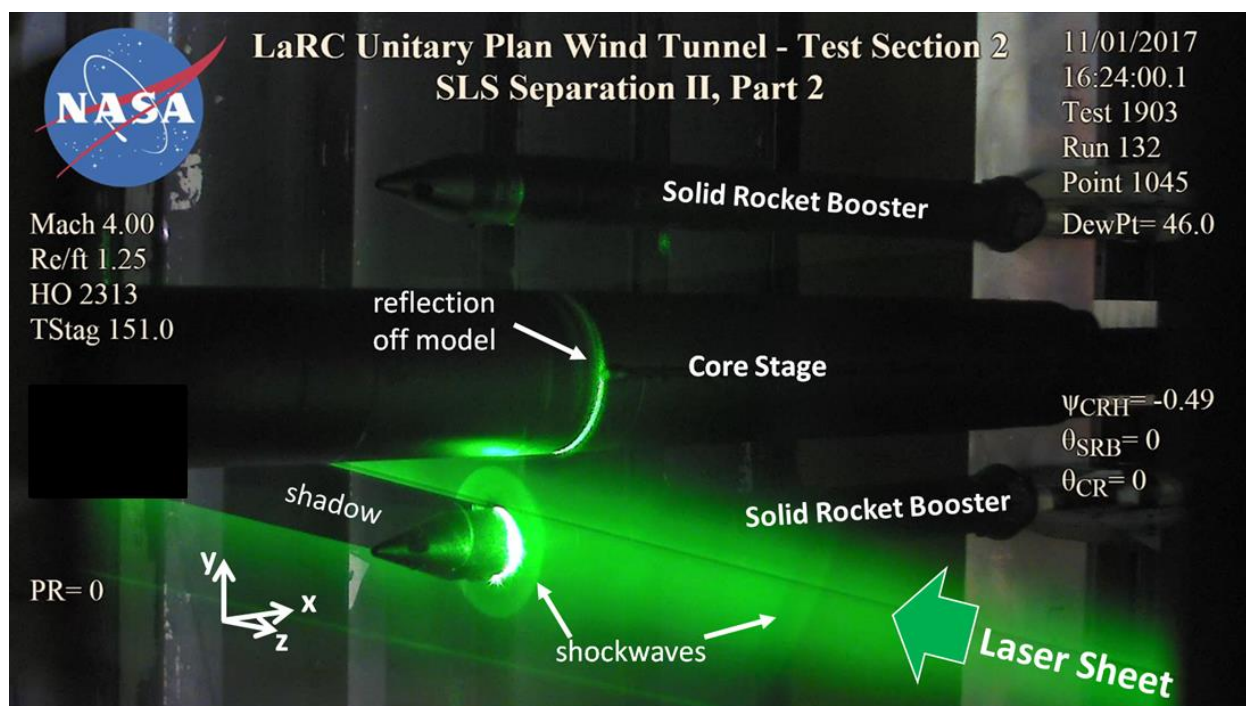


Figure 3. Annotated video frame from typical test condition. The laser sheet enters the image from the bottom right as indicated. Flow is from left to right. Further details are explained in the text. The subsequent images in this report are cropped on the top and bottom. In this figure, Δx is at nominal condition (0% of motion).

During testing, numerous combinations of jet pressure and SRB position were studied. The two SRBs always moved in tandem. Video was continuously recorded during the experiment and subsequently the videos were divided up into shorter segments for which a specific parameter was being varied, namely, jet plenum pressure (PR) or SRB position (Δx , Δy). These video segments are summarized in Table 1. While all of these videos and still images are available from the author, still images have been selected and described for a few interesting cases below. Note that some of the videos were effectively repeats (e.g. videos 2 and 3, videos 5 and 6, and videos 9 and 11) where only the direction of motion was varied. No hysteresis was observed, so the run having the best quality images was selected for the figures.

Video	Event Description	PR (psi)	Start Time	Stop Time	Elapsed Time	Figure Number
1	Move SRB Δy , Jets off	0	16:18:30	16:19:38	0:01:08	--
2	Move SRB Δx aft, Jets off	0	16:23:00	16:23:20	0:00:20	Fig. 4
3	Move SRB Δx forward, Jets off	0	16:23:40	16:24:00	0:00:20	Fig. 5
4	PR increase from Off to Medium	0-714	16:24:00	16:25:37	0:01:37	Figs. 3,6,7,8
5	Move SRB Δx aft, Medium PR	730	16:27:05	16:28:27	0:01:22	Figs. 4,9
6	Move SRB Δx forward, Medium PR	730	16:28:35	16:30:00	0:01:25	Fig. 10
7	PR increase from Medium to High	720-1500	16:30:00	16:31:50	0:01:50	Fig. 6
8	Increase Dew Point	1500	16:32:00	16:36:00	0:04:00	--
9	Move SRB Δx aft, High PR	1500	16:36:35	16:38:00	0:01:25	Fig. 11
10	Flow Instability, SRB aft, High PR	1500	16:38:00	16:38:40	0:00:40	--
11	Move SRB Δx forward, High PR	1500	16:38:40	16:40:00	0:01:20	Figs. 4,12
12	Shut Tunnel Down	0	16:49:30	16:49:55	0:00:25	--

Table 1. Description of conditions for different measurements. SRB stands for solid rocket booster. PR is the BSM plenum pressure. Figure number refers to the figure where the data appears in the current paper.

