Schlieren diagnostic for the characterization of propellant gas flow suppression in the Shattered Pellet Injector of the ITER DMS

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The ITER Disruption Mitigation System (DMS) [1] utilizes Shattered Pellet Injection (SPI) technology [2], for which it is critical that the pellet arrives at the shattering head intact, with minimal propellant gas and debris preceeding it, in order to maintain disruption mitigation efficiency. An SPI system was developed in the ITER DMS Support Laboratory at the HUN-REN Centre for Energy Research [3] to study pellet formation, launch and shattering.

In schlieren imaging [4], density gradients are visualized by placing a camera and a point light source at twice the focal length of a spherical mirror. The y directional d deflection at the centerplane of a concave mirror with f focal length is proportional to the line integrated refractive index gradient (Eq. 1). By introducing a knife edge filtering deflections, an intensity scale can be paired to a selection of denstity gradients.

$$d = 2f \int \frac{dn}{dy} dx \qquad (1)$$

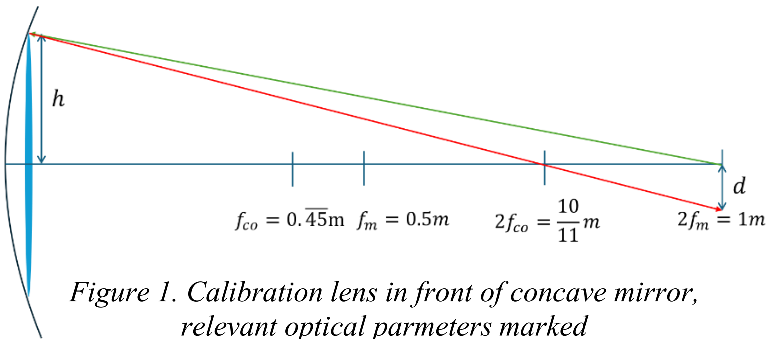

Figure 1. Calibration lens in front of concave mirror, relevant optical parmeters marked

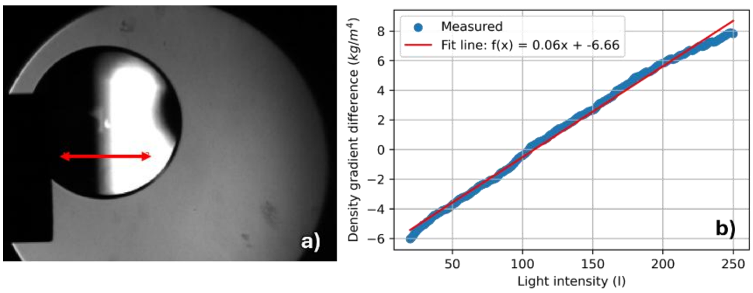

Figure 1. Schlieren image of calibration lens (a), sclieren image intensity - density gradient mapping (b)

We developed and installed a schlieren diagnostic on our SPI test bench, which is now routinely operated and is capable of detecting the gas flow around the pellet mid-flight. Previously, we obtained direct evidence of propellant gas flow ahead of the pellet by observing shock waves with the schlieren diagnostic in the expansion chamber of the SPI [5,6]. A calibration was performed for quantitative analysis of schlieren measurements using a calibration lens to determine the relationship between density gradients and light-intensity variations, based on [7].

By placing a f=10m calibration lens in front of the concave mirror we introduce known refractive gradients (Fig. 1, 2). The common focal length is smaller, causing a d deflection at the original centerplane:

$$d = h \cdot \frac{2f_m - 2f_{co}}{2f_m} = h \cdot \left(1 - \frac{f_{co}}{f_m}\right)$$

If a density distribution produces the same intensity value, the two are equal:

$$d = \left(1 - \frac{f_{co}}{f_m}\right) h = \frac{1}{10} h = 2f_m \int \frac{dn}{dy} dx$$

Using this calibration, the density gradient maps of the shock waves observed behind the pellet and in the flight tube were quantified (Fig. 3, 4).

