

Feasibility Study of Retroreflective PIV

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ABSTRACT

The article describes recent tests and developments of Particle Image Velocimetry (PIV) recording and evaluation techniques that take advantage of strong forward scattering of tracer particles by collimating the light of low-power pulsed light sources onto a retroreflective background screen. Several techniques for recording and dedicated subsequent evaluation were tested of which some will be described in more detail in the following.

1. Introduction

Since the obtained contrast of conventional Particle Image Velocimetry (PIV) recordings directly depends on the particle image intensity, a high scattered light power is desirable [Adrian 1991]. To achieve this, a sophisticated choice of the scattering particles as well as the direction of illumination is often more effective and economical than increasing the laser power.

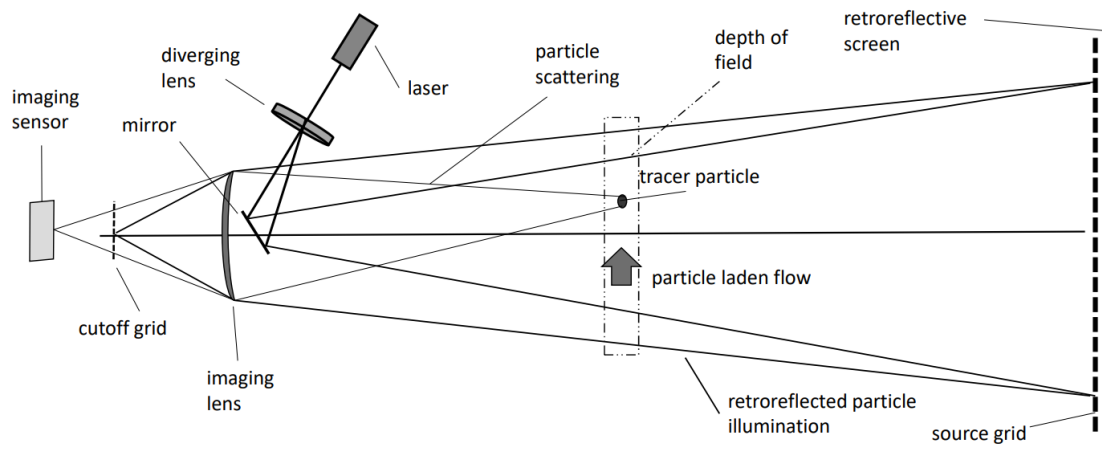


Figure. 1 Schematic representation of a retroreflective PIV setup with laser illumination via a deflection mirror in front of the imaging lens.

In general, the light scattered by small particles is a function of the particle's size, shape, orientation and the ratio of the refractive indices of the particles and the surrounding medium. Furthermore, the light scattering also depends on polarization and observation angle. For spherical particles with diameters larger than the wavelength of the incident light, Mie's scattering theory can be applied. A detailed general description and discussion are given by van de Hulst [1957] and in the context of flow velocimetry by Raffel et al. [2018]. The polar distribution of the scattered light intensity for oil particles over various diameters in air shows that forward scattering offers orders of magnitude more light than the conventionally exploited side scattering.

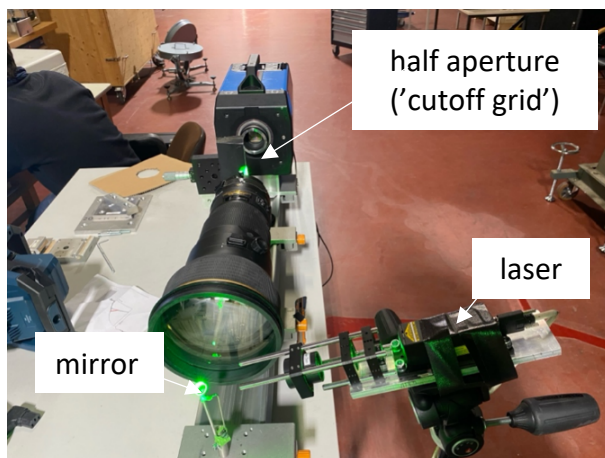


Figure 2: Retroreflective PIV setup with laser illumination from the side. A half aperture between camera and imaging lens serves as 'cutoff grid'.

