

First sub-viscous resolution near-wall PIV measurements in high-Reynolds number turbulent pipe flows

G. Bellani^{1,*}, L. Magnani¹, A. Talamelli¹, D. Schanz³, J. Klinner², C. Willert²,

1: Dept. of Industrial Engineering / CIRI Aerospace, University of Bologna, Forlì, Italy

2: Institute of Propulsion Technology, German Aerospace Center (DLR), Köln, Germany

3: Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), Göttingen, Germany

*Corresponding author: gabriele.bellani2@unibo.it

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ABSTRACT

Near-wall turbulence statistics at high Reynolds number remain difficult to measure because the relevant viscous scales become extremely small while long acquisition records are required for statistical convergence. In this work, we report high-speed, high-magnification profile PIV measurements in the CICLoPE Long Pipe facility, aimed at resolving the near-wall region of turbulent pipe flow with sub-viscous spatial resolution. Measurements were performed over the range $5,500 \leq Re_\tau < 45,500$, corresponding to viscous length scales from approximately $82 \mu\text{m}$ down to $10 \mu\text{m}$. The dataset provides statistically converged, two-component velocity measurements in a Reynolds-number range previously accessible mainly through single-point techniques. The streamwise velocity variance profiles show the expected near-wall inner peak and a systematic increase of its magnitude with Reynolds number. At lower Reynolds numbers, the results agree well with available DNS data, while the highest-Reynolds-number cases extend previous experimental evidence from CICLoPE. The observed trend is compatible with a slow, approximately logarithmic growth of the inner peak, although residual spatial-resolution effects remain detectable at the largest Reynolds numbers. Measurements of the wall-normal variance and Reynolds shear stress further demonstrate the capability of the present approach to provide simultaneous multi-component near-wall turbulence statistics in high-Reynolds-number pipe flow.

1. Introduction

The progress of direct numerical simulations (DNS) over the past two decades has enabled increasingly detailed observations of near-wall turbulence in canonical wall-bounded flows Hoyas & Jiménez (2008); Schlatter & Örlü (2010); Lee & Moser (2015); Pirozzoli et al. (2021). These datasets have substantially improved the qualitative and quantitative understanding of the mechanisms governing wall turbulence, providing support for long-standing theoretical frameworks, such as the attached-eddy hypothesis Townsend (1976); Marusic & Monty (2019), and motivating

new models for the Reynolds-number dependence of turbulent statistics at asymptotically large Reynolds numbers Marusic et al. (2010); Smits et al. (2011); Chen et al. (2018); Smits et al. (2021). This remains a central problem from both a fundamental and an engineering perspective, since many flows of practical relevance, including atmospheric flows, aeronautical and naval applications, and geophysical flows, are characterized by very large Reynolds numbers.

Among the important open issues are the Reynolds-number scaling of near-wall quantities such as the streamwise velocity variance, the Reynolds shear stress, and their spectral signatures Marusic et al. (2010); Hultmark et al. (2012); Örlü et al. (2017); Pirozzoli et al. (2021); Smits et al. (2021). However, numerical simulations alone cannot provide conclusive evidence over the Reynolds-number range required to discriminate between competing asymptotic behaviours, because the achievable Reynolds numbers remain limited by computational cost. Experiments therefore play a crucial role, provided that they can deliver sufficiently resolved and statistically converged measurements in the immediate vicinity of the wall.

Progress on these questions requires velocity measurements with very high spatial and temporal resolution, sufficient dynamic range, and robust statistical convergence at friction Reynolds numbers far exceeding $Re_\tau \sim 10^4$. Achieving this goal relies on facilities capable of generating high-Reynolds-number wall-bounded flows under well-controlled conditions. Several facilities have provided important datasets in this range, including the Princeton Superpipe Zagarola & Smits (1998); Hultmark et al. (2012) and large-scale boundary-layer facilities Baars et al. (2016). A distinct challenge of high-Reynolds-number turbulence, however, is the increasingly broad range of spatio-temporal scales that must be resolved experimentally. Indeed, the friction Reynolds number, $Re_\tau = \frac{u_\tau R}{\nu}$, may be interpreted as the ratio between the largest geometry-dependent length scale, here the pipe radius R , and the viscous length scale $l^* = \nu/u_\tau$. Thus, for turbulent pipe flow, the physical length scale associated with one viscous unit decreases as R/Re_τ , making near-wall measurements progressively more demanding as Re_τ increases.

The Long Pipe facility at CICLoPE, the Center for International Cooperation in Long Pipe Experiments, was specifically designed to address this challenge Talamelli et al. (2009); Bellani & Talamelli (2016). With a pipe diameter of $D = 0.9$ m and a length of 111.15 m, the facility generates fully developed turbulent pipe flow up to $Re_\tau \approx 50,000$, while maintaining viscous length scales of the order of $10 \mu\text{m}$ at the highest Reynolds numbers. Due to the strict requirements in terms of dynamic range, frequency response, statistical convergence, and spatial resolution, previous high-Reynolds-number campaigns at CICLoPE have been largely based on hot-wire anemometry Örlü et al. (2017); Baidya et al. (2019); Zimmerman et al. (2019); Zanon et al. (2021); Zheng et al. (2022); Dacome et al. (2025); Zanon et al. (2025). These measurements have provided valuable datasets, but they require careful consideration of spatial-resolution effects in the near-wall region at the largest Reynolds numbers Hutchins et al. (2009). Furthermore, they are mostly limited to single-point and single-component measurements, since the near-wall region is hardly accessible

with multi-wire probes.