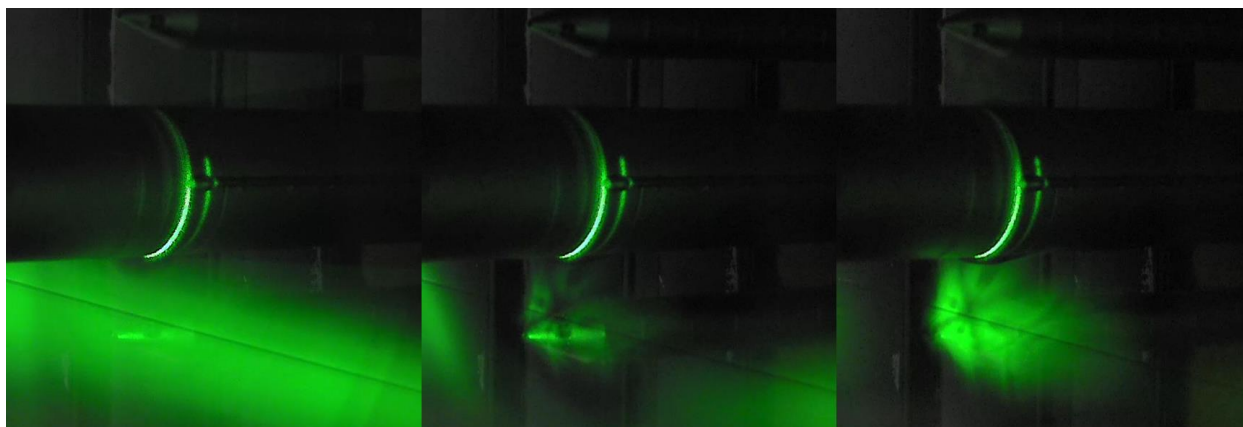


Figure 4. Comparison of flowfield for a single aft SRB position ($\Delta x=21\%$ of motion) with three different pressures of the booster separation motor (BSM), PR equal to zero (left) 728 psi (middle) and 1509 psi (right).

To provide a quick overview of the results, Fig. 4 shows some of the major effects observed during the laser light sheet flow visualization. The left image shows an image of the flow with no pressure applied to the solid rocket BSMs and with the SRB pulled back to 21% of its range of motion (hereafter referred to as “motion” where 0% is the furthest upstream position of the motors and 100% is the furthest downstream position; 0% is considered the nominal position for the purposes of this redacted manuscript). For this $\Delta x = 21\%$ position the left hand SRB is just downstream of the laser sheet and can barely be seen in the left panel, through the light sheet. The flow visualized in front of the SRB appears very smooth except for the weak shadow (thin diagonal line) originating from a chip on the facility window. As in Fig. 3, a pair of concentric oblique shock waves originating from the upstream part of the model are seen at the far right of the image. Very close to the model, there is a decrease in the intensity of the scattering, probably due to the sublimation / evaporation of the seed particles near the vehicle surface which is warmer ($\sim 150^\circ\text{F}$) than the surrounding fluid. In the middle panel of the figure the left hand SRB is at the same position but the pressure of supplied warm dry air to the BSM has been increased to PR = 728 psi. A few major differences are observed: (i) The presence of the jet has displaced much of the incoming seeded air shown in the PR = 0 case as evidenced by the decrease in signal in most of the near-vehicle region illuminated by the laser sheet. (ii) The laser intensity appears to be fairly constant by inspecting the scattered light off the model surface, so the lack of signal intensity suggests a lack of particles in the gas flow. (iii) Some scattering appears to be occurring close to the exit of the four jet nozzles, resulting in a four-fold symmetric pattern. (iv) The center of these jet patterns has a lack of signal, indicating that the fluid originating from the nozzle is unseeded but that some seed source is generated in the plume. Comparing the middle and the right-most figure which has the highest jet pressure, PR = 1509 psi, it is observed that the scattering is much more intense for the higher jet pressure case, which suggest that the process generating the scattering is enhanced by higher jet pressures or larger ratios of pressure between the jet pressure and the oncoming flow. While the source of this scattering is not clearly known it is likely one of the following: (a) condensation and/or freezing of residual water vapor in the high pressure dry air system, (b) condensation or clusters of molecular oxygen in the jet or (c) condensation or clusters of molecular nitrogen in the jet. The BSM fluid was heated but only to 150°F , so condensation is likely considering that the CFD predicted the jets expand beyond Mach 10.⁷ Whichever of these is the cause, the resulting seed particles effectively visualize the near-field underexpanded jet structure allowing comparisons with CFD.⁷ The near-BSM-exit source of scattering apparently sublimates or evaporates as the jet plume slows down and warms, causing a contrast between the seeded high-speed tunnel fluid and the unseeded jet plume fluid. Thus, in regions illuminated by the laser, absence of scattering signal suggests jet plume fluid (except very near the exit of the BSMs). In subsequent figures, these phenomena will be described in more detail.

B. Variation of Streamwise SRB Position with PR = 0.

Figure 5 shows the SRBs at five different streamwise positions varying from the most upstream position (0% of motion) to a position where it is retracted from the laser sheet (21% of motion), all at PR = 0. This series of images shows that the shock wave visualized near SRB in Fig. 3 is a conical shock that originates at the nose of the SRB. Once the SRB is retracted from the laser sheet the flow is uniform upstream of the SRB.

