

On the spatial and temporal development of reverse flow- and high wall-shear stress events in ZPG-TBL

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Abstract

The 3D Lagrangian particle tracking method Shake-The-Box (STB) [1] and, subsequently, the data assimilation (DA) methods FlowFit3 [2] and a novel PINN implementation [3] have been applied to measure time-series of flow fields in a narrow wall-attached parallel volume of a zero-pressure-gradient (ZPG) turbulent boundary layer (TBL) at various Reynolds numbers. The measurement volume has an extension of ~ 60 mm along flow direction, up to 15 mm in spanwise- and 2 mm in wall-normal direction. The STB experiments have been conducted in the 1m-WT facility of DLR in Göttingen at relatively high particle image densities (~ 0.07 ppp) using μm -sized DEHS particles and high-repetition pulse lasers at up to 38.1 kHz. More details are given in [4]. Almost all features of the flow inside the viscous sub-, buffer- and lower logarithmic- layer in space and time at Reynolds numbers up to $Re_\theta = 5,455$ have been resolved. The gained data consists of long time-series of 3D velocity, acceleration and pressure fields given by FlowFit3 (see Figure 1, 5 and 6) and short time series of high-resolution PINN data assimilation (see Figure 7 and 8), as well as a huge amount of long Lagrangian particle trajectories. Selecting the viscous sublayer part of the measurement volume provides time-series of the 2D distributions of both components of the instantaneous wall-shear stresses $\tau_{u,w}$. Extreme events of high positive- and of rare negative wall-shear stresses are selected to understand the multi-scale-interaction of their spatial and temporal development and the small scale local topologies of vortical- and streaky structures responsible for such intermittent events in the near-wall region.

1. Introduction

The role of coherent flow structures of various wave-numbers during the interaction of high Reynolds number turbulent boundary layer flows with the wall and their contribution to the formation and dynamics of the instantaneous wall-shear stress fields is not fully understood yet. For example, local back-flow close to the wall and thus negative wall-shear stress- and on the other side very high positive wall-shear stress events are rare phenomena in ZPG-TBL. The outer layer consists of long, meandering high- and low-speed structures, so called very large-scale motions (VLSM). Several studies have shown that the near-wall flow is modulated under the footprints of such VLSM in the outer layer [7][8][10]. The VLSM, either negative or positive streamwise elongated u' -streaks, extend in y -direction down to the wall, leaving large-scale imprints on the higher frequency velocity fluctuations close to the wall. While rare back-flow events are locally often caused by spanwise (inclined) vorticity [5][6][7] with a relatively high flow velocity on top of the responsible vortex they are generally located more often in VLSM of negative u' -streaks (see [8] and time-series of measured LPT velocities $y^+ < 3$ in Fig 2). On the other side, we will

show in our present contribution that very high-wall shear stress events are often organized in large-scale wave package-like form with repeating clusters of strong vortical and turbulent movements (like “turbulent spots” inside the TBL), which in general are appearing more often within VLSM of meandering positive u' -streaks, similar to the analyses of [10] based on DNS data.

However, so far only few experimental data are available for the investigation of reverse flow events [4][6][7], which up to now cannot support statistical *and* spatial and temporal highly resolved 3D insights into the involved flow structure dynamics and topologies, which might finally allow unfolding a more precise cause-and-effect chain of their multi-scale development and dynamics for Reynolds numbers beyond the capabilities of DNS. In contrast, very high positive wall-shear stress (τ_u) events contribute significantly to the viscous drag of moving vehicles due to corresponding strong instantaneous wall-normal velocity gradients close to the surface. These strong shear events induce the development of new hairpin-like vortical structures, which are important features of the so called near-wall cycle. Further on, depending on the strength and wall normal amplitude of the evolving local Q2 dynamics the stronger vortex heads can create upstream positive pressure gradients and thus might start the self-organization of hairpin-packages [9] which can grow further upwards while extending as well in spanwise directions until the boundary layer edge is reached [12]. The upper bulges of such packages can modulate the TNTI (turbulent non-turbulent interface) of the TBL (see Figure 9) and further induce a large-scale waviness of the entrainment dynamics [13], which can then influence again the VLSM and thus the near wall dynamics and so on. Overall, it is of great importance to enhance the understanding of the multi-scale dynamics of extreme τ_u and τ_w events, related sweep- (Q4) -streak interactions and ejections (Q2), both from a fundamental and an engineering point of view. With the full present data evaluation of all 10 (12) time-resolved STB runs per Reynolds number (see Table 1) with in total more than 600 m of flow convecting through the near wall measurement volume we will be able to provide statistics of the dynamics of extreme negative and positive τ_u and τ_w events for all four investigated moderate Reynolds numbers in the near future.

In our STB experiment in the 1mWT of DLR Göttingen the used DEHS particles had $\sim 1.5 \mu\text{m}$ diameter and Stokes numbers below $St \ll 0.1$, so that they can be considered as fluid elements in the investigated incompressible TBL flow. It is common knowledge that for all wall-bounded flows the mean skin-friction velocity u_τ is of eminent importance for scaling the boundary layer flow connected with attached eddies by viscous units, which allow collapsing the mean velocity and Reynolds stress profiles normal to the wall up to the outer logarithmic region of a TBL flow. In order to obtain the desired instantaneous friction velocity distribution u_τ and the two wall-shear-stress components $\tau_{u,w}$ and its mean and fluctuation values a local gradient estimation has to be calculated from the measured individual particle tracks in close proximity of the wall ($y^+ < 4$).

$$u_\tau = \sqrt{\frac{\tau_u}{\rho}} = \sqrt{\nu \frac{\partial u}{\partial y}}|_{y=0} \text{ with } \tau_u = \mu \frac{\partial u}{\partial y}|_{y=0}$$

The spanwise wall-shear stress component τ_w can be obtained in an analogue way by the wall-normal gradient of the w -component of each instantaneous particle velocity vector.

