

Volumetric Lagrangian Particle Tracking in high Reynolds number pipe flow

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Keywords: Pipe flow, Lagrangian Particle Tracking, Shake-The-Box, Profiles

ABSTRACT

We present statistical and instantaneous results from a time-resolved 3D measurement of pipe flow at $Re_\tau = 19,200$, captured in the CICLoPE facility and evaluated via Shake-The-Box. Using a high speed laser and camera system, most of the data was recorded in many short time-resolved sequences of 30 snapshots each; this mode combines the accuracy of time-resolved processing with the statistic independence of double-frame recordings.

Profiles of velocities and Reynolds stresses could be extracted from 0.4 to $3600 y^+$, which show very good coherence with expected results based on comparisons to DNS at a slightly lower Reynolds number. The location of the first peak of streamwise fluctuations is found at $16.3 \pm 0.5 y^+$. The huge number of statistically independent and highly accurate particle data allows for the first time to extract high-resolution profiles of acceleration and the corresponding variances at such high Reynolds number. Continuous fields of velocity and vorticity can be extracted from the particle tracks at each time instant and may give access to further investigations, e.g. vorticity statistics (see Thoroddsen et al. 2026).

1. Introduction

Volumetric Lagrangian Particle Tracking was carried out in the CICLoPE long pipe facility at Reynolds numbers up to $Re_\tau = 45,800$. The Long Pipe facility of University of Bologna is located at Predappio, Italy and features a main tube, 0.9 m in diameter and 111.15 m in length (see Figure 1, left) (Talamelli et al. 2009, Bellani and Talamelli 2016). The huge dimensions result in high Reynolds number pipe flows, while retaining sufficiently large viscous length scales ($\approx 10 \mu\text{m}$ @ $Re_\tau = 45,000$) to allow the application of micro-sensor based and optical metrology.

While wall-bounded flows appear in many varying configurations in applications such as for energy, environment and transportation industries, the pipe flow is unique for comparisons with theory and computations allowing exact comparisons that also avoid non-homogeneous boundary conditions or end conditions in transverse flow direction. Although the Superpipe facility at Princeton university, USA, achieves an order of magnitude higher Reynolds number compared to the CICLoPE facility of the University of Bologna in Forli, Italy, the much-improved access to the flow through the pipe and the better spatial resolution for the measurements allowing a wider variety of accurate measurement techniques.

The aim of this experimental undertaking is the determination of highly resolved wall-normal profiles of velocities, Reynolds stresses and accelerations of all three components using Lagrangian particle tracking (LPT, Schröder and Schanz 2023) in a range of high Reynolds number regimes. These are beyond the capabilities of DNS and relevant for quantifying the growing trends of first and second peak of streamwise velocity fluctuations and its pre-multiplied spectra.

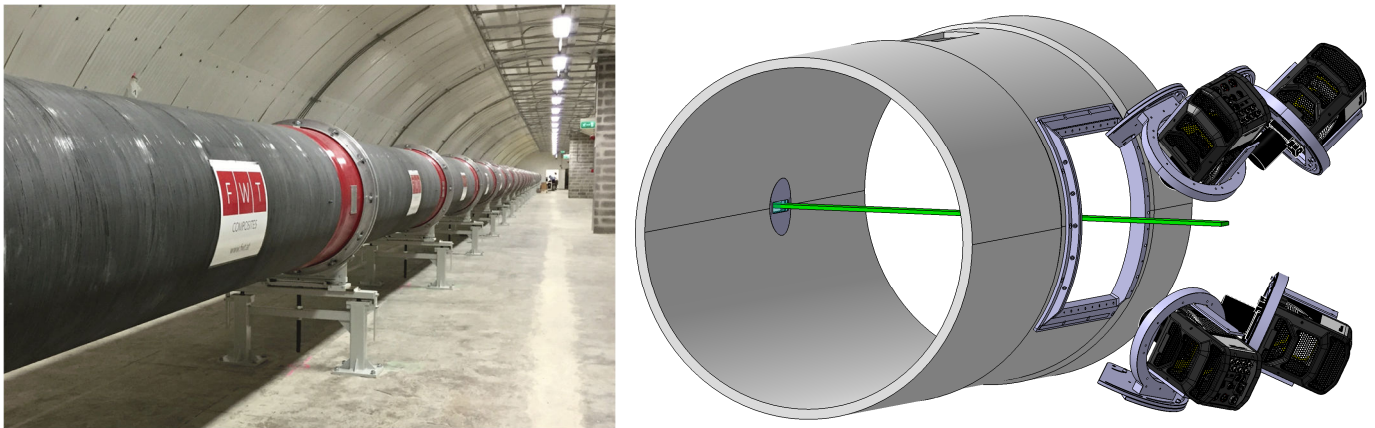


Figure 1: Photograph of the main tube of the CICLoPE facility (left). Rendered sketch of the purposely-built test section module with a window for laser-entry, opposite of a large curved-glass observation window. Four high-speed cameras in special holders simultaneously record the illuminated wall-region from different viewing angles (right).