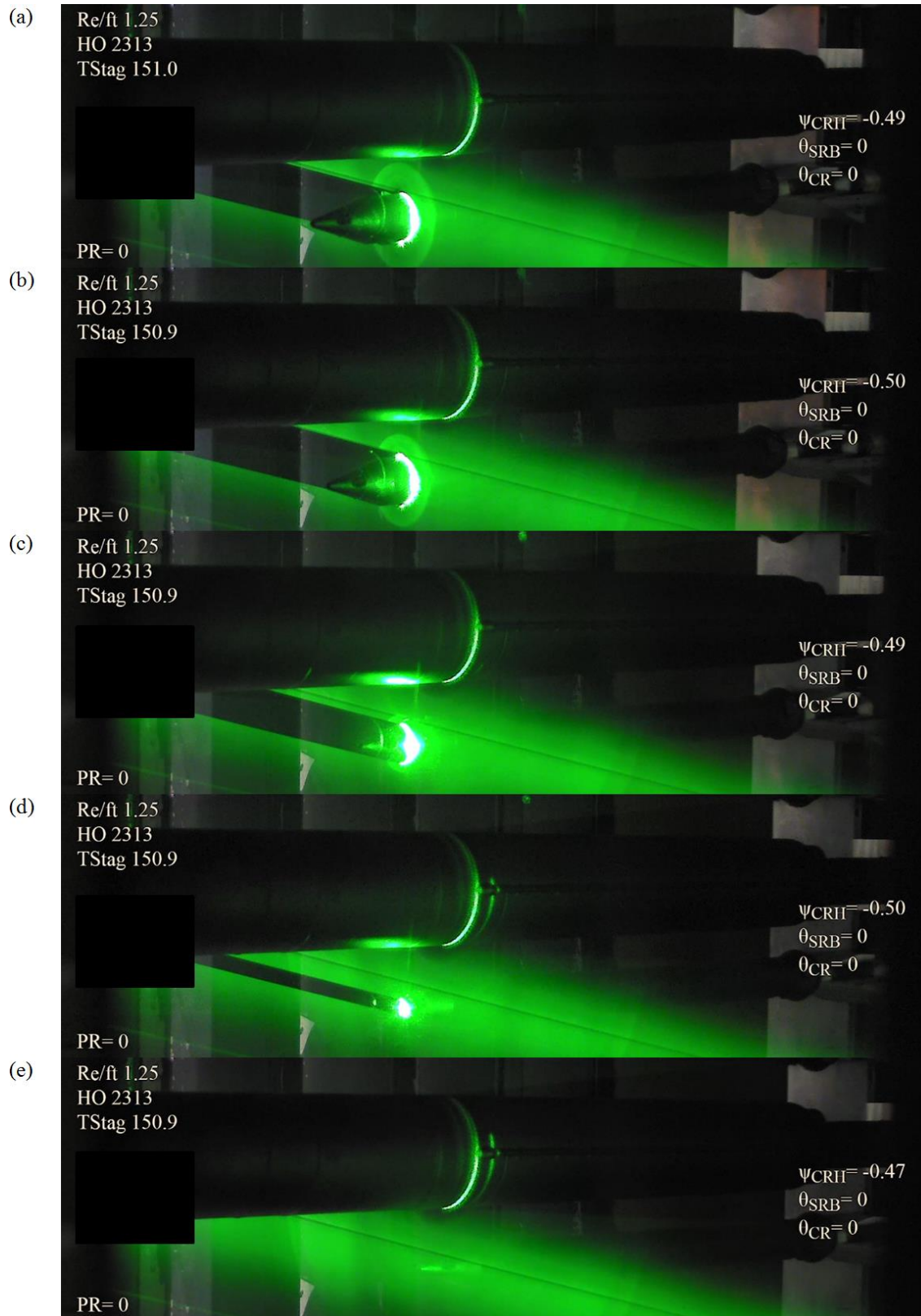


Figure 5: SRB moved forward with jets off for small steps in Δx : (a) 0% (b) 3% (c) 9% (d) 16% (e) 21% of motion. $PR = 0$.

C. Fixed, Nominal SRB Position with Varying BSM Pressure.

Figures 4-6 shows the SRBs at the nominal (0% of motion) streamwise position while PR is varied. The three figures show large, medium and small changes in PR. In Fig. 6, the top panel (a) shows a repeated measurement of the data in Fig. 3 and Fig. 5(a). In Fig. 6(b) which is only 25% of the maximum pressure, the flowfield looks completely different. The conical shockwave around the nose of the SRB has disappeared and there is a lack of scattered light (lack of seeded fluid) in the vicinity of the SRB, despite the fact that the laser scattering off the SRB indicates ample and constant laser illumination. This absence of scattered light, indicating the presence of plume fluid, is evident in the +z direction along the top of the laser sheet in Fig. 6(b). Note that the BSMs are upstream of the laser sheet, near the nose of the SRB. As PR continues to increase the plume fluid is seen to expand out, filling more of the field of view, as expected. In Figs. 6(b)-(e), the pair of conical shocks originating from the core stage are no longer observed.

One should keep in mind that these images are averaged over $\sim 1/60^{\text{th}}$ of a second (16.7 msec) so there may be interesting and important higher-frequency unsteady effects that are not shown in these images. One effect of this temporal averaging is that an apparent smooth gradient is observed between the seeded freestream fluid and the unseeded plume fluid in these images. Instantaneous images might show a sharp interface between these fluid streams.

Figure 7 shows the behavior of the flow in a smaller range of PR from 0 to 220 psi which is about 15% of the maximum pressure used. As PR is increased, the plume is observed to expand the conical shock wave away from the SRB. By the final image, Fig. 7(e) the conical shock wave has disappeared or merged with the two conical shocks originating from the core stage, forming a more diffuse shock structure observed at the far right of Fig. 7(e) but which is not clearly observed in Figs. 6(b)-(e) which had higher PR. For these higher PR images (Figs. 6(b)-(e)), the outermost shock system could be further out of the field of view of the camera.

While observing the video live during the wind tunnel test, the shock wave around the SRB shown in Figs. 7(b)-(d) was observed to suddenly jump from one position to another at a $PR = 219 \pm 1$ psi. Figure 8 captures this effect by showing a very small range of pressures corresponding to 13.4%, 14.0%, 14.5%, 14.7% and 15.4% of the maximum PR in Figs. 8(a)-(e) respectively. The sudden movement of the shock wave occurred at 14.6% of the maximum PR. Thus, a 0.2% change in PR causes a gross change in the flowfield. The cause of this sudden change is unknown and is a topic for future investigation experimentally or computationally.