In the present work the resulting experimental LPT data and its data assimilations are used for time-resolved 3D analyses of coherent structures, specifically of sweep-streak and vortical interactions in the buffer layer leading to rare back flow [5][6][7][8][10] and very high wall-shear stress events [10][11]. The vortical topologies and rapid dynamics related to reverse flow- (see Figure 7, left-top to left-bottom) and to very high-wall shear stress events (see Fig 8) including the accompanied pressure and acceleration

fields will be one topic of this and future investigations. As these events are statistically rare the involved larger-scales of the surrounding flow features are taken into consideration in order to understand their intermittent nature at both outer branches of the u -fluctuation velocity PDF (see Figure 7, bottom-right), while the amplitudes and roles of accompanied wall-normal- and spanwise velocity and acceleration components will be analyzed as well. The available experimental data-set is much larger than what has been used for this preliminary investigation, which is based on two out of ten time-resolved STB runs of the $U_\infty = 15$ m/s case only (see Table 1).

U_∞ [m/s]	Re_τ	Re_θ	Viscous unit μm	Acquisition freq [kHz]	Sensor size	Images per run	Number of runs
7.5	793	2306	48.1	18.0	2048 × 512	85,000	10
10	995	2997	37.0	23.9	2048 × 512	85,000	10
15	1352	4160	25.5	30.0	2048 × 400	115,000	12
20	1762	5455	19.5	38.1	2048 × 304	140,000	10

Table 1: Experimental test cases of ZPG-TBL measured by 3D STB in the 1m-WT of DLR Göttingen

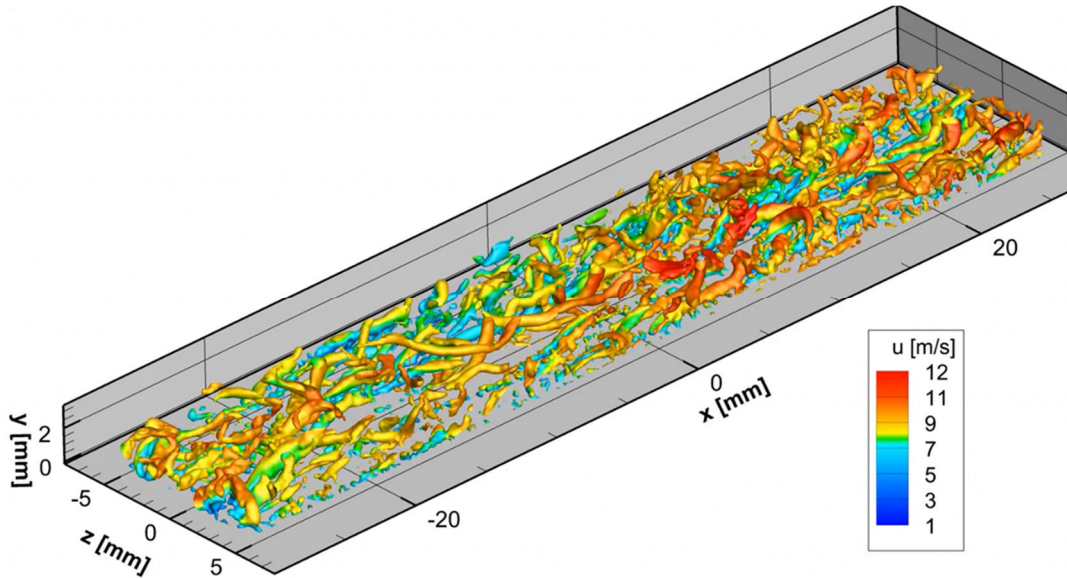


Figure 1: Snapshot of time-resolved vortical flow structures in the region between $0 < y^+ < 78$ by iso-surfaces of Q -value ($Q = 5,000,000/\text{s}^2$) color coded by u -velocity for $U_\infty = 15$ m/s at $Re_\theta = 4,160$ or $Re_\tau = 1,352$ from linear FlowFit3 data assimilation

2. Measuring extreme wall-shear stress events

A time-resolved and 3D measurement of the near-wall TBL flow including both instantaneous wall-shear stress distributions τ_u and τ_w requires an exact and simultaneous tracking of a large number of particle trajectories in the viscous sub- and buffer layer of a TBL flow. At relevant Reynolds numbers the viscous length scale l^+ is in the range of a few to tens of micrometers so that wall position and vibration corrections should be reconstructed in the range of less than a micrometer in order to estimate quantities for the small derivative step in y -direction with low uncertainty (see details in [4]).

In Figure 2 top and bottom a time series and a zoom-in of the detected numbers of particles below and above indicated u -velocity thresholds within the first $0 < y < 70 \mu\text{m}$ or $y^+ < 3$ above the wall are shown for one run (out of 10) with 115,000 time steps á $33 \mu\text{s}$ or a total $T = 3.795$ sec of TBL flow at $U_\infty = 15$

m/s or $Re_\tau = 1,352$, which corresponds to ~ 60 eddy turnover times Tu_τ / δ . It can be clearly seen, that extended time periods with very low-velocities at $y^+ < 3$ are alternating with wave package-like formations of quasi-periodic multiple events of very high wall-shear stresses which are convecting through the measurement volume. The long meandering nature of elongated positive and negative u' -velocity streaks of VLSM can cause these extended regions of low- and high shear velocities close to the wall. A wave package like shape of alternating or quasi-periodic events of high positive and low wall shear stresses detected over time in the near wall region of our measurement volume requires a closer look. The meandering feature of the VLSM can deliver a good explanation for this behavior, as the periods of extended low velocity regions close to the wall seems to produce similar oscillations as the higher velocity regimes. But that the VLSM of extended positive u' -velocity periods seem to create a type of wave-packet of clusters with increasing and reducing amplitude of high wall-shear stress events (see Figure 2 -bottom) might need further investigations.