2. Experimental realization

A test section segment was designed specifically for this near-wall LPT measurement and an accompanying TOMO-PIV measurement of several regions farther away from the wall (see Thoroddsen et al. 2026). Multiple windows allow sufficient optical access to introduce a high-speed laser light volume and for a multi-camera system required for high-precision volumetric measurements (see Figure 1, right). The segment was installed prior to the measurements, replacing the standard test-section. A large curved glass window was purchased and an adjustable frame was designed and built by DLR such that all four cameras had equal viewing conditions on the (glass) wall and the measurement region perpendicular to it (see Figure 2, middle). A system of *Vision Research Phantom V2640* cameras was set up in a pyramidal forward scattering

configuration in front of the curved window (see Figure 2, left). To this end, camera mounts, allowing free rotation of the camera body and of the viewing angle, were constructed. The cameras were equipped with $f = 100$ mm *Zeiss Macro-Planar* lenses, installed via Scheimpflug adapters. Illumination was provided by up to four high-speed lasers (a Photonics Industries DM2-532-DH double cavity laser with a maximum pulse frequency of 50 kHz each and a DM2-532-100 double cavity laser, each with a maximum pulse frequency of 30 kHz) that were differently operated, depending on the required repetition rates. The laser light was shaped to a rectangular cone with a streamwise length of 12 mm and a spanwise extension of 3 mm (being the depth direction of the camera system). The common volume of the four cameras extended in radial direction from the wall to approx. 80 mm into the pipe.

The air-flow was seeded using theater smoke of Propantriol and Glycol aqueous mixture (Hazebase, Base L), resulting in about 1-micron droplets. The seeding was introduced directly behind the test section, so that it traveled around the whole pipe facility, before entering the test section. A continuous operation would have resulted in excessive amounts of particles; therefore, the seeder was operated in intermittent puffs. While for the fully time-resolved sequences (lasting only around 4s), reasonably stable seeding conditions could be assured, the much longer 'chunked' runs (see below) exhibit varying and decaying seeding density (see Figure 5, left).

All cameras retained the full image height of 2048 px, however the camera width was significantly reduced (244 px and 144 px at the highest Reynolds numbers), such that the image constitutes a thin slice - just enough to fully record the high aspect ratio of the illuminated volume (see Figure 4). This reduction allowed to increase the recording rate of the camera to limit the particle shift to

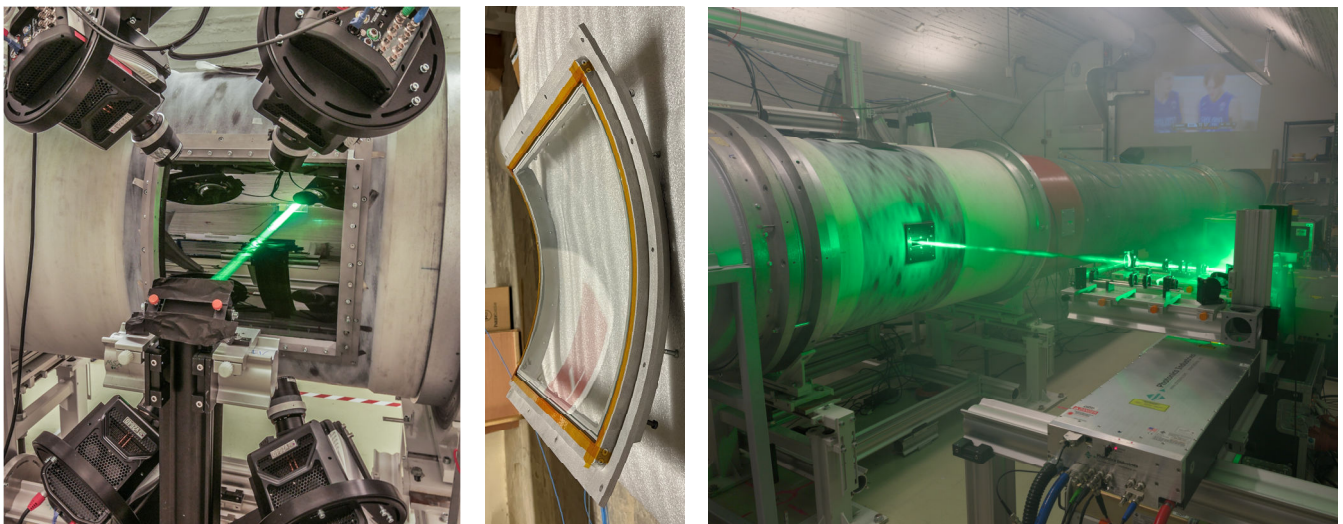


Figure 2: Photograph of the installed camera system in front of the test section module with volumetric laser light sheet entering on the opposite side (left); photograph of the curved glass window, fabricated for multi-camera viewing (middle); back-side of the test section, showing the laser entry (right).

around 10 px per frame. For the lowest Reynolds number ($Re_\tau = 19,200$), a camera rate of 50.0 kHz was used and a single DM2-532-DH laser was operated at the same frequency. For the higher velocities, a double illumination strategy was applied. For the two intermediate Reynolds numbers, the cameras and two DM2-532-DH lasers were operated at a common frequency (40.0 and 50.0 kHz, respectively), however a delay of half the inter-frame time was applied to the lasers, such that each camera image is illuminated twice and the resulting time-series of particle illuminations has double the camera frequency. See Figure 3 for an example of both recording modes. The highest Reynolds number required effective rates well above 100 kHz. Reducing the camera width further to 144 px yields a camera frequency of 72.464 kHz. Running both cavities of the DM2-532-DH at 48.309 kHz and both cavities of the DM2-532-100 at 24.155 kHz allows, with the appropriate delays, to generate a seamless illumination at 144.928 kHz (double the camera frequency).

Table 1 summarizes the test cases and some important experimental parameters. Pressure probes along the pipe wall are used for a direct determination of the wall shear stress, which in turn allows calculating the shear velocity u_τ , the viscous length scale l^* and the friction Reynolds number Re_τ .