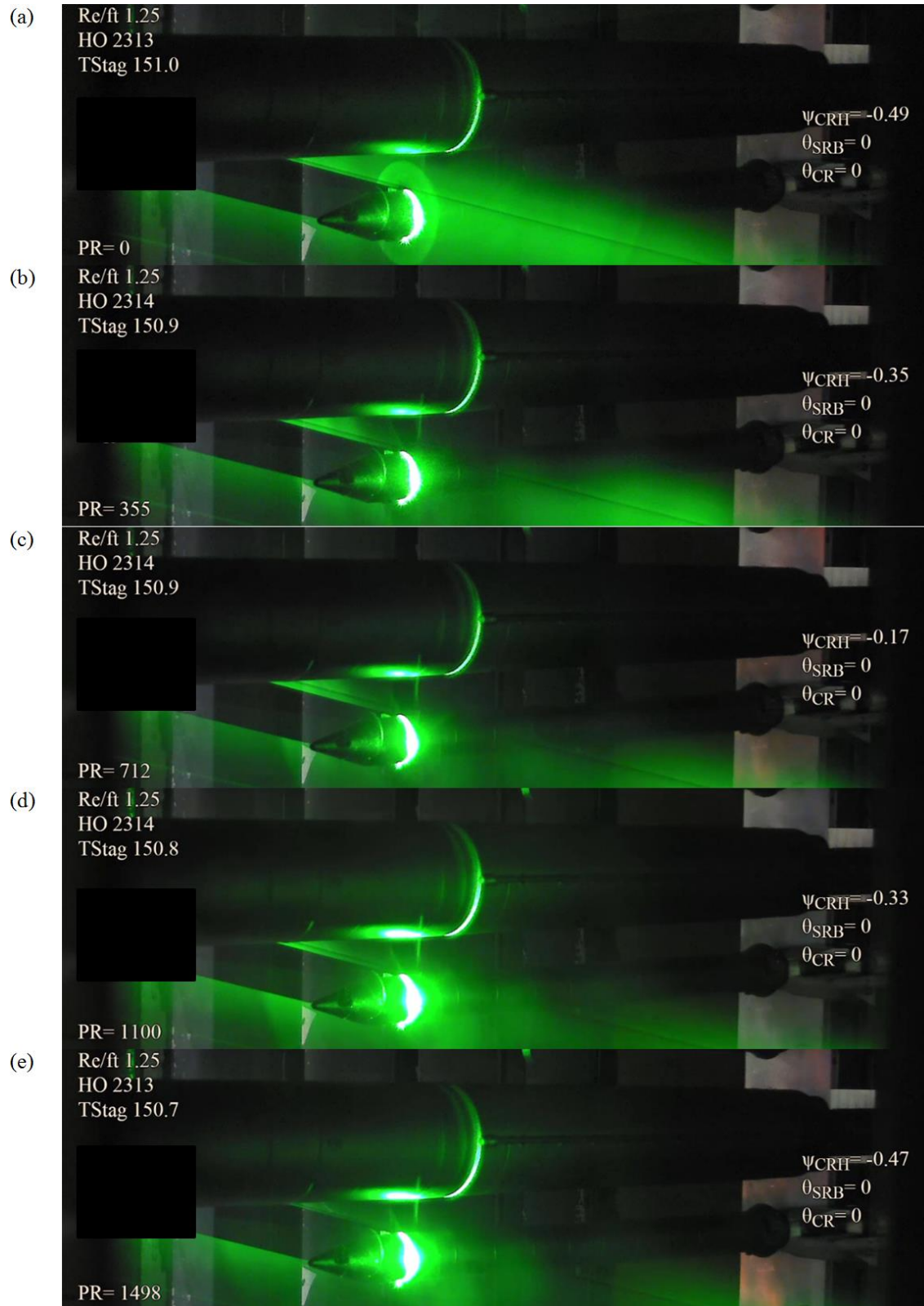


Figure 6: Increasing BSM pressure from PR = 0 psi to 1500 psi: (a) 0 psi (b) 355 psi (c) 712 psi (d) 1100 psi (e) 1498 psi. Δx is at nominal condition (0% of motion).