These limitations motivate the development of advanced velocimetry techniques capable of providing simultaneous multi-component measurements in the near-wall and logarithmic regions while satisfying the stringent accuracy requirements of high-Reynolds-number turbulent pipe flow. In particular, applying particle image velocimetry (PIV) close to the wall in this regime requires pushing the limits of conventional implementations: near-wall reflections must be minimized, a sufficient number of tracer particles must be maintained in the near-wall region, temporal resolution must be high enough to resolve the relevant dynamics, and the number of samples must be large enough to ensure statistical convergence. At the same time, the measurement must retain the dynamic range required to characterize turbulence intensities and Reynolds stresses with sufficient accuracy.

In this work, building on the high-speed near-wall PIV approach presented by C. E. Willert et al. (2017) and leveraging the unique characteristics of the CICLoPE Long Pipe, we report a two-dimensional, two-component PIV campaign specifically designed to achieve sub-viscous spatial resolution in the near-wall region of high-Reynolds-number turbulent pipe flow, see Fig. 2. Measurements are performed over the range $5.500 \leq Re_\tau < 45.500$. Sub-viscous-scale spatial resolution is achieved through high-magnification imaging and high-speed acquisition, combined with a two-dimensional Shake-the-Box Lagrangian particle-tracking approach. The resulting dataset is resolved in time, attains a level of statistical convergence comparable to state-of-the-art hot-wire measurements, and provides simultaneous multi-component velocity information unaffected by spatial-resolution corrections if not –to a limited extent– for the highest Reynolds number case (see Table 1).

2. Experimental setup and methodology

2.1. The Long Pipe facility

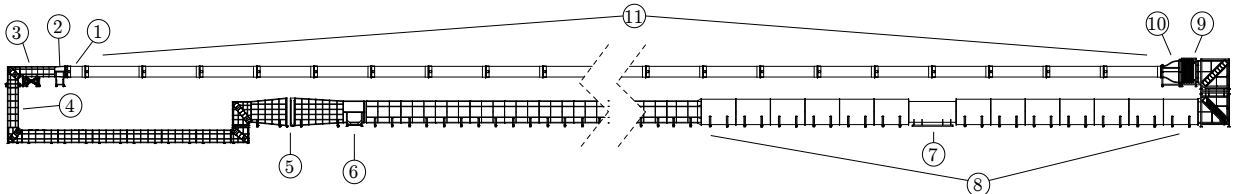


Figure 1. Overview of the Long Pipe facility. 1) Test Section. 2) Round to rectangular removable shape converter. 3) 1D diffuser. 4) Vertical slotted diffuser. 5) Heat-exchanger and filter. 6) Rectangular to round shape converter. 7) Axial fans. 8) Noise absorbing sections. 9) Honeycomb and screens. 10) 4:1 contraction. 11) Pipe, $L = 111.15$ m, $D = 0.9$ m.

Measurements are performed in the Long Pipe facility in CICLoPE (Center for International Co-operation in Long pipe Experiments). The Long Pipe is embedded in closed-loop circuit operating with air at atmospheric pressure (see fig. 1). The Pipe has an inner radius R of 0.45 m and a total length $L=111.15$ m. The length-to-diameter ratio of approximately 124 ensures fully-developed turbulent flows at the downstream measuring location. For further details about the CICLoPE facility, refer to Bellani & Talamelli (2016); Fiorini (2011).

Reynolds numbers in the range $5.500 \leq Re_\tau < 45.500$ are achieved by varying the incoming-stream velocity. The friction Reynolds number can be interpreted as the ratio of the outer length scale over the inner length scale, $Re_\tau = R/(\nu/U_\tau)$. Hence, the large outer length scale of $R = 0.45$ m, the viscous length scale ν/U_τ remains larger than $10 \mu\text{m}$ as Re_τ increases up to 45.500. Thus, it is possible to perform accurate turbulence measurements with hot-wire probes of diameter in the range $1 - 5 \mu\text{m}$ having an aspect ratio of $L/D=200$.

The Long Pipe is made of 22 modular elements of ≈ 5 m of length, plus one 1.5 m long section at the downstream end (element 1 in fig. 1), where measurements have been performed. Each section is provided with 4 access ports of 150 mm of diameter. These can be adapted to host probes' traversing mechanism or, as for this measurement campaign, to provide optical access. At the measurement station, air flow density ρ and kinematic viscosity ν are obtained according to the ideal gas law and the Sutherland law, by monitoring ambient pressure and air flow temperature.

The centerline velocity U_{cl} is measured by a Prandtl tube connected to a high-accuracy differential pressure transducer, with a total uncertainty smaller than 0.16%. Static pressures along the pipe length are acquired by a digital multipoint pressure scanner Initium. The streamwise pressure gradient is calculated by fitting static pressures within the last 40 m before the measuring station to provide an estimate of wall shear stress τ_w according to $\tau_w = -dP/dx \cdot R/2$. The friction velocity $U_\tau = \sqrt{\frac{\tau_w}{\rho}}$ is obtained within an estimated uncertainty of 0.06% Fiorini (2011).

2.2. Experimental conditions

The experimental conditions were selected to cover a wide range of friction Reynolds numbers, from $Re_\tau = 5.500$ to $Re_\tau = 45.500$. The characteristic velocity, length and time scales of the present campaign are reported in table 1. The friction velocity u_τ was estimated from the imposed pressure gradient, and the corresponding viscous length and time scales were computed as ν/u_τ and ν/u_τ^2 , respectively.