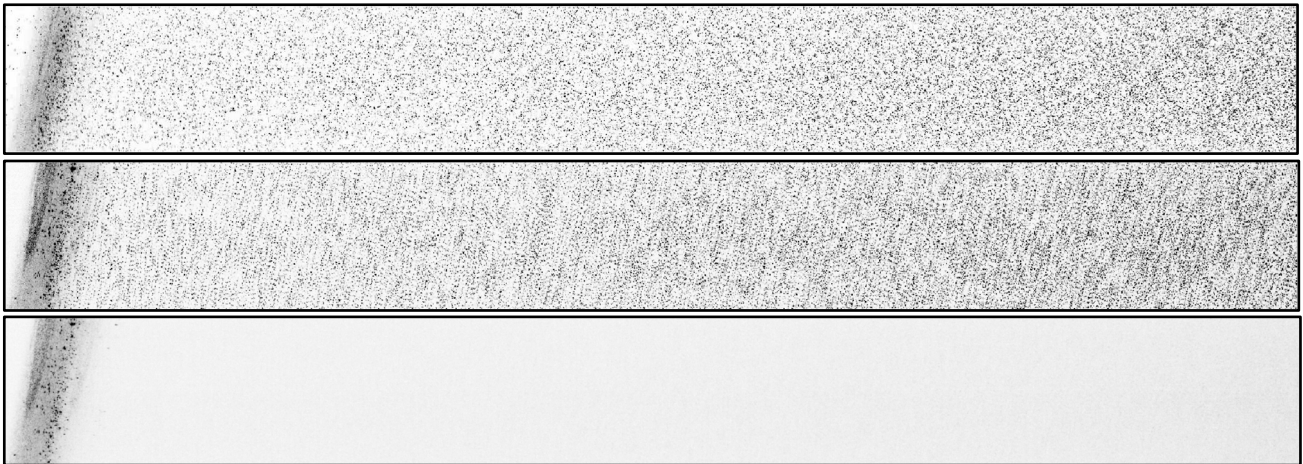


Figure 3: Top: Image of a single camera from a recording at $Re_\tau = 19,200$, showing particle images of the illuminated Propantriol/Glycol droplets. Middle: the same for a recording at $Re_\tau = 28,650$, showing double illuminated images of each particle. Bottom: Sliding minimum image around the time-steps shown in the middle, highlighting the glass wall as a faint glow and a number of illuminated inclusions.

The reduction of image size allows to fit a large number of images into the RAM of 144 GB per camera (218,584 images with 244 px width and 325,830 with 144 px, each equating to around 4 seconds of flow). To account for the fact that the second peak of streamwise fluctuation is dominated by long-living large-scale structures, only few measurement runs were performed in a fully time-resolved fashion, as these results show a strong temporal dependence. Instead, many

short time-series of 30 consecutive images each ('chunks') were recorded at frequencies of 40-100 Hz. These frequencies are chosen to nearly match the integral time scales $T_\lambda = R/U_{cl}$, so that each chunk would be nearly statistically independent. For each Reynolds number up to 130,000 chunks were captured, allowing a broad sampling of the large-scale structures and good statistical convergence even for higher order moments (see e.g., Klewicki and Falco 1990).

Table 1: Selected parameters of the different measurement cases. U_{cl} denotes centerline velocity, l^* the viscous length scale, u_τ the shear velocity, N_{chunks} the total number of independent chunks over all runs (30 time-steps each), N_{TR} the number of fully time-resolved sequences (218,584 time-steps each, performed in addition to the chunked runs). Non-equal recording and laser frequency indicate double illuminations of each camera frame.

U_{cl}	Re_τ	l^*	u_τ	N_{TR}	N_{chunks}	f_{chunks}	Rec. freq	Laser freq.	Img height	Img width
<i>m/s</i>		μm	<i>m/s</i>			<i>Hz</i>	<i>kHz</i>	<i>kHz</i>	px	px
19.7	19,200	23.4	0.648	7	49,357	40	50	50	2048	224
30.3	28,650	15.7	0.967	5	91,663	60	40	80	2048	224
40.2	37,250	12.1	1.258	5	105,765	100	50	100	2048	224
50.2	45,800	9.8	1.548	-	129,861	96.6	72.464	144.928	2048	144

3. Data evaluation

The camera system was calibrated using a single image of a double-sided LaVision 3D calibration target (10 cm edge length). The geometrical calibration was refined by Volume-Self-Calibration (Wieneke 2007). The spatially varying imaging conditions of the particles were determined using a calibration of the Optical Transfer Function (Schanz et al. 2013).

Current processing is limited to the $Re_\tau = 19,200$ – case, as the processing of the double-illuminated image still needs to be fully implemented in the current evaluation scheme. The data of each 30-images chunk was evaluated using the DLR implementation of the Shake-The-Box (STB) algorithm (Schanz et al. 2016), using advanced iterative particle reconstruction (IPR, Wieneke 2011, Jahn et al. 2021). Images were pre-processed by subtracting a sliding minimum image over 40 consecutive images, which include 10 images from the following chunk in order to avoid partly cutting away the images of very slowly moving particles close to the wall (see Figure 3, bottom). This sliding minimum was multiplied with a factor of 1.15 to account for laser intensity and scattering variations. The images were further processed by spatial intensity normalization to account for the varying particle image intensity, changing with the local forward scattering angle. After the tracking process, the raw tracks are temporally filtered using the B-Spline based *TrackFit* approach (Gesemann et al. 2016, Gesemann 2021). The position amplitude spectrum of the raw tracks is used to derive a filtering frequency, optimally suited to suppress noise, while retaining

the physical signal for the data at hand. The spectrum additionally allows to determine a particle position accuracy, which is estimated to around $5\ \mu\text{m}$ after fitting.

As also argued in Thoroddsen et al. (2026) we refrained from using a cylindrical coordinate system, but instead use a cartesian coordinate system with origin at the wall, with the x-axis signifying the streamwise direction, the y-axis pointing from the wall to the centre of the pipe and the z-axis, being the spanwise component, approximates the azimuthal. The thin volume extends only 3 mm in spanwise direction, leading to only a minimal curvature of the wall, such that the use of radial bins proved not necessary for the current dataset.