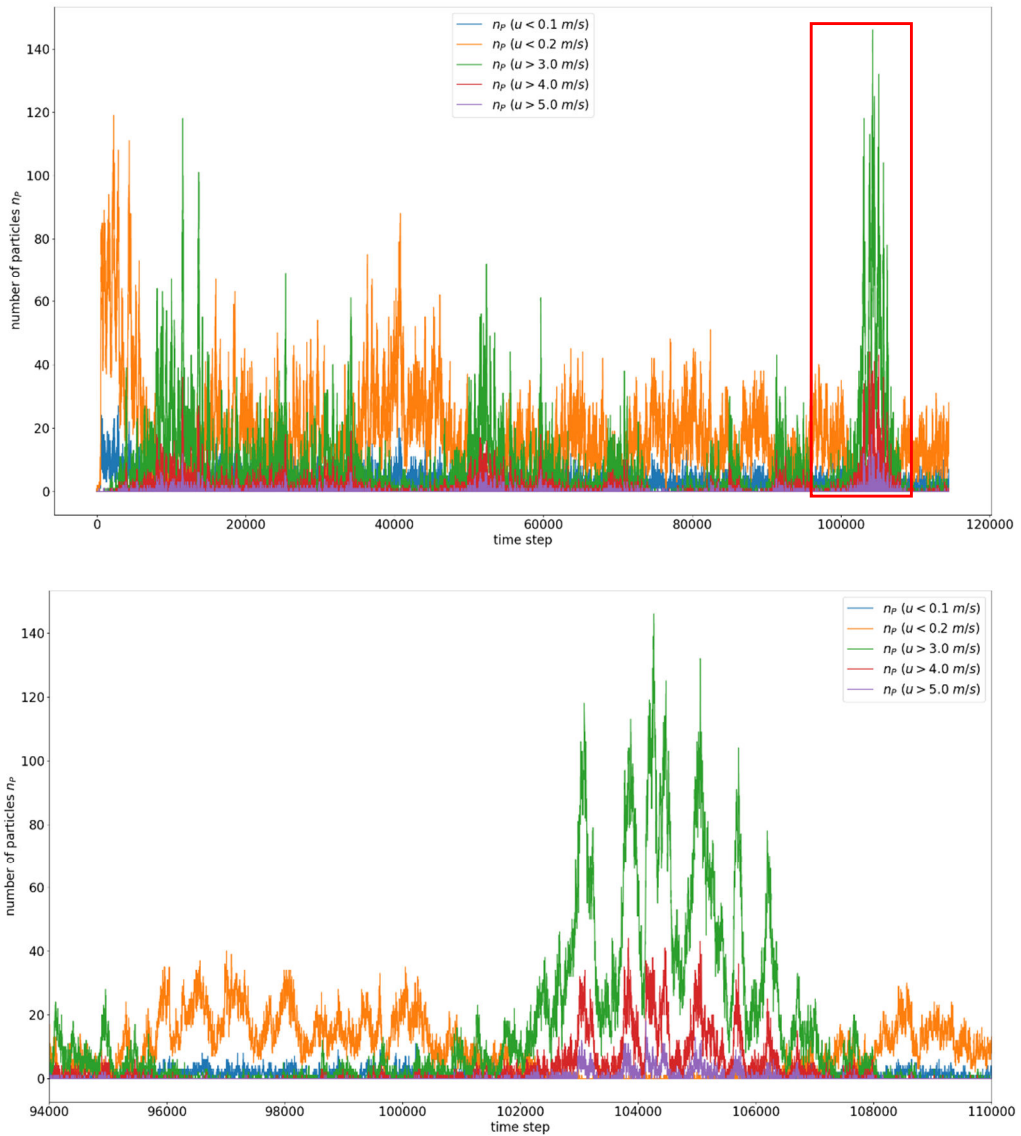


Figure 2: Time series of number of high and very low u -velocities of particle tracks larger than $u = [3.0 \text{ (green); } 4.0 \text{ (red), } 5.0 \text{ (purple)}] \text{ m/s}$ and smaller than $u = [0.2 \text{ (orange); } 0.1 \text{ (blue)}] \text{ m/s}$ below $70 \mu\text{m}$ or $y^+ < 3$ above the wall in the measurement domain of $60 \text{ mm} \times 12 \text{ mm}$ in x – and z - directions of one full run (top) and temporal “zoom-in” into the last “wave package” of high u - velocity events in the viscous sublayer or corresponding high wall-shear stress events (bottom). One time-step = $33 \mu\text{s}$.

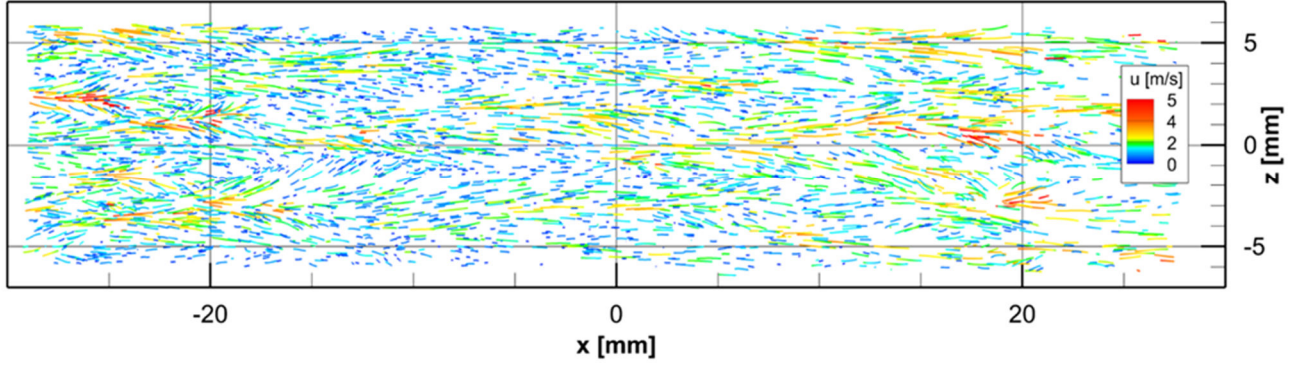


Figure 3: Instantaneous particle tracks (20-time-steps) color coded by u -velocity in a $115 \mu\text{m}$ sliced volume between $0 < y^+ < 4.5$ for $U^\infty = 15 \text{ m/s}$ at $\text{Re}_0 = 4,160$.