The table also summarizes the main experimental requirements. As Re_τ increases, the viscous length scale decreases from approximately $82 \mu\text{m}$ to $10 \mu\text{m}$, making the spatial resolution of the near-wall region increasingly demanding. Following common criteria for resolved measurements of turbulence intensities, the effective measurement resolution should remain below approximately

Table 1. Experimental cases of the present experimental campaign and related velocity, length and time-scales

Centerline velocity [m/s]	U_{cl}	5.1	10.0	19.8	30.0	39.9	49.7
Reynolds number	Re_τ	5 500	10 100	18 900	27 700	36 200	45 500
Friction velocity [m/s]	u_τ	0.193	0.347	0.650	0.950	1.25	1.54
Viscous length scale [μm]	ν/u_τ	81.8	44.5	23.9	16.3	12.4	10.1
Viscous time scale [$s \times 10^{-4}$]	ν/u_τ^2	4.2	1.28	0.37	0.17	0.1	0.06
Integral time scale [$s \times 10^{-3}$]	$\Lambda_C = R/U_c$	88	45	23	15	11	9
Minimum acq. freq [kHz]	$0.5 u_\tau^2/\nu$	1.2	3.9	13.5	29.4	50.0	83.3
Minimum acq. duration [s]	$T_{min} = 7.000 \times \Lambda_C$	616	315	161	105	77	63

20 viscous units Hutchins et al. (2009); C. E. Willert et al. (2017). Temporal resolution is constrained by the viscous time scale: here, the minimum acquisition frequency is estimated as $0.5 u_\tau^2/\nu$, which increases from 1.2 kHz to more than 80 kHz across the investigated range.

Finally, the minimum acquisition duration was estimated from the integral time scale $\Lambda_C = R/U_c$, assuming a record length of $7000 \Lambda_C$. This provides a practical target to reduce the statistical uncertainty of the mean velocity below approximately 0.5% and that of the variance to about 1%, assuming samples separated by one integral time scale to be approximately independent. The resulting constraints require the present measurements to combine sub-viscous spatial resolution, high-speed acquisition and sufficiently long records to obtain converged near-wall mean and fluctuation statistics.

2.3. Experimental technique

The High-Speed PIV measurement approach shown in Fig. 2 follows the same methodology initially introduced by C. Willert (2015). A high-speed camera (Vision Research T4040) is fitted with a telephoto macro lens (Nikon Micro Nikkor 200/4) and captures a narrow field of view (FOV) of $(1.5 \times 23.5 \text{ mm}^2)$. The magnification was set to unity ($M = 1.00 \pm 0.01$) such that each camera pixel corresponds to $9.27 \mu m$ in physical space. This size slightly exceeds the viscous length scale at the highest Reynolds number ($l^* = \nu/u_\tau = 10.1 \mu m$, see Table 1). The field of view was illuminated with a thin laser light sheet formed by the collimated beams of a dual resonator high-speed laser (Innolas/Iradion, Nanio Air, $2 \times 10 \text{ W}$), capable of providing laser pulses up to 400 kHz. For time-resolved, high-speed measurements camera frame rate and laser pulsing frequency were adjusted to produce particle image displacements of about 25 pixel at the centerline velocity. This ensured that the fastest particles were captured at least 5 times while transiting the field of view, thus enabling the possibility of tracking individual particle trajectories. Further measurements were acquired at lower camera framing rates (in frame-straddle mode) to capture a large number of nearly statistically independent velocity samples.

Table 2. PIV acquisition parameters for near-wall turbulent pipe flow measurements. PIV sample size: 32×6 pixel; light-sheet thickness $\approx 200 \mu m$; number of effective samples N_{eff} based on eddy turn-over time $\Lambda_c = R/U_c$.

Table 3. PIV acquisition parameters for near-wall turbulent pipe flow measurements. PIV sample size: 32×6 pixel; light-sheet thickness $\approx 200 \mu m$; number of effective samples N_{eff} based on eddy turn-over time $\Lambda_c = R/U_c$.

Centerline velocity [m/s]	U_{cl}	5.1	10.0	19.8	30.0	39.9	49.7
Reynolds number	Re_τ	5 500	10 100	18 900	27 700	36 200	45 500
Effective PIV volume size	IW_{x^+}	3.63	6.67	12.4	18.2	23.9	29.4
	IW_{y^+}	0.7	1.3	2.3	3.4	4.5	5.5
	IW_{z^+}	2.5	4.5	8.4	12	16	20
HS-PIV sampling rate [kHz]	f_{acq}	20	40	80	110	150	$(40)^1$
Laser pulse delay [μs]	Δt	50	25	12.5	9.09	6.67	4.5
	$\Delta t u_\tau^2 \nu^{-1}$	0.12	0.19	0.34	0.53	0.67	0.67
Number of sequences		42	42	42	42	42	42
Samples per sequence	N_{HS}	25 638	25 638	25 638	25 638	42 591	20232
LS-PIV sampling rates [kHz]	f_{acq}	0.5 / 2	1 / 4	2 / 8	3 / 12	4 / 16	5 / 20
Number of sequences		4 / 4	4 / 4	4 / 4	8 / 8	8 / 8	4 / 4
Samples per sequence	N_{LS}	106 546	106 546	106 546	106 546	106 546	106 546
Independent samples	N_{eff}	6 600	6 500	6 400	12 400	7 500	6 500