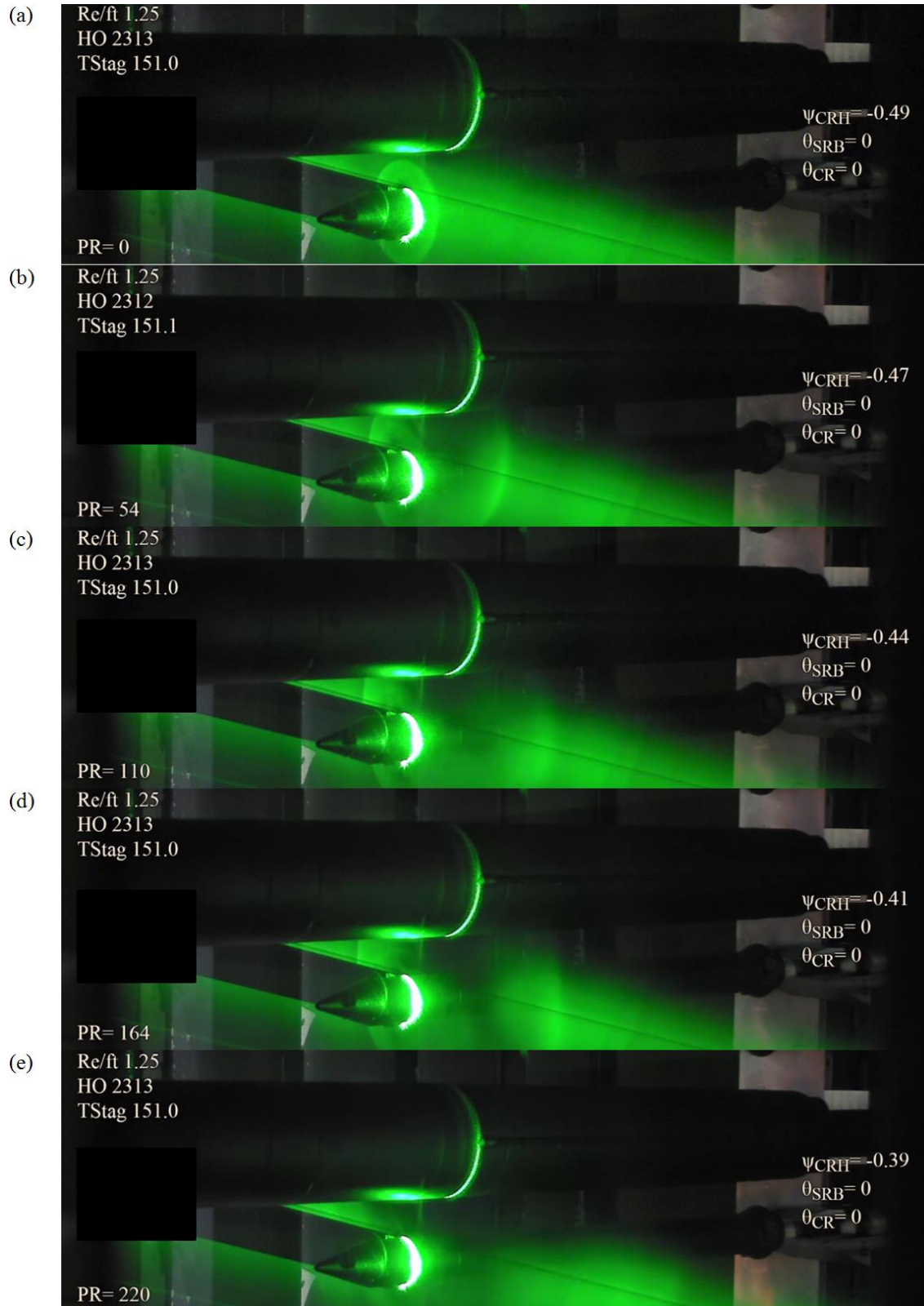


Figure 7: Increasing BSM pressure in smaller increments from PR = 0 psi to 220 psi: (a) 0 psi (b) 55 psi (c) 110 psi (d) 165 psi (e) 220 psi. Δx is at nominal condition (0% of motion).

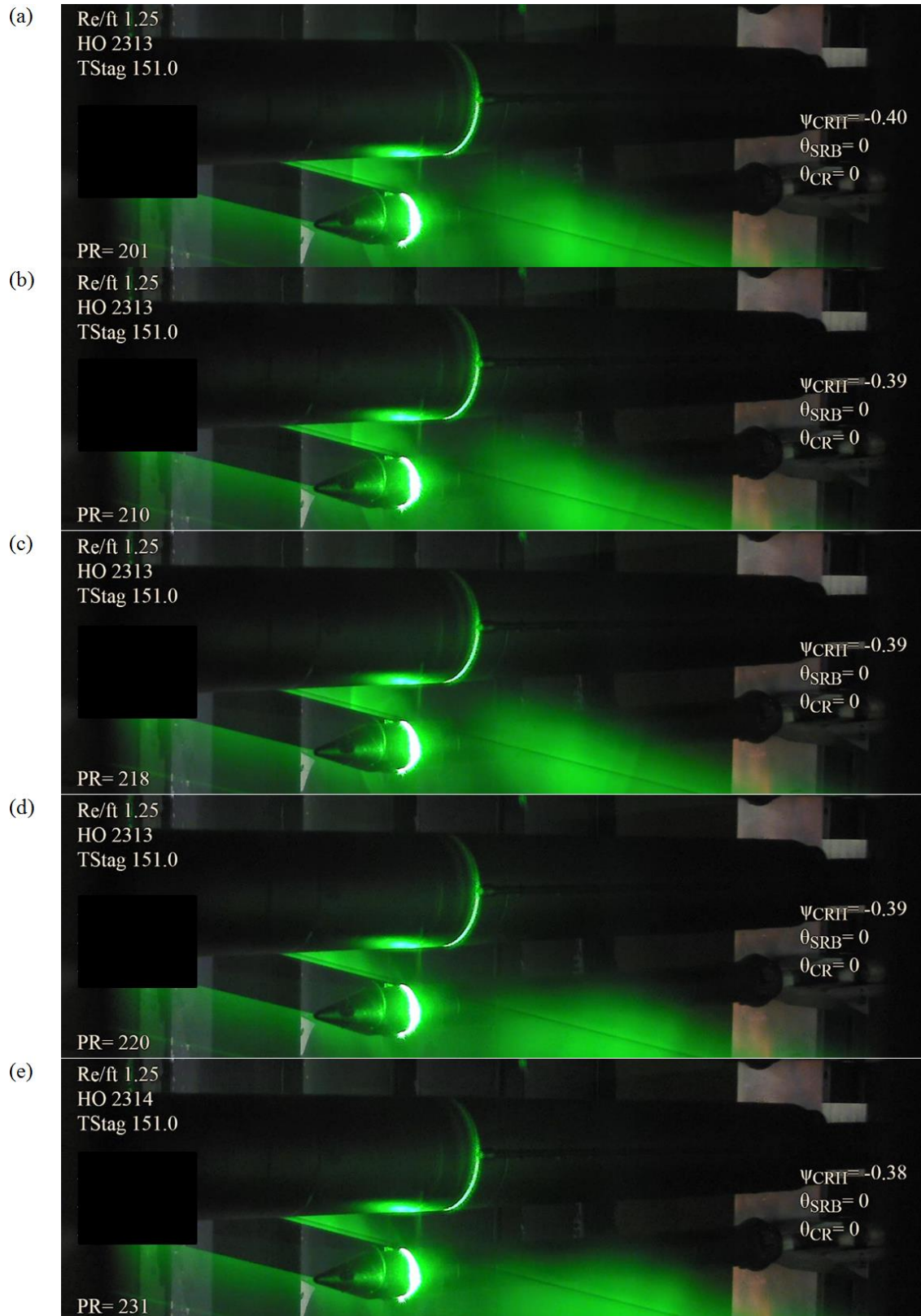


Figure 8: Increasing BSM pressure in even smaller increments from PR = 201 psi to 231 psi: (a) 201 psi (b) 210 psi (c) 218 psi (d) 220 psi (e) 231 psi. Δx is at nominal condition (0% of motion).

D. Variation of Streamwise SRB Position with activated BSMs.

Figures 9-12 show the left-hand SRB at different Δx streamwise positions (holding the Δy and Δz positions constant) with an intermediate PR of ~ 730 psi (Figs. 9 and 10) and the maximum PR of ~ 1500 psi (Figs. 11 and 12). Figure 9 shows the SRB moving over its full range of motion from 0% to 100% with $PR = 730 \pm 6$ psi. Ignoring Fig. 9(b) momentarily the main effect observed when the SRB is moved aft is that the unseeded plume fluid is observed to propagate well forward of the nose of the SRB, even with the SRB at 75% of maximum movement. The orientation of the forward BSMs shown in Fig. 10 of Ref. 7 is partially upstream and partly orthogonal to the streamwise direction and angled towards (but not directly at) the core stage. Given the orientation of the forward BSMs and also the large pressure ratio between the PR and the freestream pressure (~ 7000 for the 730 psi case and 14,000 for the 1500 psi case) large jet plumes having significant forward upstream influence are expected.