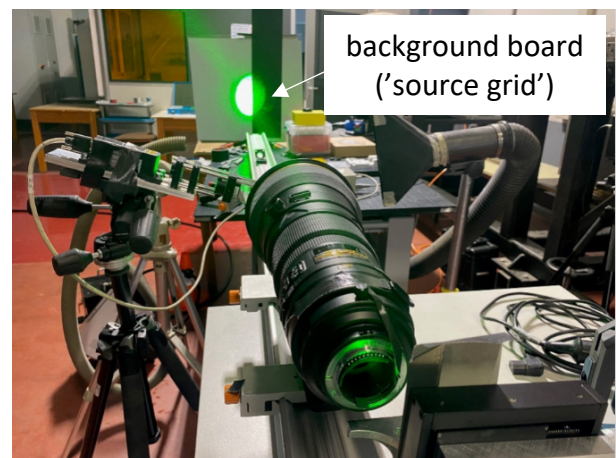


Figure 3: Example of a retroreflective PIV recording photographed in viewing direction from the camera to the retroreflective background. A dark upright board serves as 'source grid'.

A recently published article [Raffel et al. Exp. In Fluids 2024] describes tests and developments of PIV recording and evaluation techniques that take advantage of strong forward scattering of tracer particles by in-line recording set ups. The disadvantage of the in-line PIV setups is that the size of the measurement volume is limited by the size of the lenses used and that optical access to the test section is required on two opposite sides of the experiment. A cost-effective and simple way to avoid some of the disadvantages of the in-line optical setting can be achieved by using a retroreflective film, as shown in Fig.1. The direct light beam that is not refracted by tracer particles is shaded by combining a positive grid ('source grid', in the background) with a negative grid ('cutoff grid', close to the camera). The combination of the two grids cuts off the light beams along the direct line of sight, but can be surpassed when the light beams between the two grids are deflected by tracer particles. All particles located in the focal plane of the imaging lens are sharply imaged on the image sensor. The grids can consist, for example, of half apertures, lines, a

checkerboard, or dot patterns. The imaging configurations used in this study are similar those used in retroreflection focusing schlieren techniques as described by Heineck et al. [1994].

The setup shown in Figs. 1-3 demonstrates the feasibility of the imaging arrangement proposed above. The light source – mounted on a tripod on the left-hand side in Fig. 3 – was a laser with a continuous power of just 250 mW. The imaging lens – in the foreground of the image – was a standard 400 mm Nikon lens. The camera had a sensor with 2016×2016 pixels. The tracer particles were generated using a CTS1000 particle generator with a nominal particle size of approximately $2\text{--}3\ \mu\text{m}$.

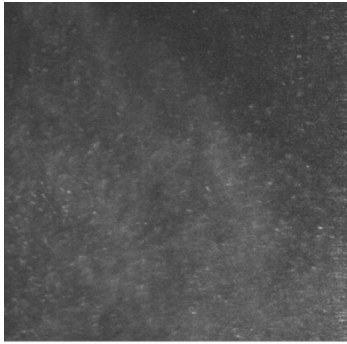


Figure 4: Retroreflective PIV image raw.

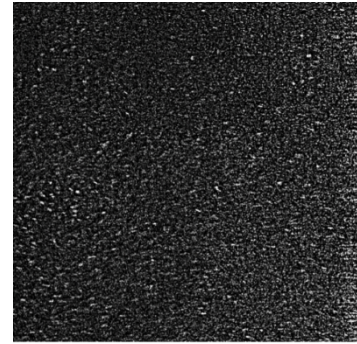


Figure 5: Digitally high-pass filtered image.

Figure 4 shows a typical result of a retroreflective PIV image taken with the above-mentioned setup. It can be seen that the image is dominated by residual light caused by lens errors and lens contamination, as well as by scattered light from out-of-focus particles. After digitally applying a temporal high-pass filter, see Fig. 5, the residual background intensity was reduced and the images of the focused particle illumination became clearly visible.