¹ Frame-straddling

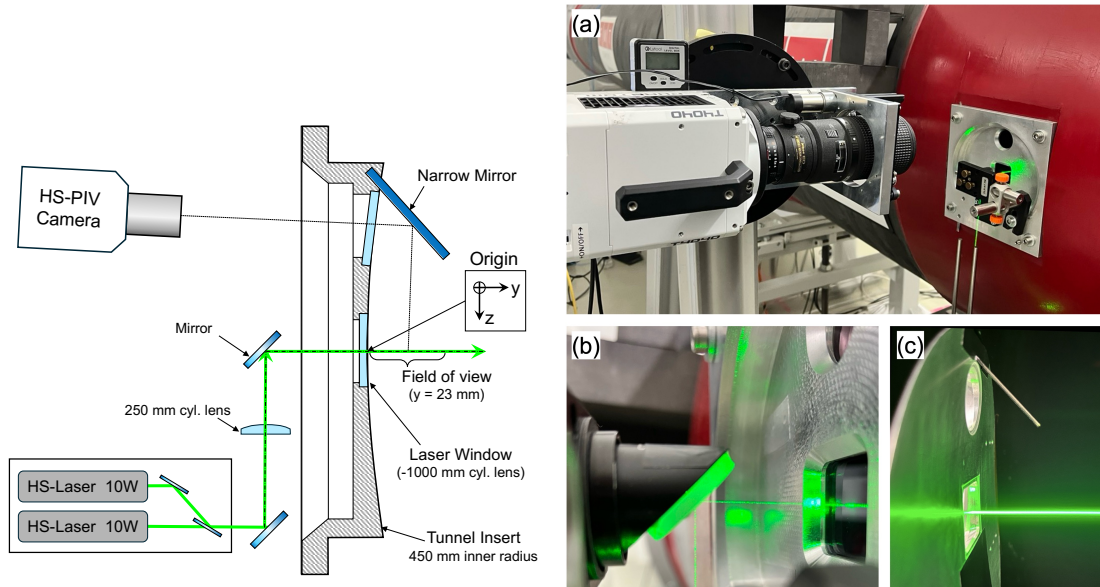


Figure 2. Left: Schematic of the measurement setup for high-speed profile PIV on the test section of the CICLoPE Long Pipe facility. Right: Photographs of the setup for high-speed profile PIV on the test section of the CICLoPE long pipe facility (a), (b) thin laser light sheet prior to entering the test section, (c) view of measurement domain inside the tunnel showing the thin laser light sheet and viewing mirror above

Profile PIV measurements were performed over the full range of conditions reported in table 1, corresponding to $5.500 \leq Re_\tau \leq 45.500$. For each case, the effective number of large-eddy turnover

times was estimated as:

$$N_{\text{eff}} = \frac{T_{\text{acq}} U_{cl}}{R}, \quad (1)$$

where T_{acq} is the total acquisition time. In all cases, N_{eff} exceeded 6,000, thus satisfying the criteria discussed in the previous section and reported in table 1). While such record lengths are common in single-point techniques such as HWA and LDA, they remain uncommon for multi-point, image-based measurements such as PIV due to camera on board memory constraints and computational effort.

The importance of large sample counts is illustrated in Fig. 3, where each grey line represents the streamwise velocity variance $\langle uu \rangle$ computed over a time interval of 0.23 s, corresponding to 25 638 images and $N_{\text{eff}} = 15.5$. It is interesting to note that the statistical dispersion is fairly uniform across from the inner-peak to the overlap region. This can be explained by the fact that while the turbulent intensity is much larger in the inner region, the integral time scales tend to increase away from the wall, where in fact a significant scatter is observed for these short acquisition bursts. The large scatter among these short records emphasizes the need for long acquisitions to obtain converged near-wall fluctuation statistics.

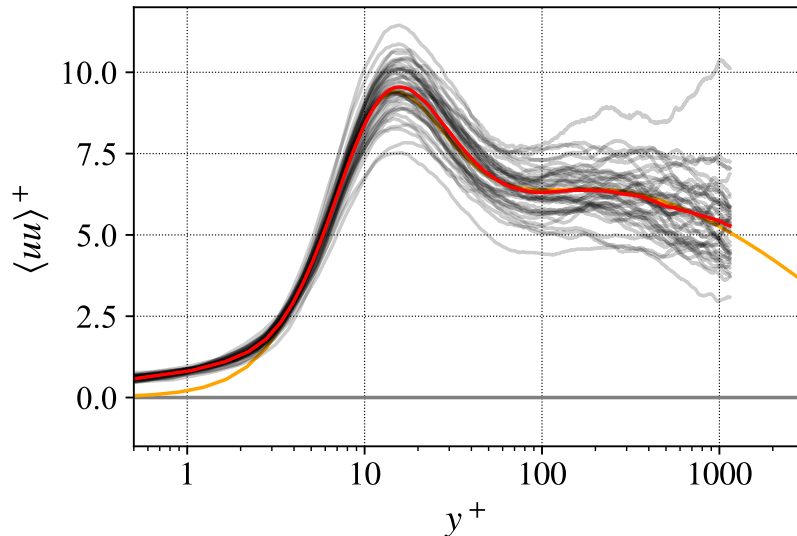


Figure 3. Example of statistical scatter in short-duration runs. Profiles of the streamwise velocity variance $\langle uu \rangle$ for 42 image sequences, each with a duration of 0.23s at $U_{cl} = 30$ m/s and $Re_\tau = 27700$.

Figure 4 illustrates the imaging conditions at the highest Reynolds number, ($Re_\tau = 45000$) and ($U_{cl} = 50$ m/s), where light scattering at the glass wall is particularly severe. Since the flare pattern varies both between consecutive frames and over longer times, a moving-average background was subtracted from each image. This pre-processing strongly reduced wall reflections and improved particle visibility in the near-wall region, as shown in Fig. 4c.

The preprocessed images were then analysed using a coarse-to-fine iterative cross-correlation algorithm in PIVview v.4.0 (PIVTEC GmbH). The final interrogation window was 32×6 pixels, corresponding to approximately $300 \mu\text{m}$ in x and $55 \mu\text{m}$ in y . The resulting velocity records showed only mild pixel-locking artefacts, as reported in Fig. 5.