Figure 10 shows visualizations obtained near the exit of the BSM just upstream of the nose of the SRB. By showing these closely spaced images the evolution of the shape of the plume in the near field can be observed. As the SRB is moved further aft, the plume shape expands as expected for an underexpanded jet flow. The four-fold symmetry of the jet plume originates from the four jet nozzles shown in Fig. 2.

This highest PR case is shown in Figs. 11 and 12. Similar to Fig. 9, Fig. 11 shows the SRB at 5 different positions over the full range of motion from 0% to 100%. Again the main effect is that the plume displaces most of the seeded freestream fluid except that this effect is much more pronounced in Fig. 11 than Fig. 9. The extra factor of two in PR appears to greatly expand the upstream influence. Even at the furthest downstream location of the SRB (Fig. 11(e)) the plume is clearly visualized in the measurement plane. Thus the upstream influence of the BSMs could affect the flowfield even near the forward section of the core stage. In future work the laser should be scanned towards the nose of the core stage to determine the extent of the influence of this plume.

Similar to Fig. 10, Fig. 12 shows visualization of the near-field plume for the $PR = 1500$ psi case which is the maximum PR. This plume is much brighter and more clearly defined and larger than the corresponding lower pressure case shown in Fig. 10. Again the four-fold symmetry is observed and seen to grow as the SRB is moved further aft. The right side of the plume appears to develop a complicated shock structure (a pair of linear structures oriented at a 45 degree angle) as it moves aft. Reference 7 shows comparisons between these visualizations and CFD.

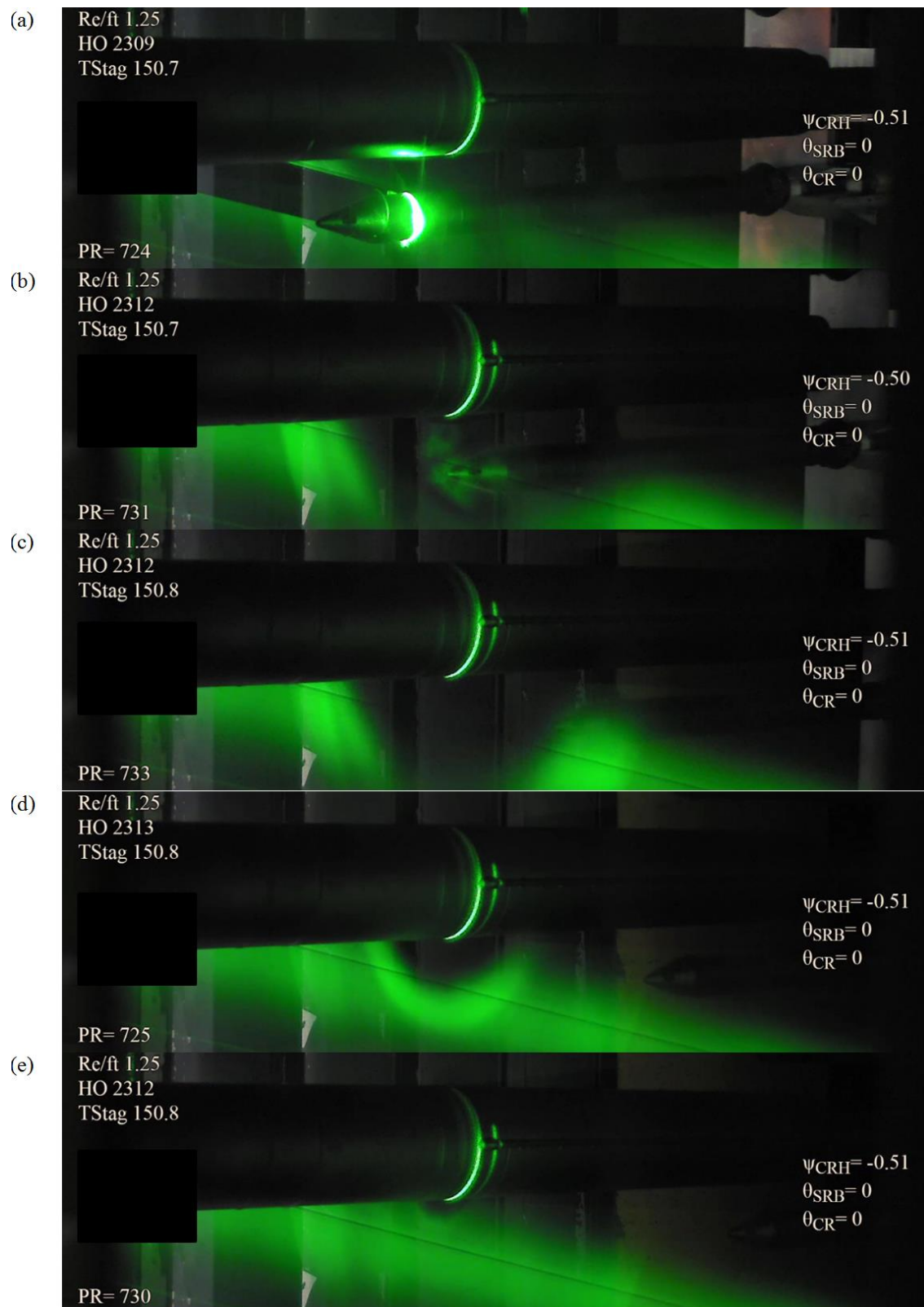


Figure 9: SRB moved aft with PR = 730 psi for large steps in Δx : (a) 0% (b) 25% (c) 50% (d) 74% (e) 99% of motion.