2. Retroreflective PIV Tests on a Convective Flow

Figure 6 depicts an improved retroreflective PIV setup using laser illumination via fiber bundles and a collimating lens instead of a mirror blocking parts of the light path. In the experiment described in the following, the laser light retroreflected through the source grid - which consisted of dark black dots airbrushed onto the retroreflective screen behind the test section - and was imaged on a source grid - a perforated metal shield behind the imaging lens. The majority of the emitted light is hindered from reaching the imaging sensor, with only small exceptions caused by lens imperfections and pollutions. With respect to in-line PIV, here the image is subject to the imperfections of both retroreflective screen and the residual scattering of laser light from the dark

paint dots on that screen. On the other hand, this configuration allows for a relatively wide field of view compared to in-line PIV without the need of expensive large format lenses or mirrors.

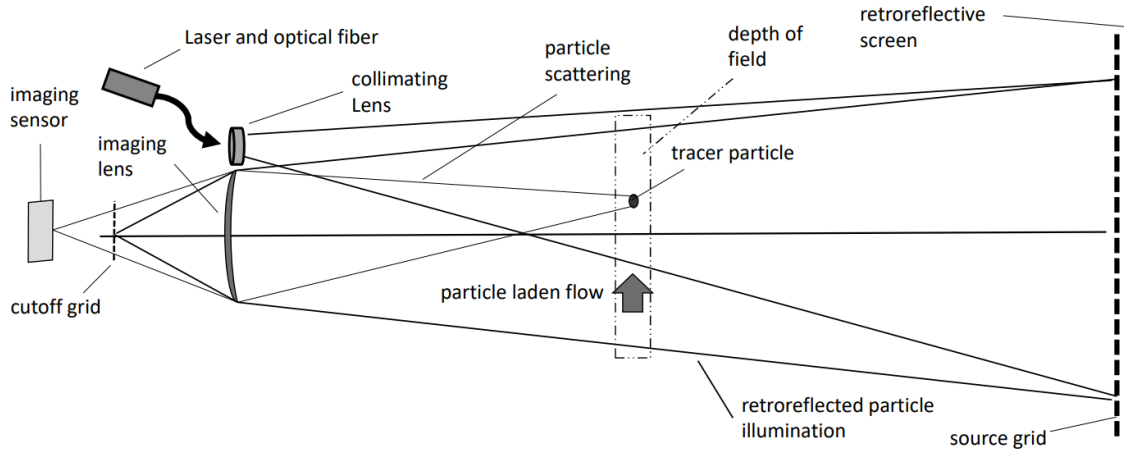


Figure. 6 Schematic representation of a retroreflective PIV setup with CaviLux laser illumination via a fiber bundle and a collimating lens.

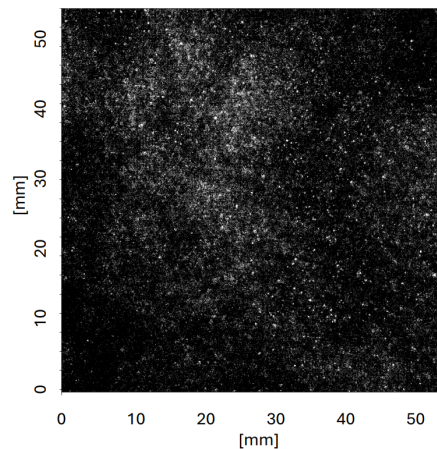


Figure 7: Retroreflective PIV sample recording, using a shuttered CaviLux laser and fiber light delivery, image digitally high-pass filtered.

To test the setup on a convective flow, the light of a low-cost diode-pumped pulsed solid-state laser (CaviLux smart, $\lambda = 640$ nm (visible red), $P(\text{short time}) = 400$ W) was expanded to a beam width of about 400 mm over a distance of 4 m using a set of collimating lenses. The light output was essentially monochromatic with low degree of coherence, mitigating chromatic aberrations and speckle. The laser used is capable of generating arbitrary pulses or bursts of pulses with precisely adjustable duration of the length of each individual pulse, and adjustable time delay between pulses. However, the pulse energy was limited, and double pulses with a pulse delay below 1 ms did not yield sufficient pulse energy. The illuminated volume was imaged by a high-