Two passes of STB were applied, resulting in the tracking of up to approx. 32,000 particles over the illuminated domain, corresponding to a seeding density of approx. $N_l = 0.08\ \text{ppp}$ (see Figure 4). Despite the presence of inclusions in the glass wall, which are visible in all images as bright particle-image-like spots, a successful tracking close to the wall is possible due to the four different viewpoints and the temporal consistency. The inclusions can be reconstructed and tracked, so that they can be used as measurements of possible vibrations of the wind tunnel wall and cameras mounting structure, however this proved to be not necessary for the investigated Reynolds number, where vibrations still remain well-controlled.

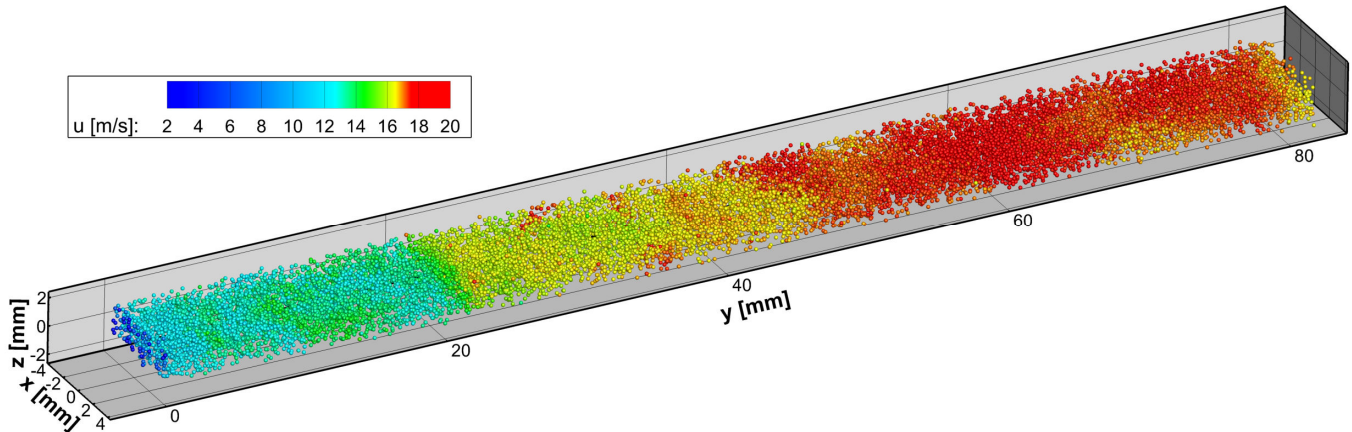


Figure 4: Instantaneous STB result at $Re_\tau = 19,200$, showing approx. 30,000 particles as spheres, color-coded by their streamwise velocity.

As mentioned above, the seeding density varied along the time required for recording the 7051 chunks per measurement run (around 3 minutes). Figure 5, left shows the number of tracked particles at the middle time-step (15) over the processed chunks for a selected run. It can be seen that the particles periodically increase and decrease due to certain 'puffs' of the seeder reaching the measurement volume. Overall, the density is declining due to particles evaporating over time. While at the beginning around 30,000 particles can be tracked, only around 5,000 are so at the end. Such a scenario would cause problems for window-based methods like (PIV); however, the

tracking approach is agnostic to a reduced particle number if the results are used for statistical purposes.

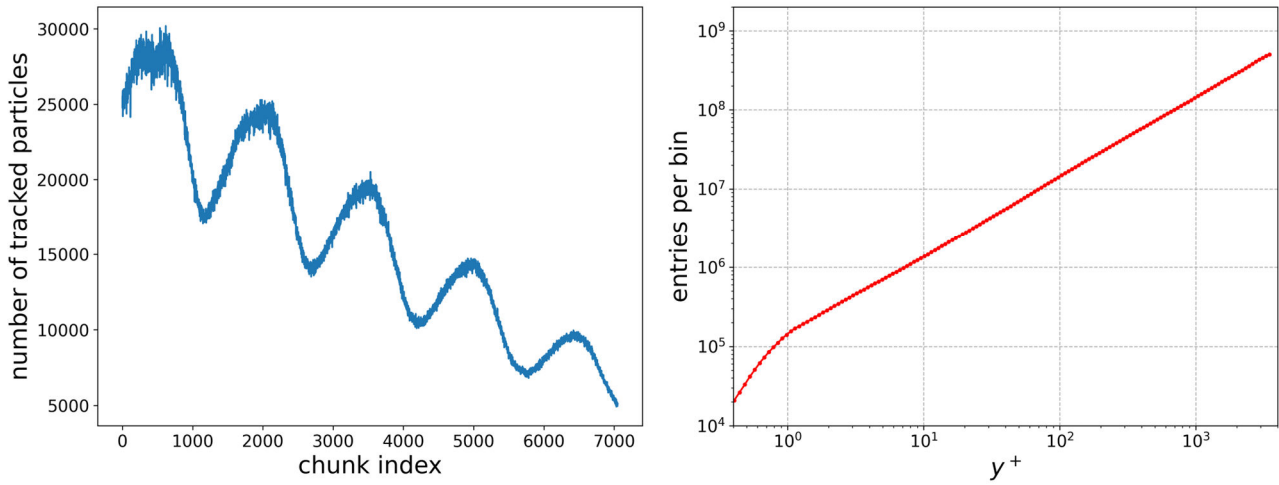


Figure 5: Left: Number of particles tracked at the middle time-step of each chunk. Oscillations of seeding density and evaporation of particles over time can be witnessed. Right: Number of particle entries in the log-10 spaced bin.