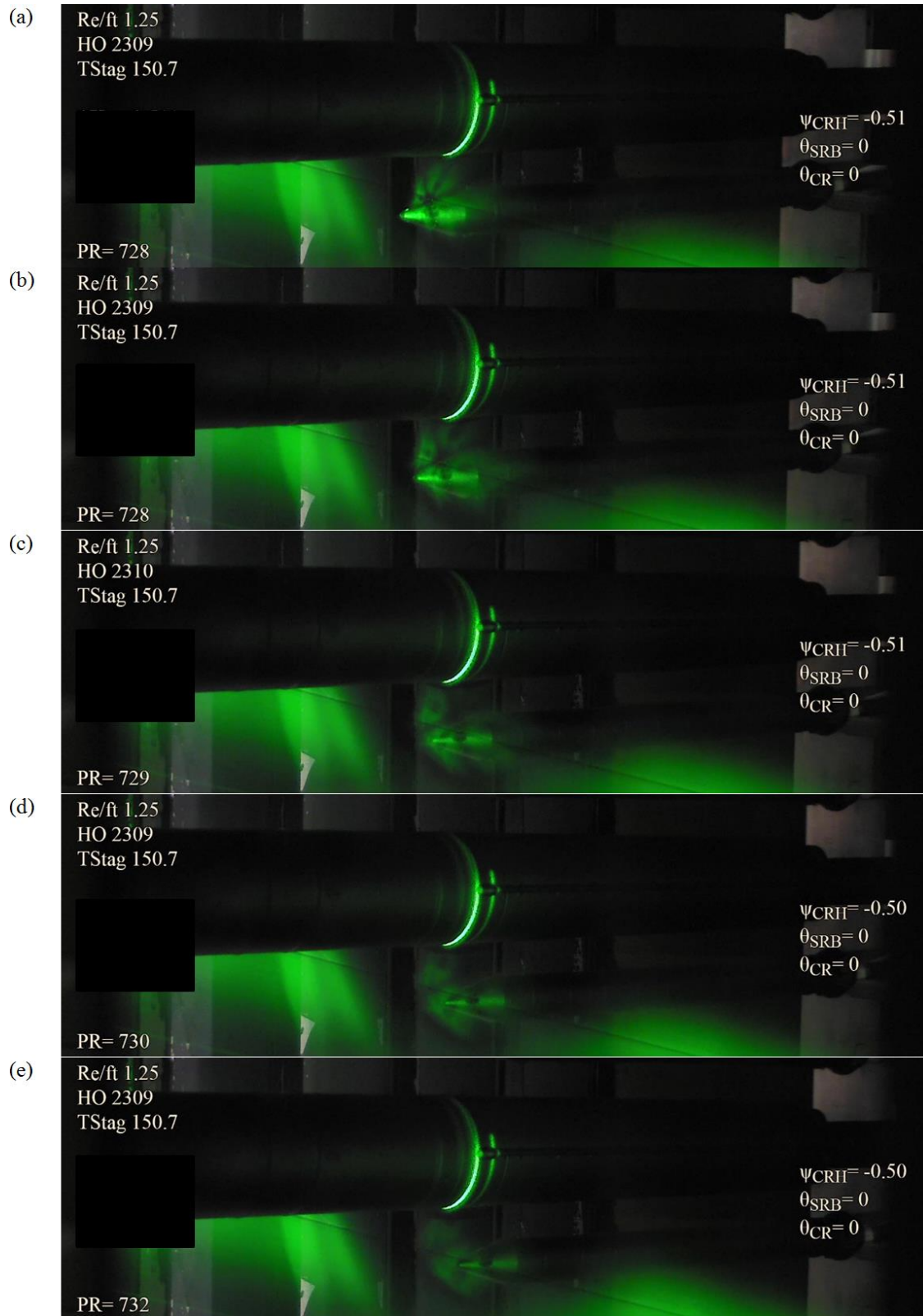


Figure 10: SRB moved forward with PR = 730 psi for small steps in Δx : (a) 18% (b) 21% (c) 24% (d) 27% (e) 30% of motion.