speed CMOS camera (PCO.Dimax S4) with an acquisition rate of 0.5 kHz, an image exposure time of $19\ \mu\text{s}$, and a resolution of 2016×2016 pixels. It was fitted with an $f = 300\ \text{mm}$ wide field lens (Schneider-Kreuznach, 1:5.6). The imaging lens' distance to the measurement volume was 1005 mm. With the lens aperture set to $f\# = 5.6$, the depth of field was estimated at 17 mm. In the current sample case, the ejector ultrasonic DEHS atomizer was placed in a glass wall convection cell, with the generator providing both flow tracers and a constant low-speed airflow crossing the field of view in upward direction. A series of 500 images was recorded within 1 second.

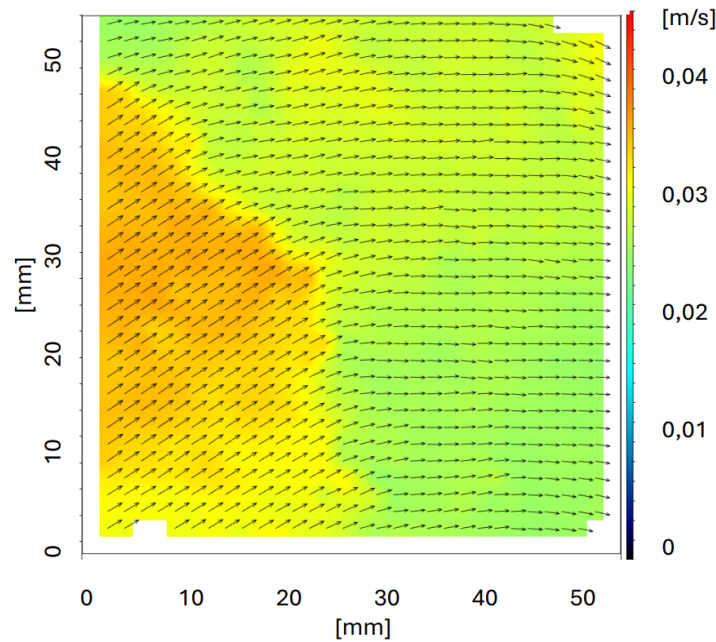


Figure 8: Instantaneously measured flow field of the convective flow.

As described above, retroreflective PIV generates increased image background intensity levels caused by lens imperfections, lens contamination and out-of-focus tracer particles. The front and rear glass walls of the convection cell were slightly tilted with respect to the optical axis in order to avoid reflections of the laser light on the camera. An ultrasonic seeding device provided a dense stream of di-ethylhexyl sebacate (DEHS) tracer particles with an approximate diameter of $D_p = 4\ \mu\text{m}$. The tracer particles were fed into the test section of the convection cell, which avoided excess particles in the vicinity of the measurement volume, thereby reducing light scattering by particles outside of the region of interest. The light scattered by particles within the depth of field of the imaging lens was well concentrated on a few pixels and could therefore be enhanced by digital image filtering.

The image evaluation was made with LaVision DaVis 11.1. To reduce background noise, the time-averaged image was subtracted from each instantaneous image, resulting in clearly identifiable particles with good contrast, as shown in Fig. 7. For the correlation, a time-resolved multi pass approach was used, with initial interrogation windows of 256×256 pixels, a final window size of 128×128 pixels, and a window overlap of 50% to increase vector density. Figure 8 shows a representative instantaneous flow field.