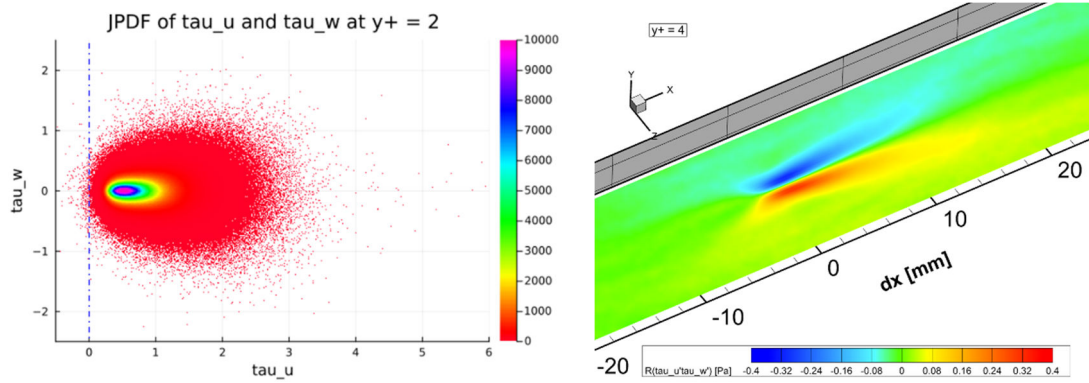


Figure 4: Normalized joint PDF scatter plot of τ_u and τ_w based on velocities of particle tracks measured in a thin slice around $y^+ = 2$ showing rare backflow and high τ_u in conjunction with high τ_w -events (left) and two-point correlation function of τ_u and τ_w at $y^+ = 4$ with an elongated shape in x -directions indicating the role of streamwise vortices for the τ_u wall-shear stress distributions (right)

Using each individual Lagrangian particle track of our STB evaluation in the viscous sublayer $y^+ < 4.5$ (see Figure 3), which is optimally filtered using the TrackFit approach [14] in order to calculate their local velocities and accelerations as first and second derivatives of a weighted 3rd order temporal B-spline, delivers a huge data set (approximately 1.5×10^8 track velocities per run within $y^+ < 4.5$) as input for single- and two-point statistics with a high-spatial resolutions of the corresponding statistical properties of e.g. τ_u and τ_w . The JPDF in Fig. 4 of τ_u and τ_w shows a high likelihood of joint high spanwise-wall-shear stresses with high streamwise τ_u events. The central part of the joint PDF around the mean values is elongated in x -direction resembling the streaky u' -pattern of the near wall u -velocity field. At the mean τ_u position of the JPDF the values are often accompanied by small τ_w values indicating a low spanwise exchange of the near-wall streaks. Left of $\tau_u = 0$ very few negative values can be found in the JPDF scatter plot. For these rare backflow events small probabilities of joint large τ_w can be seen, which indicate that local backflow is mainly driven by spanwise and less by streamwise vorticity. The two-point correlations of the two measures in Fig 4 (right) are indicating a high likelihood of neighboring symmetric positive- and negative spanwise wall-shear stresses τ_w each pointing towards the centerline in case of a streamwise positive wall-shear stress event at dx and $dz = 0$ (or very rare for $\tau_u < 0$ as well vice versa). The elongated downstream form of significant correlation values of spanwise wall-shear stress τ_w can be attributed to extended counter-rotating streamwise vortices which transport high-momentum positive u' fluid towards the wall producing a positive τ_u event in the mean sense.

3. Large-scale modulation of the viscous sublayer velocity by VLMS

In order to highlight the difference of the two mentioned regimes visible in the time-traces of high- and low velocity events close to the wall in Figure 2 one can see the corresponding different degrees of vortex population in the four subsequent FlowFit data assimilations with $100\ \mu\text{s}$ time steps in-between each snapshot number by a wall parallel plane of color-coded u -velocities at $y^+ = 3$ together with Q -value iso-contours at $6,800,000\ 1/\text{s}^2$ in Figure 5 during convection of a VLMS with negative u' -velocity and in Figure 6 during convection of a VLMS with positive u' -velocity. The very large-scale modulation of the near wall u -velocity produces two different global shear-stress regimes (wrt to our measurement volume size) and corresponding local vorticity dynamics. As known from literature, VLMS of high- and low-speed streaks in the upper logarithmic region (“second peak” of $\langle u'u' \rangle$) can extend instantaneously over stream wise length of 15 to 20 times the boundary layer thickness (see [7] by Taylor expansion). Such large domains in all three dimensions have been already captured instantaneously in large-scale measurements using time-resolved 3D STB measurements of LED illuminated HFSB in a ZPG-TBL at slightly higher Reynolds numbers [15].