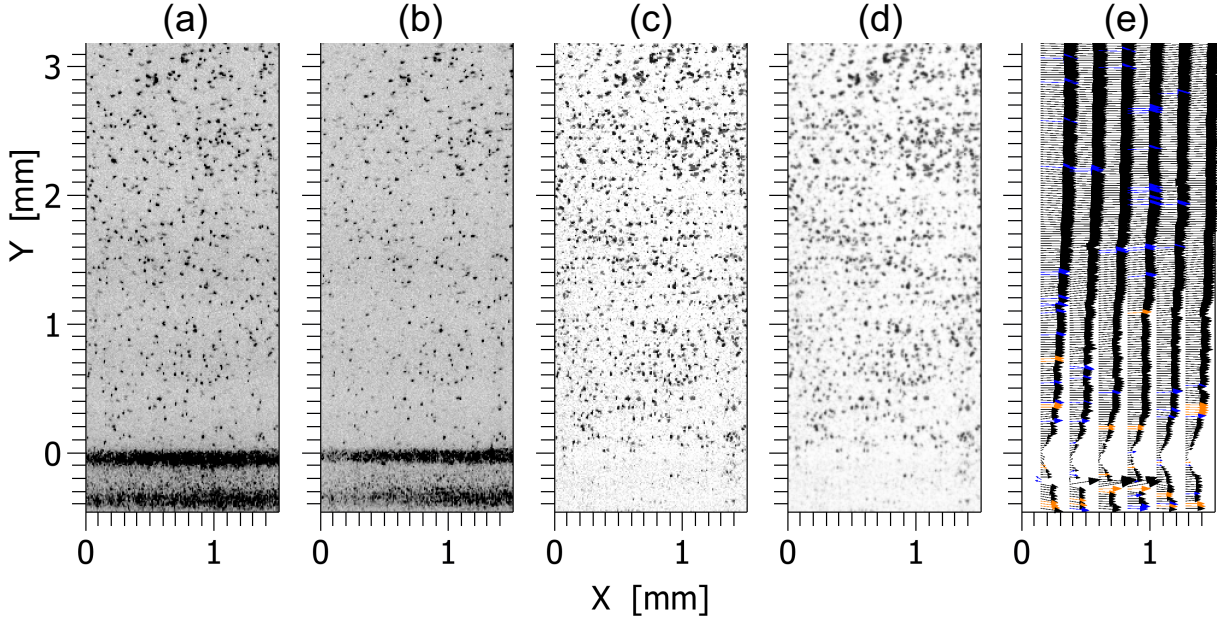


Figure 4. Near-wall detail of image pair (a,b) of 160 pixel width acquired at $U_{cl} = 50 \text{ m/s}$ ($Re_\tau = 44,700$), after background removal (c), low-pass filtering (d) and the measured displacement profiles retrieved for each image pair (e). Blue vectors are 2nd choice estimates, orange are interpolated outlier vectors.

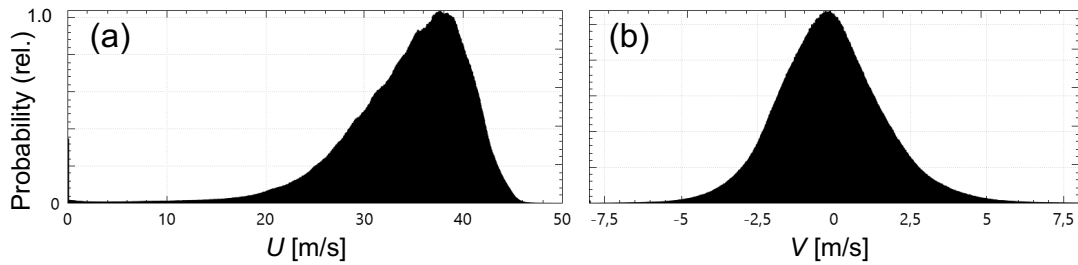


Figure 5. Probability distribution for both velocity components U, V at $U_{cl} = 50 \text{ m/s}$ obtained from 42 velocity records of 0.5s duration each (5.3×10^8 samples).

3. Results

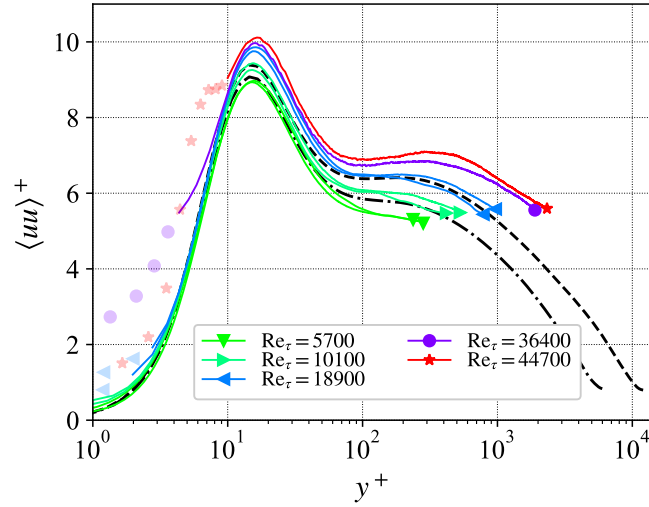


Figure 6. Profiles of the streamwise velocity variance $\langle uu \rangle^+$ for all investigated Reynolds numbers in viscous scaling. Faded symbols are represent under-resolved data points near the wall. Dashed/dotted lines indicates DNS prediction of turbulent pipe flow at $Re = 6000$ (---) and $Re = 12000$ (---) by Pirozzoli (2024).

The quality and convergence of the present measurements are first assessed in terms of the second-order velocity statistics. Figure 6 shows the streamwise velocity variance profiles, $\langle uu \rangle^+$, for the investigated Reynolds-number range. The profiles exhibit the expected near-wall inner peak at $y^+ \approx 15$, followed by a gradual decrease towards the logarithmic and outer regions. At the lower Reynolds numbers, the present data are in good agreement with available DNS profiles, supporting the reliability of the measurement and processing approach in the range where numerical reference data are available.