3. Retroreflective PIV Wind Tunnel Tests on a Cylinder in Cross-Flow

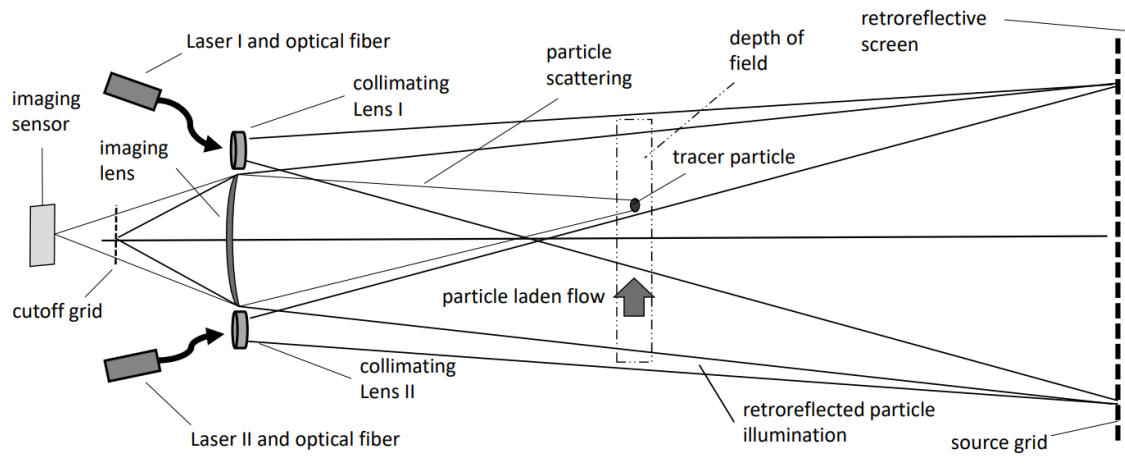


Figure. 9 Schematic representation of a retroreflective PIV setup with illumination by two CaviLux lasers in conjunction with fiber bundles and collimating lenses next to the imaging lens.

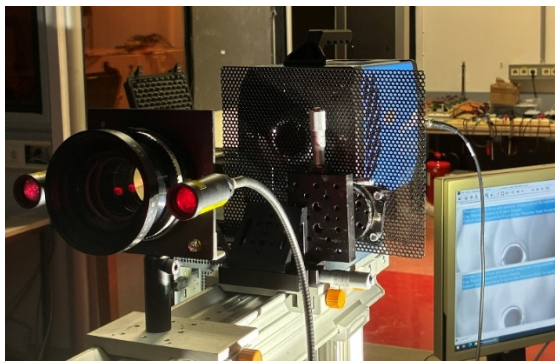


Figure 10: Retroreflective PIV setup with illumination by two CaviLux lasers via fiber bundles and collimating lenses next to the imaging lens. A perforated metal sheet between camera and imaging lens serves as 'cutoff grid'.

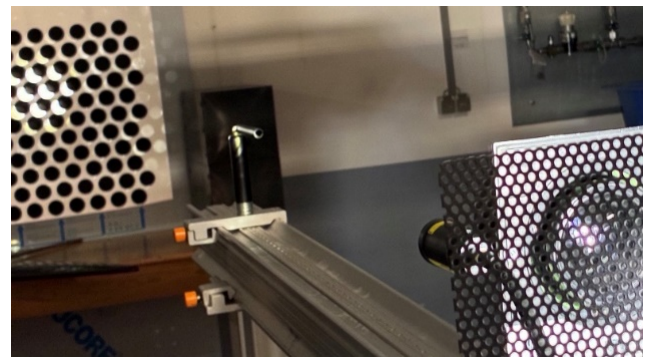


Figure 11: Image of the retroreflective background, photographed in viewing direction from the camera. Airbrushed dark circles on the background serve as 'source grid'

To overcome the limitations placed by the low pulse energy at short pulse time delays of the CaviLux laser, the setup was upgraded with a second CaviLux light source, see Figs. 9-11,

providing the second pulse of the required PIV double exposure, again with red light at $\lambda = 650$ nm. The pulse duration was set to $10\ \mu\text{s}$ with a pulse energy of approximately 4 mJ. The lens system was retained from the previous setup. A commercially available water atomizer was used in order to generate particles of approximately $10\ \mu\text{m}$ in diameter, which were added to the flow upstream of the test section of the wind tunnel. Figure 12 shows a sample recording with flow from left to right. The shear layers and especially the wake of the cylinder are already visible in the seeded flow. A filter implemented in the processing software DaVis was used to filter out intensity contributions which were not caused by particles, compare Fig. 12 and Fig. 13. The chosen filtering method involved subtracting the minimum intensity value within the whole set of recorded images of each individual pixel.