4. Statistical results

Seven runs, each consisting of 7051 chunks of 30 time-steps, were processed on the DLR CARO Cluster. Once the parameters were optimally set, the parallelization allowed a fast processing (around 20 minutes per run).

The tracked particles of time-steps 5 to 25 of all chunks are used to generate highly resolved profiles of the TBL properties. The volume is divided in thin wall-parallel containers (*bins*) with a certain wall-parallel extension. All particles located in a specific bin (over the entire dataset) are collected to deduce the local averaged velocities, Reynolds stresses and accelerations. For better visualization and noise suppression away from the wall, we chose a logarithmic bin spacing, resulting in sub-viscous unit extension close to the wall ($0.05 y^+$, around $1 \mu\text{m}$). At the location of the first peak a resolution of around $1 y^+$ is realized, while at a wall-distance of $300 y^+$ the bins span around $15 y^+$. At the end of the measurement volume, deep in the logarithmic layer, the bins exceed 4.8 mm in size ($195 y^+$). The number of entries within each bin varies considerably with their extension (see Figure 5, right). In the outer parts up to 500 million entries are recognized, while close to the wall around 20,000 particles are found within a bin. In total the profiles range from 0.4 to $3600 y^+$. Over most parts of the measurement area, a homogenous seeding density is attained (visible as the straight line in the logarithmic plot), only at around 1 wall-unit ($23.4 \mu\text{m}$) from the wall the curve is visibly deviating, likely due to a general decrease of particles at the wall,

combined with the increasing presence of the imaged wall inclusions, which interfere with the particle images.

Figure 6 shows the binning results in terms of the average streamwise velocity profile U^+ (left) and the averaged wall-normal and spanwise components v^+ and w^+ (right). All values are normalized with the inner units l^* and u_τ . The profiles are compared to DNS data at $Re_\tau = 12,000$ (Pirozzoli 2024) and high-resolution PIV evaluations by Willert et al. (2017) at $Re_\tau = 18,900$. It can be seen that the near-wall region is captured accurately by the STB data, despite the lower particle numbers in these bins. Down to $0.4 y^+$ a very good overlap with the DNS profile is attained, while the PIV results slightly overestimate this region, which may be due to the averaging effects of the correlation window or to the experimental setup with a mirror within the flow as discussed later. In the left-hand side of Figure 6, a downward deviation from the DNS profile in the log-region is visible and expected to a certain extent, given the higher Reynolds number of the experimental data. The comparison of the DNS results of Pirozzoli (2024) with extensive data from CICLoPE shown in Figure 2 of Nagib et al. (2026), focused on the centerline velocity, reveals that the mean velocity resulting from the DNS is somewhat higher by less than 1% compared to several measurements from CICLoPE, and the earlier results from the Superpipe (Zagarola and Smits 1998) especially at the highest Re_τ of 12,000.

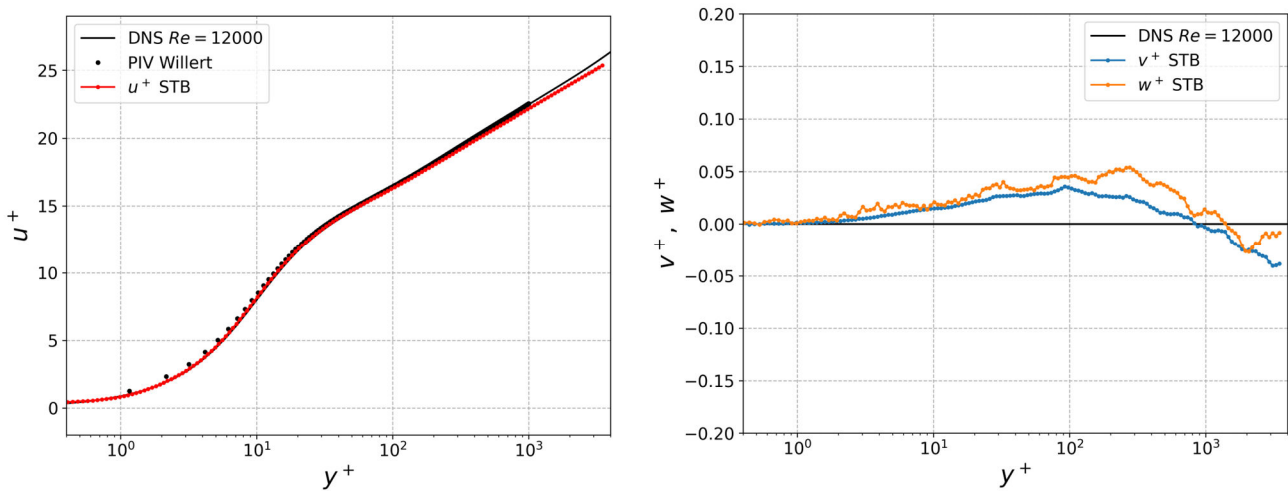


Figure 6: Profiles of streamwise velocity (left) and wall-normal as well as spanwise velocity (right), gained by bin averaging of STB data at $Re_\tau = 19,200$, compared to DNS at $Re_\tau = 12,000$ (Pirozzoli 2024) and PIV data at $Re_\tau = 18,900$ (Willert et al. 2017)

The wall-normal and streamwise velocity components should in theory show a constant zero. However, a placement of the calibration target is only possible to a certain accuracy and any rotation will show up as a bias effect of the velocity and acceleration values. To counteract this effect, the coordinate system was rotated such that the average values of v and w are close to zero. Rotations of 0.6 degree along the x -axis, -0.28 degree around y and 0.3 degree around z were

applied. The resulting profiles of normalized v and w are shown in Figure 6 (right). Residual velocities of less than 0.15 percent of the centerline velocity are registered, possibly due to geometric imperfections of the curved glass (see also discussion on accelerations below)

Other potential explanations of these very small deviations would be any residual development of the flow towards a fully developed condition and any small swirl or longitudinal secondary flows. However, both of these are excluded for the test section location of the CICLoPE facility given the care in its design in regard to upstream flow conditioning with a honeycomb and multiple screens, and the length to diameter ratio of the pipe upstream of the location of the measurements. Nagib et al. (2017) and references therein confirmed the fully developed conditions.