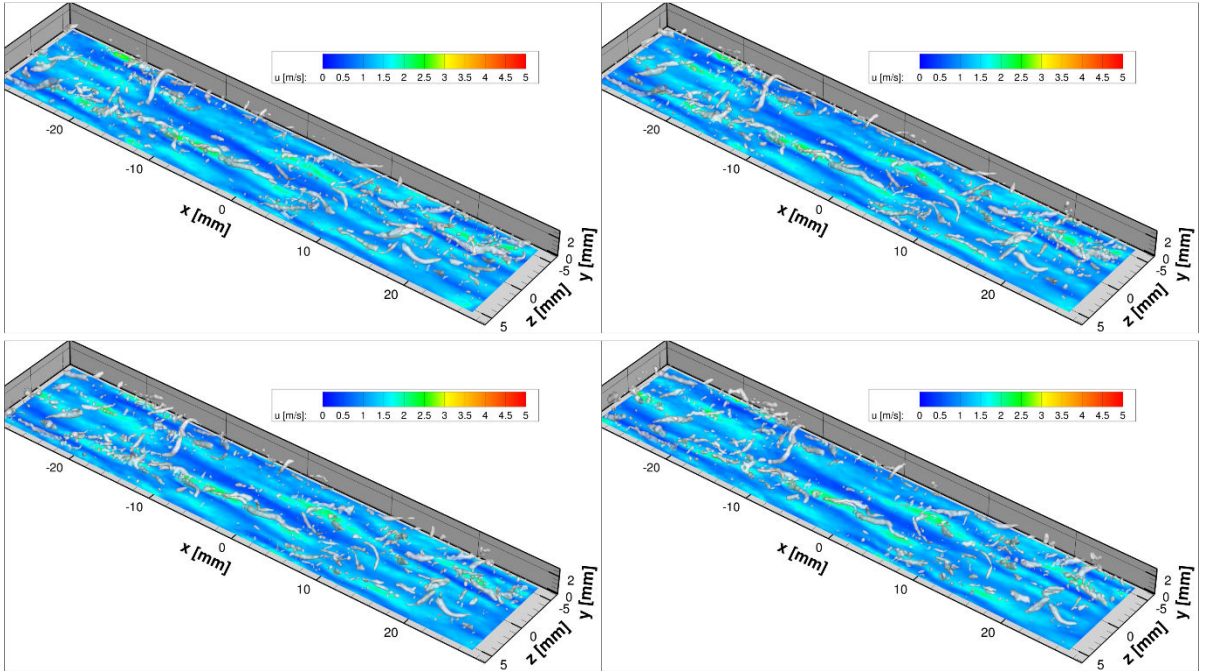


Figure 5: Time-series of snapshots of vortical flow structures inside a *VLMS negative u' streak* between $0 < y^+ < 78$ by 3D iso-surfaces of Q -value ($Q = 6,800,000/\text{s}^2$) and a plane at $y^+ = 3$ color coded by u -velocity at $Re_0 = 4,160$ from linear FlowFit3 data assimilation

Figure 5 shows a flow situation with a VLMS at negative u' -velocity where clearly the typical $\sim z^+ = 100$ distance streaky u' -velocity pattern of the near wall region is visible, but at relatively low overall velocities. The number and dynamics of the stream- and spanwise vortices indicated by grey surfaces of Q -iso-contours is low and the vortices move over the $300\ \mu\text{s}$ without significant changes confirming Taylor’s frozen turbulence hypothesis for such small time intervals even under this relatively high mean shear flow condition close to the wall.

When looking at Figure 6 near the wall of a VLMS at positive u' -velocities the flow situation has changed dramatically: The overall flow velocity at $y^+ = 3$ has increased by almost a factor of two and due to the increased shear stress a much higher population of vortices with higher amplitudes indicated by the same threshold Q -value of iso-contour surfaces as in Figure 4 can be clearly detected. Furthermore, the vortices undergo much more morphological changes and interactions during the shown $300\ \mu\text{s}$ time span as compared to Figure 4. The clusters of vortical dynamics result in many patches of very

high wall-shear stress events (orange to red color) inside the high-speed streaks of the typical $\sim z^+ = 100$ distance streamwise elongated near wall u' -velocity pattern, especially induced by strong streamwise meandering vortices. Over much longer time spans (shown by movies during the oral presentation) many individual clusters or spots of strong turbulence (more extended in stream- and spanwise directions than typical hairpin-packets [9]) are convecting through the measurement volume as indicated in the wave-packet form of Figure 2-bottom. The quasi periodic appearance of such strong “turbulent spots” inside the TBL flow might be explained by the waviness of boundary layer edge which is governing the entrainment dynamics as shown in Figure 9 and the sketch in Figure 10 [13]. Those might induce the meandering of VLSM, which can cause a similar picture. The corresponding scales in time- and space need to be further examined and compared to the elongated streaks of VLSM (see e.g. [7][15]) in further experimental investigations e.g. using embedded multi-scale 3D LPT at high Reynolds numbers.

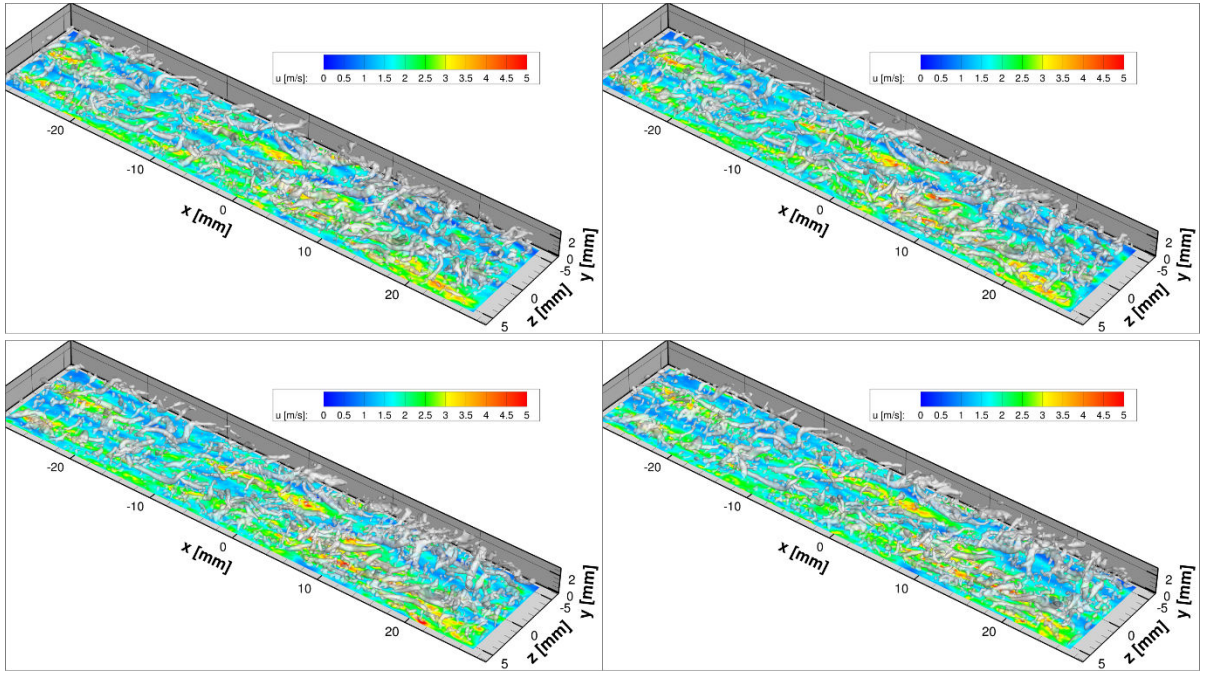


Figure 6: Time-series of snapshots of vortical flow structures inside a *VLSM positive u' streak* between $0 < y^+ < 78$ visualized by 3D iso-surfaces of Q -value ($Q = 6,800,000/s^2$) and a plane at $y^+ = 3$ color coded by u -velocity at $Re_\theta = 4,160$ from linear FlowFit3 data assimilation