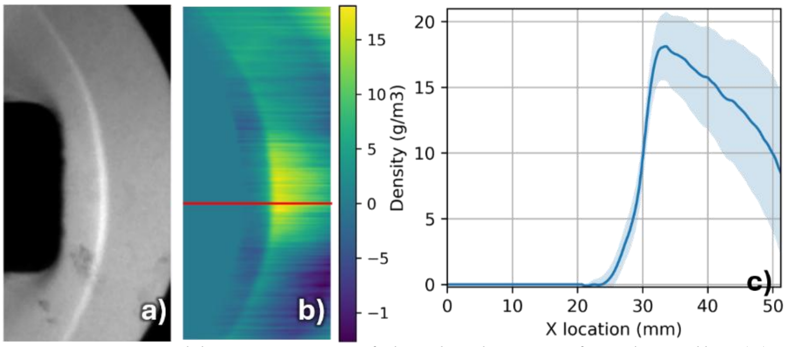

Figure 2. Schlieren image of the shockwave after the pellet (a), the reconstructed density-image with the maximum density jump marked with red (b), and profile the largest density jump (c)

Integrating the gradient maps horizontally reconstructs the density map. The integration is started from the start of the shockwaves to minimize the error of the density jump, cumulating from the uncertainty of the density gradients. Largest density jump measured after pellet was $18.1 \pm 2.6\ g/m^3$ while at inlet of the flight tube was $3.16 \pm 0.34\ g/m^3$.

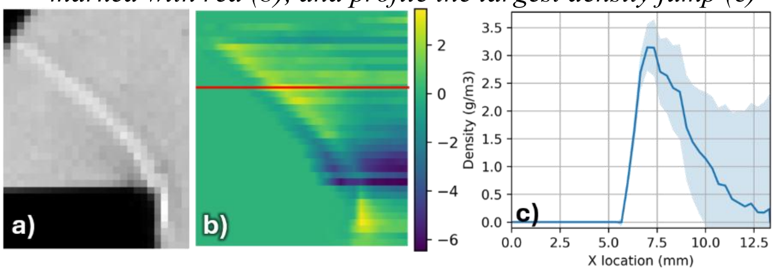

Figure 4. Schlieren image of the shockwave at the flight tube (a), the reconstructed density-image with the maximum density jump marked with red (b) and profile the largest density jump (c)

According to ITER requirements, a gas suppressor chamber was installed in place of the expansion chamber to retain propellant gas. Two protruding rods were placed in the second half of the suppressor, to generate observable shockwaves. With the schlieren diagnostics installed observing the gas flow around the rods, no shock wave was detected during the passage of the pellet. Four milliseconds after the pellet passed, a faint shock wave generated by the propellant gas flow was observed (Fig. 5). By line integrating the intensity profiles in different angles, and choosing the steepest intensity jump, the angle of the shockwave was determined to be 24.2°. The corresponding Mach-number is:

$$\sin(\alpha) = \frac{v}{c} = \frac{1}{M};\ M = 2.439$$

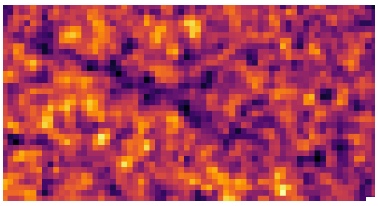

Figure 5. #1708, background subtracted schlieren intensity at protruding rods 4 ms after pellet

Figure 6. S... thetic 1D reconstructed s... en intens... shockwave ... uding

Using the corresponding steepest intensity profile, a 1D intensity reconstruction of the schlieren intensity profile was carried out (Fig. 6). Using the calibration, the density profile was reconstructed (Fig. 7). The maximum density jump, $0.588 \pm 0.248 \frac{g}{m^3}$, was only a fraction

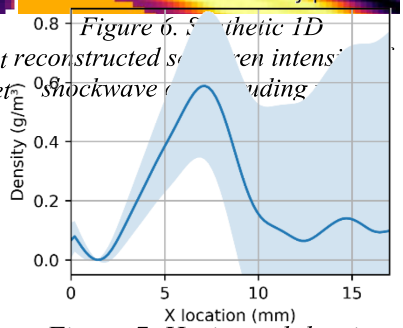

Figure 7. Horizontal density profile of 1D reconstructed

of the one measured in the expansion chamber, proving that an even smaller density perturbation occurs during the passage of the pellet, confirming the gas retention effectiveness of the suppressor.