The corresponding Reynolds stresses (see Figure 7) show a very good agreement to the DNS data close to the wall. The first turbulence peak of $u'u'$ is located at around $16.3 y^+$ and reaches a maximum value of 9.79. This is a bit below the prediction by Marusic et al. (2017), which yields 10.01, however in close agreement with the value of 9.82 obtained at $Re_\tau = 22,892$ by hot-wire measurements in the Long Pipe facility, although this measurement required a spatial resolution correction, see Orlu (2017). The PIV result shows a slightly lower maximum of 9.65, likely due to the window averaging effect. A recent high-resolution PIV campaign performed in the same facility confirms the observed trend which is well approximated by a logarithmic trend of $\langle u'u' \rangle^+ = 0.63 \log(Re_\tau) + 3.5$ (Bellani et al. 2026), in agreement with a similar trend, but with a slightly higher intercept, as proposed by Marusic et al. (2017).

These correlations are based on a logarithmic trend deduced from the attached-eddy hypothesis. One earlier correlation based on extensive experimental data also from boundary layers and a more recent trend based on a power law with Reynolds number are referenced in the brief note by Nagib et al (2024); see equation 3 and equation 1, respectively. The predictions from them are much closer to the current measured value and the one from Willert et al. (2017); i.e., 9.86 from the power relation and 9.64 from the experimental correlation.

It is also interesting that the current measurements validate the earlier results by Willert et al. (2017) except very near the wall as shown in Figure 7 for $u'u'$ that were corrected to educe-out a periodic part of the signal, which was originally assumed to be slight vibrations affecting the pipe wall. The recent high-Resolution PIV investigation clarified that this periodic part of the signal was due to the oscillation of the mirror used to image the PIV, and that no measurable vibration of the pipe is present at all operating conditions of CICLoPE. The recent high-resolution PIV campaign results are closer to the current measurements especially for $v'v'$ and $w'w'$, shown in the righthand side of Figure 7.

At this Reynolds number, the region of the second-peak still appears largely plateau-like around y^+ in the range 100 to 300, however a statistically converged local maximum is already present and located at $220 y^+$. The PIV-results predict slightly larger values in this region, which might be caused by a lower level of convergence. Higher Reynolds number data listed in Table 1, and yet to be processed, should shed better clarity on the development of the second peak, whose existence is still a topic of discussion.

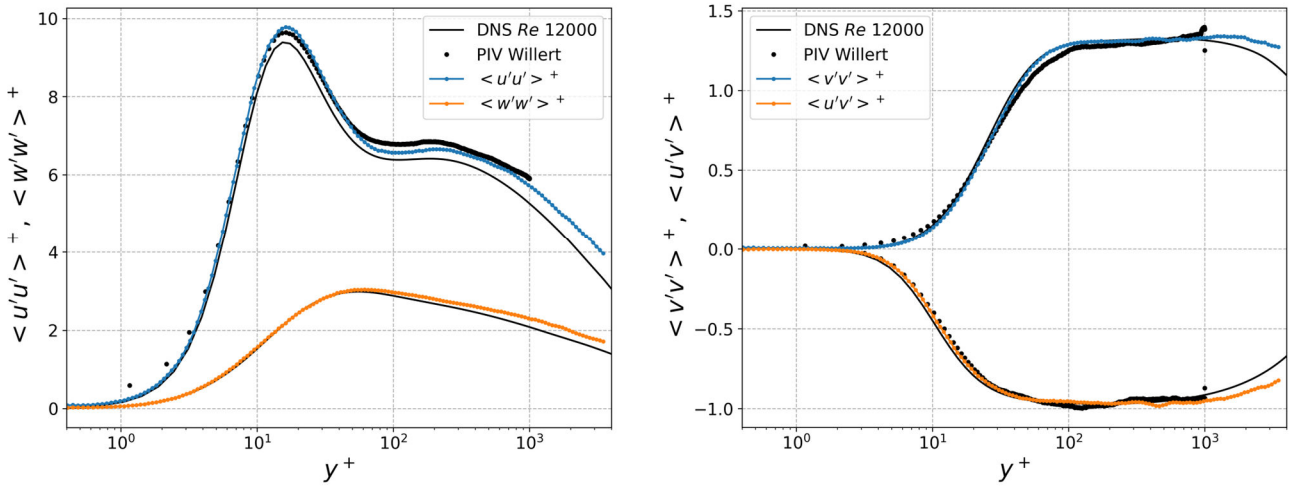


Figure 7: Profiles of Reynolds stresses, gained by bin averaging of STB data at $Re_\tau = 19,200$, compared to DNS at $Re_\tau = 12,000$ (Pirozzoli 2024) and PIV data at $Re_\tau = 18,900$ (Willert et al. 2017)

The $v'v'$ and $u'v'$ components accurately follow the DNS profile close to the wall. For the PIV results a spatial filtering effect is visible in the flattened curve, especially for the $v'v'$ case. As argued in Willert et al. (2026), this effect increases with Reynolds number. STB evaluations of these cases will show to what extent this effect may be alleviated using single-particle approaches (see also Kähler et al. 2012 for a similar discussion). The remaining waviness in the outer regions might be a combination of glass imperfections and convergence effects. The latter could be alleviated by advanced binning processes that treat the particle trajectory as continuous instead of consisting of discrete time-steps.