4. Reverse flow event

Negative wall-shear stresses and reverse flow events are typically coincident in ZPG-TBL flows, because reverse flow happens with a very high probability in the first two viscous units of the TBL flow. Inside the viscous sublayer the related negative flow structure therefore immediately produces a footprint of a small region of negative τ_u values. In Figure 7 three subsequent time-steps ($\Delta t = 100 \mu s$) of the velocity fields are displayed, which are picked out of an advanced PINN data assimilation [3] result over 100 time steps before and after the local backflow event, which used the measured LPT data as training input. The PINN reconstruction provides a short time-resolved high resolution- and smooth representation of the velocity (and pressure) fields even in such high shear flow close to the wall. In Figure 7 it is nicely visible that the interaction of a relatively large spanwise vortex, which is slightly inclined in wall-normal direction, together in interaction with a streamwise vortex is governing the dynamics of the local backflow event indicated by blue color inside the $y^+ = 3$ plane showing color coded u -velocity contour fields. Downstream of this event the large spanwise vortex is guiding negative v and positive u' -fluid towards the wall creating a relatively strong wall-shear event, while upstream of it even

a second smaller backflow event under a follow-up spanwise vortex can be detected. A more general analyses of the temporal development of flow topologies involved in such near wall backflow events by using the present large experimental LPT data set as input for many short time series of PINN data assimilation by selecting the rare negative wall-shear events within all four measured Reynolds numbers is foreseen for a full journal publication .

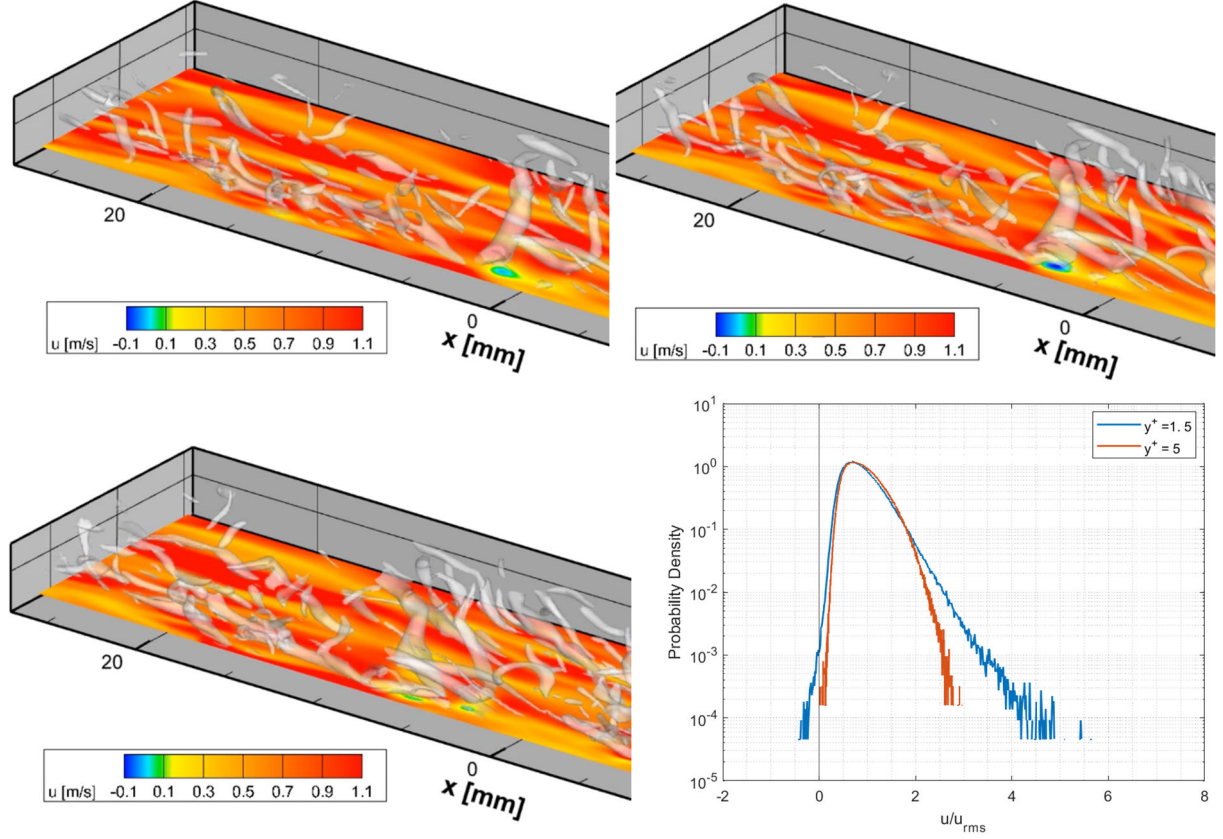


Figure 7: Three time-steps of the interaction of a larger spanwise with a streamwise vortex leading to reverse flow close to the wall indicated by blue color in a plane at $y^+ = 3$ calculated by PINN data assimilation with flow from *right to left* (top- to bottom left) and normalized PDF of the u -velocity from bin averaging at a mean wall distances of $y^+ = 1.5$ and $y^+ = 5$ (bottom-right). Negative and high positive values demonstrate intermittency of the PDF at both extreme branches, especially for $y^+ = 1.5$.