By assembling the consecutive frames into one image, a panorama picture can be created, which is suitable to overview the entire launch process [6]. During a pellet launch a dark cloud of hydrogen microfragments arrive before the pellet, as can be seen on the schlieren and shadowgraphy panorama images (Fig. 8). The panorama images from the two diagnostics have synched velocity evolution, normed and background subtracted intensity, the same start and end

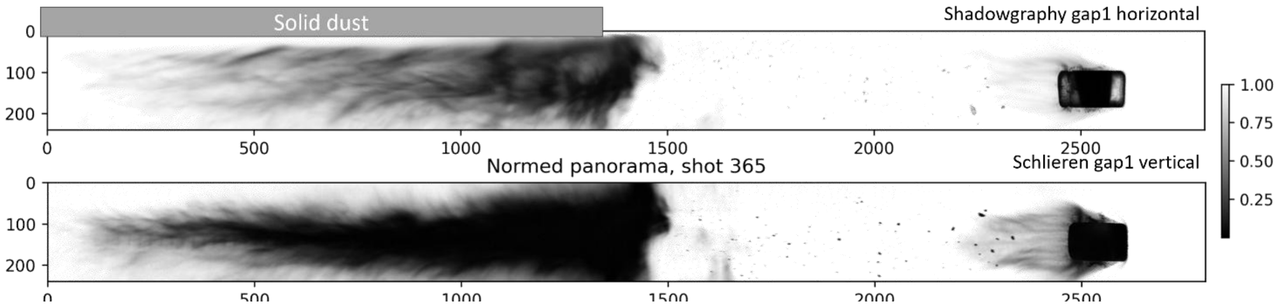

Figure 8. Panorama image of Shadowgraphy (top) and Schlieren (bottom) diagnostics observing the same pellet launch at the same position. The pellet travels from right to left

times, the same width, and they are scaled to the same array size for better comparison.

We can estimate the amount of dust material from the intensity change seen in the diagnostics. In the backlit shadowgraphy image, the cloud is partially transparent. In schlieren imaging, all microfragments scatter the light passing through, appearing fully black in the final image. The intensity of each pixel is determined by the portion of microfragments blocking the light, described by Beer's law:

$$I_{schlieren} = 1 - \exp\left(-N\frac{A_p}{A_{px}}\right) = \frac{I_{shadow}}{t}$$

In the normed average panorama intensity (Fig. 9), the shadowgraphy intensity is fitted to the non-clipping section of the schlieren intensity indicated with two red dots, to determine the t transparency:

$$\left\langle\frac{I_{shadow}}{I_{schlieren}}\right\rangle = 0.485 \pm 0.085 \;\; \text{(data of 67 shots)}$$

Using Beer's law on each pixel, and estimating the average maximal diameter of microfragments by the cloud dimensions, a lower bound for total dust material volume can be determined:

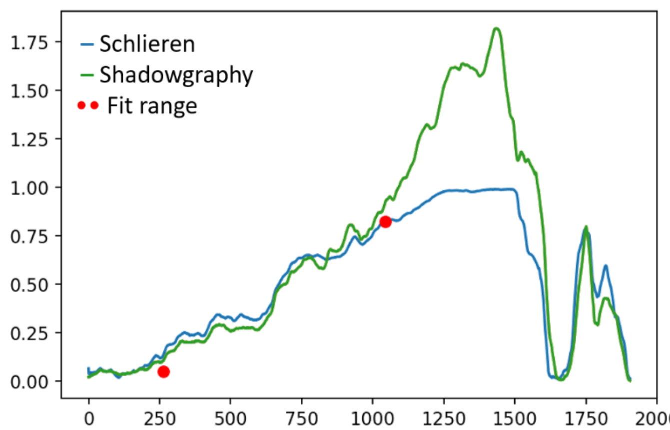

Figure 9. #365, normed average schlieren and shadowgraphy panorama intensity

$$V_{dust} > 360 \pm 120\, mm^3; \quad V_{dust} > 1.86 \pm 0.62\%\, V_{pellet}$$

These results demonstrate that the suppressor effectively reduces propellant gas flow during pellet launch, and characterize the amount of dust microfragments produced during launch, providing critical information for the ITER DMS and highlighting the capabilities of Schlieren diagnostics.

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