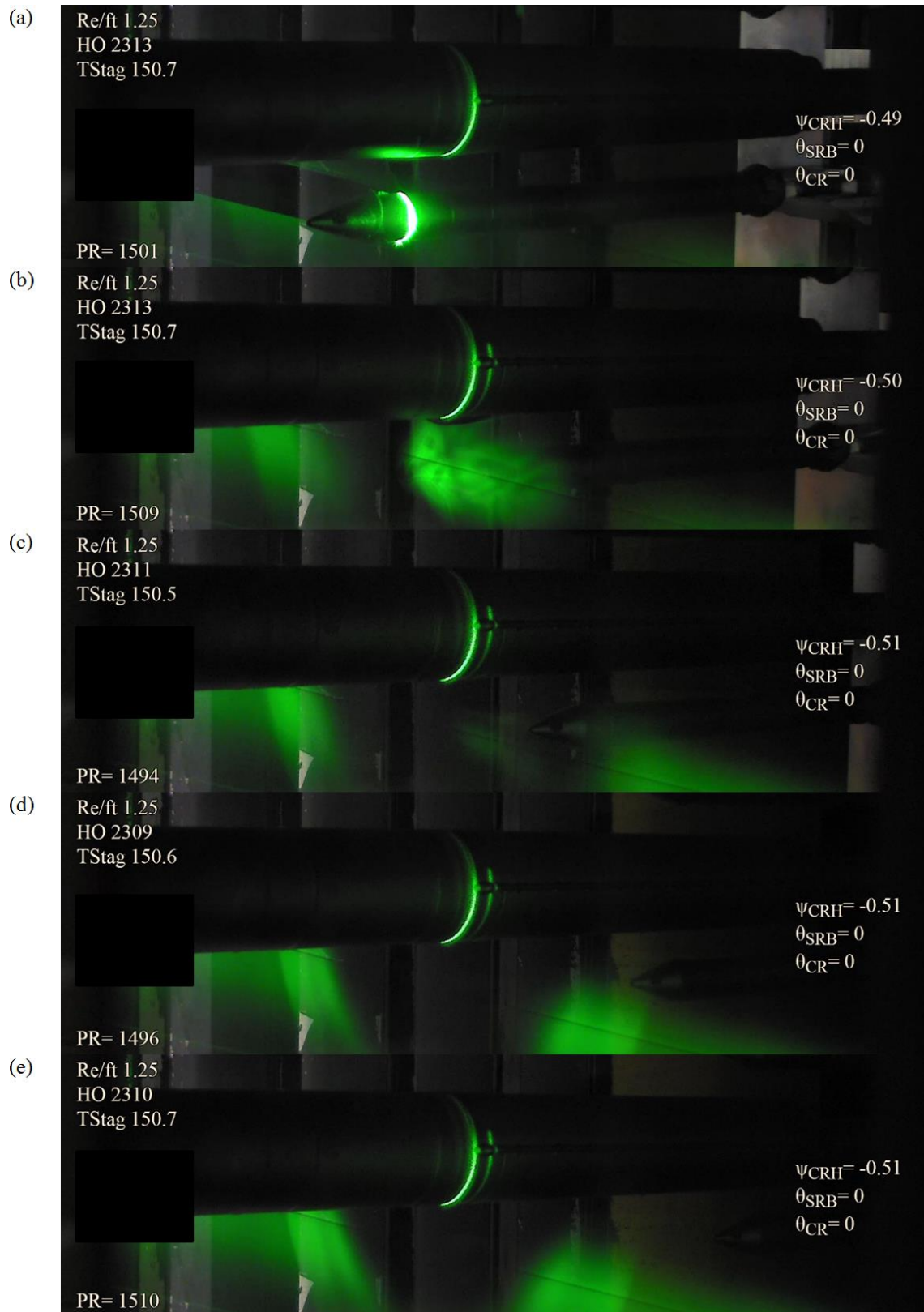


Figure 11: SRB moved aft with PR = 1500 psi for large steps in Δx : (a) 0% (b) 24% (c) 48% (d) 75% (e) 100% of motion.

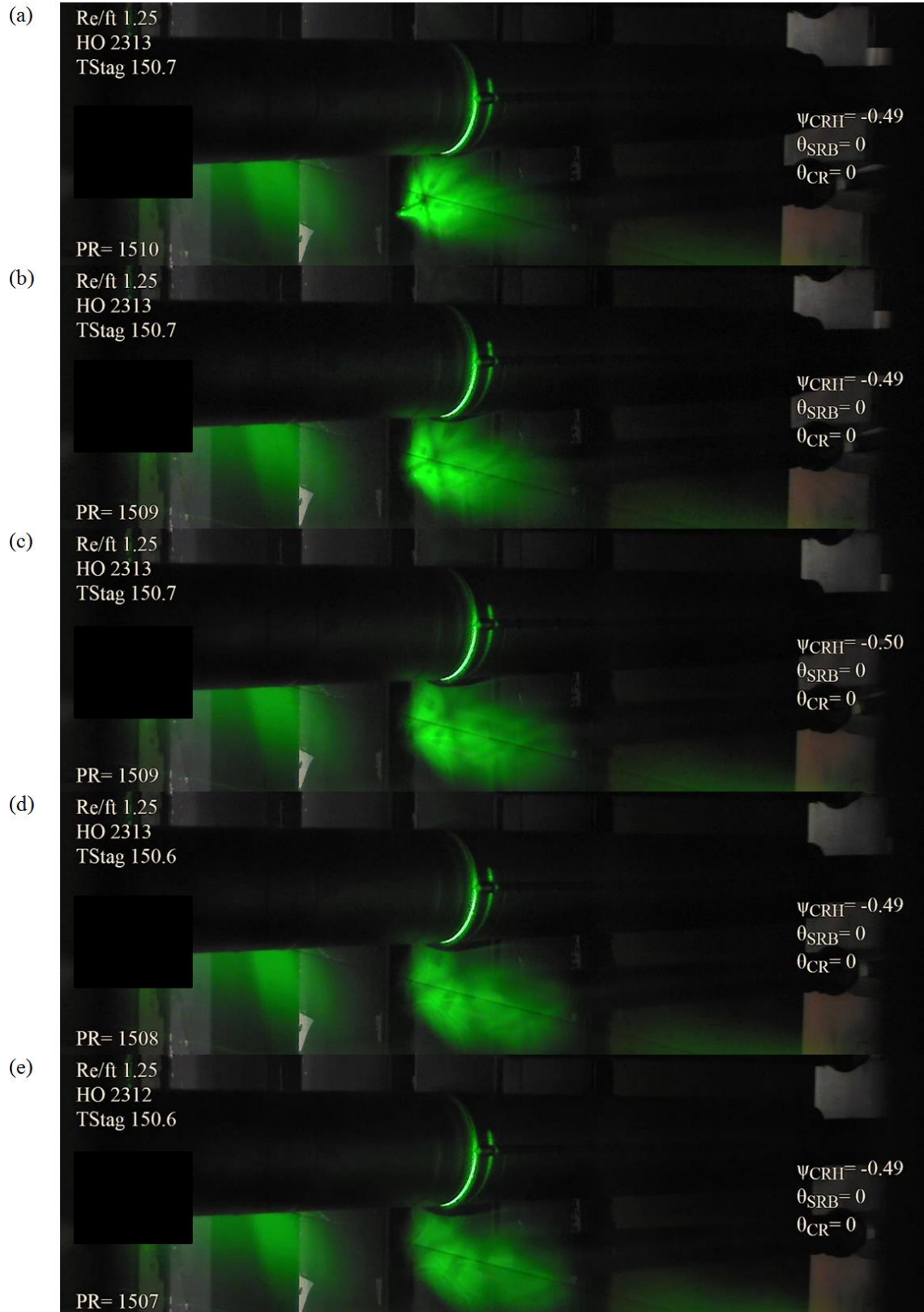


Figure 12: SRB moved forward with PR = 1500 psi for small steps in Δx : (a) 18% (b) 21% (c) 24% (d) 27% (e) 30% of motion.

IV. Conclusions

This paper reports planar flow visualization based on scattering off ice crystals seeded into a Mach 4 flow. A fixed laser sheet oriented perpendicular to the flow direction was used to visualize flow structures including shock waves and plume shapes originating from the core stage, solid rocket boosters and booster separation motors of the SLS vehicle. The position of the solid rocket boosters and the supply pressure to the booster separation motors were varied while visualizing the flow. The laser light sheet visualization allowed identification of the locations of shock waves, and the shapes and sizes of the different plumes. The data provides visualization of flow structures in the spanwise plane, which complements schlieren imaging that integrates over this spanwise dimension. These visualizations were compared to computational fluid dynamics simulations in a companion paper.

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