As Re_τ increases, the inner peak of $\langle uu \rangle^+$ increases systematically, while the outer part of the profile develops a broader region of elevated variance. The faded symbols in Fig. 6 identify data points affected by insufficient spatial resolution, mostly in the immediate vicinity of the wall. These points are therefore excluded from the quantitative interpretation of the near-wall peak. Apart from these biased points, the profiles show a consistent Reynolds-number trend and confirm that the present measurements capture both the inner peak and the beginning of the logarithmic region over an unprecedentedly broad Reynolds-number range for image-based velocimetry.

The Reynolds-number dependence of the maximum streamwise variance is summarized in Fig. 6. The present data extend the available experimental evidence at CICLoPE to the highest Reynolds number considered here and follow the increasing trend observed in lower-Reynolds-number DNS and in corrected hot-wire measurements. Within the present range, the data are more consistent with a logarithmic growth of the inner peak than with a slow saturation as predicted by asymptotic

theories based on bounded dissipation and/or asymptotic expansions ((Chen & Sreenivasan, 2025; Monkewitz & Nagib, 2015)).

The logarithmic function that best fits the present experimental data is:

$$u_{peak}^{\prime 2} = 0.63 \log(\text{Re}_\tau) + 3.5 \quad (2)$$

This expression follow very closely the $u_{peak}^{\prime 2} = 0.63 \log(\text{Re}_\tau) + 3.8$ law proposed by Marusic et al. (2017). This observation supports the interpretation of the near-wall peak as being increasingly influenced by large-scale motions at high Reynolds number, in line with attached-eddy-based descriptions of wall turbulence. However, because the highest-Reynolds-number case is the most demanding in terms of spatial resolution, this conclusion should be regarded as preliminary until the remaining resolution effects are further quantified.

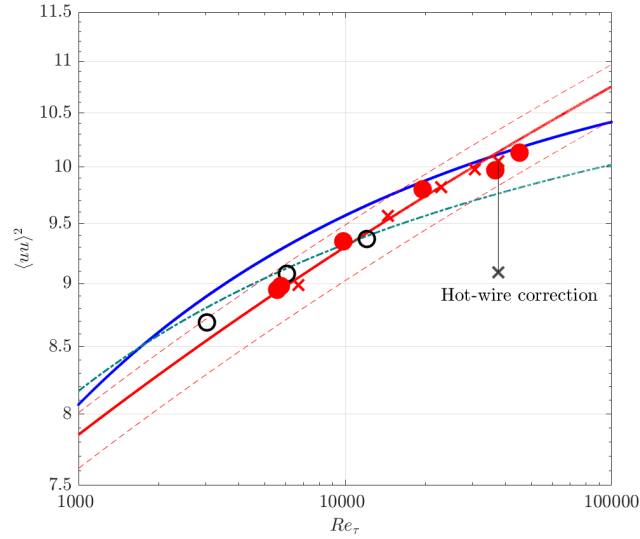


Figure 7. Reynolds number dependence of the maximum streamwise variance $\langle uu \rangle$ for all investigated Reynolds numbers. Red filled circles are the present measurements. Open circles are from DNS of pipe flows by Pirozzoli (2024). The crosses are the hot-wire measurements from Fiorini (2011) with spatial resolution corrections obtained with $L^+ \leq 21$. Solid blue line according to prediction by Chen & Sreenivasan (2025). Dashed-dotted line show the asymptotic prediction by Monkewitz & Nagib (2015). The solid red line is the logarithmic best fit from all experimental data from the Long Pipe $u_{peak}^{\prime 2} = 0.63 \log(\text{Re}_\tau) + 3.5$, while the dashed line represent the $\pm 2\%$ deviation.

3.1. Spatial-resolution effects

With increasing flow velocity the viscous scale reduces such that the finite size of the PIV sample size introduces spatial averaging effects.

This is particularly noticeable at the highest Reynolds number, $\text{Re}_\tau = 44\,700$, for which the stream-wise velocity variance $\langle uu \rangle$ is plotted in Fig. 8 (Right). At this Reynolds number the viscous scale

matches the pixel scale such that a 6-pixel high sampling window results in a noticeable underestimation of the inner peak at $y^+ \approx 15$. Three processing configurations are compared, with effective window sizes ranging from $30x^+ \times 2.8y^+$ to $45x^+ \times 5.6y^+$. Spatial filtering effects proportional to interrogation window size are well documented in the literature (Segalini et al., 2014), however, there is little or no quantitative data for wall-bounded turbulence in this Reynolds number range.

A similar behaviour is observed in high-resolution hot-wire measurements made in the same facility (Fiorini, 2011). These are shown in Fig. 8 (Right). The measurements at $Re_\phi = 38,000$ are obtained with a hot-wire length of $250 \mu\text{m}$, corresponding to $L^+ = 21$, a value comparable to the length of the PIV IA. The figure shows that the measured variance is significantly attenuated ($\approx 10\%$) at the inner peak when compared to the value corrected with the approach proposed by Smits et al. (2011), contradicting the classic accepted limit of $L^+ = 20$ to avoid spatial filtering. This seems to be the case also for image-based measurements when the sampling volume is anisotropic and when gradients are strong in both the wall-normal and streamwise directions.

The sensitivity observed in Fig. 8 is important for the interpretation of high-Reynolds-number PIV measurements. In the present data, the smallest interrogation window provides the highest estimate of the inner peak and the least attenuated profile, suggesting that the remaining spatial-resolution bias is limited but still non-negligible at the highest Reynolds number. Furthermore, both figures show an attenuation of the variance due to insufficient resolution in a region extending well beyond the buffer region, up to $y^+ 300\text{-}400$. This imposes some caution in interpreting "maxima" of the inner-scaled streamwise variance as they might be an artifact introduced by insufficient resolution.