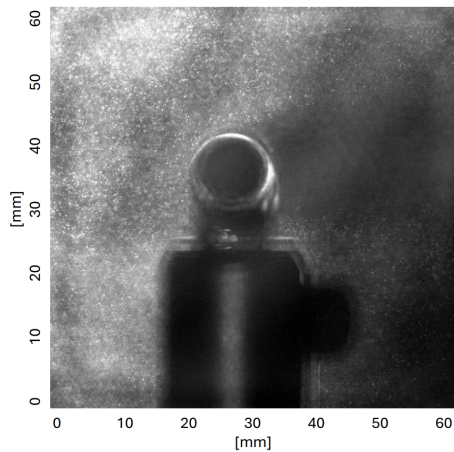


Figure 12: Raw particle images around the cylinder in cross flow. Insufficient power of the second laser required larger particles of about $10\ \mu\text{m}$ diameter, resulting in a void in the wake of the cylinder.

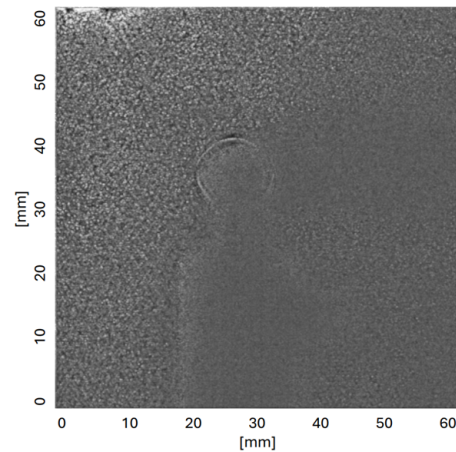


Figure 13: Preprocessed particle image before cross-correlation.

The measurement area was just about $60 \times 60\ \text{mm}^2$, limited by the power of laser light. The average measured free stream velocity was approximately 5 m/s, with the turbulent wake of the cylinder being clearly visible in the center of the measurement region, see Fig. 14. Note that the vertical mounting post of the cylinder blocks the line of sight of the camera, but is located outside the test section. Hence, the post does not influence illumination or flow, and does not leave a visible wake itself. The cross-correlation coefficient varied between 0.25 and 0.6, with the highest values being reached in the external flow and the lowest values in the turbulent wake.

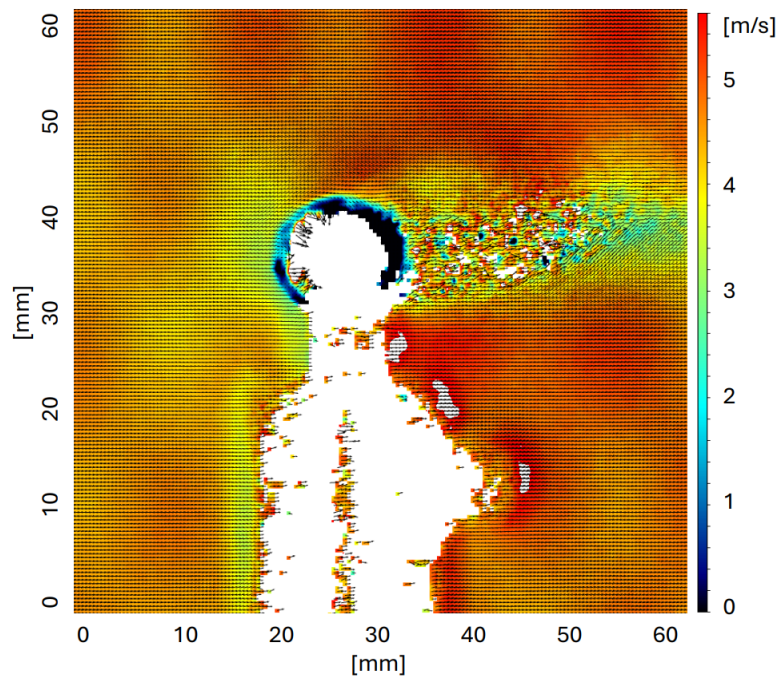


Figure 14: Averaged measured velocity field around the cylinder in cross flow. A particle void in the wake of the cylinder resulted in reduced correlation strength in the wake region.