The large amount of accurate particle tracks allows estimation of profiles of higher-order derivatives as well. Figure 8 (left) shows profiles of the average acceleration for all components of space, normalized according to $a_i^+ = a_i * \nu / u_\tau^3$. The negative streamwise acceleration $-a_x^+$ shows a distinct peak at around $8 y^+$, while the positive wall-normal acceleration a_y^+ peaks at $17 y^+$, corresponding to the location of the first peak of streamwise velocity variances. These are very unique measurements especially in a pipe flow at high Reynolds numbers and will require careful

analysis and comparisons for a better understanding of their physical implications in wall-bounded turbulence.

The spanwise acceleration is deviating from the expected zero-values by symmetry, likely due to density inhomogeneities in the observation window or the slight misalignment of the target discussed earlier in connection with the right-hand side of Figure 6.

To follow the curvature of the pipe wall, the glass had to be bent along the circumferential direction, which potentially leads to compressions in the material, which might introduce apparent accelerations in the wall-normal and spanwise direction. Such effects might explain the increased acceleration statistics seen e.g. at around $100 y^+$. In the log-region all acceleration profiles collapse to zero. Below $2 y^+$ the effects of wall inclusions compromise the accuracy of the particle tracks too much to allow for a reliable acceleration measurement.

Figure 8 (right) displays all six components of the acceleration variances. $\langle a'_x a'_x \rangle^+$ exhibits a maximum at $6.8 y^+$, followed by an extended shoulder, while $\langle a'_z a'_z \rangle^+$ and especially $\langle a'_y a'_y \rangle^+$ show a more symmetric shape, peaking at $23 y^+$ and $32 y^+$, respectively. The mixed term $-\langle a'_x a'_y \rangle^+$ shows a broader distribution with a flat peak at $28 y^+$, followed by a fall-off towards zero (in contrast to the other discussed components, which appear to reach a plateau that might be caused by acceleration noise). The other mixed terms are close to zero everywhere. The acceleration variances seem to suffer less from effects caused by imperfections in the window glass, which can be understood, as the influence should cancel out.

The results on accelerations and their variances compare well with experimental and DNS results provided by Stelzenmuller et al. (2017), though those were gained in turbulent channel flow at much lower Reynolds number.

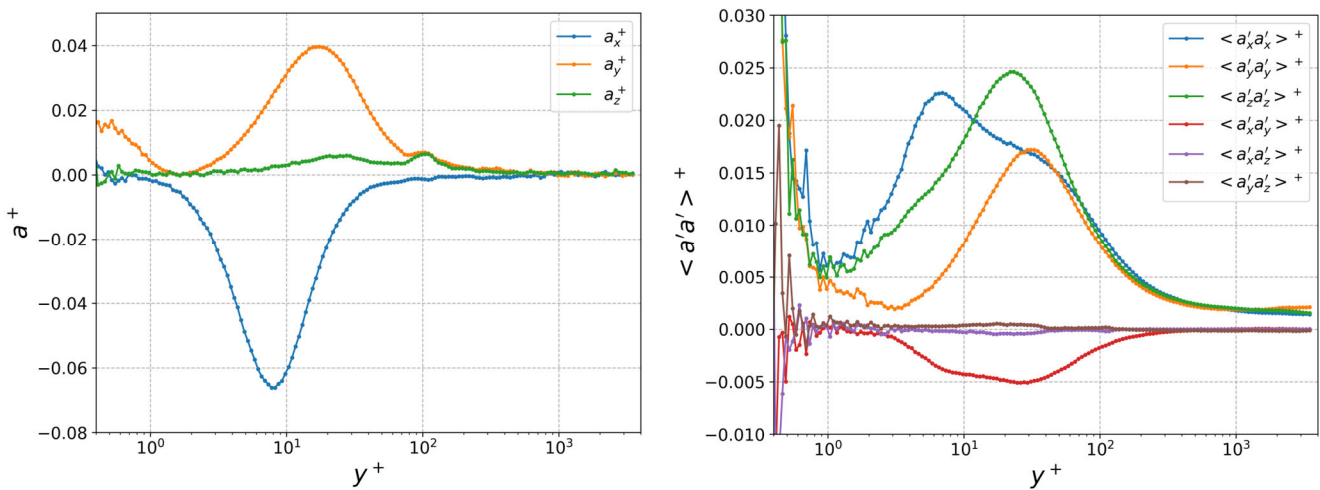


Figure 8: Profiles of average accelerations (left) and their variances(right), gained by bin averaging of STB data at $Re_\tau = 19,200$.

4. Volumetric results

The dense sampling of the flow by the particles allows reconstructing instantaneous volumes of velocity and its gradients. To this end the data assimilation scheme *FlowFit3* (Godbersen et al. 2024, Gesemann et al. 2016) is applied. The method fits the values of a staggered grid of B-splines to the particle velocity (optionally their acceleration) while assuring divergence-freeness of the solution (conservation of mass). Additionally further regularization of the optimization via the Navier-Stokes equations can be applied.

Figure 9 shows reconstructions of three successive time-instants from an example measurement run. Vortical structures are identified using isosurfaces of Q-criterion. Close to the wall stronger and better-defined vortices are reconstructed, while the structures far away from the wall are weaker and less stable. The temporal consistency is reasonable and gives hope that the data can be used e.g. to extract spectra (when applied to long consecutive time-series) or to augment the accompanying work by Thoroddsen et al. (2026), which concentrates on the statistics of vorticity in volumes away from the wall.