5. High positive wall-shear stress events

Very high wall-shear stresses are produced by local Q4- or sweep events often organized by clusters of stream- and spanwise vortices or highly “turbulent spots” within the TBL (see Figure 6) caused by VLSM areas of positive u' approaching the area in close vicinity of the wall (as indicated in Figure 2). The highly turbulent spots with packages of strong vortical interaction with the near-wall negative and positive u' -velocity streaks in the viscous sublayer are seemingly created by the overall strong shear induced by this VLSM induced large scale Q4- or sweep event, as the overall u -velocity at $y^+ = 3$ in our measurement domain is almost doubled during the presence of such a VLSM with positive u' -velocities. A further understanding of the repetition characteristics (see Figure 2) of these turbulent packets or spots convecting through the measurement domain requires a simultaneous knowledge of the dynamics of the larger flow scales up to the VLSM above and surrounding the wall. A model of these dynamics is already existent in the literature based on experimental and numerical investigations, but cannot directly link the involved temporal development of 3D flow structures and multi-scale momentum exchanges for sufficiently high Reynolds numbers yet. Nevertheless, a descriptive attempt is made later in this chapter.

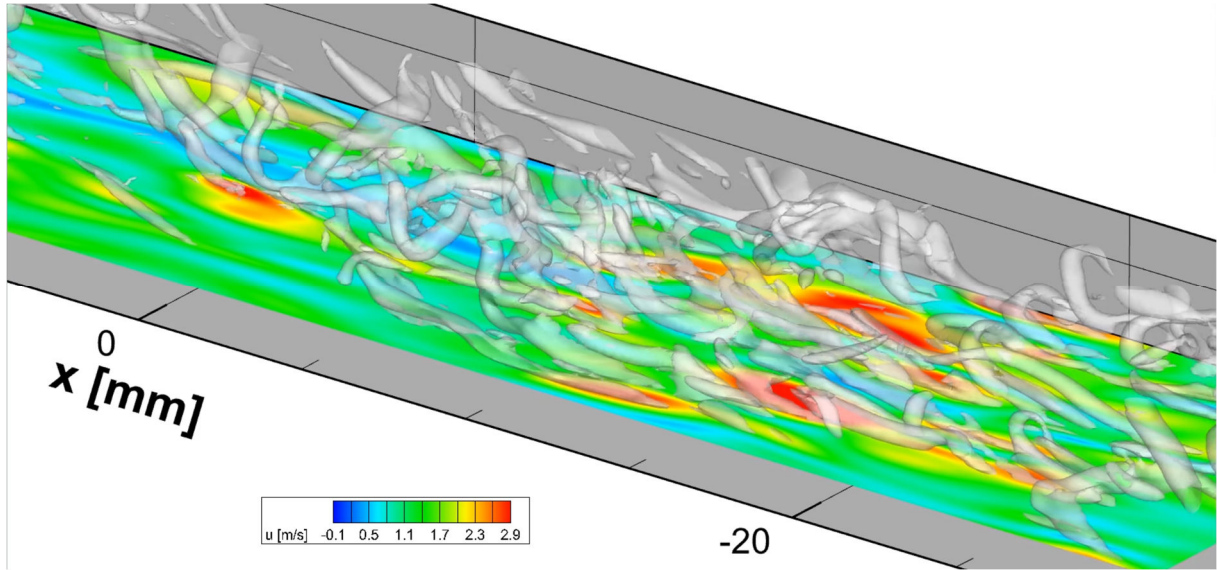


Figure 8: One time-steps of the interaction of a many streamwise and spanwise vortices leading to a streaky package of high positive wall-shear stresses indicated by red color (high u -velocity) in a plane at $y^+ = 3$ calculated by PINN data assimilation of experimental LPT tracks with flow from *right to left*

Instantaneous results of a large field Stereo PIV experiments in a ZPG-TBL [12] gained in another wind tunnel facility at DLR in Göttingen (SWG) are shown in Figure 9 at a Reynolds number based on the momentum loss thickness of about $Re_\theta = 10,000$ and $U = 15$ m/s. Figure 9 - top shows an instantaneous velocity field with color coded u -velocity component measured perpendicular to the flat plate (xy -plane). Axes metrics are based on viscous scaling. Cascade-shaped $\sim 45^\circ$ inclined coherent patterns of fluid with similar u -velocity values can be recognized. They vary in size and velocity in correspondence to their distance from the wall and their stages of growth. As a result, coherent patterns with slower- and faster streamwise velocities in higher wall distances overlap smaller coherent patterns with alternating faster- and slower convective velocities in direct vicinity of the wall. At the outer part of the TBL, large elevated bulges of lower velocities beyond the mean δ_{99} thickness are visible with velocities on their tops slightly higher than the freestream one. Furthermore, downstream and spanwise of these bulges (typically formed by very large hairpin-packets) negative v -velocity fields or sweep events (Fig. 9 - bottom) can be identified leading to large scale high u -velocity patterns closer to the wall inducing strong shear stresses at the wall.

This illustrates that slower low-momentum fluid from layers that are closer to the wall is transported upwards in such inclined hairpin-like structures whereas downstream (and spanwise) of such events fluid with higher streamwise velocities away from the wall is transferred towards the surface within large scale motions. A closer look at Fig. 9 - bottom shows the ramped-like fluid transport that is also visible in the v -velocity distribution. Upward motions with positive v along the inclination line are downstream followed by negative v velocities which indicate rotational movements. The motion of larger scale high momentum fluid towards the wall is creating a stronger vortical pattern (a spot of high turbulent motion) when approaching the surface due to induced shear instabilities. Strong positive wall-shear stress events are located in these regions (see Fig. 8). From a wall-fixed view enhanced turbulent motions are alternating with more quiescent regions (see Fig. 2 and compare Fig. 5 and 6).