The present PIV measurements allow to access with unprecedented detail the wall-normal velocity variance, $\langle vv \rangle^+$, and the Reynolds shear stress, $-\langle uv \rangle^+$, for the same Reynolds-number range, as shown in Fig. 9. Both quantities show the expected increase from the wall towards the logarithmic region and approach values consistent with DNS trends where reference data are available. The wall-normal variance reaches a broad plateau of approximately constant magnitude, while the Reynolds shear stress approaches values close to unity over an extended wall-normal range, as expected for a fully developed turbulent pipe flow away from the viscous sublayer.

The highest-Reynolds-number profiles show a delayed rise in the near-wall region compared with the lower-Reynolds-number cases. This behaviour is consistent with the increased sensitivity to spatial resolution already observed for $\langle uu \rangle^+$. Nevertheless, the overall shape and magnitude of both $\langle vv \rangle^+$ and $-\langle uv \rangle^+$ remain physically consistent, indicating that the measurement provides meaningful multi-component turbulence statistics up to $Re_\tau \simeq 45,000$. In particular, the simultaneous availability of $\langle uu \rangle^+$, $\langle vv \rangle^+$, and $-\langle uv \rangle^+$ represents a significant extension with respect to single-component hot-wire measurements in the same Reynolds-number range.

However, the noticeable effects on the highest Reynolds number case corroborates the view that the peak of the variance for this higher Reynolds number case might still be underestimated.

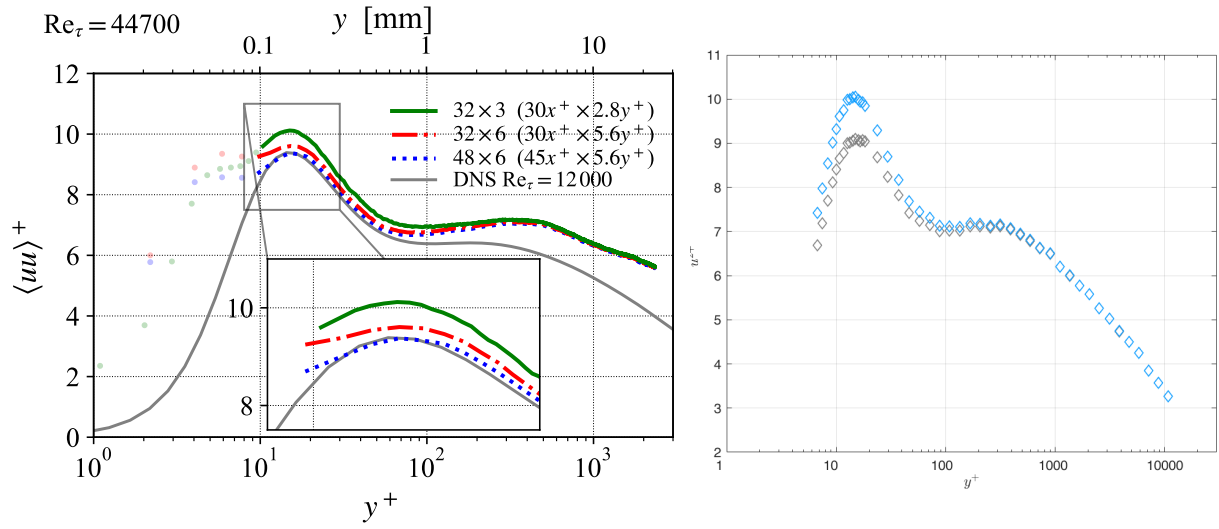


Figure 8. Left: Effect of PIV sampling window size on the streamwise velocity variance $\langle uu \rangle$ at $U_{cl} = 50$ m/s ($Re_\tau = 44700$) obtained from 21 velocity records of 0.5 s duration. Right: $\langle uu \rangle$ measured by Hot-wire at $Re_\phi = 38.000$ and $L^+ = 21$. The Black diamonds show the uncorrected values, the blue ones values corrected for spatial resolution effects.

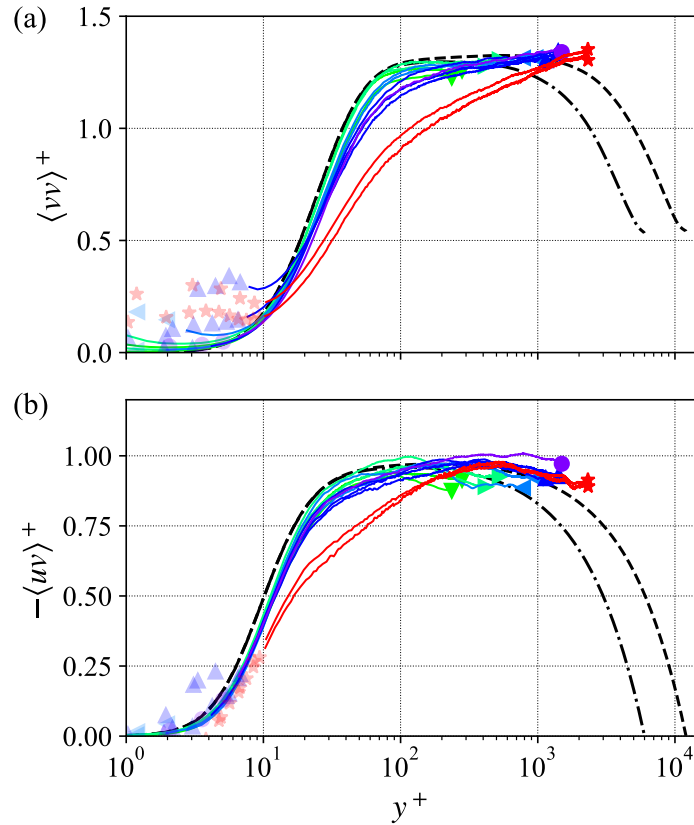


Figure 9. Profiles of the wall-normal velocity variance $\langle vv \rangle$ (a) and Reynolds shear stress $\langle uv \rangle$ (b). Color-coding and symbols corresponding to Fig. 6. Dashed/dotted lines indicates DNS prediction of turbulent pipe flow at $Re = 6000$ (—) and $Re = 12000$ (---) by Pirozzoli (2024).