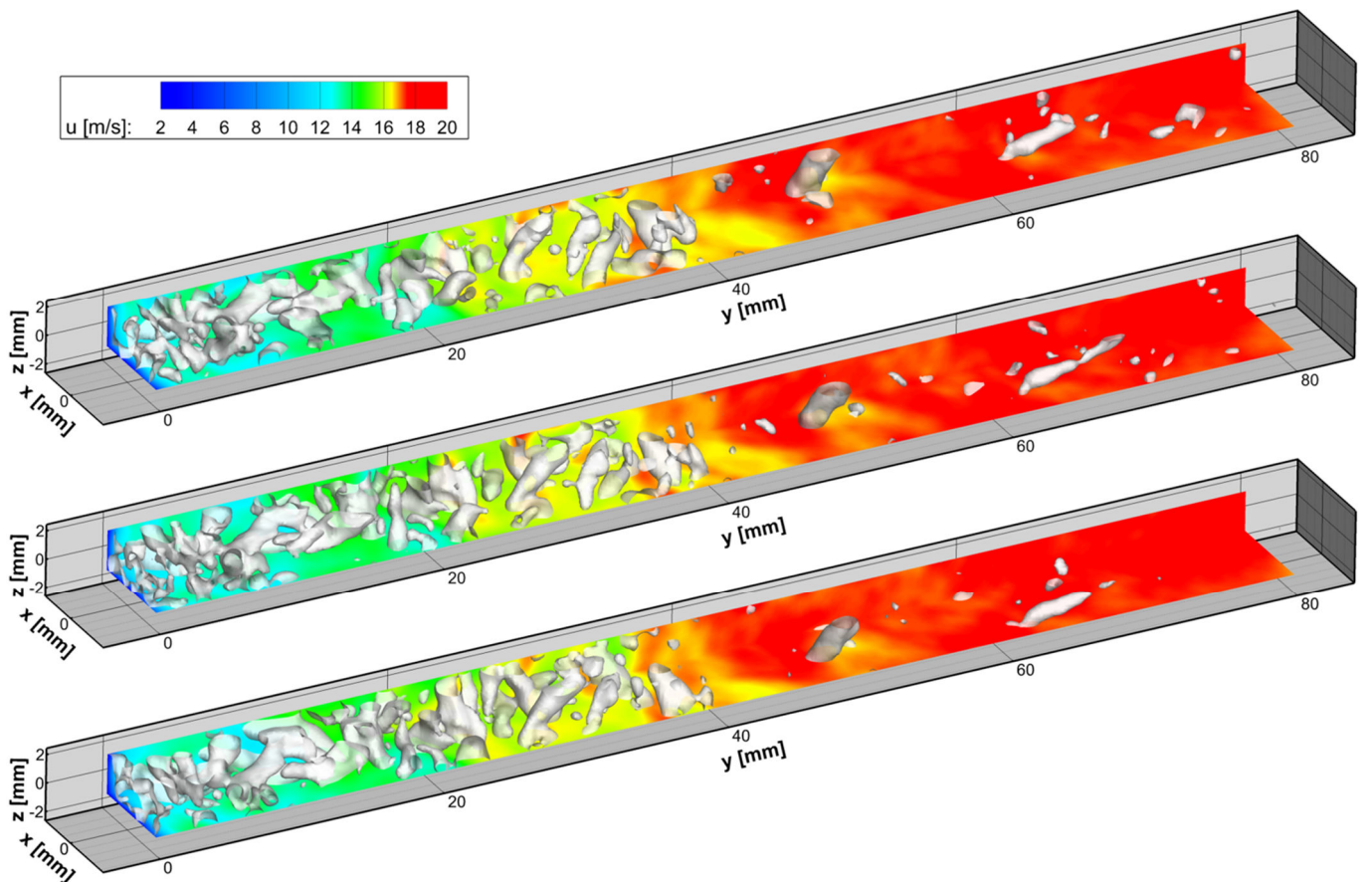


Figure 9: FlowFit reconstructions of three successive instances (each spaced 4 recording time-steps apart, middle one corresponding to particles of Figure 4). Shown are iso-surfaces of Q-criterion, as well as stream-wise and wall-normal planes, color-coded by streamwise velocity.

5. Conclusions and Outlook

We presented statistical results from a time-resolved 3D measurement of pipe flow at $Re_\tau = 19,200$, captured in the CICLOPE facility and evaluated via Shake-The-Box. More image data of flows up to $Re_\tau = 45,800$ is available and will be processed in the near future. The data shows the great potential of 3D Lagrangian Particle Tracking to resolve fine scales in averaged data, both near the wall, as well as in regions of strong shear, while still capturing an extended measurement domain. The location of the first peak of streamwise fluctuations is found to be at $16.3 \pm 0.5 y^+$, which puts it slightly further out than expected by DNS results, however in-line with the PIV results by Willert et al. (2017).

The current large volume of results, including the three higher Reynolds number cases yet to be fully processed, demonstrate that in facilities like CICLOPE, experimental results can provide a multitude of details that can readily and extensively be compared to computational data, especially DNS of turbulent flows - but at much higher Reynolds numbers that may not be achievable before a few decades.

Continuous fields of velocity and its gradients can be extracted from the particle tracks at each time instant by application of FlowFit data assimilation, that will allow investigations on flow structures and statistics e.g. on vorticity (see Thoroddsen et al. 2026).

For the higher Reynolds number cases, a modified STB tracking will be employed that accounts for double illuminated images, as detailed in Schanz et al. (2019). The gained data will give access to the trends of the first and second peak of turbulence activity and many further properties that can be extracted from highly resolved particle data.

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