2. Conclusions and Outlook

The feasibility of retroreflective PIV recording has been investigated with several configurations. The setups varied in the form of the source and cutoff grid, the arrangement of illumination, and the size, type and velocity of the flow field examined. In general, relatively low laser power and overall low-cost equipment was needed in comparison to standard PIV, and the Field of View was easily scalable when compared to in-line PIV.

In the experiment described in Chapter I, a single 400 W laser was used while recording a convective flow at velocities below 10 cm/s, limited only by the illumination frequency of the laser. The processing of the recorded images required relatively low effort, e.g. given the inherent mitigation of laser speckle.

With the relatively large seeding particles used in the experiment described in Chapter II, the particle following behavior with the flow was relatively poor. However, this is rather a result of the choice of seeding than a shortcoming of the measurement technique, wherefore the overall results appear promising to the authors.

The retroreflective PIV techniques show potential for PIV measurements in open spaces, since they allow for the use of low power lasers, even when small tracer particles with diameters in the range of 2–5 μm are being used. The techniques worked best with high particle

concentrations in the regime of the focal plane, but low particle concentrations in the surrounding area. It can be summarized that tracers within the imaging path, which are out of focus, will significantly reduce image contrast. Similarly, intermediate surfaces such as test section windows and lenses should be kept clean and scratch-free.

The depth of the measurement domain is defined by the DoF of the imaging lens. A combination of long focal length with large aperture and a considerable working distance can achieve a DoF in the millimeter range. For highly three-dimensional flows a limited depth of field requires the reduction of the separation time between both exposures to prevent loss of particle image pairing, just as in conventional PIV where the light sheet thickness defines the DoF.

The presented imaging arrangements generated a relatively high background intensity level on which brighter particle images can be detected. Ideally this background is constant in time such that it can be removed through subtraction. The technique is assumed to work well in combination with event-based cameras, which rely on contrast changes.

Similar to self-aligned focusing schlieren (SAFS) [see, for example, Page et al. 2025], a retroreflective PIV setup can be modified so that the light source projects a pattern onto a background, while the same pattern is used as an aperture. The advantages of this setup are that the alignment depends only on the adjustment of the respective Rochon prism, see Fig. 15, and that no additional pattern is required on the background. This makes the entire setup less sensitive to external disturbances such as vibrations, as the optical alignment is insensitive to motion of the retroreflective screen relative to the rest of the optical setup, which can, in turn, be easily mounted on a rigid body.

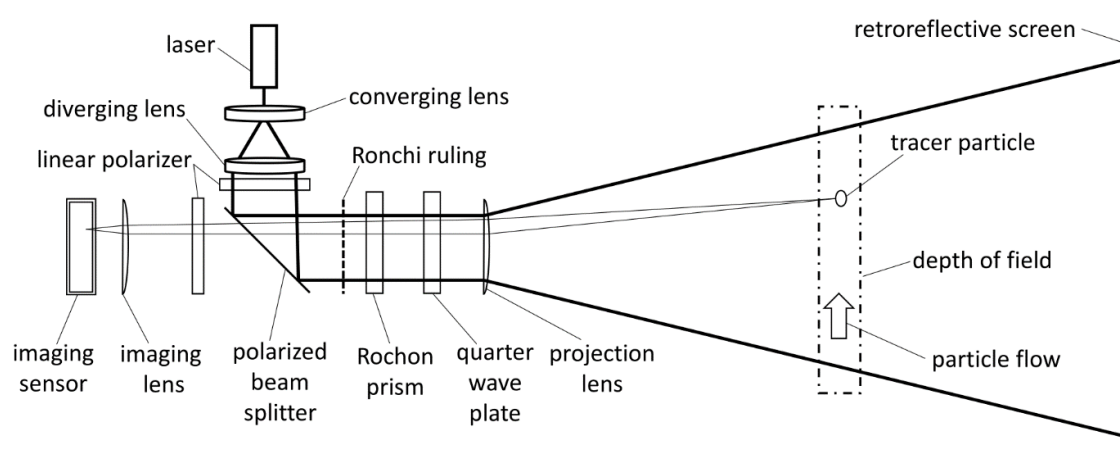


Figure 15: Proposed self-aligning retroreflective PIV setup.

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