3.2. Potential of 2D Shake-the-Box processing

A further assessment of the processing strategy is provided in Fig. 10, where conventional cross-correlation processing is compared with data gained by applying a two-dimensional version of the Shake-the-Box method (Schanz et al., 2016) at $Re_\tau \simeq 27,000$.

The comparison indicates that the Lagrangian particle-tracking approach has the potential to increase the effective spatial resolution of the measurement while preserving the statistical trends obtained with the standard PIV processing. This is particularly relevant near the wall, where the smallest dynamically important scales are comparable to the optical resolution of the present setup.

The preliminary Shake-the-Box results suggest that part of the spatial-filtering effect observed in the cross-correlation data can be reduced by exploiting individual particle trajectories (as argued (Kähler et al., 2012)). This is expected to improve the estimate of the inner peak of $\langle uu \rangle^+$, as well as the near-wall behaviour of $\langle vv \rangle^+$ and $-\langle uv \rangle^+$. The complete processing of the dataset with this approach will therefore be an important step to further quantify the residual resolution effects and to strengthen the interpretation of the Reynolds-number scaling of the near-wall turbulence statistics.

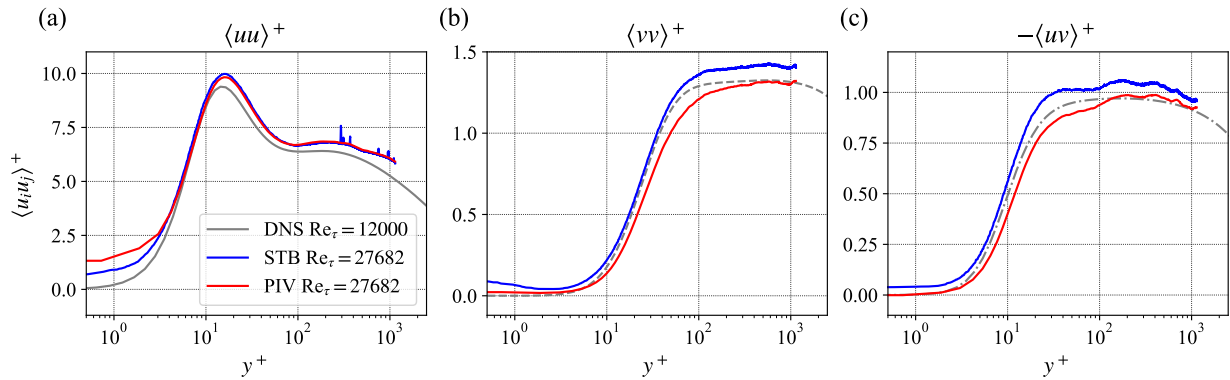


Figure 10. velocity variances determined at $Re_\tau = 27\,000$ using cross-correlation processing (red) and 2D-STB (blue); DNS (gray) by Pirozzoli (2024); (a) variance of the streamwise component u , (b) wall-normal velocity variance, (c) Reynolds shear stress of $\langle uv \rangle$.

4. Conclusions and outlook

High-speed, high-magnification profile PIV measurements were performed in the CICLoPE Long Pipe facility over the range $5,500 \leq Re_\tau < 45,500$. The measurements were designed to address the main experimental requirements of high-Reynolds-number near-wall turbulence: sub-viscous wall-normal resolution, sufficiently high temporal resolution, and long acquisition records for statistical convergence. The resulting dataset provides simultaneous two-component velocity infor-

mation in a Reynolds-number range previously accessible mainly through single-point techniques such as hot-wire anemometry.

The measured streamwise velocity variance profiles show the expected near-wall inner peak and a systematic increase of its magnitude with Reynolds number. At the lower Reynolds numbers, the profiles are consistent with available DNS data, while at the highest Reynolds numbers they extend previous experimental evidence from CICLoPE. The observed trend of the inner peak is compatible with a slow, approximately logarithmic growth with Re_τ , in agreement with attached-eddy-based interpretations of high-Reynolds-number wall turbulence. Conversely, the present data do not provide clear support for an early saturation of the inner peak within the investigated Reynolds-number range.

The analysis also shows that spatial resolution remains a critical issue at the largest Reynolds numbers. The comparison between different interrogation-window sizes indicates that spatial filtering can affect not only the immediate near-wall region but also part of the overlap region. For this reason, the highest-Reynolds-number results should still be interpreted with some caution. Nevertheless, the measured wall-normal variance and Reynolds shear stress exhibit physically consistent trends and demonstrate the capability of the present approach to provide multi-component turbulence statistics close to the wall.

Preliminary results obtained with two-dimensional Shake-the-Box processing indicate a promising route to further reduce spatial-filtering effects by exploiting individual particle trajectories. The complete processing of the dataset with this approach is expected to improve the effective spatial resolution and to provide a more robust assessment of the Reynolds-number scaling of the near-wall Reynolds stresses.

Overall, the present results demonstrate that high-speed, high-magnification PIV can provide statistically converged, multi-component measurements of near-wall turbulence at Reynolds numbers previously accessible mainly to single-point techniques. The data reproduce the expected structure of the Reynolds stresses, agree with lower-Reynolds-number DNS where comparison is possible, and extend the experimental trend of the streamwise variance inner peak towards $Re_\tau \simeq 45,000$. The availability of simultaneous, spatio-temporally resolved multi-component measurements will enable further analysis on fundamental quantities such as: scaling of mean gradients and turbulent productions, inner and outer spectral scaling, two-points multi-component correlations.

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