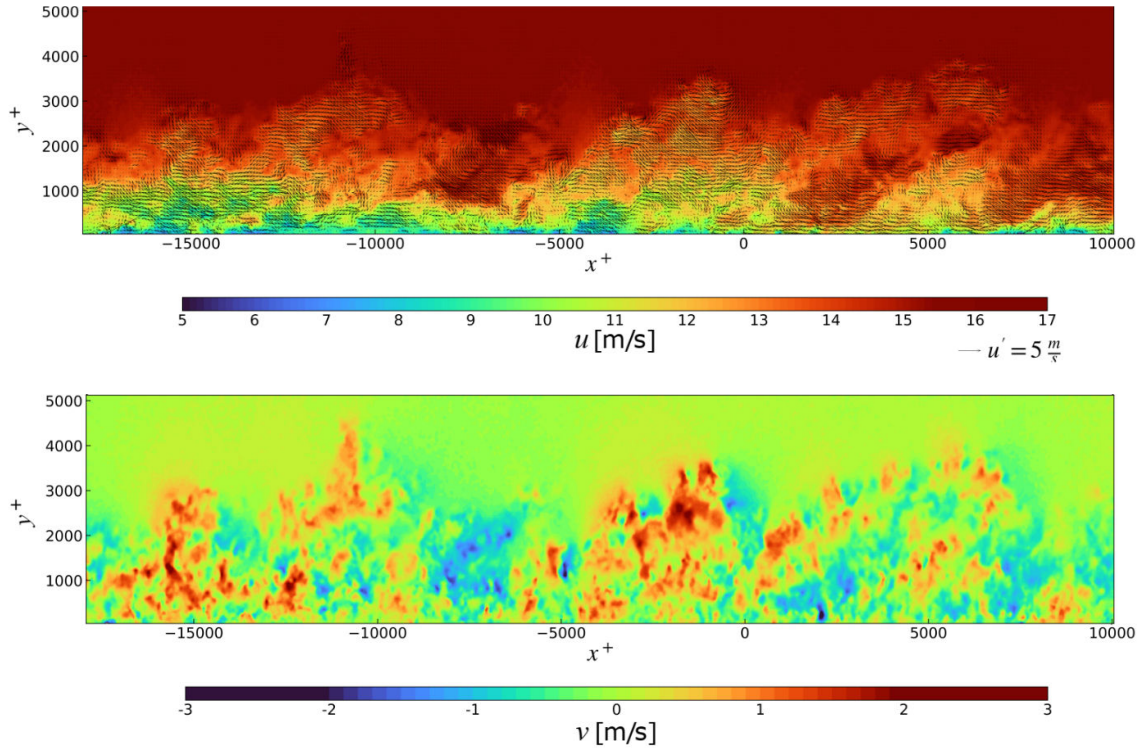


Figure 9: Large scale velocity structures in a $Re_0 = 10,000$ ZPG-TBL SPIV measurement at $U = 15$ m/s with u-component (top) and v-component (bottom) color coded (Voss, 2025). Waviness of TBL outer region and VLSM are visible with related (multi-scale) momentum transport away from and towards the wall

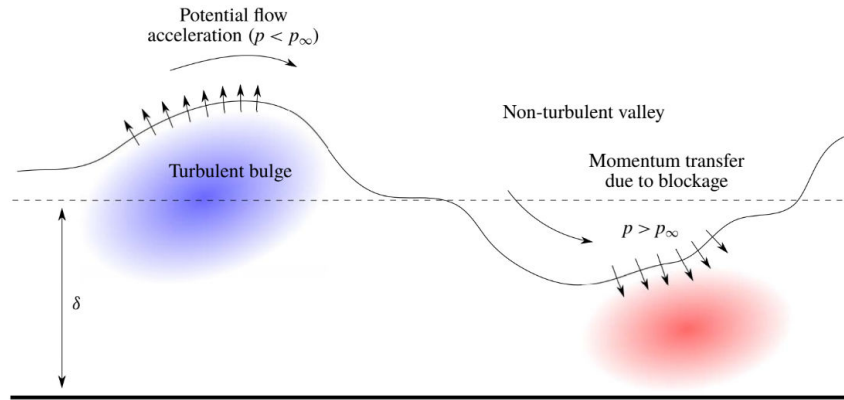


Figure 10: Large-scale dynamics of bulges of large-scale ejections and sweeps at the TNTI interface of a ZPG-TBL flow after *Reuther and Kähler (2020), JFM vol.897, Fig 4. [13]*

The large-scale dynamics governed by the TNTI as explained in the sketch of Figure 10, which is embedded in a theoretical context of experimental and numerical investigations over the past decades in [13] can explain one source of alternating large-scale regions of wall-shear stresses. Regarding the involved time-scales they can as well cause of the meandering of VLSM. Both effects together can lead to the shown time-traces of large-scale regions of lower- and higher wall-shear stresses in our restricted measurement volume close to the wall.

6. Conclusion

A time-resolved 3D Lagrangian Particle Tracking experiment at high particle image densities has been carried out at four moderate Reynolds numbers in the near wall region of ZPG -TBL flows in the 1-meter wind tunnel of DLR Göttingen delivering a huge data-set of densely distributed Lagrangian particle positions, velocities and accelerations. The particle trajectories in the near -wall volume have been reconstructed by the DLR own STB software applying a precise correction procedure of wall-vibrations (for details see [4]). Analyzing the time-series of a single run over 3.795 sec at $U_\infty = 15$ m/s by counting the number of tracer particles below and above certain thresholds indicate a large-scale variation of stronger- and weaker shear flow regions close to the wall, which is consistent with previous findings regarding the imprint of VLSM. We visualized and analyzed the local near wall flow dynamics in our measurement volume with respect to the presence of VLSM with corresponding large-scale negative u' - and large-scale positive u' -velocities, respectively in Figure 5 and 6. Two-point-correlations and (joint) PDFs of the two components of wall-shear stresses have been calculated and connected to the instantaneous visualizations of shear flow and vortical structures using FlowFit and PINN data assimilation. An individual backflow event (see Figure 7) and a cluster of very high wall-shear stress events (see Figure 8) together with their local spatial and temporal flow topologies have been visualized at high temporal and spatial resolution using PINN DA. The development of both rare events has been displayed by iso-contours of Q-values indicating vortices and a plane of color-coded u -velocity at $y^+ = 3$ and put in relation to the literature, especially towards the influence of (V)LSM in ZPG-TBL flows.

With the existing huge amount of time-resolved 3D velocity (gradient) field- and Lagrangian particle tracking data of the near-wall TBL flows at four different moderate Reynolds numbers several investigations of flow structure dynamics and Lagrangian particle statistics have been and will be performed in future work. Especially, an extensive investigations of the dynamics of rare reverse flow topologies and extreme positive wall-shear stress events in a spatial and temporal sense is foreseen.

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